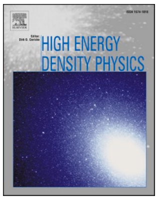
High Energy Density Physics 52 (2024) 101129

Contents lists available at ScienceDirect

High Energy Density Physics

journal homepage: www.elsevier.com/locate/hedp



Fundamental physics opportunities with multi-petawatt- and multi-megaJoule-class facilities

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ARTICLE INFO

Keywords:
Inertial fusion and extreme intensity physics

ABSTRACT

In this invited paper, I will touch on some highlights from my research career in the Clarendon Laboratory and in the Central Laser Facility, Rutherford Appleton Laboratory, obtained working in partnership with many outstanding international collaborators. These fall under the three broad themes. The first is novel laser-plasma interactions. The second theme is that of extreme field physics using multi-petawatt laser facilities. The third theme is that of inertial fusion studies. All of these studies indicate that an international, dual-use, 20-MJ Inertial Confinement Fusion (ICF)/Inertial Fusion Energy (IFE) facility, with the first 2-MJ at high repetition rate supplying single-shot high energy amplifiers, will open many new exciting avenues for both fundamental physics and high energy density science in the decades ahead.

Edward Teller Medal Award. On New Year's Day 2018, Dr Benjamin Franta wrote a fascinating article in *The Guardian* (a British broadsheet newspaper), describing Edward Teller's little-publicised speech in November 1959 at the *Energy and Man* symposium. This meeting was organised by the American Petroleum Institute and the Columbia Graduate School of Business to celebrate the 100th anniversary of the American Oil Industry. Dr Franta reports that Edward Teller provided some of the first warnings to the audience that the continued burning of fossil fuels was unsustainable for the environment. Edward Teller argued that new sources of power would be needed to provide humankind's energy requirements into the 21st Century and beyond to mitigate global warming from increasing concentrations of carbon dioxide in the Earth atmosphere.

To my mind, the article reinforced my admiration for Edward Teller's talent, presience, strategic patience, leadership and visionary forward thinking for physics and engineering. Certainly, it underpinned his unwavering support for all forms of fusion research, including inertial confinement fusion that was invented (somewhat earlier than the symposium lecture) in his laboratory by John Nuckolls and colleagues. It is one that has now culminated in the achievement of ignition in the laboratory, reported elsewhere at the 2023 IFSA conference. Consequently, I am delighted to be considered worthy of being in receipt of the 2023 Edward Teller Medal Award and to be in the august company of current and previous Medal winners.

Career Summary. To put my work into context, between 1990 and 2021 I was a research scientist at the Central Laser Facility (CLF), Rutherford Appleton Laboratory (RAL), rising to become Individual Merit Fellow of UKRI-STFC and a member of its Senior Leadership Team. In the latter role, I was responsible for horizon scanning for new science opportunities using high power laser facilities. I was appointed Professorial Research Fellow at the University of Oxford in 2012 and Supernumerary Fellow to University College Oxford (one of the oldest of Oxford's constituent Colleges) in 2015, where I am now Dean of Degrees.

Currently, I am visiting Professor to Imperial College London (from 2006) and Shanghai Jiao Tong University (from 2011). I am very proud of being elected a Fellow of the American Physical Society, a Fellow of the Institute of Physics and appointed William Penney Fellow to AWE plc. My current h-index is 77 (from Google Scholar). To date, I have published 360 scientific papers and received 25,170 citations. Between 2011 – 2017, I was Divisional Associate Editor for *Physical Review Letters*, advising the wider editorial board on high energy density plasma physics research matters. I was a founding member of the University of Rochester's Omega Laser User Group Executive Committee, on which I served from 2008 – 2016, to raise the visibility and good governance of the Laboratory for Laser Energetics‘ high power laser facilities.

Selected Scientific Highlights. 20 TW – 20 PW. In 1984, I started my research career as a PhD student at Royal Holloway, University of London under the supervision of Dr Eric Wooding and Dr Michael Key (internal and external advisors, respectively) working on direct-drive

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https://doi.org/10.1016/j.hedp.2024.101129
Received 31 March 2024; Received in revised form 18 June 2024; Accepted 25 June 2024

inertial confinement fusion (ICF). During my PhD, I constructed and qualified a time-resolved monochromatic X-ray imaging device and used it, along with buried metallic layered targets, to study the uniformity of ablation for spherical implosions using the Vulcan laser facility. Vulcan was at that time a 12-beam compression facility with a dodecahedral irradiation geometry, limited to peak power of three TeraWatts [1,2]. Following my PhD defence in 1988, I was awarded a Japan Society for the Promotion of Science Post-Doctoral Fellowship to study at the Institute of Laser Engineering, Osaka University, Japan. There, I continued my direct-drive research and contributed to the demonstration of ×600 liquid density compression campaign using the 20-TW GEKKO XII high power laser facility. Specifically, I showed good agreement between X-ray emission observed from initially buried metallic signature layers and radiation hydrodynamic simulations [3]. On my return to the United Kingdom, I was appointed to the RAL. At first, I contributed to the UK's X-ray laser programme, led by the Universities of York (Geoff Pert), Essex (Greg Tallents), Oxford (Justin Wark), the Queens University Belfast (Ciaran Lewis) and the RAL (Mike Key). A notable achivement was the first demonstration of saturation of a collisionally excited XUV laser by the consortium in 1991, working in collaboration with a team from France [4].

Following that accomplishment, I was appointed leader of the CLF's experiment support team (where I helped recruit the late Dr David Neely to the laboratory - an extraordinary talented physicist and colleague, whose friendship and collaboration over three decades meant a great deal to me). In that leadership role, between 1992 - 1996 I guided many of the first high intensity picosceond-duration laser-plasma experiments using the 20-TW chirped pulse amplification beamline, again working in collaboration with eminent colleagues from the CLF (Steven Rose and Colin Danson), Imperial College London (Farhat Beg, Tony Bell, Paul Lee and Bucker Dangor) and the University of Oxford (Justin Wark and Jie Zhang), among others. In 1994, the concept of fast ignition of fusion targets was first proposed [5]. The idea was attractive because, with x600 compression, only a few kJ of particle energy needs to be deposited on the side of the compressed DT fuel to form and initiate a fusion burn wave. Unfortunately, compressed densities of only $\sim$10 gcm^{-3} were possible using the Vulcan laser facility at the time, indicating it was more important to undertake basic energetic particle generation, acceleration and energy transport experiments to understand the fundamentals of laser-plasma interactions in this, as yet, uncharted regime. These included: proton and ion beams accelerated from laser irradiated foil targets [6] (with the first proposal for ion-beam driven fast ignition [7]), high harmonic generation from oscillating plasma surfaces [8], bright neutron production from laser-irradiated deuterated targets [9] among many others [10].

Following these studies, I was appointed to the CLF's plasma physics group from 1996, working under the guidance of Steven Rose. There followed notable achievements in my collaboration with Imperial College London that now included the newly appointed academic Karl Krushelnick, along with talented students and post-doctoral researchers Matt Zepf, Michael Tatarakis and Eugene Clark, among others. It was clear, even then, that future inertial fusion power plants must compete on cost with renewable energy sources (wind, solar, geothermal etc.) in the electricity market. This demands further substantial reductions in the size and capital costs of laser-drivers. To this end, I conducted a series of pioneering fast ignition inertial fusion experiments, in collaboration with close friends and colleagues at RAL, Imperial College and at Osaka University (inspired in part by the outstanding research by Steve Hatchett and Max Tabak at LLNL [11]), that have now received over one thousand three hundred citations [12,13].

The realisation of the fast ignition-related heating experiments at the RAL and Osaka University quickly led to the construction of PW laser facilities at both laboratories, with the blessing and support of the NIF Directorate at LLNL, who had recently closed the NOVA PW facility to make way for the NIF. Working in collaboration with ILE colleagues, we were able to confirm the energy transfer scaling of the cone-guided fast ignition concept to implosions with these much larger PW laser-pulse energies in Japan, paying particular attention to pre-pulse conditions [14]. I was delighted to receive recognition from both the American Physical Society for this body of work (the 2006 Award Excellence in Plasma Physics Research with Max Tabak, Scott Wilks, Ryosuke Kodama and Kazuo Tanaka), and from the Anglo-Japanese Daiwa Foundation (with the 2007 Diawa Adrian Prize as Team Leader for UK-Japan calloraborations in High Energy Density Science). It is somewhat unfortunate that financial constraints, imposed following the 2008 financial crisis on national science budgets, have somewhat curtailed promising follow-on cone-guided fast ignition results from independent researchers [15]. Hopefully, the success of ignition on the NIF will allow these studies to resume in future.

At the CLF, I identified experimentally, along with my then-PhD student Dr James Green and UK colleagues, an intensity-dependent angular divergence of the fast electron beam using PW laser pulses, working in close collaboration US and Japanese colleagues [16]. This then initiated an extensive, successful theoretical and experimental campaign to explore ways to mitigate the beam divergence issue, including innovative resisitivity gradients [17,18] (the experiment was led by Matt Zepf), double-pulse concepts [19,20], along with the Habara-Kodama-Tanaka whole-beam self-focusing mechanism with Ben Spiers, Luke Ceurvorst, Matt Hill and AWE colleagues [21].

Following my 2001 promotion to plasma physics group leader, my interests broadened to include laser-plasma wakefield accelerators, which was also conducted in collaboration with colleagues at Imperial College London, UCLA and Strathclyde. I played an important role in the success of the 2004 *dream-beam* experiments [22], recognised by the 2013 award by the Institute of Physics' Celia-Payne-Gaposchkin Medal and Prize "*For his pioneering contributions to the physics of fast particle generation and energy transport in relativistic laser- plasma interactions*."

Selected Scientific Highlights. 20 PW – 20 EW. One of the unexplained issues with the cone-guided fast ignition experiments at Osaka University was the anomalous stopping of the fast electrons in the compressed fuel. The compressed hollow-CH spherical targets were measured to have an areal density of $\sim$ 100 mg/cm^2 at peak compression using X-ray opacity techniques. This value is insufficient to stop MeV fast electrons needed to heat the target and produce the observed neutron yield. My colleagues and I explored the idea of using beam-plasma instability growth as a potential mechanism to explain the stopping, both analytically [23] and computationally [24], with some success. I later drew upon this concept, once ignition was proven to be more difficult than anticipated on the NIF, to develop the idea of auxiliary heating [25,26] as a way of providing the final stroke to the hotspot formation for isobaric implosions, both for direct [27,28] and indirect drive targets [29]. When combined with the performance of low-convergence ratio wetted foam targets and ArF drivers, it provides a potential route for high gains using the Nuckolls‘ dual hemisphere conceptual design, as well a route to more robust ignition on NIF. Our most recent calculations using a multi-scale simulation toolkit, developed between Oxford, IBM Research, Warwick and UKAEA, indicate that high intensity laser pulses from multi-PW facilities are preferred, as the fast electrons must have sufficient energy to penetrate through the compressed fusion fuel to enter to central hotspot and initate the energy cascade process (Fig. 1).

1. The Zero Vector Potential (ZVP) absorption mechanism for multi-PW laser pulses. One of the first experiments that I planned for the Vulcan PW facility (with Brendan Dromey, Matt Zepf and others) was the generation of high brightness harmonics into the X-ray regime. Our collaboration were delighted to observe up to the 400th harmonic orders in the first experiment we performed on the machine, largely the result of using double plasma mirrors to improve the intensity contract ratio [30]. This was quickly followed with observations of $>$ 3000 harmonics, into the X-ray regime [31]. The X-ray harmonics were observed to be emitted into a 4° cone angle, in

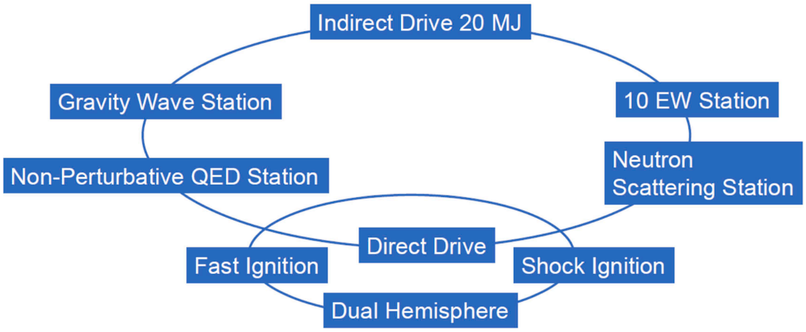

Fig. 1. A conceptual dual-use ICF/IFE facility.

contrast with earlier experiments using the 20 TW and 100 TW beamlines where a more isotropic emission distribution was observed. This puzzling discrepancy required a much fuller understanding of the underlying energy absorption and generation process - one that is provided, in essence, by a pseudo-capacitor model. I helped Teodora Baeva, Sergei Gordienko and Alex Robinson undertake this study using a 1D model [32], before extending the analysis later to 3D [33] and then into the laser-QED regime, the latter two with my former PhD student, Dr Alexander Savin [34]. The mechanism indicates that exceptionally bright X-ray harmonics are generated in the multi-PW regime, along with attosecond duration nano-Coloumb electron bunches. My current PhD student, Miss Robin Timmis, is currently finishing the analysis of an X-ray harmonics experiment on the Orion PW laser facility at AWE plc.

2. Photon-Photon Scattering. Perturbative QED is an exceptionally successful quantum field theory that lies at the foundations of quantum mechanics. It provides many orders of magnitude precision and provides an exquisit explanation for the Lamb shift, as one example. However, it remains the case that the *non-perturbative* QED regime has not been explored to date, leaving questions such as the appropriate conditions to use the Heisenberg – Euler and/or Born – Infeld models. Working with Mattias Marklund and colleagues from Sweden and the RAL, nearly twenty years ago I helped show that photon-photon scattering from the virtual electron-positron vacuum is possible using multi-petawatt laser pulses arranged in an orthogonal focusing geometry [35]. More recently, my former PhD student, Dr Ramy Aboushelbaya, working with the same team showed that laser pulses with orbital angular momentum provide an additional level of discrimination in order to measure real-photon – real-photon scattering for the first time [36]. These provide limits to both QED processes and potentially those that include Beyond Standard Model physics and, along with them, new horizons for multi-PW laser facilities now under construction world-wide.
3. Gravitational Wave Generation. In new research, now accepted for publication for Physical Review D, the potential of twisted light for the generation of gravitational waves in the high frequency regime is explored for the first time by my student, Mr Eduard Atonga, working with my team from Oxford (Dr Ramy Aboushelbaya), alongside colleagues from the University of Grenoble-Alps (Dr Killian Martineau and Dr Aurélien Barrau) and Krakow (Dr Chunshan Lin). Focusing on Bessel beams, novel analytic expressions and numerical computations for the generated metric perturbations and associated powers are presented in reference [37]. The work provides the induced strain estimates for both nanosecond- and picosecond-duration laser pulses. The former assumes the success of the beam combiner approach discussed in the next section. Compelling evidence is provided that the properties of the generated gravitational waves, such as frequency, polarisation states and direction of emission, are controllable by the laser pulse parameters and optical arrangements. We are currently working on detection methods, with some positive preliminary results. The work provides evidence that a next-generation 20 MJ ICF laser facility (10 MJ for high gain, plus some energy for contingencies) will be able to address important questions of extraordinary significance for fundamental physics.
4. Brightest Possible Thermal Neutron Source. In 2007, Prof Andrew Taylor FRS (along with Mike Dunne and others, including myself) proposed that merging the fields of Inertial Fusion Energy (IFE) with those of neutron scattering science could be disruptive, given the orders-of-magnitude improvements in source brightness that are expected, compared with conventional accelerators and fission reactors [38]. Following the recent ignition result on NIF, it is timely to revisit this question. In particular, whether research into the use of high repetition rate lasers, operating in the 1–2 MJ level to test IFE concepts at full-scale, could be used as a suitable thermal neutron source, in which stockpile stewardship questions could be not otherwise be addressed using such a device. It is possible that the division between high yield and high gain (i.e. ICF and IFE) research concepts could then be reduced and moved under the same umbrella.
5. Plasma Amplifiers. The 100 PW laser facility, the Station for Extreme Light (SEL) is now under construction in ShanghaiTech University in China and is due for completion in 2026 / 27. The laser pulse will be coupled to the SHINE X-ray Free Electron Laser beam in due course. The SEL beam diameter is nearly one-metre in diameter. The target chamber is eight-metres in diameter and has three levels of access, similar to the NIF. The SEL facility heralds an extraordinary opportunity for fundamental physics studies. With these considerations in mind, the beam size is becoming a limiting factor to the laser power that can be provided to target and, in order to approach the ExaWatt regime (indeed even exceed this frontier) new ways of amplifying laser pulses to the required energy and pulse duration are required. In 2011, RAL's Dr Raoul Trines, with input from myself and colleagues at the CLF, IST and St Andrews, suggested that plasma amplifiers are suitable routes to explore [39]. Since then, we have proposed methods to transfer ultraviolet nanosecond pulse durations to picosecond ones [40], (with my then PhD student, Dr James Sadler) optimise the amplification process by immediately entering the non-linear regime [41] and explore new geometries to improve the output beam quality [42]. In addition, the cross-beam energy transfer (CBET) process has been successfully demonstrated on the NIF [43]. A beam combiner, comprising pump beams with a single seed beam, was used in a co-propagating geometry. Energy transfers of 25 % from pump to seed beams were measured. In principle, it is possible to combine many more of the laser beams of NIF or a future ICF laser facility, in order to generate a beam of extraordinary energy and power. One could imagine such a beam then being used as a pump for a secondary Raman amplifier, as illustrated in Fig. 2.

Summary

Over the course of my career spanning four decades, I have witnessed

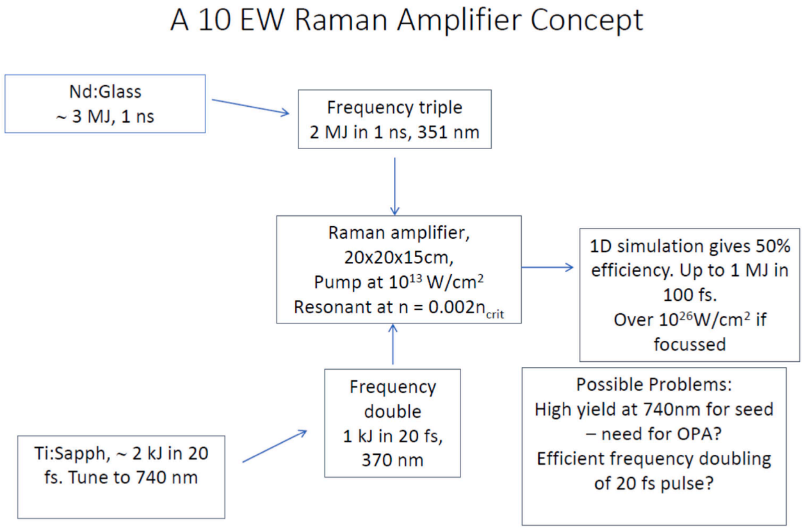

Fig. 2. An outline of a 10 EW laser concept (from a discussion with Dr James Sadler).

similar decadal increases in the available laser power to target. Laser systems with peak powers between 20 – 100 PW are now being constructed and commissioned. I have given a personal view of where new physics will provide new avenues to optimise fusion energy science, high energy density physics and in fundamental physics that will be of enormous significance over the coming decades as peak powers to target enter the exawatt regime. Of course, this overview has omitted many fascinating topics on which I have worked with colleagues throughout the world during the last forty years. To them, please accept my apologies for the space limitations in this short overview article. To my colleagues in the Indirect Drive consortium, huge congratulations to the achievement of fusion ignition. To my nominator, referees and the Edward Teller Medal Award committee, thank you so much for your support. Together, let us look forward to the future physics with optimism, determination and enthusiasm.

CRediT authorship contribution statement

Peter A Norreys: Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

My work has been principally supported by: the United Kingdom Research and Innovation’s Science and Technologies Facilities Council (UKRI-STFC); the United Kingdom Research and Innovation’s Engineering and Physical Sciences Research Council (UKRI-EPSRC) and the Oxford Centre for High Energy Density Science (OxCHEDS).

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