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EDUCATION IN BEAM PHYSICS AND ACCELERATOR TECHNOLOGY
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A Class on Spin Dynamics in Accelerators and the Physics and Technology of Polarized Beams
USPAS Spin Class 2020
June 15-19, 2020
Melville, Long Island, New York
Held in the US Particle Accelerator School Summer Session: June 15-26, 2020
https://uspas.fnal.gov/programs/2020/stonybrook/courses/spin-dynamics.shtml
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Kick-off workshop
Search of a muon EDM using the frozen spin technique at PSI
15-19 February 2020
PSI, Villigen
Confédération des Helvètes

Polarization at RHIC and at the Electron Ion Collider

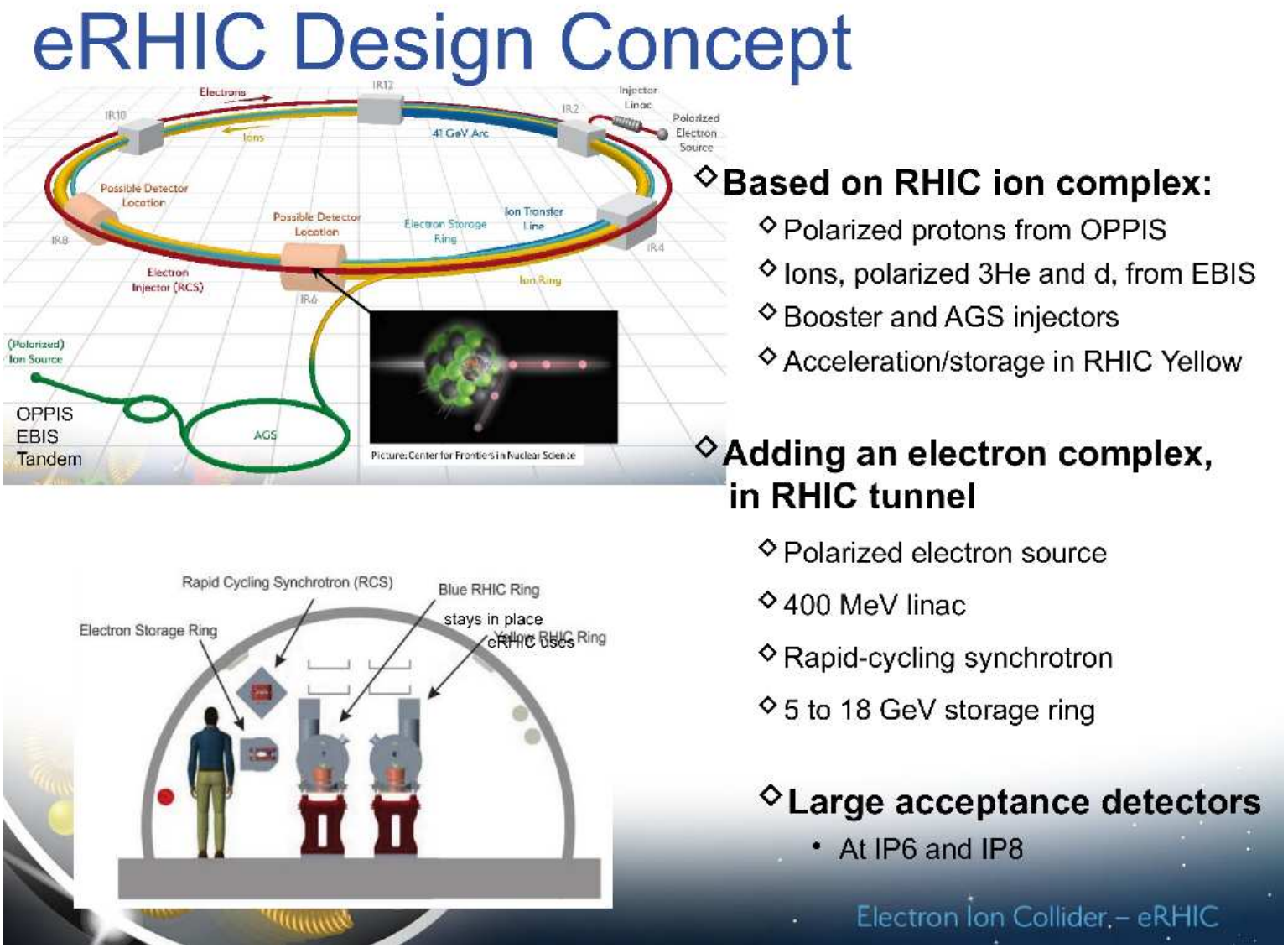
Spin Simulation Techniques

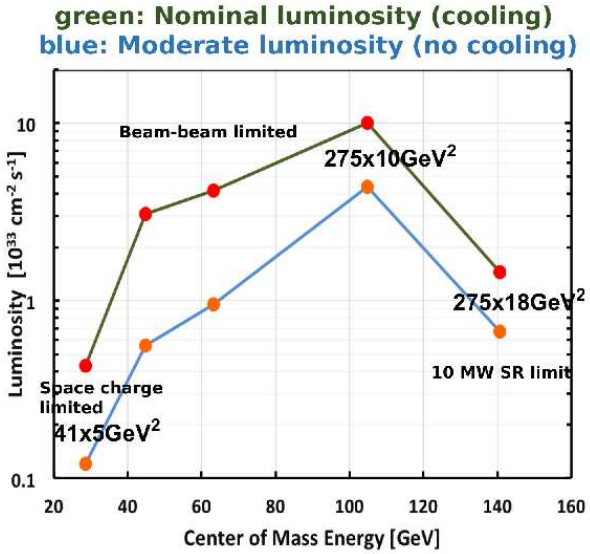
François Méot
Collider-Accelerator Department
Brookhaven National Laboratory

Contents

The Electron-Ion Collider

"The announcement by DOE of CD-0 and site selection for the EIC occurred on January 9, 2020: DOE selected BNL to host the EIC. The facility is estimated to cost between $1.6B and $2.6B."





Design goals:

- Lumi $10^{33} - 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Polarization >70% (p, 3He, D)
- *com* energy span: 29 - 140 GeV, e-p; 28-89 GeV/n, e-ion

Table 1.3: Initial luminosity parameters.

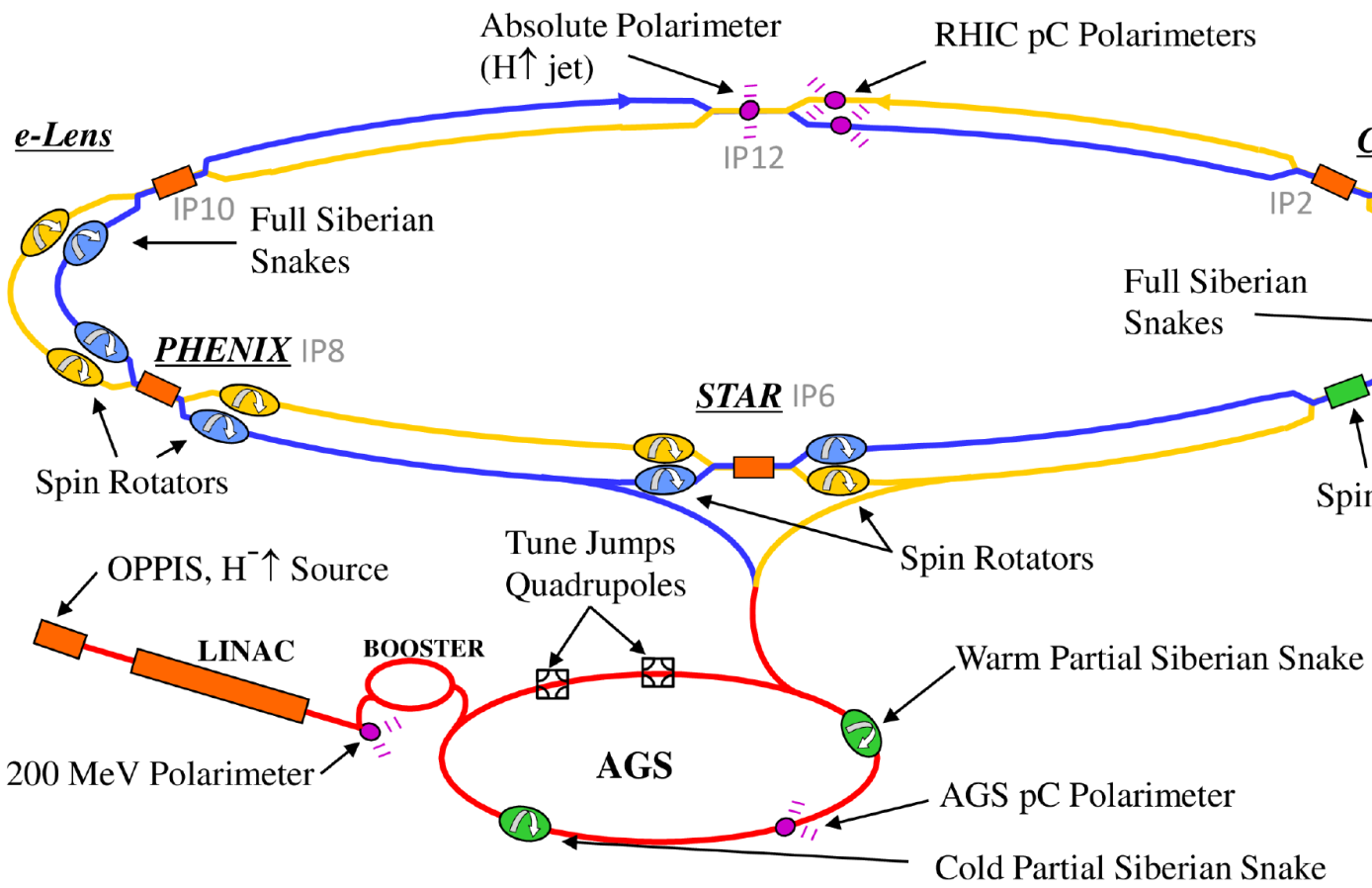
Parameter	hadron	electron
Center of mass energy [GeV]	104.9	
Energy [GeV]	275	10
Number of bunches	290	
Particles per bunch [10^{10}]	10.2	22.0
Beam current [A]	0.37	0.8
Horizontal emittance [nm]	17.9	20.0
Vertical emittance [nm]	8.5	4.2
Hor. β-function at IP β_x^* [cm]	90	81
Vert. β-function at IPβ_y^* [cm]	5.9	12.1
Horizontal/Vertical fractional betatron tunes	0.3/0.31	0.09/0.12
Horizontal divergence $d\sigma_x^*/ds$ [mrad]	0.141	0.157
Vertical divergence $d\sigma_y^*/ds$ [mrad]	0.380	0.186
Horizontal beam-beam parameter ξ_x	0.0079	0.1
Vertical beam-beam parameter ξ_y	0.0029	0.085
IBS growth time longitudinal/horizontal [hours]	8/18	-
Synchrotron radiation power [MW]	-	2.95
Bunch length [cm]	9.9	1.9
Hourglass and crab reduction factor	0.74	
Luminosity [10^{33} cm^{-2}sec^{-1}]	1.05	

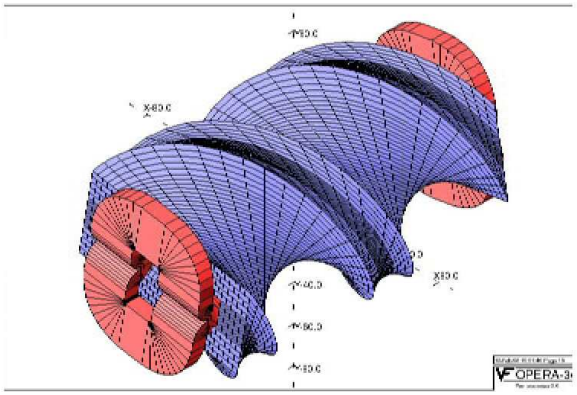
Table 1.1: Maximum luminosity parameters.

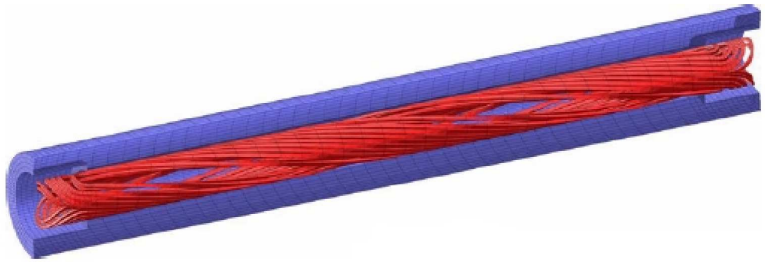
Parameter	hadron	electron
Center-of-Mass Energy [GeV]	104.9	
Energy [GeV]	275	10
Number of Bunches	1320	
Particles per Bunch [10^{10}]	6.0	15.1
Beam Current [A]	1.0	2.5
Horizontal Emittance [nm]	9.2	20.0
Vertical Emittance [nm]	1.3	1.0
Hor. β-function at IP β_x^* [cm]	90	42
Vert. β-function at IPβ_y^* [cm]	4.0	5.0
Hor./Vert. Fractional Betatron Tunes	0.305/0.31	0.08/0.06
Horizontal Divergence $d\sigma_x^*/ds$ [mrad]	0.101	0.219
Vertical Divergence $d\sigma_y^*/ds$ [mrad]	0.179	0.143
Horizontal Beam-Beam Parameter ξ_x	0.013	0.064
Vertical Beam-Beam Parameter ξ_y	0.007	0.1
IBS Growth Time longitudinal/horizontal [hr]	2.19/2.06	-
Synchrotron Radiation Power [MW]	-	9.18
Bunch Length [cm]	5	1.9
Hourglass and Crab Reduction Factor [16]	0.87	
Luminosity [10^{34} cm^{-2}sec^{-1}]	1.05	

1 Hadron polarization at eRHIC

Polarized proton beams at the RHIC complex



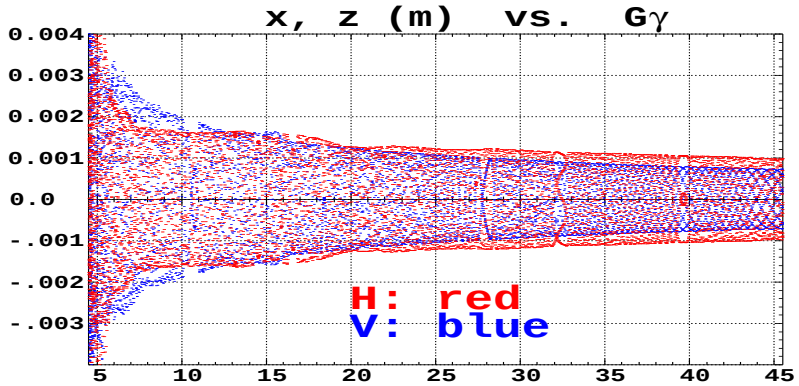




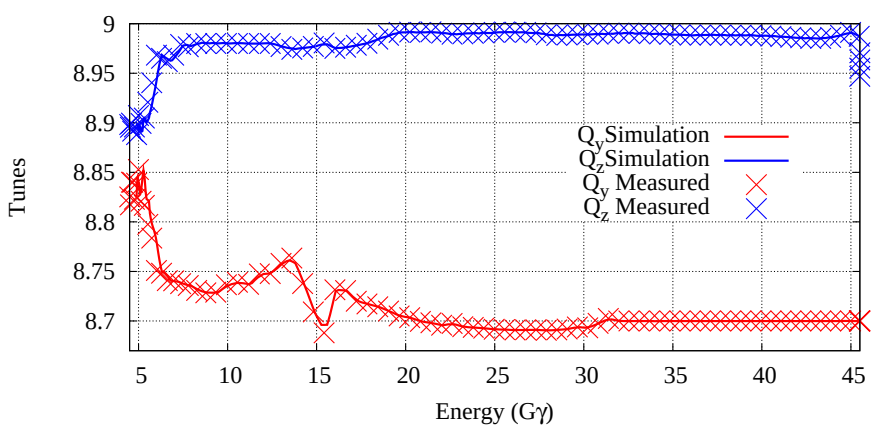
• AGS

◇ **An on-line model of the AGS uses the 3-D OPERA field maps of the two helical snakes**

◇ **Full acceleration cycle simulations are part of polarization transmission and improvement studies (thousands of particles, 150000 turns, 30minutes/cycle on NERSC CPU cluster)**

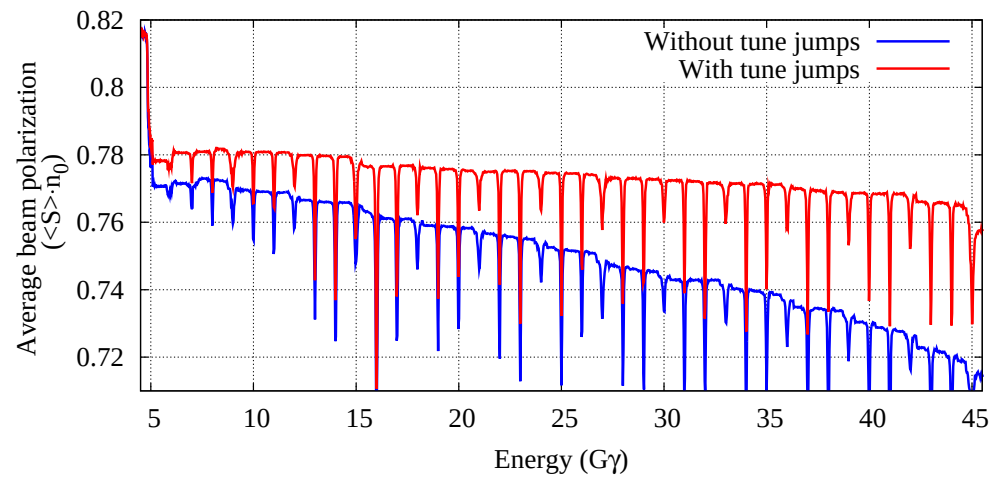


Particle excursion over full AGS cycle.



Tunes, measured and modeled.

◇ **Optimization of AGS parameter settings routinely based on simulations.**
[Y. Dutheil, BNL C-AD, PhD dissertation, April 2015].



Evolution of the polarization along AGS acceleration cycle, 10^3 particles, 6-D bunch.
Loss at $G\gamma \sim 5$ (a pair of weak vertical intrinsic resonances) and at $G\gamma = 36 + Q_y$ in the present hypotheses.

Ref.: Y. Dutheil, BNL C-AD, PhD dissertation, https://public.bnl.gov/docs/cad/Documents/Spin%20dynamics%20modeling%20in%20the%20AGS%20based%20on%20a%20stepwise%20ray-tracing%20method.pdf.

• RHIC (1): Acceleration cycle to 100 GeV

◇ **Goal: comparison of polarization transport with two different optics:**

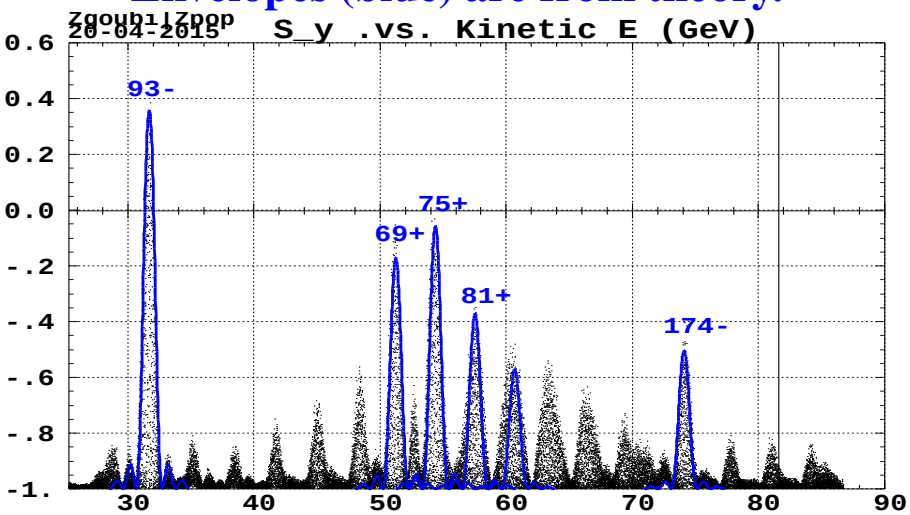
- a new, Run 15 optics

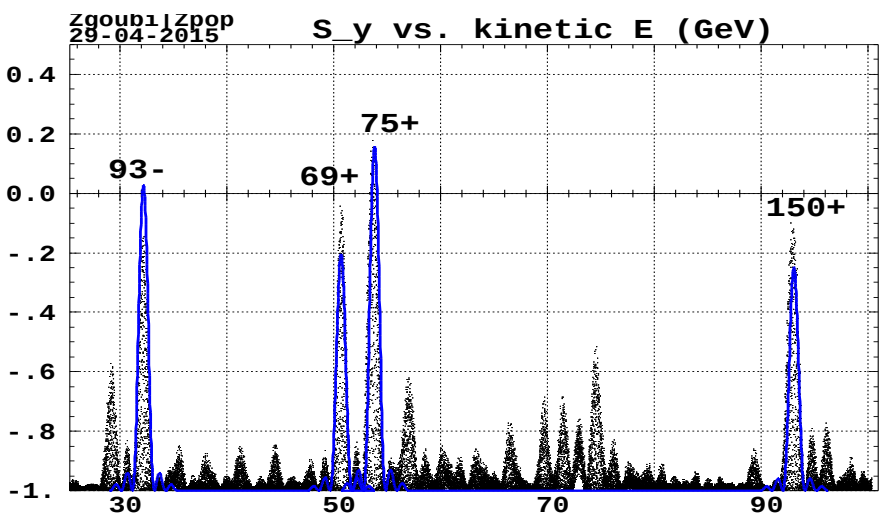
- earlier Run 13 optics

◇ **Isolated snake resonance:** $< S_y >= 1 - 8\frac{|\epsilon|^2}{\lambda^2}\sin^2\frac{\pi\lambda}{N_s}(1 - \frac{|\epsilon|^2}{\lambda^2}\sin^2\frac{\pi\lambda}{N_s})$

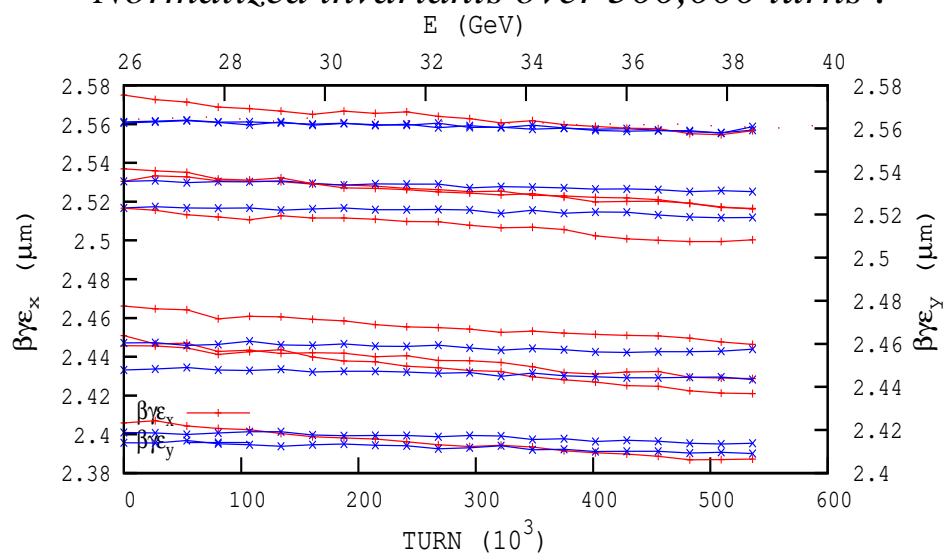
8 particles on 10 rms invariants are plotted.

Envelopes (blue) are from theory.



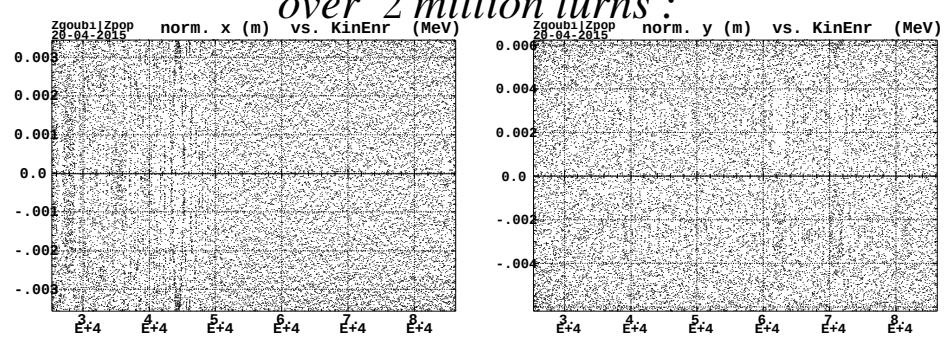


Normalized invariants over 500,000 turns :



$x \times \sqrt{(p/p_0)}$ *and* $y \times \sqrt{(p/p_0)}$

over 2 million turns :



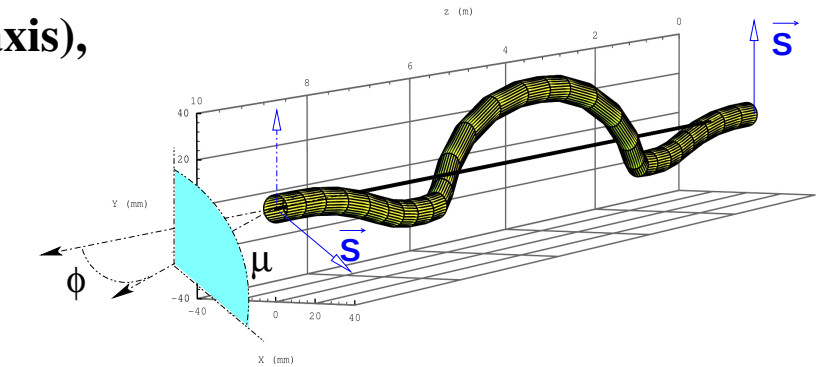
• RHIC (2): use snake field maps → orbit defect tilts ñ

$$\begin{cases} x = x_0 + \frac{B_0}{k^2 B\rho}\left[\cos(ks+\alpha) - \cos(\alpha)\right] + \left[x_0' + \frac{B_0}{kB\rho}\sin(\alpha)\right] s \\ y = y_0 + \frac{B_0}{k^2 B\rho}\left[\sin(ks+\alpha) - \sin(\alpha)\right] + \left[y_0' - \frac{B_0}{kB\rho}\cos(\alpha)\right] s \end{cases} \xrightarrow{\alpha=0} \begin{cases} x = x_0 + \frac{B_0}{k^2 B\rho}\left[\cos(ks) - 1\right] + x_0' s \\ y = y_0 + \frac{B_0}{k^2 B\rho}\sin(ks) + \left[y_0' - \frac{B_0}{kB\rho}\right] s \end{cases}$$

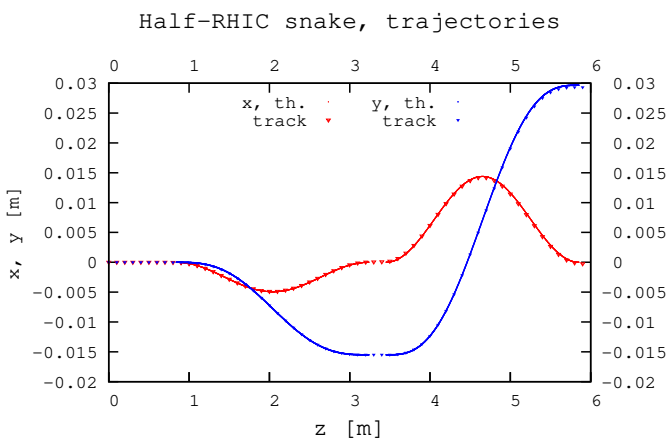
◇ $x_0,\ ,x_0',\ y_0, y_0'$ **the initial coordinates (taken wrt snake axis),**

◇ α **the angle of the field to the vertical at entrance,**

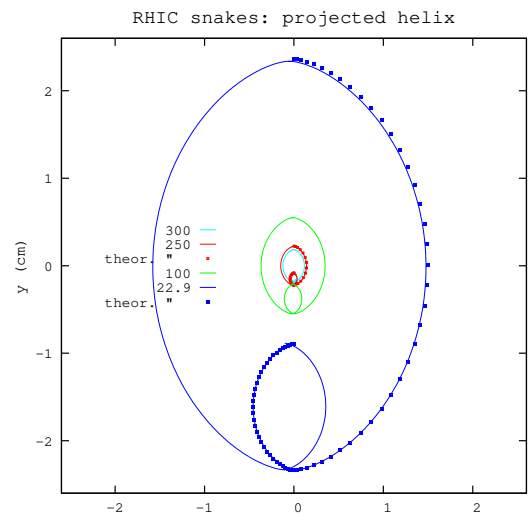
◇ **k = pitch =** $2\pi/L = 2.61800$**, length** $L = 2.4$ **m.**



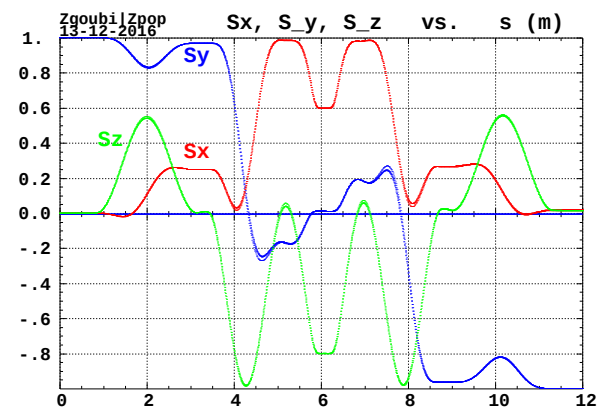
• **From a field map model** ***(i.e.*, field map of a 10.4 meter, 4-module RHIC snake) :**



x and y vs. distance at injection energy, half the snake (5.2 meter).



Non-circular, (x,y) projection , theory and numerical, 23, 100, 250, 300 GeV.

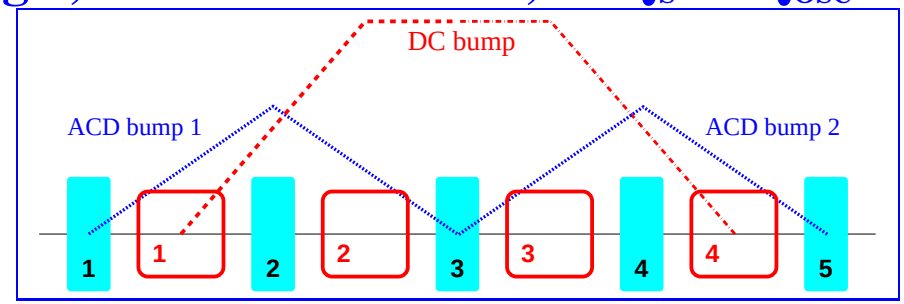


Spin components along orbits .

• RHIC (3): Spin flipper

◇ **Sweep Q_{osc} through $Q_s = \frac{1}{2}^+$: a matter of a $10^4 \sim 5 \times 10^5$ turn tracking around RHIC**

◇ **AC-dipole + DC-rotator assembly excites a single, isolated resonance, at $Q_s = Q_{osc}$.**



Spin flip efficiency vs. crossing speed :
Very good accord obtained between measurements and numerical simulations

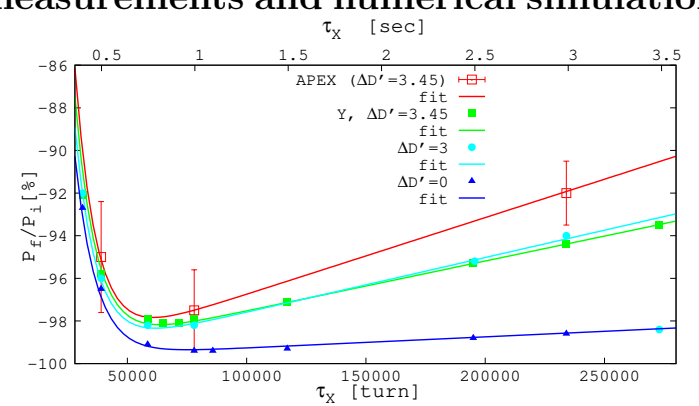
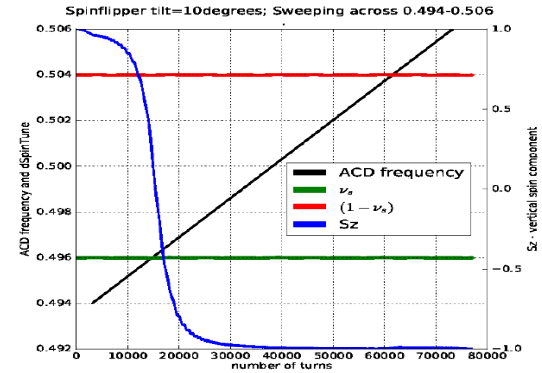
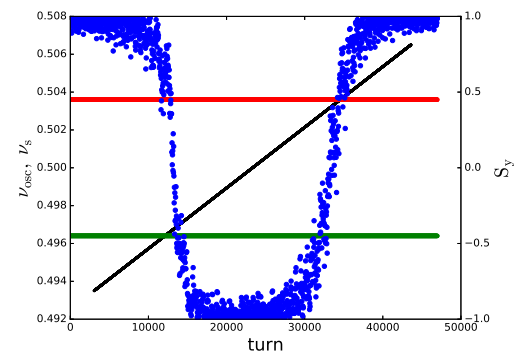


Image at $1 - Q_s$ is not excited:

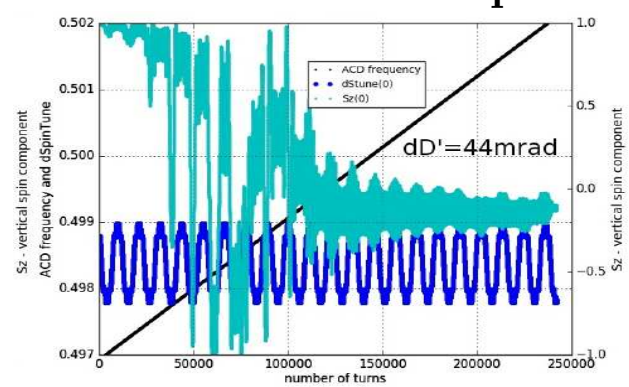


Frequency mis-match of ACD1-3 (or ACD3-5) oscillator excites $Q_s = 1 - \frac{1}{2}^+$:



Multiple crossing:

$$\delta\nu_s = \frac{1 + G\gamma}{\pi} \Delta D' \frac{\Delta p}{p}$$



Towards eRHIC

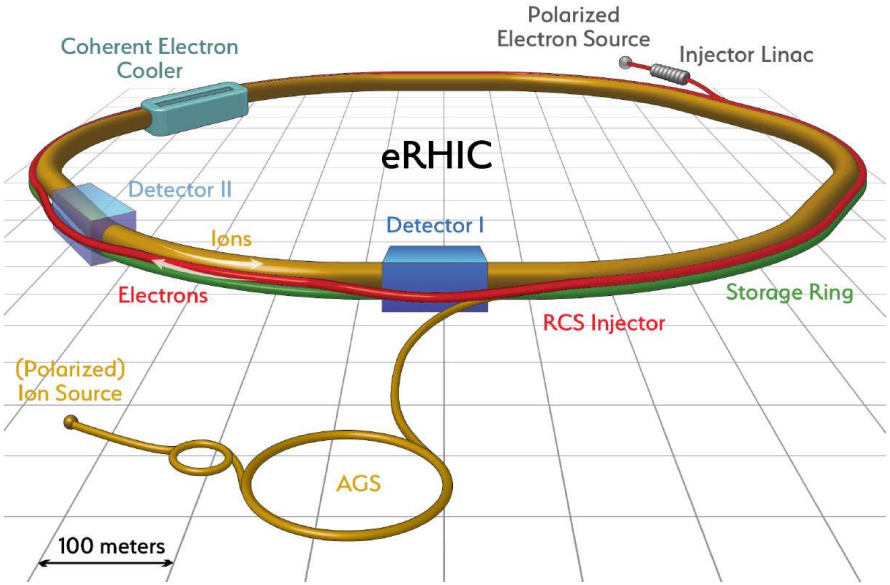


Table 1.10: eRHIC proton beam parameters.

Parameter	Moderate luminosity without cooling			High luminosity with cooling		
Beam energy [GeV]	41	100	275	41	100	275
Bunch intensity [10^{11}]	0.6	1.1	1.1	0.11	0.6	0.6
RMS Horizontal normalized emittance [mm mrad]	3.3	4.5	4.1	2.0	3.6	2.7
RMS Vertical normalized emittance [mm mrad]	2.5	2.5	2.5	0.11	0.19	0.38
Longitudinal bunch area [eV sec]	0.5	0.6	0.8	0.2	0.4	0.4
RF frequency [MHz]	225	225	563	563	563	563
RF voltage [MV]	8	11	24	8	16	18
RMS momentum spread [10^{-4}]	15	8.7	6.6	10.3	9.1	4.6
RMS bunch length [cm]	13	11	7	7.5	7	5
Longitudinal emittance IBS growth time [hours]	10.3	8.0	10.1	3.2	2.4	2.2
Horizontal emittance IBS growth time [hours] (without coupling)	8.0	13.7	9.2	2 0	2.0	2.1

- **Goal proton polarization at eRHIC: 70% up to 275 GeV.**

For the record: today, using 2 snakes: close to 60% at best, at 255 GeV.

- **Add polarized 3He beams: polarization to 70%, also requiring 6 snakes.**
- **Add polarized Deuteron beams, 70%.**

• Booster: add ^{3}He instrumentation

Spin Tracking Helium-3 through 12-

From Run14: normalized 95% emittance, $\varepsilon_N = 4.78\pi$ *mm mrad* measured at MW006.
$\varepsilon_N = 5.0\pi$ *mm mrad* used for the simulations, $\sigma_y = 2.65mm$.
$\alpha = 2.654x10^{-6}$

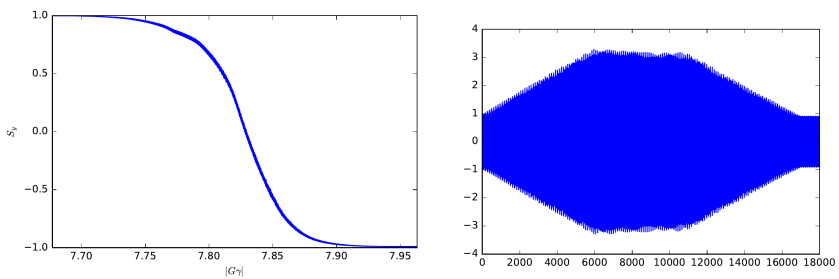
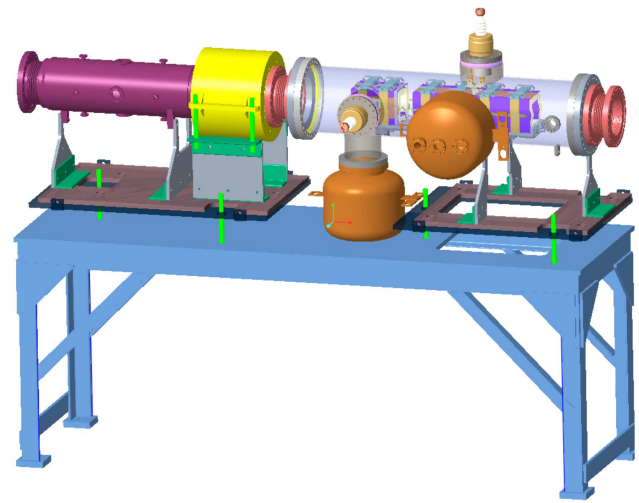


Figure : Example for 12- resonance. Left: Ensemble average of S_y with Gaussian bunch, $B_m l = 18.1$ *Gm*, $P_f = -99\%$. Right: Bunch motion through the AC-Dipole ramp.

◇ **AC dipole & tune kicker at booster E3 straight:**



◇ $\mathbf{f_{osc} \approx 250\,kHz}$

◇ **This year, 2020:**

- Will establish crossing $G\gamma = 0 + Q_y$ ($Q_y \approx 4.2$) with polarized protons.
- Spin dynamics conditions similar to ^{3}He crossing $12 - Q_y$ for eRHIC.

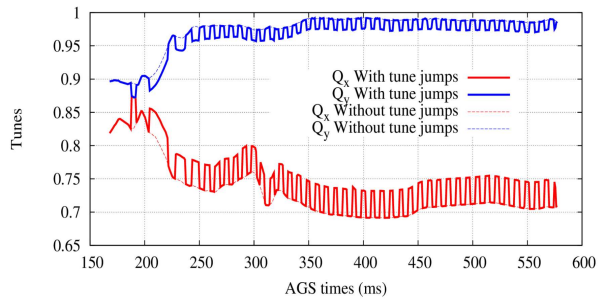
Refs.: K. Hock et als., BNL C-AD,
https://public.bnl.gov/docs/cad/Documents/Overcoming%20proton%20and%203He%20intrinsic%20resonances%20in%20the%20AGS%20Booster%20with%20an%20ac%20dipole.pdf;
https://public.bnl.gov/docs/cad/Documents/Intrinsic%20resonances%20and%20AC-dipole%20simulation%20of%203He%20in%20the%20AGS-Booster.pdf.

• ^{3}He in AGS

◇ **AGS with ^{3}He : G= -4.18. AGS partial snakes are 2.3 times stronger than for protons (14% and 25%).**

◇ **This is ok for overcoming 1.5 times stronger resonances.**

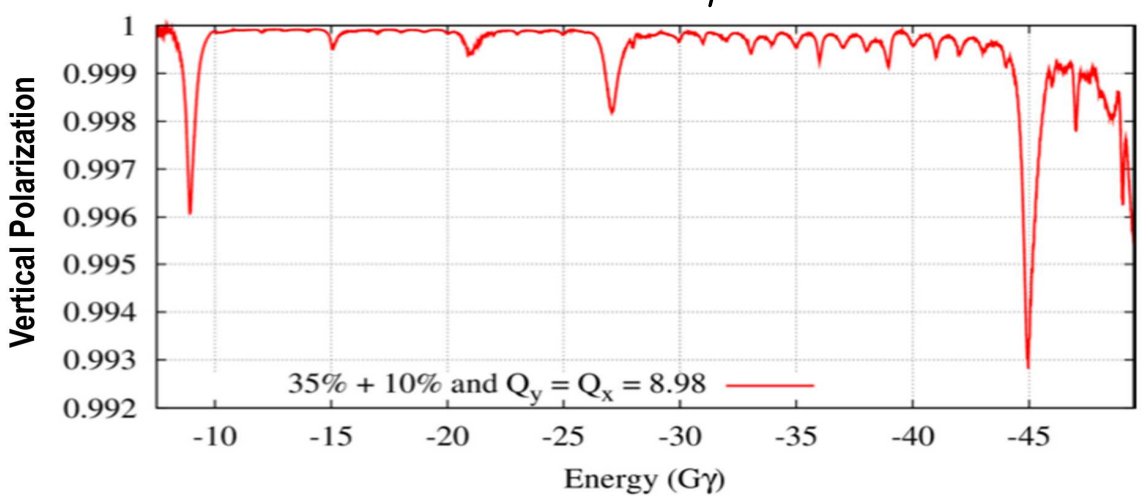
◇ **Issue here : snakes induce $\vec{n}_0$ tilt resulting in harmful 81 resonance series $G\gamma = \text{int.} \pm Q_x$, stronger with ^{3}He.**



◇ **A possibility : stronger cold snake/wider spin tune gap to put both Q_x, Q_y in the gap**

◇ **Proof-of-principle simulation :**

a 2000-^{3}He bunch in 15π μm emittance :

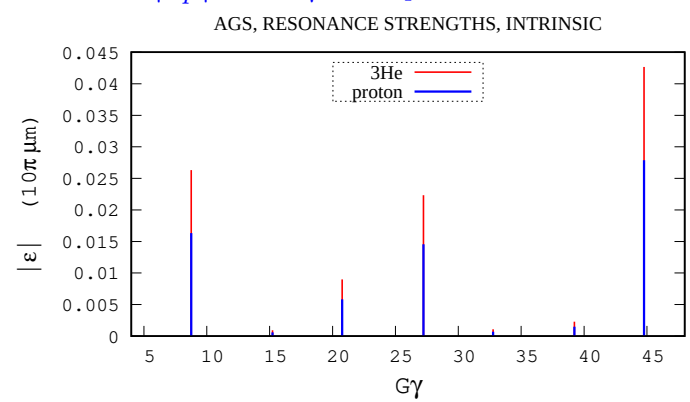


◇ ***With ^{3}He, snakes are $|G_{^3He}|/G_p$=2.3 times stronger than for protons :***

		Warm snake	Cold snake
B max (T)			3
B nominal (T)		1.5	2.1
snake angle (deg.)	proton :	≈ 11	≈ 21
	$^3He^{2+}$:	26	44
"% snake"	proton :	6	12
	$^3He^{2+}$:	15	25

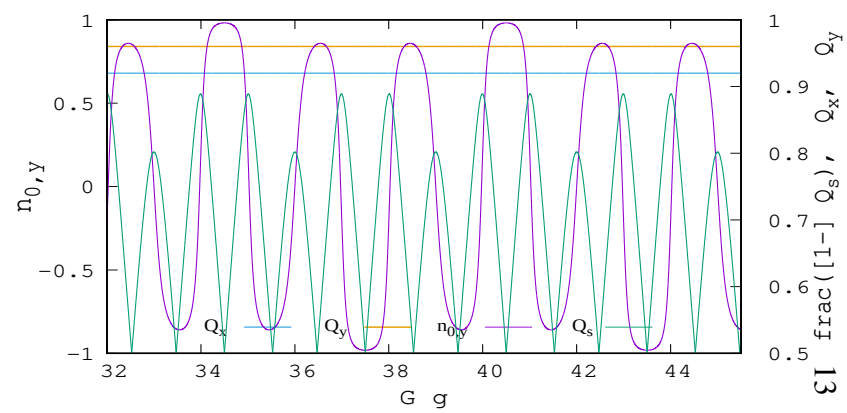
◇ ***At identical normalized emittance, strengths of intrinsic resonances satisfy***

$$\frac{|\epsilon_{^3He}|}{|\epsilon_p|} = \sqrt{\frac{|G_{^3He}|}{G_p}} \approx 1.5$$



◇ ***Q_x and Q_y in spin gap***

$\Rightarrow$ **$G\gamma = \text{int.} \pm Q_{x,y}$ *never happens :***

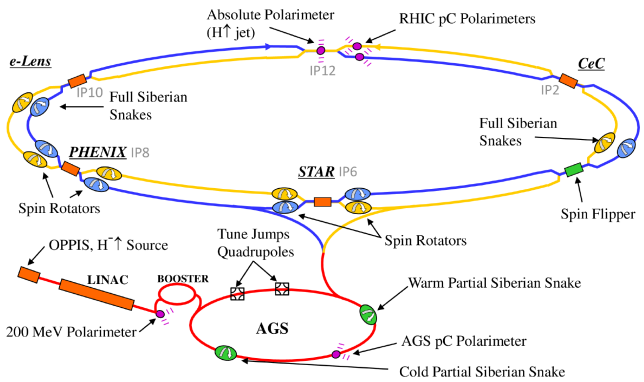


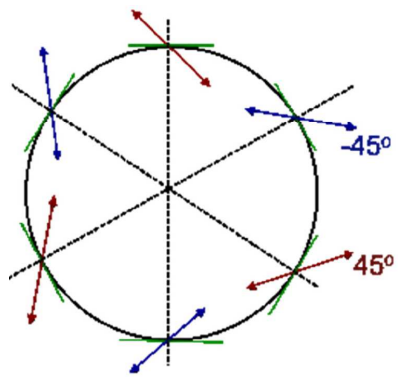
• RHIC with 6 Snakes

◇ **Polarization goal at store, 42∼275 GeV : 70%**

◇ **RHIC Blue and Yellow rings today reach 60% polarization in 255 GeV proton runs, with 2 snakes per ring.**

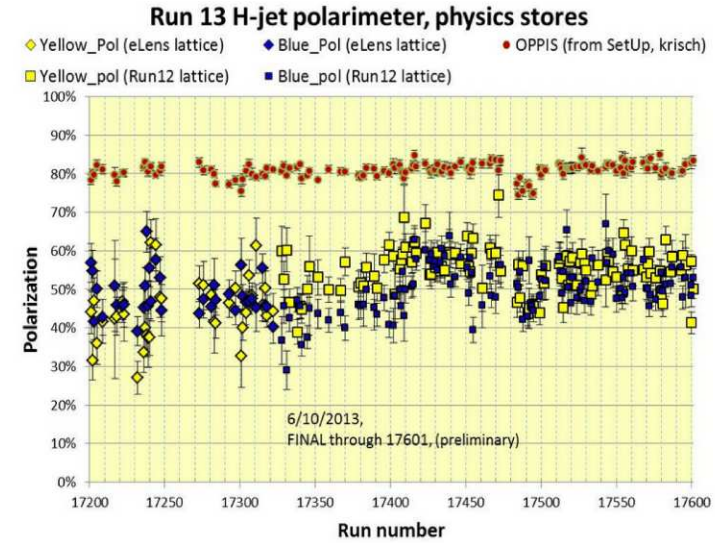
◇ **Stronger ^{3}He resonance strength ($\times 1.5$) require more snakes.**

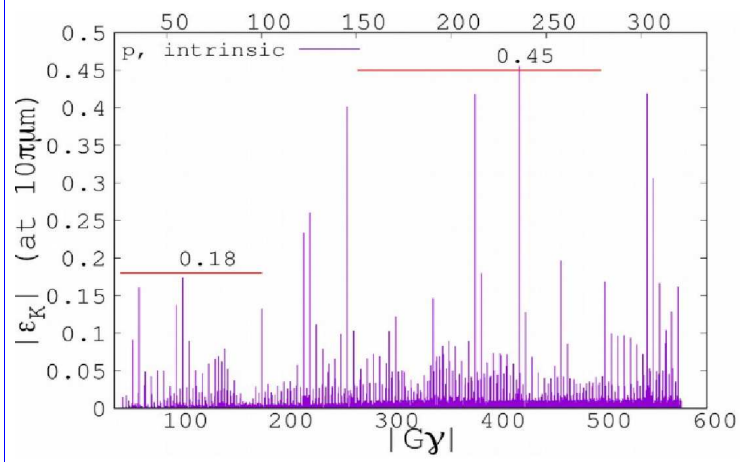




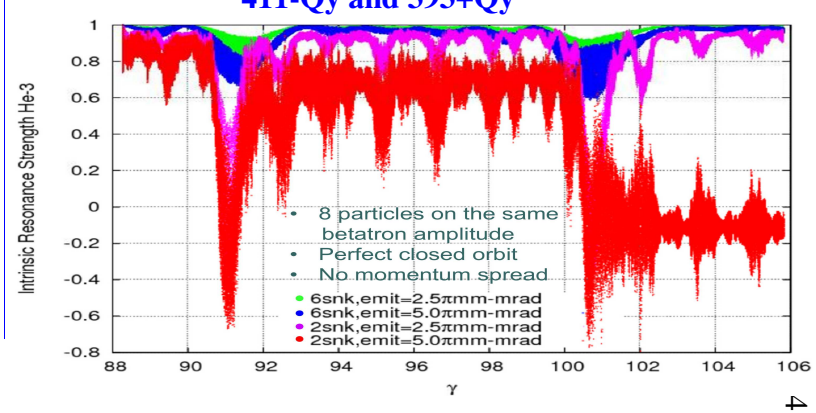
◇ **Foreseen scheme :**

- **6 snakes ensure** $N_{snakes} > 5|\epsilon_{int}|_{max} \approx 4$,
- $2\pi/6$ **distance ensures energy-independent** Q_s,
- **snake axes at** $\phi_k = \pm 45^o$ **yield** $Q_s = \frac{1}{\pi}\sum_{k=1}^{6}(-)^k\phi_k = 3/2$
- **build 4 additional snakes from existing, like-helicity, rotator modules**





A glimpse on snake resonance crossing simulations, 411-Qy and 393+Qy



2 Electron polarization in eRHIC

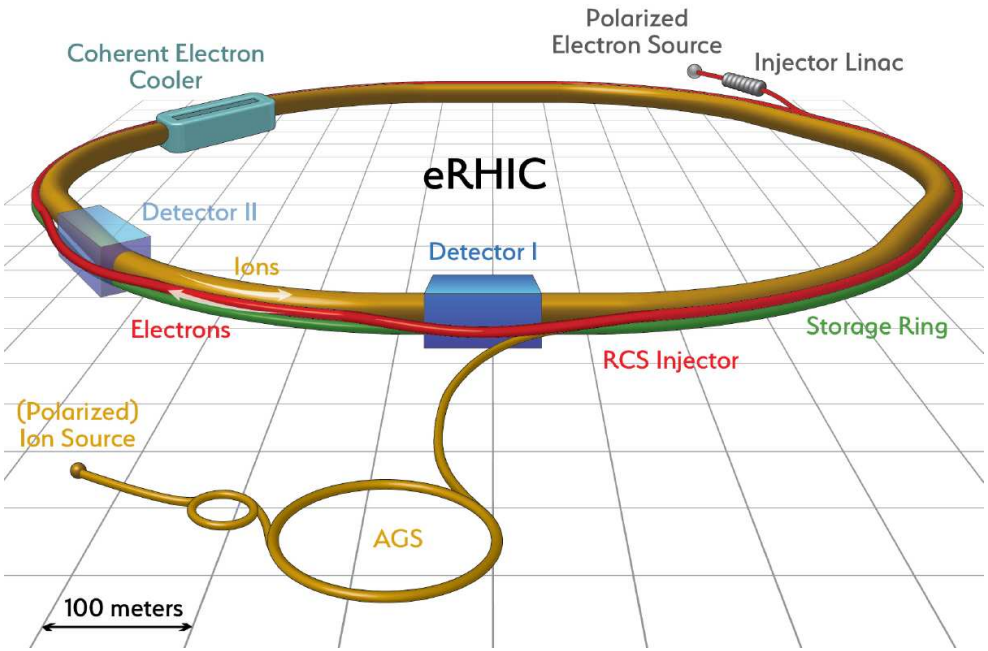


Table 1.6: Parameters of the beam optics in the arcs for different beam energies. At the lowest energies $E_e < 10\,\text{GeV}$, the short dipole in each half-cell is reversed, thus creating a super-bend. This increases radiation damping and damping decrement, provides the required beam emittances, and prevents the bunch length from becoming too short.

Parameter	5 GeV	10 GeV	18 GeV
Phase advance per cell [degrees]	60	60	90
Horizontal emittance [nm]	20	20	22
Relative energy spread [10^{-4}]	5.8	5.5	10.0
Transverse damping time [turns]	7750	5450	940
Natural chromaticity x/y	-96.2/-89.5	-96.2/-89.5	-101.2/-99.6
Momentum compaction factor [10^{-3}]	1.03	1.04	0.53
Quadrupole strength k_{QF} [m^{-2}]	0.215	0.215	0.283
Quadrupole strength k_{QD} [m^{-2}]	0.216	0.216	0.279
Hor./Vert. sextupole families/sextant	3	3	2
Arc β_x^{max} [m]	27.7	27.7	26.5
Arc β_y^{max} [m]	27.4	27.4	26.8
Arc maximum dispersion [m]	0.95	0.95	0.57
Quadrupole aperture requirement x/y [mm]	30/30	30/30	30/30

Studies in eRHIC include SR induced spin diffusion :

STOCHASTIC ENERGY LOSS BY SR $\Longrightarrow$ SPIN DIFFUSION

- Sokholov-Ternov self-polarization - time scale 30 minutes at 18 GeV in eRHIC eSR

- Spin diffusion causes depolarization $\rightarrow$ ring design has to work out time constant as large as possible.

- The result is an asymptotic equilibrium polarization - goal at the EIC: 70%

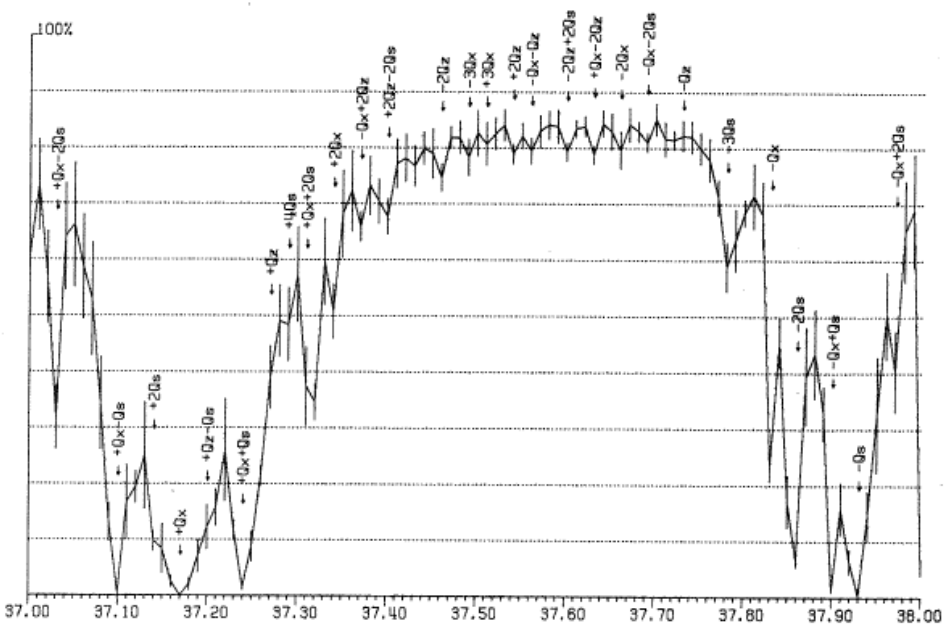
Ref.: eRHIC pCDR, BNL C-AD (2018), to be published.

• Polarization lifetime in eRHIC storage ring

• **Typically:**

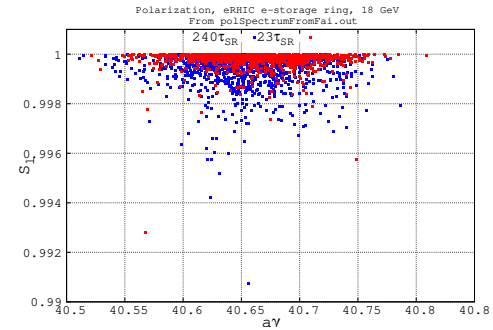
(i) track particles and spins, including Monte Carlo SR,

(ii) produce polarization landscape,
***i.e.*, $\mathrm{P_{eq}}$ versus ring rigidity setting**
Cf. J. Kewisch, DESY Rep. 83-032, 1983, using SITROS:



HERA-e, linear, res. non-corrected

• **Spins tracked over tens of damping times in eRHIC, 18 GeV**



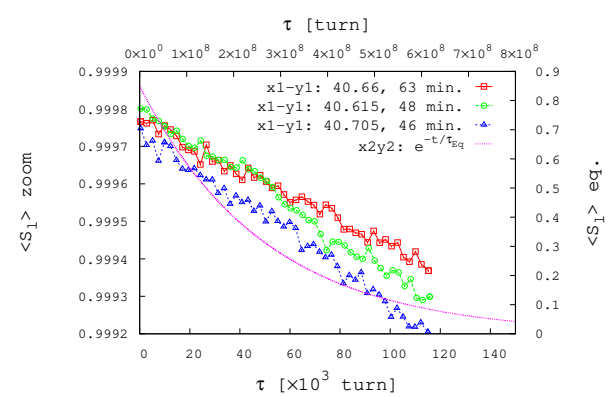
• **Polarization decay with time:**

The diffusion time constant τ_{D} is obtained from linear regression
$\mathrm{P/P_0} = \exp(-\mathrm{t}/\tau_{\mathrm{D}}) \approx 1 - \mathrm{t}/\tau_{\mathrm{D}}$.

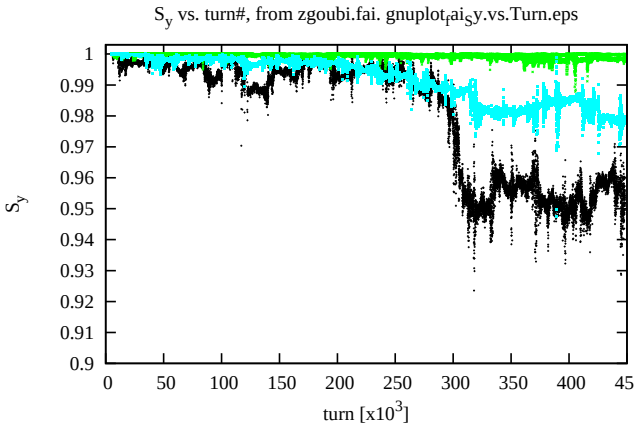
Given that $\tau_{\mathrm{eq}} = (1/\tau_{\mathrm{ST}} + 1/\tau_{\mathrm{D}})^{-1}$.
then, $\mathrm{P_{eq}}$ stems from

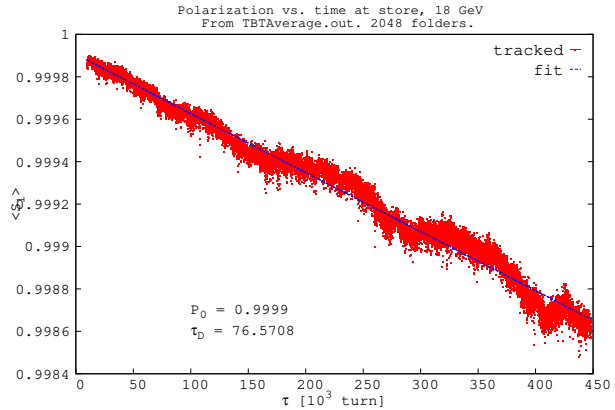
$$\boxed{\mathrm{P_{eq}} = \mathrm{P_{ST}} \times \tau_{\mathrm{eq}}/\tau_{\mathrm{ST}}},$$

Polarization vs. time at store, 18 GeV

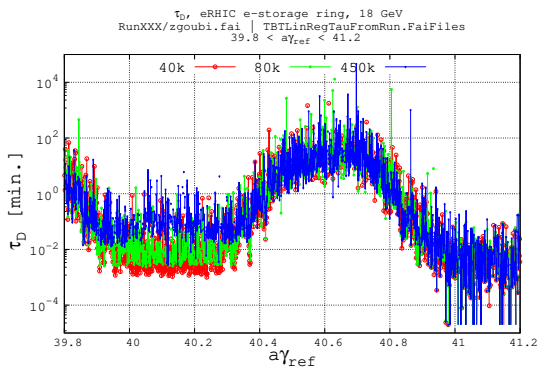


• Exploration: an ergodic approach to polarization lifetime:

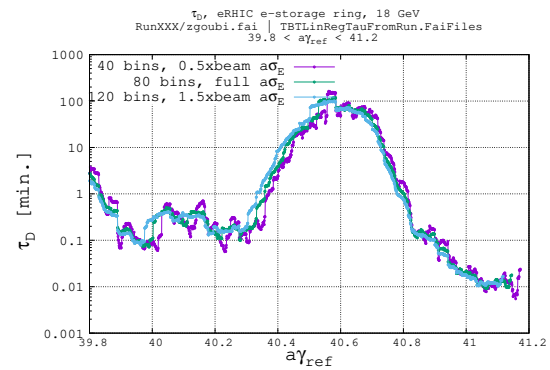




Stochastic spin motion observed at IP, single particle. A linear regression on $\mathrm{P}/\mathrm{P_0} = \exp(-\frac{\mathrm{t}}{\tau_\mathrm{D}}) \approx 1 - \frac{\mathrm{t}}{\tau_\mathrm{D}}$ provides the diffusion time constant τ_D.



An energy scan of the diffusion time constant provides the diffusion landscape.

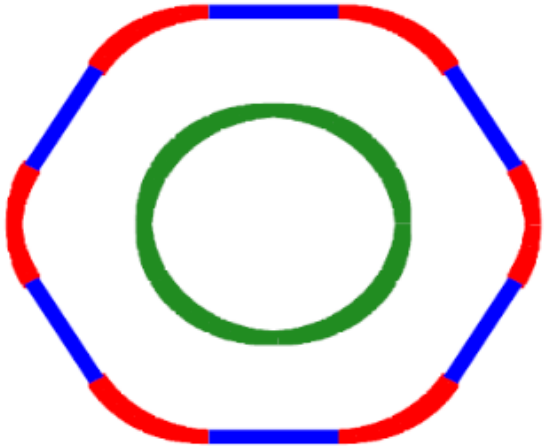


Sliding average of the diffusion time constant over the energy scan.

Ref.: F. Méot, An ergodic approach to polarization in eRHIC electron storage ring, https://public.bnl.gov/docs/cad/Documents/An%20ergodic%20approach%20to%20polarization%20in%20eRHIC%20electron%20storage%20ring.pdf

Injector : Rapid cycling synchrotron

- Full Energy Injector Accelerates 400 MeV, 10 nC bunches from the linac, to full collision energy, 5-18 GeV.
- 100-200 ms acceleration ramp, 1 Hz repetition rate
- 95% spin transmission w/ rms orbit 1 mm, gradient error 0.1%
- RF system: normal-conducting 563 MHz cavities (located at IR10), total voltage 72 MV. Stainless steel vacuum chamber



• Spin-transparent lattice, principle :

◇ Strong resonances occur at/near $Q_s = nPM \pm [Q_{arcs}]$

◇ Take P×M =6 arcs×32 cells/arc = 192, and

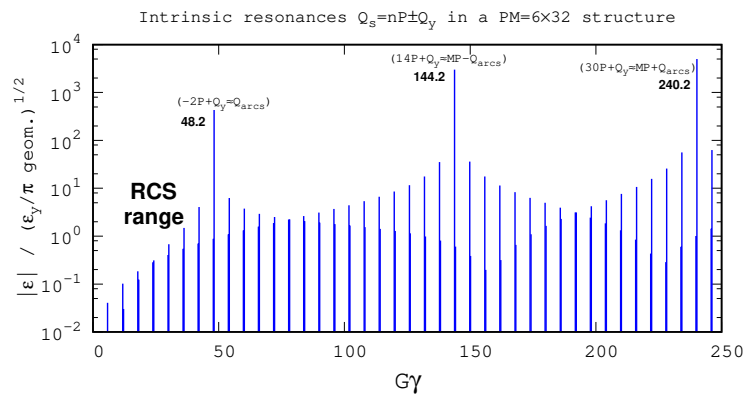
$Q_{arcs} > a\gamma_{max}$ (arc-cell $Q_y \approx 0.25$ or more)

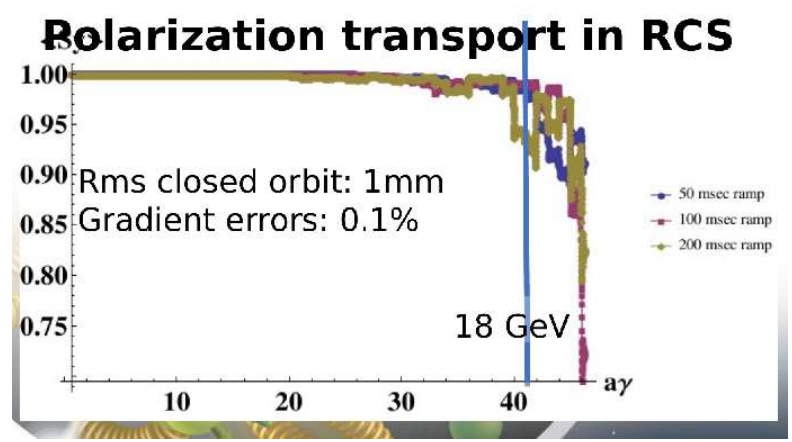
- first strongest imperfection resonance at $Q_s = 0 + [Q_{arcs}] = 48$
- with $Q_y = 60.2$ here, first strong intrinsic resonance is at

$Q_s = Q_y - 2P = 48.2$ closest to $0 \times PM + [Q_{arcs}]$,

◇ both are to the right of the useful range:

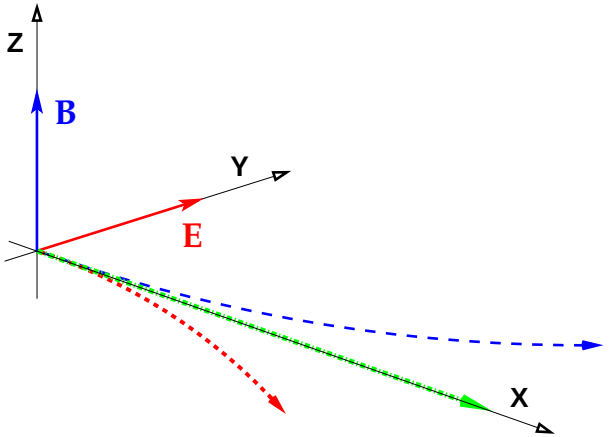
for $E: 400\ \text{MeV} \rightarrow 20\ \text{GeV}$, spin tune $Q_s : 0.9 \rightarrow 45.4$,



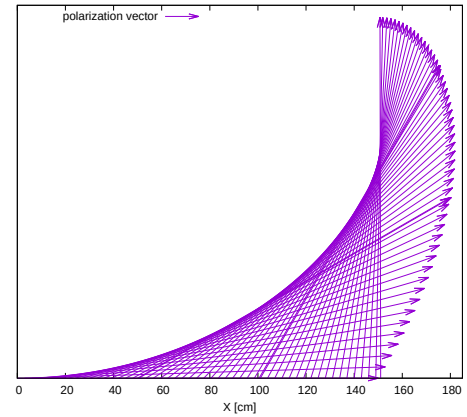


• Wien filter spin rotator (2019)

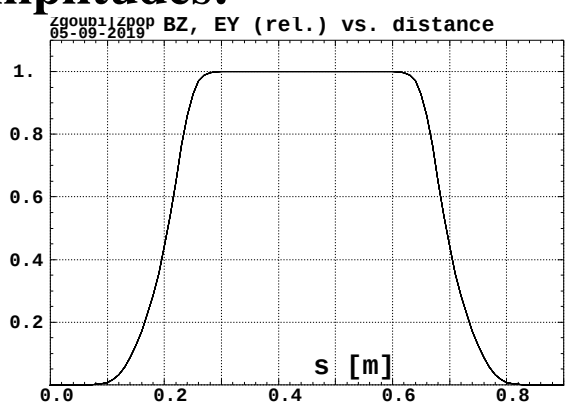
• 350 keV electrons. Principle:

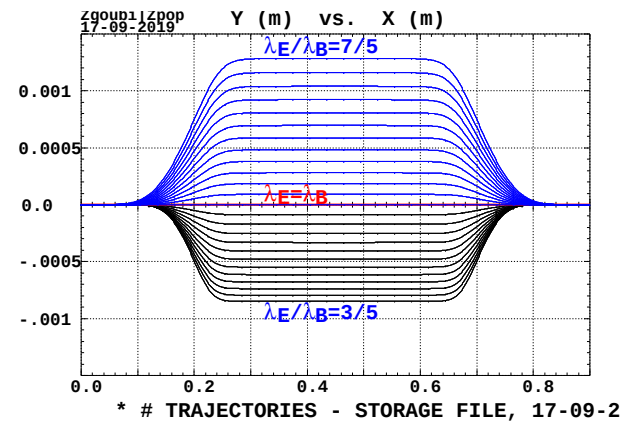


• Spin Z-rotation, from longitudinal ($\parallel \hat{X}$) to transverse ($\parallel \hat{Y}$) over 150 cm:



• Unequal E and B fringe field extents cause a shift of the orbit inside the Wien filter. The orbit is anyway zeroed at the exit, while maintaining $\theta_s = 30$ deg, by adjusting E and B amplitudes:



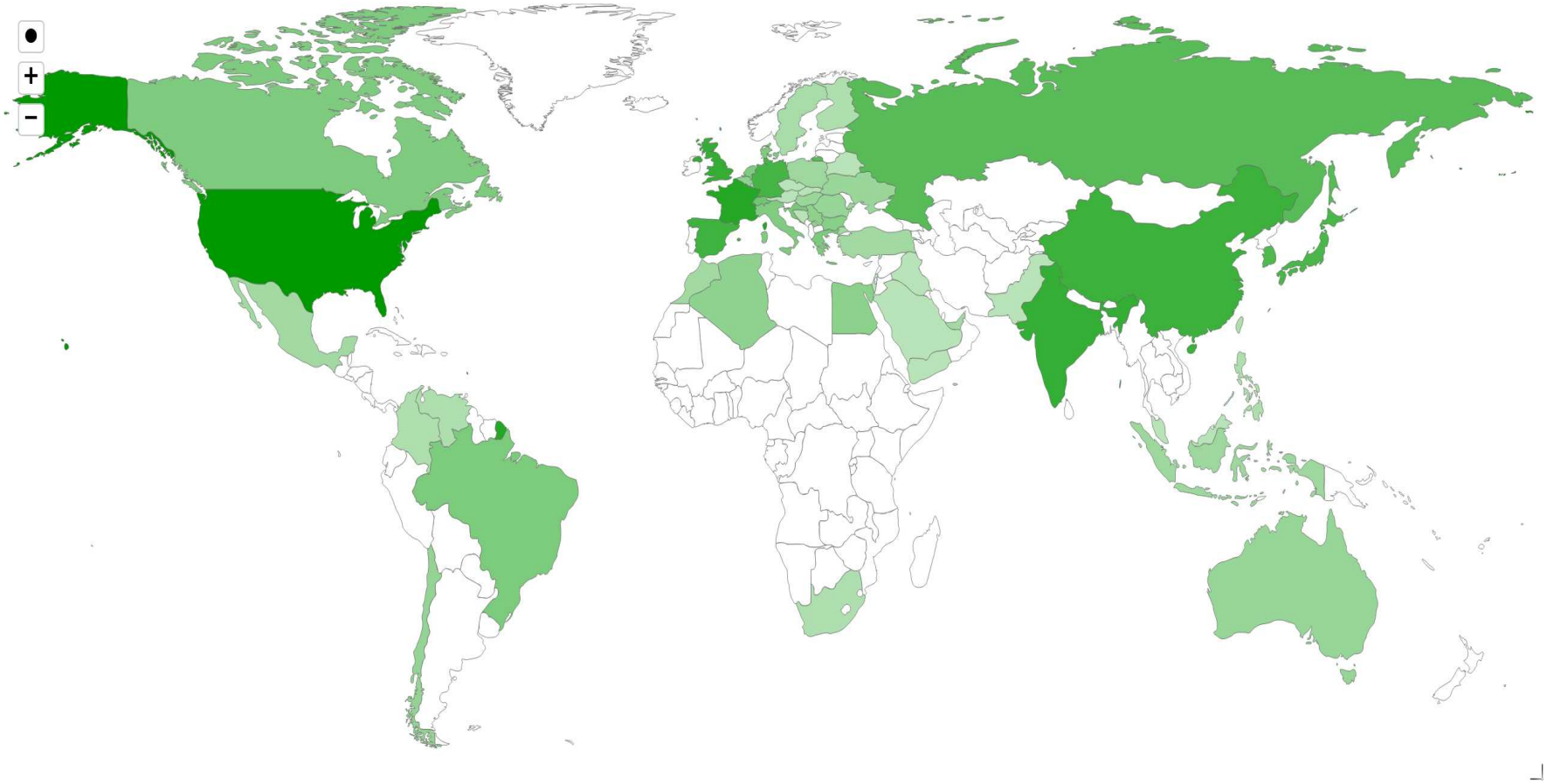


3 Spin simulation techniques

- **A couple of slides about the code used in these simulations**

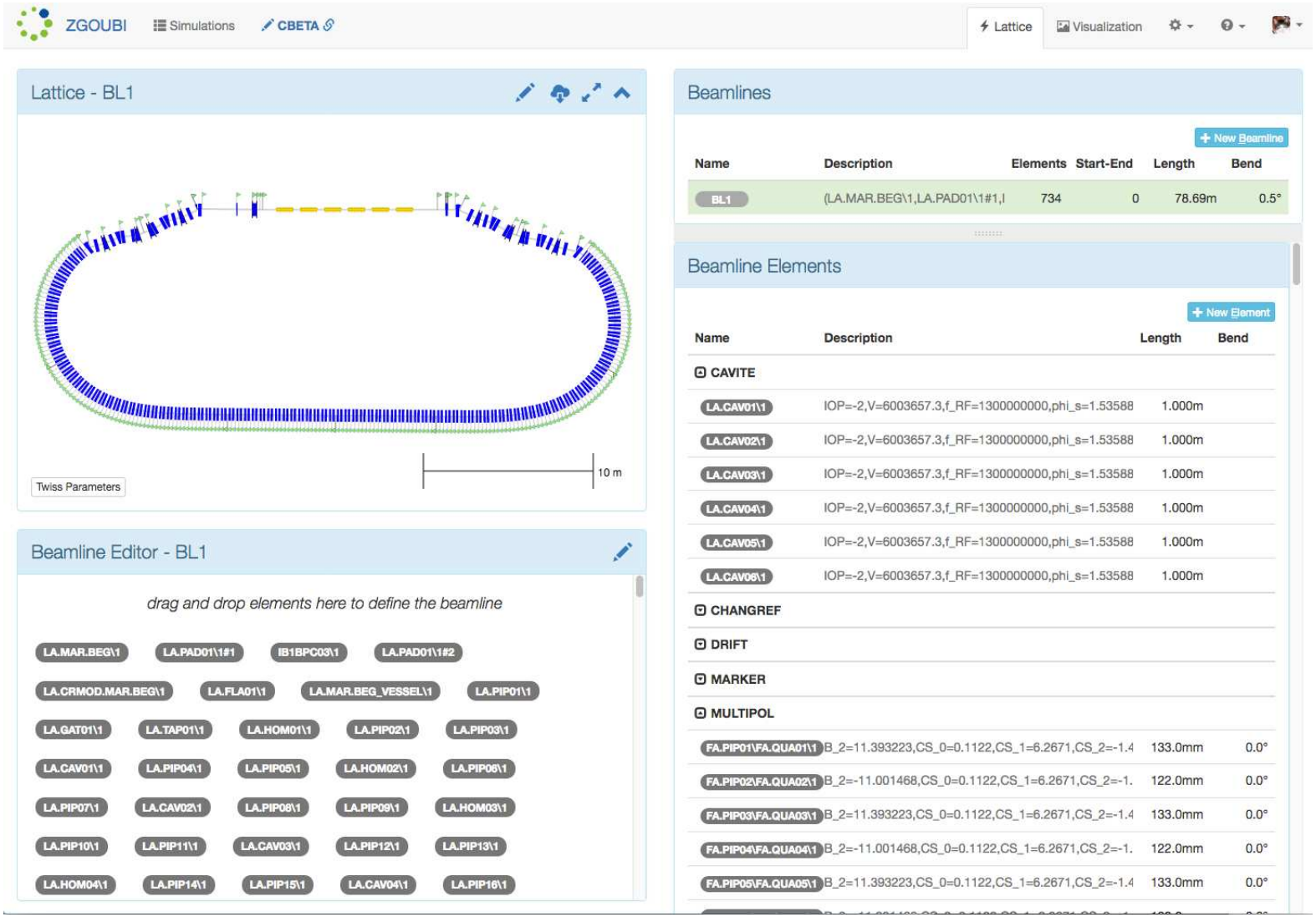
https://sourceforge.net/projects/zgoubi/files/stats/map

◇ **A stepwise ray-tracing technique: First version: 1972... ∼half a century ago!**
◇ **Spin installed in the late 1980s, for a partial snake project at Saturne, Saclay**
◇ **Code "repository-ed" in sourceforge in 2007**
◇ **4000 downloads at this day (63 depuis la Confédération des Helvètes)**



- **DOE FUNDED SBIR (Radiasoft, Boulder, CO, 2018-2020)**

◇ **This includes development of a graphical interface under SIREPO (Paul Moeller/Radiasoft)**



Ref.: https://beta.SIREPO.com/#/accel

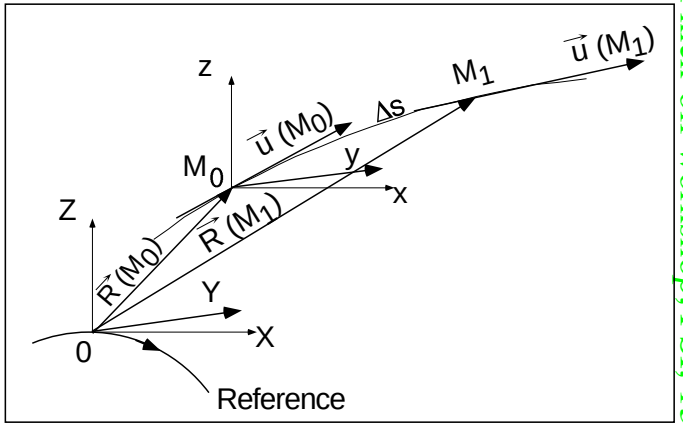
• NUMERICAL INTEGRATOR

◇ What needs be solved:

$$\frac{d(m\tilde{v})}{dt} = q\,(\tilde{E} + \tilde{v} \times \tilde{B})$$

$$\frac{d\tilde{S}}{dt} = \frac{q}{m}\,\tilde{S} \times \tilde{\omega}$$

$$\tilde{\omega} = (1 + \gamma G)\tilde{B} + G(1 - \gamma)\tilde{B}_{//} + \gamma(G + \frac{1}{1+\gamma})\frac{\tilde{E} \times \tilde{v}}{c^2}$$



G : gyromagnetic factor, γ : Lorentz relativistic factor,

c : velocity of light, q : charge, m :mass.

◇ ODE solver: Taylor series in the step size Δs:

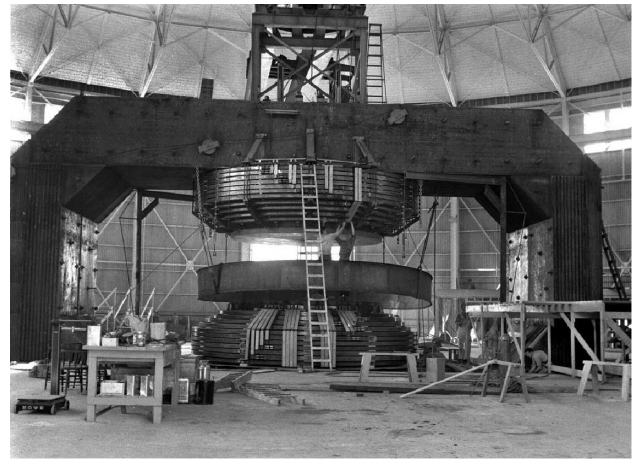
$$\tilde{a}(M_1) \approx \tilde{a}(M_0) + \frac{d\tilde{a}}{ds}(M_0)\,\Delta s + ... + \frac{d^n\tilde{a}}{ds^n}(M_0)\,\frac{\Delta s^n}{n!} \qquad (1)$$

- Solving particle motion : $\tilde{a}$ **stands for position** $\tilde{R}$ **or velocity** $\tilde{v}$**.**

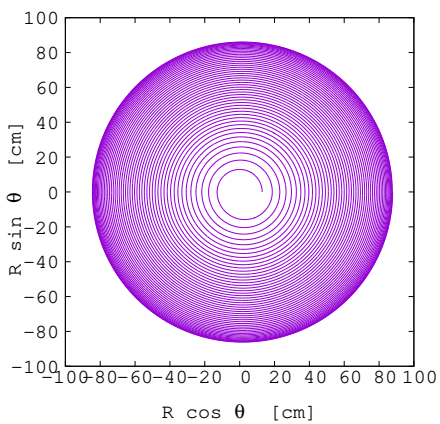
- Solving spin motion : $\tilde{a}$ **stands for the spin** $\tilde{S}$

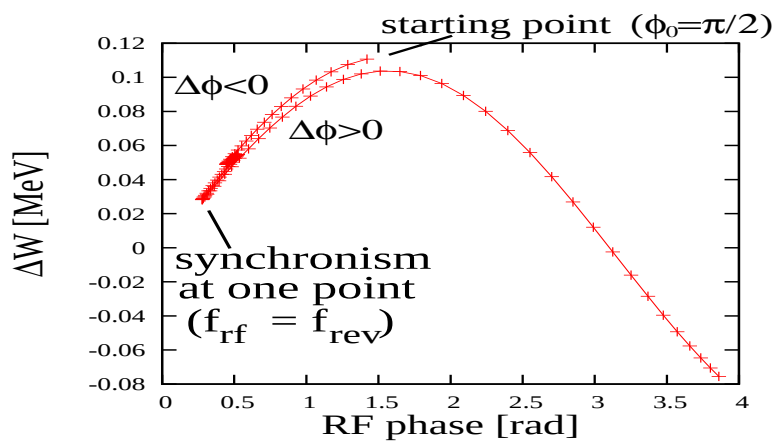
• **A note in passing: stepwise ray-tracing is as good at accelerating in a cyclotron ...**

◇ **184 inch cyclotron at Berkeley, 100MeV/u ions (1940s)**



◇ **Double-Dee acceleration to 10 MeV in 50 turns.**
Accuracy on time computation is critical:





$$[\cos\phi](\mathbf{W}) = \cos\phi_0 + \pi\left[1 - \frac{\omega_{\mathrm{RF}}}{\omega_{\mathrm{rev}_0}}\left(1 + \frac{\mathbf{W}}{2m_0c^2}\right)\right]\frac{\mathbf{W}}{q\hat{V}}$$

• **... as it is at tracking polarization in large colliders... we've seen that!**

THANK YOU FOR YOUR ATTENTION