Siberian Snakes and Spin Manipulations

From controlling spin to taming snakes.

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Thomas Roser
Spin Physics Symposium
November 14, 2009

Spin Dynamics in Rings

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

$$d\mathbf{S}/dt = -(e/\gamma m)\,[(1+G\gamma)\mathbf{B}_{\perp} + (1+G)\,\mathbf{B}_{||}\;] \times \mathbf{S}$$

Lorentz Force equation:

$$d\mathbf{v}/dt = -(e/\gamma m)\,[\;\mathbf{B}_{\perp}\;] \times \mathbf{v}$$

- For pure vertical field:
  Spin rotates Gγ times faster than motion, $\nu_{sp} = G\gamma$
- For spin manipulation:
  At low energy, use longitudinal fields
  At high energy, use transverse fields

Spin Tune and Depolarizing Resonances

Depolarizing resonance condition:

Number of spin rotations per turn = Number of spin kicks per turn
Spin resonance strength ε = spin rotation per turn / 2π

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]

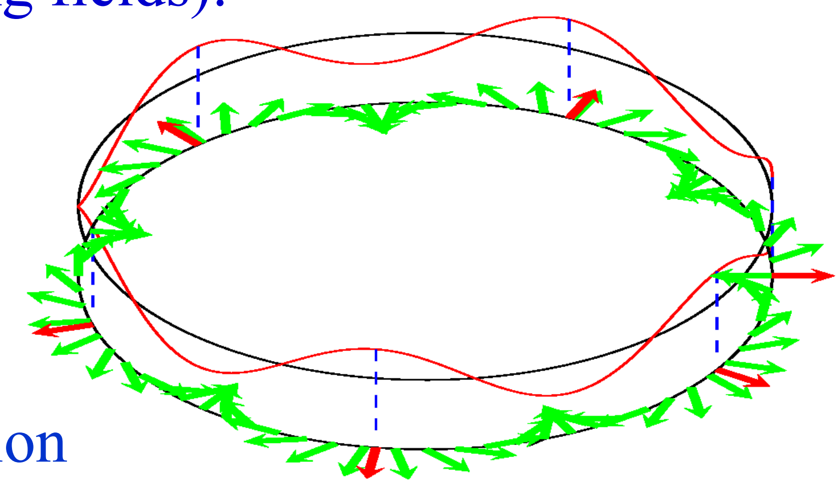

Illustration by W.W. MacKay

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

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Spin Resonance Crossing

Froissart-Stora: $\frac{P_f}{P_i} = 2\,e^{-\left(\frac{\pi \varepsilon^2}{2\alpha}\right)} - 1$ [α: crossing speed]

Non-adiabatic ($\varepsilon^2/\alpha \ll 1$) ↔ Adiabatic ($\varepsilon^2/\alpha \gg 1$)

$P_f/P_i = 1$ $P_f/P_i = -1$

Imperfection Resonances:

Correction Dipoles (ε small) Partial Snake (ε large)

Intrinsic Resonances:

Pulsed Quadrupoles (α large) Rf Dipole (ε large)

Lattice modifications (ε small) Strong Partial Snake (ε large)

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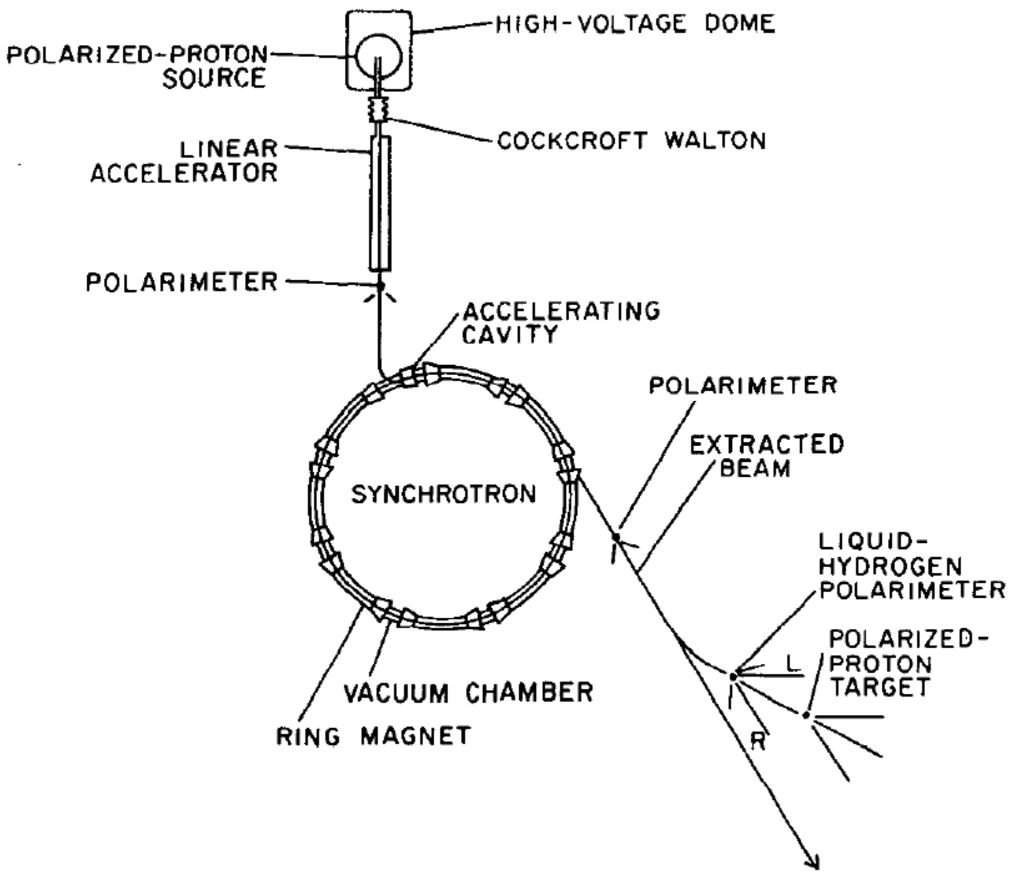
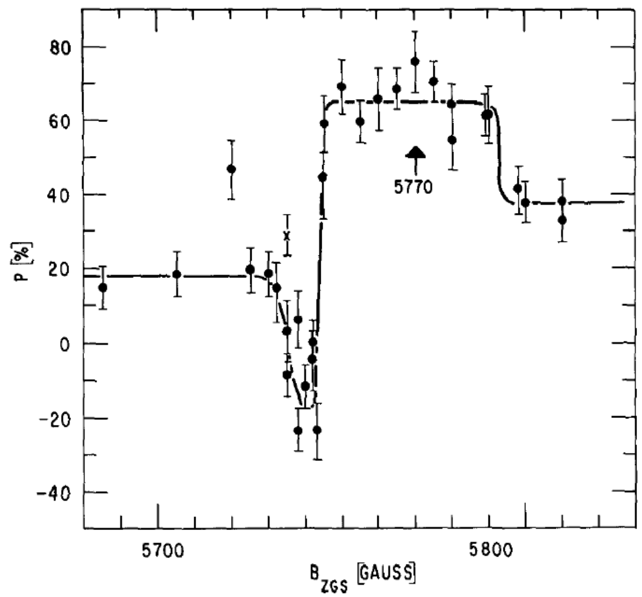
Polarized Proton Accelerations at the ZGS

ZGS (up to 70% at 12 GeV/c)
Weak resonances ($\varepsilon_{max} \sim 0.002$)

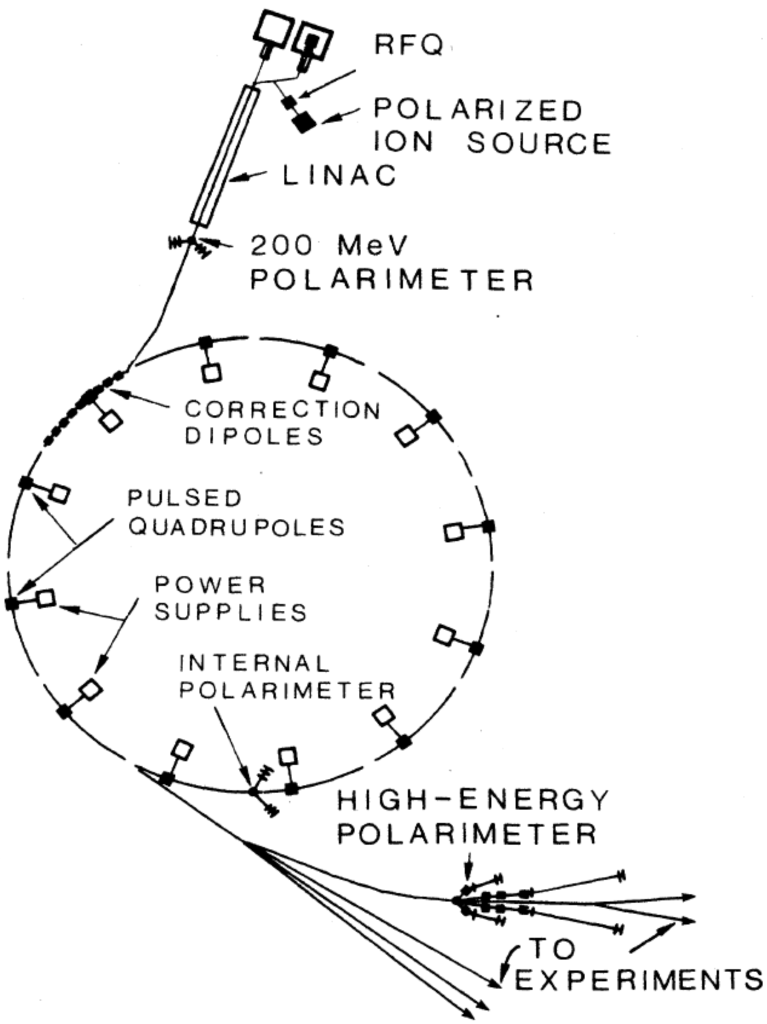
Timing of betatron tune jump
using polarization measurement



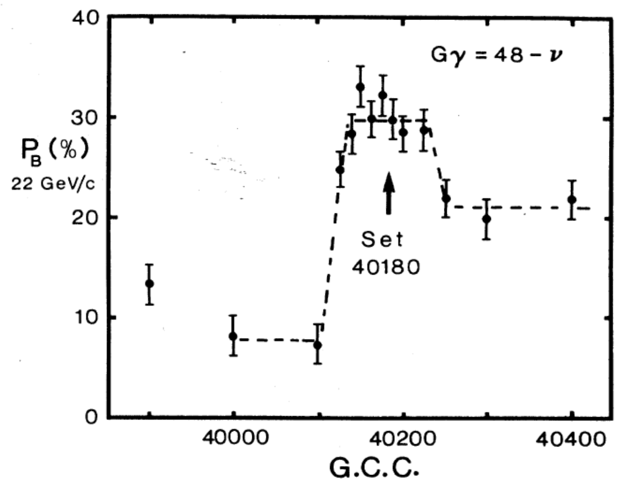


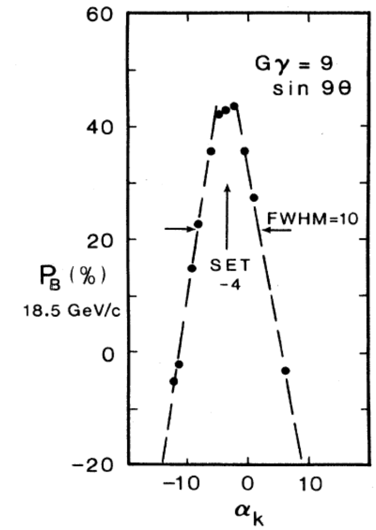
Polarized Proton Acceleration at the AGS

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



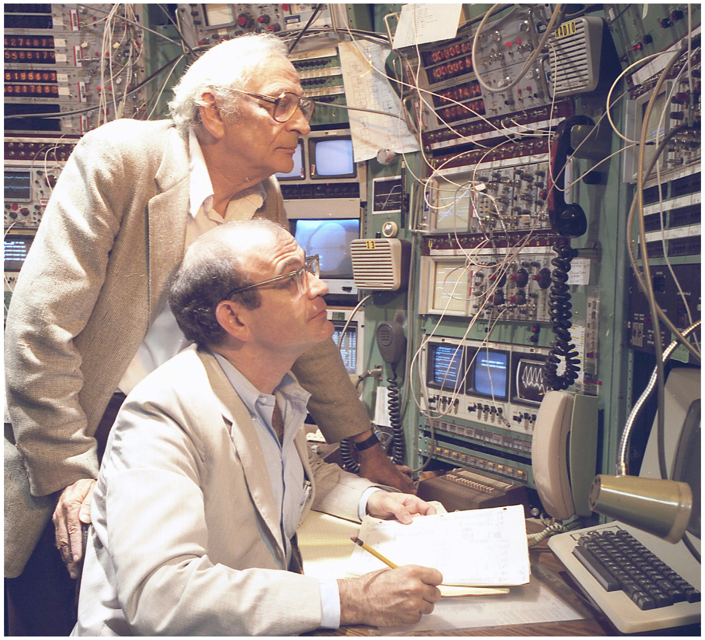


Setting up polarized proton acceleration to 22 GeV required:

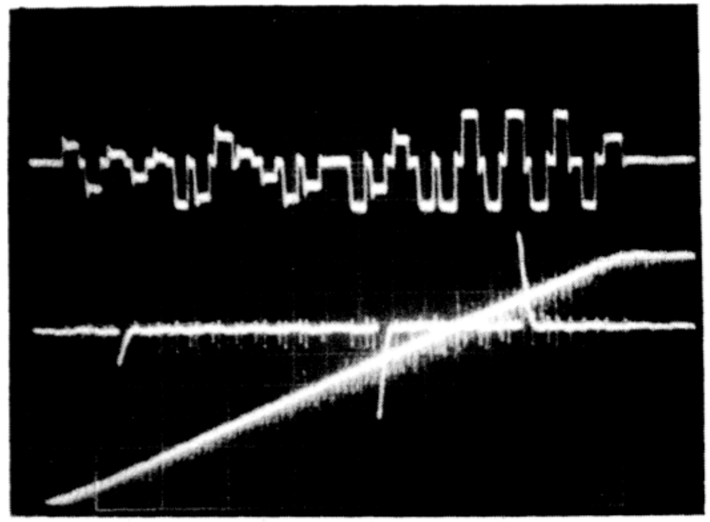
- 6 pulsed quadrupole timing scans and
- 2 × 40 harmonic corrector scans (sin + cos)

➔ Many shifts spent in trailer, to operate the polarimeters, and in MCR (my entry to accelerator physics) and also many dinners at Sea Basin, Carving Board, …

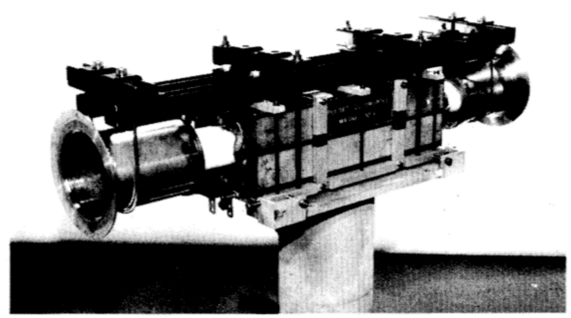
Polarized Proton Acceleration at the AGS (cont'd)



Alan Krisch and Larry Ratner adjusting the timing of betatron tune jump and the strength of the dipole correctors in the AGS MCR.



Dipole corrector strength and pulse quadrupole timing during acceleration ramp to 16 GeV



One of ten ferrite quadrupoles used for tune jumps in the AGS

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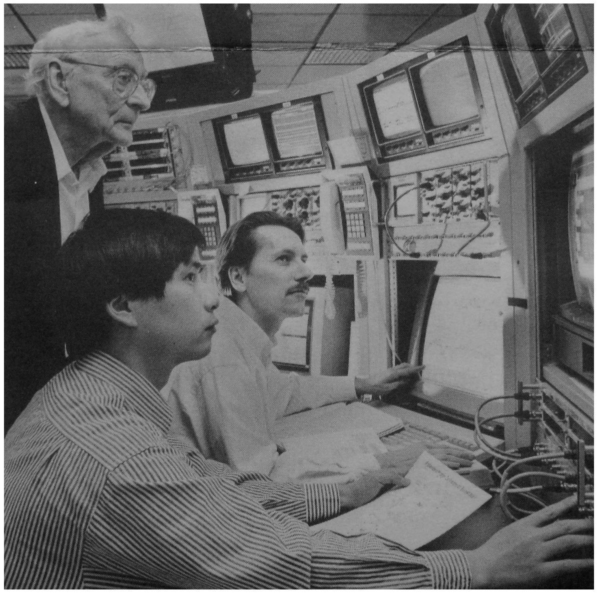
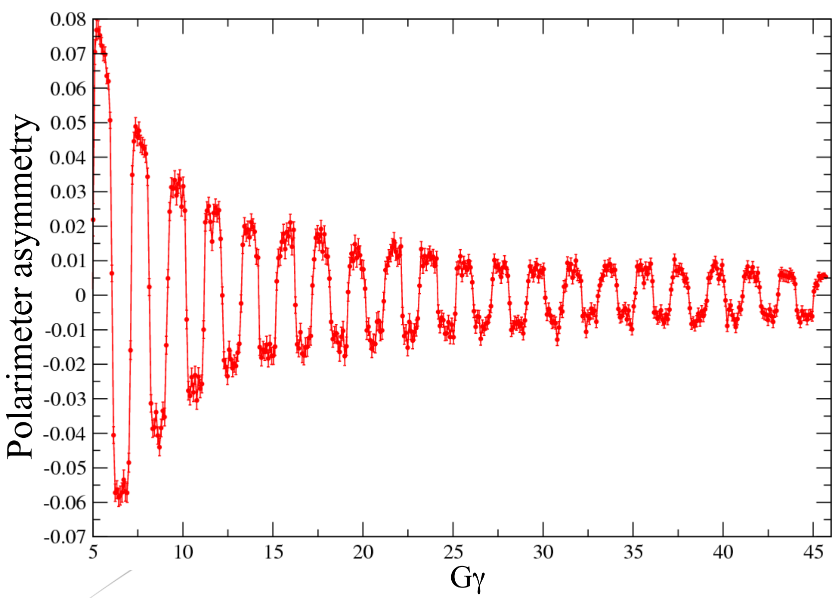
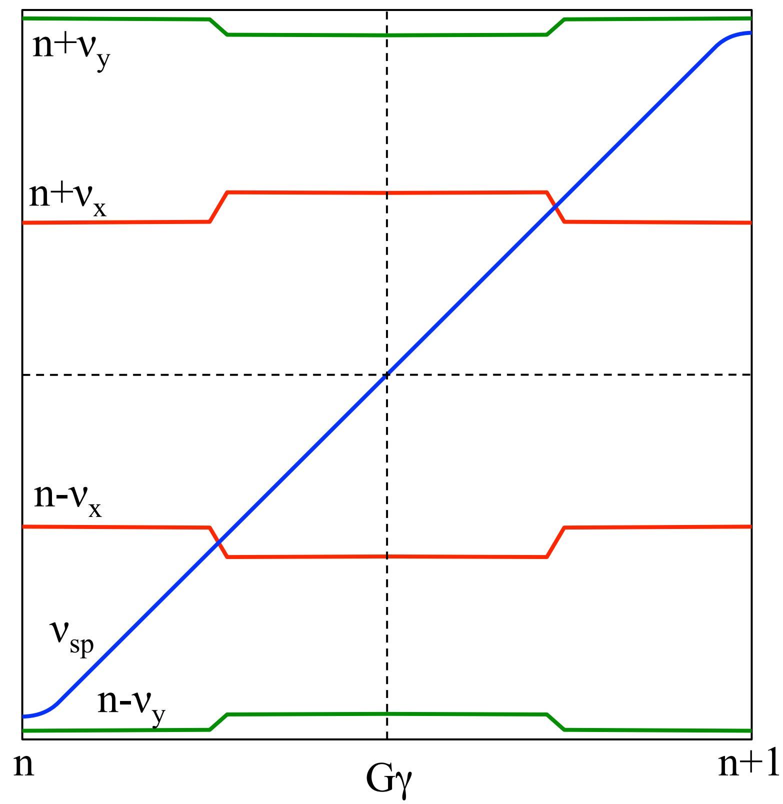
In Alan's Foot Steps: Polarized Protons in the AGS Today



Larry Ratner, Haixin Huang and TR in AGS MCR.

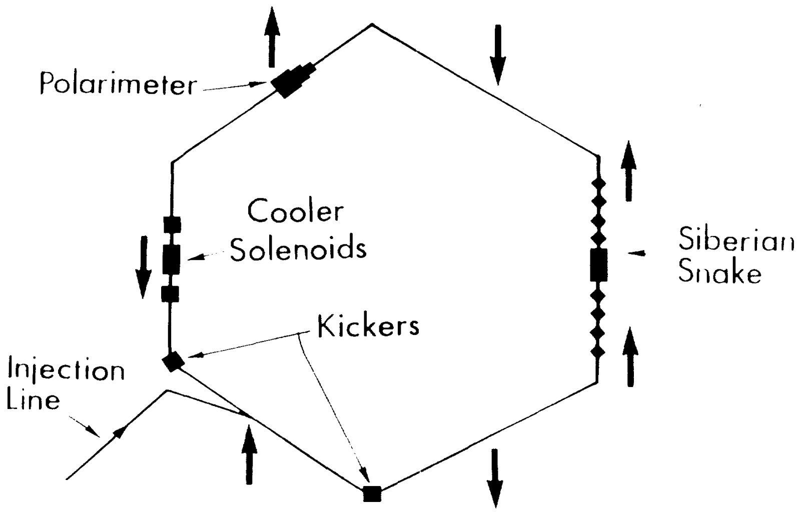
- Two strong partial Siberian snakes
- Vertical betatron tune at 8.98
- Pulsed quadrupoles (they are back!) to jump across the many weak horizontal spin resonances driven by the partial snakes.

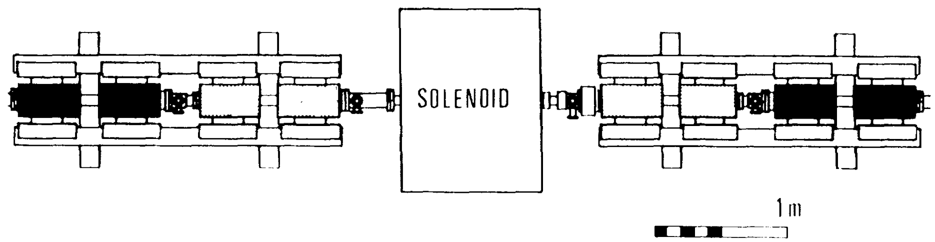


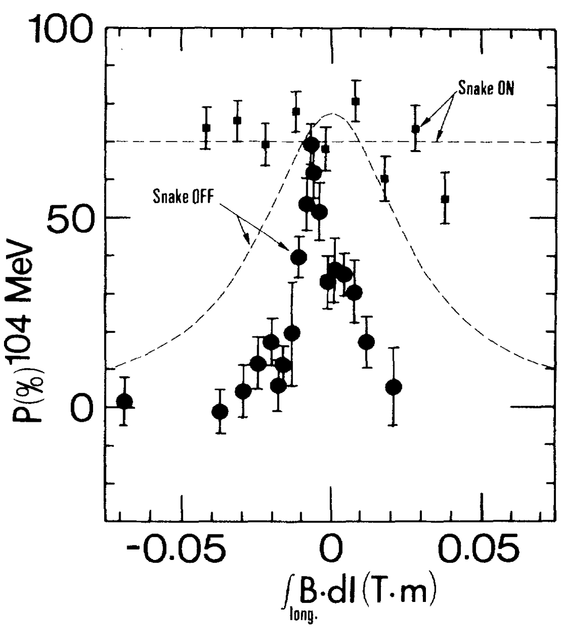


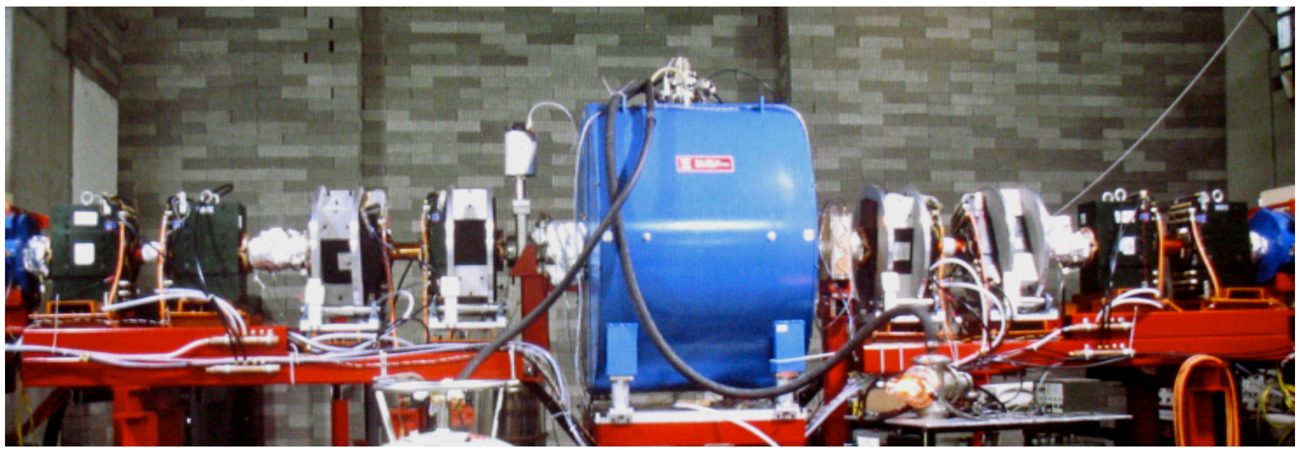
First Siberian Snake Test at IUCF

- Full Siberian snake: 180° spin rotator without changing particle orbit.
- First full solenoid Siberian snake with optical correctors: 4 straight and 4 rotated quadrupoles ($\Delta\nu_{x,y} = 0{,}1$)

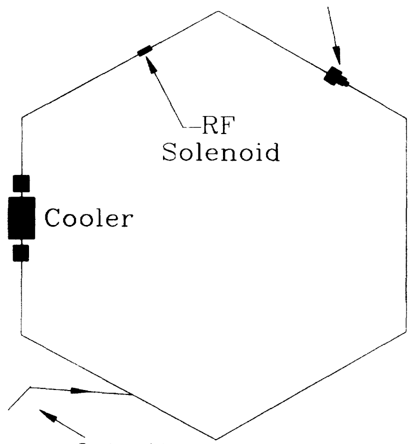




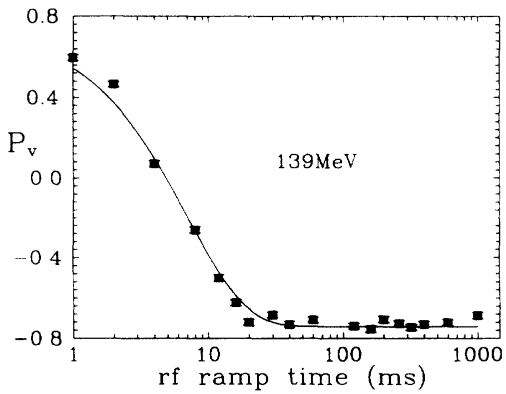


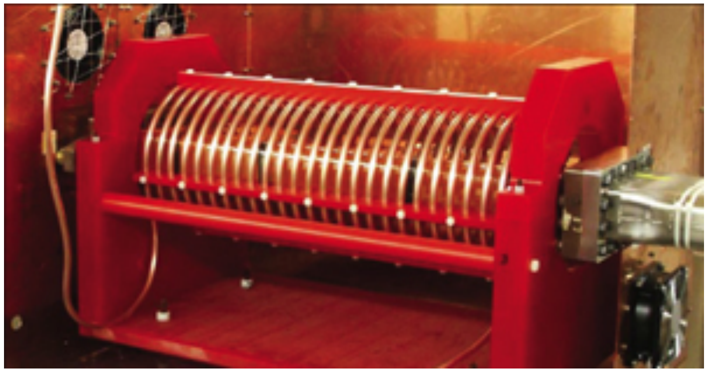


Rf Dipole and Solenoid Experiments at IUCF

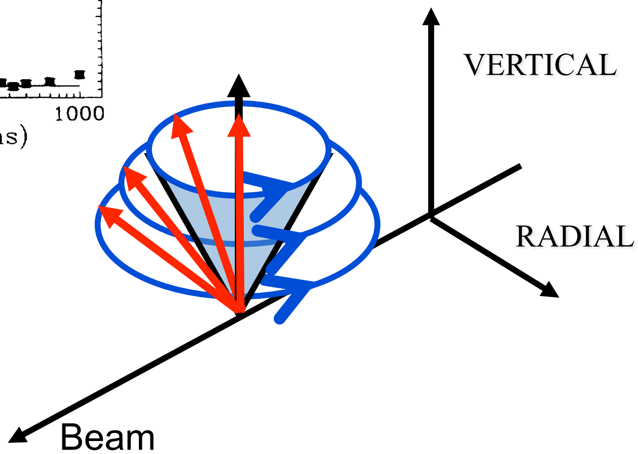


- Use spin resonance driven by rf solenoid or dipole to induce spin flip
- Successful spin flip of 139 MeV polarized proton beam
- 99 % spin flip efficiency, using air-core rf solenoid





COSY rf solenoid similar to original rf solenoid at IUCF



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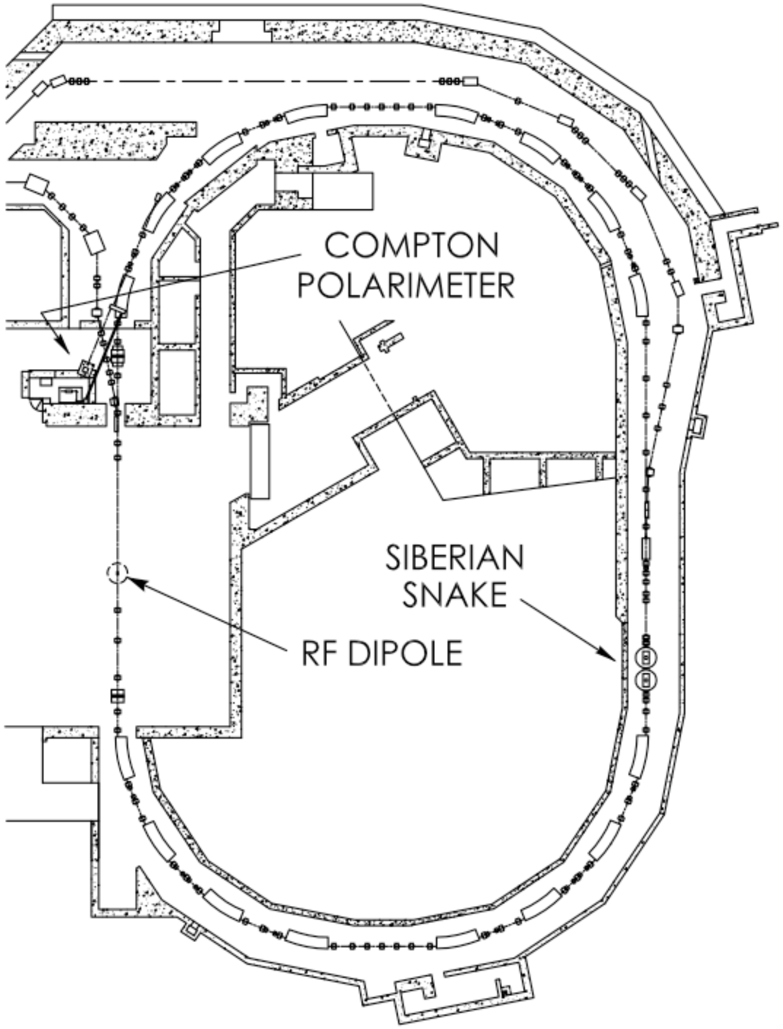
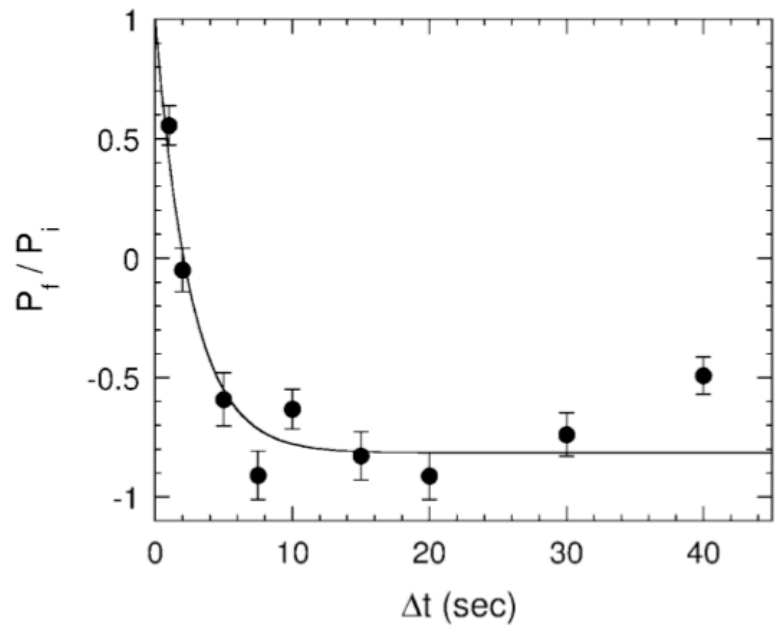
Rf Dipole Experiment at Bates



- Successful spin flip of 669 MeV horizontally polarized electron beam
- 94 % spin flip efficiency with almost full Siberian snake, using air-core rf dipole



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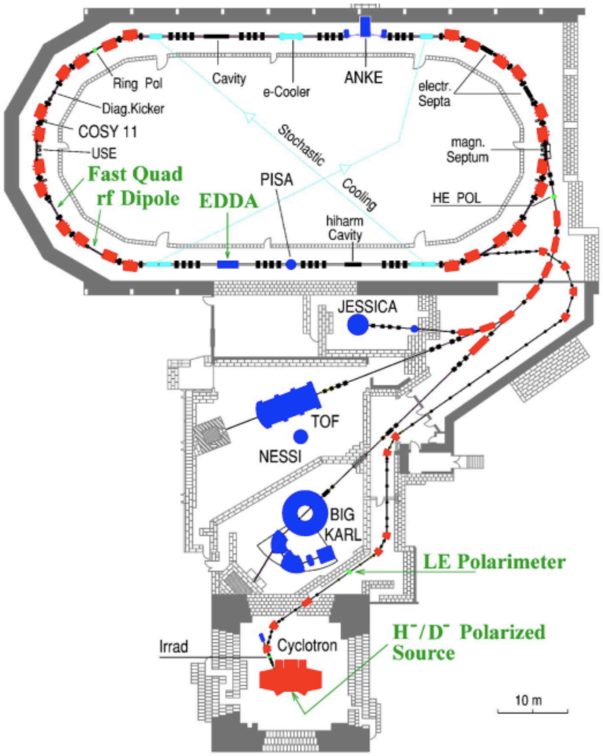
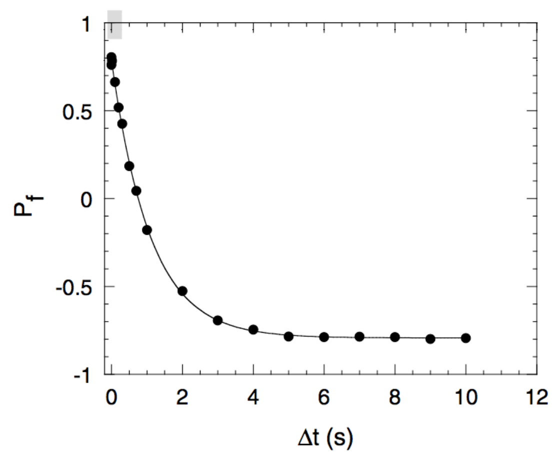
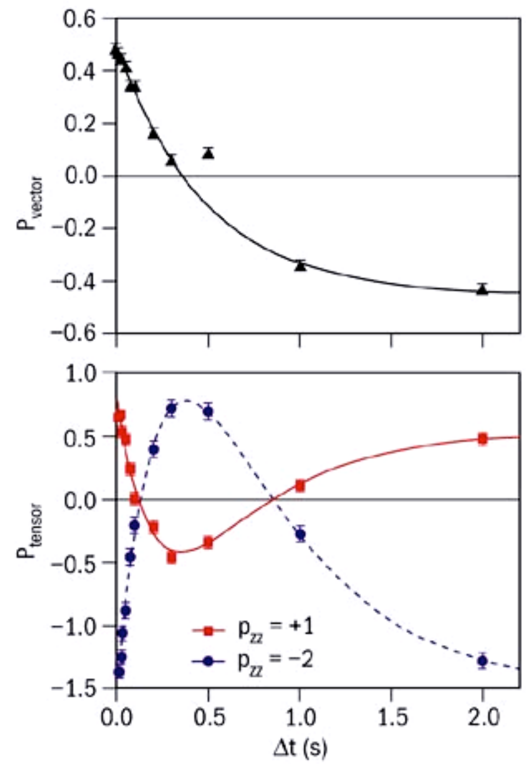
Many Spin Flipping Experiments with p↑ and d↑ at COSY



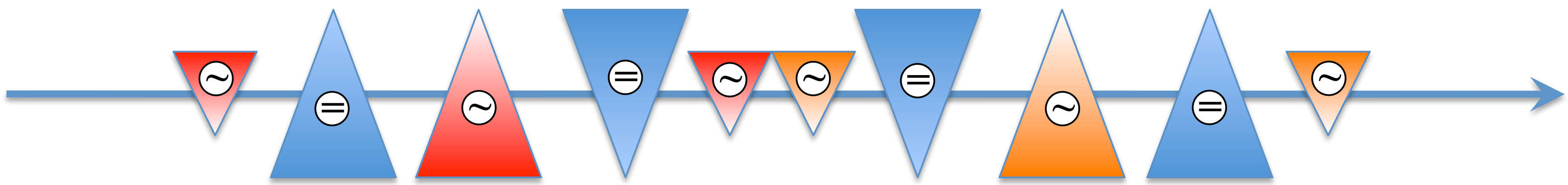
- Spin flipping of 1.93 GeV polarized proton beam with 99.3 % efficiency
- Efficient spin flipping of Spin-1 deuteron beams
- Rf dipole resonance strength is sum of direct effect of rf field and field of lattice quadrupoles sampled by induced orbit oscillation



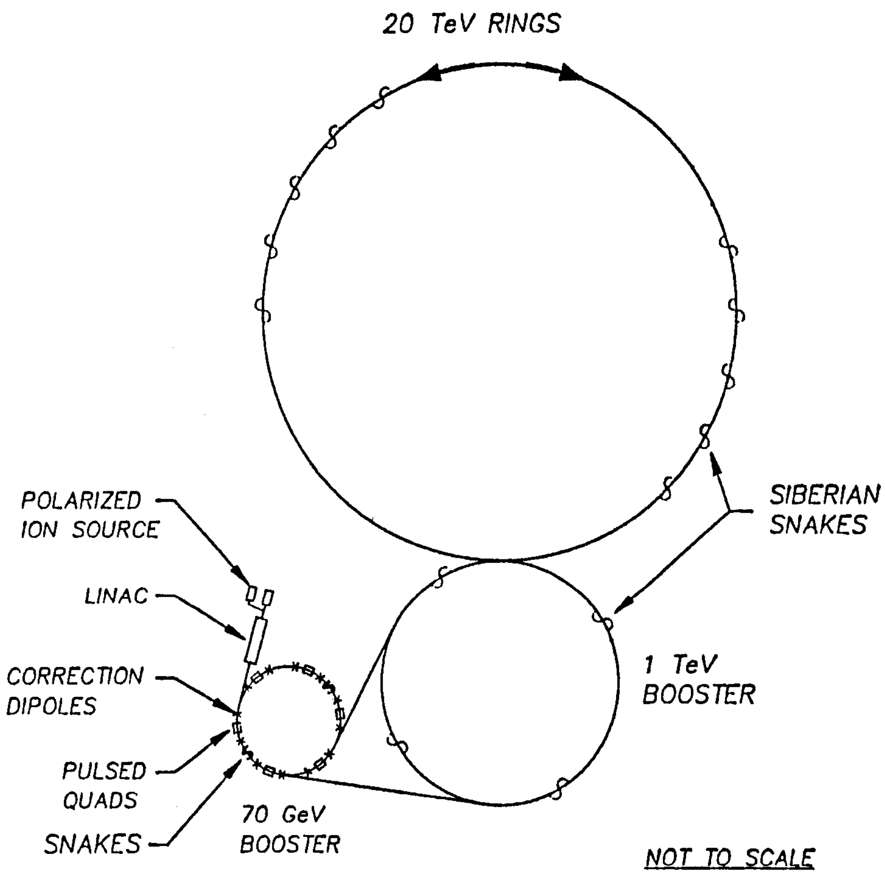


RHIC Spin Flipper Design

- RHIC spin flipper design is based on these spin flipper experiments
- For spin tune = ½ we need two rf resonance driving fields with orthogonal axis
- To avoid contribution from orbit effect we need to eliminate orbit residuals:
  2 radial rf dipole three bumps interleaved with a vertical field DC four bump



Polarizing the SSC? You must be kidding!



- Pioneering workshop in 1985, organized by O. Chamberlain, E.D. Courant, A.D. Krisch, and K.M. Terwilliger
- Very ambitious goal before Siberian snake demonstration or polarized beam above 20 GeV
- Design: 26 Siberian snakes per ring
- Space for snakes was reserved in SSC lattice
- This design effort was critical for the RHIC polarized proton collider project

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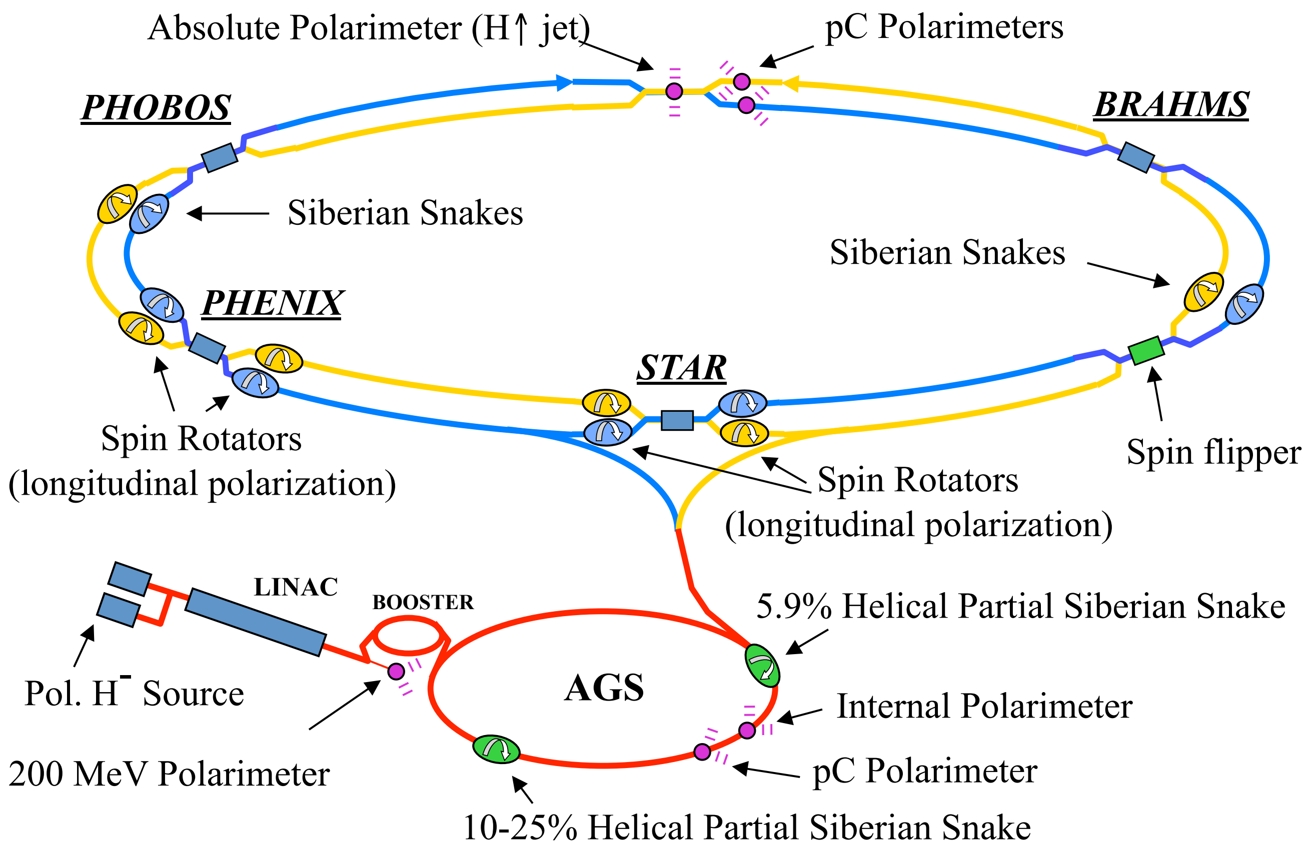
RHIC – First Polarized Hadron Collider



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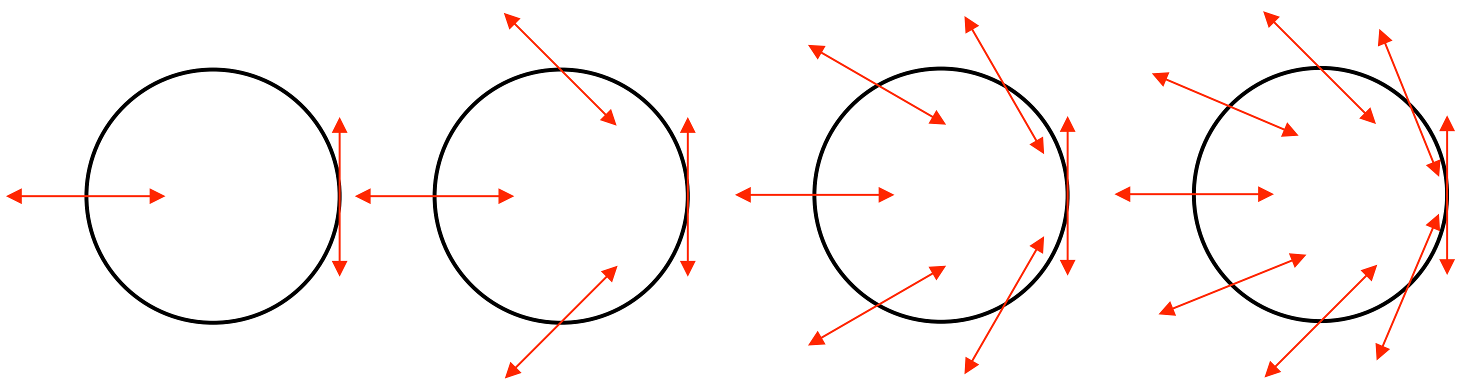
Multiple Siberian Snakes for High Energy Rings

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

Imperfection resonances $\varepsilon \propto$ **Energy**

Intrinsic resonances $\varepsilon \propto \sqrt{\text{Energy}}$

		E_{max}/GeV	$\sqrt{E_{max}/\text{GeV}}$
Partial Siberian snakes (AGS, $\delta \sim 27°$)	$\varepsilon < 0.07$	**24**	**5**
One full snake	$\varepsilon < 0.25$		
Two full snakes (RHIC)	$\varepsilon < 0.5$	**250**	**16**
16 full snakes (LHC?)	$\varepsilon < 4$	**7000**	**84**



2 Snakes (RHIC) $\Delta\alpha = 90°$

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

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

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

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

Summary

Alan's vision of high energy spin experiments using polarized beams and colliders has been realized!

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