CONCEPT FOR A POLARIZED ELECTRON-NUCLEON COLLIDER UTILIZING THE HESR STORAGE RING AT GSI/FAIR

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Abstract

The feasibility of a polarized electron-nucleon collider (ENC) with a center-of-mass energy up to 14 GeV for luminosities exceeding 10^{32} cm^{-2}s^{-1} is presently studied. The proposed concept utilizes the planned 15 GeV/c High-Energy Storage Ring (HESR) at the future International Facility for Antiproton and Ion Research (FAIR) [1] for protons/deuterons and integrates an additional 3.3 GeV electron ring (Fig. 1). Calculations of cooled beam equilibria including intra-beam scattering and beam-beam interaction have been performed using the BetaCool code [2]. A special design of the interaction region (IR) is required to realize back-to-back operation of the HESR storage ring [3] in fixed target mode together with the elaborated collider mode. For polarized proton/deuteron beams additional equipment has to be implemented in several machines of the acceleration chain and HESR to preserve the beam's polarization [4]. A corresponding scheme for polarized electrons is currently under investigation.

In this presentation the required modifications and extensions of the HESR are discussed and the proposed concept is presented.

INTRODUCTION

Lepton/Nucleon scattering experiments become especially effective if both particle species are spin polarized. Such experiments are (or have been) performed at COMPASS or HERMES at typical c.m.-energies of $s^{1/2} \sim 10$ GeV with fixed targets. Whereas the kinematical coverage of such experiments is quite adequate for many of the major questions arising, their statistical efficiency is not. In addition, many difficulties arise from the fixed target geometry. This calls for a high luminosity colliding machine operating with at least the same value of s.

We propose to extend the HESR storage ring facility - presently under construction at GSI/FAIR - by an additional electron ring. This yields an opportunity to create a double polarized collider on a comparatively short timescale with reasonable investment. We see this Electron/Nucleon Collider at FAIR (ENC@FAIR) as a follow up to the pbar/p annihilation experiments (PANDA, [5]) which will start in the middle of the next decade at the HESR.

DESIGN OVERVIEW

The HESR storage ring will provide ion beams with a maximum momentum of 15 GeV/c. A 3.3 GeV electron ring will be integrated into the HESR tunnel, yielding a c.m. energy of $s^{1/2} = 14$ GeV in head on collisions with protons ($s^{1/2} = 9.3$ GeV for deuterons).

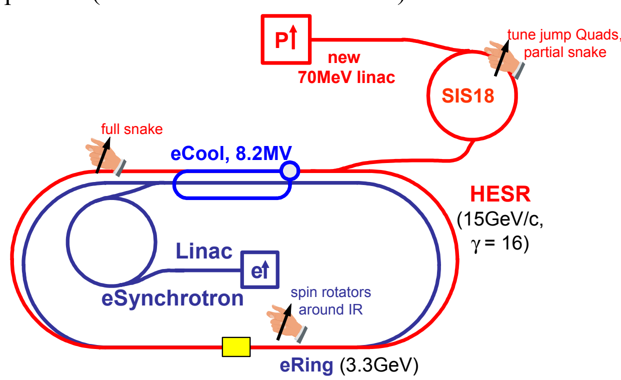

Figure 1: Scheme of the ENC@FAIR (not to scale) for electron-proton collisions.

The challenge for the electron ring will be to combine sufficiently high polarization lifetime under collision (as already achieved even at lower energies e.g. at NIKHEF [6]) with bunch populations and -numbers which are characteristic for e+/e- colliders like DAPHNE [7].

Whereas it is presently unclear if satisfyingly large polarizations of antiproton beams can be obtained [8] the production [9] and transport of polarized protons or deuterons through the FAIR injector chain is feasible, as well as spin stable operation of the HESR, since its cooler solenoid may be operated as Siberian snake with only moderate additional effort by adding additional solenoids together with skew quadrupoles [10] and possibly helical dipoles [4]. We therefore believe that sufficiently stable high polarization ($P_e = P_{ion} \sim 0.8$) and arbitrary direction of spin at the interaction point (IP) is achievable (for deuterons only transversal polarisation at the IP seems to be feasible). Further aspects of HESR and electron ring operation for ENC@FAIR are discussed below.

It seems attractive to use the central part of the PANDA detector for the collider experiments, e.g. because of its large solid angle coverage, which would also represent a cost efficient solution. It is nevertheless clear that the boundary conditions imposed by PANDA call for a very careful design of the interaction region. A conservative IR design which is compliant with PANDA and all experiments presently under investigation for the ENC allow for a β^* of 0.3 m and a bunch spacing of 5.76 m (100 stored bunches) which limits the luminosity to $1{\cdot}10^{32}\,cm^{-2}s^{-1}$. Much more detailed studies, in close collaboration with detector specialists, are under way with the target to allow for $\beta^* = 0.1$ m and a bunch spacing of 2.88 m, which would increase the luminosity to $4{\cdot}10^{32}\,cm^{-2}s^{-1}$.

ENC@FAIR will make use of the electron cooler at HESR in order to conserve transverse and longitudinal emittance. For proton operation, the HESR cooler must be upgraded to 8.2 MeV at d.c. currents of several amperes. The simultaneous achievement of these cooler parameters has not been demonstrated yet, but does not seem unrealistic. A dedicated r.f.-system must be incorporated into HESR to allow for multi bunch operation (h = 200) at collision energy. A bunch length $\sigma_L \leq 0.1$ m is foreseen to avoid excessive luminosity reduction by the hourglass effect. Another extension of the HESR r.f.-system is required by the task of accumulating a sufficient number (~100) of polarized bunches at injection energy which leads to strong space charge forces at this stage.

Bunch populations at collision energy have to be maximized, examples for the counteracting effects being, e.g. space charge (Laslett-) tune shifts (ions) and broad band impedances (electrons).

We have summarized the considerations presented here in a first parameter list for ENC@FAIR (Table 1) allowing for a peak luminosity of $L = 4{\cdot}10^{32}\,cm^{-2}s^{-1}$. The numbers in brackets are based on the requirements of the conservative IR design and it's worth mentioning that these parameters are achievable with present day technology.

Table 1: ENC parameter set for electron-proton collisions

	HESR / 15GeV	eRing / 3.3GeV
$\varepsilon^{geom.}$ [mm mrad]	0.125	
β^* [m] (at IP)	0.1 (0.3)	
l_{bunch} [m]	0.1 (0.3)	< 0.1
$n_{particle}$ / bunch [10^{10}]	3.6 (5.4)	23
h [bunches / ring]	200 (100)	
I_{tot} [A]	0.6 (0.45)	3.82 (1.91)
$P_{synchr.rad.loss}$ [kW]		1600 (800)
$f_{collision}$ [MHz]	104 (52)	
$\Delta Q_{Laslett}$	0.1 (0.05)	
$\xi_{x,y}$ [beam beam param.]	0.014	0.01 (0.015)
Lumi. [10^{32} cm^{-2} s^{-1}] (including hour-glass red.)	**4.4 (1.1)**	
Polarisation [%]	80	80

CONSERVATIVE IR DESIGN

Experience gained at HERA suggests that acceptable background and beam lifetime conditions require a free aperture of 20σ for electrons and 12σ for protons in the IR [11]. For the given beam emittance this leads to β^*~0.3 m because of compliance with the desired detector acceptance which is presently supposed to have its lower limit at angles of 2º. Fig. 2 illustrates how the additional demands - avoiding parasitic collisions 2.88 m away from the IP and beam focussing outside the detector region - can be achieved.

Focussing for the electrons will be provided by superconducting quadrupole triplets whereas normal conducting 'septum' quadrupoles will be used for the proton beam after a sufficient beam separation is achieved.

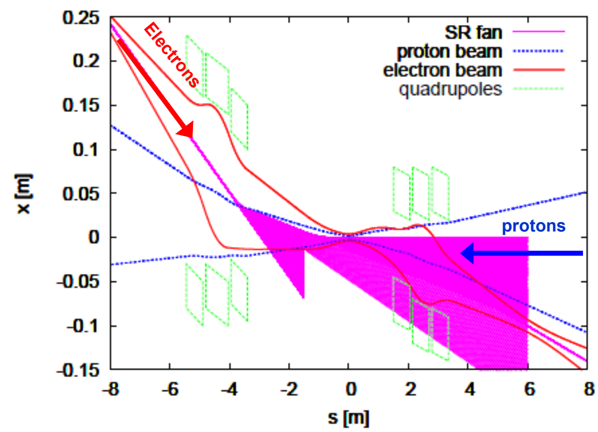

Figure 2: First conservative approach for an IR design with electron triplets. Red: electrons 20σ envelope. Blue: protons 12σ envelope. Magenta: electron SR fan.

The dipole field of a forward spectrometer dipole together with an additional dipole component in the PANDA main solenoid may be used to superimpose the beams at the IP and to separate them again. SR power levels (in the order of 10 kW) are manageable, but specific measures like special upstream absorbers (s = -1.8 m in Fig. 2) and a large aperture sc triplet downstream have to be taken.

THE HESR AS NUCLEON RING

The HESR has been designed to accelerate and store antiproton beams for use in experiments with internal targets in the momentum range from 1.5 to 15 GeV/c [1]. To reach the desired beam performance high-energy electron cooling with electron energies up to 4.5 MeV and high-bandwidth stochastic cooling from 2 to 6 GHz will be applied.

In the collider mode of ENC, polarized protons/deuterons will be accelerated in the HESR up to 15 GeV/c. For the delivery of high intensity polarized polarized proton and deuteron beams a CIPIOS type ion source in combination with an RFQ would be appropriate. Pre-acceleration of polarized beams would be possible via the planned proton linac resp. the UNILAC and SIS18. A dedicated beam line from SIS18 to HESR has already been proposed for HESR commissioning with protons. The acceleration in HESR would occur with one resp. two high-intensity bunches carrying the whole beam intensity required for collision. To get the anticipated number of bunches a complicated re-bunching process in combination with phase-space cooling has to be performed to minimize beam losses. BetaCool calculations have been carried out to evaluate equilibrium beam distributions for protons and deuterons during collision. The model calculations assume a Gaussian beam distribution in phase space over all degrees of freedom. It includes Electron cooling (EC) and Intra-beam scattering (IBS). For EC the Parkhomchuk model [12] of the friction force is utilized and for IBS the Martini model [13] using ring lattice functions imported from the MAD program. The electron cooler for the HESR has the same design parameters as those required for experiments with internal targets, but has to be extended to electron energies of 8.2 MeV (proton operation). Beam distributions at the IP are used for the simulation of luminosity and beam-beam parameters. Several beam dynamics issues need detailed particle tracking to guarantee stable beam operation. Most critical are beam losses during the re-bunching process, space charge forces and beam-beam tune shift.

THE ELECTRON RING

In order to avoid the excitation of coherent beam-beam oscillations, a number of 200 bunches and a bunch repetition rate of about 104 MHz was chosen both for the electron and the nucleon ring. The maximum electron beam current is mainly limited by single bunch coherent beam instabilities driven by broad-band impedances. A design value of 4 A was derived as an upper limit from an empirical comparison of maximum beam intensities achieved in e+/e- colliders, which corresponds to $2.3\cdot10^{11}$ electrons per bunch (see [14],[15],[16]). In addition, collective multi-bunch instabilities have to be suppressed by an optimization of the vacuum-chamber's coupling impedance, a damping of all harmful cavity HOM's and the implementation of dedicated bunch by bunch feed-back systems, which seems to be possible using established technology developed for modern synchrotron light sources.

Power loss due to synchrotron radiation, which has to be compensated by an adequate r.f.-system operated at an integer harmonic of the bunch repetition frequency, should be limited to less than 2 MW. This requires a considerably large bending radius of more than 21 m. It is planned to use a radius close to the proposed one of the HESR bends to further decrease the required r.f. power and to allow for an installation of the electron ring in the HESR accelerator tunnel as a cost saving option. Superconducting RF-systems recently developed and successfully operated at 3rd generation light sources offer high acceleration gradients combined with efficient HOM-damping capability ([17],[18]).

The operation with polarized beams requires a successful suppression of beam depolarization due to spin diffusion caused by the emission of synchrotron radiation. The simplest approach, an implementation of a full snake in the straight section opposite to the interaction region, which in addition would enable us to direct the electron spins arbitrarily at the IR, would limit the depolarization time to less than 20 minutes at 3 GeV beam energy which is not acceptable. A transverse spin orientation in the arcs and the use of spin rotators in order to generate a longitudinal polarization at the IR appear to be unavoidable and in addition could allow an operation with polarized positrons generated by the Sokolov-Ternov-mechanism. In a first and quite simple approach, it is planned to use a combination of a solenoid and a bending magnet as spin rotator. In order to decrease the influence of depolarizing imperfection resonances, the electron ring will be operated at a spin tune of $\gamma a = 7.5$ which corresponds to a beam energy of 3.3 GeV.

Dispersion suppression in the straight sections and the generation of a round beam of rather large beam emittance require a sophisticated lattice, which will be based on a combination of FODO and double-bend achromat cells. Detailed investigations of accelerator optics and depolarization times in view of lattice optimization have been started recently.

CONCLUSION

ENC@FAIR is a promising attempt to realize an electron nucleon collider within the next decade since it will make use of infrastructure to be installed shortly at GSI/FAIR. Our first investigations indicate that a luminosity of $1\cdot10^{32}\,cm^{-2}s^{-1}$ is achievable using present day techniques only. By a careful and sophisticated interaction region design, in close collaboration with detector specialist, one can aim for a luminosity of $4\cdot10^{32}\,cm^{-2}s^{-1}$. However, the interdependence of a variety of parameters – like spin dynamics, beam-beam interaction, electron cooling of relativistic ion beams, collective effects and extensive r.f. bunching – presents a complex problem, making ENC@FAIR a formidable challenge for accelerator physics and physicists. Our team will continue investigations with the goal to provide a first order design report by the end of 2012.

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