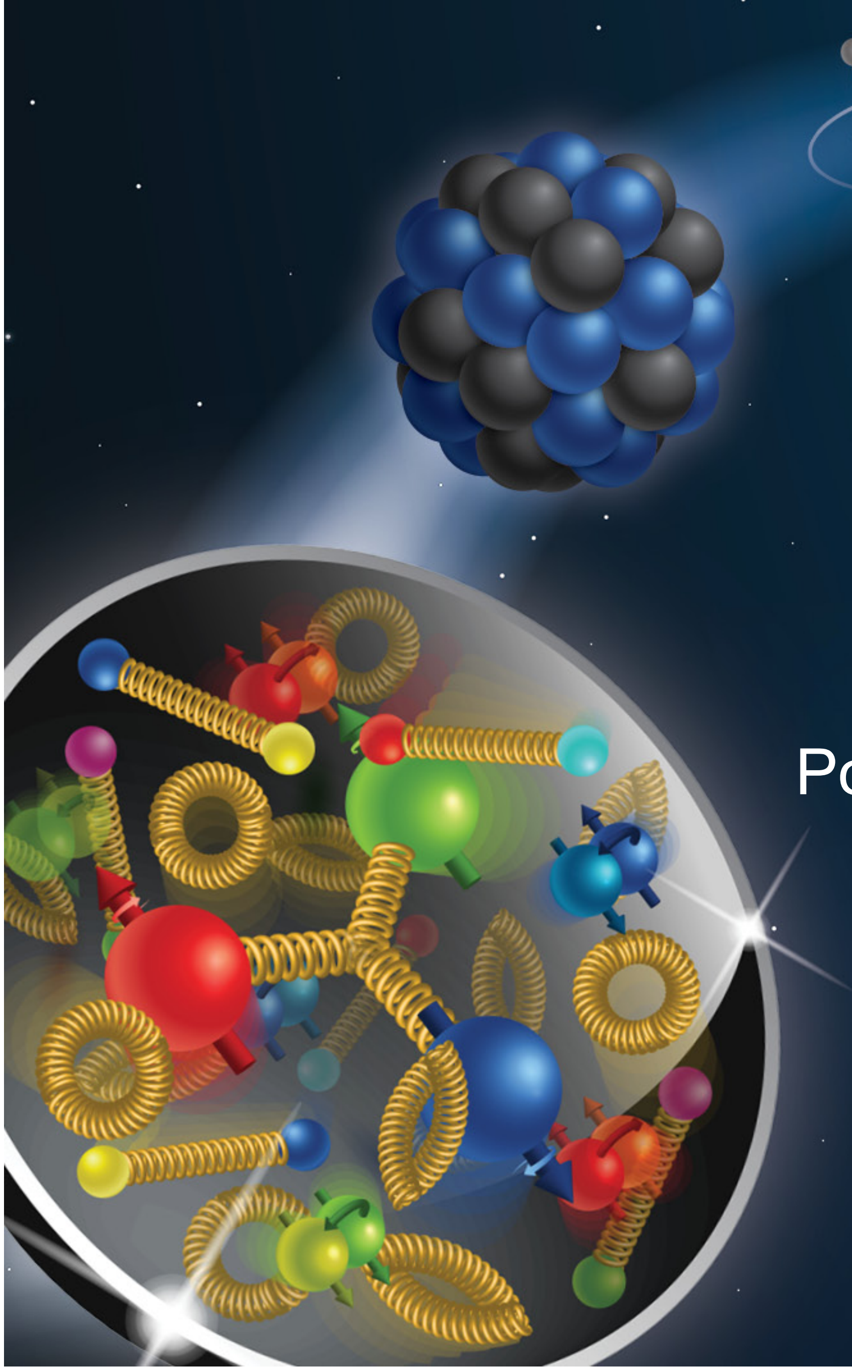


Polarized Light Ions in eRHIC

Polarized Light Ions in EIC Workshop

February 5-9, 2018

Vadim Ptitsyn

Brookhaven National Laboratory

Electron Ion Collider – eRHIC

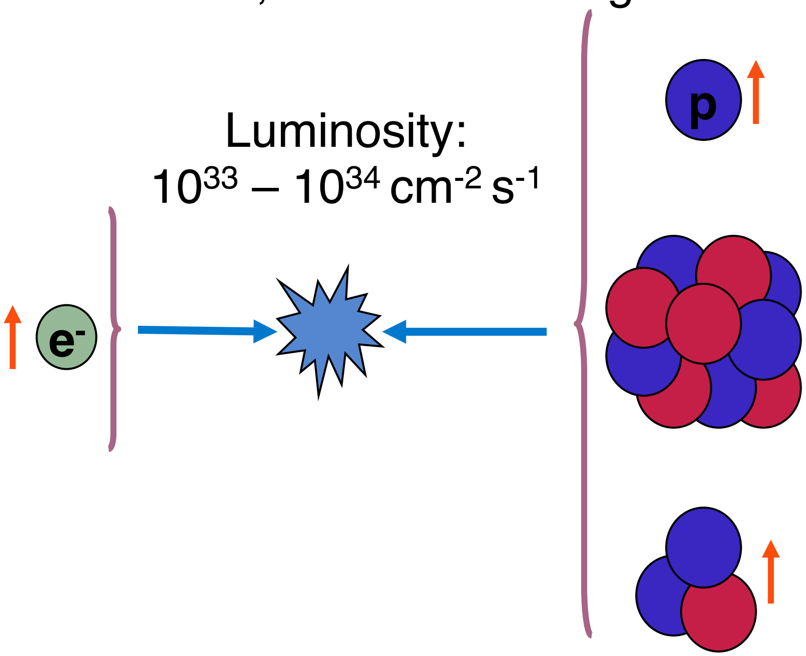
BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

eRHIC: Electron Ion Collider at BNL

Add an electron accelerator to the existing \$2.5B RHIC
including existing RHIC tunnel, detector buildings and cryo facility

80% polarized electrons:
5 – 18 GeV

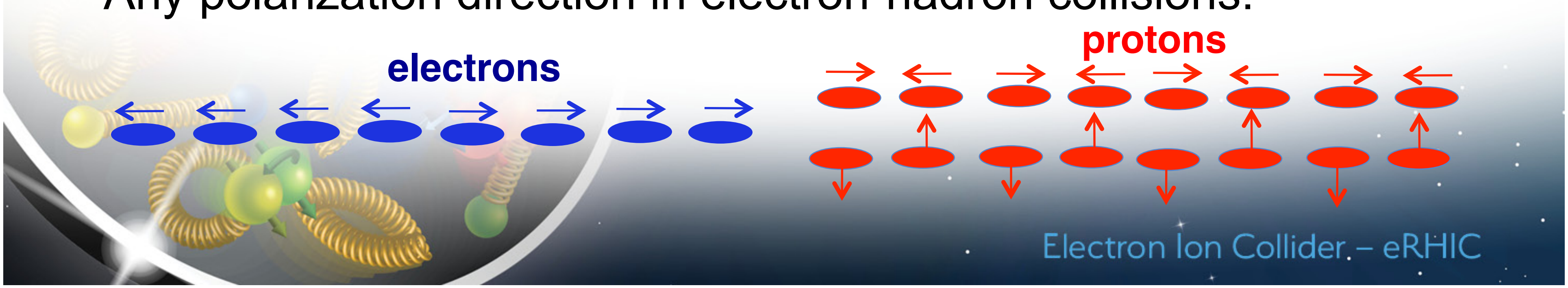


70% polarized protons
41 - 275 GeV

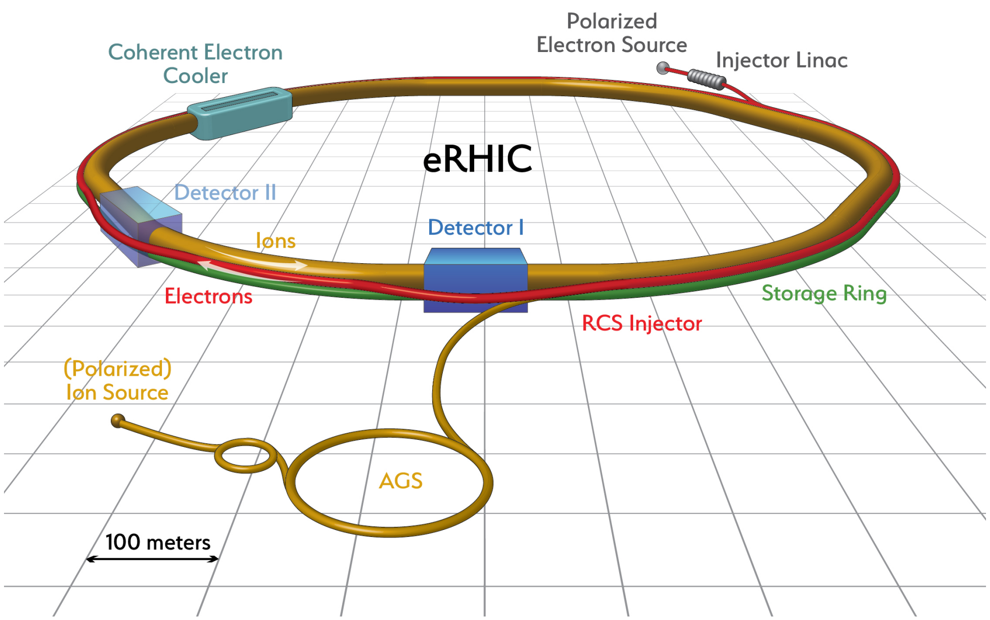
Light ions (d, Si, Cu)
Heavy ions (Au, U)
41 – 110 GeV/u

Pol. light ions (He-3)
41 - 184 GeV/u
Deuterons (?)

- Center-of-mass energy range: 30 – 140 GeV
- Full electron polarization at all energies
  Full proton and He-3 polarization with six Siberian snakes
- Any polarization direction in electron-hadron collisions:



pCDR eRHIC Design Concept

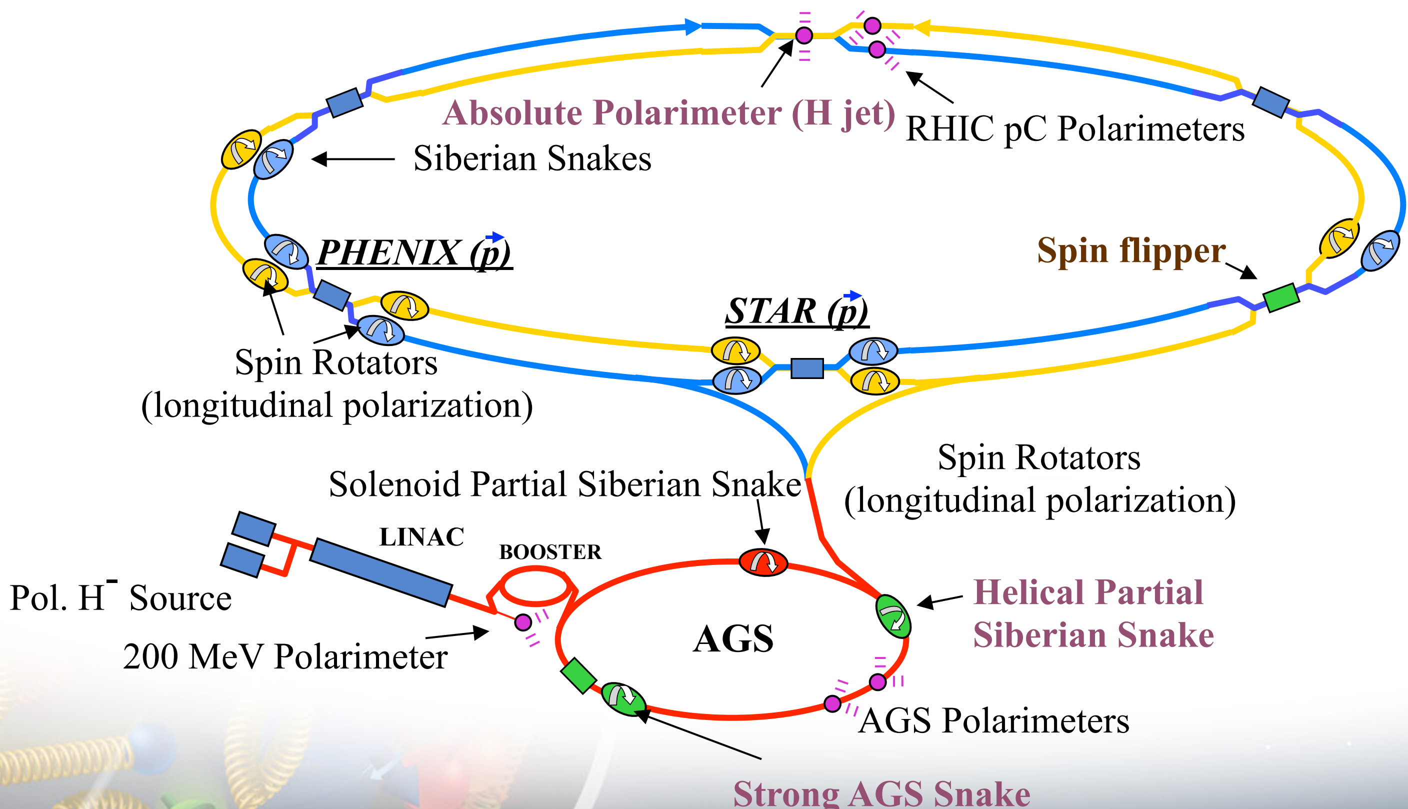


- Added electron storage ring (5-18 GeV)
  - Up to 2.5 A electron current.
  - 10 MW maximum RF power (administrative limit)
- Flat proton beam formed by cooling
- On-energy polarized electron injector
  (RCS is a cost-effective injector option)
- Polarized electron source and 400 MeV injector linac: 10nC, 1 Hz

Alternative approach based on electron ERL accelerator has been thoroughly explored in the past. Technological risks were recognized and are being addressed by R&D. This approach is presently considered as a cost-effective alternative.

eRHIC, polarized protons

- **RHIC: only polarized proton collider in the world. Up to 65% at 100 GeV, up to 57% at 255 GeV.**
- **eRHIC will take favor of existing hardware in RHIC and in the injector chain to accelerate polarized protons (up to 275 GeV) and He-3 (up to 184 GeV/u) .**



Spin resonances

Depolarizing resonance condition:

Number of spin rotations per turn = Number of spin kicks per turn
Spin resonance strength ε = spin rotation per turn / 2π

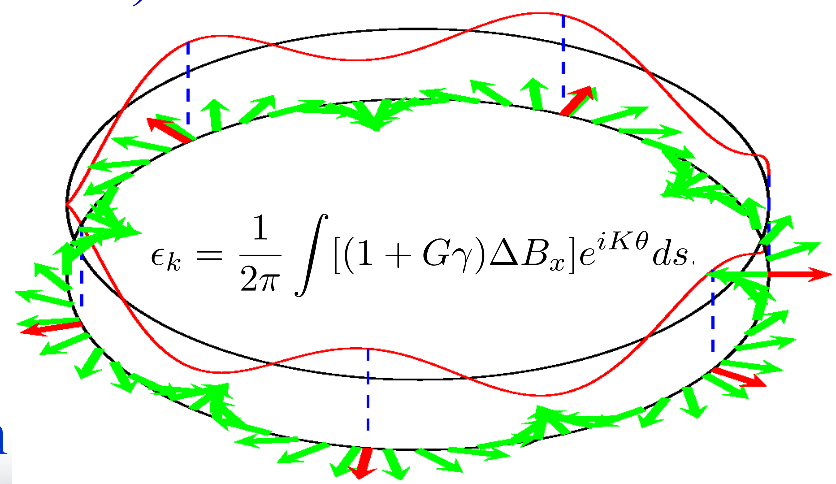
Imperfection resonance (magnet errors and misalignments):

$\nu_{sp} = n$

Intrinsic resonance (Vertical focusing fields):

$\nu_{sp} = Pn \pm Q_y$

P: Superperiodicity [RHIC:3]
Q_y : Betatron tune [RHIC:29.68]



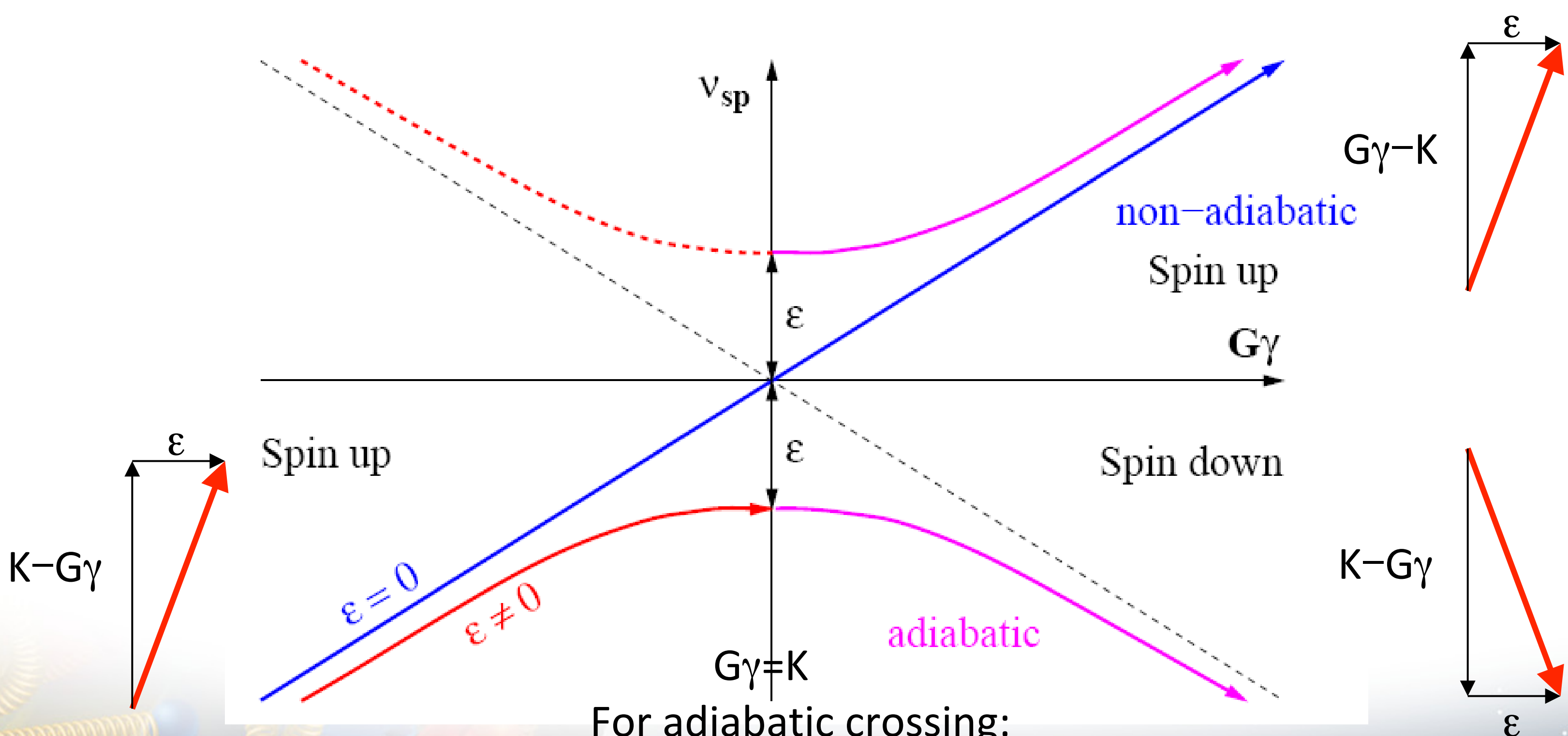
Weak resonances: some depolarization
Strong resonances: partial or complete spin flip

Spin Resonance Crossing

Froissart-Stora: $\dfrac{P_f}{P_i} = 2\, e^{-\left(\frac{\pi \varepsilon^2}{2\alpha}\right)} - 1$ [α: crossing speed]

Non-adiabatic ($\varepsilon^2/\alpha \ll 1$) $\leftrightarrow$ Adiabatic ($\varepsilon^2/\alpha \gg 1$)

$P_f/P_i = 1$ $P_f/P_i = -1$



For adiabatic crossing:
spin is in the horizontal plane
at the resonance

Technologies for spin resonance crossing

Non-adiabatic ($\varepsilon^2/\alpha << 1$)	↔	Adiabatic ($\varepsilon^2/\alpha >> 1$)
$P_f/P_i = 1$		$P_f/P_i = -1$

Imperfection Resonances:

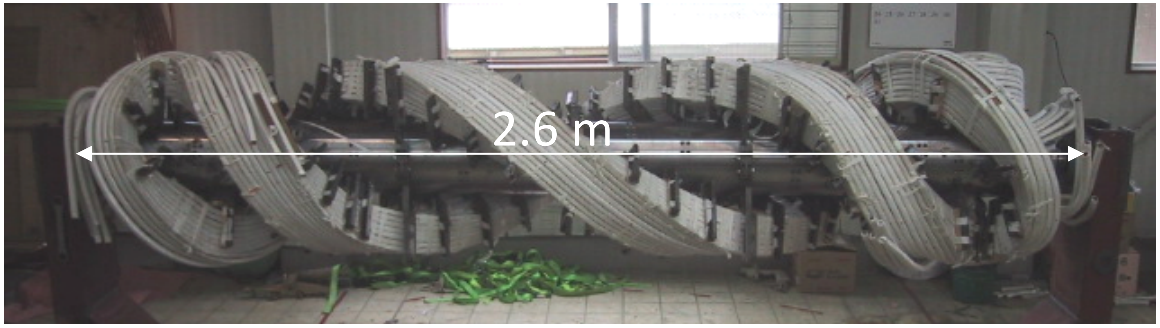
Correction Dipoles (ε small) (RHIC Booster)	Enhanced oribt excursion (ε large) (RHIC Booster)
	Partial Snake (ε large) (AGS, IUCF)

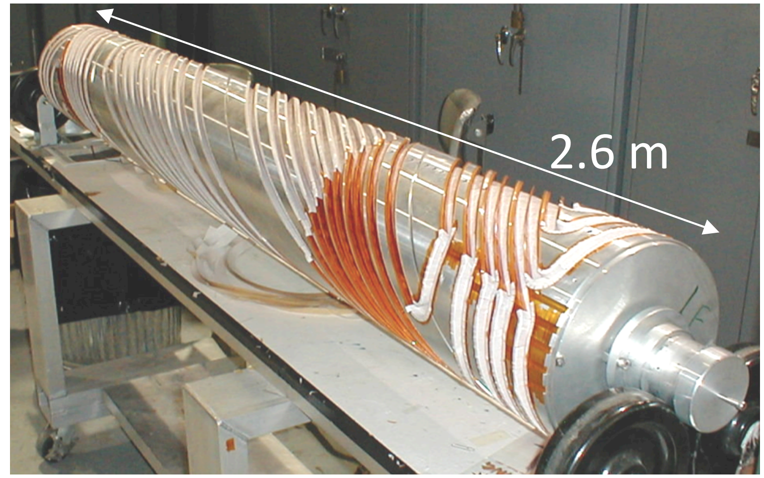
Intrinsic Resonances:

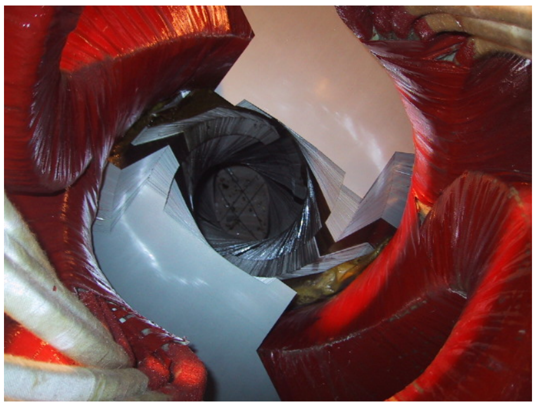
Pulsed Quadrupoles (α large) (ZGS,AGS)	RF Dipole (ε large) (AGS past)
Lattice modifications (ε small)	Strong Partial Snake (ε large) (AGS present)

Ultimate tool:
Full Siberian Snakes in RHIC (2 per ring) prevent first-order spin resonance conditions. Weak depolarization still possible due to high-order spin resonances.

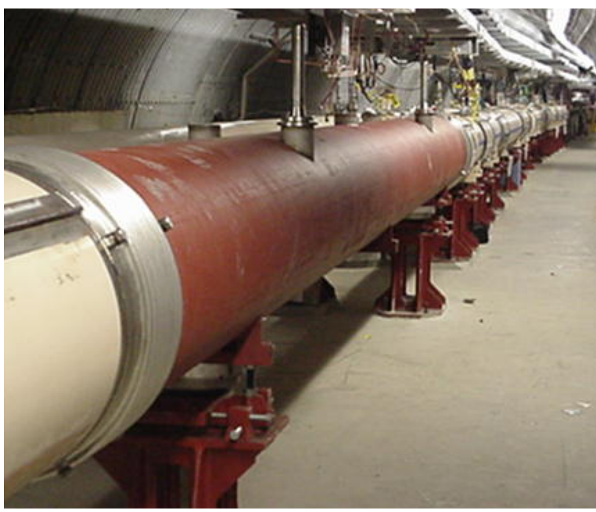
Siberian Snakes

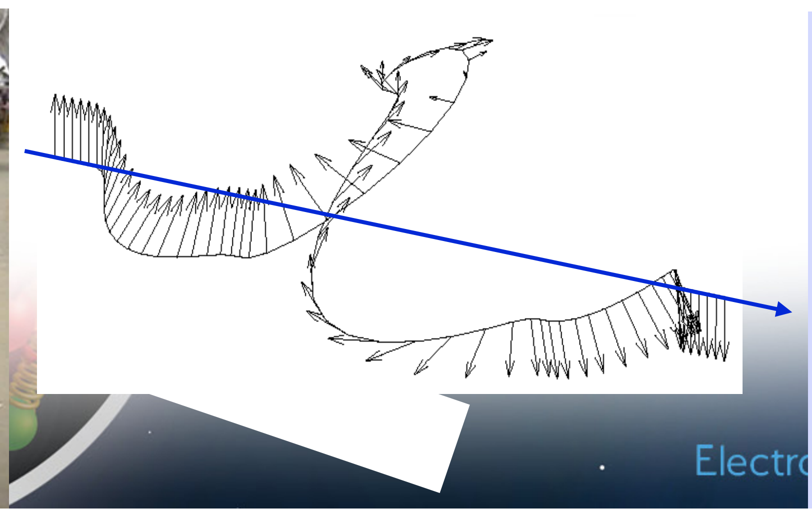


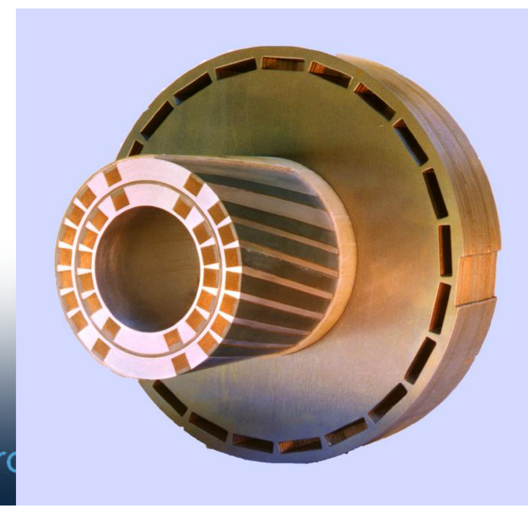




- AGS Siberian Snakes: variable twist helical dipoles, 1.5 T (RT) and 3 T (SC), 2.6 m long
- RHIC Siberian Snakes: 4 SC helical dipoles, 4 T, each 2.4 m long and full 360° twist





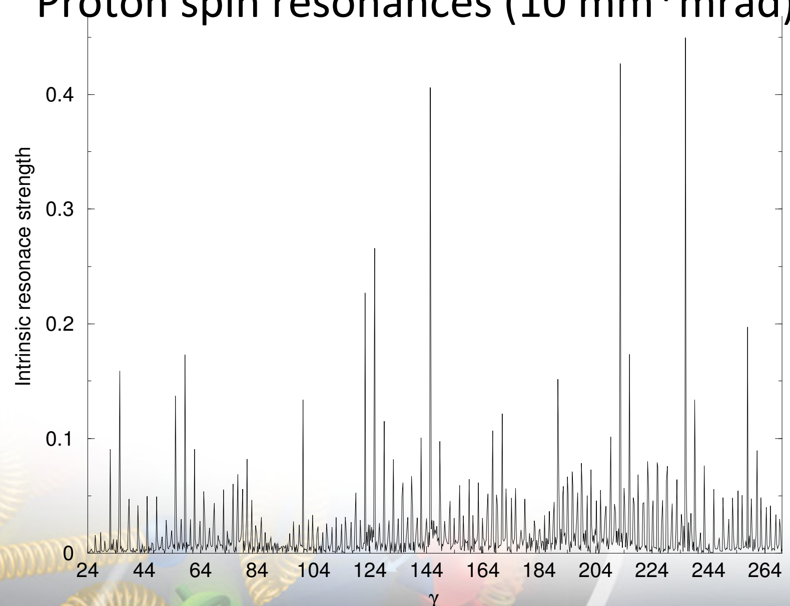


Polarized $^3He^{+2}$ in RHIC and eRHIC

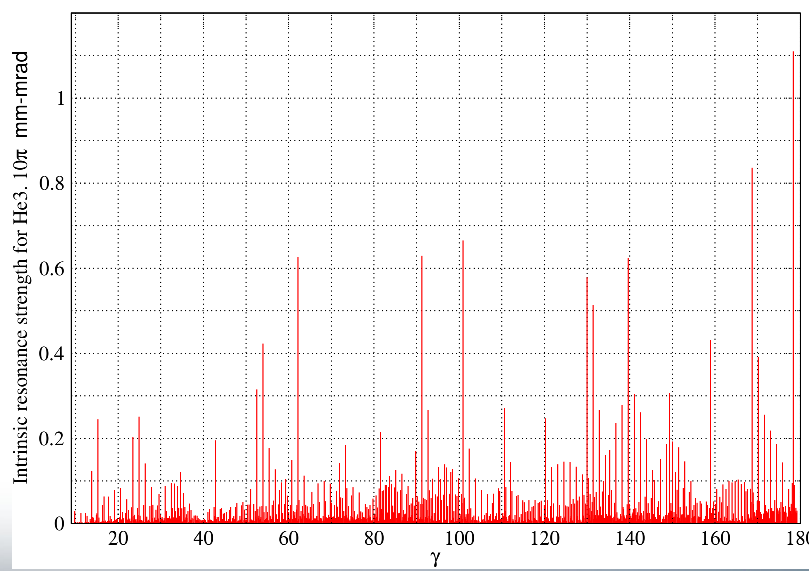
- RHIC Siberian snakes and spin rotators can be used for the spin control, with less orbit excursions than with protons.
- More spin resonances. Larger resonance strength.

	p	$^3He^{+2}$
m, GeV	*0.938*	*2.808*
G	*1.79*	*-4.18*
E/u, GeV	*24-275*	*16-183*
$\|G\gamma\|$	*46.5-525.5*	*72.6-819.4*

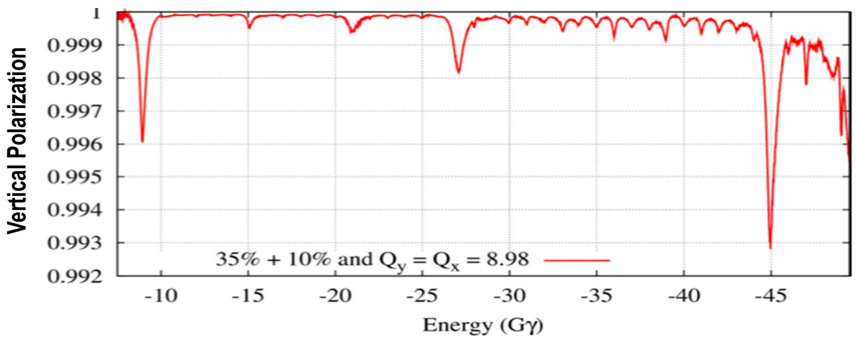
Proton spin resonances (10 mm*mrad)



He-3 spin resonances (10 mm*mrad)



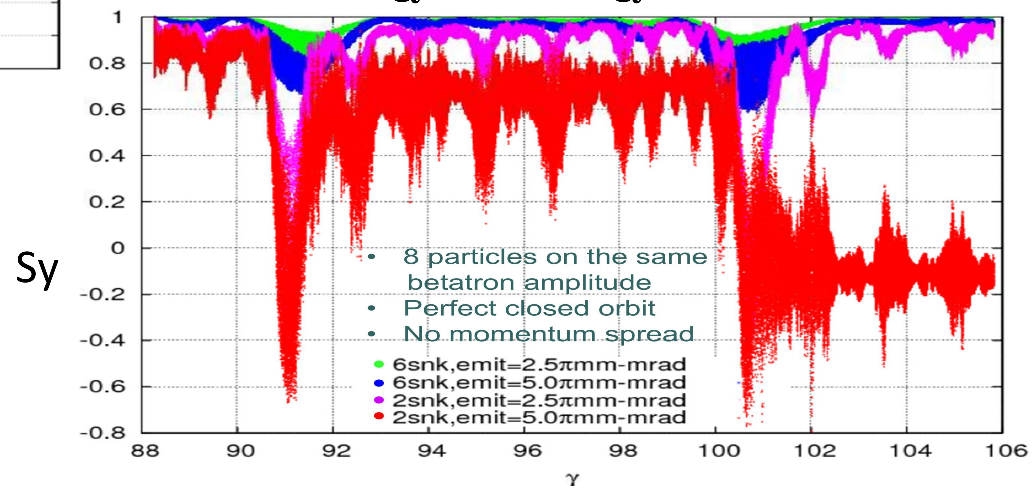
He-3 polarization preservation simulations



AGS

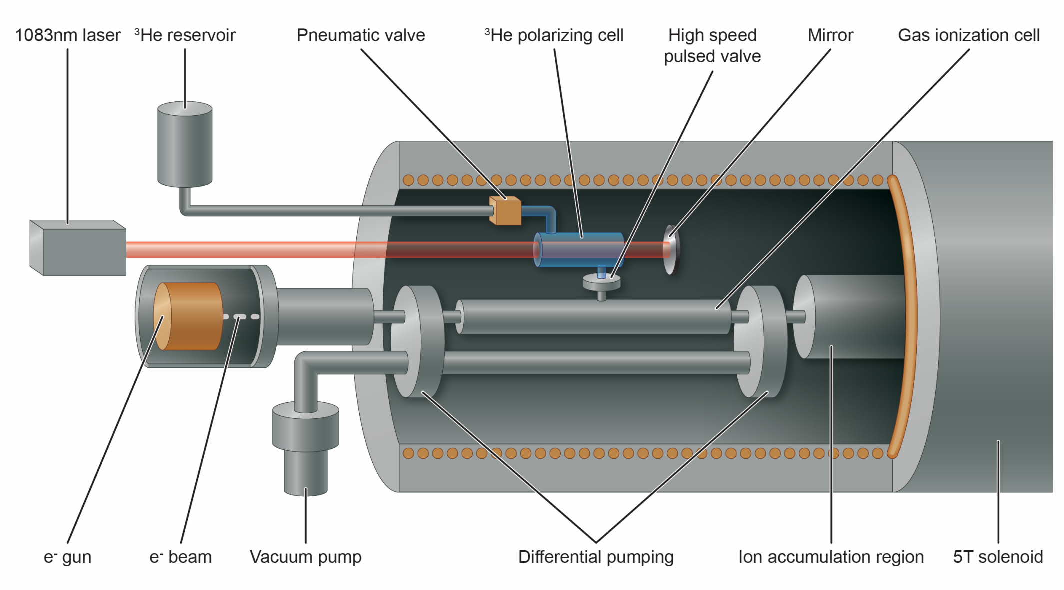
F. Meot,
ZGOUBI simulation

RHIC
411-Qy and 393+Qy



- For successful acceleration of He-3 the number of Snakes has to be increased from present 2 to 6.
- This increase of the Snake number is included in the baseline eRHIC design.
- It will eliminate also weak polarization experienced by RHIC polarized protons.

Polarized He-3 source



- Developed by **BNL-MIT collaboration**
- He-3 is polarized using Metastability Exchange Optical Pumping (MEOP) mechanism
- Ionized in the ionization cell using electron beam (up to 10A)
- High magnetic field (5T solenoid)
- The source will be realized as an extension of existing EBIS ion source

Requirements for RHIC polarized He-3 source:

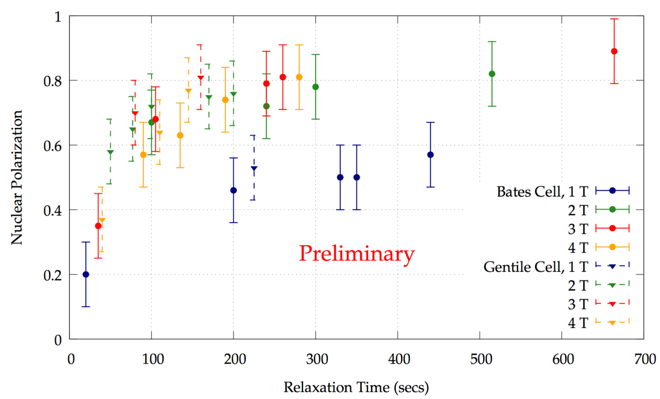
- Intensity ~ $2 \cdot 10^{11}$ $3He^{++}$ ions in 10 us pulse ~4.0 mA
- Maximum polarization > 80%
- Compatibility with the operational EBIS for heavy ion physics

Polarized He-3 development facility at BNL

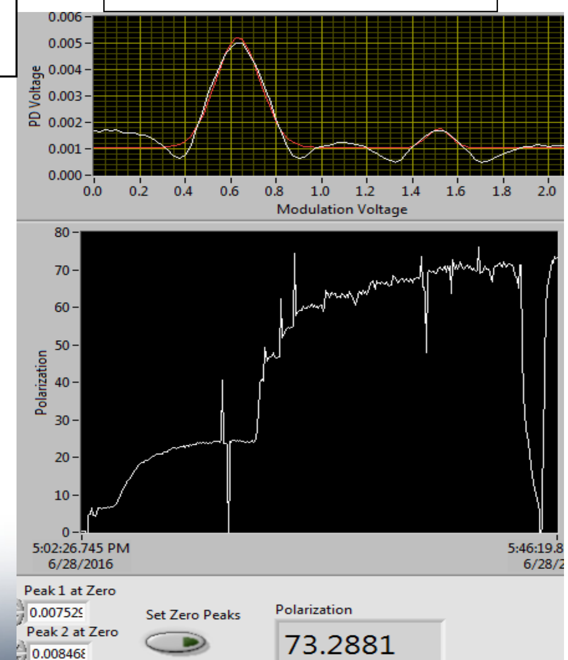
Initial test have been done in MIT. Presently extensive tests are ongoing in the BNL:

- Testing the propagation of a 6 Amp electron beam through the narrow drift tube and the constrictions and ion extraction from residual gas.
- Test with external ion injection using the high-speed pulsed valve design
- Tests of MEOP in high field, using OPPIS solenoid
- Testing gas-purification system
- Tests of NMR polarimeter

80-84 % polarization was measured with sealed 3H-cell in high magnetic field.



73 % polarization in the "open" cell



RHIC Hadron 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

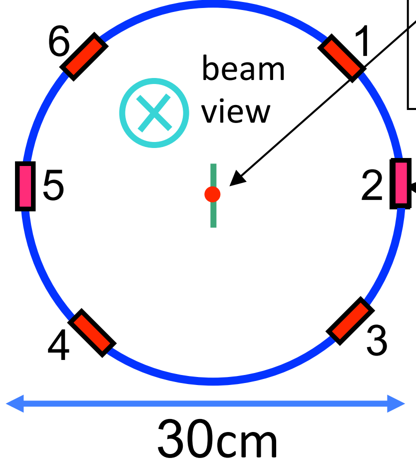
- Very fast and high precision ⇒ main polarization monitoring tool
- Measures polarization profile (polarization is higher in beam center) and lifetime
- Needs to be normalized to HJet

Local Polarimeters (at PHENIX and STAR IRs)

- Defines spin direction in experimental area

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

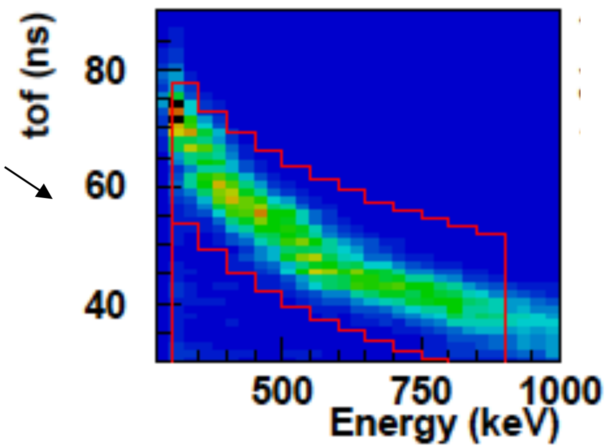
Proton-Carbon Coulomb-Nuclear Interference Polarimeter



Ultra-thin carbon ribbon target
~ 100 mono-layers think, 10μm wide

Si strip detectors for recoil carbon
(TOF, E_C)

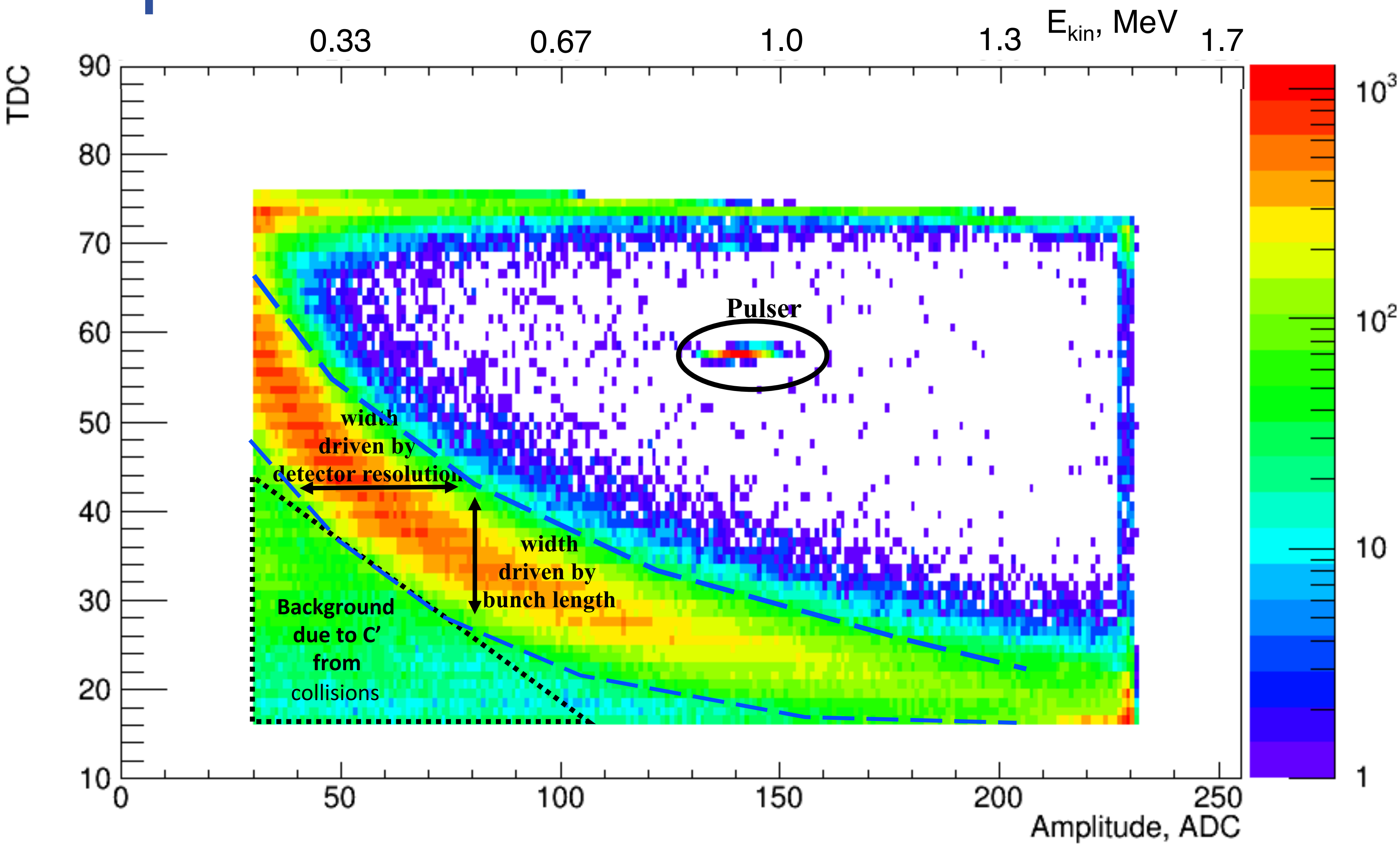
$$p^{\uparrow}C \rightarrow p^{\uparrow}C$$



$$P_B = \frac{\varepsilon_{LR}}{A_N}, \quad \varepsilon_{LR} = \frac{N_L - N_R}{N_L + N_R}$$

- $A_N \approx 0.015$, originates from anomalous magnetic moment of proton
- At high energy A_N is independent of beam energy
- Negligible emittance growth per polarization measurement
- Due to radiation cooling carbon target survives beam heating
- Measures polarization and beam profile

pC: details of measurement



Polarized H-Jet Polarimeter

Left-right asymmetry in elastic scattering due to spin-orbit interaction:

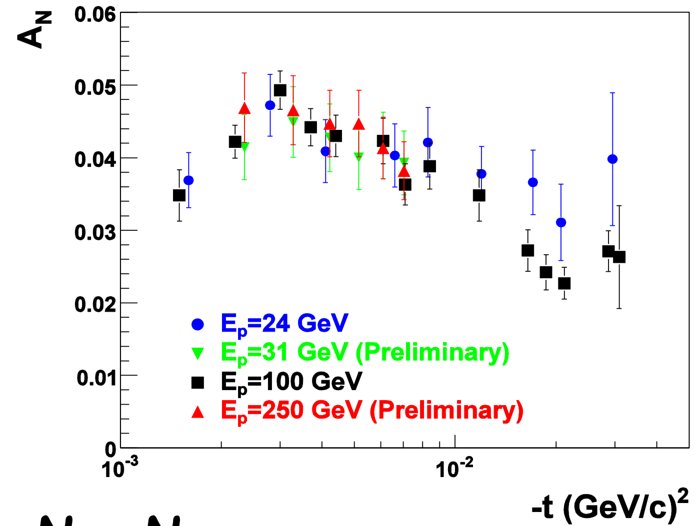
interaction between (electric or strong) field of one proton and magnetic moment associated with the spin of the other proton

Beam and target are both protons

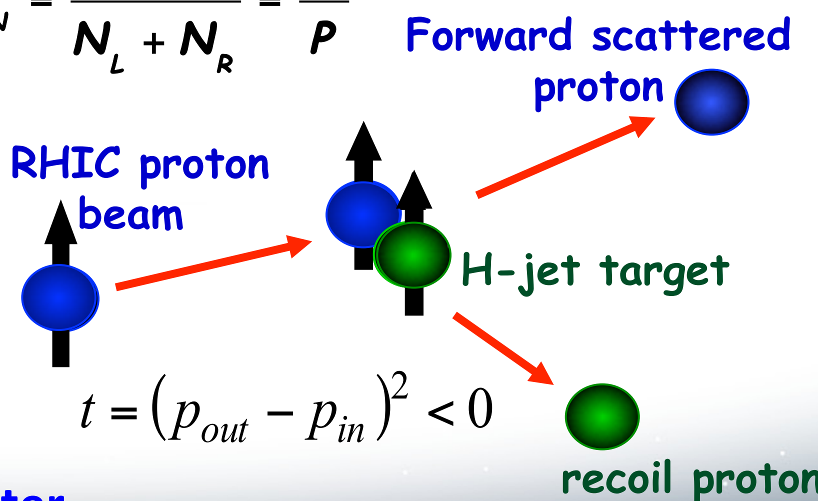
$$A_N(t) = \boxed{\frac{\varepsilon_{\text{target}}}{P_{\text{target}}}} = \boxed{\frac{\varepsilon_{\text{beam}}}{P_{\text{beam}}}}$$

$$\Rightarrow \boxed{P_{beam} = P_{\text{target}} \frac{\varepsilon_{beam}}{\varepsilon_{\text{target}}}}$$

P_{target} is provided by Brett-Rabi Polarimeter



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



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

He-3 polarimetry

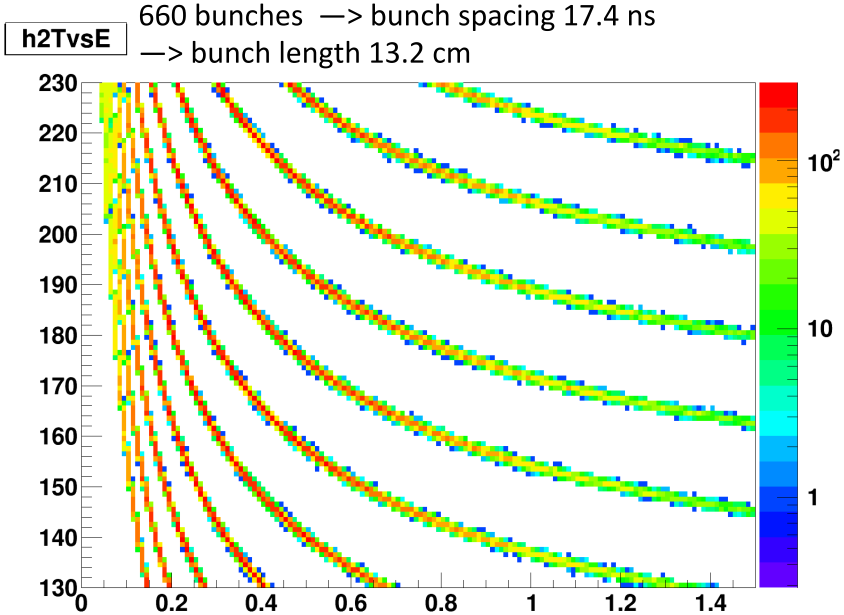
- Additional background source: He-3 break up on the polarimeter target.
  - What is the level of background due to He-3 beam breakup?
  - What is the analyzing power of the events coming from He-3 beam breakup?
- Optimization of polarimeter chamber, RF shielding to reduce interference from the beam induced fields
- Absolute polarimetry:
  would H-jet + He-3 beam work as absolute polarimeter?

  Considerably simplify switching between polarized proton and polarized 3He runs
- eRHIC (EIC) common challenge for pol. protons and He-3 polarimeter:
  - much shorter bunch distance than in RHIC
- Studies are ongoing

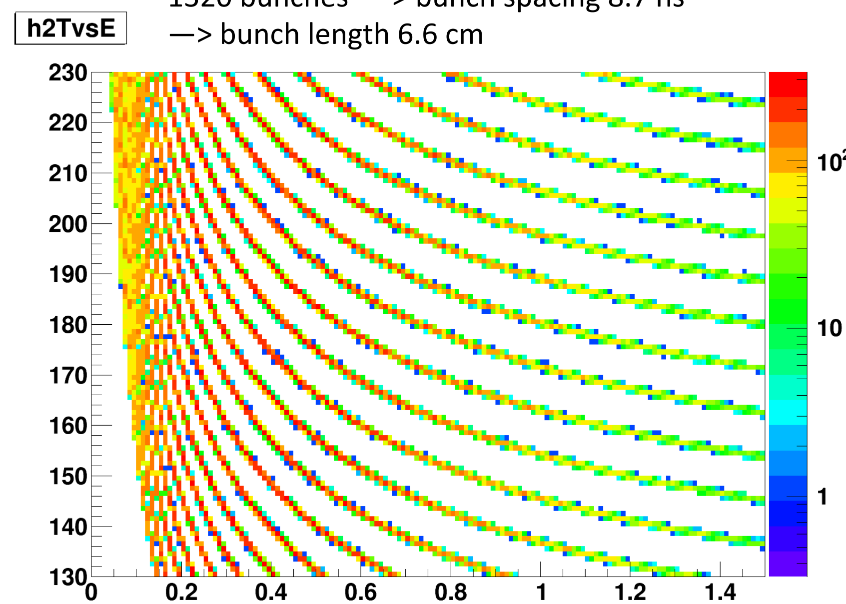
pC: eRHIC with 660 and 1320 bunches

E.Aschenauer and A. Poblaguev

660 bunches —> bunch spacing 17.4 ns
—> bunch length 13.2 cm



1320 bunches —> bunch spacing 8.7 ns
—> bunch length 6.6 cm



- increased bunch number smears signal “bananas” together at low E_{kin} → lose data with high statistics high analyzing power
- No background included and no smearing in horizontal due detector energy resolution and energy loss in target
  - → smearing need to increase lower cut on E_{kin} → lose data with high statistics high analyzing power
  - → collision related background smears from bunch-50 to bunch-49 and lower → impact on measuring bunch polarisation → especially bad for + - transitions

Will make correlation between measured polarization and polarization in collisions very hard

Polarized He-3 progress and plans

- Spin dynamics at the acceleration in the injector chain and in RHIC is being studied. Increasing the number of Snakes in RHIC to 6 is required.
- Successful acceleration of unpolarized $^{3}He^{+2}$ beam in Booster and AGS has been demonstrated.
- Carbon target polarimeter in AGS was getting events from unpolarized beams
- RHIC EBIS ion source is being modified to provide capability of polarized He-3. (Completion in 2020)
- In 2020: test of polarized polarized He-3 acceleration through the injector chain (Booster, AGS, RHIC injection). Includes polarimetry testing.

Possibility for polarized deuterons in eRHIC

- Unpolarized deuteron beam has been used in RHIC in the course of its ion physics program.
- Present RHIC/eRHIC physics program does not include polarized deuterons.
- However the possibility of acceleration of polarized deuteron in RHIC was evaluated in the past by accelerator scientists and shown feasible*. (See, for instance, E.Courant, AGS/RHIC/SN Note 66, 1997)*

	p	$^3He^{+2}$	*d*
m, GeV	*0.938*	*2.808*	*1.876*
G	*1.79*	*-4.18*	*-0.14*
E/u, GeV	*24-275*	*16-183*	*12-138*
$\lvert G\gamma \rvert$	*46.5-525.5*	*72.6-819.4*	*1.9-20.9*

Small deuteron G:
- Much higher magnetic field required for spin rotation
- But:
  - Weaker resonances
  - Small number of resonances

Polarized deuteron acceleration in eRHIC hadron ring

- Expected spin resonance strength:
  - Imperfection resonances: σ_{co} < 0.3 mm , ε_{imp} < 0.004
  - Intrinsic resonances: ε_{int} ~0.0005-0.002

- Taking advantage of small number of resonances one can address particular resonances, causing troubles, by applying known accelerator technologies:
  - Controlled enhancement of imperfection resonances by making vertical orbit wave (using dipole correctors) synchronous with spin rotation. 1 mm orbit wave creates 0.002-0.02 resonance strength (depending on the energy)
    (technology used in RHIC Booster for polarized protons)
  - Ultimate solution, a partial snake, based on 15 T*m solenoid ($\varepsilon_{imp\,\sim}$ 0.0022), can be added providing full spin flip at each of 19 imperfection resonances.
    (technology used in AGS for polarized protons)
  - Enhancement of strong intrinsic resonances by creating coherent betatron oscillations using AC dipole.
    (technology used in past in AGS for polarized protons)
  - Speed up crossing of weaker intrinsic resonances using betatron tune jump
    (technology used in AGS and IUCF)

- Increased machine setup time (compared with a setup relying on Siberian Snakes for protons and 3He) but feasible.

Deuteron longitudinal polarization

- Helical spin rotators require unreasonably large field (~300T*m)
- Approach: arrange vertical orbit wave through the arcs synchronous with spin rotation and move the beam energy to an integer spin tune.

That is somewhat similar to Figure-8 approach (using small fields for deuteron polarization control) but works at particular deuteron energies ($G\gamma$ = int):

$$E_d\ (\mathrm{GeV}) = 131.5,\ 124.9,\ 118.4,\ 111.8,\ \ldots \text{ and so on}$$

- The orbit wave parameters:
  - The spin tune spread: $G\gamma^*(\Delta p/p)_{rms} = 0.01$
  - The vertical orbit wave of ~3-4 mm amplitude is needed to overcome the spin tune spread and ensure the polarization is in transverse plane.
  - Proper phase of the orbit wave provides longitudinal polarization at the experimental point.

Summary

- Polarized He-3 will utilize devices and techniques presently used to accelerate polarized protons in the injector chain and in RHIC ring.
- Number of Snakes in the hadron ring must be increased to 6 to guarantee the polarization preservation
- Testing of polarized He-3 source components is underway. The source, as an extension of RHIC EBIS source, should be ready in 2020.
- Testing of polarized He-3 acceleration through the injector chain is expected in 2020.
- High energy He-3 polarimetry will use similar approaches as polarized prot-jeton polarimeters (Carbon target polarimeter and polarized He-3-jet or H polarimeter). Studies are underway.
- Acceleration of polarized deuteron looks feasible, involving a number of state-of-the-art technologies.
  Further polarized deuteron studies, including detailed simulations, can be arranged if a clear eRHIC physics program interest is declared in this topic.

Acknowledgements to:

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