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BNL-81849-2009-CP

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Presented at the Particle Accelerator Conference (PAC09)
Vancouver, B.C., Canada
May 4-8, 2009

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Abstract

Design of a medium energy electron-ion collider (MeRHIC) is under development at the Collider-Accelerator Department at BNL. The design envisions construction of a 4 GeV electron accelerator in a local area inside and near the RHIC tunnel. Electrons will be produced by a polarized electron source and accelerated in energy recovery linacs. Collisions of the electron beam with 100 GeV/u heavy ions or with 250 GeV polarized protons will be arranged in the existing IP2 interaction region of RHIC. The luminosity of electron-proton collisions at the 10^{32} $cm^{-2}s^{-1}$ level will be achieved with 50 mA CW electron current and presently available proton beam parameters. Efficient proton beam cooling at collision energy may bring the luminosity to 10^{33} $cm^{-2}s^{-1}$. An important feature of MeRHIC is that it serves as a first stage of eRHIC, a future electron-ion collider at BNL with both higher luminosity and energy reach. The majority of MeRHIC accelerator components will be used in eRHIC.

INTRODUCTION

The design development for a future electron-ion collider eRHIC has been underway in recent years at BNL [1,2,3]. eRHIC will be based on the addition of an electron accelerator to the existing RHIC machine, providing the capability of physics experiments with polarized electron-proton and electron-ion collisions. In the present design of eRHIC, the energy recovery linacs are used for the acceleration of the electron beam to energies as high as 20 GeV.

A staged approach for eRHIC has recently been adopted, based on a gradual increase of electron beam energies and design luminosities [4]. In the first stage, an 4 GeV electron beam will collide with protons and ions circulating in RHIC. This medium energy electron-ion collider is named MeRHIC.

During the course of the last several months, the initial design of MeRHIC has being developed, including the lattice of major machine components, evaluation of main factor defining the beam dynamics, and the design of superconducting energy recovery linacs. Since MeRHIC is envisioned as the initial stage of eRHIC, the major components of MeRHIC, such as the SRF linac modules, the injector system and some of recirculation pass magnets will be re-used in eRHIC.

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.

GENERAL SCHEME

In the present design all components of the electron accelerator for MeRHIC are placed near the IR2 interaction region of RHIC. This region has an asymmetric experimental hall, well-suited for asymmetric energy electron-ion collisions, and a wide (7.3m) long straight section of the RHIC tunnel on one side from the IR, a convenient location for an electron linac. The electron beam is initially produced by a high current polarized electron source, then accelerated to 100 MeV in a 10 MeV linac and 90 MeV energy recovery linac. Further acceleration is done by multiple passages through two separate energy recovery linacs (ERLs), with an energy increase of 0.65 GeV per linac pass. To reach 4 GeV, three passes through the linacs are needed. After colliding with protons or ions at the IR2 collision point, the electron beam is decelerated to 10 MeV in the main and 90 MeV ERLs and directed to the beam dump. Recirculation of the electron beam between the main linacs is realized by three vertically-arranged magnet lines or recirculation passes. There are two electron machine layouts under consideration. In the first, both main linacs are placed inside the RHIC tunnel. In the other, only one ERL is placed in the tunnel while the other is placed in parallel on the outer side of the tunnel. The cost of both approaches is comparable, but the latter has some construction advantages.

The main design parameters of the proton and ion beams for MeRHIC have been chosen to be close to those already demonstrated at RHIC, or those planned in near future for RHIC operation with proton-proton (or ion-ion) collisions. Taking advantage of RHIC's ability to provide a wide range of beam energies, MeRHIC will use 50-250 GeV protons and 30-100 Gev/n gold ions. High proton beam polarization (60%), achieved in RHIC, is crucial for the experiments planned with electron-proton collisions.

Table 1 presents beam parameters and design luminosities that can be achieved in MeRHIC electron-proton collisions. Proton baseline parameters do not assume transverse or longitudinal cooling. With these baseline parameters the luminosity of e-p collision is at the 10^{32} $cm^{-2}s^{-1}$ level. Some "upgrade" options that can lead to higher luminosities have been also considered. The highest luminosity (~9 10^{32} $cm^{-2}s^{-1}$) can be achieved if transverse and longitudinal cooling of 250 GeV protons can be realized. Coherent electron cooling technology may serve as a possible candidate for high-energy cooling of MeRHIC protons if further development of this cooling method demonstrates its efficiency [5].

Table 1: MeRHIC parameters for e-p collisions.

	Baseline		High-energy cooling	
	p	e	p	e
Energy, GeV	250	4	250	4
Bunch spacing, ns	107		107	
Bunch charge, nC	32	5	32	5
Average current, mA	280	46	280	46
Normalized emittance, mm.mrad 95% for p, rms for e	15	73	1.5	7.3
rms emittance, nm	9.4	9.4	0.94	0.94
beta*,cm	50	50	50	50
rms bunch length, cm	20	0.2	5	0.2
Beam-beam for p, disruption parameter for e	0.0015	3.1	0.015	7.7
Peak Luminosity, 10^{32} $cm^{-2}s^{-1}$	0.93		9.3	

INJECTOR

One of most challenging components of MeRHIC, and eRHIC is a high-current polarized electron source. For MeRHIC the polarized source should produce 46 mA average electron current. An R&D program, conducted by MIT-Bates and BNL, is underway to explore and resolve issues related to high current production: limited cathode lifetime due to the ion back-bombardment, the surface charge limit, and cathode cooling. The design approach is based on increasing the cathode area and possible application of a ring-shaped emission pattern from the cathode. A design of a polarized gun with adequate cooling has been developed and further plans include building a test chamber, demonstrating the active cooling, and a gun prototype for high current studies. A Gatling gun approach, where a gun has multiple cathodes, arranged along a circle, is also under consideration. The total beam current at the Gatling gun exit is produced by combining bunches coming from the individual cathodes on one trajectory using a RF combiner.

Besides the gun, the injector part of MeRHIC includes a spin rotator (Wien-filter type), an insertion that provides ballistic bunch compression from 250ps to 7ps, the 10 MeV pre-accelerator linac and the 90 MeV energy recovery linac.

SUPERCONDUCTING LINAC

Acceleration of the electrons to 4 GeV in MeRHIC will be done in the superconducting accelerating structures of the energy recovery linacs. This is the fundamental component of the machine design, since it will be also used on next stages of the eRHIC project when the electron energy will be increased to 10-20 GeV. The demand for the high average current of the electron beam dictates the use of the energy recovery approach as well as the choice of superconducting RF structure.

The basis of the accelerating structure is a 704 MHz SRF cavity which has been developed in BNL for high average current applications [6]. Since the electron beam passes the same linac six times during the acceleration and the deceleration, the total electron current going through the linac reaches 280 mA. The cavity design minimizes the power going into high-order modes (loss factor 0.6 V/pC) and provides the capability of effective damping excited HOMs. One important advantage is a considerably increased current threshold of multipass beam breakup.

Each of the two ERLs of MeRHIC accelerates the electron beam by 0.65 GeV on one pass. One of the important goals of the linac design is to make the linacs as compact as possible, which permits their placement in straight sections of RHIC tunnel. In present design the accelerating structure of each linac includes 36 cavities, with 18 MeV energy gain per cavity. Focusing elements (quadrupole doublets) are placed between the strings of 6 cavities. The entire structure, including the focusing elements, is kept at cryogenic temperatures to minimize the linac length.

The focusing system, based on a scaled quadrupole gradient approach, maintains the beta-functions within same range for all energies of beam passage through the linacs. Such a linac lattice simplifies the design of merger/separator insertions, which serve to combine the beam trajectories from different recirculation passes into the linac.

RECIRCULATION PASSES AND IR

The electron beam passes through each of two energy recovery linacs three times during acceleration and deceleration. The recirculation passes are needed to provide transport of electron bunches of different energies between the linacs during acceleration and deceleration. Several important requirements had to be satisfied in the lattice design of the recirculation passes. The isochronous condition ($M_{56} = 0$) is provided by the lattice to guarantee ideal energy recovery for off-momentum electrons. In addition, the lattice allows for flexible adjustment of M_{56} for fine tuning. A large dipole magnet filling factor (~90%) minimizes the dipole magnet strength as well as the power of synchrotron radiation losses. All magnets of the recirculation passes are warm magnets. The recirculation passes for different energies have similar optics. A vertical arrangement of the recirculation passes has been chosen, which may allow a common vacuum chamber for all passes instead of separate vacuum chambers. Since the revolution frequency of the protons beam varies noticeably between 50 and 250 GeV, a path length adjustment insertion is included into each recirculation pass. Combined with a slight variation of the frequency of linac cavities, this allows matching of the bunch repetition frequency of the electrons to that of the protons.

The present design of the experimental detector for the electron-ion collider includes a 4 T central solenoid and two strong dipole magnets (3Tm each) on each side of the detector. The interaction region design of MeRHIC accommodates the experimental magnets as part of the merging/separating scheme to organize the head-on collisions of the proton and electron beams. The critical issue of the protection of experimental area from synchrotron radiation has been resolved with the addition of small field (0.05T) dipoles for the final bending of the electron beam into the detector. In such way the hard synchrotron radiation coming from strong upstream bending magnets can be effectively collimated [7,8].

BEAM DYNAMICS

Most of the compelling beam dynamics issues have been evaluated for MeRHIC design.

Beam-beam interactions in the linac-ring colliding scheme have several distinctive features. Detailed simulations have been done for MeRHIC beam parameters to explore several beam-beam effects: the disruption of the electron beam by the collisions, the kink instability of the proton beam, and the incoherent growth of the proton beam. All those effects were found to be at acceptable levels for MeRHIC [9].

Multipass beam-breakup instability has been studied in simulations using the GBBU code [10]. The instability threshold is considerably higher than the design electron beam current in MeRHIC, especially for the scaled gradient linac lattice (Figure 1).

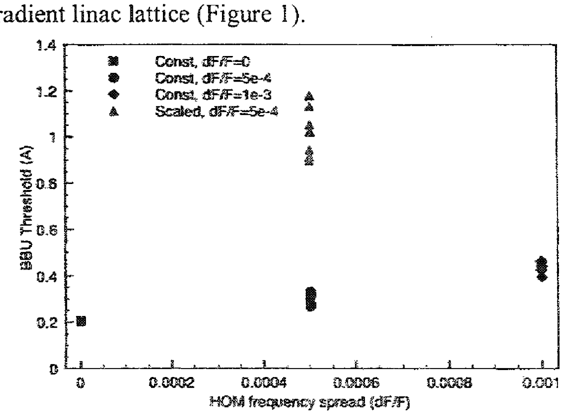

Figure 1: Simulated BBU threshold versus HOM frequency spread. Results are shown for constant gradient and scaled gradient variants of the linac optics.

Another bunch intensity related effect, energy losses due to the interaction of the beam with induced wakefields in the ERL cavities, was found to be very important. The beam energy losses due to this effect are comparable with the losses from the synchrotron radiation. The combined loss power from the interaction with cavity wakes and synchrotron radiation reaches 680 kW. The compensation of these energy losses has to be done to minimize the energy difference between the beams moving in the same recirculation pass on acceleration and deceleration stages. To provide compensation of the energy losses additional cavities (two 2nd harmonic and one 1st harmonic) are installed at three locations. Energy losses from coherent synchrotron radiation were estimated to be negligible.

The largest contribution to the beam momentum spread was found to be from the cavity wakefields (10% at 100 MeV). The momentum spread compression scheme using the optics of 100 MeV transport line has been considered and found possible.

Contributions to the beam halo and possible beam losses from Toushek and beam-gas scattering have been evaluated. Toushek scattering was found to be dominant effect, but with a proper collimation scheme the related beam losses should not present problems.

CONCLUSIONS

The development of main aspects of 4 GeV electron accelerator for MeRHIC project have been the subject of intensive work in recent months. An initial design of the machine, based on the energy recovery linacs and several recirculation passes, has been created. Major beam dynamics issues have been considered. R&D for the polarized electron source, a crucial part of the MeRHIC and eRHIC designs, is underway.

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