EIC-FCC-ee collaboration on polarized electron beams

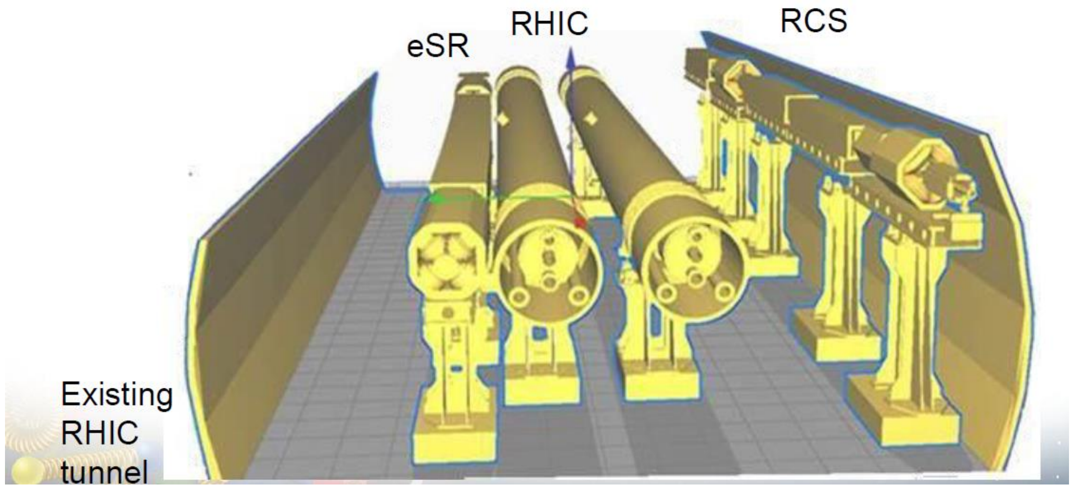
Preamble: the EIC project is approved.
It consists in upgrading the RHIC facility at Brookhaven (BNL) to provide e-p and e-ion collisions
by adding an electron booster and a storage ring (familiar?)

The project design and construction is planned for the years 2020-2030 with start of operations in 2030. *→

The electron storage ring has a number of features in common with the FCC-ee rings, esp. FCC-ee-Z, (current, RF, etc..) including the extensive use of beam polarization, transverse in the rings, rotation to longitudinal at IR and back.

This offers a number of **synergies** and the interesting possibility of **running experience before the start of FCC-ee**

First meeting on 5 November https://indico.cern.ch/event/971271/ , mostly to inform each other about the projects
much left to understand towards concrete workplan/time scales



Key parameters of NSLS-II, EIC and FCC-ee (Z pole)

	NSLS-II	EIC	FCC-ee Z pole (W)
Beam energy [GeV]	3	10 (18)	45.6 (80)
Bunch population [10^{11}]	0.08	1.7	1.7
Bunch spacing [ns]	2	10	15, 17.5 or 20
Rms bunch length [mm]	4.5-9	10	3.5 from SR 12 w. beamstrahlung
Beam current [A]	0.5	**2.5 (0.27)**	**1.39**
RF frequency [MHz]	500	591 or 394	400
SR power / beam / meter [W/m]	900	7000	600
Critical photon energy [keV]	2.4	9 (54)	19 (100)

Potential collaboration topics: superconducting RF systems, efficient RF power sources, beam instrumentation, impedance models, beam instabilities and their mitigation, higher-order mode heating, beam feedback systems, interaction region (IR) design including masking and shielding of synchroton radiation from dipoles and quadrupoles, SC final-focus quadrupole system, synchrotron-radiation monitors and handling equipment associated with the IR, self-polarization (or depolarization), strategies for spin-orbit matching, and simulation tool adaptations or developments of new tools, polarimeter design, and the arc vacuum system

15:00 → 15:05 **welcome and short introduction on EIC-FCC collaboration**
Speaker: Michael Benedikt (CERN)
EIC-FCC collaborati... | EIC-FCC collaborati...

15:05 → 15:15 **EIC physics use of polarization, requirements on polarization levels and measurement precision**
Speaker: Vadim Ptitsyn (Brookhaven National Laboratory)
EIC_Physics and Po... | EIC_Physics and Po...

15:15 → 15:25 **FCC-ee --Physics use of polarization and requirements**
Speaker: Alain Blondel (Universite de Geneve (CH))
AB-FCC-ee-polarizat... | AB-FCC-ee-polarizat...

15:25 → 15:35 **EIC: plans for implementation and operation of polarized beams, and polarimetry**
Speaker: Fanglei Lin
2020_11_05_Collab...

15:35 → 15:45 **FCC: plans for implementation and operation of polarized beams, and polarimetry**
Speaker: Eliana Gianfelice-Wendt
FCC_polarization.pdf

15:45 → 15:55 **EIC-particular challenges and foreseable difficulties.**
Speaker: Eliana Gianfelice-Wendt
EIC_challenges.pdf

15:55 → 16:05 **FCC-ee-particular challenges and foreseable difficulties.**
Speaker: Dr Jorg Wenninger (CERN)
FCCee.Pol-Ecal.Cha... | FCCee.Pol-Ecal.Cha...

16:05 → 16:25 **discussion on possible domains of collaboration**

16:25 → 16:35 **actions and next steps**

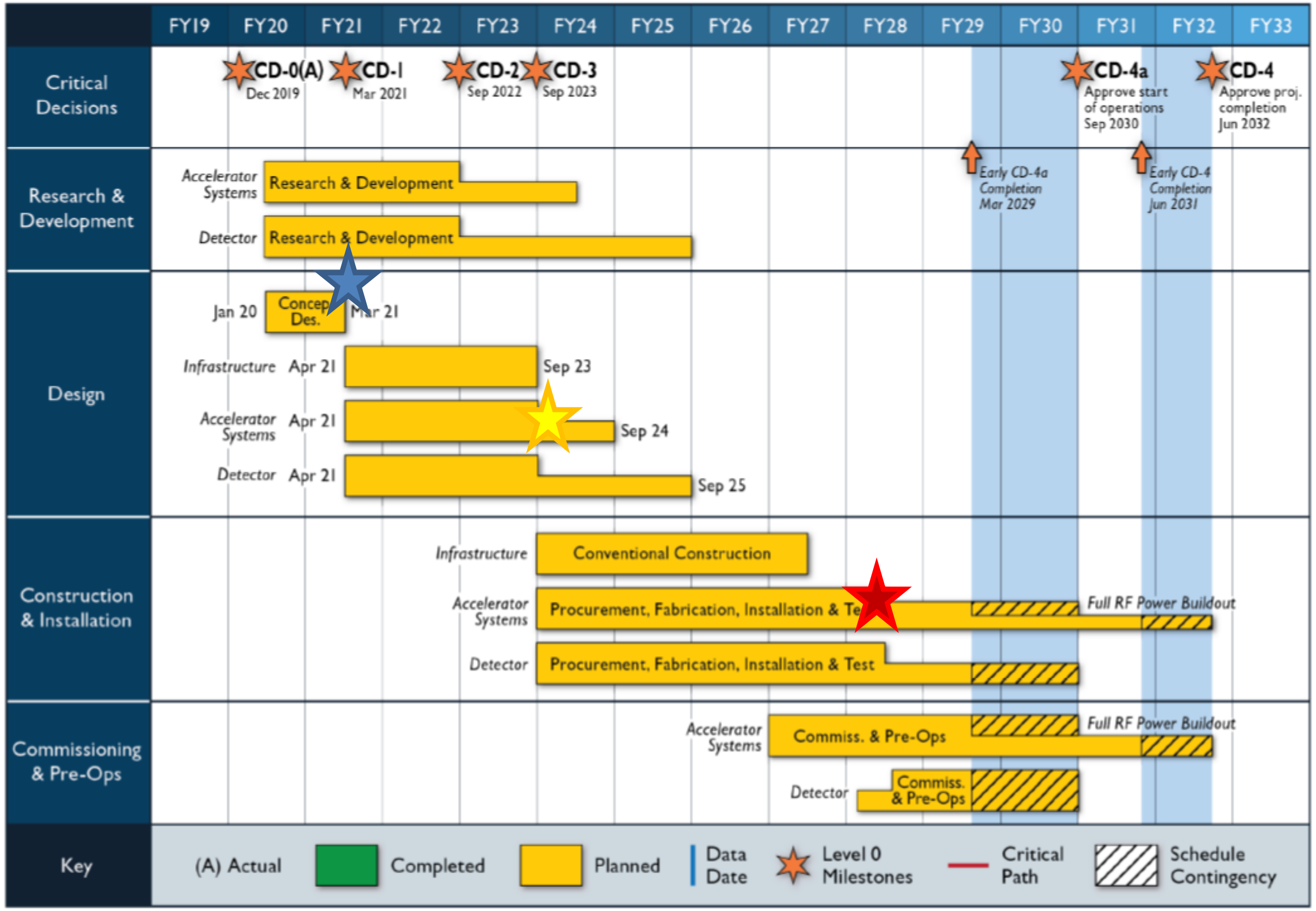
EIC reference schedule

As of my understanding

Concept of system

Detailed design and Distribution of work

Complete R&D Construction Installation



allows common development of hardware for the EIC followed by production for FCC-ee

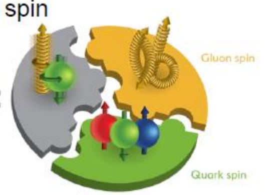
EIC: polarized-electron – polarized-hadron scattering

Performing experiments by flipping longitudinal spin of electrons
e- injected in ring from a polarized e- source (similar to SLC). Spin rotations and store.
+ colliding with various (longitudinal or transverse) ion spin state.
-- Measurement precision required ±1% P.(1± 0.01) P≈75%

EIC Measurements Requiring Polarized Beams

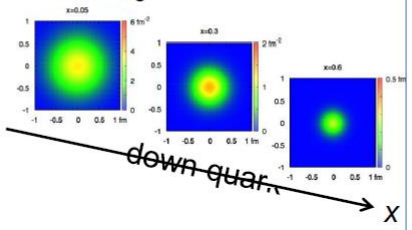
Spin structure of nucleons and nuclei

Quark, gluon and quark and gluon orbital momenta contribution to nucleon spin



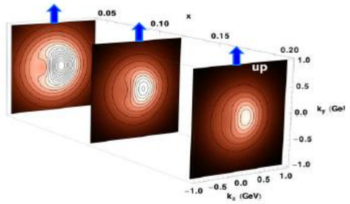
Tomography Spatial Imaging

Spin-dependent 2+1D coordinate space images from exclusive scattering



Tomography Transverse Momentum Dist.

Spin-dependent 3D momentum space images from semi-inclusive scattering

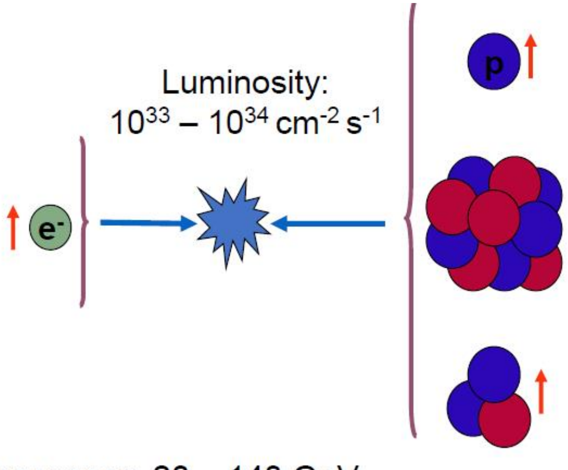


Double longitudinal spin asymmetries with scattering longitudinally polarized electrons off longitudinally polarized protons.

Single spin asymmetries with scattering (un)polarized electrons off transversely and longitudinally polarized protons.

polarized electrons: 5 – 18 GeV

Luminosity: $10^{33} - 10^{34}\ cm^{-2}\ s^{-1}$

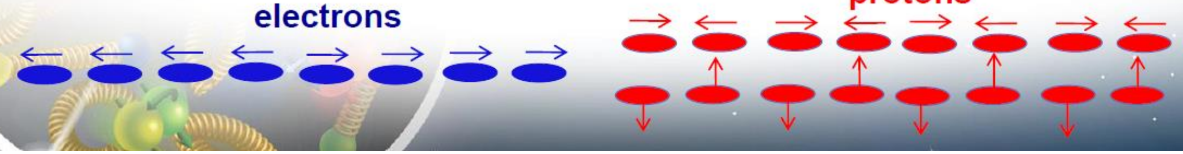


polarized protons 41 - 275 GeV

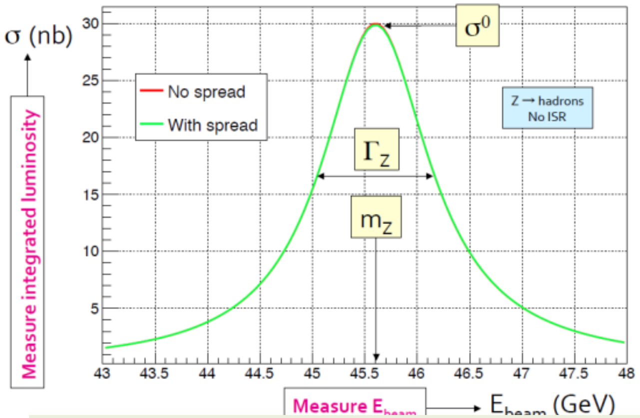
Light ions (d, Si, Cu)
Heavy ions (Au, U)
41 – 110 GeV/u

Pol. He-3
41 - 184 GeV/u
Pol. d (?)

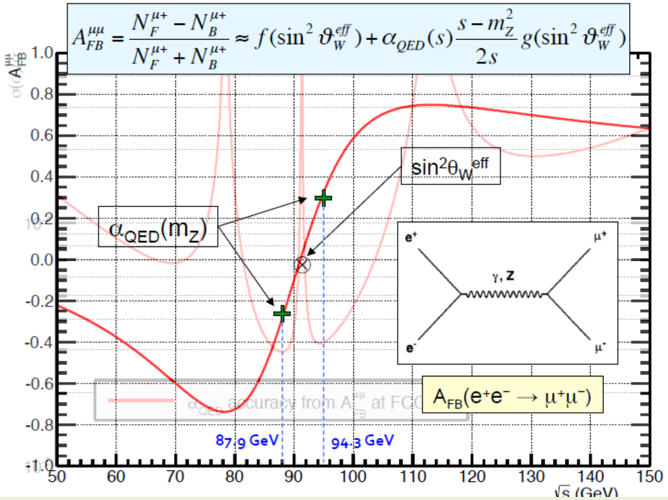
- Center-of-mass energy range: 20 – 140 GeV
- At least 70% electron polarization at all energies
  70% proton and He-3 polarization with six Siberian snakes
- Any polarization direction in electron-hadron collisions:



FCCee polarization



Z line shape → m_Z and Γ_Z



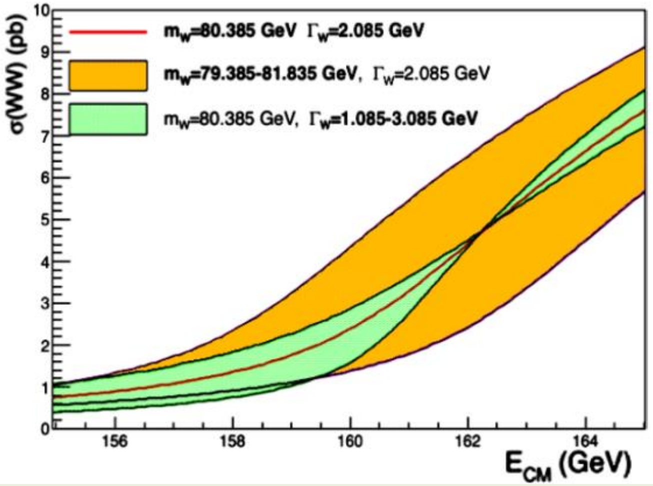
at the same time $A_{FB}^{\mu\mu}(\sqrt{s})$ → $\sin^2\theta_W^{eff}$, $\alpha_{QED}(m_Z)$

natural build up of transverse polarization sped up with wigglers.
Use polarization for ± 100keV ECM calib. for precision measurements of Z,W, H

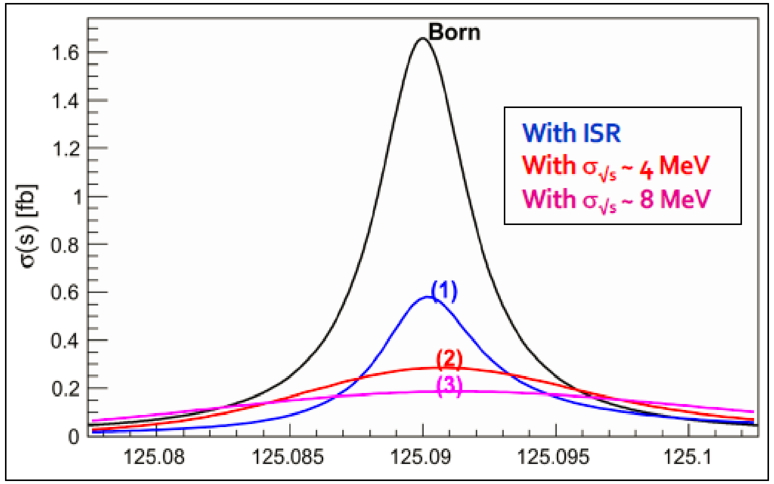
200 'pilot' bunches will be stored at the beginning of fills with polarization wigglers ON, for about 1 hour to develop about 5-10% transverse polarization.

After a first energy calibration, the full luminosity run will comprise regular calibrations (1/10 min) on pilot bunches.

Polarimeter/spectrometer used both for depolarization measurement and for monitoring of relative beam energy variations.



WW threshold → m_W and Γ_W

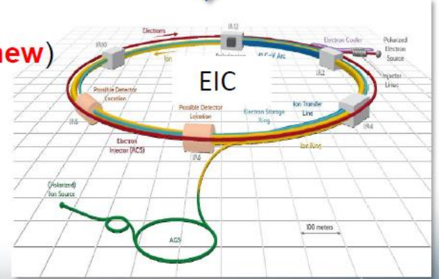


Higgs s-channel production need to know E_{cm} σ_{ECM} → $y_e = m_e$?

EIC Overview

Design based on **existing RHIC Complex**
RHIC is well maintained, operating at its peak

- **Hadron storage RHIC Yellow Ring 40-275 GeV** (existing)
  - 1160 bunches, 1A beam current (3x RHIC)
  - bright vertical beam emittance 1.5 nm
  - strong cooling (coherent electron cooling)
- **Electron storage ring 2.5–18 GeV** (new)
  - many bunches,
  - large beam current, 2.5 A ➔ 9 MW S.R. power
  - S.C. RF cavities
- **Electron rapid cycling synchrotron 0.4- 18GeV** (new)
  - 1-2 Hz
  - Spin transparent due to high periodicity
- **High luminosity interaction region(s)** (new)
  - L = $10^{34}cm^{-2}s^{-1}$
  - Superconducting magnets
  - 25 mrad Crossing angle with crab cavities
  - Spin Rotators (longitudinal spin)
  - Forward hadron instrumentation



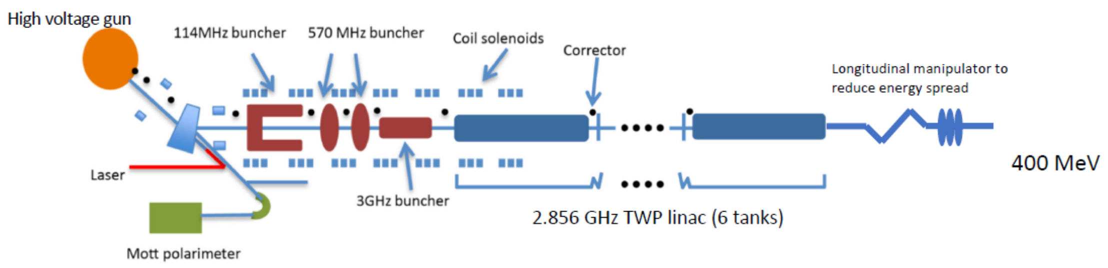
Design of Polarized Electrons in EIC

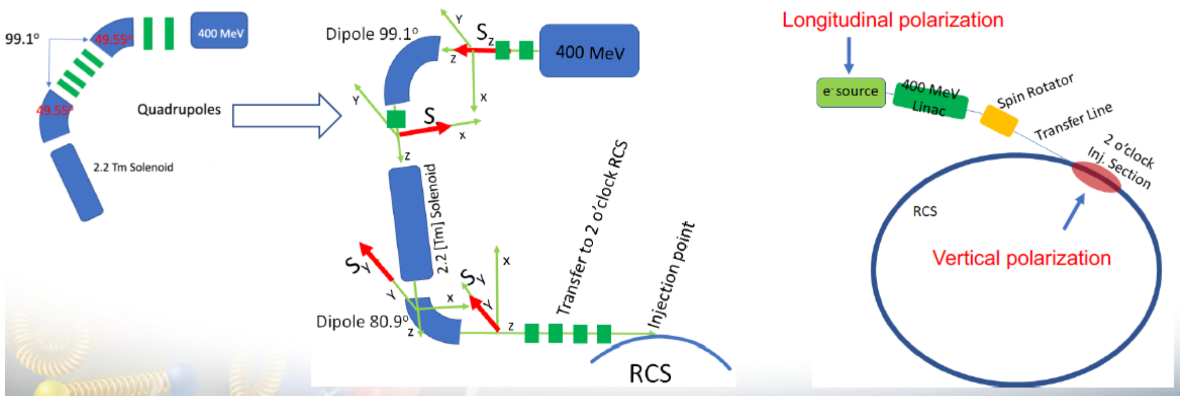
- Polarized Electron Pre-Injector:
  - Providing up to **85% polarized electron beams**
- Rapid Cycling Synchrotron (RCS):
  - Spin resonance free lattice by having a periodicity of 96 and a tune with an integer value of 50, **> 95% polarization transmission**
- Electron Storage Ring (ESR):
  - Highly polarized electrons with two opposite polarization helicities are injected in to the ESR
  - Polarization is vertical in arcs to avoid spin diffusion and longitudinal at IP for physics experiments
  - Spin rotators rotate the spin from vertical in arcs to longitudinal at IP
  - Spin matching is implemented to preserve high asymptotic polarization and extend the polarization relaxation time
  - Electron bunches regular replacement down to a few minutes at highest beam energy 18 GeV is needed to obtain **a high average polarization 80%**

(transverse + longitudinal?) polarization measurement in RCS, needed for diagnostic and optimization
expect 95% conservation of polarization degree.
Precise polarization measurement in the storage ring.

Electron Pre-Injector

E. Wang, J. Skaritka



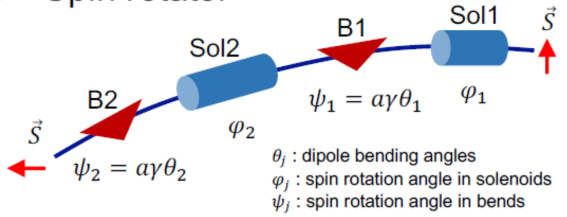


85% polarized electron beams are generated and transferred to RCS

Electron Storage Ring

V. Ptitsyn, E. Gianfelice-Wendt

- Spin rotator

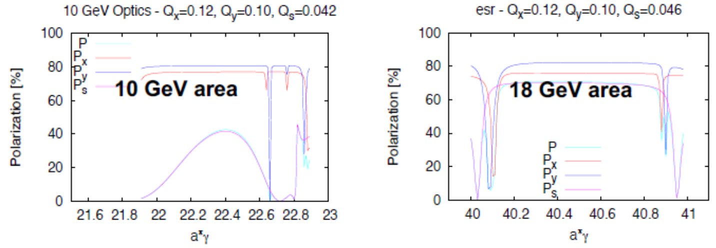


θ_j : dipole bending angles
φ_j : spin rotation angle in solenoids
ψ_j : spin rotation angle in bends

$$\tan\varphi_1 = \pm\frac{\cos\psi_2}{\sqrt{-\cos(\psi_1+\psi_2)\cos(\psi_1-\psi_2)}}$$

$$\cos\varphi_2 = \cot\psi_1\ \cot\psi_2$$

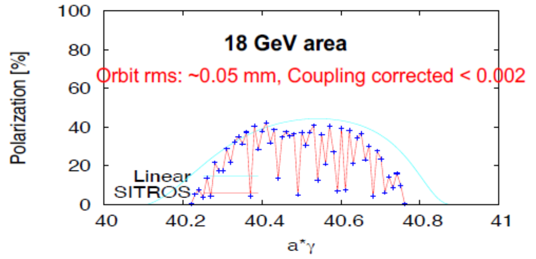
- Spin matching @ 18 GeV



- Simulation with errors

Assumed quadrupole RMS misalignments

horizontal offset	δx^Q	200 μm
vertical offset	δy^Q	200 μm
roll angle	$\delta\psi^Q$	200 μrad

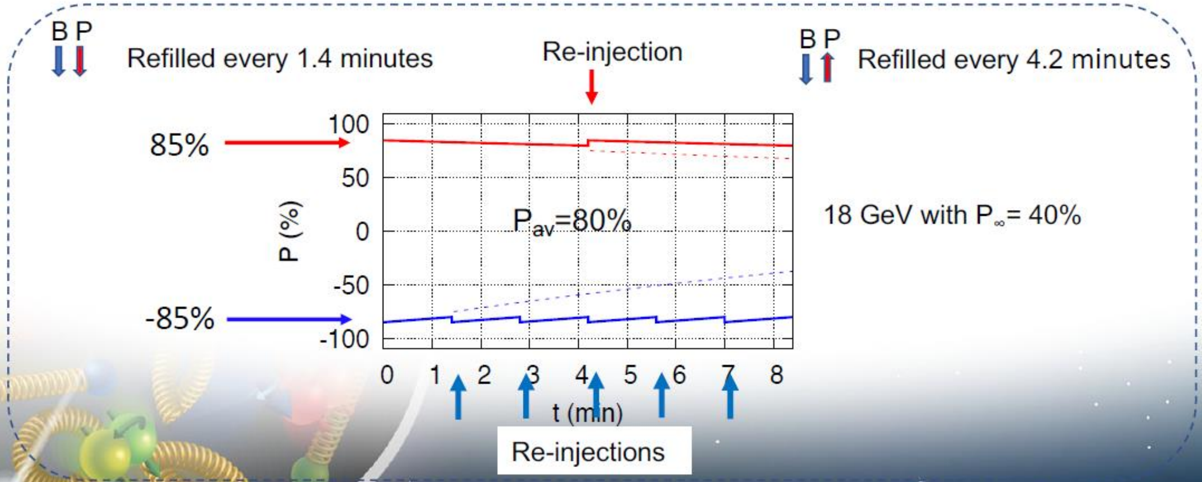


- Spin matching is performed to minimize depolarization at 18 GeV area
- Longitudinal spin matching can not be done perfectly at 10 GeV. However, the depolarization at 10 GeV area is ~16 times slower. Thus, averaged polarization >70% can still be achieved under the imperfect spin matching

EIC running mode :
depolarization time should be >> longer than the time between injections

Electron Storage Ring

- In the EIC, ESR electron bunches are regularly replaced. With high initial polarization of 80-85% injected from RCS and proper refill rate, > 70% average polarization can be reached.
  - 18 GeV:
    - for 2.8 min refill: 40% asymptotic polarization => 80% average polarization
  - 10 GeV:
    - For 10 min refill: 15% asymptotic polarization => 80% average polarization



Quite a large amount of work to do for full spin-matching of the system:

-- arcs with transverse polarization
-- spin rotators at energies from 5 to 18 GeV
-- detector solenoid and final focus
-- beam-beam depolarization

Depolarization is particularly damaging for the bunches that are polarized antiparallel with the natural orientation opposite to magnetic field.

My impression:
-- need to design "polarization tuning knobs"
-- continuous measurement of polarization in 3D Px, Py, Pz is necessary to provide a reliable average for the experiment and for tuning the system.

Polarization at FCC-ee

Simulations of spin are performed by Eliana Gianfelice on SLIM/SITROS (including imperfections) and simulation of misalignments and luminosity by Tessa Charles *in a different time zone.*

➔ run into machines that are sometimes pathological, (not the same code or machines, convergence is slow.)

➔ other work to do: simulation and statistics on possible shifts between

-- tune spin (measured by resonance depolarization)

-- the beam energy

-- the centre-of-mass energy

$$\frac{\partial \hat{n}}{\partial \delta}(\vec{u}; s) = \vec{d}(s) = \frac{1}{2}\Im\Big\{(\hat{m}_0 + i\hat{l}_0)^* \sum_{k=\pm x,\pm y,\pm s} \Delta_k\Big\}$$

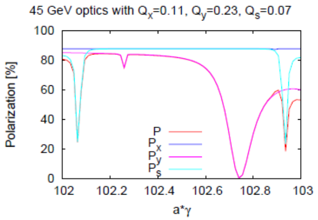
$$\Delta_{\pm x,\pm y} = (1+a\gamma)\frac{e^{\mp i\mu_{x,y}}}{e^{2i\pi(\nu \pm Q_{x,y})} - 1}\frac{[-D \pm i(\alpha D + \beta D')]_{x,y}}{\sqrt{\beta_{x,y}}} J_{x,y}$$

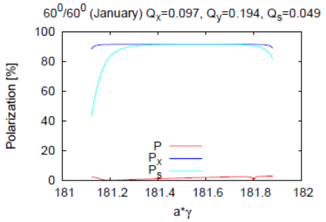
$\equiv f_{x,y}$

The same 45 GeV optics have been scaled to 80 GeV

- no wigglers
- no tapering (from previous simulations it seemed not crucial):
  - main FODO circuits adjusted for compensating sextupoles feed-down effect.

For some seeds P_y limits P although ϵ_y and D_y are small.





x_{rms} (μm)	y_{rms} (μm)	D^y_{rms} (mm)	ϵ_x (nm)	ϵ_y (pm)	$\lvert C^-\rvert$
26	11	2	0.222	0.5	0.0014

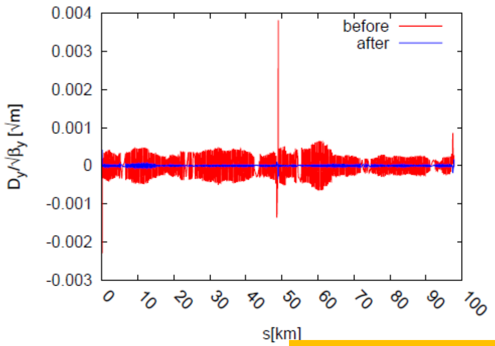
x_{rms} (μm)	y_{rms} (μm)	D^y_{rms} (mm)	ϵ_x (nm)	ϵ_y (pm)	$\lvert C^-\rvert$
144	11	2	0.792	0.1	< 0.001

Well corrected machine (ϵ_y a factor $\approx$ 20 smaller than design), but P few percent at 80 GeV in linear approximation, limited by the vertical motion... Is this an *artifact*?

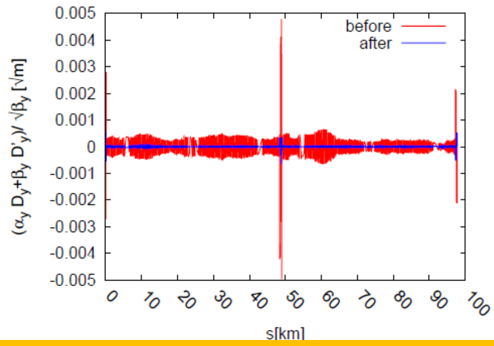
In some short regions f_y is much larger than in the rest of the ring!

- Attempts of correcting the f_y "spikes" with the skew quadrupoles were unsuccessful
  $\rightarrow$ vertical correctors used for minimizing f_y.

$\Re(f_y)$



$\Im(f_y)$



Would such a machine arise in real life after dispersion correction for high luminosity?

Polarization measurement: EIC

Electron Polarimetry in ESR

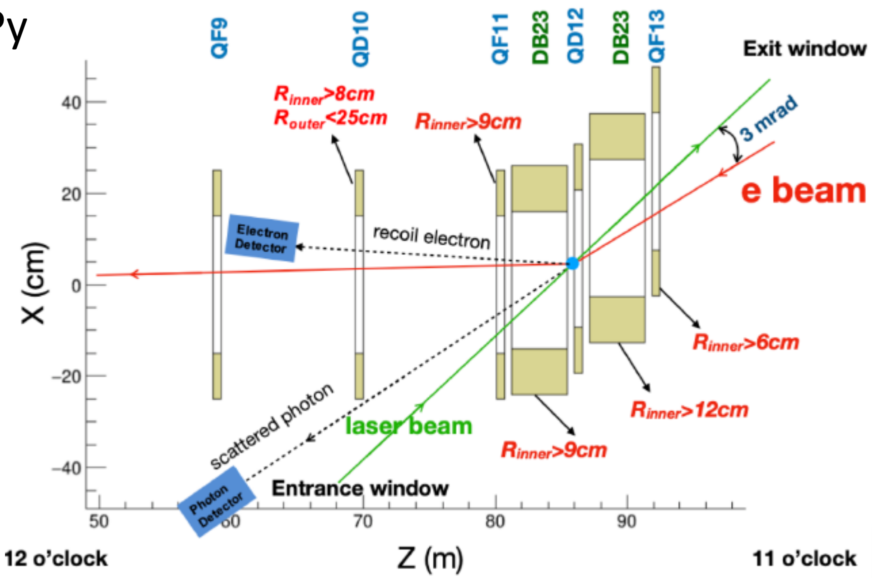
EIC CDR

Compton polarimeter

Plans for electron polarimetry in the EIC electron storage ring (ESR) include

- a Compton polarimeter at IP 12, where the electron beam is primarily vertical polarized.
- A Compton polarimeter near the primary detector in the vicinity of IP 6, where the beam will be a mix of longitudinal and transverse polarizations, is also under investigation; since the region of the ring is extremely crowded, care must be taken in the assessment of whether a polarimeter can be accommodated.

This seems to indicate that 3D polarimetry is desirable: Pz, Px, Py



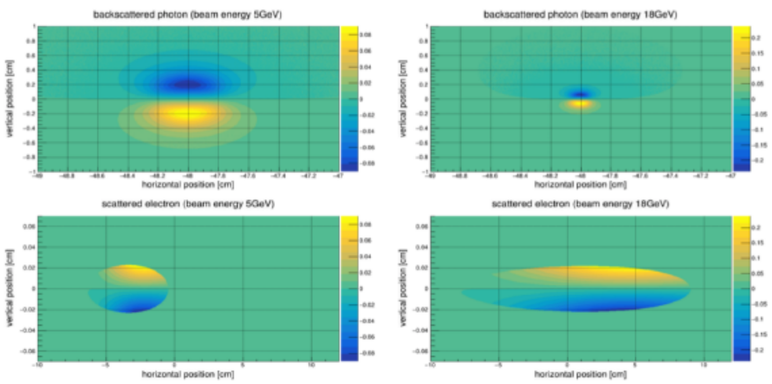


Table 8.6: Asymmetries, measurement times needed for a 1% statistical measurement for one bunch and needed luminosities for three different beam energies for a 532 nm laser.

E_{beam} [GeV]	σ_{unpol} [barn]	$\langle A_\gamma \rangle$	t_γ[s]	$\langle A_e \rangle$	t_e[s]	L[1/(barn·s)]
5	0.569	0.031	184	0.029	210	1.37E+05
10	0.503	0.051	68	0.050	72	1.55E+05
18	0.432	0.072	34	0.075	31	1.81E+05

Polarization measurement: FCC

Polarimetry

Compton polarimeter

Beam polarization will be measured by Compton polarimeter(s).

- Solid-state pulsed laser with $\boldsymbol{\lambda}$=532 nm.
- Measurement of the scattered $e^{\pm}$, in addition to photons, is planned. At low energy (few GeV), it allows a *direct* measurement of the beam energy with good accuracy (50 KeV). Here it allows to get the needed accuracy with some 1e9 bunch population.
- With a repetition frequency of 3 KHz and $N_b \approx$ 1e10, the photon rate will be 2e6 s^{-1}, the precision 1% over 1 second and bunch lifetime 1.4 h.

FCC polarimeter sketch

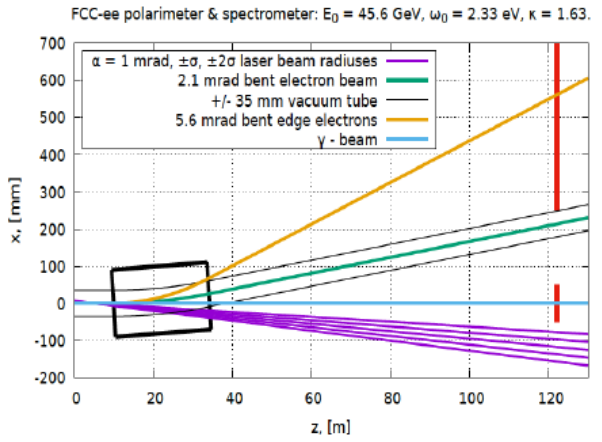


Figure 27. Sketch of the polarimeter with the lattice dipole (L = 24.12 m, θ_0 = 2.13 mrad, B = 0.0135 T, R_0 = 11302 m), the vacuum chamber and the particle trajectories. Red vertical bars on the right side indicate the location of the scattered particles detectors 100 m away from the centre of the dipole.

Yu.N. Munchnoy courtesy

Expect to perform the energy measurement in 10 minutes (needs some planning!)
Also we would like to measure the colliding beams to make sure they have P_L &P_T=0

ISSUES at DESIGN LEVEL ...

... will probably be issues at the time of operations!

EIC: (Eliana)

The "local coupling" knob has been embedded in the experiment solenoid compensation scheme by Vasiliy Morozov.

Beam-beam studies (by Yun Luo group) however have shown a detrimental effect on the proton beam.

This simple idea must be revisited: "flat-to-round" scheme?

In conclusion...

EIC electron storage ring challenges for getting the needed asymptotic polarization:

- Well corrected orbit (few tens of microns); why large polarization was achieved in HERAe at 27 GeV with $\approx$ 1 mm rms orbit?
- Well corrected betatron coupling: working point very close to linear coupling difference resonance.

Open questions:

- Matching of proton beam size without destroying polarization.
- Beam-beam effects on polarization: SITROS calculations for HERAe were (too) pessimistic.

FCC: Jorg Wenninger

- The tools and codes used for FCC optics and beam dynamics (currently MADX, SAD) must in the future integrate calculations / tracking of spins and transverse polarization.
  - Avoid import/export of lattice configurations including errors between codes as this complicates significantly the machine optimization.
  - Integrate simulation of the local energy and of the resonant depolarization process.
- A robust operation model must be established with transversely polarized bunches circulating in parallel to high luminosity operation.
  - Non-colliding, low intensity bunches for energy calibration.
  - During initial phase of filling, need to polarize witness bunches with wigglers, followed by high current bunch filling and operation.
  - Identify working points compatible with high luminosity and transverse polarization.
- A polarimeter, possibly for e+- and γ, must be designd, compatible with the high beam currents.
  - Move from conceptual design to a technical design including detailled simulations.
- The depolarization process must be studied further to optimize the machine settings and to develop an operational depolarization procedure.
  - Impact of synchroton motion, in particular at W.
  - Attainable accuracy and possible systematic biases.
  - Design of the RF kicker.
- Moving from an average beam energy measurement by resonant depolarization to the local centre-of-mass energy involves an important number of corrections that must be controlled to high accuracy.
  - Distributed energy loss from SR and impedances, RF voltage distribution, local dispersion and collision offsets etc.
  - Systematic shifts arising from dispersion at the IP must be controlled through ‚near perfect' head-on collisions – adequate diagnostics and procedures.
  - Many systematic effects have been identified, but not all of them can be considered ‚under control'.

Moving forward

Two directions for collaboration EIC-FCC-ee are clear:

-1- identify or develop computer code that allows to perform on the same machine

-- orbit tuning and trimming operations (both)

-- luminosity optimization (both)

-- simulation and optimization of spin (both)

-- calculation of difference between spin-tune and beam energy as in $\nu = a \cdot E_b/m_e$ (both)

See what labs ‘policy’ says on this.

-2- Development and implementation of polarimeter

The conceptual designs are the same Compton polarimeter measuring both transverse and longitudinal polarization.

A polarimeter is a fun little accelerator/particle physics experiment with many evil details...

A collaboration on this should include experts from various labs and could form a very nice international collaboration.