# DESIGN OF A FIELD-EMISSION X-BAND GUN DRIVEN BY SOLID-STATE RF SOURCE *

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*Abstract*

We present the design of a field-emission X-band gun designed to be powered using a solid-state RF source. The source of the electron beam is a field emission nano-tip array. The RF gun is intended to be a beam source for 1 MeV solid-state driven linac for deployment on a satellite to map magnetic fields in the magnetosphere. The gun has to satisfy strict requirements on both average and peak power consumption, as well as rapid turn on time. In order to achieve low power consumption, the RF gun operates at relatively low accelerating gradient of 2 MeV/m. The beam exit energy is ~20 keV for an RF power 1.5 kW. Each cell of the RF gun is separately powered by commercially available, GaN high electron mobility transistors. In proof of principle experiments we successfully powered a 9.3 GHz accelerating cavity with a 100 W transistor and a 1% duty cycle.

## INTRODUCTION

One of the recommendations from the most recent NASA Decadal Survey [1] is the need for technology development to trace the field lines between the magnetosphere and ionosphere. Specifically, the report suggests a high-energy electron beams injected along the magnetic field from a spacecraft in low earth orbit could be used to detect the ionospheric footprint [2]. Relativistic electron beams can be detected via several diagnostic means: an ionization channel visible to ground-based radars; optical emissions generated by ionization, dissociation, and discharge processes; Bremsstrahlung X-rays radiated by electron deceleration; and particles energized through discharge processes could be measured by particle detectors.

Active, space-based particle injection experiments have enabled scientific investigations of space plasmas since at least the 1950s [3]. However, these controlled experiments were mainly based on relatively low energy electron beams (<40 keV). Higher energy experiments have not been undertaken, due in major part to technological constraints. Existing ground based accelerator designs are ill-suited to applications in space, where size, weight and power limitations place severe constraints on the device design. In addition, there are also requirements to withstand high mechanical stress from launch and issues with heat dissipation in a space environment. However, it is now conceivable to design compact linear accelerators that can generate relativistic electron beams (500 keV to ~2 MeV) efficiently (~30% DC power-to-beam efficiency) and with small devices because of advances in high-efficiency accelerating structures along with the development of efficient solid state RF sources [4].

Here, we present the preliminary design of a field-emission X-band gun to be powered using a solid-state RF source. The source of the electron beam is a field emission nano-tip array. The electron beam produced by this design should be compatible with the parameters shown in Table 1, which were calculated assuming that the orbit average power available from the spacecraft is 250 W.

Table 1: Electron-beam Parameters for Linac

| Parameter Range | Value |
|---|---|
| Exit Energy (E) | < 0.5 to 2 MeV |
| Injection Energy (E) | 20 keV |
| Beam Energy spread (ΔE/E) | ≤ ±2% |
| Peak Current ($I_{peak}$) | up to 20 mA |
| Pulse Length | 1 to 50 $\mu$s |
| Duty Cycle | ≤ 1% |
| Peak Beam Power ($P_{peak}$) | up to 10 kW |
| Average Beam Power (2.5 kHz, 4 $\mu$s pulses) | up to 100 W |

Designs for the class of accelerators that would be used to achieve these beam parameters typically use a thermionic emitter with an initial electrostatic acceleration to 10s kV followed by a series of tapered length accelerator cavities (injector section) powered by a magnetron RF source to bring the electron velocity up to near the speed of light for efficient acceleration in the main linac. Thermionic emitters with electrostatic acceleration are efficient and well-proven designs but require high voltage and associated high-voltage standoff ceramics. Additionally, with the limited length of the gun and RF power available, the electron beam capture (fraction emitted that exits the linac) will be low. This wasted electron beam current requires excess electrical power to generate and produces an additional heat load – two significant challenges particularly for spacecraft.

To overcome these limitations, we are proposing the use of a field emitter RF gun design which uses RF fields at the emitter to induce emission and provide the initial acceleration of the beam. Use of this gun type would allow elimination of all high voltage requirements, associated ce-

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ISBN 978-3-95450-182-3

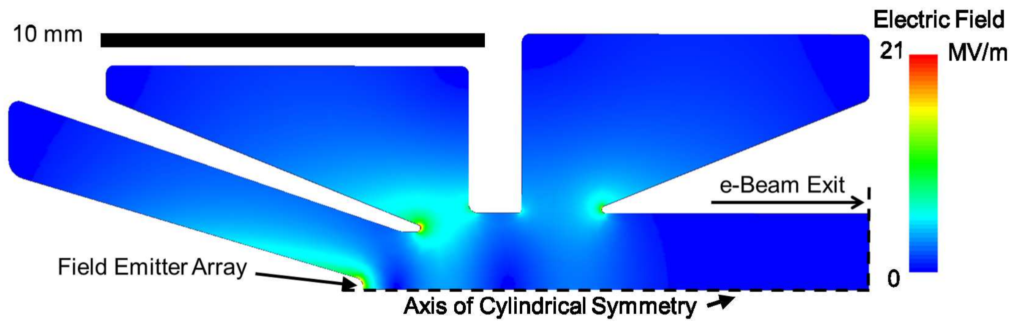


Figure 1: Electric field distribution in the RF gun.

ramic insulators and constant power draw of the heater for a thermionic cathode. The electron beam is only emitted during the correct phasing of the RF field enabling >90% electron beam capture.

## LOW-POWER LOW-BETA GUN DESIGN

We have done a preliminary study for a RF gun that would be appropriate for a 1 MeV, 10 mA accelerator. The RF electron gun geometry and electric field distribution are shown in Fig. 1. The RF electron gun consists of the three RF cavities operating in the standing-wave $\pi$-mode with an exit energy of 20 keV. To decrease peak power, increase efficiency and enable the use of solid-state RF sources, we aim to keep the accelerating gradient low at ~2 MeV/m. With a low gradient and a high frequency of operation the spacing between the cells of the injector will need to be $< \lambda/2$, where $\lambda$ is 3.2 cm at 9.3 GHz. A protruding nose cone is used to enhance the surface electric fields at the point of emission while maintaining a low gradient. The accelerating gap of each cavity is closely spaced to maximize capture. This necessitates the use of geometrically 'distorted' cavities for maximizing filling factor. As an added benefit, an electron gun with low $\beta = v/c$ can maintain an overall transverse focusing thereby increasing electron beam capture and potentially eliminating the need for a solenoidal magnet straddling the electron gun.

In Fig. 2 we show the on-axis real and imaginary component of the electric field for our modeled electron gun. The field distribution of the RF gun is highly asymmetrical, due to the competing aims of limiting the peak power requirement by lowering the accelerating gradient and achieving high field strength at the emitter. The peak surface field at the emitter location, without including the enhancement from the field emitters themselves, needs to be >20 MV/m to achieve a sufficient current. The field amplitude and spacing was optimized to provide acceleration for an electron with an exit energy of 20 keV and an average accelerating gradient of ~2 MeV/m.

The energy and sampled electric field for a single particle at the highest exit energy of the gun is shown in Fig. 3. The particle sees only accelerating fields as it propagates through the cells indicating that the spacing is appropriate for a low energy particle. We note that the particle traverses

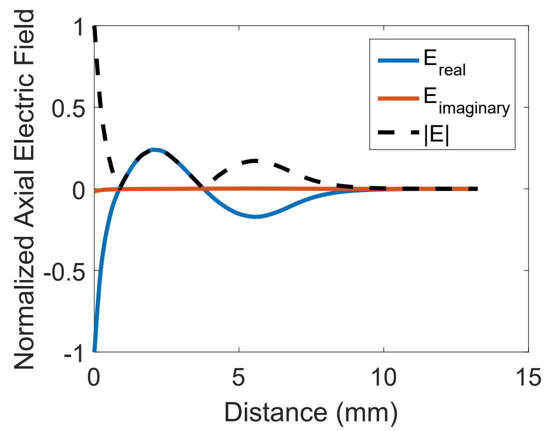


Figure 2: On-axis electric field for RF electron gun. The field is strongly peaked on the cathode and drops rapidly as the cell length increases.

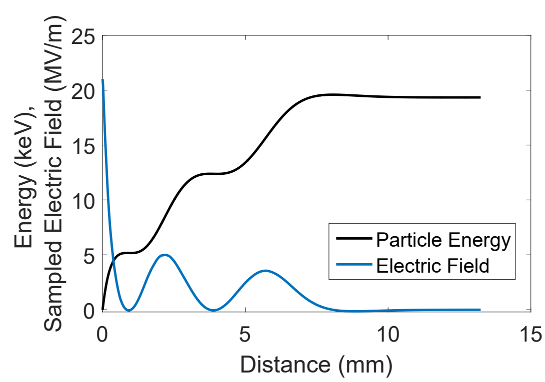


Figure 3: Single particle simulation of for optimal energy gain, with both the particle energy and the sampled electric field show vs. distance. The RF gun requires 1.5 kW of RF power to achieve this field strength.

three accelerating gaps in less than $< \lambda/3$. The particle exit energy for all launch phases is shown in Fig. 4. The launch phase is referenced to the peak energy gain for the single particle shown in Fig. 3 at a phase of $0^o$. The peak exit energy is nearly 20 keV and this is achieved with only 1.5 kW of RF power or operating at a 1% duty cycle envision in the

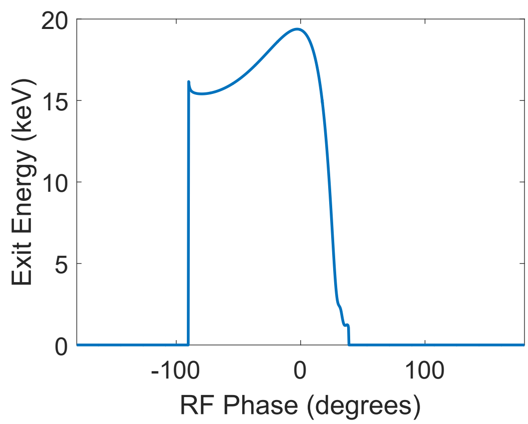


Figure 4: The exit energy as a function of the launch phase for the RF gun. The phase is reference with respect to the peak energy gain for the single particle shown in Fig. 3.

experiment corresponds to 15 W, or a small fraction of the anticipated power requirements of the linac, Table 1.

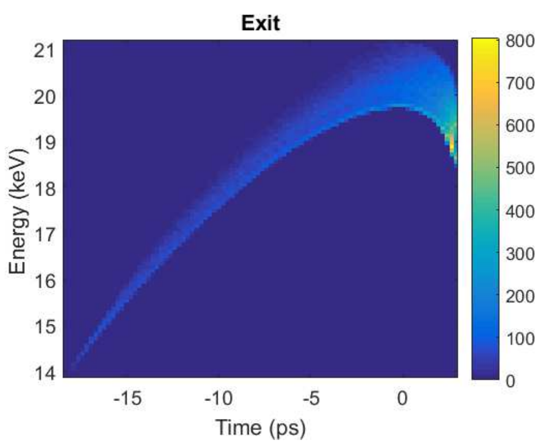


Figure 5: The longitudinal phase space of the electron bunch at gun exit in time vs electron energy.

To simulate the full electron beam emitted from a field emitter array we utilize the measured experimental values from [5] for a diamond field-emission array operating in a L-band RF gun and the individual performance of these emitters measured in [6], where single tips were able to produce up to 15 $\mu$A of current in DC tests. For our emitter we assume they operate with a peak current of 1 $\mu$A a full order of magnitude below the peak current in DC testing, and 3 orders of magnitude below the average current produced per tip when operated at 1% duty in our design. The emitter array radius is 300 $\mu$m and operates well below the space charge limit. There is no static magnetic field in the model. The electron gun was simulated with the space-charge particle tracking code PARMELA [7]. In Fig. 5 a histogram of the 10 mA electron bunch at the gun exit is shown in time and energy, with the colorbar showing the number of electrons per bin. Over 90% of the emitted electrons exit the gun, with the beam parameters listed in Table 2.

Table 2: Electron-beam Beam Parameters at the Exit of the Electron Gun Labeled in Fig. 1

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $x_{rms}$ | 574 $\mu$m | $x'_{rms}$ | 58 mrad |
| $z_{rms}$ | 444 $\mu$m | $\Delta E/E$ | 0.032 |
| $\epsilon_x$ | 1.3 mm-mrad | $\epsilon_z$ | 2.5 mm-mrad |
| Energy | 19.3 keV | $\gamma$ | 1.038 |

## SOLID-STATE RF SOURCE

Solid-state power amplifiers have become increasingly attractive solutions for achieving 100s of Watts to kilo-Watts (kW) of peak and average power for their cost-effective implementation in radar and maritime applications. In a prototype experiment, a 100 W X-band solid-state amplifier chain was used to power a single RF cavity resonator [8]. The X-band solid-state amplifier consisted of a three stage chain with a power-added-efficiency of 35%, capable of producing in excess of 100 W of peak power at 10% duty. Wideband driver stage (30 dB of gain) and two power stages (10 dB of gain) employing commercially available, matched and fully-packaged GaN on SiC HEMTs were utilized. Using a test cavity made of copper that has a loaded Q of about 3400, the RF power produced by the solid-state source was coupled to a test cavity inside which the field gradient reached the level of 1.2 MV/m, see test setup in Fig. 6. Operating the cavity in air allowed us to induce and observe breakdown events both visually and with significant rise in the reflected power, without damage to the RF source.

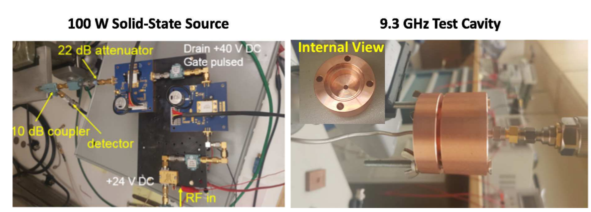


Figure 6: (left) Assembly of the three stage 100 W amplifier chain. Isolators are placed between stages. (right) 9.3 GHz cavity powered by solid-state source. The cavity is critically coupled from one side and weakly coupled from the other side using coaxial probes, loaded Q factor is 3200.

## CONCLUSION

We have presented the design of a field-emission X-band gun with a beam exit energy is ~20 keV and requiring only 1.5 kW of RF power. The RF gun is designed to by the beam source for 1 MeV linac and was modeled with 10 mA of current. Each cell of the RF gun will be separately powered by commercially available, GaN high electron mobility transistors. In proof of principle experiments we successfully powered a 9.3 GHz accelerating cavity with a 100 W transistor and a 1% duty cycle.


ISBN 978-3-95450-182-3

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