Beam polarization in the EIC electron storage ring

Content:

- Introduction
- Assessing needed polarization
- Polarization in presence of misalignments
  - v5.2 and v5.5 optics
- σ_y^* knobs
- Summary

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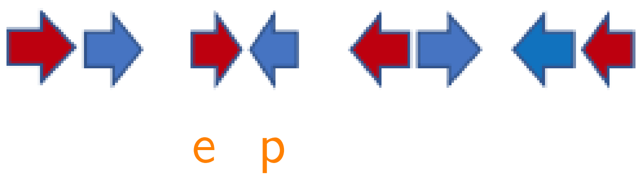
Radiative polarization and the EIC electron storage ring

Experiments require

- Large electron (and proton) polarization
  - $< \boldsymbol{P} >_t \geq 70\%$
- Longitudinal polarization at the IP with *both* helicities within the *same* store
- Energy
  - protons: between 41 and 275 GeV
  - electrons: 5 (or 6), 10 and 18 GeV



While high proton polarization is routinely achieved in RHIC, electron beam polarization is a new field at BNL.

In storage rings lepton beams may become spin polarized through the Sokolov-Ternov effect. In an ideal planar and w/o rotators ring the periodic solution to Thomas-BMT equation, $\hat{\boldsymbol{n}}_{\mathbf{0}}$, is vertical and the polarization builds up in the vertical direction.

- asymptotic polarization: $\boldsymbol{P_\infty}$=92.4%
- polarization build-up rate:

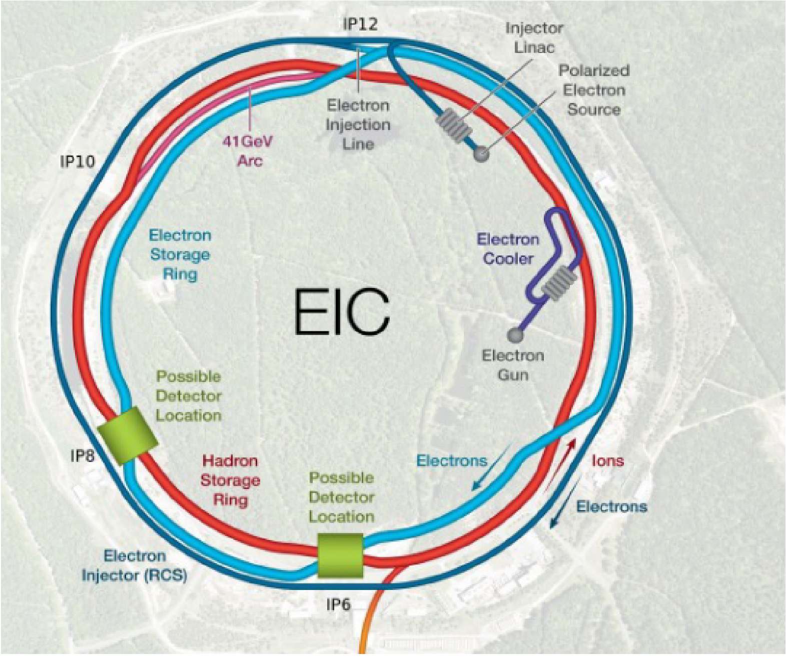
$$\boldsymbol{\tau_p^{-1} = \frac{5\sqrt{3}}{8} \frac{r_e \hbar \gamma^5}{m_0 C} \oint \frac{ds}{|\rho|^3}}$$

In actual rings, $\hat{\boldsymbol{n}}_{\mathbf{0}}(\boldsymbol{s})$ is not perfectly vertical and the beam has finite vertical size: photon emission leads to spin diffusion which lowers $\boldsymbol{P_\infty}$ (and $\boldsymbol{\tau_p}$).

Because experiments call for simultaneous storage of electron bunches with *both* spin helicity, Sokolov-Ternov effect is not an option.

- A full energy polarized electron injector is needed: electron bunches are injected from the RCS into the storage ring with high *vertical* polarization (≈ 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 pair of solenoidal spin rotators left and right of the IP.

Schematic view of the EIC storage rings and RCS



Sokolov-Ternov effect tends to polarize e^- anti-parallel to the bending field, *upwards* for the clockwise rotating electrons.

Assessing the needed asymptotic polarization P_∞

Depending on equilibrium polarization, Sokolov-Ternov effect may have a strong impact on the initial high beam polarization.

Polarization vs. time

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

In presence of depolarizing effects

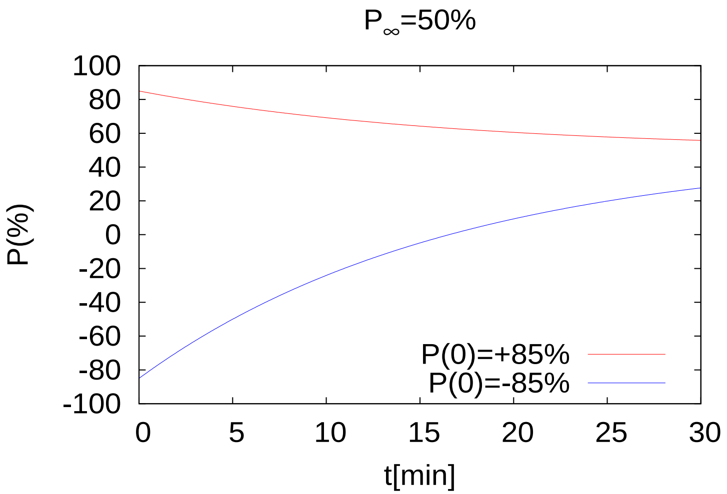
asymptotic polarization (unknown)

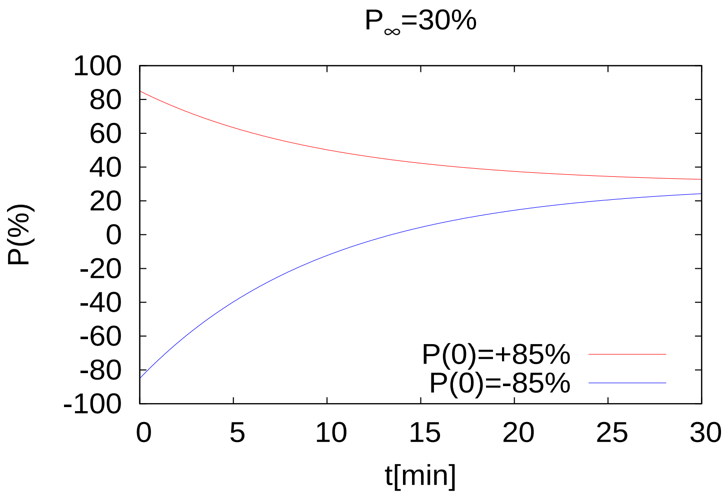
$$\frac{1}{\tau_p} \simeq \frac{1}{\tau_{\mathrm{BKS}}} + \frac{1}{\tau_{\mathrm{d}}} \quad \text{and} \quad P_\infty \simeq \frac{\tau_p}{\tau_{\mathrm{BKS}}} P_{\mathrm{BKS}}$$

diffusion time (unknown)

- P_{BKS} and τ_{BKS} (Baier-Katkov-Strakhovenko generalization of Sokolov-Ternov quantities when $\hat{n}_0$ is not everywhere perpendicular to the velocity) are known for the *nominal* lattice.
- τ_d and P_∞ in the *actual* machine are unknown, but they are related.

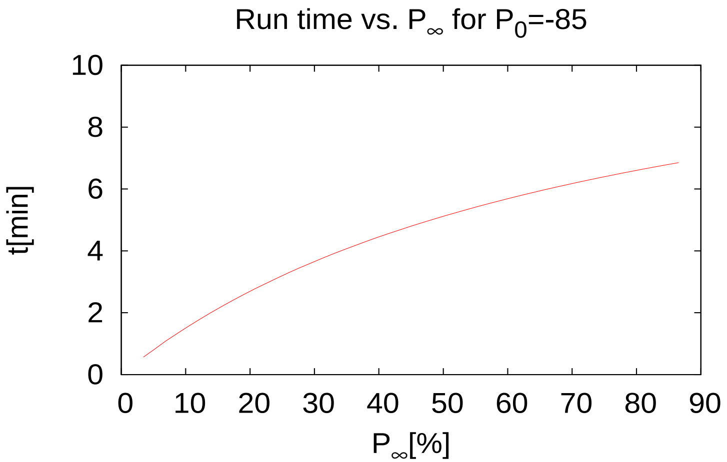
P for bunches polarized parallel or anti-parallel to the bending field

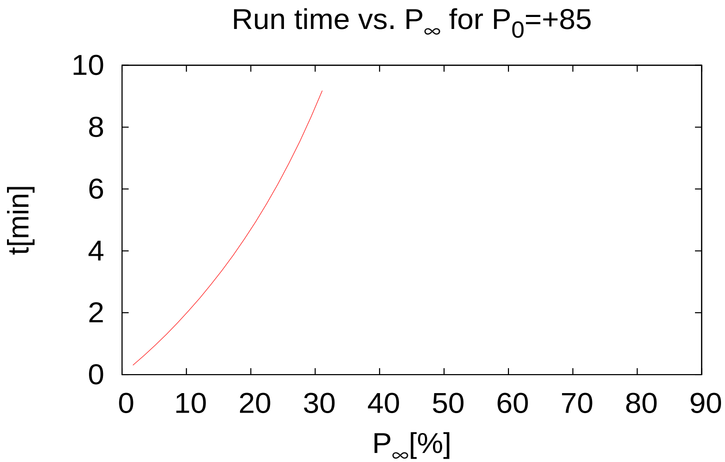




- If P_∞ <85% also the up-polarized bunches will suffer depolarization.
- Lower P_∞, faster the depolarization.

Run time vs. P_∞ for $< P >$=70% for bunches polarized parallel or anti-parallel to the bending field





Computational tools

- MADX for computing the optics and simulate mis-alignments.
- J. Kewisch SITROS (1989) Monte Carlo tracking of particles with stochastic photons emission at user chosen dipoles.
  - It tracks an initially fully polarized beam in the *absence* of polarization build-up. For small t
    $$P(t) \simeq P(0)\mathrm{e}^{-t/\tau_d} = P_{\mathrm{BKS}}\mathrm{e}^{-t/\tau_d}$$
    The TBT average spin projection onto $\hat{n}_0$ is fitted to find τ_d.
    τ_p and P_∞ are evaluated from
    $$\frac{1}{\tau_p} \simeq \frac{1}{\tau_{\mathrm{BKS}}} + \frac{1}{\tau_{\mathrm{d}}} \qquad \text{and} \qquad P_\infty \simeq \frac{\tau_p}{\tau_{\mathrm{BKS}}} P_{\mathrm{BKS}}$$
  - 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.
    - Computation of polarization related to the 3 degree of freedom separately: useful for disentangling problems!

Optics

The electron storage ring (esr) optics is still undergoing some adjustments.
We will consider only the 18 GeV case, the most challenging, and 2 quite different (for polarization) optics:

- esr optics from 2019 (Version-5.2), 1 IP, β_y^*=0.048 m
  - $P_{bks} \simeq$ 82.7 %
  - $\tau_{bks} \simeq$ 35.5 min
- esr optics from 2022 (Version-5.6), 1 IP, β_y^*=0.057 m
  - $P_{bks} \simeq$ 86.5 %
  - $\tau_{bks} \simeq$ 36.8 min

In both cases

- fractional tunes q_x=0.12 and q_y=.10, close to the integer and to the difference linear coupling resonances;
- e-beam vertical size $\sigma_y^* \approx 12\ \mu$m for matching p-beam size.

Machine misalignments

Assumed quadrupole RMS misalignments

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

In order to maximize the asymptotic polarization, the ideal planar ring conditions should be reproduced:

- closed orbit (in particular vertical)
- betatron coupling
- vertical dispersion

must be corrected as well as possible.
In version 5.2 a generous scheme was considered to explore the maximum polarization achievable:

- A BPM (dual plane reading) close to each quadrupole $\longrightarrow$ 546 BPMs;
- Horizontal and vertical correctors close to each quadrupole $\longrightarrow$ 2x546 correctors.

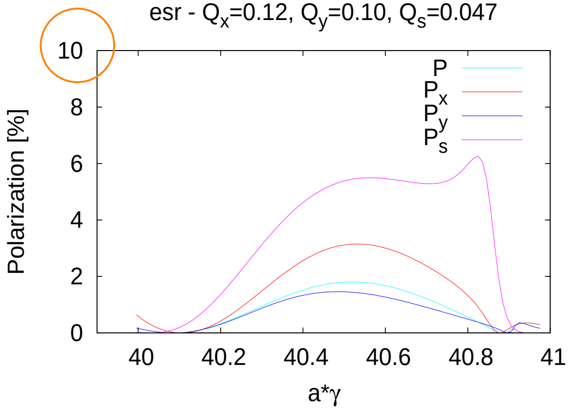
v5.2

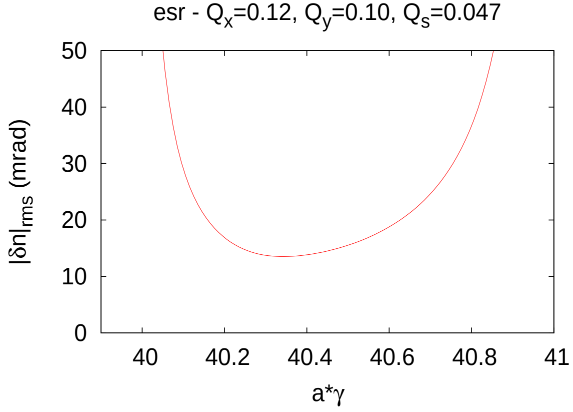
MAD-X failed correcting the orbit for v5.2 due to the coupling in the region between solenoids (36 quads). An "external" SVD used for correcting horizontal and vertical closed orbit simultaneously.

One particular error realization:

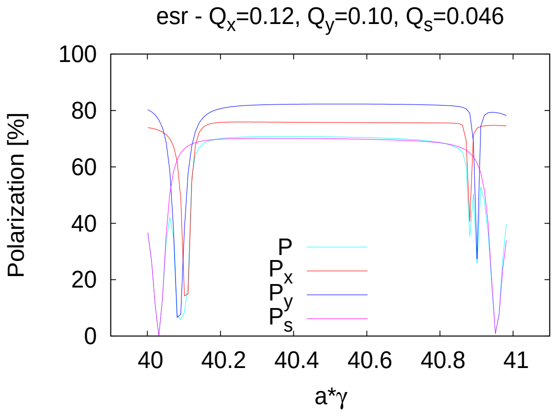
	q_x	q_y	x_{rms} (mm)	y_{rms} (mm)	$D_{y,rms}$ (m)	ϵ_x (μm)	ϵ_y (μm)	$\|C^-\|$
Bare	.3	.2	4.80	11.6	2.057			
SVD	.3	.2	0.25	0.20	0.036	0.0288	0.0003	
	.12	.10	0.35	0.36	0.089	0.025	0.0073	0.014
SITF	.12	.10	0.41	0.38	-	0.024	0.0068	

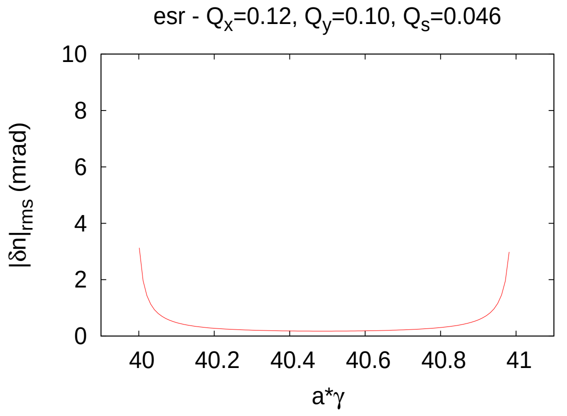
Resulting Polarization.





Unperturbed optics for comparison.

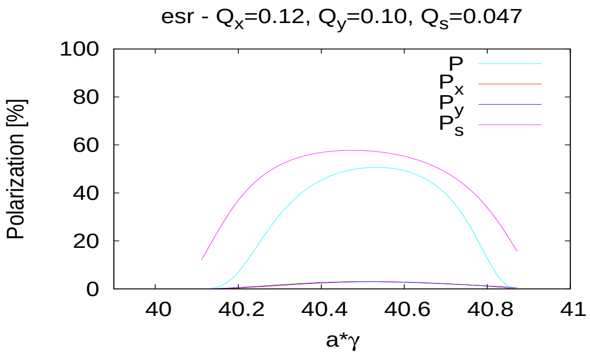


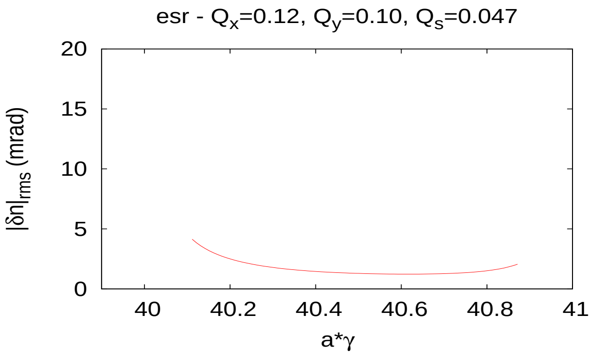


Correcting betatron coupling and $\delta\hat{n}_0$ gave marginal improvement.

Try a more aggressive orbit correction!

	q_x	q_y	x_{rms} (mm)	y_{rms} (mm)	$D_{y,rms}$ (m)	ϵ_x (μm)	ϵ_y (μm)	$\|C^-\|$
1th SVD	.3	.2	0.25	0.20	0.036	0.0288	0.0003	
2d SVD	.3	.2	0.09	0.08	0.024	0.0280	0.0002	
lumi	.12	.10	0.19	0.15	0.044	0.0245	0.0048	
3th SVD	.12	.10	0.05	0.05	0.025	0.0244	0.0053	
+MICADO	.12	.10	0.05	0.04	0.024	0.0245	0.0050	0.017



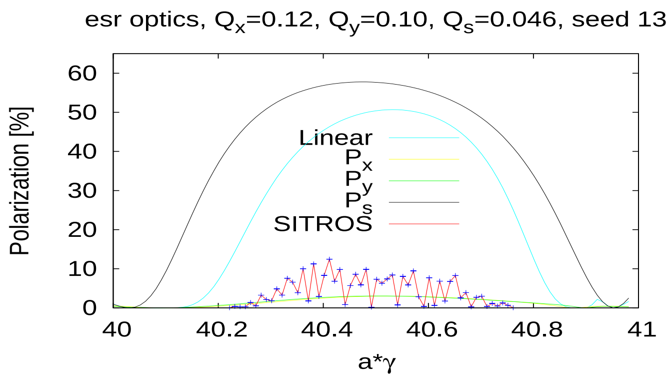


- The aggressive orbit correction led to larger *linear* polarization and smaller $\delta\hat{n}_0$.
- The small P_x and P_y may result in strong higher order resonances.

Polarization from SITROS tracking, *before* betatron coupling correction.

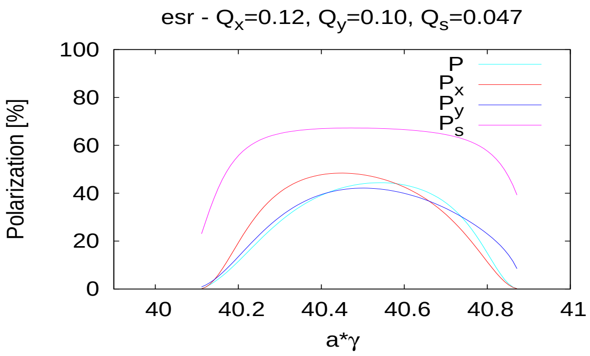
Beam size at IP

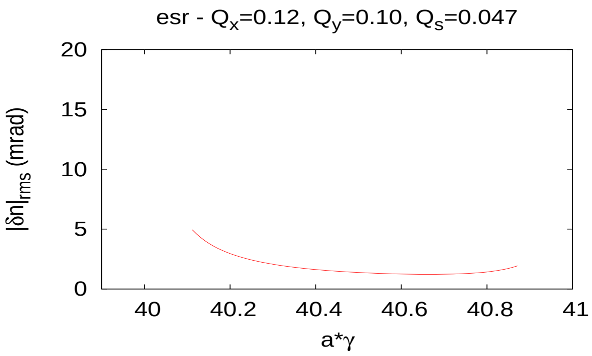
	σ_x (mm)	σ_y (μm)	σ_ℓ (mm)
Analytic	0.096	20.5	8.384
Tracking	0.085	21.3	8.347



- SITROS polarization is larger then $P_{x,y}$, but much smaller than P^{lin}.
- Polarization too small for esr $\longrightarrow$ betatron coupling must be corrected!

After reducing $|C^-|$ from 0.017 to 0.0018:

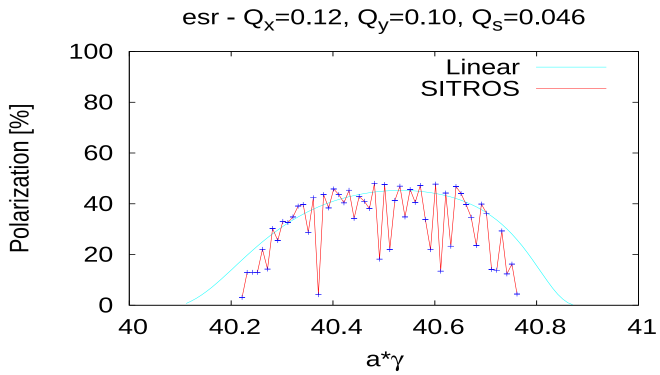




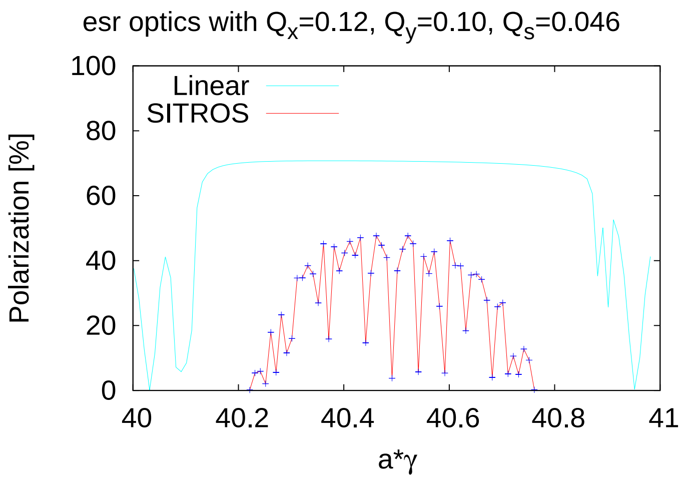
SITROS tracking after coupling correction.

Beam size at IP

	σ_x (mm)	σ_y (μm)	σ_ℓ (mm)
Analytic	0.111	1.758	8.543
Tracking	0.107	2.044	8.357



SITROS tracking for unperturbed v5.2 optics for comparison.



- Aggressive closed orbit and betatron coupling correction restored the 40% polarization level, but σ_y^* is about 6 times too small for matching p-beam.

Matching e^-/p sizes at IP

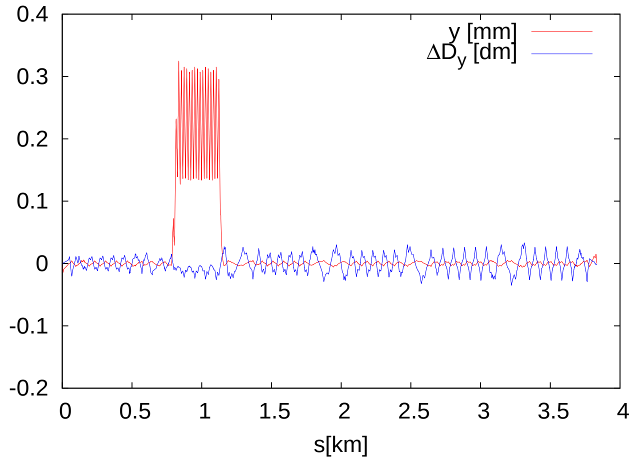
For increasing the beam size at the IP we may try

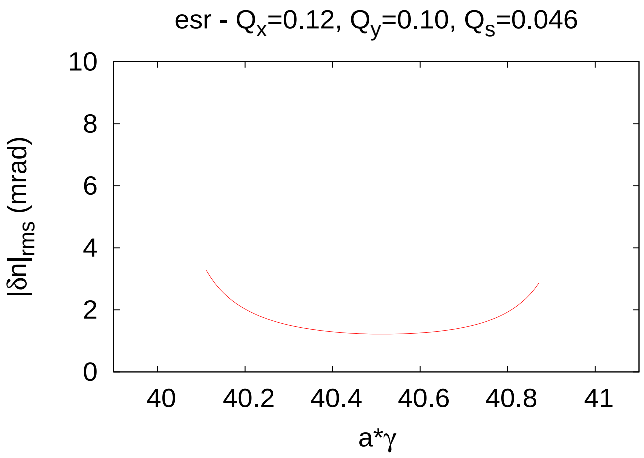
- Increasing vertical emittance by adding
  - a) a long vertical bump trough the arc sextupoles;
  - b) a vertical orbit bump in a straight section without quadrupoles.
- Introducing local coupling at the IP by 2 pairs of skew quads: ruled out by beam-beam simulations.

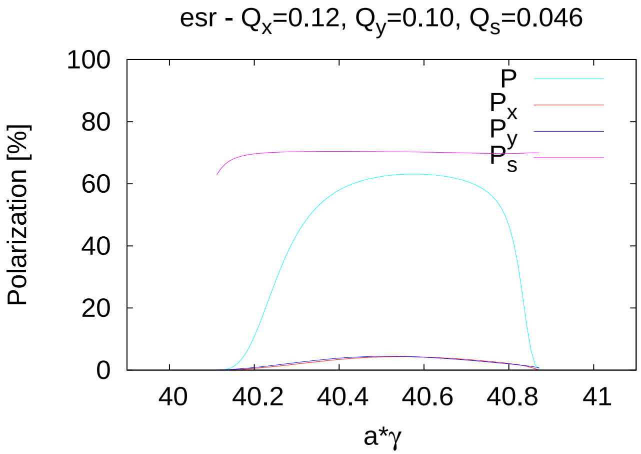
ϵ_y knob

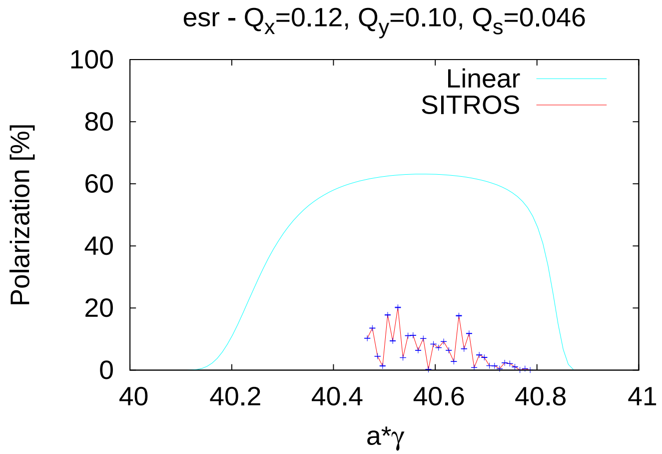
Long bump in arc sextupoles increases ϵ_y through betatron coupling. It is not an option for v5.2.

For ϵ_y= 3 nm (unperturbed machine):





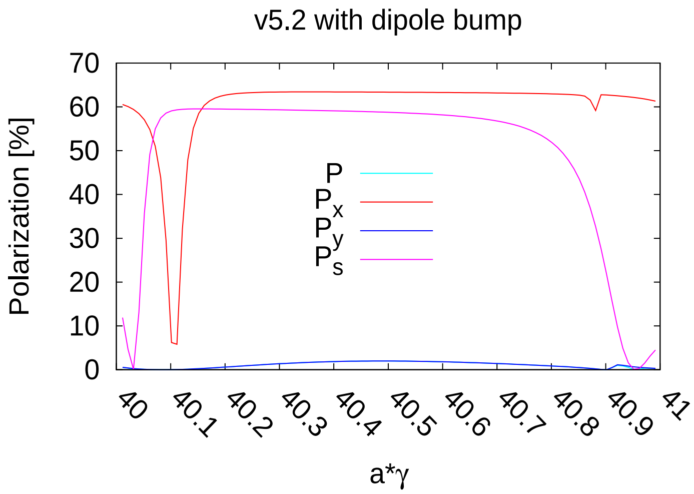




D_y knob

Emittance is generated by the dispersion bump. Found a 16 m long drift for inserting 3 vertical bending magnets.

Polarization with ϵ_y=3 nm

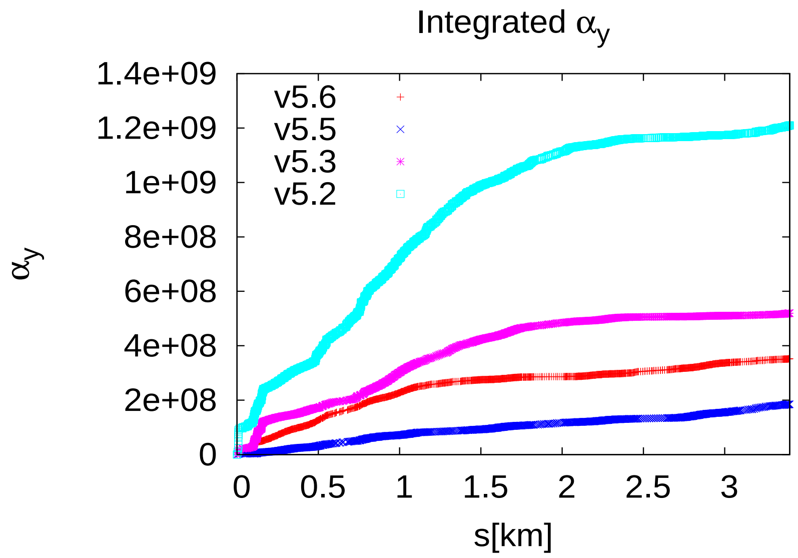


For working, the bump must be *spin matched*!

Instead of changing the optics at that location, we may try finding a better location.

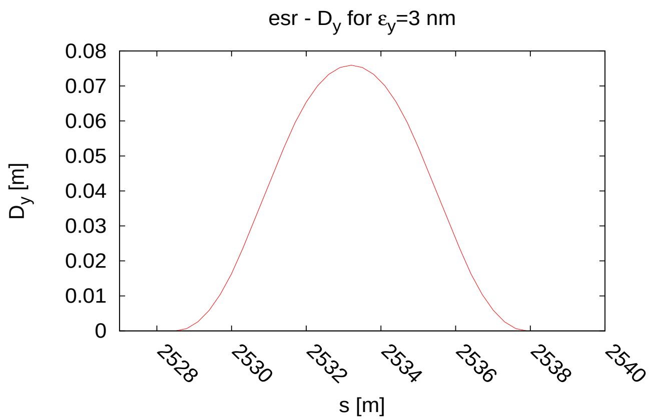
$$\alpha_d \equiv \frac{1}{\tau_d} \propto \oint \frac{ds}{|\rho|^3} \frac{11}{18} \left| \gamma \frac{\partial \hat{n}}{\partial \gamma} \right|^2$$

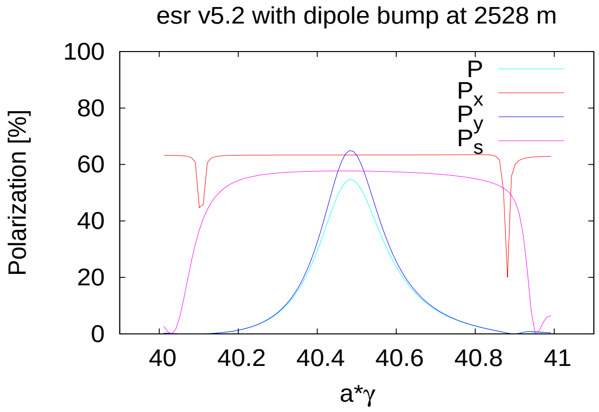
Where $\gamma \frac{\partial \hat{n}}{\partial \gamma} \approx 0$ then $1/\rho$ may become non vanishing w/o contributing to the diffusion rate. Better location at 2528 m.

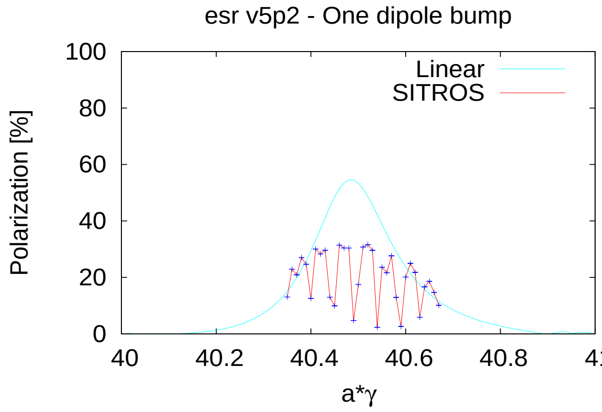


Dispersion

Polarization



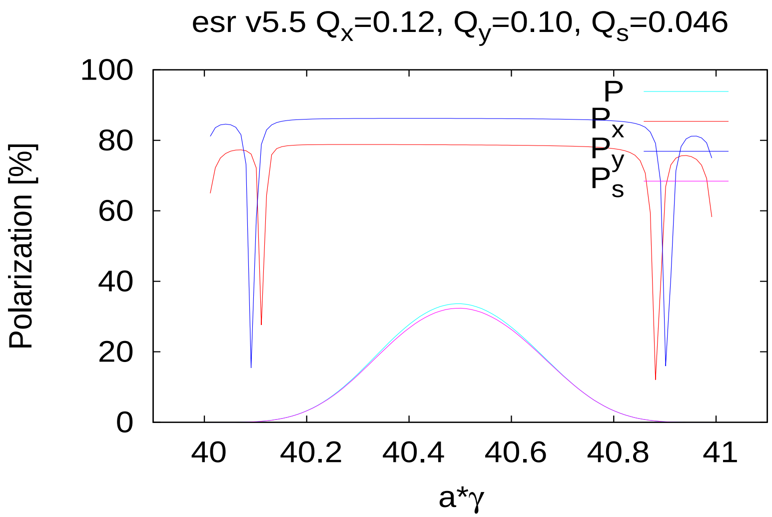


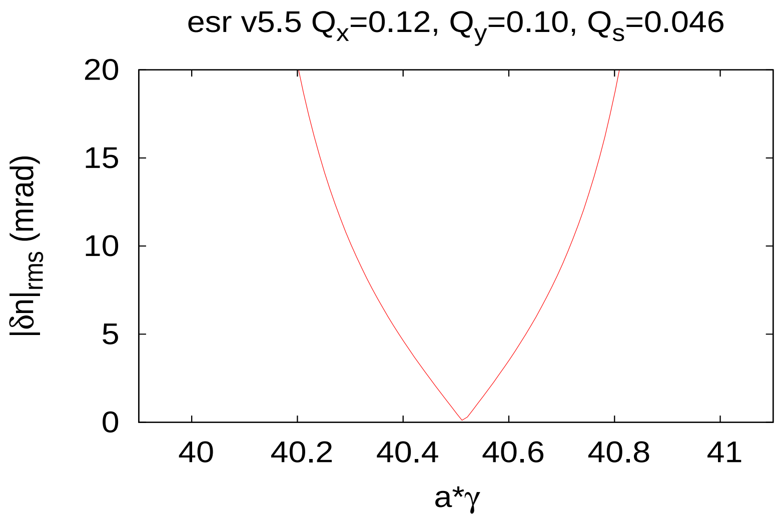


v5.5 Optics

Rotator solenoids scheme changed.

Polarization for the *unperturbed* v5.5 optics.





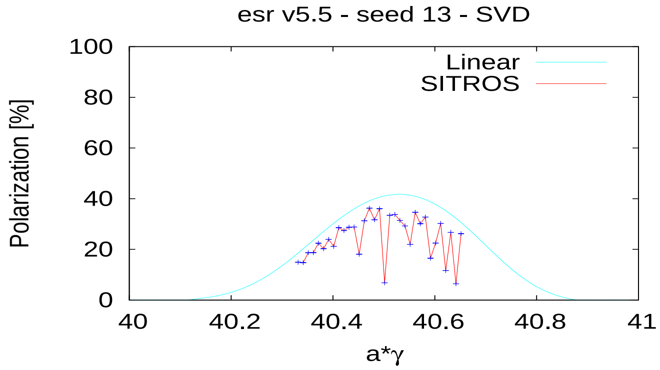
- Large $\boldsymbol{\delta\hat{n}_0}$ limits $\boldsymbol{P_s}$:
  - maximum polarization is 34% even in linear approximation and w/o errors, still sufficient by tailoring the bunch replacement time.

One error realization, same rms misalignments and "generous" correction scheme as for v5.2, but more "relaxed" correction.

	q_x/q_y	x_{rms} [mm]	y_{rms} [mm]	ΔD_x [m]	ΔD_y [m]	ϵ_x [nm]	ϵ_y [nm]	$\lvert C^-\rvert$
bare	.27/.20	6.5	14.8	1.232	2.665			
SVD	.27/.20	0.64	0.49	0.059	0.064			
-	.12/.10	1.42	1.01	0.176	0.237			0.016
+SR	.12/.10	1.44	0.92	0.198	0.215	17.95	101.6	0.016
+MICADO (1+1)	.12/.10	0.30	0.13	0.017	0.038	23.87	3.80	0.013
SITF	.12/.10	0.29	0.13	-	-	22.71	3.74	-

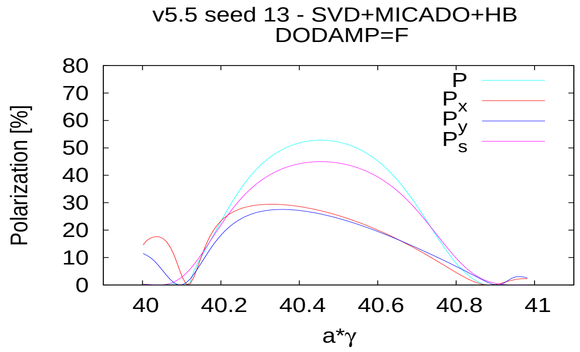
SITROS polarization w/o coupling correction.

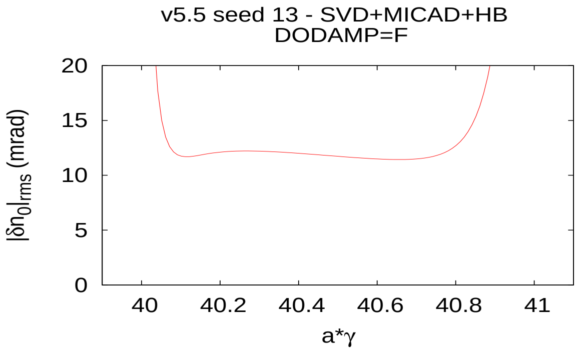
	σ_x (μm)	σ_y (μm)	σ_ℓ (mm)
Analytic	124.05	11.09	8.335
Tracking	89.11	10.25	8.336



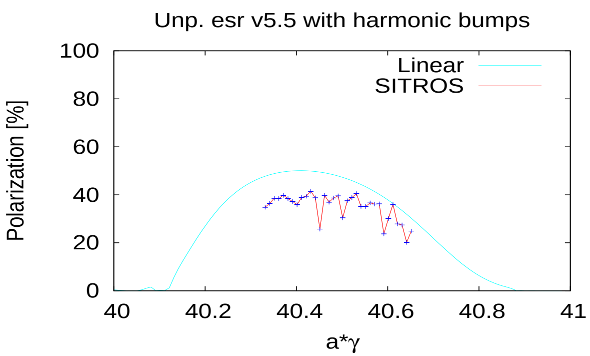
The beam size at IP is almost as required and polarization sufficient.

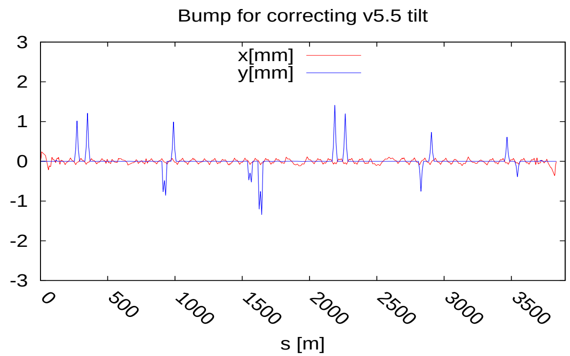
Tried to improve polarization through the harmonic bumps setting $a\gamma$ between 40 and 40.5: $\delta\hat{n}_0$ at 40.5 increased but much more flat $\delta\hat{n}_0(a\gamma)$ and polarization improved wrt the unperturbed case!





The harmonic bumps can be used for improving the v5.5 polarization!





Summary

- Differences of the sensitivity to errors for different optics. It can be explained by the different $\gamma\frac{\partial \hat{n}}{\partial \gamma}$.
- With the current rotator scheme the unperturbed polarization is much lower but the machine being less sensitive to errors it does not need a pushed correction procedure.
  - Closed orbit of $\approx 100\ \mu$m is fine.
  - Coupling correction may be not crucial to reach 35% polarization.
  - Currently a less generous correction scheme (as in HERAe) considered for the machine arcs
    - 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;

    $\longrightarrow$ All together: 271 CHs, 242 CVs and 242 BPMs. It seems sufficient!
  - $\boldsymbol{\sigma}_y^*$ knobs may be not needed.

THANKS!