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U.S. DEPARTMENT OF ENERGY

High Energy Polarized Proton Accelerators in the USA

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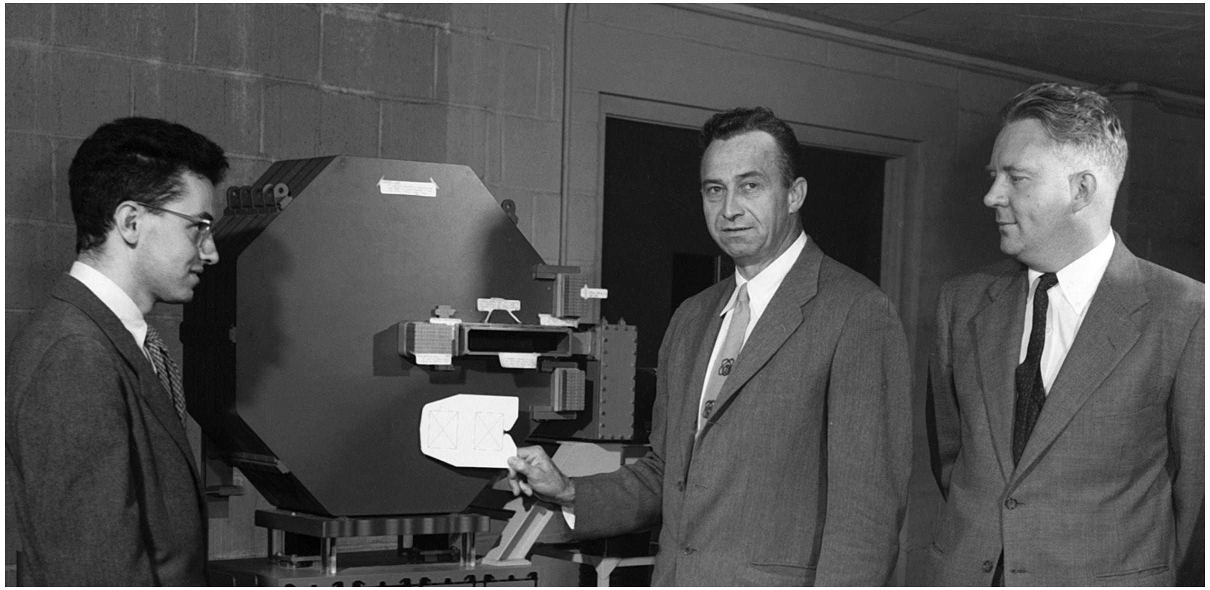
In Memory

Ernest D. Courant

1920 - 2020

- 1948 Courant joined the BNL team that was building the Cosmotron
- He co-invented and developed the strong focusing principle, the basis of most modern accelerators including RHIC
- “Little did I know when I joined Brookhaven back in 1948 that accelerator physics would be my whole career,” Courant said at the 2010 RHIC/AGS Users’ Meeting.
- Courant also coined the name “Siberian snake” and first proposed the use of helical dipoles for Siberian snakes
- Long-term member of the International Spin Physics Committee



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In Memory
Satoshi Ozaki
1929 - 2017

- Master’s degree from Osaka University and Ph.D. from MIT
- Developed first multi-purpose detector, the AGS Multi-Particle Spectrometer, at BNL
- Project leader and Director of the 30 GeV electron-positron collider TRISTAN in Japan, the world’s highest energy e+e- collider at the time
- He returned to BNL in 1989 to lead the successful RHIC construction project
- Central to the establishment of RIKEN BNL Research Center
- Strong supporter of the RHIC Spin Collaboration and polarized protons in RHIC
- 2013: Order of the Sacred Treasure, Gold Rays with Neck Ribbon for the promotion of Japan-US cooperation in physics

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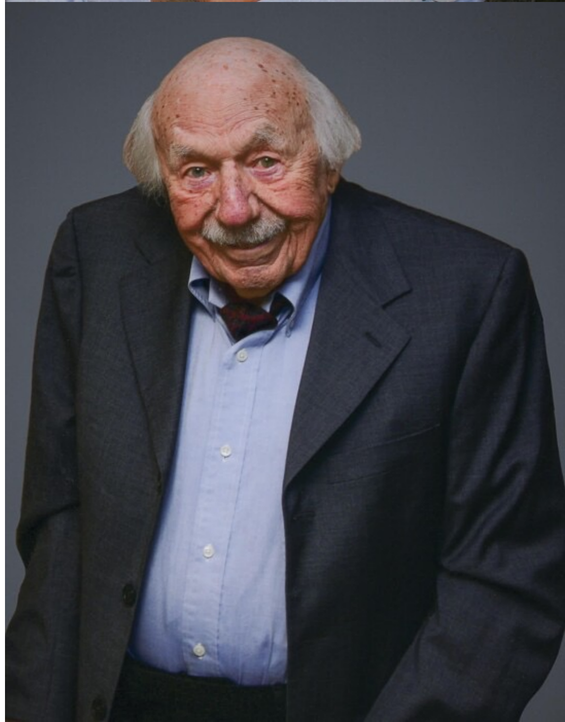
In Memory

Willy Haeberli

1925 - 2021

- Ph.D. in Physics from University of Basel (at the time a center of nuclear spin physics)
- Professor of Physics at University of Wisconsin, Madison
- Foundational contributions in spin-polarized beams and targets as a tool to study spin effects in nuclear and particle physics.
- Development of pure, spin-polarized gaseous targets of hydrogen or deuterium for use primarily in high energy storage rings
- RHIC absolute polarimeter using polarized atomic hydrogen
- Long-term member of the International Spin Physics Committee
- Personal note: Willy was a collaborator in my thesis experiment and greatly benefited from his sage advice.



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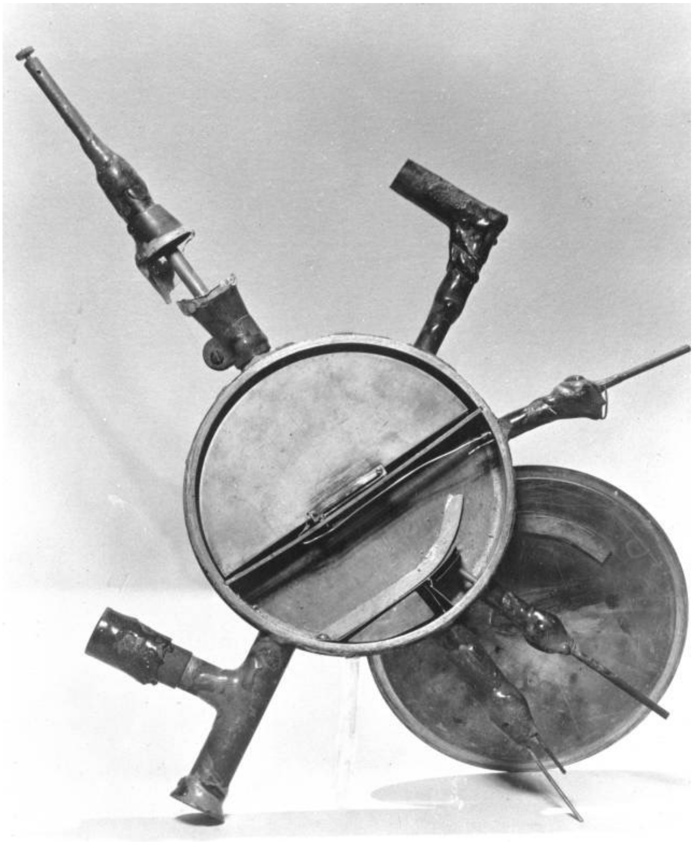
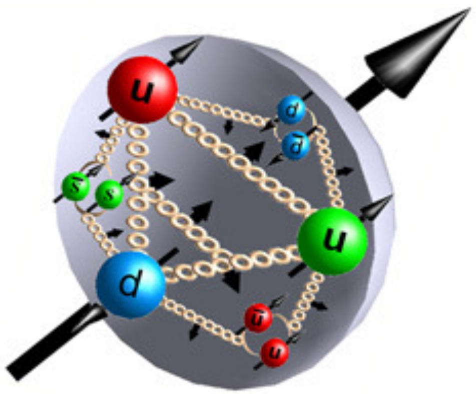
Acceleration of Polarized Beams



- Progress in accelerator technology is motivated by and has driven advances in particle and nuclear physics
- This started with Ernest Lawrence’s first cyclotron (1931) and continues to this day.
- The exploration of spin in nuclei and nucleons required the development of polarized sources and the acceleration of polarized beams
- I will focus on the acceleration of polarized protons from MeVs to 100s of GeV.



Spin Dynamics in Rings

- Precession Equation in Laboratory Frame: (Thomas [1927], Bargmann, Michel, Telegdi [1959])

  $dS/dt = -(e/\gamma m)\,[(1+G\gamma)B_{\perp} + (1+G)\,B_{\parallel}] \times S$ (G=(g-2)/2 : anomalous gyromagnetic ratio)

- Lorentz Force equation:

  $dv/dt = -(e/\gamma m)\,[\quad B_{\perp} \quad] \times v$

- For pure vertical field: Spin rotates $G\gamma$ times faster than motion, spin tune $\nu_{sp} = G\gamma$

- For spin manipulation: At low energy, use longitudinal fields
  At high energy, use transverse fields

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Depolarizing Spin Resonances

- Depolarizing resonance condition:
  - Number of spin rotations per turn = Number of spin kicks away from stable direction per turn
  - Spin resonance strength ε = Number of full spin rotations due to resonance per turn
- Imperfection resonance (magnet errors and misalignments):

$$\nu_{sp} = n$$

- Intrinsic resonance (Vertical focusing fields):

$$\nu_{sp} = Pn \pm \nu_y$$

P: Superperiodicity [AGS: 12]
ν_y : Betatron tune [AGS: 8.75]

- Weak resonances: some depolarization
- Strong resonances: partial or complete spin flip

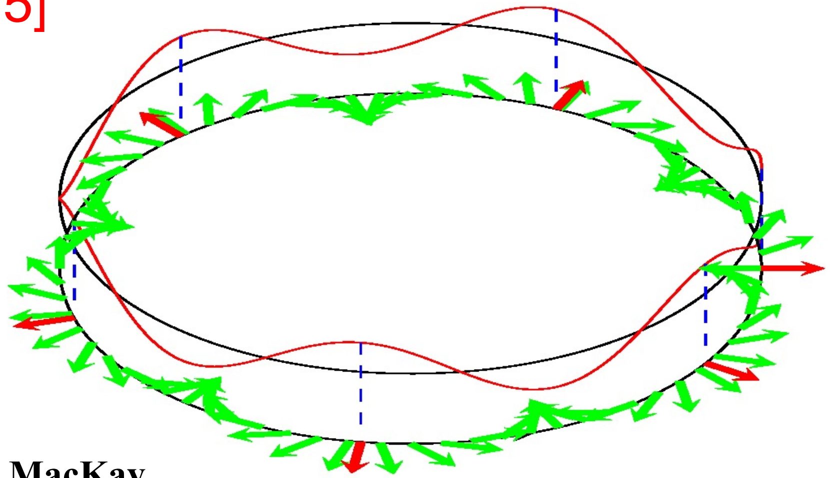
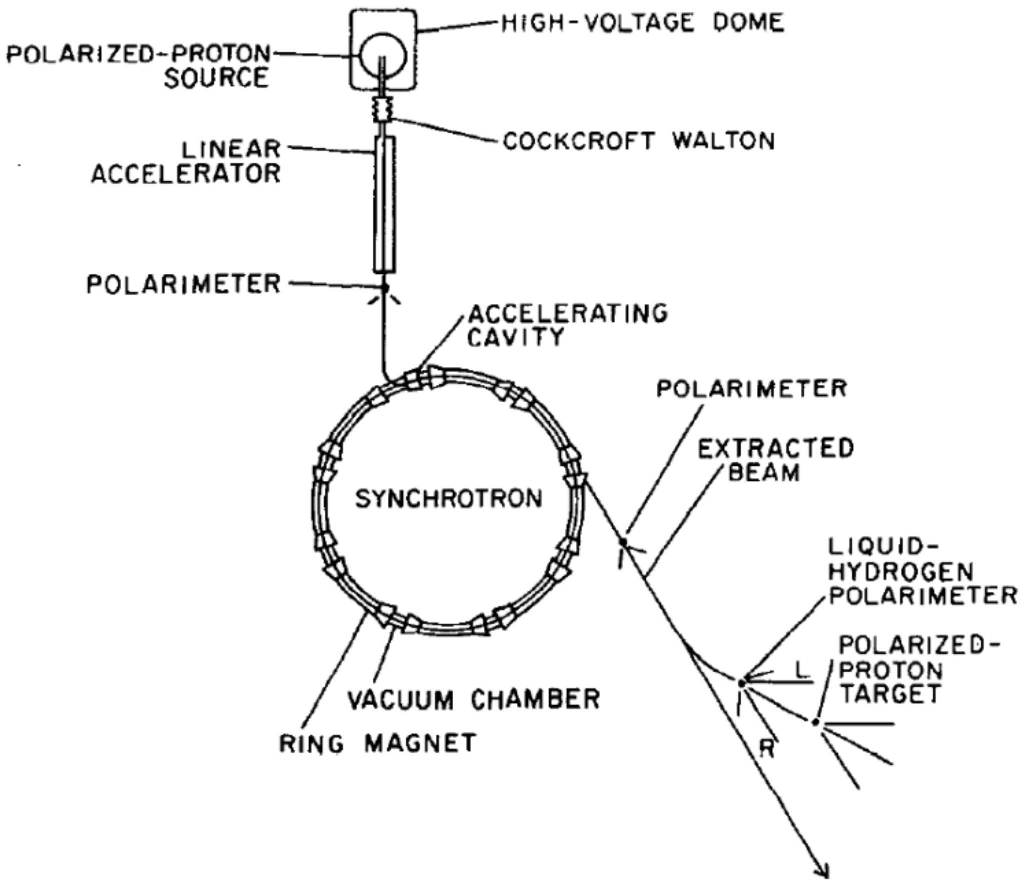


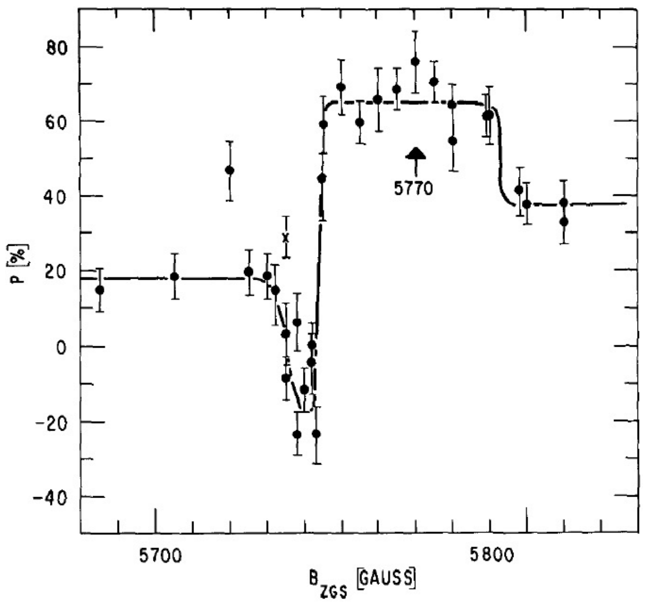
Illustration by W.W. MacKay

Polarized Proton Accelerations at the ZGS

- ZGS (up to 70% at 12 GeV/c): Weak resonances (ε_{max} ~ 0.002)

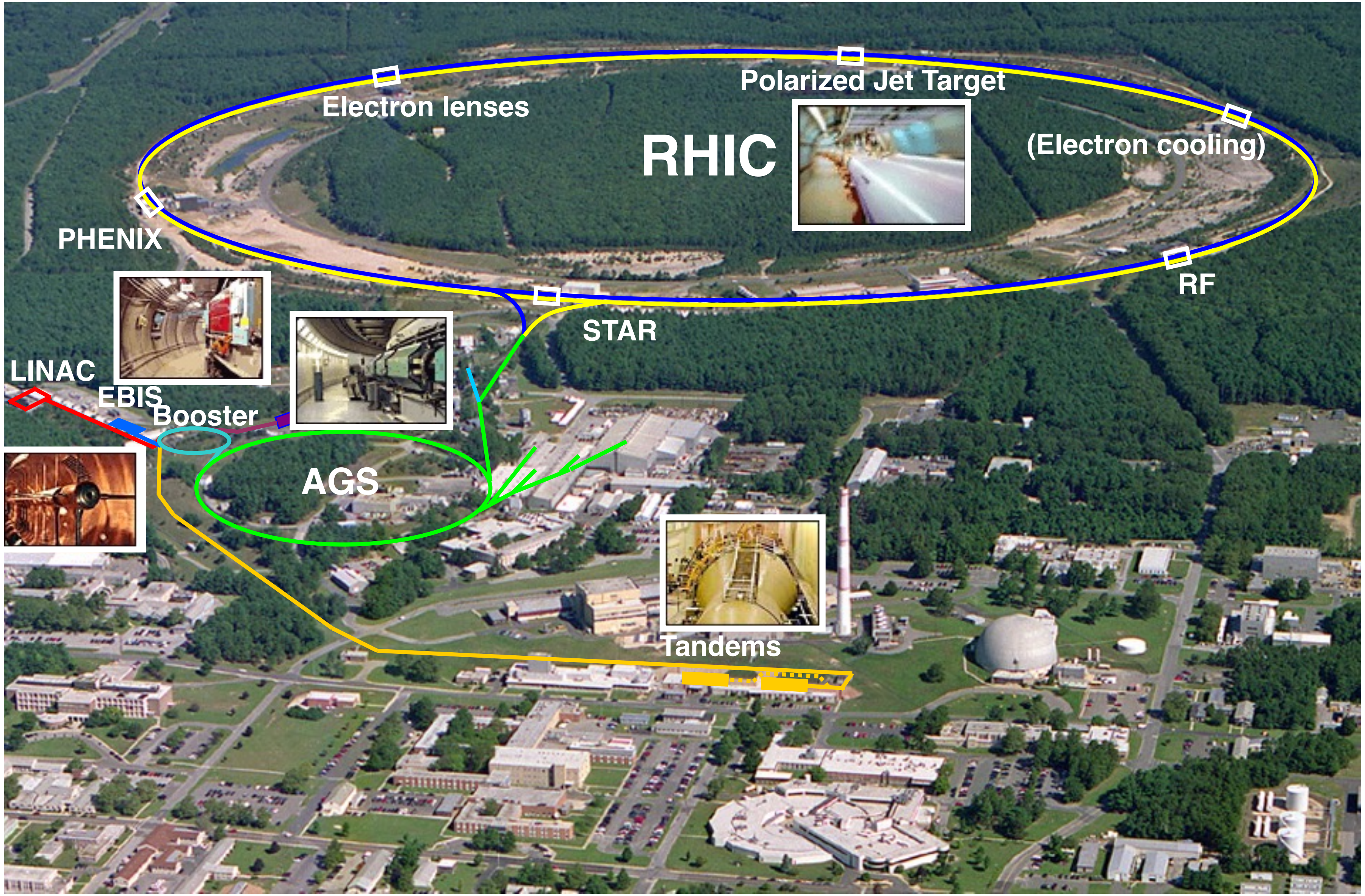


- Timing of betatron tune jump using polarization measurement



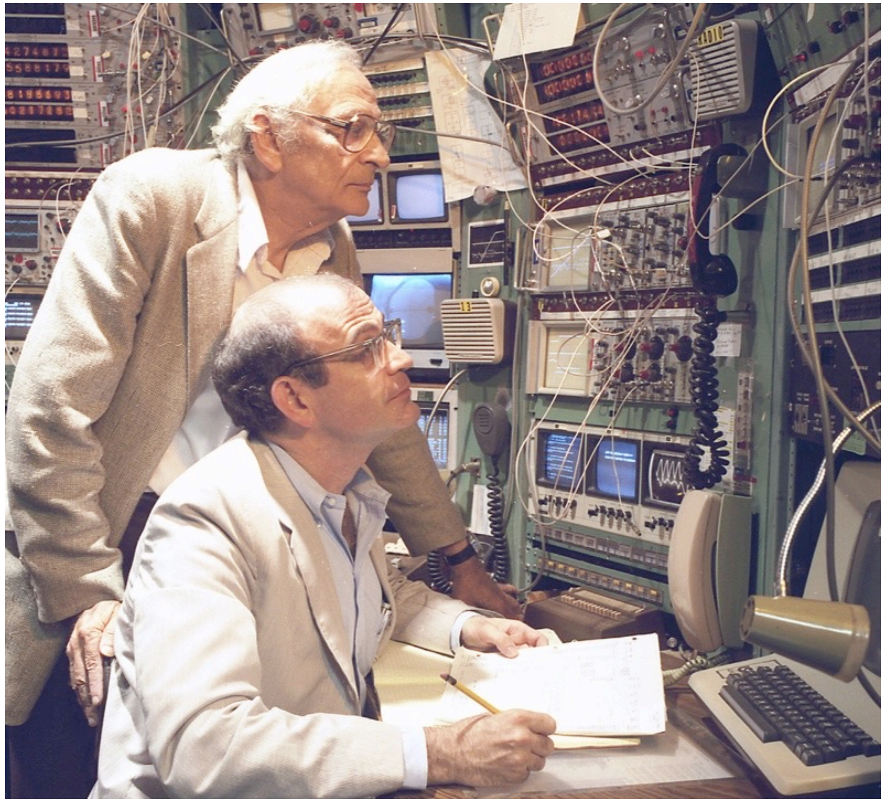
The RHIC Accelerator Complex

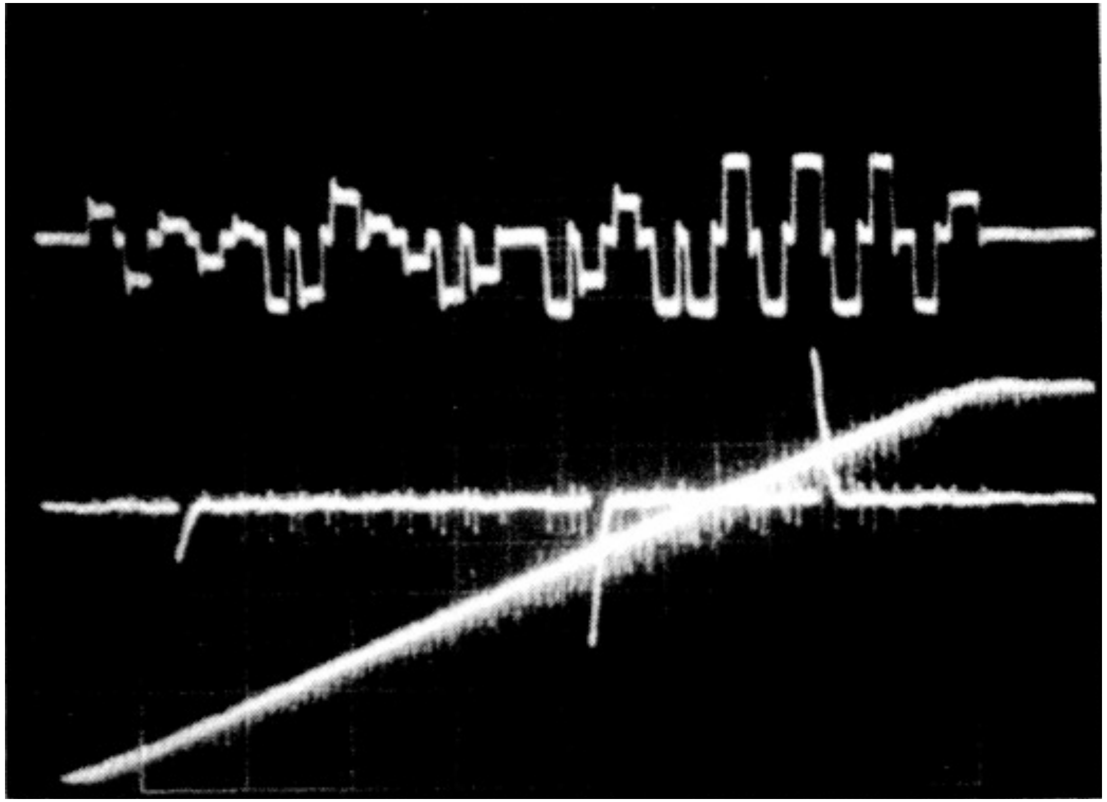
- Highly flexible and only US Hadron Collider
- Injectors also provide beams for unique applications



First Effort to Accelerate Polarized Protons in AGS

- In the 1980s, Alan Krisch and Larry Ratner led the first effort to polarize the AGS by correcting the approximately 50 imperfection and intrinsic depolarizing resonances. This was a truly heroic effort!





1/95 correction dipole; 1/10 pulsed quadrupole; main field

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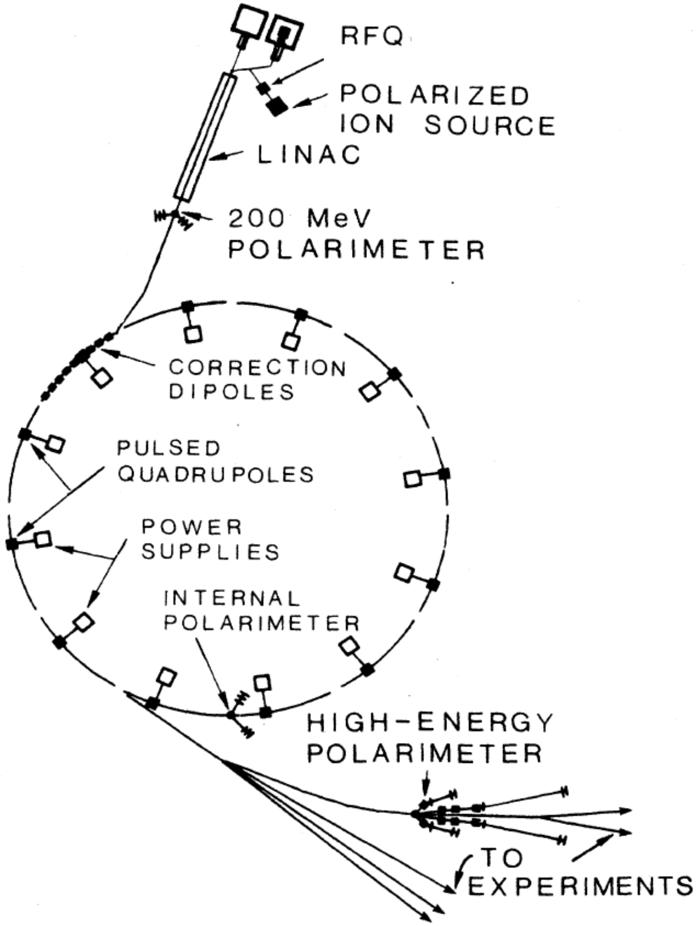
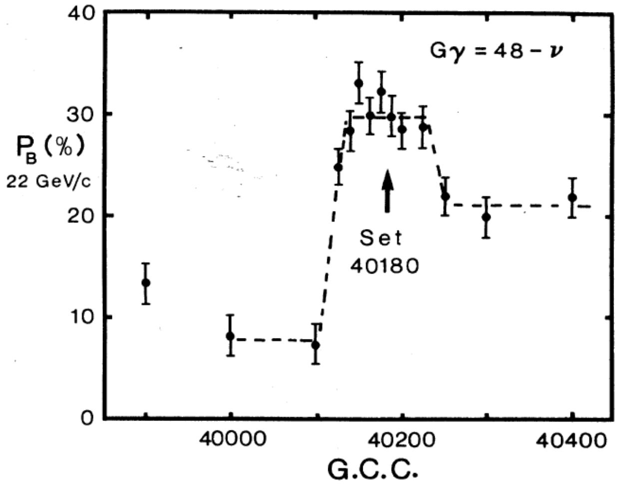
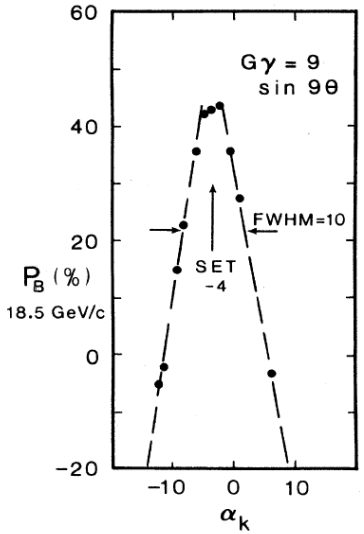
First Effort to Accelerate Polarized Protons in AGS (cont'd)

- AGS (up to 42% at 22 GeV/c): Strong resonances ($\varepsilon_{max} \sim 0.03$)

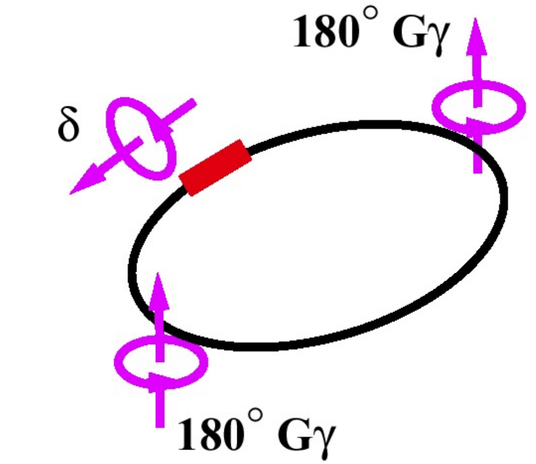


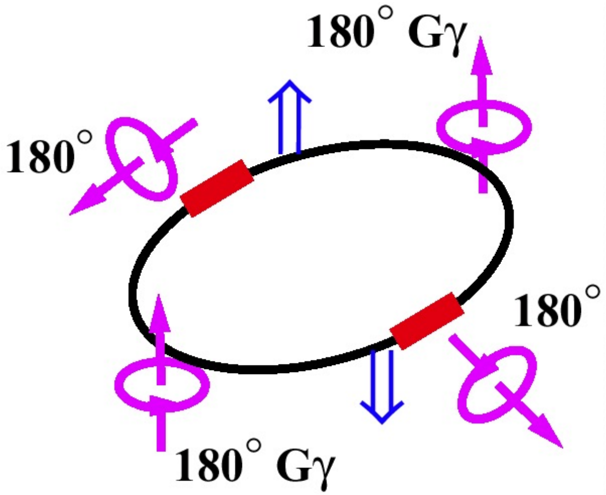
- Timing of betatron tune jump and adjusting dipole correction strength using polarization measurement
- Setting up polarized proton acceleration to 22 GeV required:
  - 6 pulsed quadrupole timing scans and
  - 2 × 40 harmonic corrector scans (sin + cos)





Siberian Snakes (Local Spin Rotators)





$$\cos(180^\circ \nu_{sp}) = \cos(\delta/2) \cdot \cos(180^\circ G\gamma)$$

- $\delta \neq 0^\circ \rightarrow \nu_{sp} \neq n$
  - No imperfection resonances
  - Partial Siberian snake (AGS)
- $\delta = 180^\circ \rightarrow \nu_{sp} = ½$
  - No imperfection resonances and
  - No Intrinsic resonances
  - Full Siberian Snake (Ya.S. Derbenev and A.M. Kondratenko)
- Two Siberian Snakes (RHIC): $\nu_{sp} = (\alpha_2 - \alpha_1)/180^\circ$ ($\alpha_{1,2}$: angles between snake axis and beam direction)
  - Orthogonal snake axis: $\nu_{sp} = ½$ and independent of beam emittance

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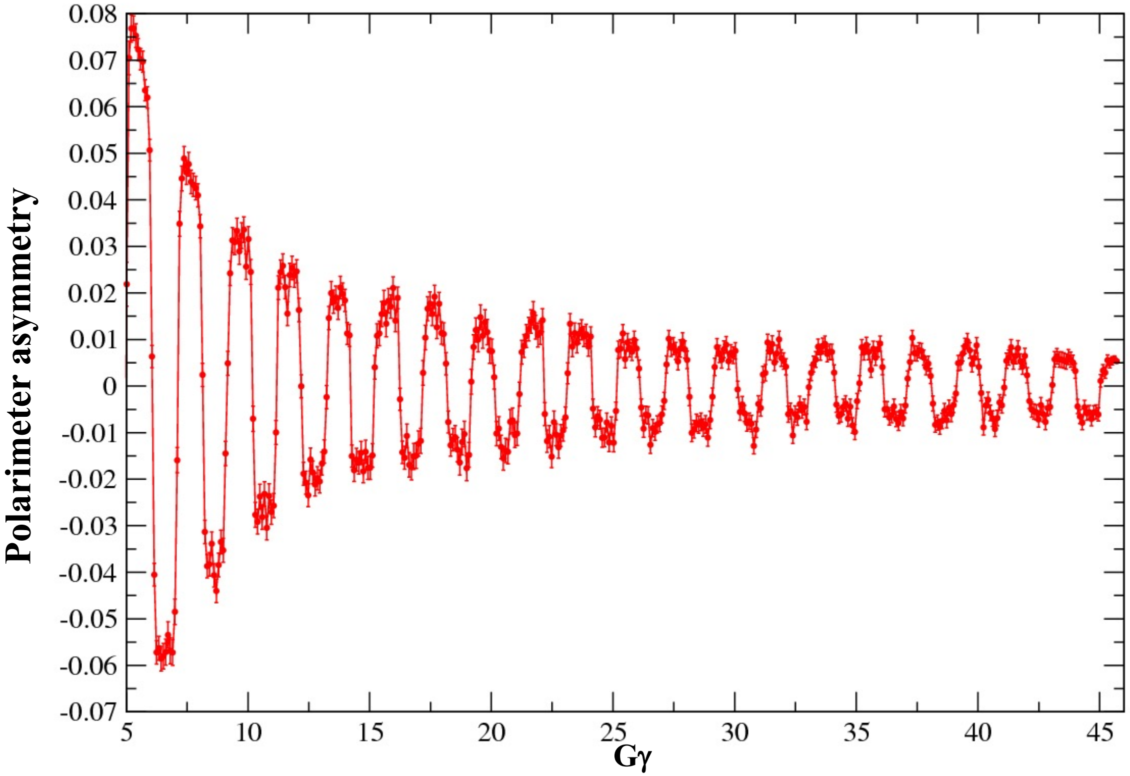
Polarized Protons in the AGS Today

- Two strong partial Siberian snakes using variable-pitch helical dipoles
- Vertical betatron tune at 8.98!
- Pulsed quadrupoles to jump across the many weak horizontal spin resonances driven by the partial snakes.

Larry Ratner, Haixin Huang and TR in AGS MCR.



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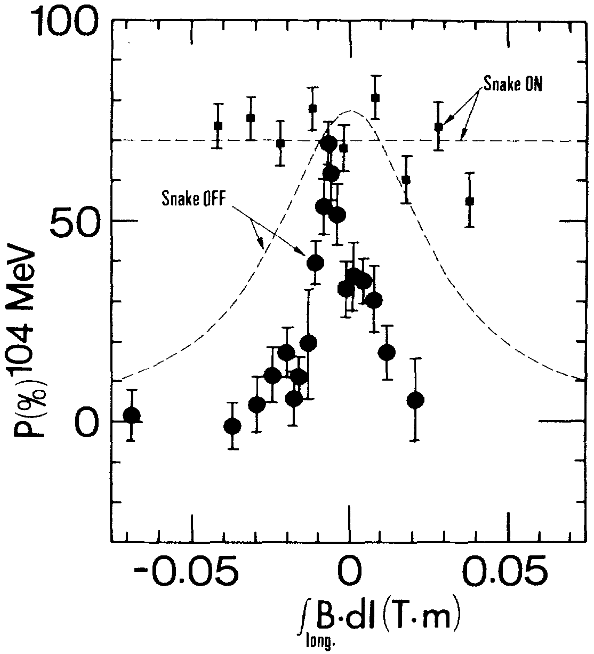
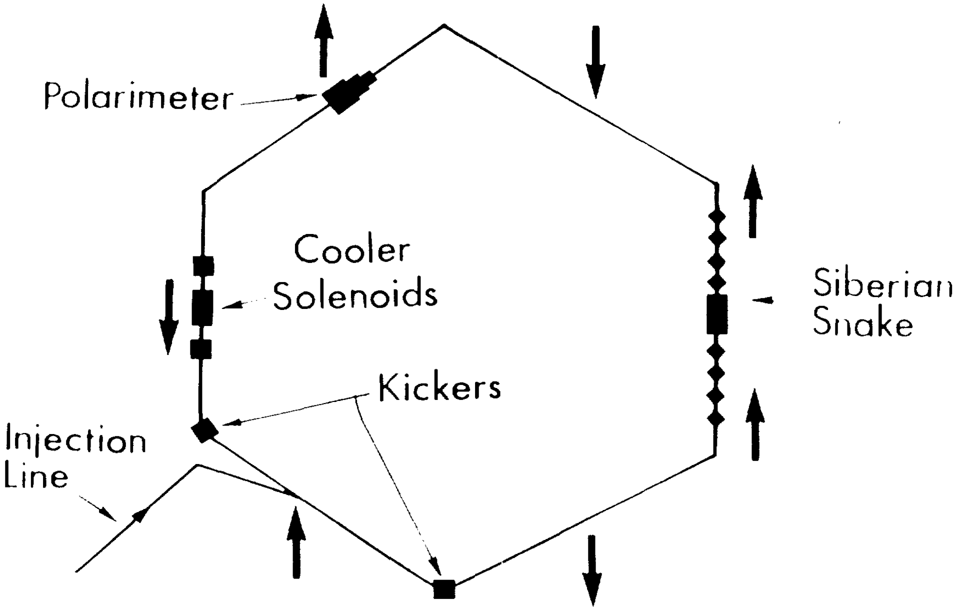
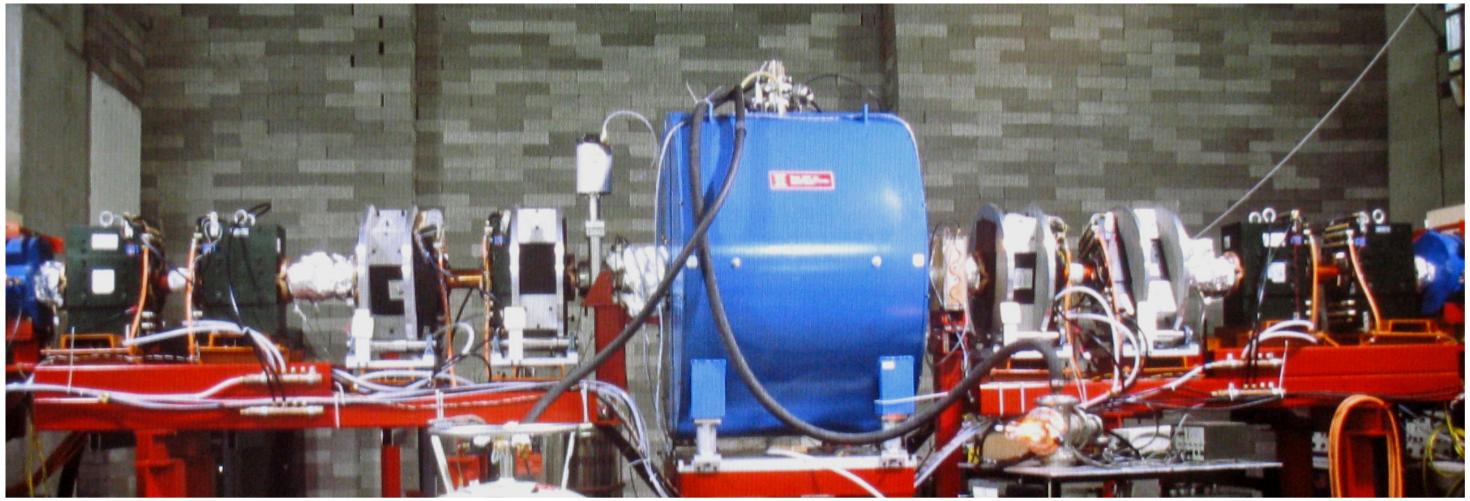
First Siberian Snake Test at IUCF



- Full Siberian snake: 180° spin rotator without changing particle orbit.
- First full solenoid Siberian snake with optical correctors: 4 straight and 4 rotated quadrupoles (0 and 360 degrees betatron phase advance)





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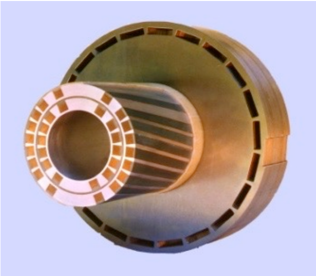
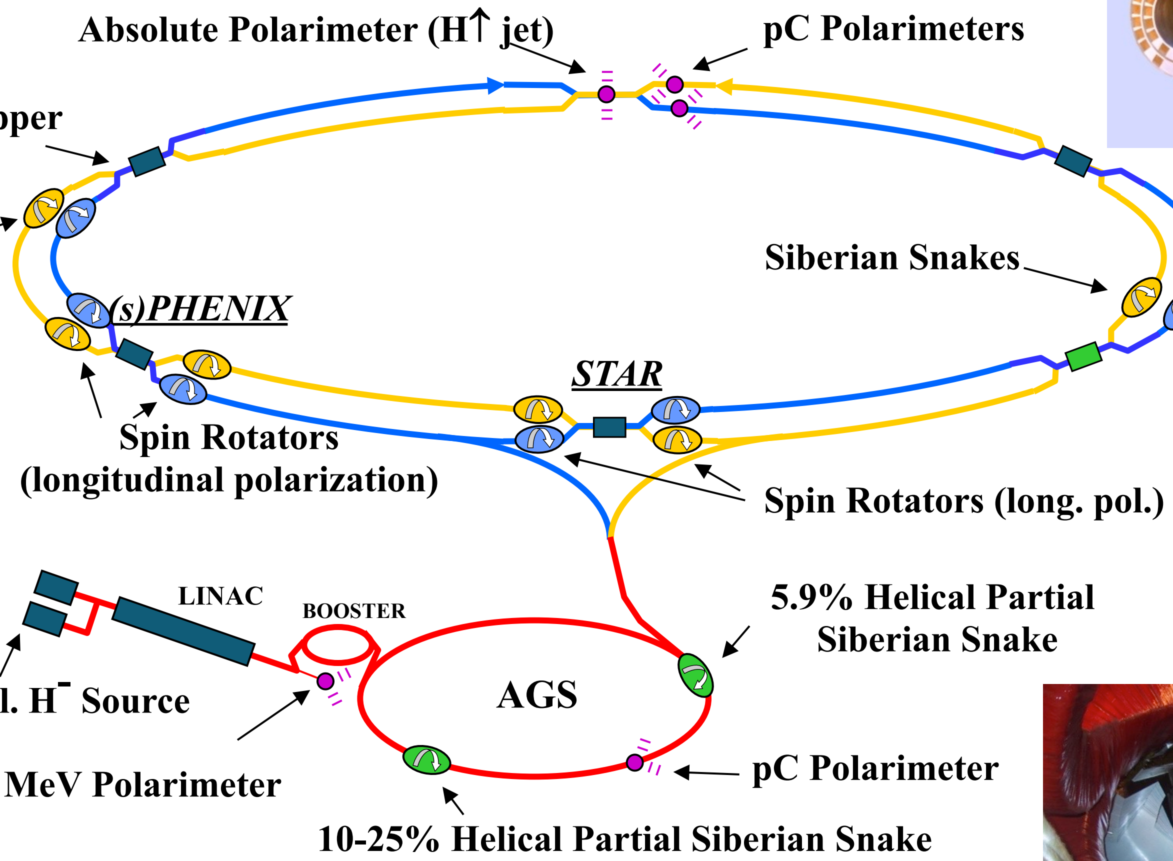
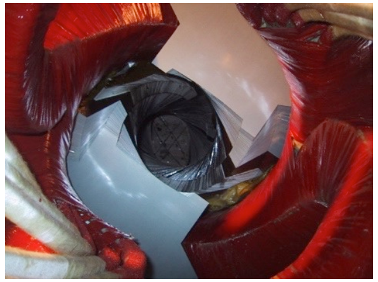
RHIC – First Polarized Hadron Collider

- Two full Siberian snakes per ring preserve proton polarization to 255 GeV
- Spin direction control at detectors with spin rotators
- Minimally invasive polarimeters; also measure polarization profiles
- Absolute polarimeter using world's most intense polarized H jet







BNL - High intensity polarized H- source

- Developed as BNL, TRIUMF, KEK, INR collaboration
- 1.0 mA in 300 μs (1.8 x 10^{12} protons per pulse); 83% polarization
- One source pulse is captured and accelerated for one bunch in RHIC
- With inefficiencies and scraping to lower emittance and higher polarization bunch intensity in RHIC is 2.5 x 10^{11} polarized protons

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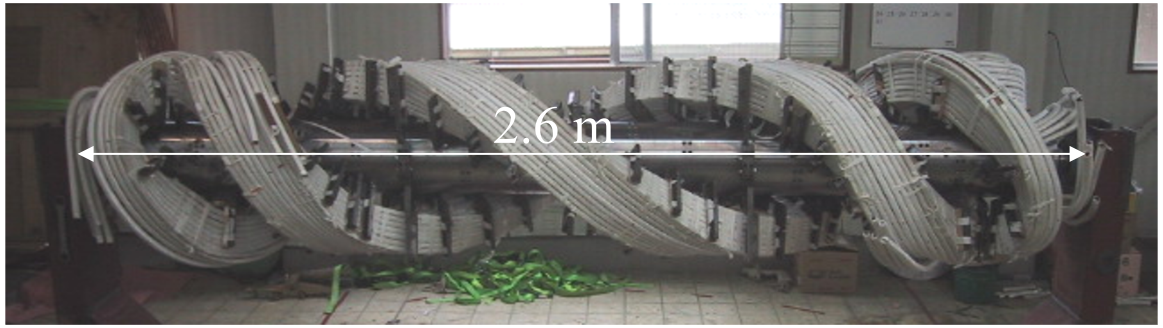
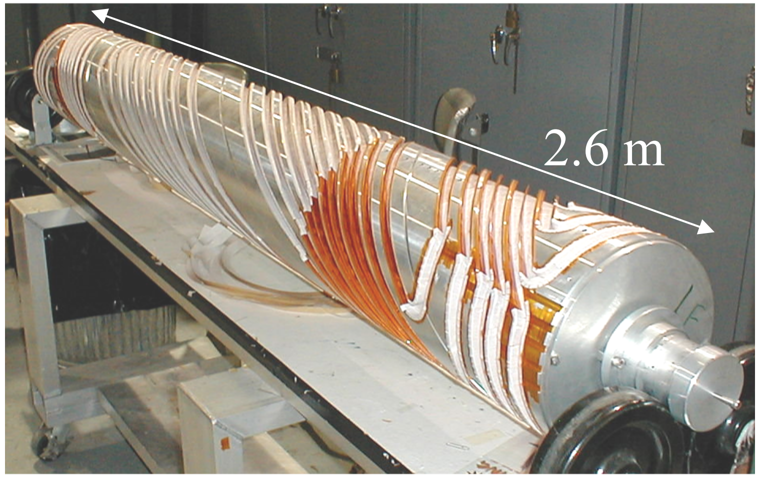
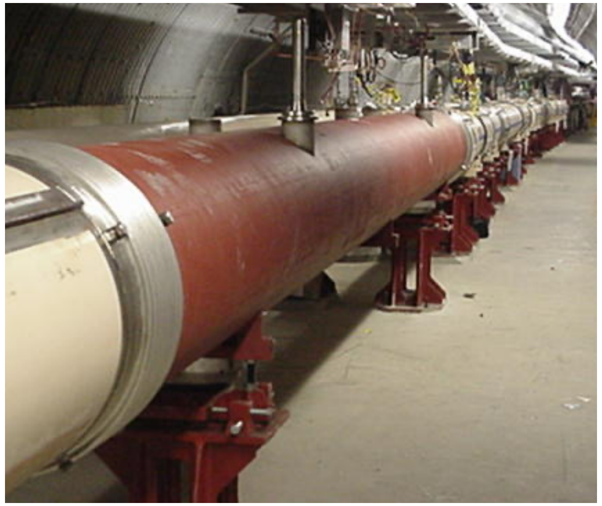
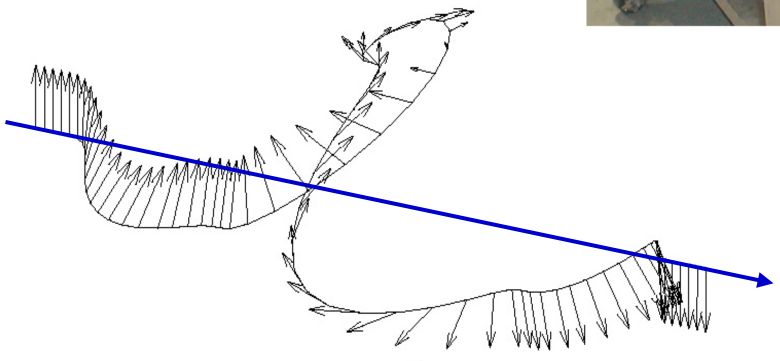
AGS and RHIC Siberian Snakes

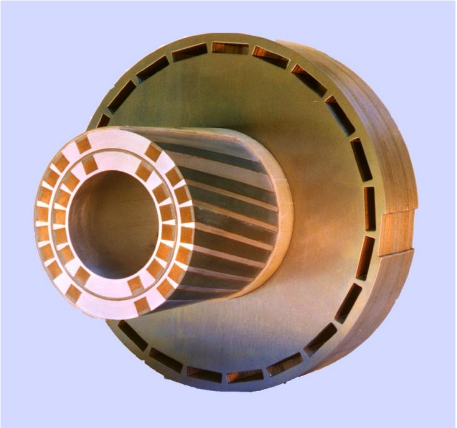
- AGS Siberian Snakes: variable twist helical dipoles, 1.5 T (RT), built in Japan, and 3 T (SC), 2.6 m long
- RHIC Siberian Snakes (funded by RIKEN): 4 SC helical dipoles, 4 T, each 2.4 m long and full 360-degree twist











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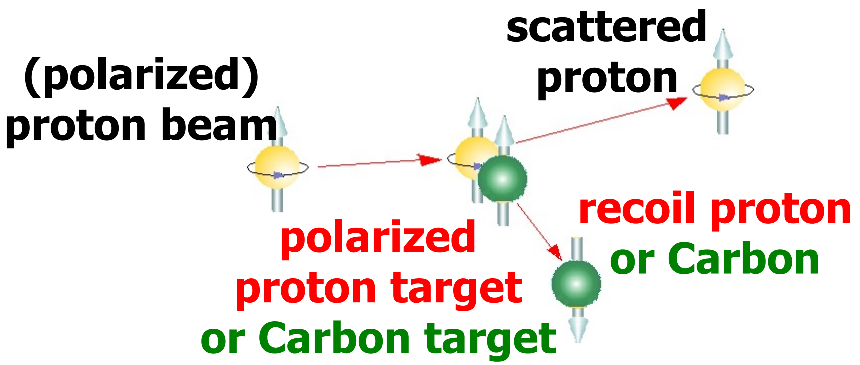
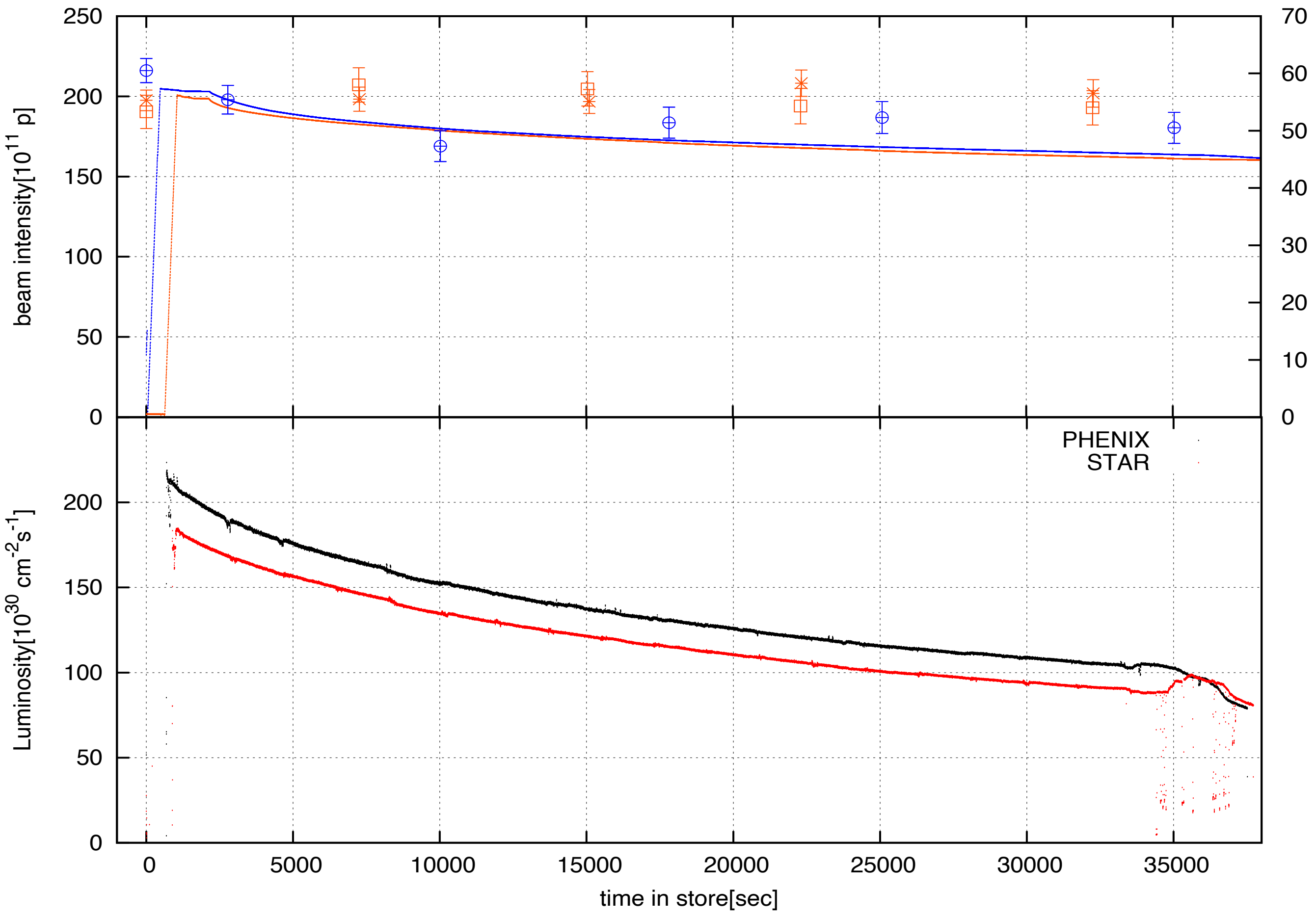
RHIC Polarimetry



- Absolute polarimeter (Pol. Hjet)
  - Polarized hydrogen jet target allows for absolute beam polarization measurement: $P_{\text{Beam}} = P_{\text{Target}} \frac{\varepsilon_{\text{Beam}}}{\varepsilon_{\text{Target}}}$
  - Jet target thickness of ~ 1×10^{12} cm^{-2} achieved
  - Jet pol. 92 ± 2 % measured with Breit-Rabi polarimeter
  - Analyzing power A_N ~ 0.044 (24 – 255 GeV)
- Relative polarimeters (proton-carbon)
  - Measure horizontal and vertical polarization profiles
  - Fast measurements (~ 2 minutes)
- Local IP polarimeters (forward neutron production)
  - Significant asymmetry, calibrated with Hjet
  - Used to adjust transverse polarization component to zero

Polarized Proton Collisions at 255 GeV Beam Energy

- Reached ~57% average polarization in 14 best stores
- Little polarization loss on ramp and during store
- Peak luminosity: 2.5×10^{32} cm^{-2} s^{-1}
- Requires excellent control of orbit, tune and coupling



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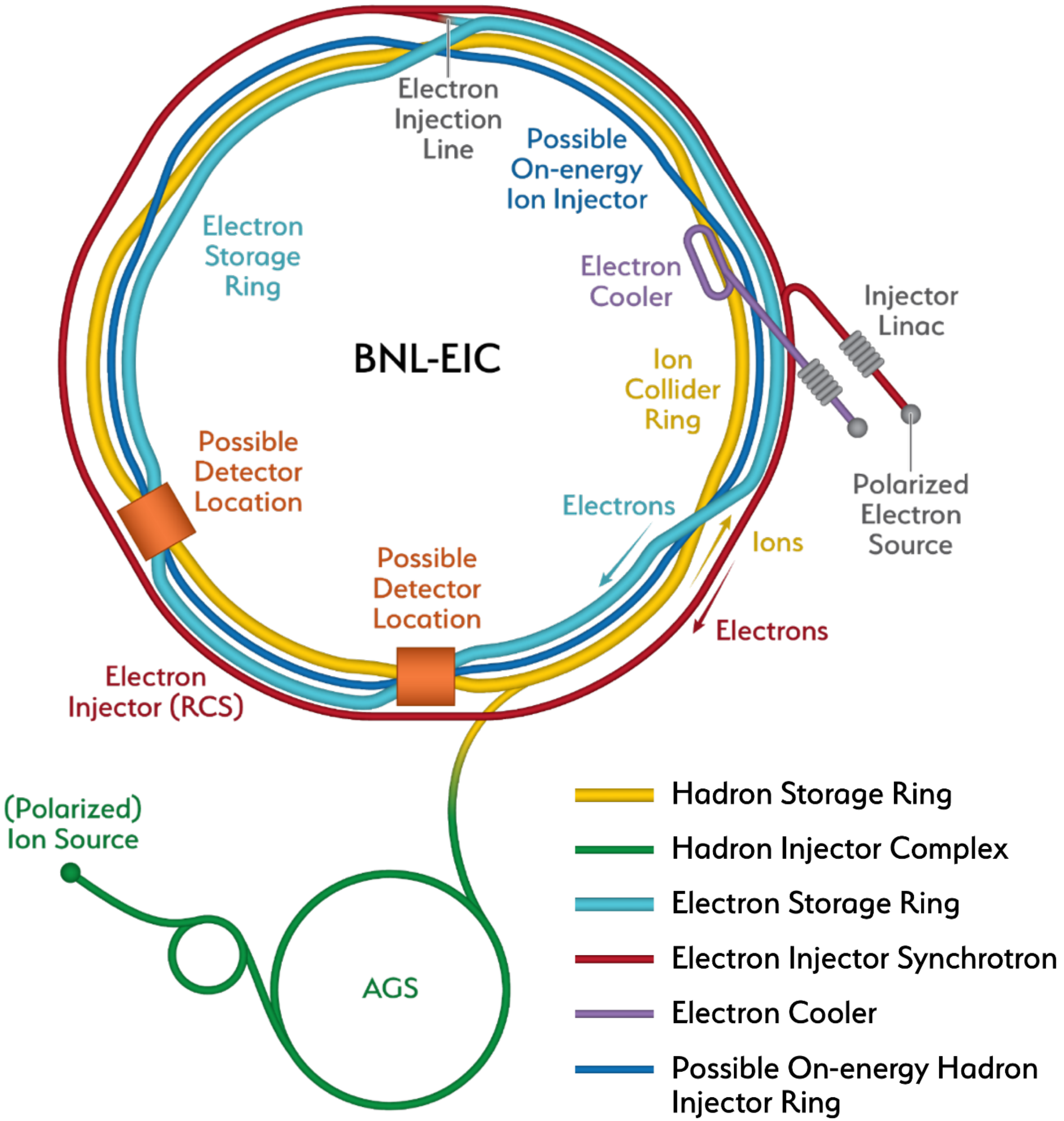
Electron Ion Collider

- Use existing RHIC accelerator complex
  - Up to 275 GeV polarized protons
  - Existing: tunnel, detector halls & hadron injector complex
- Add 18 GeV polarized electron accelerator in the same tunnel
- Achieve high luminosity, high energy polarized e-p/A collisions with full acceptance detector
- Strong hadron cooling needed for highest luminosities



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Multiple Siberian Snakes for High Energy Rings

- Spin rotation of Siberian snake (δ) >> Spin rotation of resonance driving fields (strength ε)

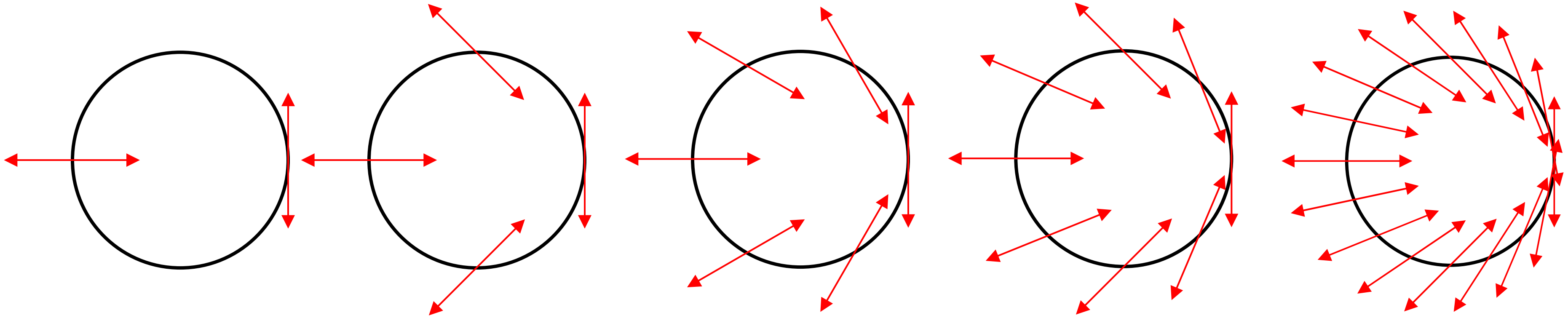
- Imperfection resonances: $\varepsilon \propto$ Energy; Intrinsic resonances: $\varepsilon \propto \sqrt{\text{Energy}}$

		E_{max}/GeV	$\sqrt{E_{max}/\text{GeV}}$
Partial snakes (AGS, $\delta \sim 27°$)	$\varepsilon < 0.07$	24	5
Two full snakes (RHIC)	$\varepsilon < 0.5$	250	16
16 full snakes (LHC?)	$\varepsilon < 4$	7000	84

- Intrinsic resonance strengths increase slowly and can be addressed with multiple snakes
- Imperfection resonance strengths increase faster and require ever better vertical orbit corrections

Multiple Siberian Snakes (cont'd)

- S.R. Mane showed that for a single strong intrinsic resonance the spin tune does not depend on the beam emittance if the snake axes angle increases in equal steps from one snake to the next.
- This may be a good starting point for a multiple snake design.



2 Snakes (**RHIC**)
$\Delta\alpha$ = **90°**

4 Snakes (HERA-p)
$\Delta\alpha$ = 45°

6 Snakes (**EIC**)
$\Delta\alpha$ = 30°, **90°**

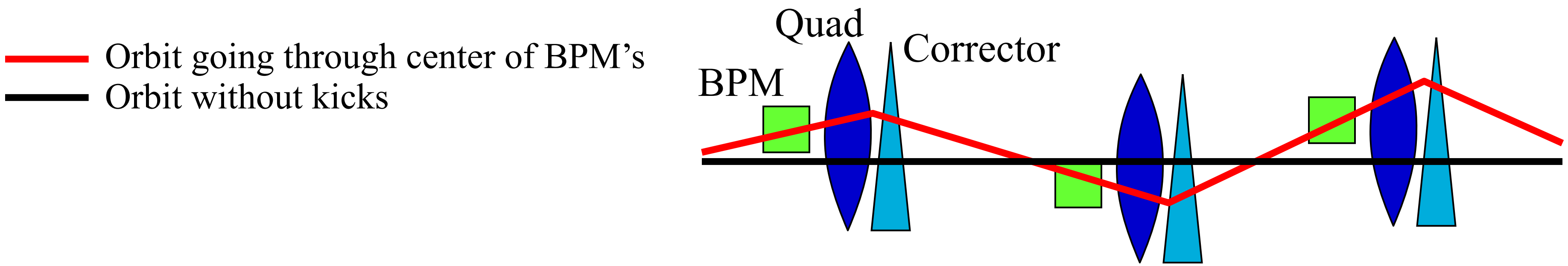
8 Snakes (HERA-p)
$\Delta\alpha$ = 22.5°, 67.5°

16 Snakes (LHC, 2 per arc)
$\Delta\alpha$ = 11.25°, 33.75°, 56.25°, 78.75°

Global Imperfection Resonances – the Ultimate Energy Limit?

- Residual orbit distortion after orbit correction drives imperfection resonance with a strength that is not affected by (multiple) Siberian snakes
- Resonance strength needs to be less than 0.05 (S. Y. Lee and E. D. Courant, Phys. Rev. D 41, 292 (1990))
- At RHIC (250 GeV) this corresponds to ~250 µm residual orbit error (OK)
- At LHC (7 TeV) this corresponds to ~10 µm residual orbit error ! (LHC orbit accuracy ~ 200 µm)
- Need beam-based quadrupole offset measurement, same as minimized vertical dispersion
- Flatten actual beam orbit using H and V beam position monitors and correctors at each quadrupole:

Correct orbit to minimize kicks:



Summary

- Exceptional progress in polarized proton acceleration from a few MeV to colliding polarized protons at 510 GeV based on seminal contributions from Ernest Courant, Satoshi Ozaki, Willy Haeberli and many, many more.

- The ultimate limit for polarized proton acceleration might be if the depolarization can occur in a single turn from a ”random” destructive orbit distortion pattern. The only remedy is an extremely flat beam orbit, which is likely not feasible at energies beyond the LHC.