High power electron gun for metal additive manufacturing based on superconducting technology

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ABSTRACT

E-beam additive manufacturing is a rapidly growing industry. Electron guns capable of reaching higher energies and higher average power can enable larger melt pools, higher production speed, and permit broader range of materials for metal additive applications. Such electron guns require technologies beyond those normally achieved with DC high voltage sources. As an example, superconducting radio frequency (SRF) technology is an option to achieve higher energy and higher power with excellent efficiency. However, current SRF technology requires complex cryogenic systems to safely handle cryogenics gases or liquids such as Helium. Such complexity severely restricts their usage to R&D facilities. In this talk, we introduce and describe, for the first time, a novel technique based on SRF technology to build a high power, high energy electron gun for advanced metal additive manufacturing applications. Our design is based on a technique which eliminates liquid Helium entirely. Our method dramatically reduces the complexity and thus allows building practical, efficient, and modern electron sources for additive manufacturing.

Keywords: e-beam, SRF, superconducting, additive manufacturing, metal printing, Niobium cavity

1 INTRODUCTION

In this work, we describe a SRF gun for additive manufacturing applications espcially for metal additive manufacturing, which is currently served by lasers and e-beams. We focus on efficient, high power e-beam source (~ 50 kW-1 MW) with tunable energy and current capabilities. We anticipate that the higher power operation will enable printing larger build volume faster or substantially increase the throughput of smaller objects. The unique value propositon of this technology is the energy-efficiency and compactness. Also, MeV scale beams give us the potential to focus to small spot sizes to < 20 microns.

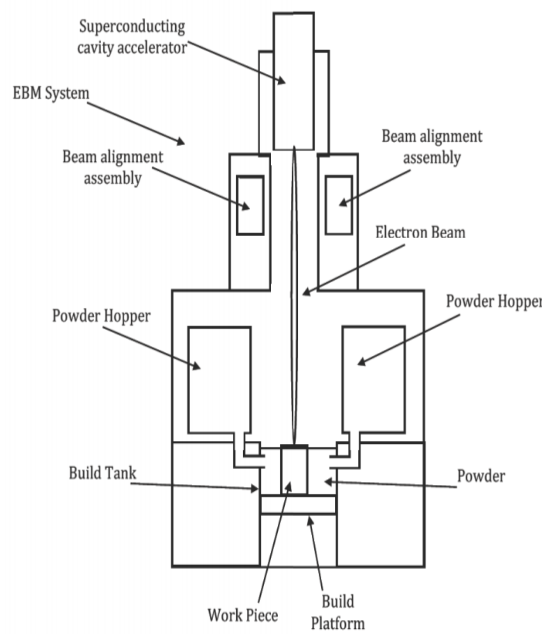

Figure 2: schematic of a 3D printer housing a conduction cooled SRF electron gun.

2 ELECTRON GUN

For our baseline concept the electron gun is directly integrated into a 1 1/2 cell 650 MHz superconducting cavity. The first or “gun” cell is shorter (it is approximately a half cell so we use that term in the text below) and use a cell shape scaled from a 1300 MHz β=1 elliptical cavity designed for the European x-ray source (XFEL). We have simulated performance of gun cells of various lengths in the range of 0.3-0.8 of the length of a regular cell. Optimization of cavity parameters such as Epeak/Eacc and Bpeak/Eacc was done with COMSOL for various scale factors. Beam simulation used SMASON near the cathode and ASTRA for beam dynamics in the rest of the cavity. Our results show that the optimal scale for the gun cell is 0.7.

A summary of main cavity parameters for the optimal scale 0.7, electric and magnetic fields distribution are given in Figure 2.

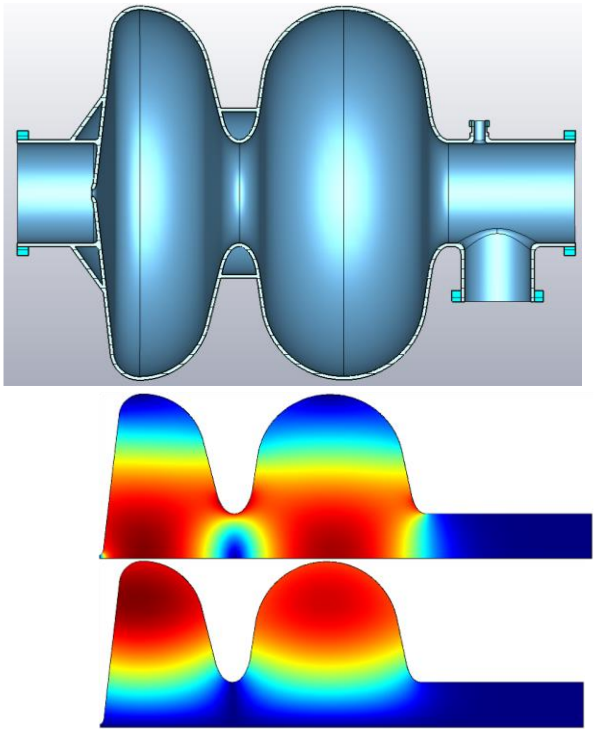

Figure 2: The mechanical design and the electromagnetic fields distribution with maximum field at the cathode for a 650 MHz cavity. The single cell has the longitudinal dimension of *β wavelength.*

The operation of a thermionic cathode directly inside a superconducting cavity presents new challenges. Efficient beam capture and acceleration requires bunches with small temporal duration and low energy spread. Challenging limits exist for beam loss to 4K cavity surfaces (< few Watts) due to the choice of SRF technology and cooling method. Finally, cathode material migrating into the SRF cavity surface could lead to lower cavity Q0 and higher 4K heat loads. (Note: If cavity surface contamination issues cannot be mitigated, the integrated gun could be replaced with a warm gun delivering electrons at about 10 keV from a cathode located far from the SRF cavity surface. The result is a less compact but more conservative solution.)

The thermionic-emission process can be temporally shortened by using a 2nd harmonic RF field. Simulations of shorter electron-bunch duration yields very low beam losses on the SRF cavity surface while providing electron-beam parameters with good duration and energy spread, comparable to the required values.

A miniature standard commercial thermionic cathode (Ø=3.5 mm) provides the needed beam currents while introducing very small heat loads. The proposed RF Gun with a tungsten dispenser thermionic cathode is intended to be cost-effective, simple, and have a long operating lifetime. Optimization of the RF phase of the gun RF with respect to the main cavity RF allows minimization of the output bunch's energy spread, duration, and beam losses during the acceleration in the SRF cavity.

Since losses in the superconducting acceleration structure are very small, a total of 250 kW of RF input power is required for beam acceleration. A small additional amount (e.g. 10%) of RF power will be required for control and regulation. The frequency and phase of the RF input of the RF gun will be determined using signals from a pickup in the acceleration cavity. Precise amplitude and phase control of the RF are not needed since there is not a requirement for precise control of the accelerator output energy. It is likely that beam loss control in sweeping magnets may be what sets the overall energy spread requirements. A small fraction of the power from the RF source will be directed to the gun. A small signal at the operating frequency of 650 MHz (from the probe, for example) will go to a frequency multiplier and then to a solid-state amplifier to create the second harmonic (1300 MHz) for the RF gun. The phase of the first harmonic and the second harmonic can be adjusted at low power levels to allow optimization of injection and acceleration.

3 CONDUCTION COOLED CAVITY

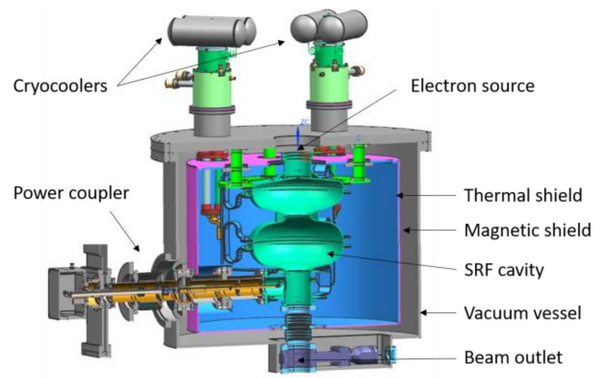

Figure 3: Cryostat housing the conduction cooled SRF electron gun.

Our cryostat concept for an industrial printer with the cavity mounted vertically is shown in Figure 3. It consists of a vacuum vessel, thermal shield, and magnetic shield encompassing a 1-1/2 cell 650 MHz superconducting cavity. The thermal shield intercepts the room temperature thermal radiation that would otherwise impart on the superconducting cavity. The magnetic shield, made of high magnetic permeability material, reduces the ambient magnetic field in the cavity space, which would otherwise interfere during RF operation of the superconducting cavity. An electron gun as described above is integrated into the cryostat launching the electrons into the gun half-cell cavity. RF power is fed to the accelerator via an ultralow loss coupler installed near the downstream of the cavity. The beam exits the accelerator through a thin low-Z material vacuum window. The cooling source for both the 80 K thermal shield and superconducting cavity is a set of closed cycle cryocoolers. In figure 2, there are two cryocoolers, which can be the standard 4 K units offered by Cryomech and Sumitomo Cryogenics [1]. High thermal conductivity aluminum links will connect the crycoolers to the SRF gun cavity. Systematic modeling of RF heat dissipation and thermal conduction through the aluminum link has indicated that the cryocooler pair with 4 W of cooling power will hold the cavity near 4.5 K during operation. The cryostat is radically simple in that it contains no liquid nitrogen or helium; thereby eliminating complex cryogen handling systems and potential safety hazards such as overpressuzation and oxygen deficiency. These features make our SRF electron gun system attractive especially for industrial settings [2].

4 COATING

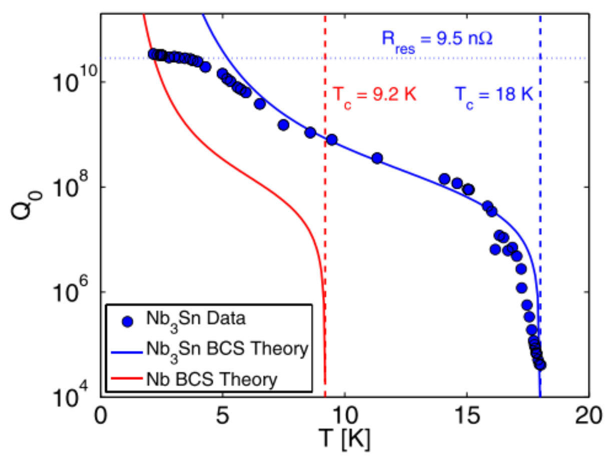

Fig 4. Q0 vs T from BCS theory vs measurement. Nb3Sn, with nearly double the Tc of Nb (indicated with dashedlines),offers high Q0 even at relatively high temperatures.

Use of a superconductor with higher transition temperature (Tc) such as Nb3Sn [3] (Tc= 18 K) can dramatically increase the efficiency of RF operation at 4 K compared to a pure Niobium cavity (Tc= 9 K). Recently, a 1.3 GHz single cell niobium cavity coated with Nb3Sn has been demonstrated to operate at gradients of 14-18 Megavolts/m with a quality factor of 2 x 10^{10} at 4 K. Based on this demonstrated coating performance, we can reliably predict that a 650 MHz 4.5 single cell accelerator cavity operated at ~ 10 MV/M will dissipate less than 2.5 W at 4K. This low 4K heat load will enable efficient, simple conduction cooling of the cavity via commercial 4K cryocoolers. Recent research also indicates that the cavity Q is degraded due to flux pinning by external magnetic fields, necessitating good magnetic shielding against external fields. The magnetic shield shown in figure 2 will shield the cavity from external magnetic fields. In addition, it is suspected that thermo-currents resulting from dissimilar materials (Nb vs Nb3Sn) during cool down can lead to magnetic fields and trapped flux. A slow cooldown through superconducting transition can be brought out by controlling the cooldown rate of the two cryocoolers. Overall, the use of magnetically shielded Nb3Sn coated cavities cooled by cryocoolers is the key enabler of our concept accelerator

5 POWER SOURCE

The use of magnetrons can reduce the cost/Watt of RF power by a factor of 5 while achieving efficiencies more than 80% leading to substantial cost, weight, and size reductions. Fermilab has demonstrated excellent RF phase and amplitude control with a single cell SRF cavity using proprietary (PCT/US2014/058750) technology based on a single injection-locked, 1-kW, 2.45-GHz magnetron .

6 CONTROLS

As the ultimate users of the device will include operators, the accelerator control system must be designed for turnkey and highly reliable operation. In this module, we envision an independent, robust, and intelligent control system with remote diagnostics that can maintain stable operation for long periods of time without intervention.

The control system's major functions are: 1) to control the phase and amplitude of the fundamental RF frequency (650-MHz) in the presence of beam loading to maintain the beam output energy; 2) to control the output current and thus the beam power; and 3) to monitor beam diagnostics and interlocks to provide machine and personnel protection.

The system goal is to operate at MeV energy and at a constant power. Continuous monitoring of both the beam current and supplied RF power will allow us to ensure a constant beam energy and power. The control system must also facilitate adjusting the beam power levels at the request of the user and facilitate automatic startup, stand-by, and shutdown of the accelerator at the request of the user. Our RF control scheme assumes that the drive frequency of the 650-MHz cavity will be adjusted to track the cavity's resonant frequency via tracking of an off-resonance phase modulated sideband. For the thermionic cathode option, a model of the relationship between the cathode field, cathode temperature, and the resultant beam current will be created using both simulation and (once the system is commissioned) measurement results. In this case, the system will continually monitor the cathode temperature, RF field, and downstream current monitor to update the model. Model predictive control using power and current measurements, RF controls, and the cathode heater settings will be used for the RF ramp during the turn-on process.

For the field emitter cathode option, we would need to track, correlate, and control the output current with respect to the gating voltages. Control of cathode and gun sub-system is critical, so we envision building and testing a 1 ½ cell gun to validate design choices before building the first article 4 ½ cell accelerator.

The control execution will primarily occur in firmware (e.g. FPGAs). For the first article test accelerator, we envision that the user interface will be coded in LabVIEW, and the data acquisition system will use NI data acquisition modules. The control architecture will be designed to accommodate a variety of RF sources, as we will likely start testing the SRF gun and test accelerator with COTS RF power systems based on IOTs or solid state systems before purpose-designed 650 MHz magnetron RF sources are available. The machine protection system will monitor the cryocooler, temperatures, beam current, cathode temperature (for a thermionic cathode), and the RF field readings

7 CONCLUSION

We introduce and describe, a simple, novel ebeam printing system based on SRF technology to build a high power, high energy electron gun for advanced metal additive manufacturing applications. Our design is based on a technique which eliminates liquid Helium entirely. Our method dramatically reduces the complexity and thus allows building practical, efficient, and modern electron sources for additive manufacturing.

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