ULTRA-HIGH GRADIENT COMPACT S-BAND ACCELERATING STRUCTURE*

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Abstract

In this paper, we present the radio-frequency design of the DECA (Doubled Energy Compact Accelerator) S-band accelerating structure operating in the pi-mode at 2.856 GHz, where RF power sources are commonly available. The development of 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. 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. Such gradients can be achieved utilizing shape-optimized elliptical irises, dual-feed couplers with the "fat-lip" coupling slot geometry, and specialized fabrication procedures developed for high gradient structures. The thermal-stress analysis of the DECA structure is also presented.

The machining of the first DECA cell has been carried out at Radiabeam and the installation/conditioning plan of the full structures at the Accelerator Test Facility at Brookhaven National Laboratory (BNL-ATF) is also discussed.

INTRODUCTION

There is growing demand from the industrial and research communities for high gradient, compact RF accelerating structures. The commonly used S-band SLAC-type 3-m structure has an operating gradient of only about 20 MV/m. There is significant interest in more compact high-energy linear accelerators for field applications in the areas of homeland security [1,2] and radiotherapy [3], as well as future compact drivers for free-electron lasers and Compton light sources [4]. To date, the most productive approach towards reaching higher operating gradients in Linacs was to advance the technology originating in the conventional L-band and S-band devices towards higher frequencies. Significant research was performed under the NLC program to demonstrate successful high gradient operation of X-band (11.4 GHz) and Ku-band (17 GHz) [5,6]. These efforts, without doubt, will continue to expand the frontier of RF accelerator systems capabilities in the future. However, for the commercially viable linear accelerator, transitioning towards X-band and higher frequencies is not practical due to the lack of industrially available high peak power RF sources in X-band and beyond. The proposed development of the DECA structure aims at a moderate goal of doubling the available RF gradient at S-band while taking full advantage of the mature and commercially available S-band high power klystron technology.

*Work supported by US DOE grant # DE-SC000866
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RF DESIGN

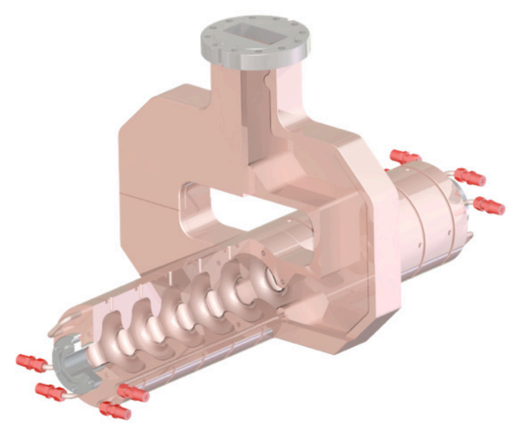

Figure 1: DECA structure.

The DECA accelerator consists in an 11-cells disk-loaded structure, as shown in Figure 1, which is similar to existing traveling wave accelerating structure designs.

Cell Design

The 2D profile of the single cell is shown in Figure 2. A thorough study for the choice of the final shape has been performed. The cell length is set by the mode phase advance, which we have chosen to be 180 degrees (π-mode). Operation at an accelerating gradient at 50 MV/m and above requires special attention to the minimization of surface electric and magnetic fields. The tips of the irises are areas where the surface electric field is locally very intense. Thus, in order to mitigate possible breakdowns, a thorough study of the cell shape and corresponding electric field distribution has been carried out using the codes SuperFish and HFSS for 2D and 3D simulations, respectively. The choice of an elliptical shape for the iris allows to achieve an electric field, at the iris tips, with intensity lower than the case with iris circular profile.

Also, an optimization process by using SuperFish for the main RF parameters, such as quality factor and shunt impedance, has been carried out. The results are listed in Table 1. The rounding of the cell edge noticeably improves the quality factor and reduces the wall power consumption.

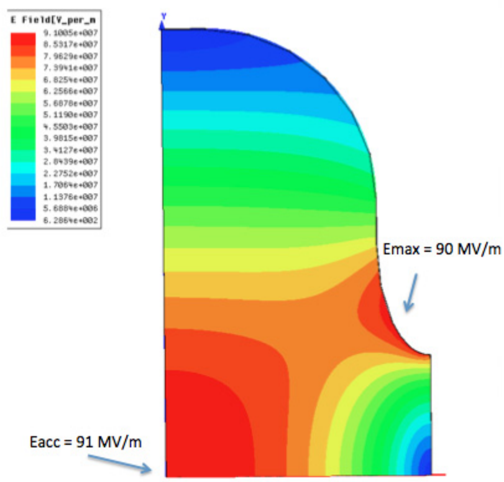

Figure 2: 2D profile of half cell of the DECA structure; electric field distribution is also shown.

Table 1: Main RF Parameters

Parameter	Simulated value
f_π	2.856 GHz
R_S	93 MΩ/m
Δf	2.5 MHz
Q_0	19,500
R/Q	143.2 Ω
E_{acc}	50 mV/m
E_{max}/E_{acc}	1.8
P_{diss}/cell	2.4 MW

RF Breakdowns

RF breakdowns are arcs in high-power RF vacuum devices which interrupt RF power flow and produce bursts of X-rays and bright flashes of visible light. This process results in pulse shortening and high-power spikes.

Simulations with HFSS show that the peak value of the electric field along the axis of the DECA structure is 91 MV/m (accelerating gradient 50 MV/m) for an input power of about 26 MW, which is consistent with SUPERFISH results. Also, from the picture of the electric field amplitude inside the structure and on the cell surface (Figure 6), we can see that the peak value on the surface is about 90 MV/m, in perfect agreement with Table 1.

RF Pulsed Heating

RF pulsed heating results in material deformations and is driven by intense surface magnetic fields; in the case of the DECA structure, the most intense fields are located at the coupling slot area.

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

THERMAL/STRESS ANALYSIS

The thermal analysis of the DECA structure has been carried out by using Ansys13. The average power that the DECA accelerator has to support is relatively low, since we are assuming a 26 MW input power and a pulse length of about 1.4 μs and 1.5 Hz repetition rate, which equates to an average power of 73.5 W. Thus, no intensive cooling system is required aside from temperature stabilization so that the resonant frequency is stable. A quarter section of the structure has been simulated and is shown in Figure 3. 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.

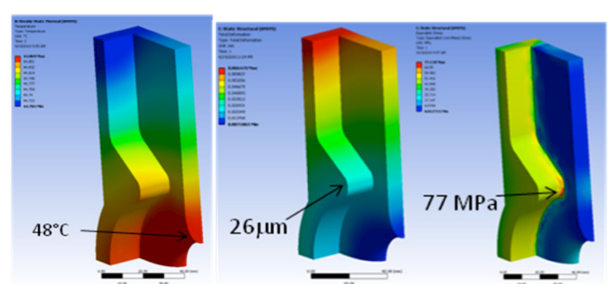

Figure 3: left) temperature distribution; right) stress analysis.

Stress analysis is also performed with Ansys. The total deformation and equivalent (von-Mises) stress for the DECA cell are shown in Figure 3. The deformation produces a frequency shift, adjustable by moving the tuners. The von Mises stress measure the yield strength (given in terms of pressure) of the metal, above which the material starts to deform plastically, i.e. non-reversible change of its shape. In the present case, a maximum value of 26μm around the cell is observed, while 77 MPa stress (below the safe threshold for copper) is located at the coupling slot area.

CELL MACHINING

The engineering and machining of the DECA cells is on-progress at Radiabeam. Recently, one copper cell has been fabricated, see Figure 4, by using polycrystalline diamond cutting tools for turned geometries. These types of tools are necessary to achieve the superior quality of surface finishes (~6 micro-inch RMS) that are required when concerned about RF breakdown.

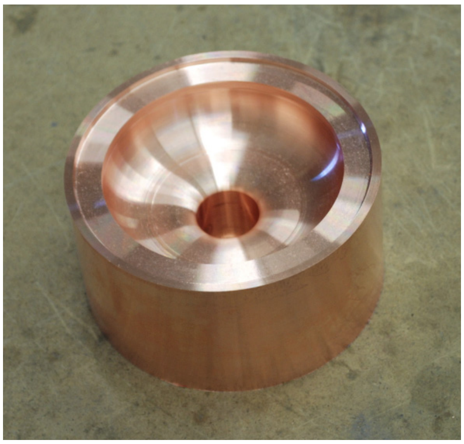

Figure 4: DECA cell (half).

INSTALLATION/CONDITIONING PLAN

In order to perform high power tests, we plan to deliver two DECA structures to BNL-ATF.

The testing procedure will consist of two parts: initial processing and characterization of the breakdown behavior or measurement of the breakdown rates (number of breakdowns per pulse) vs. RF power and pulse length. For initial processing, first we detune the SLED and set short ~100 ns RF pulse length. We will ramp klystron power up while monitoring vacuum, radiation and RF signals for RF breakdowns and multipacting. After a breakdown we will switch off RF and wait for vacuum to decrease and restart the RF power ramp from low levels. After we reach full klystron power or breakdown rate of one breakdown in 100 RF pulses, we will increase pulse length by 50 ns and repeat the procedure from low power levels.

The power source is represented by a Klystron. The nominal output power is about 40 MW with a pulse length of 4μs. In order to increase the amount of power, a SLED is employed. The power multiplication is expected to be a factor of 3 so that it is possible to achieve 120 MW.

Initial tests on the Klystron in diode mode (no RF power) have recently been carried out at BNL-ATF. Figure 5 shows a picture of the oscilloscope reading the voltage (red) and current (yellow) of the Klystron.

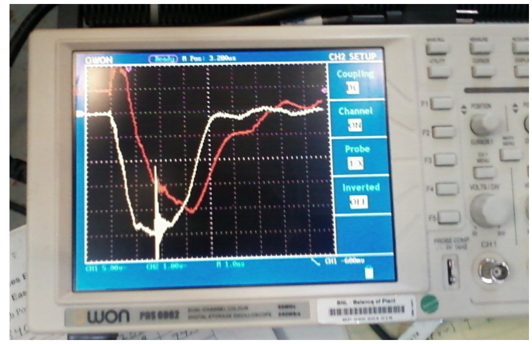

Figure 5: current (red) and voltage (yellow) pulses from Klystron in diode mode (no RF) for initial conditioning.

CONCLUSIONS

The design of the DECA compact high-gradient accelerating structure involves 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 machining of the DECA cells is on-progress at Radiabeam and we started the initial conditioning of the Klystron at BNL-ATF for the subsequent high power tests.

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