AN ULTRA-HIGH REPETITION RATE S-BAND RF GUN

L. Faillace, L. Palumbo, Università La Sapienza/INFN-LNF, Rome, Italy
B. Spataro, INFN-LNF, Rome, Italy
A. Fukasawa, B.D. O'Shea, J.B. Rosenzweig, UCLA, Los Angeles (CA), USA
P. Frigola, RadiaBeam Technologies, Los Angeles (CA), USA

Abstract

We present here a preliminary design, including RF modelling, cooling, and thermal stress and frequency detuning, of an 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 LNF-INFN 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 a 100 Hz repetition rate, working 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 modelling 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 is completely eliminated by using a dual feed system of external coupling to the waveguide, while a "race track" geometry is exploited in order to strongly decrease the quadrupole mode.

Since couplers represent critical area for both RF pulsed heating[4] and related thermal stress and breakdown problems, a thorough study of the iris shape choice on the electric field has been carried out in order to mitigate these problems. Additionally, the cell-to-cell iris shape, thickness and radius have been chosen to achieve a low value of the surface electric field, avoiding possible breakdowns, and a high enough value of frequency difference between the two gun coupled resonant (0 and π) modes.

A transient analysis of the RF gun response has also been performed. Similarly 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 of the cavity are carried out by using the code ePhysics [5]. We have studied several geometries, for cooling channels, including a novel channel shape that is allowed only using advanced conformal fabrication techniques, typified by using Direct Metal Free Forming (DMF^3)[8].

RF GUN DESIGN

The RF Gun cavity consists of one full cell (half-wavelength) and an upstream cathode cell of relative length 0.6 compared to the full cell. The 3-D model of the structure is shown in Fig.1. The dual feed power system allows to erase the dipole field component and the "race track" geometry is exploited in order to strongly decrease the quadrupole mode. The coupling geometry chosen has been based on "Z-coupling" design with a rounded coupling window, with a thickness of 3mm, in order to reduce the temperature rise at the power-coupling ports due to the RF pulsed heating.

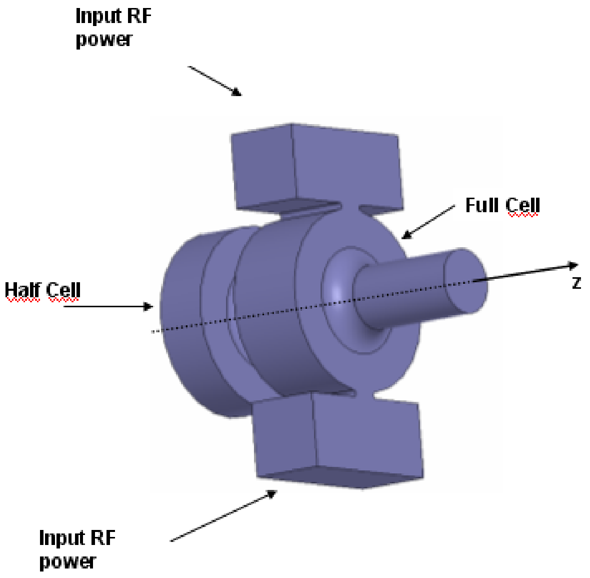
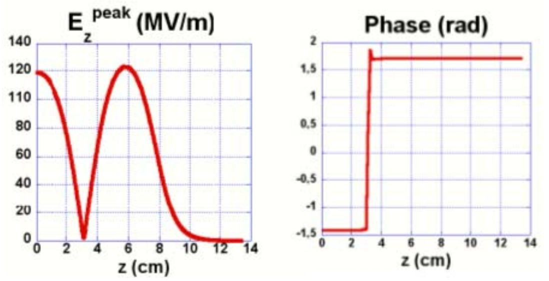


Figure 1: 3-D surface model of the Gun, from HFSS.

In Fig.2 are given the plots of the amplitude and phase of the axial electric field of the π-mode resonant at 2.856 GHz with a Q_0 of about 13500. The frequency separation between the 0 and π-modes is approximately 15 MHz, brought up to 24 MHz using elliptical irises. The value of the coupling coefficient β=1.17 is chosen from beam loading considerations [6] and power source parameters (Table 2).



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

The main electromagnetic parameters of the RF Gun are listed in Table 1.

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**
Q_{ext}	**11490**
R_s/Q_0	**3630 Ω/m**
E_{peak}	**120MV/m@P_{RF}10MW**

Table 2: High power RF system parameters; related beam-loading currents

τ_{RF} (pulse length)	**3 µs**
f_{RF} (repetition rate)	**100 Hz**
T_{RF} (pulse period)	**10 ms**
DC_{RF} (τ_{RF}/T_{RF}) (RF duty factor)	**$3*10^{-4}$**
P_g (Peak power)	**10 MW**
f_b(beam frequency)	**286 MHz**
Q_b (beam charge)	**1 nC**
I_b (beam current)	**286 mA**

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 1.5mm. In order to quantify the temperature rise, a useful formula [3,7] is employed:

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

where τ_{RF} is the pulse length, σ is the electrical conductivity, δ is the skin depth, ρ' is the density, c_ε is the specific heat and k is the thermal conductivity of the metal.

In present case, the peak value of $H_{\|}$ (nearly $3.9\mathrm{x}10^5$ 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.

Quadrupole component

The most sensitive field component to the asymmetry of the Gun is the azimuthal magnetic one, H_ϕ. Therefore a thorough study, using a Fourier analysis, has been performed in order to quantify the deviation of this component the monopole behavior 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=2mm in order to diminish H_ϕ.

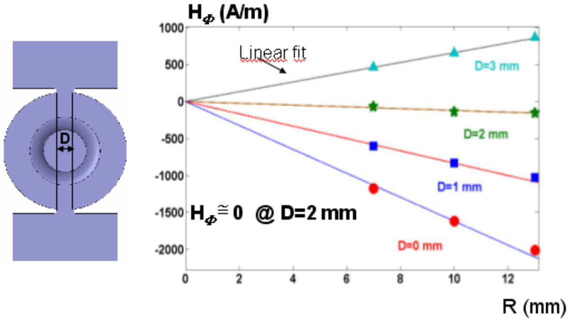


Figure 3: Cross-section of the full cell: D is the offset quantity by which the two cell arcs are drifted apart.

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 analysis of the RF Gun has been carried out by using ePhysics coupled with HFSS. Six conformal channels and four snake-like around the coupling iris regions with star-shaped cross-sections provide cooling, as shown in Figure 4. 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. These are features that are possible only with DMF^3 techniques. Two different thermal boundary conditions are applied: free (natural) convection on the copper cavities' outer walls, with a room temperature of 24 °C; and forced convection on the channels' inner walls, considering an input water temperature of 24 °C flowing with a velocity of 4 m/sec. The average power inside the gun is 3 kW, considering the power source parameters (Table 2) and a 100 Hz repetition rate.

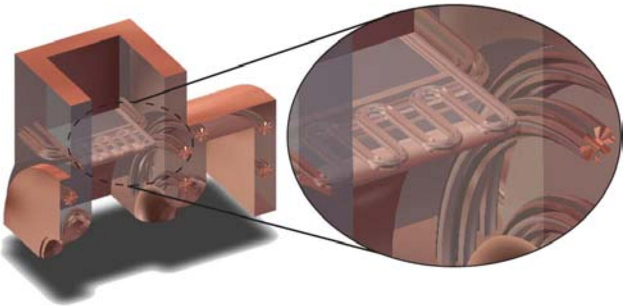


Figure 4: Quarter section of the RF Gun with star-shaped, conformal cooling channels. Detailed image shows the snake-like channels at the coupling window.

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.5. 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 8º C, 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.

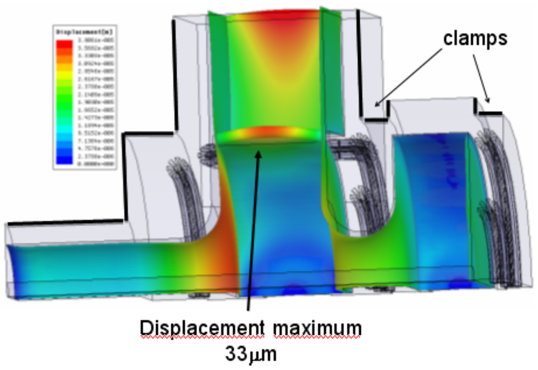


Figure 5: Quarter section of the RF Gun with wall displacemen distribution.

CONCLUSIONS

The design of the RF gun for SPARX has 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. This study we have reported here presents a first pass at addressing all of these design constraints together, with extremely promising results. In the future one may further refine the overall RF design by choosing an even larger radius of curvature for the waveguide coupling iris port structure, to mitigate RF heating.

We can see 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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