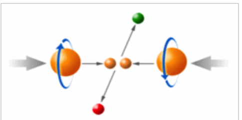

Physics of Polarized Protons/Electrons in Accelerators

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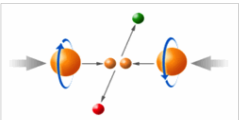
Outline

- Introduction
  - What is polarized proton/electron beam?
  - Why high energy polarized beams?
- Physics of polarized protons in accelerators
  - Spin dynamics
  - Challenges in accelerating polarized protons to high energy
  - Brief history of high energy polarized proton beams development
- Brief introduction of polarized electrons in accelerators
- Summary



Polarized Proton/electron Beam

- Proton/electron, as spin half particle
  - **Spin vector**

$$S = <\psi|\sigma|\psi>; \quad \text{Here, } \psi \text{ is spin state of the particle}$$

  - **Intrinsic magnetic moment**

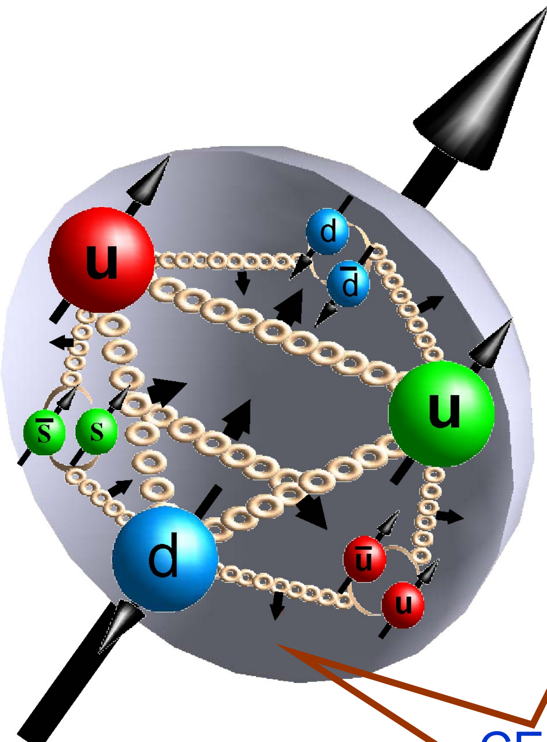
$$\vec{\mu} = \frac{g}{2}\frac{q}{m}\vec{S}; \qquad \text{and } \frac{dS}{dt} = \vec{\mu} \times \vec{B} \text{ in the particle's frame}$$

- Polarized proton/electron beam
  - **Beam polarization**, with $N_{\pm}$ is the number of particles in the state of $\psi+$(up state) and $\psi-$(down state), respectively

$$P = \frac{N_{+} - N_{-}}{N_{+} + N_{-}}$$

Why Polarized Beams?

- Study proton spin structure



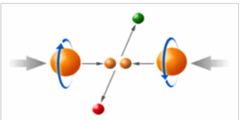
Spin contribution from quarks

Spin contribution from all the gluons

$$S = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L_q + L_g$$

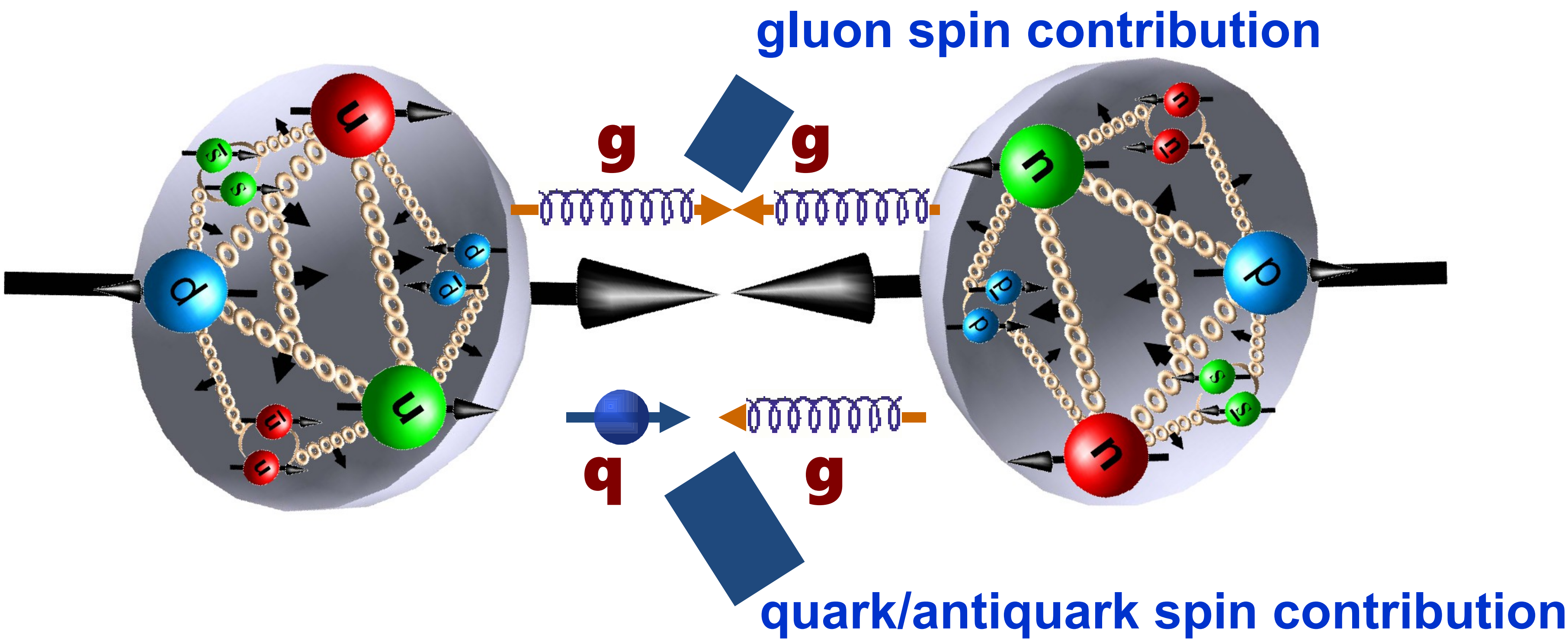
Orbital angular momentum of quarks and gluons

CERN EMC and SLAC SMC:
ΔΣ ~ 20%!



Why high energy polarized protons?

High energy proton proton collisions:
gluon gluon collision and gluon quark collision



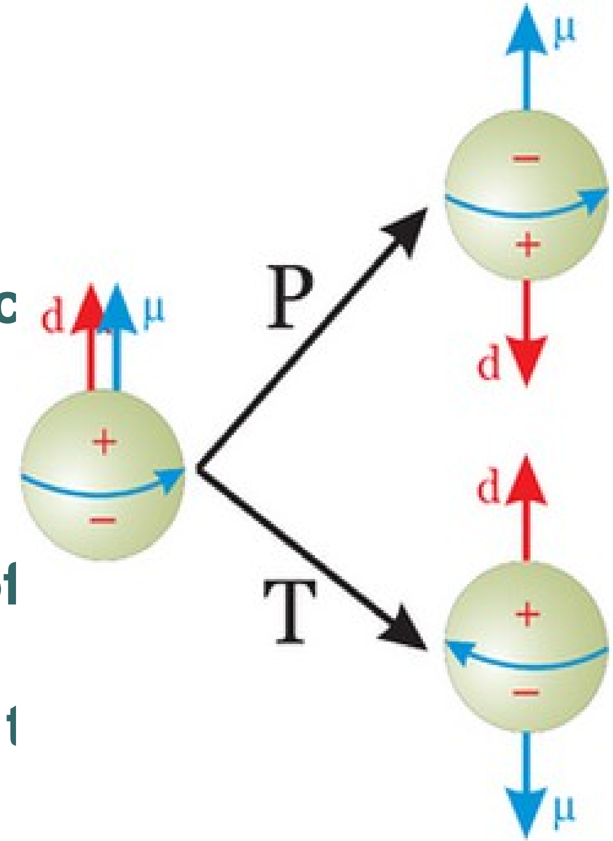
Why Polarized Beams?

- Search for Electric Dipole Moment

Describes the positive and negative charge distribution inside a particle

It aligns along the spin axis of the partic and violates both Parity and Time Reversal.

Hence, significant EDM measurement of fundamental particles is an effective probe of CP-violation, could be the key t explain the asymmetry between matter and antimatter



“Deuteron & proton EDM Experiment”, Yannis K. Semertzidis, BNL

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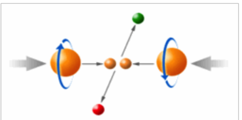

Spin motion in a circular accelerator

<u>Thomas BMT Equation: (1927, 1959)</u>

L. H. Thomas, Phil. Mag. 3, 1 (1927); V. Bargmann, L. Michel, V. L. Telegdi, Phys. Rev. Lett. 2, 435 (1959)

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

Spin vector in particle's rest frame

Magnetic field along the direction of the particle's velocity

Magnetic field perpendicular to the particle's velocity

- G is the anomoulous g- factor, for proton,
  G=1.7928474
- **γ:** Lorenz factor

Spin tune Q_{s}: number of precessions in one orbital revolution:

$$\mathbf{Q_s} = \mathbf{G}\gamma$$

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Spinor

- **Thomas-BMT equation**

$$\frac{d\vec{S}}{ds} = \vec{n} \times \vec{S} = [G\gamma\hat{y} + (1+G\gamma)\frac{B_x}{B\rho}\hat{x} + (1+G)\frac{B_{//}}{B\rho}\hat{s}] \times \vec{S}; \quad ds = \rho d\theta$$

$$\vec{S} = <\psi | \vec{\sigma} | \psi>; \text{ with } \psi = \begin{pmatrix} u \\ d \end{pmatrix}$$

- **Equation of motion of spinor**

$$\frac{d\psi}{d\theta} = -\frac{i}{2}(\vec{\sigma} \cdot \vec{n})\psi = -\frac{i}{2}H\psi$$

- **Spinor transfer matrix *M***

$$\psi(\theta_2) = e^{-\frac{i}{2}H(\theta_2 - \theta_1)}\psi(\theta_1) = M(\theta_2, \theta_1)\psi(\theta_1)$$

Spinor Transfer Matrix

- **A dipole**

$$n = G\gamma\hat{y} \quad M(\theta_2,\theta_1) = e^{-iG\gamma(\theta_2-\theta_1)\sigma_3/2}$$

- **A thin quadrupole**

$$\vec{n} = (1+G\gamma)(\frac{\partial B_x}{\partial y} l / B\rho) y\hat{x} = (1+G\gamma)kly\hat{x} \qquad M = e^{-i(1+G\gamma)kly\sigma_1/2}$$

- **A spin rotator which rotates spin vector by a precession of χ around an axis of $\hat{n}$,** $M = e^{-i\chi\hat{n}\cdot\hat{\sigma}}$
- **One turn matrix of a ring with a localized spin rotation at θ**

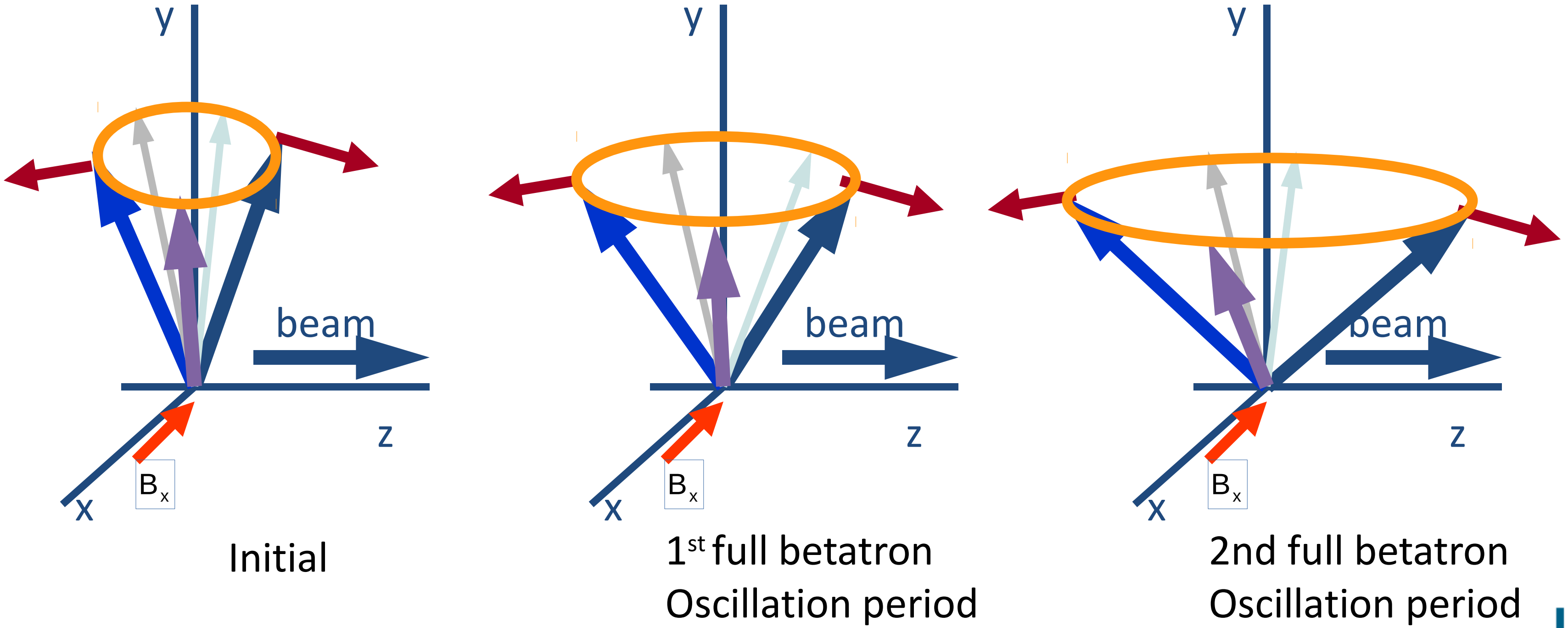
$$\mathrm{OTM} = e^{-\frac{i}{2}2\pi Q_s \hat{n}_{co}\vec{\sigma}} = e^{-\frac{i}{2}G\gamma(2\pi-\theta)\sigma_3} e^{-\frac{i}{2}\chi\hat{n}_e\cdot\vec{\sigma}} e^{-\frac{i}{2}G\gamma\theta\sigma_3}$$

Spin tune becomes,

$$\cos\pi Q_s = \cos G\gamma\pi\cos\frac{\chi}{2} - \sin G\gamma\pi\sin\frac{\chi}{2}(\hat{n}_e\cdot\hat{y})$$

Depolarizing mechanism in a synchrotron

- horizontal field kicks the spin vector away from its vertical direction, and can lead to polarization loss
  - dipole errors, misaligned qadrupoles, imperfect orbits
  - betatron oscillations
  - other multipole magnetic fields
  - other sources



Depolarizing Resonance

- **Imperfection resonance:**
  - Source: dipole errors, quadrupole misalignments
  - Resonance location:

    Gγ = k, k is an integer
  - Resonance strength:
    - Proportional to the size of the vertical closed orbit distortion

❖ For protons, imperfection spin resonances are spaced by 523 MeV

❖ Between RHIC injection and 250 GeV, a total of 432 imperfection resonances

Depolarizing Resonance

Intrinsic resonance:

- Focusing field due to the intrinsic betatron oscillation
- Location:

$$G\gamma = kP \pm Q_y$$

P: super periodicity of the accelerator,

Q_y : vertical betatron tune

- Resonance strength:
  - Proportional to the size of the betatron oscillation
  - When crossing an isolated intrinsic resonance, the larger the beam is, the more the polarization loss is. This is also known as the polarization profile

Stable Spin Direction

- an invariant direction that spin vector aligns to when the particle returns back to the same phase space, i.e.

$$\hat{n}_{co}\left(I_z, \phi_z, \theta\right) = \hat{n}_{co}\left(I_z, \phi_z + 2\pi, \theta\right)$$

Here, I_z and ϕ_z are the 6-D phase-space coordinates.

- For an ideal machine, i.e. the closed orbit is zero, the stable spin direction is along the direction of the guiding field

- The stable spin direction $\hat{n}_0$ for a particle on the closed orbit is the eigenvector of its one turn spin transfer matrix

$$M(\theta + 2\pi, \theta) = e^{-\frac{i}{2} 2\pi Q_s \hat{n}_0 \cdot \vec{\sigma}}$$

Stable Spin Direction

- $\hat{n}_{co}(I_z, \phi_z, \theta)$ is function of phase space

- For particles on closed orbit, stable spin direction can be computed through one-turn spin transfer matrix. $\hat{n}_{co}$ is also know as $\hat{n}_0$

- For particles not on closed orbit, since in general the betatron tune is non-integer, the stable spin direction is no longer the eigen vector of one turn spin transfer matrix. Algorithms like SODOM[1,2], SLIM[3], SMILE[4] were developed to compute the stable spin direction

[1] K. Yokoya, Non-perturbative calcuation of equilibrium polarization of stored electron beams, KEK Report 92-6, 1992
[2] K. Yokoya, An Algorithm for Calculating the Spin Tune in Accelerators, DESY 99-006, 1999
[3] A. Chao, Nucl. Instr. Meth. 29 (1981) 180
[4] S. R. Mane, Phys. Rev. A36 (1987) 149

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Stable Spin Direction

- $\hat{n}_{co}(I_z, \phi_z, \theta)$ is function of phase space

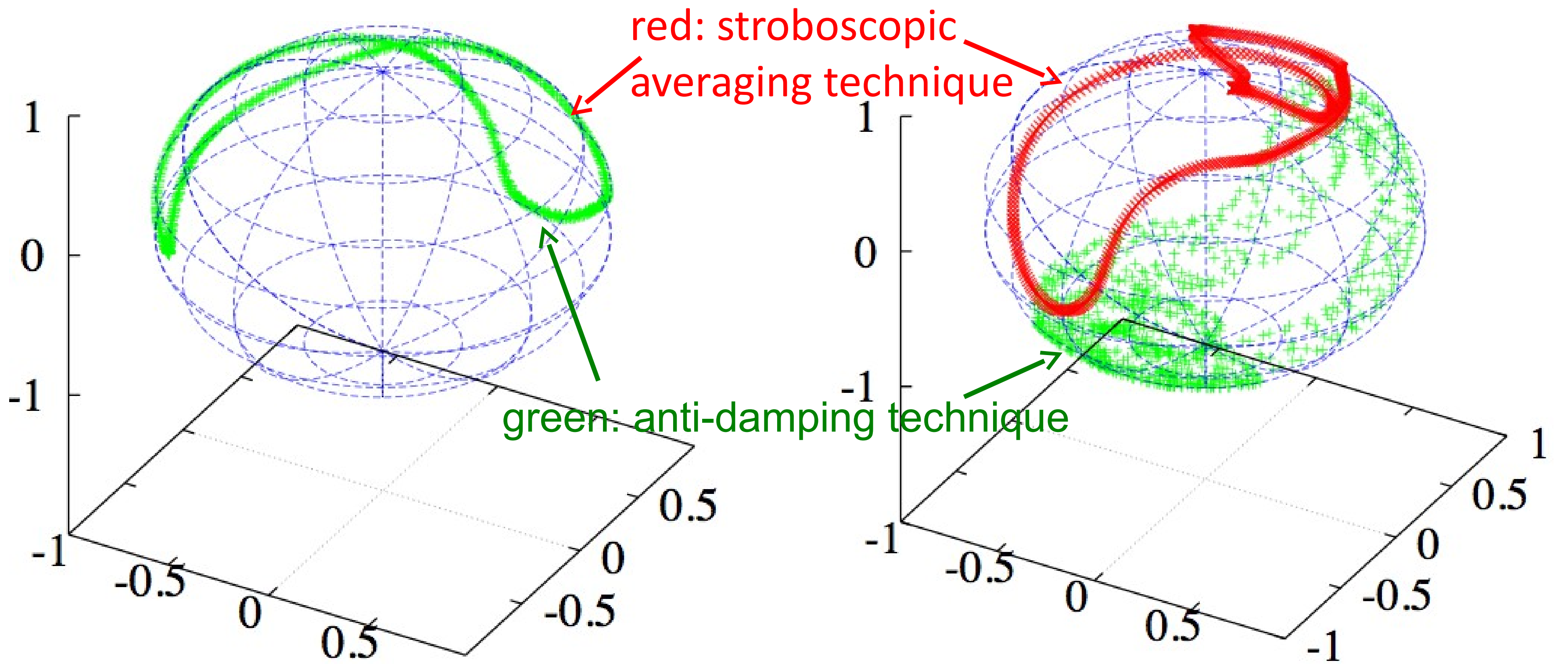
- It can also be calculated numerically with stroboscopic averaging, a technique developed by Heinemann, Hoffstaetter from DESY[1]

- One can also compute $\hat{n}_{co}$ through numerical tracking with adiabatic anti-damping technique, i.e. populate particles on closed orbit first with their spin vectors aligned with $\hat{n}_0$. The particles are then adiabatically excited to the phase space during which spin vector should follow the stable spin direction as long as it is far from a spin resonance

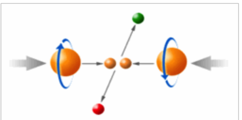
[1] K. Heinemann, G. H. Hoffstatter, Tracking Algorithm for the Stable Spin Polarization Field in Storage Rings using Stroboscopic Averaging, PRE, Vol. 54, Number 4

Stable Spin Direction

- **Particles on a 20π mm-mrad phase space**
- **Particles on a 40π mm-mrad phase space**



D. P. Barber, M. Vogt, The Amplitude Dependent Spin Tune and The Invariant Spin Field in High Energy Proton Accelerators, Proceedings of EPAC98



Resonance Crossing

- **In a planar ring, for a single isolated resonance at**

$$G\gamma = K$$

  - **Frossiart-Stora formula[1]: 1960**

$$p_f = p_i(2e^{-\pi|\varepsilon_K|^2/\alpha} - 1) \quad \text{with} \quad \alpha = d(G\gamma)/d\theta$$

and resonance strength is

$$\varepsilon_K = \frac{1}{2\pi}\int [(1+G\gamma)\frac{\Delta B_x}{B\rho} + (1+G)\frac{\Delta B_{//}}{B\rho}]e^{iK\theta}ds$$

[1] Froissart-Stora, Depolarisation d'un faisceau de protons polarises dans un synchrotron, NIM (1960)

Resonance Crossing

- **For an imperfection**

$$\varepsilon_K \propto G\gamma\sqrt{<y_{co}^2>}$$

  - No depolarization dependence on the betatron amplitude

- **For an intrinsic resonance**

$$\varepsilon_K \propto G\gamma\sqrt{\varepsilon_{y,N}/\beta\gamma}$$

  - Source of **polarization profile**, i.e. polarization depends on the particle's betatron amplitude in a beam
  - For a Gaussian beam,

$$p_f = p_i \frac{1-\pi\left|\epsilon_{K,rms}\right|^2/\alpha}{1+\pi\left|\epsilon_{K,rms}\right|^2/\alpha}$$

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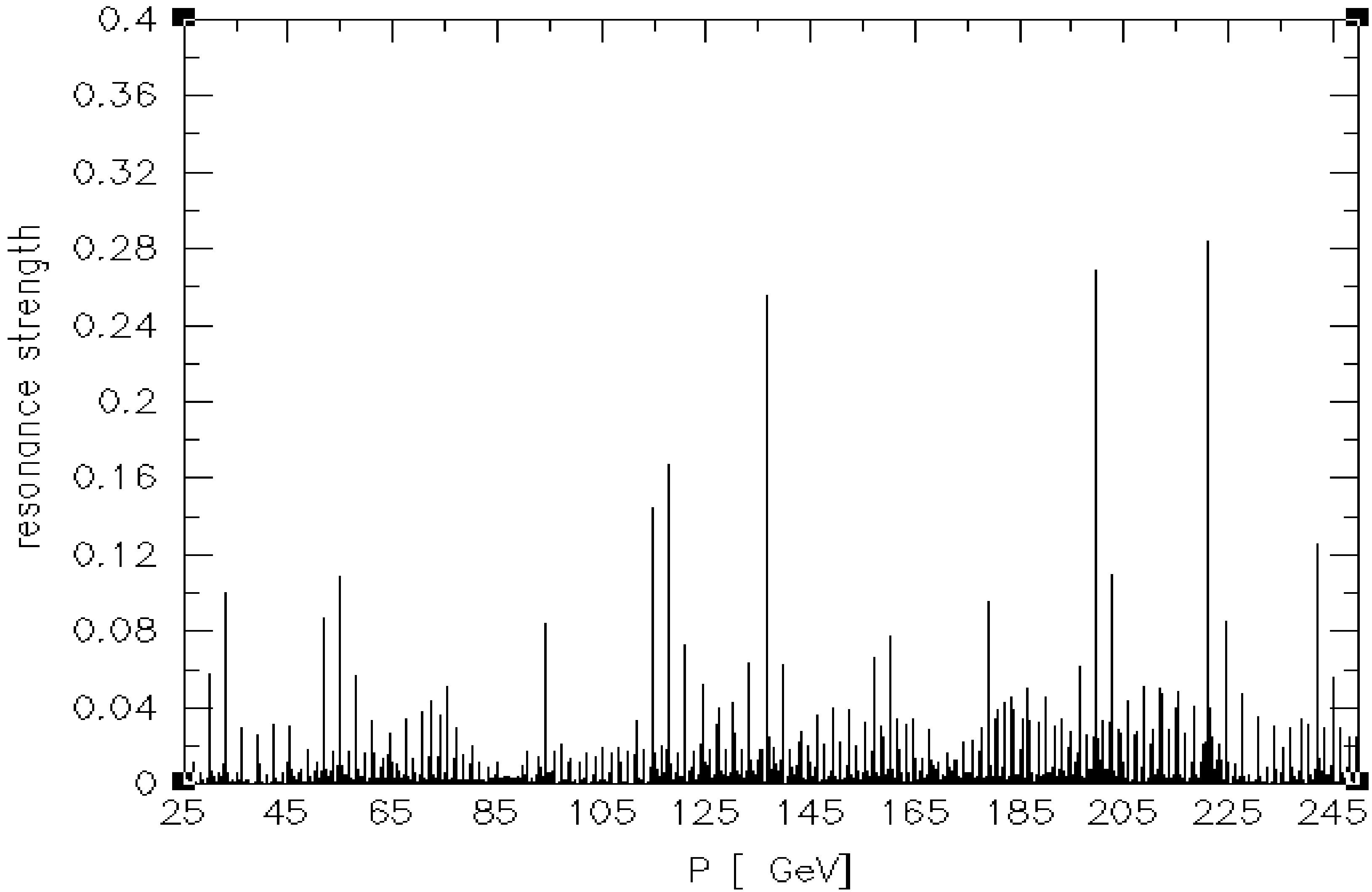
RHIC Intrinsic Spin Depolarizing Resonance



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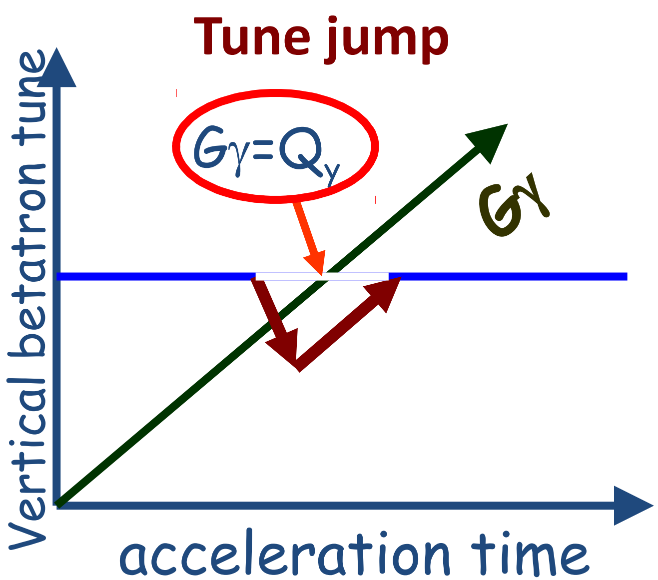
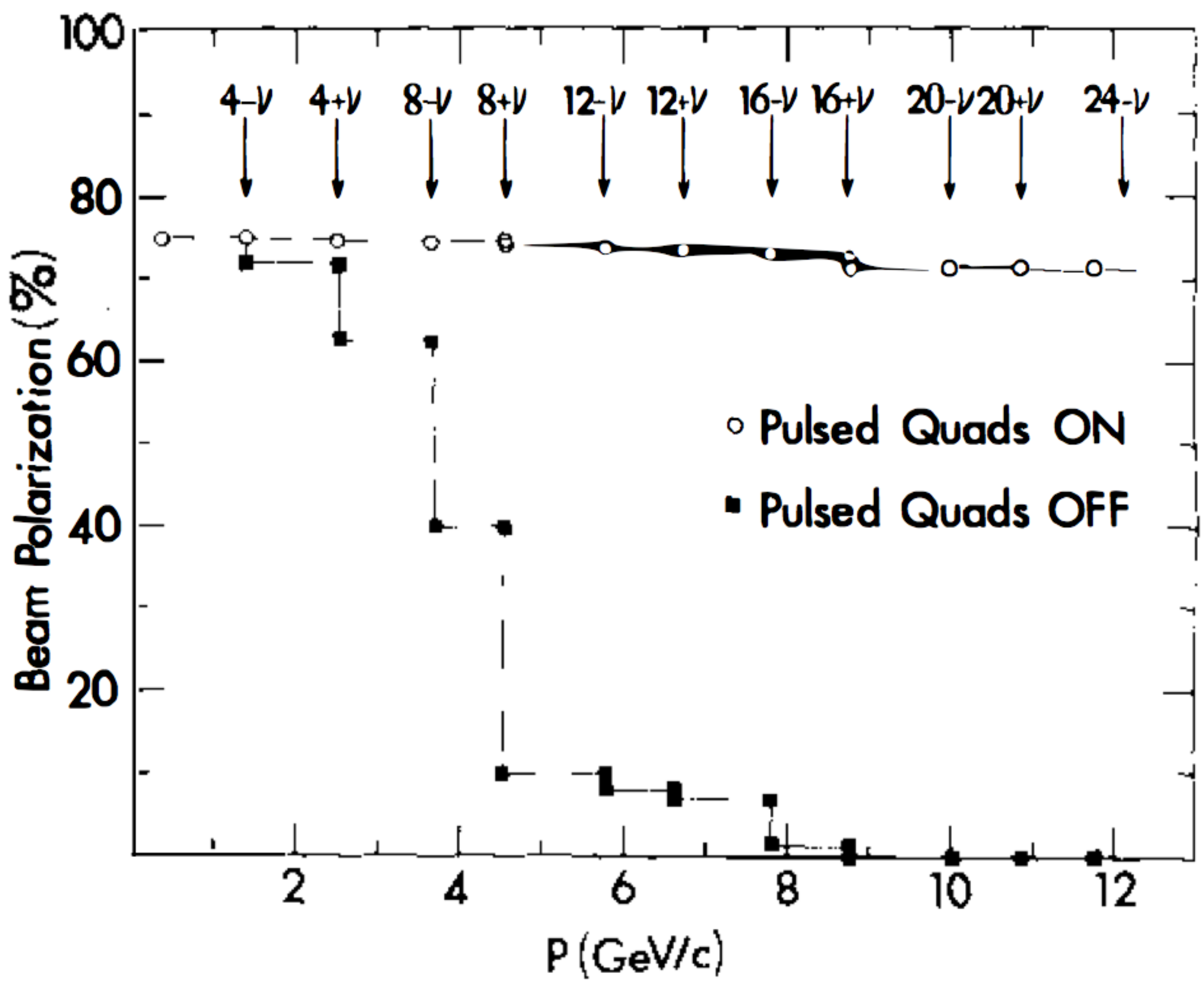
Overcoming Depolarizing Resonance

- **Harmonic orbit correction**
  - to minimize the closed orbit distortion at all imperfection resonances
  - Operationally difficult for high energy accelerators
- **Tune Jump**



- *Operationally difficult because of the number of resonances*
- *Also induces emittance blowup because of the non-adiabatic beam manipulation*

Zero Gradient Synchrotron Tune Jump



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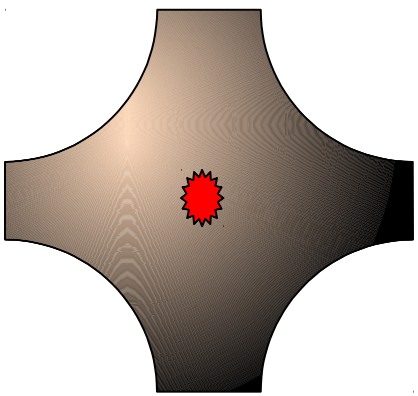
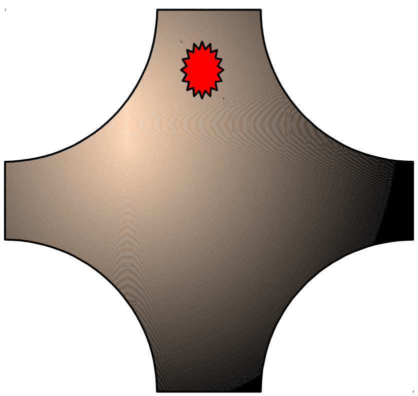
Overcome Intrinsic Resonance w. RF Dipole

- Adiabatically induces a vertical coherent betatron oscillation
  - Drive all particles to large amplitude to enhance the resonance strength
    - full spin flip with normal resonance crossing rate
  - Easy to control and avoid emittance blowup
  - Employed for the AGS polarized proton operation from 1998-2005



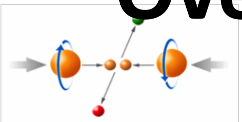
Without coherent oscillation

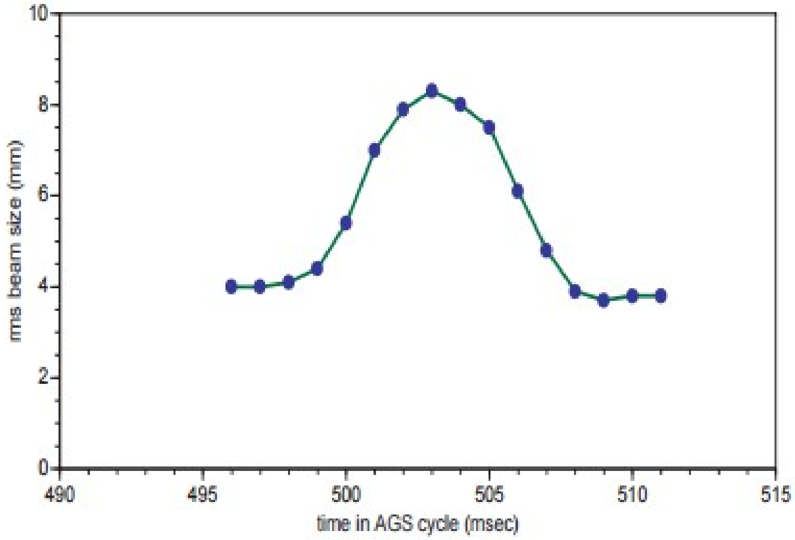


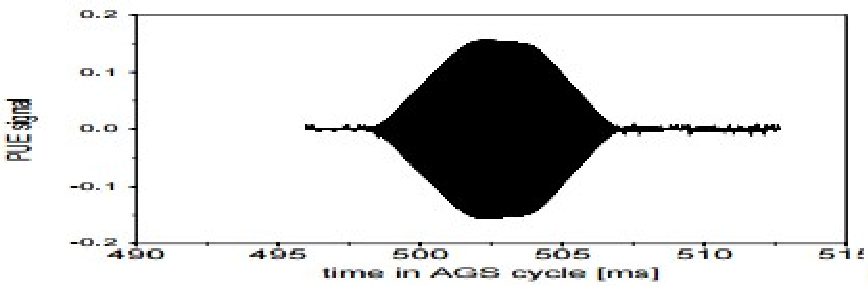
With coherent oscillation

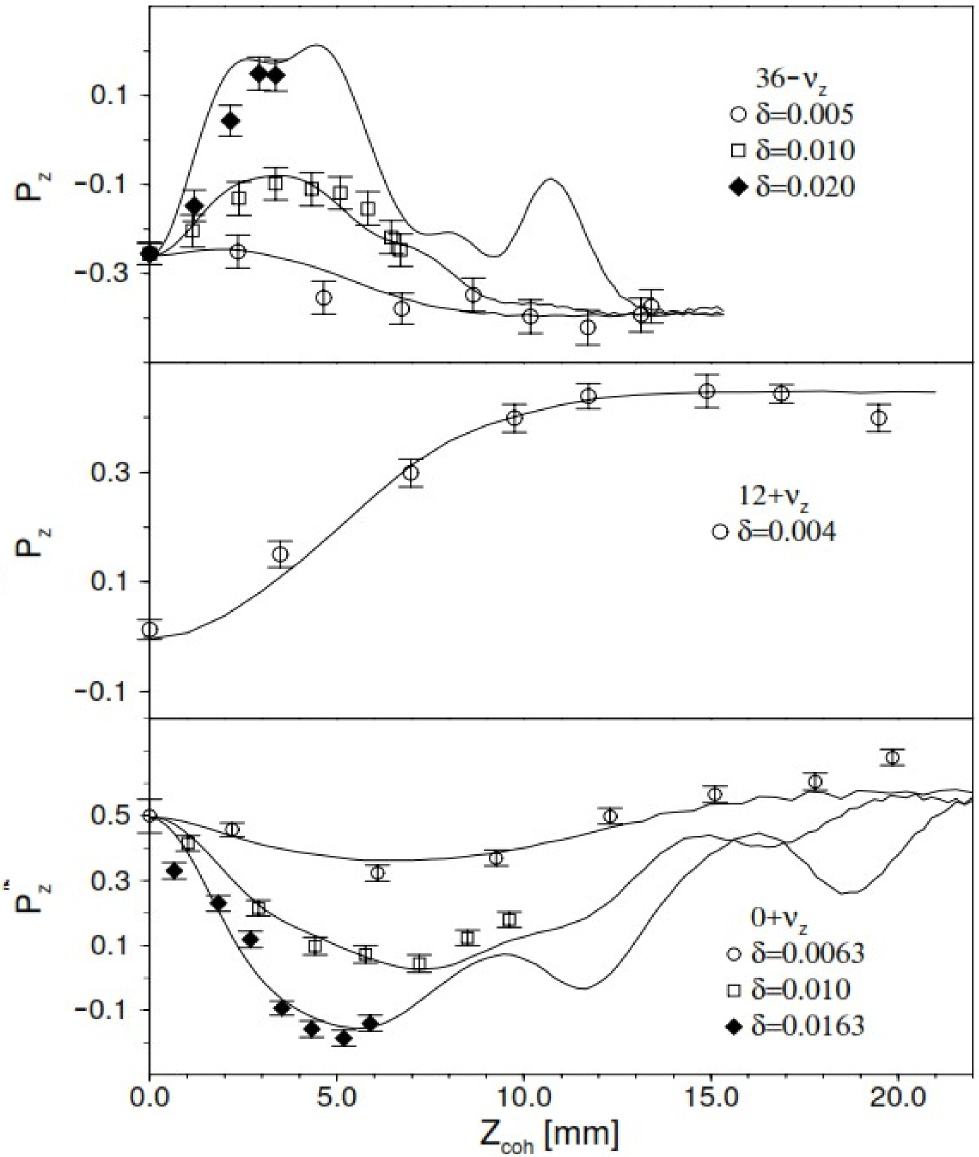
- **Can only be applied to strong intrinsic spin resonances**

Overcome Intrinsic Resonance w. RF Dipole









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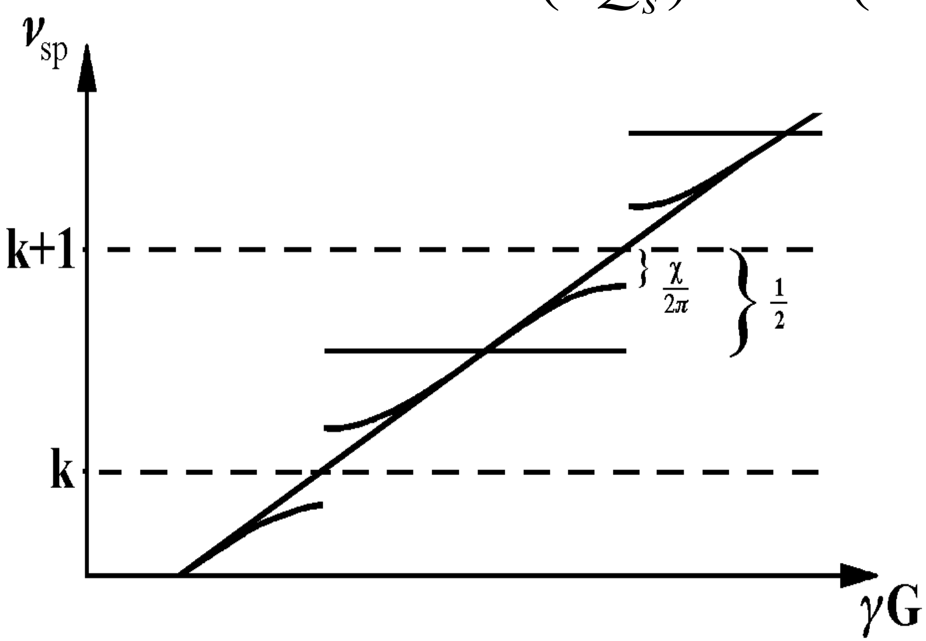
Partial Siberian Snake

- rotates spin vector by an angle of ψ<180°
- Keeps the spin tune away from integer
- Primarily for avoiding imperfection resonance
- Can be used to avoid intrinsic resonance as demonstrated at the AGS, BNL.

$$\cos(\pi Q_s) = \cos(G\gamma\pi)\cos(\frac{\psi}{2})$$



Dual partial snake configuration

- For two partial snakes apart from each other by an angle of ϑ, spin tune the becomes

$$\cos\pi Q_s = \cos G\gamma\pi \cos\frac{\psi_1}{2}\cos\frac{\psi_2}{2} - \cos(G\gamma(\pi-\theta))\sin\frac{\psi_1}{2}\sin\frac{\psi_2}{2}$$

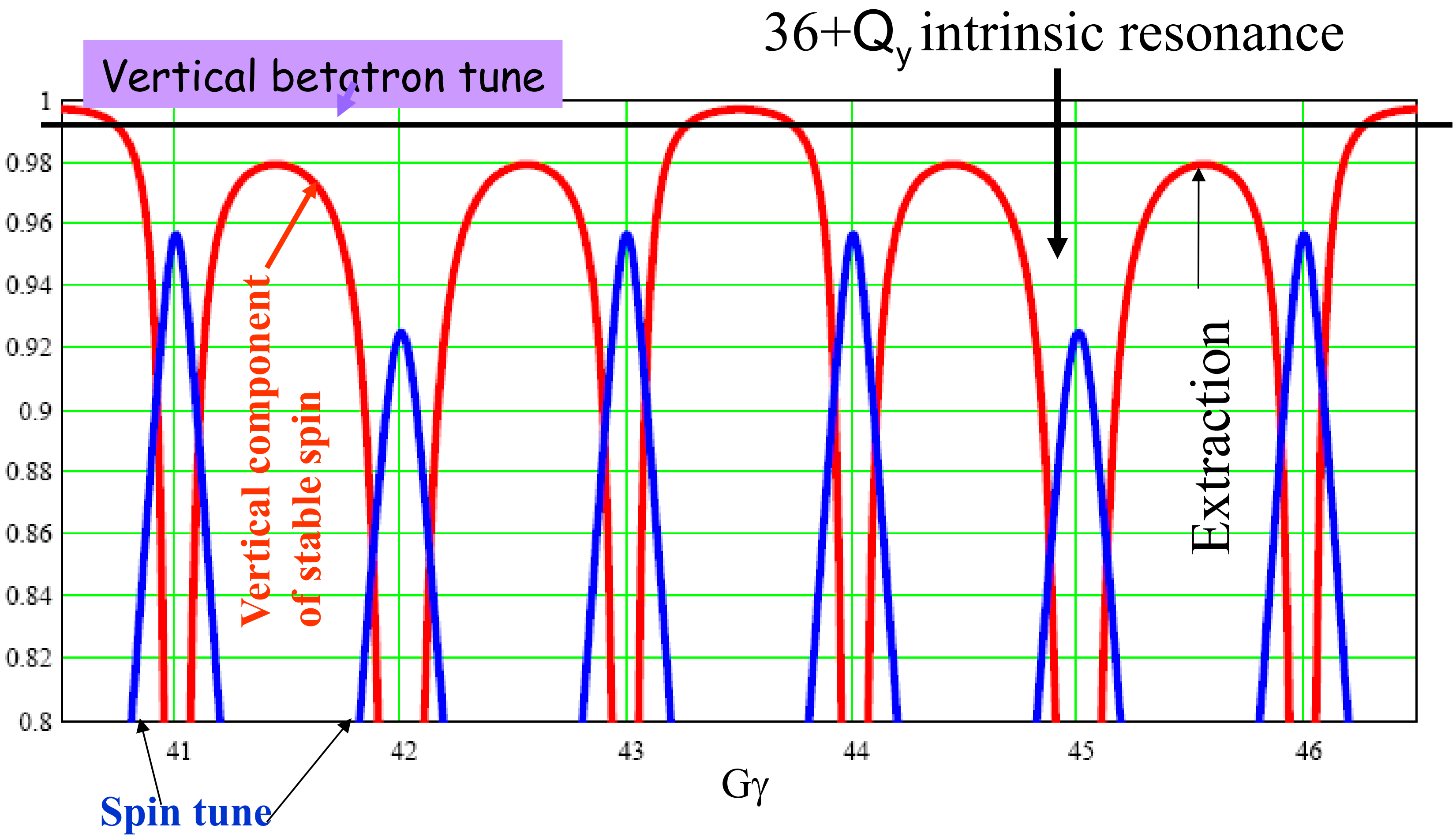
- Spin tune is no-longer integer, and stable spin direction is also tilted away from vertical

- The distance between spin tune and integer is modulated with Int[360/ϑ]. For every integer of Int[360/ϑ] of Gγ, the two partial snakes are effectively added. This provides a larger gap between spin tune and integer, which can be wide enough to have the vertical tune inside the gap to avoid both intrinsic and imperfection resonance

- Stable spin direction is also modulated

Courtesy of T. Roser

Spin tune with two partial snakes

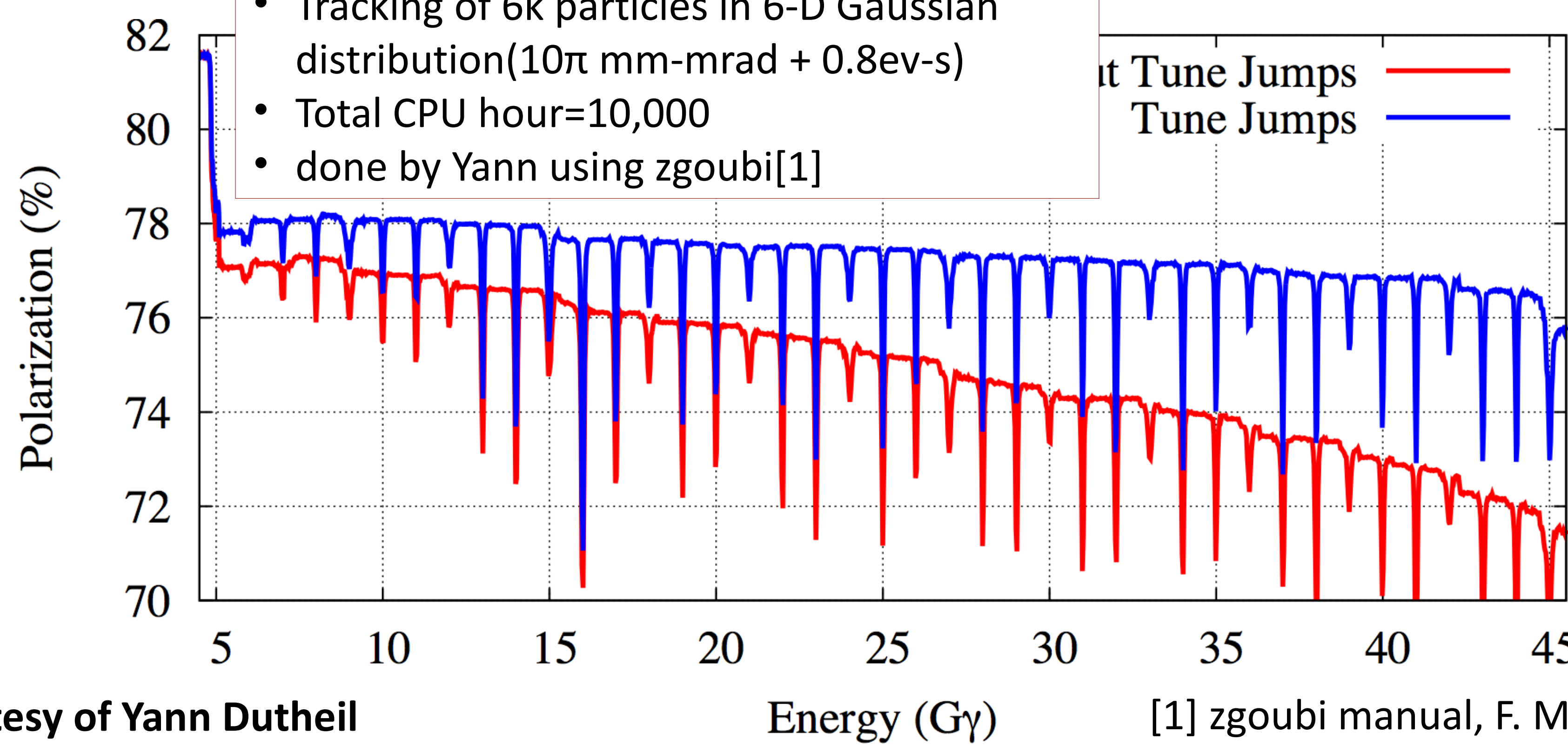


$$\cos\pi Q_s = \cos G\gamma\pi \cos\frac{\Psi_w}{2}\cos\frac{\Psi_c}{2} - \cos G\gamma\frac{\pi}{3}\sin\frac{\Psi_w}{2}\sin\frac{\Psi_c}{2}$$

Horizontal Resonance

- Stable spin direction in the presence of two partial snakes is no long along vertical direction
  - vertical fields due to horizontal betatron oscillation can drive a resonance at $G\gamma = kP \pm Qx$
  - Each is weak, and can be cured by tune jump

- Tracking of 6k particles in 6-D Gaussian distribution(10π mm-mrad + 0.8ev-s)
- Total CPU hour=10,000
- done by Yann using zgoubi[1]

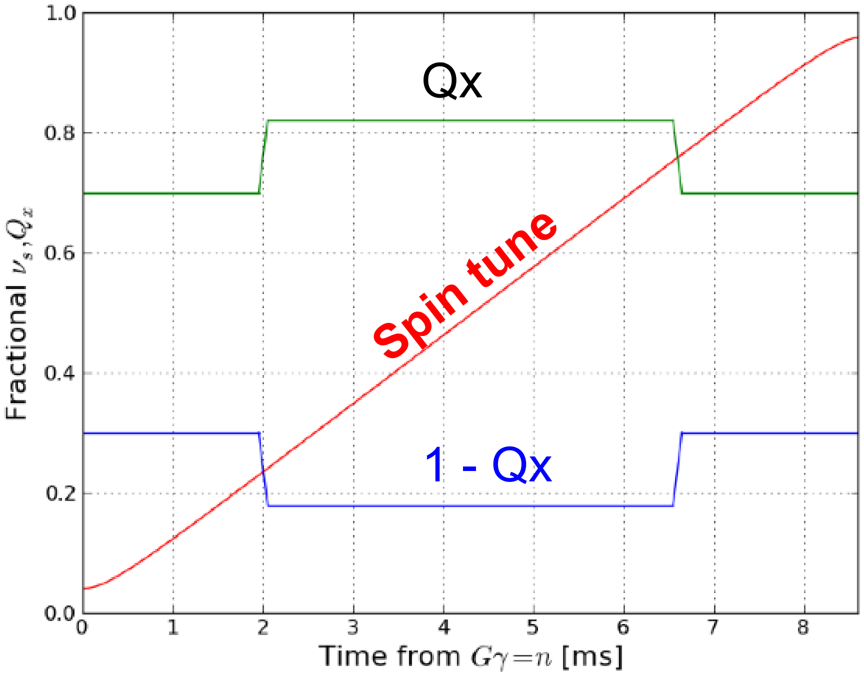


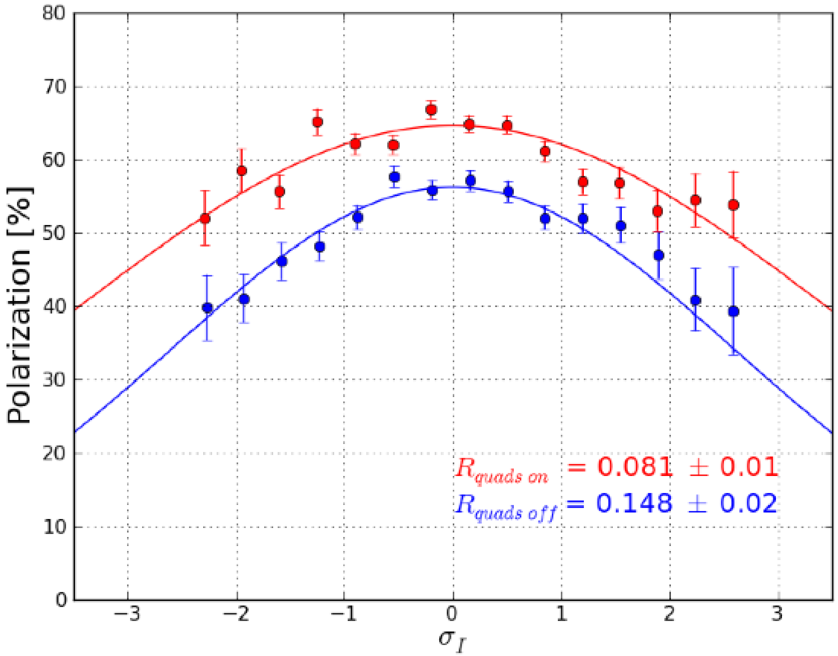
Courtesy of Yann Dutheil

[1] zgoubi manual, F. Meot

Overcome Horizontal Resonance

- AGS horizontal tune jump quadrupoles to overcome a total of 80 weak horizontal spin resonances during the acceleration

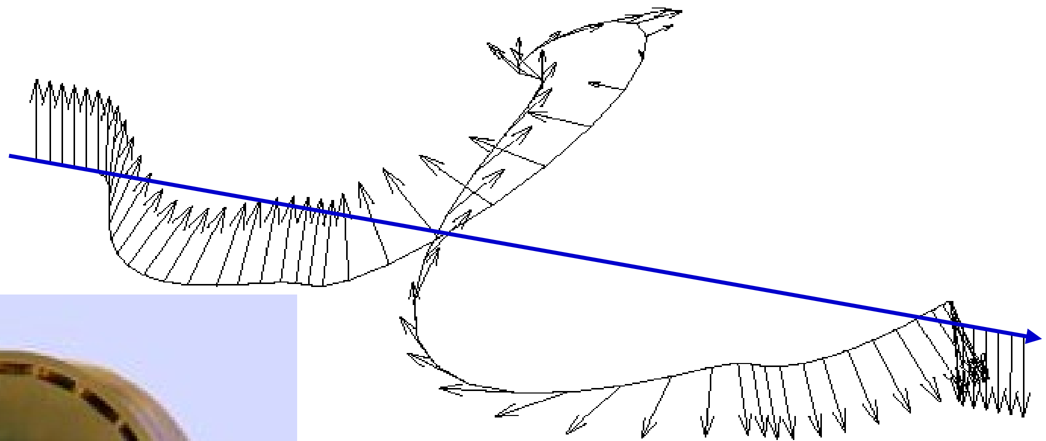


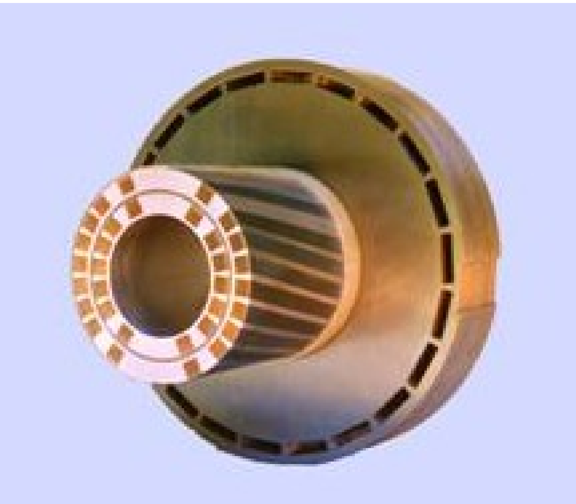


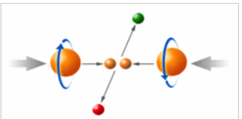
V. Schoefer *et al*, INCREASINGTHEAGSBEAMPOLARIZATIONWITH80TUNEJUMPS, Proceedings of IPAC2012, New Orleans, Louisiana, USA

Full Siberian Snake

- A magnetic device to rotate spin vector by 180°
- Invented by Derbenev and Kondratanko in 1970s [*Polarization kinematics of particles in storage rings, Ya.S. Derbenev, A.M. Kondratenko* (Novosibirsk, IYF) . Jun 1973. Published in Sov.Phys.JETP 37:968-973,1973, Zh.Eksp.Teor.Fiz 64:1918-1929]
- Keep the spin tune independent of energy







Snake Depolarization Resonance

- S. Y. Lee, Tepikian, Phys. Rev. Lett. 56 (1986) 1635
- S. R. Mane, NIM in Phys. Res. A. 587 (2008) 188-212

- Condition

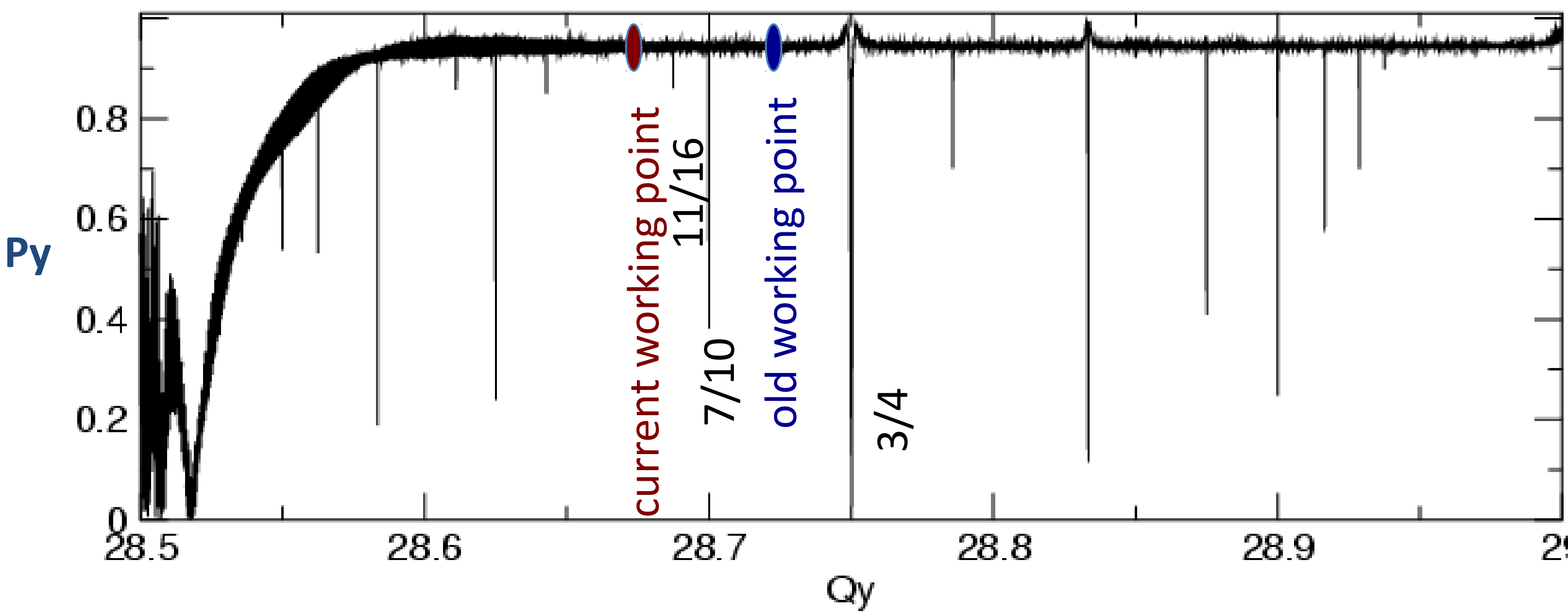
$$mQ_y = Q_s + k$$

- even order resonance

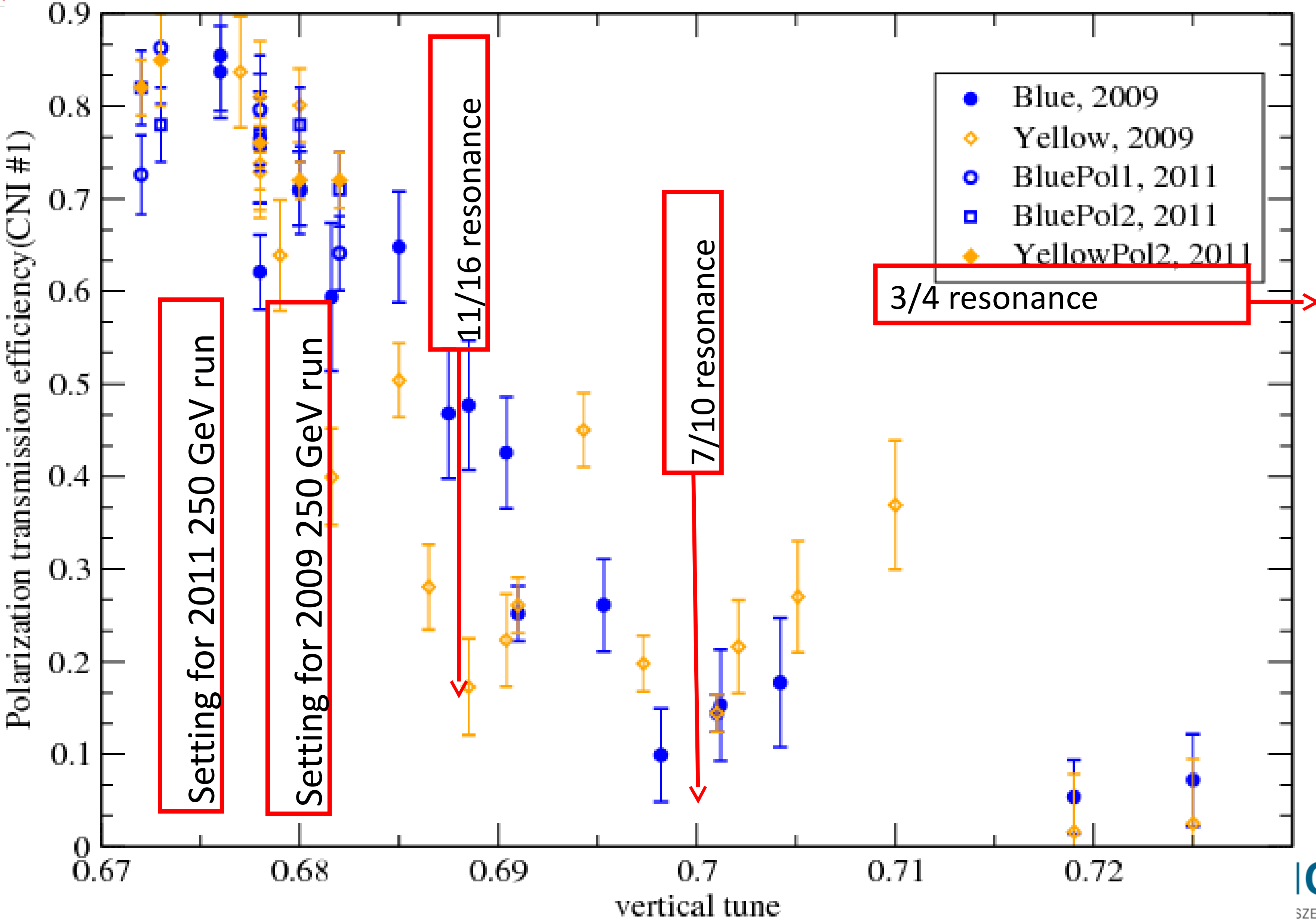
- Disappears in the two snake case if the closed orbit is perfect

- odd order resonance

- Driven by the intrinsic spin resonances



Snake resonance observed in RHIC



Avoid polarization losses due to snake resonance

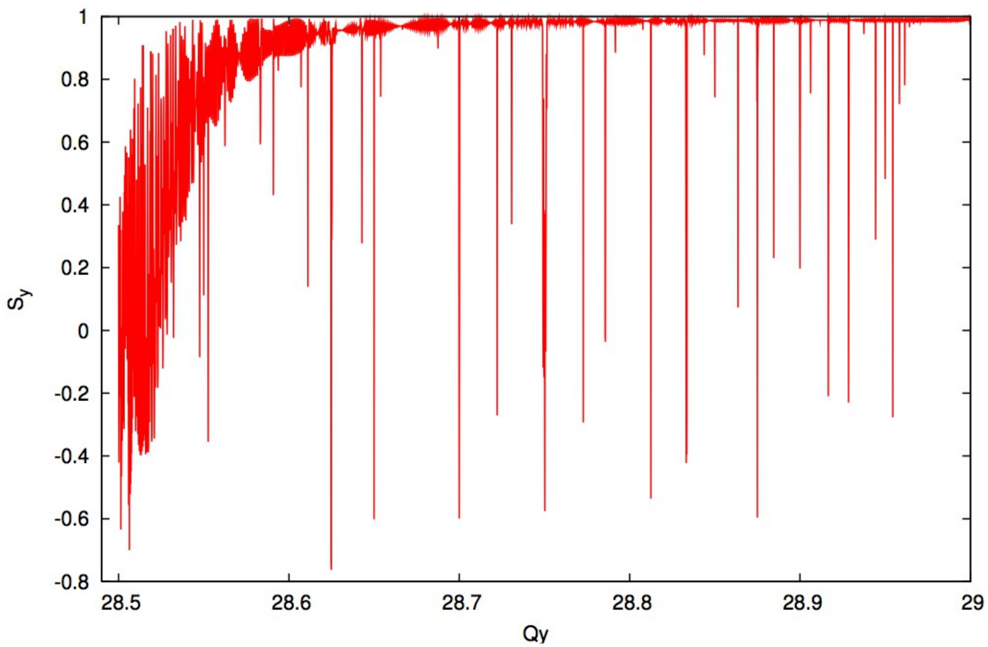
- Adequate number of snakes

$$N_{snk} > 4\left|\varepsilon_{k,\max}\right| \qquad Q_s = \sum_{k=1}^{N_{snk}} (-1)^k \phi_k$$

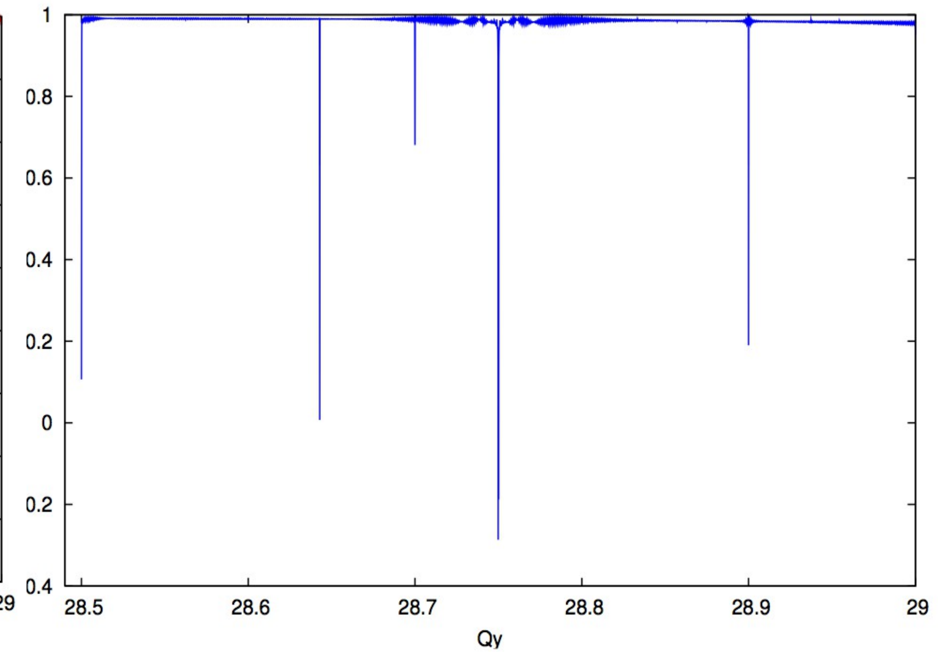
ϕ_k is the snake axis relative to the beam direction

- Minimize number of snake resonances to gain more tune spaces for operations

He-3 with dual snake



He-3 with six-snake



Avoid polarization losses due to snake resonance

- Adequate number of snakes

$$N_{snk} > 4\left|\varepsilon_{k,\max}\right| \qquad Q_s = \sum_{k=1}^{N_{snk}} (-1)^k \phi_k$$

ϕ_k is the snake axis relative to the beam direction

- Keep spin tune as close to 0.5 as possible
  - **Source of spin tune deviation**
    - Snake configuration
    - Local orbit at snakes as well as other spin rotators. For RHIC,

angle between two snake axes

$$\Delta Q_s = \frac{|\Delta\phi|}{\pi} + (1+G\gamma)\frac{\Delta\theta}{\pi}$$

H orbital angle between two snakes

  - **Source of spin tune spread**
    - momentum dependence due to local orbit at snakes
    - betatron amplitude dependence

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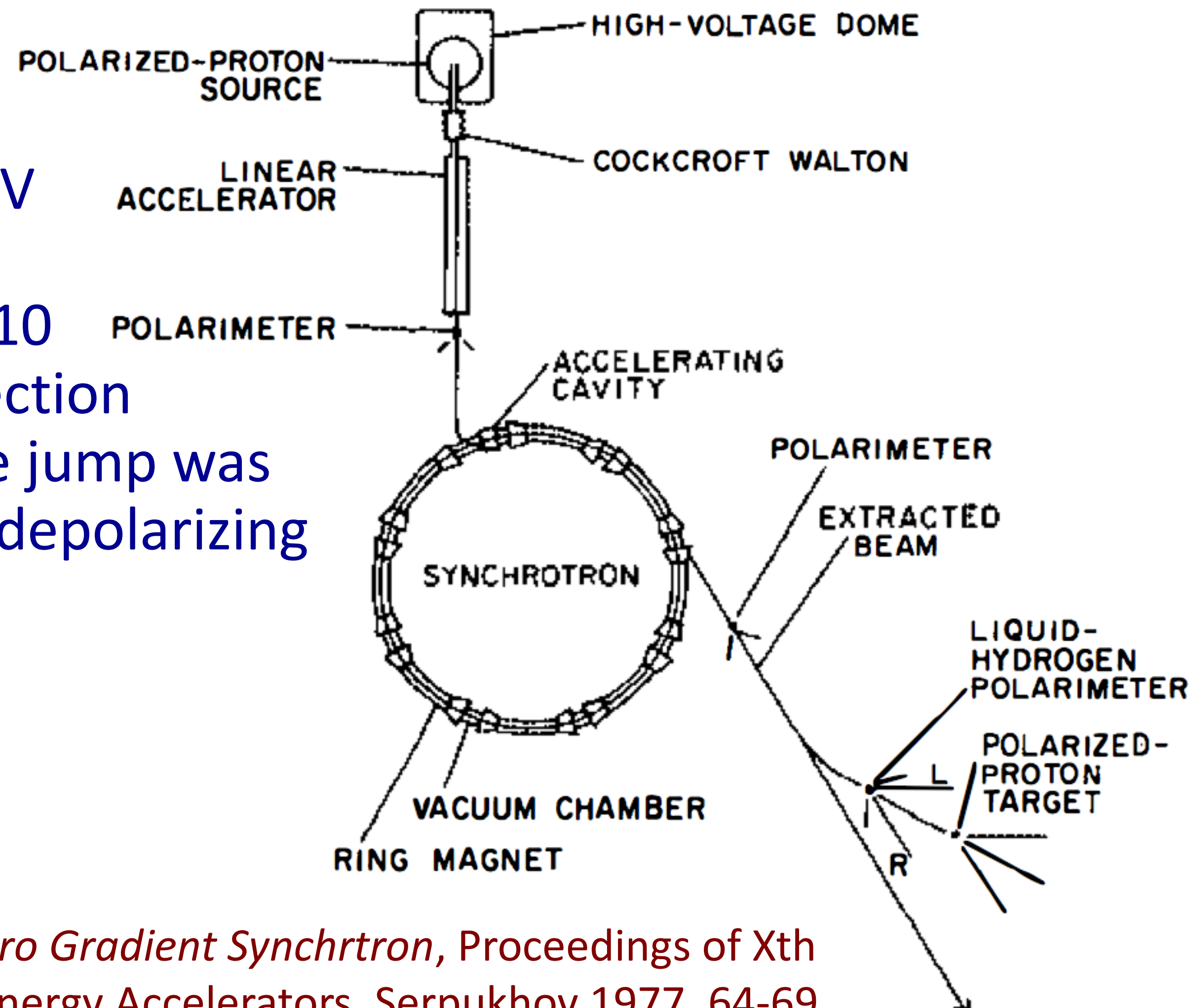
History of High Energy Polarized Proton Beams

ZGS at Argonne National Lab

- **1969~1973:**
  - proton energy 1-12 GeV
  - Polarization 71%
  - Beam intensity: 9x10^10
  - Orbital harmonic correction together with fast tune jump was used to overcome the depolarizing resonances



L. G. Ratner, *Polarized Protons at Zero Gradient Synchrtron*, Proceedings of Xth International Conference On High Energy Accelerators, Serpukhov 1977, 64-69

History of High Energy Polarized Proton Beams

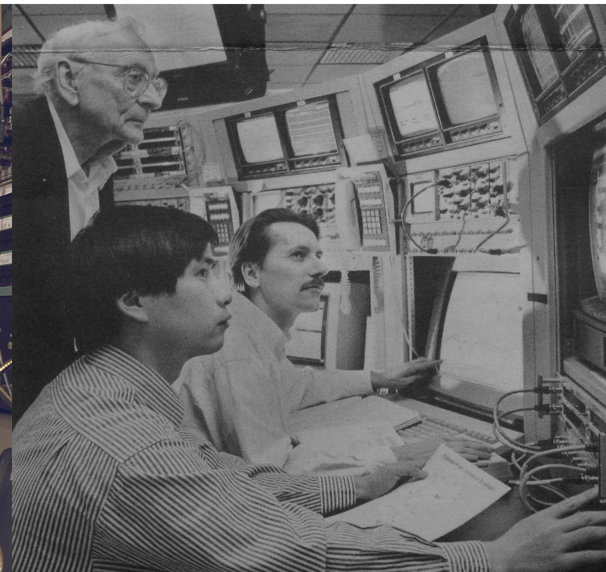
Brookhaven AGS : 1974~present

1980s

Alan Krisch and Larry Ratner in the AGS MCR.

~ 40% polarization at 22 GeV, **7 weeks** dedicated time for setup

1990s

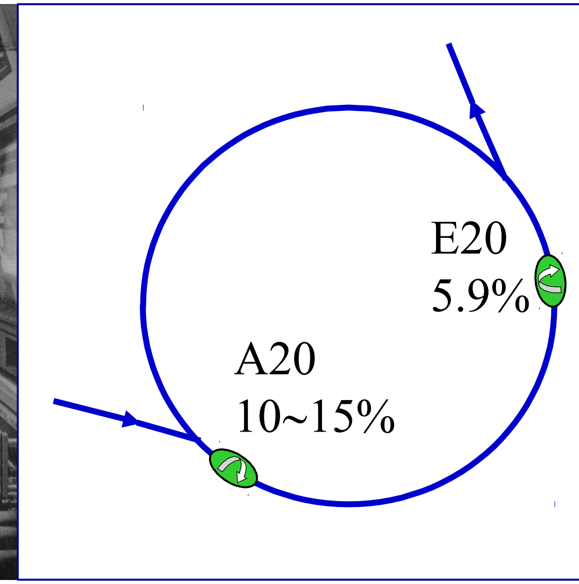


5% snake +RF dipole

~ 2 weeks setup parasitic to RHIC Ion program

50% at 24 GeV

2006 - now



6% warm helical snake +10% cold helical snake

~2 weeks setup

65%-70% at 24 GeV

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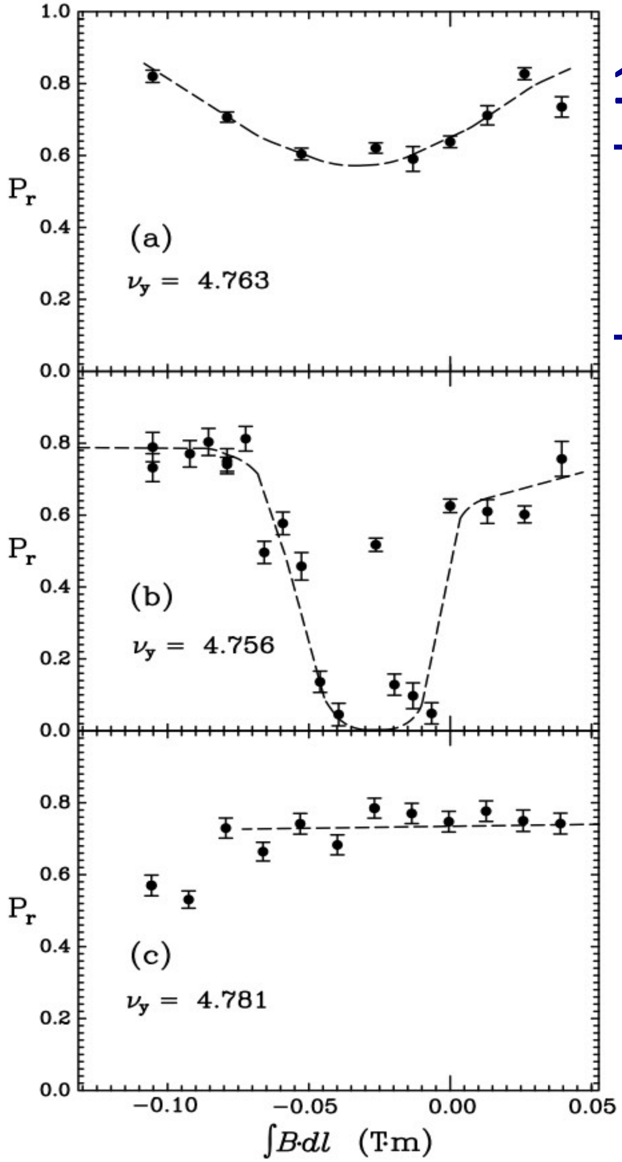
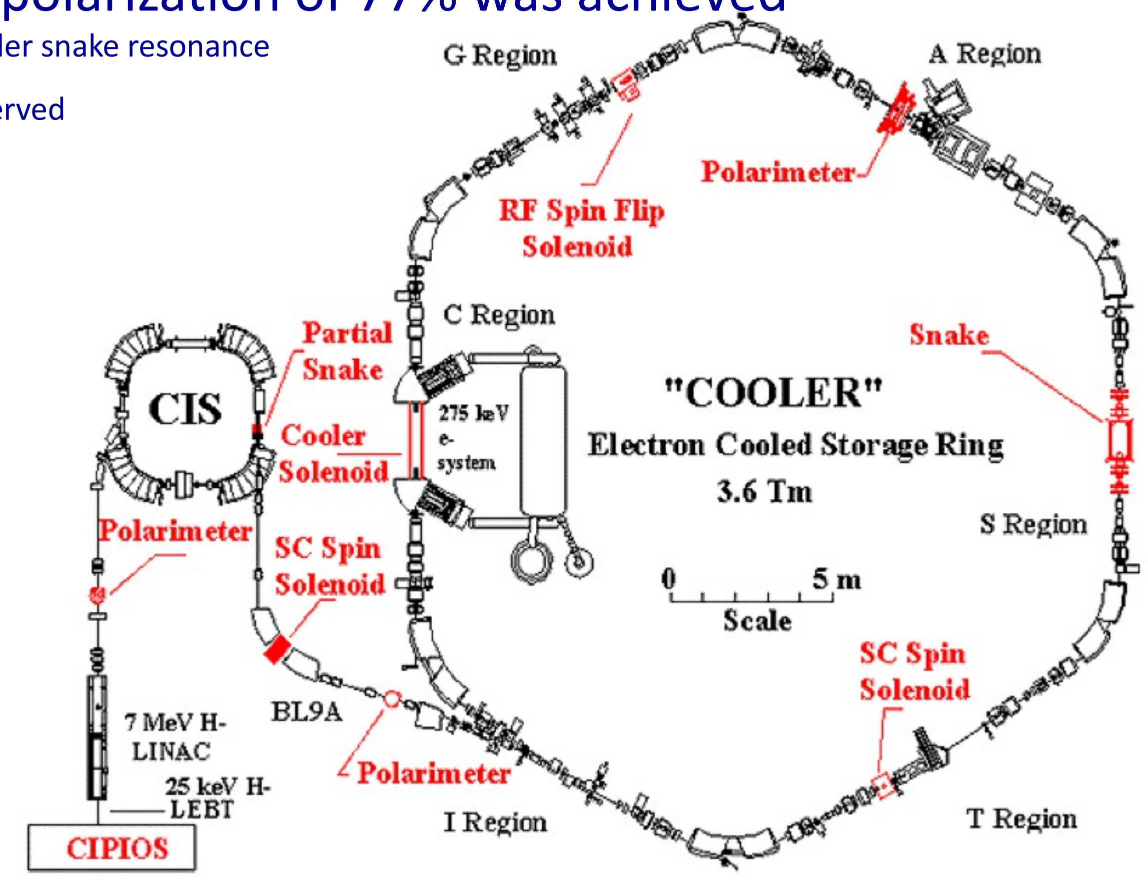
History of High Energy Polarized Proton Beams

Cooler Ring at Indiana University Cyclotron Facility



1985 -- 2002:

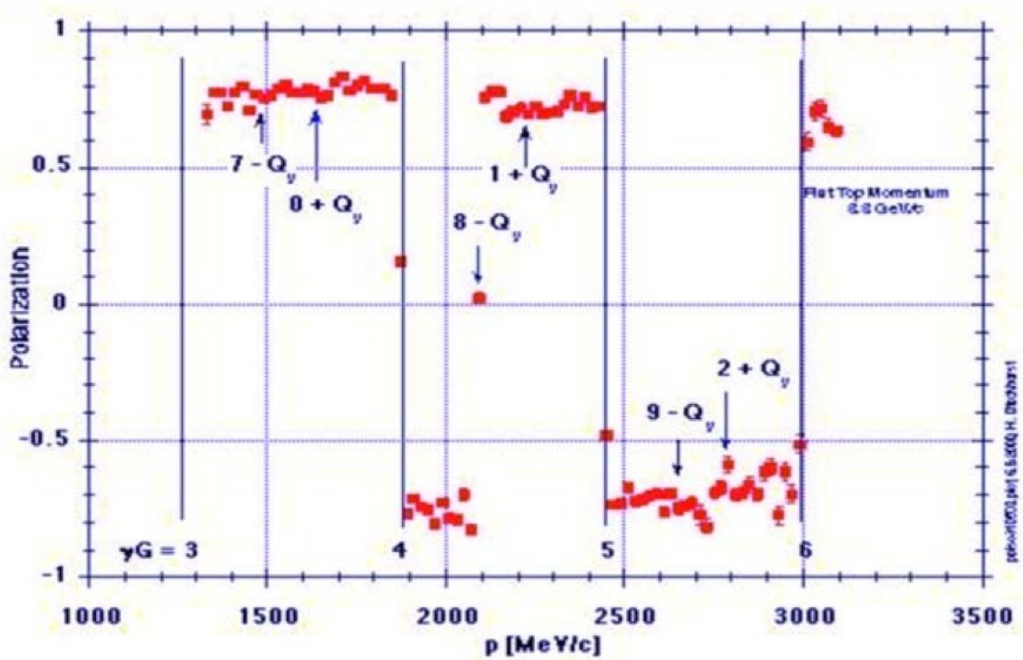
- Successfully accelerated polarized protons up to 200MeV with a super-conducting solenoid snake. Best polarization of 77% was achieved
- 2nd order snake resonance was observed

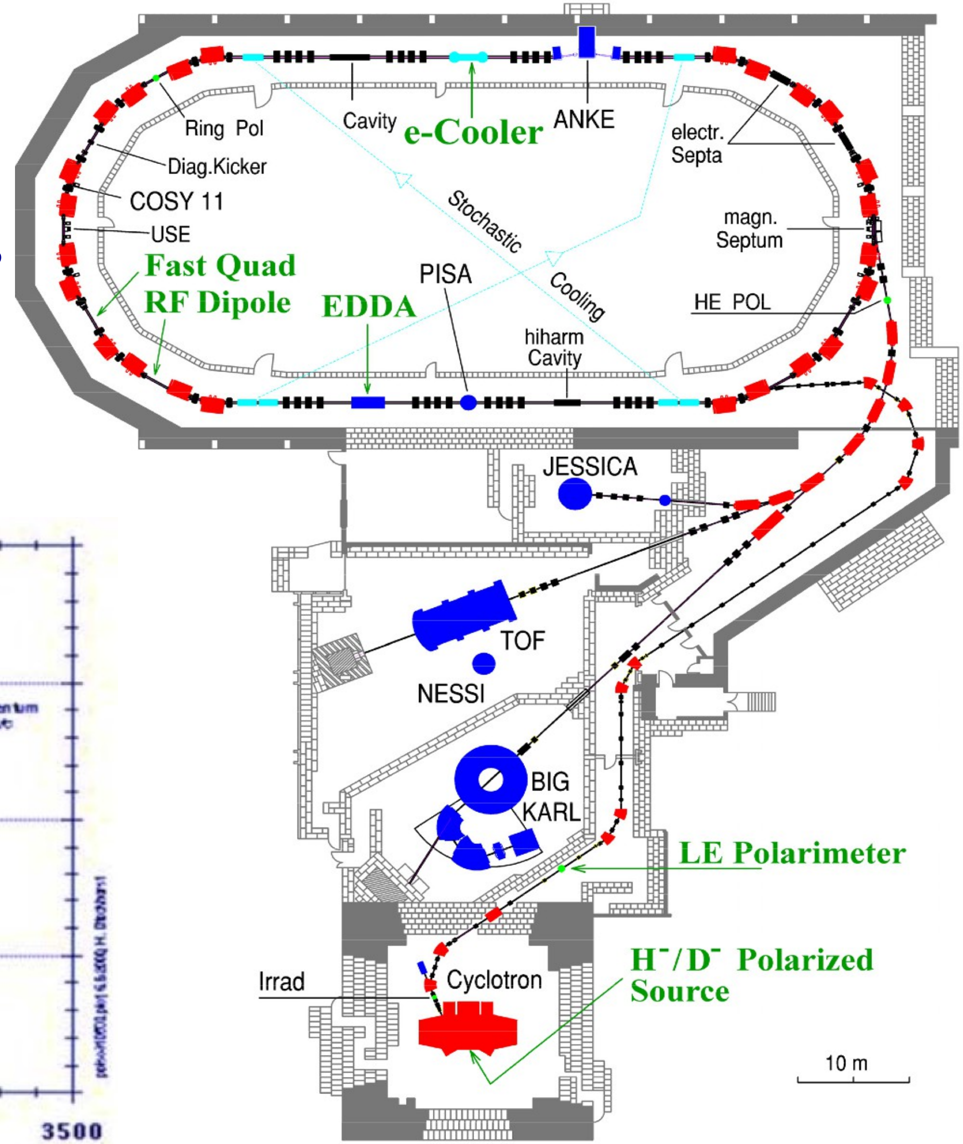


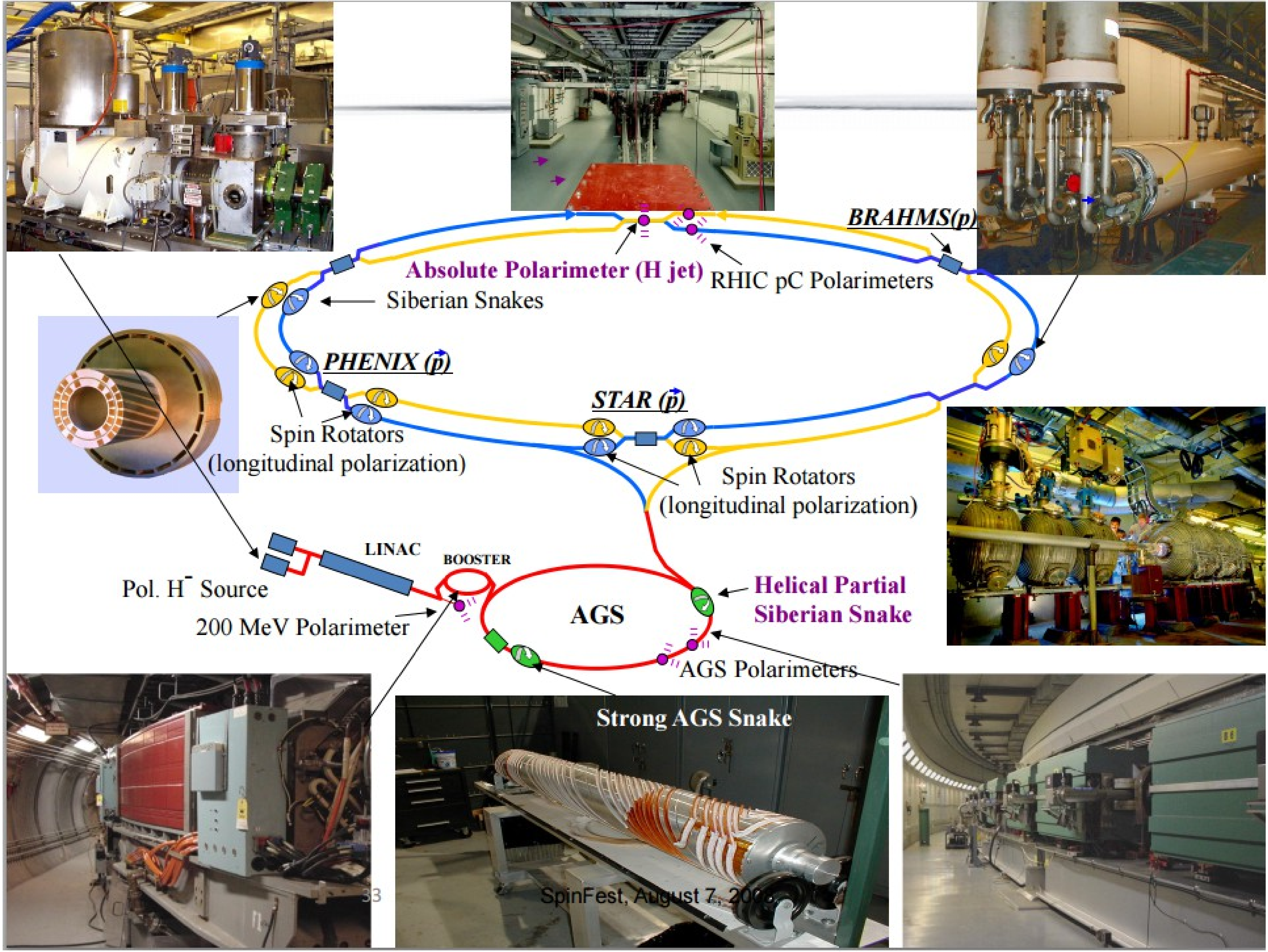
History of High Energy Polarized Proton Beams

COSY (Cooler Synchrotron ring) at Julich, Germany

- **1985 -- present:**
  - proton energy: 3 GeV/c
  - Full spin flip at each imperfection resonance with vertical correctors
  - Fast tune jump with an air-core quadrupole at each intrinsic spin resonance

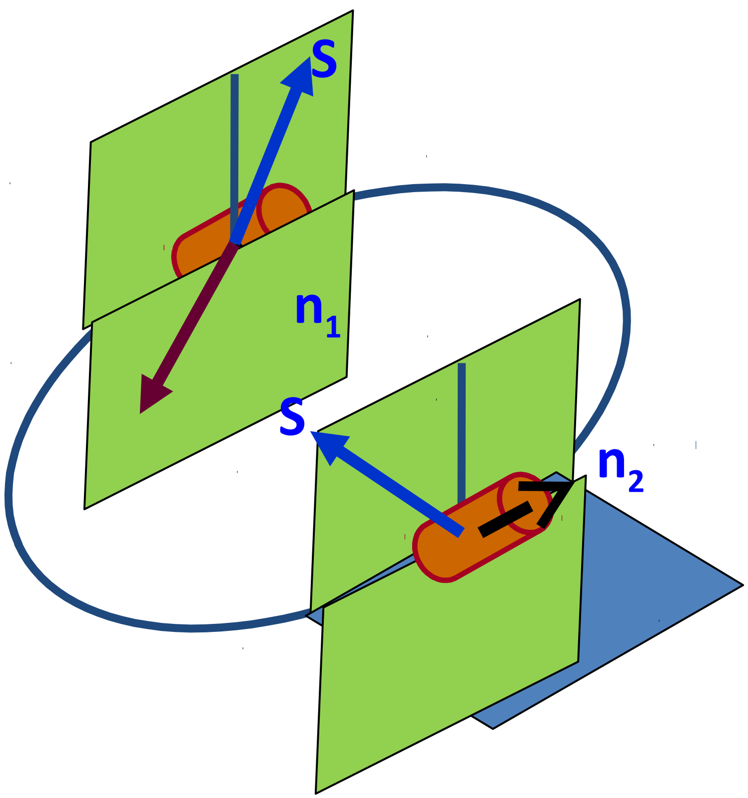




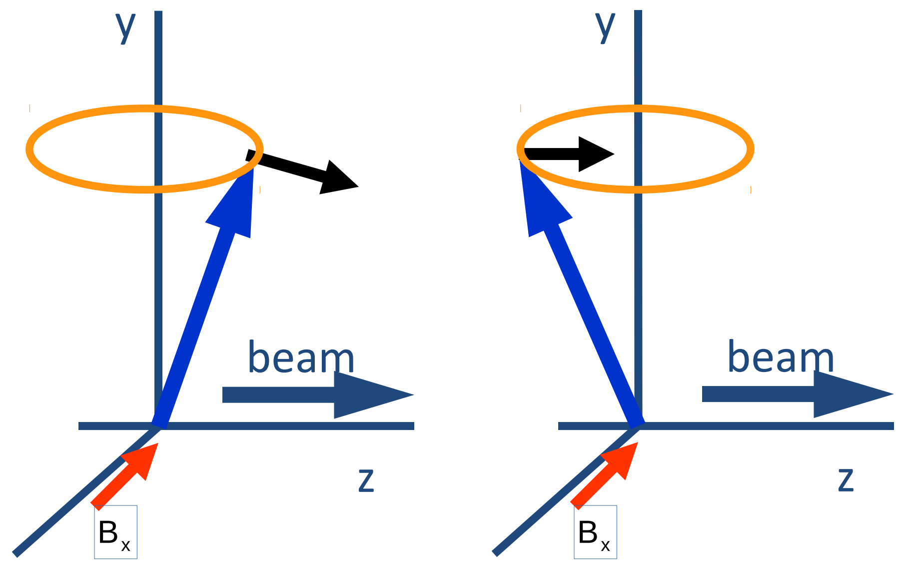

Absolute Polarimeter (H jet)
RHIC pC Polarimeters
BRAHMS(p)
Siberian Snakes
PHENIX ($\vec{p}$)
STAR ($\vec{p}$)
Spin Rotators
(longitudinal polarization)
Spin Rotators
(longitudinal polarization)
LINAC
BOOSTER
Pol. H$^-$ Source
200 MeV Polarimeter
AGS
Helical Partial
Siberian Snake
AGS Polarimeters
Strong AGS Snake

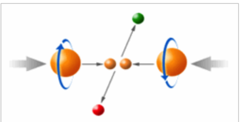
Dual Snake Set-up

- Use one or a group of snakes to make the spin tune to be at ½



- Break the coherent build-up of the perturbations on the spin vector



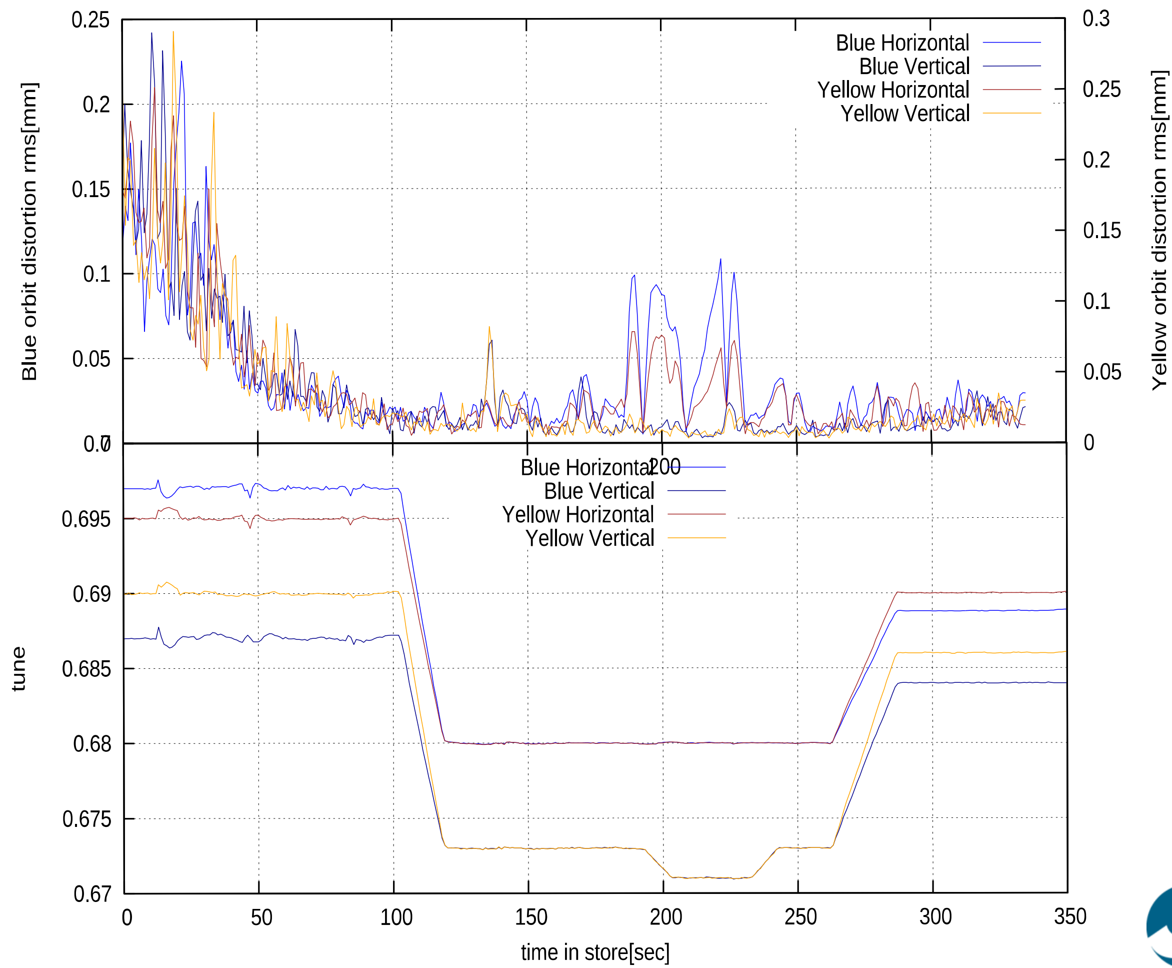


How to avoid a snake resonance?

- Adequate number of snakes
- Keep spin tune as close to 0.5 as possible
- Precise control of the vertical closed orbit
- Precise optics control
  - Choice of working point to avoid snake resonances
    - near 3rd order resonance. Current RHIC operating tune is chosen to be Qy=0.673 for acceleration beyond 100 GeV
    - near integer tune, much weaker snake resonances
      - However, it requires very robust linear optics correction
  - Minimize the linear coupling to avoid the resonance due to horizontal betatron oscillation

Precise Beam Control

- Tune/coupling feedback system: acceleration close to 2/3 orbital resonance
- Orbit feedback system: rms orbit distortion less than 0.1mm



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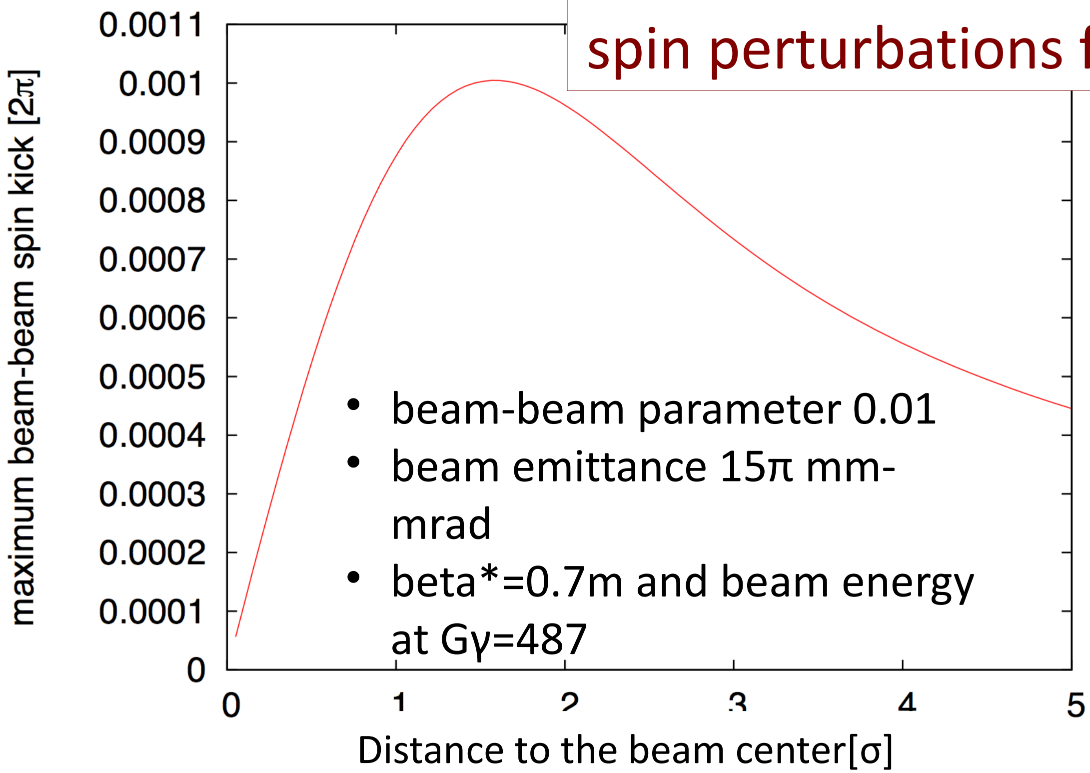
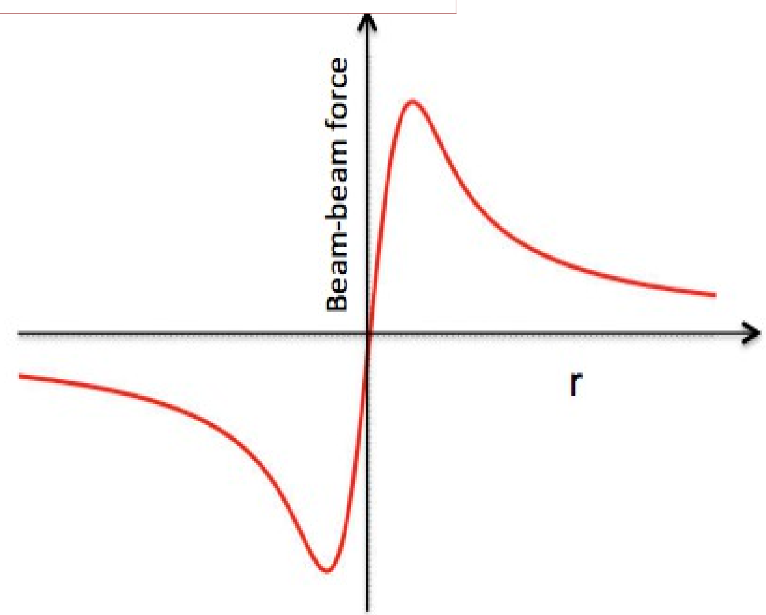
Beam-beam Effect on Polarization

- Beam-Beam force on spin motion
  - For a Gaussian round beam, particle from the other beam sees

$$\vec{E} = \frac{qN}{2\pi\varepsilon_0 l r}\left[1-\exp\left(-\frac{r^2}{2\sigma^2}\right)\right]\hat{r} \qquad \vec{B} = \frac{1}{c}\vec{\beta}\times\vec{E}$$

The effect is much weaker than the spin perturbations from the lattice





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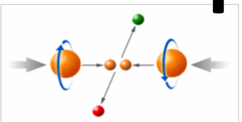
Polarization Performance and Beam-beam

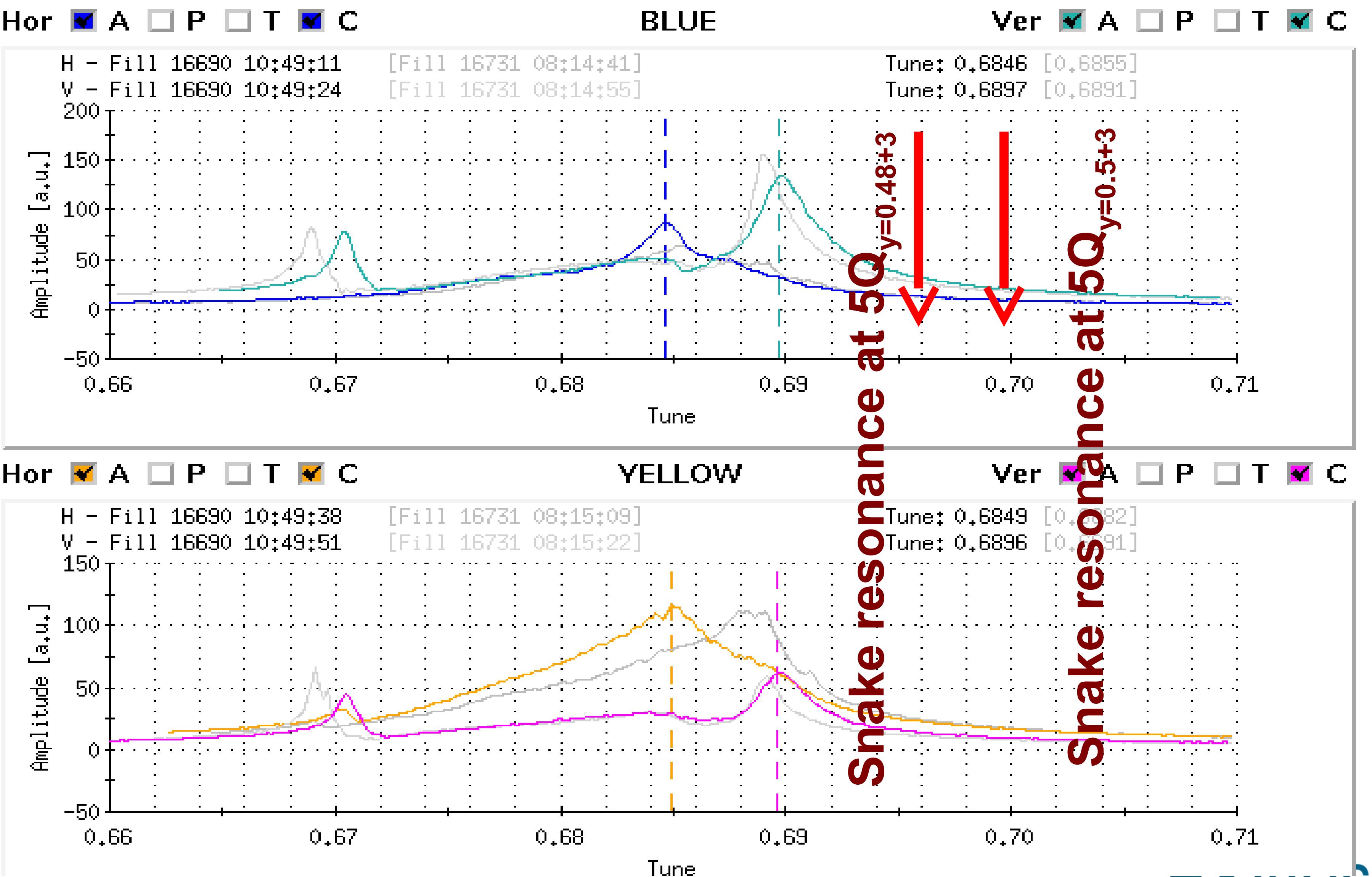


- Beam-Beam induces tune shift of

$$\xi = \frac{N r_0 \beta^*}{4\pi\gamma\sigma^2}$$

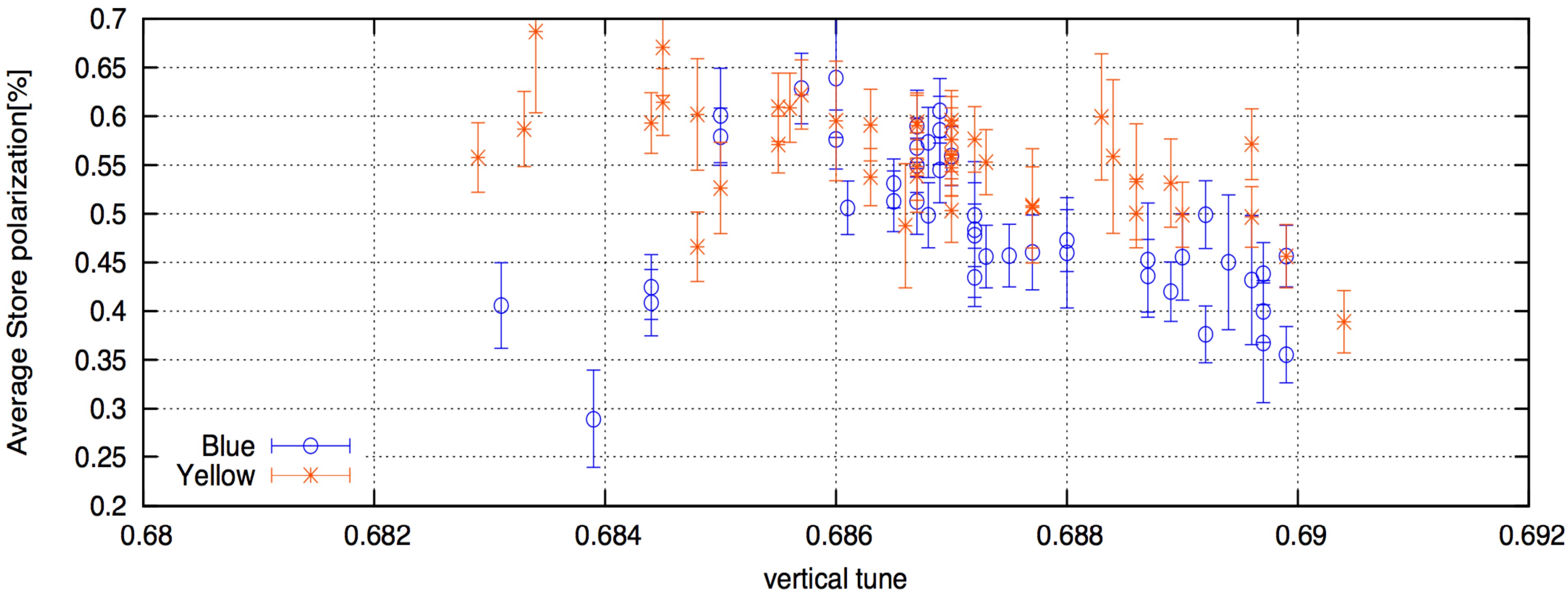
- It also induces an incoherent tune spread, which can populate particles on
  - orbital resonances, and causes emittance growth
  - snake resonances, and result in polarization loss during collision

A Typical BTF of RHIC Beam in Collision



Average Store Polarization vs. vertical tune

- The closer the vertical tune towards 0.7, the lower the beam polarization
- The data also shows that the direct beam-beam contribution to polarization loss during store is weak



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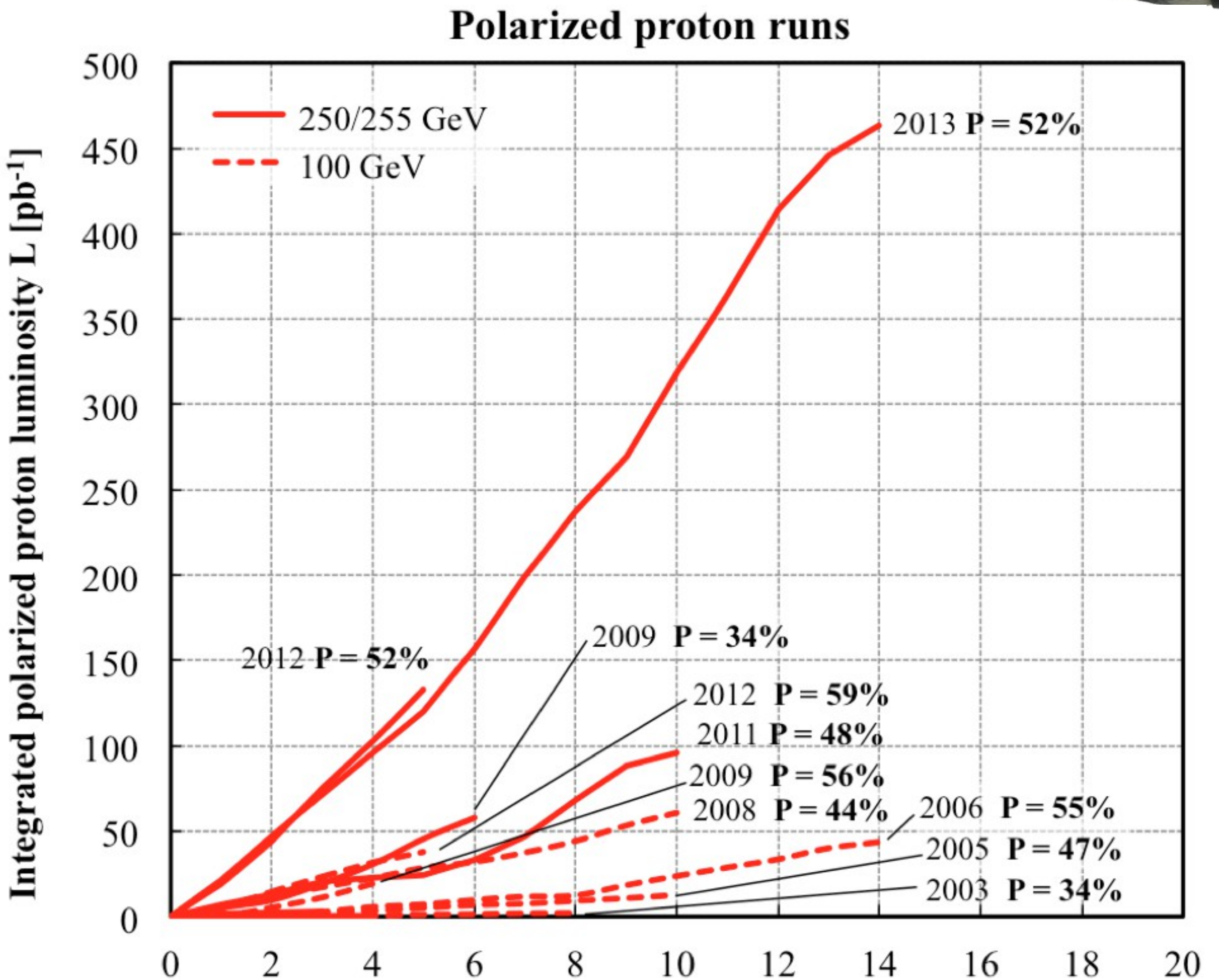
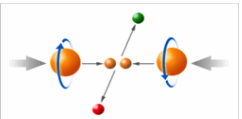
RHIC Polarized Proton Performance



Courtesy of W. Fischer

Polarization as measured by H Jet target, average of the entire beam distribution. For 250(255) GeV, sharper polarization profile was observed and hence, effective polarization is ~ 20 % higher



Polarized Electrons

- High energy polarized electrons, on the other hand, is quite different due to Sokolov-Ternov effect,
  - Discovered by Sokolov-Ternov in 1964
  - Emission of synchrotron radiation causes spontaneous spin flip

  - The difference of probability between the two scenarios allows the radiative polarization build up $P(t)=P_{max}(1-e^{-t/\tau_{pol}})$, where $P_{ST}=8/5\sqrt{3}$ and polarization build up time is

$$\tau_{pol}^{-1}=5\frac{\sqrt{3}}{8}\frac{e^2\hbar\gamma^5}{m^2c^2\rho^3}=5\frac{\sqrt{3}}{8}c\lambda_e r_e\frac{\gamma^5}{\rho^3}$$

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Polarized Electrons

- For electron, rule of thumb of polarization build up time

$$\tau_{pol}^{-1} = 3654 \frac{R/\rho}{B[T]^3 E[GeV]^2}$$

S. Mane et al, Spin-polarized charged particle bams

	VEPP[10]	VEPP2-M[11]	ACO[8,9]	BESSY[44]	SPEAR[45]	VEPP4[46]
E(GeV)	0.640	0.625	0.536	0.800	3.70	5.0
τ_p(min)	50	70	160	150	15	40
P(%)	52	90	90	>75	>70	80
	DORIS II[47]	CESR[48]	PETRA[49]	HERA[19]	TRISTAN[50]	LEP[51]
E(GeV)	5.0	4.7	16.5	26.7	29	46.5
τ_p(min)	4	300	18	40	2	300
P(%)	80	30*	80**	70**	75**	57**

- What's the polarization buildup time at RHIC@250GeV and LHC@1TeV?

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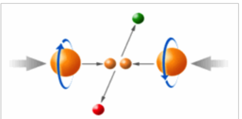
In a planar circular accelerator

- where the magnetic field is distributed piece-wisely

$$P_{\infty} = \frac{8}{5\sqrt{3}} \frac{\left\langle \left|\rho^{-3}\right| \hat{n}\cdot\hat{b} \right\rangle}{\left\langle \left|\rho^{-3}\right| [1 - \frac{2}{9}(\hat{\beta}\cdot\hat{n})^2] \right\rangle}$$

$$\tau_p^{-1} = \frac{5\sqrt{3}}{8} c \lambda\!\!\!^{-}_c r_e \gamma^5 \left\langle \left|\rho^{-3}\right| \left[1 - \frac{2}{9}\left(\vec{\beta}\cdot\vec{n}\right)^2\right] \right\rangle$$

- Clearly, a single snake or other configurations which lays the stable spin direction in the horizontal plane, can cancel the S-T radiative polarization build-up



Now, let's add in spin diffusion

- An emission of a photon yields a sudden change of the particle's energy, as well as its spin phase

$$P_\infty = \frac{8}{5\sqrt{3}} \frac{\left\langle |\rho^{-3}| \hat{b} \cdot [\hat{n} - \gamma \frac{\partial \hat{n}}{\partial \gamma}] \right\rangle}{\left\langle |\rho^{-3}| [1 - \frac{2}{9}(\hat{\beta} \cdot \hat{n})^2 + \frac{11}{18} \left| \gamma \frac{\partial \hat{n}}{\partial \gamma} \right|^2] \right\rangle}$$

$$\tau_p^{-1} = \frac{5\sqrt{3}}{8} c\lambda\!\!\!^{-}_c r_e \gamma^5 \left\langle |\rho^{-3}| \left[1 - \frac{2}{9} \left(\vec{\beta} \cdot \vec{n} \right)^2 + \frac{11}{18} \left| \gamma \frac{\partial \hat{n}}{\partial \gamma} \right|^2 \right] \right\rangle$$

Synchrotron Sideband

- Spin tune is modulated due to synchrotron oscillation

$$\gamma = \gamma_0 + \Delta\gamma \cos\psi \quad \text{with} \quad \psi = \nu_s \theta + \phi_0$$

$$\nu = G\gamma = \nu_0 + G\Delta\gamma \cos\psi \quad \text{with} \quad \nu_0 = G\gamma_0$$

- Hence, the spin-orbit coupling factor averaged over all synchrotron phase becomes

$$\left\langle \left|\vec{\Gamma}\right|^2 \right\rangle = \left|\gamma \frac{\partial \hat{n}}{\partial \gamma}\right|^2 = \nu_0^2 \varepsilon_K^2 \sum_m \frac{J_m^2\left(\Delta\nu / \nu_s\right)}{\left[\left(\left(\nu_0 - K\right)^2\right) - \nu_s^2\right]^2}$$

C. Biscari, J. Buon, B. Montague, CERN/LEP-TH/83-8

Depolarizing Resonance @ SPERA

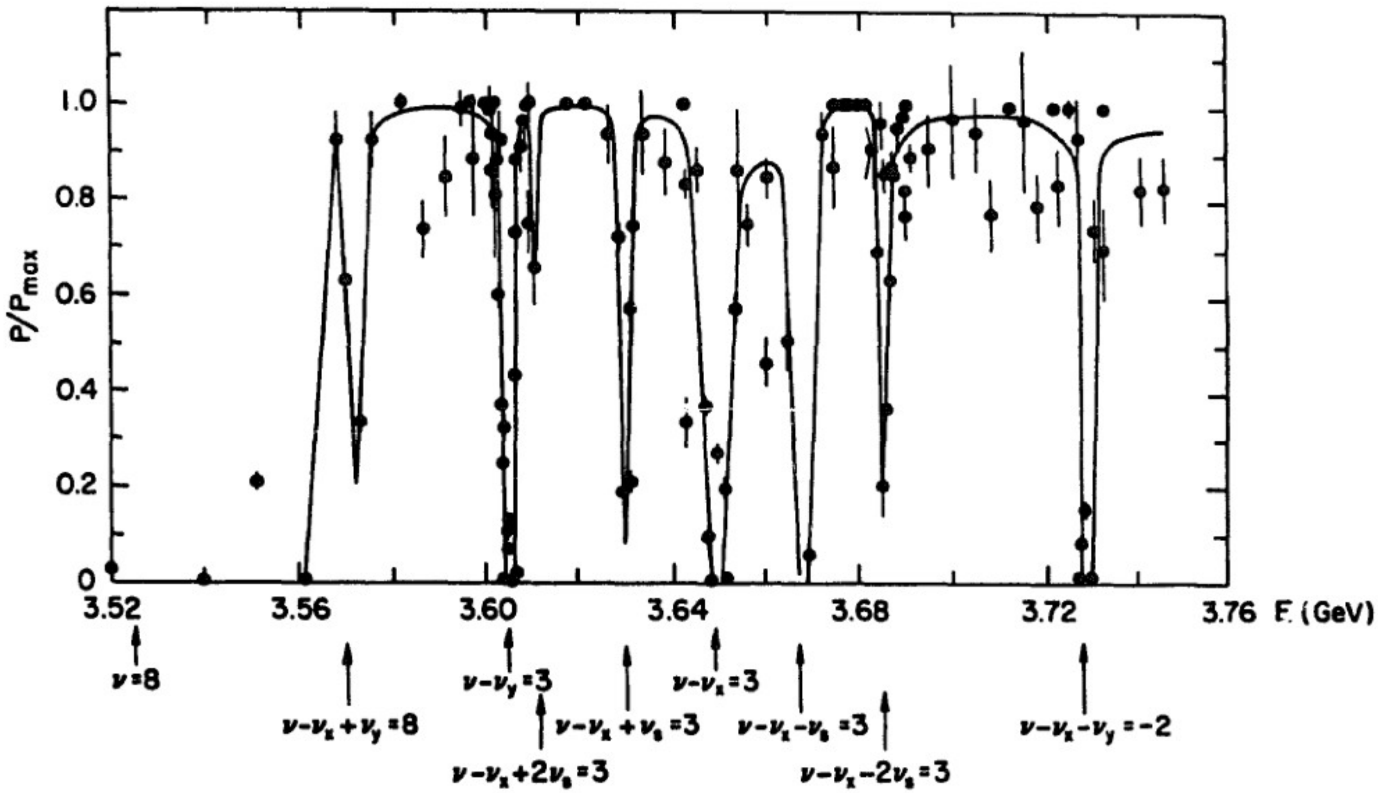
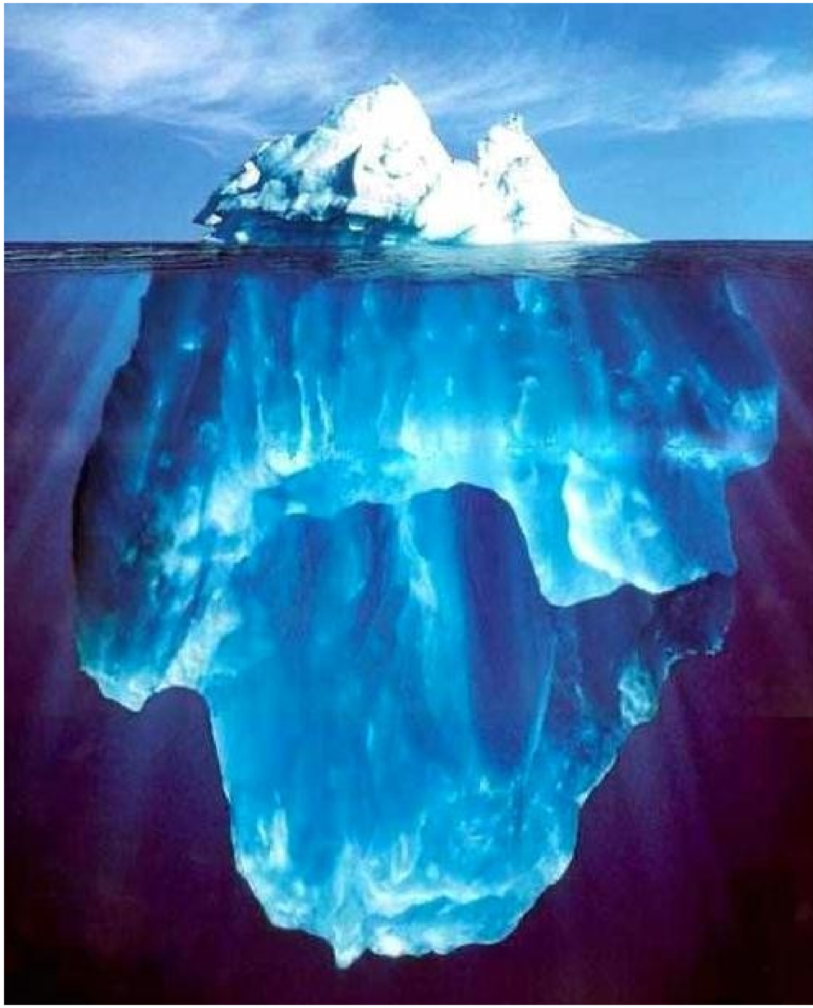


Fig. 1. Polarization measurements at SPEAR (from ref. [2]). The quantity P_{max} is $8/(5\sqrt{3}) = 92.4\%$. The curve is a guide for the eye, not a theoretical calculation. Various resonances have been identified in the data. The orbital tunes are called $\nu_{x,y,s}$ instead of $Q_{x,y,s}$. The spin tune is ν. A single beam of positrons was circulated when making measurements. The graph is not a single experiment, but a compilation of many runs.

What’s Missing in this talk

The iceberg ☺



Linear spin dynamics
- 1^{st} order depolarizing resonance
- Techniques for preserving polarization

Non-linear spin dynamics
- High order depolarizing resonance

Spin tracking
- Robustness and modern architect
- Optimization, spin matching

Spin manipulation
- Spin flipping
- Spin tune-meter

Polarimetry

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To the great minds who pioneered

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Achieved Performance and Projection

p↑- p↑ operation	2009	2012	2013	2015
Energy	GeV	100/250	100/255	100
No of collisions	…	107	107	107
Bunch intensity	10^{11}	1.3/1.1	1.3/1.8	1.85
Beta*	m	0.7	0.85/0.65	0.65
Peak L	**$10^{30}cm^{-2}s^{-1}$**	**50/85**	**46/165**	**115**
Average L	**$10^{30}cm^{-2}s^{-1}$**	**28/55**	**33/105**	**63**
Polarization P	**%**	**56/35**	**59/52**	**56/57.4**

- Polarization quoted here is from Absolute Polarimeter using polarized H Jet

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