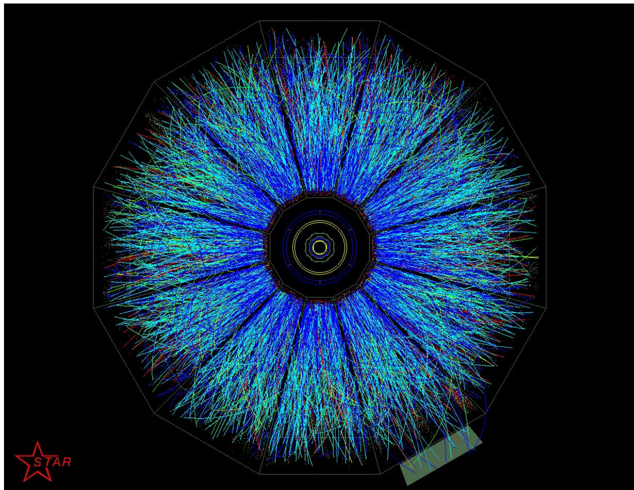
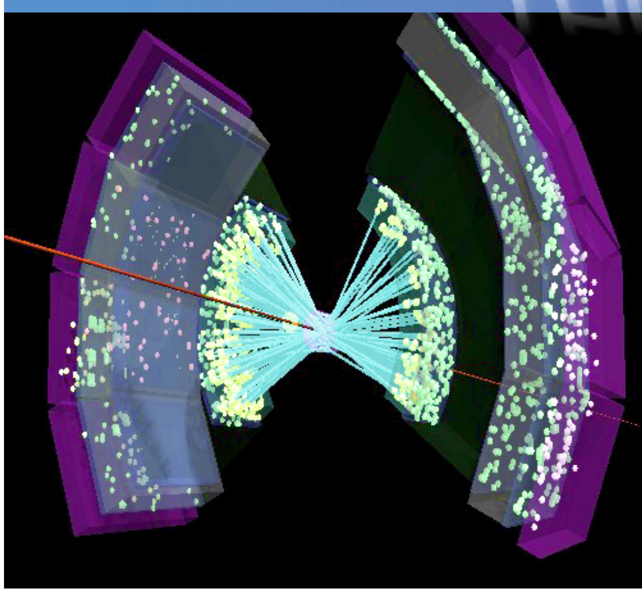


THE RELATIVISTIC HEAVY ION COLLIDER

THE ONLY COLLIDER IN THE US



BROOKHAVEN NATIONAL LABORATORY

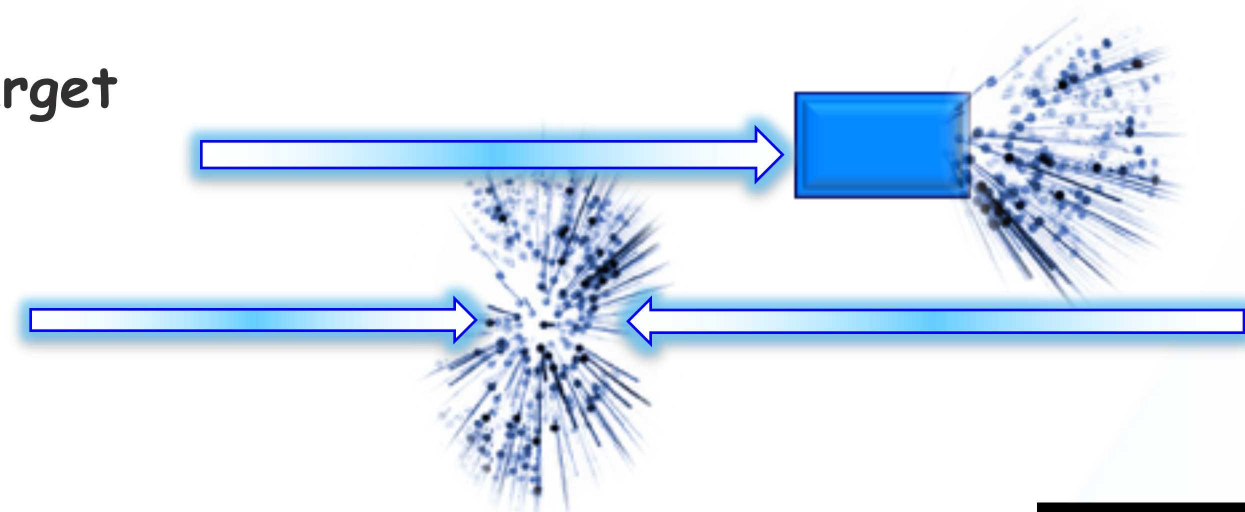
a passion for discovery

U.S. DEPARTMENT OF ENERGY | Office of Science

PARTICLE ACCELERATORS

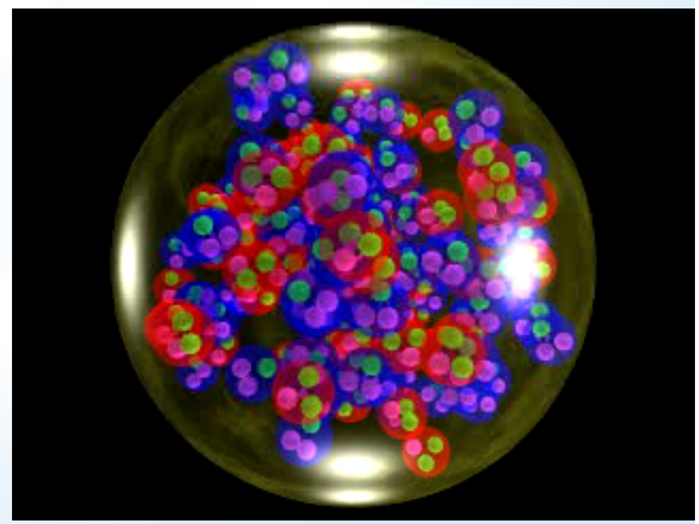
Large scientific instruments that produce and accelerate subatomic particles and 'smashes them'

- Fixed target
- Collider

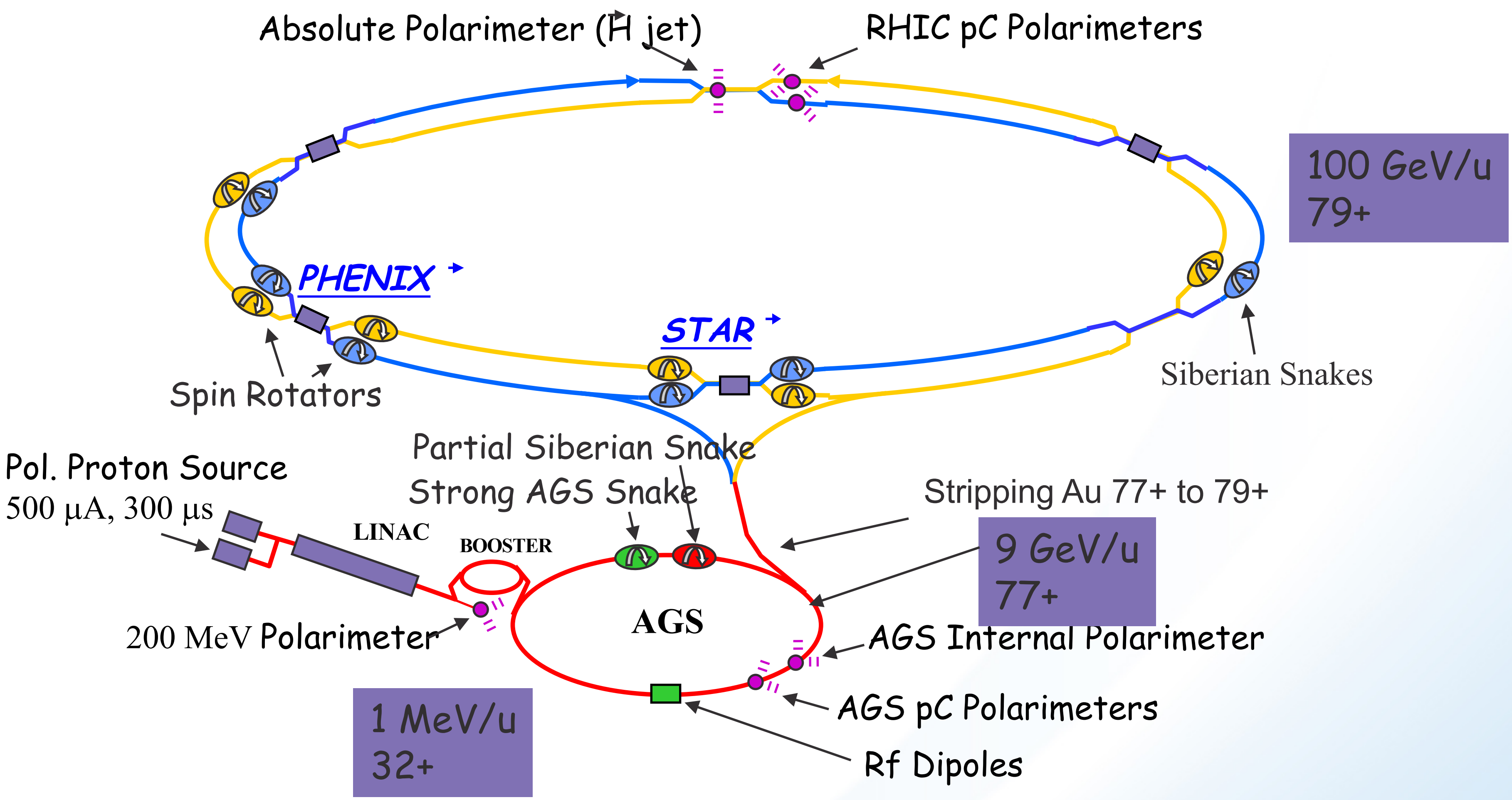


Particles: electrons, positrons, protons, anti-protons, ions…..
(atoms stripped of electrons: nuclei)

Nuclei → protons + neutrons
→ quarks + gluons



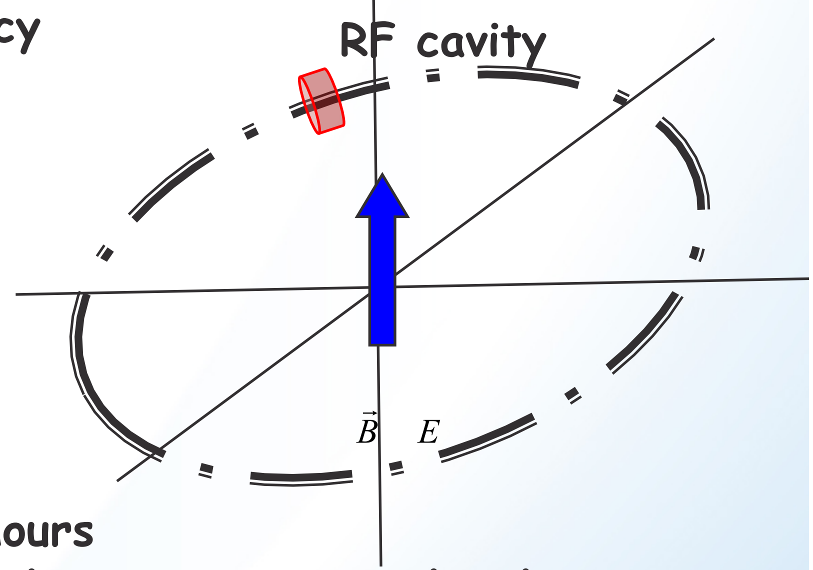
THE RHIC COMPLEX



SYNCHROTRONS AND STORAGE RINGS

Synchrotrons (Booster, AGS):

- Circular machines used to rapidly accelerate particles to higher energies
- The acceleration comes from the electric field with an oscillating frequency synchronized with the particle's revolution frequency
- Typical cycle time: 1 sec



Storage rings (RHIC):

- Circular machines used to store beams over many hours
- May be used to slowly accelerate beams from injection to top energy in minutes

THE LORENTZ FORCE

Charged particles are guided by magnetic fields, using the Lorentz force:

$$\vec{F} = q \bullet \left(\vec{v} \bullet \vec{B} \right)$$

F : force
q : electric charge of the particle
v : particle velocity
B: magnetic field

Vector equation: F is perpendicular to v and B

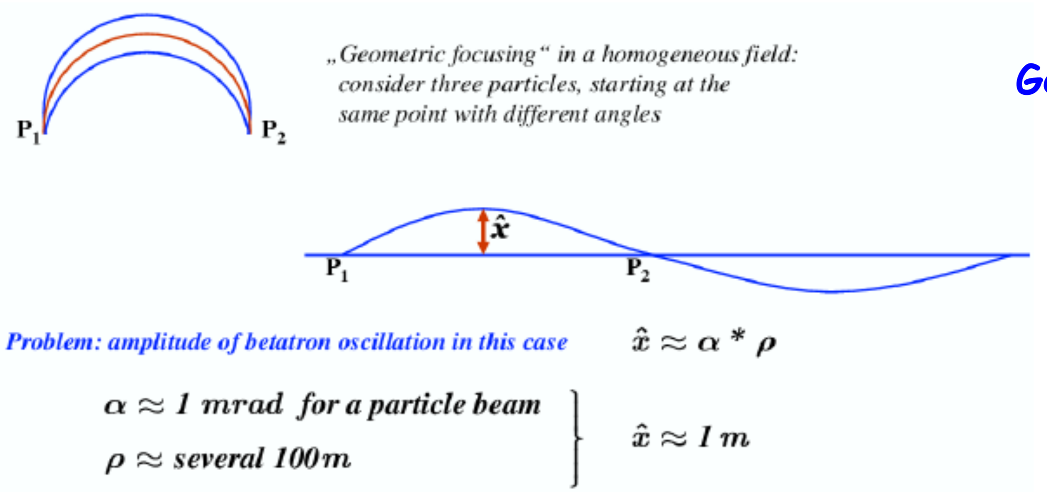
Important consequence:
Magnetic fields can only deflect particles, but cannot change their velocity (or energy)

BASICS OF CIRCULAR ACCELERATOR

- bending dipole
  - Constant magnetic field
  - Keeps particles circulating around the ring
- quadrupole
  - Magnetic field proportional to the distance from the center of the magnet.
  - Keeps particles focused
- radio frequency cavities
  - Electric field for acceleration and keeping beam bunched longitudinally

WEAK FOCUSING

- In a homogeneous dipole field, all particles travel on circles with slightly different centers depending on initial particle direction:

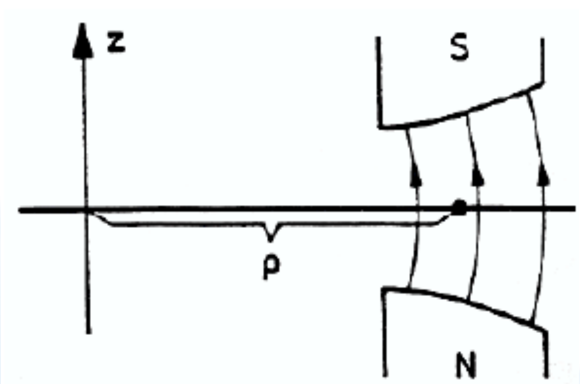


Geometric focusing in the horizontal plane

The vertical plane

Without vertical focusing, particles inevitably spiral out of the horizontal plane

Solution: Provide a restoring force F_z/z



Modified pole faces provide horizontal field component $B_x(z) = z \cdot dB/dz = z \cdot const.$

→ Restoring force $F_z = q \cdot v \cdot z \cdot dB/dz$ (harmonic oscillator)

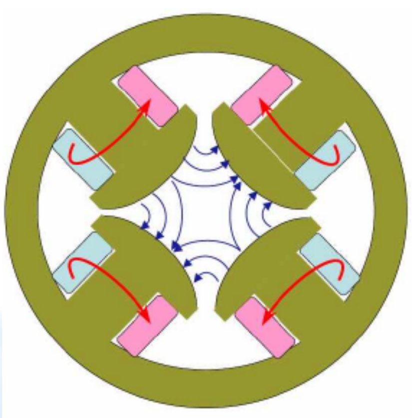
SUMMARY OF WEAK FOCUSING

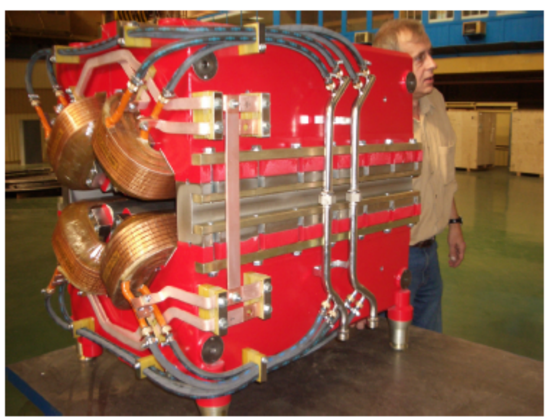
- Simultaneous bending and focusing by combined-function magnets (dipoles with modified pole face shape)
- Typical beam size: 1m
- Requires large vacuum chambers (beam pipes) that become more and more impractical in larger machines

Remedy: Separate bending and focusing functions (= "strong focusing")

Strong focusing

Quadrupole magnets focus the beam in one plane, and de-focus in the other

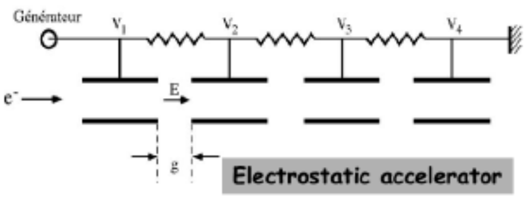


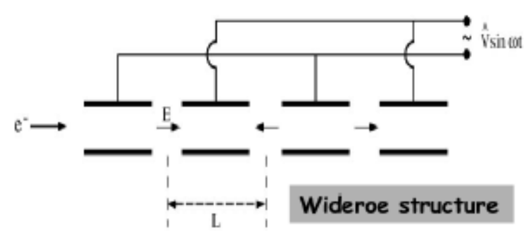


- Alternate focusing and defocusing quadrupoles
- Typical beam size: 1mm to 1 cm
- Beam optics described by matrix multiplication

LONGITUDINAL DYNAMICS

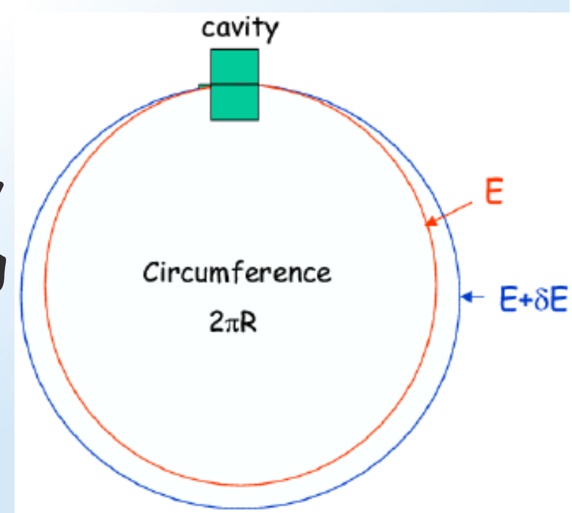
- How does an accelerator accelerate the beam?
- Magnetic fields only deflect the beam, but electric fields can change the beam energy



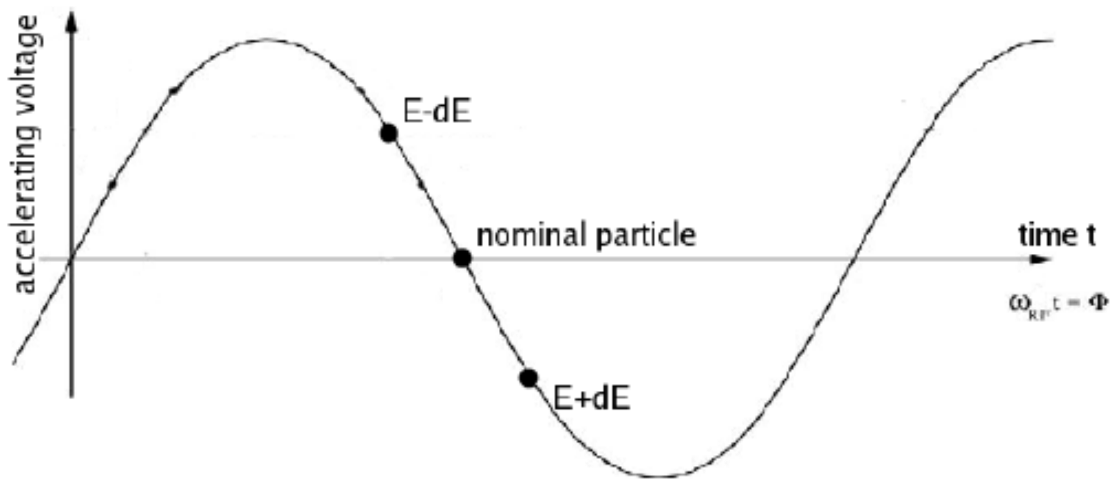


While the particle is inside the field-free drift tube, the polarity changes

- A highly relativistic particle (v~c) with an energy $E+\delta E$ is heavier $(E+\delta E=(+\delta m)c^2)$ then the nominal particle at energy E, and therefore travels at a larger radius $R+\delta R$.
- Since the pathlength (circumference) $2\pi(R+\delta R)$ at this larger radius is larger while the velocity v is practically unchanged, the particle arrives late at the accelerating section (cavity).



LONGITUDINAL DYNAMICS



At fixed energy (no acceleration):

- the nominal particle receives no longitudinal kick, so its energy E remains unchanged
- a particle with higher energy E + δE arrives at a later time, receives a negative kick, and gets decelerated
- a particle with lower energy E – δE arrives early, receives a positive kick, and gets accelerated

To accelerate the entire beam, gently increase the dipole field to reduce the path length, so all particles arrive early and get accelerated

Polarized proton beams
Or
How to do magic with an accelerator

WHAT IS SPIN? FROM GOOGLE…

- revolve quickly and repeatedly around one's own axis, "The dervishes whirl around and around without getting dizzy”
- twist and turn so as to give an intended interpretation, "The President's spokesmen had to spin the story to make it less embarrassing”
- a distinctive interpretation (especially as used by politicians to sway public opinion), "the campaign put a favorable spin on the story"

WHAT IS SPIN?

- Classical definition
  - the body rotation around its own axis

- Particle spin:
  - an intrinsic property, like mass and charge
  - a quantum degree freedom associated with the intrinsic magnetic moment μ_S.

$$\mu_s = (1 + G)\frac{q}{m}S$$

q: electrical charge of particle

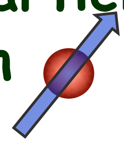
m: particle mass

G: anomalous gyromagnetic factor, describes the particle internal structure.

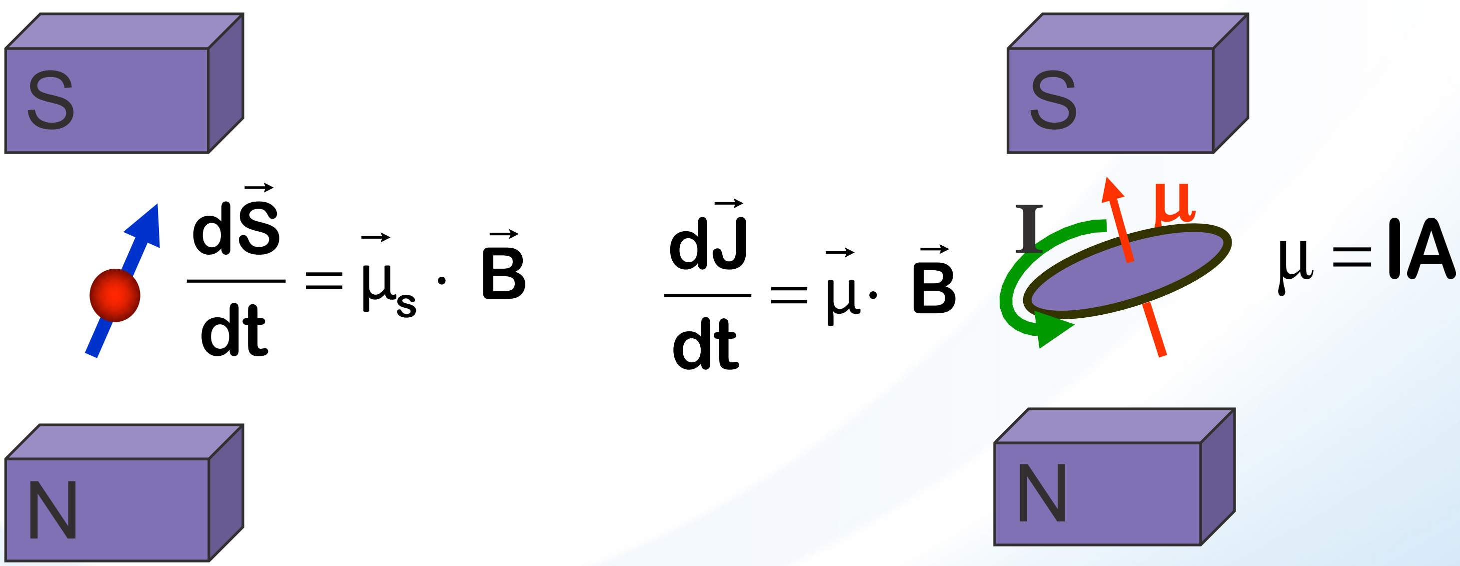
For particles:
point-like: G=0
electron: G=0.00115965219
muon: G=0.001165923
proton: G=1.7928474

SPIN VECTOR AND SPIN-ORBIT INTERACTION

- **Spin:** single particle
  - pure spin state aligned along a quantization axis
- **Spin vector S:** a collection of particles
  - the average of each particles spin expectation value along a given direction



- Spin orbit interaction

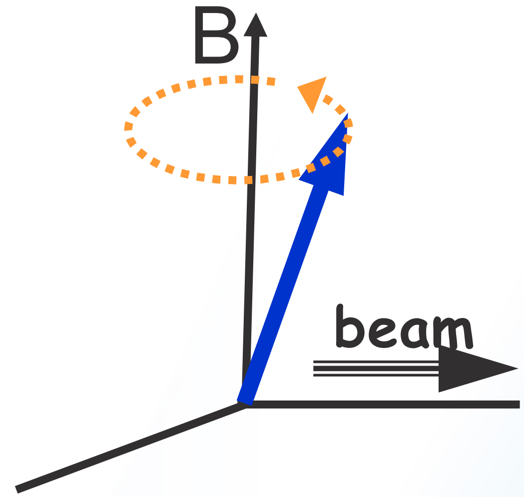


SPIN DEPOLARIZING RESONANCE

- In a perfect accelerator, spin vector precesses around the bending dipole field direction: vertical
- Spin tune Q_s: number of precessions in one orbital revolution. In general,

$$Q_s = G\gamma$$

G: anomalous magnetic moment
γ: relativistic Lorentz factor



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

$$G\gamma = k$$

k is an integer

- Intrinsic resonance
  - Source: horizontal focusing field from betatron oscillation
  - Resonance location:

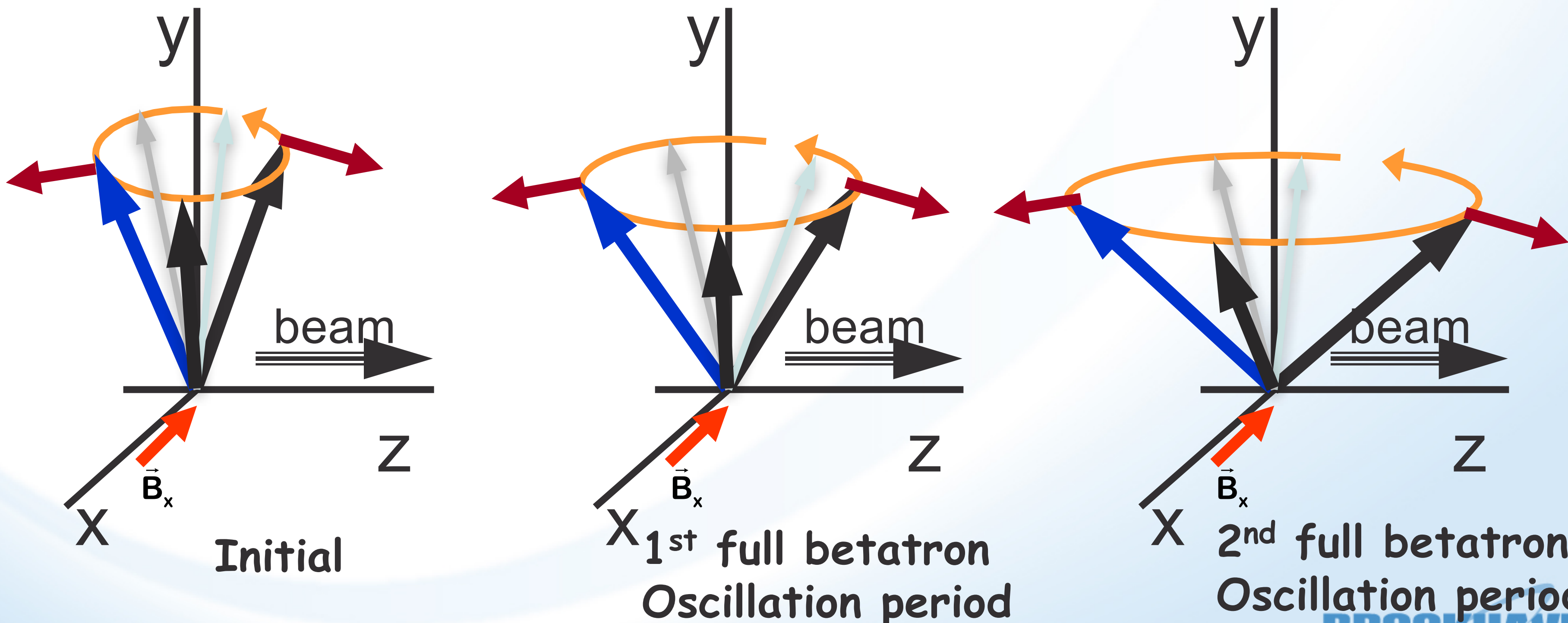
$$G\gamma = kP \pm Qy$$

P is the periodicity of the accelerator,

Qy is the vertical betatron tune

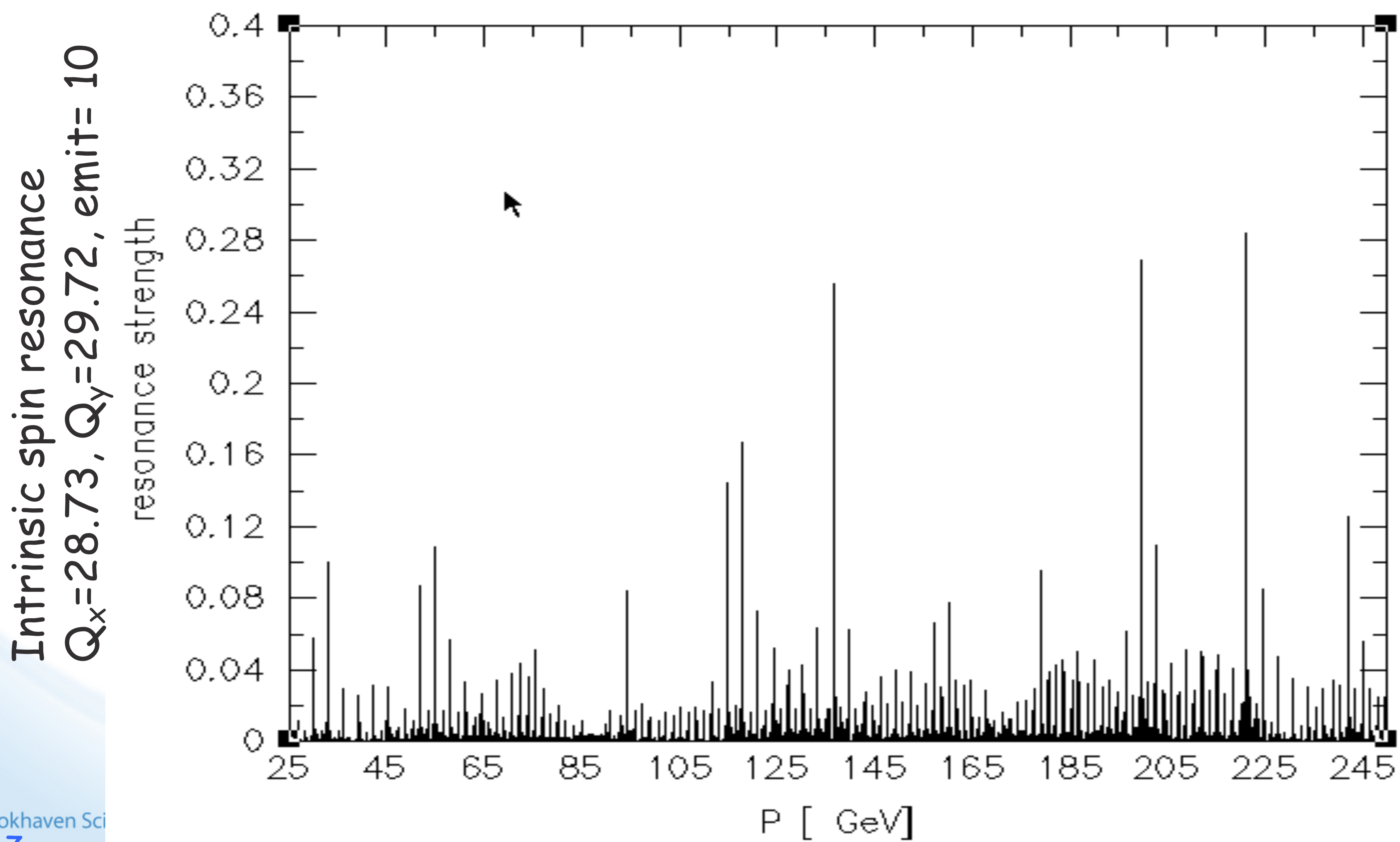
POLARIZED PROTON ACCELERATION CHALLENGES: PRESERVE BEAM POLARIZATION

- **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



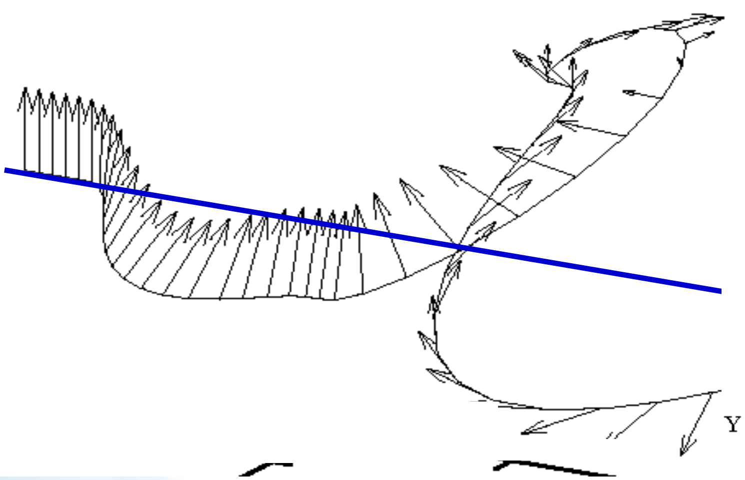
SPIN DEPOLARIZATION RESONANCE IN RHIC

For protons, imperfection spin resonances are spaced by 523 MeV the higher energy, the stronger the depolarizing resonance

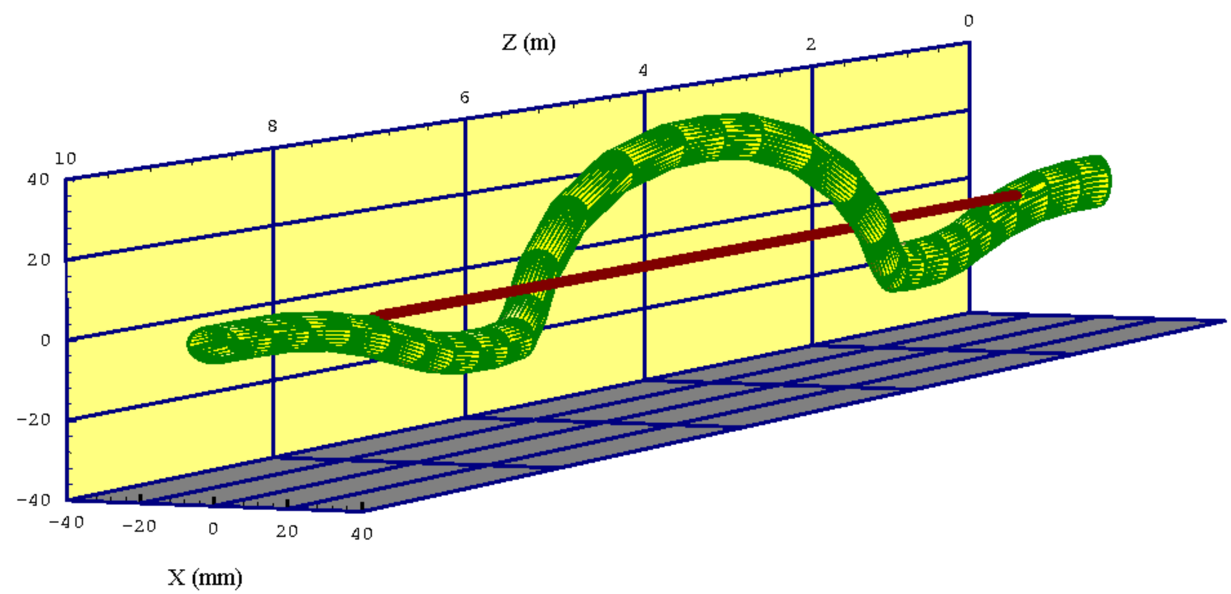


INNOVATIVE POLARIZED PROTON ACCELERATION TECHNIQUES: SIBERIAN SNAKE

- First invented by Derbenev and Kondratenko from Novosibirsk in 1970s
- A group of dipole magnets with alternating horizontal and vertical dipole fields
- rotates spin vector by 180° about a horizontal axis, the stable spin direction remains unperturbed at all times as long as the spin rotation from the Siberian Snake is much larger than the spin rotation due to the resonance driving fields. Therefore the beam polarization is preserved during acceleration. An alternative way to describe the effect of the Siberian Snake comes from the observation that the spin tune with the Snake is a half-integer and energy independent.

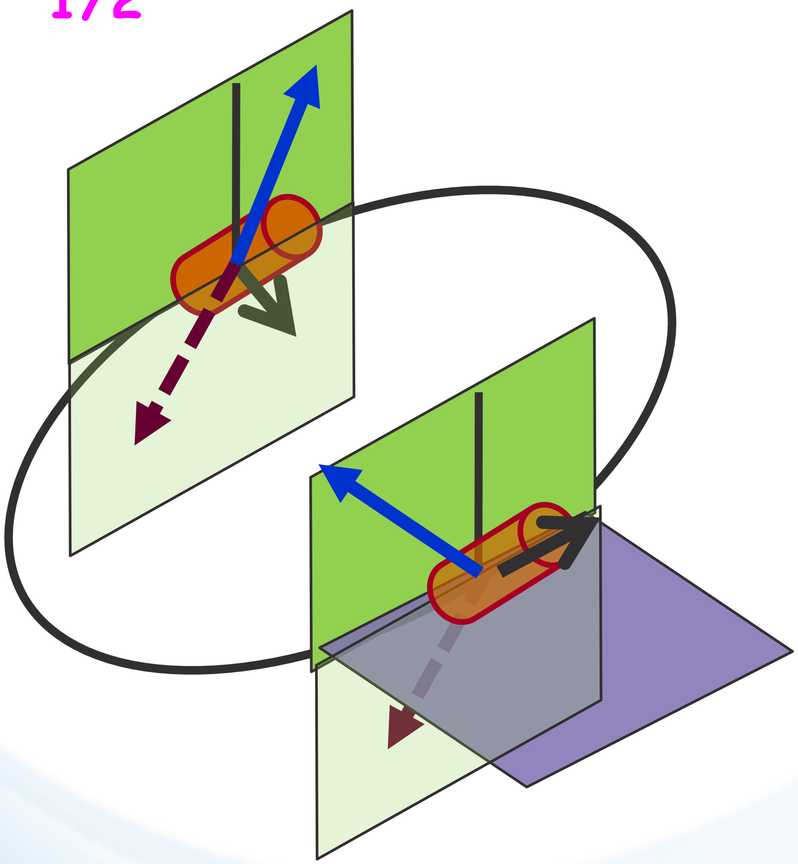


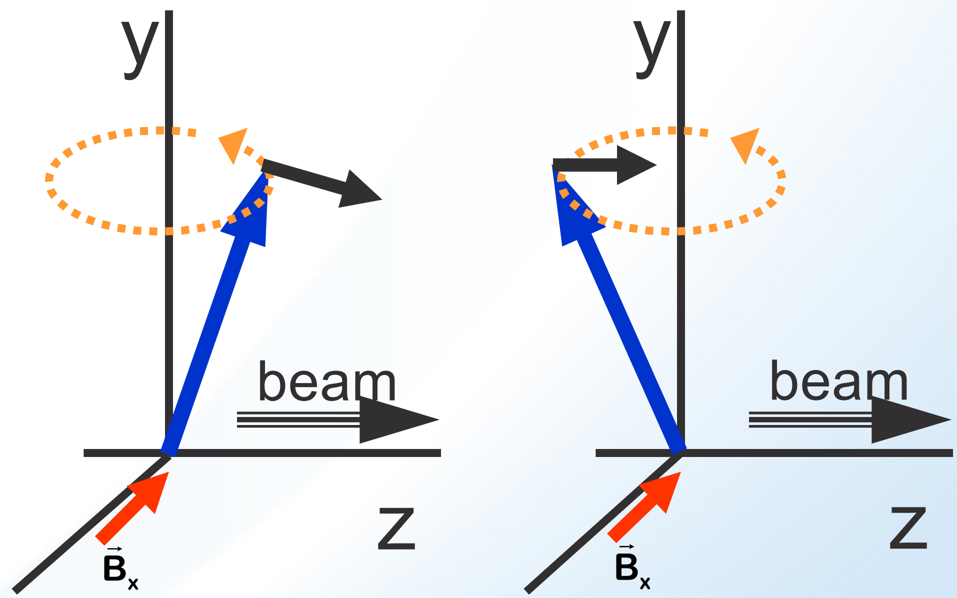
Particle trajectory in a snake:

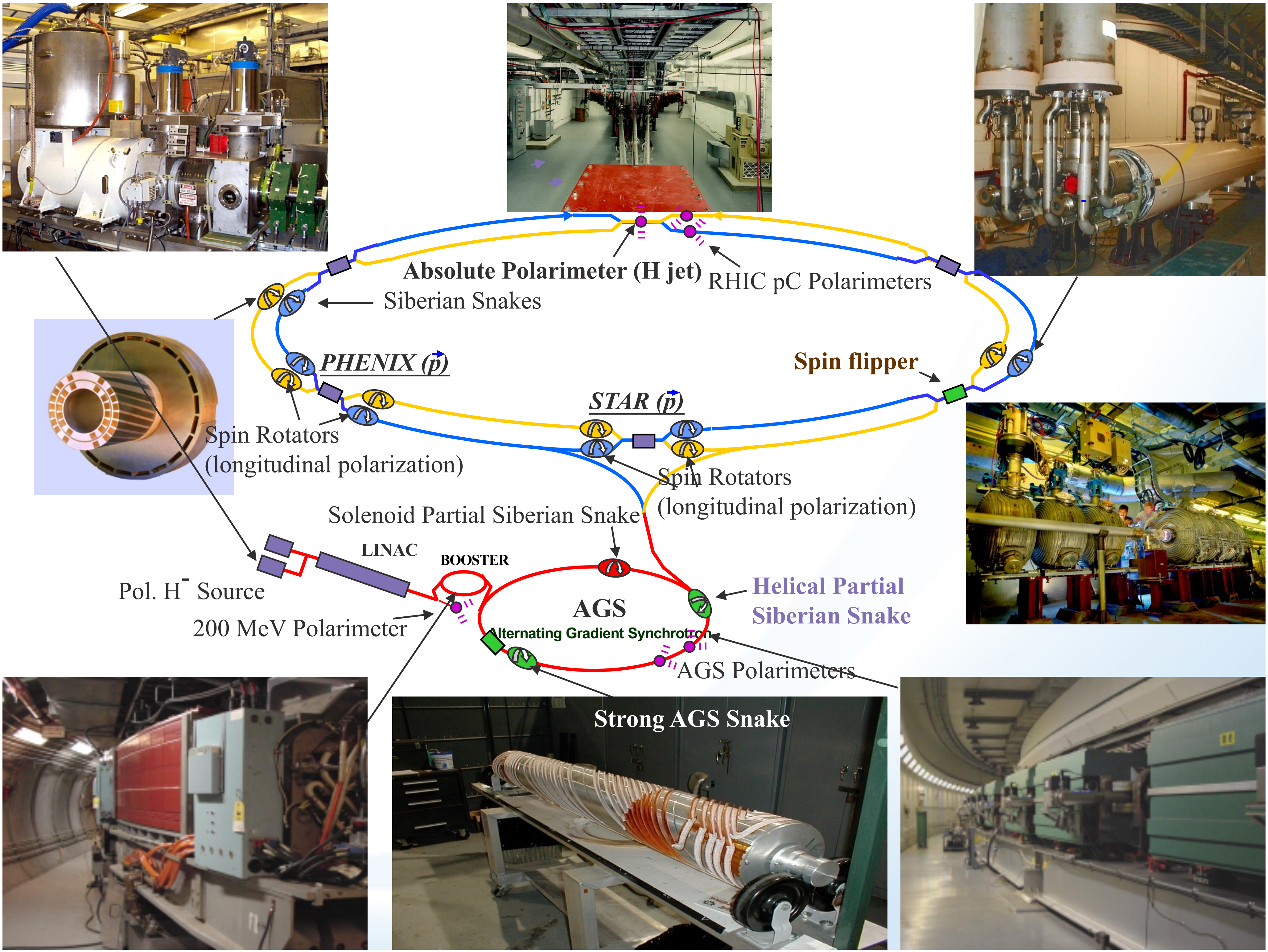


HOW TO PRESERVE POLARIZATION USING SIBERIAN SNAKE(S)

- Use one or a group of snakes to make the spin tune to be 1/2
- Break the coherent build-up of the perturbations on the spin vector

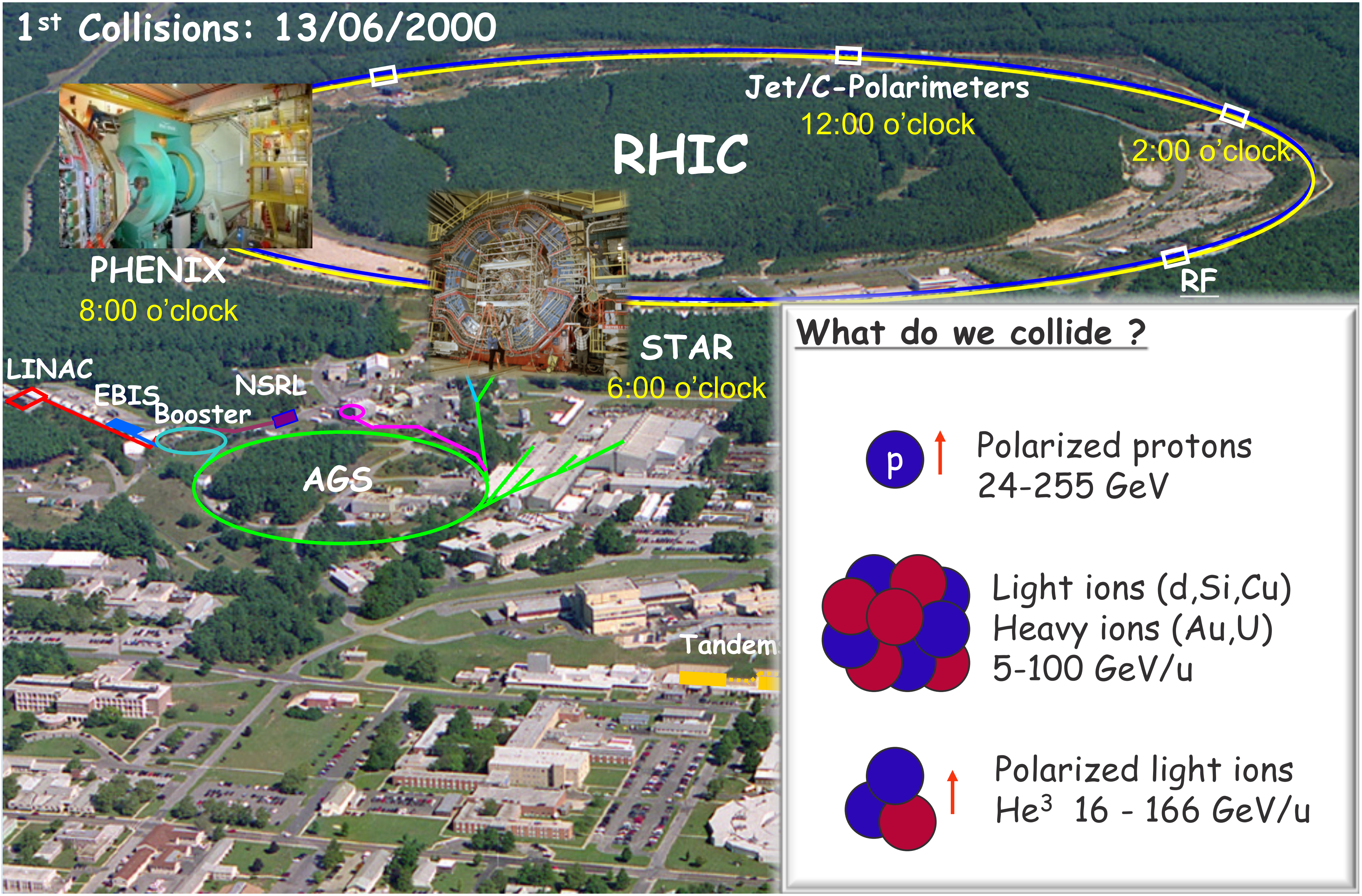






Absolute Polarimeter (H jet)
RHIC pC Polarimeters
Siberian Snakes
PHENIX (p)
Spin flipper
STAR (p)
Spin Rotators
(longitudinal polarization)
Spin Rotators
(longitudinal polarization)
Solenoid Partial Siberian Snake
LINAC
BOOSTER
Pol. H⁻ Source
200 MeV Polarimeter
AGS
Alternating Gradient Synchrotron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

RHIC @ BROOKHAVEN NATIONAL LAB



What do we collide ?

p — Polarized protons
24-255 GeV

Light ions (d,Si,Cu)
Heavy ions (Au,U)
5-100 GeV/u

Polarized light ions
He^3 16 - 166 GeV/u

THE RHIC PROJECT CHRONOLOGY

- 1989 RHIC design
- 1991 construction starts
- 1996 commissioning AtR injection lines
- 1997 sextant test (1/6 of the ring)
- 1999 RHIC engineering/test run
- 2000 first collisions
- 2001-02 Au-Au run, polarized p run
- 2003 deuteron-Au run, pp
- 2004 Au-Au physics run and 5 weeks pp development
- 2005 …..

RHIC is also a giant engineering challenge:
magnets (3000+ industry and lab built superconducting magnets)
cryogenics (2 weeks to cool down to 4.2K) ,instrumentation, etc.

RHIC OPERATIONS

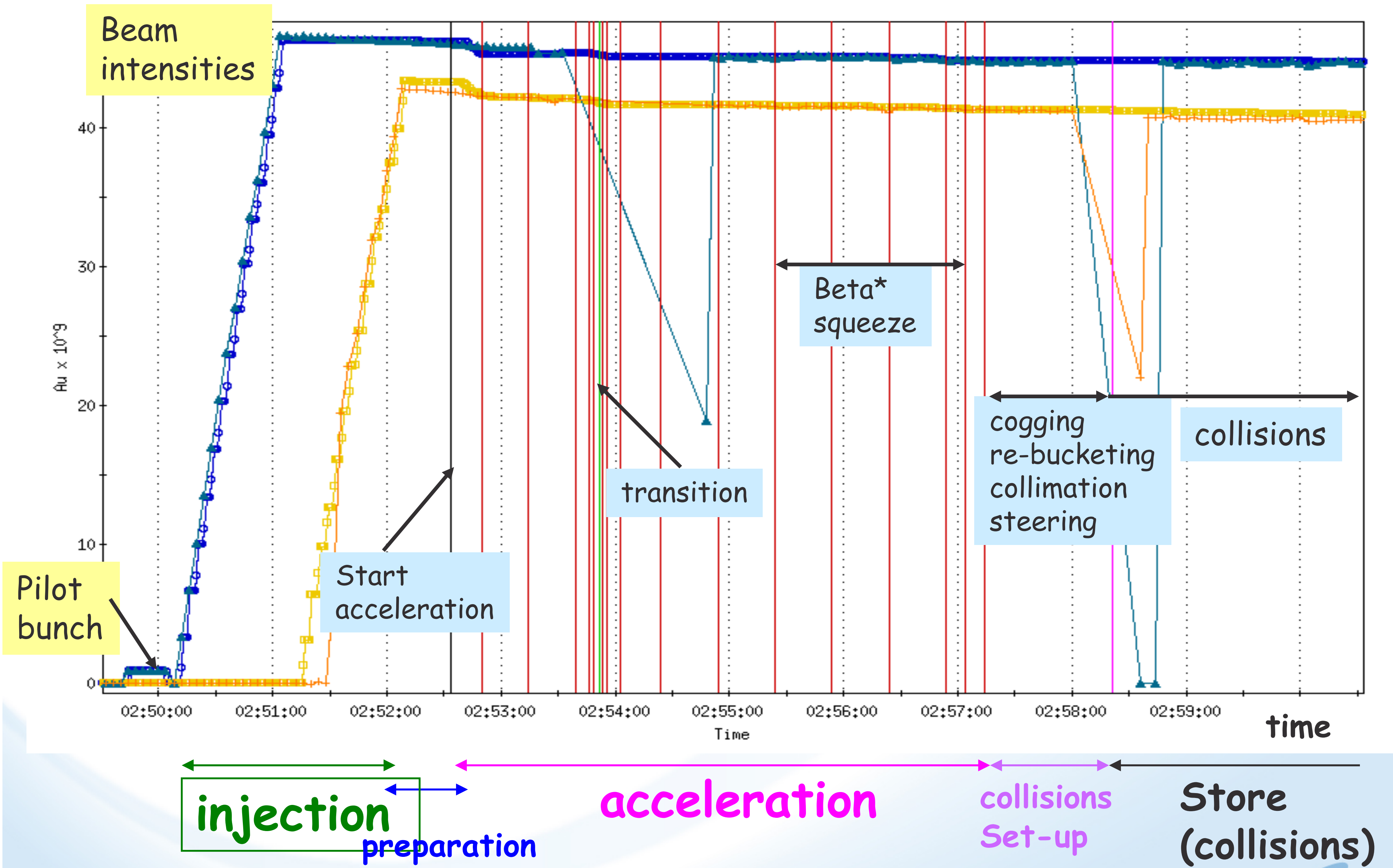
The operation of RHIC and its injectors is a rather challenging endeavor….

RHIC operates for ~5-6 months/year – 24h/day 7 days/week

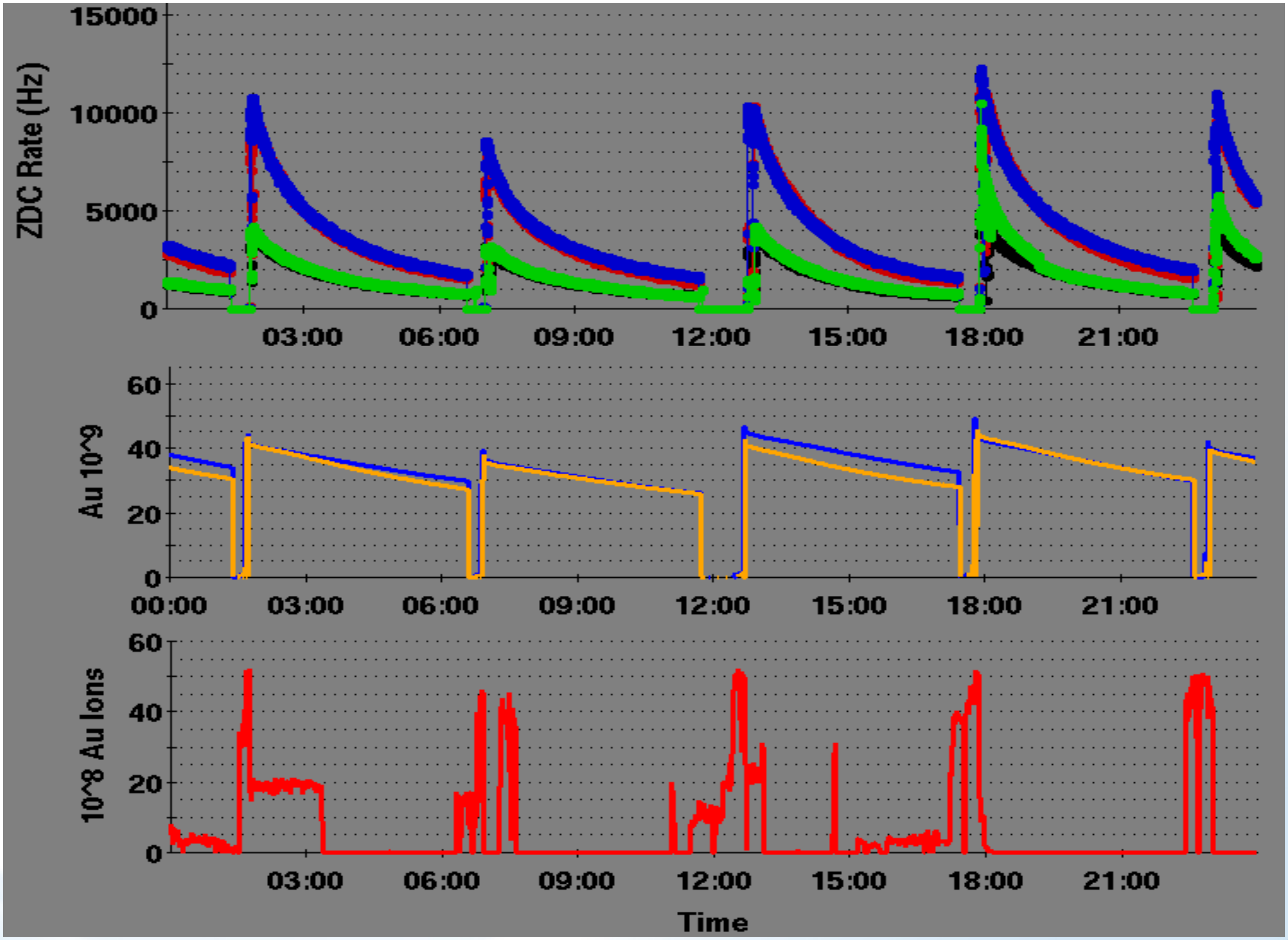
RHIC Shutdown 6-7 months, for machine improvements (other programs are run by the injectors, Tandem delivering ions for industrial R&D, Booster delivering ions for NASA experiments, etc.)

- CONTROL ROOM : remote access to instrumentations and controls
- Accelerator physicists, shift leaders (machine initial set-up, new developments, beam experiments)
- Operations group: operation coordinator, operators ("routine' operations, shifts 1 OC + 2 operators)
- Technical support (engineers and technicians on call and/or site for system diagnosis and trouble-shooting)

INJECT, ACCELERATE, COLLIDE……!

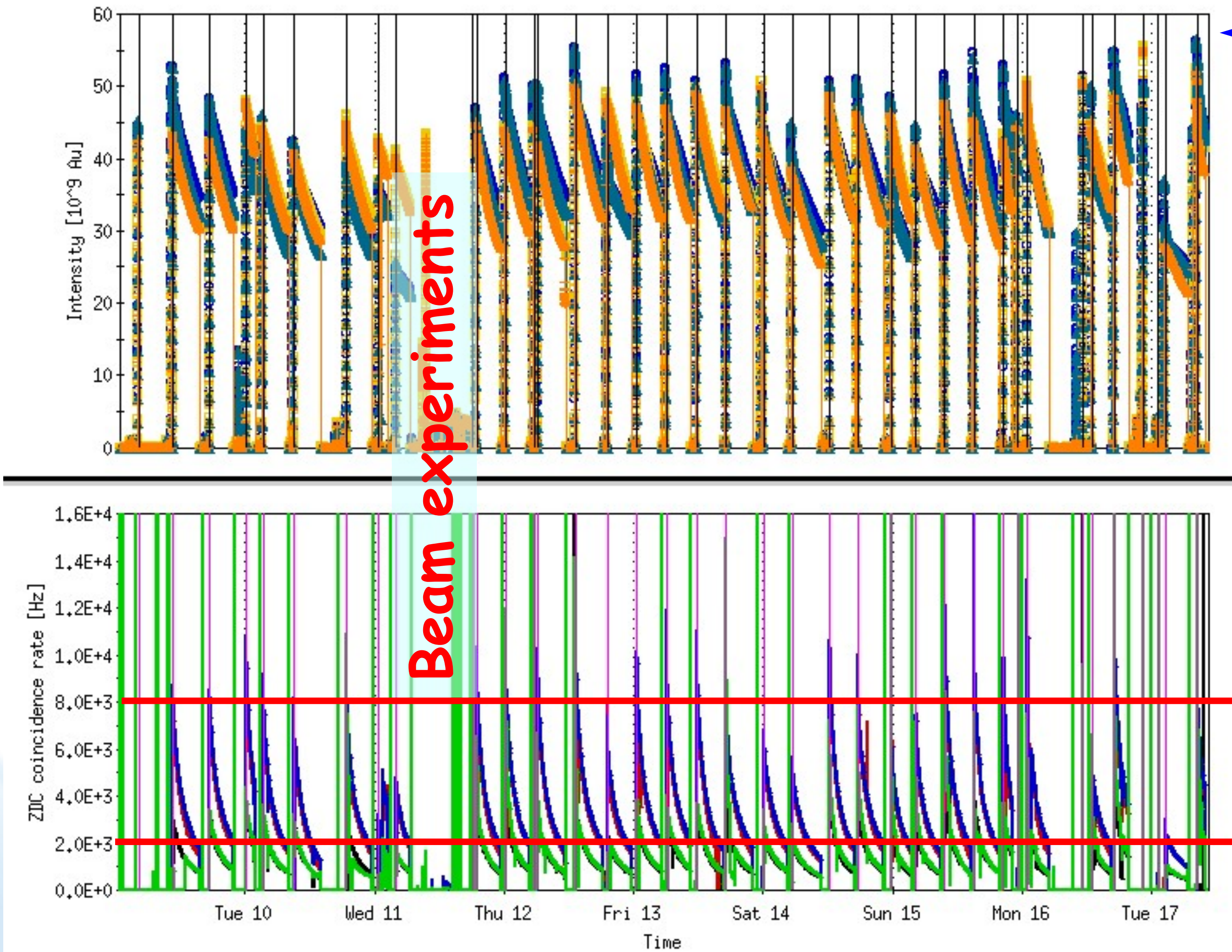


A DAY IN THE LIFE OF RHIC…



A WEEK IN THE LIFE OF RHIC…

Week 9 Feb to 17 Feb [66% of calendar time in store]

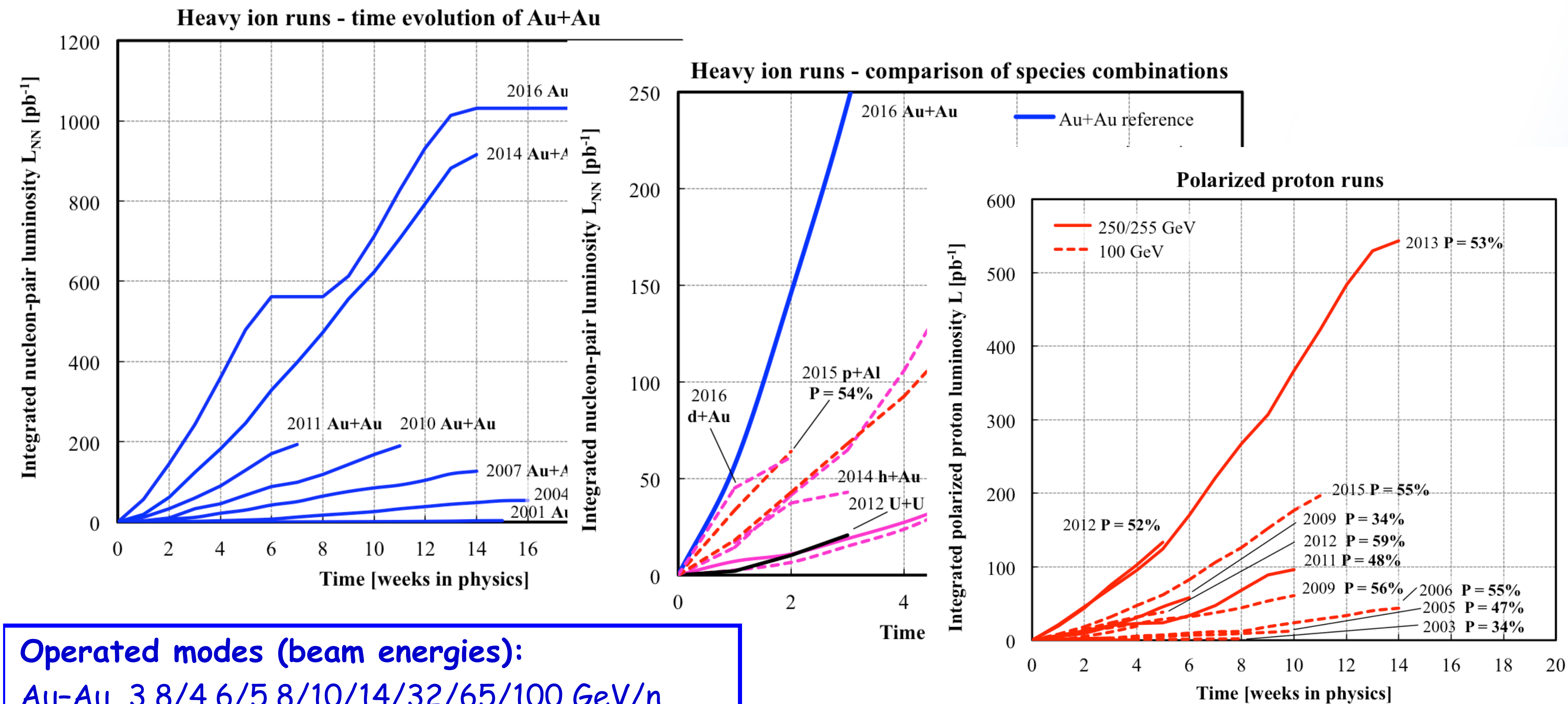


60×10^9 Au intensity

enhanced luminosity

design luminosity

A FEW YEARS IN THE LIFE OF RHIC…



Operated modes (beam energies):

Au-Au 3.8/4.6/5.8/10/14/32/65/100 GeV/n

d-Au* 100 GeV/n

Cu-Cu 11/31/100 GeV/n

p↑-p↑ 11/31/100, 250 GeV

Planned or possible future modes:

Au – Au 2.5 GeV/n (~ SPS cm energy)

U – U 100 GeV/n

p↑ – Au* 100 GeV/n

Cu – Au* 100 GeV/n (*asymmetric rigidity)

Achieved peak luminosities (100 GeV, nucl.-pair):

Au-Au 195×10^{30} cm^{-2} s^{-1}

p↑-p↑ 60×10^{30} cm^{-2} s^{-1}

Other large hadron colliders (scaled to 100 GeV):

Tevatron (p – pbar) 43×10^{30} cm^{-2} s^{-1}

LHC (p – p) 37×10^{30} cm^{-2} s^{-1}

FIGURE OF MERIT OF POLARIZED PROTON COLLIDER

❑ Luminosity:

➢ number of particles per unit area per unit time. The higher the luminosity, the higher the collision rates

$$L(t) = \frac{1}{4} f_0 N \frac{n^2(t)}{{}^{2}_{rms}(t)}$$

→ # of particles in one bunch

# of bunches

Transverse beam size

❑ beam polarization

➢ Statistical average of all the spin vectors.
  - ➢ zero polarization: spin vectors point to all directions.
  - ➢ 100% polarization: beam is fully polarized if all spin vectors point to the same directions.

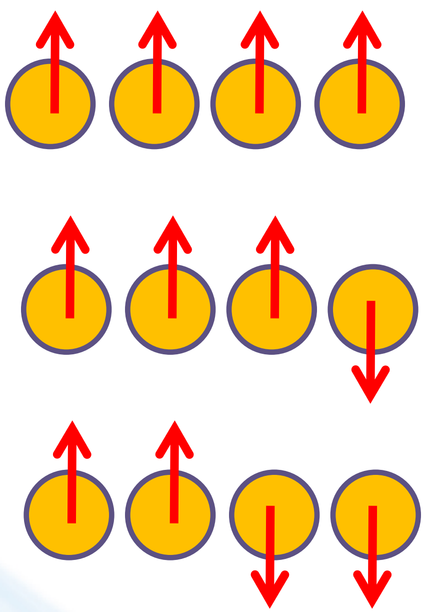
How do we know the protons are polarized

WHAT IS BEAM POLARIZATION?

Simple example: spin-1/2 particles (proton, electron)
Can have only two spin states relative to certain axis *Z*: S_z=+1/2 and S_z =-1/2

$$P = \frac{N_{S_Z=+1/2} \quad N_{S_Z=\ 1/2}}{N_{S_Z=+1/2} + N_{S_Z=\ 1/2}}$$

$|P|<1$

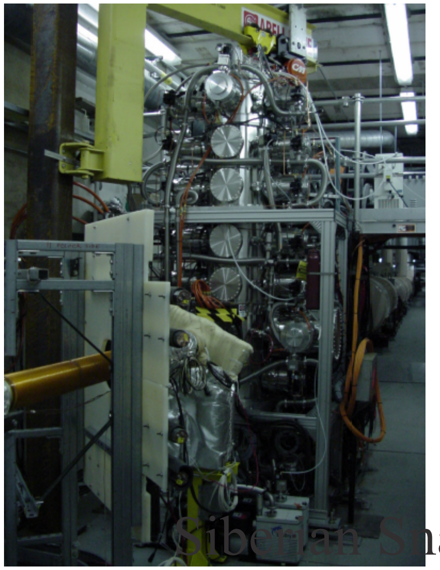


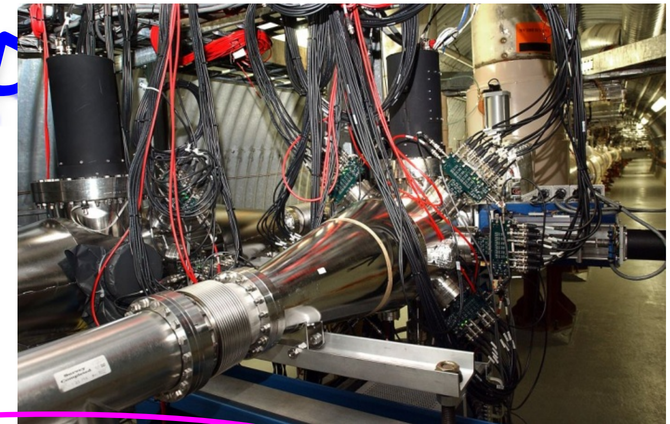
$$P = \frac{4 \quad 0}{4+0} = 1$$

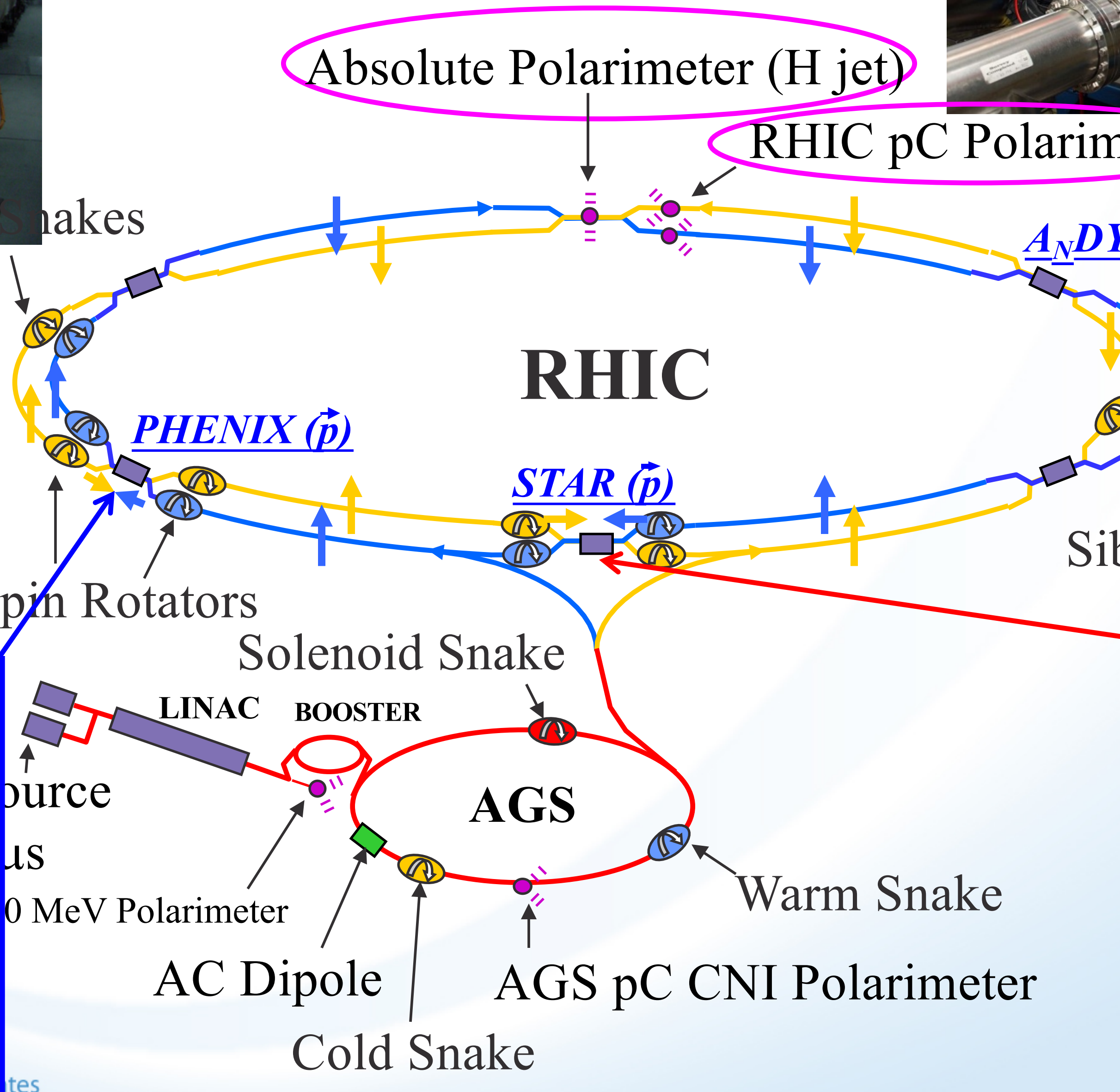
$$P = \frac{3 \quad 1}{3+1} = 0.5$$

$$P = \frac{2 \quad 2}{2+2} = 0$$

RHIC AND







Absolute Polarimeter (H jet)
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$A_N DY$ ($\vec{p}$)
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LINAC
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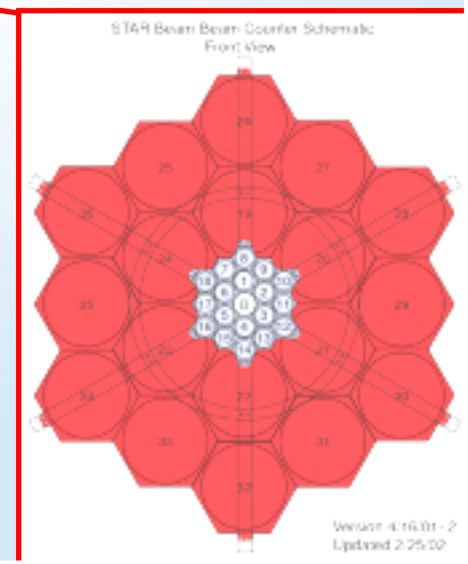
AGS
ource
us
0 MeV Polarimeter
Warm Snake
AC Dipole
AGS pC CNI Polarimeter
Cold Snake
tes



STAR Beam Beam Counter Schematic
Front View

RHIC POLARIMETRY

Polarized hydrogen Jet Polarimeter (HJet)

- Source of absolute polarization (normalization of other polarimeters)
- Slow (low rates ⇒ needs looong time to get precise measurements)

Proton-Carbon Polarimeter (pC) @ RHIC and AGS

- Very fast ⇒ main polarization monitoring tool
- Measures polarization lifetime and profile (polarization is higher in beam center)
- Needs to be normalized to HJet

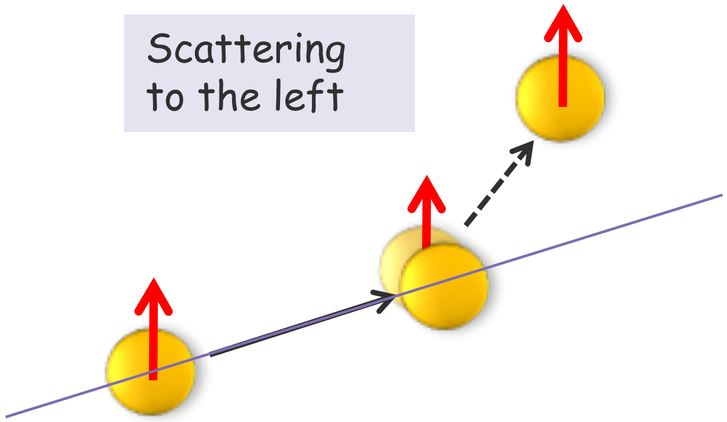
Local Polarimeters (in PHENIX and STAR experiments)

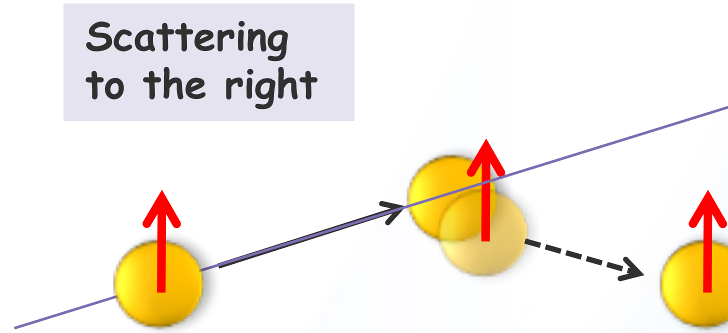
- Defines spin direction in experimental area
- Needs to be normalized to HJet

All of these systems are necessary for the proton beam polarization measurements and monitoring

HOW TO MEASURE PROTON BEAM POLARIZATION

There are several established physics processes sensitive to the spin direction of the transversely polarized protons



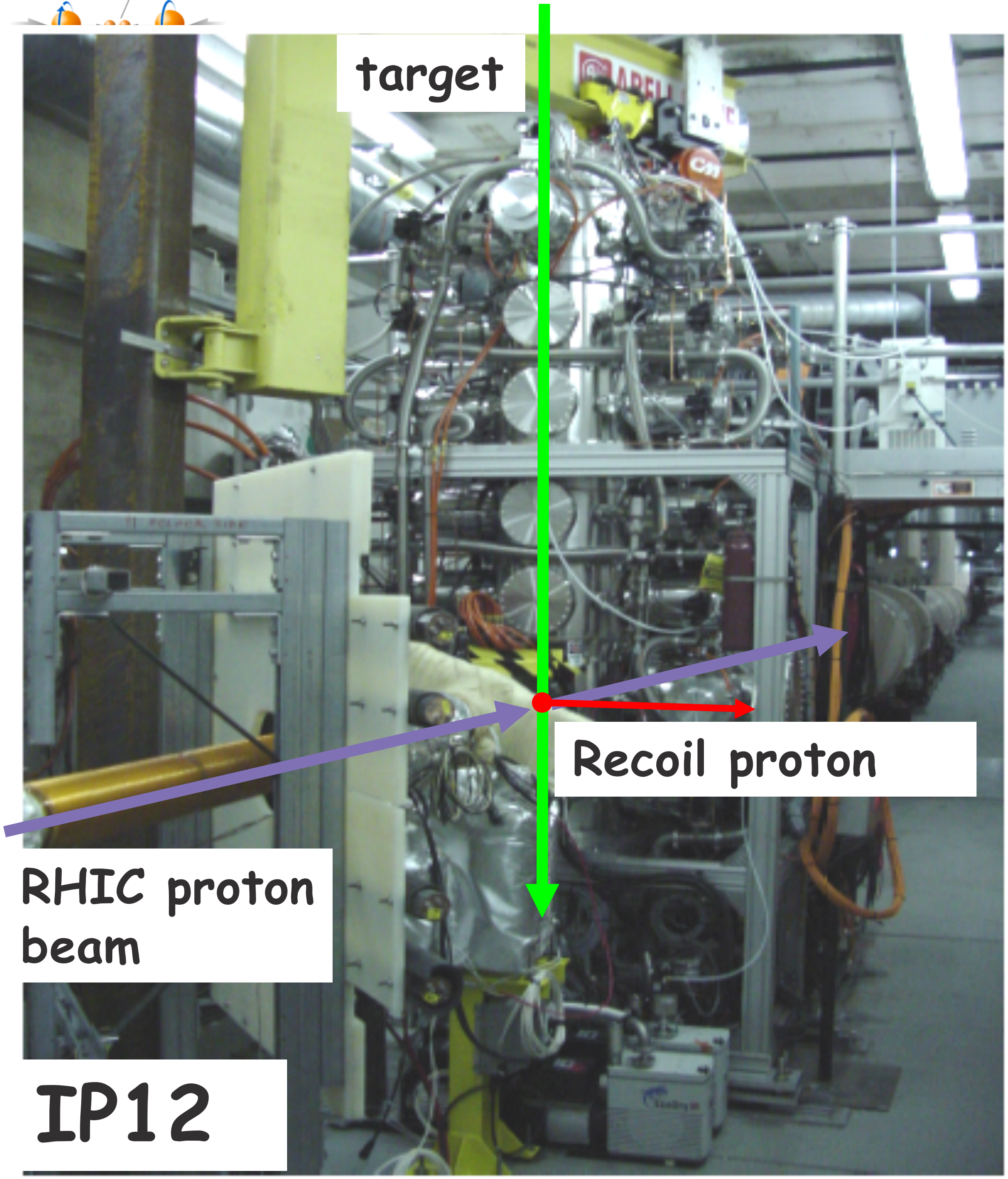


$$\varepsilon = \frac{N_{left} - N_{right}}{N_{left} + N_{right}} = A_N P$$

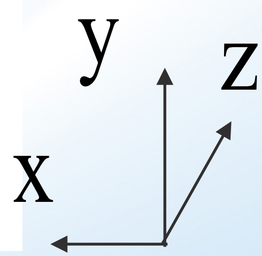
A_N – the Analyzing Power ($|A_N| < 1$)
(left-right asymmetry for 100% polarized protons)

Once A_N is known: $P = \frac{}{A_N}$

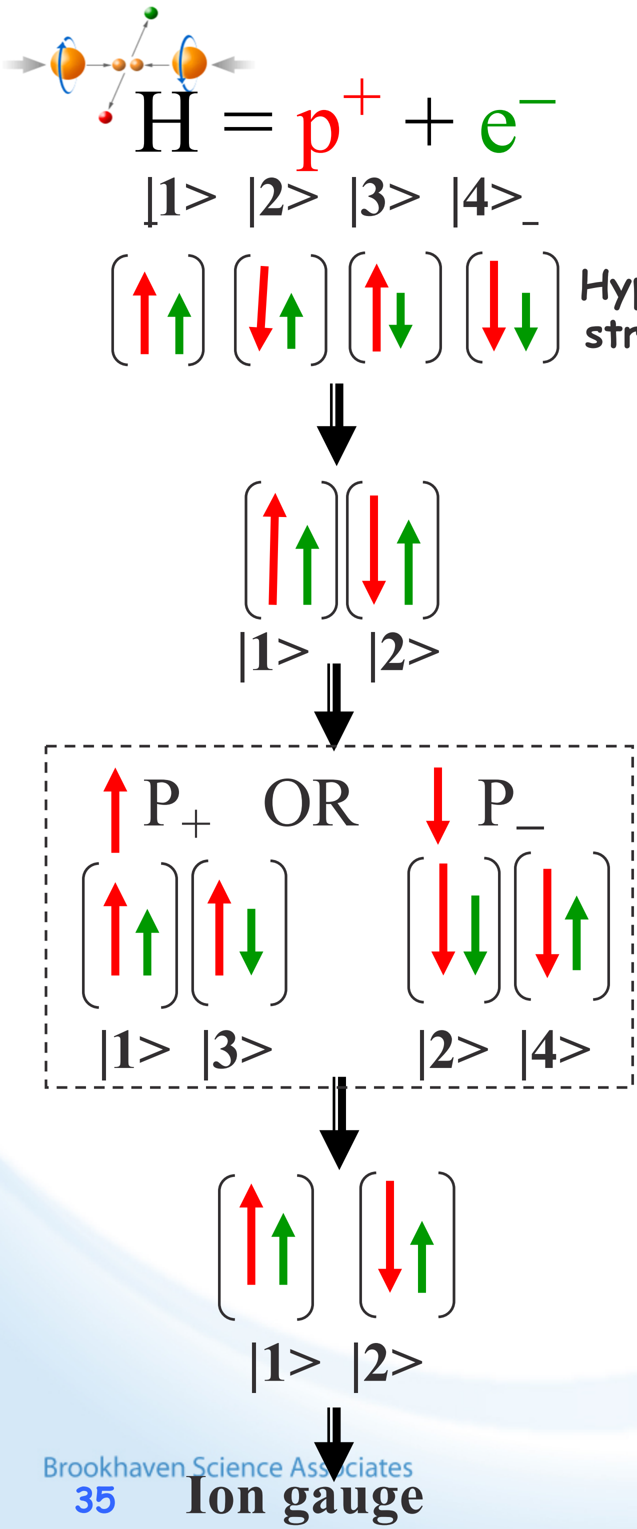
H-JET SYSTEM

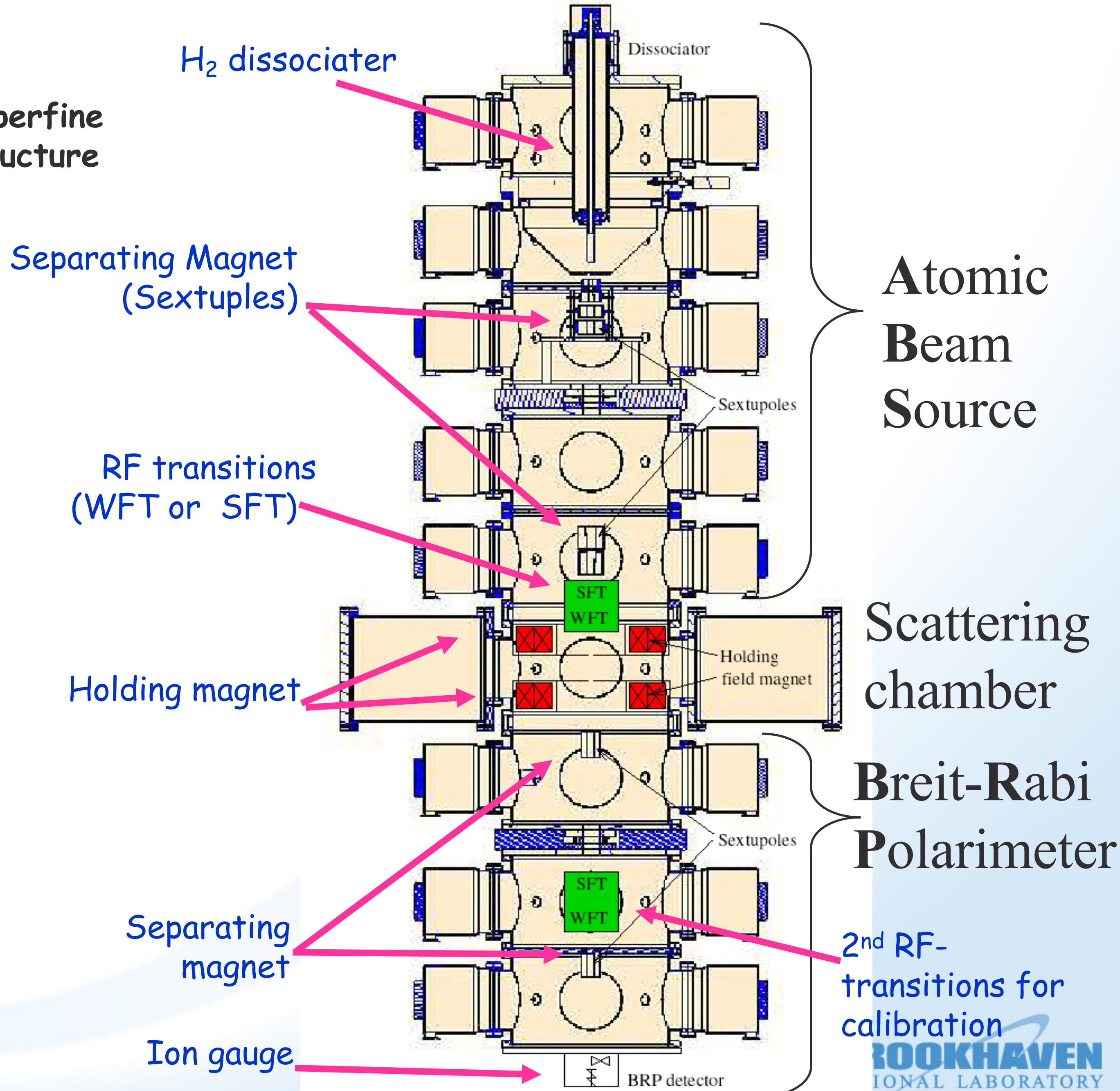


- Height: 3.5 m
- Weight: 3000 kg
- Entire system moves along x-axis –10 ~ +10 mm to adjust collision point with RHIC beam.



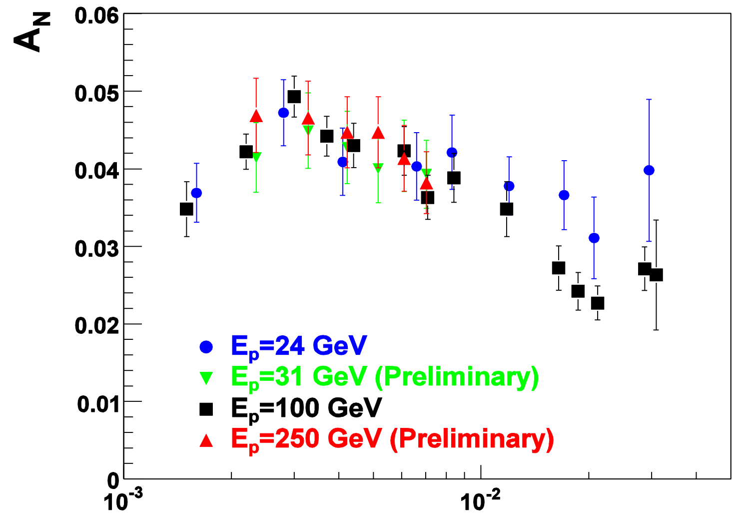
H-JET TARGET SYSTEM





POLARIZED H-JET POLARIMETER

Left-right asymmetry in elastic scattering due to spin-orbit interaction:
interaction between (electric or strong) field of one proton and magnetic moment associated with the spin of the other proton

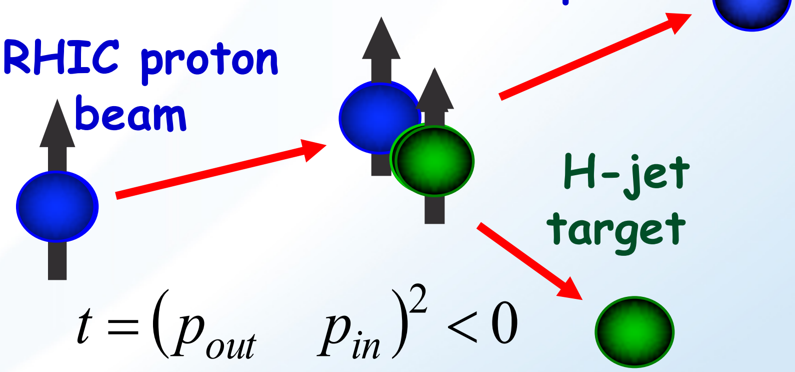


$$A_N = \frac{N_L - N_R}{N_L + N_R} = \frac{\varepsilon_N}{P}$$

Beam and target are both protons

$$A_N(t) = \frac{\text{target}}{P_{\text{target}}} = \frac{\text{beam}}{P_{\text{beam}}}$$

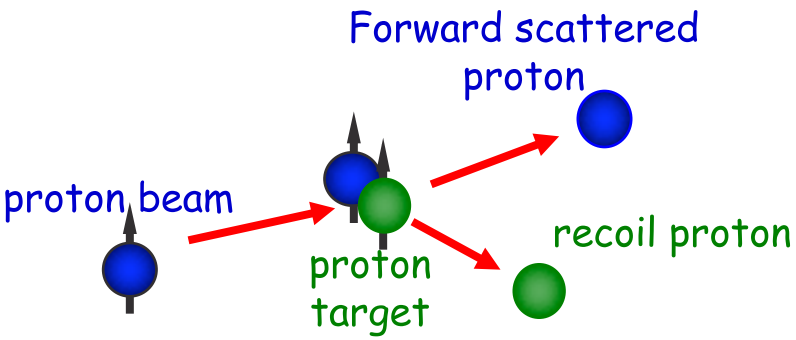
$$P_{beam} = P_{\text{target}} \frac{beam}{\text{target}}$$

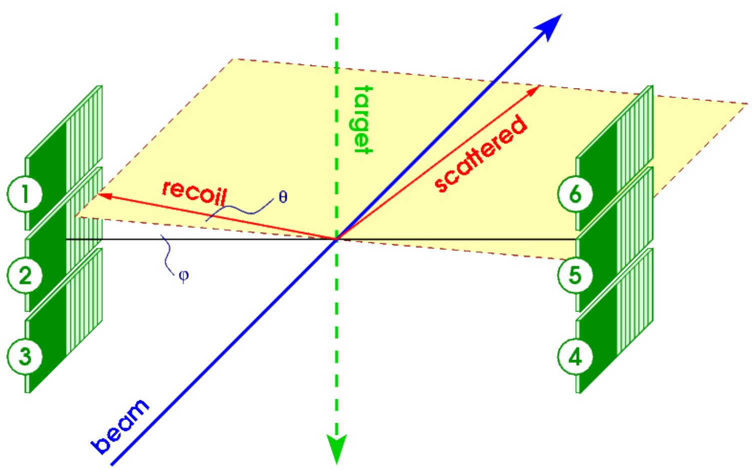


$$t = (p_{out} \quad p_{in})^2 < 0$$

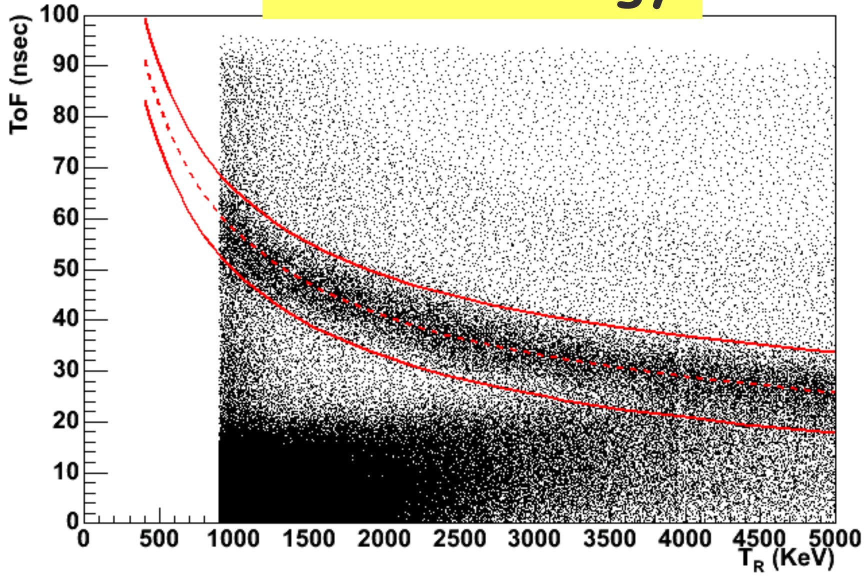
P_{target} is provided by Breit Rabi Polarimeter

H-JET: IDENTIFICATION OF ELASTIC EVENTS

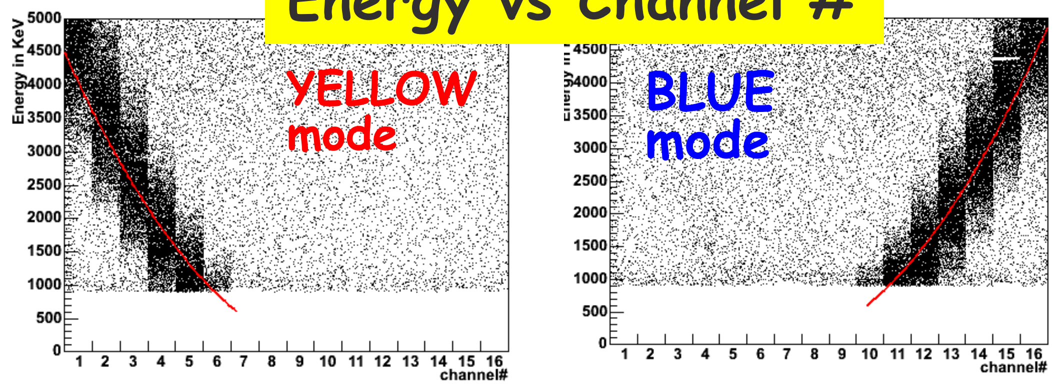




ToF vs Energy



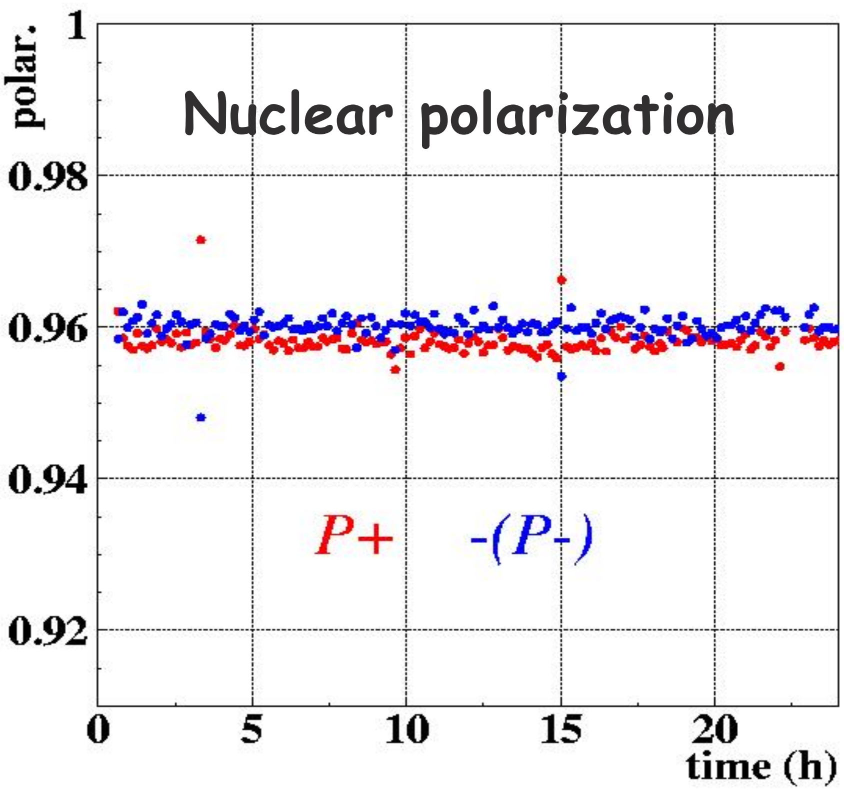
Energy vs Channel #



Array of Si detectors measures T_R & ToF of recoil proton.
Channel # corresponds to recoil angle θ_R.
Correlations (T_R & ToF) and (T_R & θ_R) → the elastic process

H-JET: P_{TARGET}

Source of normalization for polarization measurements at RHIC



1 day

Polarization cycle:
(+/ 0/ –) = (500/50/500) s

Breit-Rabi Polarimeter:

Separation of particles with different spin states in the inhomogeneous magnetic field (ala Stern-Gerlach experiment)

Nuclear polarization of the atoms:

95.8% ± 0.1%

After background correction:

P_{target} = 92.4% ± 1.8%

Very stable for entire run period !

H-JET

Example Plots

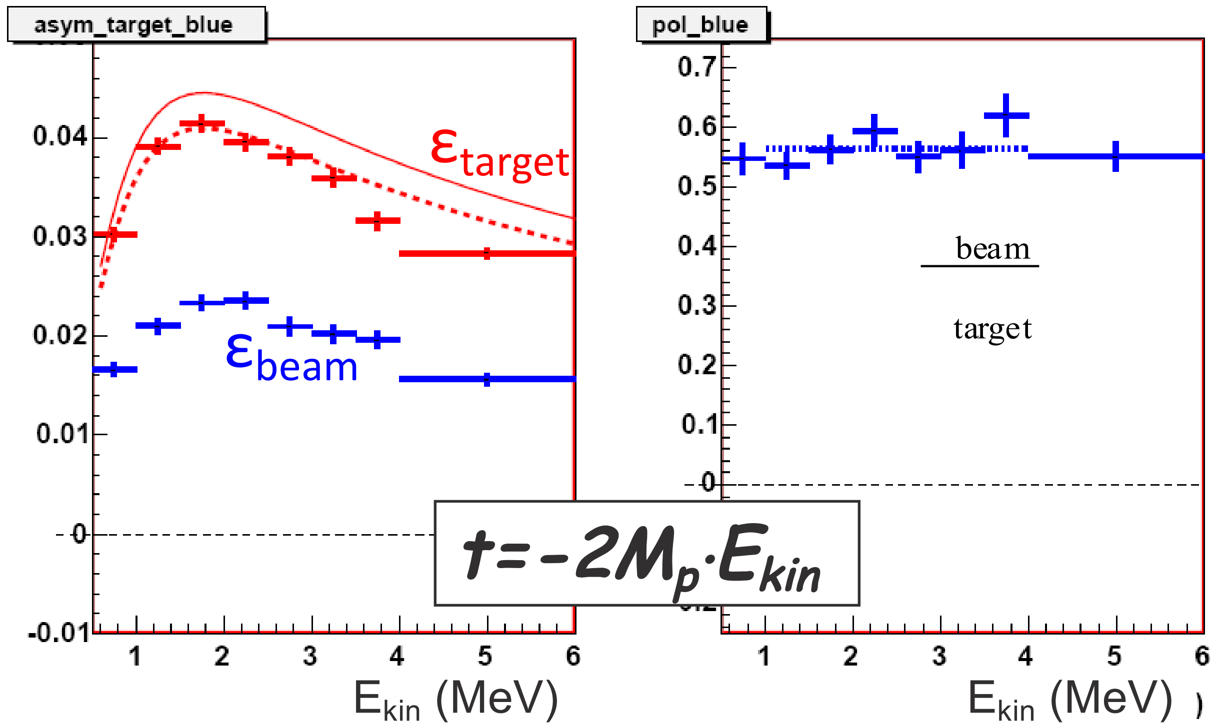
$$P_{beam} = P_{target} \frac{beam}{target}$$

Use the same statistics (with exactly the same experimental cuts) to measure

ε_{beam} and ε_{target}

(selecting proper spin states either for beam or for target)

→ Many systematic effects cancel out in the ratio



Provides statistical precision $\delta(P)/P$ ~ 0.10 in a store (6-8 hours)

HJet Provides very clean and stable polarization measurements but with limited stat. precision

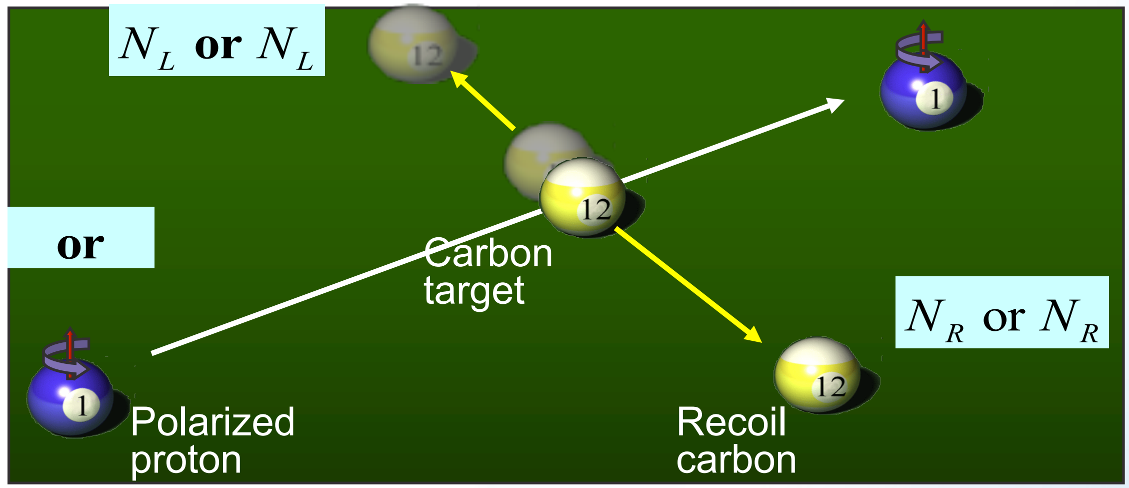
⇒ Need faster polarimeter!

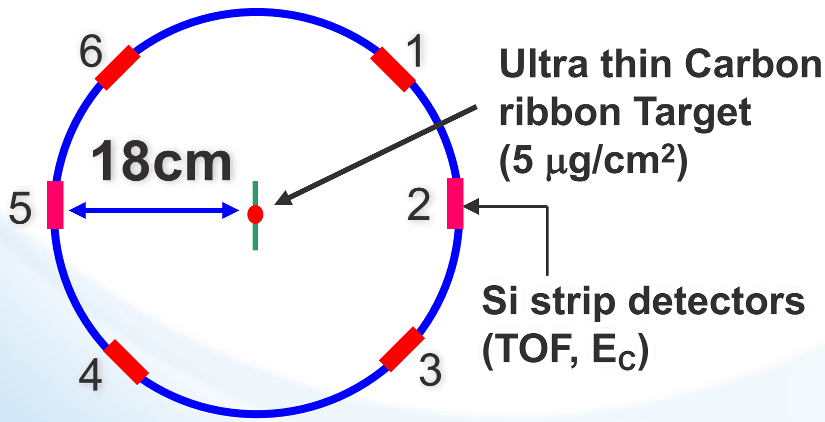
P-CARBON POLARIMETER:

Left-right asymmetry in elastic scattering due to spin-orbit interaction:
interaction between (electric or strong) field of Carbon and magnetic moment associated with the spin of the proton

$$P_{beam} = \frac{N}{A_N^{pC}}$$

$$_N = \frac{N_L \quad N_R}{N_L + N_R}$$





Target Scan mode (20-30 sec per measurement)

Stat. precision 2-3%

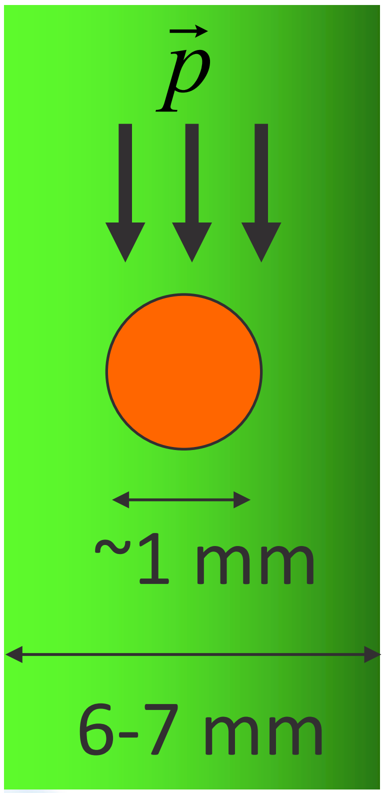
Polarization profile, both vertical and horizontal

Normalized to H-Jet measurements over many fills (with precision <3%)

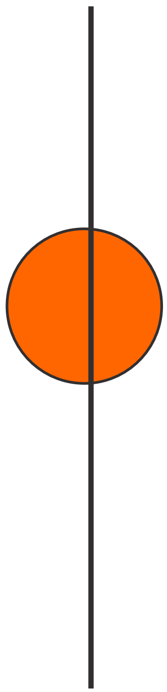
POLARIZATION PROFILE

If polarization changes across the beam, the average polarization seen by Polarimeters and Experiments (in beam collision) is different

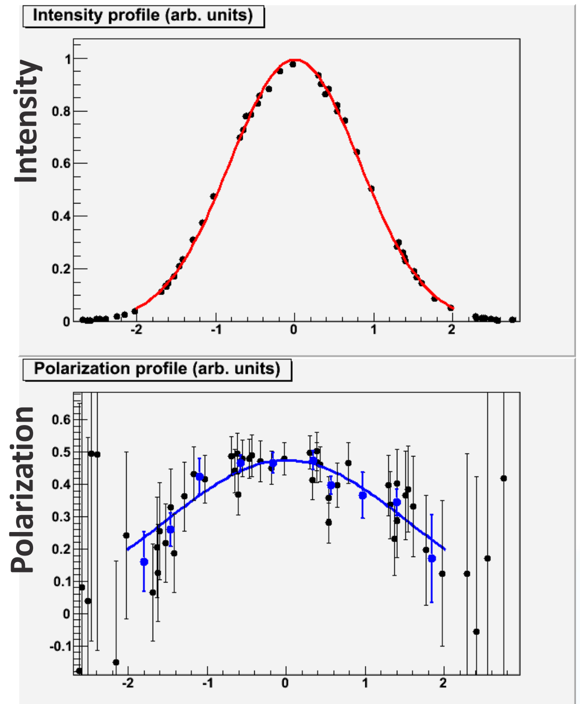
H-Jet



pC

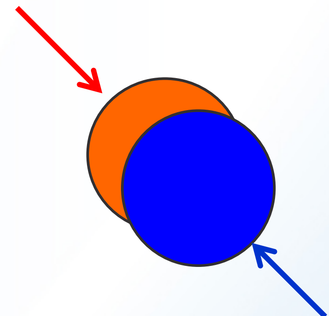


Scan C target across the beam in both X and Y directions



Target Position

Collider Experiments



$$\langle P_1 \rangle = P_1(x,y) \otimes I_1(x,y) \otimes I_2(x,y)$$

$x = x_0$

$$\langle P_1 \rangle = P_1(x,y) \quad I_1(x,y)$$

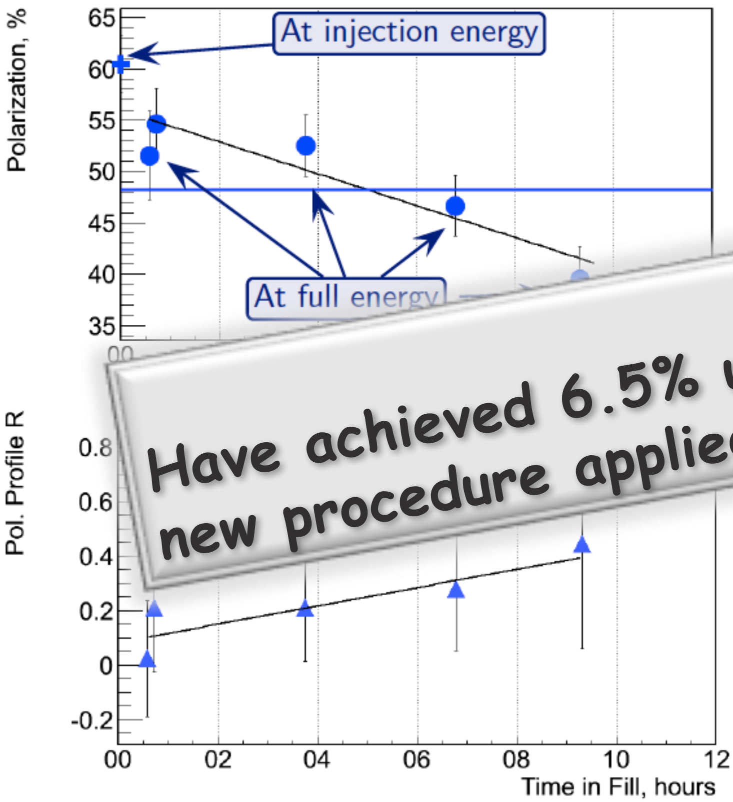
$$\langle P_1 \rangle = P_1(x_0,y) \quad I_1(x_0,y)$$

$$R = \frac{I^2}{P^2} \qquad \frac{\langle P \rangle_{Exp}}{\langle P \rangle_{HJet}} \approx 1 + \frac{1}{4}(R_X + R_Y)$$

P*$_{1,2}$*(x,y) **– polarization profile,** ***I*$_{1,2}$*(x,y)*** **– intensity profile, for beam #1 and #2**

RHIC HADRON POLARISATION

Account for
beam polarization decay through fill → $P(t)=P_0 \exp(-t/\tau_p)$
growth of beam polarization profile **R** through fill



Result:
Have achieved 6.5% uncertainty for DSA and 3.4 for SSA
new procedure applied to 2009 to 2015 data

Collider Experiments

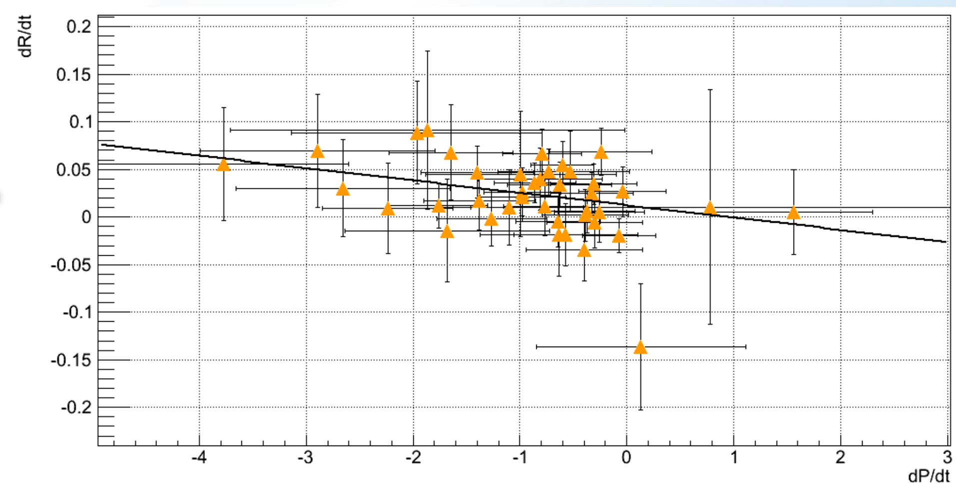
pCarbon polarimeter

$\langle P_1 \rangle = P_1(x_0, y) \quad I_1(x_0, y)$

$= x_0$

$R = \frac{\sigma_I^2}{\sigma_P^2}$

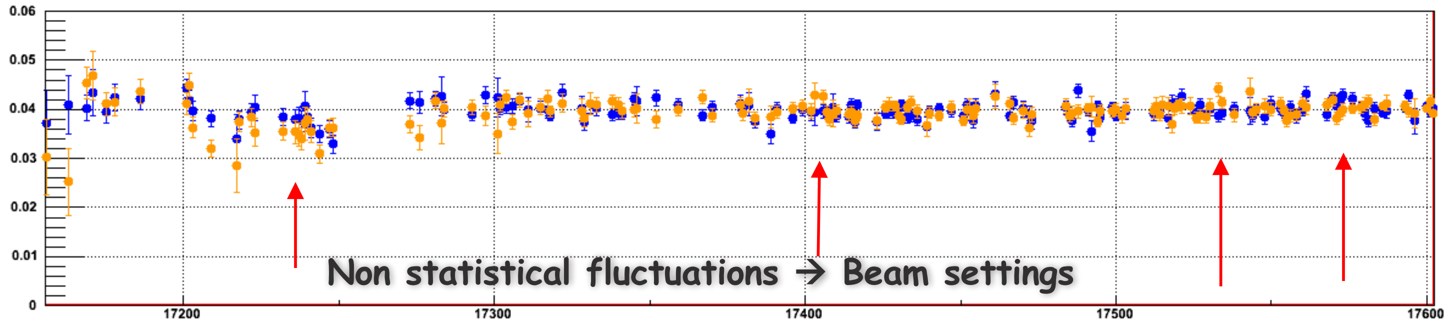
to dR/dt
for all 2012 fills
at 250 GeV



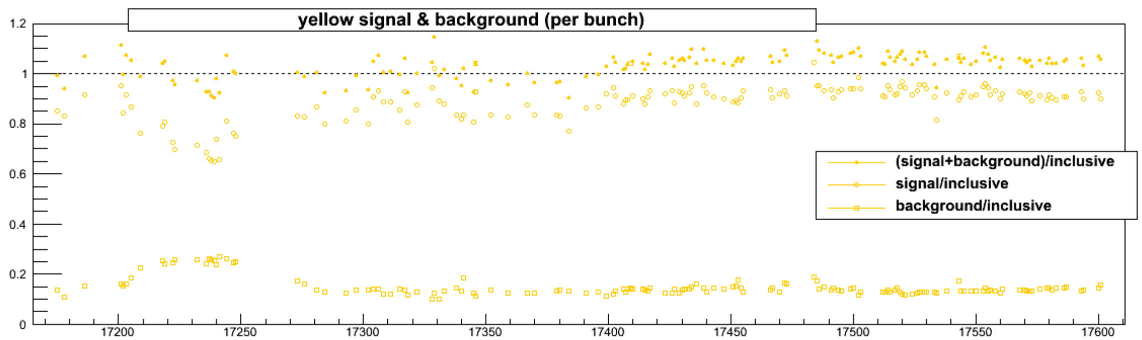
Polarization lifetime has consequences for physics analysis
→ different physics triggers mix over fill
→ different <P>

RHIC POLARIMETRY: OPS EXAMPLES FROM RUN-13

H-Jet: Analyzing power $A_N = \varepsilon / P_T$



→ developed method determine background fraction and correct for it



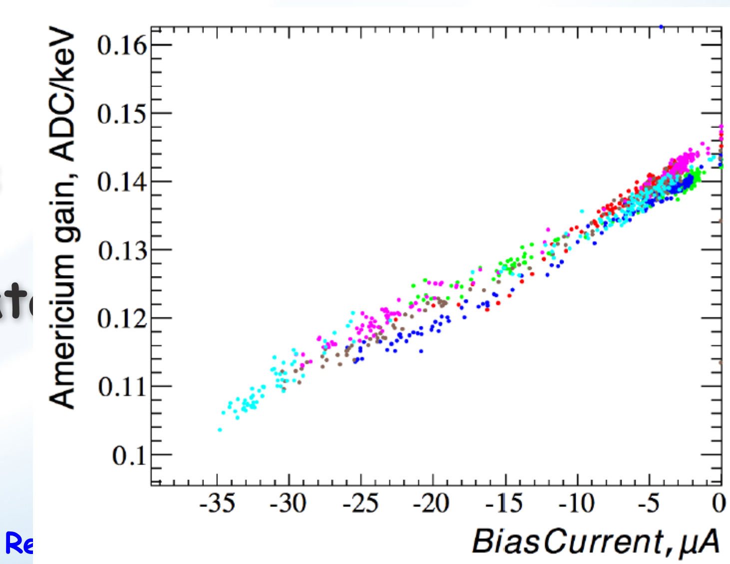
p-Carbon:

gain variations up to 25%

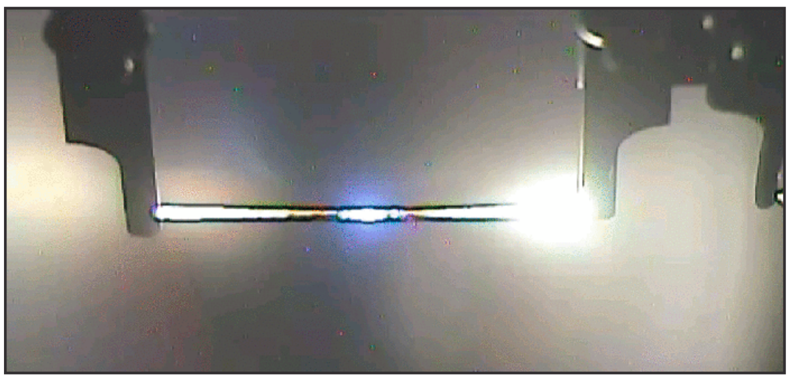
correlated with bias current variations

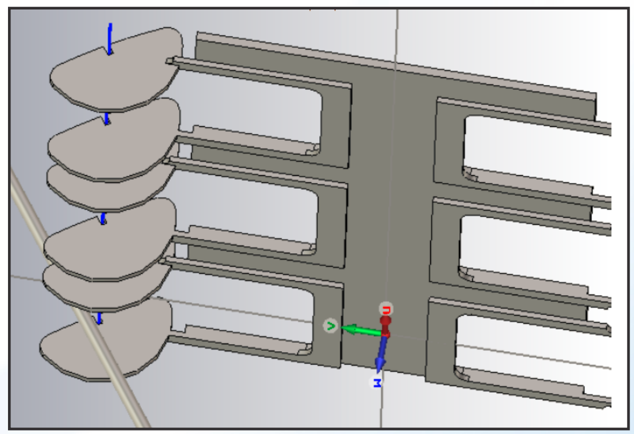
→ monitored through α-calib. runs

→ corrections are applied to all the dat

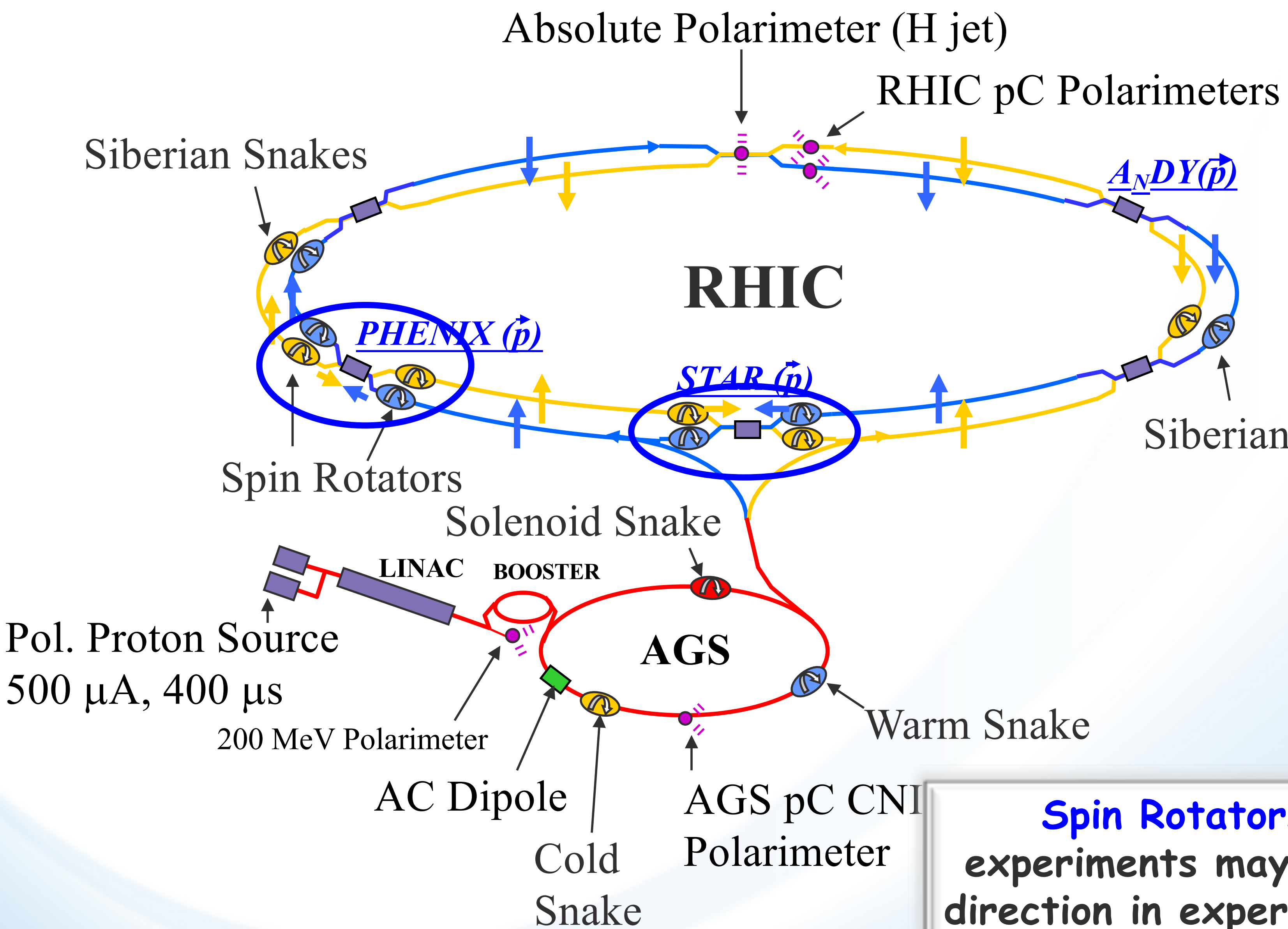


- H-Jet:
  - measure molecular fraction in the H-Jet prior to run-15
    - currently dominant systematics
  - new Si-detectors: → bigger acceptance & better resolution
- pC-polarimeters
  - continue the regular α-calibrations at every end of the fill
  - redesign the Si-ceramic board to have better gain stability
  - improve target lifetime with new target holders to reduce heating
    tested in Run-14 with Au/He-3 beams → reduced heating/glowing





NEED FOR LOCAL POLARIMETERS



Spin Rotators around experiments may change spin direction in experimental areas

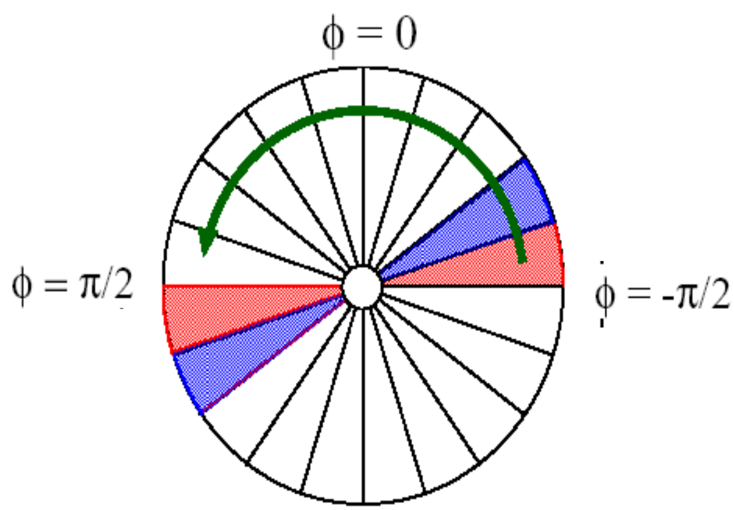
⇒ **Need to monitor spin direction in experimental areas**

MONITOR SPIN DIRECTION

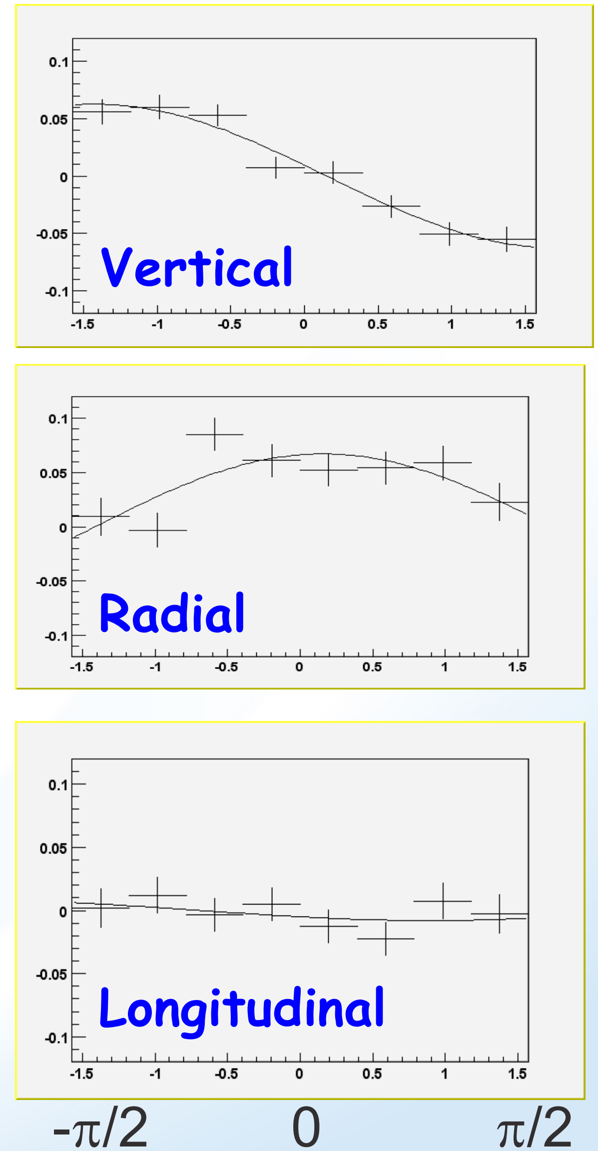
Measures transverse polarization P_T ,
Separately P_X and P_Y

$$P_L = \sqrt{P^2 \quad P_T^2}$$

Longitudinal component:
P – from CNI polarimeters



Asymmetry vs ϕ

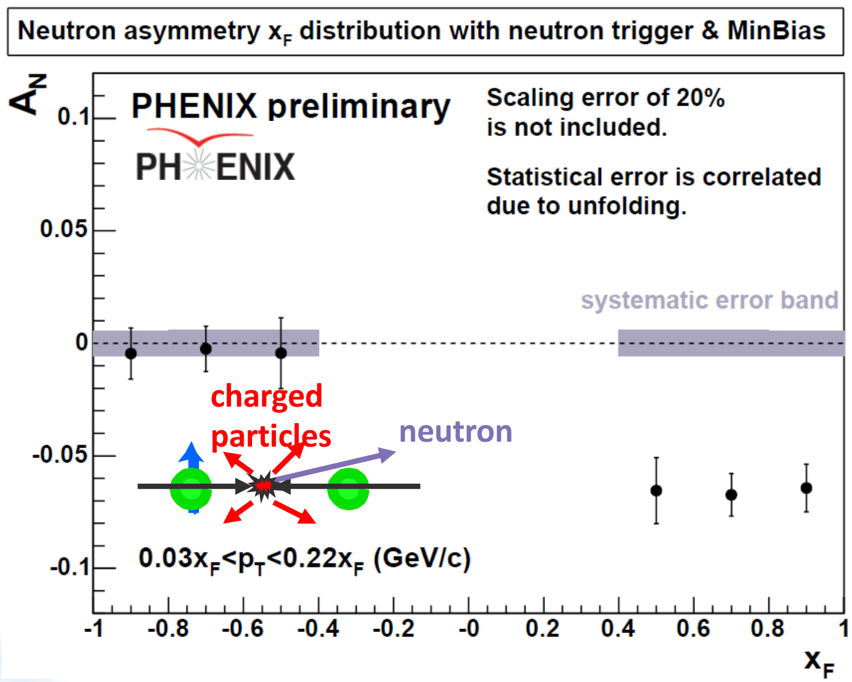


Vertical → ϕ ~ ±π/2
Radial → ϕ ~ 0
Longitudinal → no asymmetry

LOCAL POLARIMETER: PHENIX & STAR

PHENIX

Utilizes spin dependence of very forward neutron production discovered in RHIC Run-2002 (PLB650, 325) detected in zero degree calorimeter

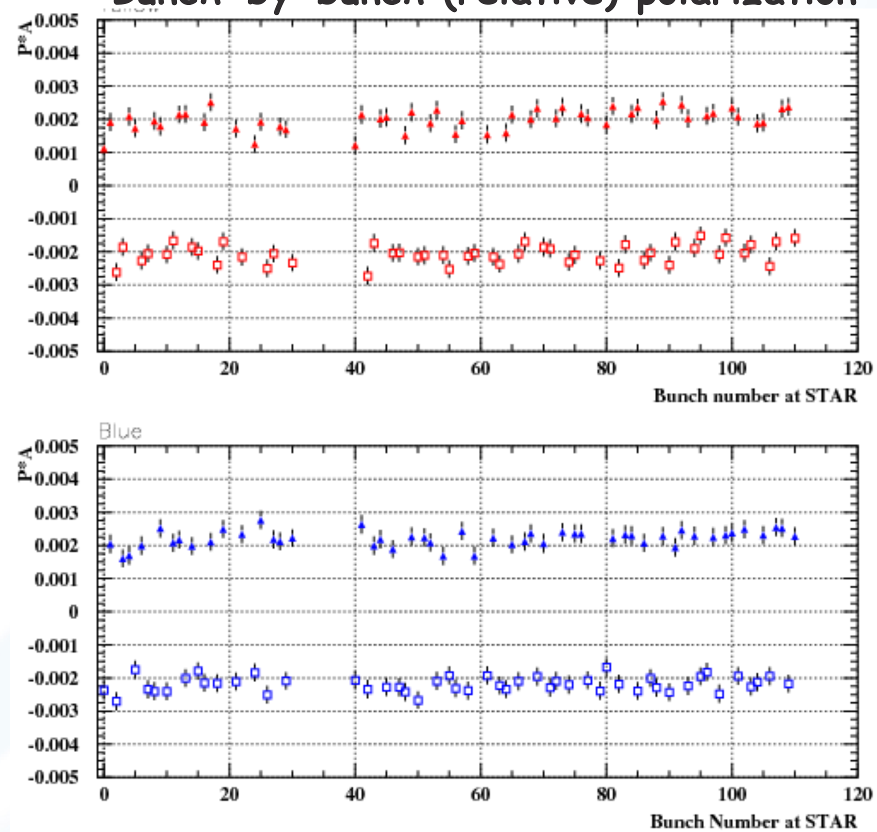


Quite unexpected asymmetry
Theory can not yet explain it
But can be used for polarimetry !

STAR

Utilizes spin dependence of hadron production at high x_F measured in beam-beam counters $3.3<|\eta|<5.0$

Bunch-by-bunch (relative) polarization



NOW WE HAVE THE POLARISED PROTON BEAM
AND
KNOW WHAT THE POLARISATION IS, WHAT IS NEXT

How do we measure things
→ Detectors

BROOKHAVEN NATIONAL LABORATORY

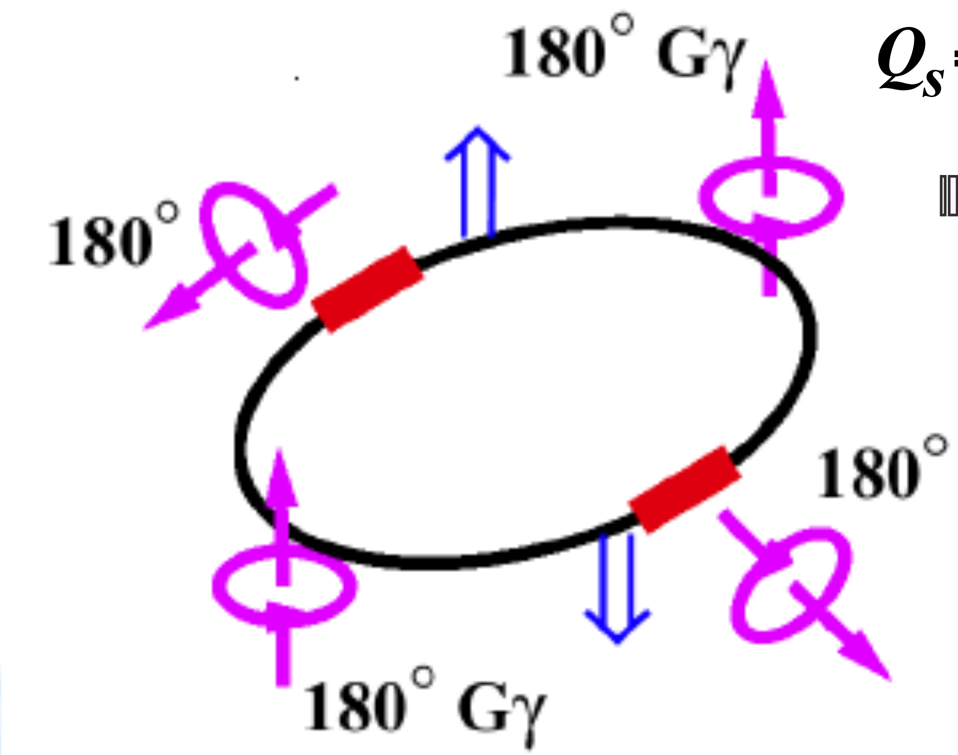
a passion for discovery

U.S. DEPARTMENT OF ENERGY | Office of Science

BACKUP

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*



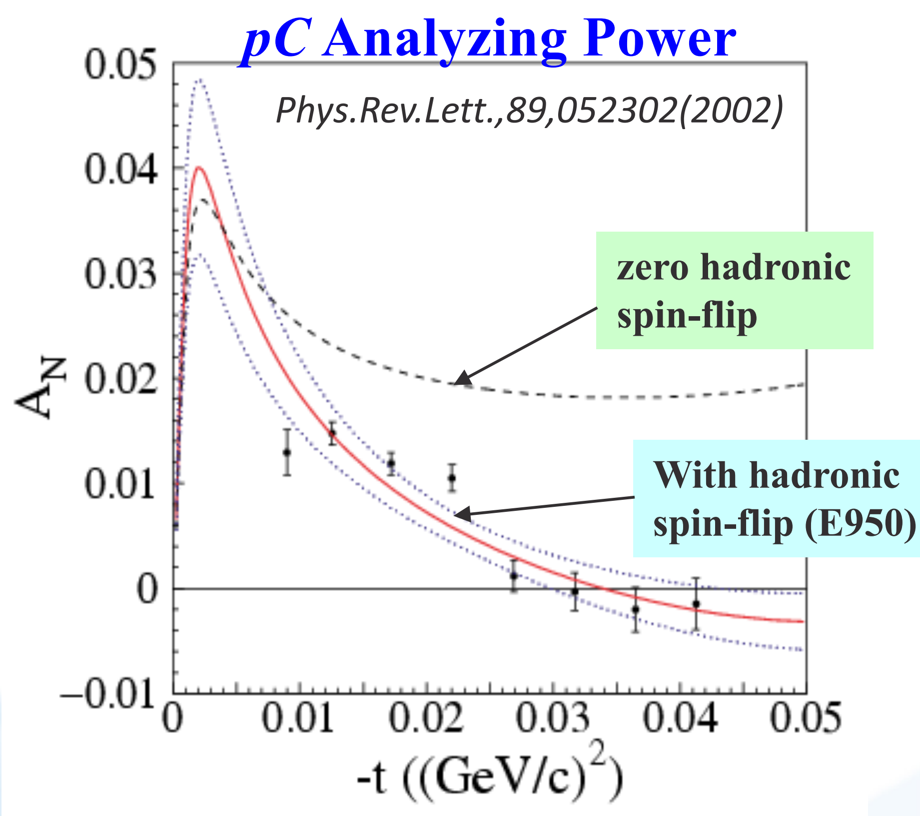
$$Q_s = \frac{1}{\pi}|\varphi_1 - \varphi_2|$$

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

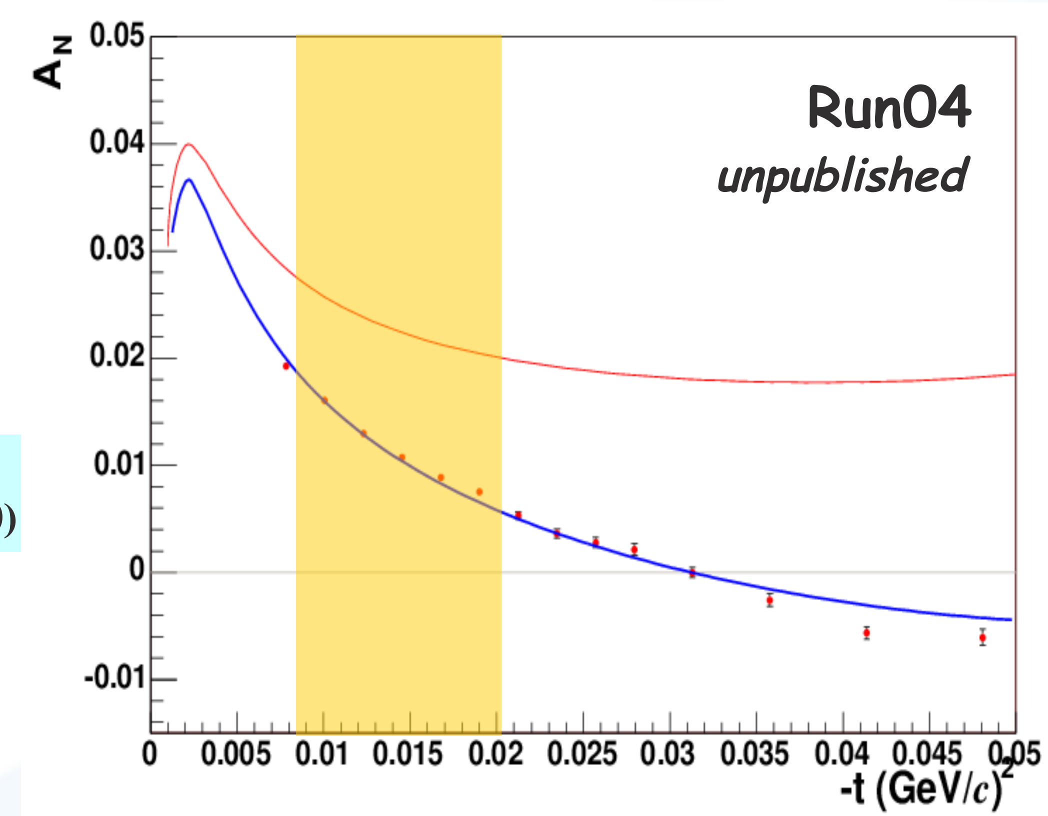
PC: A_N

Elastic scattering: interference between electromagnetic and hadronic amplitudes in the Coulomb-Nuclear Interference (CNI) region

$$A_N \quad C_1 \; {}^{em}_{flip}{}^{*} \; {}^{had}_{non\ \ flip} + C_2 \; {}^{em}_{non\ \ flip}{}^{*} \; {}^{had}_{flip}$$



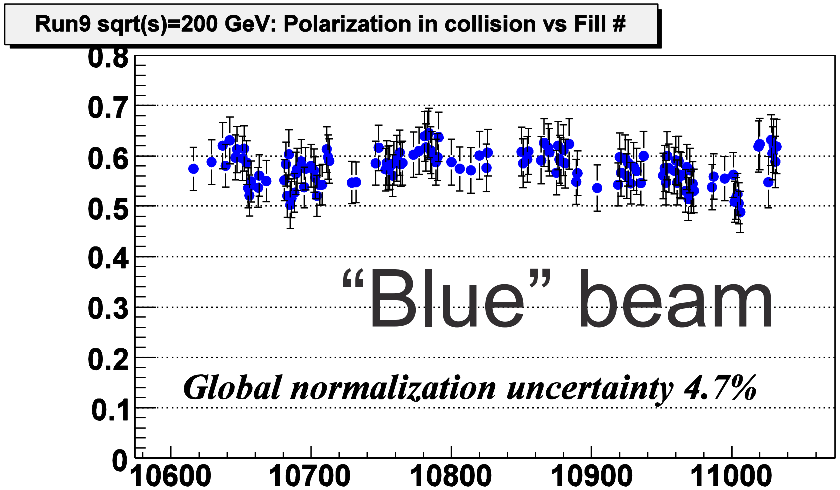
E_{beam} = 21.7GeV

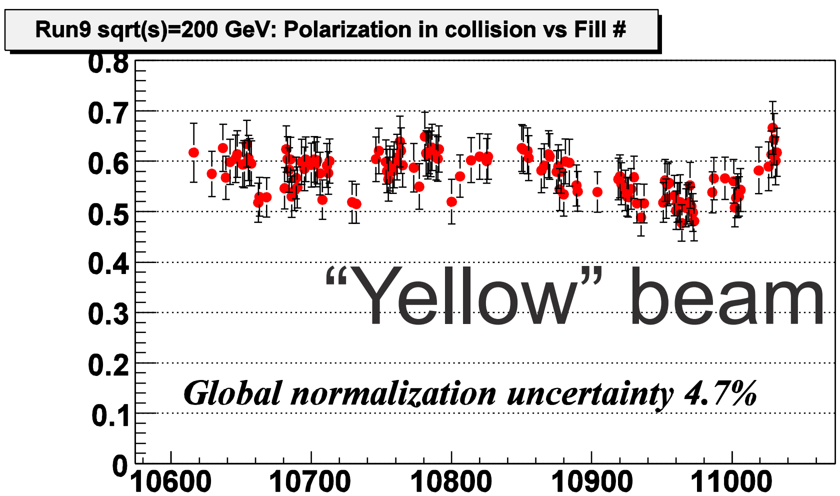


E_{beam} = 100 GeV

PC+HJET: POLARIZATION VS FILL

Run-2009 results (E_{beam}=100 GeV)





✓ Normalized to HJet
✓ Corrected for polarization profile (by pC)

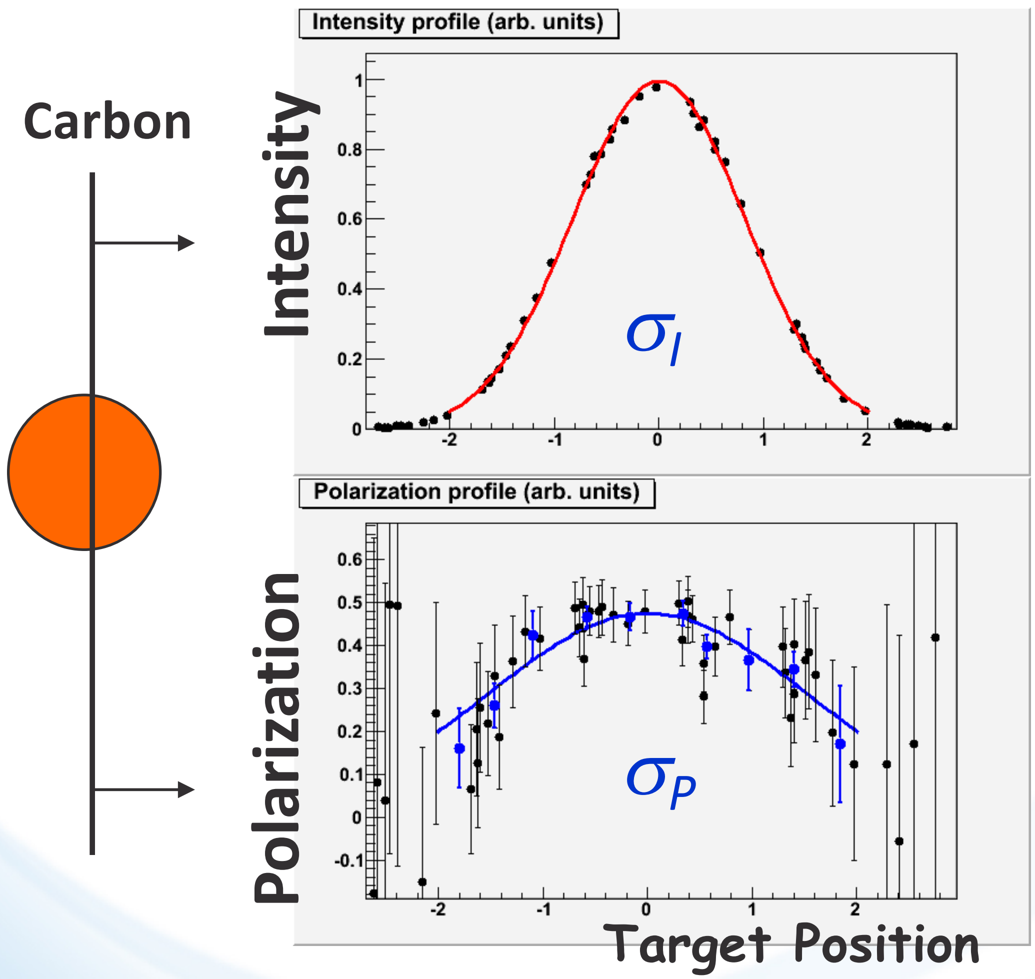
$\delta P/P < 5\%$

Dominant sources of syst. uncertainties:

- ~3% - HJet background
- ~3% - pC stability
  (rate dependencies, gain drift)
- ~2% - Pol. profile

POL. PROFILE AND AVERAGE POLARIZATION

Scan C target across the beam
In both X and Y directions



$$R = \frac{{}^{2}_{I}}{{}^{2}_{P}}$$

$$\frac{\langle P \rangle_{Exp}}{\langle P \rangle_{HJet}} = \frac{\sqrt{(1+R_X)\cdot(1+R_Y)}}{\sqrt{\left(1+\frac{1}{2}R_X\right)\cdot\left(1+\frac{1}{2}R_Y\right)}} \approx 1 + \frac{1}{4}(R_X + R_Y)$$

Ideal case: flat pol. profile ($\sigma_P = \infty \Rightarrow R = 0$)

Run-2009:

E_{beam}=100 GeV: R~0.1 ⇒ 5% correction

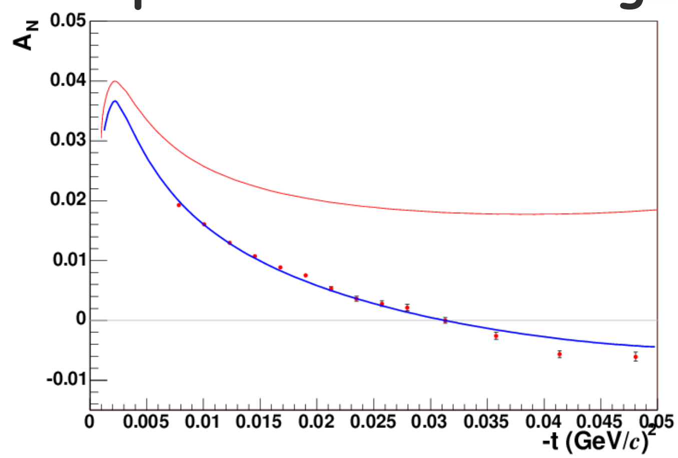
E_{beam}=250 GeV: R~0.35 ⇒ 15% correction

POLARIZATION MEASUREMENTS

$$P = \frac{\ }{A_N} = \frac{1}{A_N} \frac{N_{Left} \quad N_{Right}}{N_{Left} + N_{Right}}$$

A_N depends on the process and kinematic range of the measurements

pC elastic scattering



$-t = 2M_C \cdot E_{kin}$

Precision of the measurements

$$(P) = \frac{1}{A_N} \frac{1}{\sqrt{N}}$$

$N = N_{Left} + N_{Right}$

For $\delta(P)=0.01$ and $A_N \sim 0.01 \Rightarrow N \sim 10^8$!

Requirements:

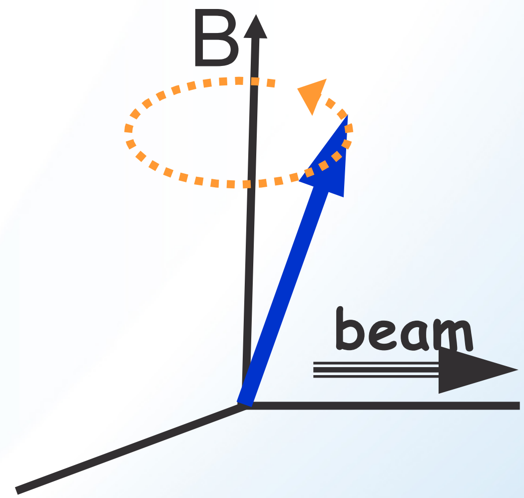
Large A_N or/and high rate (N)

Good control of kinematic range

SPIN MOTION IN CIRCULAR ACCELERATOR: THOMAS BMT EQUATION

$$\frac{d\vec{S}}{dt} = \vec{\ } \cdot \vec{S} = \frac{e}{m}[G\,\vec{B}\ + (1+G)\vec{B}_{//}] \cdot \vec{S}$$

Spin vector in particle's rest frame

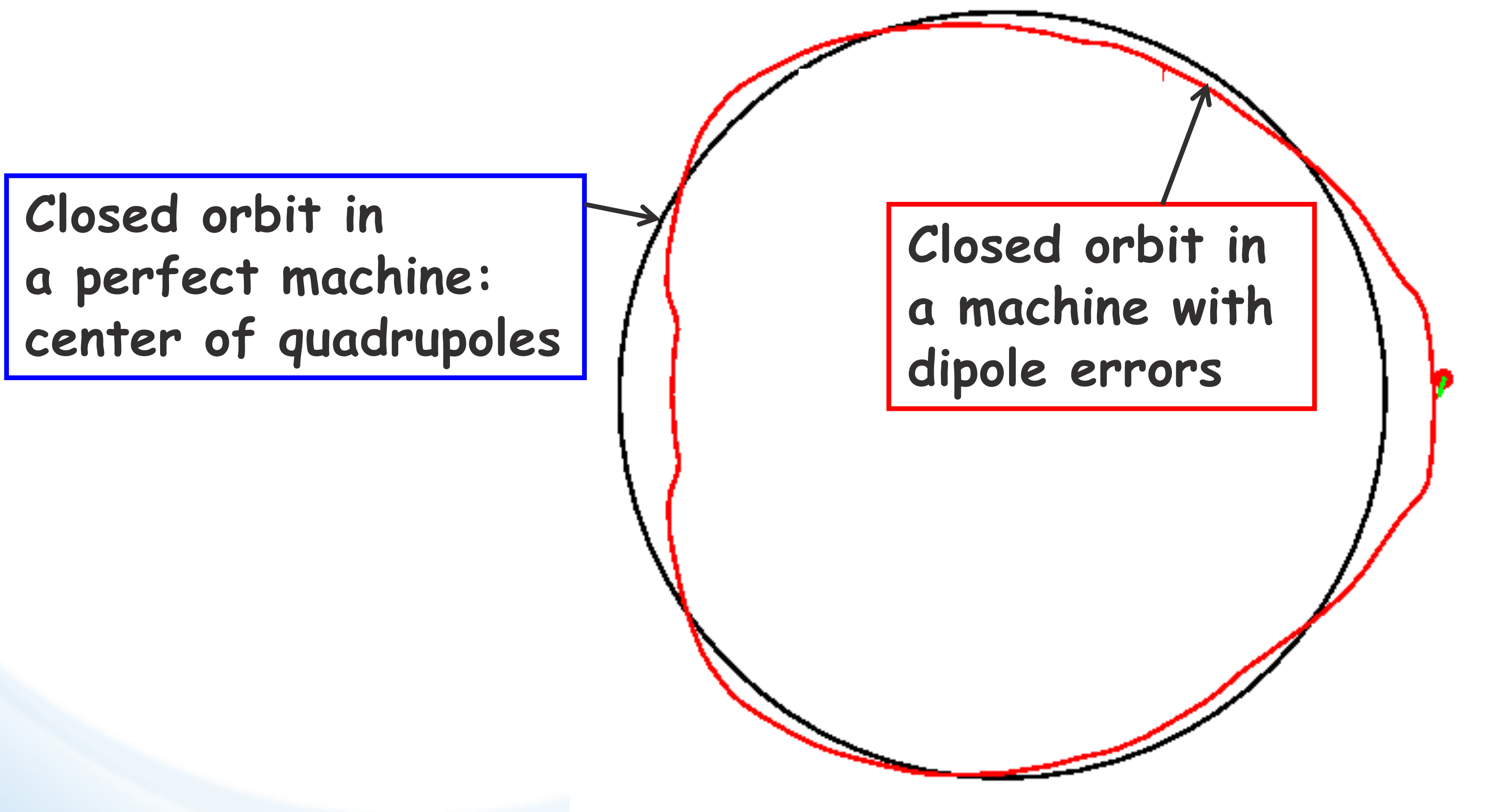


- In a perfect accelerator, spin vector precesses around the bending dipole field direction: vertical
- Spin tune Q_s: number of precessions in one orbital revolution. In general,

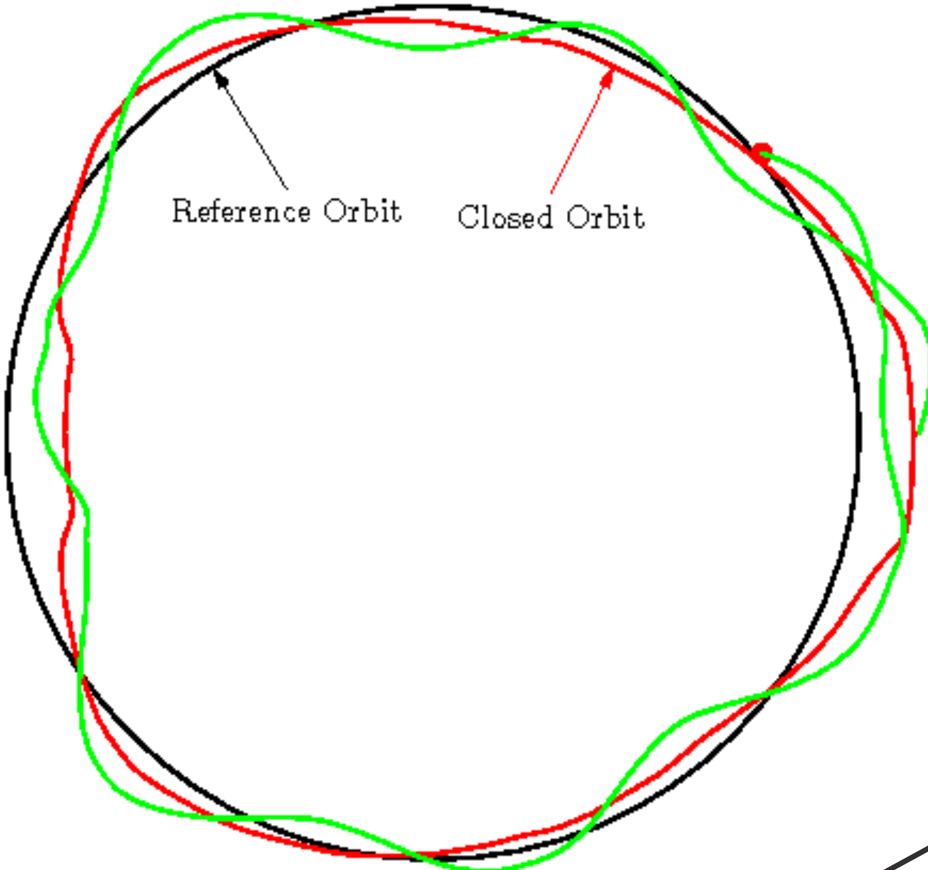
$$Q_s = G\gamma$$

CLOSED ORBIT IN A CIRCULAR ACCELERATOR

Closed orbit: particle comes back to the same position after one orbital revolution



BETATRON OSCILLATION IN A CIRCULAR ACCELERATOR

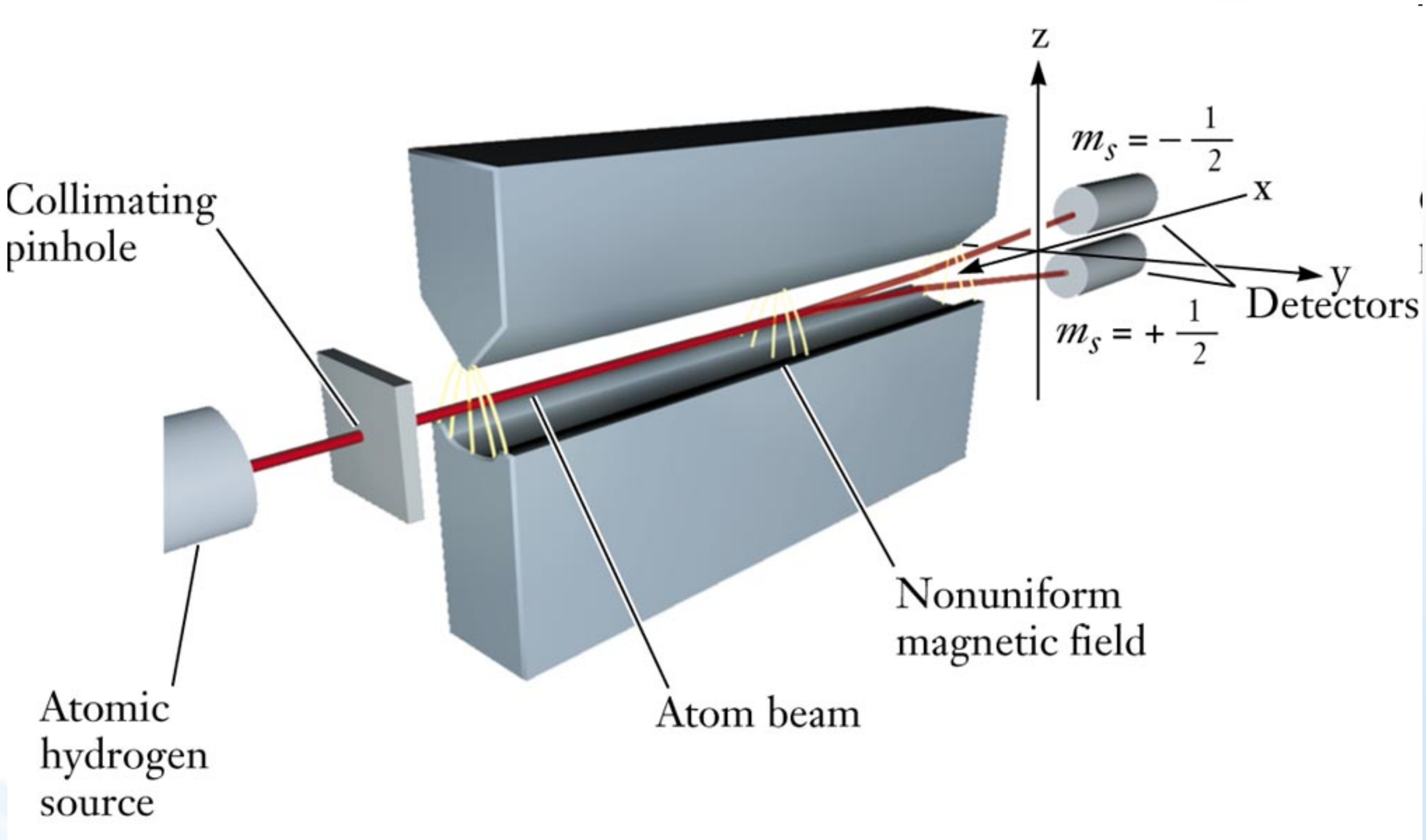


Betatron tune: number of oscillations in one orbital revolution

$$y(s) = \sqrt{2 \quad _y J} \cos(2 \quad Q_y \quad (s) + \quad _y)$$

Beta function

Separation of spin states in the inhomogeneous magnetic field



THE RHIC ACCELERATOR SYSTEM