SRF PHOTOINJECTOR FOR PROOF-OF-PRINCIPLE EXPERIMENT OF COHERENT ELECTRON COOLING AT RHIC*

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Abstract

Coherent Electron Cooling (CEC) based on Free Electron Laser (FEL) amplifier promises to be a very good way to cool protons and ions at high energies. A proof of principle experiment to demonstrate cooling at 40 GeV/u is under construction at BNL [1]. One of possible sources to provide sufficient quality electron beam for this experiment is a SRF photoinjector. In this paper we discuss design and simulated performance of the photoinjector based on existing 112 MHz SRF gun and newly designed single-cavity SRF linac operating at 704 MHz.

INTRODUCTION

Presently, two efficient techniques are used for cooling hadron beams; electron cooling [2], and stochastic cooling [3]. Unfortunately, the efficiency of traditional electron cooling rapidly falls with the increase in the beam's energy. From other hand the efficiency of traditional stochastic cooling, while independent of the particles' energy, rapidly falls with the number and the longitudinal density of particles.

The BNL CEC Proof of principal experiment is aiming to demonstrate in the first time the cooling of high energy ion beam (energy of 40 GeV) using electron bunches. The cooling concept is based on already demonstrated technologies (such as high-gain FELs) and well understood processes in plasma physics (see [4] for details of CEC).

The required electron beam parameters for demonstration of proof of principal CEC at RHIC Au ion beam are shown in Table 1.

THE LAYOUT AND MAIN COMPONENTS

The layout of electron beam injector based on SRF gun is shown on Fig. 2. For the purpose of this test we will use as much as possible: existed, already designed or to be completed soon components. The relatively long electron bunch (~400 psec) is generated in 112 MHz SRF gun [5] by KCs_2Sb photocathode and accelerated by the RF field in the gun to 2 MeV. The gun cross–section is shown on Fig. 1. Photocathode is located in a high electric field. Immediate acceleration of the electrons to a high energy reduces emittance degradation caused by a strong non-linear space charge forces. The low RF frequency of the gun reduces the RF curvature effect to the beam. Then two 500 MHz cavity and long drift space with focusing solenoids are used to provide ballistic compression by 10-15 times. After beam is almost compressed to required peak current the beam is accelerated by 704 MHz SRF linac to 22 MeV. Then electron beam merged with ion beam by set of dipole and quadrupole magnets. All RF cavities will operate at the harmonic of the RHIC beam's revolution frequency of 78.2 kHz.

Table 1: The Main Electron Beam Parameters for the CeC Demonstration Experiment

Parameter	Units	
Electron beam energy	MeV	21.8
Charge per bunch	nC	0.5-4
Normalized emittance	mm-mrad	5
Peak current in FEL	A	60-100
RMS energy spread, relative		$1x10^{-3}$
Electrons per bunch		$3.1\text{-}6.2x10^9$
Repetition rate	kHz	78.2

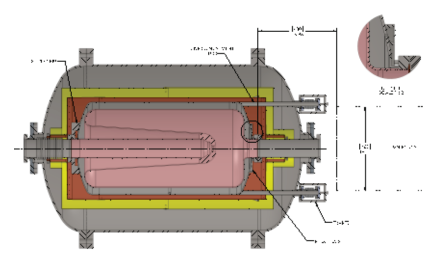

Figure 1: Cross-section of 112 MHz SRF gun with proposed modification. Two tuners will be added for precise setting of the resonant frequency.

A five-cell 704 MHz 20 MV superconducting cavity for high-current applications which is under development at BNL [6] is planned to use in CEC POP test (Fig. 3).

RESULTS OF BEAM DYNAMICS SIMULATION

In proposed cooling scheme the information is carried by the electron beam (both its density and the energy modulation). Then FEL is used for amplification [4].

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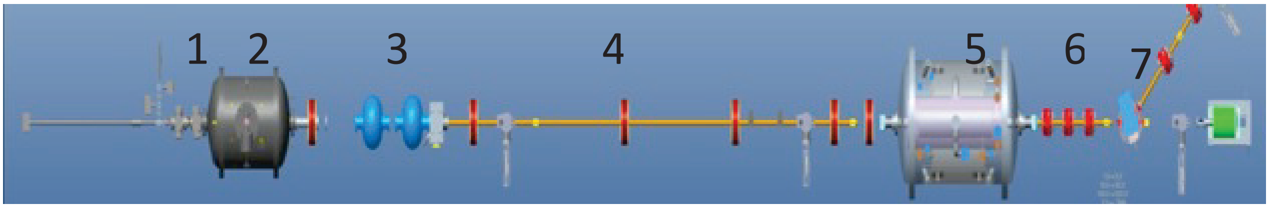

Figure 2: The layout of the CEC PoP experiment electron beam driver: 1) Cathode interchange lock-load mechanism; 2) 112 MHz SRF gun in cryomodule; 3) 500 MHz NC bunching cavities; 4) solenoids; 5) 704 MHz 5cell SRF linac in Cryomodule; 6) quadrupole magnets; 7) dipole magnet.

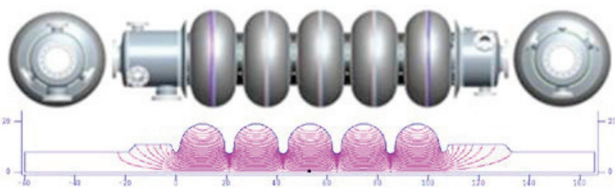

Figure 3: BNL3 20 MeV 704 MHz SRF linac and result of SUPERFISH field simulation.

The FEL amplification is in very strong dependence on the peak current. Therefore there is additional requirement for uniformity of electron current distribution along the beam. The effective charge of the electron beam participated in the process of coherent cooling of the ion beam can be writing in the simple way [7]:

$$Q_{eff} = e^{-\alpha} \int_{-\infty}^{\infty} I(t) e^{\alpha \left(\frac{I(t)}{I_{max}} \right)^{1/3}} dt ,$$

where Q_{eff} is the effective charge, $I(t)$ is the beam current, I_{max} is the maximum peak current, $e^{\alpha}=100$. For example for Gaussian distribution the effective charge calculated by this equation is only 65% of full charge in the bunch. PARMELA [8] tracking code was used for beam dynamic simulation from the cathode to the end of the linac.

The results of simulations are summarized in Figs. 4-8.

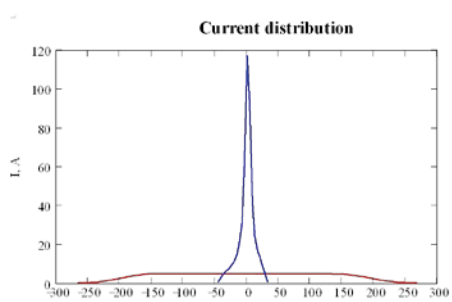

Figure 4: Initial (red) and final (blue) current distributions for Q=2 nC, Ugun=2 MeV, Ubuncher 2x250 keV.

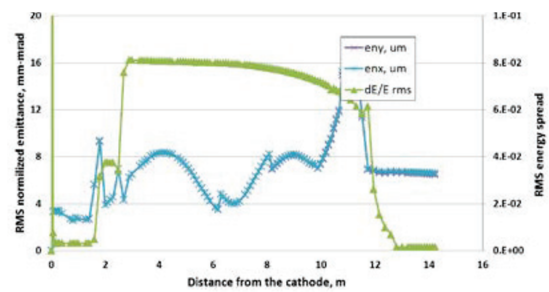

Figure 5: Normalized emittances and energy spread along the CEC POP injector line (full distribution). Final emittance 6.6 mm-mrad and final energy spread $1.6x10^{-3}$.

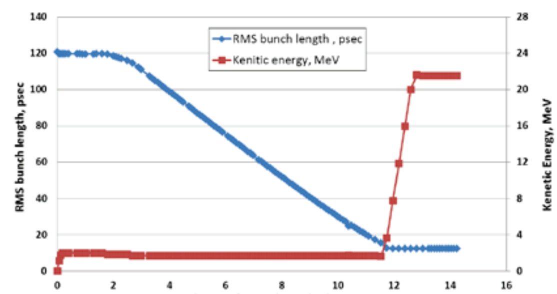

Figure 6: Energy and rms bunch length along the CEC POP injector line (full distribution).

The core of the beam is the most interesting and useful for cooling part of the electron beam. Instead of using average parameters of the full beam we calculate the energy spread and normalized emittance for the part of the beam in ± 10 psec interval from the center Figs. 7-8.

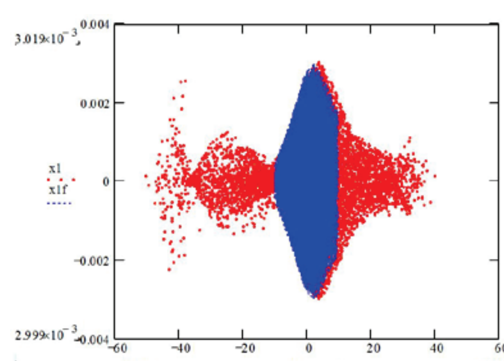

Figure 7: Full particle distribution (in red) and beam core ± 10 psec (in blue). The core charge is 1.3 nC.

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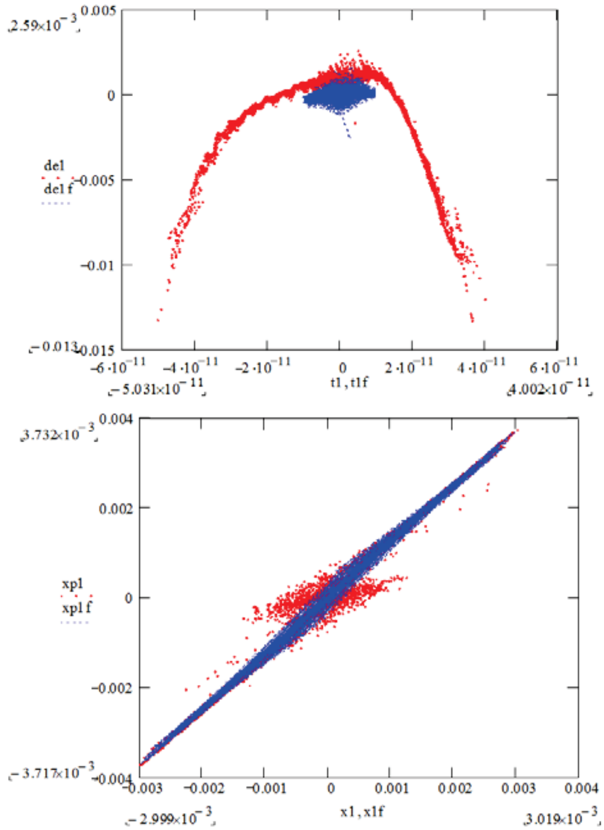

Figure 8: Longitudinal (top) and transverse (bottom) phase space plot at final energy. Red dots full beam, blue dots represent only the core of the beam ~75% of the full charge. For all particles: the rms energy spread 2.1x10^{-3}, normalized emittance 8.6 mm-mrad, for 75% of the beam: the rms energy spread 3x10^{-4}, normalized emittance 3.3 mm-mrad.

Table 2: Results of PARMELA Simulations

Parameter	**Units**	**Full**	**Core**
Initial peak current	A	10	10
Gun beam energy	MeV	2	2
Final beam energy	MeV	21.8	21.8
Charge per bunch	nC	2	1.3
Effective charge	nC	0.95	0.81
Fanal peak current	A	110	110
Normalized emittance	mm-mrad	6.6	3.3
RMS energy spread		1.6x10^{-3}	3.3x10^{-4}

SUMMARY AND CONCLUSIONS

- We assume that tails of the electron bunch due to very low intensity will not contribute in heating process as well as not contribute in cooling one.
- Beam dynamics studies demonstrated that 112MHz SRF cavity based accelerator may be used as an injector for CEC POP experiment.
- Downstream 500MHz buncher cavities allow to start with initial ~400 psec pulse. Ballistic compression provides sufficient increase of peak beam current while mountain good enough uniformity of bunch distribution.
- Results of beam simulation summarized in Table 2.
- The detailed studies of beam dynamics through out all CEC POP test system (gun, Linac, transport, FEL) are required.

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