Polarization Studies for the eRHIC electron Storage Ring

Outline

- Setting the frame: experiment requirements.
- Radiative polarization essentials.
- Radiative polarization and the eRHIC storage ring.
- Simulations of polarization in the eRHIC storage ring.
- Summary and Outlook.

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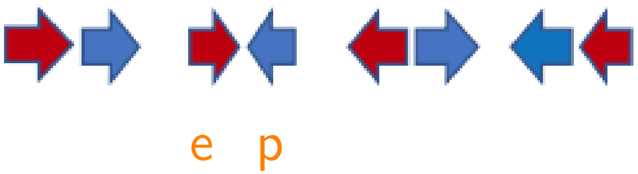
Experiment polarization requirements

Experiments require

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

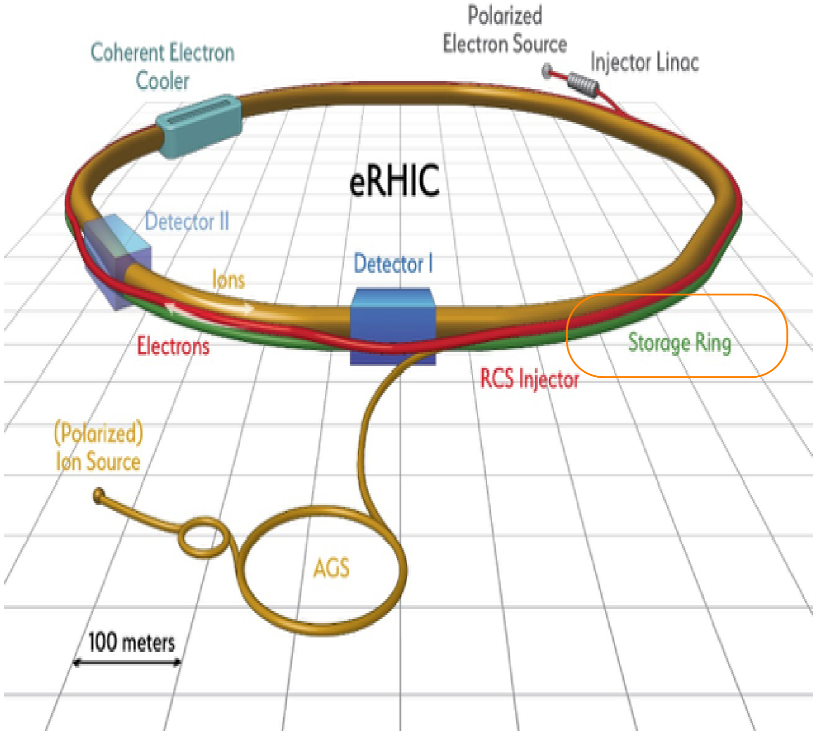


- Energy
  - protons: between 41 and 275 GeV
  - electrons: between 5 and 18 GeV

High proton polarization is already routinely achieved in RHIC.

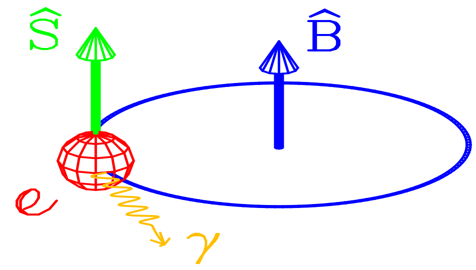
Studies are needed instead for the electron beam.

eRHIC layout



Radiative polarization

Sokolov-Ternov effect in a homogeneous constant magnetic field: a small amount of the radiation emitted by a $e^{\pm}$ moving in the field is accompanied by *spin flip*.



Slightly different probabilities $\rightarrow$ *self polarization!*

- Equilibrium polarization

$$\vec{P}_{\mathrm{ST}} = \hat{y} P_{\mathrm{ST}} \qquad |P_{\mathrm{ST}}| = \frac{|n^+ - n^-|}{n^+ + n^-} = \frac{8}{5\sqrt{3}} = 92.4\%$$

e^- polarization is anti-parallel to $\vec{B}$, while e^+ polarization is parallel to $\vec{B}$.

- Build-up rate

$$\tau_{\mathrm{ST}}^{-1} = \frac{5\sqrt{3}}{8} \frac{r_e \hbar}{m_0} \frac{\gamma^5}{|\rho|^3} \quad \rightarrow \quad \tau_p^{-1} = \frac{5\sqrt{3}}{8} \frac{r_e \hbar\, \gamma^5}{m_0 C} \oint \frac{ds}{|\rho|^3} \text{ for an \textit{ideal} storage ring}$$

In eRHIC electrons (clock-wise rotating) self-polarization is *upwards*.

A perfectly planar machine (w/o solenoids) is always *spin transparent*.

This property is lost in presence of

- spin-rotators
  - spin transparency partially restored by *optical spin-matching*
- mis-alignments

Derbenev-Kondratenko expressions for non-homogeneous constant magnetic field involve averaging across the phase space and along the ring

$$\vec{P}_{\rm DK} = \hat{n}_0 \frac{8}{5\sqrt{3}} \frac{\oint ds < \frac{1}{|\rho|^3} \hat{b} \cdot (\hat{n} - \frac{\partial \hat{n}}{\partial \delta}) >}{\oint ds < \frac{1}{|\rho|^3} \left[1 - \frac{2}{9}(\hat{n}\cdot\hat{v})^2 + \frac{11}{18}(\frac{\partial \hat{n}}{\partial \delta})^2\right] >} \qquad \hat{b} \equiv \vec{v} \times \dot{\vec{v}} / |\vec{v} \times \dot{\vec{v}}|$$

periodic solution
to T-BMT eq. on c.o.

randomization of particle spin
directions due to photon emission
$(\delta \equiv \delta E/E)$

Polarization rate

$$\tau_{\rm DK}^{-1} = \frac{5\sqrt{3}}{8} \frac{r_e \gamma^5 \hbar}{m_0 C} \oint ds < \frac{1}{|\rho|^3} \left[1 - \frac{2}{9}(\hat{n}\cdot\hat{v})^2 + \frac{11}{18}\left(\frac{\partial \hat{n}}{\partial \delta}\right)^2\right] >$$

Perfectly planar machine (w/o solenoids): $\partial\hat{n}/\partial\delta$=0.

In general $\partial\hat{n}/\partial\delta \neq$0 and large when

$$\nu_{spin} \pm mQ_x \pm nQ_y \pm pQ_s = \text{integer} \qquad \nu_{spin} \simeq a\gamma$$

- Polarization time may be greatly reduced.
- $P_{\mathrm{DK}} < P_{\mathrm{ST}}$.

Tools

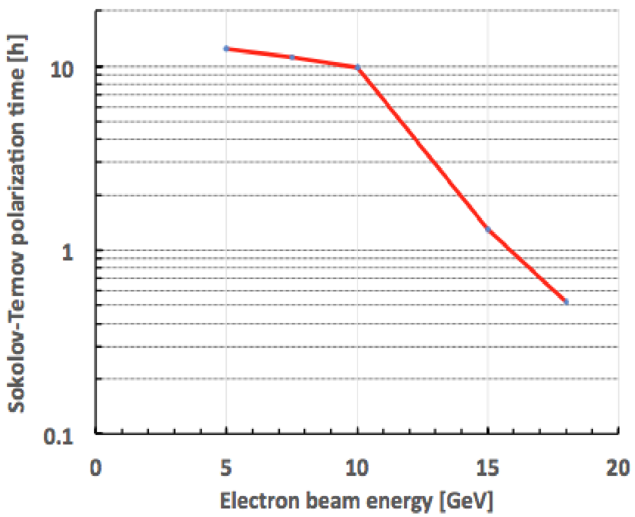
Accurate simulations are necessary for evaluating the polarization level
to be expected in presence of misalignments. Evaluation of D-K expressions is difficult.

- MAD-X used for simulating quadrupole misalignments and orbit correction
- SITROS (by J. Kewisch) used for computing the resulting polarization.
  - Tracking code with 2nd order orbit description and non-linear spin motion.
  - Used for HERA-e in the version improved by M. Böge and M. Berglund.
  - It contains SITF (fully 6D) for analytical polarization computation with *linearized* spin motion.
    - Useful tool for preliminary checks before embarking in time consuming tracking.
    - Computation of polarization related to the 3 degree of freedom separately: useful for disentangling problems!

Radiative polarization and the eRHIC storage ring

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.



In the eRHIC 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.

Polarization builds-up exponentially

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

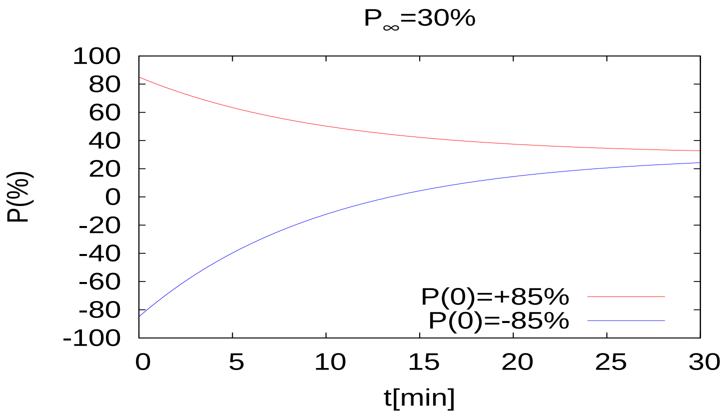
In the presence of depolarizing effects it is

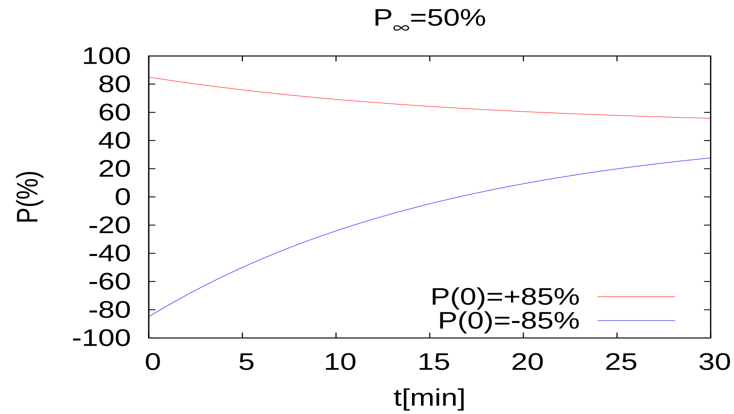
$$P_\infty \simeq \frac{\tau_p}{\tau_{\mathrm{BKS}}} P_{\mathrm{BKS}} \qquad \text{and} \qquad \frac{1}{\tau_p} \simeq \frac{1}{\tau_{\mathrm{BKS}}} + \frac{1}{\tau_{\mathrm{d}}}$$

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

- P_{BKS}=90%
- τ_{BKS}=30 minutes.

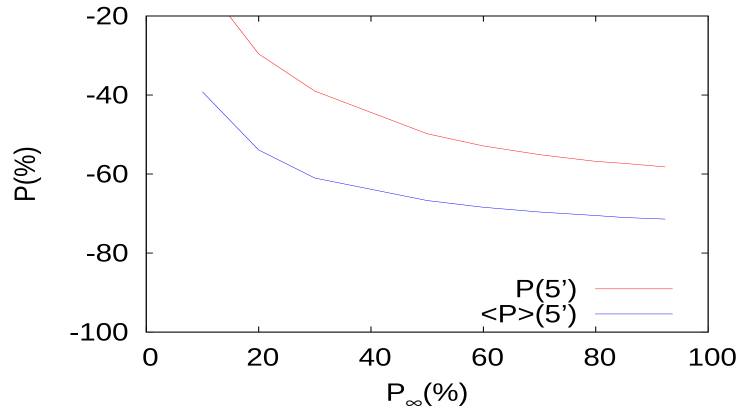
P for bunches polarized parallel or anti-parallel to the bending field





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%!



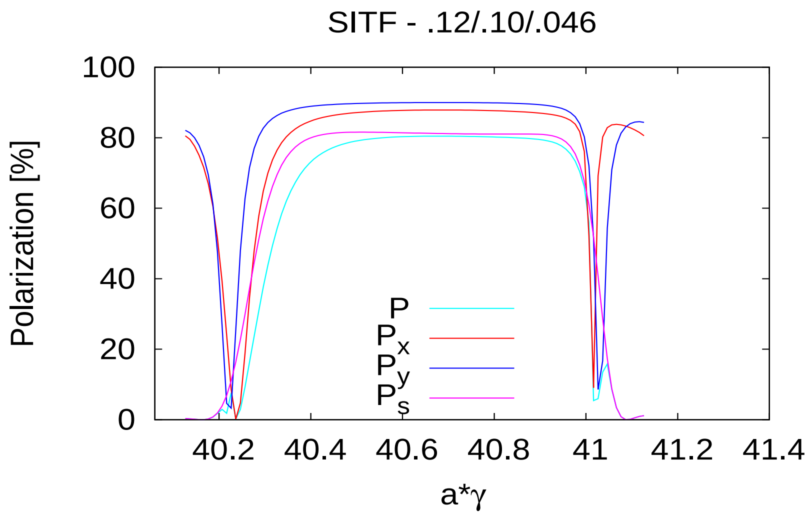
$\rightarrow$ No much gain pushing P_∞ above ≈50%.

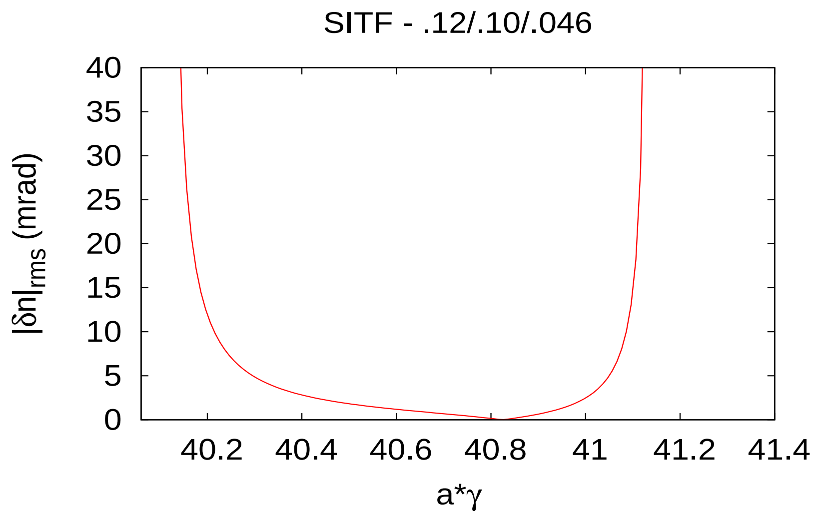
Simulations for the eRHIC storage ring

- Energy: 18 GeV, the most challenging.
- Simulations shown here are for the "ATS" optics with
  - 90^0 FODO for both planes;
  - β_x^*=0.7 m and β_y^*= 8 cm.
- Working point for luminosity: Q_x=60.12, Q_y=56.10, Q_s=0.046

Ideal machine

Ideal machine (with solenoidal rotators), polarization in linear approximation

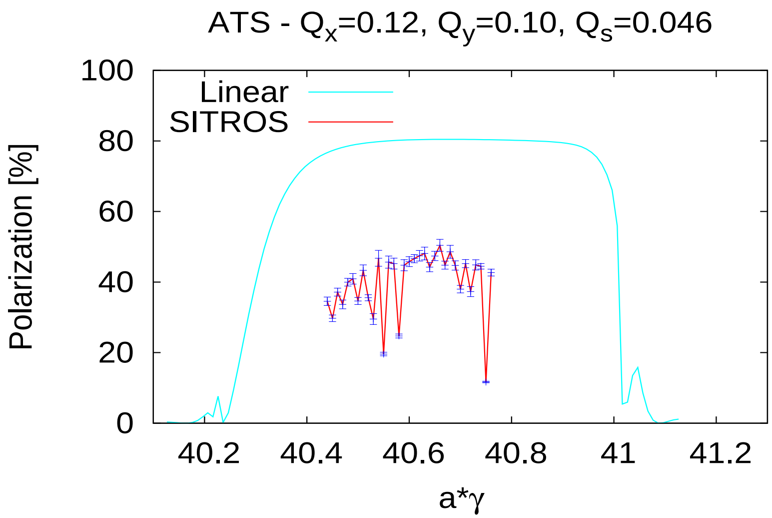




scan with constant solenoid strengths

$\delta\hat{n}_0$ small

- The strong solenoids shift the spin tune by $\Delta\nu_{spin} \simeq 0.124$.



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

Large difference between linearized calculation and tracking: SITROS artifact? Zhe Duan agreed to cross check results with his code using PTC by E. Forest.

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

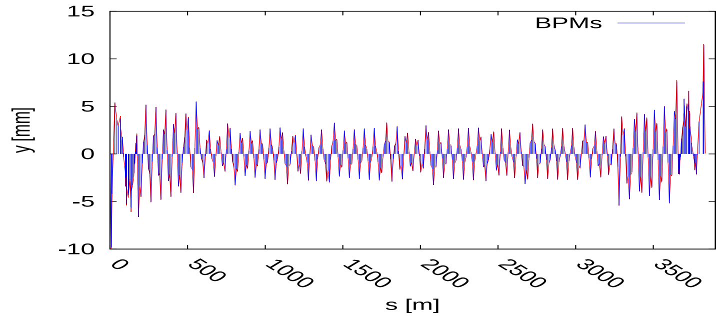
- switch off sextupoles;
- move tunes to 0.2/0.3;
- introduce errors;
- correct orbit (MICADO/SVD);
- turn on sextupoles;
- tunes back to luminosity values.

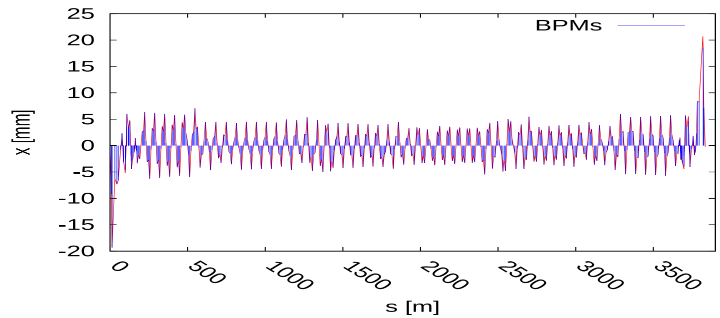
MAD-X fails correcting the orbit!

Example with only $\delta y^Q \neq 0$ 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
→ "external" program used for correcting horizontal and vertical orbits simultaneously.

Coupling and vertical dispersion correction with skew quads

Vertical dispersion due to a skew quad

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

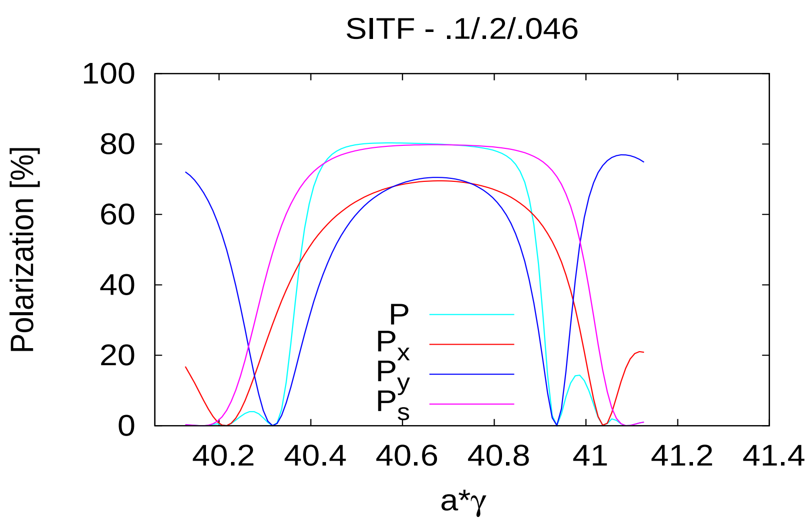
Coupling functions

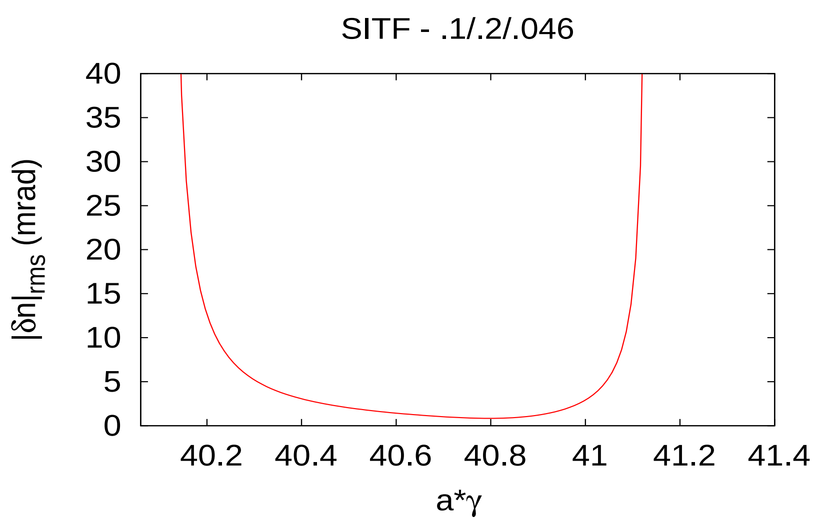
$$w_\pm(s) \propto \sqrt{\beta_x^{skq} \beta_y^{skq}(s)}$$

Introduced 46 independently powered skew quadrupoles in arc locations where $D_x^{skq}\sqrt{\beta_y^{skq}}$ and $\sqrt{\beta_x^{skq}\beta_y^{skq}(s)}$ are large.

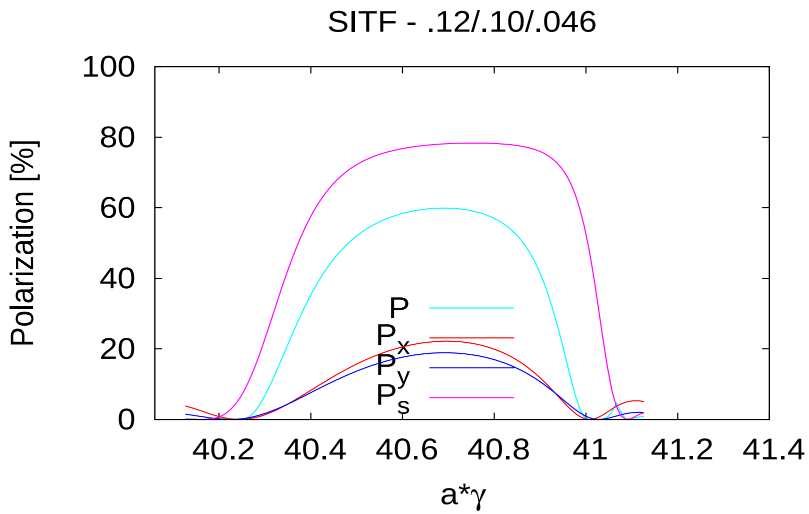
One error realization

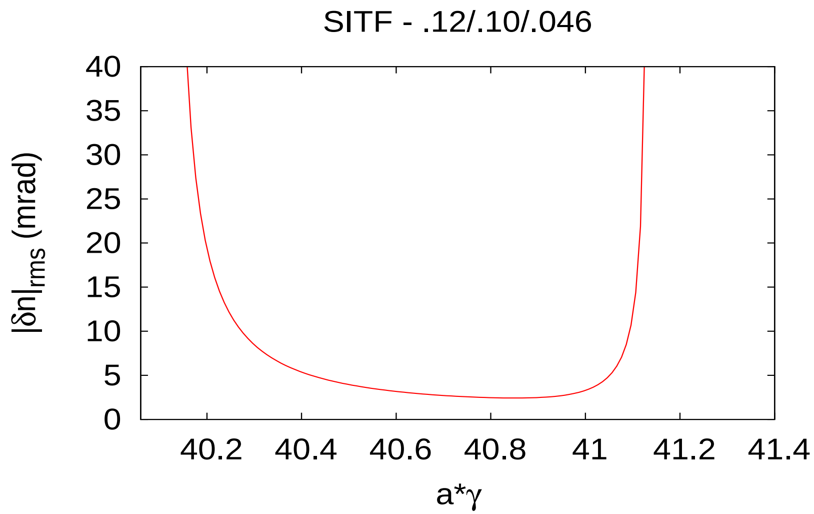
- after orbit correction
- with Q_x=60.10, Q_y=56.20 (HERA-e tunes).



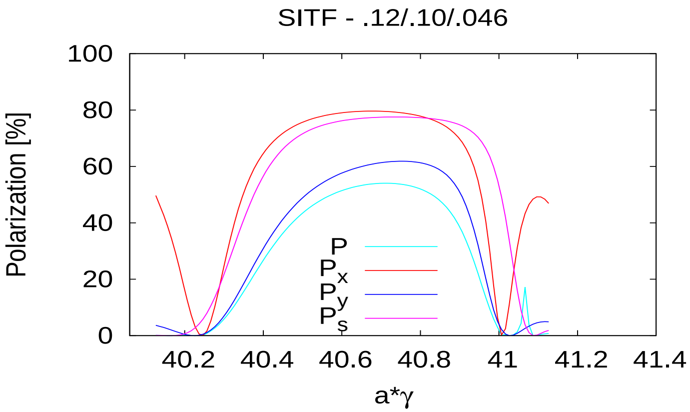


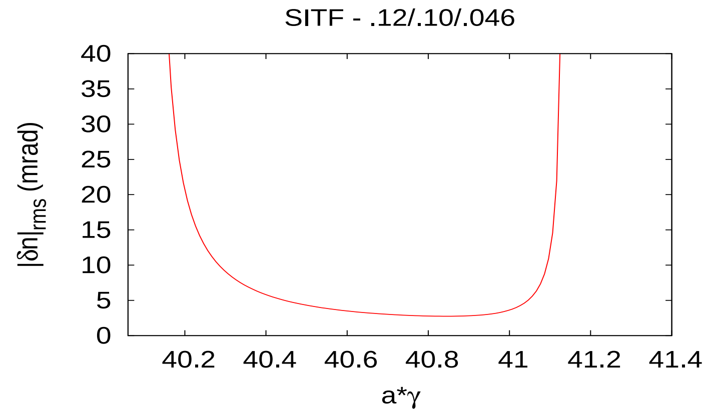
Same error realization, betatron tunes moved to $\boldsymbol{Q_x}$=60.12, $\boldsymbol{Q_y}$=56.10 w/o skew quads, $|C^-|$ ≈0.01.

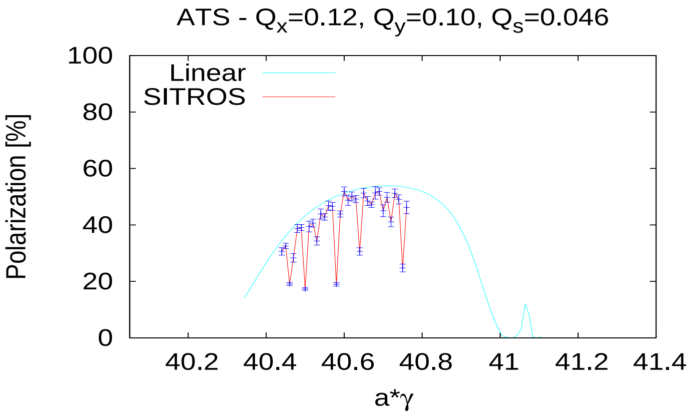




Same error realization, betatron tunes moved to Q_x=60.12, Q_y=56.10 with skew quads, $|C^-| \approx$0.002.



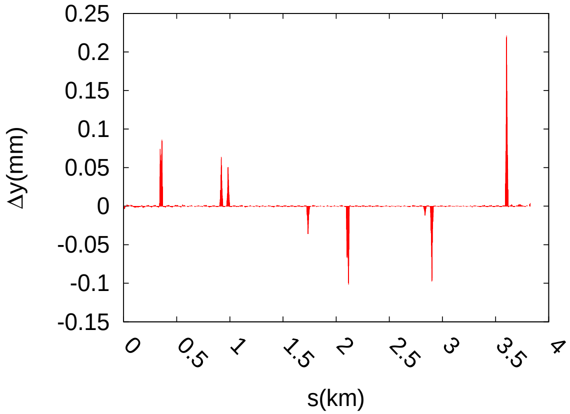


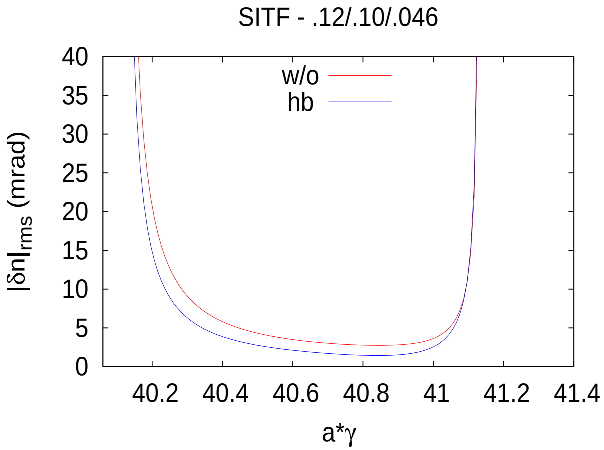


Beam size at IP

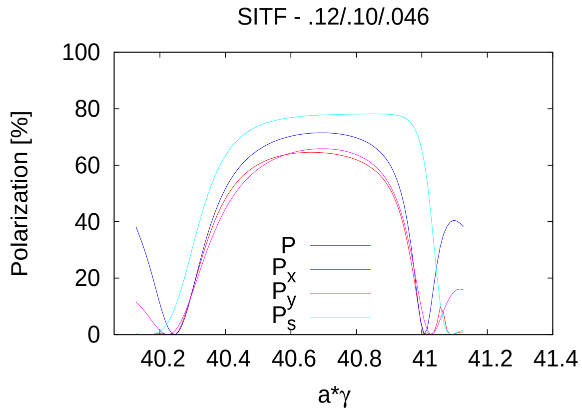
	σ_x [mm]	σ_y [μm]	σ_ℓ [mm]
SITF	0.121	1.718	6.984
SITROS	0.138	3.126	6.969

Adding $\hat{\boldsymbol{n}}_{\mathbf{0}}$ correction by *harmonic bumps*



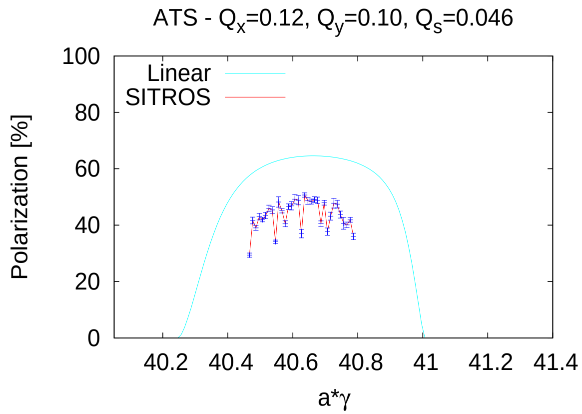


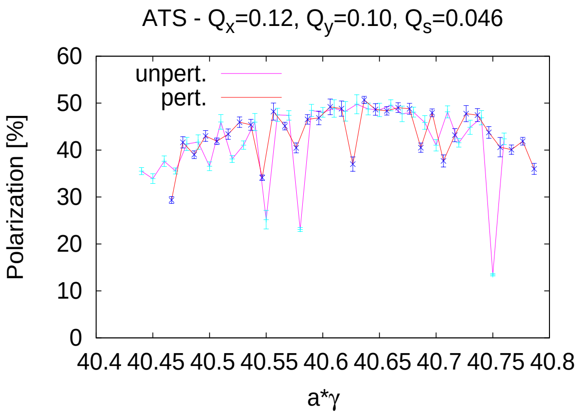
Effect on vertical orbit



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





The level of polarizations is the same as for the *unperturbed* optics.

Summary and Outlook

Polarization studies for the eRHIC storage ring have started.

- 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%.
- BPMs errors need to be included!
- Luminosity working point requires linear coupling correction. Here the benefits of a *local correction* using 46 skew quadrupoles have been shown.
  - the use of correctors for dispersion and of (fewer?) skew quads for betatron coupling correction is an alternative to be tried.
- Comparisons with different codes (Bmad, PTC).
- Beam-beam effects need to be addressed.

Back-up slides

Polarization evolution formulas

The exponential grow

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

follows from the fact that

$$\frac{dn^+}{dt} = n^- w_\mp - n^+ w_\pm \quad \text{and} \quad \frac{dn^-}{dt} = n^+ w_\pm - n^- w_\mp$$

The Derbenev-Kondratenko polarization rate

$$\tau_{\mathrm{DK}}^{-1} = \frac{5\sqrt{3}}{8}\frac{r_e\gamma^5\hbar}{m_0 C}\oint < \frac{1}{|\rho|^3}\Big[1 - \frac{2}{9}(\hat{n}\cdot\hat{v})^2 + \frac{11}{18}\Big(\frac{\partial\hat{n}}{\partial\delta}\Big)^2\Big] >$$

may be written as

$$\tau_{\mathrm{DK}}^{-1} = \tau_p^{-1} \simeq \tau_{\mathrm{BKS}}^{-1} + \tau_d^{-1}$$

with

$$\tau_{\mathrm{BKS}}^{-1} = \frac{5\sqrt{3}}{8}\frac{r_e\gamma^5\hbar}{m_0 C}\oint ds \frac{1}{|\rho|^3}\Big[1 - \frac{2}{9}(\hat{n}_0\cdot\hat{v}_0)^2\Big]$$

and

$$\tau_d^{-1} = \frac{5\sqrt{3}}{8}\frac{r_e\gamma^5\hbar}{m_0 C}\oint ds < \frac{1}{|\rho|^3}\Big[\frac{11}{18}\Big(\frac{\partial\hat{n}}{\partial\delta}\Big)^2\Big] >$$

Similarly for $\boldsymbol{P_\infty}$

$$\vec{P}_{\mathrm{DK}} = \hat{n}_0 \frac{8}{5\sqrt{3}} \frac{\oint ds < \frac{1}{|\rho|^3} \hat{b} \cdot (\hat{n} - \frac{\partial \hat{n}}{\partial \delta}) >}{\oint ds < \frac{1}{|\rho|^3} \left[1 - \frac{2}{9}(\hat{n} \cdot \hat{v})^2 + \frac{11}{18}(\frac{\partial \hat{n}}{\partial \delta})^2\right] >} \qquad \hat{b} \equiv \vec{v} \times \dot{\vec{v}} / |\vec{v} \times \dot{\vec{v}}|$$

$$P_\infty = P_{\mathrm{DK}} \simeq P_{\mathrm{BKS}} \frac{\tau_d}{\tau_{\mathrm{BKS}} + \tau_d} = P_{\mathrm{BKS}} \frac{\tau_p}{\tau_{\mathrm{BKS}}}$$

Approximations done

- $\hat{n} \cdot \hat{v}$ is evaluated on the closed orbit,
- $\hat{b} \cdot \frac{\partial \hat{n}}{\partial \delta}$ has been neglected. In general it is small.