Beam polarization in eRHIC
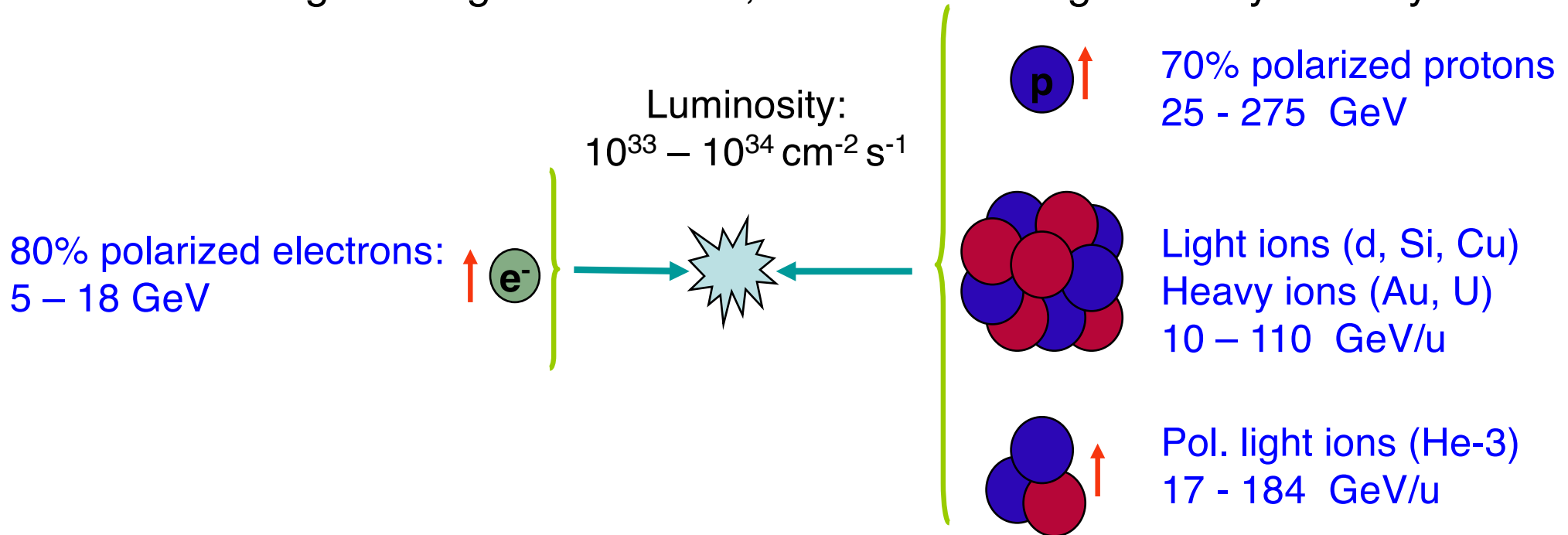
V. Ptitsyn (BNL)

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

p 70% polarized protons
25 - 275 GeV

Luminosity:
$10^{33} - 10^{34}$ cm^{-2} s^{-1}

80% polarized electrons:
5 – 18 GeV

e$^-$

Light ions (d, Si, Cu)
Heavy ions (Au, U)
10 – 110 GeV/u

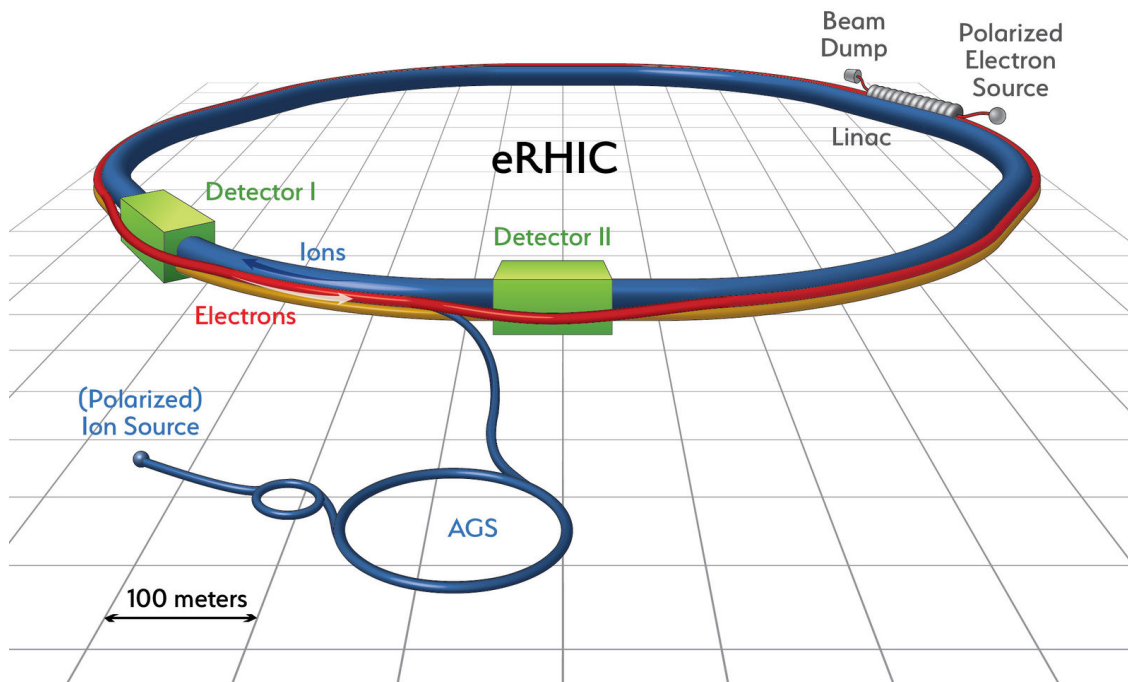Pol. light ions (He-3)
17 - 184 GeV/u

- Center-of-mass energy range: 20 – 145 GeV
- Full electron polarization at all energies
  Full proton and He-3 polarization with six Siberian snakes
- Any polarization direction in electron-hadron collisions:

electrons

protons
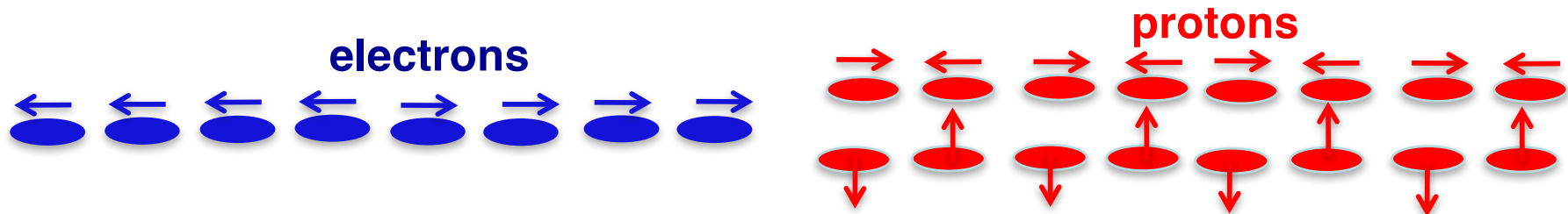
*** It is possible to increase RHIC ring energy by 10%**

EIC realization at BNL: eRHIC

- ➤ Recirculating linac is used to accelerate electron to required energy (5-18 GeV)
- ➤ Several recirculation passes (red curve) are placed in existing RHIC tunnel .
- ➤ Multiple electron-hadron interaction points (IPs) and detectors.
- ➤ Two design options are being considered: Ring-Ring (RR) and Linac-Ring (LR)
- • RR: the linac is used as an full energy injector in a storage ring (yellow curve)
- • LR: yellow curve presents top energy recirculation loop; the linac is energy – recovery linac
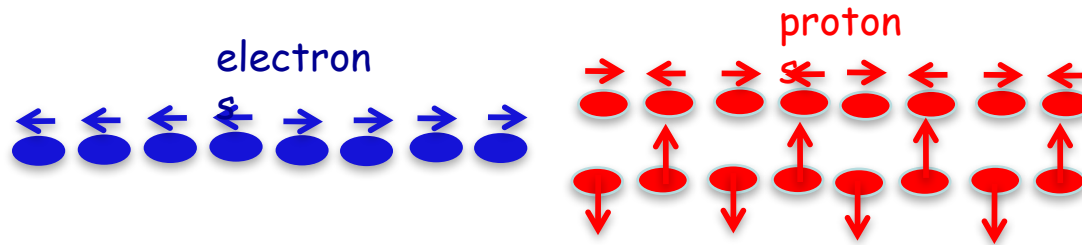
Two considered design options
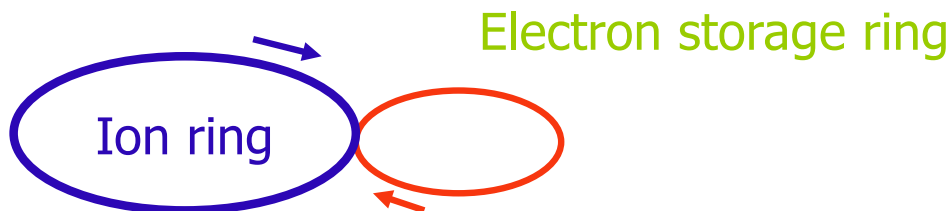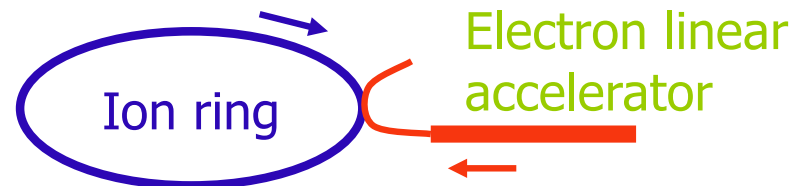
Electron Polarization in LR eRHIC

electron   proton

- 85-90% longitudinally polarized e-beam produced by the e-gun. (DC gun with strained-layer super-lattice GaAs-photocathode)
- Direction of polarization can be switched by changing helicity of laser photons to create complex bunch-by-bunch polarization patterns
- Wien spin filter in the injector to transform the polarization from longitudinal to vertical
- Linac accelerator -> No depolarizing resonances!
- A spin rotator before the interaction region to transform vertical polarization to longitudinal one at the interaction point

Spin dynamics and polarization preservation is straightforward.
Main challenge: high current (50 mA polarized electron source) with at least few hours cathode lifetime.

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Low risk polarized source approach

- 4 mA polarized electron beam current was demonstrated in dedicated experiments in JLab

  Although the Jlab gun design is not optimal for high bunch charge mA scale operation: small cathode size, no cathode cooling

- Low risk eRHIC polarized source employs eight JLab-like guns (possibly with improved gun geometry, cathode size and cathode cooling) and combining scheme to produce up to 50 mA current at the source exit
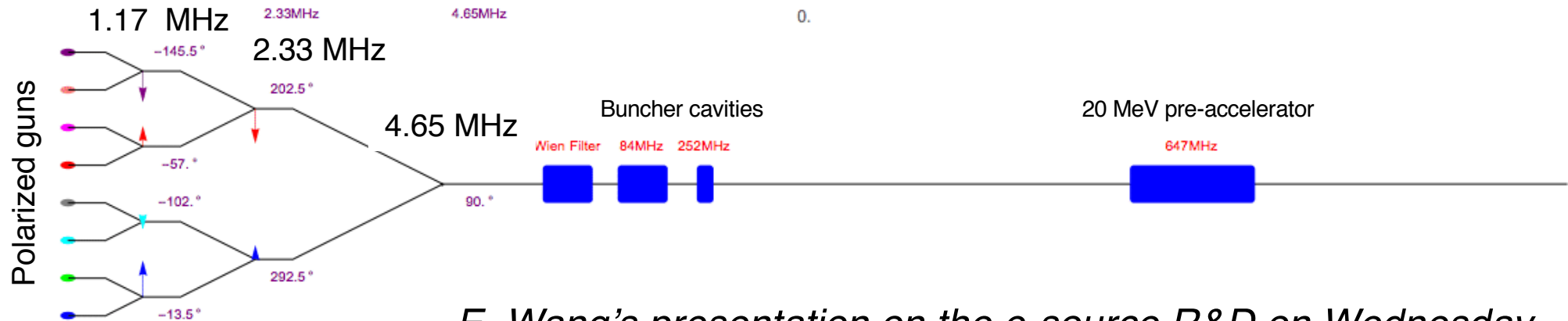
E. Wang's presentation on the e-source R&D on Wednesday

Field distribution of cooper plate deflector, used in combining scheme
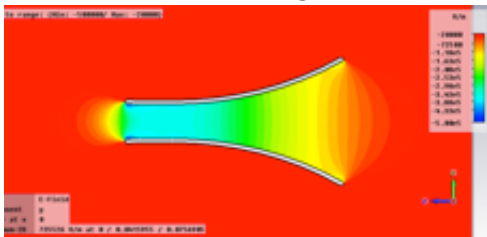
- On-going studies (2016-2017):
  - Finalizing the technicalities of the combining scheme
  - Detailed 3D simulations of high-charge bunch transport through all injector components
  - Experimental studies of single cathode lifetime dependencies (using a Gatling gun prototype)
  - Measurements of surface charge limit for SL cathodes using cathode preparation system.
  - Building a gun prototype

Achieving high polarization in the Ring-Ring eRHIC

Electron polarization levels achieved in various electron storage rings
J.Wenninger, as referred in S.R. Mane, Yu. M. Shatunov and K. Yokoya,
Report on Progress in Physics 68 1997 (2005).

eRHIC storage ring energy range: 5-18 GeV
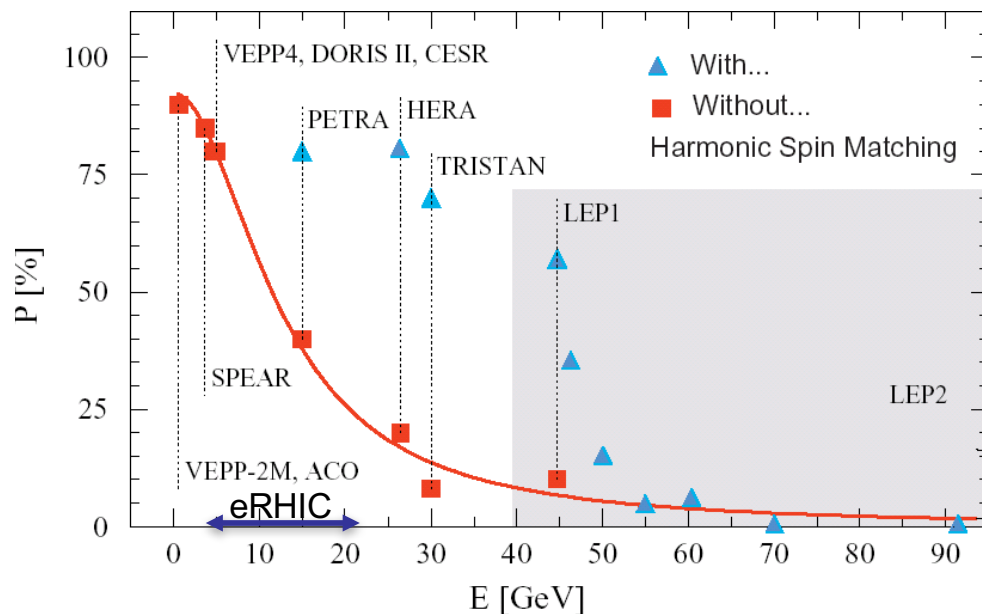
The accelerator technology to achieve high polarization at high energies includes:

- highly efficient orbit correction,
- beam-based alignment of Beam Position Monitors relative to quadrupole field centers
- harmonic spin matching
- well controlled betatron coupling
- spin matching of spin rotator insertion

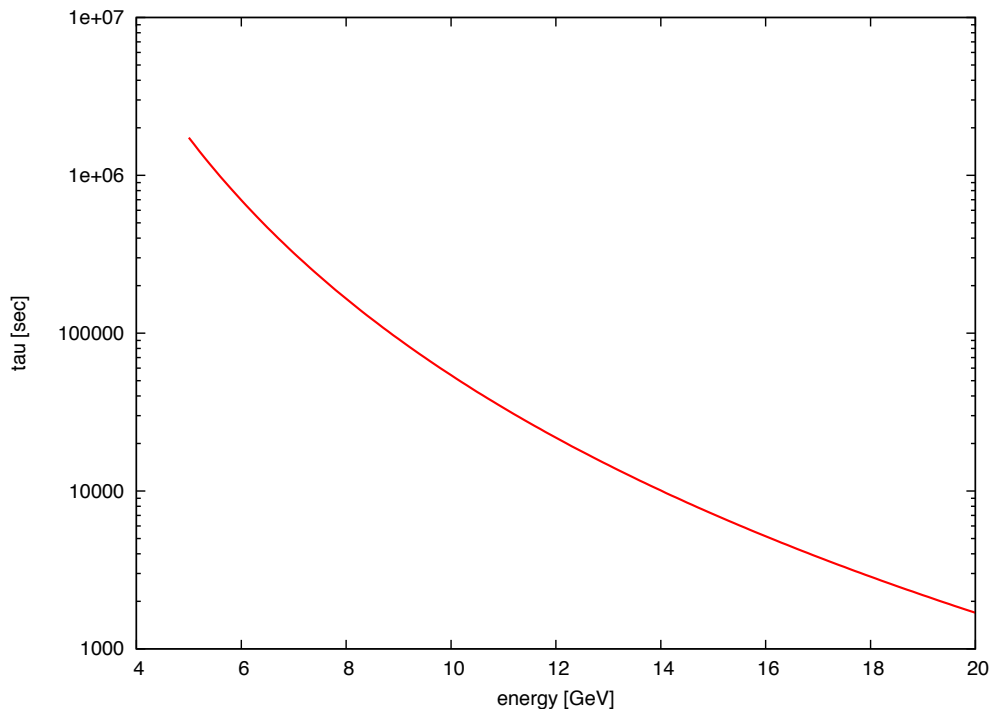D.P. Barber, et al., Phys. Lett. 3434B 436 (1995).

R. Assmann et al., EPAC'94, London, p.932 (1994).

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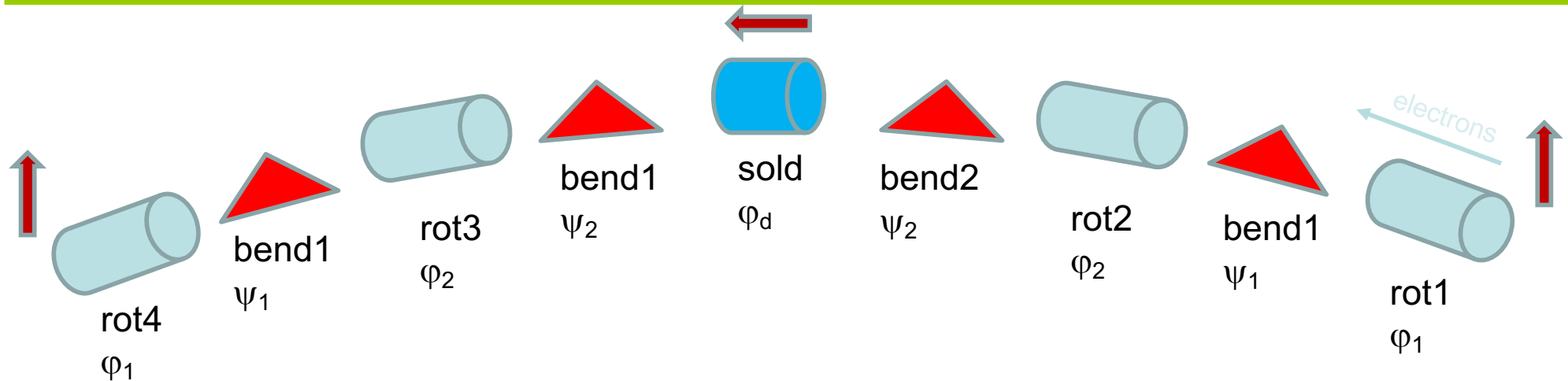
eRHIC RR polarization

Sokolov-Ternov polarization time in the eRHIC electron storage ring as a function of energy.

➢ **Circulating electron beam contains both bunches with the polarization up and bunches with the polarization down.**

➢ **ST process effectively depolarizes bunches with initial 'up' polarization.**

➢ **Replacing single bunches with 1 Hz rate is planned to maintain high polarization level**
~6 min to replace all circulating bunches

➢ **The full energy injector: a recirculating linac operating in pulsed mode**
(a rapid cycling synchrotron with highly symmetric structure is also considered, V.Ranjbar's talk)

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Spin rotator scheme: the same for LR and RR

rot4 φ_1 bend1 ψ_1 rot3 φ_2 bend1 ψ_2 sold φ_d bend2 ψ_2 rot2 φ_2 bend1 ψ_1 rot1 φ_1
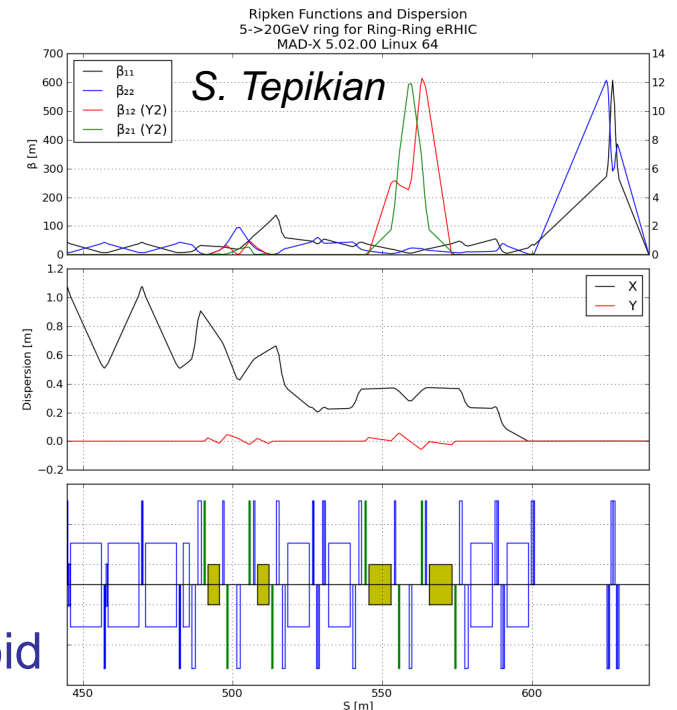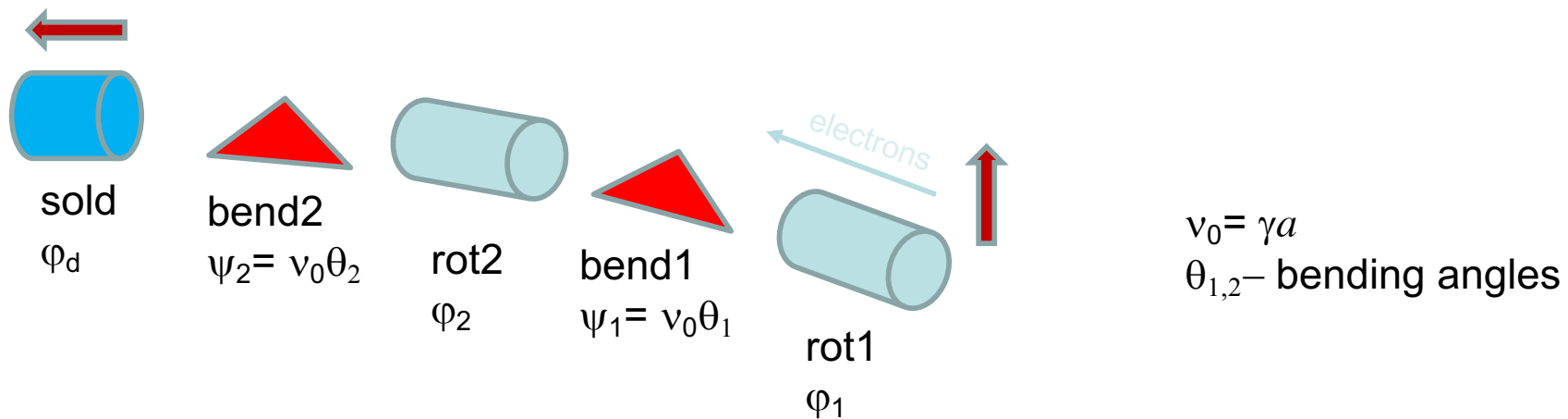
electrons

Spin Rotator consideration:

- Must operate in the whole energy range: from 5 to 18 GeV
- Helical or normal dipole magnet rotator: very large orbit excursions
- Practical solution: **Interleaved solenoids and dipole bends**
- Similar approach as for the JLEIC rotator.

Basic lattice requirements to the rotator insertions:
- Betatron coupling is compensated around each solenoid
- Vertical dispersion is constrained to inside the rotators

Ripken Functions and Dispersion
5->20GeV ring for Ring-Ring eRHIC
MAD-X 5.02.00 Linux 64

S. Tepikian

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Spin rotation angles

sold
φ_d

bend2
$\psi_2 = \nu_0 \theta_2$

rot2
φ_2

bend1
$\psi_1 = \nu_0 \theta_1$

rot1
φ_1

electrons

$\nu_0 = \gamma a$
$\theta_{1,2} -$ bending angles

Connection between solenoidal rotation angles and dipole bend spin rotation angles to convert vertical spin to longitudinal:

$$\tan \varphi_1 = \pm \frac{\cos \psi_2}{\sqrt{-\cos(\psi_1 + \psi_2)\cos(\psi_1 - \psi_2)}}$$

$$\cos \varphi_2 = \cot \psi_1 \, \cot \psi_2$$

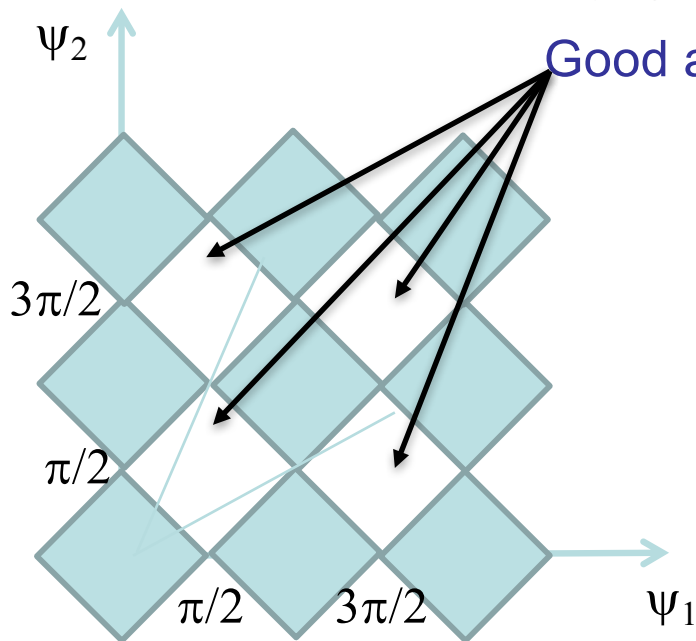Spin'16

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Spin rotator bend angle choice

For 5 GeV rotator min required $\theta_2 + \theta_1 = 138.4$ mrad

Good areas of spin rotation angles in bends:

$$\frac{\pi}{2} + \pi n < \psi_2 + \psi_1 < \frac{3\pi}{2} + \pi n$$

$$-\frac{\pi}{2} \pm \pi n < \psi_2 - \psi_1 < \frac{\pi}{2} \pm \pi n$$

Energy range conditions:

$$\left(\frac{\pi}{2} + \pi n\right)\frac{E_r}{\theta_1 + \theta_2} < E < \left(\frac{3\pi}{2} + \pi n\right)\frac{E_r}{\theta_1 + \theta_2}$$

$$\left(-\frac{\pi}{2} \pm \pi n\right)\frac{E_r}{\theta_1 - \theta_2} < E < \left(\frac{\pi}{2} \pm \pi n\right)\frac{E_r}{\theta_1 - \theta_2}$$
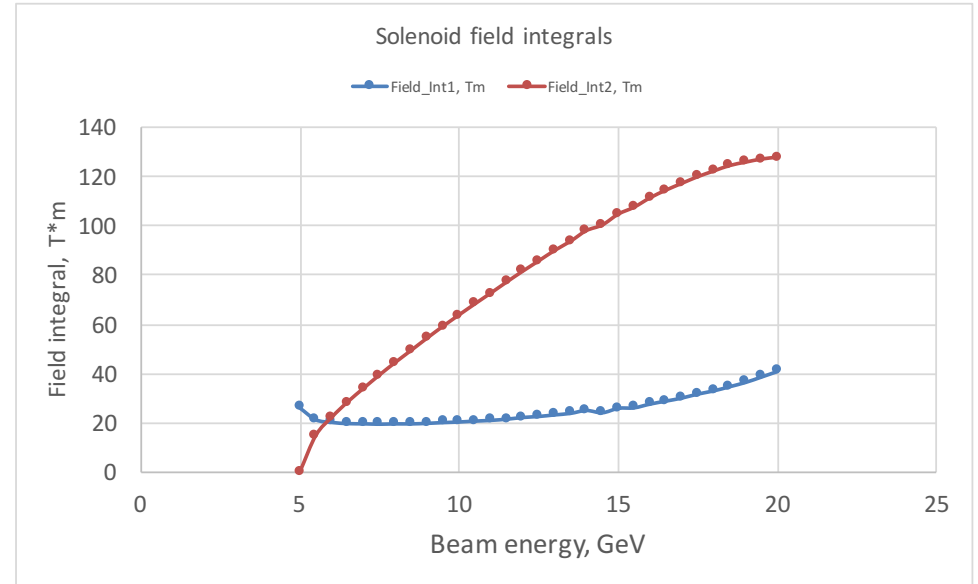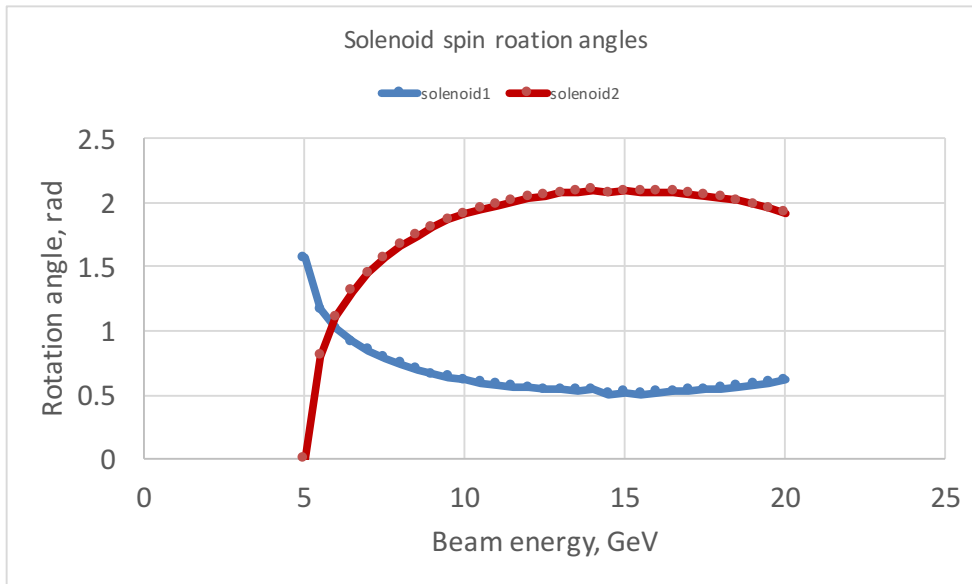
where E_r = 0.441 GeV

The whole energy range (5-18 GeV) can be covered at following choices θ_1 and θ_2:
1) θ_1 = 46.1 mrad, θ_2 = 92.2 mrad or
2) θ_1 = 92.2 mrad, θ_2 = 46.1 mrad *(this one demands ~twice larger solenoid field)*

ψ_2

$3\pi/2$

$\pi/2$

$\pi/2$ $3\pi/2$ ψ_1

Spin rotator parameters

Provides longitudinal polarization in IP throughout the whole energy range.


	18 GeV	5 GeV
1st rotator solenoid field integral , T*m	33.2	26.1
2nd rotator solenoid field integral , T*m	121.9	0
1st bend angle, mrad	46.1	
2nd bend angle, mrad	92.2	

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Depolarization caused by the rotators in the RR design

- Spin rotator insertions locally decoupled.
- No vertical dispersion leaks to outside of the rotator areas.
- No any machine errors.
- <u>No specific spin matching done</u>

Polarization relaxation time vs energy
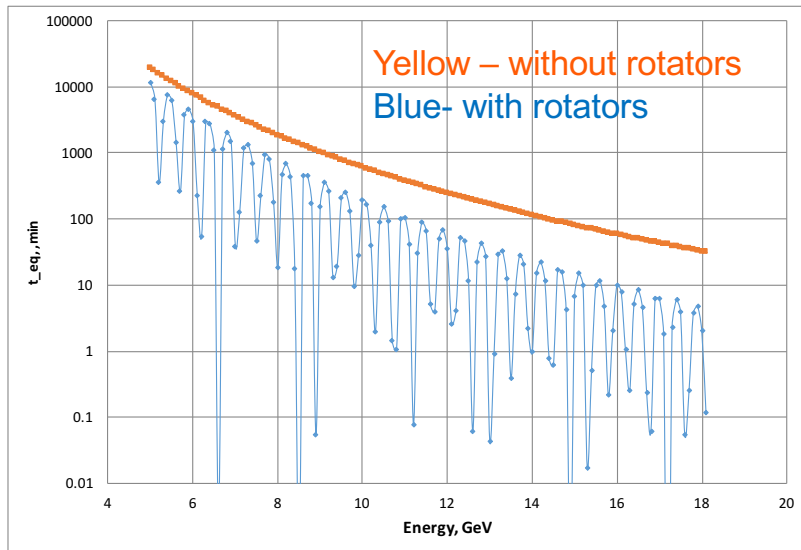
Average polarization (assuming 6min re-fill time) over all bunches having initial polarization - 85%

Yellow – without rotators
Blue- with rotators
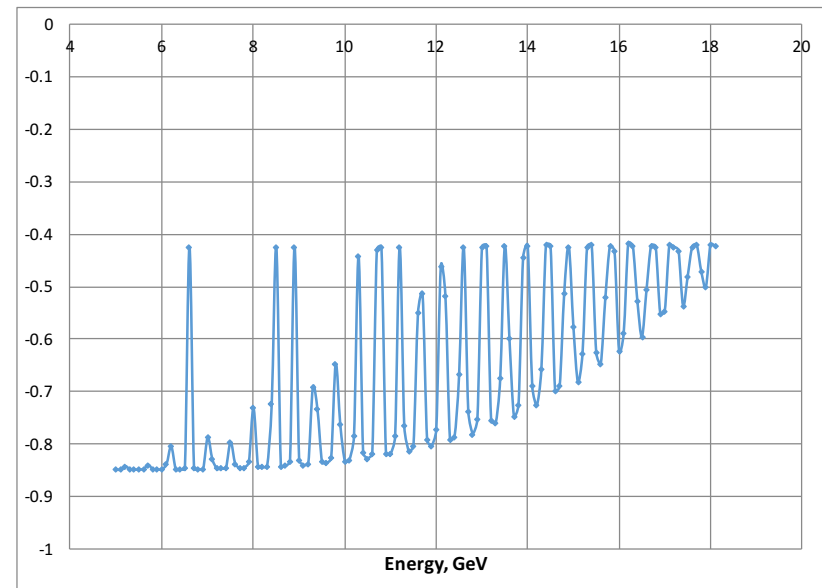
Spin matching is absolutely required above 14.5 GeV to achieve the average polarization 70% or more

Polarization evolution

Synchrotron radiation introduces both polarizing and depolarizing effects which lead to the equilibrium polarization:

$$P(t) = (P_0 - P_{eq})\, e^{-t/\tau} + P_{eq}$$

Derbenev-Kondratenko: (1973)

$$P_{eq} = -\frac{8}{5\sqrt{3}} \frac{\alpha_-}{\alpha_+}$$

$$\tau^{-1} = \frac{5\sqrt{3}}{8} \frac{\hbar\, r_0}{m} \gamma^5\, \alpha_+$$

$$\alpha_- = \left\langle \oint \frac{d\theta}{|\rho|^3} \hat{\boldsymbol{b}}(\boldsymbol{n} - \boldsymbol{d}) \right\rangle$$

$$\alpha_+ = \left\langle \oint \frac{d\theta}{|\rho|^3} \left[1 - \frac{2}{9}(\boldsymbol{n}\hat{\boldsymbol{v}})^2 + \frac{11}{18}|\boldsymbol{d}|^2 \right] \right\rangle$$

$$\boldsymbol{d} = \gamma \frac{\partial \boldsymbol{n}}{\partial \gamma}$$

defines strength of depolarization and kinetic polarization

taken at const x, x', y, y'

Analytical expressions for F$_5$

In spin response formalism the depolarizing vector **d** is presented by F_5 component of spin response function set. (V. Ptitsyn, Yu. M. Shatunov, S.R. Mane, NIM A608, p.225 (2009)).

One can write analytical expressions for two different parts of F_5:

$$F_{5\gamma}(\theta) = \frac{1}{e^{i2\pi\nu_{sp}} - 1} \int_{\theta}^{\theta+2\pi} \left(\tilde{\mathcal{W}}^T(\theta) D(\theta) + \mathcal{W}_6(\theta) \right) d\theta$$

resonantly increases when spin tune approaching integer
(more exactly integer +- synchrotron tune)

- $\mathcal{F}$ is a matrix of orbital motion eigenmodes

- $\tilde{\mathcal{W}}$ Is a vector incorporating dipole and solenoid fields and spin motion eigenvectors

$$F_{5\beta}(\theta) = -\sum_{j=1}^{4} \frac{(\mathcal{F}^{-1}D)_j(\theta)}{e^{i2\pi(\nu_{sp}+\nu_j)} - 1} \int_{\theta}^{\theta+2\pi} \left(\tilde{\mathcal{W}}^T \mathcal{F} \right)_j (\theta) d\theta$$

resonantly increases when spin tune approaching betatron tune

Spin matching approach: Nullify these integrals over the rotator insertion to get $F_5 = 0$ in the arcs

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Spin matching conditions for eRHIC rotators

$$\nu_0 H(D') + \sum_{rot:\, j=1,2,3,4} \varphi_j k_{sj} - \nu_0 \sum_{bends:\, j=1,2,3,4} \psi_j k_{yj} = 0$$

$$H(f_1') = 0 \ and \ H(f_1'^*) = 0$$

where

$$H(a) = \frac{\varphi_1}{2}\left(I_{1ent}(a) + I_{1ex}(a)\right) + \frac{\varphi_2}{2}\left(I_{2ent}(a) + I_{2ex}(a)\right)$$

$$I_{n\ ent/ex}(a) = (k_x a_x + k_y a_y)_{n\ ent/ex}$$

- spin complex eigen-vector $\boldsymbol{k}$ orthogonal to the stable spin solution $\boldsymbol{n_0}$
- D is the dispersion function and f_1 is the eigen mode of betatron motion corresponding to the horizontal motion in the arcs
- $\nu_0 = G\gamma$

Example of 2 conditions on dispersion function at the exit/entrance of the 8 rotator solenoids (for 18 GeV):

$$11.31 D'_{x1} + 9.62 D'_{x2} - 5.95 D'_{y2} - 28.60 D'_{x3} - 21.85 D'_{y3} - 6.75 D'_{x4} + 35.35 D'_{y4} - 6.75 D'_{x5}$$
$$+ 35.35 D'_{y5} + 34.64 D'_{x6} - 9.77 D'_{y6} - 4.30 D'_{x7} - 2.66 D'_{y7} - 5.06 D'_{x8} = 0.83$$

$$-24.43 D'_{x3} + 10.92 D'_{x4} + 21.85 D'_{y4} + 10.92 D'_{x5} + 21.85 D'_{y5} + 14.66 D'_{x6} - 19.54 D'_{y6}$$
$$- 8.60 D'_{x7} - 5.32 D'_{y7} - 10.11 D'_{x8} = 0.52$$

Ongoing eRHIC RR polarization work

1. Optimizing spin rotators insertion to fully satisfy the spin matching conditions at least at high electron energies.

2. Spin simulations with misalignment and magnet errors, including synchrotron motion.

3. Depolarizing effect of detector solenoid. Betatron coupling compensation for detector solenoid.

eRHIC, polarized protons

- **RHIC: only polarized proton collider in the world. Up to 60% polarization achieved in the polarized proton runs at 100 and 255 GeV.**

- **eRHIC will take favor of existing hardware in RHIC and in the injector chain to accelerate polarized protons up to 275 GeV.**
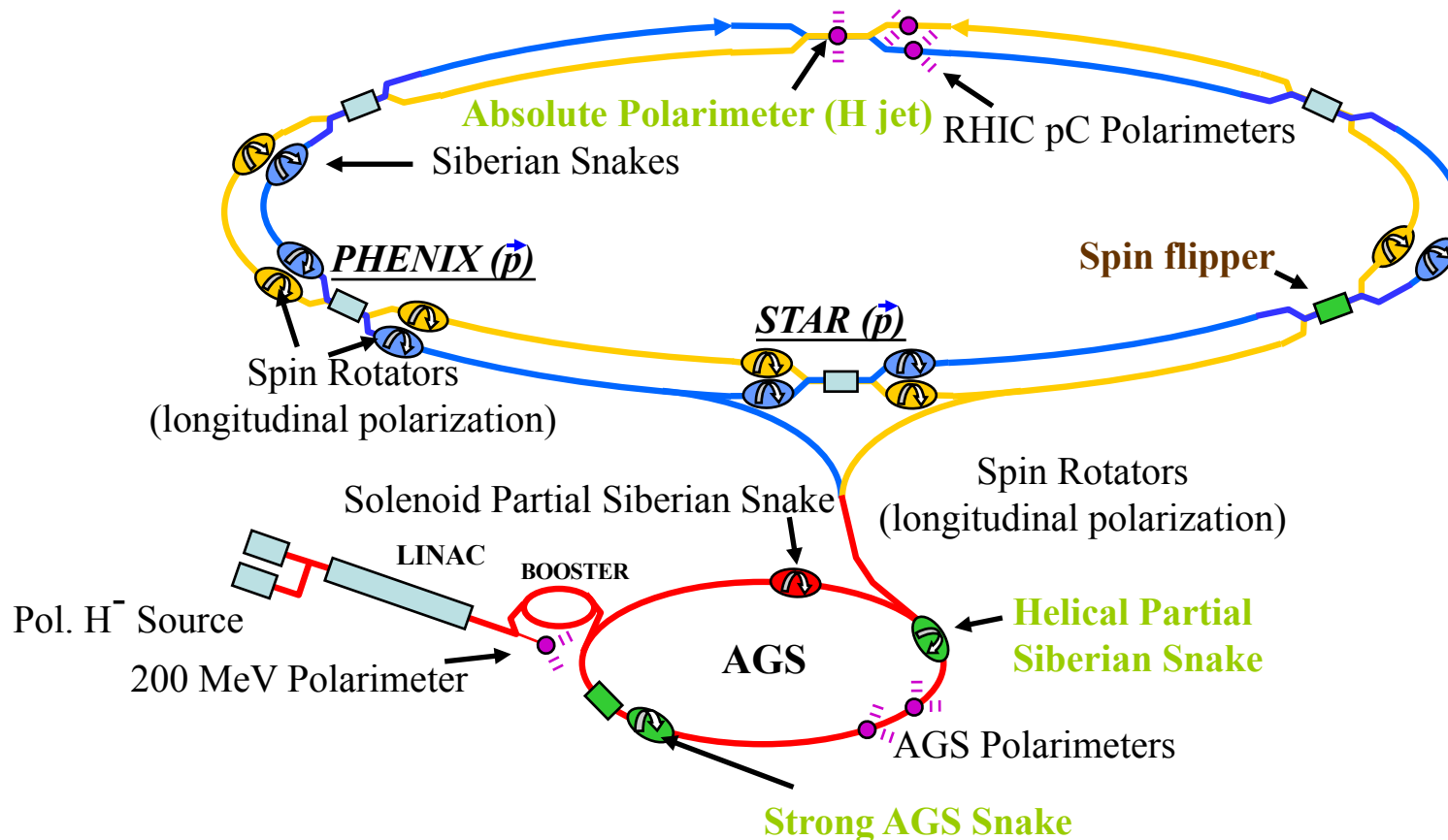
# Improving proton polarization to fully satisfy eRHIC goals

Polarization	
OPPIS source	~80%
AGS extraction	~65-70%
RHIC, 255 GeV	~53-58%

Polarization loss happens after 100 GeV

Possible developments:
- Working point near integer (allowed by recent success of 10 Hz orbit feedback):
  - less number of high-order spin resonances
  - reduced strength of those resonances
- Smaller transverse emittance from injectors
- Increasing the number of the Snakes

For isolated spin resonance (Courant-Lee).
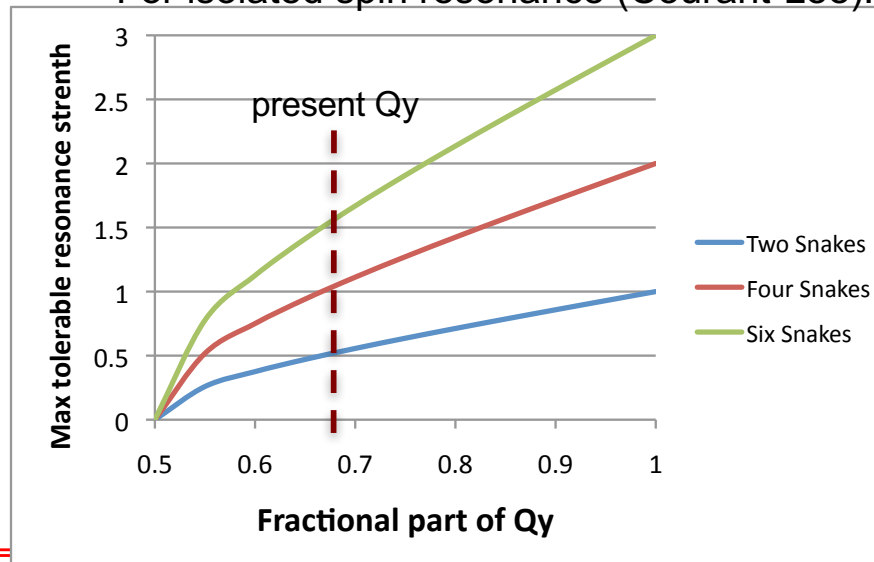
Polarized ^{3}He^{+2} for eRHIC

- 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.
- 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
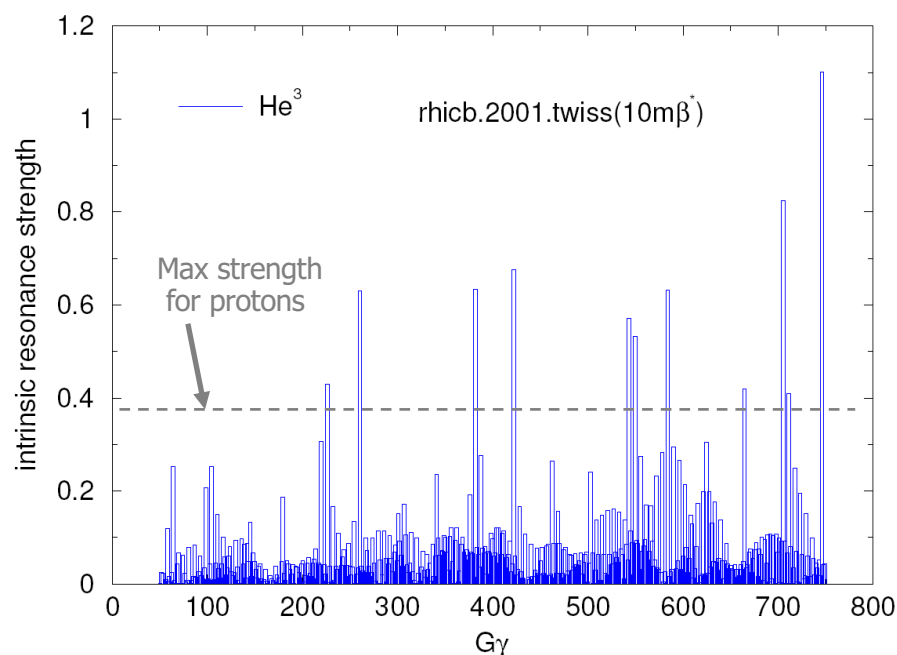
	$^3He^{+2}$	p
m, GeV	2.808	0.938
G	-4.18	1.79
E/n, GeV	16.2-166.7	24.3-250
γ	17.3-177	25.9-266
$|G\gamma|$	72.5-744.9	46.5-477.7

Polarized He-3 development facility at RHIC
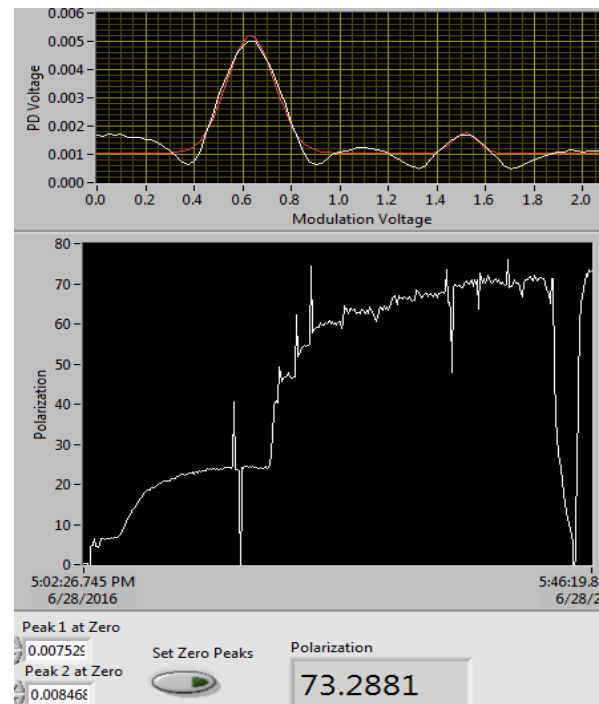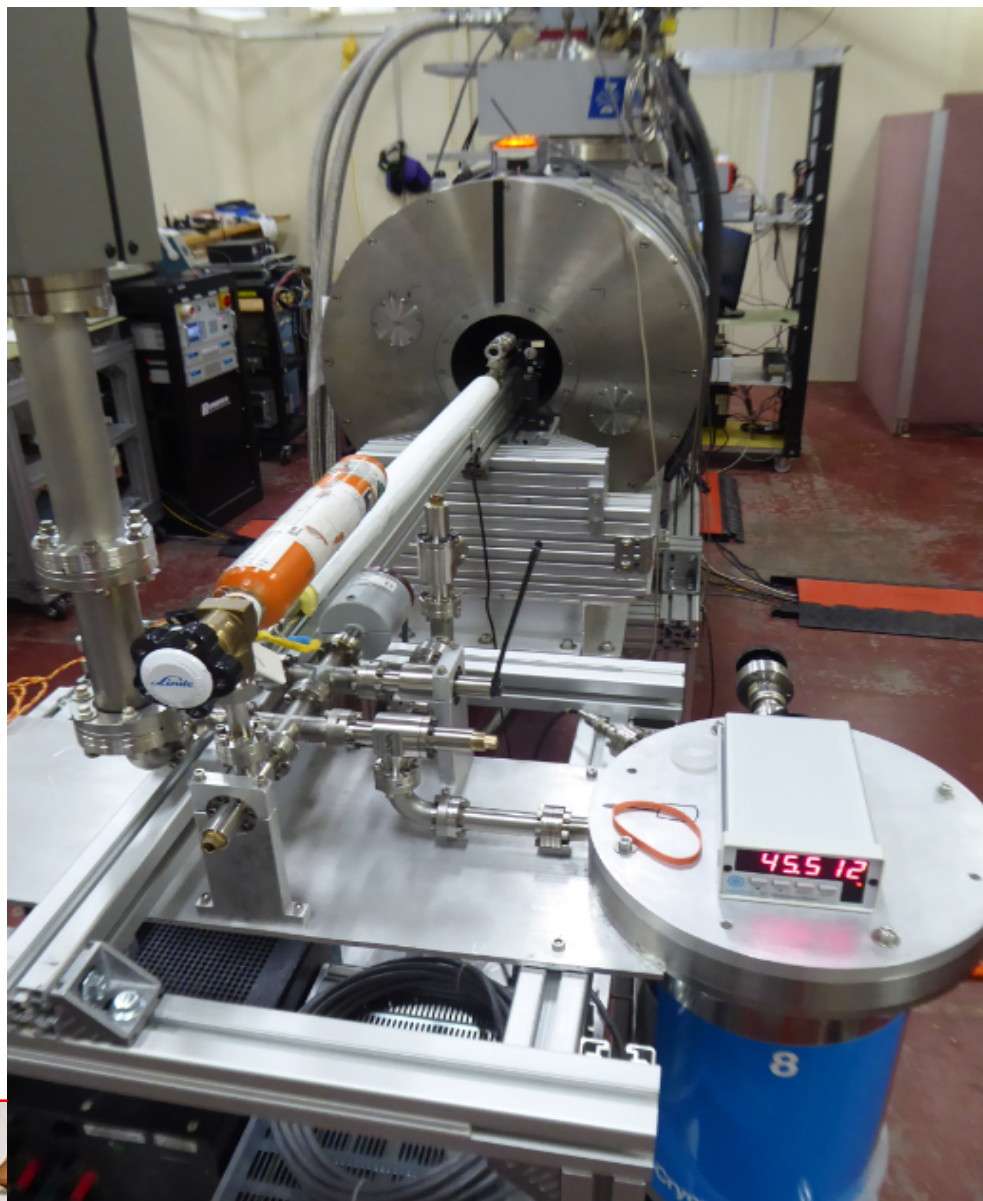
73 % polarization in the "open" cell

A.Zelenski talk on Tuesday, Parallel VII, at 16:40

Summary

- Polarized beams of electrons, protons and light ions are essential component of the future electron-ion collider eRHIC.

- Polarized electron beam challenges are being addressed:
  – High average current polarized source for linac-ring scheme.
  – Minimizing depolarization in ring-ring scheme. Realizing spin matching of complex rotator scheme.

- Polarized proton and light ions beams:
  – RHIC: state-of-art technology in place and working well for polarized protons.
  – Increasing the number of Snakes (and other developments) are expected to improve the polarization up to 70%
  – Polarized He3 development is underway: polarized source, polarization preservation during the acceleration, increased number of Snakes in RHIC.