DEVELOPMENT OF AN ULTRA-HIGH REPETITION RATE S-BAND RF GUN FOR THE SPARX PROJECT

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Abstract

We present here the design, including RF modeling, cooling, and thermal stress and frequency detuning, of a single feed S-Band RF Gun capable of running near 500 Hz for application to FEL and inverse Compton scattering sources. The RF design philosophy incorporates many elements in common with the LCLS gun, but the approach to managing cooling and mechanical stress diverges significantly. We examine the new proprietary approach of RadiaBeam Technologies for fabricating copper structures with intricate internal cooling geometries. We find that this approach may enable very high repetition rate, well in excess of the nominal project this design is directed for, the SPARX FEL.

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 can be found in [6].

Electromagnetic field higher multipole components inside the Gun have been shown [4] to contribute to beam emittance growth, resulting in beam brightness decrease and concomitant degradation of FEL performance. The dipole field component, although asymmetry due to single feed, is completely eliminated by using two identical coupling holes and two waveguides one of which acting as a dummy load. Furthermore, a "racetrack" geometry is exploited in order to strongly decrease the quadrupole mode.

Moreover, the RF model of the Gun is employed in the code PARMELA to allow preliminary beam dynamics simulations.

Finally, 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]. We have studied several geometries for cooling channels, both standard cylindrical cooling channels and a novel channel shape that is only allowed using advanced conformal fabrication techniques, typified by using Direct Metal Forming (DMF3)[8].

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.

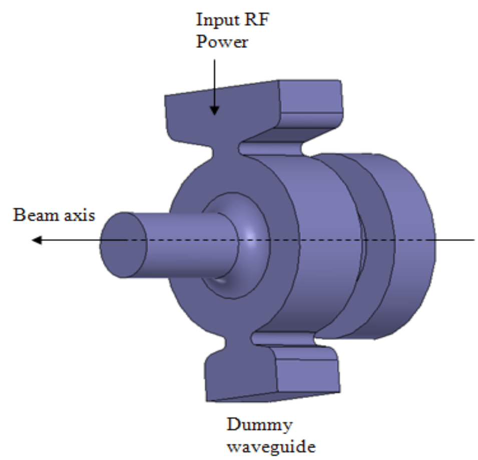

Figure 1: 3-D surface model of the Gun, from HFSS.

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	13500
Qext	11490
R_s/Q_0	3630
Epeak	120MV/m@P_{RF}10MW

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

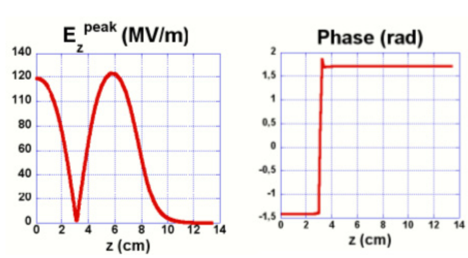

Figure 2: amplitude and phase profiles of the electric field along the longitudinal axis of the Gun.

RF Pulsed Heating

It is critical to minimize the RF heating of the metal surfaces in the gun in order to allow 100 Hz or higher operation. The limiting sector of the structure is apparently found at the edges of the power-coupling ports. In order to keep the temperature rise below 60°, rounded coupling iris shapes have been used. Moreover, the use of a *Z*-coupling geometry simplifies fabrication and reduces pulsed heating since edges are only along one dimension. The rounding radius of the *Z*-coupling iris is 3mm. In order to quantify the temperature rise, a useful formula [3, 7] is employed:

$$\Delta T = \frac{|H_{\parallel}|^2 \sqrt{\tau_{RF}}}{\sigma\delta\sqrt{\pi\rho' c_\varepsilon k}}$$

where τ is the pulse length, σ is the electrical conductivity, δ is the skin depth, ρ' is the density, $C\varepsilon$ is the specific heat and is the thermal conductivity of the metal.

In present case, the peak value of $H_{||}$ (nearly 3.9x10^5 A/m for an input RF power of 10 MW) obtained from simulations is located at the couplers region. This field value causes a temperature gradient of about 56° C, a little below the threshold of 60° C, which is considered a sensible upper limit. Problems may arise if the power is significantly higher than 10 MW.

Dipole and Quadrupole Components

The most sensitive field component to the asymmetry of the Gun is the azimuthal magnetic one, $H\phi$. Therefore a thorough study, using a Fourier analysis, has been performed in order to quantify the deviation of both dipole and quadrupole components from the monopole behaviour.

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

The quadrupole component is cancelled out by using a race-track geometry with offset D. Results are shown in Fig.4 and it is evident how it is possible using a value D=3.8 mm in order to diminish $H\phi$.

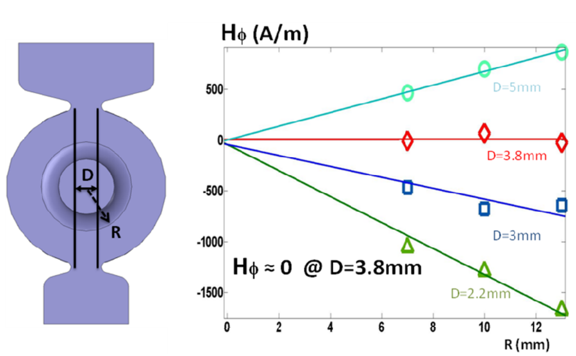

Figure 3: Cross-section of the full cell: D is the offset quantity by which the two cell arcs are drifted apart.

Preliminary Dynamics Simulations

A preliminary check of beam dynamics, using the code PARMELA, has confirmed the beam energy gain at the exit of the RF Gun equal to 5.5 MeV.

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. In the geometry presented here the input waveguide is connected to the coupling window with an angle bigger than 90° allowing to insert cooling channels in the very proximity, as far as machining issues are concerned. Moreover, it is possible to increase this angle for a better cooling system design. A close-up of the coupling window is shown in Fig.4.

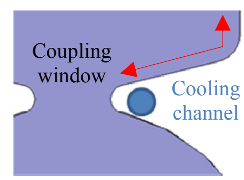

Figure 4: close-up of the coupling window.

Figure 5 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.

Two different thermal boundary conditions are applied: free (natural) convection on the copper cavities outer walls, with a room temperature of 20°C; and forced convection on the channels inner walls, considering an input water temperature of 20°C flowing with a velocity of 4 m/sec. 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.6). It has been verified that the temperature distribution shows a linear behavior with the repetition rate.

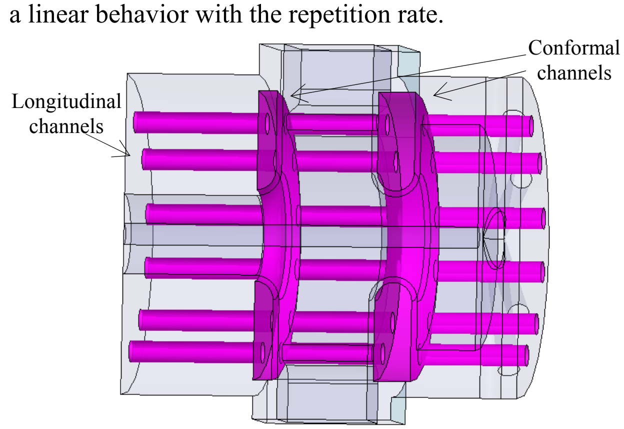

Figure 5: cooling system.

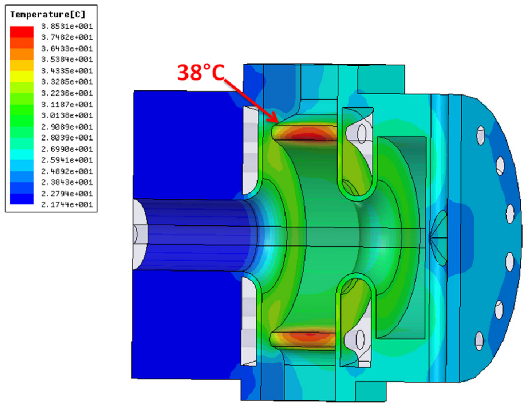

Figure 6: temperature distribution.

The use of DMF[3] techniques makes possible the machining of a cooling system with a better performance in terms of temperature distribution.

Six conformal channels and four snake-like around the coupling iris regions with star-shaped cross-sections provide cooling, as shown in Figure 7. Such 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.

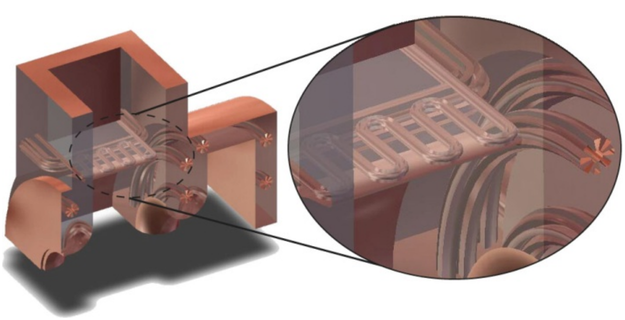

Figure 7: Quarter section of the RF Gun with star-shaped, conformal cooling channels. Detailed image shows the snake-like channels at the coupling window.

Comparing the case of a fairly standard geometry, with circular cross-sectional dia. of 6 mm, to that of the shaped, conformal and "snake" geometry available only through DMF[3], we see that star-shaped cross section and snake geometry allows cavity wall temperatures to be kept significantly lower than the case with cylindrical channels, by 25 °C. Assuming the same overall temperature increase, this yields the immediate possibility of pushing the rep rate up to 170 Hz.

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, as shown in Fig.7. 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 8ºC, which is only ~60% of the maximum allotted LCLS gun temperature change from the no-RF to full power operation condition. Thus, using the LCLS design philosophy as a guideline, one may also consider augmenting the average power by approximately 1.62. This implies that the repetition rate envelope that we may infer rises to ~500 Hz.

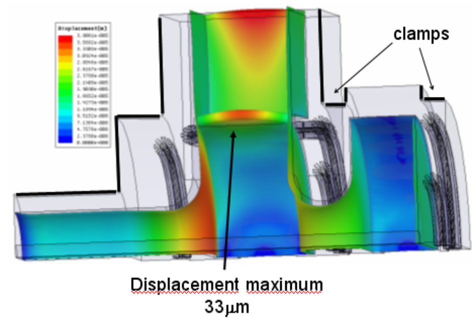

Figure 8: Quarter section of the RF Gun with wall displacement distribution.

CONCLUSIONS

The choice of designing a single feed RF gun for the SPARX project leads to deal with many intersecting elements: RF field optimization and symmetrization, beam dynamics, RF heating (pulsed and average), and thermo-mechanical distortion, and RF performance in the presence of distortions. At the same time, this geometry allows to avoid mismatching between the two ports and a simple RF power system. The study we have presented here addresses all of these design constraints together, with extremely promising results.

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.

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