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ULTRA-HIGH GRADIENT COMPACT S-BAND LINAC FOR LABORATORY AND INDUSTRIAL APPLICATIONS*

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Abstract

There is growing demand from the industrial and research communities for high gradient, compact RF accelerating structures. The commonly used S-band SLAC-type structure has an operating gradient of only about 20 MV/m; while much higher operating gradients (up to 70 MV/m) have been recently achieved in X-band, as a consequence of the substantial efforts by the Next Linear Collider (NLC) collaboration to push the performance envelope of RF structures towards higher accelerating gradients. Currently however, high power X-band RF sources are not readily available for industrial applications. Therefore, RadiaBeam Technologies is developing a short, standing wave S-band structure which uses frequency scaled NLC design concepts to achieve up to a 50 MV/m operating gradient at 2856 MHz. The design and prototype commissioning plans are presented.

INTRODUCTION

In this paper, we present the radio-frequency design of the DECA S-band accelerating structure operating at 2.856 GHz in the pi-mode (RF power sources are commonly available at this frequency). The design is heavily influenced by NLC collaboration experience with ultra high gradient X-band structures of interest to high energy physics community. Upon development the DECA structure will offer an ultra-compact drop-in replacement for a conventional S-band linac in research and industrial applications such as drivers for compact light sources, medical and security systems. From an R&D point of view, the DECA accelerator will be a valuable research project of its own – to investigate the frequency scaling of RF breakdown mechanisms and corresponding design limitations of high gradient structures. The electromagnetic design has been performed with the codes SuperFish and HFSS. The choice of the single cell shape derives from an optimization process aiming to maximize RF efficiency and minimize surface fields at very high accelerating gradients, i.e. 50 MV/m and above. This gradient value is twice the current gradient in SLAC-type linacs, hence the name DECA (Doubled Energy Compact Accelerator). Such gradients can be achieved utilizing shape-optimized elliptical irises, dual-feed couplers with the "fat-lip" coupling slot geometry, "race-track" geometry [5] and specialized fabrication procedures developed for high gradient structures.

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RF DESIGN

The DECA accelerator consists in a disk-loaded structure, which is similar to existing TW accelerating structure designs. The 2D profile of the single cell in shown in Fig. 1. A thorough study for the choice of the final shape has been performed. The cell period *d* is set by the mode phase advance, which we have chosen as π. The iris is characterized by an elliptical shape with major and minor axes *2A* and *2B*, respectively. The inner radius of the iris is *Riris* and the thickness is *2A*. The cell radius *Rc* is a derived number given by setting the cell resonant frequency to 2.856 GHz. Operation at an accelerating gradient approaching 50 MV/m requires special attention to minimization of surface electric and magnetic fields. The tips of the irises are areas where the surface electric field is locally intense. Thus, in order to mitigate possible breakdowns, a thorough study of the cell shape choice on the electric field has been carried out using the codes SuperFish and HFSS for 2D and 3D simulations, respectively. SLAC TW Linacs operate with a gradient such that the electric field peak at the iris areas reaches a value of 110MV/m, that we assume as a "safety threshold".

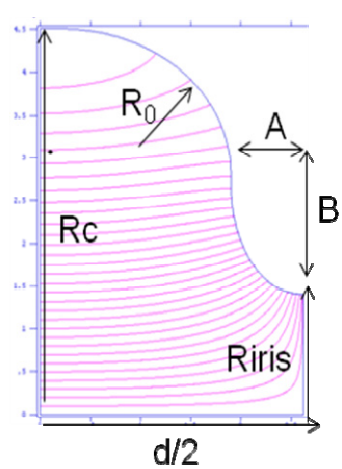

Figure 1: 2D Section of the DECA Cell.

The reason for choosing such a cell geometry is the consequence of a comparison study between a cell with two different iris profiles, circular (standard pill-box) and elliptical (DECA cell). It follows that the use of elliptical irises allows to keep the surface electric field peaks below the value at the cathode, that in the present case is about

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95 MV/m. In Table 1, we list the main RF parameters of the DECA cell, for both cases, circular and elliptical iris.

Also, it has to be noticed that the use of a rounded edge (curvature radius *R0)* produces an increase in the value of the quality factor of more than 20% and it is possible to achieve a shunt impedance of 78.5 MΩ/m for aperture radius R_{iris} =16 mm. This is crucial for power consumption issues.

Table 1: Main DECA Cell RF Parameters

	Circular iris	**Elliptical iris**
$\mathbf{f_\pi}$	2.856 GHz	2.856 GHz
Δf	3 MHz	3 MHz
$\mathbf{Q_0}$	15,500	18,800
$\mathbf{R_S}$	57.8 MΩ/m	78.5 MΩ/m
$\mathbf{E_{peak}}$ **(axis)**	95 MV/m	95 MV/m
$\mathbf{E_{max}}$ **(iris)**	106 MV/m	85 MV/m
$\mathbf{E_{max}/E_{peak}}$	1.11	0.89

The mode separation Δf=3MHz is the result of the choice of a number *N*=11 of main cells for the final DECA structure. The 3D model is shown in Fig. 2. The RF simulations have been carried out with HFSS v12. The power is fed through an optimized 3dB splitter. The tuning system consists of "push" uni-directional tuners. As for the cooling, standard longitudinal channels are used because of the low repetition rate operation at ATF, 1.5 Hz with average power of a few tens of watts.

The DECA section used in HFSS and the correspondent on-axis electric field are given in Fig. 3.

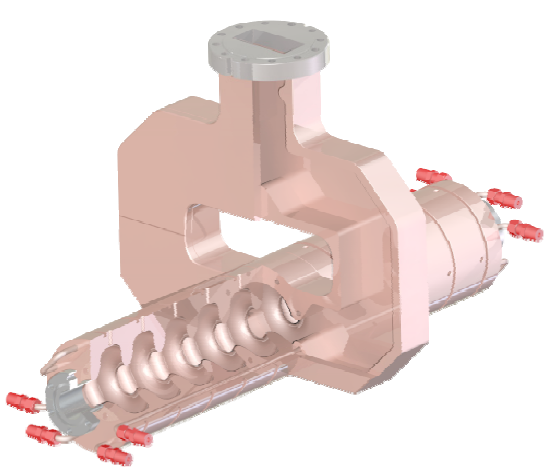
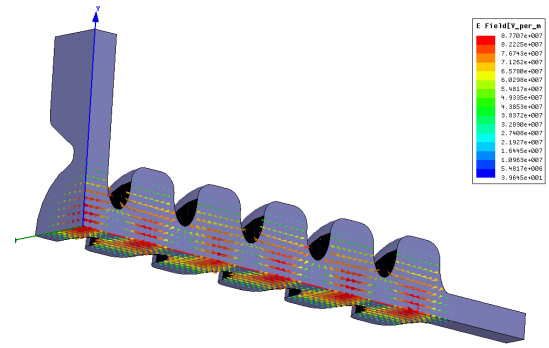


Figure 2: 3D model of the DECA structure.

Preliminary Dynamics Results

A preliminary check of beam dynamics, using the code PARMELA, has confirmed the beam energy gain at the exit of the DECA structure equal to nearly 30 MeV.



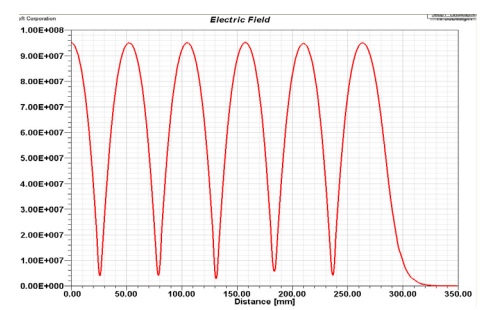


Figure 3: Above, Section of the DECA Cavity Used in HFSS; Below, On-axis Accelerating Electric Field.

RF Breakdowns

RF breakdowns are arcs in high-power RF vacuum device which interrupt RF power flow, produce burst of X-rays and bright flash of visible light. This process results in pulse shortening and high-power spikes.

Simulations with HFSS show that the peak value is 95 MV/m (accelerating gradient 50 MV/m) for an input power of about 28 MW, which is consistent with SUPERFISH results. Also, from the picture of the electric field amplitude inside the structure and on the cell surface (Fig. 4), we can see that the peak value on the surface is about 85 MV/m, in perfect agreement with Table 1.

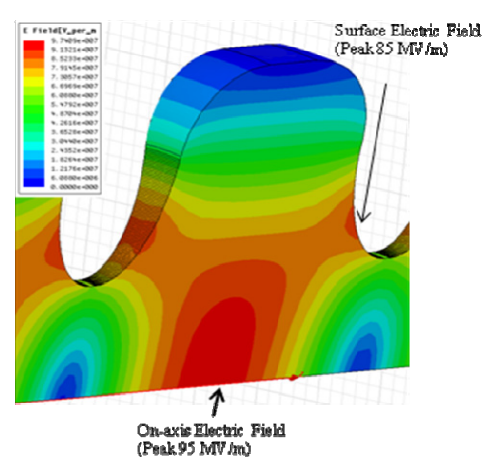


Figure 4: Amplitude of the electric field inside and on the surface of the cells

RF Pulsed Heating

RF pulsed heating due to intense magnetic fields that is usually peaked at the coupling slot area.may become a cause of significant material deformations.

Simulations show that magnetic field reaches a peak equal to $H_{max} = 2.8*10^5$ A/m for an input RF power of 28 MW and pulse length 1.4 µs. This field value causes a temperature rise of about 20 ° C, that is far below the threshold of 110 °C in the case of copper [4].

THERMAL-STRESS ANALYSIS

The thermal analysis of the DECA structure has been carried out by using Ansys12.1.

The average power that the DECA accelerator has to support is relatively low, since we are assuming a 28 MW input power and a pulse length of about 1.4 µs and 1.5 Hz repetition rate, that means an average power of 73.5 W. Thus, no intensive cooling system is required but only for temperature stabilization so that the resonant frequency is stable. A quarter section of the structure has been simulated and shown in Fig. 5.

The ambient temperature is 22 °C. The temperature distribution is uniform throughout the whole coupler with a peak value of 48 °C at the coupling iris.

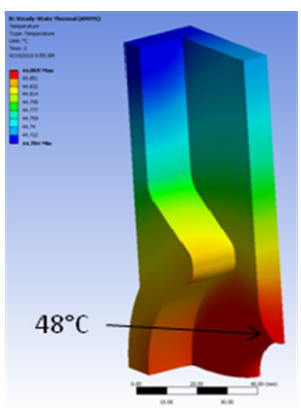


Figure 5: Temperature Distribution

Stress analysis is also performed with Ansys. The total deformation and equivalent (von-Mises) stress for the DECA cell are shown in Fig. 6. A max value of 26µm around the cell is observed, while 77 MPa stress is located at the coupling slot area.

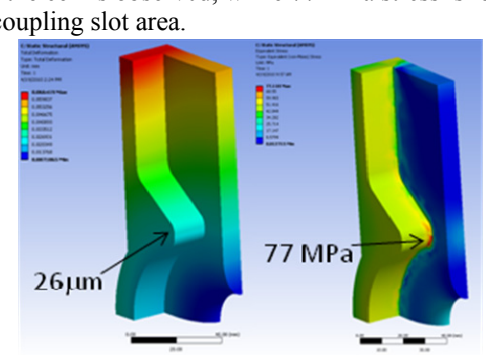


Figure 6: Left, Total Deformation; Right, Equivalent (von-Mises) Stress.

INSTALLATION PLAN AT ATF

The RF system for the installation of two DECA structures at ATF is sketched in Fig. 7. A 40 MW RF power, from an RF klystron, is tripled in a SLED. The output power is about 120 MW with a puls length of 1.4µs. A series of directional couplers (summarized by one only in the picture) deliver the high power to the DECA accelerators and reduce the risk of reflected power back toward the source.

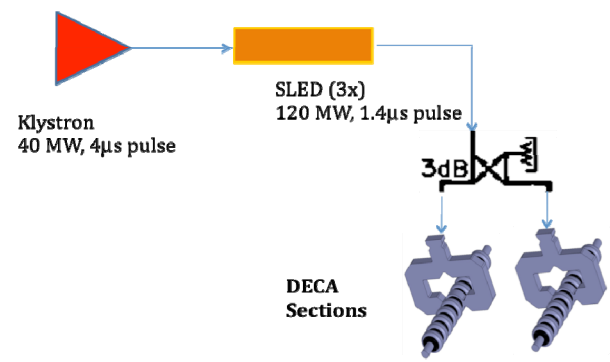


Figure 7: RF System for Two DECA Structures.

CONCLUSIONS

The DECA structure, high accelerating gradient cavity, has many intersecting elements: RF field optimization and symmetrization, beam dynamics, RF pulsed heating and thermo-mechanical distortions. In order to meet all these aspects in a high field environment, novel features in the geometry of the cells have been employed, such as 'fat-lip' coupling slot, 'race-track' for the coupler cell, elliptical cell-to-cell irises and rounded cell edges.

The main purpose is to study RF breakdown mechanisms and corresponding design limitations of high gradient structures but its versatility makes it also suitable for high energy physics and industrial applications.

The next step will be the fabrication of the DECA accelerator and high power tests at BNL-ATF.

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