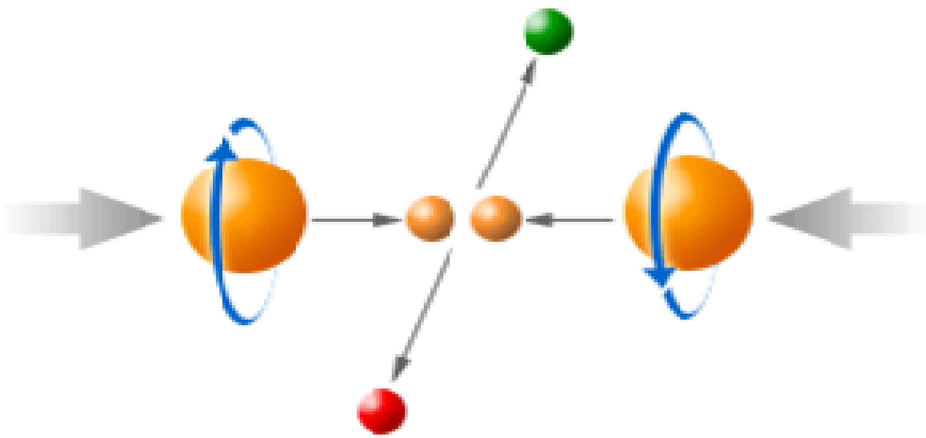
Polarized Protons and Siberian Snakes



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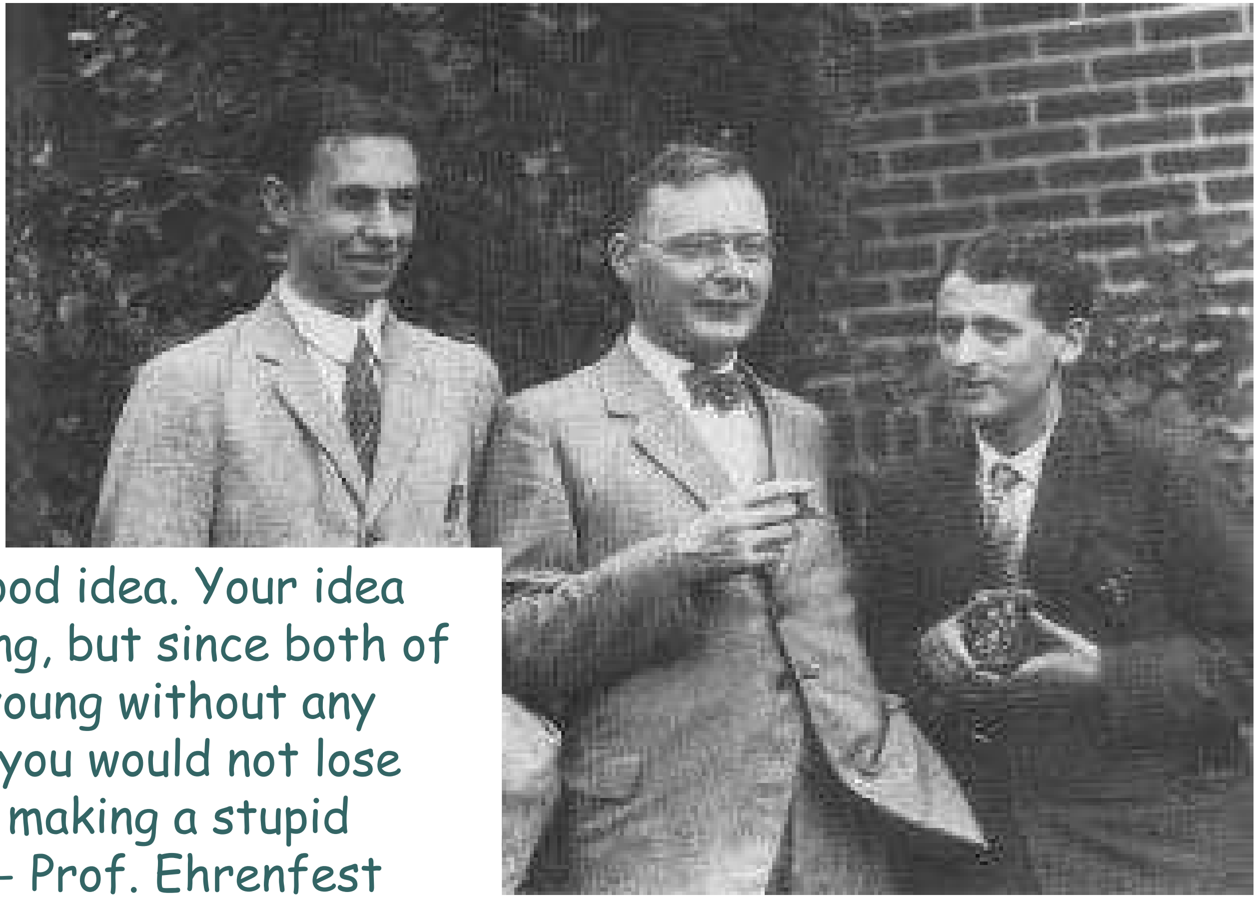
Outline

- **Introduction: why polarized protons**
  - spin “crisis”
- **Accelerating polarized protons to high energy**
  - beam dynamics in a synchrotron
  - spin dynamics
  - challenges and solutions
- **Siberian Snake**
  - RHIC: the first polarized proton collider
- **Summary**

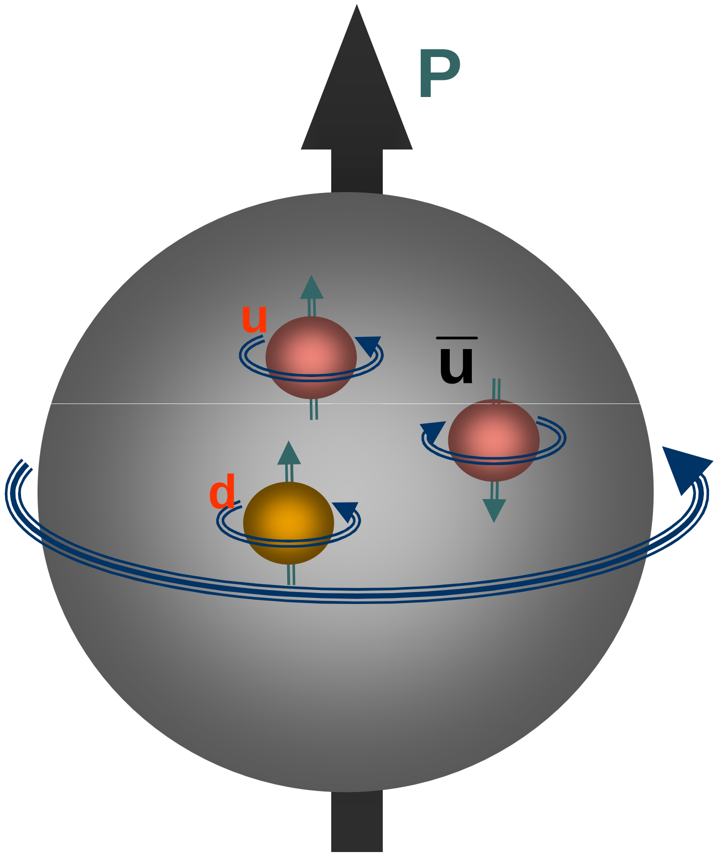
Discovery of Spin: 1925



"This is a good idea. Your idea may be wrong, but since both of you are so young without any reputation, you would not lose anything by making a stupid mistake." --- Prof. Ehrenfest

G.E. Uhlenbeck and S. Goudsmit, Naturwissenschaften 47 (1925) 953. A subsequent publication by the same authors, Nature 117 (1926) 264,

Spin Crisis:
what makes up the proton spin?

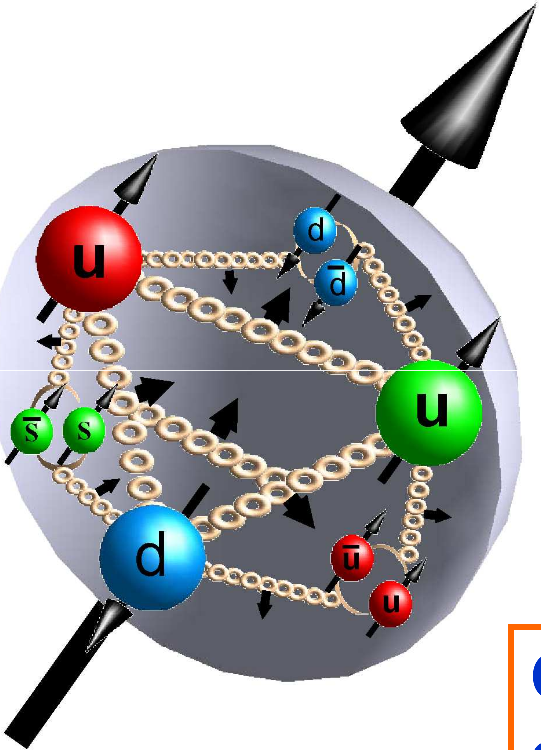


Sum of spins of all quarks

$$S = \frac{1}{2} = \frac{1}{2}\Delta\Sigma$$

CERN EMC, SMC:
$\Delta\Sigma$ ~ 20%!

Current model:
Proton spin sum-rule



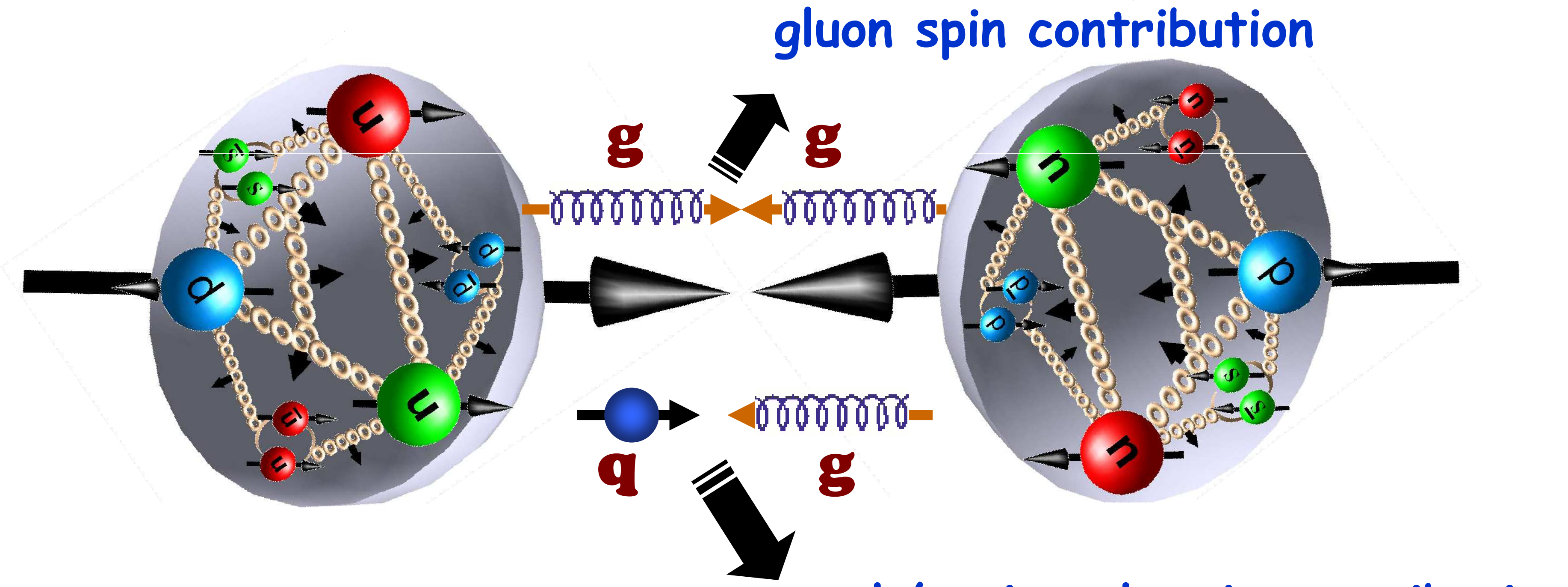
Spin contribution from all the gluons?

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

Orbital angular momentum of quarks and gluons?

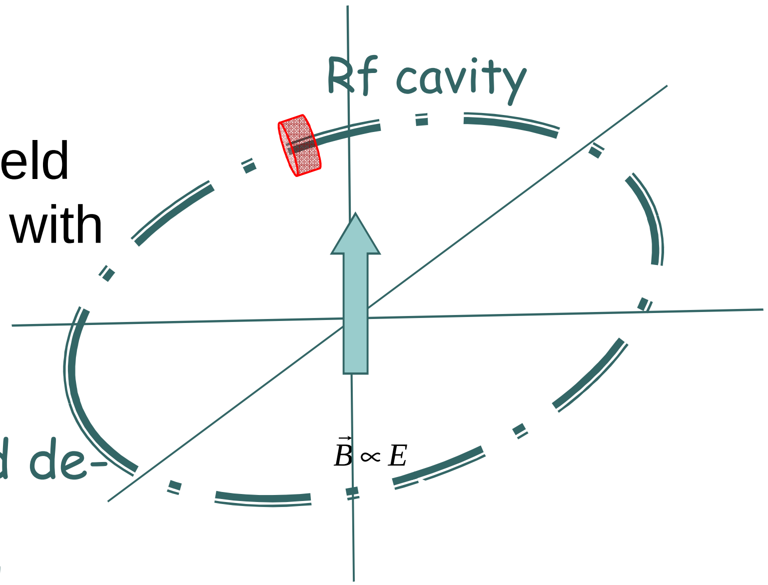
Quest to unveil the proton spin structure:

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

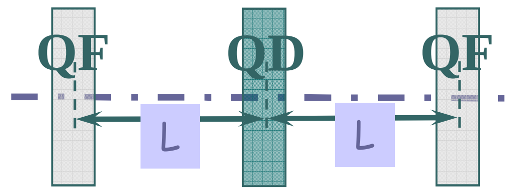


Synchrotron

- The acceleration comes from the electric field with an oscillating frequency synchronized with the particle's revolution frequency



- Alternating gradient
  - *A proper combination of focusing and de-focusing quadrupoles yields a net focusing force in both horizontal and vertical planes*



- FODO cell: most popular building block for synchrotrons

$$\begin{pmatrix} x \\ x' \end{pmatrix}_2 = \begin{pmatrix} 1 & 0 \\ \frac{1}{-2f} & 1 \end{pmatrix} \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{1}{f} & 1 \end{pmatrix} \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{1}{-2f} & 1 \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix}_1$$

Beam motion in a circular accelerator

- **Closed orbit**
  - A particle trajectory remains constant from one orbital revolution to the next
  - Closed orbit distortion: deviation from the center of the beam pipe

- **Betatron oscillation**
  - An oscillatory motion around the closed orbit from turn to turn

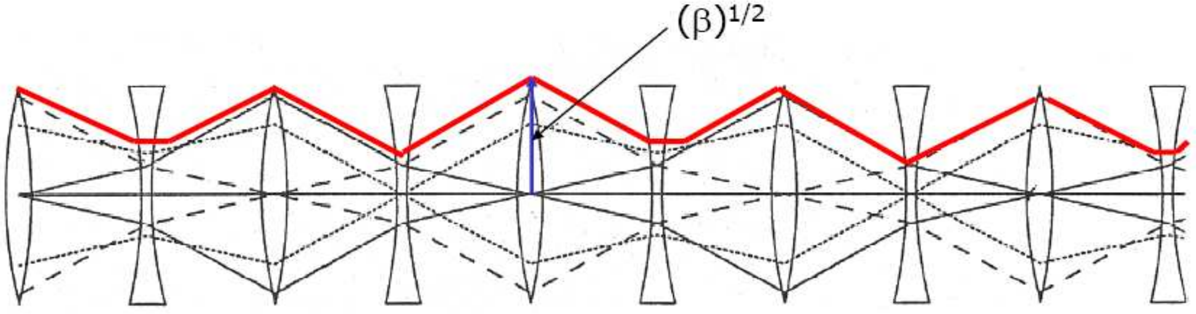
$$\frac{d^2x}{ds^2} + K_x(s)x = 0 \quad \Longrightarrow \quad x(s) = \sqrt{2\beta_x J}\cos(2\pi Q_x \theta(s) + \chi_x)$$

Particle motion in a synchrotron

- Betatron oscillation:

$$x(s) = \sqrt{2\beta_x J}\cos(2\pi Q_x \theta(s) + \chi_x)$$

  - Beta function: the envelope of the particle's trajectory along the machine
  - Betatron tune: number of betatron oscillations in one orbital revolution



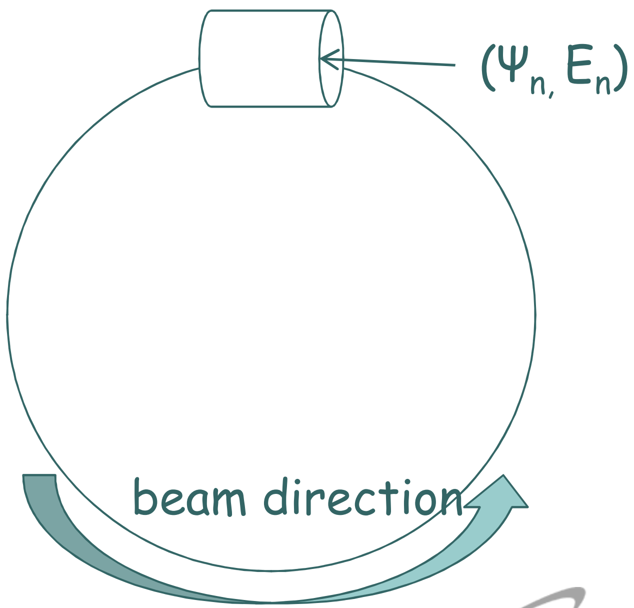
RF cavity

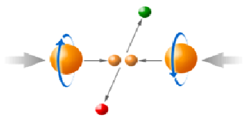
- Provide an oscillating electrical field to
  - accelerate the charged particles
  - keep the particles longitudinally bunched, i.e. focused

- A metallic cavity
  - resonating at a frequency integer multiples of the particle's revolution frequency

$$E_z(r,t) = E(r)e^{i2\pi f_{rf} t}$$

$$B_\theta(r,t) = B(r)e^{i2\pi f_{rf} t}$$





Spin motion: Thomas BMT Equation

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

Spin vector in particle's rest frame

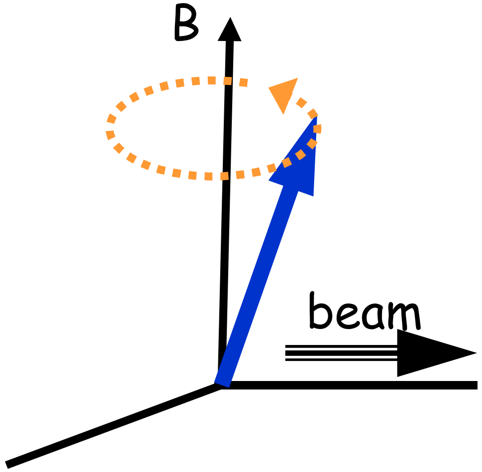
Magnetic field along the direction of the particle's velocity

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

Magnetic field perpendicular to the particle's velocity

Spin motion in a circular accelerator

- In a perfect accelerator, spin vector precesses around its guiding field along the vertical direction

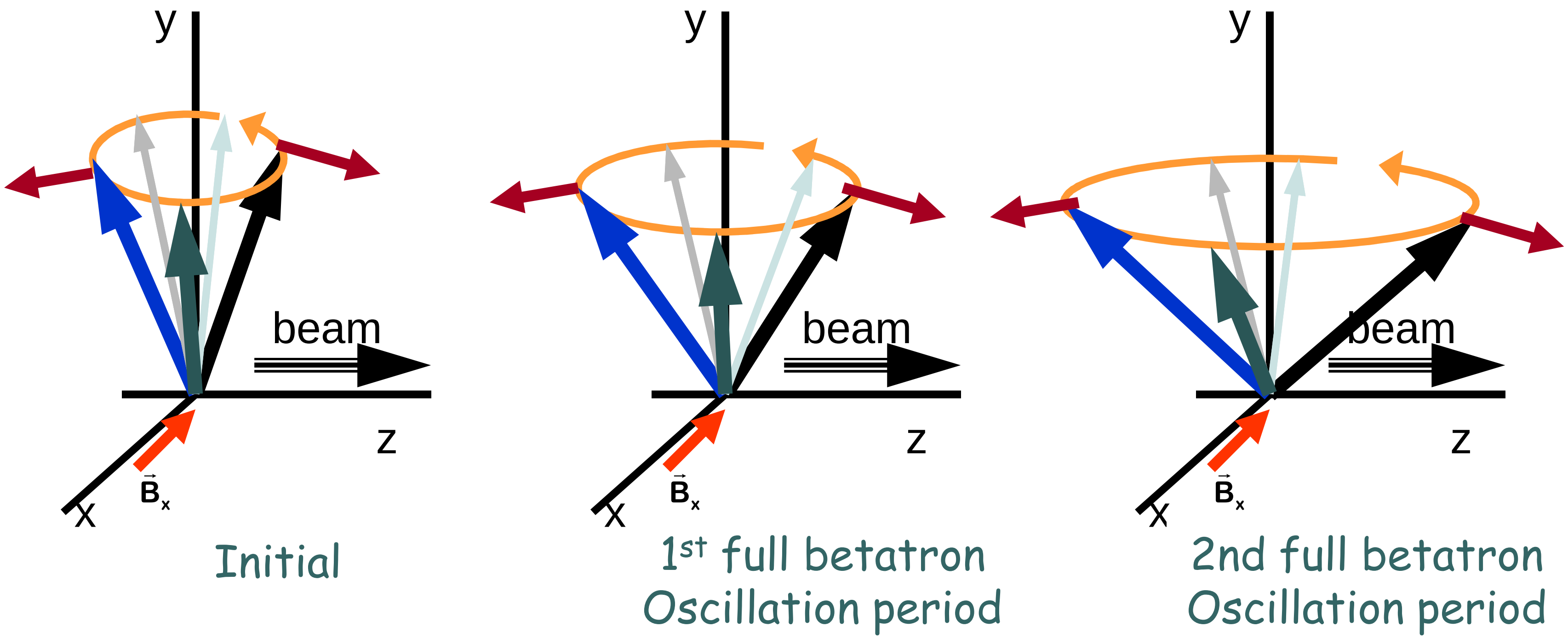


- Spin tune Q_s: number of precessions in one orbital revolution. In general,

$$Q_s = G\gamma$$

polarized proton acceleration challenges: preserve beam polarization

- Depolarization(polarization loss) mechanism
  - Come from the horizontal magnetic field which kicks the spin vector away from its vertical direction
  - Spin depolarizing resonance : coherent build-up of perturbations on the spin vector when the spin vector gets kicked at the same frequency as its precession frequency



imperfection spin resonance

- Source
  - dipole errors, quadrupole mis-alignments
- Resonance location:

  $G\gamma = k$, k is an integer
- Resonance strength:
  - Proportional to the size of the vertical closed orbit distortion

Intrinsic spin resonance

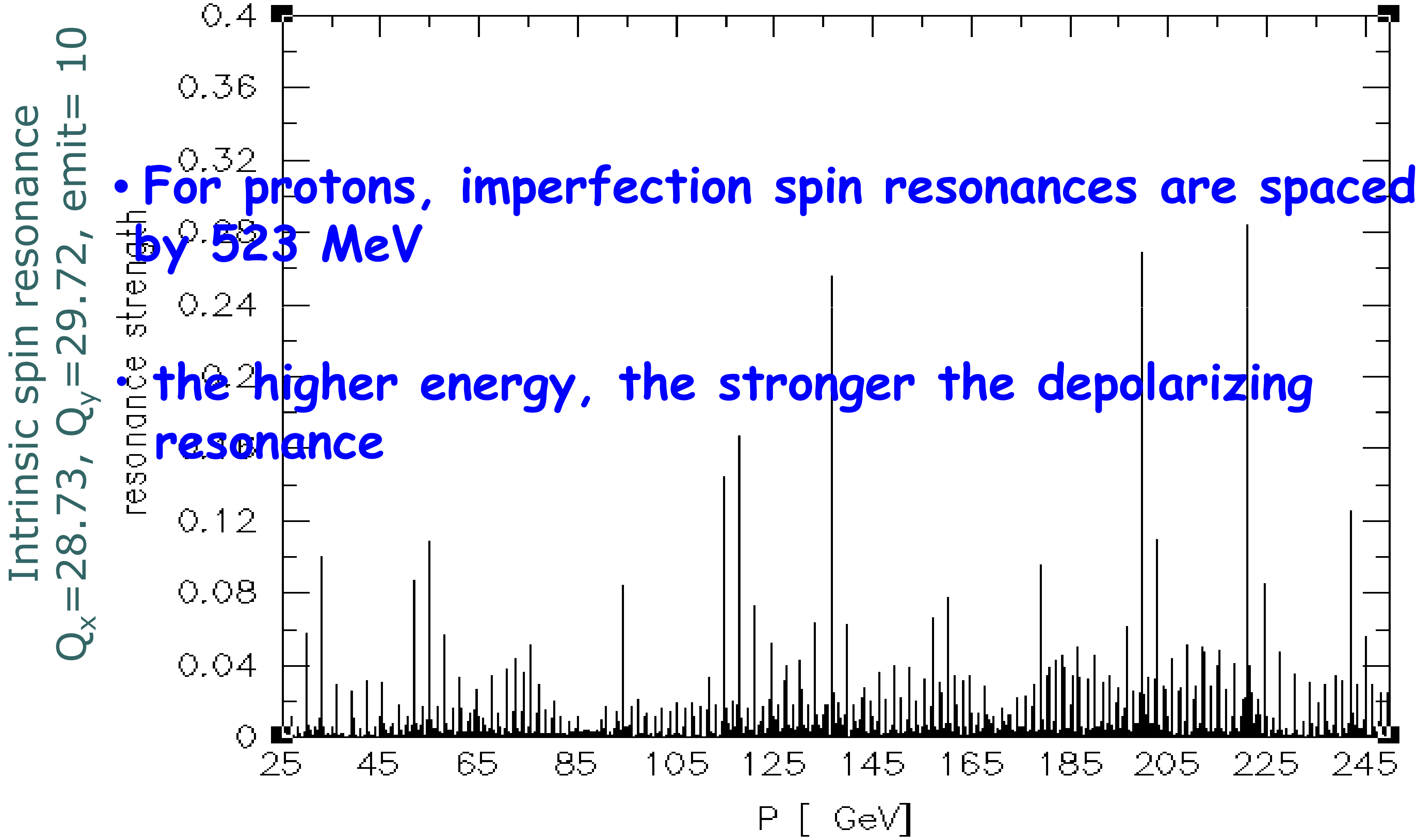
- **Intrinsic resonance**
  - Source: focusing field due to the intrinsic betatron oscillation
  - Resonance location:

$$G\gamma = kP \pm Qy,$$

P is the super periodicity of the accelerator, Qy is the 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

Spin depolarization resonance in RHIC



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

- the higher energy, the stronger the depolarizing resonance

Single resonance crossing

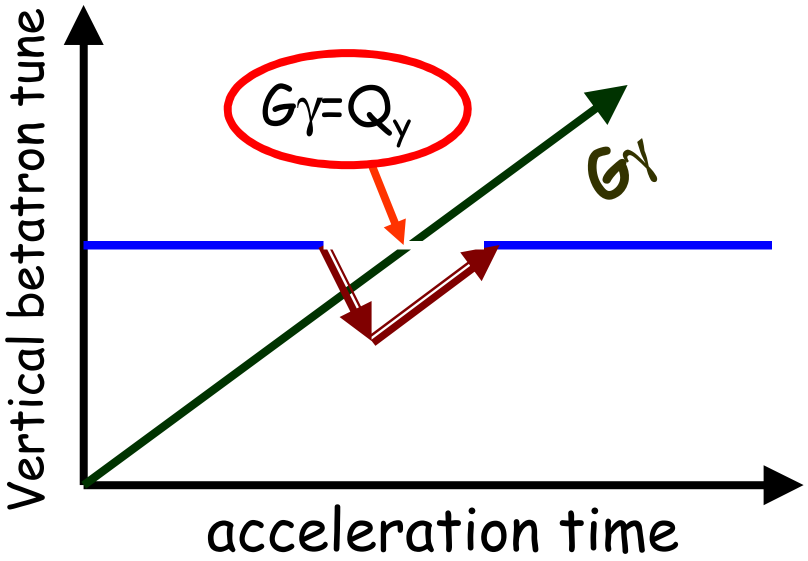
- **Frossart-Stora formula**

$$P_f = P_i \left(2e^{-\frac{\pi |\varepsilon|^2}{\alpha}} - 1 \right)$$

ε is the strength of the resonance.
α is the speed of resonance crossing

overcoming spin depolarizing resonances techniques

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

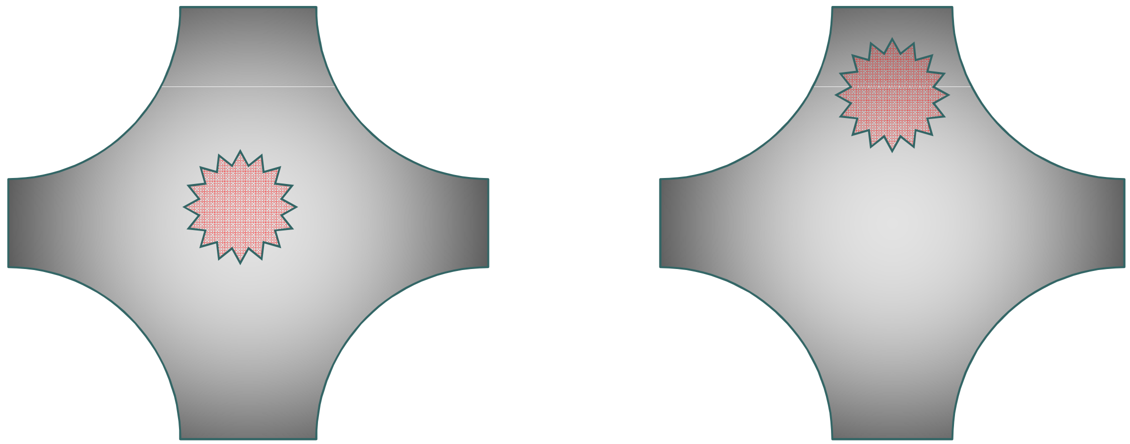


- *Operationally difficult because of the number of resonances*
- *Also induces emittance blowup because of the non-adiabatic beam manipulation*

overcoming spin depolarizing resonances techniques

- **AC dipole**
  - **Induce full spin flip by using an AC dipole to adiabatically excite a coherent betatron oscillation with large amplitude**

Quadrupole: horizontal
Magnetic field linearly
Proportional to the offset
From magnet center

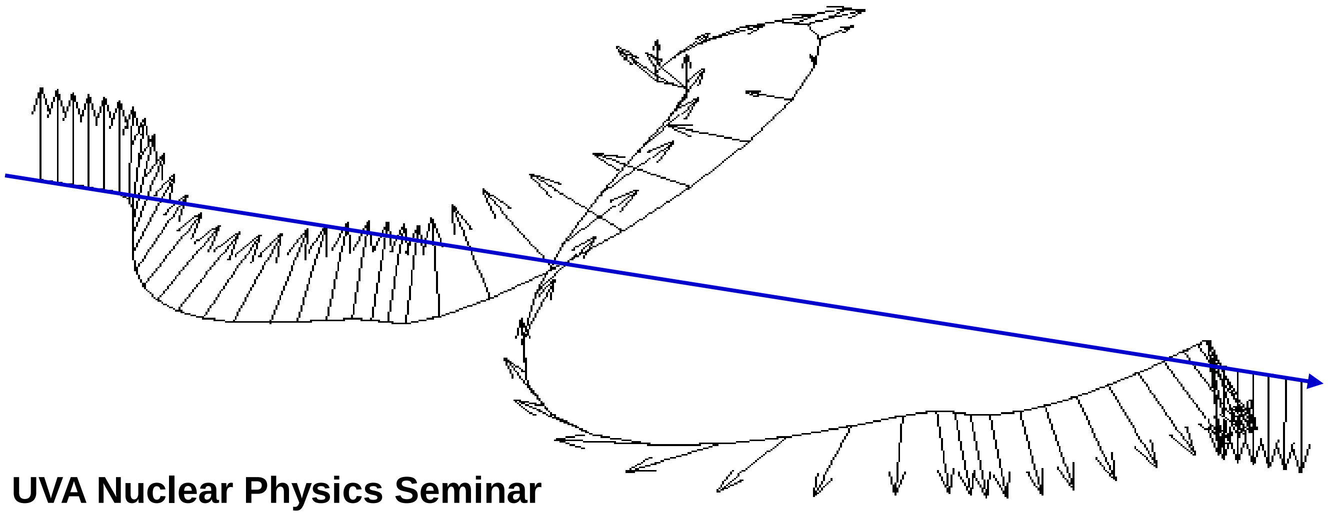


w.o. coherent oscillation   With coherent oscillation

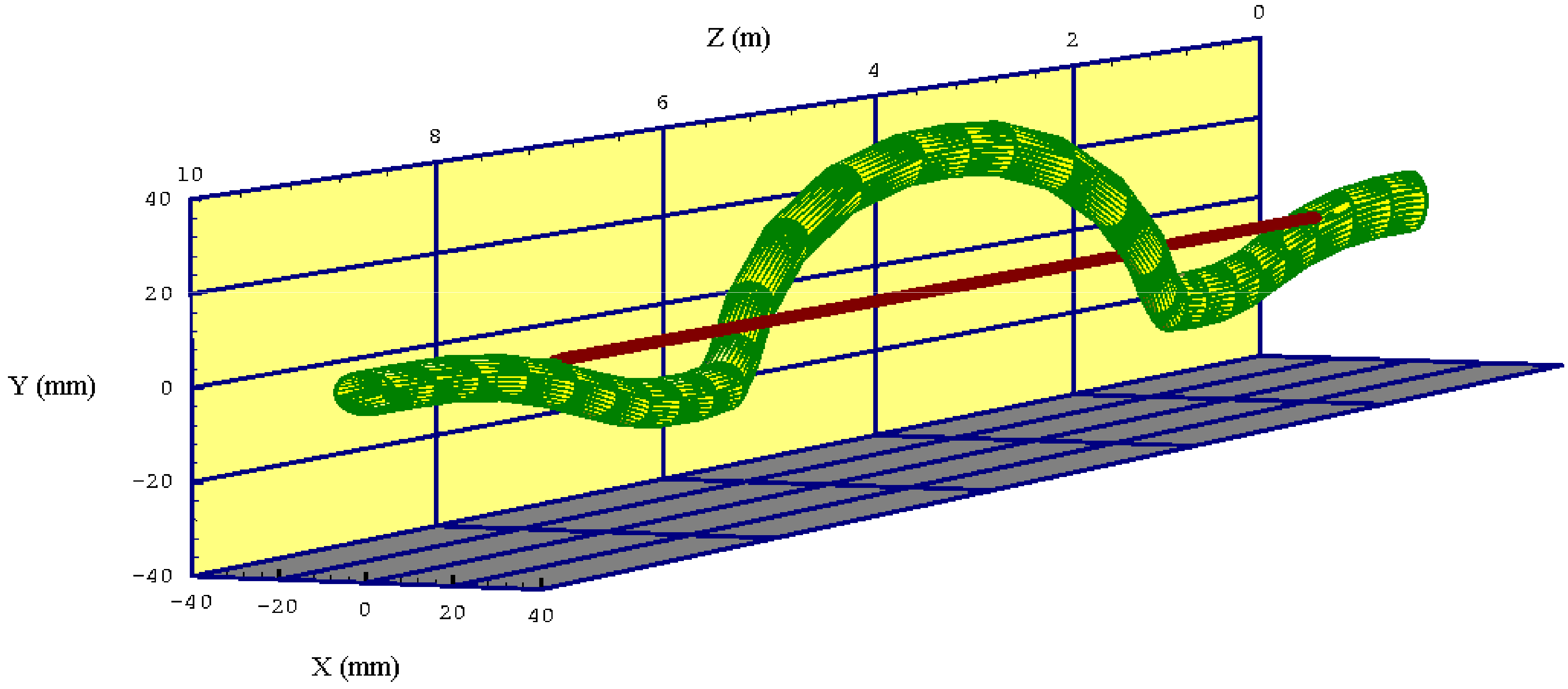
  - ***Can only correct strong intrinsic spin resonances***

Innovative polarized proton acceleration techniques: Siberian snake

- First invented by Derbenev and Kondratenko from Novosibirsk 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.64:1918-1929,1973]
- A group of dipole magnets with alternating horizontal and vertical dipole field rotates spin vector by 180^o

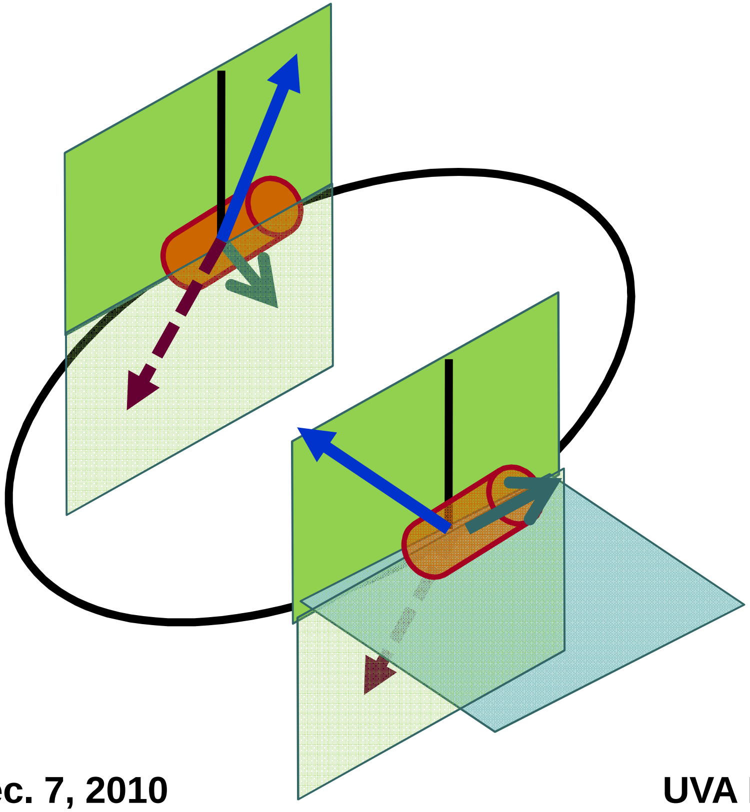


Particle trajectory in a snake:

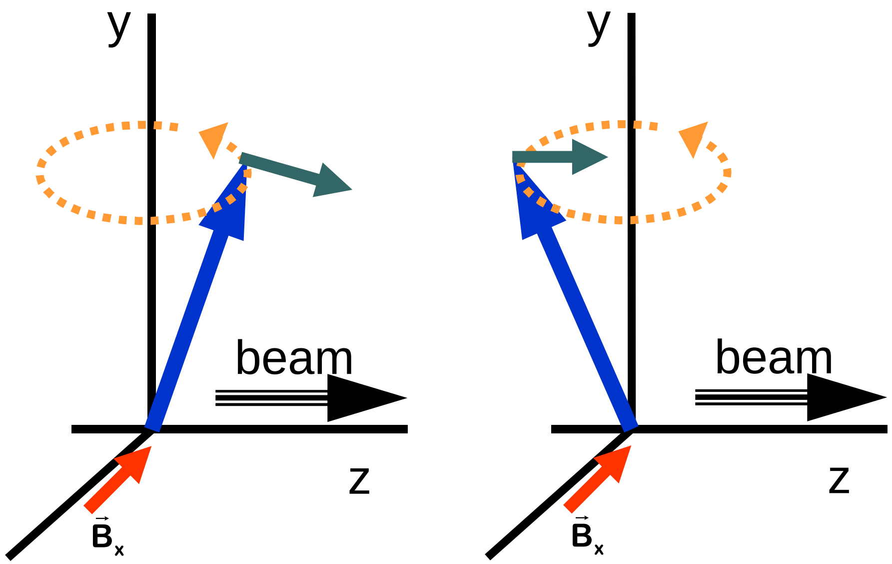


How to preserve polarization using Siberian snake(s)

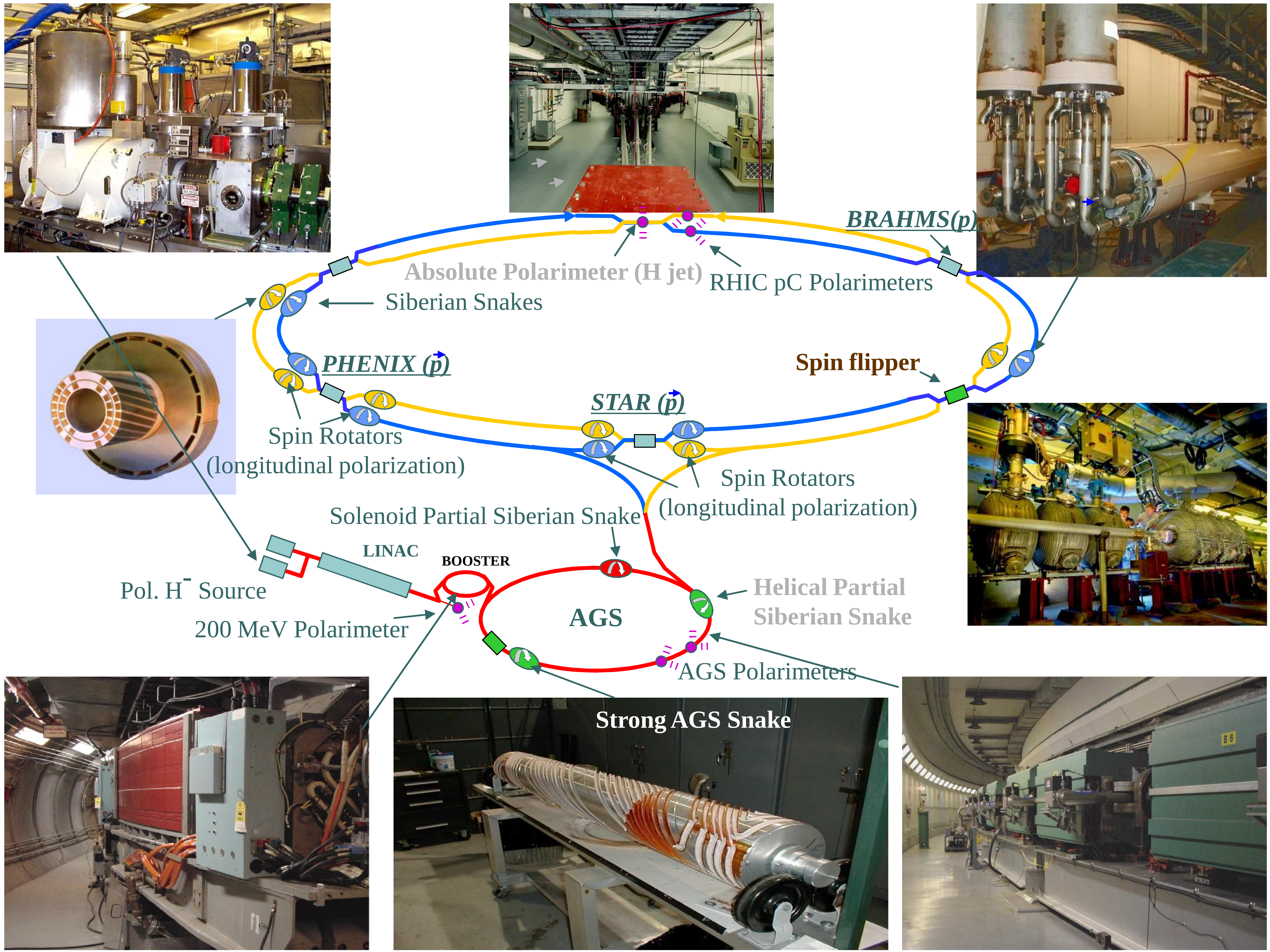
- Use one or a group of snakes to make the spin tune to be at ½



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



Accelerate polarized protons in RHIC



BRAHMS(p)
Absolute Polarimeter (H jet)
RHIC pC Polarimeters
Siberian Snakes
PHENIX (p)
Spin flipper
STAR (p)
Spin Rotators
(longitudinal polarization)
Spin Rotators
(longitudinal polarization)
Solenoid Partial Siberian Snake
LINAC
BOOSTER
Pol. H⁻ Source
Helical Partial
Siberian Snake
AGS
200 MeV Polarimeter
AGS Polarimeters
Strong AGS Snake

Polarized proton setup in the Booster

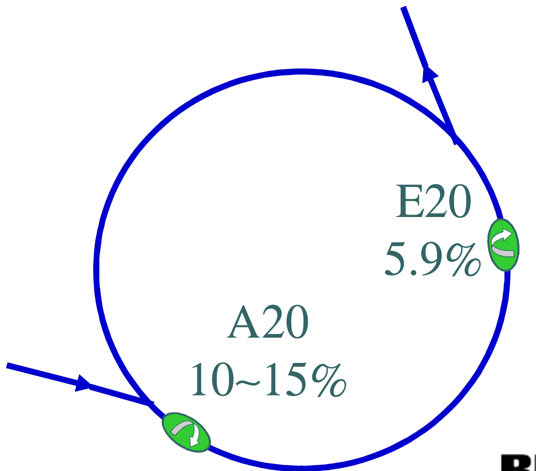
Booster

- Kinetic Energy: 200MeV ~ 1.42 GeV
- Intrinsic spin resonances are avoided by setting the vertical betatron tune above the spin precession tune at extraction
- A total of 2 imperfection resonances and they are corrected by the harmonic correction of the vertical closed orbit closed orbit

Polarized proton setup in the AGS

- **AGS (Alternating Gradient Synchrotron)**
  - Energy: 2.3 GeV ~ 23.8 GeV
  - A total of 41 imperfection resonances and 7 intrinsic resonances from injection to extraction
    - **One 5.9% partial snake plus one 10~15% partial snake**

$$\cos\pi Q_s = \cos G\gamma\pi \cos\frac{\Psi_1}{2}\cos\frac{\Psi_2}{2} - \cos G\gamma\frac{\pi}{3}\sin\frac{\Psi_1}{2}\sin\frac{\Psi_2}{2}$$



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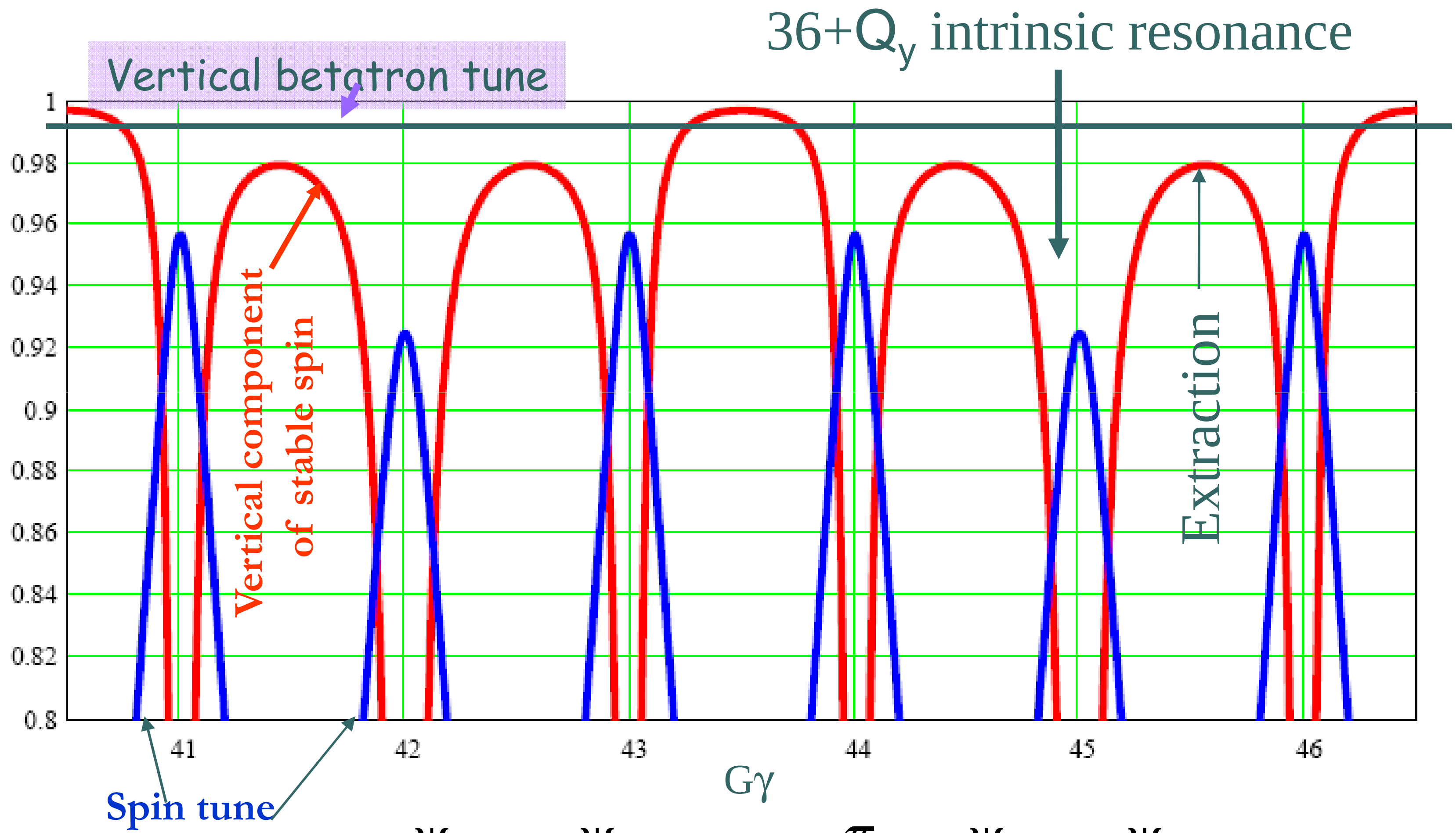
Courtesy of T. Roser

Spin tune with two partial snakes



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

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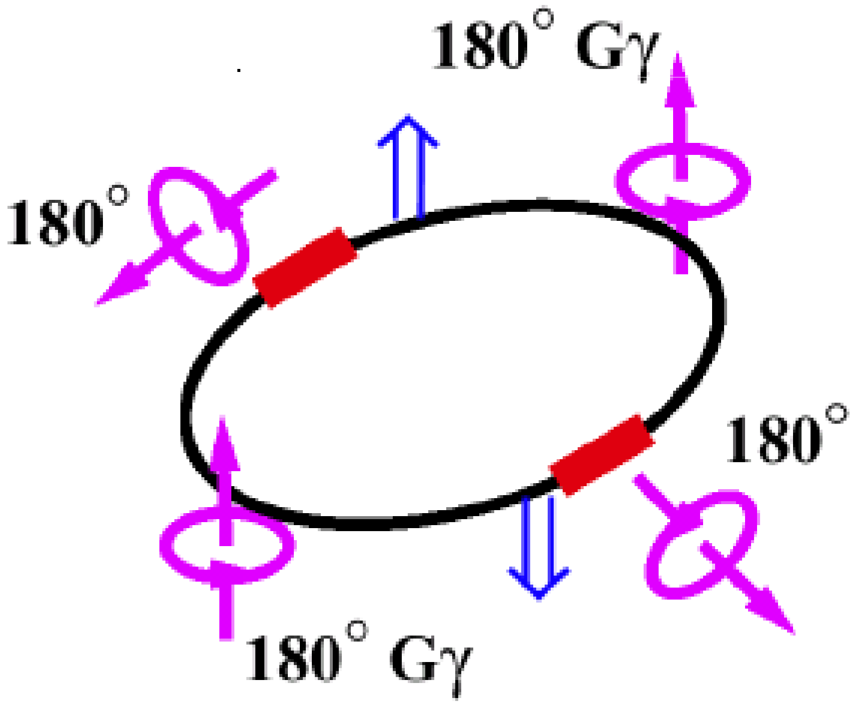
AGS polarized proton development

	imperfection	intrinsic	Setup time	Energy GeV	Int [10^{11}]	Pol [%]
1988	Harmonic correction	Fast tune jump	Months	21.7	0.108	42
1994	5%solenoid partial snake	Fast tune jump	2 weeks	23.0	0.05	31
1998	5%solenoid partial snake	AC dipole @ 3 strong intrinsic resonance	2 weeks	23.0	0.05	37
2000	New polarized H- source with high current high polarization					
2005	5%helical partial snake	AC dipole @ 4 strong intrinsic resonance	2 weeks	23.8	1.0	50
2005	5% helical partial snake +10% super-conducting helical partial snake		2 weeks	23.8	1.5	65

Polarized proton acceleration setup in RHIC

- **Energy: 23.8 GeV ~ 250 GeV (maximum store energy)**
  - A total of 146 imperfection resonances and about 10 strong intrinsic resonances from injection to 100 GeV.
    - ***Two full Siberian snakes***



$$Q_s = \frac{1}{\pi}\left|\varphi_1 - \varphi_2\right|$$

$$\Rightarrow \quad Q_s = \frac{1}{2}$$

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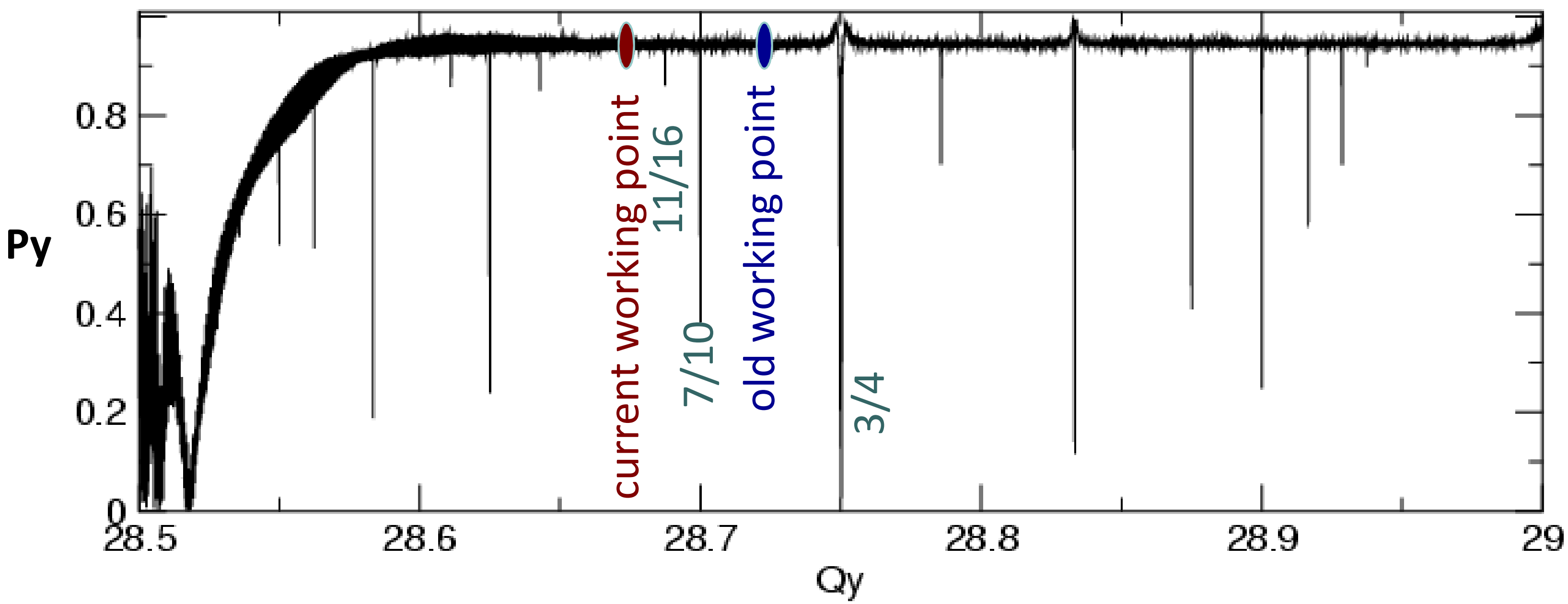
snake depolarization resonance

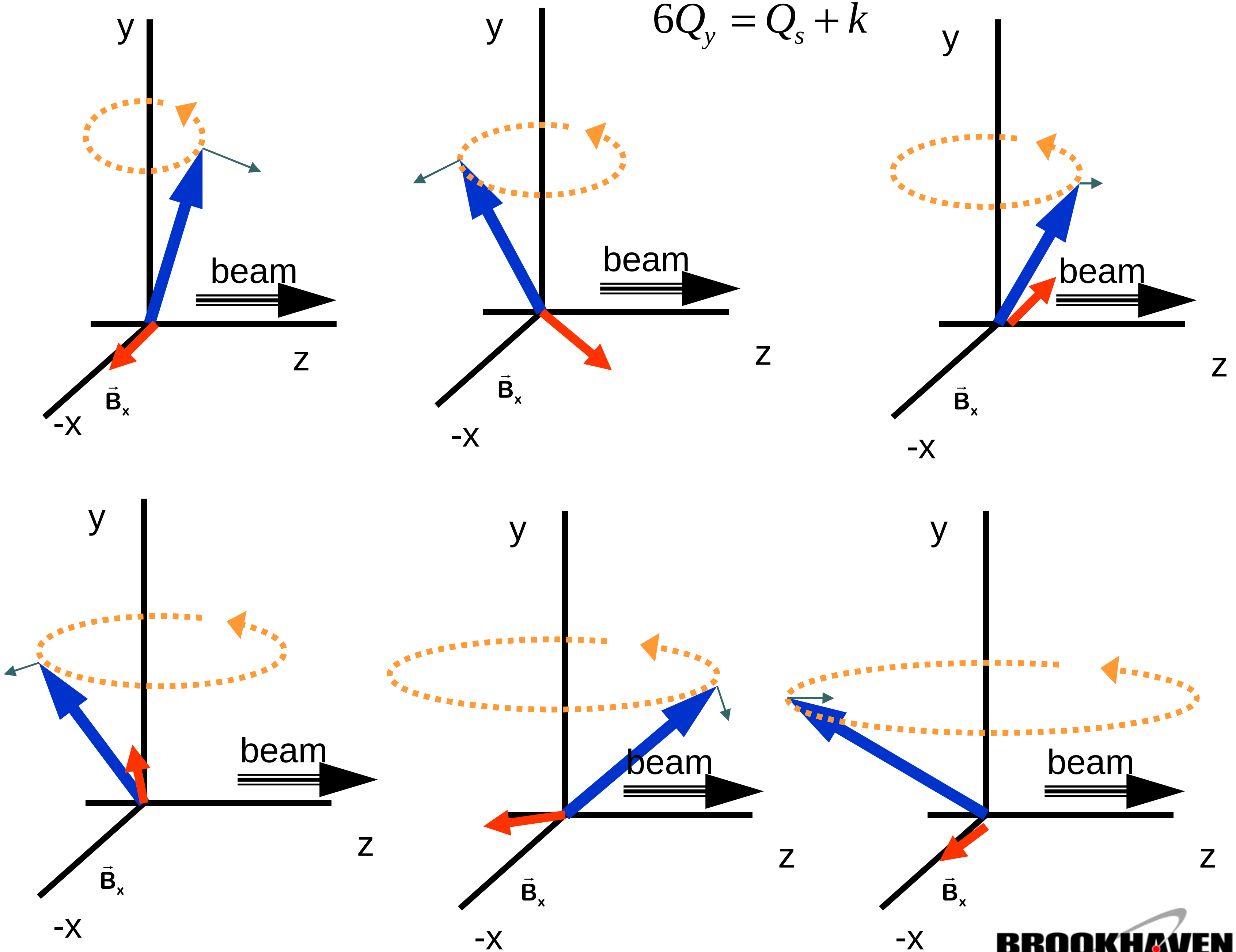
- Condition

$$mQ_y = Q_s + k$$

- even order resonance
  - Disappears in the two snake case like RHIC if the closed orbit is perfect
- odd order resonance
  - Driven by the intrinsic spin resonances



$$6Q_y = Q_s + k$$



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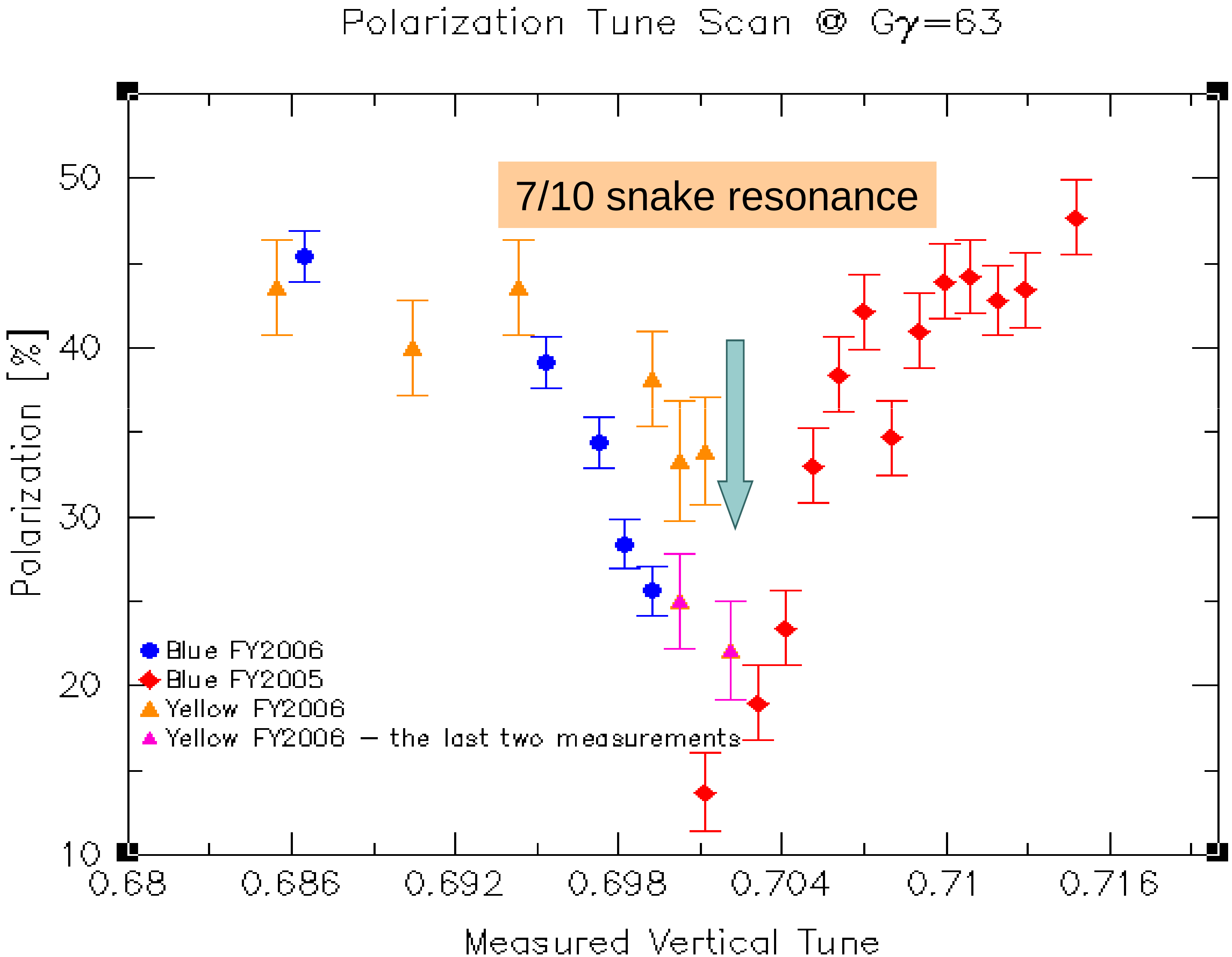
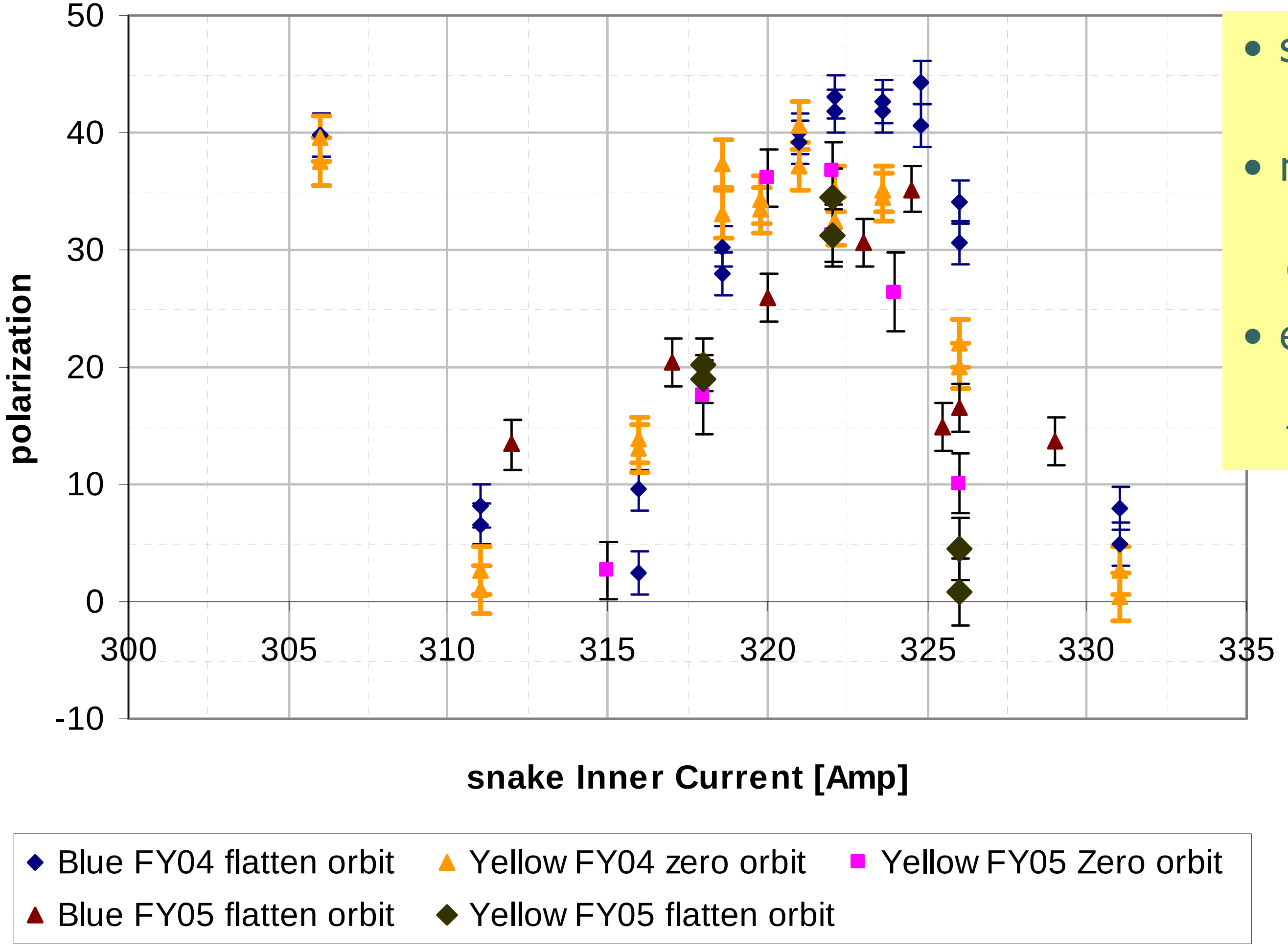
Snake resonance observed in RHIC



How to avoid a snake resonance

- Keep the spin tune as close to ½ as possible
  - snake current setting



- set the vertical tune to 0.745
- measure the beam polarization with different snake current
- expect no depolarization if the corresponding spin tune is very close to 0.5

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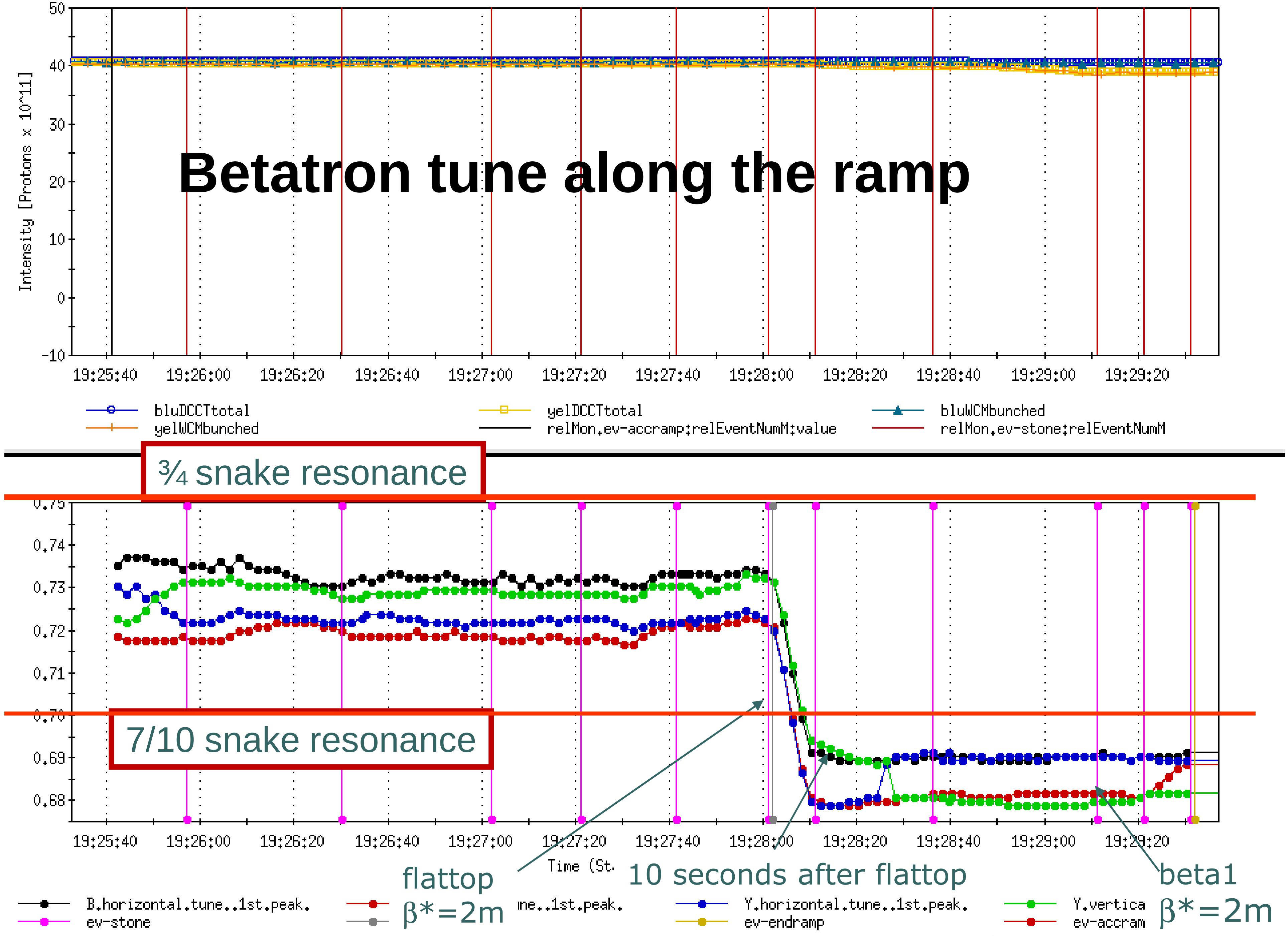
How to avoid a snake resonance

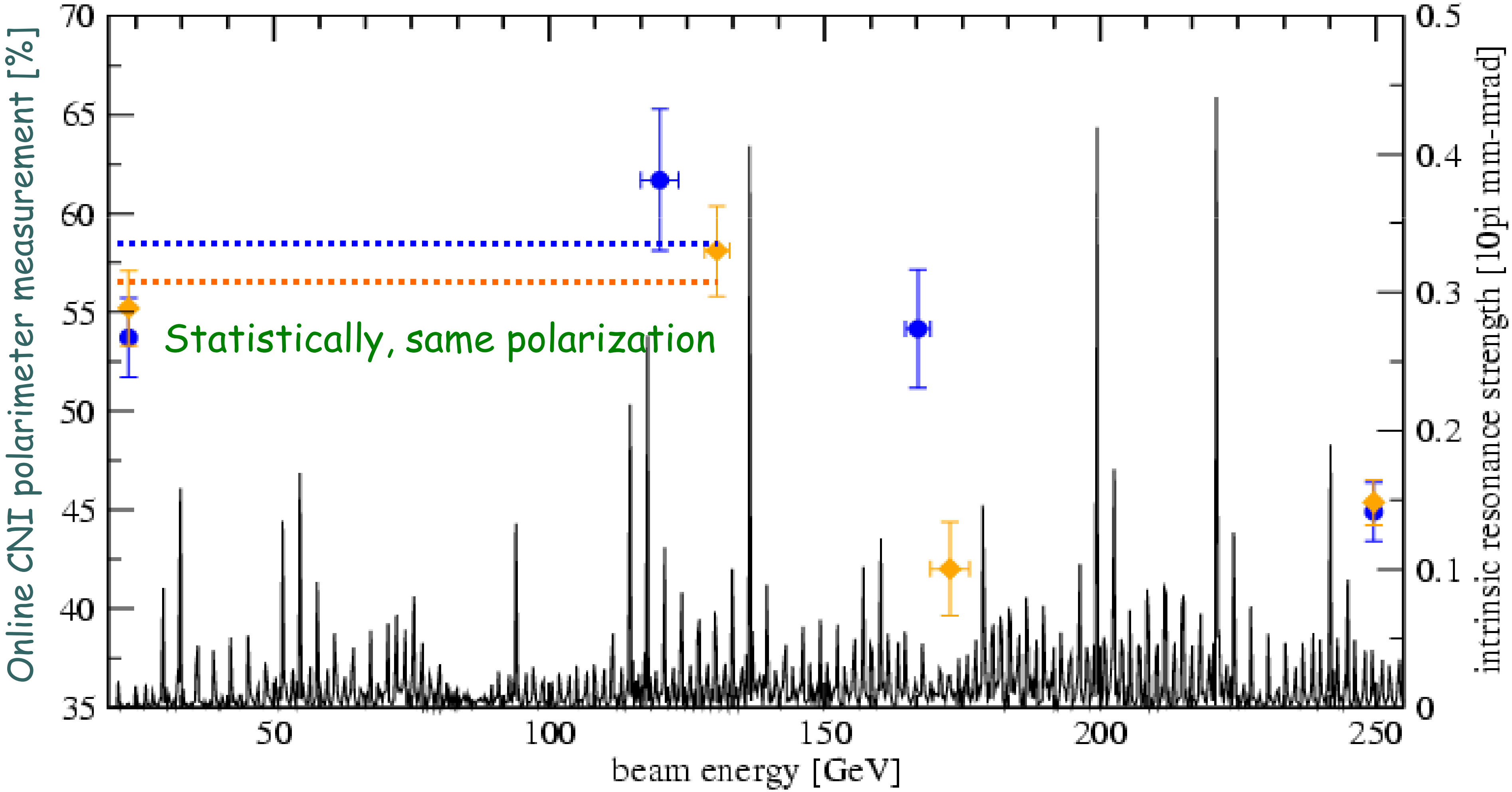
- Keep the spin tune as close to ½ as possible
  - snake current setting
  - Keep the horizontal orbit at the two snakes parallel
- Keep the vertical closed orbit as flat as possible
  - orbit control
- Keep the betatron tunes away from snake resonance locations
  - Precise tune control

Betatron tune along the ramp

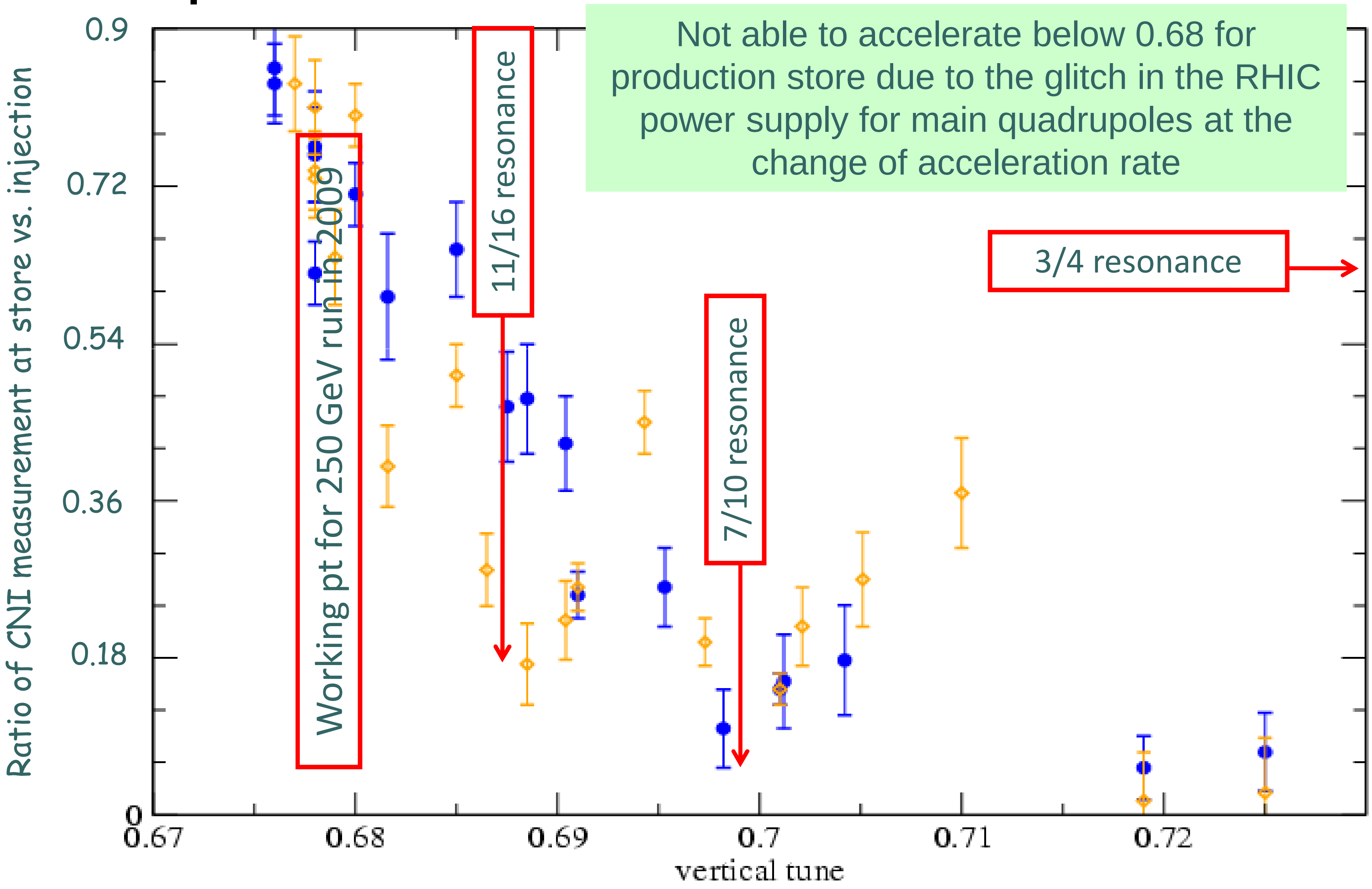


RHIC Polarization vs. Beam Energy

- 100 GeV and above measurements use analyzing power calibrated at 100 GeV using H Jet polarimeter
- Estimated systematic error of analyzing power is ~10%



Measured Snake Resonance Spectrum



Reach polarization of 70% or higher

- RHIC:
  - accelerate close to 0.675 between 100 GeV and 250 GeV
  - Tighter control of local orbit at rotators during store
  - CNI polarimeter improvement
- AGS:
  - Horizontal tune jump quad to avoid polarization losses at horizontal resonances
- Source:
  - Upgrade to achieve ~90% polarization

Summary

- High energy polarized protons are desirable for unveiling the secret of the proton spin structure
- Accelerating polarized protons in a circular accelerator is challenged by the depolarizing mechanisms during the acceleration
- The great invention of Siberian snake made it possible for preserving polarization when accelerating protons to high energy
- RHIC as the world's first high energy polarized proton collider has been successfully accelerating polarized protons up to 100 GeV with no polarization loss
- With the new tune to avoid snake resonance, it is promising to preserve 90% or higher polarization up to 250 GeV in the coming RHIC pp run

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