THE RELATIVISTIC HEAVY ION COLLIDER
THE ONLY COLLIDER IN THE US
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 $\rightarrow$ protons + neutrons $\rightarrow$ quarks + gluons
The RHIC Complex

- Absolute Polarimeter (H jet)
- RHIC pC Polarimeters
- Pol. Proton Source: 500 µA, 300 µs
- Spin Rotators
- Partial Siberian Snake
- Strong AGS Snake
- Stripping Au 77+ to 79+
- 100 GeV/u 79+
- 9 GeV/u 77+
- 1 MeV/u 32+
- 200 MeV Polarimeter
- LINAC
- Booster
- AGS Internal Polarimeter
- AGS pC Polarimeters
- Rf Dipoles

E.C. Aschenauer

Brookhaven National Laboratory

NNP SS@MIT, July 2016
**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
Charged particles are guided by magnetic fields, using the Lorentz force:

\[ \vec{F} = q \cdot (\vec{v} \cdot \vec{B}) \]

- \( F \): 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)
- **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
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

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 $B_x(z) = z \cdot dB/dz = z \cdot \text{const}$. 
  - 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
How does an accelerator accelerate the beam?

- Magnetic fields only deflect the beam, but electric fields can change the beam energy.

A highly relativistic particle \( v \approx c \) with an energy \( E + \delta E \) is heavier \( (E + \delta E = (+\delta m)c^2) \) than 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).
At fixed energy (no acceleration):

- the nominal particle receives no longitudinal kick, so its energy $E$ remains unchanged.
- a particle with higher energy $E + \delta E$ arrives at a later time, receives a negative kick, and gets decelerated.
- a particle with lower energy $E - \delta E$ 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"
**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 $\mu_s$.

**Equation:**
\[ \mu_s = (1 + G) \frac{q}{m} S \]

$G$: 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: 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

$$\frac{d\vec{S}}{dt} = \mu_s \cdot \vec{B}$$

$$\frac{d\vec{J}}{dt} = \mu \cdot \vec{B}$$

$\mu = IA$
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
$\gamma$: relativistic Lorentz factor

Imperfection resonance

- Source: dipole errors, quadrupole misalignments
- Resonance location:

$$G\gamma = k$$

$k$ is an integer

Intrinsic resonance

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

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

$P$ is the periodicity of the accelerator,
$Q_y$ is the vertical betatron tune
- **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
For protons, imperfection spin resonances are spaced by 523 MeV the higher energy, the stronger the depolarizing resonance.
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 $180^\circ$ 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:
- 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
E.C. Aschenauer

**AGS**

**Alternating Gradient Synchrotron**

**PHENIX** (p)

**Linac Booster**

**Pol. H**

- **Source**
- **Solenoid Partial Siberian Snake**
- **Spin Rotators** (longitudinal polarization)
- **RHIC pC Polarimeters**
- **Absolute Polarimeter (H jet)**
- **Siberian Snakes**
- **Spin flipper**
- **STAR** (p)
- **Siberian Snakes**
- **Spin Rotators** (longitudinal polarization)
- **200 MeV Polarimeter**
- **AGS**
- **Helical Partial Siberian Snake**
- **AGS Polarimeters**
- **Strong AGS Snake**
What do we collide?

- Polarized protons: 24-255 GeV
- Light ions (d, Si, Cu): 5-100 GeV/u
- Heavy ions (Au, U): 5-100 GeV/u
- Polarized light ions: He³ 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.
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......!

Beam intensities

Pilot bunch

Start acceleration

transition

Beta* squeeze

cogging re-bucketing collimation steering

collisions

INJECT, ACCELERATE, COLLIDE......!

Store (collisions)

Brookhaven Science Associates

NNP SS@MIT, July 2016
Week 9 Feb to 17 Feb [66% of calendar time in store]

60x10^9 Au intensity

Beam experiments

enhanced luminosity
design luminosity
Achieved peak luminosities (100 GeV, nucl.-pair):
- Au-Au: \(195 \times 10^{30}\) cm\(^{-2}\) s\(^{-1}\)
- p\(^+\)-p\(^+\): \(60 \times 10^{30}\) cm\(^{-2}\) s\(^{-1}\)

Other large hadron colliders (scaled to 100 GeV):
- Tevatron (p - pbar): \(43 \times 10^{30}\) cm\(^{-2}\) s\(^{-1}\)
- LHC (p - p): \(37 \times 10^{30}\) cm\(^{-2}\) s\(^{-1}\)

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)
Luminosity:
- number of particles per unit area per unit time. The higher the luminosity, the higher the collision rates

\[ L(t) = \frac{1}{4} f_0 N \frac{n^2(t)}{r_{\text{rms}}^2(t)} \]

- # 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 $S_z=-1/2$

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

$|P| < 1$

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

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

$P = \frac{2}{2+2} = 0$
RHIC AND POLARIMETRY

E.C. Aschenauer

NNP SS@MIT, July 2016

STAR (p)

PHENIX (p)

AGS

LINAC

BOOSTER

Pol. Proton Source

500 µA, 400 µs

Spin Rotators

Solenoid Snake

Siberian Snakes

200 MeV Polarimeter

AGS pC CNI Polarimeter

AC Dipole

Cold Snake

Warm Snake

Absolute Polarimeter (H jet)

RHIC pC Polarimeters

A_{NDY} (p)
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
There are several established physics processes sensitive to the spin direction of the transversely polarized protons.

\[ \varepsilon = \frac{N_{\text{left}} - N_{\text{right}}}{N_{\text{left}} + N_{\text{right}}} = A_N P \]

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

Once \( A_N \) is known:

\[ P = \frac{\varepsilon}{A_N} \]
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.

IP12

RHIC proton beam

Recoil proton

target

E.C. Aschenauer

Brookhaven National Laboratory

NNP SS@MIT, July 2016
\[ H = p^+ + e^- \]

\[ |1\rangle \quad |2\rangle \quad |3\rangle \quad |4\rangle \]

Hyperfine structure

\[ \begin{array}{c|c|c|c}
|1\rangle & |2\rangle & |3\rangle & |4\rangle \\
\hline
\uparrow & \uparrow & \downarrow & \downarrow \\
\downarrow & \downarrow & \uparrow & \uparrow \\
\end{array} \]

\[ H_2 \text{ dissociater} \]

Separating Magnet (Sextuples)

RF transitions (WFT or SFT)

Holding magnet

Separating magnet

Ion gauge

Atomic Beam Source

Scattering chamber

Breit-Rabi Polarimeter

2nd RF-transitions for calibration

BRP detector

E.C. Aschenauer

Brookhaven Science Associates

NNP SS@MIT, July 2016
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.

Beam and target are both protons

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

\[ P_{\text{beam}} = P_{\text{target}} \cdot \frac{P_{\text{beam}}}{P_{\text{target}}} \]

\[ A_N = \frac{N_L - N_R}{N_L + N_R} = \frac{\epsilon_N}{P} \cdot t (\text{GeV}/c)^2 \]

Forward scattered proton

RHIC proton

H-jet target

Recoil proton

\[ t = (p_{\text{out}} - p_{\text{in}})^2 < 0 \]

\[ P_{\text{target}} \] is provided by Breit Rabi Polarimeter

E.C. Aschenauer

Brookhaven National Laboratory

Brookhaven Science Associates

NNP SS@MIT, July 2016
Array of Si detectors measures $T_R$ & ToF of recoil proton. Channel # corresponds to recoil angle $\theta_R$. Correlations ($T_R$ & ToF) and ($T_R$ & $\theta_R$) → the elastic process
Source of normalization for polarization measurements at RHIC

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:

\[ P_{\text{target}} = 92.4\% ± 1.8\% \]

Very stable for entire run period!

Polarization cycle:
(+ / 0 / - ) = (500/50/500) s
\[ P_{\text{beam}} = P_{\text{target}} \frac{\varepsilon_{\text{beam}}}{\varepsilon_{\text{target}}} \]

Use the same statistics (with exactly the same experimental cuts) to measure \( \varepsilon_{\text{beam}} \) and \( \varepsilon_{\text{target}} \) (selecting proper spin states either for beam or for target).

\( \rightarrow \) Many systematic effects cancel out in the ratio.

Provides statistical precision \( \delta(P)/P \approx 0.10 \) in a store (6–8 hours).

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

\( \Rightarrow \) Need faster 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.

\[ P_{\text{beam}} = \frac{N}{A_p^C} \]

\[ N = \frac{N_L}{N_L + N_R} \]

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

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

\[ X = X_0 \]

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

\[ R = \frac{2}{P} \frac{\langle P \rangle_{\text{Exp}}}{\langle P \rangle_{\text{HJet}}} \approx 1 + \frac{1}{4}(R_x + R_y) \]

**H-Jet**

\[ \vec{p} \]

\[ \sim 1 \text{ mm} \]

\[ 6-7 \text{ mm} \]

**Collider Experiments**

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

Intensity profile (arb. units)

Polarization profile (arb. units)
Account for beam polarization decay through fill → \( P(t) = P_0 \exp(-t/\tau_p) \)
growth of beam polarization profile \( R \) through fill

\[
P(t) = P_0 \exp(-t/\tau_p)
\]

\( \langle P \rangle = P(x_0, y) \quad I_1(x_0, y) \)

\[
R = \frac{\sigma^2_I}{\sigma^2_P}
\]

\( R = \frac{\sigma^2_I}{\sigma^2_P} \)

Result:

Have achieved 6.5% uncertainty for DSA and 3.4 for SSA.

New procedure applied to 2009 to 2015 data

\( \frac{dP}{dt} \) to \( \frac{dR}{dt} \)

for all 2012 fills at 250 GeV

Polarization lifetime has consequences for physics analysis
→ different physics triggers mix over fill
→ different \( \langle P \rangle \)

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

Non statistical fluctuations $\rightarrow$ Beam settings

$\rightarrow$ developed method determine background fraction and correct for it

p-Carbon:

gain variations up to 25%
correlated with bias current variations
$\rightarrow$ monitored through $\alpha$-calib. runs
$\rightarrow$ corrections are applied to all the data
H-Jet:
- measure molecular fraction in the H-Jet prior to run-15
  - currently dominant systematics
- new Si-detectors: $\rightarrow$ bigger acceptance & better resolution

pC-polarimeters
- continue the regular $\alpha$-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 $\rightarrow$ reduced heating/glowing
NEED FOR LOCAL POLARIMETERS

Absolute Polarimeter (H jet)

RHIC pC Polarimeters

Siberian Snakes

Spin Rotators

Solenoid Snake

Pol. Proton Source
500 µA, 400 µs

200 MeV Polarimeter

AC Dipole

Cold Snake

AGS pC CNI Polarimeter

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 $P_Y$

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

Longitudinal component:
$P$ - from CNI polarimeters

$\phi = 0$

$\phi = \pi/2$

$\phi = -\pi/2$

Vertical $\rightarrow \phi \sim \pm \pi/2$
Radial $\rightarrow \phi \sim 0$
Longitudinal $\rightarrow$ no asymmetry

Asymmetry vs $\phi$

**Vertical**

**Radial**

**Longitudinal**

- \( -\pi/2 \)
- \( 0 \)
- \( \pi/2 \)
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

STAR

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

Quite unexpected asymmetry
Theory can not yet explain it
But can be used for polarimetry!
NOW WE HAVE THE POLARISED PROTON BEAM AND KNOW WHAT THE POLARISATION IS, WHAT IS NEXT

How do we measure things → Detectors
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*

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

\[ Q_s = \frac{1}{2} \]
Elastic scattering: interference between electromagnetic and hadronic amplitudes in the Coulomb-Nuclear Interference (CNI) region

\[ A_N = C_1 \text{em}^* \text{had flip} + C_2 \text{em} \text{non had flip}^* \text{had flip} \]

E.C. Aschenauer
NNP SS@MIT, July 2016
Run-2009 results ($E_{\text{beam}}=100$ 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
Scan C target across the beam 
In both X and Y directions

Intensity profile (arb. units)

Intensity

Polarization profile (arb. units)

Polarization

Target Position

\[ R = \frac{2}{\frac{I}{2P}} \]

\[ \langle P \rangle_{\text{Exp}} = \frac{\sqrt{(1+R_X) \cdot (1+R_Y)}}{\sqrt{(1+\frac{1}{2}R_X) \cdot (1+\frac{1}{2}R_Y)}} \approx 1 + \frac{1}{4}(R_X + R_Y) \]

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

Run-2009:

\( E_{\text{beam}}=100 \text{ GeV}: R \sim 0.1 \Rightarrow 5\% \text{ correction} \)

\( E_{\text{beam}}=250 \text{ GeV}: R \sim 0.35 \Rightarrow 15\% \text{ correction} \)
Polarization Measurements

\[ P = \frac{1}{A_N} = \frac{1}{A_N} \frac{N_{Left}}{N_{Left} + N_{Right}} \]

\( A_N \) depends on the process and kinematic range of the measurements.

Precision of the measurements

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

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

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

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

Closed orbit in a perfect machine: center of quadrupoles

Closed orbit in a machine with dipole errors
The betatron tune is the number of oscillations in one orbital revolution. The equation for the horizontal position of a particle in a circular accelerator is given by:

\[ y(s) = \sqrt{2} J \cos(2 \beta_y(s) + \phi_y) \]

where \( y(s) \) is the horizontal position, \( J \) is a constant, \( \beta_y \) is the betatron tune, and \( \phi_y \) is the phase advance. The reference orbit is the ideal orbit, and the closed orbit is the actual orbit due to betatron tune. The beta function is the factor that affects the curvature of the orbit.
Separation of spin states in the inhomogeneous magnetic field
THE RHIC ACCELERATOR SYSTEM

Booster Ring
AGS
Switchyard

Tandem
Van de Graaff

RHB
Blue Ring
Yellow Ring

Brookhaven Science Associates
59
NNP SS@MIT, July 2016
E.C. Aschenauer