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EXPLORATION OF HIGH-GRADIENT STRUCTURES FOR 4th GENERATION LIGHT SOURCES

S.J. Smith*, S.G. Biedron, T. Bolin, S.I. Sosa
Department of Electrical and Computing Engineering,
University of New Mexico, Albuquerque, NM 87131, USA
B. Carlsten, F. Krawczyk,
Los Alamos National Laboratory, Los Alamos, NM, USA
J. Cary, D. Cheatham,
Tech-X Corporation, 5621 Arapahoe Ave, Suite A, Boulder, CO 80303, USA

Abstract

As the energy, scale and therefore the cost of large-scale accelerator projects, such as X-ray free-electron lasers (XFELs) increases, new technologies must be developed in order to minimize costs and maximize efficiency wherever possible. One obvious way to reduce costs is to reduce the length of accelerating sections by utilizing higher accelerating gradients. A smaller footprint lowers the accelerator cost.

Here we present the results of a study into the various structure options for FEL linacs, contrasting different frequencies and potential geometries. An investigation into the possibility of utilizing cryo-cooled traveling wave (TW) electron structures which allow for higher gradient operation due to the anomalous skin effect (ASE) is also detailed.

Finally, we give simulation results from the commercial code *VSim 9*, for a hypothetical TW high gradient C-band structure design utilizing cryo-cooled technology. Breakdown effects, pulsed heating, tolerances, efficiencies and potential rf sources are also explored, all within the framework of typical FELs and their requirements.

INTRODUCTION

Free Electron Lasers (FEL), most recently in the soft to hard x-ray regime, have proven to be invaluable instruments of discovery, enabling new developments in a broad range of disciplines. The driver of the FEL is typically a normal- or super-counducting radio-frequency (rf) accelerating structure-based electron beam linear accelerator (linac). With the need for higher electron beam energies capable of generating hard x-rays, the linac becomes longer and the costs quickly become prohibitive if one only relies on state-of-art accelerating technology. Alternative approaches need to be found to overcome this problem.

One way of reducing the associated costs of a longer linac is to reduce the size of the cavities while increasing their gradient of acceleration. In the last few decades, there have been many efforts on the development of high-gradient structures operated at cryogenic temperatures. In the early 90s for Neutral Particle Beam (NPB) defense applications; some of these include the operation of a 2.5 MeV copper plated Radio-frequency Quadrupole (RFQ) at cryogenic temperatures at LANL [1] and a 7.5 MeV Continuous Wave Deuterium Demonstrator linac at Argonne operating at 26 K [2]. There were also studies on standing wave pillbox and side-coupled structures operating at liquid nitrogen temperatures [3]. In this latter study, peak surface fields of up to 300 MV/m were achieved in S-band with a Q-factor enhancement of 2.7. In another study conducted in Moscow, an X-band disk-loaded structure was operated at 77 K, with a Q-factor enhancement of 2.5 seen with 50 MV/m surface electric fields for a 300 kW input power [4]

In more recent years, interest has been renewed on the application of normal-conducting resonant structures operating in the S, C and X-bands for the acceleration of electrons. For example, there is a comprehensive study showing the feasibility of using a normal-conducting C-band linac for a TeV-class electron-positron collider [5]. Similarly for FEL applications, a performance comparison between S, C, and X-band linacs for FEL suggests a number of advantages of using C-band over S or X-band structures [6]. Some of the advantages are: better control over the rf jitter, reduced non-linearity in the longitudinal beam phase space and better control over the energy chirp and projected energy spread, which in turn produces a narrower photon beam bandwidth [6].

Cryogenic Operation of Normal-Conducting Linacs

Even though conventional superconducting cavities have good performance when operated at high-duty cycles and for high-energy beams, they are not an ideal choice for high-gradient applications, as the gradient is limited by the maximum surface magnetic field, 55 MV/m for a well-prepared niobium cavity [7]. Furthermore, the cost of the required liquid helium cryogenic infrastructure at 26 K makes the normal-conducting technology more affordable for high-gradient compact machines. Nonetheless, the performance of normal-conducting C-band linacs can be further improved in terms of accelerating gradient by operating the cavities at cryogenic temperatures.

In general, for normal-conducting rf structures, the limiting factor on the accelerating gradient is the rf vacuum breakdown. The rf vacuum breakdown is typically characterized by the breakdown rate and has been linked to movements of

* samiam94@unm.edu

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defects in the crystalline structure of the metal, which are induced by mechanical stresses driven by surface heating from the rf fields [8]. Experiments suggest that structures with a more rigid material achieve higher voltage gradients.

By cooling the cavities to cryogenic temperatures, e.g. 77 K or lower for copper, both the surface resistance and thermal expansion coefficient decrease, which effectively yields a more rigid copper cavity, enabling higher accelerating gradients to be reached. The reduction in surface resistance at cryogenic temperatures is well described through the *anomalous skin effect*: as the temperature of the metal decreases, the skin depth of the metal decreases while the mean free path of electrons increases. In this limit, Ohm's law can no longer be used to describe the dynamics of the electrons in the metal. By cooling the copper structures to low temperatures, the surface resistance can be reduced by a factor of 4-5 compared to that at room temperature.

Recent work on cryo-cooled copper cavities at SLAC and UCLA on standing wave X-band structures also found that when cooled to temperatures 20-50 K, these structures have reduced breakdown rates for the same accelerating gradient due to reduced dislocation mobility and RF pulsed heating [9, 10]. Similarly, there has also been an interest in using this technology for photocathode guns, exploiting the improvement in the accelerating gradient [11, 12].

Special care must be taken in the fabrication techniques for these type of structures. A common fabrication process involves having the halved structures brazed together. Brazing the copper, however, makes it softer, thus limiting the acceleration gradient. It then becomes preferred to fabricate using processes that preserve the integrity of the material. See for example [13] for an X-band structure design based solely on milling.

EM MODEL OF A C-BAND STRUCTURE

Geometry of the TW Single-Cell Cavity

In this paper, we present the case study of a TW, C-band structure with 5.712 GHz its operating frequency. We perform electromagnetic analysis of the structure usign *VSim 9*. *VSim 9* is a flexible, multiplatform, multiphysics simulation software tool developed by Tech-X and based on the *Vorpal* engine [14]. It can be used for a wide variety of electromagnetic and charged particle problems [15].

The geometry of the structure is shown in Fig. 1 and Table 1 presents the relevant parameters describing the geometry of the cavity.

Initial Simulation

First, a pre-designed arbitrary C-band TW cavity modeled in CAD is imported into *VSim 9*. A distributed current source is then used to excite the cavity around the frequency of interest. Following this, the current source is switched off and the simulation continued whilst saving the electric and magnetic fields periodically, depending on the mode and mode spacing. A filter-diagonalization method (FDM) method as detailed in [16] is then used to extract the eigenmodes of the structure.

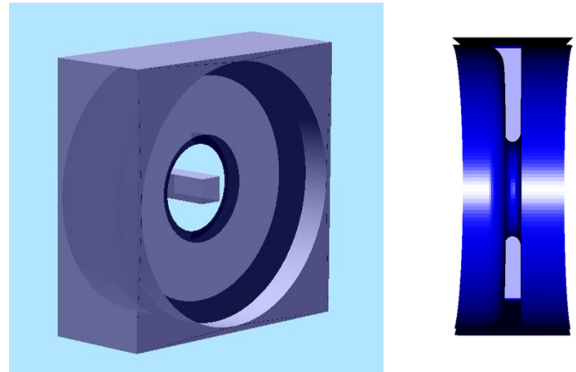

Figure 1: Model of a traveling wave, C-band structure and the cross section view.

Table 1: Parameters Describing the Geometry of the Single-Cell Cavity

Parameter	Value	Units
Frequency	5.712	GHz
Cell length	17.495	mm
Outer radius	21.13	mm
Iris radius	7	mm
Phase advance	$2\pi/3$	rad

Periodic boundary conditions along the accelerating axis of the cavity were used, with a $2\pi/3$ rad phase shift, to capture the correct mode of a traveling wave device. Figure 2 shows the resulting electric field distribution of the structure in the fundamental mode. The amplitude of the longitudinal electric field along the axis is also shown in Fig. 3, with the correct frequency of 5.712 GHz also obtained.

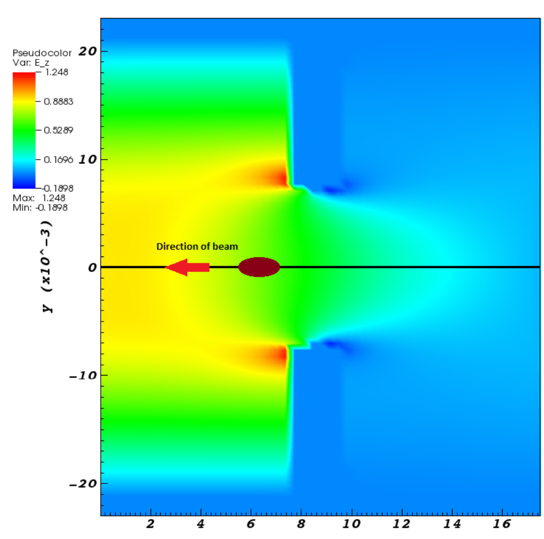

Figure 2: Electric field distribution in the C-band structure corresponding to the fundamental mode at 5.712 GHz.

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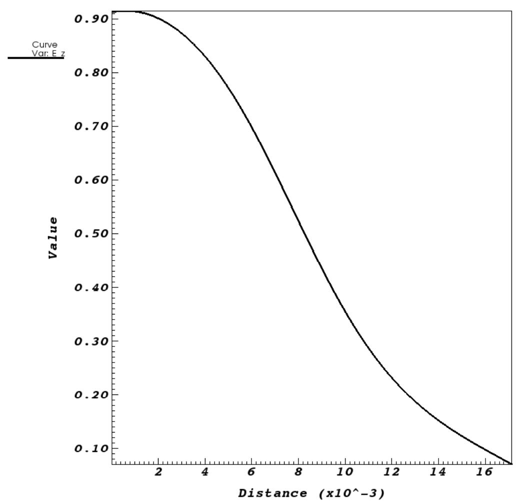

Figure 3: Electric field along the axis of the TW cavity.

SUMMARY AND FUTURE WORK

The use of normal-conducting structures operating at cryogenic temperatures for FEL linacs is an interesting, near-term prospect for achieving high-gradient capability and low rates of rf vacuum breakdown. In this contribution, we presented recent studies for using cryo-cooled C-band structures for FEL applications. Using the electromagnetic solver *VSim 9*, we present a simple initial simulation for a simple TW C-band structure.

Following these initial simulations, a number of other cavity geometries will be investigated in order to identify good candidate geometries for use in a cryo-cooled linac for FEL. A multi-cell structure will be simulated and the frequency shift due to cryogenic cool-down investigated, along with tuning methods for the cavities. Beam dynamics studies will be performed using the Particle-in-Cell (PIC) suite of *VSim 9*, together with studies of wakefield effects and beam requirements of new FEL devices. Following these simulation studies, we have plans to manufacture a prototype structure and test it at high power and cryogenic temperatures.

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