The polarization of the EIC electron beam

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Outline

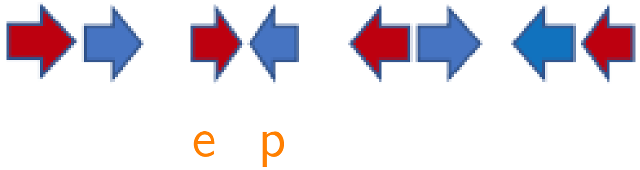
- Introduction
- Assessing needed polarization
- e-beam polarization in the RCS
- Results for the 18 GeV case
- Knobs for increasing $\boldsymbol{\sigma_y^*}$
- Summary

Introduction

The electron-ion collider (EIC) aims to collide polarized electrons with a variety of polarized hadron beams at various CM energies.

Experiments require

- 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



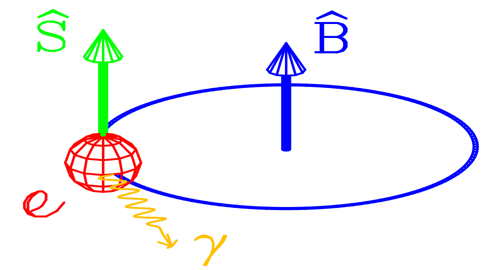
Hadron beams will to large extent exploit the already existing BNL facilities.
A second ring for the e-beam will be accommodate inside the RHIC tunnel.

Radiative polarization

1/2 spin particles in a *constant* and *homogeneous* magnetic field have two stable states:

$$\vec{S} \uparrow\uparrow \vec{B} \quad \text{and} \quad \vec{S} \downarrow\uparrow \vec{B}$$

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

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

- In storage rings lepton beams may become spin polarized through the Sokolov-Ternov effect. Polarization, if any, may build-up only in the direction of $\hat{\boldsymbol{n}}_0$ (periodic solution to Thomas-BMT equation on closed orbit).
  - In a perfectly planar machine w/o solenoids $\hat{\boldsymbol{n}}_0$ is vertical.

In actual rings photon emission leads to a *randomization* of the particle spin direction (spin diffusion) because

- $\hat{\boldsymbol{n}}_0(\boldsymbol{s})$ is not everywhere perfectly vertical
  - by design (spin rotators): can be cured by optics "spin matching";
  - because of magnet misalignments: can be cured by correcting the closed orbit and by "harmonic bumps".
- the beam has finite vertical size: cured by correcting the closed orbit and the betatron coupling.

Derbenev-Kondratenko expression for equilibrium polarization and polarization rate involve averaging across the phase space and along the ring

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

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

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

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

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

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

Distance between *imperfection* (or zeroth) order resonances: ΔE = 440 MeV.

Assessing the needed asymptotic polarization P_∞

Sokolov-Ternov effect tends to polarize the EIC esr e^- upwards.

- A full energy injector is needed for filling the ring with up and down polarized bunches.
- The polarization is turned into the longitudinal direction at the IP by pair of spin rotators.

S-T effect may impact the bunch polarization, especially at high energy.

Polarization builds-up exponentially:

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

From D-K formulas

asymptotic polarization (unknown)

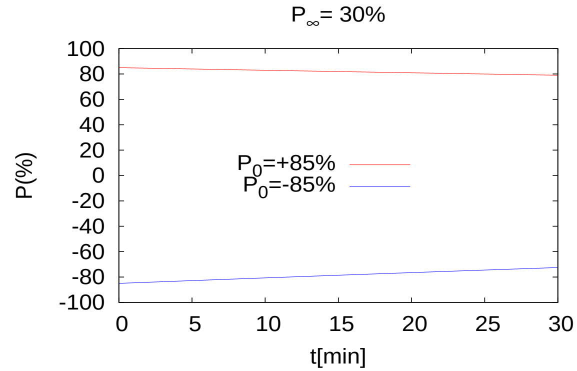
$$\frac{1}{\tau_p} \simeq \frac{1}{\tau_{\mathrm{BKS}}} + \frac{1}{\tau_d} \quad \text{and} \quad P_\infty \simeq \frac{\tau_p}{\tau_{\mathrm{BKS}}} P_{\mathrm{BKS}}$$

diffusion time (unknown)

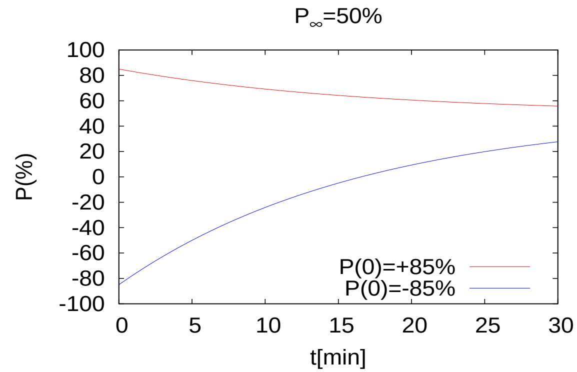
- P_{BKS} and τ_{BKS} (Baier-Katkov-Strakhovenko generalization of Sokolov-Ternov quantities) are known for the *nominal* lattice.
- τ_d and thus P_∞ are interconnected and depend on actual machine.

Some examples (older optics).

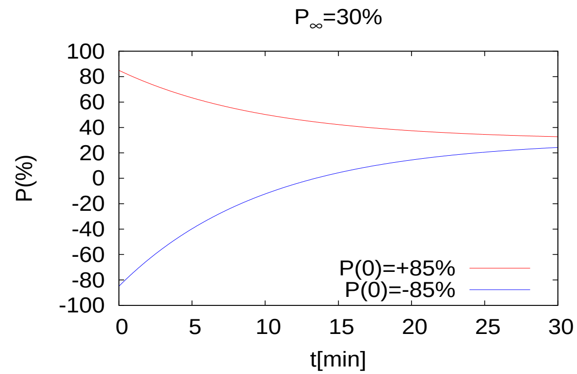
- esr optics at 9.8 GeV (Version-5.3)
  - $P_{\mathrm{BKS}} \simeq 80.8$ %
  - $\tau_{\mathrm{BKS}} \simeq 704$ min



- esr optics at 18 GeV (Version-5.2)
  - $P_{\mathrm{BKS}} \simeq 82.7$ %
  - $\tau_{\mathrm{BKS}} \simeq 35.5$ min



At high energy a small P_∞ means fast depolarization (even for the upward polarized bunches!)



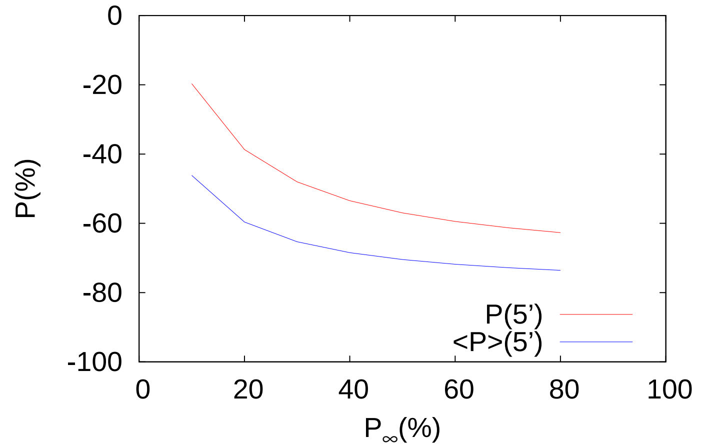
Goal: $<P>_t \gtrsim 70\%$.

10 GeV esr v-5.3

$P(t=0)$	P_∞	$P(t=60')$	$<P>_{60'}$
-85	10	-37.7	-58.7
-85	20	-54.4	-68.9
-85	30	-61.4	-72.8

$P(t=0)$	P_∞	$P(t=40')$	$<P>_{40'}$
-85	10	-50.0	-66.2
-85	20	-63.5	-73.9
-85	30	-68.7	-76.7

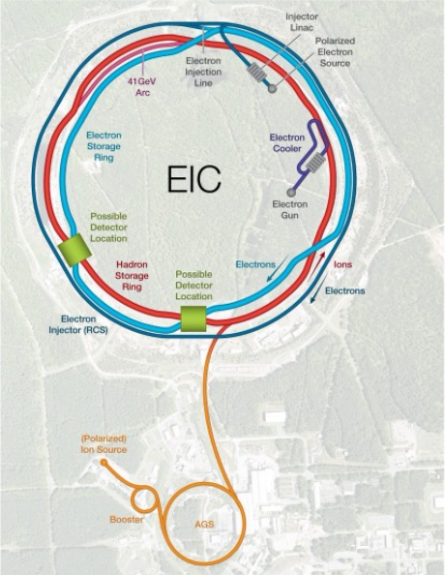
18 GeV esr v-5.2



$P(t=0)$	P_∞	$P(t=5')$	$<P>_{5'}$
-85	40	-53.5	-68.5
-85	45	-55.4	-69.5
-85	50	-57.0	-70.5

Polarization in the RCS

The Rapid Cycling Synchrotron will be hosted in the same RHIC tunnel. Longitudinally polarized bunches are accelerated through the Linac.



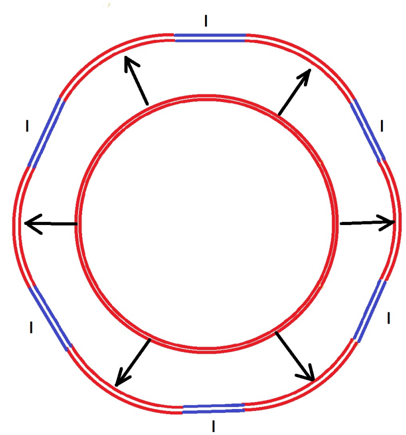
- 4 pairs of 7 nC bunches are provided at 1 Hz repetition rate.
- A dipole-solenoid spin rotator turns the bunch polarization into the vertical direction prior to injection into the RCS.
- In the RCS they are merged in a pair of 28 nC bunches and accelerated each second from 400 MeV to the top energy of 5 and 10 GeV.
  - For acceleration to 18 GeV the pair bunch current is reduced to 11 nC (10 MW radiation budget!).

The expected polarization at injection is ≈90%.

On RCS ramp to 18 GeV, ν_s varies from 1 to 41 and the beam will cross many spin-orbit resonances.

High polarization transmission in the RCS is obtained by

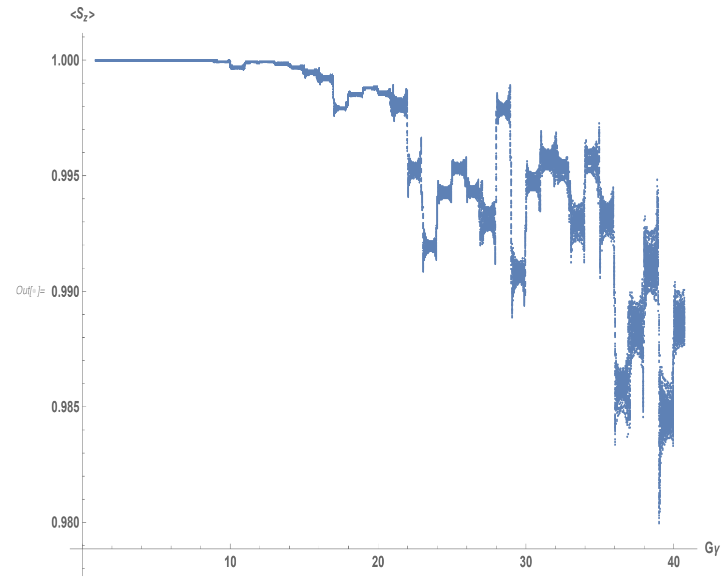
- Fast ramping (up to 0.176 GeV/ms).
- Clever design of the lattice: with a periodicity P=96 and $[Q_y]$=50 the strongest resonances $\nu_s = kP \pm Q_y$ are avoided.
  - Straight sections are needed to match the tunnel hexagon shape and in practice to accommodate injection, extraction and RF.
  - A phase advance of μ_y=$2n\pi$ ensures they do not contribute to the intrinsic spin-orbit resonances.
  - In those straight sections where dipoles had to be introduced for getting around the detectors, optics was optimized for minimizing the intrinsic resonances.



(V. Ranjbar courtesy)

DEPOL calculations and ZGOUBI (by F. Meot) tracking simulations have shown that polarization losses are below 5% for 0.176 GeV/ms ramp if

- Quadrupole vertical misalignment is minimized by compensating the quadrupole kicks by close-by correctors.
- The rms random bending magnet roll errors is kept below a "comfortable" 900 μrad.

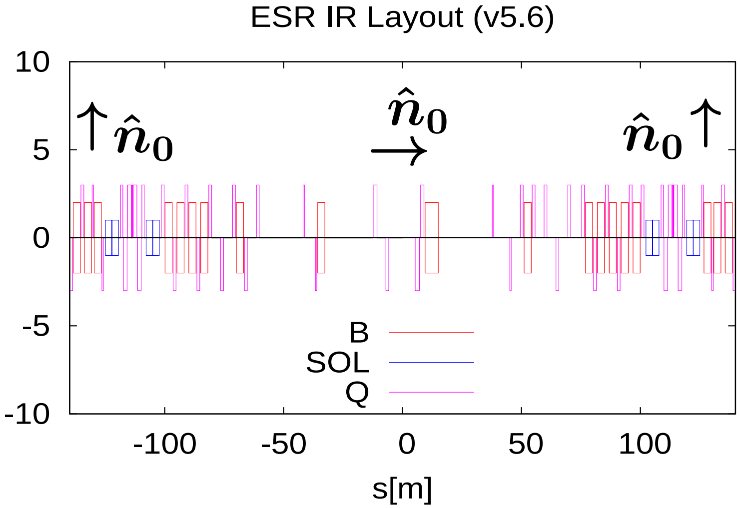


(V. Ranjbar courtesy)

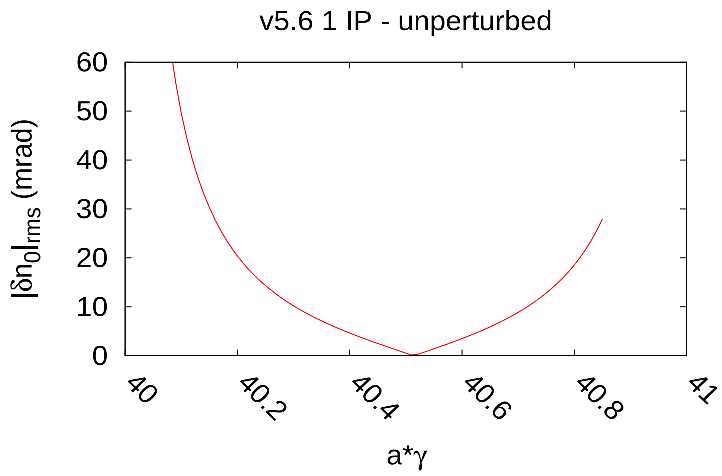
A starting polarization of $\approx \pm$ 85% in the esr is expected.

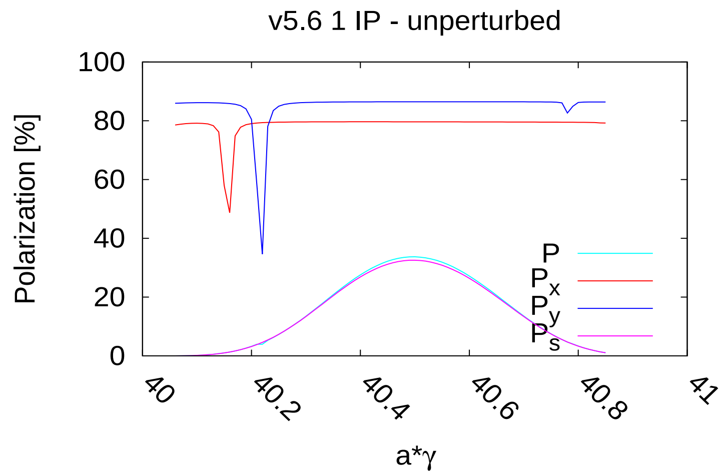
Polarization in the esr

- The emittance ϵ_x=24 nm is obtained by flexible FODO cells phase advance (90^0 at 18 GeV, 60^0 at 10 and 5 GeV) and using reverse bend at 5 GeV.
- One (or two) IP with 25 mrad crossing angle and crab RF cavities.
- A pair of solenoid based rotators left and right of the IP turn the polarization into the longitudinal direction for the experiments.



Linear spin motion approximation (SITF by J. Kewisch)





- The rms $\boldsymbol{\delta\hat{n}_0}$ vs. $\boldsymbol{a\gamma}$ shows that the v5.6 rotator design is "mono-energetic".
- The resulting polarization level is limited by the longitudinal motion (low $\boldsymbol{P_s}$).
  - The optics is not spin-matched for longitudinal motion.
  - It is expected that "large" $\boldsymbol{\delta\hat{n}_0}$ results in spin diffusion for longitudinal motion in the arcs.

Polarization in the ESR in presence of misalignments

Assumed quadrupole RMS misalignments

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

Orbit correction scheme:

- one BPM (dual plane reading) close to each vertical focusing quadrupole;
- one vertical corrector close to each vertically focusing quadrupole;
- one horizontal corrector close to each horizontally focusing quadrupole;

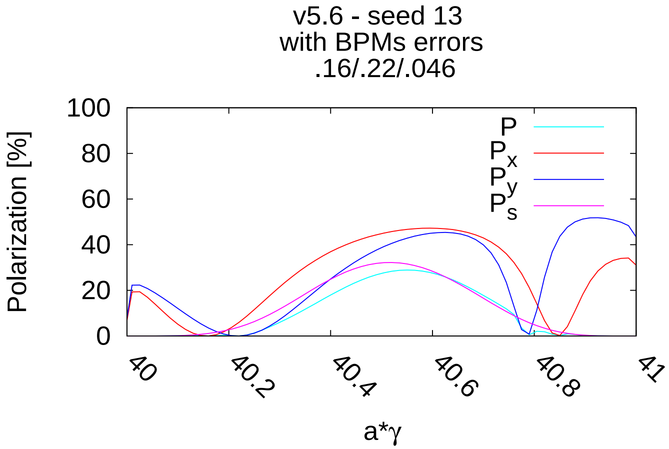
For the IR region (defined as $s < 100$ or $s > 3775$)

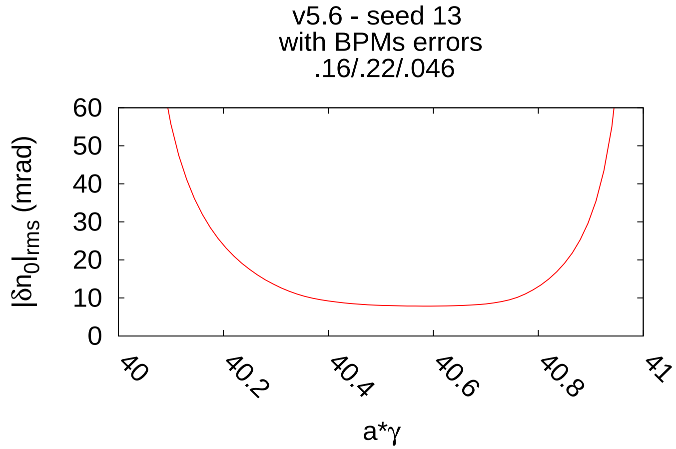
- one BPM (dual plane reading) close to each quadrupole;
- one horizontal and one vertical corrector close to each quadrupole.

All together: 271 CHs, 242 CVs and 242 BPMs.

BPMs are assumed to have the same misalignments of the near-by quadrupole and 1% rms calibration error.

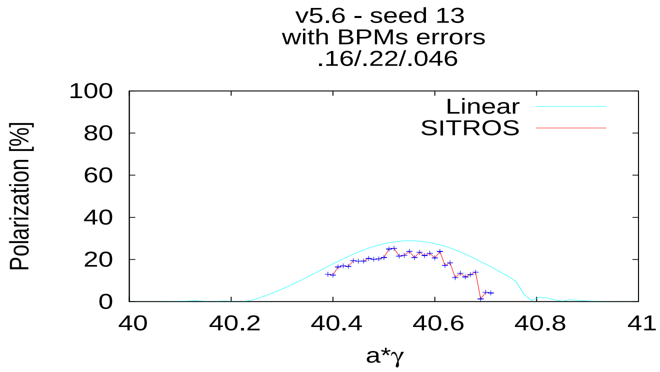
Linear polarization and $\hat{n}_0$ tilt after orbit correction (one particular seed) with x_{rms}=0.39 mm and y_{rms}=0.19 mm (optics v5.6, Q_x=55.16, Q_y=44.22)



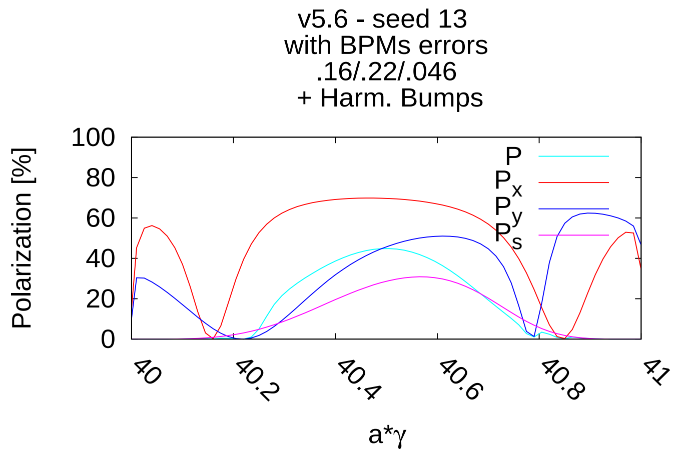


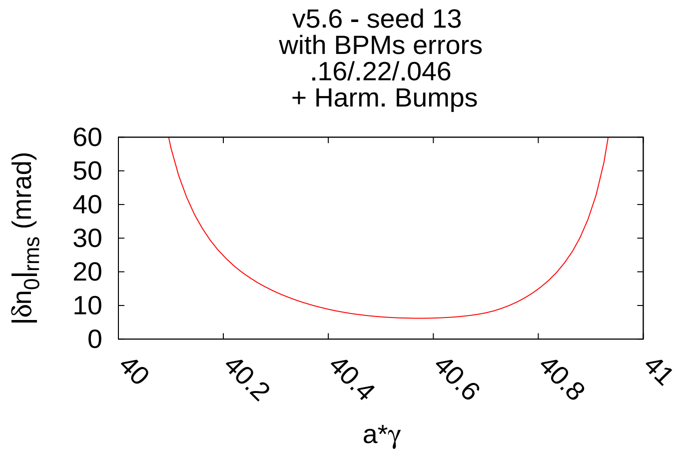
Polarization from fully non-linear spin tracking (SITROS, J. Kewisch)

	σ_x (μm)	σ_y (μm)	σ_ℓ (mm)
Analytic	120.3	4.2	8.450
Tracking	79.4	3.3	8.377

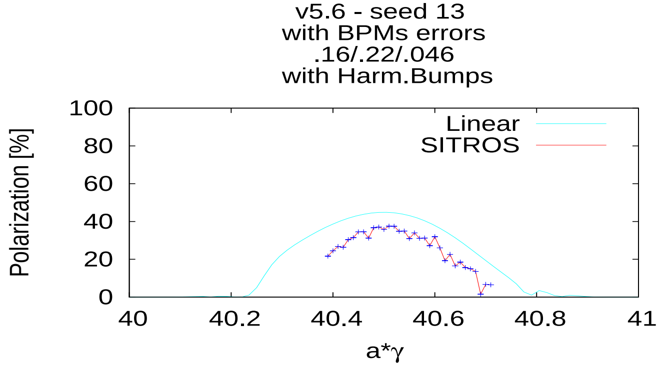


Adding harmonic bumps to minimize $\delta\hat{n}_0$





	σ_x (μm)	σ_y (μm)	σ_ℓ (mm)
Analytic	121.2	3.0	8.444
Tracking	79.8	2.6	8.423



$$\hat{P} \approx 37\%.$$

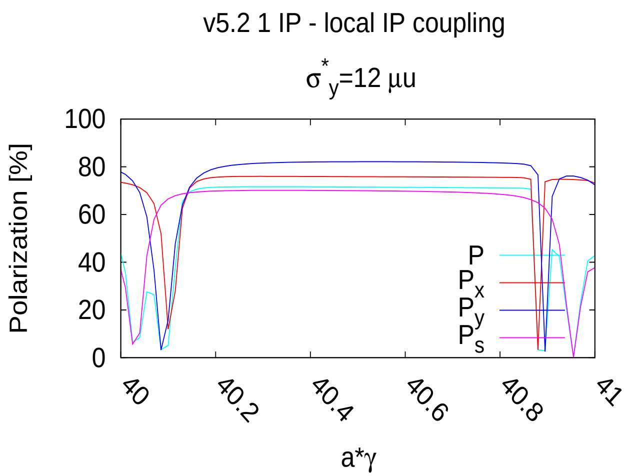
The σ_y^* problem

For reproducing the ideal Sokolov-Ternov conditions for maximum polarization, ϵ_y should be as small as possible.

From beam-beam simulations, supported by HERA experience, the proton and electron beam sizes at the IP must be *matched*: for the 18 GeV case the vertical beam size at the IP should be $\approx 10\ \mu$m.

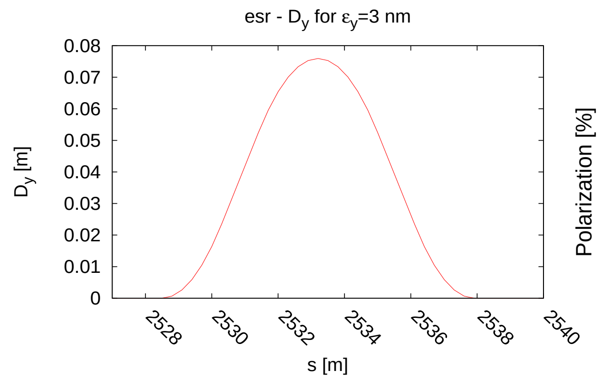
This can be realized by[a]:

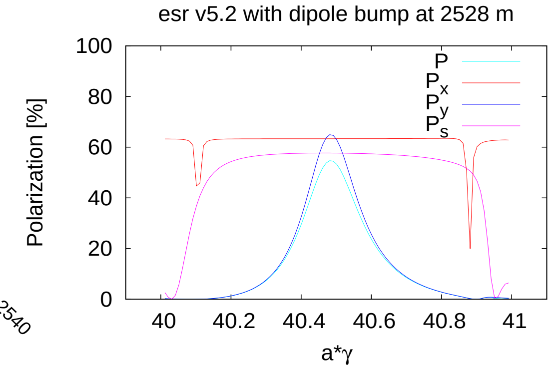
- Local betatron coupling at the IP: good for polarization but simulations indicate beam-beam it is unmanageable.



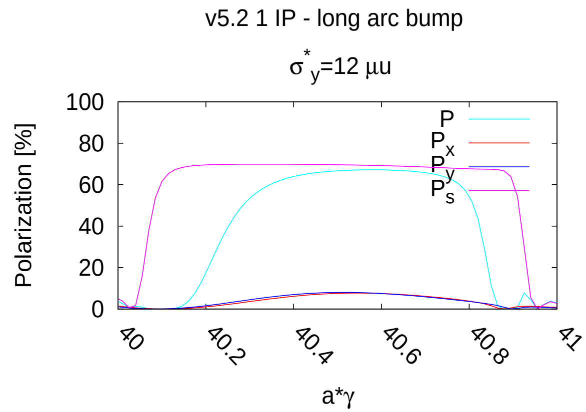
[a] Figures refer to version 5.2 with Q_x=49.12, Q_y=43.10

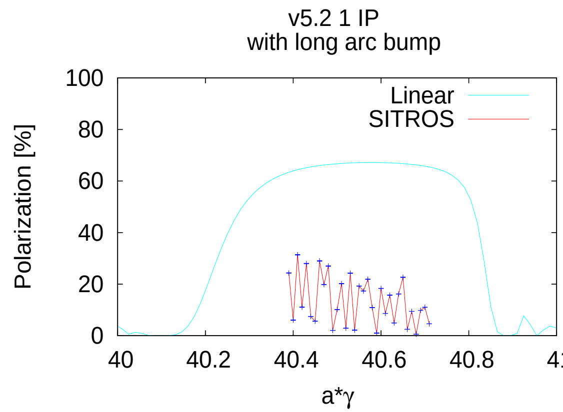
- Introducing a dispersion bump by vertical dipoles in a convenient straight section (possibly a dedicated spin matched one).





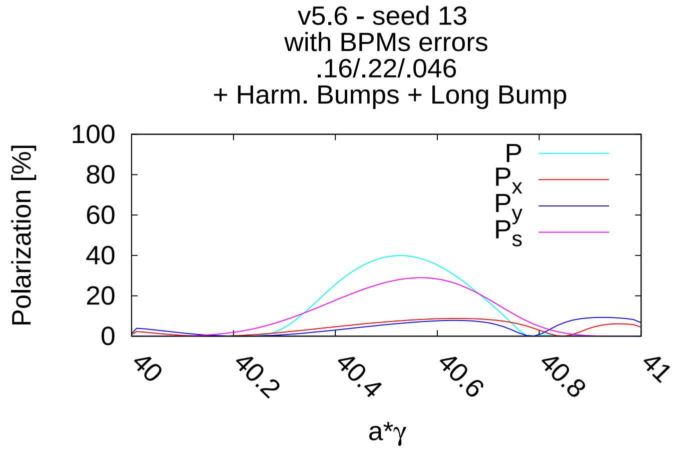
- Exciting a long vertical bump in the ring arcs: the easiest solution, but with largest impact on polarization.

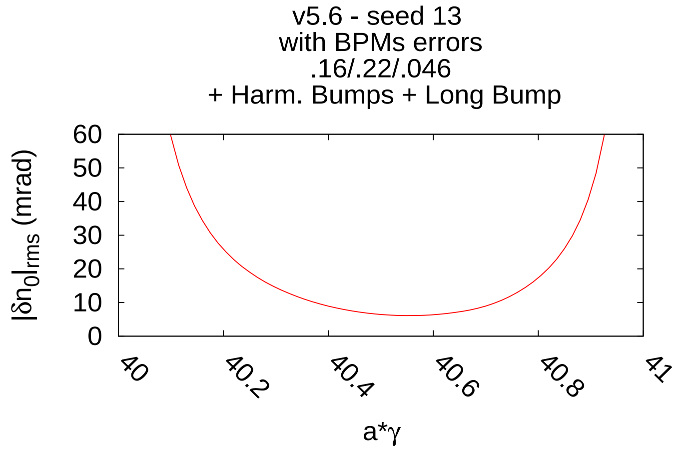




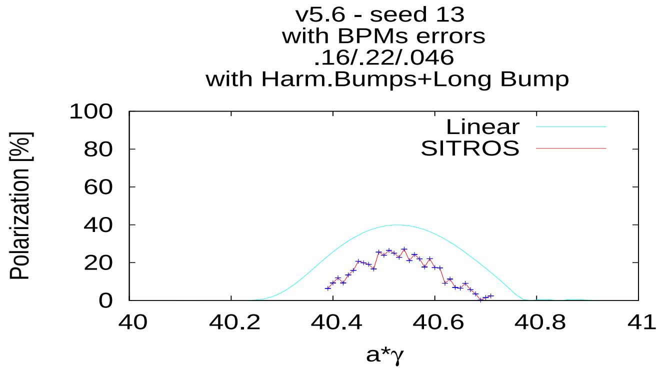
Effect of long bump to v5.6, seed 13

Adding long arc bump CV106-CV126.





	σ_x (μm)	σ_y (μm)	σ_ℓ (mm)
Analytic	111.4	14.8	8.441
Tracking	73.5	10.0	8.421



$$\hat{P} \approx 27\%.$$

Summary and Outlook

Although the polarization for the new optics design is relatively low, even for the unperturbed ring, the goal of $<70>\%$ polarization can be met with the baseline injection rate (2 bunches/s for filling esr with 290 bunches at 18 GeV).

But...

- Larger statistics needed.
- It must be still evaluated the impact on polarization of
  - Dipoles roll;
  - Beam-beam effects.

With $P_\infty \approx 27\%$ the "safety" margin is not very large.

P_∞	$P(0)$	$<P>_{3.4'}$	$P(3.4')$	$P(0)$	$<P>_{7'}$	$P(7')$
+27	-85	-70	-56	+85	+70	+59

However the injection rate may be incremented by a factor 2 if needed.

Thanks!

Acknowledgements

Thanks to R. Vanjbar for his input on the RCS.