Hadron Polarimetry

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What is Polarization?

Merriam-Webster

- Noun, po·lar·i·za·tion ˌpō-lə-rə-ˈzā-shən

1. the action of polarizing or state of being or becoming polarized: such as
   a. the action or process of affecting radiation and especially light so that the vibrations of the wave assume a definite form
   b. the state of radiation affected by this process
   c. an increase in the resistance of an electrolytic cell often caused by the deposition of gas on one or both electrodes
   d. MAGNETIZATION
   an instance of magnetizing or the state of being magnetized
   also: the degree to which a body is magnetized
2. *division into two sharply distinct opposites*
   especially: a state in which the opinions, beliefs, or interests of a group or society no longer range along a continuum but become concentrated at opposing extremes

Polarization is the average alignment of the magnetic moment of an ensemble of particles with respect to an external magnetic field.

For $s = \frac{1}{2}\hbar$:

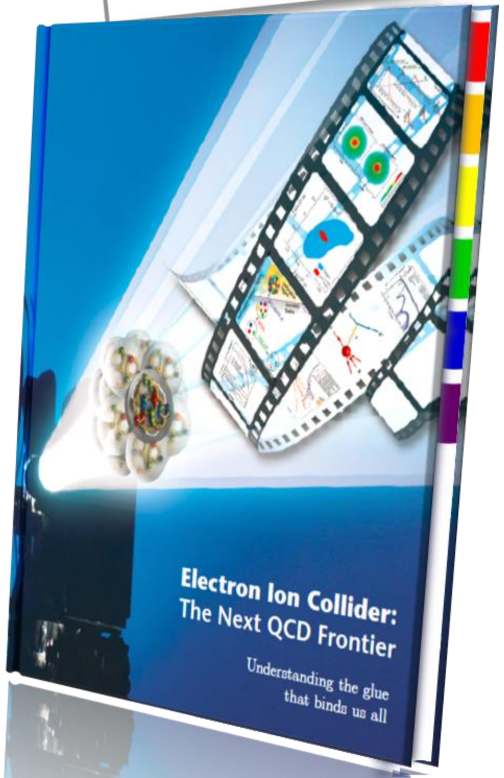
$$P = \frac{n^{+} - n^{-}}{n + n^{-}}$$

$$-1 \leq P \leq +1$$

Outline

- Introduction: A Polarized Electron-Ion Collider
- I. Polarized Particle beams
- II. Hadron Polarimetry
- Outlook / Summary

wiki.bnl.gov/EPIC/



❶ Emerging Nucleons

How are gluons, sea quarks, and their intrinsic spins distributed in space and momentum in the nucleon?

arXiv: 1212.17010

Eur. Phys. J. A52 (2016) 268

❷ Nuclear Medium

How do colored quarks and gluons and colorless jets interact with the nuclear medium?

How does the nuclear environment affect quark and gluon distributions?

❸ Gluon Saturation

What happens to the gluon density at high energy?

Are the properties of a saturated gluonic state universal among all nuclei?

The Electron-Ion Collider

- Variable center-of-mass energy:

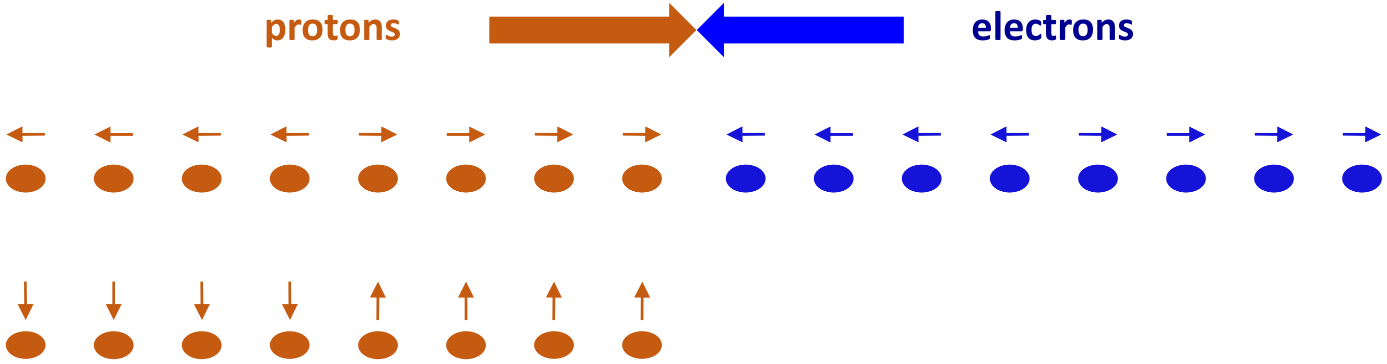
$$\sqrt{s} = 20 - 140 \text{ GeV}$$

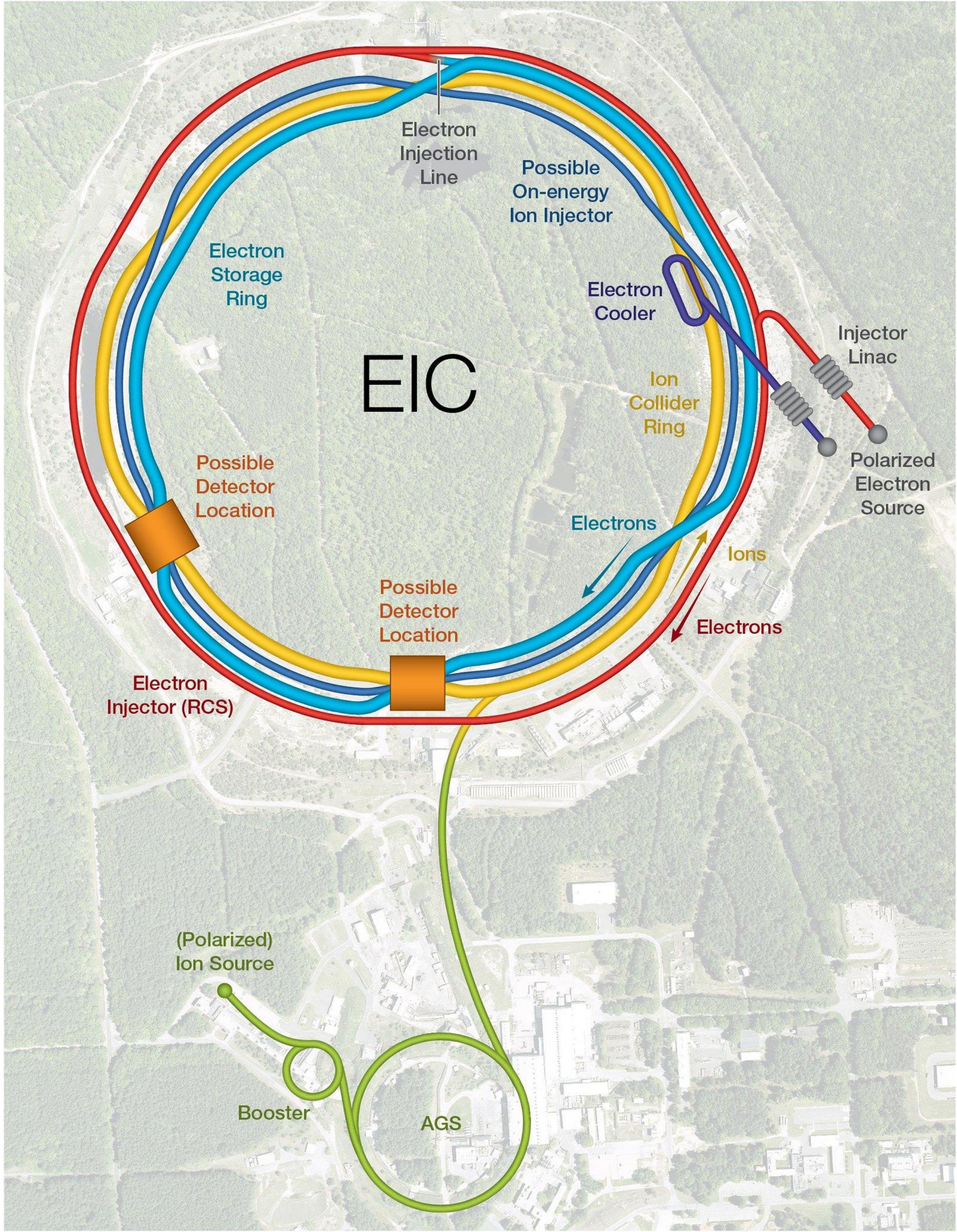
- Ion beams: protons, $^{3}\mathrm{He}$, Au, Pb, U
- High luminosity:

$$L = 10^{33} - 10^{34}\ \mathrm{cm}^{-1}\mathrm{s}^{-1}$$

- **Polarized electron and proton beams:**

$$\boldsymbol{P \approx 70\%}$$





Polarization and Figure of Merit

$$\delta f(x) \propto \delta\sigma = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

Physics observable of interest $\delta f(x)$

$$N = \int \frac{d\sigma}{d\Omega} \mathcal{L} d\Omega dt$$

$$\epsilon = \frac{N^+ - N^-}{N^+ + N^-}$$

If the measurement is fully polarized

$$\epsilon = P\frac{N^+ - N^-}{N^+ + N^-}$$

With polarization $P = \frac{n^+ - n^-}{n^+ + n^-}$

(note the assumption: $P^+ = P^-$)

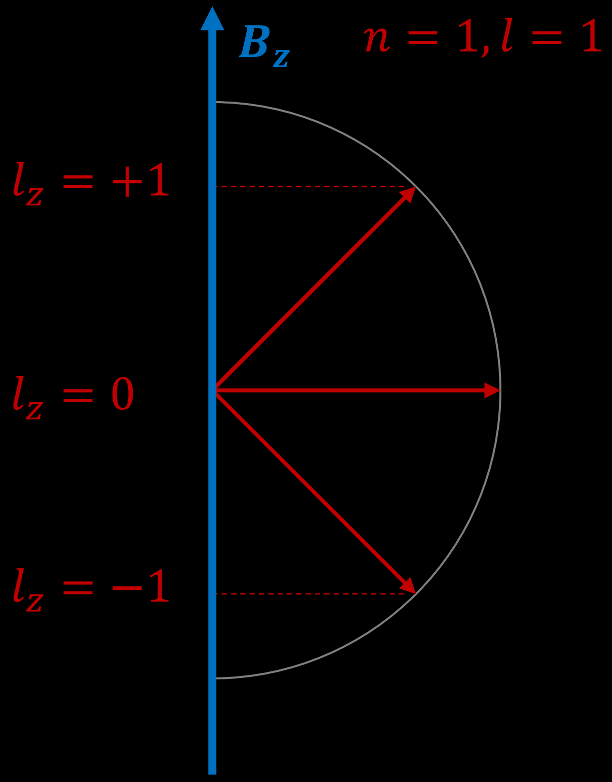
Uncertainty of physics observable $\Delta_f = \Delta_\epsilon P$

Statistical uncertainty of measurement $\Delta_\epsilon = \sqrt{N}$

Figure of merit: $FOM = NP^2$

I.
Polarized High Energy Particle Beams

Space Quantization



The spectral lines of atomic hydrogen can be explained by the Rydberg formula:

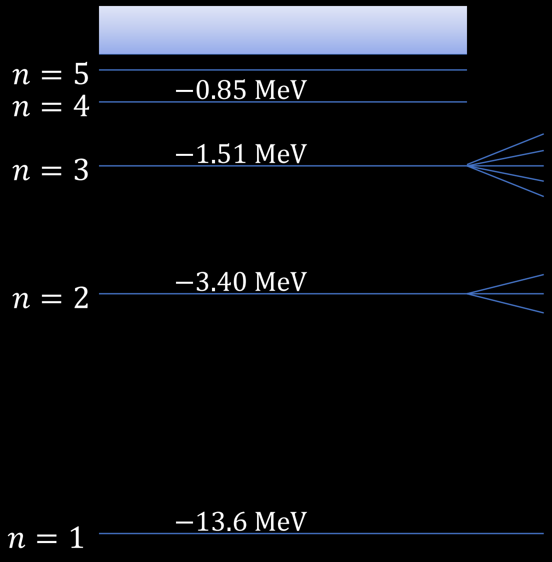
$$\frac{1}{\lambda} = R_M\left(\frac{1}{n'^2} - \frac{1}{n^2}\right)$$

An external magnetic field introduces splitting of the energy levels, $l < n$:

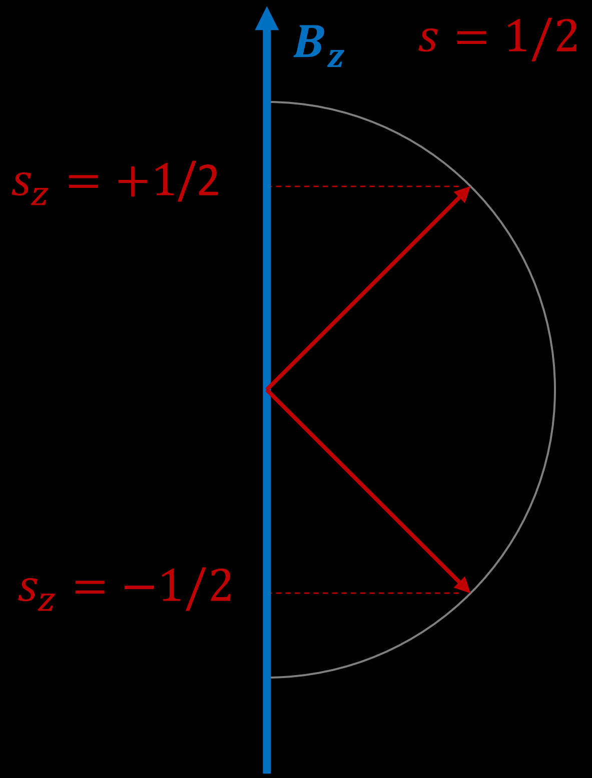
$$2l + 1$$

The orbital angular momentum l is related to a magnetic moment m, the energy splitting is:

$$\Delta W = -m\mu B_z$$



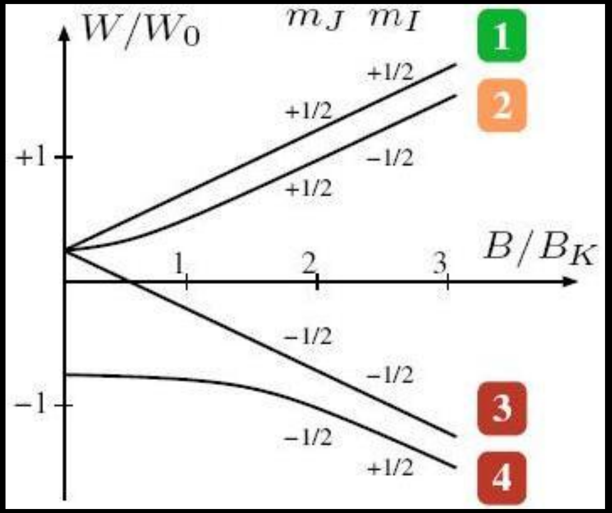
Space Quantization



The electron has a magnetic moment which is related to an intrinsic angular momentum, $s = \frac{1}{2}\hbar$.

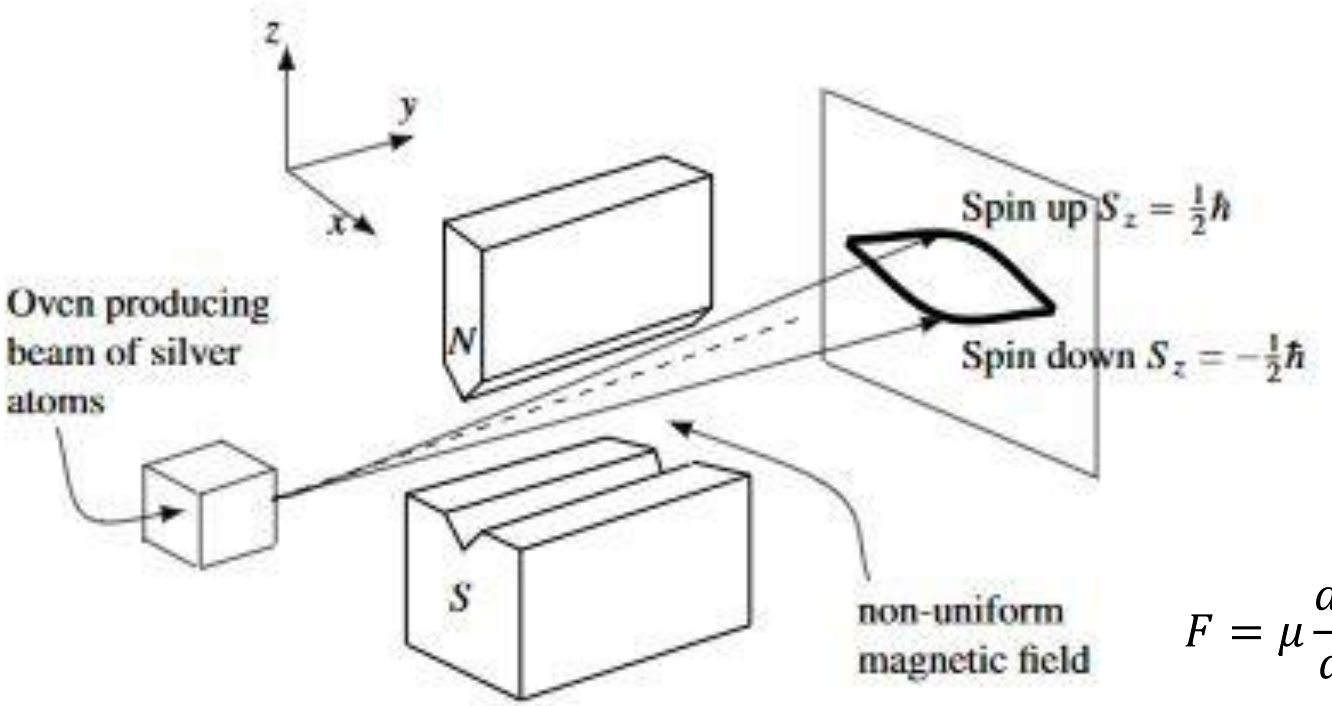
It introduces a fine splitting of the energy levels.

The magnetic moment of the nucleus introduces an additional hyperfine splitting.

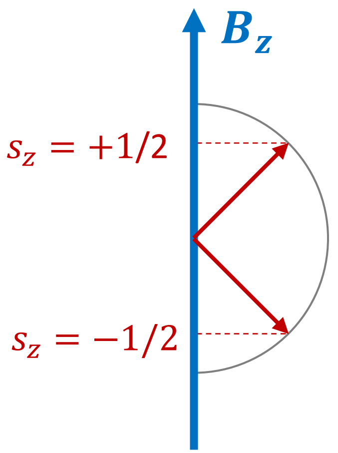


Spin Polarized Protons

- Stern-Gerlach (1922) demonstrated that the electron spin is quantized.

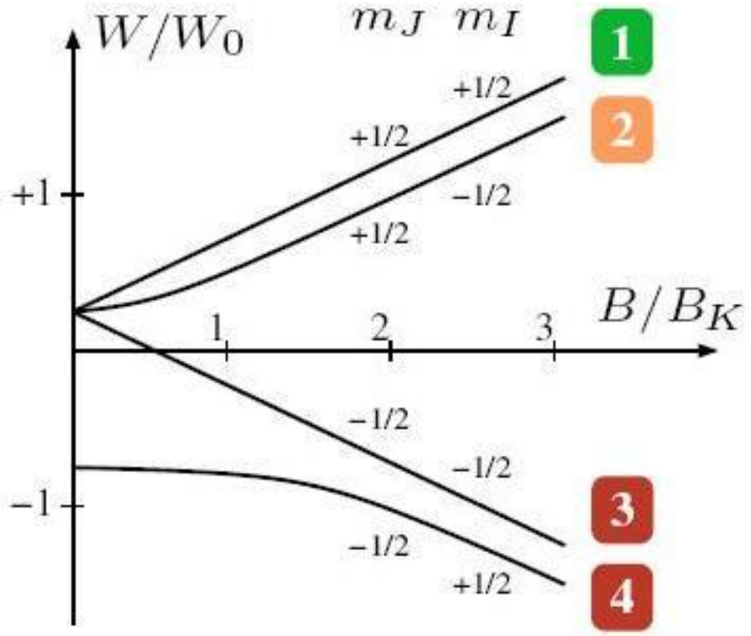


$$F = \mu \frac{dB}{dz}$$



Spin Polarized Protons

- Stern-Gerlach (1922) demonstrated that the electron spin is quantized.
- Use a similar setup as a filter to produce polarized protons.
- The magnetic moment of the nucleus is much smaller than that of the electron.



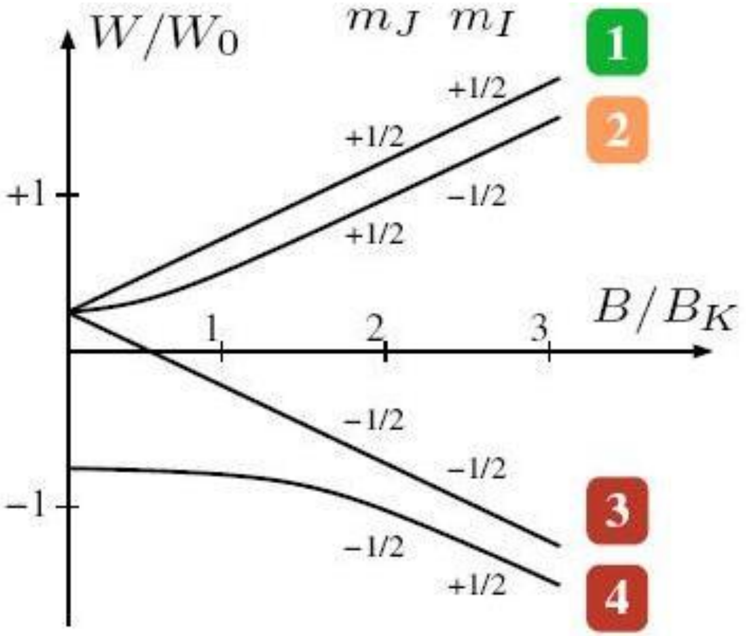
$$F = \mu \frac{dB}{dz}$$

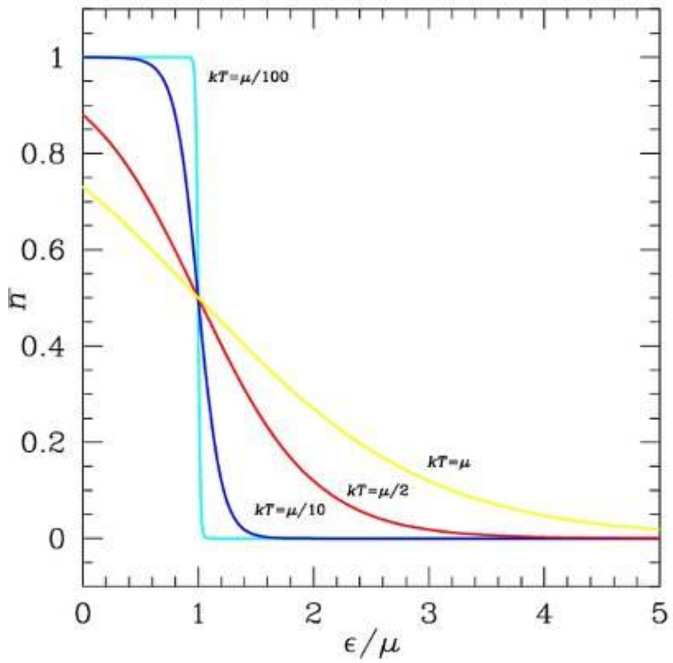
$$\Delta E = \hbar\nu$$

$$F = \mu \frac{dB}{dz}$$

Spin Polarized Protons

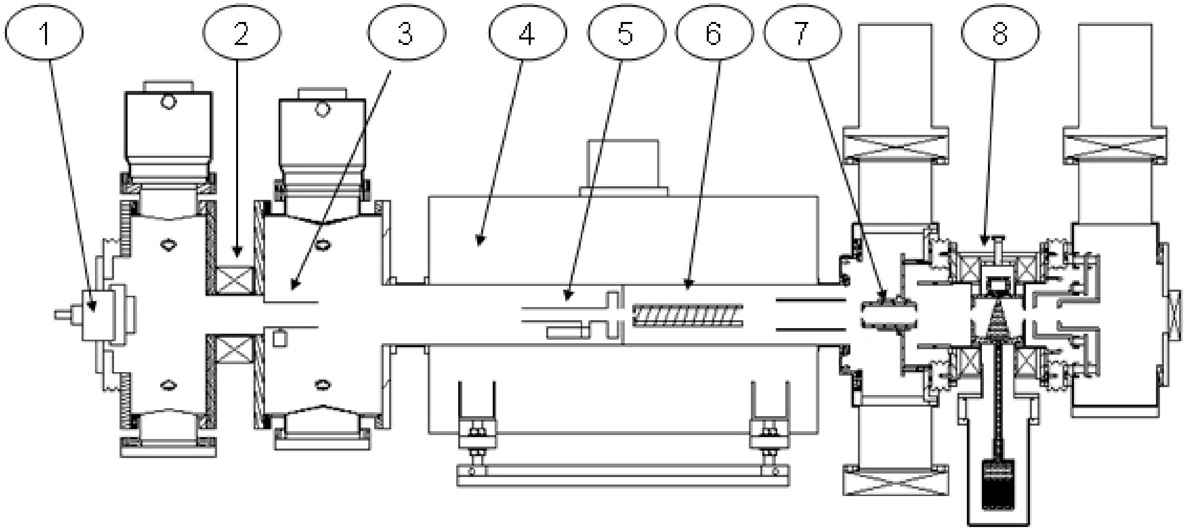
- Stern-Gerlach (1922) demonstrated that the electron spin is quantized.
- Use a similar setup as a filter to produce polarized protons.
- The magnetic moment of the nucleus is much smaller than that of the electron.
- There is a limit to the polarization (temperature, magnetic field, power of RF unit).





An Advanced Polarized Proton Source

A. Zelenski et al., J. Phys. Conf. Ser. **295** (2011) 012147



H^+ 10 keV | H^0 10 keV | $H^{0\uparrow}$ 3 keV | $H^{+\uparrow}$ 3 keV | $H^{+\uparrow}$ 35 keV

1. High brightness proton source
2. Focusing solenoid
3. Pulsed hydrogen neutralization cell
4. Superconducting solenoid 30 kG
5. Pulsed He-ionized cell
6. Optically pumped Rb cell
7. Sona shield
8. Sodium-jet ionizer

Optically Pumped Polarized Ion Source at RHIC:

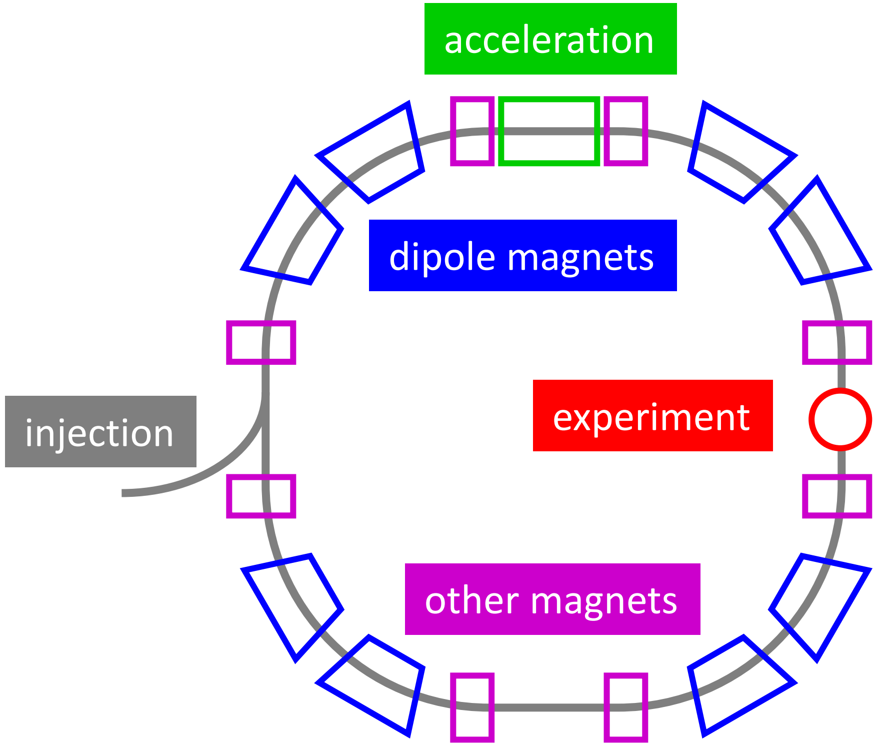
- Current $0.5 - 1.0$ mA in $300\ \mu s$
- Beam polarization $\approx 80\%$ at 35 keV

→ One proton bunch in RHIC

Particle Beam Optics

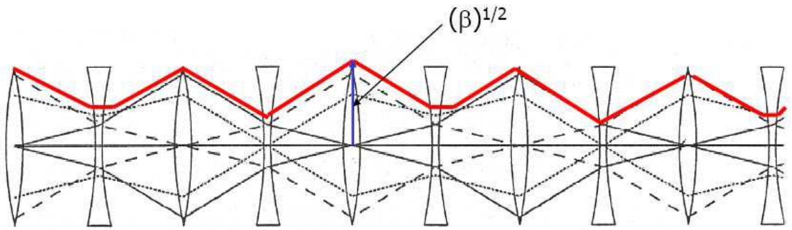
Lorentz Force:

$$\vec{F} = e(\vec{E} + \vec{v} \times \vec{B})$$



- We need to keep the particles on a circle.
- There is a closed orbit.
- Beam has a size and momentum spread.
- Particles oscillate around the closed orbit (betatron oscillation).

F0D0 lattice and orbit envelope



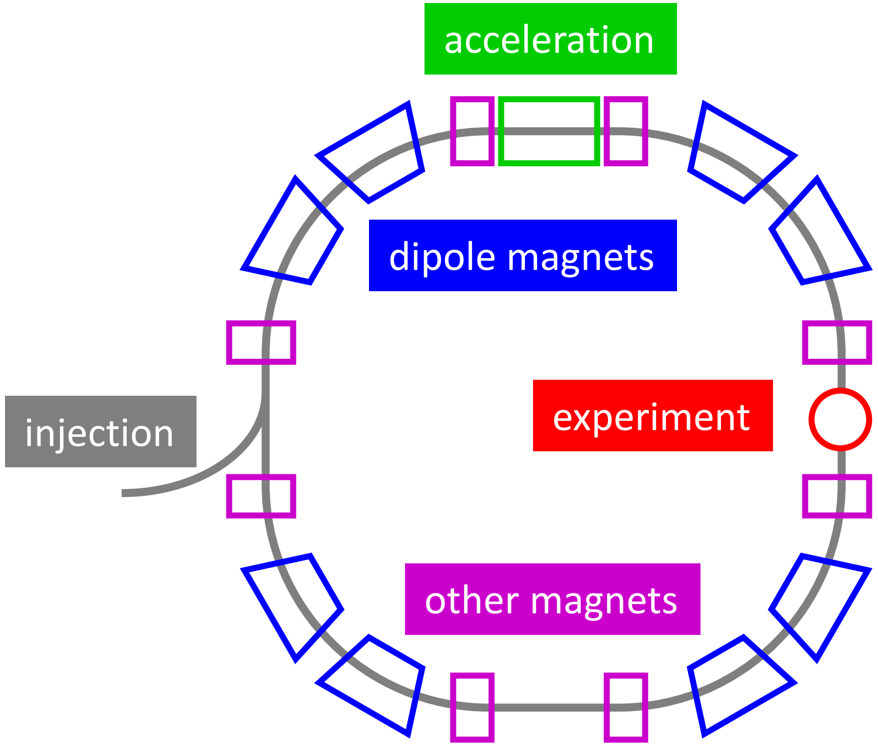
Quadrupole magnets focus in one direction only.

<u>Liouville's theorem:</u> The phase ellipse and the emittance of the beam are invariant.

Particle Beam Optics

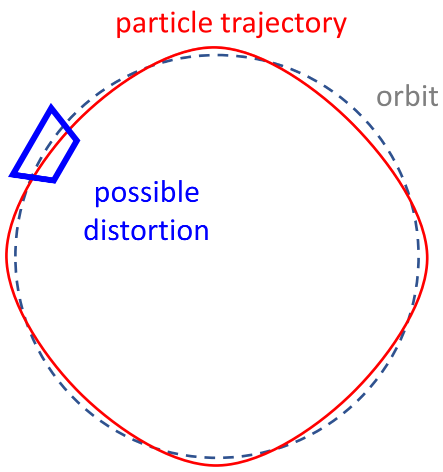
Lorentz Force:

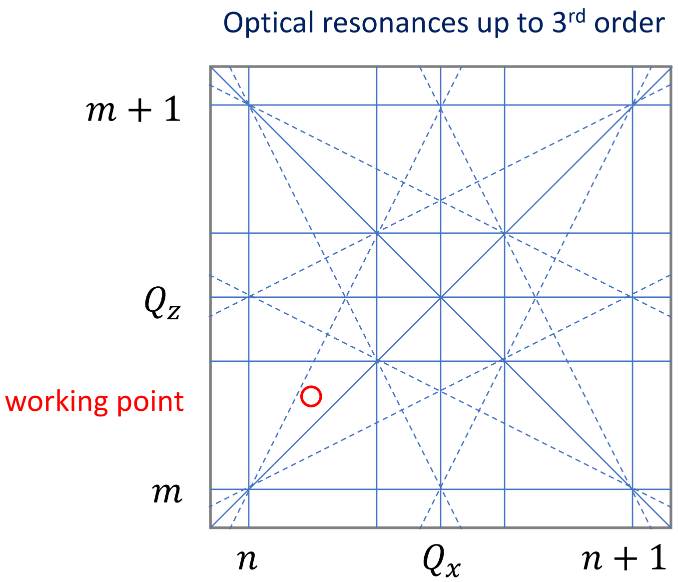
$$\vec{F} = e(\vec{E} + \vec{v} \times \vec{B})$$



- We need to keep the particles on a circle.
- There is a closed orbit.
- Beam has a size and momentum spread.
- Particles oscillate around the closed orbit (betatron oscillation).
- Periodicity can lead to resonances and beam instability

$mQ_x + nQ_z = p$ with (m, n, p) integer numbers

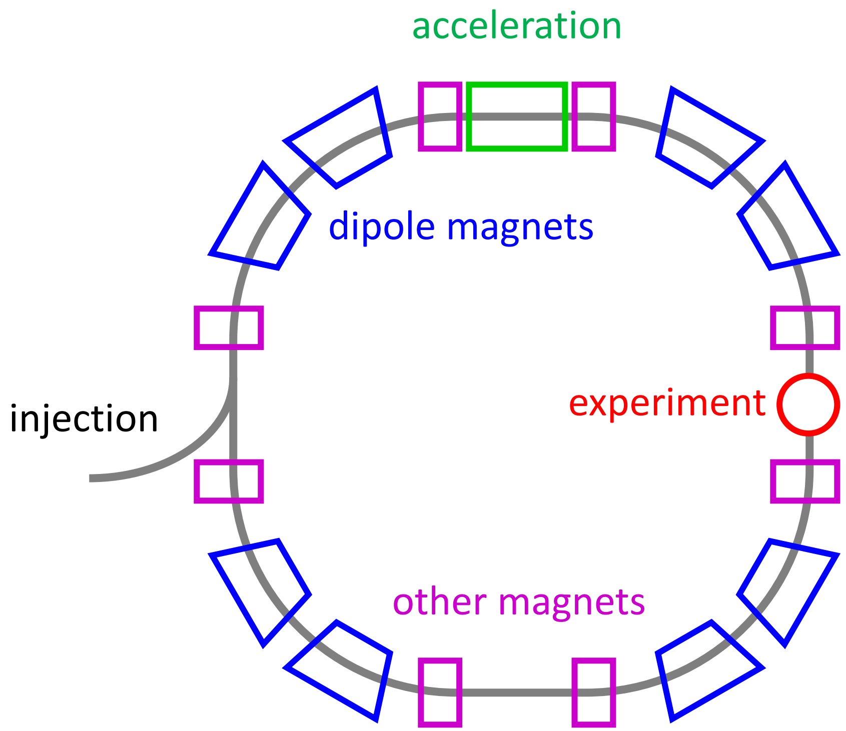




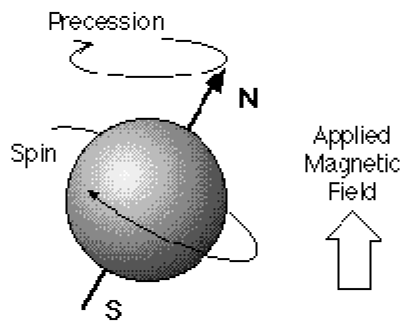
Particle Beam Optics & Spin

Lorentz Force:

$$\vec{F} = e(\vec{E} + \vec{v} \times \vec{B})$$



- We need to keep the particles on a circle.
- There is a closed orbit.
- Beam has a size and momentum spread.
- Particles oscillate around the closed orbit (betatron oscillation).
- Periodicity can lead to resonances and beam instability.
- The magnetic moment of particles precesses in magnetic fields.



$$\frac{d\vec{S}}{dt} = -\left(\frac{e}{\gamma m}\right)\left[G\gamma\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel}\right] \times \vec{S}$$

$$\frac{d\vec{v}}{dt} = -\left(\frac{e}{\gamma m}\right)\vec{B} \times \vec{v}$$

$G = 1.7928$
$\gamma = E/m$

Depolarizing Resonances

Thomas-BMT equation:

$$\frac{d\vec{S}}{dt} = -\left(\frac{e}{\gamma m}\right)\left[G\gamma\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel}\right] \times \vec{S}$$

$$\frac{d\vec{v}}{dt} = -\left(\frac{e}{\gamma m}\right)\vec{B} \times \vec{v}$$

$$G = 1.7928$$
$$\gamma = E/m$$

L.H. Thomas "The kinematics of an electron with an axis." *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 3.13 (1927)

V. Bargmann, L. Michel, and V.L. Telegdi "Precession of the polarization of particles moving in a homogeneous electromagnetic field." *Physical Review Letters* 2.10 (1959)

- The spin tune Q_s is the number of precessions per revolution.
- There are two types of depolarizing resonances
  - Intrinsic resonances

    $$\gamma G = kP \pm (\nu_y - 2)$$
  - Imperfection resonances

    $$\gamma G = k$$

The resonance strength depends on the local orbit distortion, magnetic field, and crossing speed.

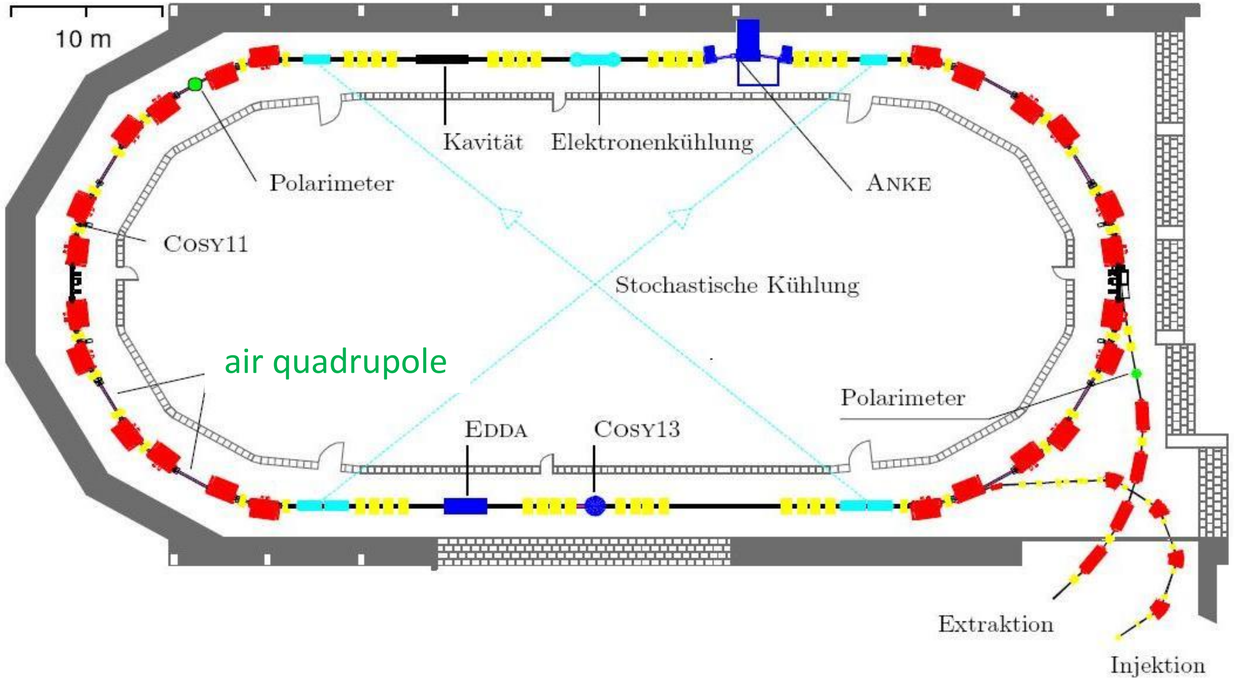
The number of resonances grows linearly with the top energy.

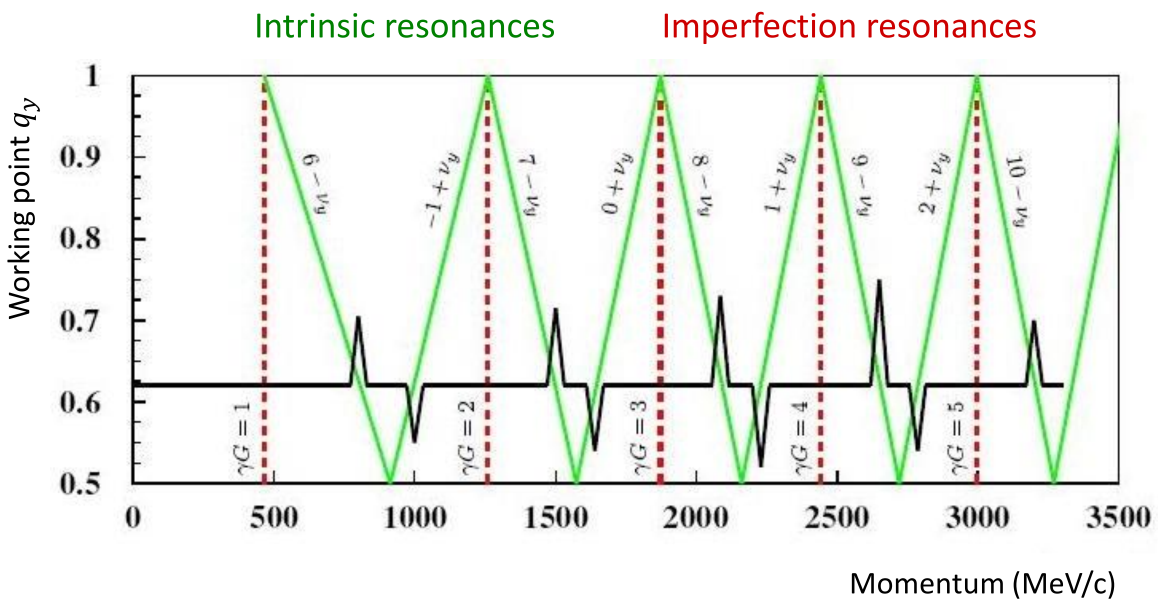
Example: COSY

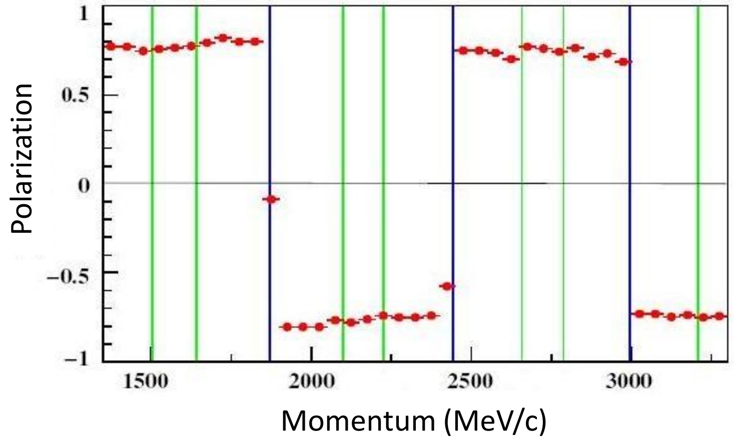
Cooler Synchrotron at FZ Jülich, Germany

Proton accelerator / storage ring

$p_{max} = 3.3$ GeV/c







The Relativistic Heavy Ion Collider

“Configuration Manual Polarized Proton Collider at RHIC.” I. Alekseev et al. (2004)

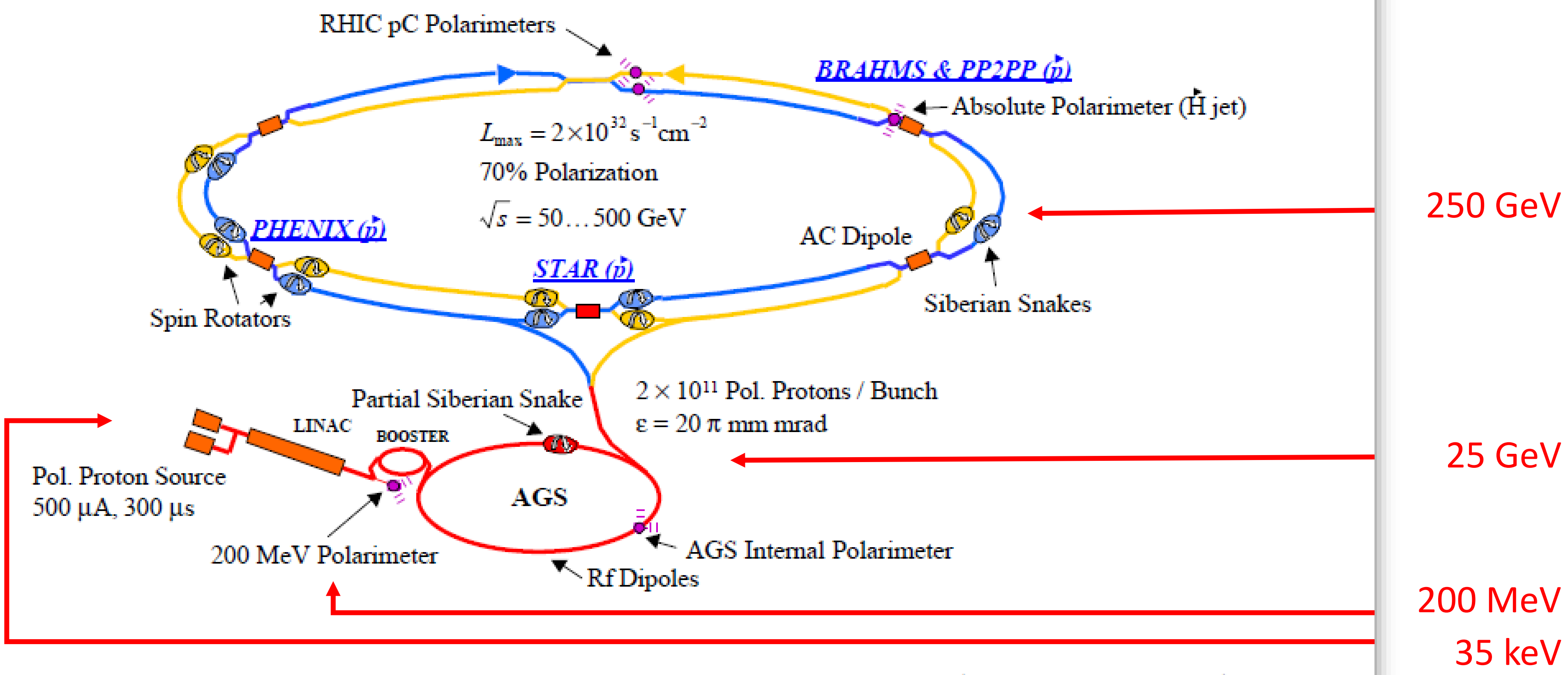
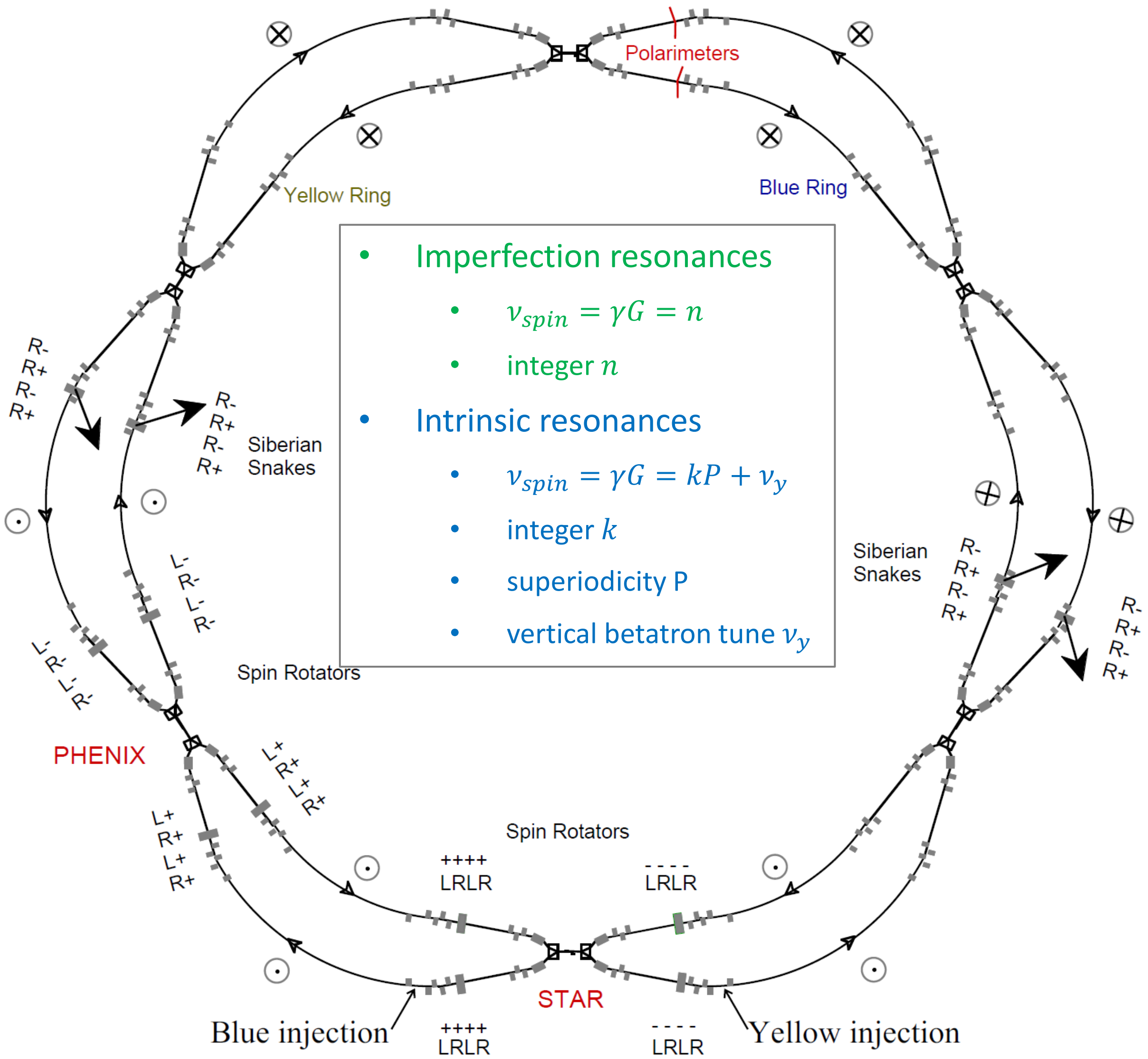
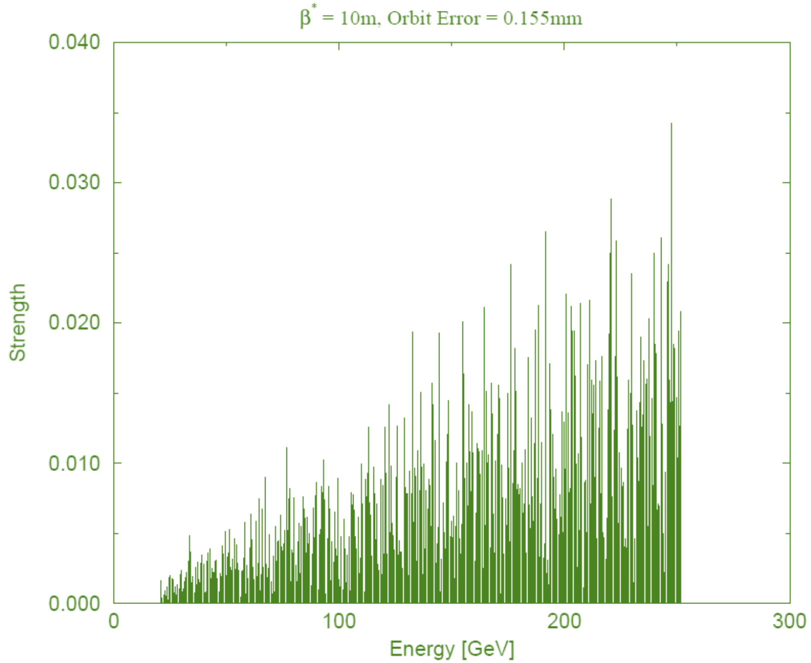


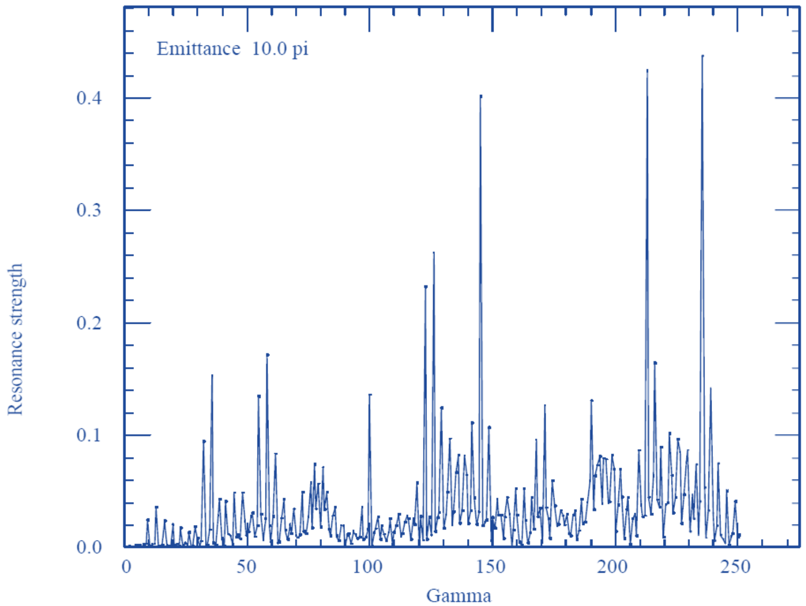
Figure 1.1: The Brookhaven hadron facility complex, which includes the AGS Booster, the AGS, and RHIC. The RHIC spin project will install two snakes per ring with four spin rotators per detector for achieving helicity-spin experiments.

Spin Resonances in RHIC



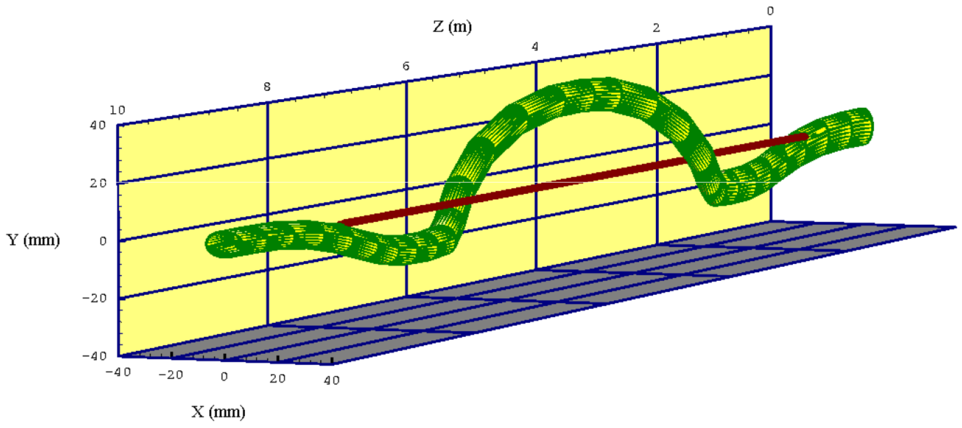
- Imperfection resonances
  - $\nu_{spin} = \gamma G = n$
  - integer n
- Intrinsic resonances
  - $\nu_{spin} = \gamma G = kP + \nu_y$
  - integer k
  - superiodicity P
  - vertical betatron tune ν_y

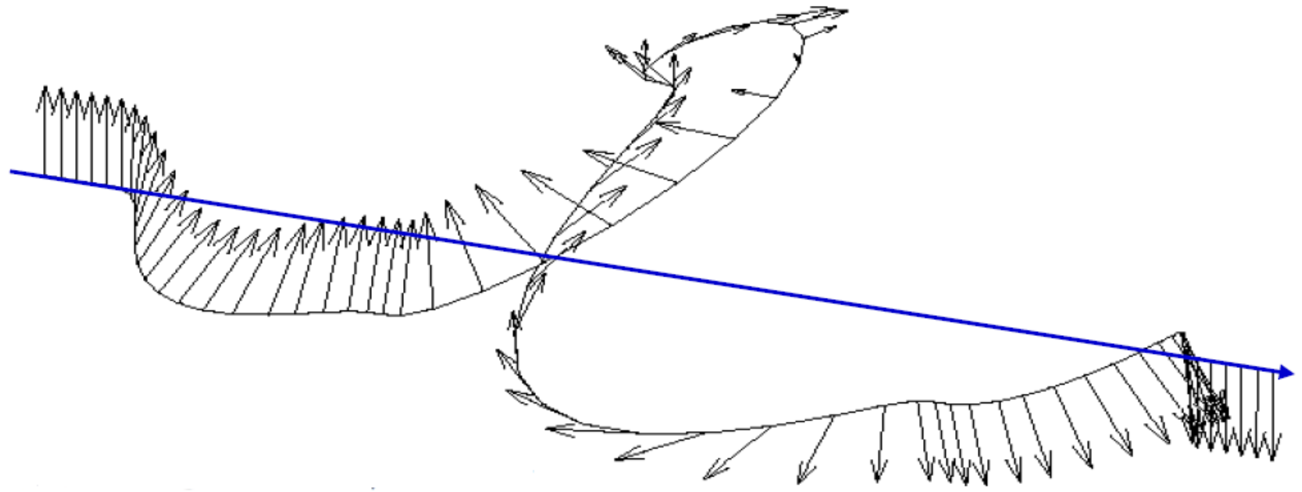


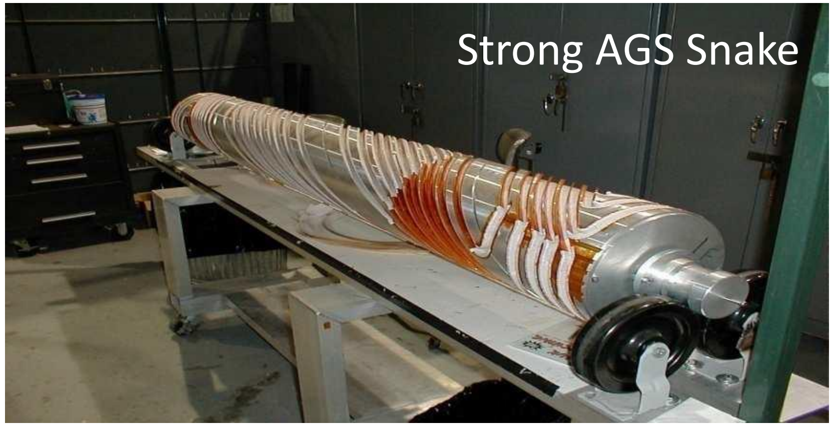


Resonance Mitigation

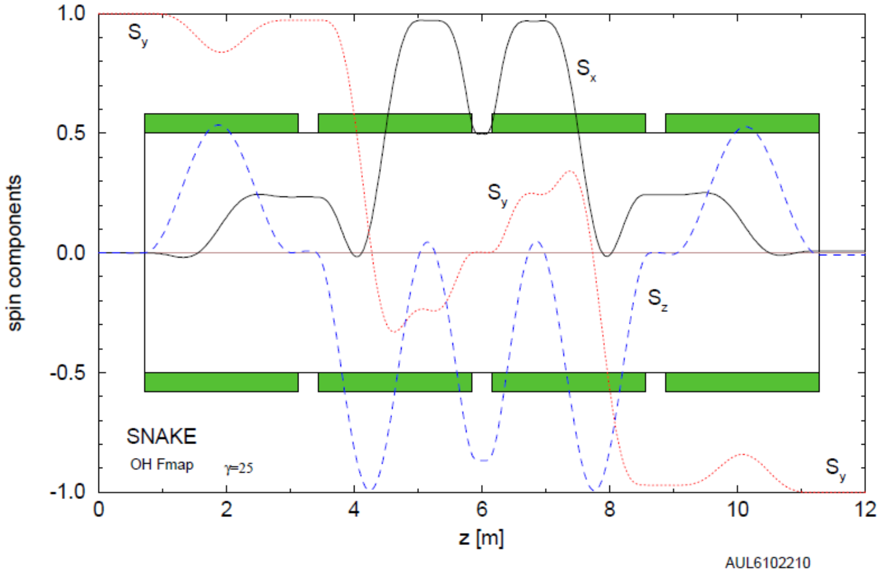
- Deliberately advance the spin precession to avoid resonance conditions
- Group of dipole magnets with alternating horizontal and vertical field directions which rotates the spin vector by 180°
- **Siberian Snakes:** Ya. S. Derbenev, A.M. Kondratenko "Polarization kinematics of particles in storage rings." Sov. Phys. JETP 37 (1973)

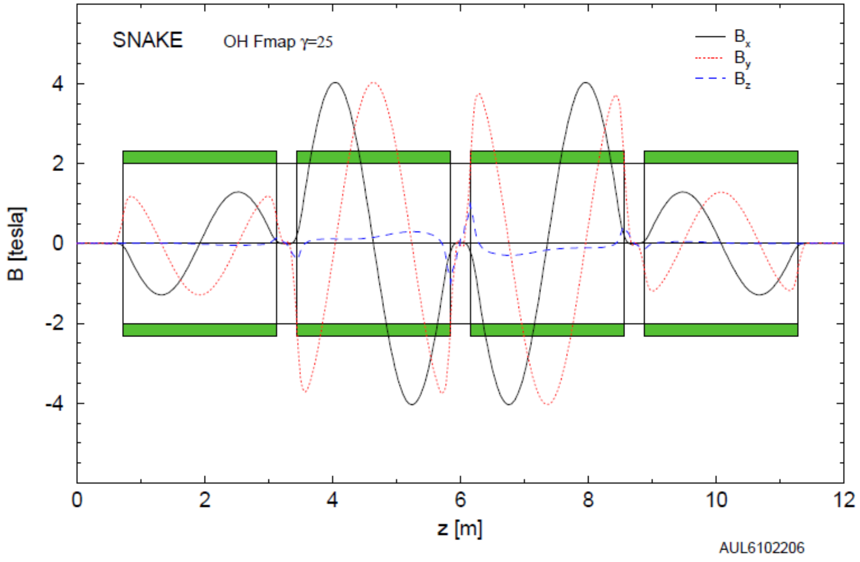


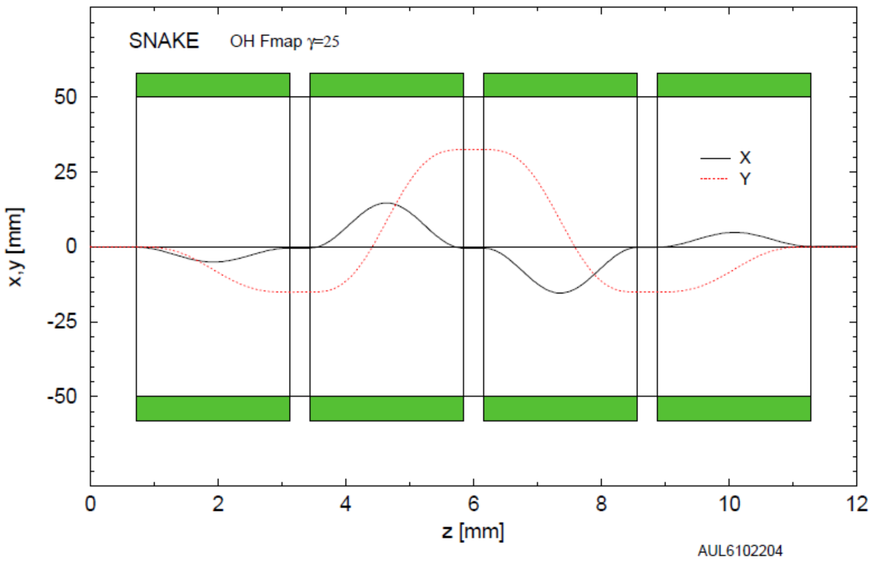




Spin Motion through Siberian Snake

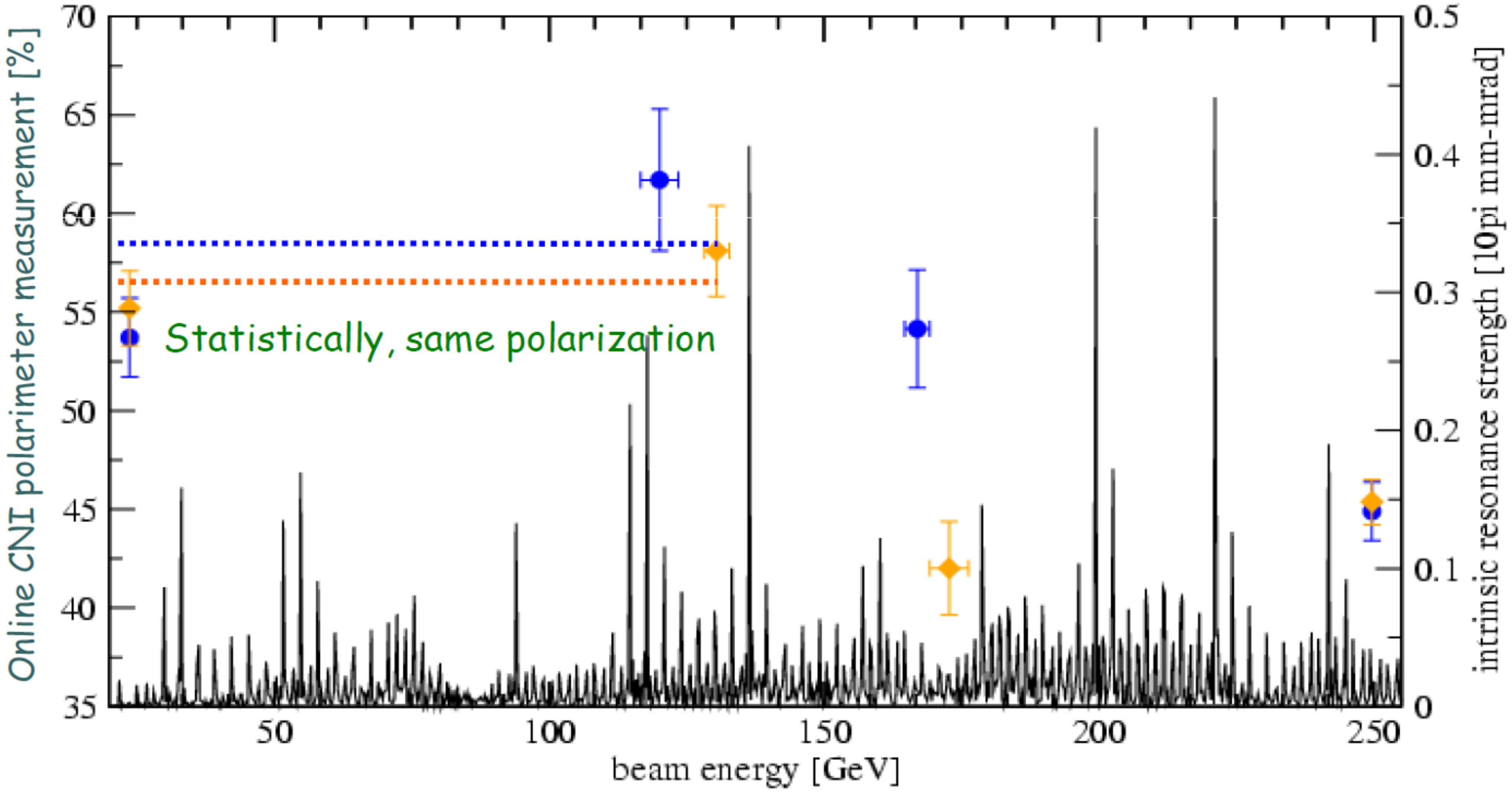




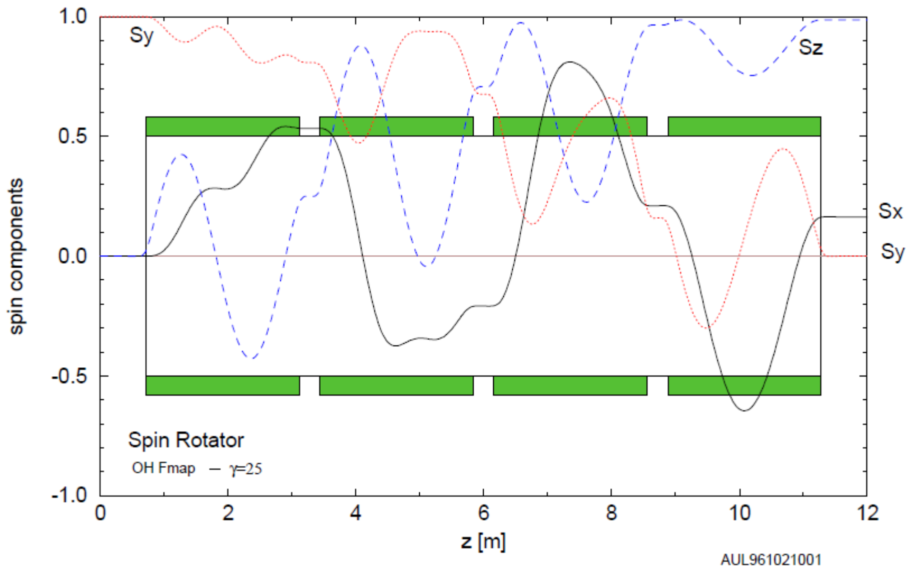


RHIC Proton Polarization

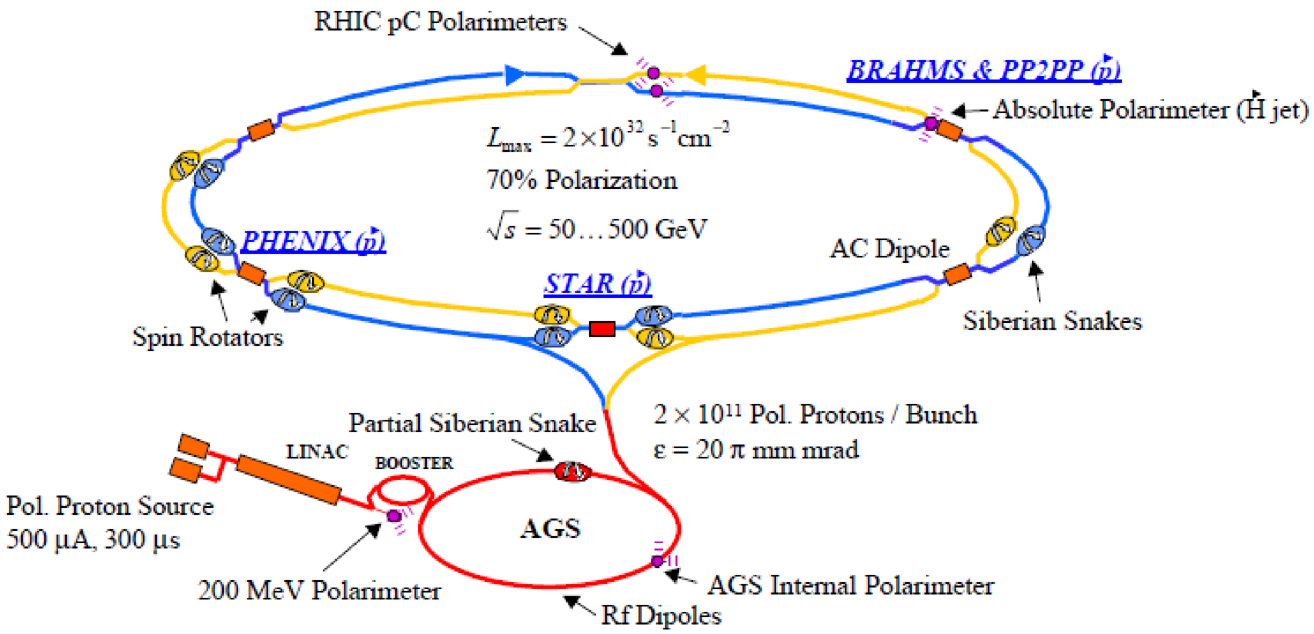
During the first 250 GeV beam operation in 2009



Spin Motion through a Spin Rotator



- The stable spin direction in a circular accelerator is vertical.
- Experiments also require longitudinal polarization.
- Spin rotators before and after each experiment.
- Transverse polarization remnant can cause systematic uncertainties in physics observables.



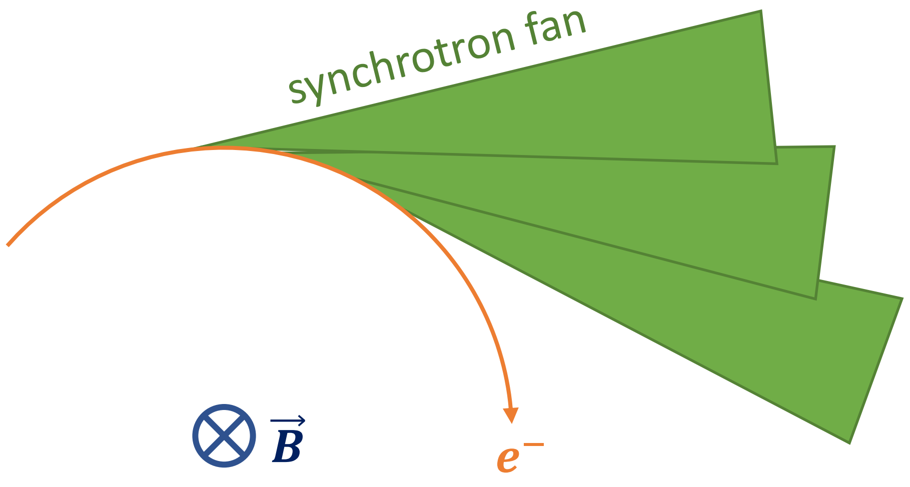
Synchrotron Radiation

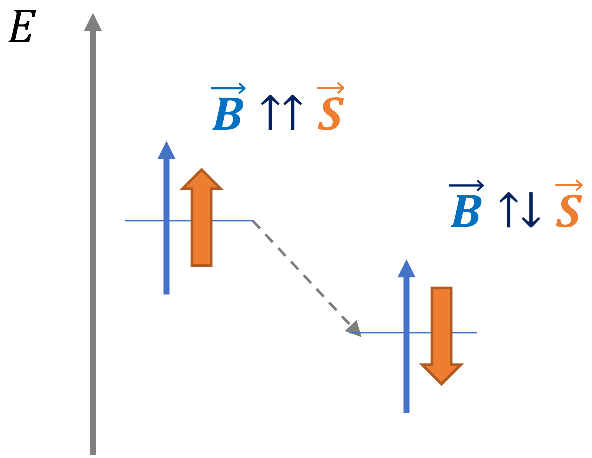
- Acceleration of electrical charge emits an electromagnetic wave.
- Relativistic boost γ in the laboratory frame turns the radiation in the direction of the charged particle.
- An electron synchrotron emits a universal, continuous spectrum with single parameter ϵ_c.
- The radiated power is $P \propto E^4/\rho$
- The emitted synchrotron radiation is polarized (electrical field in the direction of the accelerator plane).
- Synchrotron radiation leads to a polarization of the electron beam (Sokolov-Ternov effect).

$$\xi(t) = A(1 - e^{-t/\tau})$$

$$\tau = A \frac{4\pi\epsilon_0 \hbar^2}{mce^2} \left(\frac{mc^2}{E}\right)^2 \left(\frac{B_c}{B}\right)^3$$

Polarization limit $A = 92.4\%$



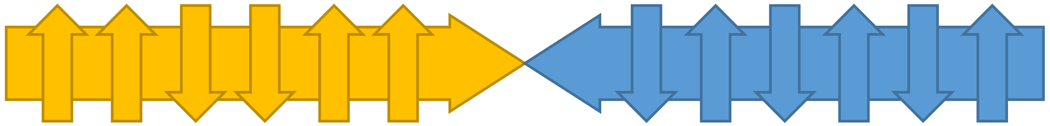


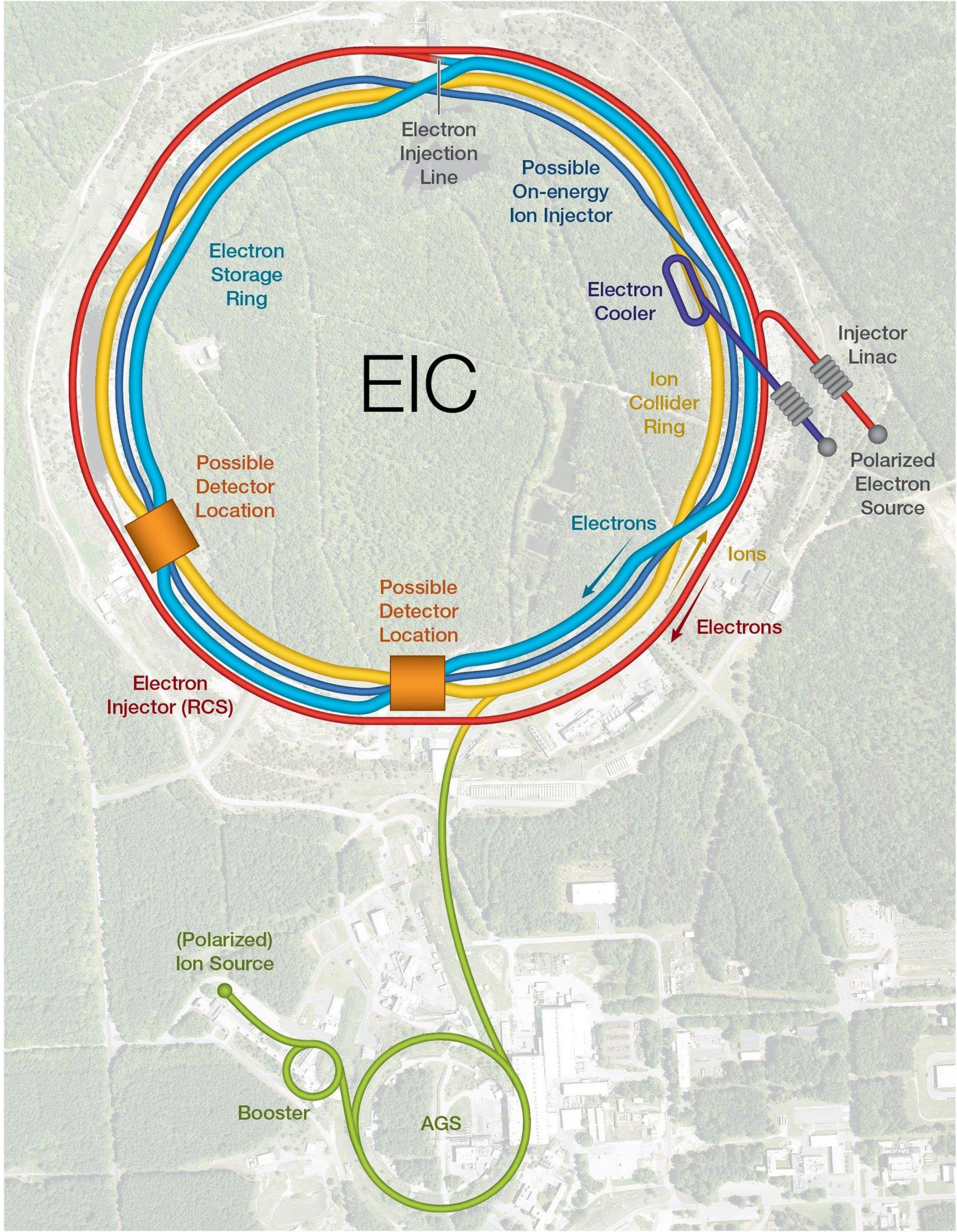
W. Eberhard "Synchrotron radiation: A continuing revolution in X-ray science" Journal of Electron Spectroscopy and Related Phenomena 200 (2015)

K. Wille "Physik der Teilchenbeschleuniger und Synchrotronstrahlungsquellen" Teubner (1996)

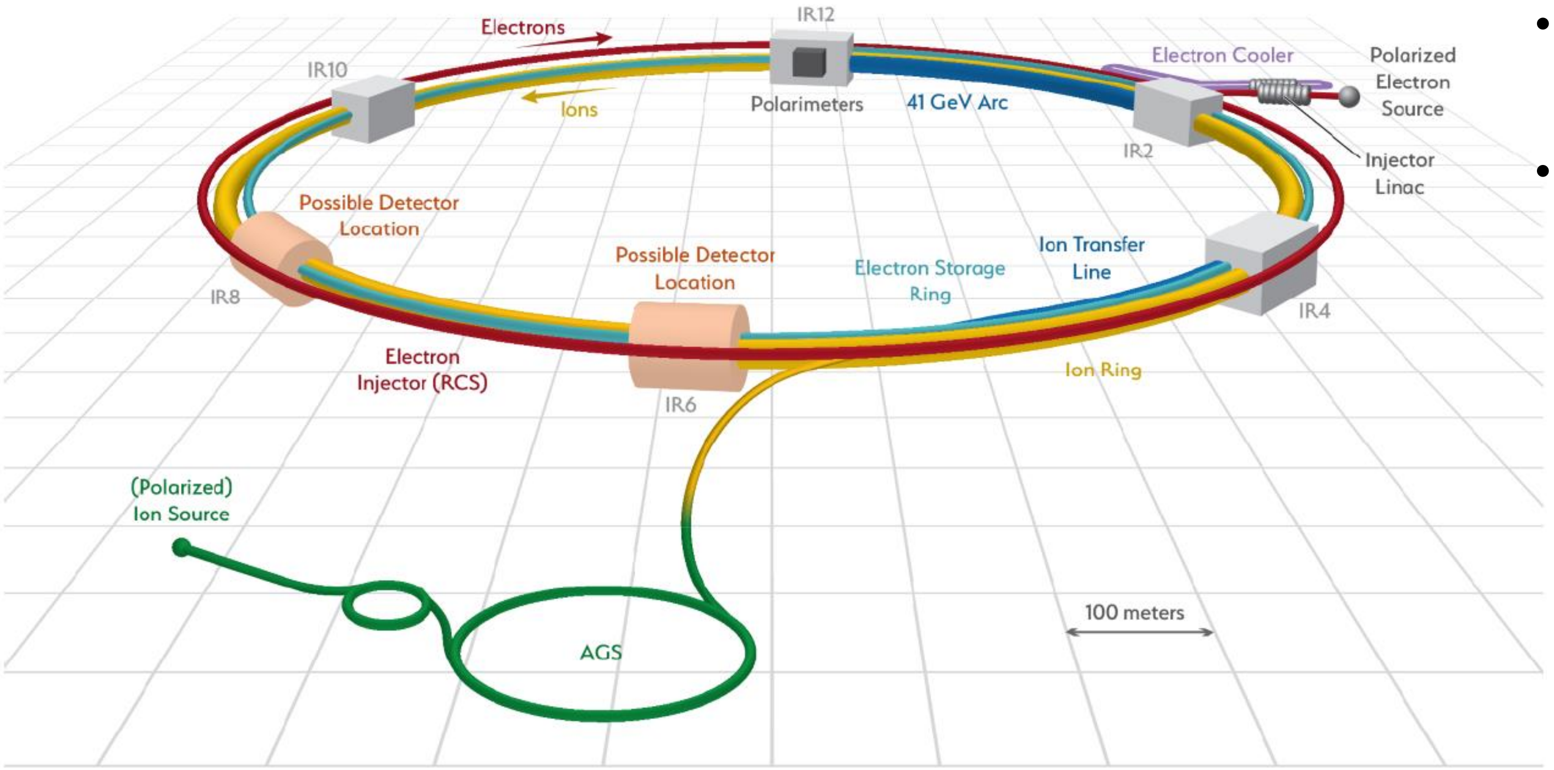
Polarized Beams at EIC

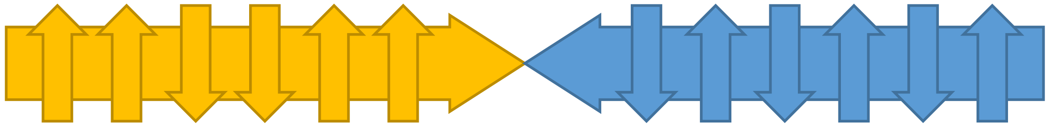
- **Proton beam polarization has to be measured between $50 - 275$ GeV.**
- Electron beam polarization has to be measured between $5 - 18$ GeV.
- Each store may be 8 hours long. Possibly shorter?
- The beams are bunched and will have alternating polarization states to reduce time-dependent systematic uncertainties.
- Bunch spacing is around 10 ns (close to 1300 bunches in each ring).





Outlook: Requirements for Polarimetry





- Required:
  - Absolute beam polarization $\Delta P/P \approx 1\%$
- Consider:
  - What do you think has to be considered for polarimetry at the EIC?
  - Polarization loss during acceleration
  - Polarization loss during storage
  - Bunch size
  - Bunch polarization pattern
  - …