

# Compact, energy efficient superconducting asymmetric ERL for ultra-high fluxes of X-ray and THz

I. V. Konoplev, A. Seryi, A. J. Lancaster, K. Metodiev, G. Burt, and R. Ainsworth

Citation: [AIP Conference Proceedings](#) **1812**, 100004 (2017); doi: 10.1063/1.4975902

View online: <https://doi.org/10.1063/1.4975902>

View Table of Contents: <http://aip.scitation.org/toc/apc/1812/1>

Published by the [American Institute of Physics](#)

---

## Articles you may be interested in

[Conceptual design of non-destructive, time profile monitor for femtosecond-long electron bunches](#)

[AIP Conference Proceedings](#) **1812**, 080002 (2017); 10.1063/1.4975888

[Concept of a staged FEL enabled by fast synchrotron radiation cooling of laser-plasma accelerated beam by solenoidal magnetic fields in plasma bubble](#)

[AIP Conference Proceedings](#) **1812**, 040003 (2017); 10.1063/1.4975850

[Integrable RCS as a proposed replacement for Fermilab Booster](#)

[AIP Conference Proceedings](#) **1812**, 100003 (2017); 10.1063/1.4975901

[Multi-color  \$\gamma\$ -rays from comb-like electron beams driven by incoherent stacks of laser pulses](#)

[AIP Conference Proceedings](#) **1812**, 100001 (2017); 10.1063/1.4975899

[Narrow bandwidth Thomson photon source and diagnostic development using laser-plasma accelerators](#)

[AIP Conference Proceedings](#) **1812**, 100005 (2017); 10.1063/1.4975903

[Concepts for a short wavelength rf gun](#)

[AIP Conference Proceedings](#) **1812**, 080005 (2017); 10.1063/1.4975891

---

**AIP** | Conference Proceedings

Get **30% off** all  
print proceedings!

Enter Promotion Code **PDF30** at checkout



# Compact, Energy Efficient Superconducting Asymmetric ERL for Ultra-High Fluxes of X-ray and THz

I. V. Konoplev<sup>1,a)</sup>, A. Seryi<sup>1</sup>, A. J. Lancaster<sup>1</sup>, K. Metodiev<sup>1</sup>, G. Burt<sup>2</sup>,  
and R. Ainsworth<sup>3</sup>

<sup>1</sup>*John Adams Institute, Department of Physics, University of Oxford, Oxford, OX1 3RH, UK*

<sup>2</sup>*Cockcroft Institute, Department of Engineering, Lancaster University, Lancaster, LA1 4YB, UK*

<sup>3</sup>*Fermilab, Kirk Road, Batavia, Illinois, IL 60510, USA*

<sup>a)</sup>Corresponding author: [ivan.konoplev@physics.ox.ac.uk](mailto:ivan.konoplev@physics.ox.ac.uk)

**Abstract.** To make the light sources compact and energy efficient, an energy recovery Superconducting RF LINAC can be used. We suggest a dual-axis, asymmetric cavity instead of conventional single axis, symmetric cavity configurations to generate average electron beam currents above 1 A, while still avoiding development of the beam breakup instability (BBU). The use of an asymmetric cavity allows one to increase the start current of HOMs participating in BBU instability development, as well as to break the positive feedback, resulting in the capability of a high average current electron beam to be driven without loss through the system. In this work, the results of experimental studies of an asymmetric cavity are presented and compared with theoretical predictions. The following steps toward design of a full-scale superconducting cavity are also discussed.

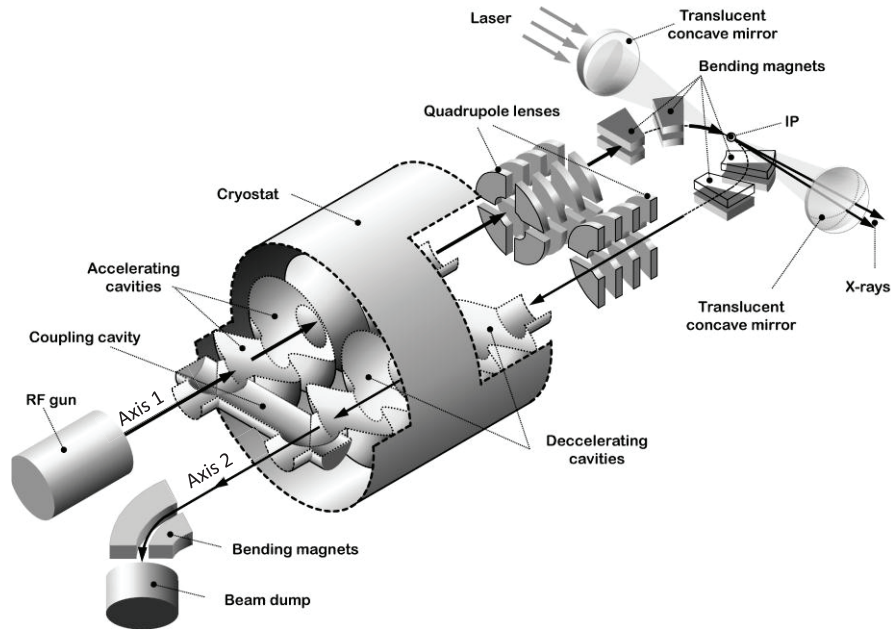
## INTRODUCTION

Today, radiation with high luminosity and high intensity is typically generated at national scale free-electron laser (FEL) and synchrotron radiation (SR) facilities, i.e., large sites over 100 meters in diameter and costing circa £0.5B. These ultra-high flux photon factories are capable of generating from THz to X-ray radiation, and are predominantly used for high resolution imaging to study a vast range of subject matter, from treatments for disease and new medicines to innovative engineering. High luminosity THz and X-ray coherent radiation are vital for many branches of science and industry. The limited number and availability of such facilities hampers the research progress, and the development of systems which could complement such photon factories can be very beneficial for many branches of science and industry. To achieve the required luminosity and intensity, a high average electron beam current is needed [1, 2]. Also, to meet the demand for cheaper and more economical systems, energy efficiency of all systems is an important issue. One possibility of reducing the energy consumption, while still driving high currents, is to employ Energy Recovery LINACs (ERLs) [3], which allow an improvement of the overall device “wallplug” efficiency. Such system’s components are based on Superconducting RF ERL, but the bunch current limitations for these systems can be severe [4, 5]. Increasing the average electron beam current above some threshold value (usually 100 mA) will lead to development of beam instabilities and beam transportation termination, naturally limiting the luminosity of the photon beam that is generated.

A novel concept [6, 7] and specific design [8] of a cavity for an ERL that will enable a SCRF ERL system generating and driving picosecond and sub-picosecond electron bunches with above 1 A average current is discussed in this paper. In the cavity considered, the BBU start current can be increased by order of magnitude [6] as compared with conventional cavities, thus allowing one to drive a high average current electron beam and increasing the brightness while maintaining high energy efficiency.

In Fig. 1, a schematic of the concept of high brightness and high intensity light source based on the cavity under consideration is shown. Indeed, to observe such a light source operating in THz or X-ray ranges, a high-current

electron beam has to be generated and driven without loss and a superconducting RF LINAC can be used to achieve this. To make the whole system compact and energy efficient, it is attractive to add the energy recovery stage and locate accelerating and decelerating stages in a single cryomodule, as shown in Fig. 1 [6,7]. At the current stage in conventional operating systems [3–5], accelerating and decelerating stages are based on a single-axis cavity, which electrons pass through during acceleration and decelerating stages. This leads to development of the BBU instability [4], as HOM readily accumulate inside such a cavity, resulting in energy recovery degradation and electron beam transportation disruption. The use of a dual-axis asymmetric superconducting cavity located in a single cryomodule for a single turn ERL is suggested as an alternative design for ERL. Both accelerating and decelerating sections of this ERL consist of the same number of cells and tuned to ensure overlap of the operating partial modes that form the cavity operating eigenmode. At the end after the decelerating stage, the beam is damped in a distributed, passive collector [9] designed to withstand the high current MeV electron beam.

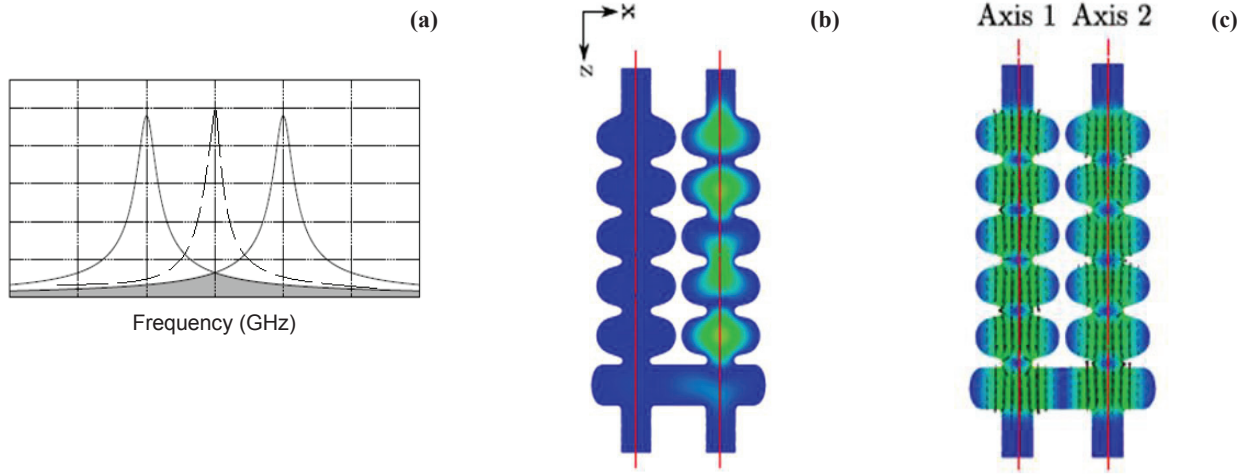


**FIGURE 1.** Schematic diagram of the SCRF ERL system proposed to generate high luminosity photons.

## ASYMMETRIC ENERGY RECOVERY LINAC: BASIC CONCEPTS

A schematic (Fig. 1) of a compact source of coherent radiation that is driven by a single turn SRF ERL is shown. The arrows illustrate the electron beam path. The system consists of photocathode injector, dual-axis ERL, beam optics, interaction region and collector. Here, we will look at the dual-axis ERL only. Let us assume, for clarity reason only, that electron beam is accelerated while it propagates along the first axis and that it is decelerated along the second axis (Fig. 1). The energy of decelerating electrons is fed back into the accelerating section of the ERL via a resonant coupler [6–8,10]. One notes that the ERL consists of two sections linked by the resonant coupler. Both sections (accelerating and decelerating) are made of the same number of TESLA-like cells [11], but each is tuned such that only the operating mode of both sections is symmetric. The high order modes (HOMs) are asymmetric and split in the frequency domain (Fig. 2(a)). Figure 2(a) is a schematic illustration of the HOM split in an asymmetric cavity, and if the system were to be symmetric, the HOMs would completely overlap each other, forming a single symmetric eigenmodes as illustrated by the dashed line. The coupling of the sections by a resonant coupler means that the sections are only strongly coupled at the set of frequencies that are common for all the three components, i.e. the coupling cell and both sections. Clearly, there is still some field leakage from one section to another, as modes may not be split far enough (Fano-like coupling) [12, 13]. The resonant coupling cell also allows introducing an RF power coupler, HOM loads, and an operating mode phase shifter, leading to possibilities for controlling energy recovery, beam dynamics and BBU. In Fig. 2(b,c) the 11-cell cavity with the contour plot of asymmetric high order

and symmetric operating modes, respectively, are shown. The design of the 11-cell cavity that is considered and shown is based on simulations conducted using the ACE3P electromagnetic suite developed at SLAC [14, 15]. Both



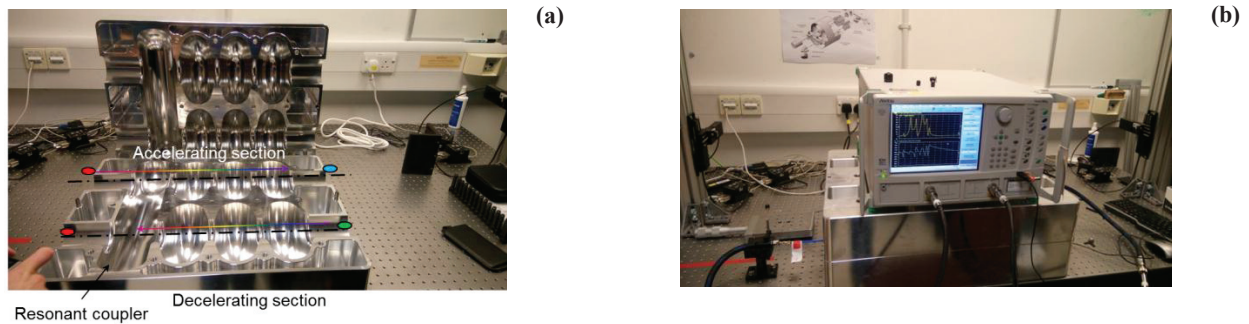
**FIGURE 2.** (a) Schematic diagram of a HOM split if accelerating and decelerating section are detuned. The dashed line indicates an eigenmode of a symmetric cavity. Contour plots are showing absolute values of E-field distributions for (b) HOM at 1.73 GHz and (c) operating mode at 1.3 GHz.

simulations in the time domain, to study wakefield formation (T3P), and frequency domain (Omega 3P) were conducted. The numerical and analytical studies of the 11-cell cavity [6] demonstrated that the BBU start current  $I_{asym}$  for the asymmetric system relates to the start current  $I_{sym}$  of symmetric system as

$$I_{asym} > \frac{(1 + N^2) I_{sym}}{2N}, \quad (1)$$

where  $N > 1$  is the voltage transformer ratio between accelerating and decelerating sections. We note that  $N=1$  for a symmetric cavity.

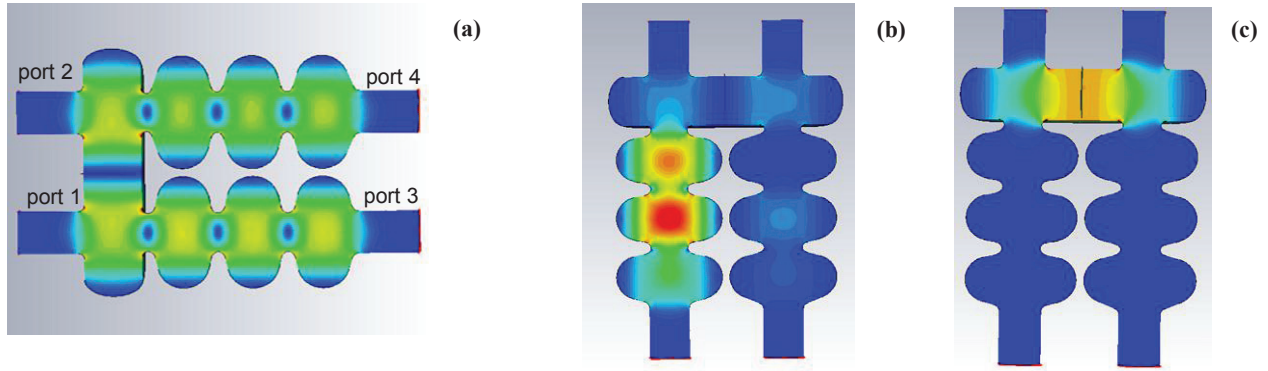
Taking into account that such a dual-axis cavity has never been RF tested before, and the fact that we expect that the number of HOMs will double (splitting of modes of conventional system), a new approach to conduct RF studies of such cavities is under development and verification.



**FIGURE 3.** (a) Photograph of the 7-cell aluminum cavity before assembly. (b) Photograph of the assembled cavity and VNA used for the preliminary RF studies.

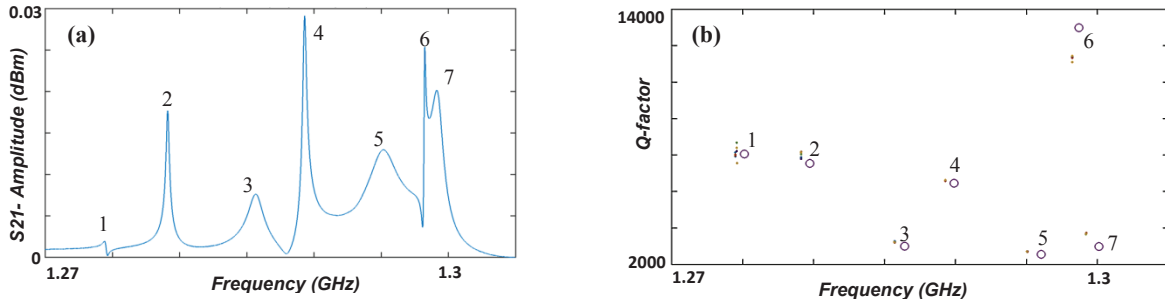
## PRELIMINARY EXPERIMENTAL STUDIES AND COMPARISON WITH THE NUMERICAL PREDICTIONS: 7-CELL CAVITY.

To conduct proof-of-principle studies, validate the experimental result against the numerical modeling, as well as to develop and test techniques of studying the 4-port cavity, a scaled-down (7-cell) aluminum resonator has been constructed (Fig. 3(a)) [10]. The cavity was machined from two blocks of aluminum using a computer controlled milling machine. The cavity was also polished and cleaned before positioning on the RF test table. One notes that the way the cavity was machined (as described) is far from optimal. Such machining was done only for preliminary RF studies and RF test technique development, as well as theory verification. It is clear that the main cut is crossing the surface currents along the cell walls, and thus affecting the modes Q-factors, including the operating mode. However such machining did not affect the frequency positions of the modes that were analyzed using S11 and S21 parameter. In Fig. 3(a), the photograph of the cavity before final assembly is shown. The cavity is assembled by combining two halves and securing them with pins and screws. The photograph shows “3+3+1” configuration, in which 6 cells are similar to a conventional 1.3 GHz TESLA cell, linked by a resonant coupler. The 7-cell cavity was modeled using CST Microwave studio and the results (contour plot of operating and parasitic modes) are shown in Fig. 4. It is clear that the modes are similar to those observed for the 11-cell cavity. One notes that Fig. 4(c) shows a contour plot of eigenmode that is specific to the cavity design, and it is associated purely with the resonant coupler.



**FIGURE 4.** Contour plots showing electric fields absolute values distribution for (a) the operating mode, and modes located at (b) 1.28 GHz and (c) 1.1 GHz.

The modes from this group are localized inside the coupler and, if necessary, these modes can be effectively suppressed by introducing a HOM coupler without interfering with the beam or operating eigenmode.



**FIGURE 5.** (a) Graph illustrating S21 as measured between ports 1 and 4 in the frequency range from 1.27 GHz to 1.305 GHz, and showing amplitude variations from 0 to 0.03 dBm. (b) Eigenmode positions and Q-factors in the frequency range from 1.27 GHz to 1.305 GHz and Q varying from 2000 to 14000.

The RF tests of the cavity were started with identification of the eigenmodes, i.e., their frequency and Q-factors were measured, and the data compared with theoretical predictions. The challenge one may have to face during the



RF studies is due to the fact that the number of eigenmodes in the cavity is effectively doubled. As a result, there are HOMs that are closely located to each other and may be difficult to distinguish. In Fig. 5(a) a graph illustrating S12 parameter in the frequency range from 1.27 GHz to 1.305 GHz is shown, and 7 modes inside this frequency range were identified. In Fig. 5(b), experimental data (solid dots) is compared with numerical predictions using CST Microwave Studio. One notes the spread of the solid dots and this is explained by different position of the RF coupler. Taking into account the way cavity was manufactured, the agreement between measurements and theoretical predictions are good. Small deviations in frequency can be explained by the presence of RF antennas inside the ports.

## CONCLUSION

The concept, design and the first scale down prototype of a novel dual-axis, asymmetric cavity for a single pass ERL were presented and discussed. The eigenmodes of such a cavity were identified and numerical predictions are compared with the experimental data. A good agreement between theory and experiment has been observed and demonstrated. We have developed and tested set of different techniques to study such complex cavities and the most promising one was presented. The next steps will be: construction and study of the 11 cell cavity; the design and the test of RF couplers for operating and HOMs. We also consider developing a phase shifters to control the RF phases of the field along the both axis independently.

## ACKNOWLEDGMENTS

The authors would like to thanks STFC UK for support this project through (STFC IAA and JAI grants). Dr. Konoplev would like to thanks The Leverhulme Trust for support via International Network Grant (IN – 2015 – 012). Mr. K. Metodieiev would like to thank JAI (Department of Physics, Oxford) for supporting his summer project dedicate to studies of dual axis cavity.

## REFERENCES

1. S. H. Gold et al., *Phys. Rev. ST Accel. Beams* **16**, 083401 (2013).
2. F. V. Hartemann, *Phys. Rev. ST Accel. Beams* **8**, 100702 (2005).
3. L. Merminga, D. R. Douglas, and G. A. Krafft, *Annu. Rev. Nucl. Part. Sci.* **53**, 387 (2003).
4. G. H. Hoffstaetter and I. V. Bazarov, *Phys. Rev. ST Accel. Beams* **7**, 054401 (2004).
5. T. Nakamura, *Phys. Rev. ST Accel. Beams* **11**, 032803 (2008).
6. R. Ainsworth, G. Burt, I. V. Konoplev and A. Seryi, *Phys. Rev. Accel. Beams* **19**, 083502 (2016).
7. A. Seryi, PCT Application PCT/GB2012/052632—Ultrahigh flux compact X-ray source.
8. R. Ainsworth, G. Burt, I. V. Konoplev and A. Seryi, PCT application PCT/GB2015/053565—Asymmetric superconducting RF structure.
9. I. Konoplev, PCT application PCT/GB2013/053101—Periodic structure as an electron beam dispersive media
10. I. Konoplev et al., in *Proceedings of the 7<sup>th</sup> International Particle Accelerator Conference*, (JACoW, Geneva, Switzerland), p. 1847 (2016).
11. B. Aune et al., *Phys. Rev. ST Accel. Beams* **3**, 092001 (2000).
12. Carlo Forestiere et al., *Phys. Rev. B* **88**, 155411 (2013).
13. G. Vaisman, E.O. Kamenetskii, and R. Shavit, *J. Phys. D Appl. Phys.* **48**, 115003 (2015).
14. L.-Q. Lee, Z. Li, C. Ng, and K. Ko, Report No. SLAC-PUB-13529 (2009).
15. A. Candel et al., *J. Phys. Conf. Ser.* **180**, 012004 (2009).