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ULTRA-HIGH GRADIENT SHORT RF PULSE GUN*

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Abstract

High brightness beams enable novel applications like x-ray free electron lasers and ultrafast electron microscopes. High brightness beams essentially consist of a large number of electrons in a small phase space volume, i.e. a high peak current. When such beams are generated from the cathode, there is a strong space charge force, which elongates the bunch and reduces its brightness. An optimal solution is to raise the accelerating voltage in the gun. However, the maximum gradient is limited by the effects of RF breakdown. The probability of RF breakdown is reduced as the RF pulse length decreases. We present a development of an electron photoinjector operating with short RF pulse, 10 ns scale. We have designed an X-band gun including the RF design, beam quality optimization, and engineering. The gun will be fed by 10 ns, 300 MW RF pulse generated at the Argonne Wakefield Accelerator Facility for two-beam acceleration experiments. We also manufactured an aluminum prototype and measured its microwave properties, most importantly, fill time. The proposed high brightness beam source can be used as the main beam in wakefield accelerators. It will find commercial applications in ultrafast electron diffraction and microscopy systems.

INTRODUCTION

High brightness electron sources are essential for future colliders. In a quest for high brightness, researchers turn to high gradient electron guns. When the beam is generated at the cathode, it has to be accelerated to higher energy before the space-charge effects elongate the bunch. The higher the gradient, the less time the space charge has to spoil the beam. Simply put, high gradient is imperative for high brightness. Unfortunately, operation at high gradient is limited by the onset of RF breakdown. One of possible solution of this problem is use a cryogenic resonator which is able to operate at higher RF fields in comparison with room temperature system [1]. However, the probability of breakdown decreases with reduction of the RF pulse length. To mitigate the breakdown problem and enable large charges to be generated in a high gradient field at the cathode, Euclid Techlabs proposes to demonstrate an ultra-high gradient electron gun fed by a nanosecond RF pulse. In recent experiment at Argonne Wakefield Accelerator facility a high peak power, short RF pulse (300 MW, 10 ns at 11.7 GHz) was demonstrated. This pulse is used to accelerate another electron beam (staging for two-beam wakefield acceleration). We propose to use this same RF pulse to establish an ultra-high gradient on the cathode surface in the short-pulse electron gun. Another possibility is using of relativistic amplifiers like relativistic klystron or so-called superradiant RF sources [2-4].

RF DESIGN

Short pulse operation is achieved by reducing the loaded Q-factor of the accelerating cavity. For f =11.7 GHz, τ = *10 ns*, the quality factor will have to be $Q \le \pi \times f \times \tau \approx 370$. The choice of frequency, in our case is determined by the availability of 11.7 GHz Argonne Wakefield Accelerator power extractor as a source of high peak power, short RF pulse [5]. The 1.5 cell RF gun design includes a coaxial coupler to keep axial field symmetry, is shown in Fig. 1. The field structure of the operating π-mode is represented in the Fig. 2. In order to avoid overlapping at low-Q 0-mode and π-mode, we decided to introduce four symmetrically placed azimuthal coupling holes in the iris. This allowed to obtain spacing between the gun modes at 250 MHz (Fig. 3).

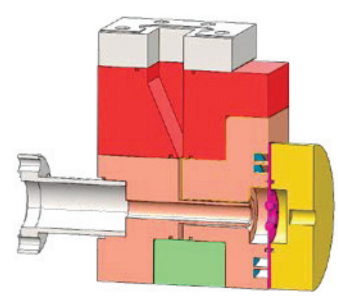

Figure 1: 11.7 GHz RF gun engineering design.

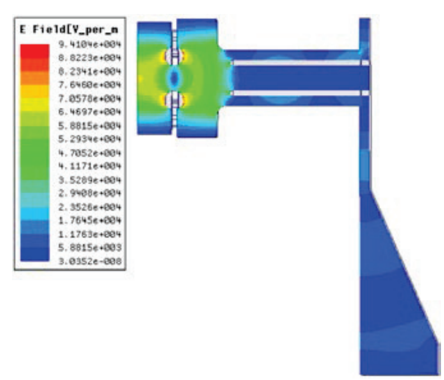

Figure 2: E-field at the operating frequency.

Simulations of gun cavity power fill process is shown in Fig. 4. With short pulse filling the cavity, the maximum field is achieved at the end of RF pulse.

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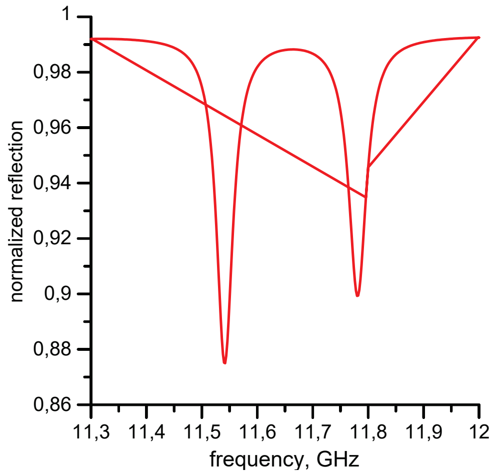

Figure 3: S_{11} characteristics of gun's resonator.

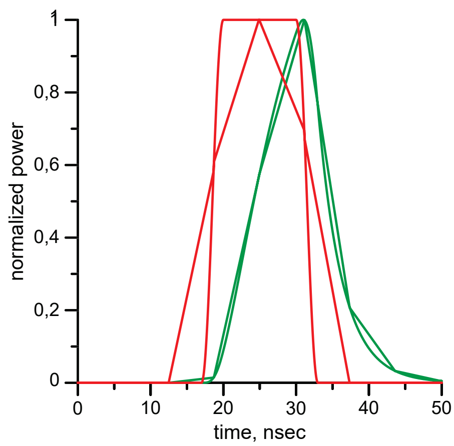

Figure 4: Simulation of energy storage in the resonator.

BEAM DYNAMICS

An optimization of the emittance was performed with an assumption that the cathode field reaches 400 MV/m. The length of the first cell was chosen to be 6 mm, the second cell has a 12.1 mm length. The Figure 5 shows accelerating field and corresponding external focussing solenoid field. The normalized B_z field distribution is shown with black curve in this figure. Key simulation parameters used in optimization are summarized in the Table 1. We used GPT and ASTRA to simulate beam dynamics. According to GPT calculations the 400 MV/m field allowed to accelerate particles up to 4 MeV (Figure 6). An ultra-low emittance, less than 0.5 mm×mrad and low energy spread (less than 10 keV) are achieved in such high-gradient X-band gun. The GPT results were successfully reproduced with ASTRA code.

Table 1: List of Parameters for the X-Band Gun

Parameter	Value
Frequency	11.7 GHz
Mode quality factor	350
Mode separation	250 MHz
RF pulse length	10 ns
RF peak power	70 MW
Maximum field at cathode	400 MV/m
Energy of electrons	4 MeV
Bunch charge	100 pC
RMS bunch radius at exit	2.2 mm
RMS bunch length at exit	0.14 mm
Normalized emittance	0.25 mm×mrad
ΔE/E	2.5×10^{-3}

Further optimization of injection phase, solenoid magnetic field, bunch length, and laser spot size. Optimization process results are shown in Figures 7-8. One can see that for 0.1 nC bunch charge the emittance is less than 0.3 mm×mrad, energy spread is as low as $2\cdot10^{-3}$. These results exceed the performance of SLAC and LNBL X-band guns [6-9].

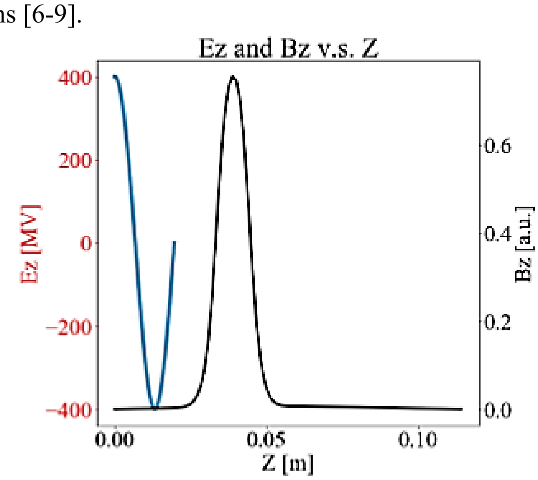

Figure 5: Longitudinal E-field distribution and Bz field distribution.

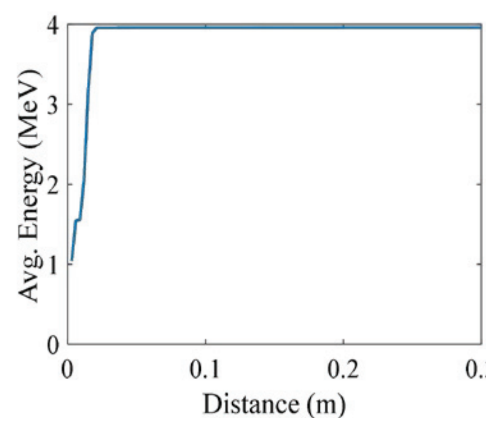

Figure 6: Energy of particles accelerated in gun resonator.

Figure 7 represents that emittance as well as the energy spread (Figure 8) dramatically depend on laser spot size (bunch radius). The optimal value was selected at 0.1 mm. Such a small laser spot on the cathode may require side input of the laser beam into the resonator. Solenoid field

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for these simulations was optimized in magnitude, position, and length. The optimal field strength was set at 0.25 T. The optimum for laser pulse length was found at 100 fs.

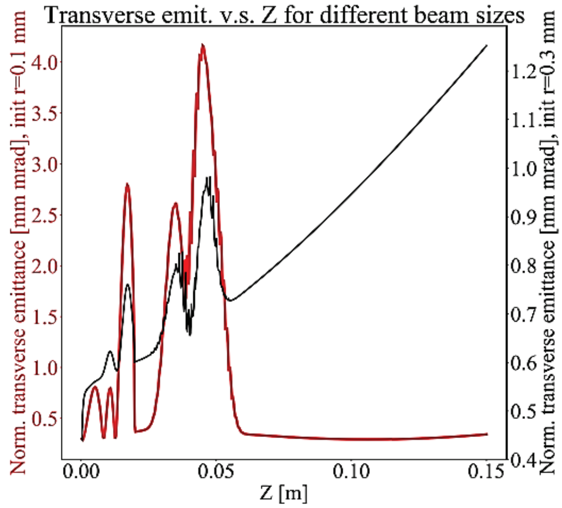

Figure 7: Bunch emittance for bunch radius 0.3 mm (black) and 0.1 mm (red).

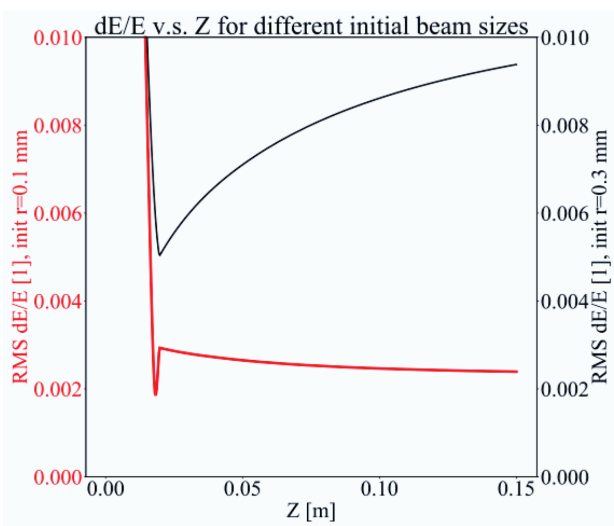

Figure 8: Energy spread for bunch radius 0.3 mm (black) and 0.1 mm (red).

COLD TEST

We produced an aluminium prototype to demonstrate, that the large loaded Q-factor and acceptable mode separation can be achieved in a practical resonator. The prototype was made of aluminium parts with a coupling iris made of copper. We used network analyzer to measure the RF properties of the gun. Measurement results are shown in Fig. 9. Mode separation of 200 MHz had been achieved.

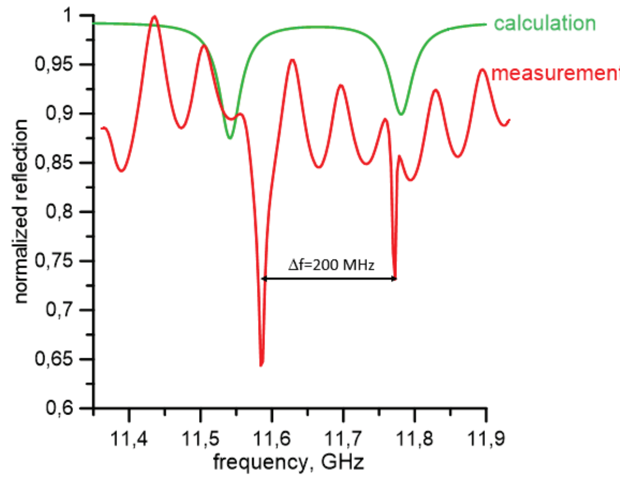

Figure 9: Measured (red) and calculated S_{11} parameters.

CONCLUSION

We produced an initial engineering design of the high-gradient, short pulse gun. This 11.7 GHz gun is designed to run at extreme 400 MV/m gradient but short, 10ns pulse. The gun can generate a beam with less than 0.3 um normalized emittance and $2\cdot10^{-3}$ relative energy spread at 0.1 nC total charge. It will require a laser with 100 um cathode spot radius and 100 fs rms pulse length. Gun structure shows a promising path to get an ultra-low emittance ~0.1 um beam.

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