Study of Electron Spin Polarization in EIC: eRHIC Storage Ring (BNL)

Outline

- Radiative polarization and the eRHIC storage ring.
- Simulations of polarization in the eRHIC storage ring.
  - Effect of mis-alignments.
- Summary and Outlook.

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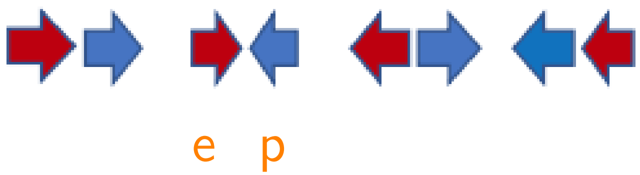
Nuclear Physics Accelerator R&D PI Meeting
Gaithersburg, November 13, 2018

Radiative polarization and the eRHIC storage ring

Experiments require

- Large proton and electron polarization ($\gtrsim 70\%$)
- Longitudinal polarization at the IP with *both* helicities within the *same* store



- Energy
  - protons: between 41 and 275 GeV
  - electrons: between 5 and 18 GeV

While high proton polarization is routinely achieved in RHIC, electron beam polarization is a new field at BNL and studies for the storage ring were ranked as high priority by the 2017 panel:

	29	BNL	CeC	Completion of the ongoing CEC demonstration experiment	High	C
	30	BNL	RR-A-1	Beam-Beam Parameter Validation	High	
⇒	31	BNL	RR-A-2	Study of Electron Spin Polarization in the Storage Ring	High	
	32	BNL	RR-A-3	Stability Study of Beams with Crab Cavities	High	

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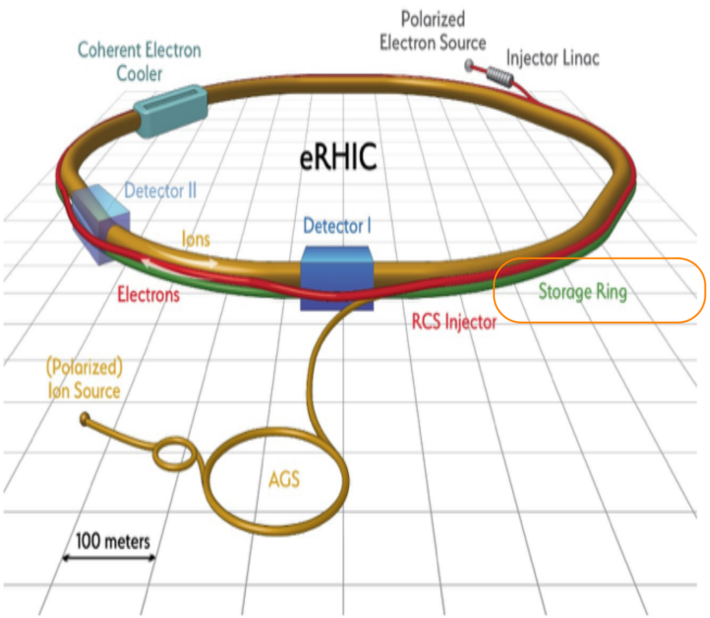
Because the experimenters call for storage of electron bunches with both spin helicities Sokolov-Ternov effect is not an option but rather a *nuisance*!

- A full energy polarized electron injector is needed: electron bunches are injected into the storage ring with high *vertical* polarization ($\approx 85\%$) and the desired spin direction (up/down).

- In the storage ring the polarization is brought into the longitudinal direction at the IP by a couple of solenoidal spin rotators left and right of the IP.



The goal of my project funded first by NP Accelerator R&D Plan in July 2017 was to study the electron beam polarization in the eRHIC Storage Ring. In particular

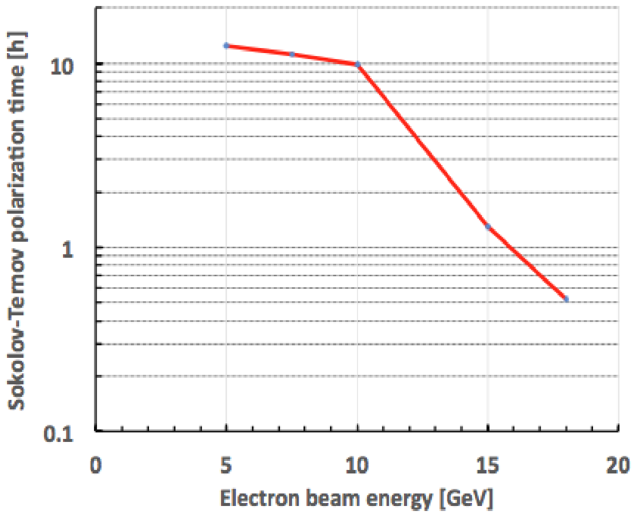
- Investigating polarization lifetime for bunches with both helicity in the same store.
  - Assessing Sokolov-Ternov asymptotic polarization to be aimed for to avoid that the beam get quickly depolarized.
- Evaluating the impact of misalignments.
  - Putting in place countermesures.
- Investigating the effect of the beam-beam force on the electron beam polarization.

The allocated NP funds were exhausted in March 2018.

For the remaining FY18, the project has been supported by a MPO (Memorandum Purchase Order) in place through March 2019.

Results shown here reflect the *current status* of the study, not only what funded by the 2017 award!

Sokolov-Ternov effect tends to polarize the electron beam in the eRHIC storage ring *upwards*.



In the planned energy range the minimum polarization time *nominally* is $\tau_p \simeq 30'$ at 18 GeV. At first sight a large time before Sokolov-Ternov effect reverses the polarization of the down-polarized electron bunches...

However the machine imperfections may quickly depolarize the *whole* beam, independently on polarization direction.

Polarization builds-up exponentially

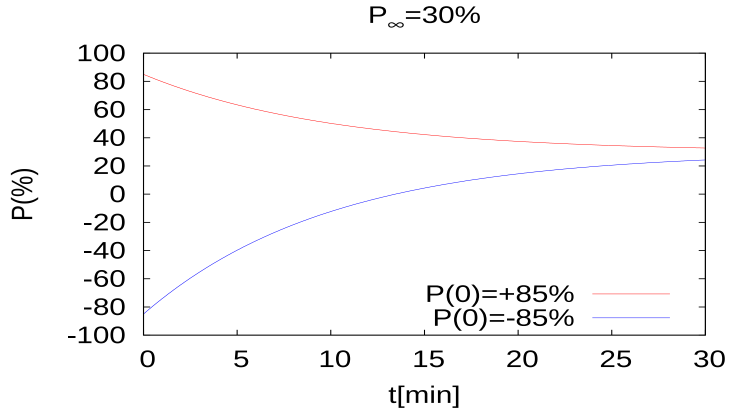
$$\boldsymbol{P(t) = P_\infty(1 - \mathrm{e}^{-t/\tau_p}) + P(0)\mathrm{e}^{-t/\tau_p}}$$

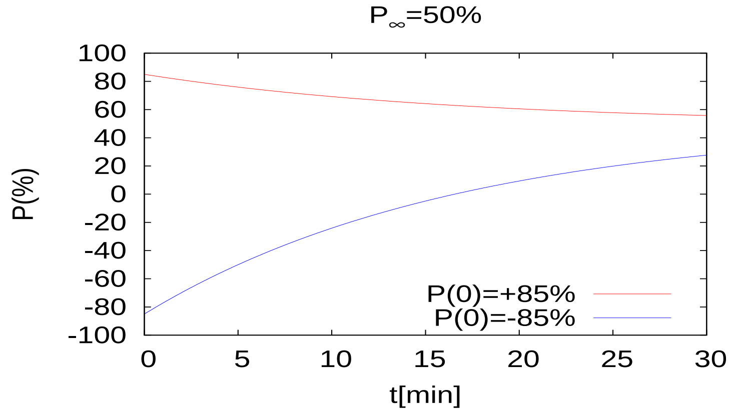
In the presence of depolarizing effects it is

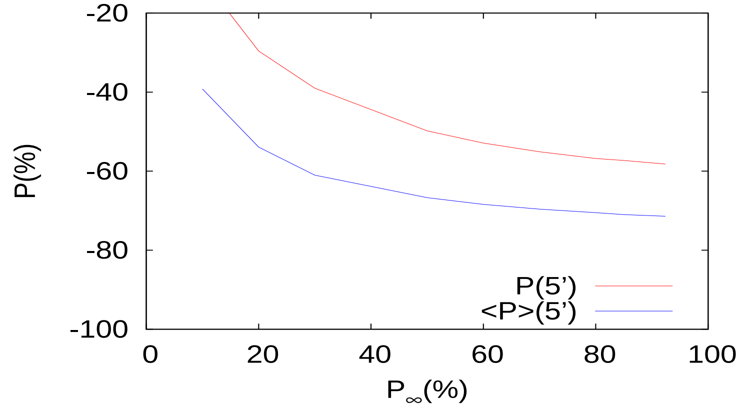
$$\boldsymbol{P_\infty \simeq \frac{\tau_p}{\tau_{\mathrm{BKS}}} P_{\mathrm{BKS}}} \qquad \text{and} \qquad \boldsymbol{\frac{1}{\tau_p} \simeq \frac{1}{\tau_{\mathrm{BKS}}} + \frac{1}{\tau_{\mathrm{d}}}}$$

$\boldsymbol{P_{\mathrm{BKS}}}$ and $\boldsymbol{\tau_{\mathrm{BKS}}}$ are the Baier-Katkov-Strakhovenko generalization of the Sokolov-Ternov quantities when $\boldsymbol{\hat{n}_0}$ is not everywhere perpendicular to the velocity.
They may be computed "analytically"; for eRHIC storage ring at 18 GeV it is

- $\boldsymbol{P_{BKS}} \simeq$90%
- $\boldsymbol{\tau_{BKS}} \simeq$30 minutes.







For instance, with P_∞=30%, after 5 minutes P decays from 85% to

- 60% for *up* polarized bunches $\rightarrow < P >$=73%
- –39% for *down* polarized bunches $\rightarrow < P >=$ –61%!

No much gain pushing P_∞ above ≈50% for down polarized bunches...

$< P >=$ -70% → P_∞=80%

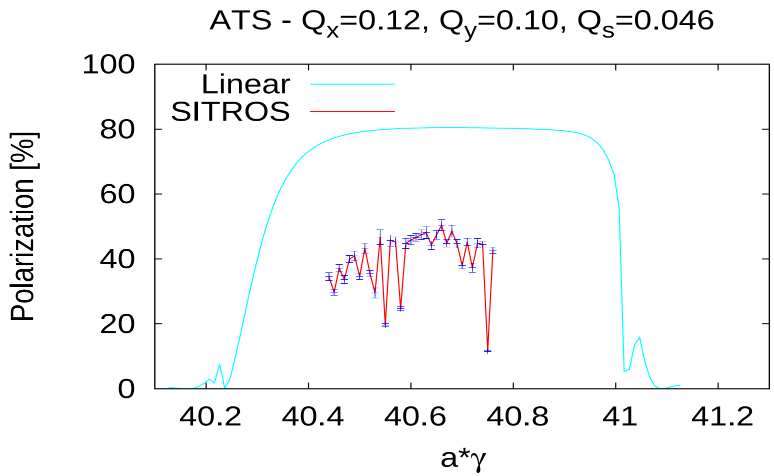
$P(0)$	P_∞ [%]	t[min]	$< P >$[%]
-85	50	4	70

Simulations for the eRHIC storage ring

- Energy: 18 GeV, the most challenging.
- BNL files must be modified for mis-alignment simulations and compatibility with SITROS, used for the polarization studies $\longrightarrow$ conversion codes.
- First simulations with now obsolete optics/tunes.
- Results shown here are for the "ATS" optics with
  - 90^0 FODO for both planes;
  - β_x^*=0.7 m and β_y^*= 9 cm.
  - Q_x=60.12, Q_y=56.10, Q_s=0.046

Tools:

- MAD-X for simulating quadrupole misalignments and orbit correction.
- SITROS package for computing the resulting polarization.
  - Tracking code with 2nd order orbit description and fully non-linear spin motion.
  - It has been used for HERA-e.
  - It contains SITF for polarization computation with *linearized* spin motion.



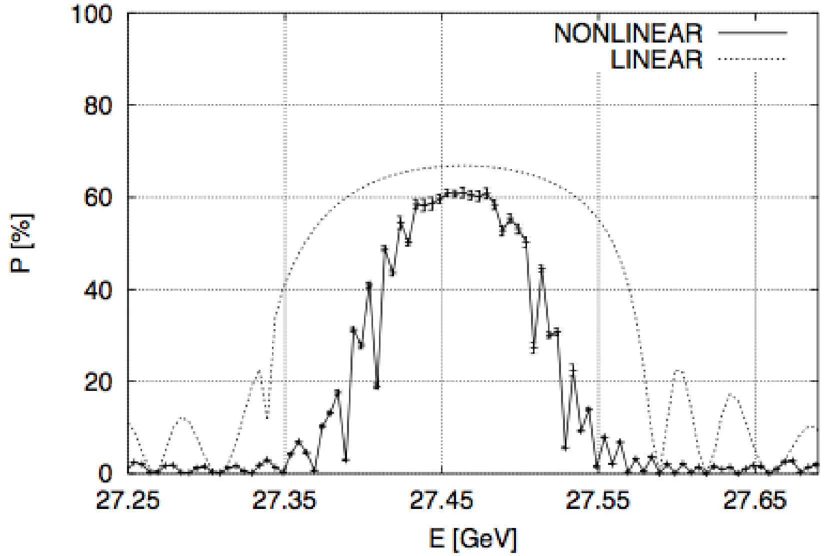
Beam size at IP

	σ_x [mm]	σ_y [μm]	σ_ℓ [mm]
SITF	0.121	0.588	6.967
SITROS	0.135	1.776	7.046

Two problems

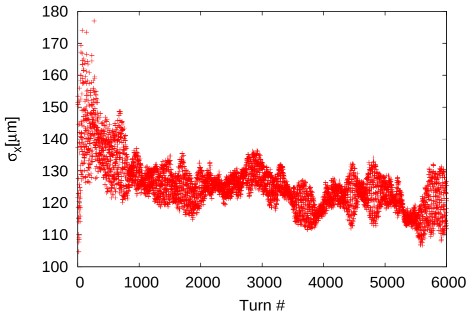
- Large equilibrium ϵ_y [a].
- Unusual large difference between linearized calculation and tracking.

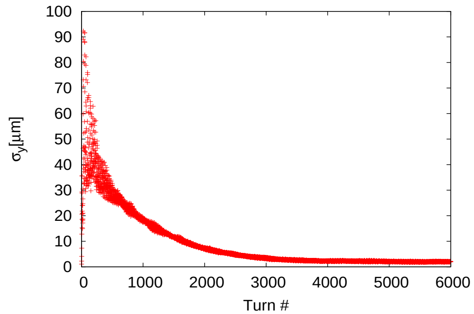
[a] It is related to the IR design in presence of SR. Same effect observed also in older optics.

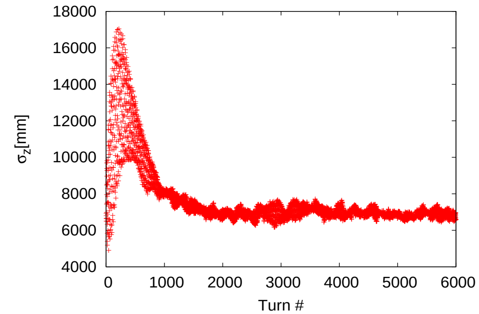


For comparison: Hera-e with 3 rotators.

Bmad (by D. Sagan) implemented on a MAC laptop for cross-checking SITROS results. 300 particles tracked over 6000 turns (typical SITROS parameters) with SR and stochastic emission with Bmad "standard" tracking.







Beam size

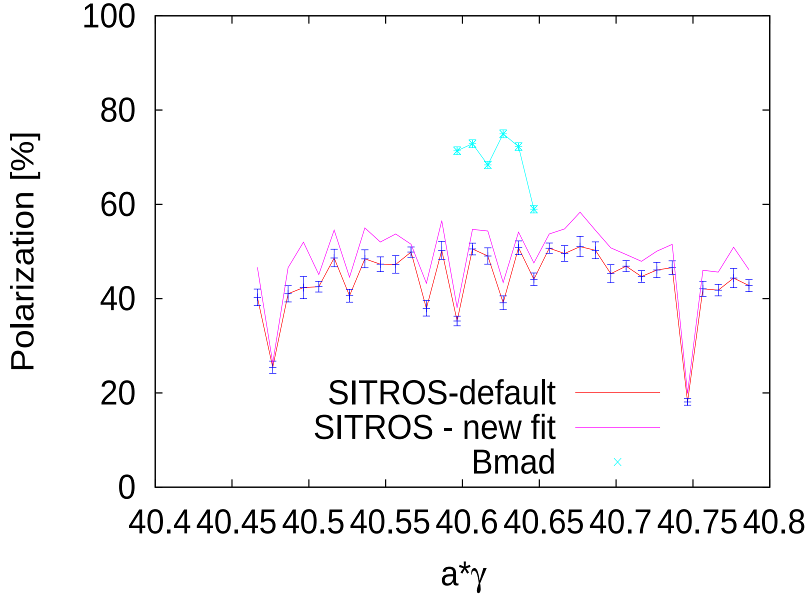
	$\boldsymbol{\sigma_x}$ [μm]	$\boldsymbol{\sigma_y}$ [μm]	$\boldsymbol{\sigma_\ell}$ [mm]	$\boldsymbol{\sigma_E}$ [%]
analytical (Bmad)	123	0.4	7.0	0.1
Bmad tracking	120	2.0	6.7	0.1
SITROS	136	1.8	7.0	0.1

The large $\boldsymbol{\epsilon_y}$ is not a SITROS artifact. Also confirmed by MAD8 and MADX-PTC.

Add spins following SITROS path:

- Once equilibrium is reached particles coordinates are dumped on file.
- Spins parallel to $\hat{\boldsymbol{n}}_{\mathbf{0}}(0)$ are added and tracking re-started.

The spin tracking is very slow:
300 particles and 3000 turns take over 24 hours for one single energy point!



D. Sagan is speeding up the tracking with spin.

Machine with misalignments

- 494 BPMs (h+v) added close to each quadrupole.
- 2x494 correctors (h+v) added close to each quadrupole.
- Magnet misalignments and orbit correction simulated by MAD-X.
- Optics with errors and corrections dumped into a SITROS readable file.

Assumed quadrupole RMS misalignments

horizontal offset	δx^Q	200 μm
vertical offset	δy^Q	200 μm
roll angle	$\delta \psi^Q$	200 μrad

Strategy

- switch off sextupoles;
- move tunes to 0.2/0.3;
- introduce errors;
- correct orbit (MICADO/SVD);
- turn on sextupoles;
- tunes back to luminosity values.

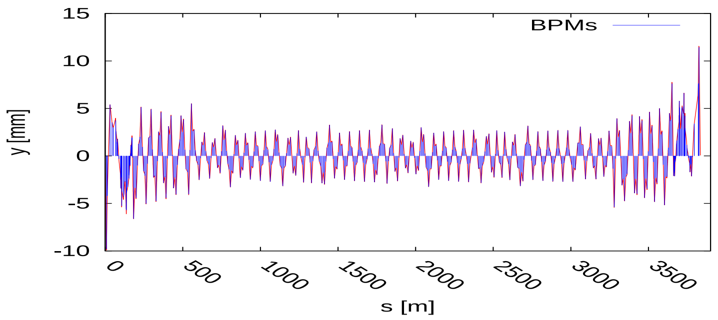
MAD-X fails correcting the orbit!

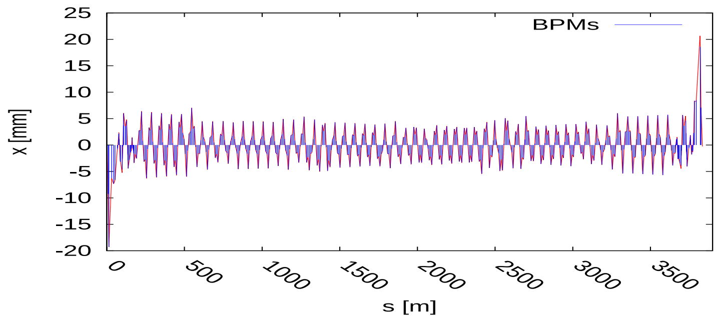
Example with only $\boldsymbol{\delta y^Q} \neq 0$ and sexts off.

Large discrepancy between what the correction module promises…

```
  Want to correct orbit of a single ring
  494 monitors and 494 correctors found in input
  494 monitors and 494 correctors enabled

 start SVD correction using         494  correctors

  CORRECTION SUMMARY:

                     average [mm]   std.dev. [mm]     RMS [mm]        peak-to-peak [mm]

  before correction: 0.763587       18.408777         18.424607        216.307978
  after correction:  0.000241       0.015902         0.015903        0.213275
```

…and the actual result!



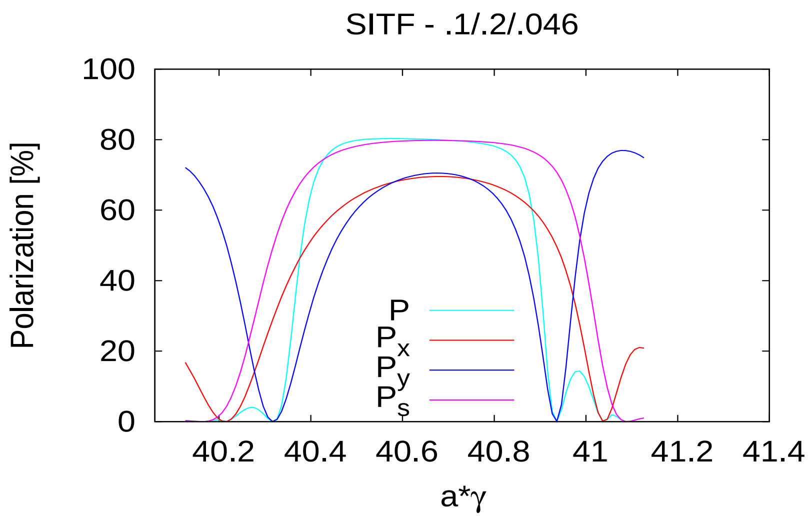


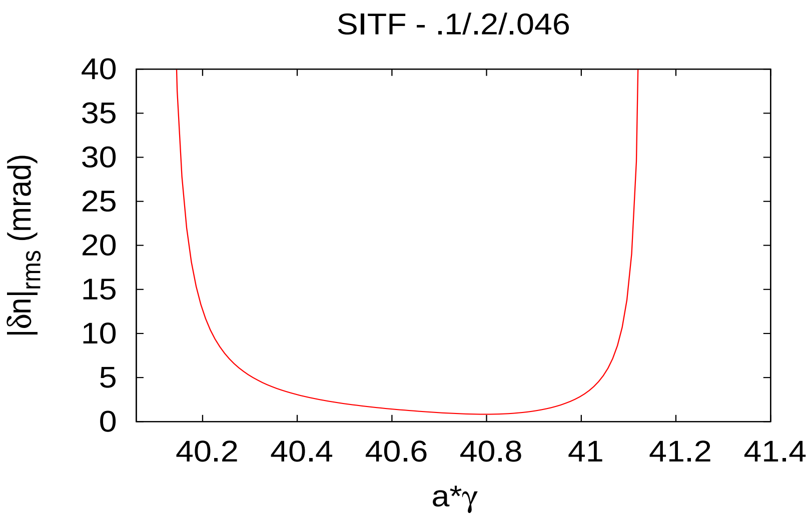
↑
Effect on horizontal plane with sextupoles off

Separate horizontal and vertical orbit correction inadequate in the rotator sections
$\rightarrow$ "external" program used for correcting horizontal and vertical orbits simultaneously.

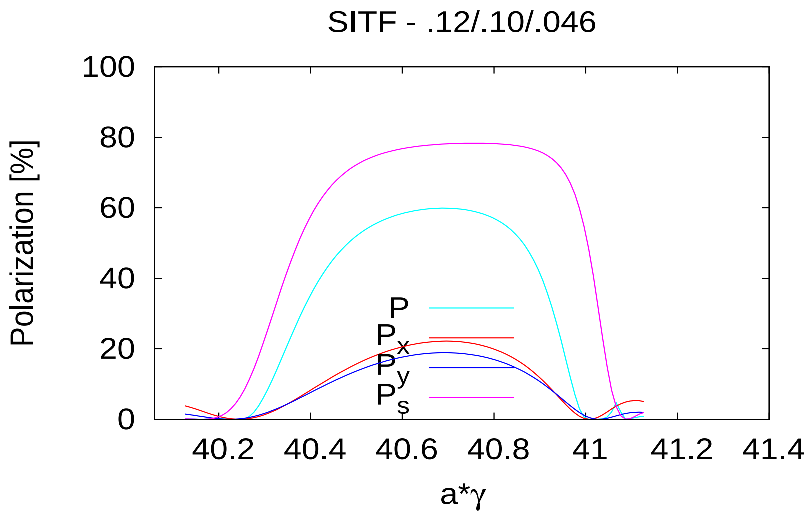
One error realization

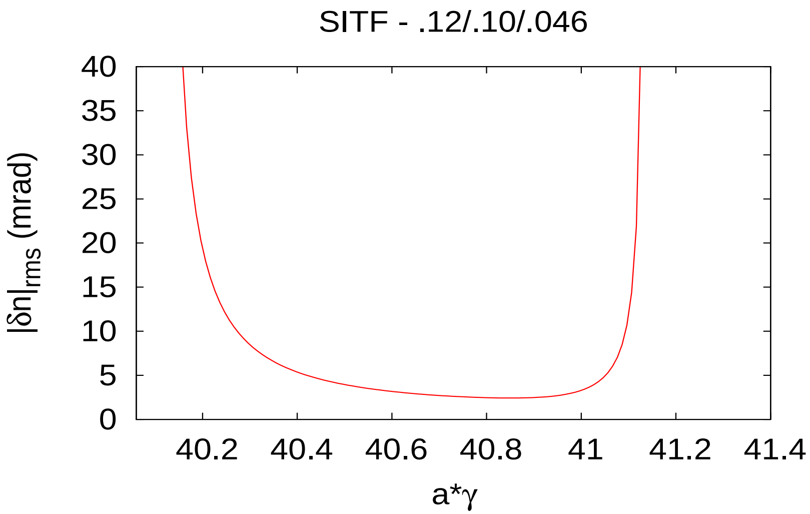
- after orbit correction
- with Q_x=60.10, Q_y=56.20 (HERA-e tunes).





Same error realization, betatron tunes moved to Q_x=60.12, Q_y=56.10 for luminosity operation; w/o skew quads, $|C^-|$ ≈0.01.





Coupling and vertical dispersion correction with skew quads

Vertical dispersion due to a skew quad

$$\Delta D_y(s) = \frac{1}{2\pi \sin \pi Q_y} D_x^{skq} \sqrt{\beta_y^{skq} \beta_y(s)} \cos\left(\pi Q_y - |\mu_y - \mu_y^{skq}|\right) (K\ell)_{skq}$$

Coupling functions

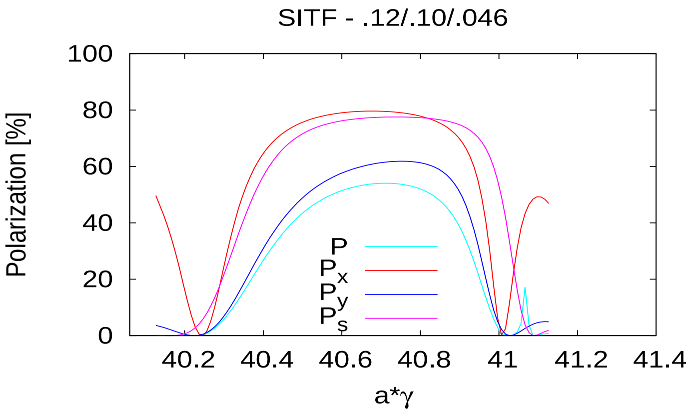
$$w_{\pm}(s) \propto \sqrt{\beta_x^{skq} \beta_y^{skq}(s)}$$

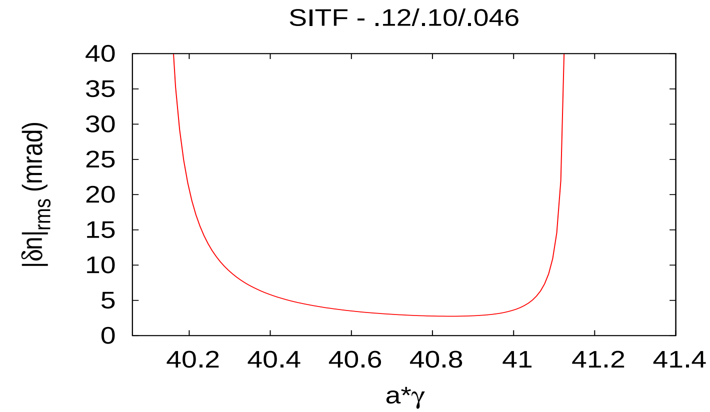
Introduced 46 independently powered skew quadrupoles in arc locations where

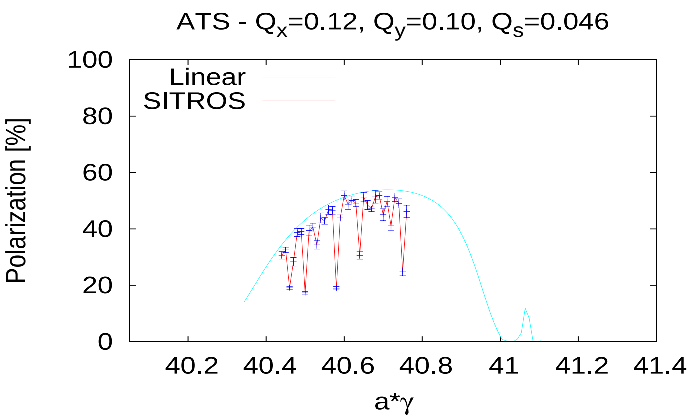
$$D_x^{skq} \sqrt{\beta_y^{skq}} \quad \text{and} \quad \sqrt{\beta_x^{skq} \beta_y^{skq}(s)}$$

are large.

Same error realization, luminosity betatron tunes with optimized skew quads, $|C^-| \approx$0.002.



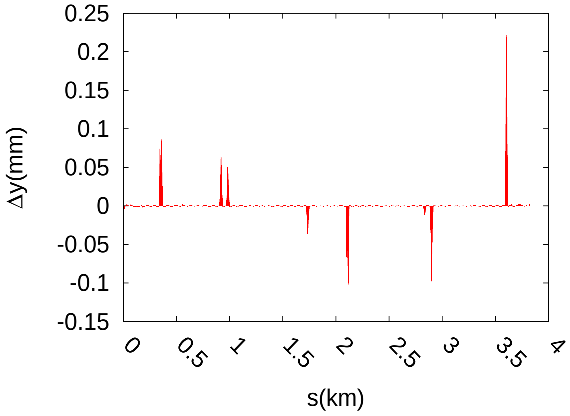


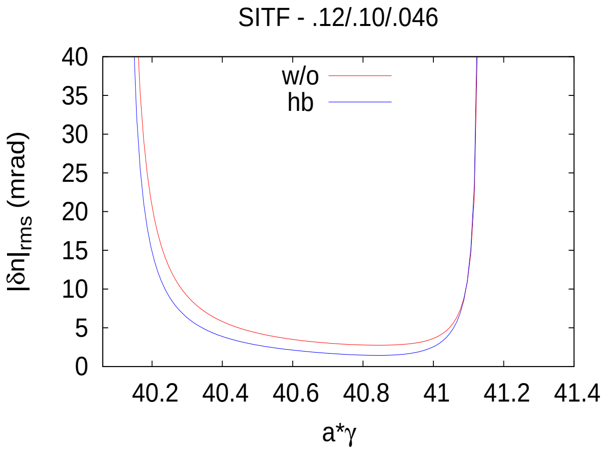


Beam size at IP

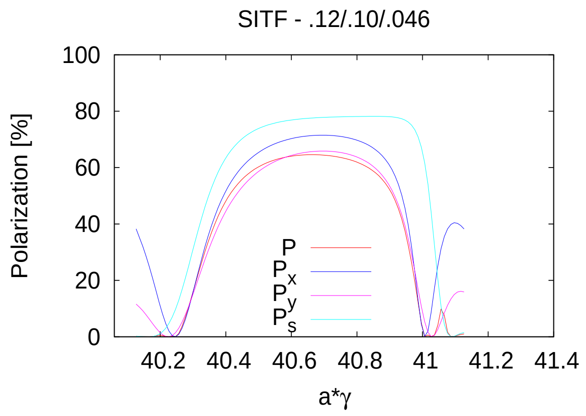
	σ_x [mm]	σ_y [μm]	σ_ℓ [mm]
SITF	0.121	1.718	6.984
SITROS	0.138	3.126	6.969

Adding $\hat{\boldsymbol{n}}_0$ correction by *harmonic bumps*



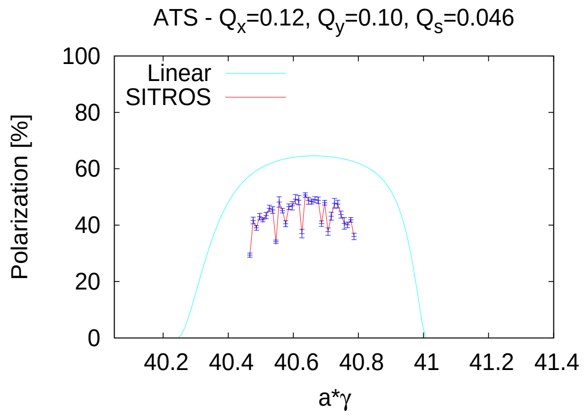


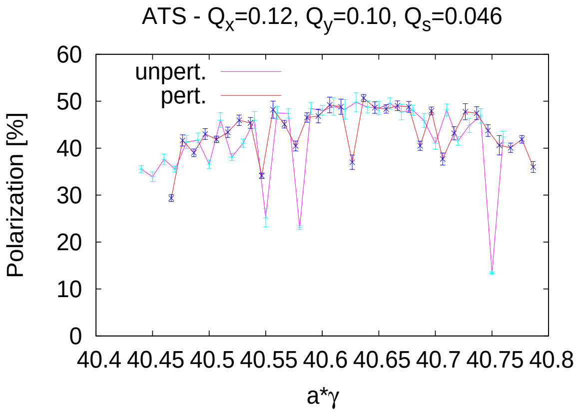
Effect on vertical orbit



Beam size at IP

	σ_x [mm]	σ_y [μm]	σ_ℓ [mm]
SITF	0.121	3.151	6.985
SITROS	0.139	4.402	7.004





Level of polarizations is as for the *unperturbed* optics. However: BPMs errors must be included and some statistics is needed!

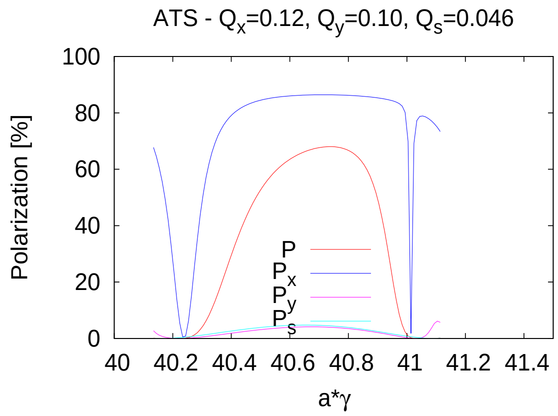
ϵ_y bump

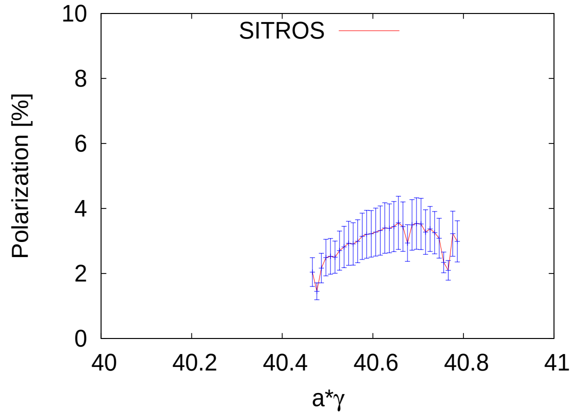
The beam vertical emittance is 1.7 pm, corresponding to $\sigma_y^* \simeq 0.4\ \mu$m. A larger beam size at the IP may be needed.

The e-beam ϵ_y may be efficiently increased by anti-symmetric bumps around low β_y locations.

As a *test* such a bump has been introduced around the IP.

Effect on polarization is detrimental. For ϵ_y= 3 nm there is no polarization!





Delivered in summary

- Beam polarization in the eRHIC storage ring has been studied.
- ATS lattice has been modified to include BPMs, correctors and skew quadrupoles.
- With conservative errors $P_\infty \approx$ 50% seems within reach:
  - for *upwards* polarized bunches (anti-parallel to the guiding field), $<P>\approx$ 80%., over 5 minutes if $P(0)$=85%;
  - for bunches polarized *downwards* the average polarization drops to 67%.
- Luminosity working point requires linear coupling correction. Here the benefit of a *local correction* using 46 skew quadrupoles has been shown.
- Harmonic bumps for the $\hat{n}_0$ axis correction have been implemented.
- Comparisons with different codes (Bmad, PTC) have started.

	July 2017 - March 2018
Funds allocated by NP Acc. R&D FOA	$80k
Actual costs to March 2018	$80k

The work is currently funded by a MPO.

To-do-list

- BPMs errors must be included in the mis-alignments simulation.
- Some statistics must be gained.
- Independent correction of betatron coupling and vertical spurious dispersion must be tried.
- A knob for controlling the vertical beam size at IP w/o affecting polarization is needed.
- Beam-beam effects need to be addressed.
- The work must be repeated for the other 2 energy values.

It is difficult to evaluate how much time will be needed to complete the work, because for some items it depends on the outcome.

Tentative Schedule

	hours	comment
BPMs errors + statistics	140	easy
betatron coupling and dispersion	140	easy
ϵ_y knob	160	the wished ϵ_y may be incompatible with polarization $\longrightarrow$ upper limit
beam-beam	180	using SITROS
beam-beam	?	Bmad/PTC