HIGH-POWER TESTS OF AN ULTRA-HIGH GRADIENT COMPACT S-BAND (HGS) ACCELERATING STRUCTURE*

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Abstract

RadiaBeam Technologies reports on the RF design, fabrication and high-power tests of a ultra-high gradient S-Band accelerating structure (HGS) operating in the pi-mode at 2.856 GHz. The compact HGS structure offers a drop-in replacement for conventional S-Band linacs in research and industrial applications such as drivers for compact light sources, medical and security systems. The electromagnetic design (optimization of the cell shape in order to maximize RF efficiency and minimize surface fields at very high accelerating gradients) has been carried out with the codes HFSS and SuperFish while the thermal analysis has been performed by using the code ANSYS. The high-power conditioning was carried out at Lawrence Livermore National Laboratory (LLNL).

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 a practical 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].

The development of the HGS structure aims at doubling the available RF gradient at S-band while taking full advantage of the mature and commercially available S-band high power klystron technology.

RF DESIGN

The RF design of the HGS cells has been carried out with the 2D code SuperFish while the design of the whole structure, including the RF coupler, has been performed by using the 3D code HFSS. The first HGS prototype consists of 5 cells, single feed.

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.

A quarter section of the 5-cell HGS prototype, used for HFSS simulations, is shown in Figure 1 with the electric field distribution inside the structure. The corresponding on-axis electric field, featuring a perfect flatness, is given in Figure 2.

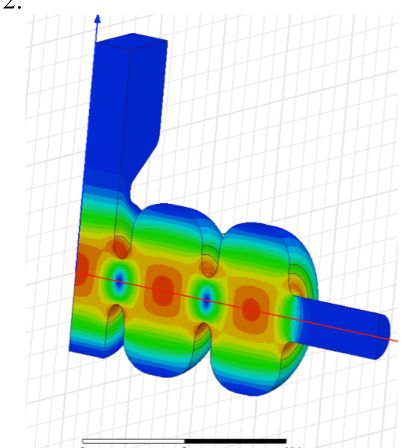

Figure 1: A quarter section of the 5-cell HGS structure; electric field distribution is shown.

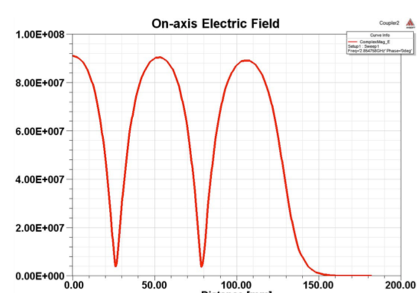

Figure 2: On-axis electric field profile for the quarter section.

An optimization process 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.

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Table 1: Main RF Parameters

Parameter	Simulated value
f_π	2.856 GHz
R_S (Effective R_S)	93 MΩ/m (51 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

Figure 3 shows the fully engineered 3D model (with SolidWorks) of the prototype, including the 3-step taper and a water jacket brazed around the cells for frequency stabilization. Also, two vertical cooling channels are brazed along the coupler sides.

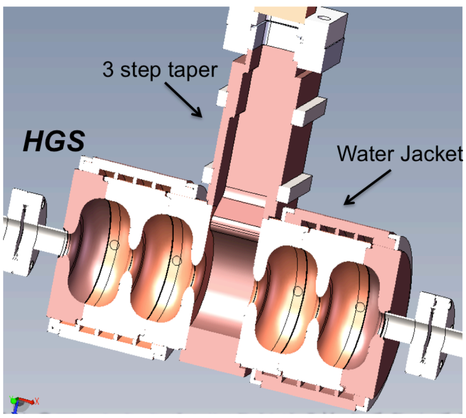

Figure 3: 3D mechanical model (SolidWorks) of the 5-cell HGS structure.

THERMAL ANALYSIS

The thermal analysis of the HGS structure has been carried out by using Ansys13. The average power that the HGS accelerator has to support during conditioning is about 600 W (15 MW max input power, pulse length up to 4 µs and max repetition rate of 10 Hz). A quarter section of the structure has been simulated and it is shown in Figure 4. The temperature distribution is uniform throughout the whole coupler with a peak value of about 39 °C at the coupling iris.

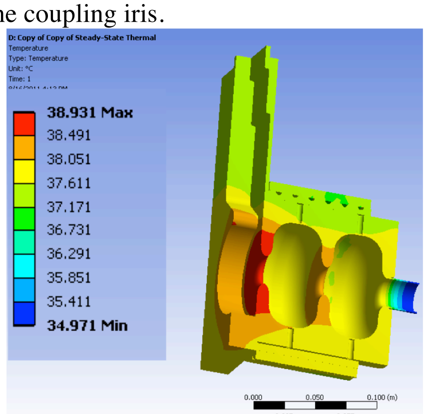

Figure 4: Temperature distribution inside the HGS.

HGS FABRICATION

The final 5-cell HGS structure has been machined and brazed, including the cooling system brazed to the structure, as shown in Figure 5.

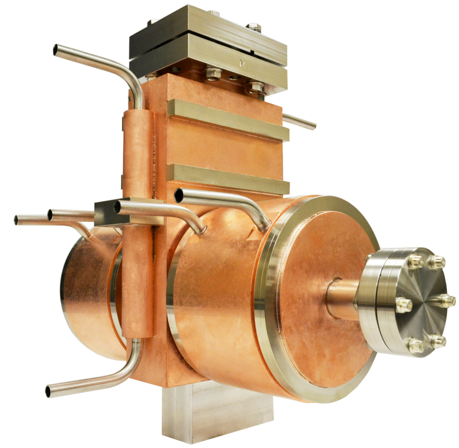

Figure 5: 5-cell HGS structure. Cooling system (frequency stabilization) is brazed to the accelerating device.

The measured reflection coefficient (showing also the coupling β=1.1 and quality factor Q=19,000) is given in Figure 6, showing good agreement with the simulated values (β =1.14 and Q=19,500).

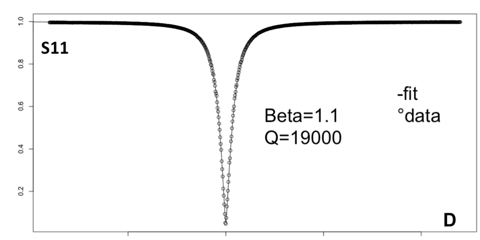

Figure 6: Measured Reflection coefficient (S11).

All the brazing steps for the HGS structure have been successfully carried out. Two water jackets are wrapped around the main cells and two separate cooling channels along the coupler. The vacuum flange used is merdinian type, to accommodate LLNL RF window flange. Figure 7 shows the measured axial electric field profile obtained with bead-pull measurements. Two different perturbative methods (resonant and non-resonant) have been applied for the data acquisition. The normalized data show good agreement.

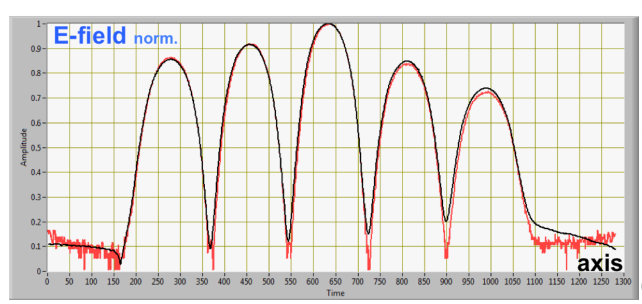

Figure 7: Axial electric field profile (bead-pull).

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INSTALLATION AND HIGH-POWER CONDITIONING AT LIVERMORE

The high-power testing procedure at LLNL consisted 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, we first set short (possible attainable minimum was ~1.35μs) RF pulse length. We then ramped up the klystron power while monitoring vacuum, radiation and RF signals for RF breakdowns. After a breakdown we switched off the RF and waited for vacuum to decrease and restart the RF power ramp from low levels. After we reached full klystron power or breakdown rate of one breakdown in 100 RF pulses, we increased the pulse length by 50 ns and repeated the procedure from low power levels.

The power source was represented by a Klystron. The nominal output power was increased up to about 16 MW with a pulse length up to 4 μs. The HGS structure installed on an optical table is shown in Fig. 8. Vacuum piping and cooling system are also visible.

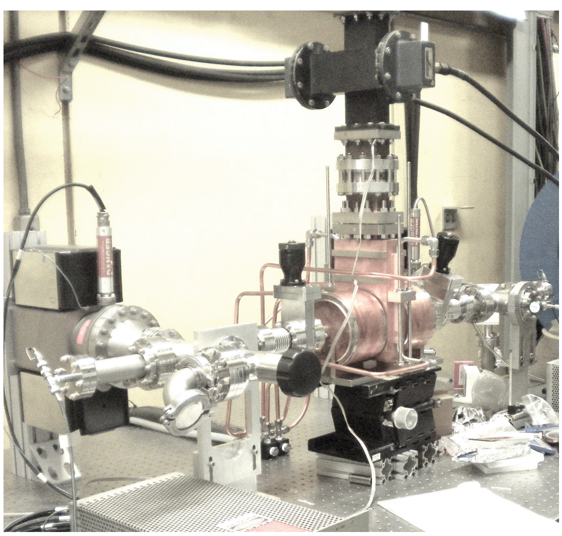

Figure 8: HGS structure installed at Livermore. Vacuum piping and cooling system are also shown.

In Fig. 9, we show the power signals from the oscilloscope.

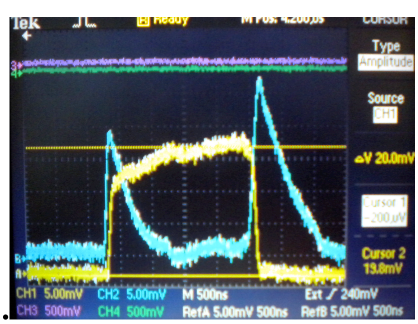

Figure 9: Power waveforms from oscilloscope. Forward (yellow) and reflected power (blue).

The breakdown rate map for the high gradient S-band standing wave structure, which will be our contribution to basic knowledge of the RF breakdown physics, is given in Fig. 10. Typical experiments of this type at SLAC, CERN or KEK take from few weeks to few months, depending on system performance. The runs at Livermore were limited to 18 days, but we were able to fill the structure with 16MW of power, translating to a gradient of about 50 MV/m as shown in Fig. 11.

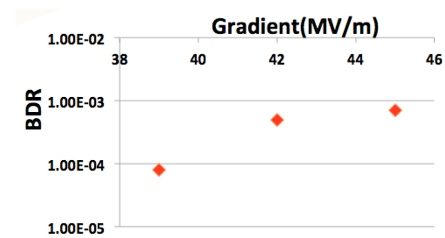

Figure 10: Map of breakdown rate.

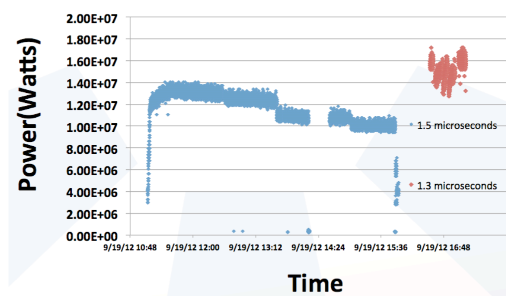

Figure 11: Monitoring of high-power conditioning.

CONCLUSIONS

In order to meet all the aspects to be concerned about when dealing with a high field environment, novel features in the geometry of the cells have been employed, such as ‘fat-lip’ coupling slot, elliptical cell-to-cell irises and rounded cell edges. The RF high-power tests of the HGS have been successfully carried out showing a maximum gradient of 50MV/m.

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