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A HIGH ENERGY *e-p/A* COLLIDER BASED ON *CepC-SppC**

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Abstract

Construction of *CepC* and *SppC*, the proposed future energy frontier circular *e+e-* and *pp* colliders in China, provides an opportunity to realize *e-p* or *e-A* collisions in a CM energy range up to 4.1 TeV. This paper presents a preliminary conceptual design of this *e-p/A* collider. The design parameters and anticipated luminosities will be given. We also discuss staging approaches to realize this collider with a low cost and at an earlier time.

INTRODUCTION

Recently, a circular *e+e-* collider (*CepC*) with a 240 GeV CM energy as a Higgs factory has been proposed at Institute of High Energy Physics (IHEP) in China. Its envisioned upgrade, a *pp* collider (*SppC*), will be built for the next energy frontier to reach 70 TeV CM energy [1]. Based on *CepC-SppC*, a multi-TeV electron-proton/ion collider, *CepC-SppC e-p/A collider* (code named *SehC* in this paper), will provide a probe (through ultra deep inelastic scatterings) that can reach unprecedentedly deep inner structure of the matters. Luminosity of the *e-p* collisions can reach middle of 10^{33}/cm^2/s [1].

DESIGN CONSIDERATIONS

An assumption of this design study is that there will be no major upgrade of *CepC* and *SppC* for realizing the *e-p/A* collisions. Thus, the *e-p/A* performance will be determined primarily by the beams that the envisioned *e+e-* and *pp* colliders could provide. The design will follow the *CepC-SppC* operational limit such as the maximum beam energies and currents, the synchrotron radiation (SR) power budget. The design will also observe limits on the parameters due to collective effects such as beam-beam interactions. However, within these limits, beam parameters such as the bunch repetition rate, bunch charges, emittance aspect ratio or crossing angles, can be altered for achieving an optimized performance.

CepC and *SppC* are two very different colliders in terms of parameters of the colliding beams. The *CepC* electron beam has 50 bunches due to a single-ring design while the *SppC* proton or ion beam has a large number of bunches varying from 3000 to 6000. This fact plus an extremely asymmetry of beam emittance aspect ratios effectively exclude the option of simultaneous operations of *e+e-* and *e-p/A* collisions in the *CepC-SppC* complex. Without this constraint, the electron beam is no longer limited to 50 bunches, it can be increased to match the bunch numbers of a proton beam from *SppC*.

Selection of the final focusing parameters for the *e-p/A* collisions is driven by the interaction region (IR) design considerations. For example, the beam spot sizes should be matched at an interaction point (IP) in order to alleviate the beam-beam effect. Nevertheless, the *CepC* lepton beam is extremely flat (the aspect ratio is as high as 333) while the *SppC* proton beam is basically round. Matching of these two beams requires very large vertical beta-star for the electron beam thus blows-up the beam-beam parameters. The operational scenario that the *e-p/A* and *e+e-* collisions will not be run simultaneously provides the opportunity to change the electron beam to a round one by utilizing the transverse optics coupling.

In the *SppC* energy regime, the synchrotron radiation and its effect on the proton or ion beam are no longer negligible. The damping time of a proton or heavy ion beam is similar or even shorter than the time of beam store. As a consequence, the proton or ion beam emittance will approach to an equilibrium value (in a balance of radiation damping and quantum excitation, and intra-beam scatterings) during the beam store. This will affect the peak luminosity as well as the integration of luminosity over one store of the beam.

The *e-p/A collider* based on *CepC-SppC* is a highly asymmetric one with an energy ratio up to 292, a highest value compared to all other *e-p/A* colliders ever been constructed or studied. The simple kinematics shows the reactant particles from collisions will go dominantly in the forward direction of the proton or ion beam. Therefore, it is expected that the forward detection of particles with extremely small scattering angles will be a critical requirement of the detector. Designing an IR to support such extreme forward detections is challenging and will require thorough studies. At the moment, as a straw-man design, we will adopt the similar final focusing parameters (beta-star β*) of the *CepC* and *SppC* colliders respectively.

Lastly, the science programs utilizing deep inelastic scatterings as a probe usually demand experimental data collected over an energy scan. This requires the *e-p/A* collider design to be optimized over a broad energy range for both electron and proton/ion beams. In this paper, we present design parameters at a representative energy point, namely, 120 GeV electron energy and 35 TeV proton energy, the highest energies that *CepC* and *SppC* could provide. Luminosities at three other electron energies corresponding to *Z, W* and *T* processes are also given.

e-p COLLISION PARAMETERS

Table 1 below presents the nominal design parameters for the *CepC-SppC e-p* collisions. There will be only one beam in the *CepC* ring, thus the electron beam current can be doubled to 33.8 mA while still under the operational limit of 100 MW total SR power. The electron beam could have thousand bunches to match the bunch pattern

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of the proton beam when the electrostatic separators of the pretzel orbital scheme are turned off. For achieving a luminosity optimization and also a better interaction region design, we not only make the electron beam emittance a round one by invoking the transverse coupling, but also enable a factor of 6.3 reduction of the equilibrium emittance by switching to a different optics for the *CepC* electron ring, namely, changing the betatron phase advance of an arc FODO cell from 60° to 135°.

There are two parameters sets in Table 1, corresponding to two operational scenarios. The first one is a *SppC-SehC* dual-program mode such that the *e-p* collisions are run simultaneous with the *pp* collisions at other detectors. In this case, the proton beam parameters such as the bunch length and transverse emittance are identical to these of the *SppC* design. However, the proton beam current is reduced to 0.86 A from the 1 A nominal value of *SppC* in order to keep the electron beam-beam parameter below 0.15 per IP. This reduces luminosity of the *pp* collisions by 14%. The bunch numbers of the both electron and proton beams are nearly 6000, maintaining a 40 MHz repetition rate (thus 25 ns bunch spacing) as well as a gap (or multiple gaps) of 5.2 km long in the beam bunch trains. The final focusing of the proton beam is also identical to that of the *pp* collisions, however, the electron beta-star is increased to 7.7 cm (as a comparison, the *CepC e+e-* vertical beta-star is only 1.2 mm) in order to match the beam spot size at an IP. The luminosity without the geometric correction is 3.4×10^{33} /cm^2/s.

In the second operational scenario, the *e-p* collisions are run in a dedicated mode without the *pp* collisions at other detectors. This permits additional adjustments of proton beam parameters for performance enhancements including nearly doubling the *e-p* luminosity to 4.7×10^{33} /cm^2/s before the geometric corrections. Specifically, the proton emittance is reduced to 2.35 mm mrad. There are also less bunches (50 ns bunch spacing) in both beams.

The two geometric correction factors to the *e-p* collision luminosity are the crab crossing and hour-glass effects. Due to small bunch spacing and high energies of the colliding beams, a finite crossing angle is introduced to enable a rapid beam separation near an IP, thus alleviate the parasitic beam-beam effect. We propose to utilize SRF crab cavities to restore a head-on collision.

It can be shown that, due to a significant increase of the electron beta-star, the luminosity reduction factors due to the hour-glass effect are 90% and 79% for the two parameter sets in Table 8.1 respectively.

Table 1: Nominal Parameters of the *e-p* Collisions based on the CepC-SppC Facility

Operational scenario		***e-p* and *pp***		***e-p* only**	
Particle		proton	Electron	Proton	Electron
Beam energy	TeV	35	0.12	35	0.12
Beam current / Particles per bunch	mA / 10^{10}	865 / 16.9	33.8 / 0.66	430/ 16.7	33.8 / 1.31
Number of bunch		5973	5973	3000	3000
Bunch spacing	ns	25	25	50	50
Normalized emittance, (x/y)	µm rad	4.1	250	2.35	250
Bunch length, RMS	cm	7.55	0.242	7.55	0.242
Beta-star (x/y)	cm	75	7.7	75	4.4
Beam-beam parameter per IP(x/y)		0.0002	0.15	0.0007	0.15
Crossing angle	mrad	0.8		0.8	
Hour-glass (HG) reduction factor		0.90		0.79	
Luminosity per IP, with HG reduction	10^{33}/cm^2/s	3.1		4.7	

The *e-p* luminosities at other energies can be estimated following a similar way. Table 2 shows luminosities at several representative electron energies. At the lower energies, the electron beam emittance is decreased and its current can be increased while still observing the SR power limit, leading to higher luminosities.

Table 2: The e-p Collisions with Different Electron Energies in a Dedicated Operation Mode

Particle		Proton	Electron	Proton	Electron	Proton	Electron
Beam energy	TeV	35	0.045 (***Z***)	35	0.08 (***W***)	35	0.175 (***T***)
Center-of-mass energy	GeV	2.51		3.35		4.95	
Beam current	mA	45	1480	254	171	645	7.5
Particles per bunch	10^{10}	0.88	28.9	5.0	3.3	25	0.29
Number of bunch		5973		5973		3000	
Bunch spacing	ns	25		25		50	
Normalized emit., (x/y)	µm rad	2.35	13.2	2.35	74.1	2.35	775
Beta-star (x/y)	cm	75	31.5	75	10	75	2.1
Beam-beam parameter / IP		0.015	0.15	0.002	0.15	0.0002	0.072
Hour glass (HG) reduction		0.991		0.94		0.57	
Luminosity/IP w/ HG correction	10^{33}/cm^2/s	13.5		8.3		1.12	

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OPERATIONAL SCENARIOS AND STAGING

As discussed above, it is unpractical to run the *e-p/A* and *e+e-* program simultaneously in the *CepC-SppC* facility. On the other hand, it is feasible to run *pp* and *e-p/A* collisions simultaneously while delivering good performances for the both colliders as illustrated in Table 1 and 2. The proton beam-beam parameters due to the *e-p/A* collisions are nominally small therefore they do not add extra perturbations to the proton or ion beam. The electron beam-beam parameter is limited to 0.15 per IP and 0.3 is the total value if there are two *e-p*/A detectors.

Presently, construction of *SppC* is envisioned a decade after completion of *CepC* and it also demands very high construction cost. A staging approach could realize an *e-p/A* program much earlier though at lower CM energies. One approach is to utilize the high energy booster (HEB) of the *SppC* injector as an ion collider ring. The HEB ring in a separate 8 km long tunnel (shown in Figure 1) can store a proton beam with energy up to 2.5 TeV. The CM energy of the *e-p* collisions is up to 1.1 TeV, close to the energy range of *LHeC*, a proposed high energy *e-p* collider based on *LHC* and currently under active studies both in the science cases and in machine design [2]. There will be only one IP in this *e-p/A* collider, thus there is no requirement of bi-pass of the beams in other detectors since the beams are in different tunnels. The design parameters of this first stage *e-p/A* collision are presented in Table 3. Its luminosity is about twice higher than the *LHeC* luminosity.

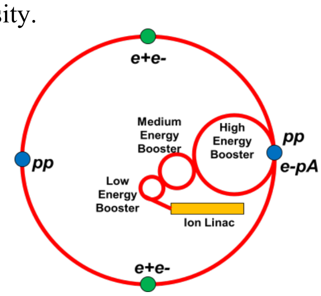

Figure 1: A schematic layout of *CepC SppC*; the high energy ion booster can be converted to a storage ring for the first stage of *e-p/A* collider.

Alternately, the *SppC* high energy booster synchrotron could be housed in the main tunnel, and made of low-cost super-ferric magnets which have a maximum field up to 3 T. The proton energy in this booster ring can reach 5.6 TeV, thus the maximum CM energy of *e-p* collisions is 1.64 TeV, about 26.5% higher than the *LHeC* energy. This version of the first stage *c-p/A* collider can support two detectors in a dedicated mode. The design parameters are also presented in Table 3, with four times higher luminosity than that of *LHeC*.

Table 3: Parameters of the First Stage *e-p* Collisions using the SppC High Energy Booster as an Ion Collider Ring

Location of the *SppC* high energy booster synchrotron		***A separate tunnel***		***Inside the main CepC-SppC tunnel***	
Particle		proton	Electron	Proton	Electron
Beam energy	TeV	2.5	0.12	5.6	0.12
Center-of-mass energy	TeV	1.09		1.64	
Beam current and particles per bunch	mA / 10^{10}	430 / 16.7	33.8 / 1.31	430 / 16.7	33.8 / 1.31
Bunch spacing	ns	50	50	50	50
Bunch repetition rate	MHz	20	20	20	20
Normalized emittance, (x/y)	µm rad	2	250	2	250
Bunch length, RMS	cm	7.55	0.242	7.55	0.242
Beta-star (x / y)	cm	10	7	10	1.58
Beam-beam parameter per IP(x/y)		0.0008	0.15	0.0016	3.15
Hour-glass (HG) reduction factor		0.852		0.684	
Luminosity per IP, with HG reduction	10^{33}/cm^2/s	3.2		5.7	

ACCELERATOR R&D

The interaction region design will likely be the most critical R&D for the *CepC-SppC e-p/A* collider. First, forward particle detection will likely be a requirement of the detector thus the IR design must fully support it. Usually, a large detector space (the distance between an IP and the first focusing magnet) are required for the both beams. In the case of the proton or ion beams, this requirement should be similar to that of *SppC*. The *CepC* detector space, like all other *e+e-* colliders, is very small in order to enabling an extreme small vertical beta-star. Making it significant larger will be one of the challenges. An increased electron beta-star should greatly help to achieve the chromatic compensation and a good dynamic aperture.

Another critical R&D of the IR design is to provide sufficient separation of the colliding beams at locations of the final focusing magnets. The separation due to the crab crossing is merely a few cm if the detector space is 25 m. It is smaller than the physical size of superconducting magnets. Additional schemes should be studied for eliminating interference on beam transports by these magnets.

Estimating beam and luminosity lifetime, evaluating and mitigating various sources and beam effects that limit these lifetimes is a critical R&D yet to be carried out. Nonlinear and collective beam dynamics, particularly the beam-beam effect, must be thoroughly studied.

Note from authors: The main results of this paper were included in the *CepC-SppC* Preliminary Design Report [1].

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REFERENCES

[1] "*CepC-SppC* Preliminary Conceptual Design Report, Vol. II Accelerator", IHEP-CEPC-DR-2015-01, IHEP-AC-2015-01 (2015).

[2] "A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector", CERN-OPEN-2012-015 and LHeC-Note-2012-002 GEN; http://arxiv.org/abs/1206.2913