ELECTRON COOLING AND ELECTRON-ION COLLIDERS AT BNL*

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Abstract

Superconducting Energy Recovery Linacs (ERL) have significant potential uses in various fields, including High Energy Physics and Nuclear Physics. Brookhaven National Laboratory (BNL) is pursuing some of the potential applications in this area and the technology issues that are associated with these applications.

The work addressed in this paper is carried out at BNL towards applications in electron cooling of high-energy hadron beams and electron-nucleon colliders. The common issues for these applications are the generation of high currents of polarized or high-brightness unpolarized electrons, high-charge per bunch and high-current. One must address the associated issue of High-Order Modes generation and damping. Superconducting ERLs have great advantages for these applications as will be outlined in the text.

INTRODUCTION

Electron-ion (and positron-ion) collisions have unique properties that make them very valuable for high-energy and nuclear sciences. Not surprisingly new questions keep coming up and the need for accelerators with greater reach and greater variety of colliding species is ever present. In particular, the need to study QCD, improve the understanding of the structure and spin structure of hadronic matter, understanding the transition from the deconfined state of free quarks and gluons in the Big Bang to stable hadron matter can be addressed with higher precision in lepton-ion collisions. High luminosity, and beam cooling are essential features of future machines. Hence, a new generation of electron-ion colliders is one of the key instruments to unravel the crucial fundamental physics questions.

In this work I will first outline the new emerging applications for SRF ERLs and the associated SRF technological and proceed to describe future BNL plans on the electron cooling of RHIC and the eRHIC electron – ion collider, including hardware developments towards these future upgrades of RHIC. In addition, I will describe a few other directions for our R&D, such as a polarized electron SRF gun, which, if successful, can eliminate the need for the electron damping ring of the ILC and provide an interesting source for eRHIC polarized beam operations, and a new storage cavity of RHIC, a 56 MHz quarter Wave resonator.

ISSUES AND TECHNOLOGIES

The luminosity of an electron-ion collider can be written in terms of the fundamental machine limits, the beam-beam parameters and angular acceptance of the IP quads as

$$L = \left(\frac{4\pi\gamma_i\gamma_e}{r_i r_e} \right)(\xi_i\xi_e)(\sigma_i'\sigma_e')f$$

where round beams of the same size are assumed at the IP and subscripts i or e denote ions or electrons. The ξ are the respective beam-beam parameters, r are the classical radii and γ are the relativistic factors, and f the collision frequency. The angular rms spreads σ' at the IP are limited by the aperture of the final focus quadrupoles. Clearly the achievable luminosity scales with the assumed beam-beam parameter and a good understanding of this limit is necessary in any machine.

The idea of using an electron Energy Recovery Linac (ERL) to collide with other leptons is not new [1]. It was later proposed in the context of electron-ion colliders [2] and recently summarized by Ptitsyn [3]. The advantages of the ERL for electron-ion colliders include a higher luminosity, given by the fact that the electron beam is used for the collision only in a single pass and thus withstands a much higher beam-beam parameter.

Round beams, naturally produced in ERLs, are optimal for maximizing the luminosity for a given beam-beam parameter, i.e. they provide for the use of round beams of equal size at the collision point(s). If the electron bunch intensity can always be adjusted to reach the ion beam-beam parameter ξ_i, the luminosity is only limited by the ion beam parameters:

$$L = \gamma_i f \, N_i \frac{\xi_i Z_i}{\beta_i^* r_i}$$

where N_i is the ion bunch intensity, Z_i is the ion charge, β_i^* is the ion beta function at the collision point. Thus, with the ERL, the luminosity can be improved for a given center-of-mass energy by reducing the energy of the electron beam while increasing the energy of the ions.

The ERL has many advantages over a storage ring: It can deliver a high polarization with full polarization transparency at all energies. It is easily integrated with multiple electron-hadron interaction points (IPs) and detectors. It does not require spin rotators for longitudinal, radial or transverse polarizations. It has a large energy range at full luminosity and full polarization. Its low emittance beams simplify the IP optics.

The technology issues associated with ERLs can be broken down to two areas. First the generation of the necessary electron beams, then the acceleration of these beams, overcoming such issue as beam breakup and safe removal of HOM power from the superconducting RF (SRF) cavities.

     FR1: Future Projects and New Ideas I

The main risk in this approach is the availability of a polarized electron source with the necessary high current, an issue that should be resolved with well-focused R&D.

ELECTRON COOLING OF RHIC

A critical technology for electron-ion colliders is electron cooling for the ion beam. High-energy electron cooling is a new technology, and so far has been demonstrated only to a relativistic beam factor γ of about 8 [4], while γ of 100 to 150 is necessary in some electron-ion colliders. In addition, cooling of colliding beams has not been done yet and no doubt there will be interesting consequences.

Cooling at the collision energy is needed when the intra-beam scattering (IBS) affects significantly the luminosity lifetime. Thus faster cooling is needed at lower energies or when the ion density is pushed higher to increase the luminosity.

Cooling a dense high energy ion beams is not easy, and requires high charge electron bunches (to make up for the high charge of the ions and overcome IBS) and low emittance (to provide a small angular spread of the electrons). This type of electron beam can be produced only by a linac. Electron cooling at these energies is under extensive investigation and prototyping at BNL [5].

The generation of beams for electron cooling places the emphasis on high-charge, up to 5 nC, high-current, up to 0.1 amperes, and low emittance, about 3 to 4 microns (normalized rms emittance). One approach that is being followed at BNL is the use of SRF laser-photocathode gun. The layout of the electron cooler ERL [6] is shown in Fig.1. The machine will be characterized by a high bunch charge and good emittance, as well as high average CW current.
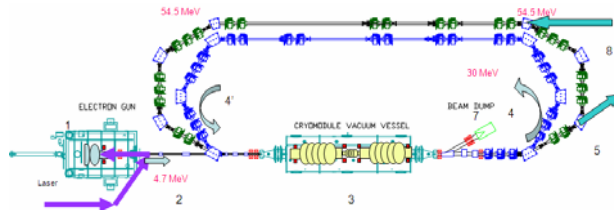

Figure 1. A 2-pass 54 MeV ERL for electron cooling of RHIC. (1)SRF Gun, (2) Injection merger line, (3) SRF Linac two 5-cell cavities and 3rd harmonic cavity, (4, 4') 180° achromatic turns, (5,6) transport lines to and from RHIC, (7) ejection line and beam dump, (8) short-cut for independent run of the ERL.

eRHIC

eRHIC is a proposed high-luminosity ion-ion and polarized protons collider [7]. eRHIC will add an electron accelerator to collide with the RHIC ions. eRHIC's preferred design uses a superconducting electron ERL for reasons outlined above.

eRHIC will provide 3-20 GeV polarized electrons and 50-250 GeV polarized protons; 100 GeV/n gold ions and 167 GeV/n polarized 3He ions. The luminosities will be over 10^{33} cm^{-2}s^{-1} for e-p collisions and similar per-nuclean

luminosity for e-Au collisions. The expected polarization is at least 70% for proton beams and over 80% for electron beams.

Initial acceleration to the energy of 0.5 GeV will be done by a smaller pre-acceleration linac. A 4 GeV ERL will be used in a five pass acceleration / deceleration scheme. The higher energy re-circulating passes of the ERL will share the RHIC tunnel with the ion rings, leading to a significant cost saving.

The design parameter tables 2,3 are based on setting the limiting value of the ion beam-beam parameter to ξ_i=0.015, which seems to be realistically achievable, based on the experience of the RHIC operation with polarized proton beams and assuming a dedicated single collision point.

The ERL is based on a 703.75MHz SRF cavity designed for ERL service (see below). The design assumes 20 MeV energy gain per cavity and a current of over 0.25 amperes. 200 cavities are used in a 600m long linac, consisting of four 150m long sections that fit in the RHIC straight sections to provide 4 GeV acceleration in one beam pass. The average luminosity is expected to be about 1/3 of the peak luminosity, leading to a luminosity integral of 530 (580) inverse picobarn per week for the protons (gold) at the higher energy.
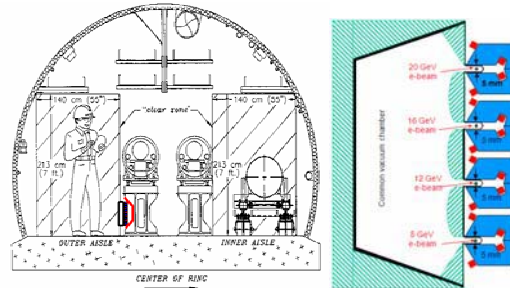

Figure 2. Left – the RHIC tunnel showing the electron beam lines of eRHIC, mounted bellow the outer ring (just below the knee of the man's figure). Right – detail of the multiple pass magnets of eRHIC, using a common vacuum chamber [8].

SRF DEVICE DEVELOPMENT

½ cell SRF gun at 703.75 MHz

As described above, the performance of the electron cooler and eRHIC require electron sources of high charge, low emittance and CW operation. Table 1 shows the parameters of the BNL-AES SRF gun. It has been optimized [9] to obtain a small emittance at a large charge by shaping the gun cavity, selection of its frequency and field.

The gun design is dictated by the objective of a high current but at a limited (1 MW) CW klystron power. Thus a single cell design is used, which allows for a high accelerating field at a limited total voltage of 2 MV.

The choice of frequency was dictated by the need to maintain the frequency a harmonic of the RHIC frequency with 360 bunch pattern of 28.15 MHz, lower the frequency to a value where beam breakup threshold

current in the ERL will be large and, finally, a frequency where CW MW klystrons are available. That led to the choice of 703.75 MHz.

This SRF gun is equipped with a demountable photocathode capable of being inserted and retracted while maintaining the vacuum integrity and cleanliness of the photoinjector.

The cavity iris had to be made small for beam dynamics reasons (reduction of effective length of the cavity). That precluded damping all HOMs through the beam pipe.

At a beam pipe diameter of 10 cm, the same as the iris of the cavity, most of the HOMs propagate adequately to the load. The reduced beam pipe size simplifies the strong coupling of the 1 MW RF power to the beam and reduces the size of the exit vacuum valve.

Table 1: BNL-AES SRF Gun Specifications [9]

Parameter	Units	Value
Frequency	MHz	703.75
Iris radius	cm	5
Equator Diameter	cm	37.9
Cavity length	cm	25
Beam kinetic energy	MeV	2
Peak electric field	MV/m	35.7
Peak magnetic field	A/m	58740
Stored energy	Joule	8.37
QR_s (geometry factor)	Ω	3.52
R/Q	Ω	96
Q_e (external Q)		37000
Longitudinal loss factor	V/pC	0.7
Transverse loss factor	V/pC/m	32

Additionally, a high temperature superconductor focusing solenoid will be inserted optimally just inside the cryomodule.

The gun propagates all but 3 of the HOMs down the beam pipe to a room temperature ferrite HOM absorber. The 3 trapped modes can be easily missed by harmonics of the beam repetition frequency and detailed calculations have shown that the effect of long range wake fields can be neglected if the beam amplitude and phase noise are under a reasonable limit. It is expected that the strong coupling of the fundamental power couplers will damp some or all of these modes. Work is in progress on this question.

5-cell accelerating cavity at 703.75 MHz

The acceleration of high-charge and high-average-current beams in SRF structures is closely related to the problems associated with High Order Modes (HOM). Dipole type HOMs may lead to the multi-bunch, multi-pass Beam Breakup (BBU) in ERLs. In addition, the large power generated by the HOMs must be safely removed

from the cavities and dumped. Good damping of all modes is thus essential both for a high current threshold of the BBU and for the operation of the cryogenic SRF cavities. The HOM power is proportional to the product of the longitudinal loss factor k_l by the average current and bunch charge. For a typical SRF cavity k_l of 10 Volts/pC, a beam with 20 nC bunch charge at 0.2 amperes average current will generate 40 kW of HOM power! This amount of power is higher than demonstrated so far. However, if the cavity loss factor can be reduced to 1 V/pC, the HOM power will be only 4 kW, a value that can be handled by existing HOM dampers.

The BNL cavity [10] is characterized by a low longitudinal loss factor of 1.1 V/pC thanks to the combination of low frequency and very large apertures of 19 cm diameter. All HOM modes are damped to Qs of better than 10^4 (most down to 10^2) thanks to the large apertures, even larger beam pipe (24 cm diameter) and beam-line ferrite damper. Simulations show about 2 ampere threshold current for the eRHIC ERL in multi-pass mode using such cavities [11]. At the same time the other performance measures of the cavity are excellent: A peak surface field to accelerating field ratio of 2 and very high stiffness (lowest mechanical mode at 100 Hz and Lorentz force detuning of 1.2 Hz/(MV/m)^2).

1.3 GHz polarized electron gun

The generation of polarized electron beams for high-energy and nuclear physics applications is well known and used routinely at various laboratories. The challenge of the ERL application comes from the need for both high-charge, high-current and long lifetime. The current density presently achieved from the surface of cesiated, strained gallium-arsenide photocathodes are sufficiently high to be scaled to the required current. Such area scaling is transparent to cathode lifetime due to ion bombardment and conductivity issues. It seems that adequate power can be provided by lasers. Since the gun must be operated at an ultra-high vacuum of better than 10^{-11} torr, a 2K superconducting gun seems to offer an advantage thanks to the good cryopumping. In addition, an extremely good emittance has been shown in simulations, making such a gun interesting for ILC polarized electron source and capable of producing the ILC bunch charge with a flat beam at an emittance better than that produced by the ILC damping ring, thus potentially saving the cost of the electron damping ring. We embarked on an experiment to carry out such a test, using an existing [13] 1.3 GHz SRF gun. The challenge is in inserting a cesiated gallium arsenide cathode into the gun while maintain the good vacuum in the insertion and gun operation [14]. Past attempts for the operation of polarized electron cathodes in non-superconducting RF guns were not successful, mostly due to poor vacuum conditions.

SRF gun are more promising thanks to cryogenic pumping even of hydrogen (at 2K), it may be possible to maintain a vacuum close to 10^{-12} torr.

Of concern would be in this case contamination of the gun cavity by evaporating cathode material and the

possibility of dark electron current from the GaAs:Cs cathode, which may damage the cathode. Obviously a good load-lock cathode insertion system must be developed. Figure 3 shows the gun mounted on a cryostat top-plate (showing the convection baffles of the top-loading cryostat) with a cathode transporter connected and in the inset the gun with the cathode clamp mechanism and the cathode transporter removed. The cathode clamp mechanism and transporter are being designed and built by Advanced Energy Systems [15].
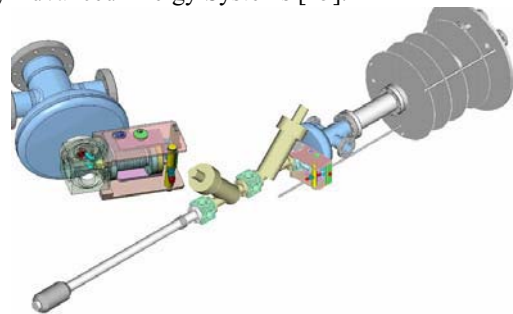

Figure 3. The polarized gun with the cathode clamp mechanism (upper left) and the gun with cathode transporter engaged.

56 MHz RHIC Storage Cavity

The use of superconducting RF storage cavities for an ion storage ring provides various advantages. In a machine which injected with a large longitudinal emittance beam, a low frequency but high voltage storage cavity helps to keeps the ion bunches in the 'bucket', sometimes eliminating the need for complex bunch gymnastics that spoil emittance. In RHIC, the use of a superconducting storage cavity at 56 MHz (harmonic 720) allows adiabatic rebucketing directly from the 28 MHz accelerating cavity. Stochastic cooling in RHIC significantly benefits from this new RHIC storage rf system based on superconducting 56 MHz cavities. Such a new storage rf system will benefit all RHIC operations, with and without any cooling, as it eliminates the satellite bunches and therefore reduces the length of the effective vertex distribution, thus leading to a higher effective luminosity.

The SRF storage cavity can be operated as an idler cavity or with very little RF drive, leading to improved reliability and stability. In a machine like RHIC, in which the vacuum is important to battle electron cloud problems, the cryogenic quality vacuum is another advantage. Finally, the large voltage, 2.5 to 3 MV conservatively from single cavity, reduces the part's count and lead to somewhat lower impedance.
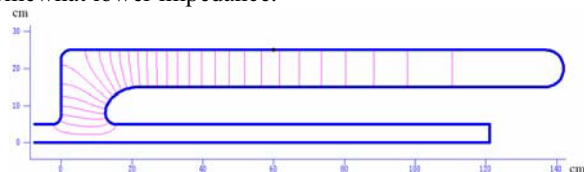

Fig. 4. Field lines in the 56 MHz quarter wave resonator.

From the Superfish calculation [16] shown in Figure 4, at a voltage of 2.4 MV the 56 MHz QWR has a stored

energy of 207 Joules. Assuming a residual resistivity of 10 nOhms, we can expect an unloaded Q of 2×10^9, (geometric factor of 20). At an operating temperature of 4.2 K the BCS surface resistivity is quite a bit smaller than 10 nOhms. Given the r/Q of 80 Ohms, we expect a liquid helium dynamic power load of 41 W. The peak magnetic field is 82 kA/m, and peak electric field 38.9 MV/m, all quite reasonable numbers.

SUMMARY

BNL's future plans include high-energy electron cooling and an electron ion collider. Superconducting RF science and technology play a significant role in these plans. An intensive R&D program is under way to develop various SRF devices, including a 5-cell, 703.75 MHz multi-ampere accelerating structure, a 703.75 MHz high-current SRF electron gun, a 1.3 GHz polarized electron SRF gun and a 56 MHz quarter-wave resonator for storage of ion beams in RHIC. These projects are in various stages of development, some just started and some have actual cavities undergoing tests. The cavity has been described in previous publications [5].

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