# *SehC*: A Very High Energy Electron-Ion Collider Based on *CepC-SppC*

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# Outline

- Introduction
- *CepC-SppC*, the Next Energy Frontier
- *e-p/A* Machine Design
- Staging Approach
- Summary

# Introduction

- Discovery of *Higgs* particle at LHC inspires new science exploration
- The relative low mass of *Higgs* boson opens possibility of a circular *e+e-* collider as a *Higgs* Factory for precision measurements.
- Such an *e+e-* collider must have a ring circumference of 50 to 100 km in order to keep synchrotron radiation power under a reasonable value (RF power budget, ~100 MW)
- The large tunnel also opens a possibility of future super proton-proton collider for the next energy frontier, reaching 70 to 100 TeV CM energy
- Presently, both CERN and IHEP (China) are actively engaged in feasibility studies
  - At CERN, it is ***FCC*** (***F***uture ***C***ircular ***C***ollider) with *FCC-ee, FCC-hh, FCC-he*
  - At IHEP, it is ***CepC-SppC*** (Circular electron-positron Collider and Super proton-proton Collider)
- In such a complex, *e-p* or *e-A* collisions can be realized without requiring substantial extra equipment and cost, thus greatly expending the science reach.
- Both e-p/A science program and machine designs are under development.

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# *CepC-SppC*: A Great Chinese Dream

- *IHEP* is positioned to build the next energy frontier colliders in China, taking a historic opportunity of
  - Unprecedented booming of Chinese economy over the last two decades
  - Strong governmental support to basic and applied science researches
  - Substantial increase of basic science research funding in recent years,

- The new proposal has two phases

  Phase 1: a circular *e+e-* collider as a Higgs Factory (***CepC***)

  Phase 2: a circular *pp* collider as an energy frontier (***SppC***)

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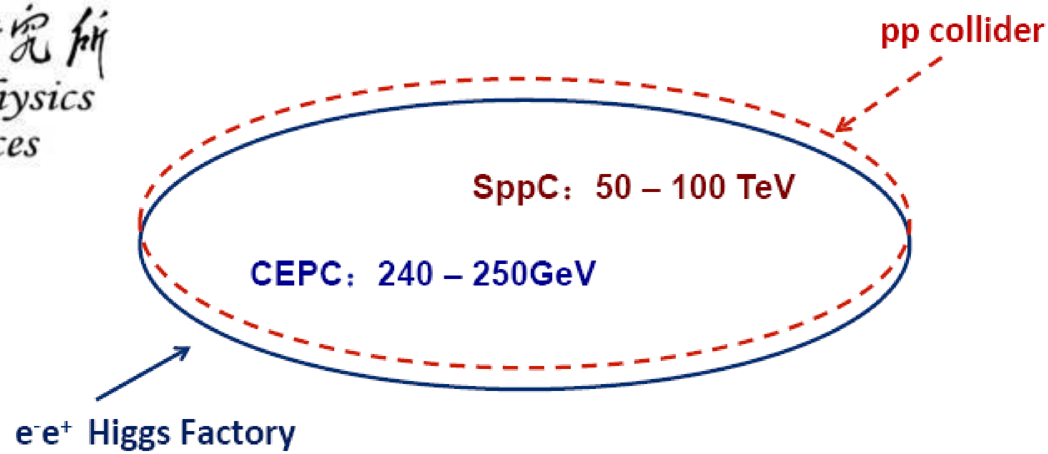
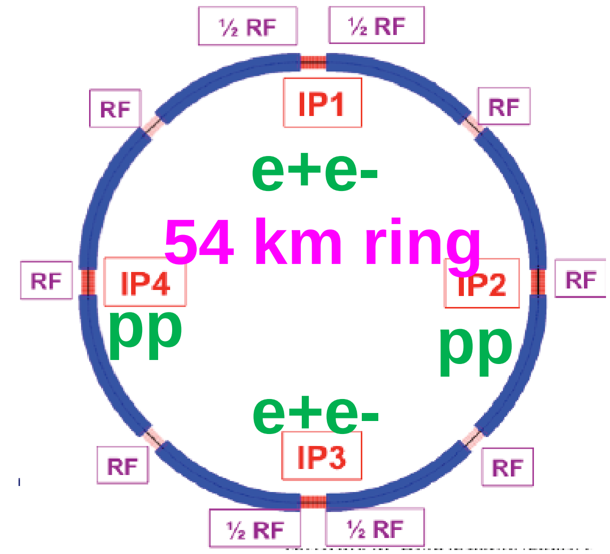


# CepC-SppC Preliminary Design

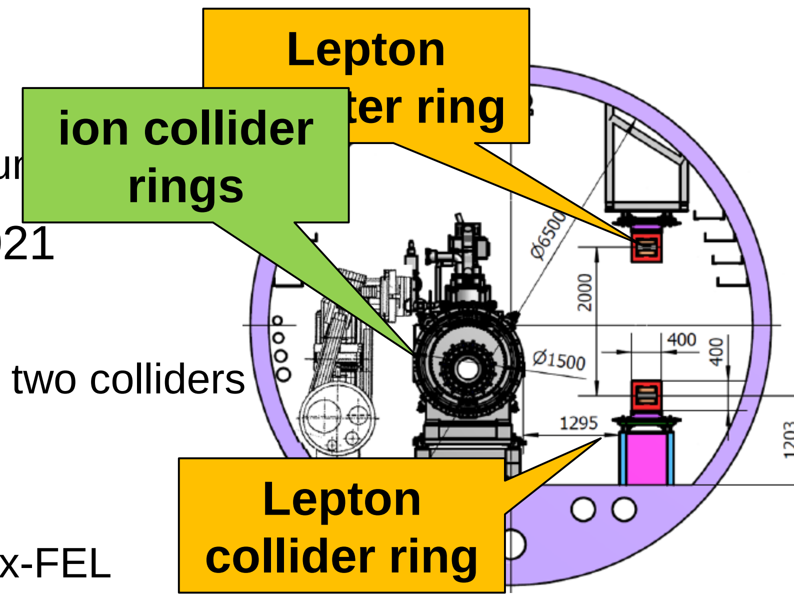
| Parameter | High Level Design Goal | |
|---|---|---|
| | | |
| Particles | | |
| CM energy (up to) | 2[illegible] GeV | 70 TeV |
| | 250 fb$^{-1}$ (per IP per year) | TBD |
| No. of IPs | 2 | 2 |

1 millions Higgs particles from 2 IPs in 10 years

$>10^{34}$ cm$^{-2}$s$^{-1}$




- Build a (54 km) underground tunnel for a Higgs factory
  - Single ring for two beams, pretzel scheme
  - 50 MW SR power per beam
- Lepton injector for Higgs Factory
  - A 6 GeV SRF electron linac
  - A full energy (120GeV) booster ring in the same tur
- Very optimistic timeline: construction begins at 2021
- Use the same tunnel for a future *pp* collider
  - Envisioned simultaneous or alternate operation of two colliders
  - Tunnel should be large enough for two colliders
- Keep options open for
  - Super Z (maybe *tt* as well); e-p and e-A colliders; x-FEL





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# Preliminary Conceptual Design Report

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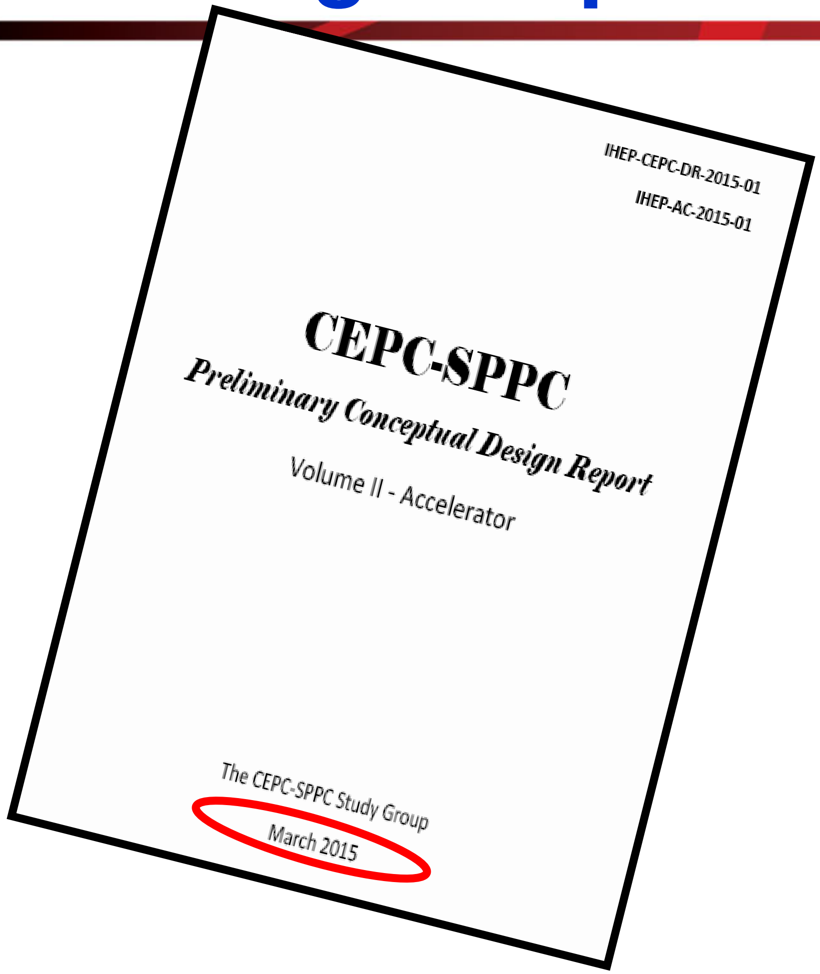


- Summary of 18 month preliminary design study
- 258 authors from 57 Chinese and international research institutes, universities and companies
- Released on March, 2015

# Possible Site of CepC-SppC

Beijing


site


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- ***e-p/A*** **Machine Design Baseline**
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# *e-p/A* Design Consideration

- **General design assumption: NO major and costly upgrade of *CepC-SppC* for realizing *e-p/A* collisions**
  ➔ *e-p/A* performance is determined by beams from *CepC-SppC*

- ***CepC e+e-* collisions and *e-p/A* collision can't be run *simultaneously***
  – Each *CepC* lepton beam has only 50 bunches due to the one-ring design while one proton beam in *SppC* has 3000 to 6000 bunches
  – *CepC* lepton beam is extreme flat (aspect ratio ~330) while a *SppC* proton is basically round, it is very difficult to have the spot sizes of two beams matched

- **Without the constraint of running *e+e-* and *e-p/A* collisions simultaneously, the electron beam in *CepC* can be reconditioned to match the proton beam for optimizing the *e-p/A* collision luminosity**
  – Increase electron bunches to 3000
  – Reduce the emittance aspect ratio to make it a round beam
  – Double the beam current (still under 100 MW SR power budget)

- **Interaction region (IR) is yet to be designed, it is expected that a forward detection is critical such that a large detector space is required for the proton beam.**

# *e-p* Nominal Design Parameters

| Operational scenario | | *e-p* and *pp* | | *e-p* only | |
|---|---|---|---|---|---|
| Particle | | Proton | Electron | Proton | Electron |
| Beam energy | TeV | 35.6 | 0.12 | 35.6 | 0.12 |
| CM energy | TeV | 4.1 | | 4.1 | |
| Beam current | mA | 860 | 33.8 | 430 | 33.8 |
| Particles per bunch | $10^{10}$ | 16.8 | 0.66 | 16.8 | 1.31 |
| Number of bunch | | 5812 | 5812 | 2924 | 2924 |
| Bunch spacing | ns | 25 | 25 | 50 | 50 |
| Bunch repetition rate | MHz | 40 | 40 | 20 | 20 |
| 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 | 7.5 | 75 | 4.35 |
| Beam spot size at IP (c/y) | μm | 9.0 | 9.0 | 6.65 | 6.65 |
| Beam-beam per IP(x/y) | | 0.0002 | 0.15 | 0.0007 | 0.15 |
| Crossing angle | mrad | ~0.8 | | ~0.8 | |
| Hour-glass (HG) reduction | | 0.904 | | 0.794 | |
| Lumi. per IP, w/ HG reduction | $10^{33}/cm^2/s$ | 3.2 | | 4.8 | |

# *e-p* Collisions at Other Representative Energies

| Particle | | *p* | *e* | *p* | *e* | *p* | *e* |
|---|---|---|---|---|---|---|---|
| Beam energy | TeV | 35.6 | 0.045 (*Z*) | 35.6 | 0.08 (*W*) | 35.6 | 0.175 (*tt*) |
| CM energy | TeV | 2.53 | | 3.38 | | 4.99 | |
| Beam current | mA | 46.8 | 1521 | 256 | 176 | 643 | 7.5 |
| Particles/bunch | $10^{10}$ | 0.89 | 28.9 | 5.0 | 3.34 | 25 | 0.29 |
| Number of bunch | | 5812 | | 5812 | | 2924 | |
| Bunch spacing | ns | 25 | | 25 | | 50 | |
| Normalized emit. | μm rad | 2.35 | 13.2 | 2.35 | 74.1 | 2.35 | 775 |
| Beta-star (x/y) | cm | 75 | 29.5 | 75 | 9.25 | 75 | 1.95 |
| Beam-beam / IP | | 0.015 | 0.15 | 0.0017 | 0.15 | 0.0005 | 0.058 |
| Hour glass (HG) | | 0.991 | | 0.931 | | 0.556 | |
| Lumi/IP w/ HG | $10^{33}$/cm$^2$/s | 14.4 | | 8.76 | | 1.17 | |

# *e-A* Collision Design Consideration

- The present *SppC* baseline supports *A-A* collisions
- The highest energy of fully-stripped lead ions ($^{208}Pb^{82+}$) in *SppC* is 14 TeV, corresponding to 35 TeV of proton energy (same magnetic rigidity)
- The conceptual design of *e-A* collisions can follow the e-p collision design
- (Perhaps) the biggest difference: the synchrotron radiation damping of the lead ions is surprisingly much stronger than that of the protons, resulting in
  - a faster damping time (however still hours) $\sim A^4/Z^5 \sim 0.5$
  - A much smaller equilibrium emittance $\sim Z^3/A^4 \sim 0.00003$
- As a result of balance between synchrotron radiation damping and intra-beam scatterings, the lead ion beam equilibrium emittance is ~0.2 μm rad

# *e-A* Collision Parameters

| **Particle** | | **Lead ion ($^{208}Pb^{82+}$)** | **Electron** |
|---|---|---|---|
| Energy | TeV/u | 14.0 | 120 |
| Beam current | mA | 423 | 33.8 |
| Particles per bunch | $10^{10}$ | 0.2 | 1.31 |
| Number of bunch | | 2924 | 2924 |
| Bunch spacing | ns | 50 | 50 |
| Bunch repetition rate | MHz | 40 | 40 |
| Normalized emittance, (x/y) | µm rad | 0.22 | 250 |
| Geometric emittance, h. / v. | nm rad | 0.15 | 1.065 |
| Bunch length, rms | cm | 7.55 | 0.242 |
| β* (x / y) | cm | 75 | 1 |
| Beam size at IP, (x/y) | µm | 3.3 | 3.3 |
| Beam-beam per IP(x/y) | | 0.0029 | 0.15 |
| Crossing angle | mrad | ~ 0.8 | |
| Hour glass (HG) reduction factor | | 0.355 | |
| Lumi/IP per nuclei, w/ HG reduction | $10^{33}/cm^2/s$ | 0.11 | |
| Lumi/IP per nucleon, w/ HG reduction | $10^{33}/cm^2/s$ | 22.5 | |

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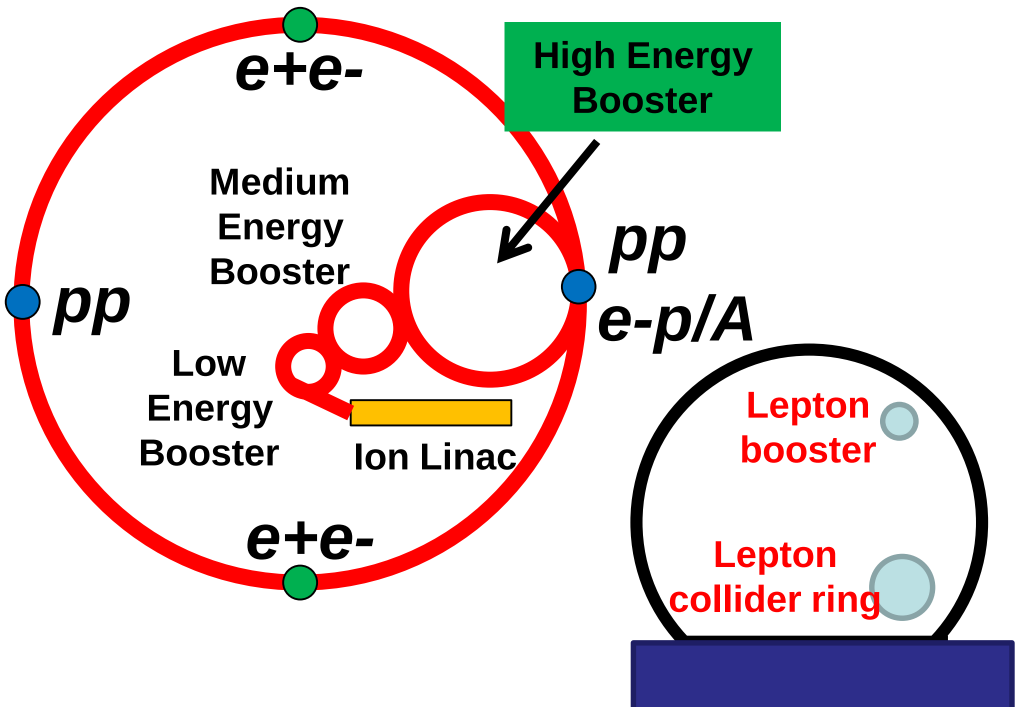
# Staging based on High Energy Booster of SppC

- Present IHEP plan: *e-p/A* is after *SppC*, which is about 2 decades away
- Cost of *SppC* is very high
- A plausible staging approach: using the high energy booster (***HEB***) of *SppC* as a proton/ion collider ring for collisions with electrons from CepC
  - Could realize *e-p/A* collisions much earlier
  - Initial construction cost is much lower
- There are two ways for HEB
  - A dedicated tunnel
  - Inside the CepC-SppC main tunnel

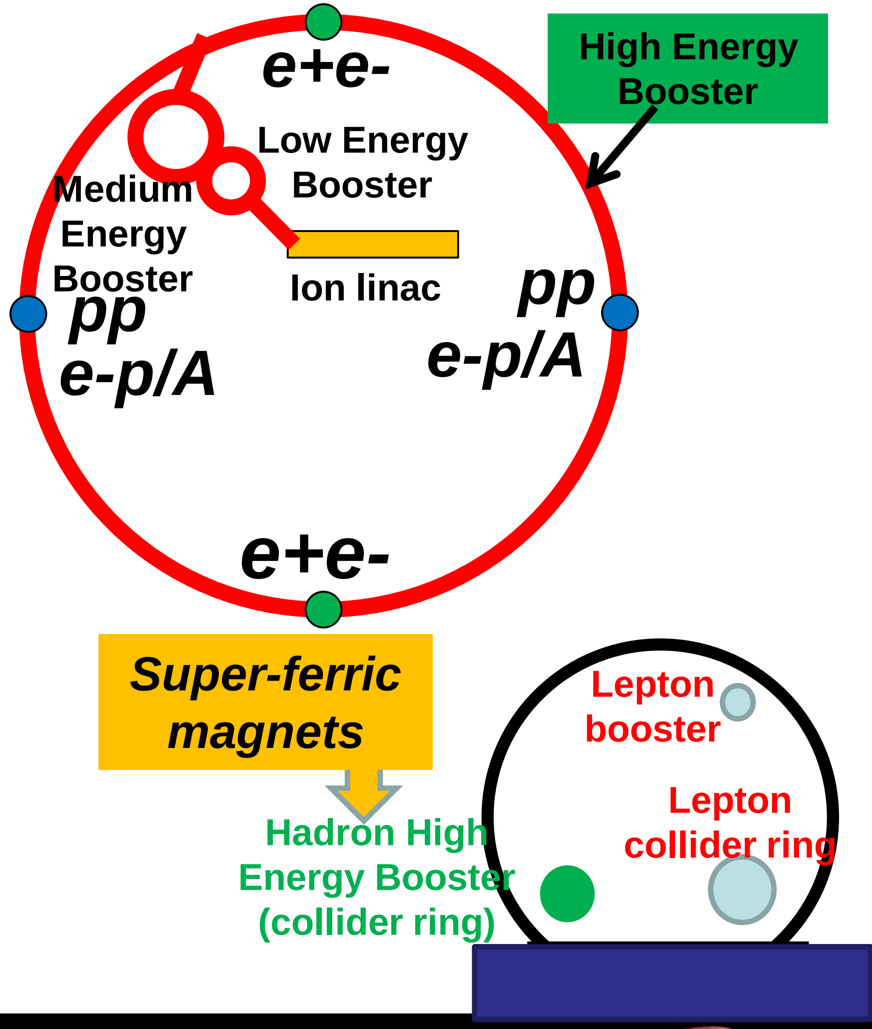
# SppC High Energy Booster (HEB)

| Location of HEB | Circum. | Energy | Dipole |
|---|---|---|---|
| | km | TeV | T |
| Separate tunnel | 7.2 | 3.2 | 12 |
| In main tunnel | 54 | 5.6 | 3 |

**Option 1: in a separate tunnel**




**Option 2: inside the CepC-SppC main tunnel**



# *SehC*-I Performance

e-p

| Location of the SppC HEB | | A separate tunnel | | Inside the main tunnel | |
|---|---|---|---|---|---|
| Particle | | Proton | Electron | Proton | Electron |
| Beam energy | TeV | 2.5 | 0.12 | 5.6 | 0.12 |
| Center-of-mass energy | TeV | 1.0 | | 1.64 | |
| No. of collision points (detectors) | | 1 | | 2 | |
| Luminosity per IP, w/ HG reduction | $10^{33}/cm^2/s$ | 5.4 | | 8.2 | |

LHeC: CM energy 1.3 TeV, luminosity (1.3 to 14.4) x $10^{33}$

e-p

| Particle | | p | e | p | e | p | e | p | e |
|---|---|---|---|---|---|---|---|---|---|
| Beam energy (HEB in the main tunnel) | TeV | 5.6 | 0.045 (Z) | 5.6 | 0.08 (W) | 5.6 | 0.120 (H) | 5.6 | 0.175 (tt) |
| CM energy | TeV | 1.00 | | 1.33 | | 1.64 | | 2.00 | |
| Luminosity per IP (with HG reduction) | $10^{33}/cm^2/s$ | 18.0 | | 18.4 | | 8.2 | | 1.57 | |

e-A

| Particle | | Lead ($^{208}Pb^{82+}$) | Electron |
|---|---|---|---|
| Beam energy (HEB in the main tunnel) | TeV | 2.21 | 0.12 |
| CM energy | TeV | 1.03 | |
| Luminosity / IP per nucleon, with HG reduction | $10^{33}/cm^2/s$ | 24.5 | |

# Staging Scenarios and Upgrade Plan

- Super-ferric magnets for the **SehC-I** collider ring: low cost, high beam energy
- Staging of **SehC** and **SppC** to fit the government funding profile
  - For example, the HEB ring can be constructed in two phases, for the first phase, only half super-ferric magnets are installed, reaching half of the maximum energy of HEB

| Stage | Phase | 1st full size (54km) hadron collider ring | | | 2nd full size (54 km) hadron collider ring | | | HEB in a separate tunnel | Optional |
|---|---|---|---|---|---|---|---|---|---|
| | | SC magnet | | Beam energy | SC magnet | | Beam energy | | |
| | | Super-ferric | High-field | TeV | Super-ferric | High-field | TeV | | |
| SehC | 1 | 50% | | 2.8 | | | | | Yes |
| | 2 | 100% | | 5.6 | | | | | |
| SehC-II | 1 | 50% | 50% | 21.5 | 50% | 50% | 21.5 | Yes | Yes |
| SppC | 2 | | 100% | 35 | | 100% | 35 | Yes | |

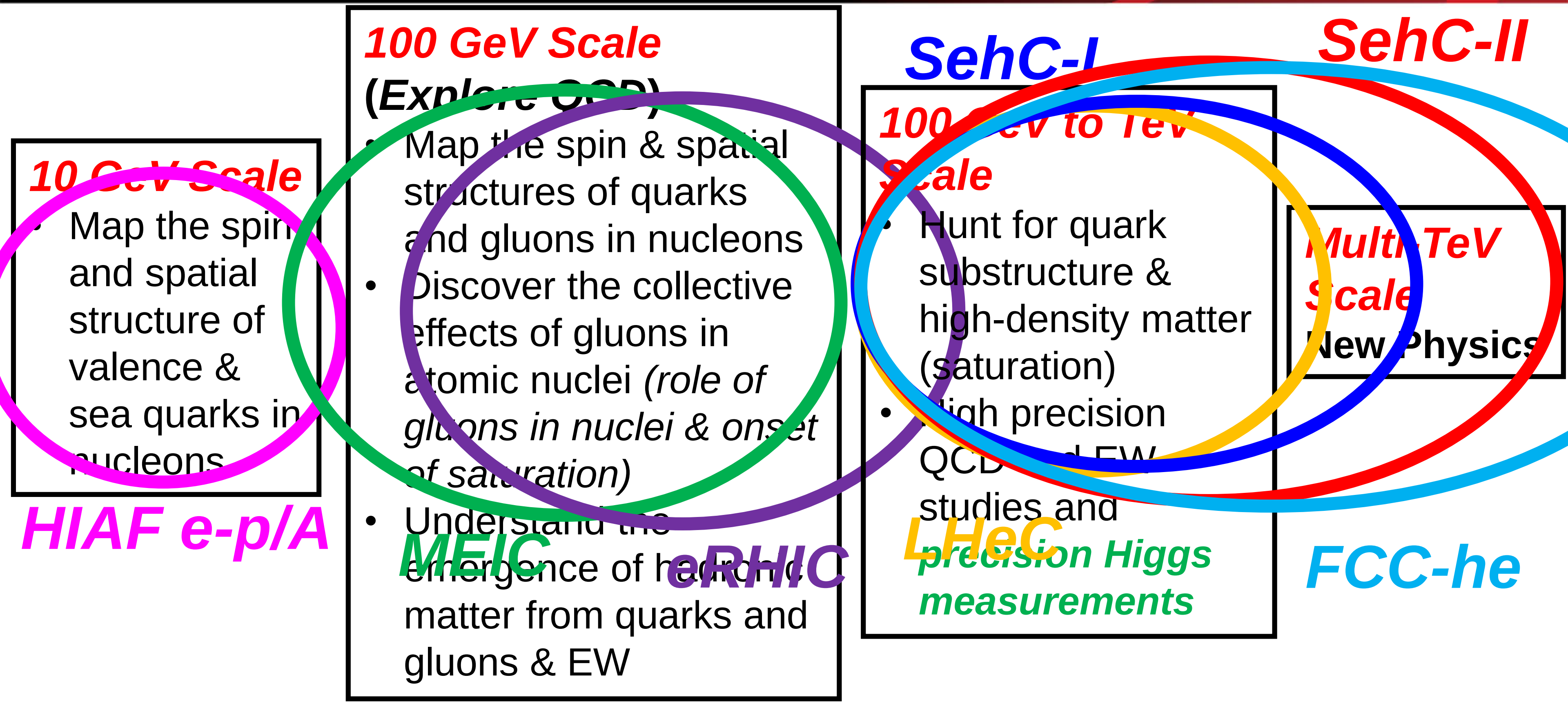
# Prospect: *SehC-I* Science Program Same as LHeC

*"It was clear that with a center-of-mass energy of about $\sqrt{s} \approx 1.5$ TeV an exciting programme of deep inelastic scattering (DIS) measurements at the energy-frontier was in reach. This would comprise searches and analyses for physics beyond the Standard Model, novel measurements in QCD and electroweak physics to unprecedented precision, as well as DIS physics at such low Bjorken x, that all the known laws of proton and gluon interaction would have to be modified to account for non-linear parton interaction effects. It had also been realised that the kinematic region, in terms of negative four-momentum-transfer squared, $Q^2$, and 1/x, accessed in lepton-nucleus interactions could be extended by 4 orders of magnitude using the ion beams of the LHC. A salient theme of the LHC therefore is the precise mapping of the gluon field, over six orders of magnitude in Bjorken x, in protons, neutrons and nuclei, with unprecedented sensitivity."*

By Prof. Max Klein, chair of the LHeC Steering Committee,
Preface of the **LHeC Design Report**

- Precision QCD and Electroweak Physics
- Physics at High Parton Densities
- New Physics at High Energy

# Compared to Sister EIC Proposals




- **SehC-I** delivers higher energy and luminosity than LHeC (means more science)
- **SehC-I** covers the entire LHeC science program, some (high end) of eRHIC science
- **SehC-I** may have a cost comparable to MEIC/LHeC but much smaller than LHeC
- **SehC-II** enters a new physics discovery regime

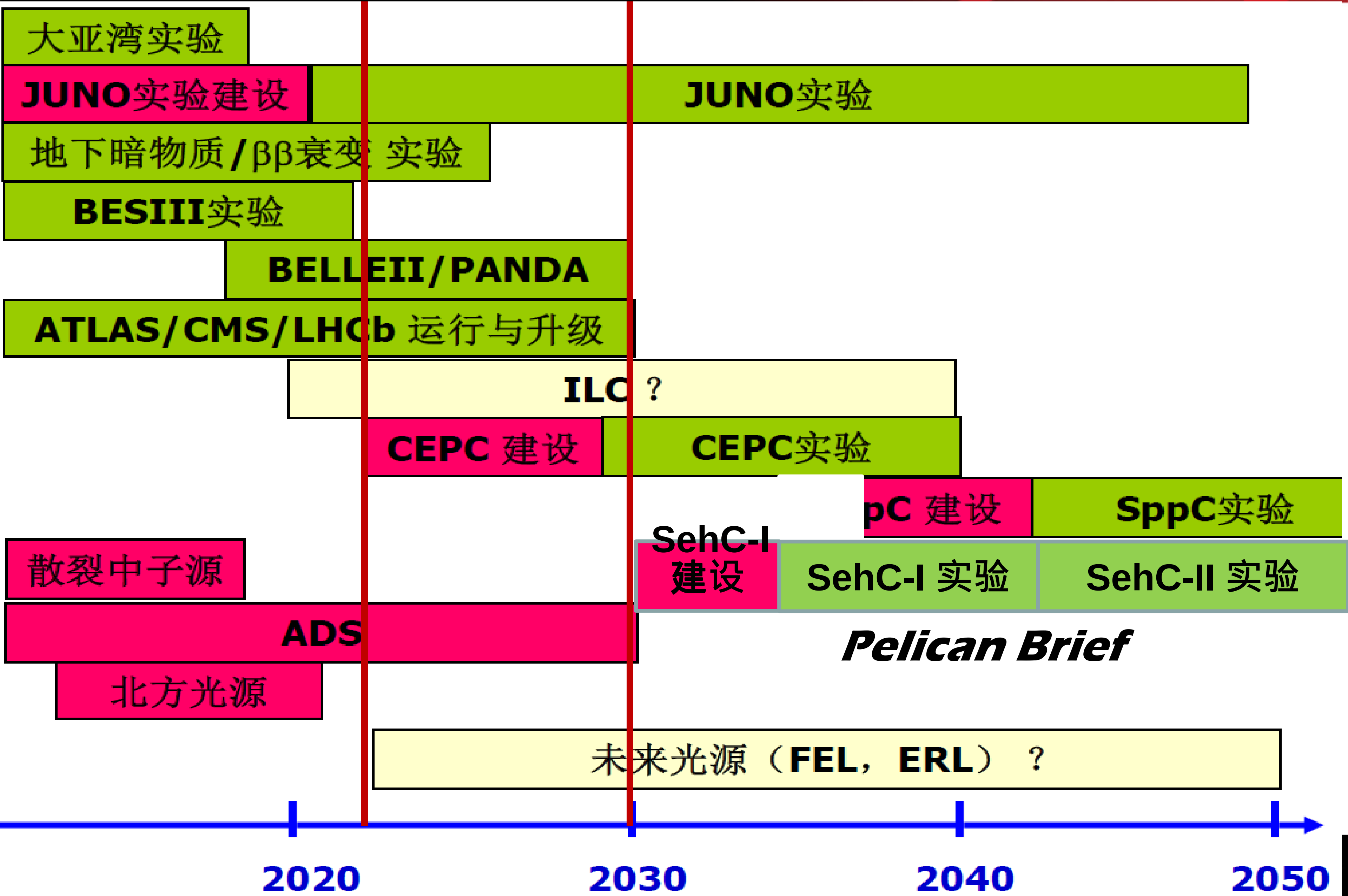
# Advantages of the Staging Approach

***SehC-I*:** SppC ***HEB*** as a ***hadron collider ring*** by ***super-ferric magnets***

***SehC-II:*** SppC full energy collider ring

- **Low Cost**: Requiring much lower construction funding for the first stage, thus improving the probability of the government approval;
- **High Cost Efficiency:** Has a cost advantage over other EIC proposals
- **Earlier Realization:** Bring this TeV+ *e-p/A* collider decades earlier, greatly increasing scientific productivity of the first stage of *CepC-SppC* proposal;
- **Good Science:** Having a well-defined science program (of LHeC) and a large international user community; deliver superior performance (CM energy and luminosity);
- **Staging *SppC*:** Provide options for staging the construction of SppC; nearly all the capital investments for SehC-I can be reused in the SppC stage;
- **Low Technical Risk:** Depending mostly on the existing technologies

# Timeline and Envision of *SehC* Staging



# Path Forward

- ***Science Study:*** Initiating a study of the science cases for SehC, enhancing the science program, in particularly, seeking to maximize the advantages of higher energy and luminosity of SehC;
- ***Detector Study:*** Initiating a study on the detector design
- ***Conceptual Design Study:*** Initiating a conceptual design of the first stage SehC; identifying and evaluating the accelerator R&D issues;
- ***Cost/Staging Study:*** Initiating a study on cost of SehC and staging/phasing options of SehC and SppC;
- ***Pre-ZDR:*** Producing a dedicated pre-conceptual design report for SehC in two (?) years

# Summary

- Chinese scientists have developed a very ambitious plan for reaching the next energy frontier
  - *CepC* will be an *e+e-* collider based Higgs factory as early as 2027
  - *SppC* will be a 70 TeV proton-proton collider for charting the unexplored territory about 10 years after CepC

- There is an opportunity to realize *e-p* or *e-A* collisions at multi-TeV energy range using planed *CepC* and *SppC* facilities

- Staging approaches has been explored to use the initial investment of *SppC* for *e-p/A* collisions

- The first-stage *e-p/A* collider based on *CepC-SppC* can reach the same science that LHeC is aiming for, since it is capable to reach a similar CM energy range and deliver similar high luminosities

# Backup Slides

# SehC-I *e-p* Design Parameters

| Location of the SppC HEB *e-p* | | A separate tunnel | | Inside the main tunnel | |
|---|---|---|---|---|---|
| Particle | | proton | Electron | Proton | Electron |
| Beam energy | GeV | 2,500 | 120 | 5,600 | 120 |
| Center-of-mass energy | GeV | 1004 | | 1640 | |
| No. of collision points (detectors) | | 1 | | 2 | |
| Beam current | mA | 430 | 33.8 | 437 | 33.8 |
| Particles per bunch | $10^{10}$ | 16.71 | 1.31 | 17.0 | 1.31 |
| Number of bunch | | 500 | 3000 | 3000 | 3000 |
| Bunch spacing | ns | 50 | 50 | 50 | 50 |
| Bunch repetition rate | MHz | 20 | 20 | 20 | 20 |
| Normalized emittance, (x/y) | µm rad | 1 | 250 | 1 | 250 |
| Bunch length, RMS | cm | 7.55 | 0.242 | 7.55 | 0.242 |
| Beta-star (x / y) | cm | 10 | 3.55 | 10 | 1.58 |
| Beam size at IP, (x/y) | µm | 6.15 | 6.15 | 4.1 | 4.1 |
| Beam-beam parameter per IP (x/y) | | 0.0016 | 0.15 | 0.0016 | 0.15 |
| Hour glass reduction factor | | 0.723 | | 0.481 | |
| Luminosity per IP, with reduction | $10^{33}/cm^2/s$ | 5.4 | | 8.2 | |

# SehC-I Design Parameters

| Particle | | p | e | p | e | p | e | p | e |
|---|---|---|---|---|---|---|---|---|---|
| Beam energy | TeV | 5.6 | 0.045 (Z) | 5.6 | 0.08 (W) | 5.6 | 0.12 (H) | 5.6 | 0.175 (t) |
| CM energy | TeV | 1.00 | | 1.34 | | 1.64 | | 1.98 | |
| Beam current | mA | 54.5 | 760 | 129 | 171 | 437 | 33.8 | 645 | 7.5 |
| Particles per bunch | $10^{10}$ | 0.88 | 12.3 | 5.01 | 6.64 | 17.0 | 1.31 | 25 | 0.29 |
| Number of bunch | | 7200 | | 3000 | | 3000 | | 3000 | |
| Bunch spacing | ns | 25 | | 50 | | 50 | | 50 | |
| Normalized emit. | µm rad | 1 | 13.2 | 1 | 74.1 | 1 | 250 | 1 | 775 |
| Beta-star (x/y) | cm | 10 | 11.2 | 10 | 3.4 | 10 | 1.55 | 10 | 0.75 |
| Beam-beam / IP | | 0.015 | 0.15 | 0.0008 | 0.15 | 0.0016 | 0.15 | 0.0004 | 0.073 |
| Hour glass (HG) reduction | | 0.904 | | 0.721 | | 0.481 | | 0.284 | |
| Luminosity per IP (with HG reduction) | $10^{33}$ /cm$^2$/s | 18.0 | | 18.4 | | 8.2 | | 1.57 | |

# SehC-I *e-A* Design Parameters

***e-A***

| Particle | | Lead ($^{208}Pb^{82+}$) | Electron |
|---|---|---|---|
| Energy | GeV/u | 2207 | 120 |
| Beam current | mA | 430 | 33.8 |
| Particles per bunch | $10^{10}$ | 0.2 | 1.31 |
| Number of bunch | | 3000 | 3000 |
| Bunch spacing | ns | 50 | 50 |
| Bunch repetition rate | MHz | 40 | 40 |
| Normalized emittance, (x/y) | µm rad | 0.22 | 250 |
| Bunch length, RMS | cm | 7.55 | 0.242 |
| Beta-star (x / y) | cm | 10 | 0.88 |
| Beam size at IP, (x/y) | µm | 3.1 | 3.1 |
| Beam-beam parameter per IP(x/y) | | 0.0028 | 0.15 |
| Crossing angle | mrad | 0.8 | |
| Hour glass (HG) reduction factor | | 0.322 | |
| Luminosity per nuclei per IP, with HG | $10^{33}/cm^2/s$ | 0.12 | |
| Luminosity per nucleon per IP, with HG | $10^{33}/cm^2/s$ | 24.5 | |