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BUILT-IN THERMIONIC ELECTRON SOURCE FOR AN SRF LINACS

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Abstract

The design of a thermionic electron source connected directly to a superconducting cavity, the key part of an SRF gun, is described. The results of beam dynamics optimization are presented which allow lack of beam current intercepting in the superconducting cavity. The electron source concept is presented including the cathode-grid assembly, thermal insulation of the cathode from the cavity, and the gun resonator design. The cavity thermal load caused by the gun is analyzed including the static heat load, black body radiation, backward electron heating, etc.

INTRODUCTION

The new concept of a compact linear accelerator for industrial application suggested in [1] is based on use of Superconducting Radio-Frequency (SRF) cavities. It allows linear accelerators (linacs) less than 1.5 meters in length to create electron beams beyond 10 MeV with average beam powers measured in 100's of kW. The compact SRF accelerator can have high wall plug power efficiencies and will require smaller radiation enclosures reducing overall installation costs. Recent technological breakthroughs are expected to reduce capital costs so that such accelerators can be cost effective for many existing and proposed industrial applications. Examples include radiation cross-linking of plastics and rubbers; creation of pure materials with surface properties radically altered from the bulk; modification of bulk or surface optical properties of materials; radiation driven chemistry; food preservation; sterilization of medical instruments; sterilization of animal solid or liquid waste, and destruction of organic compounds in industrial waste water effluents. Small and light enough to be located on a mobile platform, such accelerators will enable new in situ remediation methods for chemical and biological spills and may create entire new industries by enabling in situ crosslinking of materials. The Illinois Accelerator Research Center (IARC) of Fermilab has started design, construction, and validation of a compact, 250 kW average power linac capable of operating in a continuous wave (CW) mode; delivering beam energies up to 10 MeV; and that can be palletized and made portable for a variety of industrial applications. This will be done by exploiting recent, robust, technological advancements in SRF and RF power source technologies as well as innovative solutions for the SRF gun and cathode system. The linac employs a 4½-cells, 650 MHz Nb_3Sn-coated conduction-cooled cavity having a built-in RF gun providing average beam current of 25 mA. The general layout of accelerator is shown in Fig. 1. Recent Fermilab experiments with 650 MHz Nb_3Sn single-cell cavities [2] allow us to expect dynamic loss in the cavity of about 4 W at an energy of 7 MeV. This low loss allows use of a cryo-cooler and conduction cooling of the cavity, which simplifies the design and reduces the cost of the accelerator. However, the maximal relative current interception by the superconducting cavity walls should not exceed $\sim 6\cdot 10^{-6}$, which amounts for less than 1 W of power deposition. This means that the electron injection system should provide an accurately shaped short bunches without tails and/or halo. A separate injector placed outside the accelerator cryomodule may have problems with longitudinal dynamics – the bunch may disperse in the drift space between the injector and the accelerator.

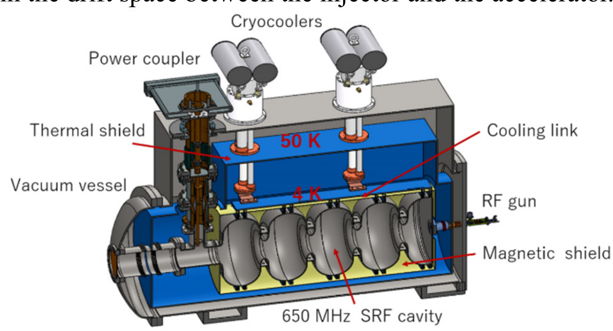

Figure 1: General layout of the 4½-cells cavity SRF linac.

The idea is to employ an internal injection scheme when the thermionic electron source is integrated into a 650 MHz superconducting cavity, i.e. a gridded cathode unit placed directly next to the cavity. In such designs the RF voltage applied to the grid-cathode gap is used together with the DC bias voltage to form the short electron bunches. This idea is widely used in normal conducting industrial accelerators, see for example [3]. The gridded thermionic electron source is used in many RF guns for SR sources [4-6].

THE DESIGN OF 1½ CELLS CAVITY PROTOTYPE

Prototype 1½ cells 650 MHz SRF cavity with a Ø = 1.5 mm cathode-grid assembly capable to deliver a 12.5 mA average beam current with a beam power of 20 kW is currently being developed in Fermilab (shown in Fig. 2).

COMSOL coupled RF - Mechanical optimization design has been performed to:

- Minimize peak surface fields and minimize cavity wall losses by maximizing R/Q.
- Achieve the desired 1.6 MeV energy and main beam parameters by optimizing the scale factor of 1st cell.
- Optimize the distance from the cathode emission surface to the cavity entrance, input iris diameter.
- Good mechanical stiffness to withstand vacuum pressure and fulfil all safety requirements etc.

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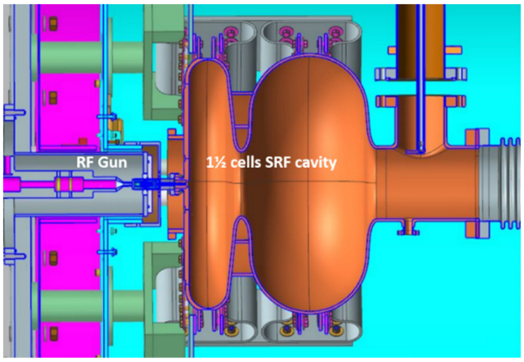

Figure 2: 1½ cells prototype general view.

MICHELLE [7] simulations have been performed to:

- Optimize the bunch energy spread.
- Optimize the beam phase duration.
- Minimize the beam losses during the acceleration.

Figure 3 shows β·γ of the beam profile for 3 different time period created by the MICHELLE. The upper plot shows the formed beam profile immediately after the cathode grid at the entrance to the cavity, the middle and lower plots show it at the entrance to the second cell and to the beam pipe, respectively.

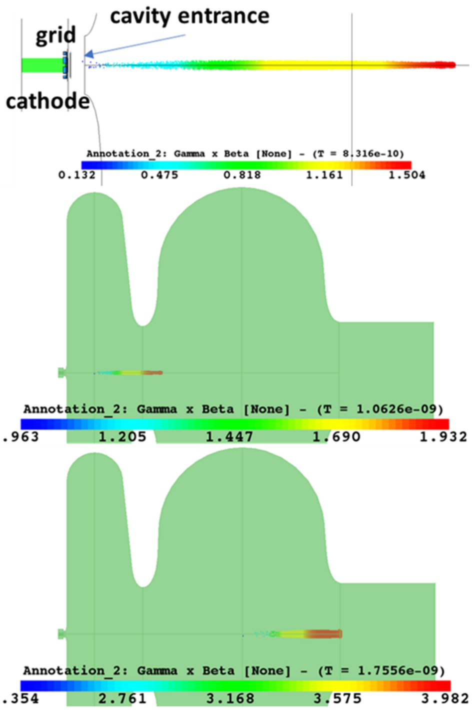

Figure 3: MICHELLE plots of the beam profile.

Beam characteristics and particle distributions at the exit of the 1½ cells cavity for the optimized parameters and geometry are summarized in several plots in Fig. 4. Top three plots: charge distribution vs. energy and phase, current vs. radius; Bottom three plots: phase vs. energy, x´-x phase-space distribution, x-y plot at the cavity exit.

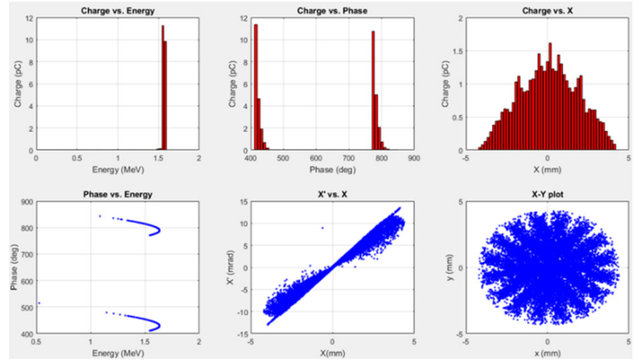

Figure 4: Particle distribution at the exit of the cavity.

Table 1:Summary of MICHELLE Results

Parameter	Value	Unit
Energy	1.6	MeV
Current	12.5	mA
Bunch charge	19.2	pC
Beam power	20	kW
Voltage $_{DC}$	300	V
Voltage $_{RF}$	385	V
Beam energy spread, rms	1.9	%
Beam phase duration, rms	6.8	º
Normalized emittance	5.2	mm·mrad
Cathode radiative heating	0.2	W
Static heat load	0.3	W
Losses on the grid	0.25	W
Back bombardment	0.3	W
Grid transparency	80	%

Up to 200 K particles was used in MICHELLE simulations. No particles losses were indicated on the cavity walls. Table 1 summarize the main beam parameters, beam and heat losses. To form a beam with the required current of 12.5 mA, it is necessary to apply to the grid-cathode gap a RF field of 385 V and DC voltage V. Optimized phase shift between RF fields in the gun and the cavity is 90°. Losses on the grid are ~0.25 W and causes additional heating of the grid by 100 °C, which is not a problem in terms of additional radiation and mechanical deformation of the grid.

EVAPORATION AND BB RADIATION

The operation of a thermionic cathode directly inside a superconducting cavity presents new challenges. First it puts a stringent demand on the beam loss and black body radiation. Second, the possibility of the cathode material migrating into the SRF cavity could lead to contamination. According to J. P. Cronin paper [8], the evaporation rate for a dispenser cathode, type 612M, at a reasonable temperature (~1050 °C) is about ~0.4 microgram/cm^2/h. Based on these estimates, for a cathode Ø = 1.5 mm and for a 4½-cell cavity with an area of ~ 20000 cm^2, less than 1.5 mono-layer will be on the cavity wall after 10 year of exploiting.

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The estimates made show that for such a cathode diameter, the black-body radiation will not exceed 0.3 W, which is acceptable.

DESIGN OF THE CATHODE-GRID UNIT

The engineering design of the cathode-grid unit has been done at HeatWave Labs, Inc. During the design optimization described above the following requirements have been identified that must be met:

- An impregnated cathode of 612M type with a 1.8 eV work function to provide electron current density greater than 10 A/cm^2 at emitter temperature of 1050 °C.
- The cathode Ø = 1.5 mm to provide low heat load (< 1W) to cryogenic environment.
- A planar shape of the cathode and grid with Pierce angle electrode. The grid transparency is higher than 80%. Planar geometry of the cathode and grid is less sensitive to dimensional errors and misalignments.
- A heater filament should be designed to avoid the heater magnetic field on the cathode.
- The heater power level < 2 W.

Figure 5 show a 3D cross-section of the cathode-grid assembly. The beam optics is determined by the shape of the grid extension electrode with Pierce angle.

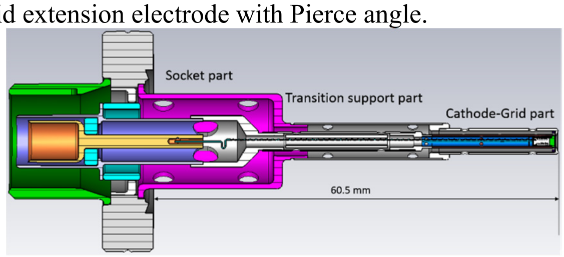

Figure 5: Cross-section of the cathode-grid assembly.

Figure 6 shows the detailed view of the socket design connection of the cathode-grid assembly with the RF gun resonator.

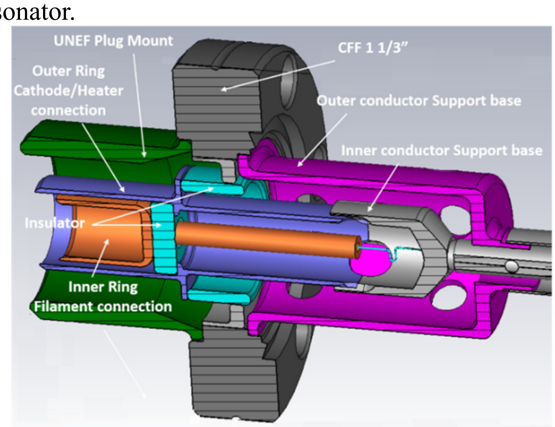

Figure 6: Socket design.

Figure 7 shows the cathode-grid area with details of the heater. To minimize the magnetic field from the filament current on the cathode, the heater wire is coiled in two layers with opposite direction of the current in each layer, forward and return wires are also twisted together. An outer conductor and the grid are grounded. The cathode and heater are at a DC bias voltage.

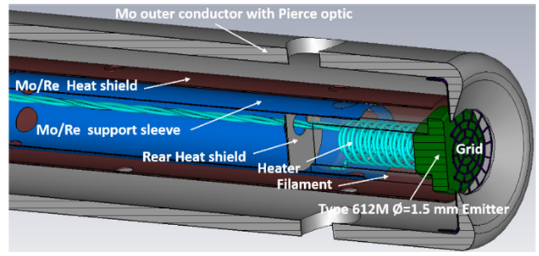

Figure 7: Detailed view of the cathode-grid area.

To minimize the heater power, the cathode is mounted using a support sleeve made of 25 µm (0.001") thick molybdenum/rhenium alloy with an additional hole pattern to reduce the thermal path to emulate a 12.5 µm thick sleeve. To reduce thermal radiation, a special thermal shield of a 25 µm thick Mo/Re has been added to the design.

CONCLUSION

The design of a thermionic electron source, i.e. a gridded cathode unit, placed directly next to the superconducting cavity has been presented. 1½ cells 650 MHz SRF cavity prototype with a beam power of 20 kW is currently being developed in Fermilab. MICHELLE simulations show that the electron injection system provide an accurately shaped short bunches without tails and zero current interception by the cavity walls. BB radiation, back bombardment and grid current intercept are at an acceptably low level.

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