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NOVEL ASPECTS OF BEAM DYNAMICS IN CEC SRF GUN AND SRF ACCELERATOR

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Abstract

A 15 MeV CW SRF accelerator has been commissioned at Brookhaven National Laboratory to test the Coherent electron Cooling concept. The accelerator consists of an SRF 113 MHz photoemission gun, two 500 MHz bunching cavities and a 704 MHz 5-cell SRF linac. In this paper, we describe our experience with this system with focus on unusual phenomena, such as multipacting in the SRF gun. We also discuss issues of wakefields in the CeC accelerator.

CEC ACCELERATOR

Coherent electron Cooling (CeC) is an advanced method of beam cooling which is based on electrostatic interactions between electron and ion beams amplified by a high-gain free electron laser (FEL) [1]. This promising method would significantly reduce cooling time of a hadron beam compared to the other known techniques. The CeC Proof of Principal (PoP) experiment is currently undergoing commissioning at Brookhaven National Laboratory, and the layout of the CeC beamline is illustrated in the figure at the top of the next page [2]. The accelerating section of the system consists of a 113 MHz superconducting photo-injector followed by the first focusing solenoid, two 500 MHz normal conducting bunching cavities, a transport section with 5 solenoids, and a 704 MHz superconducting accelerating 5-cell cavity. After the electron beam is accelerated to the velocity matching the velocity of the hadron beam circulating in RHIC, it is directed by the dogleg into the common section, where the beams co-propagate. In this paper, we present the observations during the system commissioning alongside with the simulation results, and we discuss our future plans for the wakefields and beam dynamics simulations.

113 MHz SRF PHOTO-INJECTOR

The 113 MHz photo-injector is based on a quarter-wave resonator which provides 1.05 MV of accelerating voltage, and can generate an electron bunch with charge up to 4 nC (see Fig. 1) [3–5]. This year, the gun was generating an electron beam at the third subharmonic of the RHIC revolution frequency, which is 26 kHz for the hadron's energy of 26.5 GeV/u. For the Run'18 the gun will be retuned to operating at a harmonic of RHIC revolution frequency e.g. 78 kHz. During the last run, the photo-injector demonstrated excellent performance, which showed significant improvements compared to the results of the Run'16, which was challenged by the presence of strong multipacting (MP) barriers.

Multipacting

Multipactor discharge was a major limiting factor during the previous year of commissioning. We observed that vacuum activity due to the MP would significantly increase in the presence of the external magnetic field of the first solenoid (especially for a magnetic field of about 400 Gs). The most dangerous MP level was found to be at 40 kV of accelerating voltage, which would become worse when the CsK_2Sb photocathode was inserted into the cavity. This MP level would lead to serious vacuum excursions, which were rather damaging to the quantum efficiency of the photocathode—it would deteriorate from 2-8 % to 0.01-0.1 %.

After a comprehensive study of the MP in the gun using Track3P [6], it was confirmed that the external magnetic field increases the strength of MP in the gap of the fundamental power coupler (FPC), with stable trajectories moving from the cavity side of the gun towards the bellow (see Fig. 1). The simulation results showed that the stubborn MP level at 40 kV is localized in the front rounding of the cavity and is a 1st-order multipactor discharge. See [7, 8] for a more detailed discussion of the simulation results.

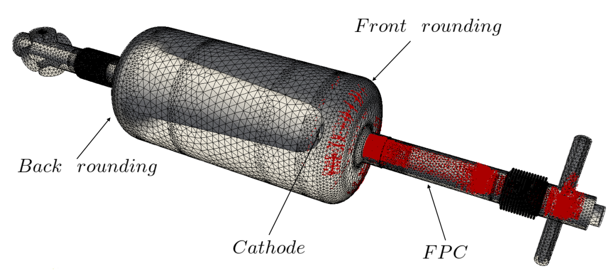

Figure 1: Geometry of the CeC photo-injector. Areas of the cavity affected by MP are shown in red.

With the knowledge of the main MP levels and their locations, operation of the gun became very intuitive. When bringing the cavity to the operating voltage, we would keep the first solenoid at zero current, and insert the FPC into position with the maximum achievable coupling using full 4 kW of available RF power in order to overcome the 40 kV MP level. After passing a voltage of about 100 kV there was no significant MP activity, and we were able to bring the cavity to the operational level by adjusting coupling via FPC position in a phase-lock loop mode.

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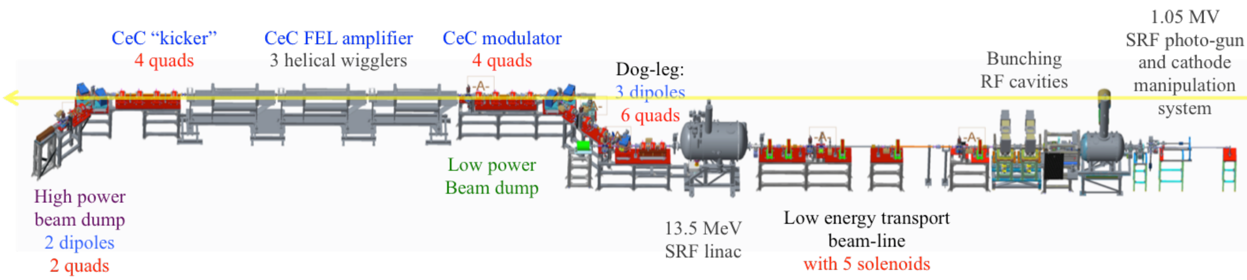

Figure 2: Schematic of the CeC experiment.

In cases when the cavity was caught onto the 40 kV MP level, the gun was turned off immediately, and left idle for about 30 minutes. We assume that this time is needed to oxidize Cs released from the surface of the cathode by the stray electron bombardment during the MP.

Overall, the gun performance during the Run'17 was stable with the photocathode maintaining high quantum efficiency and being replaced only once during 5 months of operation.

Self-Consistent Simulation

Since the photo-injector is the very first step in the beam acceleration, it is important to perform the simulations of the beam-cavity interactions taking into account the fact that it is dominated by space charge effects. One of the tools that can perform self-consistent simulations of this kind is Pic3P [6]. Pic3P solves the complete set of Maxwell-Lorentz equations self-consistently and includes space charge, retardation, and boundary effects from the first principles.

The first attempt of the simulation was performed for the 3D simplified geometry of the gun (bellows were excluded) using a mesh of about 2.2M tetrahedral elements, with enhanced mesh distribution along the beam path—meshcell size of about 0.8 mm. Initial parameters of the beam are shown in Table 1.

Table 1: Beam Parameters for the Self-Consistent Simulation of the Gun

Parameter	**Value**
Total charge, nC	0.5
Number of particles	50 000
Initial velocity β_z	0.003
Radial distribution	Uniform
Radius, mm	1.5
Longitudinal distribution	Flattop
Duration of the flattop. ns	0.5
Rise/drop time, ns	0.05

The simulation did not include the external magnetic field of the first solenoid, and focusing of the beam was only provided by the electric field distribution in the gun due to the cathode puck being recessed by 6 mm relative to the "nose" of the cavity. The preliminary results of the simulation are shown in Fig. 3-6. In order to obtain an accurate solution of the self-consistent problem, we still need to perform a mesh convergence study, and analyze the dependence of the solution on the primary number of particles in the beam, the time step and the order of curved tetrahedral elements.

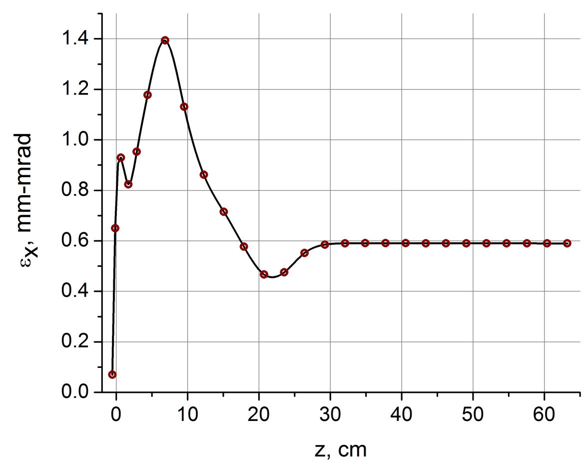

Figure 3: : Normalized transverse RMS emittance as a function of the beam position in the gun. Cathode is recessed by 6 mm.

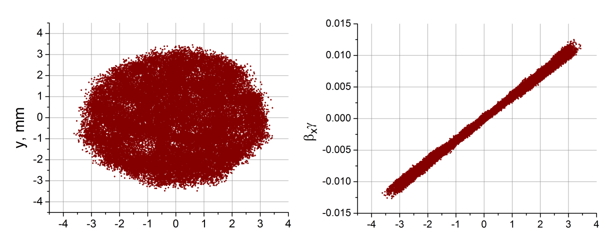

Figure 4: Transverse distribution and trace space of the bunch at z=60 cm from the cathode surface.

BEAM DYNAMICS STUDY

One of the critical processes in beam dynamics is a ballistic compression of the electron bunches from hundreds of picoseconds to about 20 psec. The required energy chirp is provided by the 500 MHz room-temperature cavities. The compressed beam is then propagated to the dogleg, where

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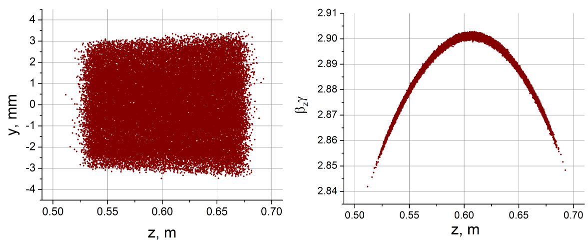

Figure 5: Longitudinal distribution and trace space of the bunch at z=60 cm from the cathode surface.

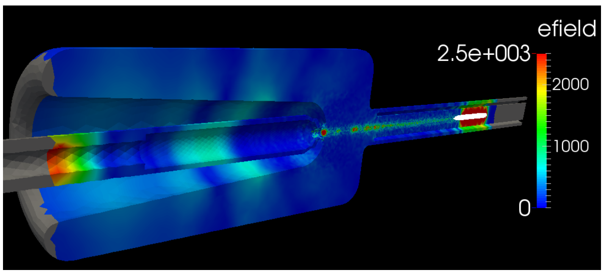

Figure 6: Electromagnetic fields induced by the electron beam in the SRF gun.

horizontal dispersion is used to analyze the beam energy spread and the bunch duration. A YAG profile monitor was used for this purpose, and the horizontal dispersion function was measured by changing the dipole magnet current. To study the longitudinal bunch structure we generated correlations between energy and time by operating the linac at ±15 degrees off-crest. Hence, the combination of the off-crest acceleration and horizontal dispersion allowed us to utilize an improvised "streak camera". The quadrupole triplet in front of the dipole magnet was used to focus "betatron motion" of the electrons at the YAG screen. An example of a measured longitudinal profile for the 1.2 nC bunch charge is shown in Fig. 7. One can see that part of the bunch has a periodic micro-bunching with a period of about 1.5 psec. Several factors can be responsible for such time structure: it can originate from the time structure of the initial laser pulse, space-charge driven micro-bunching instability or from wakefields induced by the beam in the transport channel.

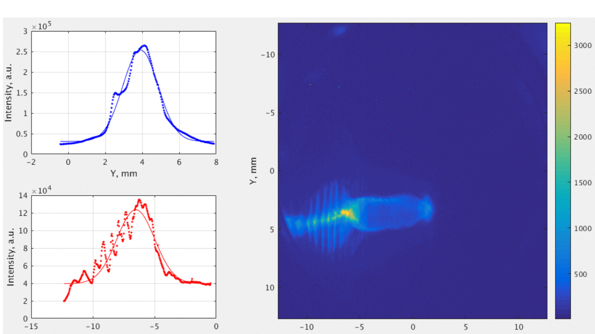

Figure 7: Periodic beam structure in the dogleg.

Numerous studies of the beam dynamics for the CeC beamline were performed throughout the years, but none of them had self-consistent simultaneous inclusion of space charge and wakefields [9, 10]. There are a number of sources of wakefields in the CeC beamline: bellows, beam diagnostics, mirrors and laser cross chamber, and other transitions in the size and shape of the vacuum chamber. We are in the process of simulating these wakefields and taking them into account in the beam dynamics simulations. With existing software for 3D simulations, such as CST Microwave Studio [11] and ACE3P [6], wakefields are calculated in non-symmetrical structures, and the resulting fields can be imported into the programs for the beam dynamics simulations. Our current plan is to perform a comprehensive wakefield study in the entire CeC system, and include the resulting fields into the IMPACT-T [12] calculations in order to see the influence of the wakefields on the beam structure.

CONCLUSION

The CeC accelerating system was successfully commissioned during this year's run. With better understanding of the multipacting events in the SRF gun, we achieved a stable operational regime, and utilized only two CsK_2Sb photocathodes during the 5 months of operation.

As a part of preparation for next year, our goal is to perform a self-consistent simulation of the SRF gun, including space charge effects and wakefields, and study the influence of the wakefields and space charge on the beam dynamics throughout the whole system.

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