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SUPERCONDUCTING RF GUN WITH HIGH CURRENT AND THE CAPABILITY TO GENERATE POLARIZED ELECTRON BEAMS

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Abstract

High-current low-emittance continuous wave (CW) electron beams are indispensable for nuclear and high-energy physics fixed target and collider experiments, cooling high energy hadron beams, generating CW beams of monoenergetic X-rays (in FELs) and gamma-rays (in Compton sources). Polarization of electrons in these beams provides extra value by opening a new set of observables and frequently improving the data quality. We report on the upgrade of the unique and fully functional CW SRF 1.25 MeV gun, built as part of the Coherent electron Cooling (CeC) project, which has demonstrated sustained CW operation with CsK_2Sb photocathodes generating electron bunches with record-low transverse emittances and record-high bunch charge exceeding 10 nC. We will extend the capabilities of this system to high average current of 100 milliampere in two steps: increasing the current 30-fold at each step with the goal to demonstrate reliable long-term operation of the high-current low-emittance CW SRF guns. We also will test polarized GaAs photocathodes in the ultra-high vacuum (UHV) environment of the SRF gun, which has never been successfully demonstrated in RF accelerators.

INTRODUCTION

High-current low-emittance CW electron beams are of great importance for existing and future scientific facilities, medical, industrial and homeland security applications, and beyond. Such beams are indispensable for nuclear and high-energy physics fixed target and collider experiments, cooling high energy hadron beams, generating CW beams of monoenergetic X-rays (in FELs) and γ-rays (in Compton sources), high-power EUV beams for manufacturing the next generation of microchips, border cargo inspection, to mention just a few. Polarization of electrons in these beams provides extra value by opening a new set of observables and frequently improving the data quality by boosting signal to background ratio.

The CW super-conducting radiofrequency (SRF) electron gun is one of the most advanced, but also one of the most challenging, technologies promising to deliver such beams [1–6]. While SRF technology is paving the way for the future accelerators, the compatibility of advanced SRF technology with complex photocathodes remains on the forefront of the modern accelerator science, and many important questions remain unanswered [7, 8].

We are aiming to upgrade the unique and fully functional CW SRF facility installed at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) by adding high-current and polarized beam capabilities. Our 1.25 MeV SRF gun, built as part of the Coherent electron Cooling (CeC) project [9, 10], has demonstrated sustained CW operation with CsK_2Sb photocathodes generating electron bunches with record-low transverse emittances and record-high bunch charge exceeding 10 nC [11, 12]. The cathodes survive many months of continuous operation. Nevertheless, the average beam current, determined by the needs of the CeC project, is limited to about 100 μA. Our goal is to extend the capabilities of this system to high average current of 100 milliampere in two steps: increasing the current 30-fold at each step. We also will test polarized GaAs photocathodes in the ultra-high vacuum (UHV) environment of the SRF gun—which has never been successfully demonstrated in RF accelerators. The upgrades include the cathode preparation and UHV cathode transfer system, and a polarimeter to measure polarization of the generated electron beam. Finally, we propose to optimize in-situ processing, including both He treatment and plasma processing, for restoring and improving performance of our gun's quarter-wave SRF cavity.

CURRENT STATUS OF THE BNL SRF GUN

At the beginning of the CeC run 2021, the gun showed poor performance and rapid decay of the cathode quantum efficiency. After a thorough investigation, it was found that the cathode end effector was severely damaged while being inserted into the cavity. This damage introduced significant particulate contamination into the gun, which required immediate cavity conditioning.

A combination of CW RF processing, High-power Pulsed Processing (HPP) and Helium processing was used with an ultimate goal to achieve 1.35 MV which is a satisfactory operational voltage required for the Coherent electron Cooling experiment (1.25 MV operational voltage with a headroom

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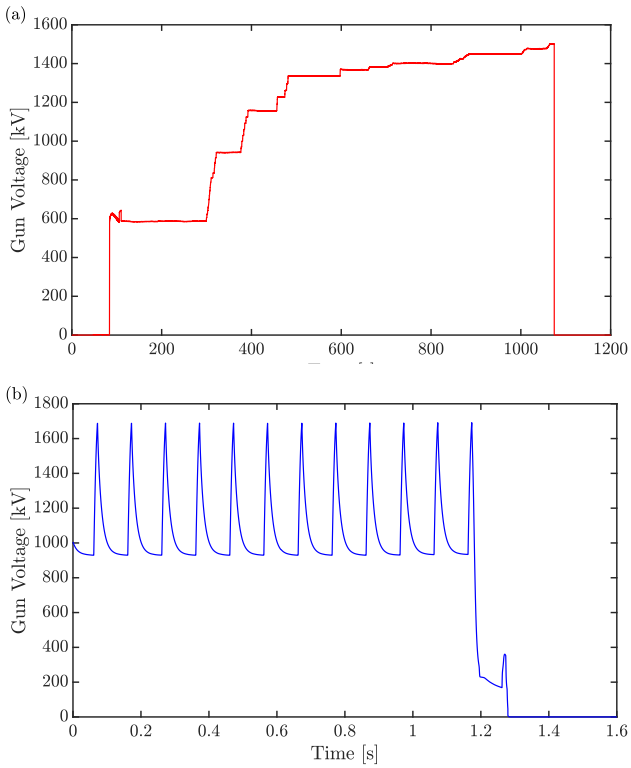

Figure 1: Maximal achieved cavity voltage in CW (a) and pulsed (b) modes after the gun conditioning.

of 0.1 MV). As a result of the cavity conditioning, the gun achieved 1.5 MV in CW and 1.7 MV in pulsed mode, which has never been demonstrated in this cavity. Figure 1 shows the cavity voltage from the pickup in pulsed and CW modes of operation.

Energy measurement using dark current in CW mode confirmed the achieved 1.5 MV cavity voltage (see Fig. 2 for the result of the energy measurement using a downstream solenoid and a beam profile monitor).

With a new cathode installed into the gun after conditioning, we were able to demonstrate a new record charge ever extracted from an SRF gun: 19.7 nC with a 500 ps bunch.

SYSTEM UPGRADES

Generating higher current from the SRF gun requires the following components to be implemented: a high repetition rate laser, high quantum efficiency (QE) photocathodes, a low loss beam transport to the high-power beam dump, and an RF system supplying power to the beam.

100 kW Fundamental Power Coupler

The current configuration of the fundamental power coupler (FPC) delivers power to the cavity from a 4 kW solid state amplifier, and also serves as a frequency tuner [13]. The coupler for the proposed system upgrade should provide 100 kW power in CW regime, and must be interchangeable with the existing coupler configuration. A conceptual design of the coupler antenna is currently under development (see

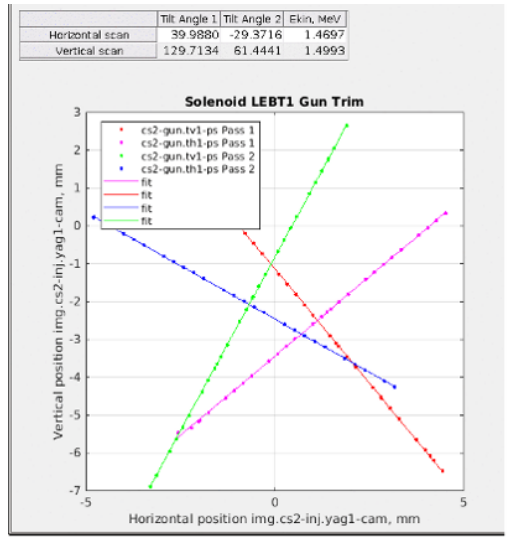

Figure 2: Energy measurement using dark current shows the achieved voltage of 1.5 MV CW.

Fig. 3 for preliminary desing of the windows and antenna configuration). The antenna provides the required coupling and frequency tuning range of 7 kHz with an expected moving range of the antenna of ~15 mm. The coupling value changes not more than 2 times in the required tuning range. Preliminary multipacting simulations have shown that multipacting exists in the regular part of the coupler. The power range for multipactor to occur is from 50 W to 20 kW. A high voltage bias is suggested to suppress multipactor, and a configuration which allows application of the high voltage bias is proposed. The expected power losses in the coupler are not high, air can be used as the cooling media. Two coupler windows will be used to increase reliability. Mechanical simulations showed that (i) stresses in the ceramic rings (and alumina gaskets) are at ~100 MPa, which is an acceptable level; (ii) a gravity antenna offset is ~0.05 mm.

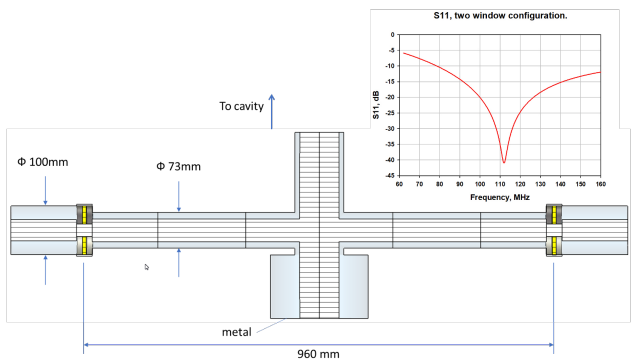

Figure 3: An example of the antenna configuration utilizing two windows with 50 kW CW per window.

CeC Laser Upgrade

The current CeC Master Oscillator Power Amplifier (MOPA) laser system will require an upgrade in order to

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support high-current gun operation. The system upgrade is ongoing and includes a possibility to provide a variety of flat pulse lengths, the regenerative amplifier will have a variable repetition rate Pockels Cell driver with up to 5 MHz. The summary of the expected performance parameters is shown in Table 1.

Table 1: Summary of the Expected CeC Laser Performance Parameters

Parameter	Unit	Min	Typ.	Max
Seed Wavelength	nm		1064.2	
Output Wavelength	nm		532.1	
Bandwidth	nm		0.05	
Pulse Duration	ps	50	350	750
Pulse Shape	-		Flat-Top	
Repetition Rate	kHz	10	78	5000
Average Power @ 532 nm	W		6	
Pulse Energy	µJ	1	75	500
Charge equivalent after spatial shaping (1% QE)	nC	2	150	1000

Compton Transmission Polarimeter

A Compton Transmission Polarimeter, which will be used to measure beam polarization when the SRF photogun employs a GaAs photocathode, is currently under development. The schematic of the current design of the polarimeter is shown in Fig. 4.

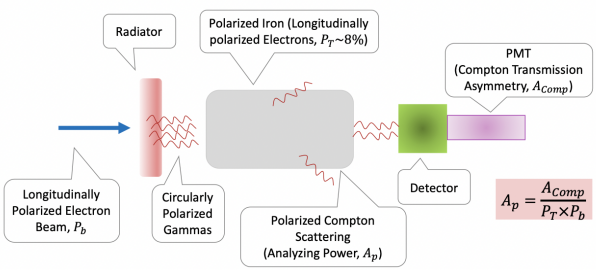

Figure 4: Schematic of the Compton polarimeter.

CONCLUSION

The efforts to upgrade the novel BNL SRF gun to demonstrate high-current performance, generation of polarized electron beams, and explore the modern cavity restoration techniques are currently under way. The system upgrades include the design of a 100 kW FPC, improved laser system, and design of a new Compton transmission polarimeter. We have tested a novel method of improving performance of an SRF gun (with respect to the dark current and X-ray radiation) with and without use of He gas. It was successful and reduced radiation and dark current 2.5-fold. The SRF gun achieved record high voltages in both CW and pulsed operation after the He conditioning. The gun delivered 500 ps, 19.7 nC bunches.

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