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HIGH CHARGE HIGH CURRENT BEAM FROM BNL 113 MHZ SRF GUN*

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Abstract

The 113 MHz superconducting gun is used an electron source for the coherent electron cooling experiment. The unique feature of the gun is that a photocathode is held at room temperature. It allowed to preserve the quantum efficiency of Cs_2KSb cathode which is adversely affected by cryogenic temperatures. Relatively low frequency permitted fully realize the accelerating field gradient what in turn helps to achieve 10 nC charge and 0.3 microns normalized emittance. We present the achieved performance and operational experience as well.

GUN DESIGN

The injector is an essential part of any accelerator, and the quality of the produced beams completely relies on its performance. Among the well-known electrostatic (DC) and normal-conducting (NC) RF photo-guns, the injectors based on an SRF cavity are rapidly gaining popularity in the generation of the high-brightness high-quality beams.

The idea of utilizing the SRF technology brings advantages and challenges [1, 2]. The biggest advantage is the reduced power losses (orders of magnitude lower compared to a NC cavity) which allow for reliable operation in continuous wave (CW) regime and generation of beams with high average current, providing a higher accelerating gradient. Another advantage is an excellent vacuum conditions inside the cavity which serves ad huge cryopump.

However, introduction of a photocathode into the SRF environment causes several complications: since the photocathode has to be replaced throughout the operation of the gun, the area around the cathode creates a condition for RF power leakage which has to be taken care of. To keep the power within the cavity, an RF choke filter has to be designed for this purpose.

Moreover, the cathodes are generally kept at room temperature creating an additional heat leak between the cold surface of the cavity and the warm cathode.

We utilized quarter-wave resonator (QWR) based geometry for our gun. The QWR cavities are specifically suitable for operation at low frequencies which allow for a generation of long bunches. This fact is beneficial for the reduction of the space charge effect in the initial stages of the beam generation, allowing to achieve higher charge per bunch. The accelerating gap in such a cavity is relatively short compared to the wavelength, which makes the field distribution in the gap close to constant. To a degree, such SRF guns are similar to DC guns but offer both high accelerating gradient and higher beam energy at the gun exit. The main RF parameters of the gun can be found in Table 1.

Table 1: RF Parameters of the Gun

Parameter	Value
Frequency, MHz	113
Quality factor w/o cathode	3.5×10^9
R/Q, Ω	126
Geometry factor, W	38.2
Operating temperature, K	4.2
Accelerating voltage, MV	1.25 (1.7)

The geometry of the SRF gun is shown in Fig. 1. The cavity body is made of bulk Nb, and, as all of the QWR geometries, has “outer conductor” and “inner conductor” parts due to the nature of this type of a cavity. The “inner conductor” is hollow and accommodates the system of the cathode insertion and extraction. The accelerating electric field is concentrated between the front wall of the cavity and the rounded part of the “inner conductor,” which we denote as the cavity “nose”. The inset in the Fig. 1 shows in detail the location of the cathode puck in the cavity nose.

The necessary half-wavelength RF choke for the reduction of the power leakage incorporates a hollow stainless-steel cathode stalk which allows insertion of a cathode puck [3, 4]. The cathode stalk is coated with layers of copper and gold to reduce heat emission into the 4 K system. It is kept at room temperature by circulating water in the channel soldered to the stalk.

The stalk does not have direct physical contact with the cold center conductor of the cavity, thus reducing the leakage of heat into the cavity only allowing the exchange of the radiated heat. The stalk is shorted at the far end to serve as a choke filter. The choke reduces the penetration of the RF field, and minimizes the voltage drop between the cathode and the cavity's center conductor. The gap between the stalk and the cavity nose at the entrance of the cavity is only 3.56 mm. The length of the stalk was shortened to account for the capacitance created by this small gap. The impedance transformer in the middle of the stalk is used to reduce the current through the short, which includes a coated bellow.

A pick-up antenna for measuring the RF voltage is located outside of the gun cryostat and is weakly coupled to the choke. The axial position of the stalk tip and, therefore, the photocathode surface with respect to the cavity nose can be manually adjusted. The latter provides us with an opportunity to optimize the initial focusing of the electron beam.

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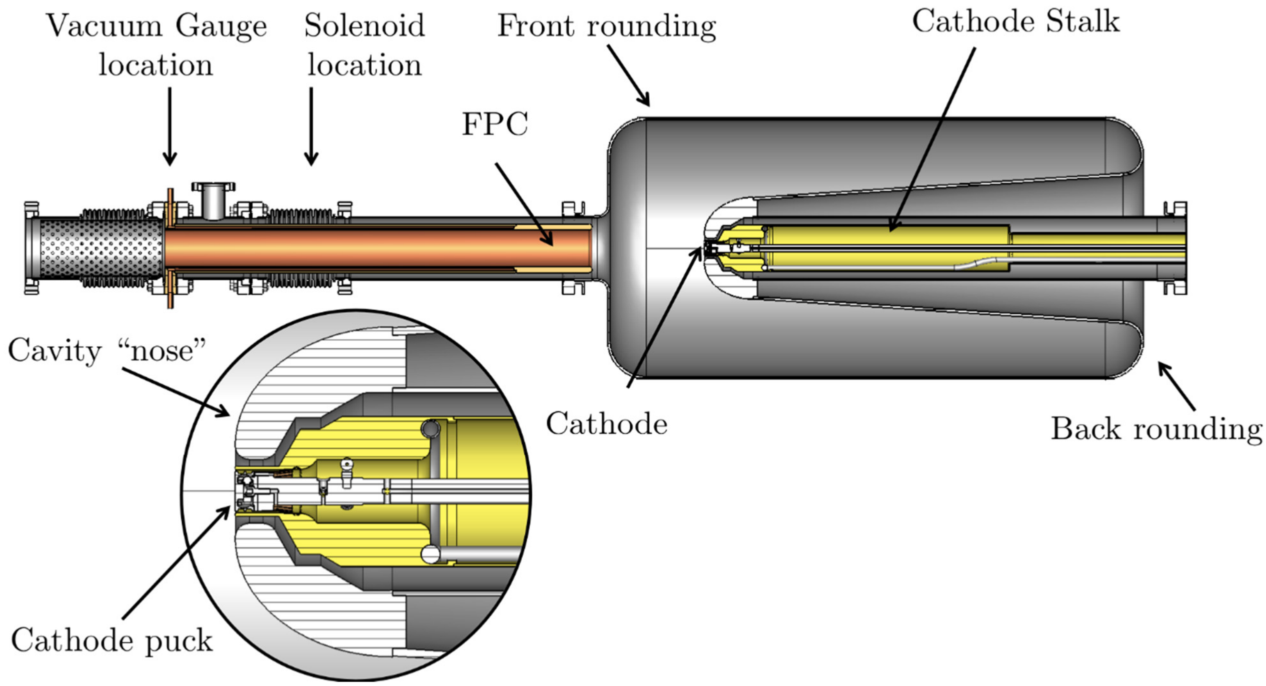

Figure 1: Cross-section of the SRF gun. The cathode is inserted through the opening inside of the cathode stalk with long manipulator. The cathode stalk serves as a field pick-up for the cavity control. The electron and laser beams are passing inside of the FPC. Electron beam focusing is done with a solenoid placed around FPC over the bellows.

The coarse tuning of the cavity frequency is provided by the two manual tuners, while the fine frequency tuning and the Low-Level RF (LLRF) feedback loops utilize the fundamental power coupler (FPC). The coaxial FPC with water cooling is incorporated in the front side of the cavity and is hollow in order to allow for the electron and laser beams propagation. The FPC is placed on a motorized translation stage, so its position can be adjusted by about 40 mm, which allows us to tune the coupling and the gun frequency. Coarse tuning range is 80 kHz and fine tuning range is 6 kHz.

The RF power to the gun is provided by a 4-kW solid-state amplifier. The first focusing element, which we denote as the gun solenoid, is located 65 cm downstream of the cathode surface and encapsulates the bellow of the FPC section. This section is followed by the laser cross which delivers the green drive laser beam to the cathode surface. The drive laser can generate up to 0.5 µJ pulse at 532 nm wavelength. The pulse duration is variable from 100 ps to 1 ns and the maximal repetition rate is 78 kHz. These laser pulses are amplified to the desirable level by a regenerative amplifier. The time structure of the delivered laser pulses is controlled by a set of Pockels cells and can provide the following configurations: single pulses, pulse trains of various duration, and CW mode. The laser pulse intensity is controlled by the cross-polarizers.

A small, 20 mm-diameter, cathode puck, shown in Fig. 2, is made of molybdenum. A high quantum efficiency (QE) CsK_2Sb photoemission coating with diameter of 8 to 10 mm is deposited in the center of its polished front surface. Small photoemissive surface contributes to less beam halo and reduces number of multipacting events.

The important feature in the design of the SRF gun is the capability of in-situ cathode puck replacements using an ultra-high vacuum (UHV) manipulator system. The UHV portable transport system ("garage") has a built-in QE measuring system. Up to three cathode pucks can be stored and transported in such a "garage" without any significant loss of QE. The garage is attached to the gun's manipulator system via a bakeable load-lock unit and is used for storing cathodes for months. Cathodes can be exchanged between the gun and the garage in about one hour, with most of the time used to slowly move the manipulators to avoid friction-driven vacuum pressure rise. Two grooves on the side of the puck allow us to insert and extract it using forks of the in-vacuum manipulators. The manipulator arm has three centering standoffs with rolling ceramic wheels, which prevent damage to the cathode during the insertion and limit the generation of particulates. The gold-plated RF spring finger contacts connect the puck with the inner surface of the stalk ensuring that the electromagnetic field does not propagate inside the cathode stalk.

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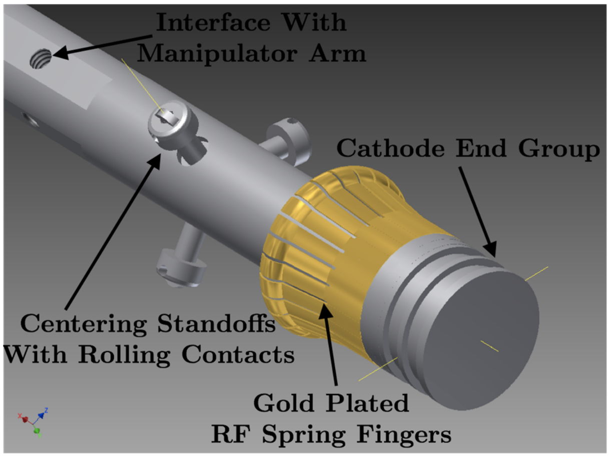

Figure 2: Cathode end assembly.

MEASUREMENT OF THE GUN PARAMETERS

Cathode Recess

The field distribution was evaluated using CST Microwave Studio (MWS) [5] with tetrahedral mesh. To reduce the computational time, an H-plane was utilized based on the symmetry of the fundamental mode field distribution. Axial symmetry of the gun allowed to 2D solver for calculating axial fields such as Poisson SUPERFISH [6]. The electric field profiles for different cathode recess (cathode position vs. nose tip) are shown in Fig. 3.

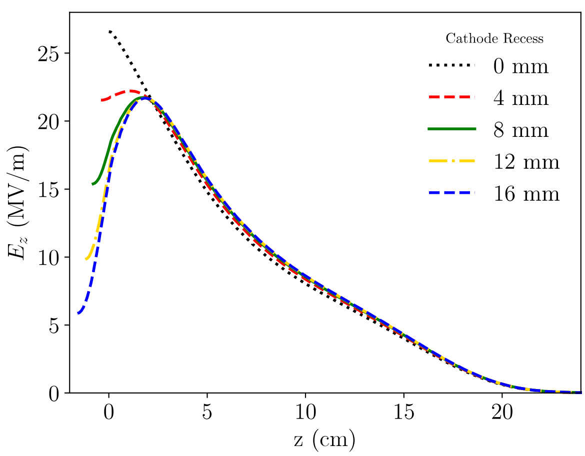

Figure 3: Electric field distribution along the gun axis for various values of the cathode recess.

As one can see the cathode position substantially changes accelerating field profiles and, hence, focusing field of the gun. With zero recess the field at the cathode is maximal but there is no focusing component. With cathode withdrawn the focusing is strong but cathode field is low and significant charges cannot be extracted due to the space charge.

The location of the cathode can be fixed relatively to the stalk but the position of the latter is not well defined due to the cavity contraction after cool down. We have developed procedure for the measuring the cathode position in the cavity based on the focusing properties of the gun cavity. For this purpose, laser spot was set to smallest value (0.25 mm) and laser intensity was reduced to suppress electron beam divergence due to the space charge forces. Under such conditions it is possible to observe the electron beam on the first profile monitor without additional focusing by solenoids. The laser spot was scanned on the cathode surface and beam position on the profile monitor was measured. From this measurement magnification factor, ratio of electron beam displacement to the laser spot displacement was found and cathode position was found from the calibration curve shown in Fig. 4.

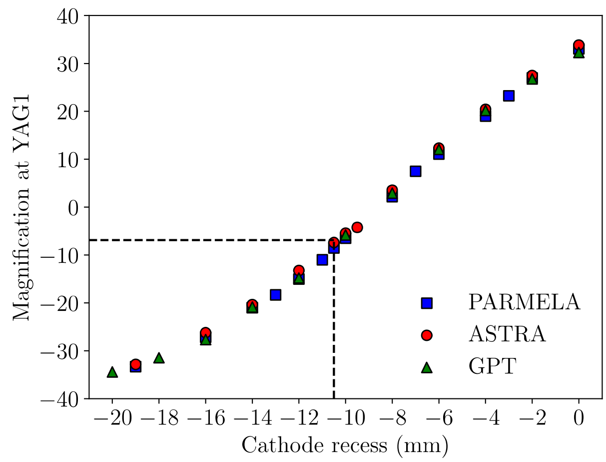

Figure 4: Magnification factor of beam displacement on the first profile monitor obtained with different tracking codes. Positive values correspond to the electron beam displacement in the same direction as laser spot motion and negative ones to the opposite direction.

Electrical Axis of the Gun

In the axially symmetric system the electron beam generated on the center of the cathode leaves gun without transverse momentum. However, manufacturing imperfections change the field distribution within the cavity. In order to determine the electrical axis of the gun, we changed the beam rigidity by scanning the gun voltage and measured the position of the electron beam on the first profile monitor. The beam position has linear dependence on the inverse beam rigidity as shown in Fig. 5.

Extrapolating the line to the infinity beam energy (inverse rigidity equal to zero) on can find coordinates of the electrical axis at the observation point and, hence, its tilt. For these measurements all of the solenoids were turned off. To guarantee that the beam stays on the screen the trajectory was adjusted two times, that is why we have three lines. But intercept for each line is approximately the same (the infinitely rigid beam is not steered by correctors).

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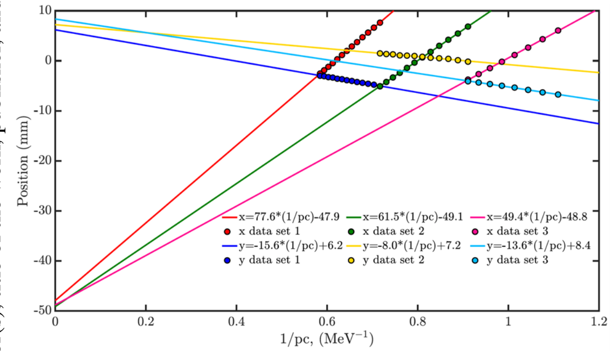

Figure 5: Horizontal and vertical position of the beam center as function of the inverse beam rigidity for three different trim sets. The intercept values and distance from the gun to profile monitor (4.27 m) give horizontal angle of -11.1±0.1 mrad and vertical angle of +1.6 ±0.2 mrad.

BEAM PARAMETERS

The first operation after insertion of a new cathode is phase scan either a drive laser or gun voltage. The result of the laser phase scan is shown in Fig. 6. The shape of the curve is trapezoidal not a triangular commonly observed in the high frequency RF guns. Moreover, the width at baseline exceeds 180 degrees due to the non-zero laser pulse length.

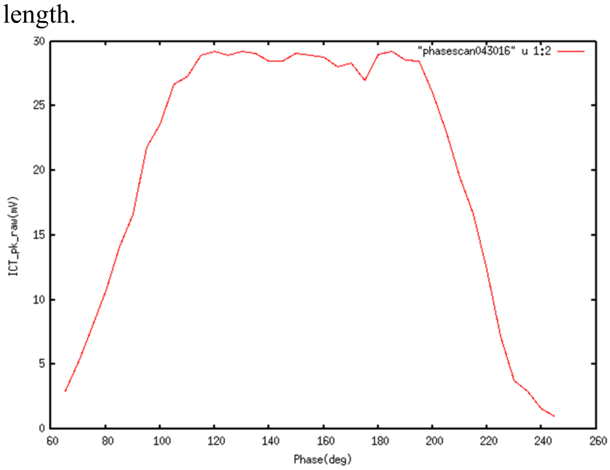

Figure 6: Dependence of the extracted charge vs. drive laser phase. The laser pulse is 0.5 nanoseconds long.

Fig. 7 shows the bunch charge dependence on the laser pulse power. The saturation becomes visible for the charges above 4 nC. In this figure we do not observe saturation but the observed maximal charge is 10.7 nC as shown in Fig. 8.

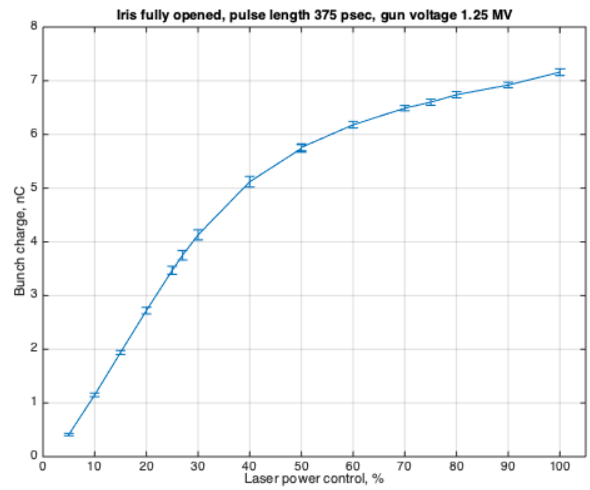

Figure 7: Dependence of the bunch charge vs laser power. Gun voltage is 1.25 MV, cathode recess is -10.5 mm, laser pulse length is 375 psec, laser spot diameter is 6 mm.

We have not tried to propagate the beam with charge close to the maximum to the high-power dump. The experiment utilized maximal charge of 1.5 nC and maximal current observed is 120 µA (repetition rate 78 kHz).

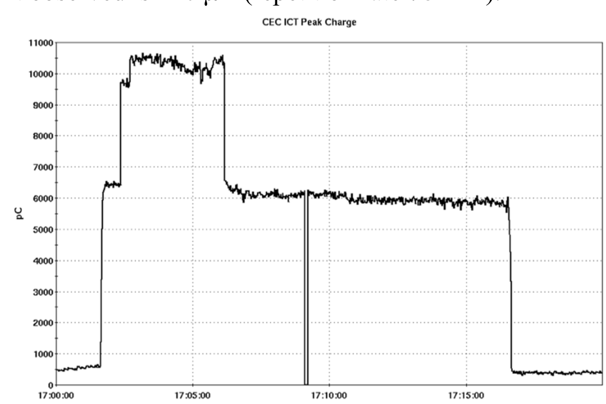

Figure 8: History of the gun charge during test.

Important beam parameter is its emittance. While we have a system of slits it is not very suitable for measurement of small emittances. Therefore, we used the solenoid scan. The dependence of the beam size on the profile monitor vs. solenoid current is shown in Fig. 9. To account for the space charge forces with tracking code to simulate the observed values. And beam parameters obtained in simulations were used actual values.

Typically, cathode lifetime in the gun was 2-3 weeks and we have cathode that was utilized for two months. Long cathode lifetime we attribute to the high vacuum in the SRF gun which serves as cryogenic pump and absence of the substantial ion bombardment. We never observed specific dip in the cathode QE in the center which is reported in most DC guns.

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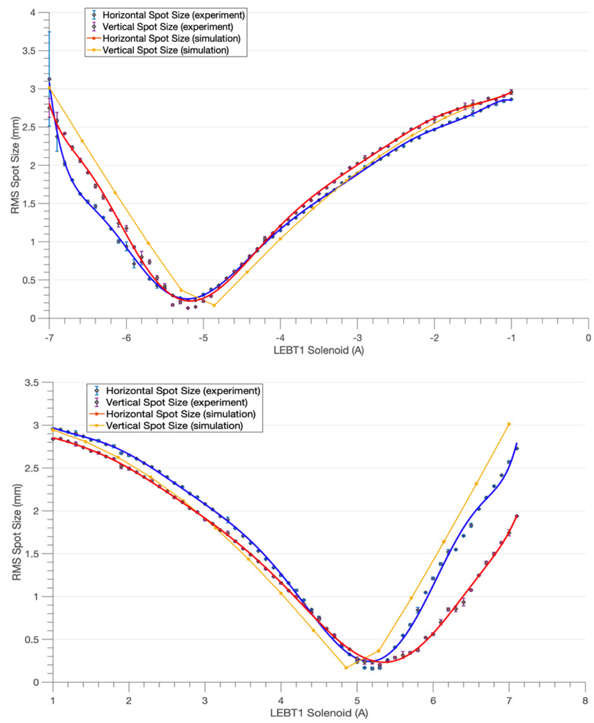

Figure 9: Dependence of the electron beam size vs solenoid current (negative on the top and positive on the bottom). Blue lines represent horizontal beam size, red lines – vertical beam size, yellow – round beam size in the simulation. Laser spot diameter was 3.3 mm, bunch charge 600 pC, bunch length 400 psec. The projected normalized emittance is 0.57 mm mrad, normalized core emittance is 0.35 mm mrad.

CONCLUSION

The low-frequency superconducting RF gun allows to generate electron bunches with record parameters both in charge and transverse emittance. Low frequency allows to generate electron beam close to conditions in DC gun but avoid QE degradation due to the ion bombardment.

High vacuum inside the SRF vacuum provides for the cathode's long lifetime.

SRF gun is an attractive electron source for the free-electron lasers and high-energy electron coolers.

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