ADVANCED CONCEPTS FOR ELECTRON-ION COLLIDER*

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Abstract

A superconducting energy recovery linac (ERL) of 5 to 10 GeV was proposed earlier as an alternative to electron storage rings to deliver polarized electron beam for electron-ion collider (EIC). To enhance the utilization efficiency of electron beam from a polarized source, it is proposed to complement the ERL by circulator ring (CR) wherein the injected electrons undergo up to 100 revolutions colliding with the ion beam. In this way, electron injector and linac operate in pulsed current (beam energy recovery) regime of a relatively low average current, while the polarization is still easily delivered and preserved. To make it also easier delivering and manipulating the proton and light ion polarization, twisted (figure 8) synchrotrons are proposed for heavy particle booster and collider ring. Same type of beam orbit can be used then for electron circulator. Electron cooling (EC) of the ion beam is considered an inevitable component of high luminosity EIC (10^{33}/s. cm^2 or above). It is recognized that EC also gives a possibility to obtain very short ion bunches, that allows much stronger final focusing. At the same time, short bunches make feasible the crab crossing (and traveling focus for ion beam) at collision points, hence, allow maximizing the collision rate. As a result, one can anticipate the luminosity increase by one or two orders of magnitude.

1 INTRODUCTION

Concepts for electron-proton (or ion) collider of energy range 5-10 GeV of electrons vs. 30 to 250 GeV of nucleons and luminosity level of 10^{33}/cm^2.s or higher with both beams polarized for studying the hadronic structure are extensively investigated through recent years [1,2]. Two possible schemes are proposed: scheme with electron storage ring (ring-ring, or RR option) with electron beam polarized by the synchrotron radiation [3], and linac-ring (LR) scheme with electron beam delivered from polarized source and accelerated by a superconducting (SRF) linac under beam energy recovery (ERL) [4]. A critical constraint of RR option is a complexity of preserving and manipulating the electron spin. The challenge to LR scenario is the necessity to approach and operate a high current polarized electron source, injector and ERL. Below we will discuss possible advances in EIC concepts, in particular merging features of two schemes, but also suggesting general improvements based on cooling effect on ion beam and new solutions of polarized ion and electron beam transports.

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2 ERL-BASED EIC WITH CIRCULATOR RING (LCR SCHEME)

In this scheme, electron bunches after acceleration in ERL are injected in a ring to circulate during a large number of revolutions colliding with ion bunches at interaction points and returning to linac in deceleration phase for energy recovery (Fig.1). The decelerated and accelerated bunch trains should overlap in order to reduce to a minimum the voltage deviation in SRF structure [14].

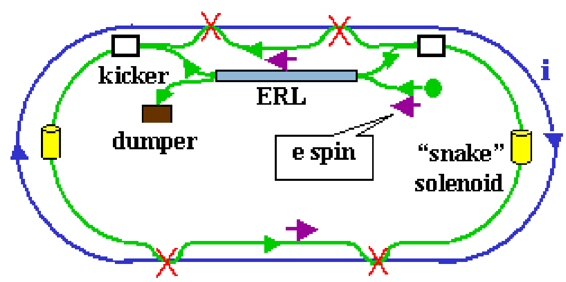


Fig.1. ERL-based EIC scheme with circulator ring

Gain in current operating in collider, obviously, is equal to number of electron revolutions in CR; this number is also equal to the "macro-duty factor" of electron current in injector and ERL. Maximum circulating current is determined by the attainable current value in macro-pulses generated by the polarized electron source. Minimum number of revolutions is limited by the admissible value of average current of electron source or ERL, while the maximum one is limited by the beam quality lifetime in CR.

One can list the following features of LCR scheme with respect to the RR: ease spin handling (no crossing spin resonances, no quantum depolarization); spin rotators around the IP are not needed; spin is not sensitive to energy change; minimum beam emittance is determined by the electron source; high order beam-beam effects less important; a shorter bunch length and larger circulating current value can be attained. With respect to the LR option, the features are as follows: photo-injector released of the loading by a high average current; beam break-up and high order RF modes issues of ERL are alleviated.

3 LINAC-ACCUMUCLATOR-RING VERSION OF EIC (LAR SCHEME)

Maximum charge per bunch in CR is determined by the capabilities of photo-injector. To overcome the related limitations of circulating current, the CR scheme might be extended to accumulator scheme: radiation damping (possibly enhanced by orbit wiggling over the arcs) could be used to accumulate electron bunches from linac in the

RF buckets of the ring. Here, one has to accept the beam parameters attainable in storage rings, while this scheme still succeeds the spin-related features of LR or LCR scheme: after circulation in collider mode, the beam can be refreshed before the radiation impacts significantly the spin. In this scheme, the SRF linac could be operated in pulse regime.

4 CONDITIONED EC AND ION EQUILIBRIUM

In order to make EC more effective against IBS, one can undertake the following measures [5]: 1) reduce to a minimum the x-y coupling along ion orbit outside cooling section; 2) enhance transverse horizontal cooling by organizing the dispersive EC. Then, one gets a minimum critical electron current to overwhelm the IBS, and a flat equilibrium ion beam. Flat electron beam in cooling section can be obtained using beam adapters [6,7] to match between magnetized electron gun and cooling section wherein the beam can be transported by solenoid (preferably at intermediate energies) or by quadrupoles.

Cooling of intense ion beams (up to a few Amps) requires a high electron current (hundreds of mA). To satisfy this request at a modest current from a source, an electron circulator-cooler ring can be incorporated with SRF (ERL) accelerator of cooling facility [5,8,9].

Once the IBS is overwhelmed, EC reduces substantially the ion transverse emittances but also the longitudinal one. Remarkably, it results in very short equilibrium bunches at quite modest parameters of ion RF bucket (1 mm bunch length of 100 GeV proton beam at energy spread 10^{-4} in 1.5 GHz SRF buckets with 5 by 10^{-3} energy acceptance), although bunch shortening can be limited by the space charge effects.

5 FLAT TO ROUND COLLIDING BEAMS

Arrangement of circular betatron modes (CM) for both beams at IP using beam adapters is a general measure to decrease the high order effects of beam-beam interaction [5,7]. The CM seems especially useful when the two transverse emittances are very different in value. In this case, the adapters reduce the phase dependence of beam-beam interaction to a minimum. That suppresses the non-linear beam-beam resonances and provides maximum stability

Flat ion beam can appear with electron cooling as discussed above, although in EIC energy range this possibility can be limited by the intra-beam space charge. Electron beam appears naturally flat in a storage ring or accumulator. In LCR scheme, e-beam of two very different emittances can be obtained by use of magnetized e-gun [7,10]. In colliders with multiple collision points, further reduction of resonance interaction can be achieved using phase interference of succeeding collisions.

6 LOW BETA-STAR WITH SHORT BUNCHES

Short ion and electron bunches allow one to design the IP with correspondently short star-focus (beta-star 1cm), hence, small transverse size of beams at collision point. Measures on compensation for chromatic and non-linear dispersion of final focus might be undertaken if needed.

7 CRAB CROSSING

Short bunches also make feasible the introduction of crab crossing that allows one practically to remove parasitic beam-beam interactions without loss of luminosity, attain a highest bunch collision frequency (up to 1.5 GHz) and release more space for detectors [11]. With ion bunches 0.5 cm as short, applying SRF deflectors of integrated magnetic field amplitude 600 G by 4 m to effect 100 GeV ion beam, one can obtain bunch tilt 0.05 rad (corresponding crossing angle 0.1 rad) at final focus parameter 3 m (Fig.2). Bend-related rotation of electron spin can be preventively compensated by Wien filter or in other way.

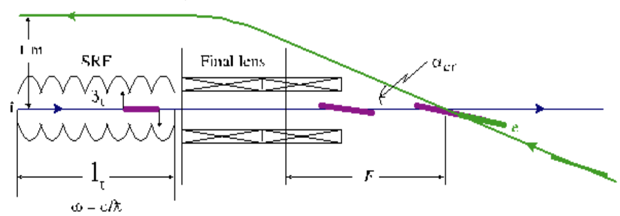
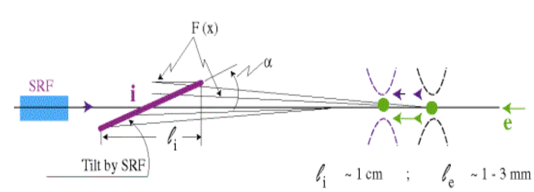


Fig.2. Crab crossing for EIC

8 TRAVELING ION FOCUS

If the ion bunches are still much longer than the electron ones, one may attempt to arrange the traveling focus for ion beam, with beta-star approaching the e-bunch length while making the ion focus point traveling with electron bunch [12]. The traveling effect can be achieved using the same SRF-kicker as for crab crossing and introducing a gradient of final focus parameter by mean of sextupole field (Fig.3).



9 POLARIZATION TRANSPORT OPTIONS

The LCR (so LAR) concept, basically, succeeds the features of LR scheme regarding the delivering and controlling the electron spin, although the “Siberian Snake” solenoids (60 TM each at 5 GeV) are needed to stabilize the longitudinal spin at interaction points (Fig.1); in rest, circulation time is short enough for depolarization effects to be insignificant. Proton polarization could be realized by mean of dipole Siberian Snakes and spin rotators in collider ring and techniques of adiabatic overcoming depolarizing spin resonances in booster. The adiabatic techniques also could be used in order to preserve the polarization of light ions at acceleration and obtain the longitudinal spin in narrow energy regions near the integer or half-integer (RF introduced) spin resonances.

An alternative to these techniques might be the twisted spin, or figure 8 EIC (Fig.4 and 5), with basic features as follows: spin precession in vertical field is compensated, i.e. the fundamental spin tune is zero; intrinsic spin resonances stay away; there is no crossing spin resonances. Using the degeneration of spin motion on ideal plane orbit, one can easily control spin direction (including flipping the spin) for all particle species at all energies in booster and collider ring by introducing solenoids in straights or horizontal dipoles along the arcs. Spin rotators around the interaction points would not be needed. Compact full snakes with longitudinal axis of spin rotation can be introduced in order to stabilize the proton spin. Twisted orbit also can be used for electron circulator-collider; after all, the circulator (arcs) could also be used as booster for ion beam.

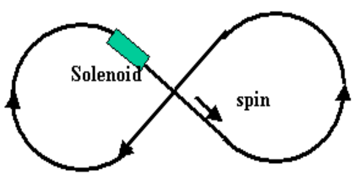


Fig. 4. Twisted spin synchrotron

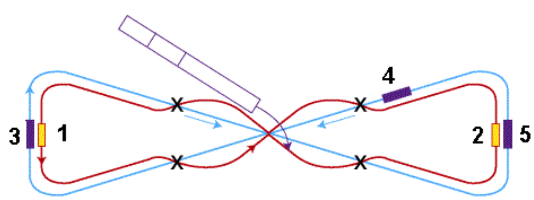


Fig. 5. Scheme of twisted spin EIC: 1,2 – solenoid snakes for electron beam; 3,4,5 – Siberian Snakes for proton beam

10 LUMINOSITY POTENTIALS

A set of parameters has been developed for design of electron-light ion collider (ELIC) at CEBAF involving energy recovery, circulator ring, electron cooling and crab crossing [13]. It indicates possibilities to approach luminosity level 10^{33} to 10^{35}/cm^2.s in ion energy region 30 to 100 GeV at ion and electron current in collider up to 2.5 A. Level 34 is anticipated based on modern polarized electron source state of art (peak current 2 A at average value 2 mA). Level 35 relies on expectations from new source technology to increase cathode quantum efficiency and lifetime by a factor of 10. In energy region above 100 GeV one could obtain ion bunches shorter than 1 cm with the possibility to extend the luminosity limits beyond the 35 level. Finally, the EIC option based on a pulse SRF linac incorporated with damping ring as accumulator of polarized accelerated electrons (mentioned in sect.3) should be comprehensively investigated as a possibility to amplify the charge per bunch of circulating electron beam.

11 CONCLUSION

The SRF ERL and polarized electron and ion beam techniques provide a potential for realization of high luminosity EIC based on three major components: 5-10 GeV electron beam, 30 to 250 GeV circulating ion beam, and electron beam 15 to 125 MeV for cooling the ion beam. The above described advances and options are proposed for further considerations and study as possible ways to improve the utilization of polarized beams delivered by linear electron and ion accelerators and raise the efficiency and luminosity of EIC.

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