EXPERIMENTAL STUDIES OF ASYMMETRIC DUAL AXIS CAVITY FOR ENERGY RECOVERY LINAC

I. V. Konoplev, A. J. Lancaster, K. Metodiev, A. Seryi, JAI, Department of Physics, University of Oxford, Oxford, OX1 3RH, UK
G. Burt[1], CI, Department of Engineering, Lancaster University, Lancaster, LA1 4YB,UK
R. Ainsworth[2] Fermilab, Kirk Road, Batavia, Illinois, IL 60510, USA

Abstract

Increasing the beam charge and repetition rate leads to appearance of beam break-up instabilities in conventional ERLs. At this stage the highest current achieved in the SRF ERL, is around 300mA and to increase it a single turn, dual axis, compact Asymmetric Energy Recovery LINAC (AERL) has been proposed [1-4]. It has been theoretically predicted that this concept enables the use of electron beams with peak currents >1A, allowing high flux radiation to be generated using conventional approaches. The AERL works by limiting the feedback between the deceleration and acceleration stages and thus increasing the start currents of the beam destructive instabilities. This is partially achieved by tuning cells to allow only the operating mode to be uniform inside the cavity and splitting the accelerating and decelerating stages [1].

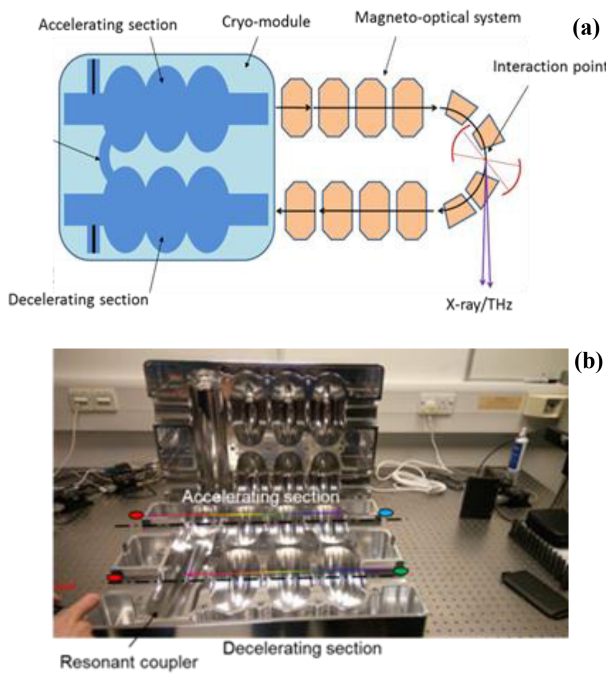


Figure 1: **(a)** Schematic diagram of the SCRF ERL system proposed to generate high luminosity photons [2]. **(b)** photograph of the 7-cell aluminium cavity.

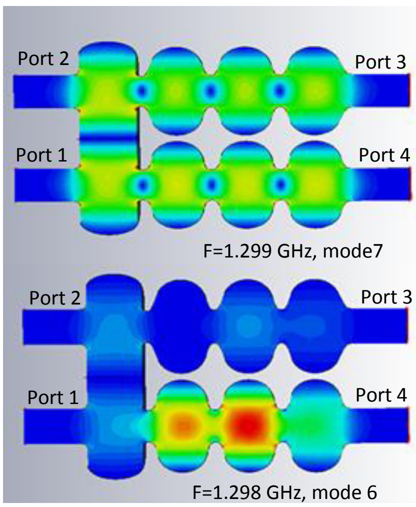
INTRODUCTION

Here we present the studies of a 7 cell, aluminium alloy prototype of the asymmetric cavity and discuss the first preliminary experimental results. We show the results of measurements of the cavity eigenmodes in pass band frequency range from 1.27GHz to 1.3GHz and compare the measurements with CST MW predictions. The field structures of operating and high-Q asymmetric modes were measured and also compared with numerical predictions. The experimental results observed are in good agreement with theoretical predictions.

BASIC CONCEPTS

High luminosity and high intensity coherent radiation is typically associated with national scale facilities like FELs and Synchrotrons, i.e., large sites 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. They are vital for many branches of science and industry but with the limited number and availability of such facilities the research progress is slow. The development of systems which could complement such factories can be beneficial for all users. To achieve the required luminosity and intensity, a high average electron beam current is needed [5, 6]. 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). Such system's components are made of superconducting materials and require additional cooling, cryogenic systems while the bunch current limitations for these systems can be severe [7,8]. Increasing the average electron beam current above some threshold value (usually 100 mA) will lead to development of beam instabilities and beam transportation termination. To solve this problem and make ERLs more attractive an asymmetric dual axis cavity has been proposed [1-4] and here we present a 7-cell prototype of the novel cavity. The prototype is discussed and the results of the cavity preliminary RF studies are compared with theoretical predictions.

In Fig. 1, a schematic of the concept of high brightness and high intensity light source based on the dual axis cavity under consideration is shown [2]. To make the system compact (reducing electron beam dump size) and energy efficient, it is attractive to add the energy recovery stage and locate accelerating and decelerating stages in a single cryo-module (blue area in figure 1a). Let us note that in conventional operating systems for accelerating and decelerating stages the same cells of a single-axis cavity are used. In this case the system is prone to development of the BBU instability [7], as HOM readily accumulate inside such a cavity. The use of dual-axis "U-shaped" (Fig.1) asymmetric superconducting cavity for a single turn ERL is suggested as an alternative to the conventional design to limit the regenerative BBU instability. Both accelerating and decelerating sections of this ERL consist of the same number of cells but individually tuned to ensure only overlap of the partial modes which form the cavity operating eigenmode. After the decelerating stage, the beam having relatively low energy (below materials' activation threshold) is damped on a distributed, passive collector [4] designed to passively disperse and withstand high power electron beam.



(a)

(b)

Figure 2: Contour plots are showing absolute values of E-field distributions for **(a)** operating mode at 1.299 GHz and **(b)** asymmetric mode at 1.298 GHz.

PRELIMINARY EXPERIMENTAL STUDIES

To conduct proof-of-principle studies, validate the experimental results against the numerical predictions and demonstrate the scalability of the concept a 7-cell aluminum cavity has been constructed (Fig. 1(b)). The 7-cell cavity was machined in the University workshop using computer controlled machinery. The photograph shows "3+3+1" configuration, in which 6 cells are similar to a conventional 1.3 GHz elliptical cavity cell, linked by a resonant coupler. The coloured dots indicate the electron bunches at different stages i.e. before and after acceleration and deceleration. The energy of decelerating electrons is fed back into the accelerating section of the ERL via a resonant coupler which can also be seen on the Figure 1b. The cells coupling 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 coupler and both sections.

We note that prior to the conducting set of experiments the CST Microwave studio was used for numerical studies. Due to the tuning of the cell the only symmetric mode is operating one (Fig.2a) while the other (non-operating modes) modes including modes from the pass band interval [1.27GHz; 1.3GHz] as well as high-order modes are asymmetric and have typical asymmetric field distribution as shown in fig.2b. The contour plots of electric field intensities of symmetric and non-symmetric modes located at F=1.299GHz and 1.298GHz are shown. The plots are generated using full 3D code CST MW studio. The modes are 6 and 7 (Fig.3) of the pass band and are the operating and the highest Q modes respectively. The cavity was assembled by combining two halves and securing them with pins and screws. The cavity was machined from two blocks of aluminium 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 is different from the conventional SC RF elliptical cavity. It is important to state that such a machining was done only for warm RF studies conducted outside the vacuum, to develop new RF test technique for the novel cavity and carry out basic verification of theoretical concepts [5-7]. Such machining is extremely convenient for RF studies as it did not affect the frequency positions of the modes and their general

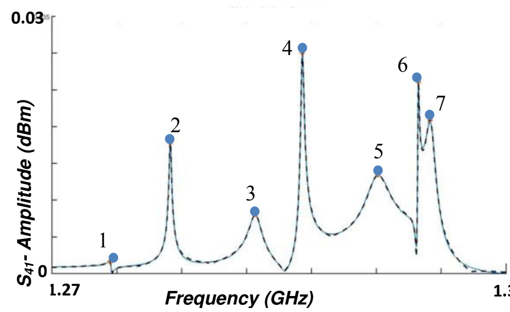


Figure 3: Graph illustrating S_{41} parameter as measured (solid line) between ports 1 and 4 in the frequency range from 1.27 GHz to 1.305 GHz and predicted using coupled modes (Fano) approximation (dashed line). The solid dot at the S_{41} maxima illustrates the position of the eigenmodes as predicted by the CST MW studio.

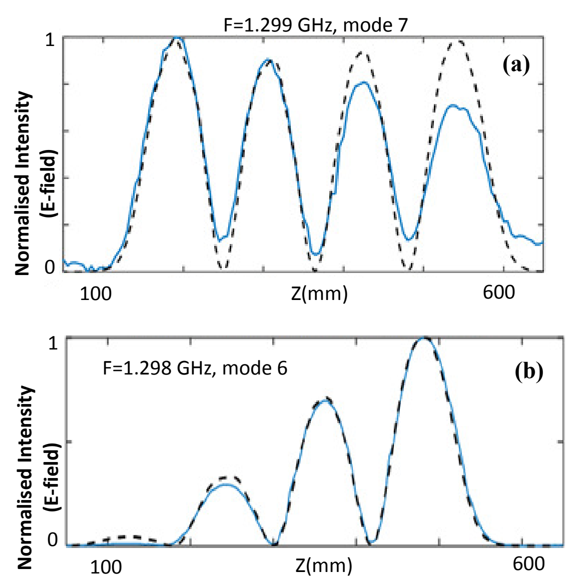


Figure 4: The graph are illustrating the normalized field intensity of the operating mode **(a)** and the nearest mode with the highest Q-factor **(b)** along axis 1 as measured (solid lines) and calculated (dashed lines) using CST MW studio.

features and properties. 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. In Fig. 3 a graph illustrating S_{41} parameter in the frequency range from 1.27 GHz to 1.305 GHz is shown. Inside this frequency range 7 eigenmodes were identified using CST MW studio a good agreement between numerical predictions and measured maxima (i.e. mode location) is clear. To build theoretical curve (dashed line) Fano model [9-11] of coupled oscillators was used. In this case the modes can be defined by the following set of coupled equations describing dumped oscillators which are experiencing external force:

$$\ddot{x_a} + \gamma_a \dot{x_a} + {\omega_0^a}^2 x_a + g x_b = F_a e^{i\omega t} \quad (1)$$

$$\ddot{x} + \gamma_b \dot{x_b} + {\omega_0^b}^2 x_b + g x_a = F_b e^{i\omega t} \quad (2)$$

where $x_{a,b}$ are the variable amplitudes of oscillator a and b, g is the coupling between oscillators and all other parameters are the same as discussed above. We note that a number of coupled modes (or oscillators in this case) can be more than two, but for the clarity reasons only two modes are considered in (1,2). By solving the equations (1,2) under the assumption of zero external force $F_{a,b}$ =0 and considering a wave solution i.e. $x_{a,b} \sim e^{i\omega t}$ one gets the expressions for $\Omega_0^n, \Gamma_n, G_n$, which are functions of $\omega_0^a, \omega_0^b, \gamma_a, \gamma_b, g$ and the amplitude A_n in the following form [9-11]:

$$|A_n| \approx A_0^n \left(G_n + 2\frac{\omega-\Omega_0^n}{\Gamma_n}\right) \Big/ \sqrt{1 + 4\left(\frac{\omega-\Omega_0^n}{\Gamma_n}\right)^2} \quad . \quad (3)$$

where A_0^n is a constant which can be defined from either initial conditions or can be normalised. Using the Tailor expansion and the same approach as before (superposition of the solutions $S_{ij} = \sum A_n(\Omega_0^n, \Gamma_n, G_n, \omega)$ calculated for a narrow frequency windows), the theoretical curve can now be constructed.

$$S_{21} = A_1 + A_2\omega + \sum_{n=1}^{N} |S_{21max}| \left(G_n + 2\frac{\omega-\Omega_0^n}{\Gamma_n}\right) \Big/ \sqrt{1 + 4\left(\frac{\omega-\Omega_0^n}{\Gamma_n}\right)^2} \quad (4)$$

We note that in the figures presented $f = \omega/2\pi$. The theoretical (dashed) line in Fig.3 describes S_{ij} measurements well and predicted positions of the eigenmodes (indicated by dots) are in a good agreement with the maxima measured (solid line). A good agreement between measured transmission coefficient and reconstructed as well as eigenmode positions predicted by MW studio (solid dots) is clear.

To study the eigenmodes' field structure along the longitudinal coordinate the RF bead-pull test table has been used and results have been compared with theoretical predictions observed using CST MW studio 3D model. In the bead-pull measurements a small (as compared with the operating wavelength) dielectric spherical bead is moved slowly from port 1 to port 4 (for clarity). The bead interferes with the field inside the cavity and the strength of the interference is measured via measuring S_{23} parameter. The square of the reflected electric field is proportional to the relative shift of the eigenmode frequency, while the relative change in the frequency is also proportional to the tangent of the phase of the S_{23} [12]. Using this technique the mode profiles (Fig.4) along one of the cavity axis (ports 4-1) were studied. In figure 4 the experimental measurements (solid lines) are compared with numerical prediction (dashed lines). Taking into account the finite accuracy of manufacturing, the agreement between measurements and theoretical predictions is good.

CONCLUSION

The first prototype of a novel dual-axis, asymmetric cavity was manufactured and studied. The eigenmodes of such a cavity were identified using numerical model and compared with experimental measurements. A good agreement between theory and experiment has been observed and demonstrated. The next steps will be: construction and study of the copper 11 cell cavity; the design and the test of RF couplers for operating and HOMs.

ACKNOWLEDGEMENT

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. Metodiev would like to thank JAI (Department of Physics, Oxford) for supporting his summer project dedicate to studies of dual axis cavity.

REFERENCES

[1] R. Ainsworth, G. Burt, I. V. Konoplev and A. Seryi, Phys. Rev. Accel. Beams 19, 083502 (2016).

[2] A. Seryi, PCT Application PCT/GB2012/052632—Ultrahigh flux compact X-ray source.

[3] R. Ainsworth, G. Burt, I. V. Konoplev and A. Seryi, PCT application PCT/GB2015/053565 — Asymmetric superconducting RF structure.

[4] I. Konoplev, PCT application PCT/GB2013/053101 — Periodic structure as an electron beam dispersive media

[5] S. H. Gold et al., Phys. Rev. ST Accel. Beams 16, 083401 (2013).

[6] F. V. Hartemann, Phys. Rev. ST Accel. Beams 8, 100702 (2005).

[7] G. H. Hoffstaetter and I. V. Bazarov, Phys. Rev. ST Accel. Beams 7, 054401 (2004).

[8] T. Nakamura, Phys. Rev. ST Accel. Beams 11, 032803 (2008).

[9] U. Fano, Phys. Rev. 124, 1866 (1961).

[10] G. Vaisman, E. O. Kamenetskii, R. Shavit, "Magnetic - dipolar-mode Fano resonances for microwave spectroscopy of high absorption matter", J. Phys. D: Appl. Phys. 48, 115003 (2015).

[11] A. E. Miroshnichenko, S. Flach, and Y. S. Kivshar, Rev. Mod. Phys. 82, 2257 (2010).

[12] J. Guillaume, "RF Bead Pull Measurements of the DQW Cavity", CERN summary report, (2015).