RF DESIGN OF A HIGH-REPETITION-RATE S-BAND PHOTOGUN*

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Abstract

In this paper, we present the RF design of a high-repetition-rate S-band photogun, emphasizing the innovative use of brazing-free technology to enhance performance and reliability. The primary objective is to optimize the structural parameters to achieve a repetition-rate of 100 Hz while simultaneously reaching a cathode field of 100 MV/m. Through simulations, we demonstrate that our optimized photogun design meets the required performance metrics, paving the way for advancements in photonic applications and high-frequency electron sources.

INTRODUCTION

High-brightness electron beams play an indispensable and central role in frontier scientific facilities such as free-electron lasers, inverse Compton scattering sources, ultrafast electron diffraction, and next-generation high-energy colliders [1–4]. Theoretical studies have shown that beam brightness is closely related to the electric field strength at the cathode surface and the repetition rate [5–7].

To increase the cathode electric field, a novel fabrication technique based on clamping technology using specially designed metal gaskets to simultaneously achieve vacuum sealing and RF contact is proposed by INFN. This approach achieve a cathode field of 120 MV/m at high repetition rate of 100 Hz and a pulse length of 1.5 μs [8]. Based on these advances, this work presents the RF design of a brazing-free S-band photogun, aiming to achieve a cathode field of 100 MV/m while operating at a repetition frequency of 100 Hz.

RF DESIGN

The photogun is a 1.5-cell standing-wave structure operating at π-mode at the frequency of 2856 MHz. Empirical formulas based on CLIC experimental data indicate that the breakdown probability scales with the 30th power of the accelerating gradient and the 5th power of the pulse length. [9]This relationship reveals that breakdown probability is extremely sensitive to the electric field. The filling time of the photogun is defined by:

$$t_f = \frac{2Q_L}{\omega} = \frac{2Q_0}{\omega(1+\beta)} \tag{1}$$

and the transient response of the cathode electric field is expressed by:

$$E_{cathode} = \frac{2\sqrt{\beta}}{1+\beta}\sqrt{\frac{P_{in}R_s}{d}}\left(1 - e^{-\frac{\omega(1+\beta)}{2Q_0}t}\right) \tag{2}$$

1.5 Cell Design

In this subsection, a 1.5 cell operating in π-mode is designed for an S-band (2856 MHz)standing-wave photogun. The geometry is shown in Fig.1(a). The iris aperture is set to 30 mm (r_{iris}=15mm) to improve mode separation and vacuum pumping speed in the cathode region [8, 10]. The disk thickness and the eliptical ratio of the chamfer is utilized to reduce the peak field at the iris. The elliptical ratio is set to 2:1 ($b/a = 2$) while the disk thickness is set to be 26.25 mm

In the simulations of the optimized cell geometry, an unloaded quality factor Q_0 of 15415 for the single cell is obtained. Considering the input pulse length of 4.5 μs from the Klystron, the output pulse length of the pulse compressor is chosen to be 800 ns for the best power efficiency. To achieve the filling efficiency exceeding 90%, a filling time t_f of 320 ns is determined by a coupling coefficient β of 4.3, and the unloaded quality factor Q_0 of 15415.

Power Divider

The power divider is designed to equally split the input power in both amplitude and phase.The geometry of the power divider is shown in Fig.1(b).The S-parameters are shown in Fig.1

Coupler Design

The coupler adopts a symmetric dual-port feeding configuration, in which two ports are used for RF power input and symmetric compensation for TE11 mode,as shown in Fig.2 following the design approach of *Huang et al.* [11] Other two ports are connected to the vacuum system for pumping, enabling high vacuum in the cathode region. The radius of the circular waveguide is designed to be 44 mm for suppressing the TE21 mode while maintaining broad bandwidth. The full structure is designed for the convenience of the clamping technology.The symmetric design effectively cancels the dipole field components induced by single-side feeding, thereby improving the uniformity of the field distribution inside the cavity and the beam quality. After optimization, the surface electric and magnetic field distributions of the coupler geometry satisfy the requirements for high-gradient operation. The S-parameters are shown in Fig.2

To satisfy the requirements of broad bandwidth, low reflection, and suppression of higher-order modes, the coupler adopts a relatively complex dual-feed geometry. In contrast to the fully brazing-free fabrication approach reported in

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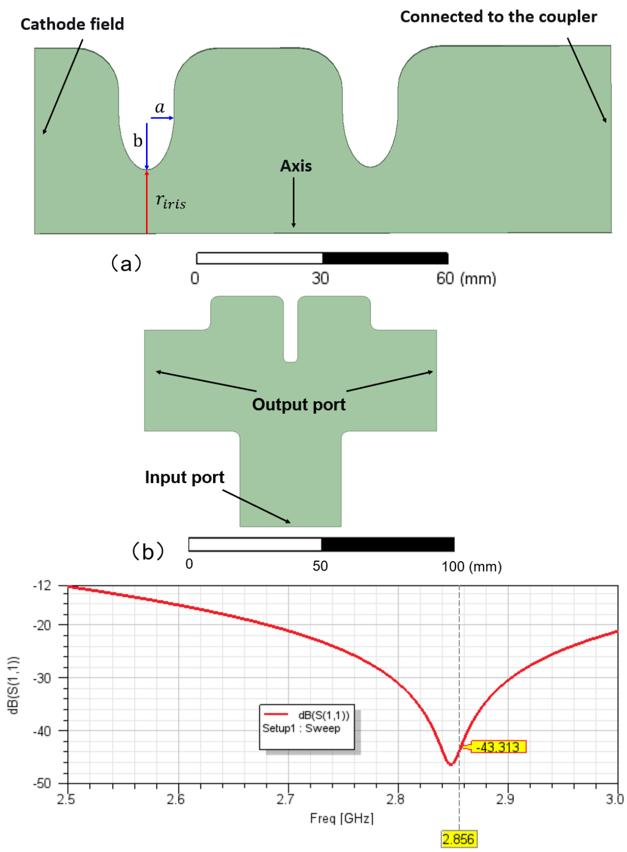

Figure 1: 1.5 cell design (a), power divider (b) and S-parameters of power divider.

Ref. [8], the application of the clamping technology to the coupler would require customized rectangular RF gaskets with tight machining tolerances, resulting in increased manufacturing complexity. Therefore, the photogun is fabricated in two separate parts. The 1.5-cell cavity is manufactured using the brazing-free clamping technology, while the coupler section is fabricated by conventional brazing. The two parts are subsequently assembled using the clamping technique with copper and stainless-steel gaskets, thereby combining the advantages of both fabrication methods.

Full Structure Design

The complete structure consists of a 1.5-cell accelerating structure combined with the coupler and the power divider is shown in Fig.3. Through optimizations the final structural parameters are summarized in Table 1. The steady-state pulsed heating is evaluated using the empirical formula [12, 13]:

$$\Delta T = 127\,|H_s|^2\sqrt{f t_p} \tag{3}$$

where H_s is the peak surface magnetic field and t_p is the RF pulse length. Based on the optimized geometry, the calculated pulsed heating is below the acceptable limit for high-repetition-rate operation. Compared with the temperature rise in Ref. [8] (less than 55°C).

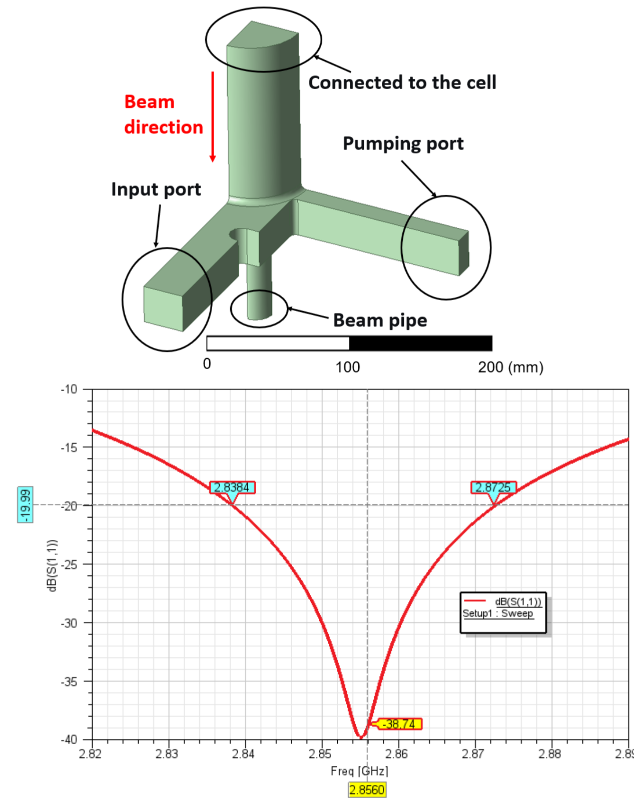

Figure 2: The coupler design and S-parameters.

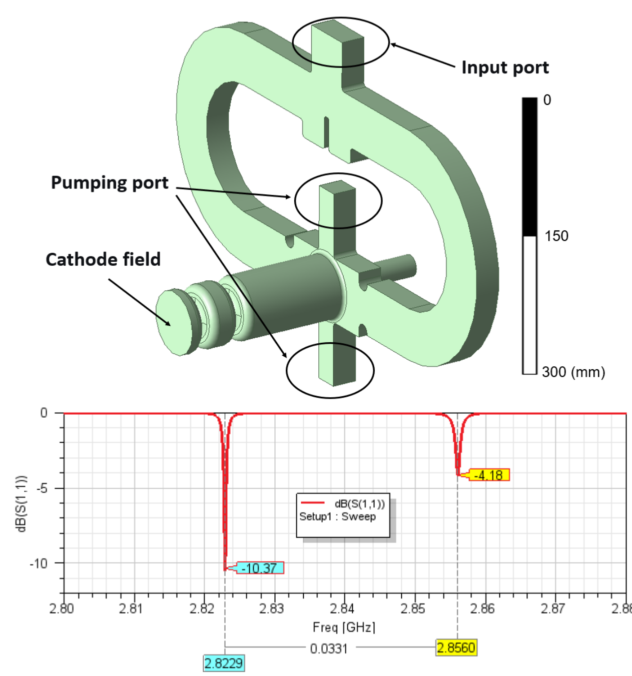

Figure 3: Full structure design and frequency sweep results.

CONCLUSION

A brazing-free S-band photogun has been numerically optimized for high-repetition-rate and high-gradient applications. Over-coupled design shortens the cavity filling time, meeting the requirements of 100 Hz repetition rate operation. Simulation results demonstrate that the design achieves

Table 1: 1.5cell gun parameters

E_{cath}	100 MV/m
Frequency	2.856 GHz
P_{diss}@ 100MV/m	4.2 MW
Peak Input power P_{in}	10.85 MW
Steady-state pulsed heating ΔT	$14°C$
Rep. Rate	100 Hz
Q_0	15415
Mode Separation	30 MHz
Coupling β	4.3
Filling time t_f	324 ns

a quality factor of 15415 at a cathode field of 100 MV/m, with high energy storage efficiency and manageable thermal load.

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