RHIC Spin Collider – Physics of Accelerating Polarized Protons and Plans

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The evolution of the polarization $\vec{P}$ of protons in a circular accelerator is governed by the Thomas-BMT precession equation

$$\frac{d\vec{P}}{dt} = -\left(\frac{e}{\gamma m}\right)\left[G\gamma \vec{B}_{trans} + (1+G)\vec{B}_{long}\right] \times \vec{P} \quad ; \quad G = 1.7928$$

This is to be compared with the Lorentz equation that governs the orbital motion:

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

For a pure vertical field the number of spin precesses per orbit revolution, also called 'spin tune', is $G\gamma$. To manipulate the spin direction at low energy a longitudinal magnetic field can be used. For example the 9 degree spin rotator used in the AGS is simply a large solenoid. However, at high energy a sequence of alternating horizontal and vertical fields has to be used. In such a wiggler-like structure the relative small orbit deflections are cancelled whereas for the much larger spin precessions the non-commutative character of rotations can not be ignored. Structures for which the total residual spin rotation adds up to 180 degrees are called Siberian Snakes. In RHIC the Snakes and the spin rotators to produce the longitudinal polarization at the interaction regions each consist of four 2.4 m long full-twist helical dipole magnets.

In a circular particle accelerator the polarization direction of the beam that is the same every turn is called the 'stable spin direction'. Other names are 'invariant spin direction' or 'spin closed orbit'. Although for a pure vertical field this direction is vertical everywhere, in general it will depend on the ring rigidity, location around the ring and the ring lattice. It does, however, not depend on the initial beam parameters or any dynamic quantities such as the acceleration rate. The stable spin direction of the AGS with the 9 degree spin rotator (Partial Snake) is mostly vertical but reverses sign whenever $G\gamma$ crosses an integer value. In RHIC two Siberian Snakes will be installed in each of the two rings separating each ring into two exactly equally long halves. In one half the stable spin direction points up and the other down. In this case the spin tune is a half-integer independent of energy.

Depolarization occurs when the stable spin direction changes so fast during acceleration that the beam polarization can't adiabatically follow it. This condition is avoided in the AGS with the 9 degree Partial Snake and in RHIC with the two full Snakes. Particles on the edge of the beam will sample the focusing fields of the ring quadrupoles and their stable spin direction becomes very sensitive to these fields when the betatron frequency is equal to the spin precession frequency (intrinsic spin resonance). This condition cannot arise in RHIC since the spin tune is a half-integer. To avoid depolarization in the AGS we excited coherent betatron oscillations of all particles while accelerating through the resonance condition. All particles then experience strong enough focusing fields that the stable spin direction moves slow enough from up to down that the beam polarization can follow it adiabatically. A maximum polarization of about 51 % has been reached in the AGS at 22 GeV.

By summer of 1999 two Snakes and one high energy polarimeter will be installed in one of the rings of RHIC. This will allow for the commissioning of polarized beam acceleration in this ring during the first year of RHIC operation starting in October 1999. The goal is to accelerate polarized beam to at least 100 GeV in preparation for a spin physics run at $\sqrt{s} = 200 GeV$ in the second RHIC year starting in October 2000.

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

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

Lorentz Force equation:

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

$$\gamma = E/m$$

- **For Pure Vertical Field:**
  Spin Rotates $G\gamma$ Times Faster than Motion
  SPIN TUNE $\nu_{sp} = G\gamma$
- **For Spin Manipulations:**
  At Low Energy, use Longitudinal Fields
  At High Energy, use Transverse Fields

Spin Resonances and Siberian Snakes

Spin Tune ν_{sp} : Number of 360° Spin Rotations per Turn

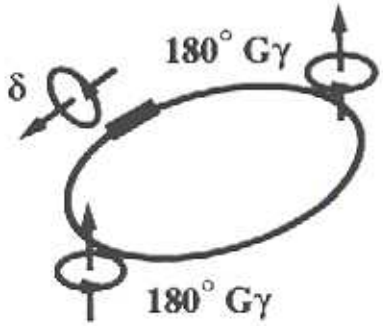
Depolarizing Resonance Condition:

Number of Spin Rotations per Turn
= Number of Spin Kicks per Turn

Only Vertical Field

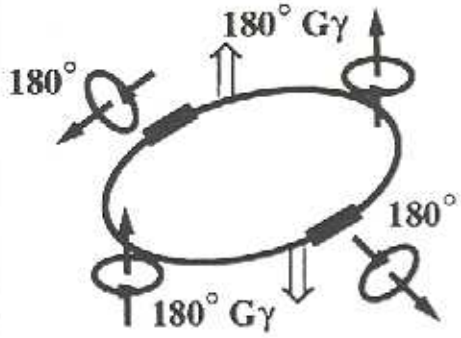
$$\left(\begin{array}{l} G\gamma = 1.79 \\ \gamma = E/m \end{array}\right) \quad \begin{array}{lllll} G\gamma & = & \nu_{sp} & = & n \quad \textit{Imperfection} \\ G\gamma & = & \nu_{sp} & = & n \pm \nu_y \quad \textit{Intrinsic} \end{array}$$

Local Spin Rotators (Siberian Snakes)



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

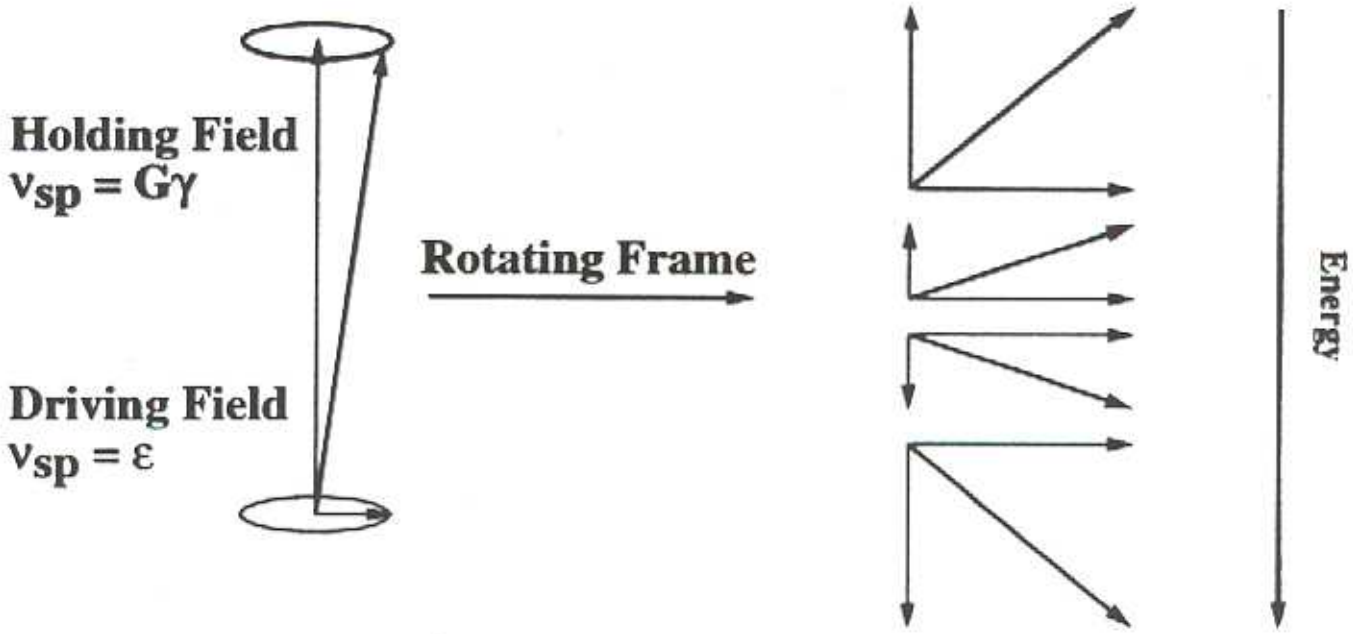
- $\delta \neq 0^\circ \rightarrow \nu_{sp} \neq n$ ⇒ No Imperfection Resonances...
  Partial Siberian Snake (AGS)
- $\delta = 180^\circ \rightarrow \nu_{sp} = ½$ ⇒ No Imperfection and No Intrinsic Resonances...
  Full Siberian Snake



Two Siberian Snakes (RHIC)

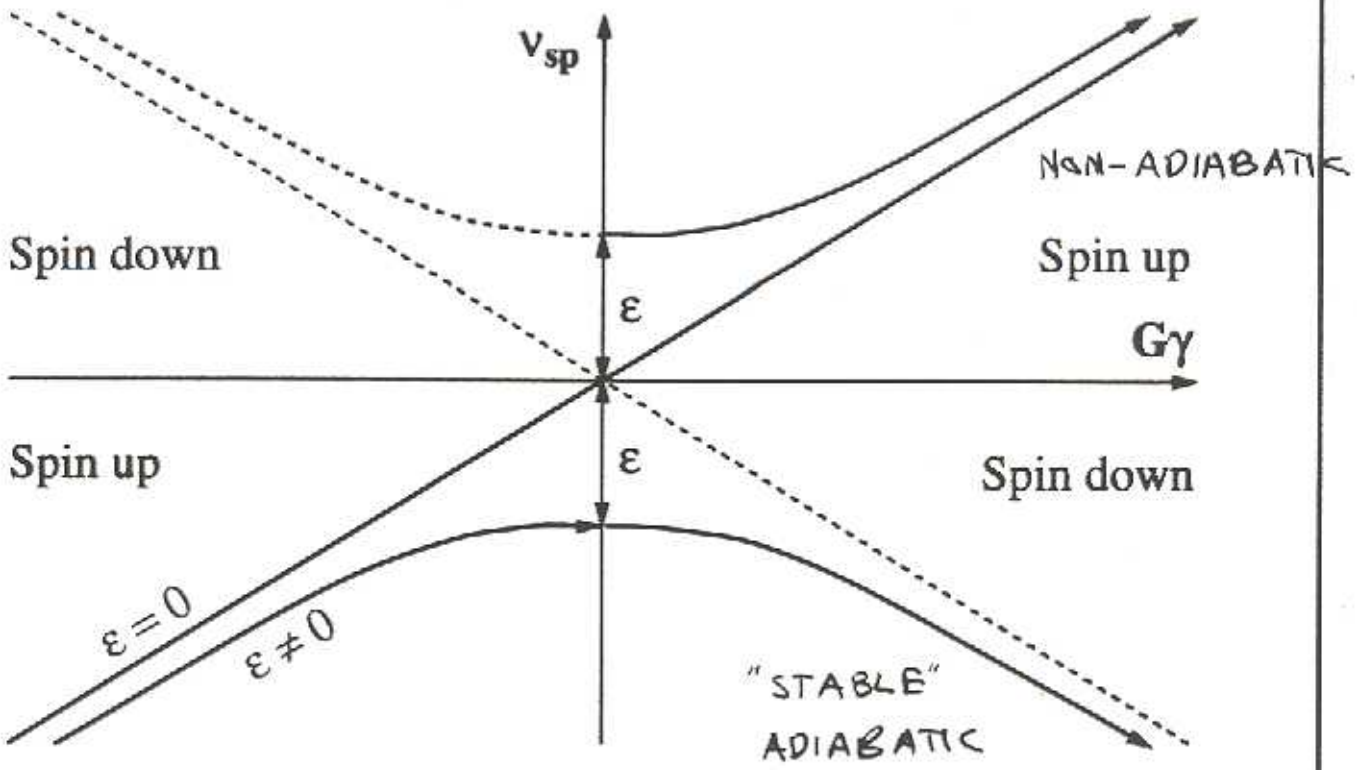
- $\nu_{sp} = ½$, Stable Vertical Polarization

Spin Resonances

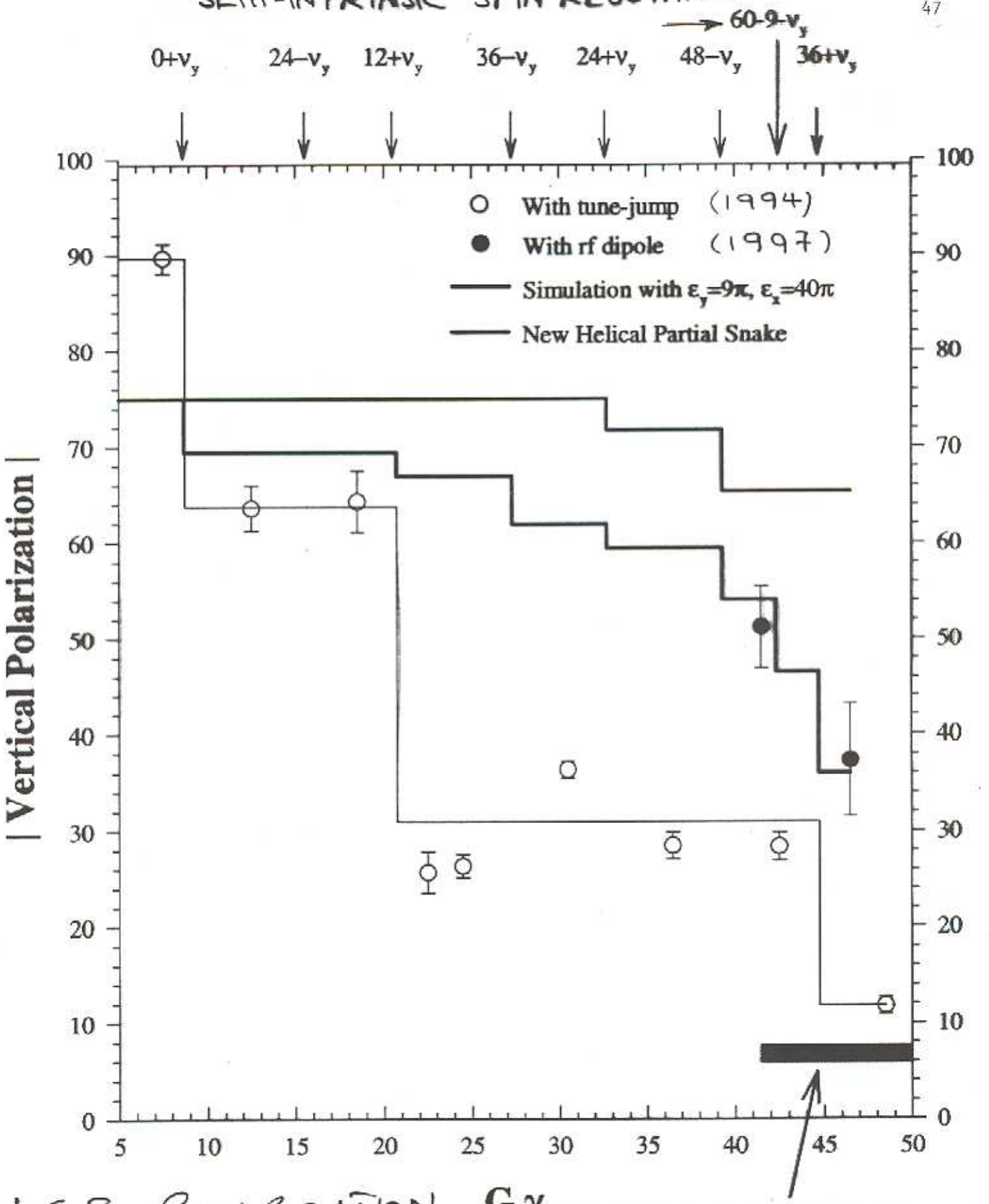


Froissart–Stora(1960): $P_{Final} / P_{Initial} = 2 \exp(\pi\varepsilon^2 / 2\alpha) - 1$

ε: Driving Field
α: Crossing Speed

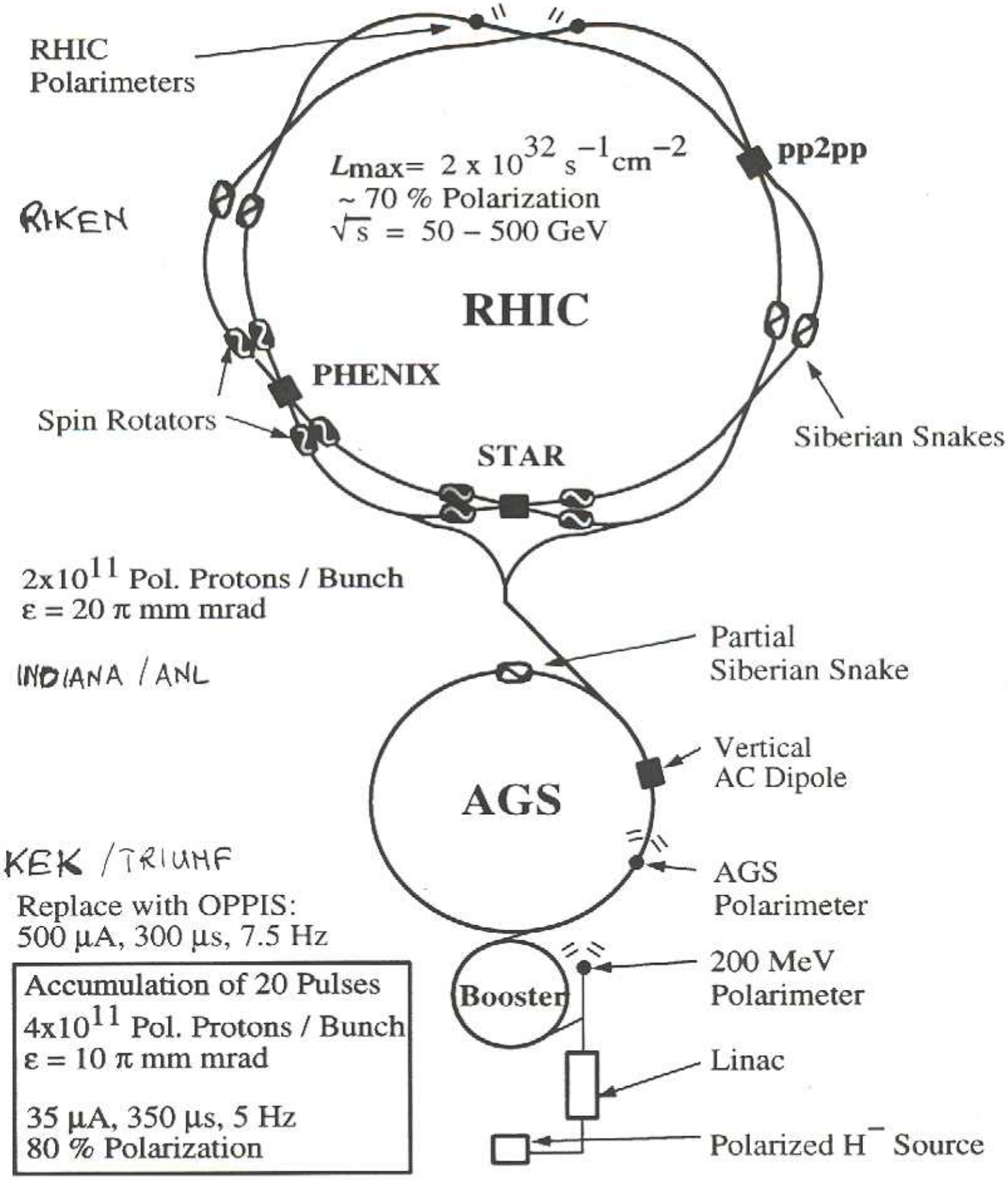


SEMI-INTRINSIC SPIN RESONANCE



AGS POLARIZATION

Polarized Proton Collisions at BNL



Important Dates and Schedule

RHIC Spin Collaboration (RSC) Proposal	**September 1992**
1. Review of Pol. Proton Accel., Feasibility	**February 1993**
AGS Partial Snake Test (E–880)	**April/ Dec. 1994**
2. Review of Pol. Proton Accel., Progress	**March 1995**
RHIC Spin Physics Review	**June 1995**
RIKEN/BNL MoU signed	**Sept. 25, 1995**
RIKEN Japan Funding for Accel. (10M$) and PHENIX Detector (10M$)	**1995 – 1999**
Final Report of Polarization Measurement Working Group	**July 31, 1996**
First Helical Dipole Prototype Complete	**October 1996**
Second Helical Dipole Prototype Complete	**January 1997**
3. Review of Pol. Proton Accel., Progress	**February 1997**
First Full Helical Dipole Complete	**May 1998**
RHIC Completion	**June 1999**
2 Snakes and one Polarimeter Installed	**September 1999**
First Polarized Beam in RHIC	**> October 1999**
All Spin Rot./Snakes and Polarimeters Inst.	**September 2000**
First Spin Physics Run in RHIC	**> October 2000**