

Cryodetector readout for direct dark matter searches

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Abstract

The next generation of cryodetector arrays for direct WIMP searches will aim to achieve large increases in WIMP-nucleon scattering target mass, an order of magnitude or more greater than existing detector arrays. The implementation of high-resolution measurements and background suppression by event discrimination will remain of paramount importance. Hardware development must be undertaken to increase the availability and density of readout channels while maintaining low-noise, low-heatload, high-radiopurity cryodetector performance. This thesis describes the development of scalable cryogenic cabling using etched metal foil fabrication techniques and the development of low-temperature high-voltage power supply for scintillation light readout using photomultiplier tubes.

Etched metal foil cables were developed for cryodetector readout. Fabrication techniques for low-heatload, low-cost cabling were developed and commissioning tests were carried out to verify low-noise performance in both low-impedance and high-impedance cryodetector readout schemes. SQUID readout cabling with a heatload cost 24 times lower than existing cabling was installed and mean SQUID noise of $5.5 \text{ pAHz}^{-\frac{1}{2}}$ was measured with low-impedance input.

Photomultiplier tubes can be used for cryogenic scintillation light measurement, a key technique in cryodetector event discrimination. A low-heatload, low-noise photomultiplier tube power supply circuit was developed. Measurements of cryogenic scintillation light from a CaWO_4 crystal were carried out using a CWG/PMT module cooled to 0.95 mK.

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Introduction

The Standard Model of particle physics has proved to be remarkably durable, providing a predictive theoretical framework for four decades of experimental discoveries. However, the astrophysical dark matter problem has evaded explanation using Standard Model particle physics. The presence of an almost inert background of stable, non-Standard-Model, relic particles has been advanced as an explanation for missing mass observed in astrophysical systems of widely ranging distance scales. The development of detector technologies to test this hypothesis, through direct detection of dark matter particles, presents a range of unique challenges which are met by novel innovations in hardware design.

Supersymmetry (SUSY), a theoretical extension to the Standard Model, can provide one or more stable, massive, weakly-interacting dark matter candidate particles, for which detection of low-energy nuclear recoils is a potential discovery channel. However, the low energies and event rates expected for this interaction make stringent sensitivity and background-rejection demands of detectors for direct dark matter searches. Cryogenic detector arrays, such as CRESST-II

and EDELWEISS-II, make use of high resolution sensors and novel discrimination techniques to meet these demands. The development of readout hardware to make high-sensitivity, stringent-discrimination detector technologies scalable and affordable for future large-scale dark matter searches is the focus of this thesis.

The observed evidence for the existence of dark matter, astrophysical inferences of dark matter candidate properties and the introduction of potential dark matter candidates are the subjects of Chapter 1.

In Chapter 2 the phenomenology of direct search experiments is described, leading to a discussion of detection strategies and introduction to the hardware design of cryodetector arrays for direct WIMP searches.

The provision of affordable, reliable cryogenic cabling is essential for the development of large cryodetector arrays. The development of etched metal foil cryodetector readout cabling was carried out and is described in Chapter 3. The specific design features developed for cryogenic cabling in a low-noise, low-heatload, high-radiopurity environment are described in detail. Fabrication, installation, testing and evaluation of etched metal foil cabling for both high-impedance and low-impedance cryodetector readout was carried out; the results of this work are discussed.

Detection of scintillation light at cryogenic temperatures is already established as a background discrimination technique, implemented using cryodetectors in the CRESST-II experiment. The application of high-sensitivity photomultiplier tubes

for cryodetector discrimination potentially offers improvements in sensitivity and reproducibility, but several practical issues must be resolved. The development of low-heatload, low-noise power supply for cryogenic photomultipliers is described in Chapter 4, together with results and evaluation of a cryogenic photomultiplier tube module tested for the first time at temperatures below 1 K.

Chapter 1

Dark matter

The term ‘dark matter’ is ascribed to the non-luminous mass observed in the behaviour of astrophysical systems over a very wide range of distance scales, from the rotation curves of galaxies to anisotropy of the cosmic microwave background (CMB). Dark matter is postulated to play a crucial role in the development of large-scale structure in the universe. In the 78 years since 1933 when Fritz Zwicky inferred the presence of missing mass in the rotation of the Coma galaxy cluster [1]¹, extensive research has attempted to place the missing matter observed in astrophysics within the canon of observed particle physics.

In this chapter I will introduce the evidence for dark matter observed in cosmology and astrophysics, the wide range of potential candidates for components of the dark matter, and the latest detection strategies for the class of candidate of particular relevance to this thesis: weakly-interacting massive particles (WIMPs).

¹See also [2].

1.1 Cosmological evidence for dark matter

Dark matter in the standard cosmological model

In the past 50 years the study of cosmology has seen the development of the quantitative standard cosmological model, providing a framework in which the ongoing development of the universe is parameterised and measured with increasing accuracy [3]. Observational data on CMB temperature, redshift-distance curves of type 1a supernovae, large scale structure and primordial element abundance have heralded an era of ‘precision cosmology’ in which the development of the universe is studied in tandem with particle physics, which describes its components. I will introduce aspects of the standard cosmological model in order to motivate experimental particle physics searches for dark matter candidates.

The Friedmann-Lemaître equations of motion (1.1) and (1.2) describe the relation between the Hubble parameter $H(t)$, the energy density ρ , and the isotropic pressure p of a universe measured using the relativistic Robertson-Walker metric.

$$H^2 \equiv \left(\frac{\dot{R}}{R} \right)^2 = \frac{8\pi G_N \rho}{3} - \frac{k}{R^2} + \frac{\Lambda}{3} \quad (1.1)$$

$$\frac{\ddot{R}}{R} = \frac{\Lambda}{3} - \frac{4\pi G_N}{3}(\rho + 3p) \quad (1.2)$$

G_N is the gravitational constant, Λ is the cosmological constant, representing a non-zero vacuum energy, and k is the curvature parameter of the Robertson-Walker metric. $k = 0$ corresponds to a geometrically flat universe, $k = 1$ corresponds to

a geometrically closed universe and $k = -1$ to a geometrically open (hyperbolic) universe.

The critical density ρ_c is defined as the energy density of a geometrically flat $k = 0$, zero vacuum energy $\Lambda = 0$ universe (1.3).

$$\rho_c = \frac{3H^2}{8\pi G_N} \quad (1.3)$$

Defining the relative density parameter as the ratio of the energy density to the critical density, we can rewrite (1.1) as (1.4) in which the total density of the universe is given by $\Omega_{tot} = \Omega_m + \Omega_r + \Omega_\Lambda$. Here Ω_m is the relative matter density, Ω_r is the relative density of relativistic particles and Ω_Λ is the ‘relative vacuum density’, defined $\Omega_\Lambda \equiv \Lambda/3H^2$.

$$\frac{k}{R^2} = H^2(\Omega_{tot} - 1) \quad (1.4)$$

The relativistic universe of the standard cosmological model is intrinsically dynamic; observed distance-redshift curves of type 1a supernovae [3] and measurements of CMB anisotropy [4] provide strong evidence that the universe is undergoing accelerating expansion while remaining very close to spatial flatness, that is to say $k \simeq 0$ and correspondingly $\Omega_{tot} \simeq 1$.

Inflation theory (see [5]) provides a mechanism for spatial flatness to arise from unstable conditions following the Big Bang by postulating a period of highly accelerated expansion during which $k \rightarrow 0$ and $\Omega_{tot} \rightarrow 1$. The density of the post-inflation universe approaches the critical density and is dominated by vac-

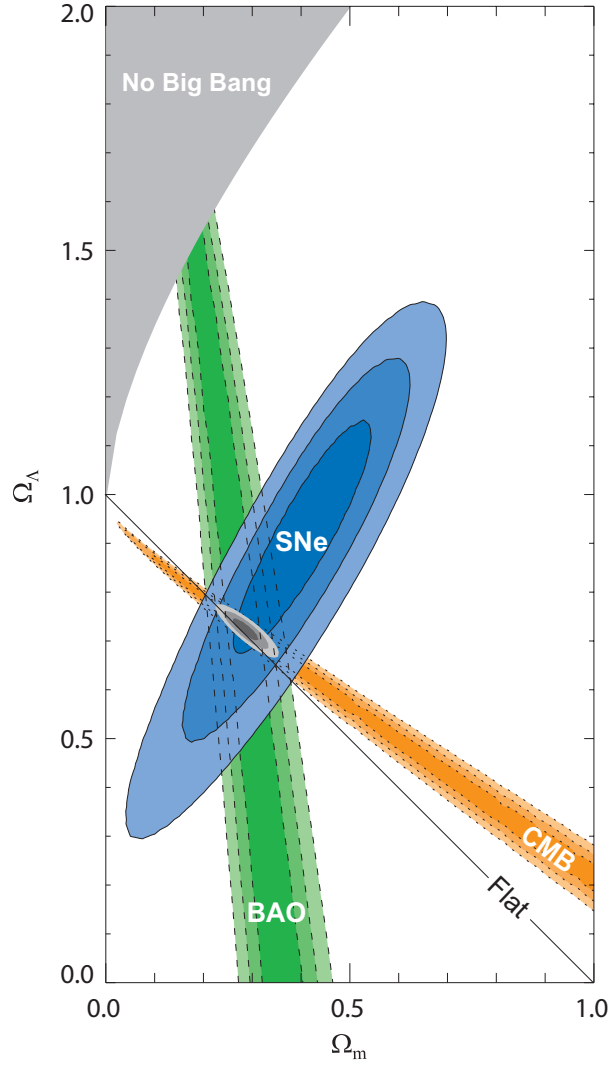


Figure 1.1: 68.3%, 95.4% and 99.7% confidence intervals in Ω_Λ - Ω_m parameter space obtained from CMB anisotropy, baryon acoustic oscillation and supernova redshift data (SNe) along with their combination (grey area). From [4].

uum energy Ω_Λ and non-relativistic matter Ω_m . This mechanism accords with observational evidence. Interpretation of data from supernova redshift data, the CMB temperature spectrum and baryon acoustic oscillations² fixes the current relative densities around $\Omega_{tot} \sim 1$, $\Omega_\Lambda \sim 0.7$ and $\Omega_m \sim 0.3$ [4] (see Figure 1.1).

CMB anisotropy

Measurements of anisotropy in CMB temperature and temperature-polarisation power spectra by the Wilkinson Microwave Anisotropy Probe (WMAP) give additional information on the composition of Ω_m , divided into baryonic matter Ω_b and non-baryonic dark matter Ω_{dm} . The position and magnitude of peaks and troughs in the temperature and temperature-polarisation correlation power spectra are sensitive to the baryonic fraction of the total matter density, due to the damping effects of baryonic and non-baryonic matter on the photons of the CMB around the time of last scattering. Current fits to the CMB power spectra constrain the density parameters; $0.9821 < \Omega_{tot} < 1.0081$, $\Omega_b = 0.0456 \pm 0.0015$, $\Omega_{dm} = 0.228 \pm 0.013$ and $\Omega_\Lambda = 0.726 \pm 0.015$ [6] (see Figure 1.2).

Big Bang nucleosynthesis

Subsequently to the Big Bang, the universe cooled to temperatures that are well understood within the Standard Model of particle physics, and the formation of

²The observation of three-dimensional structure over very large distances in the present universe allows the size of acoustic ripples in the baryon-dark matter system after CMB decoupling (known as *baryon acoustic oscillations*, BAO) to be reconstructed, giving information on the relative matter density.

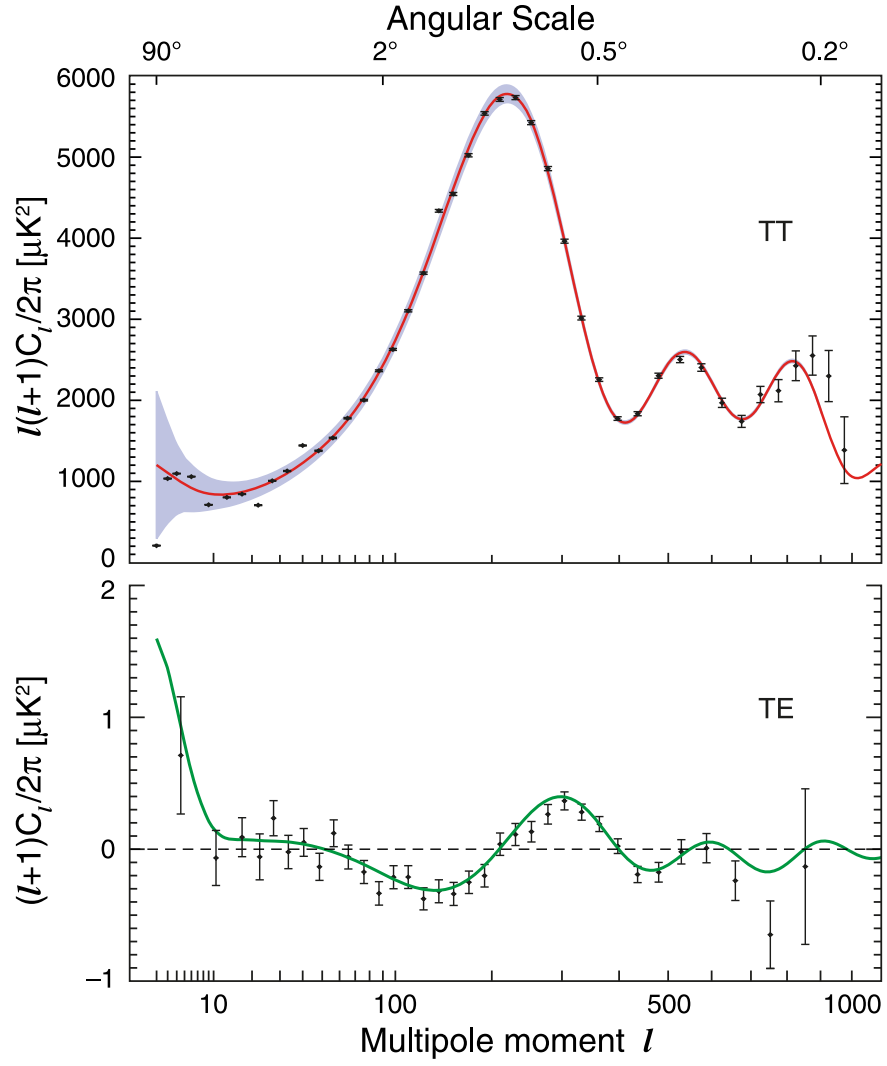


Figure 1.2: CMB temperature (*top*) and temperature-polarisation correlation (*bottom*) power spectra from 5 years of WMAP data showing fit for $\Omega_b = 0.0456 \pm 0.0015$, $\Omega_{dm} = 0.228 \pm 0.013$, $\Omega_\Lambda = 0.726 \pm 0.015$. From [6].

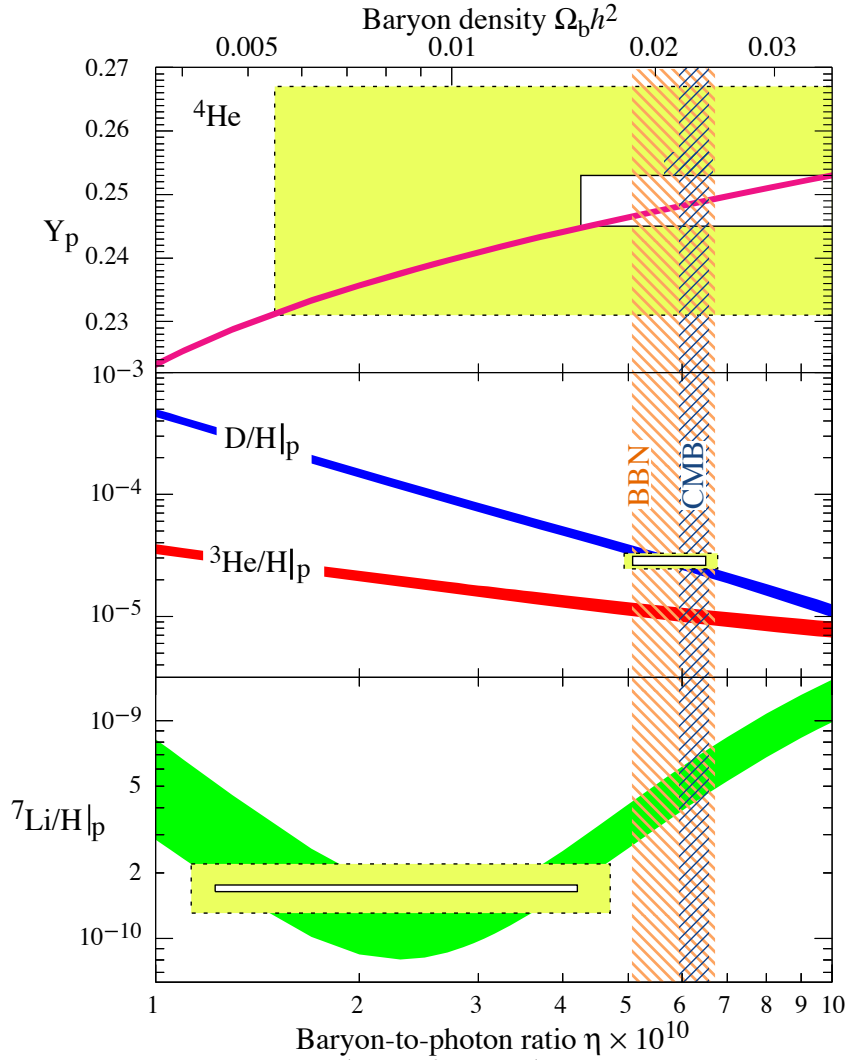


Figure 1.3: Light element abundances predicted by BBN (95% confidence bands). Boxes indicate observed abundances (inner box $\pm 2\sigma$ statistical error, outer box $\pm 2\sigma$ systematic and statistical errors). Vertical bands indicate BBN concordant baryon density and CMB-derived baryon density (for comparison) at 95% confidence level. From [3].

light nuclei (in a process known as *Big Bang nucleosynthesis* (BBN)) can be modelled as a function of the baryon density Ω_b . The abundance of primordial light nuclei can be inferred from observations (although the systematic errors arising from subsequent stellar reactions are significant for primordial ^4He and ^7Li abundance data). By combining BBN data with inferred primordial light nuclear abundances, the relative baryon density of the universe can be constrained to $0.037 < \Omega_b < 0.046$ (using $h = 0.72 \pm 0.03$) [3] (see Figure 1.3). This independent estimate of Ω_b is in accordance with the value derived from fits to CMB power spectrum data.

So we see that a combination of cosmological measurements support the existence of a significant non-relativistic, non-baryonic component to the matter density of the universe. The universe of the standard cosmological model comprises $\sim 4.6\%$ baryonic matter, $\sim 23\%$ non-baryonic matter (dark matter) and $\sim 73\%$ vacuum energy (dark energy).

1.2 Astrophysical evidence for dark matter

In this section I will describe two celebrated astrophysical observations which suggest the existence of a ‘halo’ of non-luminous matter surrounding stars, galaxies and galaxy clusters, providing evidence that dark matter comprises a large fraction of the matter in discrete systems within the cosmos. Here we will consider two examples drawn from a large body of evidence, for a more general description of

astrophysical evidence for dark matter, see [7].

Rotation curve of spiral galaxy M33

Observations of stellar rotational velocities can be related to the galactic density profile using Kepler's law. The velocity v of a star rotating on a radius R enclosing a mass M is given by (1.5).

$$v = \sqrt{\frac{GM(R)}{R}} \quad (1.5)$$

Observations of rotational velocities of stars in the spiral galaxy M33 do not exhibit the expected $v \propto 1/\sqrt{R}$ variation with the distribution of luminous matter alone (see Figure 1.4) [8]. However, Newtonian gravitation can be recovered if the galaxy is surrounded by a spherical halo of non-luminous matter, extending around the galactic disk. Figure 1.4 shows a fit to the data given by a combination of luminous matter, interstellar gas and a non-luminous dark matter halo.

Merging galaxy clusters 1E0657–558

Observations of the aftermath of the collision of two clusters of galaxies known as ‘merging cluster 1E0657–558’, or more famously as ‘the bullet cluster’, has allowed reconstruction of the gravitational dynamics of the event, which indicate that under Newtonian gravity the mass distribution of the incident clusters does not coincide with the distribution of their baryonic matter. An explanation in which baryonic matter (predominantly interstellar baryonic matter) suffers decel-

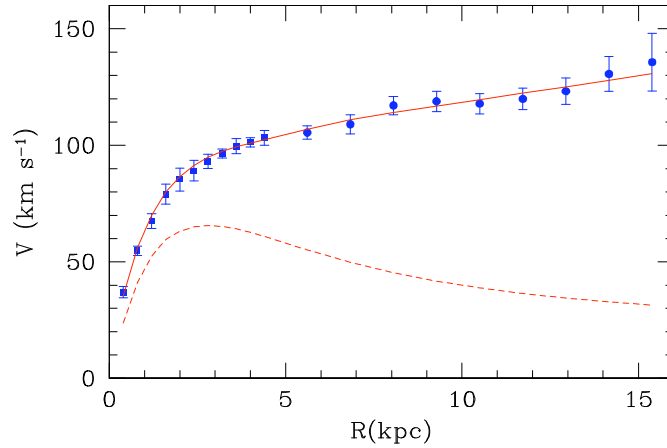


Figure 1.4: **Rotational velocities of stars in the spiral galaxy M33.** The dashed curve shows the expected rotation curve from luminous matter alone and the solid curve shows the expected rotation curve including luminous matter, interstellar gas and dark matter halo. From [8].

eration during collision while non-baryonic dark matter haloes continue on ballistic trajectories has been advanced to fit the data [3].

Further observation of the mass density of these clusters using weak gravitational lensing data independently corroborates this interpretation without recourse to many-body models of gravitational dynamics. Figure 1.5 shows baryonic matter density distribution, observed by x-ray astronomy, with total mass density, observed by gravitational lensing, superimposed. The non-coincidence of the two mass distributions is consistent with the ballistic halo interpretation [9].

1.3 Dark matter candidates

We have seen that astrophysical evidence exists on a wide range of distance scales for a significant background of non-luminous dark matter existing throughout the

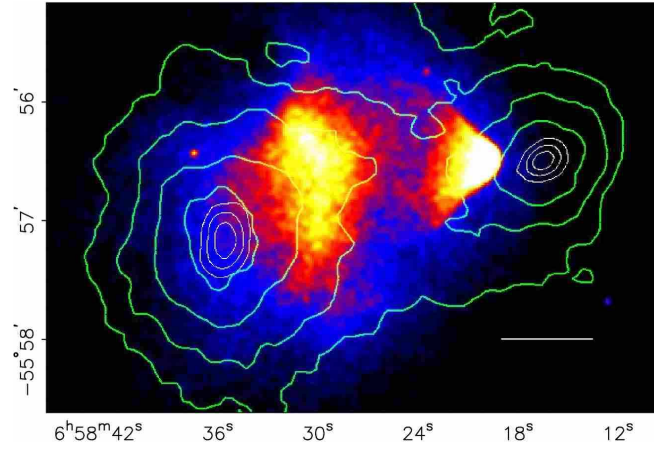


Figure 1.5: A coloured image showing baryonic matter density distribution in merging clusters 1E0657–558. Green contour lines show the mass density reconstructed using gravitational lensing. White contours show the locations of peak mass density with 68.3%, 95.5%, and 99.7% confidence levels. From [9].

cosmos. As the baryon density is constrained by BBN and BAO data, most of the dark matter must be non-baryonic³, but this does not exclude that a significant fraction of the dark matter observed in galaxies and galaxy clusters could be comprised of baryonic objects.

Astrophysics supplies many non-luminous baryonic objects; the interstellar gas and dust included in fits to galactic rotational velocity measurements is one such component. The term MACHOs (massive astrophysical compact halo objects) describes large astrophysical objects such as neutron stars, black holes and brown dwarf stars, which can be detected by observations of local gravitational microlensing of light from distant stars. Observed MACHO densities are not sufficient to

³Dark matter models of the dynamics in the ‘Bullet Cluster’ system also suggest a preponderance of non-baryonic dark matter.

comprise the full mass of galactic halo dark matter [10].

Turning to the non-baryonic dark matter, we must distinguish between ‘hot’ dark matter (particles at relativistic energies at the time of decoupling) and ‘cold’ dark matter (non-relativistic at the time of decoupling). The development of structure in the universe is strongly sensitive to the temperature of dark matter. Most models in which hot dark matter predominates tend to develop large-scale structure early, whereas models in which cold dark matter dominates form small-scale structures that then cluster under gravitational attraction to form the large-scale structure we observe in the universe today. Observations of the structure of high-redshift objects preclude a universe dominated by hot dark matter [11].

Cosmology furnishes further information about the type of non-baryonic dark matter by relating the interaction rate of non-baryonic dark matter to its density. The dark matter must remain in thermal equilibrium until the universe cools to the temperature at which it decouples from other matter. This yields the constraint on relative density Ω_X , interaction cross-section σ and velocity v given by (1.6) [12].

$$\Omega_X h^2 \approx \frac{3 \times 10^{-27} \text{cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle} \quad (1.6)$$

The typical interaction cross-section for a particle forming a relic density of cold dark matter is consistent with the weak interaction strength. Weakly interacting, massive, stable particles which would form a relic density of cold dark matter are

referred to using the generic term WIMPs (weakly interacting massive particles).

1.3.1 Non-baryonic dark matter

Neutrinos

Neutrinos are a well-observed component of the Standard Model with properties that would make them an excellent candidate for dark matter. Neutrinos are weakly interacting, electrically uncharged, of non-zero mass⁴ and produced in large quantities after the Big Bang. For these reasons, some fraction of the density of the universe will be composed of relic neutrinos produced with primordial leptons after the Big Bang.

Despite the suitability of neutrinos as a component of dark matter, relic neutrinos would be produced with relativistic energies, and as such would be *hot* dark matter. The density of hot dark matter is constrained by a combination of WMAP CMB data and large-scale structure data and so the relative neutrino density is limited to $\Omega_\nu \sim 0.001$. When coupled with estimates of the number density of primordial neutrinos, this places a cosmological limit of $\sum_j m_j < 1.7$ eV on the neutrino mass eigenstates [3]⁵.

⁴Although Standard Model neutrinos have a mass of identically zero, the observation of neutrino flavor oscillation due to mixing of different mass eigenstates has confirmed that neutrinos have a small but finite mass. Current measured bounds on the squared mass differences between neutrino mass eigenstates are $7.05 \times 10^{-5} \leq \Delta m_{21}^2 \leq 8.34 \times 10^{-5}$ eV² and $2.07 \times 10^{-3} \leq \Delta m_{31}^2 \leq 2.75 \times 10^{-3}$ eV² at 99.7% confidence level [3].

⁵Laboratory limits on the absolute scale of neutrino masses are found by observation of tritium beta decay spectra. A bound of $m_{\bar{\nu}_e} < 2.3$ eV is currently given at 95% confidence level, consistent with the cosmological constraint [3].

Although light relic neutrinos form a component of the matter density of the universe, their observed low masses and relativistic energies mean that other candidates must be considered to constitute the dominant cold component of the postulated dark matter background.

Axions

The hierarchy problem posed by the suppression of CP-violating terms in QCD can be resolved with a postulated new elementary particle, the axion, which would arise as a consequence of spontaneous symmetry breaking of a new global ‘Peccei-Quinn’ symmetry added to the Standard Model. The axion would have no electric charge and a very small mass (< 1 eV), but could have been produced at low energies after the Big Bang, so relic axions would be a suitable candidate for cold dark matter. Axions may interact with photons when subject to a strong magnetic field. Experimental work is underway searching for axion production in a polarised photon beam [13], and relic axion decay to photons [14].

Supersymmetric dark matter

Supersymmetry (SUSY) theories propose to solve hierarchy problems in the Standard Model by the introduction of a new symmetry between bosons and fermions [16]. TeV-scale supersymmetry theories would provide a natural mechanism for electroweak symmetry breaking and remove the ‘fine-tuning’ of the Higgs boson mass required in the Standard Model. Such theories also offer the possibility of

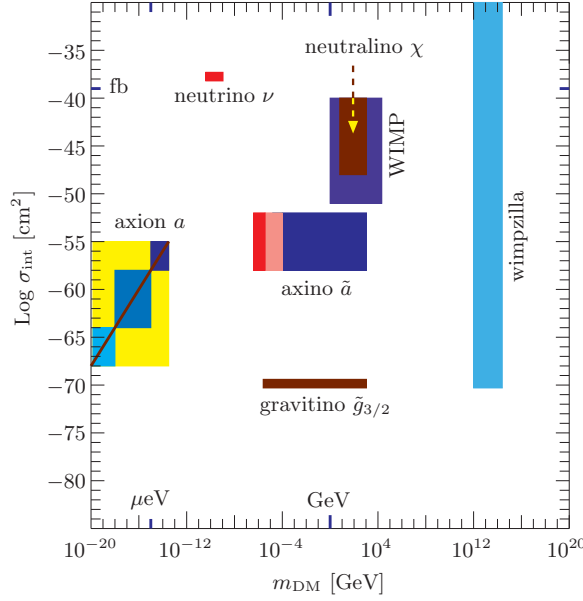


Figure 1.6: **Proposed candidates for dark matter from Standard Model (ν) and non-standard-model (a , $\bar{a}$, χ , $\bar{g}$, ‘wimpzilla’) particle physics drawn showing the proposed range of particle mass and interaction cross-section. From [15].**

unifying the electroweak and strong interactions and, because supersymmetry introduces several new particles, the potential for relic supersymmetric particles to form a relic density of WIMP dark matter.

The minimal supersymmetric Standard Model (MSSM) is an example of a supersymmetric theory in which the hierarchy problem is resolved, gauge unification is achieved and potential candidates for cold dark matter can be found. The MSSM introduces a new quantum number R (defined by (1.7), in which j is spin, B is baryon number and L is lepton number) and a new symmetry, R -parity, for elementary particles.

$$R \equiv (-1)^{2j+3B+L} \quad (1.7)$$

$R = 1$ for Standard Model particles, which in the MSSM are joined by ‘superpartners’ with $R = -1$. Each Standard Model fermion has a boson superpartner and each Standard Model boson a fermion superpartner. The lightest supersymmetric particle (LSP) would be stable as a consequence of R -parity conservation. A relic density of LSPs produced after the Big Bang would be an excellent WIMP cold dark matter candidate. The MSSM provides such an LSP in the form of the lightest neutralino $\tilde{\chi}_1^0$, a superposition of the two neutral electroweak gaugeinos (superpartners of the neutral electroweak gauge bosons) with the two neutral higgsinos (superpartners of the neutral higgs bosons). Theoretical estimates have placed neutralino mass between 10 GeV and 1 TeV with a spin-independent cross-section below 10^{-8} pb [15].

Other potential LSPs from theory include axinos (superpartners of axions) and gravitinos (superpartners of gravitons), projected ranges of mass and interaction cross-section for these particles are shown in Figure 1.6 ⁶.

1.3.2 The Large Hadron Collider

Large Hadron Collider (LHC) experiments now running at CERN, such as ATLAS and CMS, include the discovery of new non-Standard Model particles amongst their primary physics goals. The hardware and analysis methods have been designed to detect signatures indicating new particle production [17]. The designed

⁶Figure 1.6 also shows estimated mass and cross-section for ‘wimpzillas’, a proposed super-heavy particle arising from symmetry breaking at energies well above the electroweak scale.

centre-of-mass collision energy for proton-antiproton interactions is 14 TeV, opening the possibility for production of hitherto undetected particles in the coming years.

The observation of missing transverse kinetic energy is a key signature of particle production in collision events and the LHC general purpose detectors have extensive calorimeters to increase the likelihood and resolution of missing energy observations, allowing sensitive searches for new physics.

The discovery of any massive, weakly interacting stable particle at the LHC would certainly provide an excellent candidate for the postulated dark matter of astronomy and cosmology. However, direct searches for an extant background of such particles are essential to positively discover and identify the dark matter of astrophysics and cosmology within the compass of particle physics. The discovery of new particles by LHC experiments could nonetheless inform the design of future direct dark matter search experiments.

1.3.3 Alternative theories to dark matter

The long history of astrophysical observations which imply that existing gravitational theory requires additional matter density for consistency, without the empirical detection of such additional matter, has naturally led to the emergence of several theories in which modified gravitation is used to explain the observed phenomena. Theories in which additional terms are added to the gravitational

potential in both non-relativistic (MOND: modified newtonian dynamics [18]) and relativistic (TeVeS: tensor-vector-scalar gravity [19]) ways have been proposed, as well as suggestions that dark matter and dark energy could both be aspects of a single ‘dark fluid’ [20] and that a quantised gravitational theory could produce the effects ascribed here to dark matter.

While it is important to acknowledge the possibility that an explanation for the missing mass in astrophysical observations might be found without recourse to dark matter models, the absence of laboratory searches for these theories precludes further investigation of them in this work. It should also be noted that reconstruction of ‘bullet cluster’ dynamics (Section 1.2) has proved problematic in models without dark matter [9].

1.4 WIMP detection strategies

In this thesis I describe hardware development for experimental direct WIMP searches using cryogenic detectors (‘cryodetectors’). To place this work in context, I will give some introduction to the full range of strategies employed in searches for WIMP dark matter.

1.4.1 Direct WIMP searches

Attempts to detect the scattering of WIMP particles on target nuclei within the laboratory are described as *direct searches*. The search for very low event rates

($\sigma < 10^{-8}$ pb) at low energies (< 100 keV) means that background shielding and rejection are of paramount importance. Direct WIMP search experiments are built using materials of high radiopurity and extensive shielding to minimise the effect of background radiation due to naturally occurring radioisotopes. Deep underground laboratories are used to shield the detectors from radiation due to cosmic ray secondaries produced in the upper atmosphere. To decrease sensitivity to non-WIMP scattering events, many experiments employ both passive discrimination, in the form of veto detectors⁷, and active discrimination, allowing identification of recoil event type. Direct WIMP search techniques are discussed in detail in Chapter 2.

1.4.2 Indirect WIMP searches

Indirect WIMP searches attempt to detect the signature of WIMP annihilation emanating from locations in which a high WIMP density is expected. The Earth, the Sun and the centres of galaxies are expected to attract high local densities of WIMPS. Due to the large expected mass of WIMP particles, WIMP annihilation could produce a wide range of particle-antiparticle pair types, as well as high energy gamma rays. A wide range of detection techniques are used, of which several examples are given below:

⁷Muon detectors covering the exterior of the experiment, detecting muons entering the target volume, a potential origin of background events.

Neutrino detection

High energy neutrinos originating from the Sun or Earth could be a signature for WIMP annihilation within these bodies. Neutrino telescopes such as IceCUBE [21] and ANTARES [22] are searching for this signal.

High energy gamma ray detection

The correlation of high energy gamma ray signals with massive astrophysical bodies could be a signature for WIMP annihilation. Both earth-based (MAGIC [23]) and orbital (the Fermi Space Telescope [24]) gamma ray telescopes are searching for these signals.

Antiparticle detection

The PAMELA [25] and AMS probes [26] are searching for astrophysical positrons and antiprotons. The flux of these events could be boosted by WIMP annihilation.

1.5 Summary

In this chapter, we have introduced the evidence which motivates dark matter searches along with a range of dark matter candidates and detection strategies.

In Section 1.1, a range of observational evidence from Big Bang cosmology was described. The requirements for dark energy and non-baryonic dark matter in the composition of the universe are combined in the standard ‘ Λ -CDM’ model of

cosmology, in which $\sim 23\%$ of the energy density of the universe is comprised of non-baryonic cold dark matter.

In Section 1.2, a selection of the observed evidence for halo dark matter in the dynamics of astrophysical systems was introduced. This evidence complements the cosmological evidence for dark matter and motivates searches for a dark matter halo in our own galaxy.

Through a consideration of candidates and potential candidates for dark matter we can motivate the requirement for non-relativistic, non-baryonic WIMP dark matter, for which suitable candidates are found in proposed supersymmetric extensions to the Standard Model (Section 1.3). In Section 1.4, the distinction is made between direct and indirect WIMP searches.

We will proceed to examine direct WIMP searches, hardware for which is the focus of this thesis, in Chapter 2.

Chapter 2

Direct WIMP searches

Direct WIMP search experiments seek to detect nuclear recoil events due to WIMP-nucleus scattering within a body of target material.

In this chapter the phenomenology of WIMP-nucleus scattering is described, allowing parameterisation of an empirically observed nuclear recoil spectrum using WIMP mass and WIMP-nucleon cross-section. Data from direct search experiments can thus be compared with predictions derived from supersymmetry theories constrained by astrophysical data. Current empirical limits on WIMP mass and cross-section are presented.

This phenomenology motivates the design of hardware for direct WIMP search experiments. Background suppression and discrimination are introduced and a range of current direct searches are described. Two cryodetector direct search experiments, CRESST-II and EDELWEISS-II, are described in detail. The challenges in hardware design for the development of future cryodetector direct searches

which are addressed in this thesis are introduced.

2.1 Direct WIMP search phenomenology

The mechanism for WIMP-nucleus scattering in direct search detector targets is unknown but, by referring to the dynamics of the postulated dark matter halo and the expected range of WIMP mass from SUSY predictions, the observable WIMP-nucleus scattering rate may be parameterised by WIMP mass and WIMP-nucleon cross-section.

2.1.1 The local WIMP halo

The WIMP halo of our own galaxy is assumed to be isothermal, non-rotating and spherically symmetrical. The local WIMP density at the Earth has been estimated from dark matter halo models as $\rho_\chi \sim 0.3 \text{ GeVcm}^{-3}$ [27], and this value is commonly used in experimental analyses.

The halo is modelled as a cloud of non-interacting WIMPs. In this case, the WIMP velocity distribution, in the rest frame of the galaxy, is given by a Maxwell-Boltzmann distribution, truncated at the galactic escape velocity $v_e \approx 600 \text{ km s}^{-1}$ and normalised by a normalisation constant N , such that $\int f(\mathbf{v}) d^3\mathbf{v} = 1$ (2.1).

$$f(\mathbf{v}) d^3\mathbf{v} = \begin{cases} N \left(\frac{3}{2\pi v_0^2} \right)^{3/2} \exp \left(-\frac{3}{2} \frac{|\mathbf{v}|^2}{v_0^2} \right) d^3\mathbf{v} & \text{for } |\mathbf{v}| < v_e \\ 0 & \text{otherwise} \end{cases} \quad (2.1)$$

For a spherical isothermal halo the scale parameter of the Maxwell-Boltzmann

distribution (the RMS velocity) v_0 is related to the galactic rotation velocity at large radii, v_∞ , by $v_0 = \sqrt{3/2}v_\infty$. From [28], $v_\infty = 220 \pm 20 \text{ km s}^{-1}$, so $v_0 = 270 \pm 25 \text{ km s}^{-1}$.

The motion of the Earth through the halo and the rotation of the Earth about its axis introduce additional annual and daily modulation of the WIMP velocity spectrum. Rotation of the WIMP halo may also have an effect. Details of these calculations may be found in [29].

2.1.2 WIMP-nucleus scattering

The observed differential detection rate for WIMP-nucleus scattering may be found by integration (over WIMP velocity $\mathbf{v}$) of the product of WIMP speed v ($= |\mathbf{v}|$), WIMP velocity distribution $f(\mathbf{v})$ and WIMP-nucleus differential cross-section $\frac{d\sigma_N}{dE_R}(v, E_R)$ (2.2) [29].

$$\frac{dR(v)}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int d^3\mathbf{v} \left(v \cdot f(\mathbf{v}) \cdot \frac{d\sigma_N}{dE_R} \right) \quad (2.2)$$

N_T is the number of target nuclei per unit mass, ρ_χ is the local WIMP density and m_χ is the WIMP mass.

The WIMP-nucleus differential cross-section is given by (2.3).

$$\frac{d\sigma_N}{dE_R} = \frac{\sigma_N}{E_R^{max}} F^2(q) \quad (2.3)$$

Using non-relativistic kinematics, the maximum nuclear recoil energy is given

by $E_R^{max} = 2\mu_N^2 v^2 / m_N$, where m_N is the nucleus mass and μ_N is the reduced mass of the WIMP-nucleus system. The momentum transfer q is given by $q^2 = 2m_N E_R$. $F(q)$ is the nuclear form factor and σ_N is the WIMP-nucleus cross-section.

The differential cross-section is scaled by a nuclear form factor $F^2(q)$ to account for the effect of non-zero momentum transfer in nuclear scattering. The Helm form factor [30] used here is given by (2.4), where $j_1(qr_0)$ is a first-order spherical Bessel function, $s = 1$ fm is the thickness parameter for the nucleus surface and $r_0 = ((1.2A^{\frac{1}{3}})^2 - 5s^2)^{1/2}$.

$$F(q) = 3 \frac{j_1(qr_0)}{qr_0} \exp\left(-\frac{(qs)^2}{2}\right) \quad (2.4)$$

Approximate WIMP-nucleus scattering rate

In the case of a spherical isothermal WIMP halo, and ignoring the effects of the galactic escape velocity and the Earth's motion on the WIMP velocity distribution, an approximate differential scattering rate is given by (2.5) [31].

$$\frac{dR}{dE_R} \cong \frac{R_0}{E_0 r} \exp\left(-\frac{E_R}{E_0 r}\right) \quad (2.5)$$

Here $E_0 = \frac{1}{2}m_\chi v_0^2$ is the non-relativistic WIMP kinetic energy at the RMS velocity, $r = 4\mu_N^2 / m_\chi m_N$ is a kinetic factor and R_0 is the total event rate, given for $F(q) = 1$ by (2.6):

$$R_0 = \frac{2}{\sqrt{\pi}} N_T \frac{\rho_\chi}{m_\chi} \sigma_N v_0 \quad (2.6)$$

The expected differential event rate falls off exponentially with increasing nucleus recoil energy. For $v_0 = 270 \text{ km s}^{-1}$, a 100 GeV WIMP has kinetic energy $E_0 = 81 \text{ keV}$. Typical energies for nuclear recoil events due to WIMP-nucleus scattering will therefore be below 100 keV. For this reason, low energy thresholds (a few tens of keV or less) are an essential feature of detectors designed for direct WIMP searches.

2.1.3 WIMP-nucleon cross-section

The cross-section σ_N used above is the WIMP-nucleus cross section. To relate the detected WIMP-nucleus scattering rate to the target-independent WIMP-nucleon cross-section σ_n , we consider the interaction modes available in the MSSM for neutralino-nucleon scattering.

Observed WIMP-nucleus scattering rates can be expressed in terms of the WIMP-nucleon cross-section, and thus comparisons of data measured by detectors using different target nuclei can be made. Empirical data can also then be compared to predicted WIMP mass and WIMP-nucleon cross-section from MSSM theory.

We expect contributions to the WIMP interaction matrix element from scalar, pseudoscalar, vector and axial vector couplings.

In the non-relativistic limit, the WIMP-nucleus scattering cross-section will have terms in the scalar and axial vector couplings only. At low energies, coher-

ent WIMP-nucleus scattering dominates, and total cross-sections scale with the aggregate properties of the nucleus.

The spin-independent scalar WIMP-nucleon coupling sums coherently over the nucleus. The total scattering amplitude varies with nuclear mass A , and so the total spin-independent cross-section varies as $\sigma^{scalar} \propto A^2$.

The axial vector coupling is with the spin of the nucleon, therefore the coherent total scattering amplitude varies with the projection of the total nuclear spin. The spin-dependent cross-section thus varies as $\sigma^{axial} \propto \lambda^2 J(J+1)$.

A full treatment [31] gives the relations between the WIMP-nucleon cross-sections σ_n and WIMP-nucleus coherent scattering cross-sections σ_N in terms of the reduced mass of the WIMP-nucleon system μ_n and the reduced mass of the WIMP-nucleus system μ_N ((2.7) and (2.8) respectively).

$$\sigma_N^{scalar} = \frac{\mu_N^2}{\mu_n^2} A^2 \sigma_n^{scalar} \quad (2.7)$$

$$\sigma_N^{axial} = \frac{\mu_N^2}{\mu_n^2} \frac{\lambda_N^2 J_N(J_N+1)}{\lambda_n^2 J_n(J_n+1)} \sigma_n^{axial} \quad (2.8)$$

The total WIMP-nucleus coherent scattering cross-section is given by $\sigma_N = \sigma_N^{scalar} + \sigma_N^{axial}$. Due to the scaling of σ_N^{scalar} with A^2 , for nuclei of mass number $A > 30$ the spin-independent scalar cross-section dominates over the axial vector cross-section [27].

The combined effect of nuclear form factor scaling and A^2 -dependence on the spin-independent WIMP-nucleon cross-section influences the selection of target

material for direct WIMP searches.

2.1.4 WIMP detection signatures

Observation of a spectrum of non-Standard Model background events consistent with the expected WIMP-nucleus differential scattering rate (2.2) would be indicative of WIMP signal detection. Some additional features of the expected WIMP halo which could be used to confirm discovery of WIMP dark matter are given below:

Target nucleus acceptance

The dependence of WIMP-nucleus scattering rate on nuclear form factor and mass number gives variation in the expected rate of scattering events from different target nuclei. Detection of varying non-background energy spectra across detectors utilising different target nuclei could signal discovery of WIMP dark matter.

Annual modulation

The motion of the Earth through the galactic halo introduces an annual modulation to the distribution of WIMP velocities, and thus an annual modulation in the expected WIMP-nucleus scattering event rate.

The DAMA experiment [32] reported annual modulation of an observed background-subtracted event rate, but the claimed WIMP cross-section and mass bounds have been excluded at 90% confidence level by subsequent direct search experiments [3].

Directional signature

As well as modulation of the total event rate, the Earth's rotation within the WIMP halo would produce daily modulation in the direction distribution of nuclear recoils, which would provide a clear signature for the astrophysical origin of the incident particles.

The DRIFT-II experiment operates a low-pressure CS₂ gas target in which nuclear recoil tracks can be spatially resolved using ionisation measurements in a multi-wire proportional chamber. Development to scale up directional direct WIMP searches is ongoing [33].

2.1.5 WIMP parameter exclusion plots

At the present time, direct search observations have not positively identified a WIMP-nucleus scattering signal. While some claims have been made for observed events in excess of expected backgrounds ([32],[35]), there is not yet clear evidence for the direct discovery of WIMP dark matter.

In order to assess the variety of hardware techniques used in direct WIMP searches, the relative sensitivity of such experiments can be reviewed by comparison of exclusion plots in WIMP mass-cross-section parameter space. The *optimum interval method*¹ [36] is widely used in analysis of direct WIMP search

¹This statistical test entails the optimisation of the energy range of interest in order to set the most stringent limit possible on an unknown background given a small number of observed events.

data ([37],[38]) to find the mass-dependent lowest bound on the WIMP-nucleon cross-section from an observed nuclear recoil energy spectrum², without making assumptions about the physics of any underlying background spectrum.

Figure 2.1 shows recent WIMP-mass-dependent limits on WIMP-nucleon cross-section from a range of leading direct searches. The expected range of neutralino parameters from constrained minimal supersymmetric standard model (CMSSM) calculations [39] are also shown. The most stringent limits on WIMP-nucleon cross section have been set by the XENON 100 [40], CDMS [41], ZEPLIN III [42] and EDELWEISS II [43] direct searches. The technologies employed in these experiments will now be introduced in order to motivate the hardware development described in this thesis.

2.2 Background suppression

In order to search for low cross-section events at low energies, it is necessary to achieve very high suppression of background events. Cosmic rays and radioisotope activity are sources of the neutron, alpha particle, beta radiation and gamma ray backgrounds found in direct WIMP searches. In this section I will classify the techniques used for background suppression in direct WIMP searches.

²Other statistical methods, such as *maximum likelihood tests* [35] are used to derive allowed regions of parameter space for observed WIMP event rates.

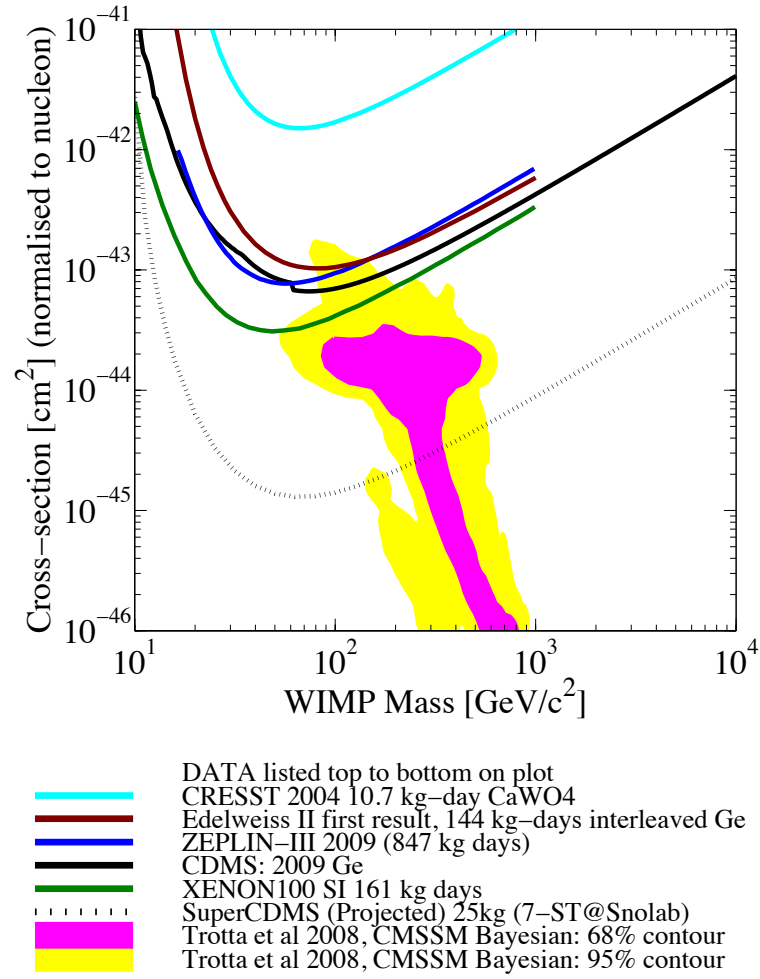


Figure 2.1: **Recent experimental limits at 90% confidence level in WIMP mass, WIMP-nucleon cross-section parameter space shown along with CMSSM neutralino expected parameters (yellow/magenta area) and the projected final sensitivity limit of the SuperCDMS experiment (dashed line).** Note that $1 \text{ pb} = 10^{-36} \text{ cm}^2$. Plot produced using [44].

2.2.1 Shielding and radiopurity

To reduce the flux of cosmic-ray induced events, detectors for direct searches are sited in deep underground laboratories. Cosmic-ray muon flux is reduced to $\sim 1 \text{ hr}^{-1}\text{m}^{-2}$ by vertical shielding of 3600 m (water equivalent) [45].

The materials used in the fabrication of detector components are carefully chosen and handled in order to minimise radioisotope contamination. The required radiopurity varies depending on which part of the detector is considered; components closest to the detector target can be required to have activity rates lower than 1 mBq/kg in the energy range of interest [46].

Veto detectors are mounted externally to surround the direct search detector target. Detection of incident radiation passing through the veto detector is used in the implementation of a temporal cut, allowing removal of events due to detected external backgrounds from WIMP search data.

2.2.2 Event type discrimination

In searches for WIMP-nucleus scattering events, the identification of recoil particle and location within the detector target allows the discrimination of background events.

Background events due to incident beta and gamma radiation predominantly scatter from electrons within the target. Detector sensitivity to these events can be suppressed by identification of nuclear recoil events.

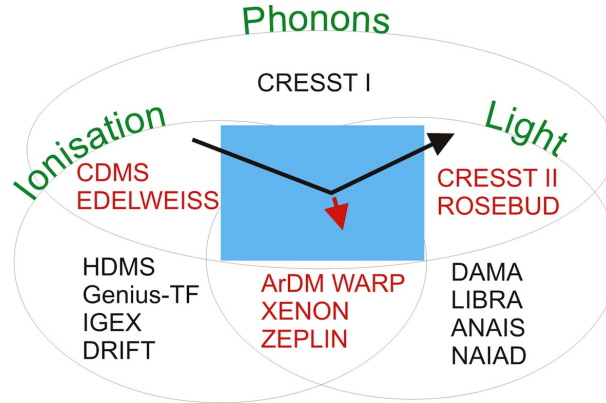


Figure 2.2: A Venn diagram showing detection methods utilised by selected direct WIMP searches. Experiments shown in red type make use of coincident detection of two event signatures for discrimination of background.

Recoil events due to incident alpha particles will occur on the surfaces of the detector target. Detector surface regions can also be susceptible to non-uniformities in signal response. If the event position within the detector target can be measured, then a *fiducial volume* may be defined, allowing discrimination of bulk events from surface events and thus minimising these effects.

In direct search experiments, recoil particle identification and location are facilitated by simultaneous measurements of different event signals. Events within detector targets yield signals produced by phonon production, scintillation light production or ionisation charge production, and coincident measurements of two of these signals are made in many current direct search experiments. Figure 2.2 categorises a number of direct WIMP search experiments by signal measurement types.

Event discrimination in cryodetectors

Cryodetectors are used in a number of current direct search experiments. The measurement of phonon signals due to scattering events within a solid detector target is made possible by the reduction in heat capacity of the target absorber crystal under cooling to low temperatures³.

The EDELWEISS and CDMS [50] collaborations utilise high-purity germanium target crystals, in which ionisation charge is measured simultaneously with phonon signal to allow event discrimination.

The CRESST collaboration uses high-purity CaWO_4 and ZnWO_4 crystals, in which tungsten nuclei are the target for WIMP-nucleus scattering, and event discrimination is effected by coincident measurement of phonon and scintillation signals.

This thesis describes new hardware for development of the technologies used in the CRESST-II and EDELWEISS-II experiments, in which event discrimination is a key feature. The hardware used to implement these measurements is described in detail in Sections 2.3 and 2.4 respectively.

Event discrimination in liquid noble gas detectors

Several collaborations are currently running *two-phase time projection chambers* for direct WIMP searches, utilising coincident scintillation and ionisation signal

³ $C(T) \propto \left(\frac{T}{\Theta}\right)^3$ by Debye's law.

measurements for background discrimination. The target material in detectors of this type is a liquefied noble gas, usually argon ($A = 39.948$, $T_{BP} = 87.3$ K) or xenon ($A = 131.29$, $T_{BP} = 165$ K), in which a high concentration of target nuclei for WIMP scattering can be achieved with low contamination and correspondingly high radiopurity.

Figure 2.3 shows a diagram of a two-phase time projection chamber (used in the ZEPLIN-III experiment). Recoil events within the target produce scintillation photons and ionised electrons. Arrays of photomultiplier tubes (PMTs) are used to detect scintillation light. Ionisation electrons are accelerated by an applied electric field into a gas layer at the top of the detector volume, where they produce an electroluminescent light signal, detected separately by the PMT array.

The relative magnitudes of the scintillation and electroluminescence signal allow discrimination of electron and nuclear recoil events, with low ionisation yield indicative of nuclear recoil events. The position of an event can be reconstructed using the spatial resolution of the PMT array coupled with the time delay between prompt scintillation and subsequent electroluminescent signals. A fiducial volume can be defined within the target liquid to exclude near-surface events.

Examples of current direct WIMP searches using liquid noble gas time projection chambers include the ZEPLIN [42] and XENON [52] collaborations.

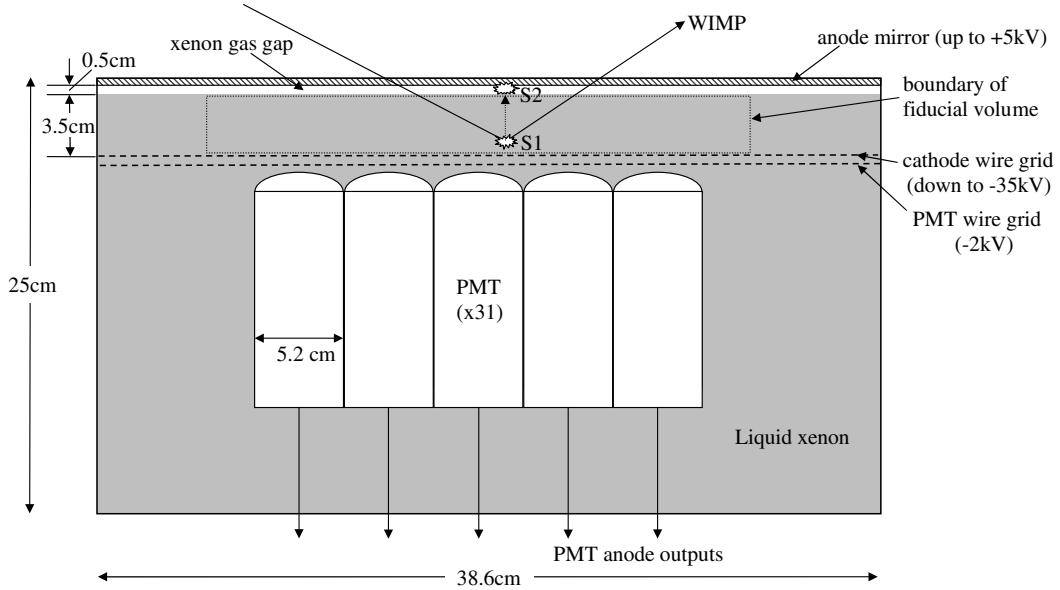


Figure 2.3: Diagram showing the two-phase time projection chamber of the ZEPLIN-III experiment [51]. S1 denotes the liquid scintillation signal at the recoil location, S2 the subsequent gas electroluminescence due to accelerated ionisation charge.

2.3 The CRESST-II experiment

The CRESST collaboration operates an array of cryogenic bolometer modules in the deep underground laboratory at LNGS (Gran Sasso, Italy) under rock shielding of 3500 m water equivalent.

The CRESST-II array consists of 10 detector modules which are cooled to a temperature of around 6–12 mK. Figure 2.4 shows a photograph of the module array mounted within a dilution refrigerator, alongside a schematic showing the components of an individual module.

Each CRESST-II module consists of a 300 g target crystal and a separate light

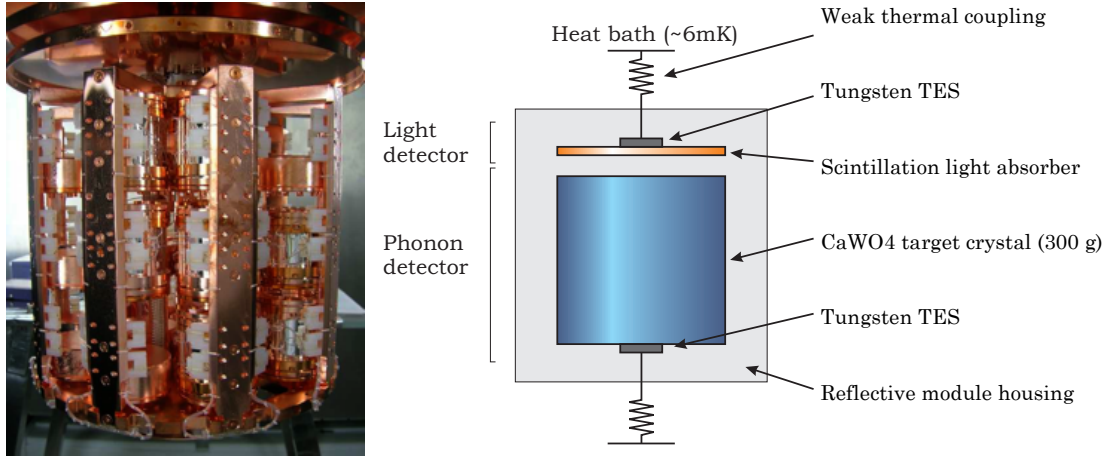


Figure 2.4: The CRESST-II cryodetector array; (*left*) photograph of the high-purity copper ‘carousel’, on which detector modules are mounted and cooled, (*right*) schematic of a detector module, showing the configuration of target crystal, scintillation light absorber and TES sensors.

absorber, mounted within a common reflective enclosure⁴. Scintillation light produced in the target crystal is absorbed by the light absorber. Phonon production in both the target crystal and light absorber is measured using a tungsten *transition edge sensor* (TES), which is described in detail in Section 2.3.1.

CRESST-II uses both CaWO₄ and ZnWO₄ target crystals, materials chosen for high scintillation light yield at millikelvin temperatures [53], [54] and high radiopurity.

Event discrimination

The simultaneous measurement of phonon signals and scintillation light production in a CRESST-II detector module allows identification of the recoil particle within

⁴One module is comprised of a target crystal and two light absorbers.

the target crystal by measurement of the *light yield* of an event. The light yield of an event is defined as the ratio of measured light detector signal energy to measured phonon signal energy. Since the energy calibration of both channels is carried out by detection of electron scattering events due to exposure of the target crystal to gamma rays, the measured light yield of electron recoil events is ~ 1 .

Nuclear recoil events can be discriminated from electron recoil events by their reduced scintillation light yield. For the recoil events of a given nucleus, the light yield is suppressed by a *quenching factor*, Q . Tungsten recoils in CaWO_4 have a measured quenching factor of $Q_W = 48.7 \pm 7.1$ at a temperature of 7 mK; a conservative value of $Q_W = 40$ is used for analysis of dark matter search data [55].

Figure 2.5 shows the energy and light yield of events detected by a CRESST-II detector module during both calibration measurements with a neutron source and measurements of low-background dark matter data.

In the neutron calibration data, distinct bands can be seen for electron scattering and elastic nucleus scattering events. The incident neutrons predominantly undergo elastic scattering from oxygen nuclei ($Q_O \simeq 9$), populating the nuclear recoil acceptance region. Inelastic neutron-nucleus scattering events in which the nucleus is raised to an excited state, emitting a gamma ray, can be seen above 47 keV in the inter-band region. Events in which the measured light yield is < 0 represent instances for which the measured scintillation signal could not be resolved from baseline noise.

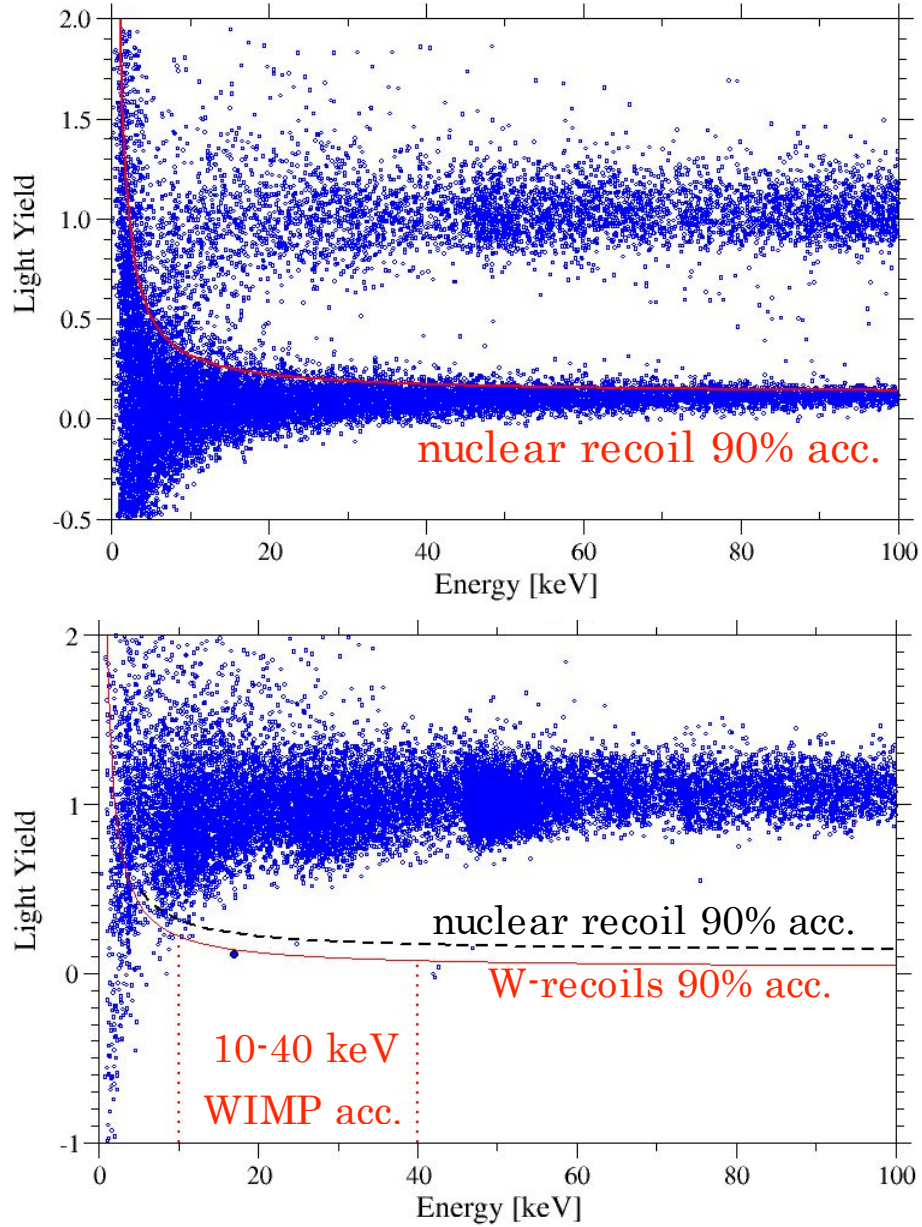


Figure 2.5: Scatter plots of events recorded by a CRESST-II detector module during (*top*) calibration with neutron source and (*bottom*) dark matter run in 2007. 90% upper bounds for all nuclear recoils and tungsten-only nuclear recoils are shown, along with upper and lower thresholds in WIMP searches. From [38].

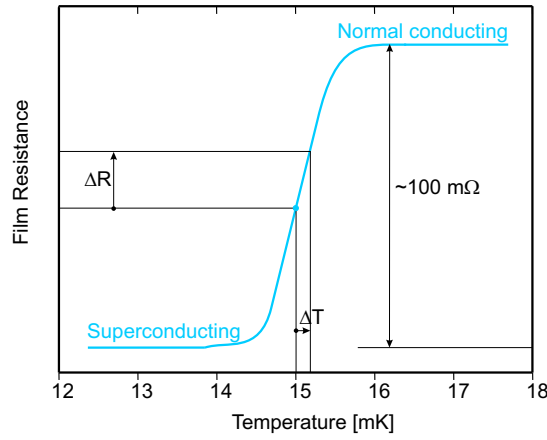


Figure 2.6: **Superconducting-to-normal transition curve in a TES film, showing resistance response ΔR to temperature change ΔT .**

The bottom plot in Figure 2.5 shows 24.11 kg.day exposure for dark matter data measurement recorded by a CRESST-II detector module. A single event can be seen in the 90% acceptance region for tungsten nuclear recoils.

2.3.1 Cryodetectors with TES-SQUID readout

The phonon and scintillation signals of a CRESST-II detector module are each measured using a cryodetector consisting of an absorber upon which a transition edge sensor (TES) is deposited. The cryodetector absorbers in question are the target crystal and the scintillation light absorber, and the TES readout system is similar in both cases.

Each CRESST-II TES consists of a thin tungsten film, stabilised at a temperature within its superconducting-normal transition (see Figure 2.6). The large variation in film resistance with temperature in this range makes the TES a highly

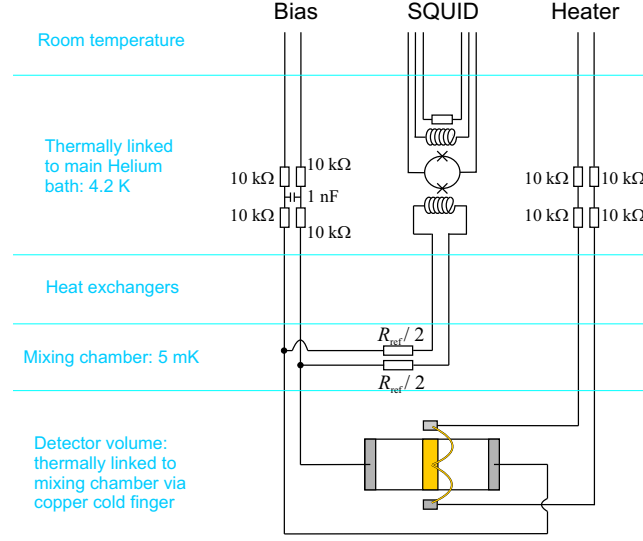


Figure 2.7: **The low-impedance bias and readout circuit for measurement of resistance variation in a CRESST-II cryodetector TES using a SQUID sensor.**

sensitive temperature sensor.

Phonon signals produced (by either particle events or absorption of scintillation photons) in the absorber are thermalised, producing a temperature pulse in the TES. Temperature pulse shape is parameterised using an empirical model [56], allowing measured pulses to be parameterised by a rise time τ_{in} , two decay times, τ_n and τ_t , and two amplitudes, A_n and A_t (2.9).

$$\Delta T_{TES} = \Theta(t) A_n \left[(e^{-t/\tau_n} - e^{-t/\tau_{in}}) + \frac{A_t}{A_n} (e^{-t/\tau_t} - e^{-t/\tau_n}) \right] \quad (2.9)$$

TES-SQUID readout circuit

The connections for TES bias, SQUID readout and heater stabilisation are shown in Figure 2.7.

A gold bond wire resistor through which a heating current flows is used to stabilise the TES at an operating temperature T_0 , within its superconducting-normal transition. Each TES is stabilised independently at a temperature chosen to optimise the linearity of its response to phonon pulses. The variation of TES resistance with temperature at this point is parameterised by α , defined $\alpha \equiv \frac{1}{R_T} \frac{\partial R_T}{\partial T} \big|_{T_0}$. For tungsten film transitions at ~ 10 mK, α can be as high as ~ 1000 K⁻¹ [57].

A *superconducting quantum interference device* (SQUID) sensor⁵ is used to measure current change in the TES readout circuit. SQUID sensors exploit the Josephson effect to perform highly sensitive magnetometric measurements. By coupling an inductive input to a SQUID sensor, accurate measurements of current change can be made. CRESST-II SQUID sensors are heatsunk to a helium bath at a constant temperature of 4.2 K.

Each TES film is connected in parallel with the input coil of a SQUID sensor and a fixed reference resistance as shown in Figure 2.7. Superconducting niobium-titanium alloy wiring is used for these connections, as typical film resistance is < 100 m Ω . For this reason TES-SQUID readout is referred to as *low-impedance* readout.

The parallel TES-SQUID circuit is subject to a bias current I_{Bias} . The change in SQUID input current ΔI_{SQUID} measured following a TES temperature pulse ΔT_{TES} is given by (2.10).

⁵See [58] for a detailed description of the design and operation of SQUID sensors.

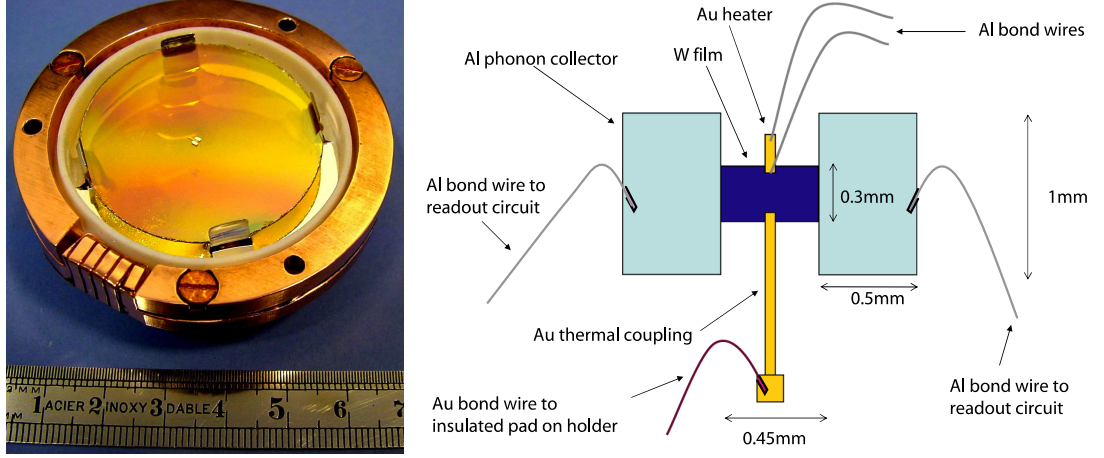


Figure 2.8: *Left*: photograph of a cryogenic light detector mounted in the top plate of a CRESST-II detector module. *Right*: detailed schematic of the tungsten TES and aluminium phonon traps mounted on the centre of a cryogenic light detector [55].

$$\Delta I_{SQUID} = I_{Bias} \left(\frac{R_{ref} R_{TES, T_0}}{(R_{ref} + R_{TES, T_0})^2} \right) \alpha \Delta T_{TES} \quad (2.10)$$

The use of a parallel bias circuit avoids the potential problem of ‘thermal runaway’, which can occur in circuits where ohmic heating in the TES increases with increasing resistance, driving the TES above its transition temperature [59].

2.3.2 Cryogenic light detectors

The development of alternative cryogenic scintillation detection techniques is the subject of Chapter 4, so some characteristics of CRESST-II cryogenic light detectors will be introduced here in detail.

The scintillation light in a CRESST-II module is partially absorbed⁶ by a silicon

⁶Around 20% of the scintillation light is detected in the light detector [60].

wafer light absorber. The resulting phonon pulse is thermalised and measured using TES-SQUID readout as described above. A cryogenic light detector is shown in Figure 2.8.

The sensitivity of CRESST-II light detectors is critically dependent upon both efficient collection of scintillation light by the silicon wafer and efficient collection of phonons by the TES.

Photon collection in the light detector can be improved with the use of a reflective lining inside the detector module and a roughened surface on the light absorber wafer [61]. The light detector TES is mounted in thermal contact with two aluminium pads deposited onto the wafer surface, designed to thermalise the phonon signal more effectively (see Figure 2.8).

The fraction of particle event energy collected as light in a CRESST-II detector module is measured by calibration of light detector response to 5.9 keV x-rays incident on the silicon absorber wafer. For 60 keV γ -rays detected in a CaWO_4 target crystal, the detected scintillation energy in an adjacent cryogenic light detector is 480 eV.

Good light detector energy resolution is observed down to phonon channel energies of 10 keV (80 eV light detector equivalent) [53], making possible the background discrimination at low energies required for direct WIMP searches.

2.3.3 Cabling for CRESST-II

Cabling for the CRESST-II readout system was designed and assembled during 2002–2003 at Oxford University.

66 TES-SQUID readout channels (sufficient for 33 detector modules) were installed for CRESST-II. A set of cables for the electrical connections shown in Figure 2.7 was required for each channel.

Three types of cabling were produced to equip the CRESST-II detectors:

Superconducting cables; niobium-titanium wire cables were used for the low-impedance bias circuit, connecting the 4.2 K SQUID sensors to the millikelvin-temperature TES sensors and reference resistors.

Manganin cables; high-impedance manganin⁷ wire cables to carry heater and bias currents from room temperature to filter boxes at 4.2 K.

SQUID readout cables; specialised composite manganin and copper wire cables were used to connect the SQUID sensors at 4.2 K to vacuum feedthroughs at room temperature. It was observed that if a low-impedance wire-pair ($< 10 \Omega$) was used for the SQUID voltage channel readout, the measured SQUID noise was reduced by 36% relative to readout using a manganin wire-pair [62]. In order to achieve optimal SQUID performance in the CRESST-II readout system, one copper wire-pair for the voltage readout was woven into each 4-wire-pair SQUID cable.

The cabling design was optimised for low heatload and low crosstalk perfor-

⁷Manganin is an alloy of copper, manganese and nickel, chosen for use in cryogenic applications due to its predictable resistance variation with temperature.

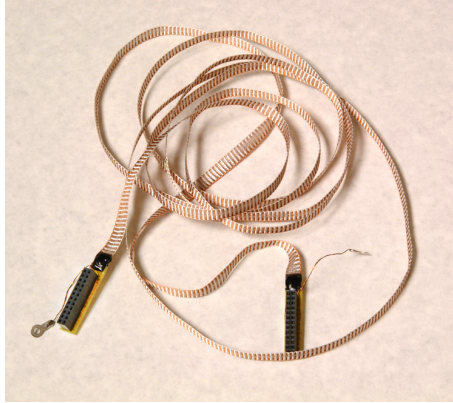


Figure 2.9: **Woven ribbon cable with 2.54 mm pitch Samtec connectors, produced for the CRESST-II readout system.**

mance. Woven ribbon cables were used in which the conducting tracks were arranged in twisted wire pairs separated by earthed shielding tracks for crosstalk minimisation [63].

Bespoke woven cables, such as the one shown in Figure 2.9, were fabricated commercially by TekData of Stoke-on-Trent. The cost of each woven cable was approximately £150 and the total cabling budget for the 66 channel readout system was around £40,000.

Heatload in CRESST-II cabling

Conductive heatload due to cabling in the CRESST-II cryostat was calculated and is quoted in Table 2.1.

The cabling installed between 290 K and 4.2 K conducts heat from room temperature to the helium bath of the dilution refrigerator, causing helium evaporation. It was essential for CRESST-II to ensure that helium refilling was not

Temperature range	Heatsink location	Heatload	Number of individual wires
290 K – 4.2 K	Main bath	201 mW	816
4.2 K – 1.5 K	1 K pot	12 μ W	432
1.5 K – 600 mK	Still	1.3 μ W	432
600 mK – 50 mK	50 mK shield	130 nW	432
50 mK – 10 mK	Mixing chamber	180 pW	432

Table 2.1: **Calculated heatload due to the CRESST-II cabling system [64].**

required more than once every 2–3 days and would not therefore disrupt data measurements.

This was achieved by using manganin wire wherever possible for cabling installed between 290 K and 4.2 K. The thermal conductivity of manganin is approximately two orders of magnitude lower than copper wire over this temperature range [65]. The calculated helium evaporation due to cabling heatload is around 6.7 l/day, and in practice the 30 l CRESST-II helium bath is refilled once every 3 days.

The cabling installed below 4.2 K was fabricated using niobium-titanium wires in a copper-nickel matrix. Niobium-titanium is superconducting in this temperature range. Superconducting connections were a necessity between the TES films, reference resistors and SQUID inputs, and their use also ensured minimal heat conduction below 4.2 K, since thermal conductivity is suppressed in a superconductor [66]. The calculated heatloads in Table 2.1 are dominated by the thermal conduction of the fine copper-nickel matrix.

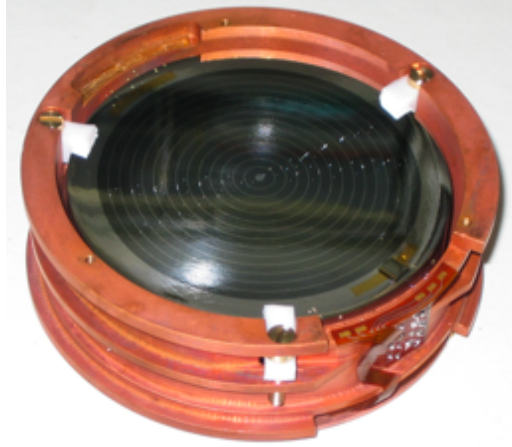


Figure 2.10: An EDELWEISS detector module mounted within a copper holder showing the NTD-Ge sensor and concentric charge collection electrodes on top of a cylindrical germanium target crystal. Image from [67].

2.4 The EDELWEISS-II experiment

The EDELWEISS collaboration operate an array of cryogenic bolometer modules in the LSM deep underground laboratory, Modane, France, under rock shielding of 4800 m water equivalent.

Figure 2.10 shows an EDELWEISS-II detector module. Each module comprises a 400 g high purity germanium crystal, which is cooled to 18–20 mK. Phonon energy and ionisation charge due to scattering events in the crystal are measured simultaneously, allowing discrimination of nuclear recoil events from electron recoil events. The measured distribution of charge collection allows the discrimination of events in the bulk of the crystal from those in surface regions.

Figure 2.11 shows discrimination of electron and nuclear recoil events in EDELWEISS data. The *ionisation yield* is the measured ratio of energy detected in the

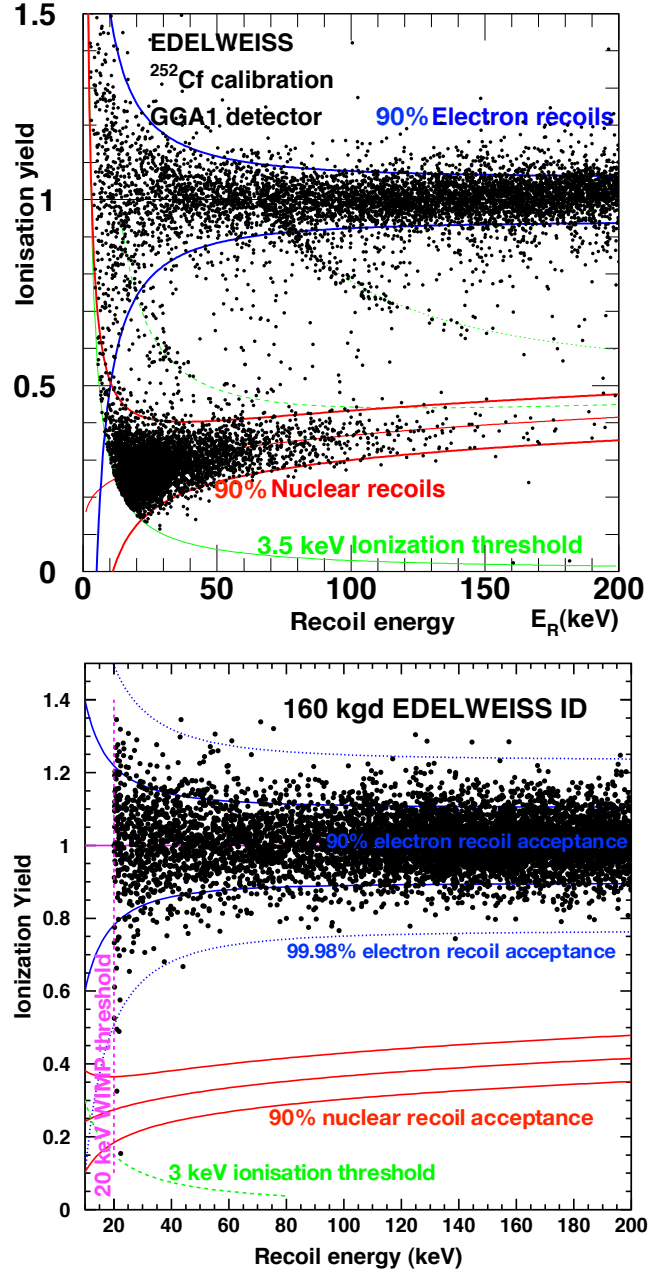


Figure 2.11: Scatter plots of events recorded using EDELWEISS detector modules during (*top*) calibration with ^{252}Cf neutron source and (*bottom*) dark matter run. Acceptance bounds are shown for electron and nuclear recoils, along with ionisation and WIMP search thresholds. From [68] and [43].

ionisation channel to energy detected in the phonon channel, where the response of each channel is calibrated by exposure of the detector module to gamma rays, so the ionisation yield of an electron recoil event is ~ 1 .

The top plot in Figure 2.11 shows events during module calibration with a ^{252}Cf neutron source. Elastic nuclear recoil events can be identified by their suppressed ionisation yield (red lines in Figure 2.11); additional bands can be identified for inelastic nuclear recoils (dashed green lines in Figure 2.11).

The bottom plot in Figure 2.11 shows events during 160 kg.day exposure for dark matter data measurement, in which additional discrimination by event location is implemented (see Section 2.4.2). One event is observed in the 90% nuclear recoil acceptance region, just above the 20 keV phonon energy threshold.

2.4.1 NTD-Ge sensors

Phonon signals produced by scattering events in the target crystal are detected using a *neutron transmutation doped* germanium (NTD-Ge) sensor glued to the crystal surface.

NTD-Ge sensors exploit the exponential temperature dependence of the low-temperature resistance of semiconducting germanium wafer which has been subjected to a high neutron flux [69]. A small piece of germanium wafer doped in this way can be prepared as a sensitive high-resistance temperature sensor.

The NTD-Ge sensors on EDELWEISS-II target crystals are connected to low-

noise cold (100 K) FET⁸ amplifiers using low-capacitance coaxial cabling. The signal is further amplified and filtered, and digitised continuously, by room temperature electronics.

The use of activated germanium for the NTD-Ge sensors could pose a background risk due to the radioactivity of the sensor. ‘NTD events’, occurring within the NTD-Ge sensor are characterised by very low ionisation energy, and are suppressed by the imposition of a 2–4 keV ionisation energy threshold (see Figure 2.11). NTD events can also be identified and removed by phonon pulse shape discrimination during data analysis.

2.4.2 Ionisation charge collection

Measurement of the ionisation charge deposited after a scattering event in the target crystal allows discrimination of electron recoils from germanium nuclear recoils.

The ionisation charge is collected using aluminium electrodes deposited on the surfaces of the target crystal. EDELWEISS-II detectors [49] use six electrodes (see Figure 2.12). Two ‘guard’ electrodes of opposed polarity collect charge deposited near the circumference of the crystal. Alternating rings of ‘fiducial’ and ‘veto’ electrodes collect charge deposit across the centre of the crystal, with potentials chosen such that the veto electrodes collect proportionately more charge deposited near the surfaces of the crystal.

⁸Field effect transistor.

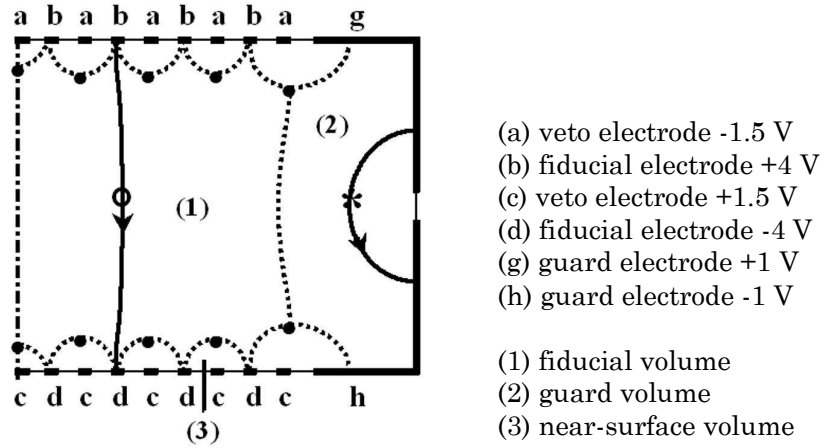


Figure 2.12: A schematic of the electrodes and field regions in an EDELWEISS-II target crystal. Dotted lines denote the boundaries of field regions and points of zero potential are marked with a solid dot. The field lines through events at $\circ$ and $\star$ are shown with solid lines. Taken from [49].

The charge collection electrodes are connected to cold FET amplifiers using low-capacitance coaxial cabling and read out using room temperature electronics. The effect of joule heating upon the phonon signal due to the applied voltage for charge collection is corrected for during data analysis.

Ionisation charge measurement allows the definition of three volumes within the target crystal; the ‘guard’ region near to the circumference of the crystal, the ‘near-surface’ region close to the flat sides of the crystal, and the fiducial volume in the centre of the crystal (see Figure 2.12). The uniform charge collection efficiency, and self-shielding from alpha particle background, within the fiducial volume allows improved discrimination of non-background nuclear recoil events.

2.5 Summary and outlook

We have seen that a wide range of evidence exists for the presence of dark matter in the observed behaviour of many astrophysical systems (Chapter 1). In Chapter 2 the phenomenological and experimental basis of direct WIMP searches was described. The necessity for high resolution at low energies, discrimination of background and apparatus of high radiopurity in direct WIMP searches was described. The hardware developed and used in the CRESST-II and EDELWEISS-II cryodetector direct searches was described.

Evaluation

The current mass-dependent upper limits on WIMP-nucleon cross-section are shown in Figure 2.1. It can be seen that in order to probe CMSSM expected WIMP parameters with direct search observations, an increase in sensitivity of some 2–3 orders of magnitude is needed to advance current experimental limits from above 10^{-8} pb to 10^{-10} pb and beyond. Future projects in which detector mass is scaled up from ~ 10 kg to ~ 1 tonne, with improved background suppression and discrimination, are planned to achieve this increased sensitivity.

We have seen that cryodetector technologies offer excellent discrimination of nuclear recoil events from electron scattering background events. This discrimination makes cryodetector technologies particularly suitable for scaling up to larger overall target mass, as the low contamination of background events in nuclear recoil

event spectra will ensure that the overall sensitivity to WIMP-nucleon scattering events scales with increasing target mass. However, realising increased cryodetector target mass poses hardware challenges, as current cryodetector technologies are sensitive to component radiopurity and readout heatload, and are costly to manufacture. This thesis describes a search for solutions to these challenges.

The CRESST detector modules, with their coincident phonon-light measurement, offer identification of the scattered nucleus, as well as discrimination between electron and nuclear scattering events. However, the necessity of running two SQUID sensors with independently stabilised TES sensors for each detector module incurs both monetary and heatload costs and increases the complexity of detector operation. To reduce the cost and heatload of SQUID cabling was one of the aims of the work in this thesis. The development of low temperature PMT modules for use in place of the CRESST-type cryogenic light detectors was another.

EDELWEISS detector modules offer identification of nuclear recoil events and discrimination of surface events, and their NTD-Ge phonon sensors offer intrinsically high-impedance low-heatload readout. NTD-Ge phonon sensors offer the additional advantage of a wider range of operating temperatures than TES sensors, without independent temperature stabilisation. One of the aims of this thesis was to develop low-cost NTD-Ge sensor readout cabling without compromising on sensor performance.

Future cryodetector direct searches

Proposed advanced cryodetector projects include the EDELWEISS-III upgrade, which aims to reach a projected lower limit of $\sim 5 \times 10^{-9}$ pb by augmenting the EDELWEISS-II detector array with new modules [72]. Work is underway to provide the additional detector mass and expanded readout capacity necessary in this upgrade.

The SuperCDMS proposal is to eventually install 145 kg germanium target mass at SNOLab, Ontario, Canada to probe the 10^{-10} pb range [70].

The efforts of the CRESST and EDELWEISS collaborations will ultimately be pooled within the EURECA collaboration [71], which will develop a mixed target nuclei cryodetector array with a proposed final mass of ~ 1 tonne to be installed in the deep underground laboratory at LSM.

With increased target mass critical to future direct WIMP searches, cryodetector readout development must focus on delivering excellent resolution and discrimination with increased scalability, simplification of production, improved reliability and reduced cost.

Chapter 3

Etched metal foil cryogenic cabling

Cabling for use in cryogenic instrument readout must be carefully designed. The readout of highly sensitive detectors must be carried out using electric connections which do not introduce excess noise to the signal, while the heat load introduced into the cryostat via conduction and ohmic heating in the cabling must be minimised.

For future dark matter searches such as EURECA and the EDELWEISS-III upgrade, in which many hundreds of readout channels are envisaged, minimisation of cost per channel is also of crucial importance. In order to address the issue of cryogenic cabling heatload and cost while maintaining excellent low-noise performance, etched metal foil cryogenic cabling was designed, fabricated and tested

using in-house facilities at the physics department of Oxford University.

Applications for etched metal foil cabling

The next generation of cryodetector direct dark matter searches, described in Section 2.5, are aiming to increase detector target mass by an order of magnitude. An inexpensive, reliable method for manufacturing low heatload cryogenic cabling will be essential in achieving this goal.

Development of low cost SQUID cabling mounted between 4.2 K and room temperature was carried out as part of a study into potential readout methods for EURECA cryogenic detectors.

The EDELWEISS-III upgrade requires an extension of the available cabling channels. Prototype etched metal foil cabling was developed for the connection between the FET amplifier mounted at 100 K and the detector modules mounted at a few tens of millikelvin.

In addition, the CryoEDM experiment runs SQUID sensors for precision magnetometry [73]. Etched metal foil cables were provided as an alternative to the expensive woven cables used for SQUID readout on this experiment.

The design and testing of the specialised etched metal foil cabling for these applications is described in this chapter.

3.1 Etched metal foil fabrication

Photolithographic processes are commonly used in the fabrication of printed circuit board (PCB) and as such the techniques are widely available and well developed. However, the application of these techniques to manufacture practical cryogenic cabling required specialist development, design and testing to overcome the challenges of low-temperature, low-noise readout. I will describe the techniques used in fabrication of etched metal foil cabling in order to show that prototype cable designs were optimised subject to the constraints of the fabrication techniques and installation environment.

3.1.1 Photolithography

Process

Stages of the photolithography process for etching tracks into a conducting foil are listed below.

Phototool: a high resolution negative image of the conducting track design is printed on acetate. This is called a ‘phototool’.

Photoresist: to etch conducting tracks into a metal foil laminated onto a suitable substrate, a ‘photoresist’ layer is adhered to the conducting foil. This photoresist layer is soluble in an organic ‘developer’ solution until exposure to ultraviolet light.

Exposure: the phototool is used to expose to ultraviolet light the foil areas intended to become conducting tracks. The UV exposure unit used is shown in



Figure 3.1: Equipment at the Oxford Physics Photofabrication Unit: (*left*) UV exposure unit; (*right*) etching bath.

Figure 3.1.

Development: the developer solution is applied to remove the photoresist from the unexposed areas.

Etching: the etchant solution is applied, removing foil in the areas from which the photoresist has been removed, leaving the desired track design intact. The etching bath used is shown in Figure 3.1. The remaining photoresist is subsequently cleaned from the tracks.

The phototools were produced by Photodata of Hitchin, Hertfordshire. Subsequent processes were carried out within the Photofabrication Unit (PFU) at the physics department of Oxford University. The materials used were copper or stainless steel foils laminated onto a flexible polyimide film substrate, such as Apical (Kaneka) or Kapton (DuPont). Polyimides have similar thermal expansion coefficients to metals and low outgassing rates. The etching agents were HCl and FeCl_3 .

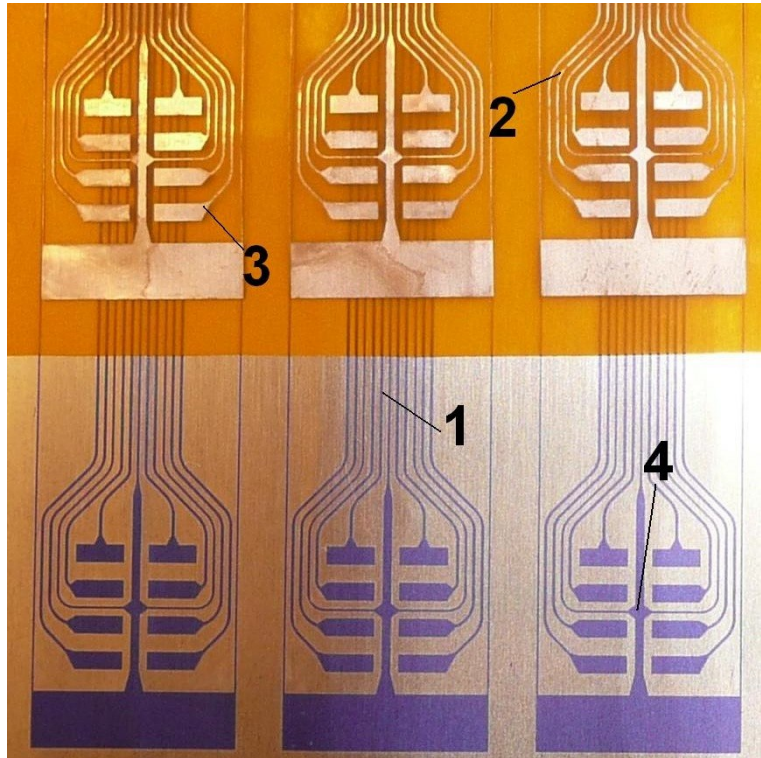


Figure 3.2: Detail of connector mounting pads. A pre-etching sheet with blue photoresist can be seen beneath a fully etched sheet. Several design features can be seen: (1) evenly spaced tracks, (2) radiused track corners, (3) teardrop join with connector pad, (4) reinforcement of vulnerable areas.

Available materials and design tolerances

The methods and facilities available imposed some constraints on cable design. Careful phototool design was essential to achieve a good yield of finished cables, minimising cable wastage due to over-etching.

The materials and etchants used placed general constraints on cable design. The steel and copper foils chosen varied between $18\ \mu\text{m}$ and $50\ \mu\text{m}$ thickness, mounted on a $100\ \mu\text{m}$ polyimide substrate. The minimum track width and spacing achievable at PFU was $50\ \mu\text{m}$ (using $18\ \mu\text{m}$ thick copper foil).

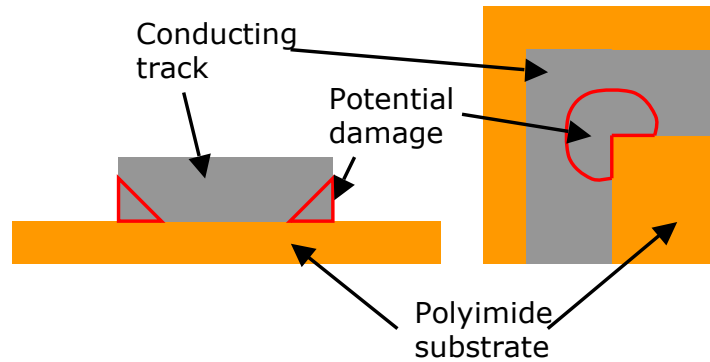


Figure 3.3: **Simplified illustration showing possible damage (red lined areas) to conducting tracks due to etching fluid build-up: (left) profile view showing under-cutting; (right) top view showing over-etching at right-angled corner.**

Ensuring the complete etching of target areas necessitated some over-etching and possible under-cutting of conductor tracks (see Figure 3.3). It was found that the risk of accidental track breakage and under-cutting during etching can be reduced by designing tracks of uniform width separated by etched areas of uniform width, so that the etching time required does not vary spatially over the cabling sheet. Etching fluids can build up on the inside of angles in non-etched (resistant) areas and tracks. This can lead to over-etching on the inside of corners and bends in conducting tracks, creating an undesired weak point in the finished cable. This risk can be negated by removing these angled junctions and bends in track design, using radiussed bends and tear-dropped junctions instead. It was found that the fine tracks used for cryogenic cable fabrication were not durable when subjected to sharp folding, developing short circuits or open tracks. For this reason the finished cables were designed as single rectangular polyimide ribbons.

Cable wastage due to breaks and short circuits can also be caused by dust and

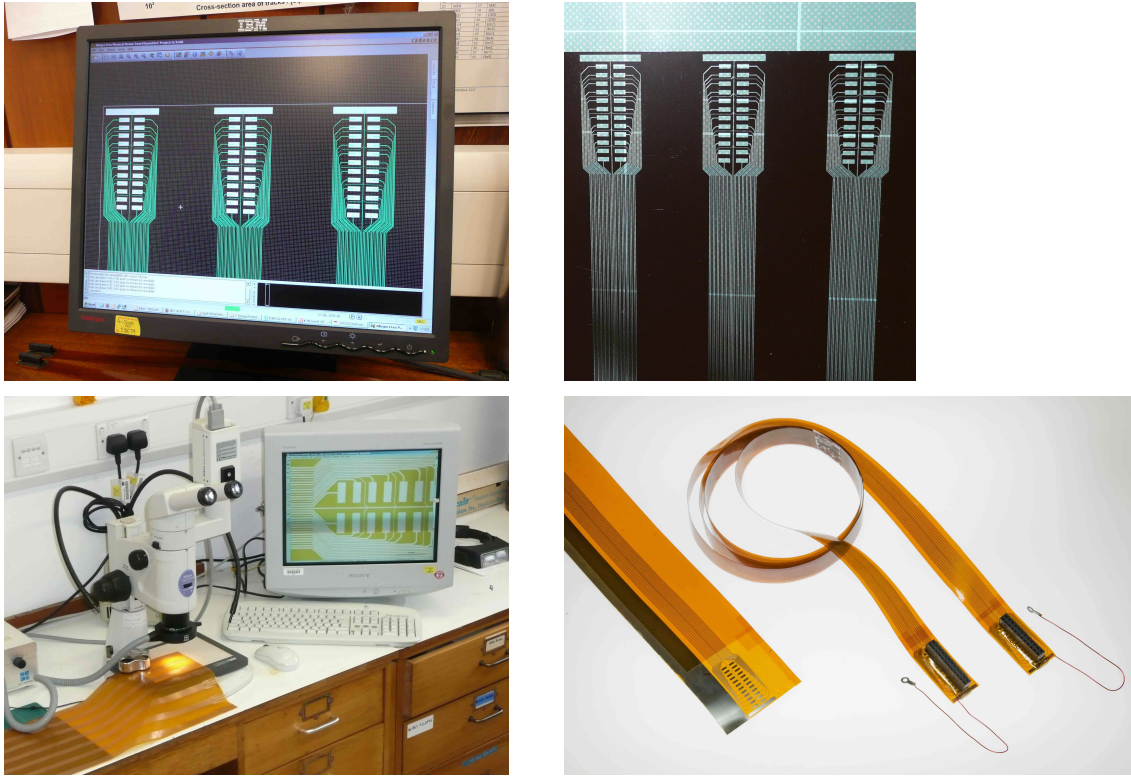


Figure 3.4: Selected stages in the fabrication of etched metal foil cables: *(top left)* inspection of phototool design; *(top right)* finished phototool; *(bottom left)* inspection of etched cable; *(bottom right)* finished cable alongside trimmed laminated cable.

dirt present during the etching process. Photolithography requires very clean, dust-free conditions, particularly during exposure of the photoresist, as dust particles will create weak areas during etching. The Oxford Physics Photofabrication Unit operates a class 10,000 cleanroom to minimise this risk and maximise the yield of good cables, essential for reducing cabling costs.

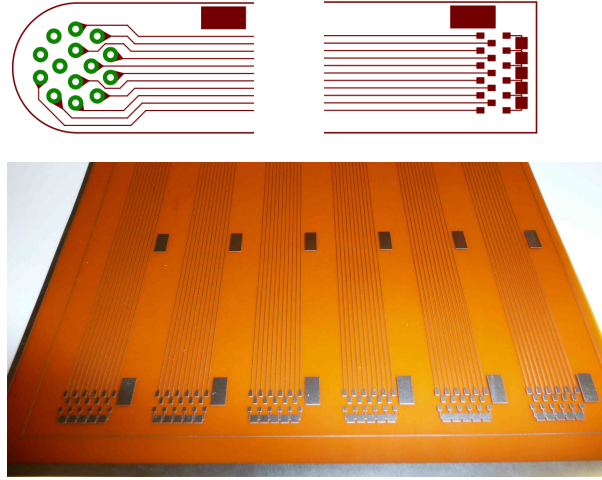


Figure 3.5: **Details of the phototool used to produce prototype cables for the EDELWEISS upgrade. A sheet of etched cables is shown.**

3.1.2 Fabrication

The complete process for producing cables by photolithography can be split into three sub-processes: design, photolithography and finishing.

In the design process a specification is defined in which the physics performance of the cable is optimised subject to the constraints described in Section 3.1.1- heatload is minimised by choice of track width and cable length, noise and bandwidth for specific applications are optimised by choice of capacitance, resistance and shielding. From this specification a phototool can be drawn using CAD software. The phototool is then printed at the required resolution by an external contractor.

The etching process is carried out as described in Section 3.1.1. Durable covering and termination of each etched track is required to complete the cables.

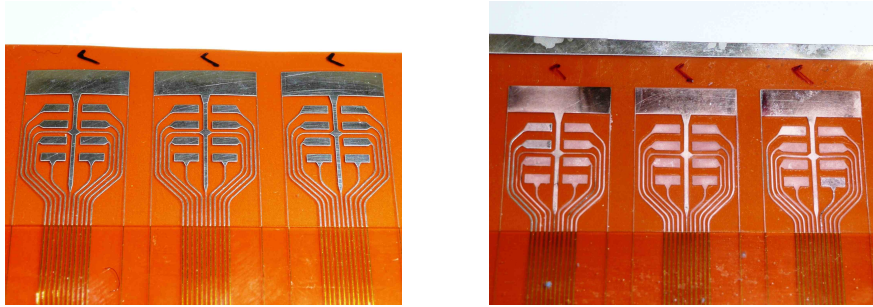


Figure 3.6: A sheet of etched steel foil 4-track-pair SQUID cables shown before and after copper plating.

Lamination

The conducting foil tracks were very susceptible to damage and accidental short circuits. After etching the cables were laminated with a layer of polyimide film, leaving only the connection pads exposed. A 1.2 m wide laminator is available at PFU, with cables longer than 1.2 m laminated in two pressings. Where earthed shielding planes for the conducting foil tracks were required, continuous layers of metal foil were laminated onto the outer surfaces of each cable.

Connectors

Careful consideration was given to providing compact, durable electrical connections for the cables. For prototype cables, a versatile connector compatible with existing fixtures and mountings was desired. For this reason, 2.54 mm pitch surface mount Samtec terminator sockets were soldered onto flat connection pads at the ends of the conducting tracks. This soldering could be made directly onto copper foil cables, but for steel foil cables it was necessary to copper-plate the connection

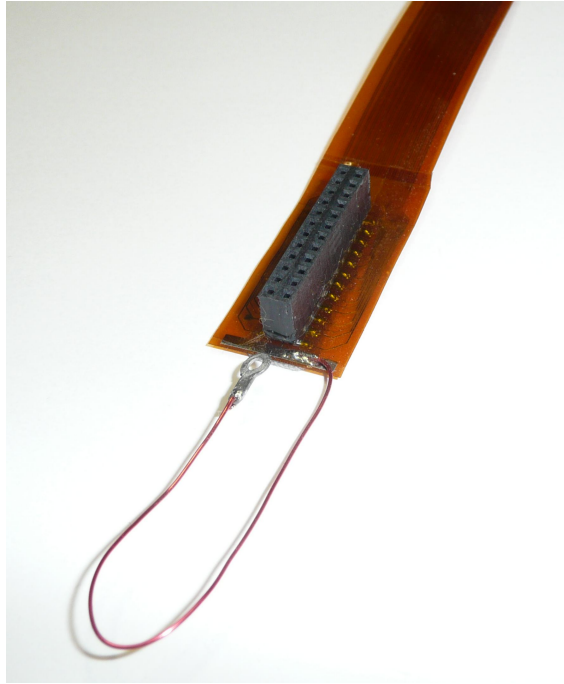


Figure 3.7: **Detail of the connector on a completed 12-track-pair SQUID cable.**

pads before soldering (see Figure 3.6). On SQUID cabling, earthed shielding tracks were provided between adjacent track pairs and a lead for securing these to earth via an M3 solder tag was provided via a pad at the end of the cable. A finished SQUID cable connector is shown in Figure 3.7.

3.1.3 Installation

Installation of etched metal foil cables within a dilution refrigerator required design and fabrication of new mountings, heatsinks and vacuum feedthroughs suitable for etched metal foil cabling. In each case attention was paid to the demands of future experimental particle physics applications: high channel density and design simplicity were paramount; heatload and cost were minimised. The aim in each



Figure 3.8: Photographs showing etched metal foil cabling after installation: *(left)* two 12-track-pair cables installed for readout of 5 SQUID sensors mounted in an Oxford Instruments K400 dilution refrigerator; *(centre)* a shielded cable installed for readout of NTD-Ge sensors within the EDELWEISS test cryostat at IPNL; *(right)* several 4-track-pair cables installed alongside their woven counterparts for readout of SQUID sensors at the CryoEDM experiment, Grenoble.

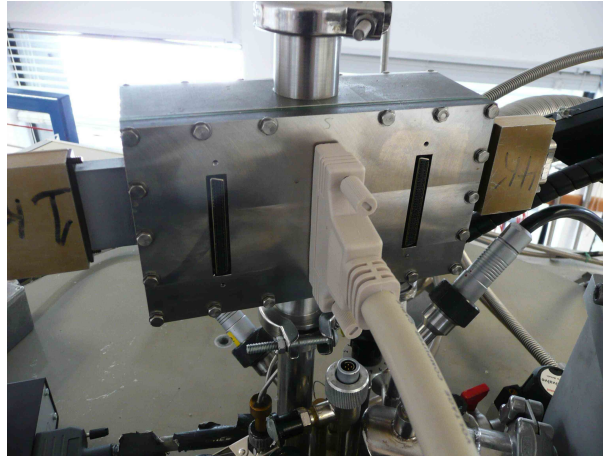


Figure 3.9: **Photograph of room temperature vacuum feedthrough box after installation.**

case is to reproduce or improve upon low noise, high resolution performance of existing systems. Three experimental installations of etched metal foil cabling are shown in Figure 3.8. In this section the installation of a new 5-channel SQUID system using etched metal foil cabling inside a K400 dilution refrigerator at Oxford University is described in detail.

Feedthroughs

The new SQUID sensors were mounted within the inner vacuum chamber (IVC) of a K400 dilution refrigerator, on a plate in direct contact with the helium-4 bath. To achieve thermal isolation of the dilution unit from the helium-4 bath the IVC must be evacuated below 10^{-6} mbar. A vacuum feedthrough box for electrical connection of the etched metal foil cables to room temperature cabling was designed and installed (Figure 3.9). The box was designed for high channel

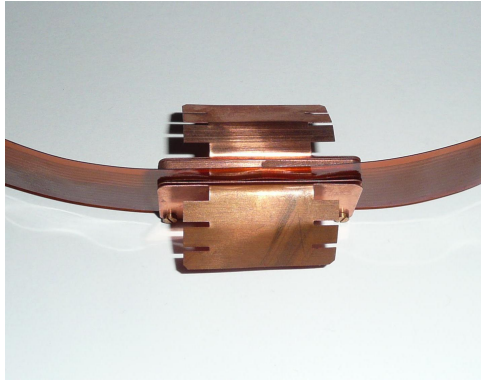


Figure 3.10: **Photograph of copper baffle design for heatsinking etched metal foil cables inside evacuated connection tubes.**

density and simplicity of construction. A PCB integrated into the vacuum wall provides direct connection between SCSI cables and etched metal foil cables for 72 track-pairs (sufficient capacity for the installation of 24 SQUID sensors). Existing connectors and cables were also accommodated in the new vacuum feedthrough box.

Heatsinks

The etched metal foil SQUID cables were installed between the room temperature vacuum feedthrough and a SQUID sensor mount at 4.2 K. Good thermalisation of the cables was essential to ensure minimal heat transfer to the SQUID mount and thus a stable running temperature for the sensors. The cables were fitted with copper baffles spaced at 15 cm intervals, designed to thermally connect the polyimide film to the IVC wall on the inside of the 25 mm tube through which the cables ran. Copper plate of 250 μm thickness was used to make compact flexible

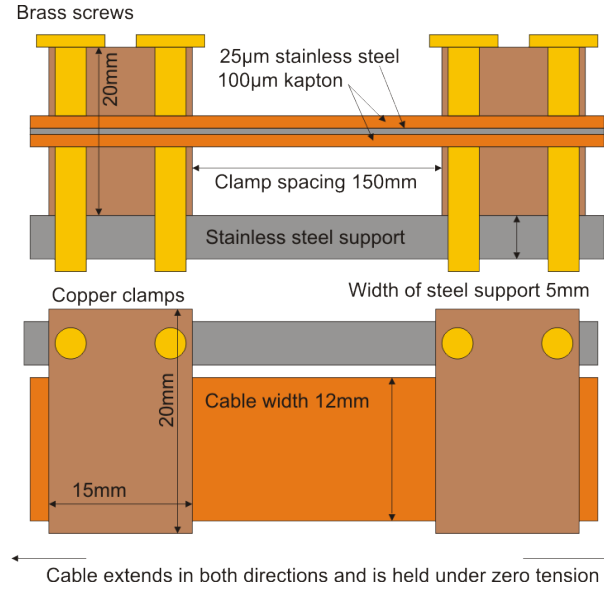


Figure 3.11: **A clamping scheme proving rigid support and heatsinking for etched metal foil cables envisaged for future purpose-built installations.**

baffles affording good thermal contact between the cables and the walls of the tube (Figure 3.10).

It will be possible in future applications to achieve higher channel density and durability using a rigid support structure for cable installation and heatsinking. In the readout of high-impedance NTD-Ge sensors variation in capacitance due to cable vibration is a significant noise source. A rigid support structure would offer control and reduction of cable vibration (see Figure 3.11).

3.2 Heatload

In this section the effects of heating by thermal conduction and resistive power dissipation in cabling will be described. Etched metal foil cabling was designed to

offer heatload reduction over existing cryogenic cabling. The heating effects due to cabling in a dilution refrigerator were considered and the causes of heating due to the cabling were modelled. Metal foils for cabling fabrication were tested and the heatload due to prototype etched metal foil cabling was calculated. Strategies for minimising the heatload due to cryogenic cabling are discussed.

3.2.1 Heatload in a dilution refrigerator

The various sources of unwanted heat in a dilution refrigerator can be divided between those which apply heating to the liquid helium bath, causing helium evaporation, and those which apply heating to the various stages of the dilution insert, acting against the cooling power of the refrigerator and reducing cryostat performance¹.

The latent heat of helium vaporisation is 21 kJ/kg, so a heatload of 30 mW applied to the helium bath of a dilution refrigerator will cause 1 l of helium evaporation daily.

Cooling power measurements for the dilution units of the Oxford Instruments K400 and S400 dilution refrigerators used in this work had been measured during cryostat commissioning (table 3.1). Although the cooling power available varies with circulation conditions, and larger, more powerful dilution refrigerators are available, these are representative values for dilution refrigerators commonly in

¹Dilution refrigerators commonly utilise a liquid helium bath to insulate a ‘dilution insert’ capable of cooling a sample in vacuum to a few mK. In-depth introductions to dilution refrigerator design and operation can be found in [66] and [75].

K400		S400	
T / mK	P / μ W	T / mK	P / μ W
4.8	0	5.0	0
11.2	2.0	10.0	2.5
16.0	5.0	23.0	20
42.0	50		
98.0	350		

Table 3.1: **Cooling power at the mixing chamber of the Oxford Instruments dilution refrigerators used in this work.**

use today. Any excess heatload acting on the dilution unit will place an upper limit on the lowest achievable cryostat base temperature.

Calculations of heatload in etched metal foil cables will be compared to the existing CRESST cabling system (see Section 2.3.3). The heatload due to the 66-channel CRESST cabling system is itemised in Table 2.1.

Etched metal foil cables must be designed to reduce heatload per channel in order to accommodate even larger numbers of readout channels in future applications. To facilitate heatload estimation and control in etched metal foil cable design, a heatload model incorporating resistive and conductive heating was developed and measurements of the resistivity of the cabling materials were carried out to furnish data for accurate heatload calculations.

3.2.2 Resistivity and thermal conduction

In metals at low temperatures, conduction electrons are the primary carriers for thermal conduction [76]. In this regime, the relation between electrical resistivity ρ and thermal conductivity κ is given by the Wiedemann-Franz law (3.1) [77]:

$$\kappa\rho = L_0T \quad (3.1)$$

$$\text{where } L_0 = \frac{\pi^2}{3} \left(\frac{k_B}{e} \right)^2 = 2.44 \times 10^{-8} \text{ W}\Omega\text{K}^{-2} \quad (3.2)$$

If the low-temperature resistivity of the metals used for etched metal foil cable fabrication is understood, the applicability of the Wiedemann-Franz law provides a mechanism for accurate calculation of the heatload due to cabling made of these metals.

Resistivity measurements

There are three dominant contributions to the resistivity of metals over the temperature range 290 K – 4.2 K; electron-phonon scattering, electron-electron scattering and electron-impurity scattering. Resistivity due to electron-phonon scattering varies as T^n in this temperature range, where $4 \leq n \leq 5$ [80]. Resistivity due to electron-electron scattering varies as T^2 [78]. At very low temperatures these contributions are negligible compared to the resistivity due to electron-impurity scattering, which is invariant with temperature variation, but strongly dependent on sample purity.

Since the cabling would be used in the temperature range in which electron-

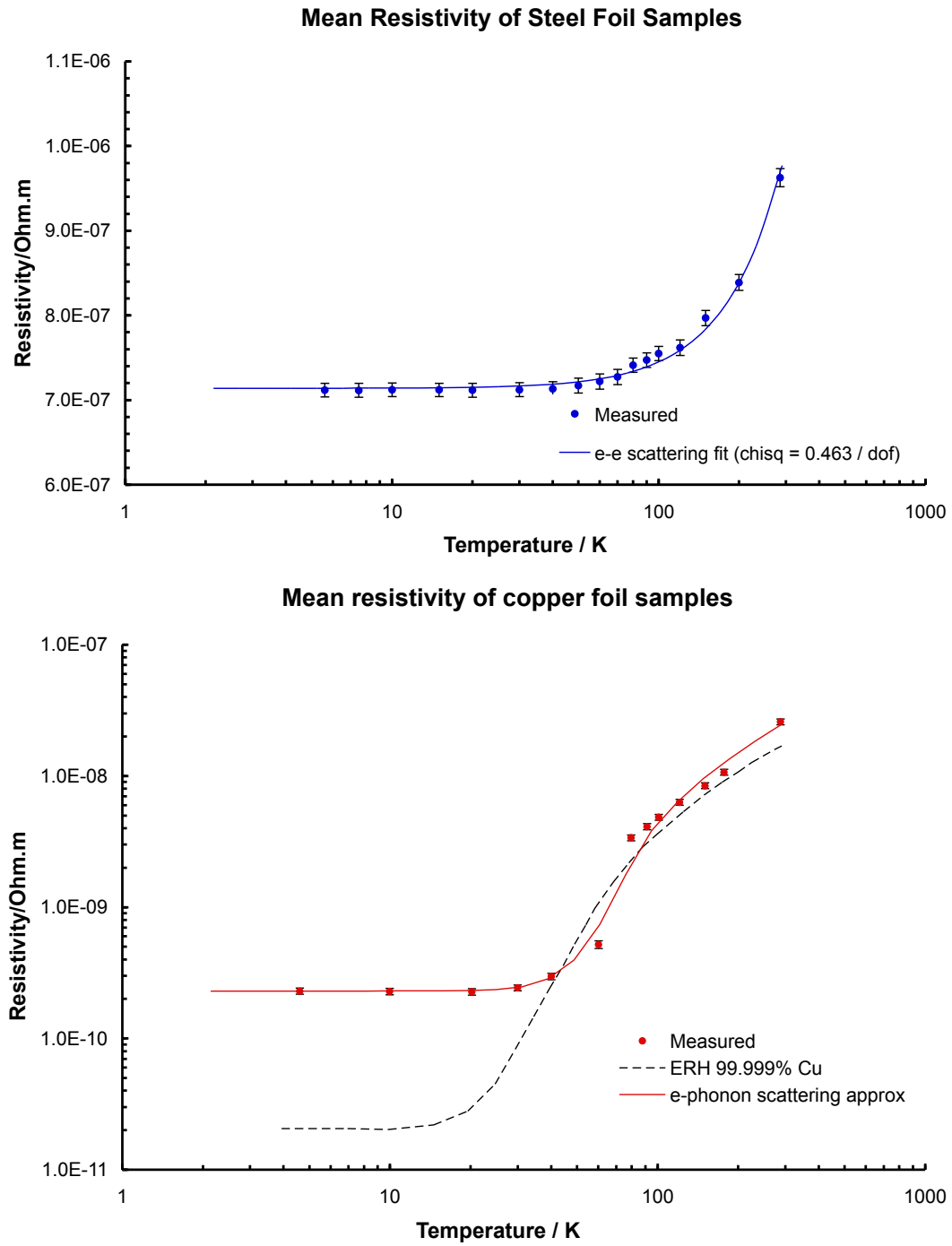


Figure 3.12: Resistivity measurements of samples of the metal foils used in the fabrication of etched metal foil cables over temperature range 4.2 K – 290 K. (*Top*) steel foil resistivity showing fit function. (*Bottom*) copper foil resistivity showing approximate function and high-purity copper resistivity reported in [79] ('ERH 99.999% Cu').

impurity scattering is the dominant contribution to resistivity, it was important to base heatload calculations on measured resistivity of the metal foils used. Measured resistivity variation for steel and copper foil samples under cooling from room temperature to 4.2 K is shown in Figure 3.12.

The results of the resistivity measurements and fitting for electron-impurity (temperature-independent) and electron-electron ($\propto T^2$) scattering showed that the steel foil resistivity was dominated by electron-impurity scattering. The low χ^2 value obtained for this fit ($\chi^2 = 0.463$ /d.o.f.) was indicative of over-estimated error bounds. The dominant contribution to the error bound estimate in these measurements was the manufacturer's stated measurement tolerance ($\pm 1\%$ in this resistance range), which appears to be a generous overestimate. Steel foil resistivity fell at low temperatures to a constant value $\sim 80\%$ of its room temperature value.

The copper foil resistivity fell under cooling to $\sim 1\%$ of its room temperature value and the temperature invariance of this residual resistivity indicated that electron-impurity scattering is the dominant resistive effect at low temperatures. The value of the low-temperature residual resistance in copper is known to be strongly dependent on sample purity. Figure 3.12 shows reported resistivity of a high-purity 99.999 % copper sample for comparison with the measured values from this sample [79]. One may conclude that the sample copper is of lower purity than this high-purity reference.

The effect of electron-phonon scattering on the temperature dependence of

Material	Resistivity function
Steel	$\rho(T) = 7.14 \times 10^{-7} + 3.13 \times 10^{-12}T^2$
Manganin	$\rho(T) = 9.0 \times 10^{-8} + 1.8 \times 10^{-12}T^2$
Copper ($T < 80$ K)	$\rho(T) = 2.30 \times 10^{-10} + 6.09 \times 10^{-19}T^5$
Copper ($T > 80$ K)	$\rho(T) = 1.07 \times 10^{-10}T - 6.34 \times 10^{-9}$

Table 3.2: **Approximate empirical functions for heatload calculations on etched metal foil cabling. Parameters for steel and copper foils from measured data, parameters for manganin calculated from reported data [79].**

copper resistivity is known to exhibit power-law behaviour in which indices exhibit temperature dependence; $\rho_{e-phonon} \propto T^{n(T)}$ [80]. A comprehensive model of copper resistivity over the temperature range 4.2 K – 290 K was outside the scope of the present work, but an empirical function in which the low temperature (< 80 K) and high temperature (> 80 K) behaviour was adequately represented was approximated to the measured data. The level of low-temperature electron-impurity scattering, unique to the copper foil available for cable fabrication, was thus included in the heatload calculation.

Empirical functions used for heatload calculations are given in Table 3.2.

Heatload calculation

As a tool for cable design, this data can be used to calculate heatload by thermal conduction and resistive dissipation by the conducting tracks. Thermal conduction between temperature reservoirs at T_1 and T_2 along a conducting track of thermal

conductivity $\kappa(T)$, length L and cross-sectional area a is given by (3.3)².

$$P_{cond} = \int_{T_1}^{T_2} dT \frac{a}{L} \kappa(T) \quad (3.3)$$

Considering a track in a steady state ($dT/dt = 0$) in which no current flows, the principle of energy conservation dictates that a constant power flows along the length of the track. Writing the instantaneous power at a point l on the track as (3.4), we can obtain a relation for the variation of temperature with length along the track (3.5):

$$P_{cond} = dT \frac{a}{dl} \kappa(T) \quad (3.4)$$

$$\frac{dl}{dT} = \frac{a\kappa(T)}{P_{cond}} \quad (3.5)$$

Now consider a track with a current I flowing through it. An additional heatload due to resistive dissipation can be found (3.6):

$$P_{res} = \int_0^L dl \frac{I^2}{a} \rho(T) = \int_{T_1}^{T_2} dT \frac{I^2}{a} \rho(T) \frac{dl}{dT} \quad (3.6)$$

Approximating the temperature profile of the track with that of the zero-current case and substituting using (3.1) we can obtain the total heatload (3.7).

$$P \simeq P_{cond} + \frac{I^2 L_0}{P_{cond}} \left(\frac{T_2^2 - T_1^2}{2} \right) \quad (3.7)$$

Using (3.1), in the case that $\rho(T) = \alpha + \beta T^2$, P_{cond} is given by (3.8).

$$P_{cond} = \frac{aL_0}{2\beta L} \ln \left(\frac{\alpha + \beta T_2^2}{\alpha + \beta T_1^2} \right) \quad (3.8)$$

²Thermal conductivity is defined by $\kappa \equiv \frac{P_{cond}L}{a\Delta T}$ for a body of constant thermal conductivity. To generalise to $\kappa(T)$ consider an element dl of a body of uniform cross-section a at a temperature T through which a power P flows. The temperature gradient is given by $dT = \frac{Pdl}{\kappa(T)a}$. Equation (3.3) can be found by integration.

For copper cabling, numerical integration was carried out over the specified temperature range.

3.2.3 Implications for cabling design

Cabling from 290 K to 4.2 K

Calculated heatload for a metal conducting track of length 1.4 m terminated at 4.2 K is shown in Figure 3.13 as a function of track cross-sectional area for typical bias currents used in low-impedance TES readout of the CRESST type (SQUID bias $\sim 50 \mu\text{A}$, TES bias $\sim 10 \mu\text{A}$). This information was used in the design process for the etched metal foil SQUID cables tested in Oxford, which are of the same length as the CRESST SQUID cables.

It can be seen that, for steel conducting tracks carrying SQUID bias currents, the heatload ($\sim 4.9 \mu\text{W track}^{-1}$) of the prototype cables lies close to the minimum achievable heatload, at which $P_{cond} = P_{res}$. The estimated heatload of existing CRESST manganin cabling is $\sim 120 \mu\text{W track}^{-1}$ with this model, in agreement with earlier studies [62].

The track profile chosen for the prototype etched metal foil SQUID cables was also, in practice, constrained by available materials and by the desire to produce durable, flexible cables for versatility of installation. Despite this, it can be seen that etched metal foil cabling offers heatload control through careful design and, in this case, a significant reduction (factor > 24) in heatload was achieved.

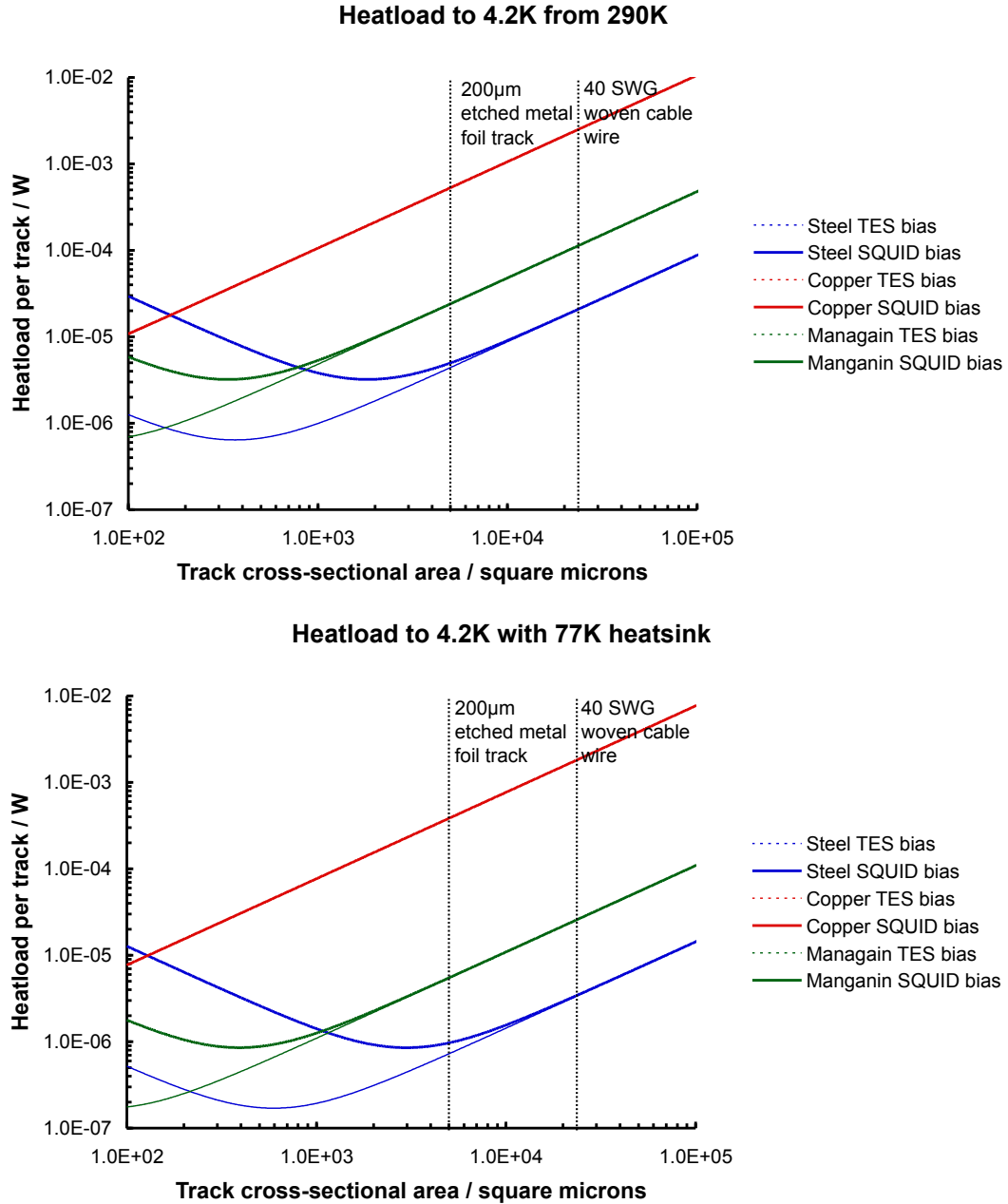


Figure 3.13: Calculated heatload at 4.2 K per track for steel, copper and manganin tracks carrying currents of $10 \mu\text{A}$ (a typical TES bias) and $50 \mu\text{A}$ (a typical SQUID bias) between 4.2 K and 290 K plotted for a range of track cross-sectional areas; (*top*) 1.4 m cable without heatsink, (*bottom*) with 77 K heatsink at 70 cm. The cross-sectional areas of the etched meal foil tracks and 40 SWG wire (used in CRESST cabling) are marked.

The lower limit that the Wiedemann-Franz law imposes on the minimum heatload for non-superconducting current-carrying cabling can be circumvented through heatsinking and pre-cooling of cabling at temperatures above 4.2 K. The lower plot of Figure 3.13 shows the effective heatload at 4.2 K of thermally anchoring the centre point of the cable to a liquid nitrogen bath at 77 K. If such a heatsink could be installed on the etched metal foil SQUID cables, the estimated effect would be to further reduce heatload to $\sim 0.97 \mu\text{W track}^{-1}$. The effect of pre-cooling cables using cold vapour evaporating from the helium bath instead of liquid nitrogen is more difficult to quantify but would also offer reduction of heatload to 4.2 K. Both of these options should be considered for applications in which heatload to 4.2 K must be tightly controlled.

Cabling below 4.2 K

The etched metal foil cables prototyped for NTD-Ge sensor readout were installed between the detector module mounted at 18 mK and a vacuum feedthrough mounted at 4.2 K without additional heatsinking. Copper cabling is too thermally conductive to be used in this temperature range, so etched steel foil cables were developed. Typical current flow was ~ 1 nA. The tracks installed were 50 cm long and $200 \mu\text{m}$ wide etched into a steel foil $25 \mu\text{m}$ thick. As the electronic behaviour for these steel cables is dominated by temperature-invariant electron-impurity scattering at low temperatures [81] (as seen in Figure 3.12), the resistivity data from 4.2 K measurements can be used to estimate heatload at 18 mK due to these cables.

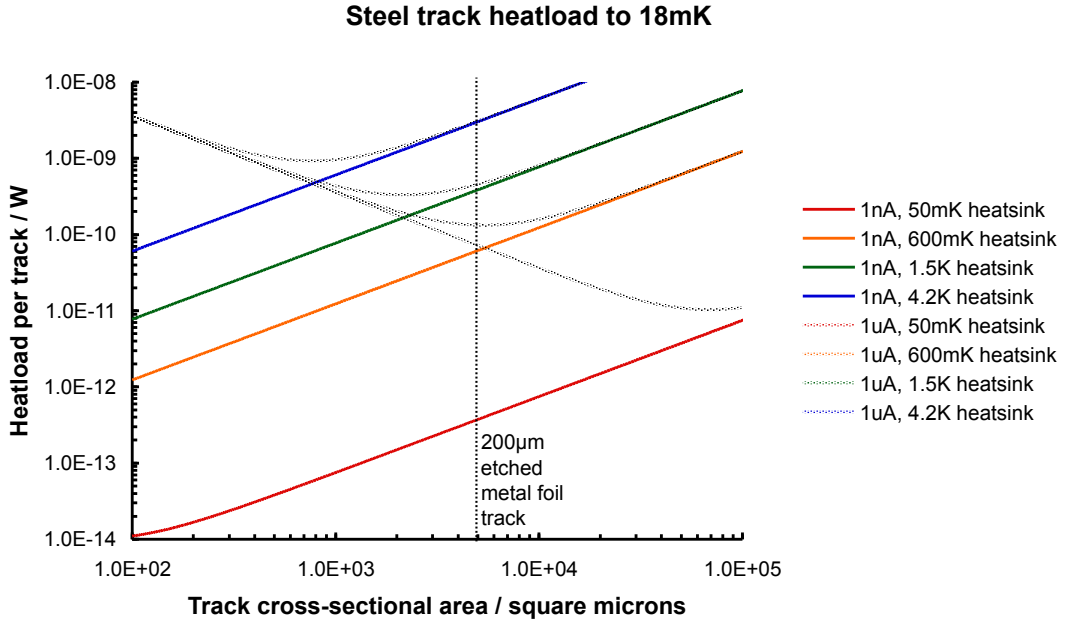


Figure 3.14: Calculated heatload as a function of track cross-sectional area for steel tracks terminated at 18 mK carrying currents of 1 μA and 1 nA. The tracks are 50 cm long and are connected to a range of heatsinks with temperatures corresponding to stages of a dilution refrigerator.

Heatload to the detector module is shown as a function of track cross-sectional area for low and intermediate currents and a range of heatsink temperatures in Figure 3.14.

It can be seen that steel foil cabling in this low-current regime offers very low heatload; many hundreds of track pairs need not exceed a few μW (the calculated heatload for the 50 cm steel cables between 18 mK and 4.2 K is $\sim 3.1 \text{ nW track}^{-1}$). This is a lower calculated heatload than the superconducting cabling used at temperatures below 4.2 K in the CRESST cryostat ($\sim 28 \text{ nW track}^{-1}$, see Table 2.1)³. It can also be seen that heatsinking is a most effective practical means

³This CRESST cabling is made of niobium-titanium conductor in a copper-nickel matrix, which is present to provide sufficient thermal conduction for the niobium-titanium

of controlling heatload at low temperatures.

3.3 Radiopurity

In Section 2.2.1 the requirement for high radiopurity standards in the fabrication of components for direct WIMP searches was introduced.

Measurements were carried out to determine the radioisotope content of cabling materials with the aim of identifying the optimum materials and techniques for fabrication of high-radiopurity etched metal foil cabling.

3.3.1 Radioactive contaminants in cabling materials

In cabling development, the minimisation of activity resulting from contaminant radioisotopes in the cabling materials is a priority. It is anticipated that etched metal foil cabling will be installed in close proximity to future detector target materials and so the potential radioactive contamination of the materials used in cable fabrication must be understood and minimised.

The metals, plastics, adhesives and etchants used in etched metal foil cable fabrication are subject to an almost endless array of potential sources of radioactive contaminants: the raw materials may contain unstable isotopes, the processes used to prepare them may allow contamination to take place or the processes of etching and lamination may cause inadvertent contamination due to airborne particles. In

to become superconducting along the whole length of wire. This thermal conduction dominates total heatload at low temperatures.

particular the radiopurity of metal alloys can vary considerably depending on the conditions of their manufacture.

The isotopes detected in samples of etched metal foil cabling materials include several found in the decay series of ^{232}Th and ^{238}U (see Appendix A). These long-lived heavy isotopes produce a series of unstable daughters on decay. Observed activity rates of short-lived daughter isotopes can be readily compared; for example, in a closed sample the observed decay rate of ^{228}Ac , which has a half-life of 6.1 hr, will be equal to the decay rate of ^{228}Ra , since the overwhelming majority of any ^{228}Ac present in the sample will be due to the decay of ^{228}Ra . Using this logic, we have used the observed activity of ^{228}Ac to estimate the activity of ^{228}Ra , the observed activity of ^{214}Pb to estimate that of ^{226}Ra , and the observed activity of ^{212}Pb to estimate that of ^{228}Th .

3.3.2 Tests of cabling materials

In order to assess the suitability of materials used for fabrication of low-heatload etched metal foil cryogenic cabling, samples of suitable insulating films and stainless steel foil were sent for testing in low-background conditions at the underground laboratory of LSM Modane. Measurements of radioactive contaminant activity levels made using an HPGe^4 detector by M. De Jesus of Institut de Physique Nucléaire de Lyon (IPNL) are given in Appendix B.

The measured samples were taken from the batched of polyimide (PI) film and

⁴High purity germanium semiconductor detector. See [84] [85].

stainless steel foil used at the Oxford Physics PFU for cable fabrication. Polyethylene naphthalate (PEN) film was sourced and tested as a potential alternative to PI for cable insulation.

The ‘untreated’ samples of PI and PEN were supplied by GTS (Ebbw Vale) and Goodfellow UK (Huntingdon) respectively. These samples were then cleaned and measured.

Samples of PI and PEN after lamination with stainless steel foil were supplied by GTS. A sample of the heat activated adhesive used by GTS⁵ for this lamination was also tested. The ‘after etching’ PI sample was taken from finished PI etched steel cabling and contains 7.1% steel foil by mass. The PEN steel foil samples were fully etched to remove all steel and subsequently tested (PEN after etching).

Measurements of radioactive contaminant activity in large samples of PI and PEN made at low background facilities at INFN Gran Sasso and BNO (Baksan, Russia) respectively have been published by the GERDA collaboration [86] [46] and these are shown for comparison with the IPNL measurements in Figures 3.15 - 3.19.

Evaluation

The small sample sizes and short measurement times that were feasible in the IPNL study limited the resolution of the reported activity measurements, precluding comparisons of activity over all of the samples for each of the radioisotopes

⁵Chemical composition not disclosed.

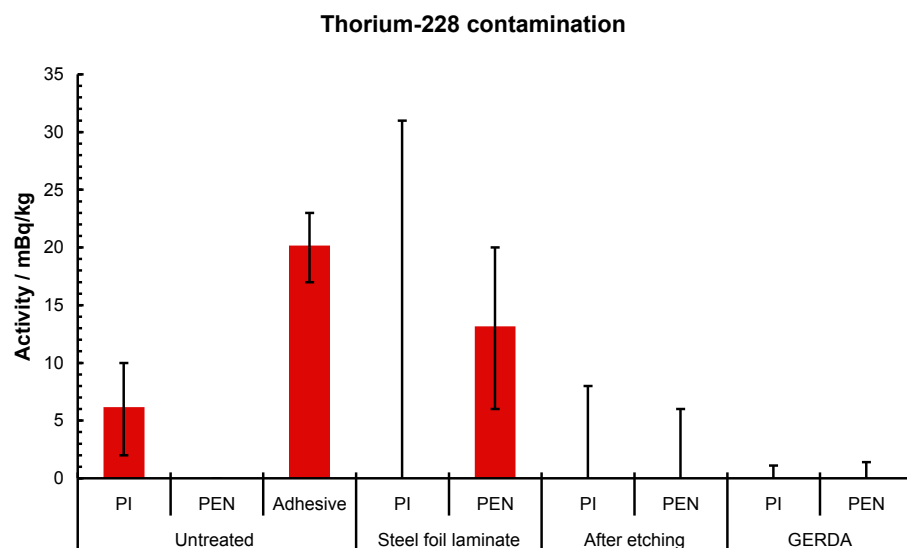


Figure 3.15: Measured activity levels of ^{228}Th contamination (untreated PEN activity did not exceed expected background). GERDA measurements shown for comparison [86].

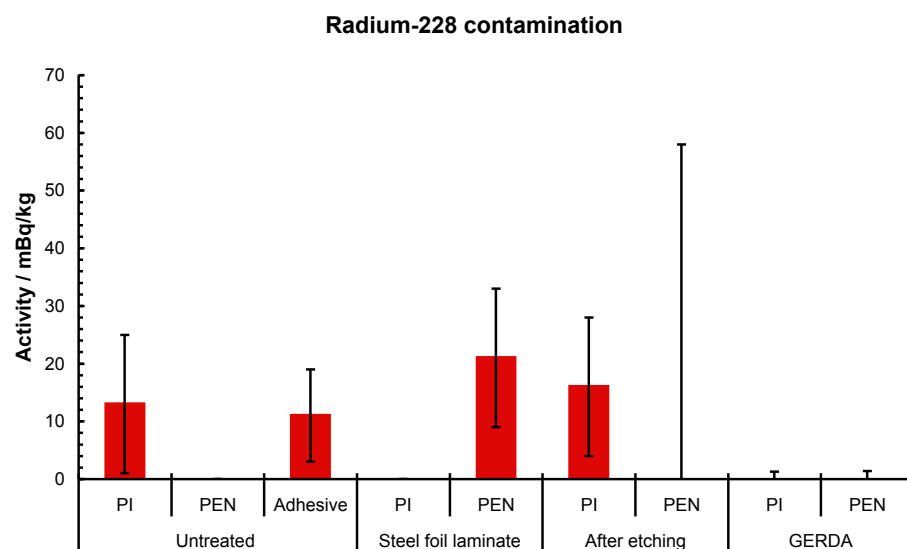


Figure 3.16: Measured activity levels of ^{228}Ra contamination (untreated PEN and steel-foil PI activity did not exceed expected background). GERDA measurements shown for comparison [86].

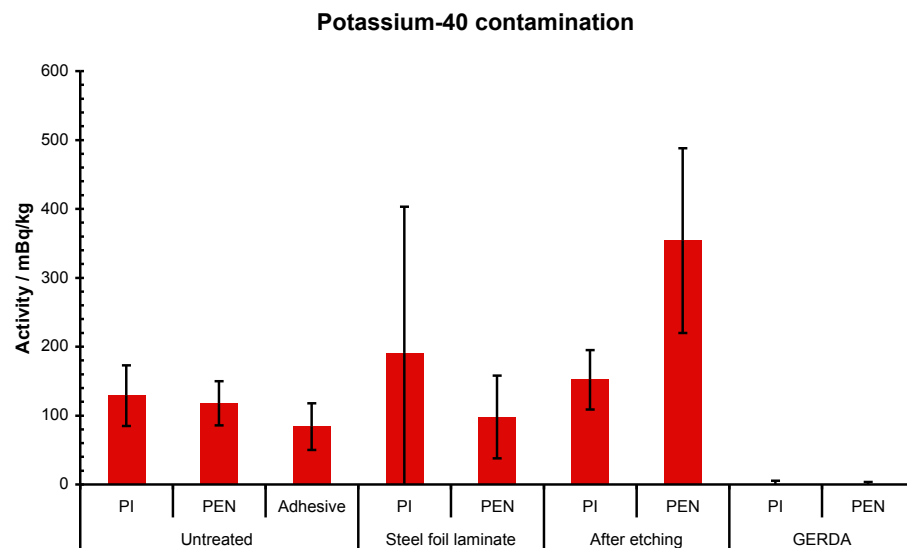


Figure 3.17: Measured activity levels of ^{40}K contamination. GERDA measurements: PI < 5.5 mBq/kg, PEN < 3.6 mBq/kg [86].

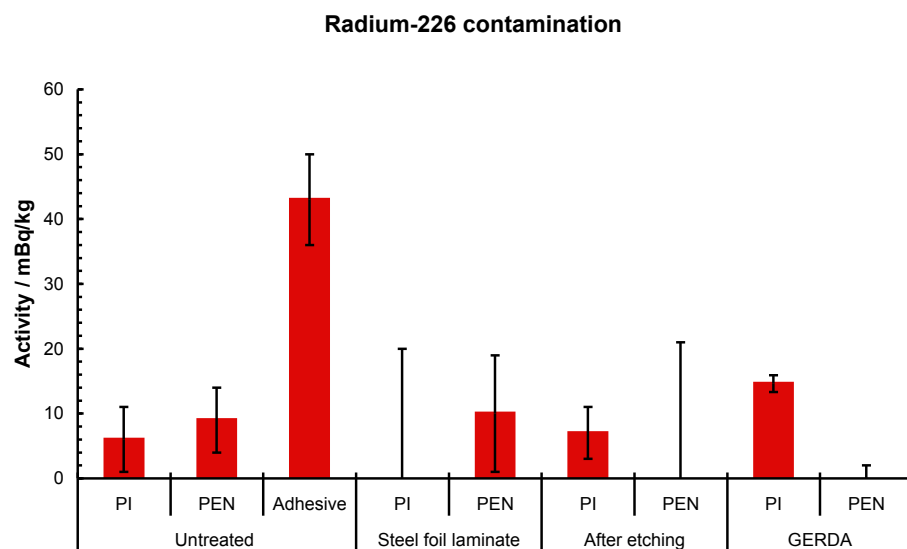


Figure 3.18: Measured activity levels of ^{226}Ra contamination. GERDA measurements shown for comparison [86].

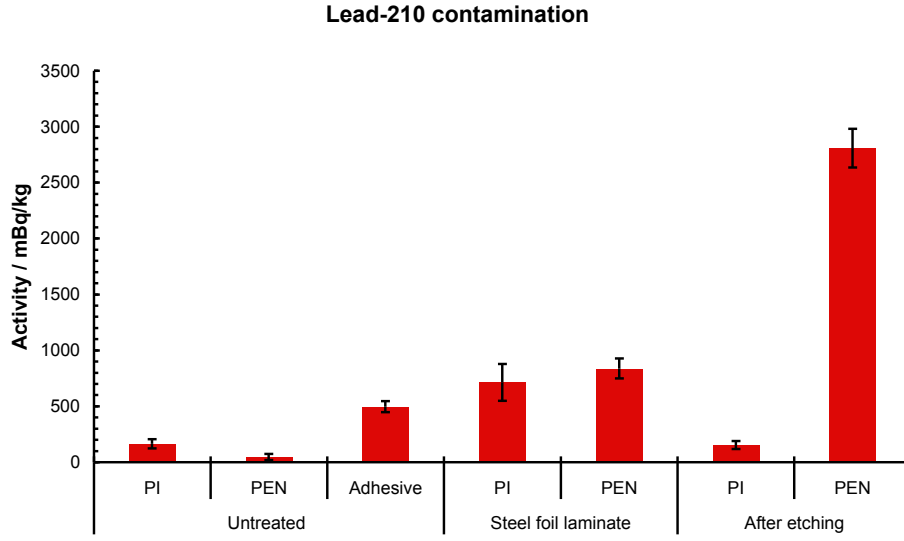


Figure 3.19: Measured activity levels of ^{210}Pb contamination (untreated PI 165(42) mBq/kg, untreated PEN 47(27) mBq/kg).

detected. In addition, the IPNL measurements of ^{228}Th , ^{228}Ra and ^{40}K show significantly more activity for samples of untreated PI and PEN than the equivalent GERDA collaboration data (figures 3.15, 3.16 and 3.17). This seems to suggest a systematic difference in the preparation, apparatus or analysis method between the IPNL data and the quoted GERDA results.

It is hard to draw a definite conclusion on the question of whether PI or PEN film is the better material for cabling fabrication from the IPNL data. In the IPNL measurements of ^{40}K and ^{226}Ra activity the contamination levels of untreated PI and PEN are comparable (figures 3.17 and 3.18). Only in ^{210}Pb activity measurements does untreated PEN have a lower contamination than untreated PI (Figure 3.19). The GERDA collaboration chose to use PEN film instead of PI on the basis of lower observed ^{226}Ra activity [86].

The untreated PI samples show similar activity in general to the etched PI samples from which the steel foil has been removed. However, the etched PEN samples show significant increased activity of ^{40}K and ^{210}Pb compared to the untreated PEN samples. This ambiguity over the effects of handling and etching the cables suggest that further radiopurity tests of the HCl and FeCl_3 etching solutions used are necessary.

PI and PEN samples with steel foil were observed to exhibit significantly higher ^{210}Pb activity than untreated PI and PEN samples (Figure 3.19). This suggests that the steel foil potentially contains some ^{210}Pb contamination, and further tests of the steel foils used in cable fabrication would help to clarify this point.

3.4 Cost and lead times

A key motivation for the prototyping of etched metal foil cryogenic cabling was to develop practical cabling that could be produced in quantity at lower cost than existing bespoke cryogenic cabling. The development of large-target cryodetectors for direct dark matter searches is contingent on the provision of affordable high-performance readout cabling. Although mass fabrication techniques introduce many economies of scale, an analysis of costs and lead times for the prototype cables fabricated for readout of SQUID and NTD-Ge sensors can help to estimate costs and lead times for large cabling projects in future.

The costs and lead times for the etched metal foil SQUID cables are itemised in

Stage	Location	Cost (inc. VAT)	Time / days
Specification	Internal	—	—
Drawing	Oxford Physics CEG	£168.00	1
Phototool printing	Photodata Ltd.	£155.00	2
Photolithography and lamination	Oxford Physics PFU	£224.00	7–10
Copper plating	Sifco Inc.	£207.56	10
Connectors and finishing	Internal	£30.67	2–3
Total		£785.23	22–26

Table 3.3: **Costs and lead times for a batch of 15 4-track-pair etched metal foil cables for readout of individual SQUID sensors. The yield for this particular batch was 13/15, making the total cost per SQUID cable £60.40.**

Table 3.3 and those for NTD-Ge sensor readout itemised in Table 3.4. Many of the costs involved are one-off expenditures of time and equipment in setting up jobs and sourcing small material quantities: for example, a phototool can be used for many etching runs, but the design is a one-off cost at the outset. A large fraction of the photolithography and plating costs are incurred during setup of etching and plating baths; repeated processes to produce several times the quantity of cabling could be carried out with costs increasing only incrementally. Delivery charges are similarly scalable. It is now also possible to draw phototool patterns using commercially available software within the group, streamlining and reducing the cost of the design stages of cable production.

It can be seen that the etched metal foil cables were prototyped quickly at costs below £100 per cable, even in small production runs. Production in quantity would allow several economies to be made, and along with improvements in channel

Stage	Location	Cost (inc. VAT)	Time / days
Specification	Internal	—	—
Drawing	Oxford Physics CEG	£168.00	1
Phototool printing	Photodata Ltd.	£21.50	2
Photolithography and lamination	Oxford Physics PFU	£224.00	7–10
Copper plating	Oxford Physics PFU	—	5
Connectors and finishing	IPNL	—	—
Total		£413.50	15–18

Table 3.4: **Costs and lead times for a batch of 6 etched metal foil cables for readout of individual NTD-Ge sensors. The yield for this particular batch was 6/6, making the total cost per cable £68.92.**

density, the potential for reducing cryogenic readout cost per channel by one or more orders of magnitude using etched metal foil cabling exists⁶.

3.5 Testing etched metal foil cabling in SQUID readout

The installation of 5 Supracon SQUID sensors mounted in an Oxford Instruments K400 dilution refrigerator was described in Section 3.1.3. These SQUID sensors were connected to a room temperature vacuum connector box via low-heatload etched steel foil cabling. A purpose-built compact copper bracket was used to heatsink the SQUID sensors to 4.2 K and the cables were heatsunk using compact

⁶For example, a production run of 100 SQUID cables, *using the same process*, would reduce the cost per cable by 36% to £38.80. It is highly likely that further savings could be achieved by increasing channel density to reduce material costs and outsourcing the etching and lamination process to larger commercial facilities.

copper baffles.

The etched steel cabling differs in some regards from the bespoke manganin/copper woven cabling used for SQUID readout in the CRESST experiment:

The recommended maximum impedance for the voltage readout wire pair of each CRESST SQUID is $<10\ \Omega$ [62]. This is implemented in woven manganin cables by weaving one copper wire pair into each CRESST SQUID cable. Etched foil cabling could not be prototyped with multiple conducting materials. Since only etched steel cabling delivered the desired low-heatload performance, the impedance of the etched foil cabling installed was $224\ \Omega$.

CRESST woven cabling also employs twisted wire pairs separated by earthed shielding wires in order to minimise crosstalk and magnetic noise pickup. It was not possible to reproduce this geometry in the etched foil cabling tested. The etched steel foil SQUID cables have parallel conducting tracks, in which earthed shielding tracks separate each track-pair. It was important to measure the effects on intrinsic SQUID noise levels of increased resistance and parallel conducting tracks in readout cabling.

To assess the suitability of low-heatload etched steel cabling for TES-SQUID readout, levels of readout noise for the new SQUID system were measured and compared to the low-noise performance achieved using the CRESST SQUID system. Open-input and low-impedance SQUID input circuits were tested.

The CRESST SQUID system was extensively characterised in [62] and is the

benchmark used here for low-noise performance in TES-SQUID readout. After installation in the LNGS underground laboratory at Gran Sasso, the 66 SQUIDs were measured to exhibit a mean white noise level of $1.2 \text{ pAHz}^{-1/2}$, with no individual SQUID sensor exceeding $8 \text{ pAHz}^{-1/2}$. This is the criteria for low-noise TES-SQUID readout against which we test the etched metal foil cable readout system.

3.5.1 Noise in low-impedance TES readout using SQUID sensors

The low-impedance TES-SQUID CRESST cryodetector readout circuit is described in Section 2.3.1. Noise sources in this cryodetector readout circuit will be described here in order to motivate the tests and measurements carried out on a SQUID system equipped with prototype etched steel foil readout cabling.

Figure 3.20 shows a simplified low-impedance TES-SQUID readout circuit, in which the sources of noise are explicitly shown⁷.

Each resistive component in the readout circuit generates a thermal Johnson white noise of RMS voltage $\langle V \rangle = \sqrt{4k_B T R \Delta f}$, where Δf is the frequency range.

The intrinsic noise of the SQUID is strongly dependent on the characteristics of the input circuit [90] [64]. However, it can be approximately modelled by a

⁷The calorimeter signal to the TES is subject to phonon noise due to random movement of energy carriers in the thermal link between the TES and the heat bath. The magnitude of this effect is given by $\langle \Delta E^2 \rangle = k_B T^2 C$ [89]. This noise is negligible in the CRESST detectors operating at $T \sim 10 \text{ mK}$, so it is not considered here.

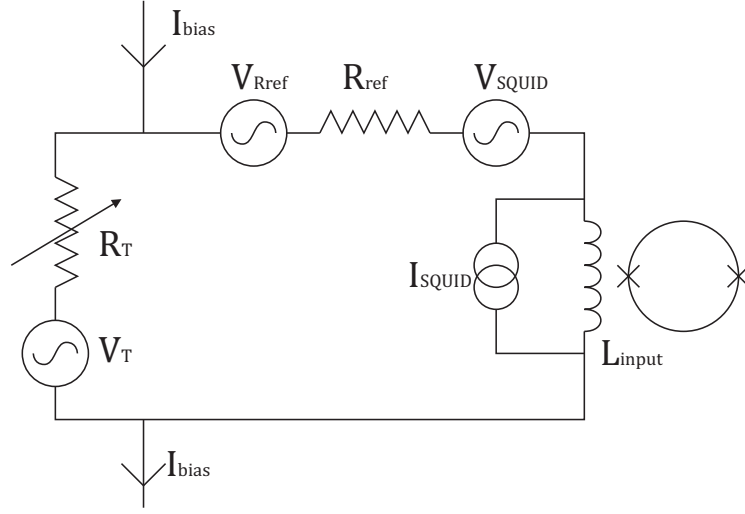


Figure 3.20: **Noise sources in a low-impedance TES-SQUID readout circuit of the type used for CRESST cryodetector readout.**

voltage noise source V_{SQUID} in series with the SQUID input and an uncorrelated current noise source I_{SQUID} in parallel with the input.

The Johnson and SQUID noise sources in Figure 3.20 are uncorrelated and can be added in quadrature to find the current noise at the SQUID input for a frequency f and bandwidth Δf (equation 3.9).

$$\langle I_{Total}^2 \rangle = \langle I_{SQUID}^2 \rangle + 4k_B \Delta f \frac{T_T R_T + T_{Rref} R_{Rref}}{(R_{Rref} + 2\pi f L_{input})^2} + \frac{\langle V_{SQUID}^2 \rangle}{(R_{Rref} + 2\pi f L_{input})^2} \quad (3.9)$$

Since we deal with an input circuit in which Johnson noise due to resistive components dominates, the intrinsic SQUID noise is dominated by the current noise source term.

Supracon CS Blue SQUID sensors	
Input coil inductance L_{input}	320 nH
Mutual inductance M_{in}	10 nH
Input coupling $1/M_{in}$	$210 \text{ nA}\Phi_0^{-1}$
Feedback coil mutual inductance M_{FB}	230 pH
Feedback coil coupling $1/M_{FB}$	$9.1 \text{ }\mu\text{A}\Phi_0^{-1}$
SQUID critical current	20–50 μA
SQUID shunt resistance	2.5 Ω
Intrinsic current noise	$1.5 \text{ pAHz}^{-\frac{1}{2}}$

Table 3.5: **Manufacturers specified open-input 4.2 K test values for the SQUID sensors used in etched steel foil cabling tests [91].**

3.5.2 Measurement of SQUID open circuit noise levels

The installation of five Supracon CS Blue SQUID sensors heatsunk to the liquid helium bath of a K400 dilution refrigerator and connected to room temperature electronics via etched steel cabling is shown in Figure 3.8. The manufacturer’s specification for these SQUID sensors is given in Table 3.5.

In order to demonstrate and characterise the effectiveness of inexpensive low-heatload etched steel foil cabling in SQUID readout, Fourier analysis of baseline noise measurements was carried out. Comparison of low noise levels achieved using the new system with those achieved using the CRESST readout system allows assessment of the suitability of etched metal foil cabling for SQUID readout.

It was desired to isolate SQUID noise intrinsic to the readout system from sources of excess noise present within the experimental setup. Intrinsic noise levels of $1.2\text{--}1.5 \text{ pAHz}^{-\frac{1}{2}}$ are achievable with this type of DC SQUID sensor. With this

high sensitivity, excess noise due to tiny discrepancies in earth potential between electronics and cryostat, pickup of background electromagnetic interference (EMI) by earth loops and vibrational noise within the cryostat can be significant relative to, or even dominant over, intrinsic SQUID noise. Excess noise contributions in a busy lab environment were carefully suppressed while maintaining legally-mandated fixed safety earth connections for each piece of equipment. However, while the apparatus was modified extensively to prevent EMI pickup, some residual 50 Hz noise was detected during SQUID testing (and can be seen in Figure 3.21). For this reason, low-noise SQUID magnetometry must be carried out in dedicated low-EMI laboratory facilities [74].

Figure 3.21 shows typical open-input noise spectra for the 5-channel SQUID system equipped with etched steel foil readout cabling. The presented wide-bandwidth spectra are composites of several overlapping narrow-bandwidth spectra measured using timebase, amplifier and filter settings to optimise the resolution of SQUID noise within each frequency range. Transient recorder timebase ranging from 1 μ s to 1 ms was used to record events of 16384 samples and, in each case, low-pass hardware filters with a roll-off frequency set one decade below the sampling rate were used to prevent aliasing⁸. Preamplifier gain set appropriately in the range 5 – 500 was used to ensure that the contribution of transient recorder noise to measured SQUID noise amplitude was negligible (< 5 mV in an amplified

⁸The apparent measurement of excess low frequency signal, due in fact to measurement of signal frequencies exceeding the sampling rate. Low-pass pre-filtering prevents the measurement of signal frequencies exceeding the sampling rate.

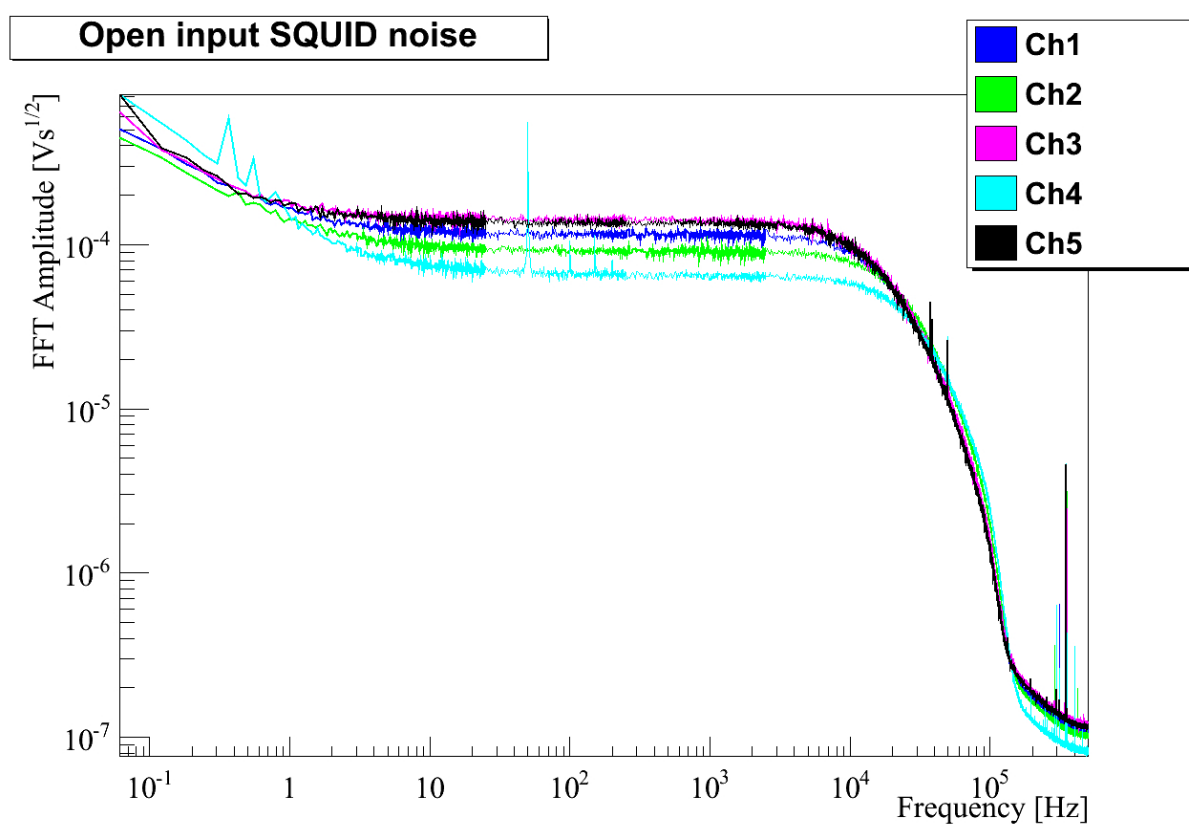


Figure 3.21: Measured open-input noise spectra measured for 5 SQUID sensors mounted at 4.2 K in a K400 dilution refrigerator.

5 V SQUID noise signal).

The measured open-input SQUID noise spectra have a white noise plateau over the frequency range 100 Hz – 10 kHz with $1/f$ noise observed at frequencies below 10 Hz. Two-decade roll-off at 100 kHz due to anti-aliasing filtering applied to the highest measured noise frequency range can clearly be seen. Observed white noise levels averaged over 100 Hz – 1 kHz are summarised in Table 3.6. The mean measured open-input white noise level for the etched steel foil cable SQUID system was $2.6 \text{ pAHz}^{-1/2}$, with no SQUID sensor exceeding a mean white noise level of $3.4 \text{ pAHz}^{-1/2}$.

3.5.3 Measurement of cold-resistor Johnson noise using SQUID sensors

After characterisation of open-input SQUID noise with etched steel foil readout cabling was completed, the SQUID sensors were connected to a reference resistor input circuit of the type shown in Figure 3.20. The aim of these tests was to measure variation in white noise level with increasing reference resistor temperature, so a superconducting connection was made in lieu of the TES. Reference resistors were mounted using Stycast resin inside a copper heatsink directly mounted to the dilution refrigerator mixing chamber. The connection between the SQUID input and reference resistor was made using carefully heatsunk superconducting niobium-titanium woven cables.

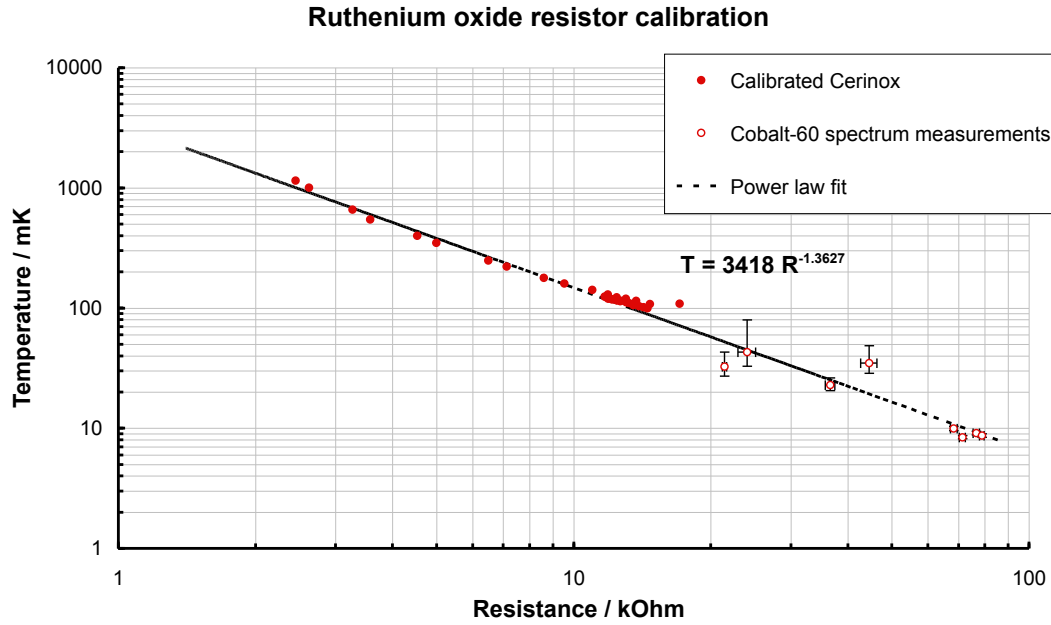


Figure 3.22: Variation of RuO_2 resistance with mixing chamber temperature measured using a calibrated Cernox resistor and ^{60}Co gamma ray spectrum thermometry.

Mixing chamber temperature was measured in the range 8 mK – 1 K using a ruthenium oxide (RuO_2) resistor. Calibrated Cernox resistor sensors were used to calibrate this sensor in the range 100 mK – 1 K and additional temperature calibration points were measured in the range 50 mK – 8 mK using ^{60}Co gamma ray spectrum thermometry [75]. The calibration measurements of the RuO_2 resistor are shown in Figure 3.22 along with a power law curve used to derive mixing chamber temperature from RuO_2 resistance measurements.

The mixing chamber and reference resistors were heated from the dilution refrigerator base temperature of 8 mK up to around 1 K, and broad-bandwidth noise spectra for each SQUID sensor were measured at a wide range of temperatures. The measured mean white noise levels for each SQUID sensor are plotted in Figure

3.23.

It was suspected during an initial run that SQUID 5 had developed an open input circuit, which was confirmed during subsequent runs in which the external input circuit was reinstalled and re-tested without improvement. It was concluded that SQUID 5 suffered from a broken input circuit on the SQUID chip itself.

Despite the reduced number of SQUID channels available it was possible to obtain good measurements of temperature-dependent Johnson noise due to a range of reference resistances from 20 m Ω to 300 m Ω ⁹.

⁹This wide range of reference resistances was installed with a view to future testing of TES sensors of variable resistance. Optimum sensitivity and linearity of output is achieved when the reference resistance closely matches the operating resistance of the TES, so a wide range of available reference resistances would allow flexibility in experimental planning.

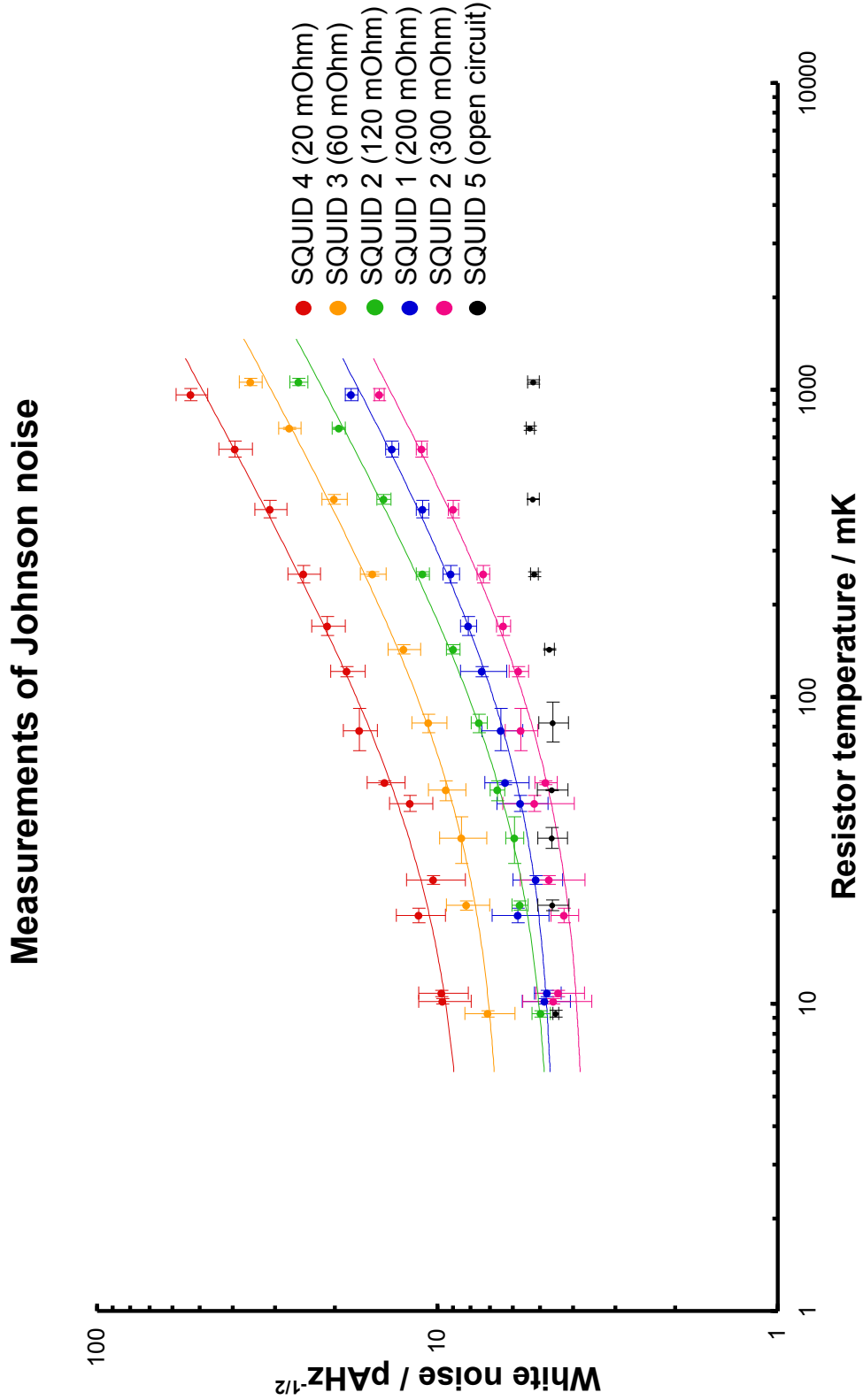


Figure 3.23: Variation in observed mean white noise level with reference resistor temperature for 5 SQUID sensors read out using etched steel foil cabling. Reference resistances in the range $20 \text{ m}\Omega - 300 \text{ m}\Omega$ were heated to temperatures in the range $8 \text{ mK} - 1 \text{ K}$. Curves of best fit for (3.10) are given.

The expected total current noise in a given frequency range Δf (in which $R_{Rref} \gg 2\pi f L_{in}$) at the SQUID input due to this input circuit (in which $R_T = 0$ and $\frac{\langle V_{SQUID} \rangle}{R_{Rref}}$ is negligible) is given by (3.10).

$$\frac{\langle I_{Total} \rangle}{\sqrt{\Delta f}} = \sqrt{\frac{\langle I_{SQUID}^2 \rangle}{\Delta f} + \frac{4k_B T_{Rref}}{R_{Rref}}} \quad (3.10)$$

Fits of (3.10) to the observed variation of Johnson noise with reference resistance and temperature reveal that the total observed SQUID noise is well described by this model, which includes only intrinsic SQUID noise and uncorrelated Johnson noise from reference resistors. Fisher's method¹⁰ for combining independent statistical tests yields a p -value of 0.988 for the hypothesis that the individual χ^2 values for these fits are drawn from a distribution of χ^2 values for fits to normally varying data sets with 11 degrees of freedom. Best fit parameters are given in Table 3.6 and best-fit curves are plotted in Figure 3.23.

The average fitted SQUID noise with the low-impedance input circuit was $5.5 \text{ pAHz}^{-\frac{1}{2}}$, which is comparable to, but higher than the low-noise performance achieved using the CRESST SQUID readout system at Gran Sasso (average noise level of $1.2 \text{ pAHz}^{-\frac{1}{2}}$).

Given the encouraging open-input noise level of $2.6 \text{ pAHz}^{-1/2}$ and the coincidence of the highest observed excess noise channels with the lowest-impedance input circuits, we cannot exclude that some of the excess noise may be due to ad-

¹⁰The p -values p_i for individual independent fits are combined to give a test statistic $X^2 = -2 \sum_i^n \ln p_i$, which is χ^2 -distributed with $2n$ degrees of freedom.

Ch.	$R_{Rref}^{nominal}$ [m Ω]	$\langle I_{SQ} \rangle^{open}$ [pAHz $^{-\frac{1}{2}}$]	$\langle I_{SQ} \rangle^{fit}$ [pAHz $^{-\frac{1}{2}}$]	R_{Rref}^{fit} [m Ω]	χ^2 / d.o.f.
1	200	2.77 ± 0.08	4.50 ± 0.33	204 ± 12	0.39
2	300	2.20 ± 0.06	3.67 ± 0.27	309 ± 16	1.02
2	120	2.20 ± 0.06	4.58 ± 0.22	123.0 ± 6.5	0.85
3	60	3.38 ± 0.11	6.41 ± 0.80	60.6 ± 5.7	0.35
4	20	1.58 ± 0.06	8.14 ± 1.09	23.5 ± 2.5	0.21
5	open	3.26 ± 0.09	—	—	—

Table 3.6: **Summary table of white noise level measurements of 5 Supracon SQUID sensors read out using etched stainless steel foil cabling.**

ditional non-thermal or constant-temperature voltage noise sources, such as EMI pickup in the 2.8 m superconducting input circuit or a tiny parasitic resistance¹¹ at 4.2 K. The CRESST SQUID noise levels were measured in a purpose-built cryostat enclosed within a Faraday cage at LNGS, which provides an excellent environment for low-noise measurements.

Despite the observed noise level exceeding the low-noise benchmark of the CRESST SQUID system, the successful operation of etched steel cabling for low-heatload readout of a multi-channel SQUID system for low-impedance readout was demonstrated. This achievement serves as a platform for further development of TES-SQUID cryodetector readout.

¹¹An unspecified and undesired additional resistance in series with a component or connection.

3.5.4 Measurement of titanium TES film transition

Following the measurement of baseline noise levels for the new SQUID system, these channels, equipped with etched metal foil cabling, were connected to TES sensors with the intention of characterising SQUID system performance in cryo-detector readout. Superconducting transition curves were measured for a pair of titanium film TES sensors mounted on small absorber crystals.

Neutron detection using cryodetectors

These measurements were carried out as part of an ongoing project within the cryodetectors group to exploit neutron capture on ${}^6\text{Li}$ to detect ultra cold neutrons with high efficiency.

The high resolution of a cryogenic bolometer could be used to resolve alpha particles resulting from ${}^6\text{Li} + n \rightarrow \alpha (2.05 \text{ MeV}) + {}^3\text{He} (2.73 \text{ MeV})$ reactions in a lithium fluoride (LiF) film deposited on the surface of a suitable absorber [92]. The longer-term aim of this work was to develop cryodetectors for use as neutron detectors in the CryoEDM experiment [73].

Installation

The absorber crystals were installed in copper holders heatsunk to an experimental plate. The experimental plate temperature was measured using a calibrated RuO_2 resistor and controlled using a heating resistor. For cooling the experimental plate was connected via a weak thermal link to the dilution refrigerator mixing chamber.

Each absorber crystal was mounted with a TES temperature sensor connected to a SQUID readout channel as shown in Figure 3.20: SQUID 1 was connected to a 5 mm $\times$ 5 mm $\times$ 50 nm titanium TES deposited on a 20 mm $\times$ 10 mm $\times$ 1 mm ZnWO₄ absorber crystal; SQUID 4 was connected to a 5 mm $\times$ 5 mm $\times$ 50 nm titanium TES deposited on a 20 mm $\times$ 10 mm $\times$ 1 mm Al₂O₃ absorber crystal. Reference resistances of 200 m Ω and 20 m Ω were heatsunk to the dilution refrigerator mixing chamber and connected in series with SQUID 1 and 4 respectively. An ²⁴¹Am source was used to illuminate the absorber crystals with 5.5 MeV alpha particles.

After extensive temperature sweeps between 10 mK and 1 K, superconducting-normal transitions were found for both TES at temperatures in the range 770–870 mK and the transition curve for each TES was measured under varying bias currents (Figure 3.24).

Evaluation

The large discrepancy between the transition temperature of bulk titanium (490 mK [93]) and the observed transition temperatures is consistent with prior observations of widely varying transition temperatures with film geometry and roughness [94] [95].

These elevated transition temperatures decrease the effectiveness of the detectors for observing particle events; temperature stability becomes more difficult and absorber heat capacity increases. The detector mounting and temperature stabilisation method was well designed for transition temperatures in the range 400–600

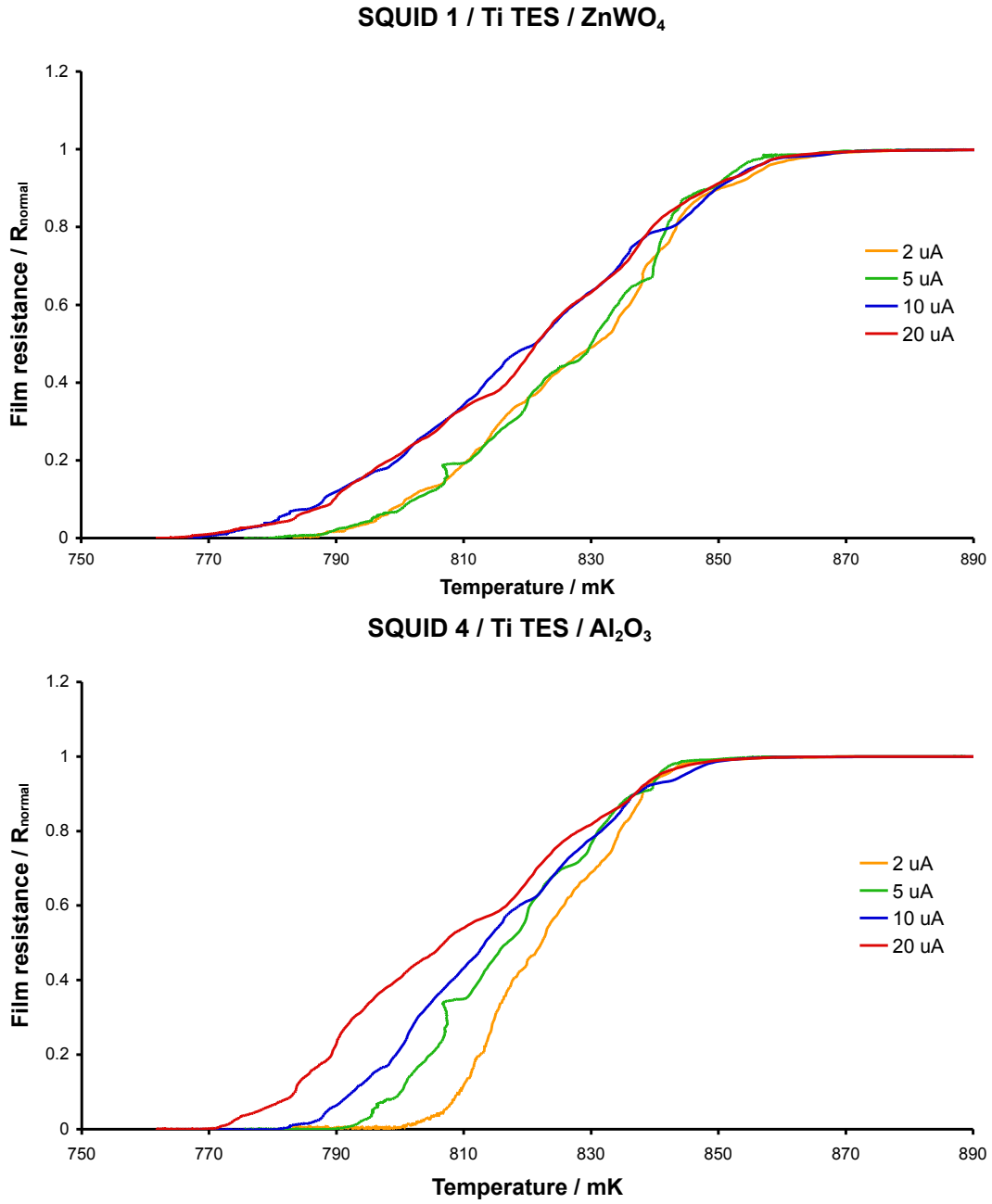


Figure 3.24: Superconducting - normal transitions of titanium film TES sensors measured using SQUIDS read out by etched metal foil cabling.

mK, but higher transition temperatures were difficult to achieve with stability. The additional heating required to sweep the experimental plate to >800 mK was observed to break the cooling cycle of the dilution refrigerator by causing excessive evaporation within the mixing chamber. To reach these temperatures required hard ‘throttling’ of the mixture flow (to reduce pressure and cooling power) while maintaining circulation.

Increased transition temperatures also reduce cryodetector sensitivity to particle events due to increased absorber heat capacity. Using Debye’s theory for dielectrics, a 4g Al_2O_3 absorber crystal ($\theta_D = 1042$ K) at 400 mK experiences a temperature rise of ~ 0.20 mK after absorbing a 5.5 MeV alpha particle. At 800 mK, the temperature rise is reduced to 0.026 mK due to the variation of heat capacity as T^3 , which corresponds to only 0.05% of the observed transition width.

It was therefore not possible to stabilise and detect 5.5 MeV alpha particles with the apparatus available within the scope of this work. A measurement of observed particle resolution using TES-SQUID readout by etched steel foil cabling would have been a useful performance demonstration. Development of cryodetectors for neutron sensors is ongoing at Oxford University.

3.6 Testing etched metal foil cabling in high-impedance

NTD-Ge readout

The EDELWEISS collaboration uses NTD-Ge sensors to detect phonon signals arising from particle events in high purity germanium crystal cryogenic bolometers [49].

Current EDELWEISS-II cabling uses individual coaxial cables which are soldered to a etched metal foil connection at each detector module. This system offers low parasitic capacitance¹² and excellent performance, but is bulky and expensive. Cost, space and radioactive backgrounds may all present problems for a scaled-up design based on this system. Etched metal foil cabling, with its reduced cost, reduced mass and higher channel density, can address these issues. As part of research and development for future EDELWEISS upgrades to higher detector mass, the suitability of etched metal foil cabling as an alternative to coaxial cabling for NTD-Ge readout was assessed.

Prototype steel foil cabling was produced using photolithographic techniques in the physics department of Oxford University for installation and testing at IPNL, where EDELWEISS-type bolometers and electronics are available in a cryogenic facility.

Strict control of parasitic capacitance and cable vibration is essential to achieve

¹²An unspecified and undesired effective capacitance in parallel over a component or connection.

performance comparable with existing coaxial readout cabling. Parasitic capacitance in etched metal foil cabling was measured and characterised and prototype etched steel foil cabling was tested in NTD-Ge bolometer readout. Results obtained with shielded etched steel foil cabling demonstrate the potential for using etched metal foil cabling in high-impedance readout.

3.6.1 Parasitic capacitance

The cryogenic modules of the type installed in the EDELWEISS cryostat are described in Section 2.4.

Calorimetric phonon signal measurement is made using NTD-Ge sensors and ionisation measurement is made using constant-voltage electrodes for charge collection. Each of these readout channels involves a high-impedance sensor, in contrast to the superconducting (low-impedance) TES sensors, therefore the parasitic capacitance of readout cabling can potentially limit sensor energy resolution.

The high effective impedance of the charge readout electrodes and short ionisation pulse times ($O(1)$ ms) mean that even parasitic cable capacitance of a few pF can distort pulse shape and restrict bandwidth due to the low-pass filtering effect of the readout cable. In addition, small variations in the parasitic capacitance due to vibration and flexing of the cabling can produce significant excess voltage noise on the ionisation signal.

The NTD-Ge sensor has an effective impedance of several $M\Omega$, but bolometer

pulses are typically of duration $O(100)$ ms and the preamplifier circuit is carefully designed to minimise pulse distortion and bandwidth reduction due to parasitic capacitance in the readout cable. Therefore the noise on the NTD-Ge sensor channel is smaller than that of the charge collection electrodes and is dominated by sensor Johnson noise. However, vibrational pickup producing variable parasitic capacitance in the cabling can still be a significant source of excess noise in NTD-Ge sensor readout.

In order to minimise the effects of parasitic capacitance on high-impedance readout, careful design is needed. We wish to minimise capacitances between separate signal tracks and between signal tracks and earth while ensuring that cryostat vibration produces minimal variation in capacitance. A balance must be struck between well-isolated signal tracks and adequate earthed shielding around the tracks.

Parasitic capacitance model for etched metal foil cabling

To ensure that the parasitic capacitance of the cabling designed for high-impedance sensor readout was well understood, the parasitic capacitance of etched metal foil SQUID cabling was measured and compared with calculated values. A model in which the track geometry and capacitance network effects for etched metal foil cabling were approximately described was developed. For this model, only the capacitance network effects due to adjacent tracks were considered and the shielding tracks were assumed to be connected to earth with zero impedance (see

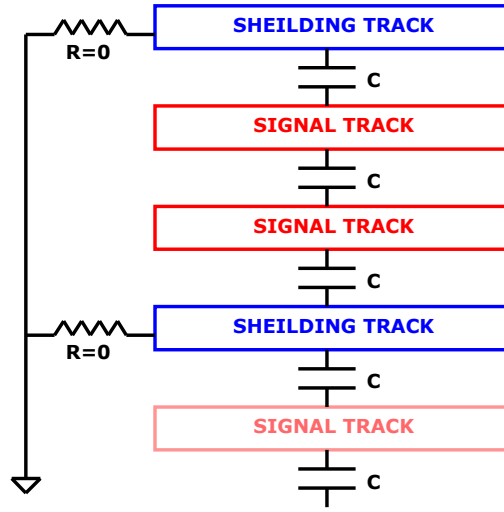


Figure 3.25: Schematic showing the approximate parasitic capacitance network model for etched metal foil cables.

Figure 3.25).

Subject to these approximations, the parasitic capacitance between adjacent signal tracks is identical to the capacitance between those signal tracks in the absence of other conductors. We call this capacitance C . The parasitic capacitance between a given signal track and earth is given by the capacitance between that track and the earthed shielding track adjacent to it, C , in parallel with the series sum of the capacitance between that track, the adjacent signal track and the earthed shielding track adjacent to that, $\frac{1}{2}C$. The sum of these parallel paths to earth is $\frac{3}{2}C$.

The capacitance C between two tracks in the absence of other conductors was calculated using an approximate geometry of parallel, infinite-length, circular-cross-sectional wires of equal diameter to the rectangular steel tracks. With these

approximations, C is given by (3.11), where ϵ_0 is the permittivity of free space, ϵ_r is the relative permittivity of the insulating material, and l , d and w are the length, pitch and width respectively of the steel tracks.

$$C = \epsilon_r \epsilon_0 l \frac{\pi}{\text{arcosh}(d/w)} \quad (3.11)$$

Similarly, the capacitance between such a track and a parallel conducting plane separated by a distance d is given by (3.12) in this model.

$$C_{\perp} = \epsilon_r \epsilon_0 l \frac{2\pi}{\text{arcosh}(2d/w)} \quad (3.12)$$

Parasitic capacitance measurements

Observed parasitic capacitances for 1.4 m long, 4-track-pair etched metal foil cables are shown in Figure 3.26.

The measured cables consisted of four pairs of $25 \mu\text{m} \times 200 \mu\text{m}$ cross-section steel signal tracks with a $25 \mu\text{m} \times 150 \mu\text{m}$ cross-section earthed steel shielding track between each pair. The tracks had a pitch of $600 \mu\text{m}$ and were laminated between two $100 \mu\text{m}$ polyimide films. The cables were mounted in copper heatsinks connected via a weak thermal link to the inner wall of an evacuated vessel cooled to 4.6 K by immersion in liquid helium. The temperature of the copper heatsink was controlled using a calibrated diode temperature sensor and heating resistor. The additional parasitic capacitance of the wiring connecting the cable under test to the capacitance meter was measured and subtracted to give the parasitic capacitance

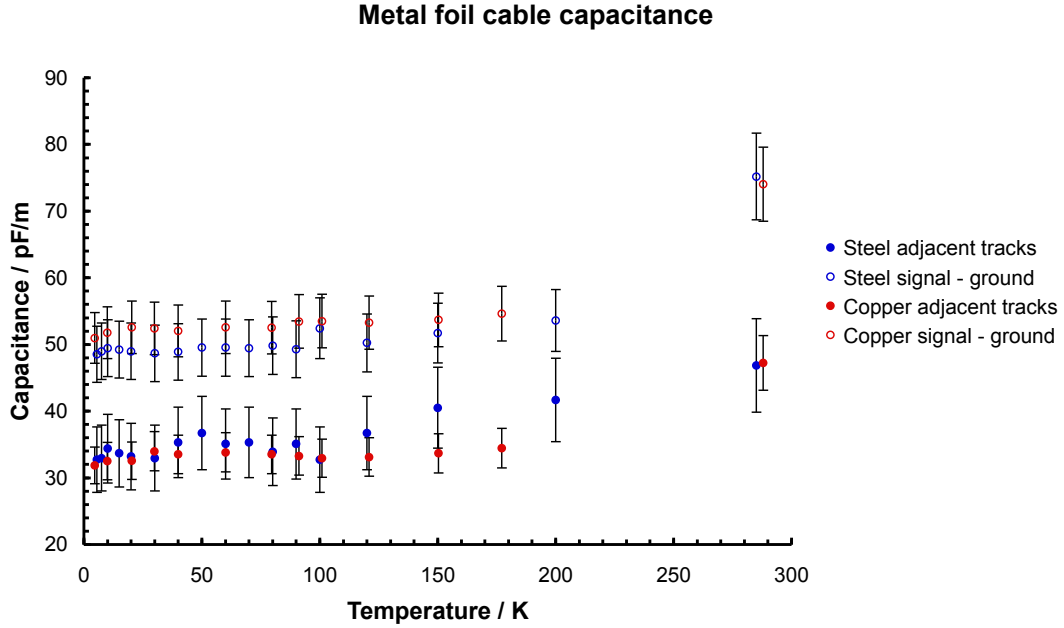


Figure 3.26: Mean measured parasitic capacitance of 1.4 m etched steel foil cables under cooling to 4.6 K.

of the cable alone.

We observe that steel-foil and copper-foil cables are of approximately equal parasitic capacitance. The weighted mean ratio between the signal-earth and signal-signal parasitic capacitances is 1.52 ± 0.05 , in accordance with the expected value of $\frac{3}{2}$ from the approximate capacitance network model. At 300 K the observed parasitic capacitance of $C = 47 \pm 5 \text{ pFm}^{-1}$ is slightly overestimated by (3.11), which gives an expected value of $C = 54.4 \text{ pFm}^{-1}$ for $\epsilon_r = 3.45$ [96].

The measured parasitic capacitance falls under cooling to 4.6 K to a value approximately 70% of its 300 K value. We attribute this effect to reduction in the relative dielectric permittivity of the polyimide insulator under cooling¹³.

¹³The effects of material contraction under cooling can be excluded; the effect of steel track contraction would act against the effect of track separation reduction (due to insulator contraction), and the respective magnitudes of these effects are 0.3% and 0.4%

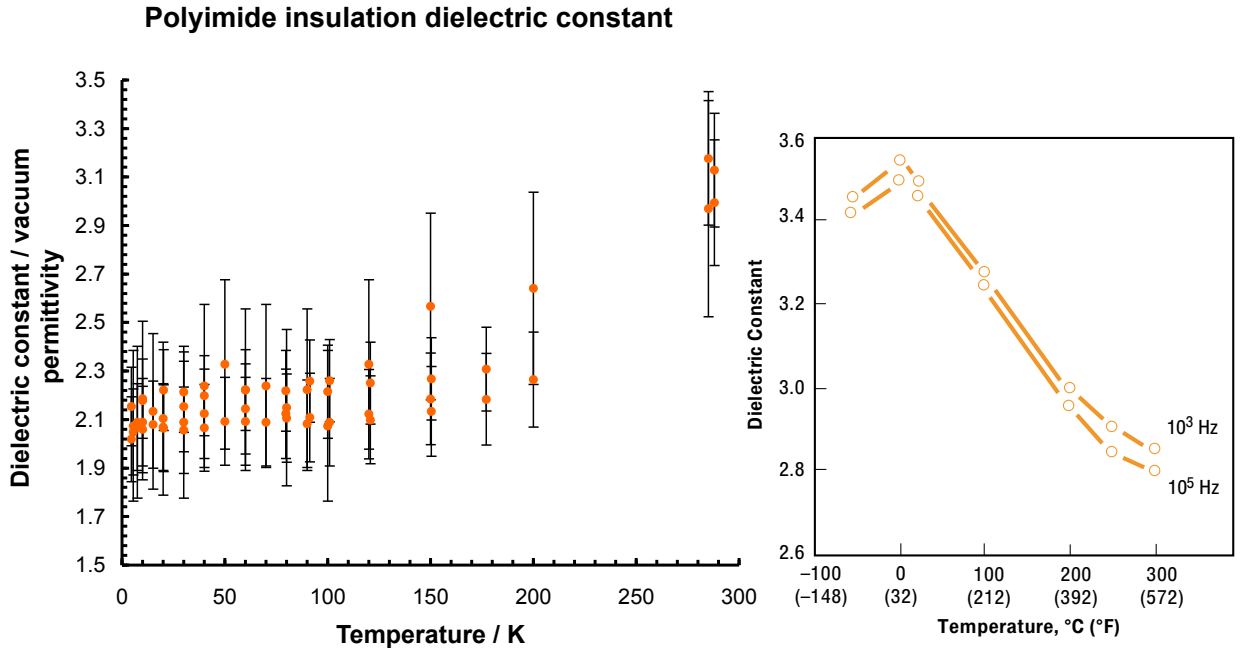


Figure 3.27: **Relative dielectric permittivity of the polyimide insulation extracted from parasitic capacitance measurements after correction for capacitance network and cable geometry (*left*). Manufacturers data is also shown (*right*) [96].**

Figure 3.27 shows the collation of relative dielectric permittivity data extracted from parasitic capacitance measurements in the temperature 4.6–300 K range alongside manufacturers data in the temperature range -70–300 °C. The measured dielectric permittivity was used in design calculations for different cable geometries.

Calculation of parasitic capacitance in high-impedance cabling

The model and data described above can be used to calculate the parasitic capacitance of the prototype etched steel foil cables supplied for testing in high- over the temperature range 300–4 K [75].

Parasitic capacitance	Calculation		Measurement
	300 K	4 K	300 K
Signal track - adjacent signal track	18.9 pF	13.2 pF	< 20 pF
Signal track - shielding plane	70.6 pF	49.4 pF	67 ± 10 pF

Table 3.7: Estimates of the parasitic capacitance in 0.48 m prototype etched metal foil NTD-Ge readout cables calculated using the model set out in this chapter. Room temperature measurements of the finished cables are shown for comparison. Note that the reduced length of the NTD-Ge readout cables results in small overall parasitic capacitance, close to the sensitivity bound of the measuring instrument.

impedance NTD-Ge readout.

Table 3.7 gives calculations of expected signal-signal and signal-earth parasitic capacitance for shielded high-impedance readout cables of 48 cm length using (3.11) and (3.12). Measurements of the parasitic capacitance in prototype high-impedance cabling were carried out for comparison and show agreement with the calculated values.

The expected effect of these parasitic capacitances on a NTD-Ge readout circuit was difficult to quantify exactly. Approximate circuit analyses suggested that parasitic capacitance of 13.2 pF and 49.4 pF would restrict NTD-Ge readout bandwidth to 33 kHz and 6.6 kHz respectively. It was therefore important to measure the effect of these parasitic capacitances on the noise and energy resolution of NTD-Ge sensors in cryodetector readout.

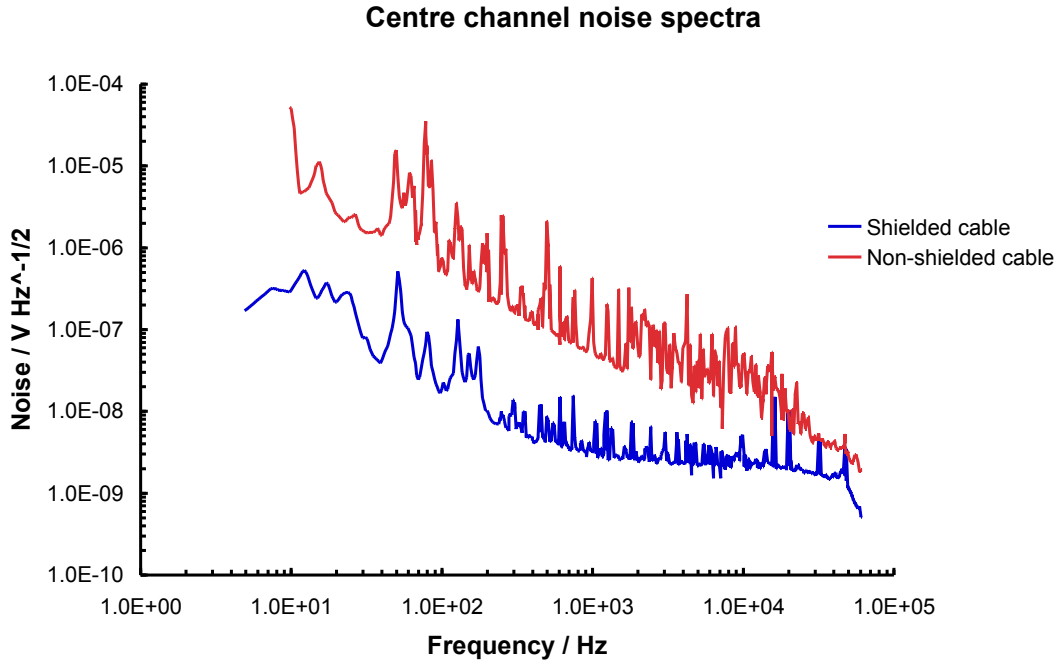


Figure 3.28: Voltage noise spectra from readout of NTD-Ge sensors mounted on germanium crystal bolometers. The red line shows initial testing of etched steel foil cabling, the blue line shows subsequent testing of etched steel foil cabling with earthed steel shielding planes. Data measurement and analysis by B. Censier (IPNL).

3.6.2 Measurements of NTD-Ge noise and energy spectra

Etched steel foil cables of 48 cm length were prototyped in Oxford subject to the considerations above and installed for cryogenic bolometer readout at IPNL by a group including A. Juillard and B. Censier (see Figure 3.8). This prototype cabling was used for the connection of NTD-Ge sensors mounted on 30 g germanium bolometer crystals (mounted at 20 mK) to FET preamplifiers mounted at 100 K.

To demonstrate the performance of the prototype cabling, and assess the capability of well-designed etched metal foil cabling for NTD-Ge readout, I will refer to noise and energy spectra measured with this apparatus by the IPNL group.

Figure 3.28 gives noise spectra measured over a wide frequency range on NTD-Ge sensor readout from a germanium bolometer. The initial testing with unshielded etched steel foil cabling showed high levels of excess noise, enough to preclude identification of particle events. Subsequent testing using cabling shielded with 25 μm laminated steel earthed shielding planes showed significant reduction in noise levels.

The reduction in variation of signal-earth parasitic capacitance due to the fixed rigid earthed shielding plane are the likely cause of the observed reduction in noise. Future cable designs and further testing should exploit and quantify this observation.

With the improved resolution afforded by the shielded cabling it was possible to obtain measurements of the γ -ray spectrum of ^{133}Ba (Figure 3.29). γ -ray peaks at 276.4 keV, 302.8 keV, 356 keV and 383.8 keV were observed. Energy resolution at 356 keV of 3.5 ± 0.5 keV FWHM and baseline resolution of 2 ± 0.5 keV FWHM was achieved. The NTD-Ge sensors developed and installed for dark matter searches by EDELWEISS have energy resolution of 2.7 – 3.5 keV FWHM at 122 keV and baseline resolution of 0.4 – 2.2 keV FWHM [68]. The use of shielded etched metal foil NTD-Ge readout cabling did not appear to degrade observed sensor resolution.

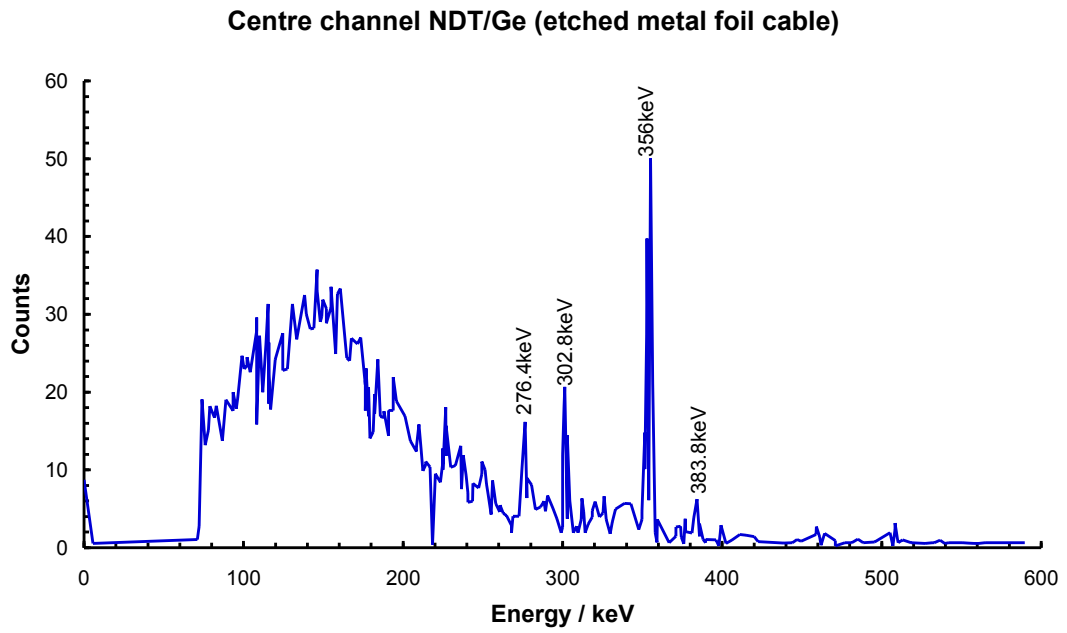


Figure 3.29: Energy spectrum of events from a ^{133}Ba source measured using an NTD-Ge sensor mounted on a germanium bolometer and read out using shielded etched steel cabling prototyped in Oxford. The data measurement and analysis was carried out by B. Censier (IPNL).

3.7 Summary

The application of etched metal foil cabling to readout systems for large-scale future cryodetector arrays has been developed, demonstrated and tested. In Chapter 2, the low-noise, high-radiopurity requirements for cryodetector readout cabling were described. With the objective of increasing detector target mass, a reduction in heatload and cost per readout channel is also required.

The implementation of etched metal foil cabling for low-impedance TES-SQUID readout and high-impedance NTD-Ge readout was described in sections 3.5 and 3.6 respectively.

Noise levels in low-impedance SQUID readout using etched metal foil cabling were measured. The observed mean noise level of $5.5 \text{ pAHz}^{-\frac{1}{2}}$ was in excess of, but comparable to, the mean noise level of $1.2 \text{ pAHz}^{-\frac{1}{2}}$ observed in SQUID sensor readout using bespoke woven cabling in a fully shielded environment. Observation of particle events in a working bolometer would certainly have been desirable to characterise the effects of noise on event resolution, but was not possible with the apparatus available.

Noise levels in NTD-Ge readout using etched metal foil cabling were measured and good resolution of particle events in a germanium bolometer was achieved. It was observed that rigid earthed shielding improved cabling performance significantly. The sensitivity of high-impedance NTD-Ge readout to parasitic capacitance means that understanding of capacitance in etched metal foil cabling

(Section 3.6.1) is an essential design tool.

The radiopurity measurements in Section 3.3 are useful in identifying areas for improvement in cabling materials; the radiopurity of metal foils used and the effects of the etching process must be studied further.

It was seen in Section 3.2 that etched metal foil cabling allows for optimisation of cabling heatload by application-specific design. In SQUID cabling, heatload reduction by a factor of > 24 over woven wire cabling can be achieved. Strategies for further reduction were discussed.

It was also seen (Section 3.4) that etched metal foil cabling can be produced at lower cost than existing bespoke woven cabling, even when prototyping a like-for-like replacement.

The developments in etched metal foil cryogenic cabling described here are of great practical benefit in the design of future readout systems. In addition to the establishment of baseline operating performance in SQUID and NTD-Ge readout, design features for rapid, economical fabrication and successful installation have been identified.

Chapter 4

High voltage supply for low-temperature photomultiplier tubes

In this chapter the development of high voltage (HV) power supplies for photomultiplier tubes (PMTs) intended for use in the detection of scintillation light at low temperatures is described.

The potential for using a Cockcroft-Walton generator (CWG) voltage multiplier as an alternative to cold voltage divider circuits or arrays of high-voltage cryogenic cables was explored. CWG components and designs were tested for suitability in low-temperature use. A prototype CWG/PMT module was fabricated and installed in an Oxford Instruments S400 dilution refrigerator. The efficiency and

stability of the CWG power supply was measured and the response and resolution of the PMT to scintillation light was characterised at temperatures down to 0.95 K.

4.1 PMT readout of cryogenic scintillators

Advantages of PMT readout for cryogenic scintillators

Photomultiplier tubes offer fast detection of low-energy photon signals and are successfully used for characterisation of scintillating materials at low temperatures [97], [54].

Photon counting methods, such as *single photon counting* and *multiple photon counting coincidence*, are particularly suited to the characterisation and readout of the slow scintillation light signals produced by cryogenic scintillators [98].

Photon counting methods require fast signal response to single photons with energies ranging down to a few eV. This is facilitated by the low threshold and rapid response of high-gain PMTs (gain >100 dB). High-gain PMTs could therefore be used to implement photon counting methods in scintillation light measurements for event discrimination in cryodetector dark matter searches. These techniques cannot be implemented using cryogenic light detectors of the type used in the CRESST-II experiment (see Section 2.3.2), as their signal rise times of $\sim 10 \mu\text{s}$ and thresholds of ~ 100 eV, are too high for detection of single photons.

PMT readout is also far less complex than readout of cryogenic light detectors.

Each cryogenic light detector requires a TES-SQUID readout channel and each TES is stabilised at a unique operating temperature. By contrast, arrays of PMTs may be successfully operated from a common power supply. PMTs are commercially mass-produced, an advantage if large-scale detector arrays are planned.

The installation of PMTs has been studied at increasingly low temperatures; use of liquid cryogens to run PMTs (and PMT arrays) at temperatures of 166 K [99], 87 K [100], 77 K [51], 29 K [101] and 6 K [102] has been carried out successfully.

Challenges in PMT readout for cryogenic scintillators

This application of PMTs to cryodetector readout requires development work on the reduction of PMT dark counts¹, optimisation of PMT light collection and provision of low-heatload, low-noise PMT power supply.

Scintillation pulses from particle events in cryodetector absorber crystals may have a duration of up to ~ 10 ms, and average dark count rates in high-gain PMTs can be as high as 20 Hz. The likelihood of finding a dark count during a particle event would preclude using PMTs for cryodetector discrimination until the average time between dark counts is much greater than the typical event duration.

Effective discrimination in the low-energy region of interest for direct dark matter searches requires good light collection in order to optimise resolution of

¹Dark counts (or dark current): PMT signal in the absence of incident photons, caused by thermionic emission on PMT dynode surfaces.

scintillation signal energy. This requirement raises a number of secondary issues; PMT quantum efficiency, light transmission, radiopurity and power supply.

The quantum efficiency of the PMT photocathode is found to exhibit strong temperature dependence, falling off by an order of magnitude or more under cooling to 29 K [101]. Development of low-temperature, high-quantum-efficiency PMTs will be required to compete with the sensitivity of cryogenic light detectors for detection of low scintillation energy particle events.

In order to minimise attenuation of scintillation light by light guides and transmission across insulating vacuum layers, the PMT would ideally be mounted as close to the scintillating target crystal as possible. However, HV PMT power supplies may pose heatload and noise problems, and PMT components, particularly photocathodes, which are commonly caesium-based, containing radioactive ^{135}Cs and ^{137}Cs , pose additional radiopurity challenges.

The work which follows in this chapter describes the development of voltage multipliers to minimise heatload and noise due to HV PMT power supplies operated at low temperatures, facilitating cryogenic PMT use for cryodetector readout.

4.1.1 PMT power supplies and heatload

To motivate the development of voltage multiplier power supplies for low-temperature PMTs, I will compare alternative schemes for supplying dynode voltages to a PMT mounted at 1 K. I will consider the heating power dissipated at 1 K for a small

PMT of the type installed during the work described here, a Hamamatsu R7725 (see Table 4.6).

The voltage divider circuit specified by Hamamatsu to provide dynode voltages for the R7725 PMT divides a DC supply voltage of 1.8 kV by 18 stages separated by 1 M Ω resistors. The dissipative heat load of this circuit is 180 mW.

A Cockcroft-Walton voltage multiplier circuit (see Section 4.2) generating a voltage of 1.8 kV under a load current of 1.8 μ A (comfortably above the average cathode current demand of 200 nA) could be a suitable low-heatload power supply for the R7725 PMT.

In order to measure CWG heatload during testing, the CWG efficiency ϵ , defined by (4.1), was measured. The average input power P_{in} was found by measuring the amplitudes of the AC input voltage and current. The DC output power P_{out} was measured by using a room temperature attenuator to monitor the CWG output voltage.

$$\epsilon \equiv \frac{P_{out}}{P_{in}} \quad (4.1)$$

The power dissipation P_{dis} inside the cryostat is given by (4.2).

$$P_{dis} = P_{in} - P_{out} = \frac{1 - \epsilon}{\epsilon} P_{out} \quad (4.2)$$

We can estimate that, for a voltage multiplier of 50% efficiency supplying a voltage of 1.8 kV under a load current of 1.8 μ A to an attenuator of resistance 1 G Ω , $P_{dis} = 3.24$ mW, a significant heatload reduction on the voltage divider power supply.

An alternative to mounting either a voltage divider or multiplier within the cryostat is to mount an array of high voltage vacuum feedthroughs carrying voltage lines from an external power supply to each dynode. High-impedance cabling could be used to conduct high voltages inside the cryostat and so with careful design the heatload could be minimised to a much greater extent².

However, the problem of providing adequate insulation for high voltage wires within a low-pressure gas environment was found to present practical problems; the spark voltage was observed to show a minimum at intermediate vacuum pressure, increasing the risk of hazardous discharge and making seamless insulation essential throughout the installed system.

The introduction of many high-voltage wires into a low-noise environment also increases the risk of EMI transmission to low-noise signal cabling. For these reasons, a voltage divider or voltage multiplier circuit installed within fully contained electromagnetic shielding, with a minimum overall length of high-voltage wiring may be preferred to extensive high voltage cryostat cabling.

4.1.2 PMT response at 6 K

An earlier study of low-temperature PMT performance was carried out at Oxford University to characterise variation in PMT response to scintillation light from a CaWO_4 crystal under cooling to 6 K [102]. A brief description of the results and

²For example, 12 steel wires carrying a maximum current of 50 μA need not produce more than a total heatload of 100 μW from room temperature to 4.2 K and 1 μW from 4.2 K to 1 K if carefully designed. See Section 3.2.2.

Temp / K	Peak position		Energy resolution FWHM / %		CaWO ₄ light ouput	Relative response of module		Relative response of PMT	
	²⁴¹ Am	⁵⁷ Co	²⁴¹ Am	⁵⁷ Co		²⁴¹ Am	⁵⁷ Co	²⁴¹ Am	⁵⁷ Co
Photon counting									
290	57±10	98±16	40	38	1	1	1	1	1
77	70±8	137±18	32	30	1.6±0.3	1.22±0.26	1.40±0.29	0.76±0.30	0.87±0.36
6	50±9	99±14	42	33	1.8±0.3	0.87±0.22	1.01±0.21	0.48±0.12	0.56±0.21
Pulse height									
290	1.35±0.24	2.89±0.46	43	37	1	1	1	1	1
77	1.86±0.24	3.63±0.35	31	23	1.6±0.3	1.37±0.30	1.25±0.23	0.85±0.36	0.78±0.29
6	0.69±0.13	1.37±0.19	45	33	1.8±0.3	0.51±0.13	0.47±0.10	0.28±0.09	0.26±0.08

Table 4.1: **The measured resolution and relative response to events in a CaWO₄ scintillator of an Electron Tubes D745B PMT under cooling. Quoted from data published in [102].**

conclusions from this study will place the results obtained subsequently with the low-temperature CWG/PMT module into context.

An Electron Tubes D745B PMT was placed in good optical contact with a CaWO₄ crystal scintillator and the whole assembly was cooled to 77 K and 6 K successively. The variation in scintillation light output from CaWO₄ under cooling was the subject of earlier studies and is well understood [103], [104], [97].

A room temperature voltage divider circuit was used with an array of high-impedance cabling to supply voltages up to 1830 V to the PMT dynodes.

Table 4.1 gives the observed variation of PMT response under cooling relative to room temperature values.

The results of this study and others indicated that PMT use at low temperatures could be achieved without compromising energy resolution. In this instance, some deterioration in relative PMT response was observed after cooling. PMT re-

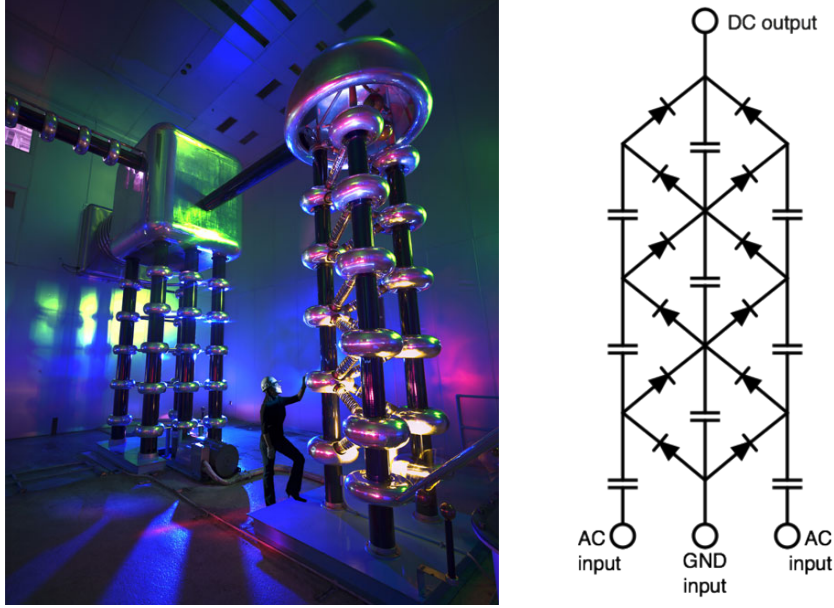


Figure 4.1: **Photograph and schematic of a large full-wave Cockcroft-Walton generator installed to provide extra high voltage for proton acceleration. This pattern of CWG design is known as *full-wave*, as the central DC capacitor chain is charged alternately during each half period of the supply voltage by two AC capacitor chains.**

sponse is dependent on several temperature dependent properties, such as window transparency, dynode multiplication and photocathode sensitivity. In particular, photocathode sensitivity and conductivity are critical parameters governing PMT gain [99].

This work was continued with the aim of testing a different PMT configuration at temperatures below 6 K, utilising a CWG voltage multiplier circuit to provide dynode voltages.

4.2 Cockcroft-Walton generators

Figure 4.1 shows a schematic and photograph of a large Cockcroft-Walton generator (CWG) installed to provide HV supply for proton acceleration at the Tevatron, Fermilab. The CWG uses a ladder of capacitors charged by an alternating supply to produce a DC high voltage. The CWG circuit was first developed using mechanical rectifiers by H. Greinacher in 1919 and has been widely used to generate high voltages for particle acceleration. The CWG built by J. D. Cockcroft and E. T. S. Walton was used in 1932 to achieve the first artificial nuclear disintegration, for which they shared the 1951 Nobel Prize in Physics. The possibility of using a small CWG module to provide high voltage supply for the dynodes of a PMT operated at low temperatures without incurring the heatload cost of a low-temperature resistive voltage divider is explored in this chapter.

4.2.1 Theory

A circuit schematic of a three-stage half-wave CWG with input transformer is shown in Figure 4.2. The basic working principle of a half-wave CWG is that of a series of nested voltage doubler circuits in which a series capacitor chain (the ‘DC chain’) is charged during one half-period of an AC supply voltage $\pm V_{IN}$ provided along a second series capacitor chain (the ‘AC chain’).

In a lossless circuit, the voltage difference between successive capacitors in the DC chain is $2V_{IN}$. In practice, the DC output voltage is reduced by several

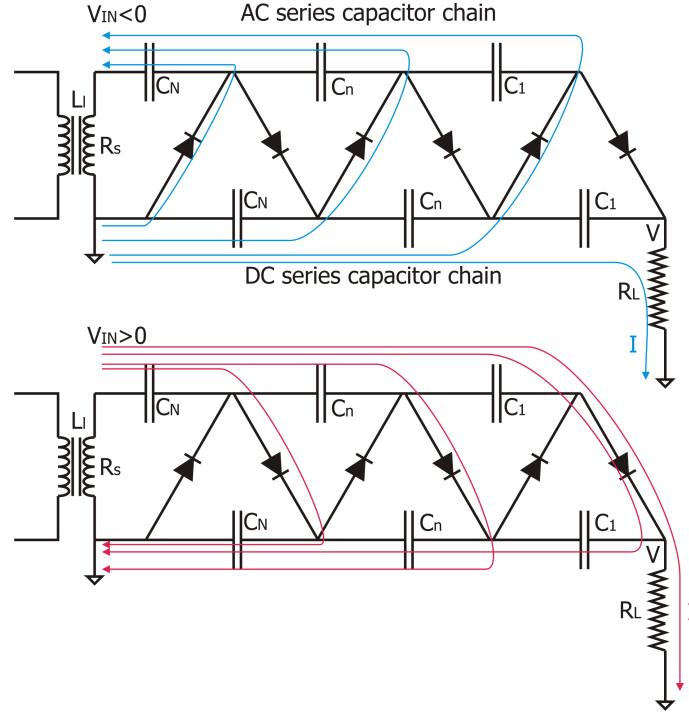


Figure 4.2: **Schematics of a three stage half-wave CWG with input transformer. Approximate current flow deduced by charge conservation during steady running conditions is shown using blue ($V_{IN} < 0$) and red ($V_{IN} > 0$) arrows.**

factors: the voltage transmission efficiency of the CWG chain, the cumulative effect of voltage drop in the diodes and the voltage drop under load current flowing through the capacitor chains. The effect of capacitive voltage drop in the DC chain also produces a ripple voltage on the output of each stage.

The voltage transmission efficiency of the network of capacitors and diodes is the primary limit on the performance of EHV³ CWG for particle acceleration and has been analytically studied by several authors [105], [106], [107], [108].

Everhart and Lorrain [105] describe the effect of charge storage in the stray

³Extra high voltage, voltage in excess of 275 kV.

shunt capacitances C_d of the diodes. This analysis is extended to include the voltage drop of the series capacitor chains under a non-zero load current by Weiner [106], who gives relations (4.3) and (4.4) for the output V_{OUT} and ripple voltage ΔV_r of an N -stage CWG with chain capacitors of uniform capacitance C .

$$V_{OUT} = 2NV_{IN} \frac{\tanh(2\gamma N)}{2\gamma N} \quad (4.3)$$

$$\Delta V_r = V_{IN} (1 - \operatorname{sech}(2\gamma N)) \quad (4.4)$$

$$\gamma = \left(\frac{N}{2fR_L C} + \frac{C_d}{C} \right)^{1/2} \quad (4.5)$$

This widely used transmission line CWG model does not adequately describe the smaller CWG designs tailored for PMT dynode voltage supply, in which the diode drop voltage is non-negligible by comparison with the CWG input voltage, and therefore has a significant effect on the CWG output.

The designs developed here for PMT dynode voltage supply utilise tapering capacitor chains⁴ to best use available space in the cryostat. The plastic-dielectric capacitors used at low temperatures become increasingly bulky for large capacitance values and space is very limited with a dilution refrigerator. To get best ‘value’ for capacitance, larger value capacitors are used for higher current CWG stages, minimising voltage drop across the capacitors without installing uniformly bulky capacitors at each stage.

⁴A schematic for a CWG design featuring tapering capacitor chains is shown in Figure 4.10.

In order to include the effects of diode forward voltage and tapering capacitance chains in CWG models, I adopted a flexible method of summation over CWG drop voltages. The methods of Takamura [109] and Hwang [110] were generalised to include tapering capacitor CWG design and non-zero diode drop voltages.

By considering the flow of charge during each cycle of the input voltage, we can deduce an approximate current flow through the CWG. When $V_{IN} > 0$, the diodes allow current to flow from the AC chain to the DC chain (red arrows in Figure 4.2); for $V_{IN} < 0$, the current flows from the DC chain to the AC chain (blue arrows in Figure 4.2). During steady operation, a constant current I is drawn by the load resistance R_L across the output voltage V_{OUT} . A charge $Q = I/f$ is discharged to the load resistance from the first capacitor in the DC chain during one full cycle of CWG operation. During each cycle a charge Q is also discharged from the first capacitor in the AC chain to the load resistance. During each cycle, the first capacitor of the AC chain also supplies a charge Q to the first capacitor of the DC chain, meaning a total charge of $2Q$ is discharged by the first capacitor of the AC chain. The first capacitors in both the DC and AC chains are supplied by the discharge of the second capacitor in the DC chain. Figure 4.2 shows the extension of this argument to give the flow of charge during both phases of the AC supply voltage.

The variation in voltage between the charging and discharging of the capacitor at each node is given by the cumulative effect of all of the voltage variations due

to the capacitors and diodes which supply charge to that capacitor. The variation in voltage across a capacitor is given by $V = Q_n/C$ and the variation in voltage across a diode by $V_d(I)$. The diodes selected for CWG fabrication have a forward voltage approximately constant in the low-current range used (see Section 4.3.3), so we approximate $V_d(I) \simeq \bar{V}_d$.

Noting that $n = 1$ denotes the highest voltage capacitors, we can write the voltage variation at a node i for $V_{IN} < 0$ and $V_{IN} > 0$ as (4.6) and (4.7), respectively. The voltage of the N th capacitor of the AC chain is supplied directly by the AC input while $V_{IN} > 0$, and so does not contribute to the variation voltage during this phase.

$$\delta V_{i,max} = \sum_{n=i}^N \left(\frac{2nI}{fC_n} + \bar{V}_d \right) \quad (4.6)$$

$$\delta V_{i,min} = \sum_{n=i}^N \left(\frac{nI}{fC_n} + \bar{V}_d \right) + \sum_{n=i}^{N-1} \left(\frac{(n+1)I}{fC_n} \right) \quad (4.7)$$

The total voltage drop ΔV is given by the sum of the variation voltages over all of the capacitors in the DC chain. The maximum voltage drop (which occurs while $V_{IN} < 0$) is given by the sum of $\delta V_{i,max}$ and the minimum voltage drop (occurring while $V_{IN} > 0$) by the sum of $\delta V_{i,max}$. In the low-current, many stages case, $\Delta V_{max} \gg (\Delta V_{max} - \Delta V_{min})$, so we use $V_{OUT} = 2NV_{IN} - \Delta V_{max}$.

$$V_{OUT} = 2NV_{IN} - \sum_{i=1}^N \sum_{n=i}^N \left(\frac{2nI}{fC_n} + \bar{V}_d \right) \quad (4.8)$$

$$= 2NV_{IN} - \frac{N^2 - N}{2} \bar{V}_d - \frac{I}{f} \sum_{i=1}^N \sum_{n=i}^N \left(\frac{2n}{C_n} \right) \quad (4.9)$$

The inequality in capacitive voltage drop over the changing phase of the input voltage gives rise to a ripple voltage ΔV_r on the output. The frequency of the ripple voltage is therefore equal to the AC supply frequency but the ripple waveform is non-sinusoidal. The amplitude of the ripple voltage is given by the difference between the highest and lowest output voltage, equal to the difference between the highest and lowest voltage drop.

$$\Delta V_r = \sum_{i=1}^N \sum_{n=i}^N \left(\frac{nI}{fC_n} \right) - \sum_{i=1}^{N-1} \sum_{n=i}^{N-1} \left(\frac{(n+1)I}{fC_n} \right) \quad (4.10)$$

$$= \frac{I}{f} \left(\sum_{i=1}^N \sum_{n=i}^N \left(\frac{n}{C_n} \right) - \sum_{i=1}^{N-1} \sum_{n=i}^{N-1} \left(\frac{(n+1)}{C_n} \right) \right) \quad (4.11)$$

Approximating $I \simeq \frac{2NV_{IN}}{R_L}$, we can derive the CWG gain $G \equiv \frac{V_{OUT}}{V_{IN}}$ and ripple factor $\frac{\Delta V_r}{V_{OUT}}$:

$$G = 2N \left(1 - \frac{1}{fR_L} \sum_{i=1}^N \sum_{n=i}^N \frac{2n}{C_n} \right) - \frac{N^2 + N}{2} \frac{\bar{V}_d}{V_{IN}} \quad (4.12)$$

$$\frac{\Delta V_r}{V_{OUT}} = \frac{1}{fR_L} \left(\sum_{i=1}^N \sum_{n=i}^N \left(\frac{n}{C_n} \right) - \sum_{i=1}^{N-1} \sum_{n=i}^{N-1} \left(\frac{(n+1)}{C_n} \right) \right) \quad (4.13)$$

In the case that all the capacitors are of equal value C and $V_d \rightarrow 0$, (4.12) and (4.13) reduce to the results given in [109]:

$$G = 2N \left(1 - \frac{1}{fCR} \left(\frac{2}{3}N^3 + N^2 + \frac{1}{3}N \right) \right) \quad (4.14)$$

$$\frac{\Delta V_r}{V_{OUT}} = \frac{1}{fCR} \left(\frac{N^2 + N}{2} \right) \quad (4.15)$$

It will be seen that in practice the transmission efficiency of the CWG-transformer system is also dependent on the effect of the complex load of the CWG on the transmission efficiency of the input transformer.

4.3 Component testing

We wished to run the CWG power supply at temperatures ≤ 4.2 K. In order to assess the feasibility of running a CWG in this temperature range, the principal components of the CWG and input transformer were tested and characterised under cooling to 4.2 K. Component types were found in which the performance under cooling was stable enough to design a practical low-temperature CWG circuit.

4.3.1 Low-temperature performance of capacitors

The variation of capacitor dielectric properties under cooling to 4.2 K is not well documented. Capacitors of a reliable and stable capacitance in the range 100 nF – 5 μ F at 4.2 K were required.

Electrolytic capacitors are known to exhibit capacitance variation in the temperature range above -50 °C due to temperature dependent variation in electrolyte

Dielectric	Nominal capacitance	77 K capacitance (%)	4.2 K capacitance (%)
Ceramic capacitors			
Standard	1 μ F	4.8 ± 2.0	2.0 ± 0.6
	680 nF	4.1 ± 1.3	1.8 ± 0.4
AVX SV	47 nF	90 ± 11	89 ± 10
	20 nF	88 ± 13	85 ± 13
AVX SK	15 nF	82 ± 14	84 ± 13
Novacap	10 nF	81 ± 14	82 ± 10
Plastic capacitors			
Polystyrene	1 μ F	87 ± 11	87 ± 12
	680 nF	85 ± 10	82 ± 14
MKT	680 nF	87 ± 12	87 ± 12
	330 nF	81 ± 8	84 ± 10

Table 4.2: **Results of measurements to assess suitability of various capacitor types for fabrication of a low-temperature CWG.**

conductivity, so non-electrolytic capacitors were chosen for testing. Readily available standard types were tested alongside specialist types designed for capacitance stability under temperature variation. A summary of the capacitance measured at 77 K and 4.2 K relative to room temperature is shown in Table 4.2. It was generally seen that standard plastic capacitors of both MKT-type and polystyrene dielectric maintained stable capacitance at low temperatures and despite their bulkier size, these capacitor types were chosen for fabrication of CWG prototypes.

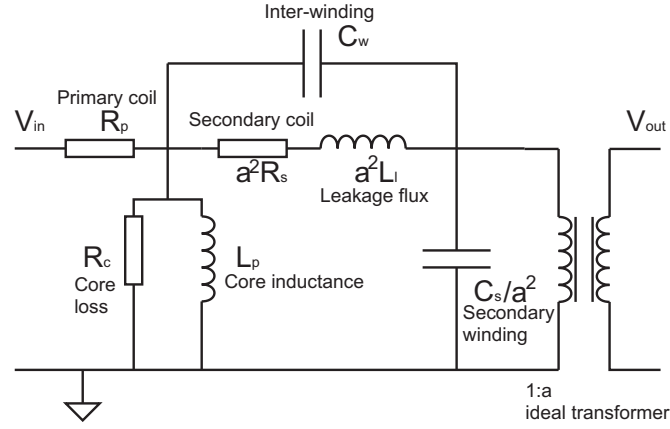


Figure 4.3: Schematic showing an equivalent circuit for a real transformer of winding ratio 1:a.

4.3.2 Low-temperature performance of transformers

Design of suitable transformers to provide the input voltage for the CWG was dependent on identifying transformer cores made of material which maintains a stable dielectric permittivity under cooling to low temperatures.

A real transformer can be represented by the equivalent circuit shown in Figure 4.3 and the output voltage of this transformer is given by (4.16) - (4.20).

$$\left| \frac{V_{out}}{V_{in}} \right| = \frac{a}{\sqrt{\Re \left[\frac{V_{in}}{V_{out}} \right]^2 + \Im \left[\frac{V_{in}}{V_{out}} \right]^2}} \quad (4.16)$$

$$\Re \left[\frac{V_{in}}{V_{out}} \right] = 1 + \frac{R_p}{R_c} - \omega^2 C_s \frac{B}{A} \left(1 + \frac{R_p}{R_c} \right) - \frac{\omega^2 C_s L_p}{1 - (\omega L_p / R_c)^2} + \frac{R_p C_s R_s}{A L_p} \quad (4.17)$$

$$\Im \left[\frac{V_{in}}{V_{out}} \right] = \omega \left(C_s R_p + \frac{C_s R_c}{1 + (R_c / \omega L_p)^2} + \frac{C_s R_s}{A} \left(1 + \frac{R_p}{R_c} \right) + \frac{B C_s R_p}{A L_p} - \frac{R_p}{L_p \omega^2} \right) \quad (4.18)$$

$$A = (1 - C_w L_l \omega^2)^2 + (C_w R_s \omega)^2 \quad (4.19)$$

$$B = L_l - C_w L_l^2 \omega^2 - C_w R_s^2 \quad (4.20)$$

Initial testing of ferrite powder core transformers revealed increasing peak transmission frequency under cooling to 4.2 K, indicating decreasing dielectric permittivity (Figure 4.4). Specialist molypermalloy powder (MPP) cores, developed for high temperature stability, were tested and exhibited stable permittivity under cooling to 4.2 K.

It was desired to maximise transformer gain and operating frequency range for this application. MPP cores were wound by AGW Electronics of Staveley, Derbyshire with a high winding density (to maximise L_p) of high-quality copper wire (to minimise R_p and R_s).

4.3.3 Low-temperature performance of diodes

The selection of rectifier diodes for the CWG was made subject to the requirements that the maximum reverse voltage be comfortably above the maximum expected

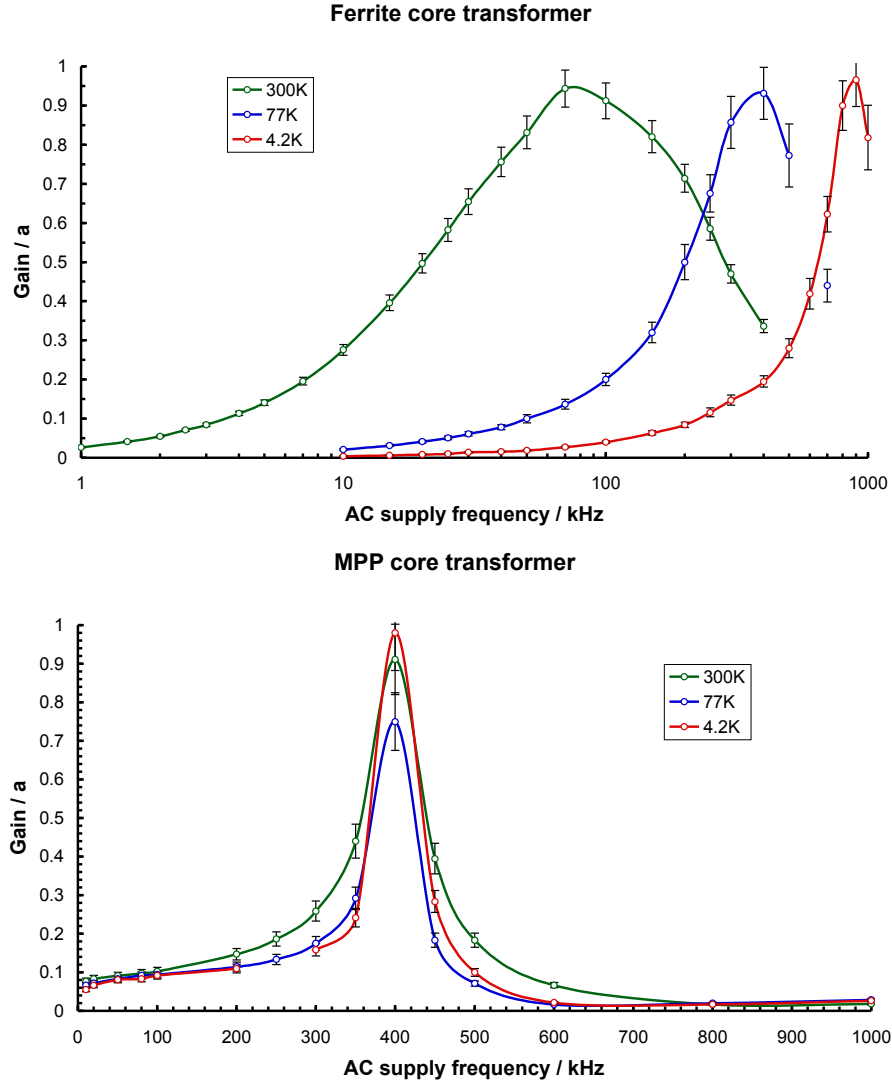


Figure 4.4: Measured stability of core permittivity of both ferrite-core and MPP-core hand wound transformers. The narrow range of operating frequencies is a consequence of the limited winding density and higher leakage inductance of hand-wound coils. The optimum frequency varies inversely with the primary inductance of the transformer core and can be seen to be strongly dependent on operating temperature in the case of the ferrite-core transformer (*top*), and constant for the MPP-core transformer tested (*bottom*).

Diode characteristic	1N4007	1N4003
Peak reverse voltage	1000 V	200 V
Parasitic capacitance	15 pF	15 pF
Forward voltage drop under 1.0 A load	1.1 V	1.1 V
Reverse current at peak voltage	5.0 μ A	5.0 μ A

Table 4.3: **Room temperature electrical characteristics for selected silicon rectifier diodes.**

voltage step (200 V), and that the reverse saturation current be negligible compared to typical current load of the CWG ($\sim 1 \mu$ A). The rectifier diodes selected would maintain these reverse characteristics under cooling to low temperatures.

A secondary consideration was that the diode forward voltage drop should not increase significantly at low temperatures. Despite the small current load of the PMT, power dissipation in the diodes due to forward voltage drop could present a significant heatload.

The equivalent capacitance of the diodes was of lower importance since the series capacitors chosen for the CWG (≥ 100 nF) were several orders of magnitude greater, rendering voltage transmission line losses negligible.

With these priorities established, the stability and forward voltage of 1N4007 and 1N4003 silicon rectifiers were tested under cooling to low temperatures. These results are shown in figures 4.5, 4.6 and 4.7.

A CWG of 18 stages with a maximum output voltage of 2 kV was envisaged from the outset. The maximum reverse voltage across any diode in the circuit was not expected to exceed 111 V under steady operating conditions, but greater

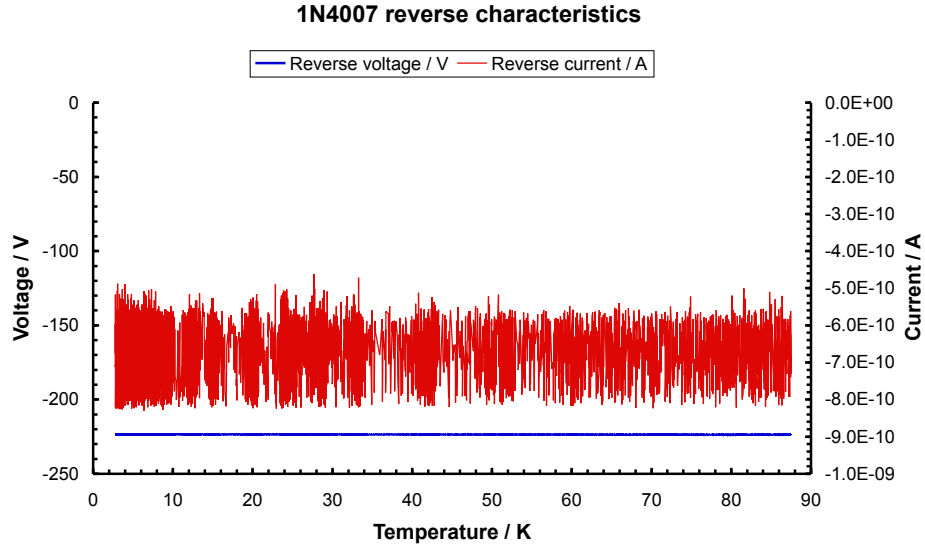


Figure 4.5: Measured saturation current under a reverse voltage of 222 V over temperature range 3.5 K to 87 K for 1N4007 silicon rectifier diode.

reverse voltages might be applied during running-up. A reverse voltage of 222 V was applied to a 1N4007 diode and the diode temperature swept over the range 3.5 K – 87 K (Figure 4.5). The measured reverse saturation current remained stable and did not exceed 1 nA, considered to be negligible compared to designed CWG operating current of 1 μ A.

The measurement of the silicon rectifier forward voltages under cooling to 3.5 K (Figures 4.6 and 4.7) did not show a uniform variation of forward voltage with decreasing temperature. Instead it was observed that at a current-dependent critical temperature the behaviour of the diodes changed markedly.

In the case of the 1N4007 diodes, a maxima in forward voltage was observed at ~ 20 K, below which the forward voltage remained steady with a small temperature

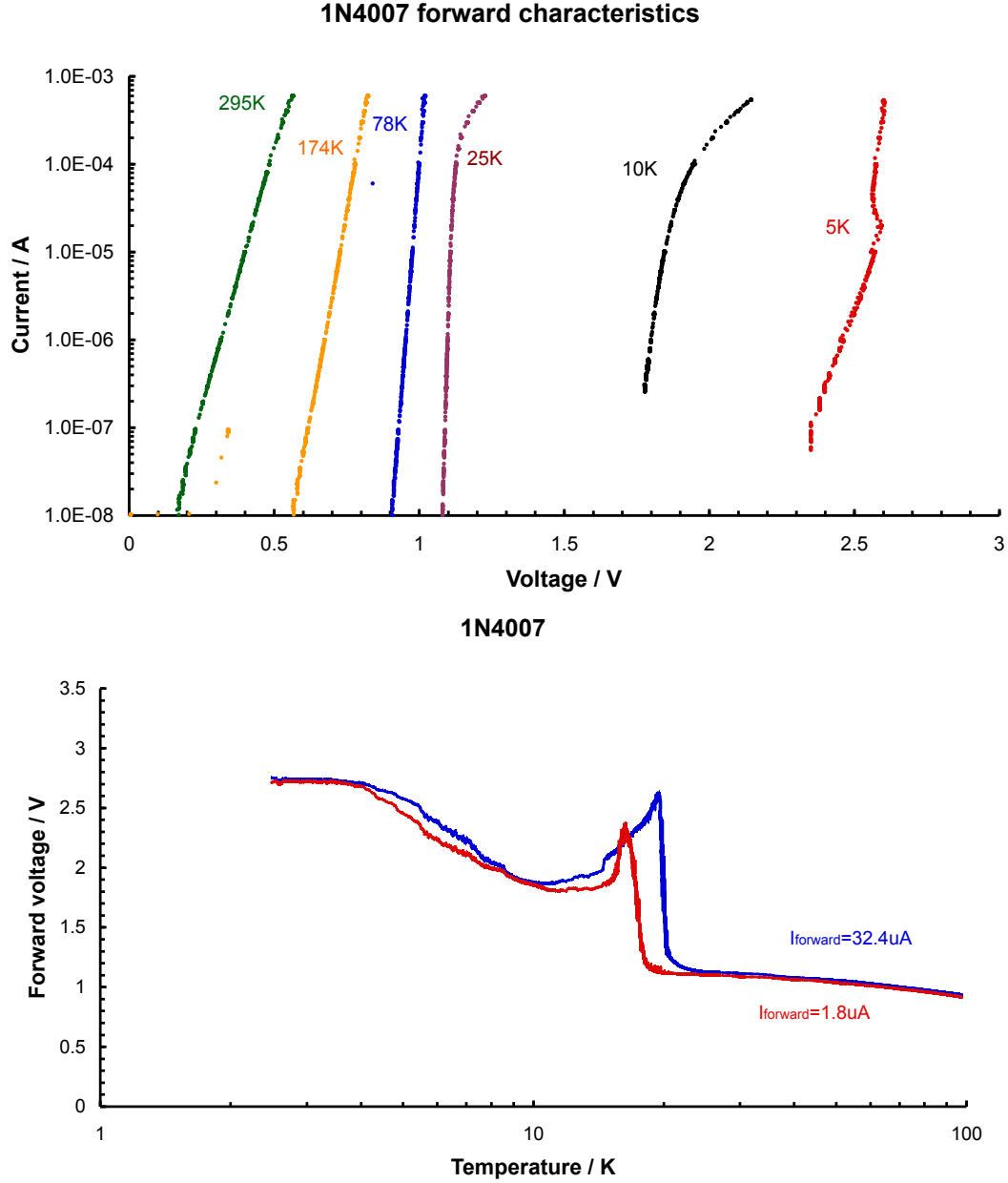


Figure 4.6: Measured temperature dependence of 1N4007 silicon rectifier diode forward voltage with forward bias currents ranging from 10 nA to 1 mA. (Top) forward I/V curves measured at 295 K, 174 K, 78 K, 25 K, 10 K, 5 K. (Bottom) forward voltage measured continuously over temperature range 3.5–100 K for bias currents $32.4 \mu\text{A}$ and $1.8 \mu\text{A}$, the highest and lowest currents used in the CWG/PMT module.

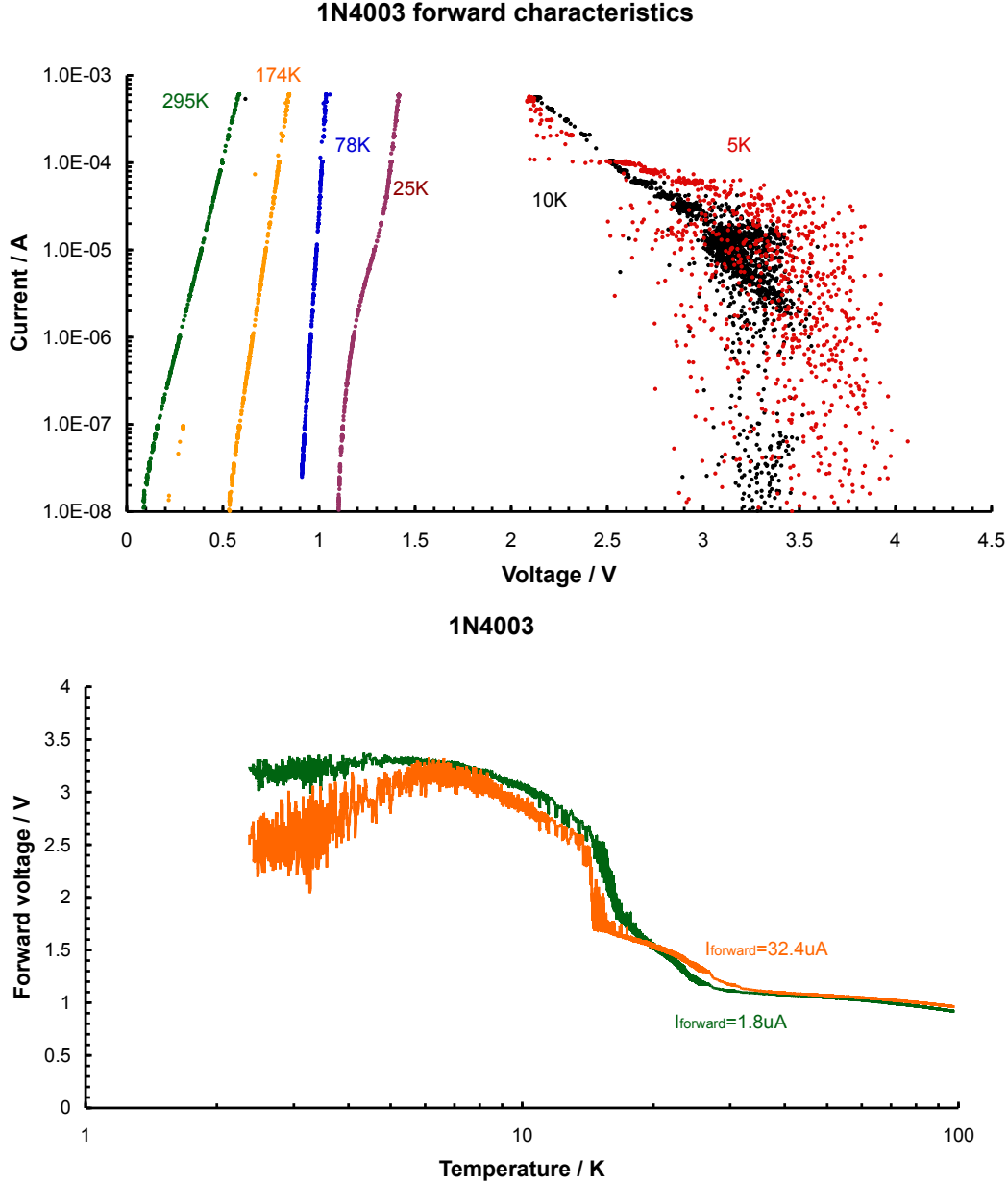


Figure 4.7: Measured temperature dependence of 1N4003 silicon rectifier diode forward voltage with forward bias currents ranging from 10 nA to 1 mA for comparison with 1N4007 data. (*Top*) forward I/V curves measured at 295 K, 174 K, 78 K, 25 K, 10 K, 5 K. (*Bottom*) forward voltage measured continuously over temperature range 3.5–100 K for bias currents $32.4 \mu\text{A}$ and $1.8 \mu\text{A}$, the highest and lowest currents used the CWG/PMT module.

dependence. However, the 1N4003 diodes displayed a marked increase in forward voltage at ~ 20 K, below which the diodes display a very unstable forward voltage, generating significant voltage noise, which can be seen in the data presented.

An explanation of this dramatic change in forward voltage below 20 K is the freeze-out of charge carriers in the silicon p-n junction⁵, rather than a variation in saturation current, which was observed to be constant over the whole temperature range (Figure 4.5). The 1N4003 diodes were considered unsuitable for fabrication of low-temperature CWG circuits.

4.4 Development of low-temperature Cockcroft-Walton generators

Equations 4.12 and 4.16–4.20 indicate that the overall voltage gain of a CWG with an input transformer is dependent on series CWG capacitance, rectifier forward voltage, transformer primary inductance, leakage inductance, core loss, winding capacitance, primary coil resistance, secondary coil resistance, load current and AC supply frequency. The complexity of this system (particularly as the electrical properties of the components vary under cooling) necessitated the testing of several prototypes to refine the final design. Data obtained from the testing of two

⁵This effect is commonly observed in silicon diodes tested for cryogenic temperature measurement: reduction of the thermal energy available to charge carriers, known as ‘freeze-out’, causes discontinuities in forward voltage under cooling, which can limit the usable range of a diode temperature sensor [111], [112].

Stages	5
Series capacitors	(300 K) 100 nF polystyrene
Rectifier diode	1N4007
Transformer winding ratio	25:150
Primary coil	0.3 Ω , 55 μ H (300 K)
Secondary coils	1.5 Ω , 1.80 mH (300 K)
Input voltage (AC peak)	5.6 $\pm$ 0.3 V
Output voltage (maximum)	313 $\pm$ 3 V
Attenuator impedance	1 M Ω

Table 4.4: **Specification of prototype 5-stage CWG and input transformer.**

intermediate designs will be presented to motivate the design features chosen for the CWG/PMT module power supply.

4.4.1 5-stage Cockcroft-Walton generator

After identifying suitable components for use at 4.2 K, it was necessary to demonstrate and study the performance of a basic transformer/CWG assembly cooled to this temperature. As soon as an MPP-core transformer was available, a 5-stage full-wave CWG was assembled and tested inside an evacuated vessel cooled by immersion in liquid nitrogen and liquid helium. The specification of this CWG generator is given in Table 4.4 and the gain over an AC supply frequency range of 150–700 kHz is shown in Figure 4.8.

This initial test signalled the potential for successful CWG operation at 4.2 K, suggesting that all of the components would function adequately, allowing high voltage gain under cooling; maximum transformer gain of 6 coupled with maxi-

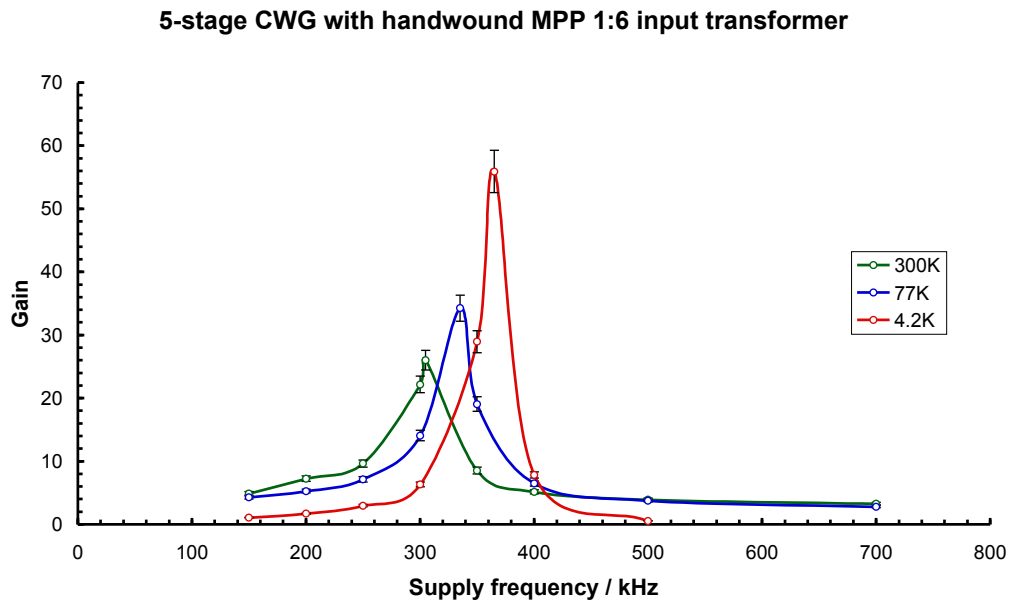


Figure 4.8: Frequency response of a 5-stage CWG equipped with the hand wound MPP-core input transformer with a winding ratio of 6 characterised in Figure 4.4. Although the bandwidth is limited by using hand wound transformer coils, the voltage gain at 4.2 K reaches 56, close to the optimal combined voltage gain for the transformer and CWG of 60.

imum CWG gain of 10 gives an optimum overall voltage gain of 60, against which the highest achieved 4.2 K gain of 56 compared favourably. However, the generator gain appeared to be strongly dependent on the power transmission of the transformer when coupled to the mainly capacitive load of the CWG. This was indicated by the narrow band of operating frequencies and by the significant improvement of peak power transmission under cooling.

The highly resonant frequency-domain behaviour of this prototype transformer-CWG system is not reproduced by (4.16) and (4.12), but we can consider it consistent with the observations of component performance under cooling after considering the effects of the complex transformer-CWG series load on the voltage transmission.

Approximation of the overall performance of the transformer-CWG system by voltage transmission in a series LCR circuit under a load resistance R_L , in which the peak transmission frequency is given by $\frac{1}{2\pi\sqrt{CL}}$ and voltage transmission at this frequency by $(1 + \frac{R}{R_L})^{-1}$, yields broadly intuitive results. Component testing revealed that the capacitors used drop capacitance slightly under cooling to 4.2 K (Section 4.3.1), the transformer inductance remains constant (Section 4.3.2) and we can expect the copper wire wound transformer coils to drop in resistance very significantly (Section 3.2.2). The increasing resonant frequency and maximum voltage efficiency of the transformer-CWG system under cooling to 4.2 K should therefore not surprise us, despite its resistance to description by expected

performance equations.

4.4.2 18-stage Cockcroft-Walton generator

After achieving respectable gain at low temperatures with a hand-wound MPP-core transformer, machine-wound MPP-core transformers were supplied by AGW Electronics. The aim of this second prototype was to achieve ample voltage and current supply for a low-temperature PMT over a broad range of operating frequencies. It was also required to test the feasibility of running a CWG in the high vacuum ($< 1 \times 10^{-5}$ mbar) environment of a dilution refrigerator IVC. A medium vacuum pressure of 1×10^{-3} mbar was achievable in the evacuated vessel used for testing. The successful operation of a CWG at full voltage in this intermediate pressure is a good indicator of adequate insulation for lower pressure operation, since expected discharge voltage is minimised at intermediate gas pressures⁶.

The specification of this CWG is shown in Table 4.5. Measured gain and ripple voltage over an AC supply frequency range of 1–1000 kHz is shown in Figure 4.9.

Testing the 18-stage CWG confirmed that the operation of a low-temperature voltage multiplier could provide sufficient voltage and current to power a small PMT for scintillation detection. A closer comparison of CWG performance with the derived performance equations was possible due to the wide-bandwidth transformer performance. With the effects of power loss due to transformer transmission reduced by higher, more uniform winding density, we can observe the expected

⁶*Paschen's Law*, see [113]

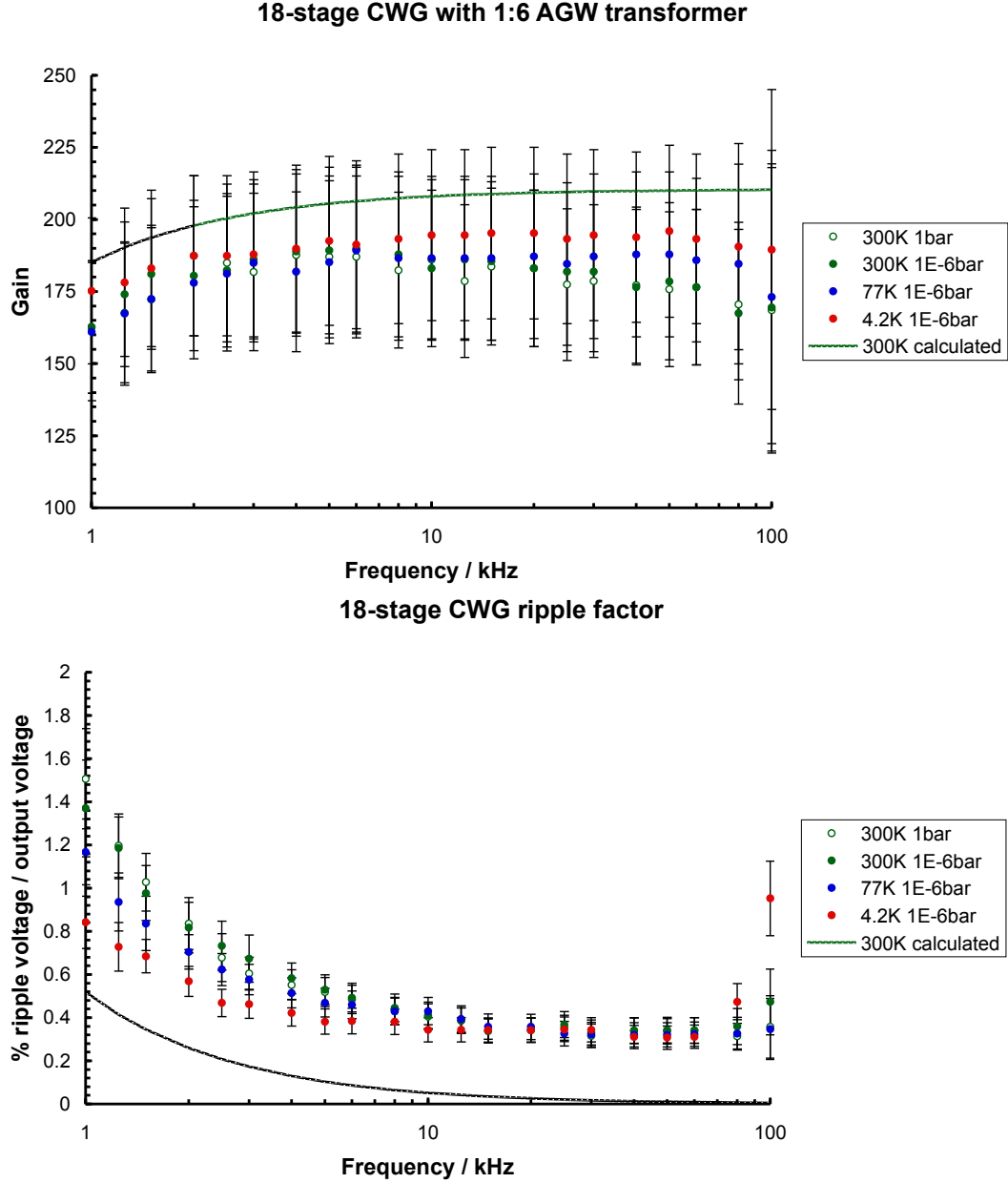


Figure 4.9: Performance of the 18-stage CWG specified in Table 4.5. (*Top*) combined transformer/CWG gain over a frequency range 1 – 100 kHz at 300 K (~ 1 bar) and 300 K, 77 K, 4.2 K (1×10^{-3} mbar). The dashed line shows combined voltage gain calculated using (4.12). (*Bottom*) ripple voltage as a percentage of output voltage for the same range of operating conditions and supply frequencies along with the value calculated using (4.10).

Stages	18
Series capacitors (300K)	MKT
Stages 18-13	2.2 μ F
Stages 12-9	1.5 μ F
Stages 8-6	1 μ F
Stages 5-1	680 nF
Rectifier diode	1N4007
Transformer winding ratio	100:600
Primary coil	1 Ω , 833 μ H (300 K)
Secondary coil	6 Ω , 28.5 mH (300 K)
Input voltage (AC peak)	15.0 $\pm$ 1.2 V
Output voltage (maximum)	2.94 $\pm$ 0.22 kV
Attenuator impedance	33 M Ω

Table 4.5: **Specification of prototype 18-stage CWG and input transformer.**

variation in CWG gain with supply frequency given by (4.12). The ripple voltage variation with supply frequency conforms with (4.10) but excess ripple was observed in this test. It was later observed that inadequate earthing of the CWG base increases the magnitude of the ripple voltage:- which is a probable cause of the excess ripple voltage observed in this test.

4.4.3 18-stage CWG/PMT module

An 18-stage CWG was designed to provide dynode voltages for a Hamamatsu R7725 PMT operated at millikelvin temperatures within an Oxford Instruments S400 dilution refrigerator. An integrated CWG/PMT module was installed and CWG efficiency was optimised in order to minimise CWG/PMT module heatload.

Spectral response	300–650 nm
Window	borosilicate glass
Photocathode material	K-Cs-Sb + Pt bialkali
Photocathode diameter	46 mm
Dynodes	12 linearly focused
Dynode material	Cu-BeO-Cs
Maximum supply voltage	2000 V
Supply voltage used	1830 V
Gain	6.7×10^6
Average anode current	200 μ A
Dark current	9 nA

Table 4.6: **Specification of the Hamamatsu R7725 PMT installed in the CWG/PMT module.**

To achieve optimal operating efficiency with minimum ripple voltage a small attenuator current of 1.8 μ A was chosen. This allowed an increase in transformer winding ratio without risk of drawing excessive current through the primary coil (< 50 mA). The CWG/PMT module was mounted via a copper bracket to the mixing chamber of the dilution refrigerator. Figure 4.10 shows a photograph of the module after installation alongside a schematic of the CWG power supply circuit.

The gain and efficiency of the CWG were measured at temperatures of 300 K, 77 K, 4.6 K and 950 mK over a frequency range of 2–30 kHz. It was observed that while the gain of the CWG was close to the combined lossless gain of the transformer-CWG system ($24 \times 36 = 864$) over a wide frequency range, the measured efficiency (defined by (4.1)) of the CWG was maximised at a resonant operating frequency, similar to the 5-stage CWG tested in Section 4.4.1.

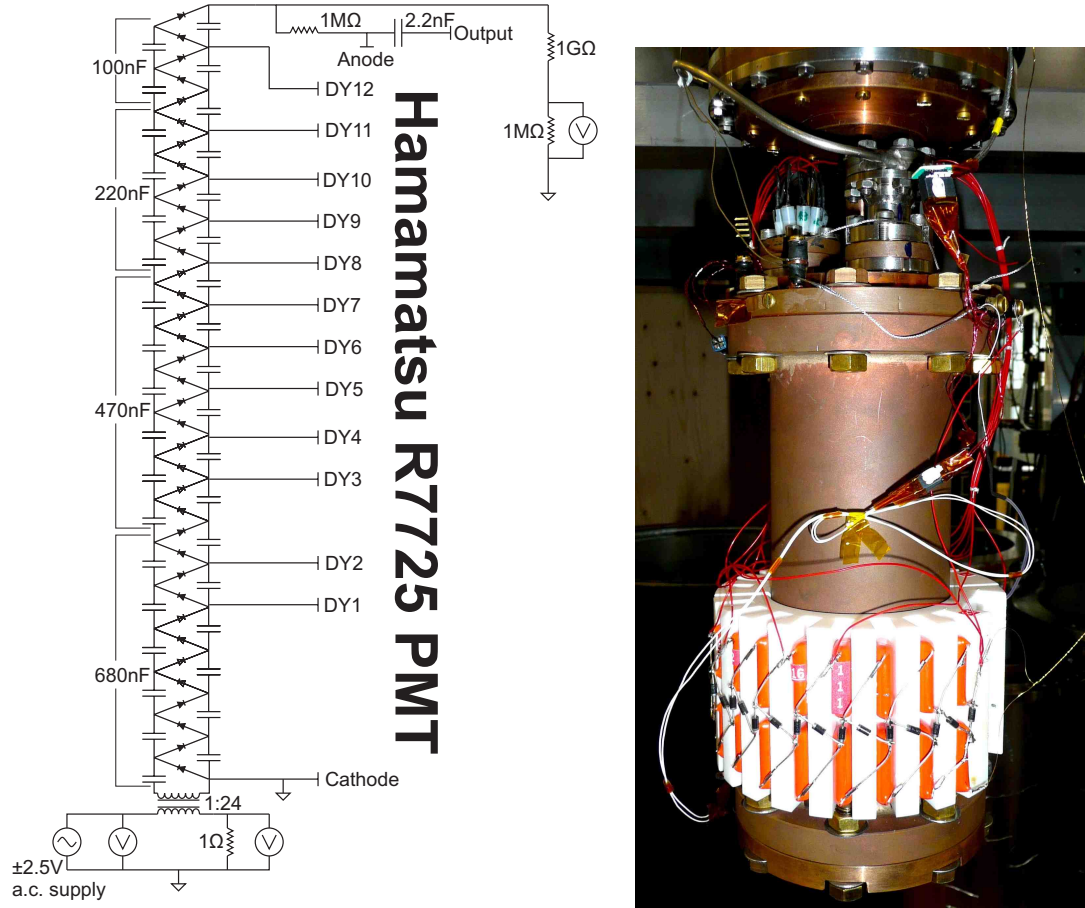


Figure 4.10: Schematic showing the power supply for the 18-stage CWG/PMT module with a photograph of the module installed inside an S400 dilution refrigerator. The 18 CWG stages generate (approximately) equidistant voltages. The dynodes are not separated by equidistant voltages, but the design of the CWG is tailored to provide the correct dynode voltages for the Hamamatsu R7725 PMT.

Stages	18
MKT Series capacitors	300 K capacitance
Stages 18-13	680 nF
Stages 12-7	470 nF
Stages 6-3	220 nF
Stages 2-1	100 nF
Rectifier diodes	1N4007
Transformer winding ratio	25:600
Primary coil	$0.5 \, \Omega$, 295 μH (300 K)
Secondary coil	$60 \, \Omega$, 144 mH (300 K)
Input voltage (AC peak)	$2.20 \pm 0.05 \, \text{V}$
Output voltage (maximum)	$1.829 \pm 0.006 \, \text{kV}$
Attenuator impedance	1 $\text{G}\Omega$

Table 4.7: **Specification of 18-stage CWG and input transformer mounted for PMT power supply.**

The resonant operating frequency was observed to increase slightly under cooling, consistent with the earlier observations. Table 4.8 gives the operating frequencies and efficiencies of the CWG used during measurements of scintillation light with the PMT.

Temperature / K	f_{in} / kHz	V_{in}^{peak} / V	I_{in}^{peak} / mA	V_{out} / V	$P_{out}/P_{in}(\%)$
300	15.7	2.1 ± 0.1	10.5 ± 0.5	1822	30 ± 3
78	17.7	2.1 ± 0.1	9.0 ± 0.5	1812	34 ± 4
4.6	20.0	2.1 ± 0.1	6.0 ± 0.2	1823	53 ± 5
0.95	20.0	2.1 ± 0.1	6.0 ± 0.2	1829	50 ± 5

Table 4.8: **Operating settings for the CWG/PMT module with power efficiency measurements.**

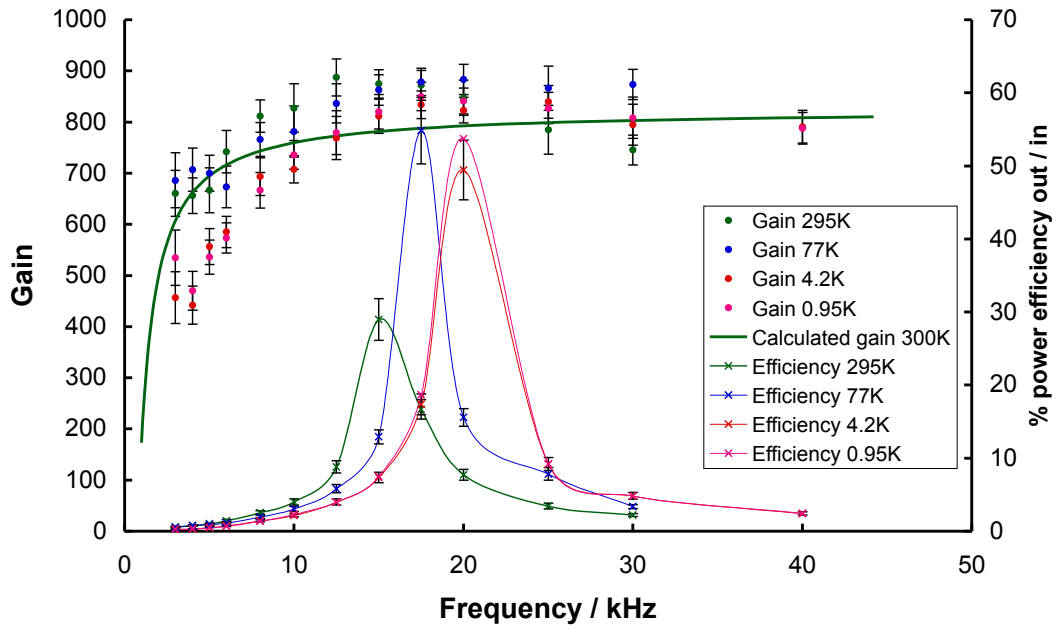


Figure 4.11: Performance of CWG installed as PMT HV supply in S400 dilution refrigerator. The CWG provides an anode voltage of 1.8 kV with an attenuator current of $1.8 \mu\text{A}$. This figure shows combined gain and power efficiency (percentage attenuator power/input power) over the range of operating frequencies and temperatures of the CWG.

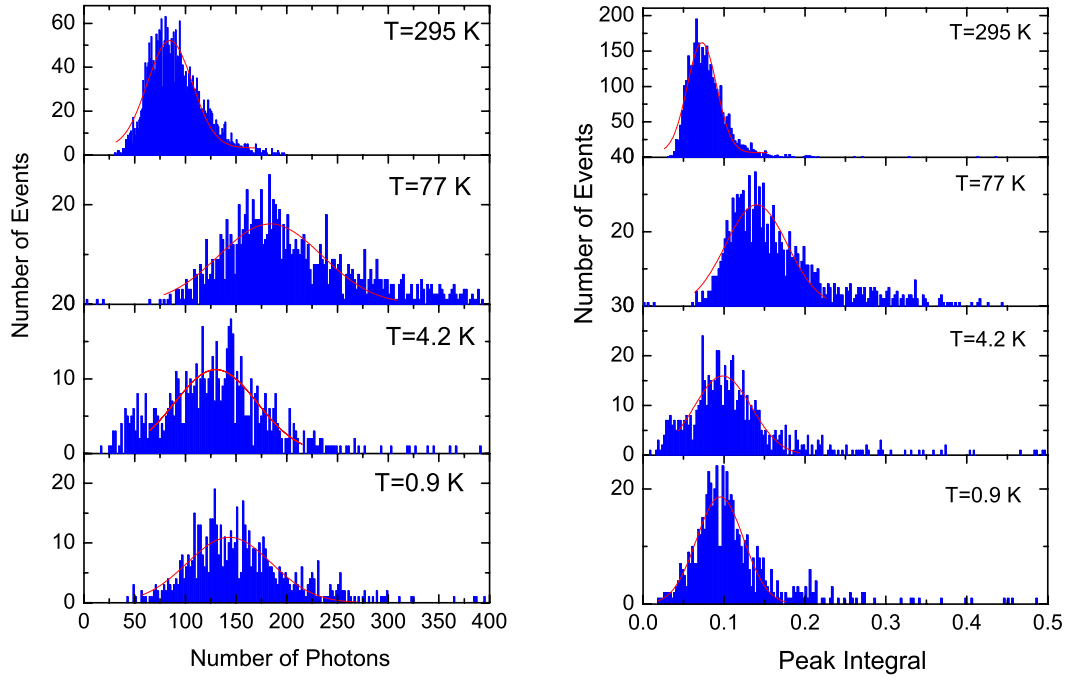


Figure 4.12: ^{241}Am γ -ray spectra measured using the CWG/PMT module at temperatures of 295 K, 77 K, 4.8 K and 0.95 K. Photon counting spectra are shown on the left, peak integral spectra on the right. Single gaussian fits are made to measure peak resolution.

4.5 PMT response with CWG power supply

An ^{241}Am 59.5 keV γ -ray source was used to irradiate the CaWO_4 crystal placed on the PMT photocathode. Due to the slow scintillation time constant of CaWO_4 at low temperatures, a copper shield was used to reduce γ -ray flux incident on the crystal and avoid detection of overlapping γ -ray events. Measurement of the γ -ray spectrum was used to characterise the variation in PMT response and resolution under cooling. Figure 4.12 shows γ -ray spectra measured at module temperatures of 295 K, 77 K, 4.8 K and 0.95 K. The observed variation in PMT resolution and response is given in Table 4.9.

Temperature / K	Peak position / a. u.	Energy resolution FWHM / %	CaWO ₄ light output	Relative response of module	Relative response of PMT
Photon counting					
290	84±19	52	1	1	1
77	183±43	55	1.6±0.3	2.18	1.36
4.8	130±34	62	1.8±0.3	1.55	0.86
0.95	143±35	58	1.8±0.3	1.70	0.94
Pulse height					
290	7.2±1.5	50	1	1	1
77	14.0±3.2	54	1.6±0.3	1.94	1.21
4.8	9.8±3.1	72	1.8±0.3	1.36	0.75
0.95	9.5±2.5	61	1.8±0.3	1.32	0.73

Table 4.9: **The measured response (relative to room temperature) of the CWG/PMT module to scintillation light emitted by a CaWO₄ crystal irradiated by 59.5 keV γ -rays from an ²⁴¹Am source.**

These results demonstrate that the response of the CWG/PMT module is broadly stable under cooling, even when normalised by the increased light yield of CaWO₄ at low temperatures. The lowest response at 0.95 K is 73 % of the room temperature response.

As a consequence of reduced photon numbers and longer scintillation decay times, the incidence of photon pile-up events is reduced at low temperatures. The light detection response using photon counting, which can deteriorate with increased pile-up events, is therefore expected to hold up better under cooling than the response measured using pulse height integration. This is observed in the data, with the photon counting response measured at 0.95 K equal to 94 % of that measured at 290 K.

In each case the measured energy resolution degrades slightly under cooling as

a consequence of reduced statistics.

We can conclude that use of a low-temperature CWG power supply does not degrade the performance of the PMT⁷. The CWG power supply circuit could be used to provide a self-contained, shielded PMT power supply, requiring only a low-voltage audio-frequency input. The design features implemented here could be incorporated in low-temperature light detector designs for future low-noise, low-heatload applications.

4.6 Operating stability at low temperatures

In this section we evaluate the performance of the CWG/PMT module by two criteria essential to the practical operation of CWG power supply circuits for low-temperature PMTs: the operating efficiency and heatload within the cryostat due to the CWG, and the stability of the high voltage output over extended running times.

4.6.1 Heatload due to CWG

The potential for low-heatload CWG power supplies depends crucially on the operating efficiency of the generator, which can be optimised by tuning the AC supply frequency. The optimum efficiency achieved at 950 mK was $50 \pm 5\%$ at a supply

⁷The improvements in the PMT response from the Hamamatsu R7725 relative to the Electron Tubes D745B described earlier could be attributed to improved stability in charge yield of the photocathode and dynodes under cooling.

frequency of 20 kHz (see Table 4.8). The heating power supplied to the cryostat at this efficiency is calculated to be 3.24 mW. This heat will be dissipated partly in the input transformer, which was heatsunk to the helium-4 bath, and partly in the diodes of the CWG, heatsunk to the cryostat mixing chamber.

The effect of this heating on the module temperature was negligible at 77 K and 4.8 K but caused instability of module temperatures below 1 K. The heating effect of the CWG is seen in Figure 4.13. During these measurements the S400 dilution refrigerator was operated without 600 mK or 50 mK shielding due to space constraints and reached a base temperature of 150 mK. After starting the CWG high voltage supply, the module temperature rose rapidly to 950 mK. The temperature was observed to return to 150 mK over a period of 2 hr after turning off the CWG. This is consistent with a heating power of 1–2 mW being applied to the mixing chamber of the dilution refrigerator (cf. Table 3.1).

As well as some further study to minimise power dissipation due to diode forward voltage and optimise the power transfer of CWG input transformers, it would be beneficial in future to heatsink low-temperature CWG power supplies to the dilution refrigerator still, where the application of ~ 1 mW heating has a beneficial effect on mixture circulation, rather than the mixing chamber where excess heat causes the base temperature to rise.

A scheme to implement such a heatsink would require a CWG built inside a conducting mount where great care is taken that each diode, capacitor and connec-

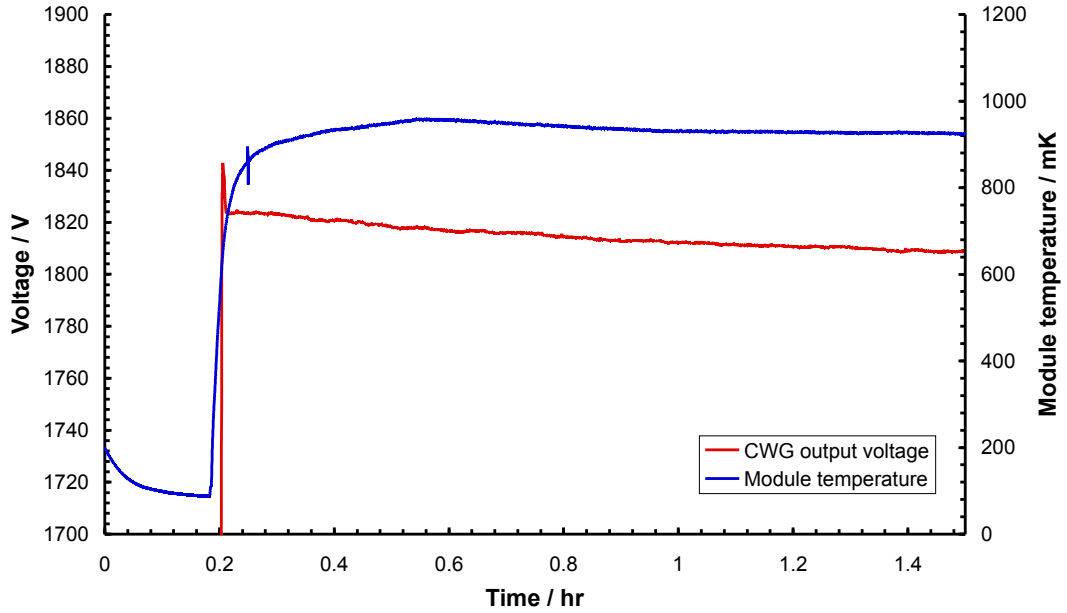


Figure 4.13: **CWG/PMT high voltage and module temperature measured over a period of 1.5 hours. The CWG was powered up at $t = 0.19$ hr.**

tion is in significantly better thermal contact with the mount than with the mixing chamber or PMT. Given the conducting contacts necessarily in place between all of the CWG components and the PMT, and the fact that the CWG components must be well insulated from their mount⁸, implementation of CWG component heatsinking to the cryostat still would require a completely new CWG/PMT module design and, although outwith the time and resources available during this project, is a potential future development⁹.

⁸The diodes, capacitors and connections of the CWG must be well insulated to prevent high voltage discharge to earth. In our setup, a PTFE mount was built and installed for this reason.

⁹Of course, such a mount would be doubly beneficial if designed to serve as EMI shielding as well.

4.6.2 Stability of output voltage

The output voltage of the CWG was observed during PMT operation to decrease during steady running by $\sim 0.7\% \text{ hr}^{-1}$ (see Figure 4.13). Subsequent repeated tests were carried out at room temperature to determine the cause of this instability using a transient recorder, amplifier and filter to precisely measure AC input voltage, frequency and HV output over several hours.

Figure 4.14 shows a typical test of 16 hours' duration. In this instance the output voltage is observed to both increase and decrease. The net variation is $\sim 0.5\% \text{ hr}^{-1}$. This drift closely follows variation in the amplitude of the AC input voltage. Extracting the variation in CWG gain over this period reveals that the gain also follows variation in AC input voltage, while the AC input frequency remains within a narrow bandwidth of 3.5 Hz at 14.857 kHz throughout this test (see Figure 4.15).

This is not unexpected: the term in (4.8) for CWG voltage drop due to diode forward voltage is independent of input voltage amplitude, meaning that the CWG gain (equation 4.12) will have a small dependence on the input voltage amplitude for non-zero diode forward voltages. This is borne out by the observed variation of gain increasing with AC input amplitude in this sample (Figure 4.16). A similar variation of CWG gain with AC input amplitude is seen in [114].

We can conclude that the drift of CWG output voltage observed during longer runs of this prototype module is due to small instabilities in the AC oscillator

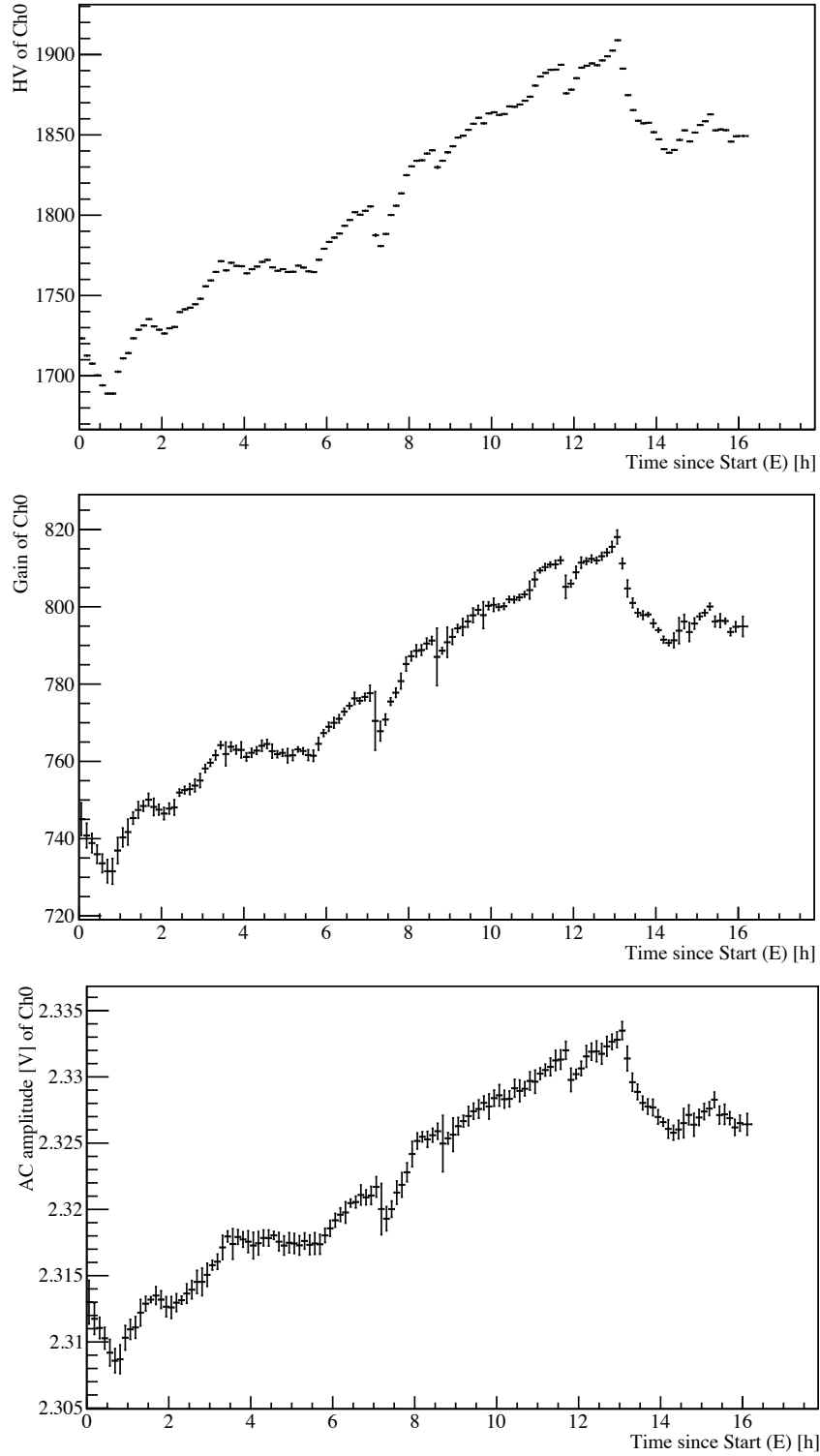


Figure 4.14: Variation in CWG HV output, combined transformer-CWG gain and AC input voltage amplitude observed over 16 hours of uninterrupted operation.

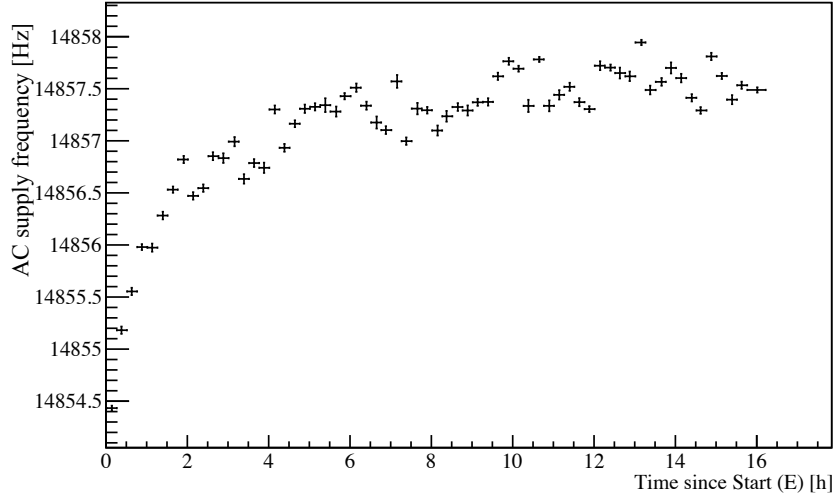


Figure 4.15: Variation in AC supply frequency observed over 16 hours of uninterrupted operation. Input waveforms were measured using transient recorder timebase $1 \mu\text{s}$ and fitted with sinusoidal function over 1 ms event duration to determine frequency.

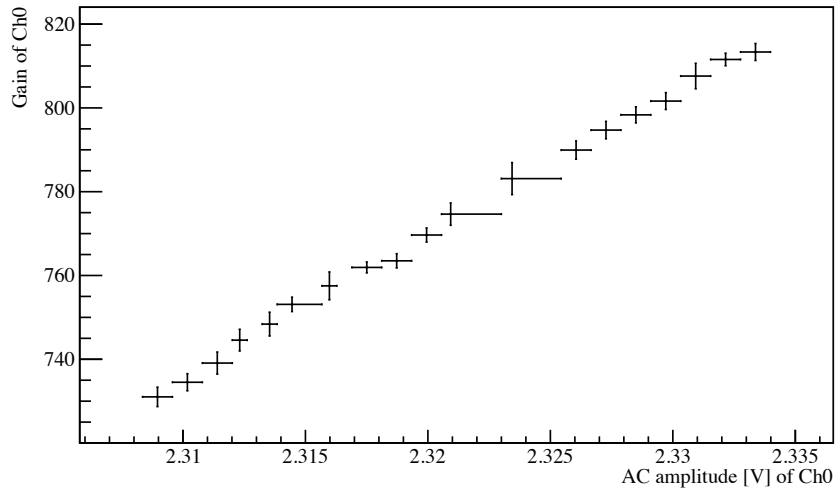


Figure 4.16: Variation of combined transformer-CWG gain (y-axis) with AC supply voltage amplitude (x-axis).

supply voltage amplitude ($\pm 2 \text{ mV hr}^{-1}$). Further designs intended for long operating runs could utilise feedback of the attenuator voltage as a reference for the AC supply voltage to improve high voltage stability.

4.7 Summary

In Chapter 2, the importance of event discrimination for background suppression in direct dark matter searches was described. This is achieved in the CRESST experiment by simultaneous measurement of scintillation light and phonon signal in each module using cryogenic light detectors.

In Section 4.1, several advantages of PMT detection for low-light cryogenic scintillation were described. However, we also acknowledged that the implementation of PMT readout for cryogenic scintillators presents a range of challenges, including heatload, PMT radiopurity, light collection, low-temperature PMT response and introduction of EMI via HV cabling inside the cryostat. The design and testing of a PMT module with a CWG voltage multiplier for dynode voltage supply was carried out to offer heatload reduction over a resistive divider circuit. The installation of a CWG power supply in a self-contained module would also be a strategy for reducing EMI risk.

The designs and components for fabricating practical small CWG circuits for PMT dynode voltages have been identified (sections 4.3 – 4.4), and successful operation of a CWG/PMT module was demonstrated with 50% power efficiency

at 0.95 K. The heatload and output stability of the CWG are understood and strategies for further improvement are suggested (Section 4.6).

Resolution of scintillation light using a PMT operated at 0.95 K powered by a CWG voltage supply was demonstrated for the first time, and the measured resolution showed no degradation relative to low-temperature (6 K) PMT tests carried out using a voltage divider circuit (Section 4.5).

Conclusions

The unifying thread of the work I have carried out and described in this thesis is the demonstration of the potential for novel cryogenic hardware to reduce the heatload, cost and complexity of cryodetector readout in direct dark matter searches. Development of larger cryodetector arrays to increase the target mass of direct WIMP searches make these economies a priority, while the low-noise, high-radiopurity performance of existing hardware must be maintained.

The testing of etched metal foil cabling for low-impedance TES-SQUID cryodetector readout, and the resulting readout noise measurements, demonstrated that etched metal foil cables could be used to achieve heatload reduction by a factor of 24 in a SQUID readout system for an array of cryodetectors in a direct dark matter search. The readout system for such a cryodetector array could be built and operated at significantly lower cost (per channel) than the CRESST-II readout system, and would not critically degrade detector performance. Given the event discrimination possible with CRESST-II cryodetectors, the expected sensitivity of such an a cryodetector array would scale with increased target mass,

probing CMSSM WIMP parameter space below the CRESST-II sensitivity limit of 4.8×10^{-7} pb [38].

The demonstrated application of low-cost low-heatload etched metal foil cabling to high-impedance NTD-Ge cryodetector readout for direct dark matter searches is a key development for the forthcoming EDELWEISS-III direct dark matter search. The increased detector target mass, coupled with the event discrimination possible using phonon-ionisation cryodetectors, will allow regions of WIMP parameter space below the EDELWEISS-II lower limit of 1.0×10^{-7} pb [43] to be probed. The EDELWEISS-III cryodetector array is expected to probe WIMP parameter space to a lower limit of 5×10^{-9} . The work described here to estimate parasitic capacitance and identify materials, good installation practices and prompt high-yield fabrication techniques has also contributed to this effort.

The high sensitivity of photomultiplier tubes to low-light yield signals makes them a suitable detector for measurement of cryogenic scintillation light signals. However, before PMTs can be used for scintillation readout of cryodetector arrays in a direct dark matter search, the issues of dark count frequency, radiopurity, power supply noise transmission and power supply heatload must be addressed. The work presented here addresses the problems surrounding the PMT HV power supply by demonstrating the use of a low-temperature CWG voltage multiplier power supply circuit optimised for cryogenic PMT power supply. The demonstration of CWG-PMT module operation for scintillation light detection at temperatures below 1 K

may also prove advantageous in the short term for the characterisation and testing of cryogenic scintillating materials for future cryodetectors.

In each case; low-impedance readout, high-impedance readout and PMT scintillation light detection, economies in heatload, complexity and cost have been demonstrated while maintaining comparable performance with existing technologies. This development and application of new technologies in practice allows further design decisions to be made in the process of developing the future large-scale cryodetector arrays, such as EURECA, which will probe the CMSSM parameter space to cross-sections of 10^{-10} pb.

Appendix A

Radioactive contaminant decay chains

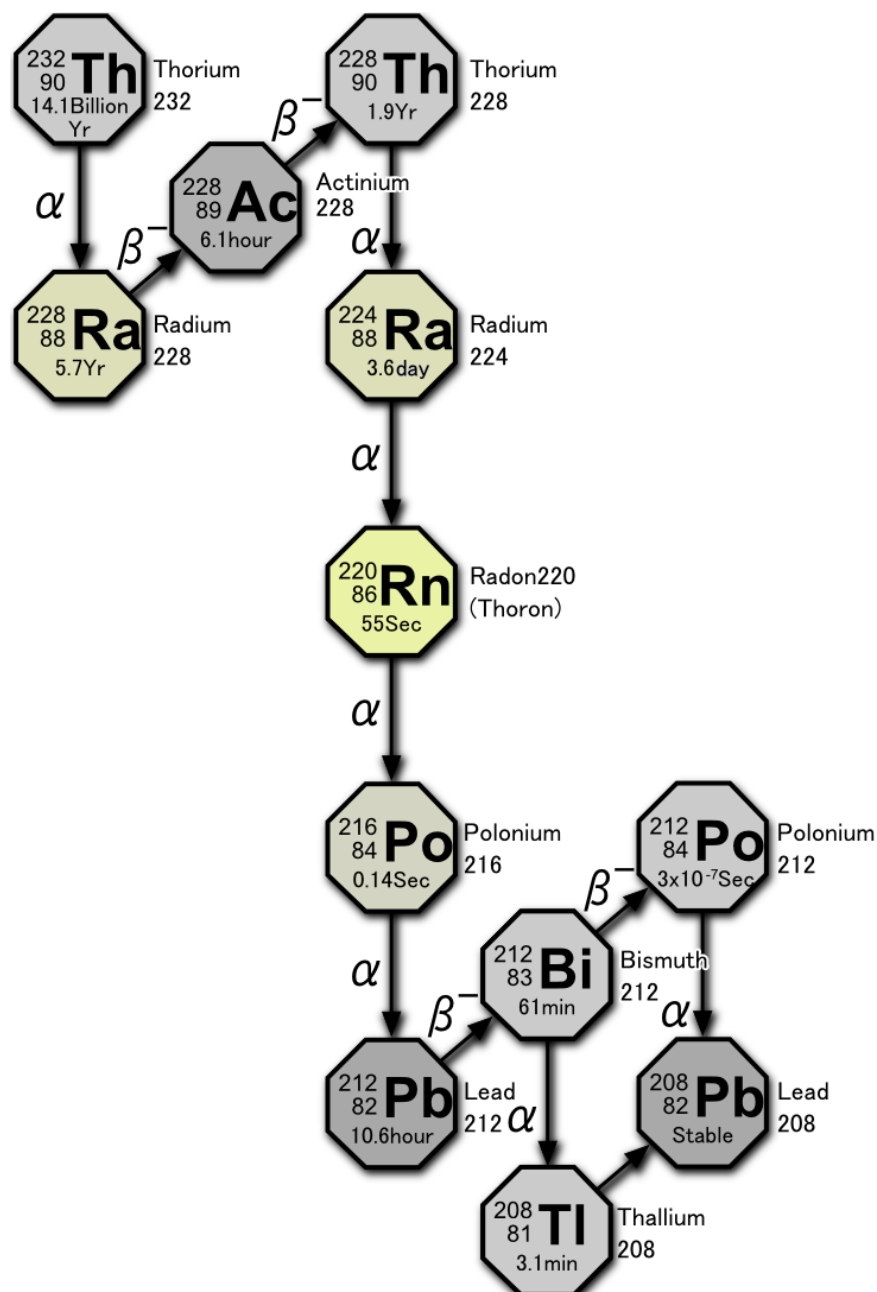


Figure A.1: Graphic showing decay series and half-lives of ^{232}Th . Reproduced under creative commons licence. Source: [82].

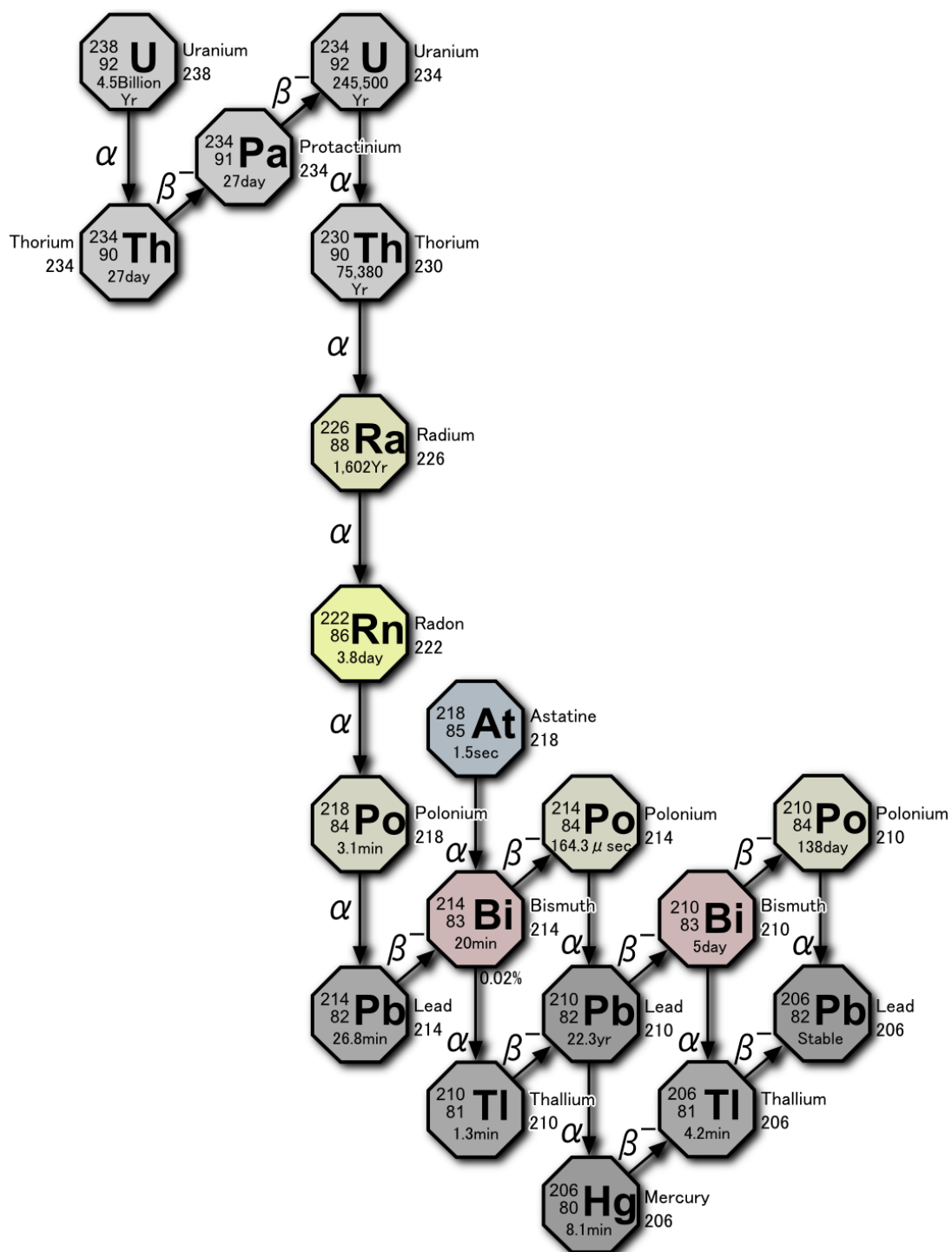


Figure A.2: Graphic showing decay series and half-lives of ^{238}U . Reproduced under creative commons licence. Source: [83].

Appendix B

Radiopurity data from tests of cabling materials

Material and treatment	Testers	Mass / g	Time / hr	Measured contaminant activity / mBq kg ⁻¹													
				232Th decay series						238U decay series							
				40K	60Co	137Cs	228Ra	228Ac	228Th	212Pb	208Tl	238U	226Ra	214Pb	214Bi	210Pb	
Polyimide (PI)	IPNL	32.3	380	129 (44)	< 9	4 (2)	13 (12)		6 (4)	4 (3)		6 (5)	8 (5)	165 (42)			
PI with steel foil		6.6	285	191 (212)	30 (15)	12 (8)	-		< 31	39 (21)		< 20	< 23	714 (165)			
PI etched steel tracks		43.3	285	152 (43)	< 7	3 (2)	16 (12)		< 8	3 (2)		7 (4)	< 10	154 (36)			
Polyethylene naphthalate (PEN)		45	284	118 (32)	-	-	-		-	-		9 (5)	7 (3)	47 (27)			
PEN with full steel foil		15.4	351	98 (60)	-	< 9	21 (12)		13 (7)	7 (6)		10 (9)	-	838 (89)			
PEN after etching		6.7	561	354 (134)	< 25	-	< 58		< 6	-		< 21	< 23	2807 (173)			
Adhesive		39	357	84 (34)	3.5 (2.8)	< 3	11 (8)		20 (3)	6 (3)		43 (7)	24 (6)	496 (49)			
PI	GERDA	851	478	< 5.5	-	-	< 1.3	< 1.1		< 27 (1.3)	14.6 (1.3)		-	-			
PEN		2050	715	< 3.6	-	-	< 1.4	< 1.4		-	< 2.0		-	-			

Table B.1: Collated low-background activity measurements for contaminant radioisotopes in the materials used for etched metal foil cable fabrication. IPNL data measured by M. De Jesus. Comparison with GERDA data [86].

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