EXPERIMENTAL CHARACTERIZATION OF THE RF GUN PROTOTYPE FOR THE SPARX-FEL PROJECT

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Abstract

The quest for high brightness beams is a crucial key for the SPARX-FEL Project. In this paper, we present the design (including RF modeling, cooling, thermal and stress analyses as well as frequency detuning) of a single feed S-Band RF Gun capable of running near 500 Hz. An alternative design with dual feed has already been designed. Also, experimental results from the RF characterization of the prototype, including field measurements, are presented. The RF design follows the guidelines of the LCLS Gun, but the approach diverges significantly as far as the management of the cooling and mechanical stress is concerned. Finally, we examine the new proprietary approach of RadiaBeam Technologies for fabricating copper structures with intricate internal cooling geometries that may enable very high repetition rate.

INTRODUCTION

The peak electron beam brightness of the SPARX project at the INFN-LNF is a crucial requirement, one which in order to meet the demands of average FEL flux, should also be achieved at a higher repetition rate than in the past. To this end, a 1.6 cell RF Gun with single feed, operating in S-band, has been studied and designed while balancing optimization of the RF parameters and the beam dynamics requirements. The RF design has been carried out using the 2D and 3D modeling codes SUPERFISH[1] and HFSS[2], respectively. The details and an alternative design in dual-feed configuration can be found in [6].

We briefly report the study of the electromagnetic field higher multipole components inside the Gun, since they have been shown [4] to contribute to beam emittance growth, resulting in beam brightness decrease and concomitant degradation of FEL performance. Although the asymmetry of the single-feed configuration, the use of identical coupling holes and two waveguides, one of which acting as a dummy load, allows to reasonably lower the dipole component. As far as the decreasing of the quadrupole component is concerned, a "racetrack" geometry is exploited.

Moreover, and most critically for the purpose of understanding the maximum repetition rate of the Gun itself, thermal and stress analyses are carried out by using the code ePhysics[5]. A novel material fabrication technique, SFF [8], allows to build more intense cooling systems so that higher rep rates can be easily handled.

Finally, experimental results of field measurements are presented.

RF GUN DESIGN

The RF Gun designed for the SPARX project is a 1.6 cell Gun with single feed (see Fig.1). This allows the use of a simpler RF power system than the case of dual feed and to avoid the possibility of phase shift between the two input waves.

The resonant electromagnetic field is a pi-mode at 2.856 GHz with a quality factor Q=13,500. The other main electromagnetic parameters are listed in Table 1.

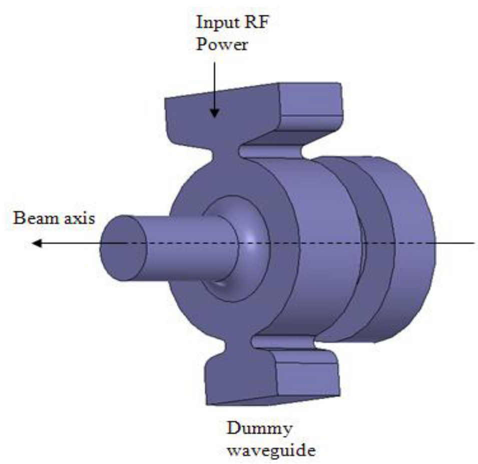

Figure 1: 3-D surface model of the Gun, from HFSS.

Table 1: RF parameters of the Gun

f_π	2.856 GHz
$\Delta f=f_\pi-f_0$	15 MHz
β	1.17
Q_0	135000
Q_{ext}	11490
R_S/Q_0	3630
E_{peak}	120 MV/m @ P_{RF} = 10 MW

In Figure 2, the on-axis electric field amplitude and phase are shown.

In present case, the peak value of the surface tangential magnetic field $H_{||}$, obtained from simulations, is about $3.9x10^5$ A/m, and it is located at the coupling slot regions. This field value causes a temperature gradient of about

56° C [4], a little below the threshold of 60° C, which is considered an upper limit in S-band operation. Problems may arise if the power is significantly higher than 10 MW.

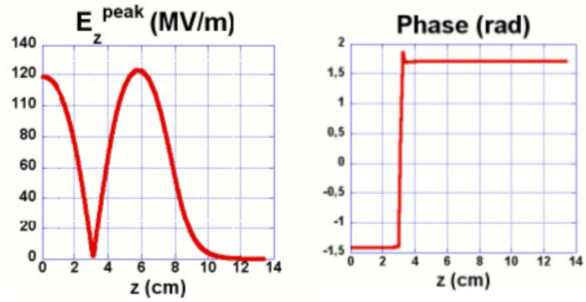

Figure 2: amplitude and phase profiles of the electric field along the longitudinal axis of the Gun.

The dipole component arises from the use of a single input waveguide. It is possible to strongly diminish it by using a symmetric waveguide with cut-off above the resonant frequency, so that it will act as a dummy load, with a coupling hole similar to the input one.

The quadrupole component is cancelled out by using a race-track geometry with offset D. Results are shown in Fig. 3 and it is evident how it is possible using a value D=3.8 mm in order to diminish $H\phi$.

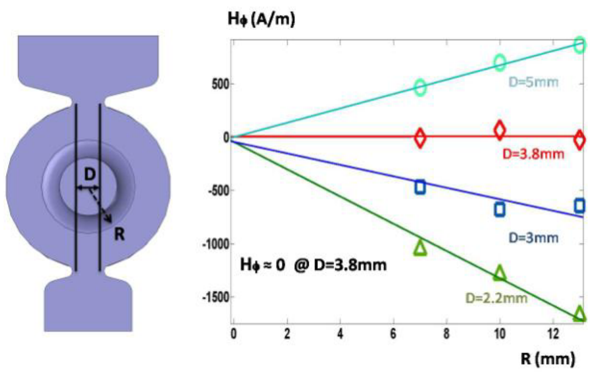

Figure 3: left, cross-section of the full cell: D is the offset; right, quadrupole component.

THERMAL AND STRESS ANALYSIS

Thermal and stress analyses of the RF Gun have been carried out by using ePhysics coupled with HFSS. The input peak power considered is 10 MW.

The hottest temperature spot due to power dissipation happens at the coupling windows.

Figure 4 shows a cooling system using cylindrical channels, with 8mm diameter, set longitudinally and behind the cathode. In order to cool down the region between the two cells it is possible to drill a conformal channel around the iris. Longitudinal and conformal channels have either the same water flux input or independent, whatever permits the proper fluid flow.

The average power inside the gun is 3 kW, for 100 Hz repetition rate.

A hot spot of 38°C for a 100Hz repetition rate is located at the coupling window, as expected (see Fig. 4). It has been verified that the temperature distribution shows a linear behavior with the repetition rate.

The use of SFF techniques, Solid Freeform Fabrication, makes possible the machining of a cooling system with a better performance in terms of temperature distribution. For example, the use of star-shaped, conformal channels would result in greatly enhanced heat transfer and more uniform cooling (no hot spots). Furthermore, the cooling channels can be designed and built to avoid going through braze/vacuum joints.

Comparing the case of a fairly standard geometry, with circular cross-sectional dia. of 6 mm, to that of the shaped, conformal and other fancy geometries available only through SFF, we see that star-shaped cross section geometry allows cavity wall temperatures to be kept significantly lower than the case with cylindrical channels, by 25 °C.

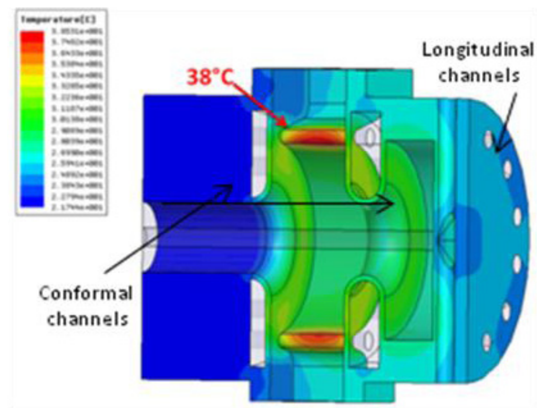

Figure 4: cooling system and temperature distribution.

For an average input power of 5 kW, that is 170 Hz repetition rate according to power source parameters, the displacement peak is about 33 µm. Thus, concerning mechanical deformation, star-shaped channels allow to use higher RF drive power with respect to ones with a standard geometry.

By using the Slater perturbation theory, we deduce a detuning in the standard case nearly +350 kHz. This is relatively small, corresponding to a change in nominal operating cooling water temperature of approximately 8°C, allowing to increase the rep rate up to 500 Hz.

In Fig. 5, we show a quarter cell machined with SFF technique. Three cooling channels with rectangular cross-section are present. A cut in the cell walls allows to see the path of the middle channel.

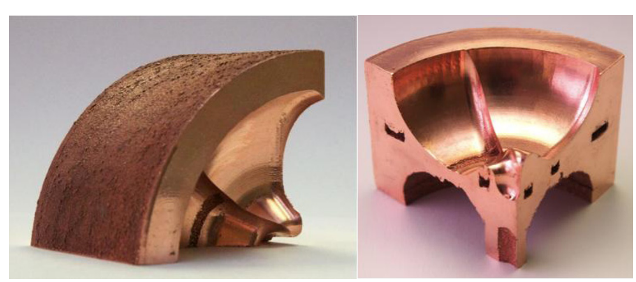

Figure 5: a quarter cell fabricated with SFF technique.

EXPERIMENTAL RESULTS

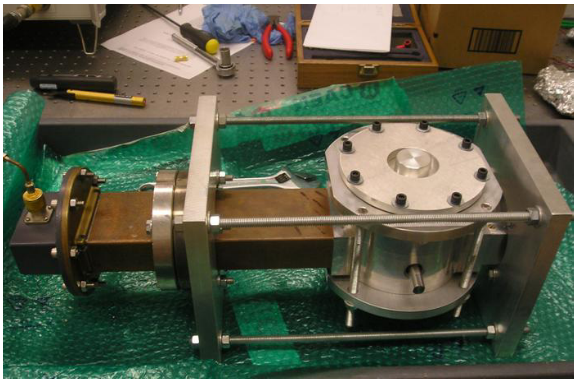

Figure 6: RF Gun prototype.

Low-power RF characterization of the Gun prototype has been performed at UCLA labs. The accelerating structure is made out of aluminum while copper has been used for the input waveguide, as shown in Fig. 6. Clamps tighten the Gun together and two tuners are present on each cell.

The main RF parameters, measured by using a Vector Network Analyzer, are listed in Table 2 together with the results obtained from simulations.

Table 2: Comparison of the RF parameters of the Gun

	Measurements	Simulations
f_π	2.852 GHz	2.856 GHz
f_π - f_0	14.5 MHz	15 MHz
Q0	10700	13500
β	0.5	1.17

A frequency shift of the π mode of 4 MHz is caused by many factors that differ from the simulations. This cold test has been performed in air instead of vacuum, that is likely to cause a shift of 1-2 MHz; humidity can produce a frequency shift of about 0.5 MHz; plus, the structure is not brazed, giving rise to loosen the RF contacts. Especially brazing could have caused a lower Q, but still reasonably close to the simulated one. The structure results to be under-coupled (β = 0.5). Low coupling could be caused by mismatching between the input waveguide and the coupler cell.

In order to quantify the electric field on-axis, bead-drop measurements have been performed making use of the Slater perturbation method. The metallic bead used was 2mm in length and 1 mm in diameter. The results are shown in Fig. 6. The higher field values observed near the cathode are due to the approaching of the bead towards the cathode plate causes repulses forces due charge images and the following electric field rise.

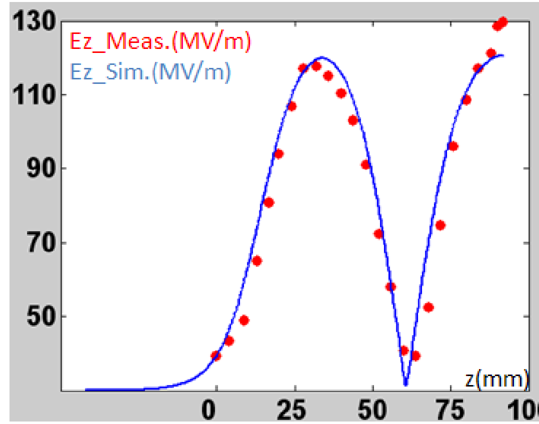

Figure 7: Electric field on-axis, measured (red dots) and simulated (blue line).

CONCLUSIONS

The design of the RF gun for the SPARX project has many intersecting elements: RF field optimization and symmetrization, beam dynamics, RF heating (pulsed and average), and thermo-mechanical distortions, and RF performance in the presence of distortions.

We have also shown that the DMF^3 approach can provide wide flexibility in cooling channel design and fabrication. With such innovations as star-shaped cross-sections, and arbitrary channel paths, one can design the cooling system even more aggressively.

The experimental results show very good agreement with the simulations, making us more confident in handling a new geometries. We refer here to the "race-track" and "Z-coupling" configurations that characterize the coupler cell.

Further measurements are being performed. In particular, the quantification of the dipole and quadrupole field components.

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