e^- Polarization in EIC electron storage ring

Content:

- Assessing needed polarization
- Results for the unperturbed optics
- Results for the perturbed optics
- knobs for increasing $\boldsymbol{\sigma_y^*}$

Eliana GIANFELICE

First Meeting on the Science and Instrumentation of the Second Interaction Region for the EIC

March 18, 2021

Assessing the needed asymptotic polarization P_∞

Sokolov-Ternov effect tends to polarize e^- anti-parallel to the bending field, ie upwards in EIC electron storage ring. The impact on downwards polarized bunches may be significant at high energy.

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

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) are known for the *nominal* lattice.
- τ_d and thus P_∞ depend on actual machine.

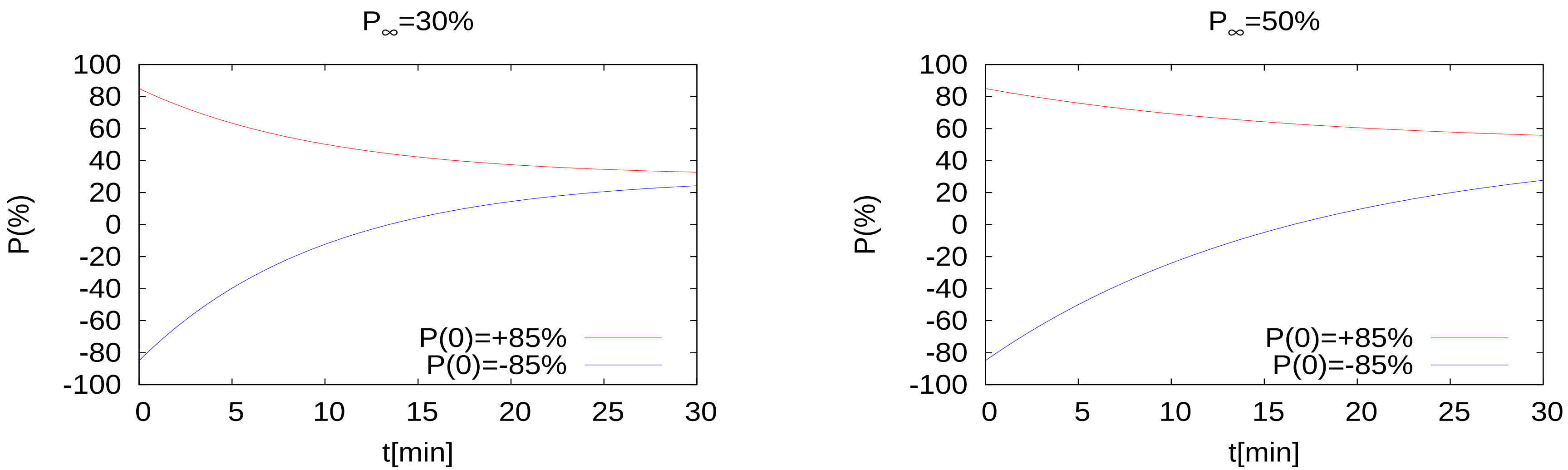
Once we fix a value for P_∞, also τ_p is fixed.

Optics

- esr optics, 10 GeV (Version-5.3)
  - $P_{bks} \simeq 80.8$ %
  - $\tau_{bks} \simeq 704$ min

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

18 GeV

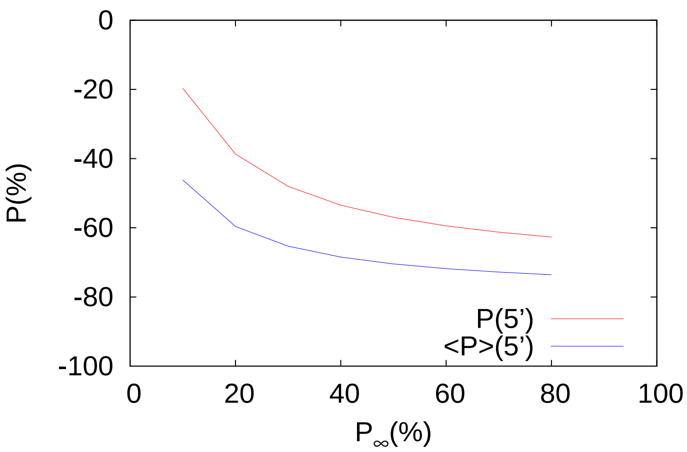


10 GeV esr v-5.3

$P(t=0)$	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



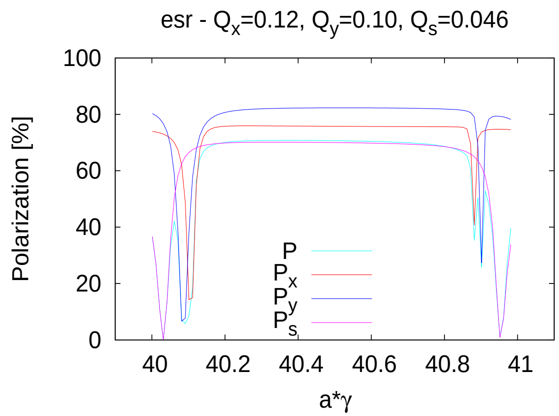
$P(t=0)$	P_∞	$P(t=5')$	$< P >_{5'}$
-85	40	-53.5	-68.5
-85	45	-55.4	-69.5
-85	50	-57.0	-70.5

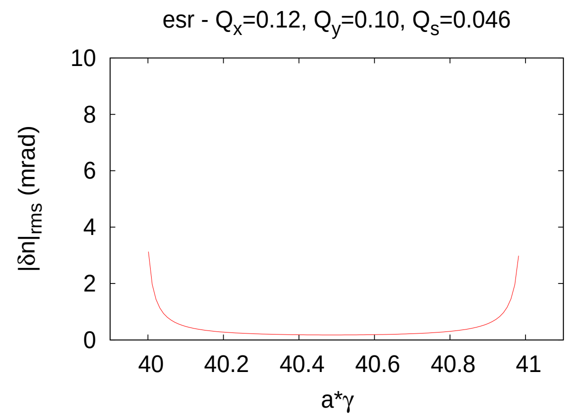
Computational tools

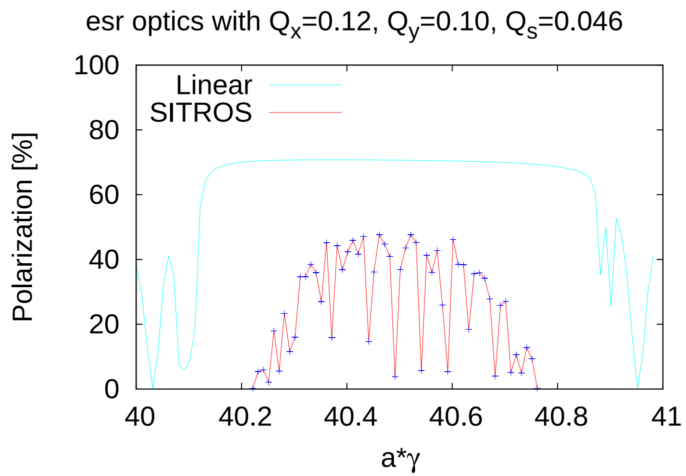
- MADX for computing the optics and simulate mis-alignments.
- SITF (part of SITROS package) for computing polarization in linear spin motion approximation (as SLIM, but it digests thick lenses).
- SITROS Monte Carlo tracking of particles with photons emitted at user chosen dipoles
  - first w/o spins for finding equilibrium
  - thus with spins parallel to $\hat{\boldsymbol{n}}_0$. 2th order orbit description and fully non-linear spin motion.
    - The diffusion time τ_d is evaluated after some thousands turns and P_∞ evaluated from

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

Results for the unperturbed machine: 18 GeV





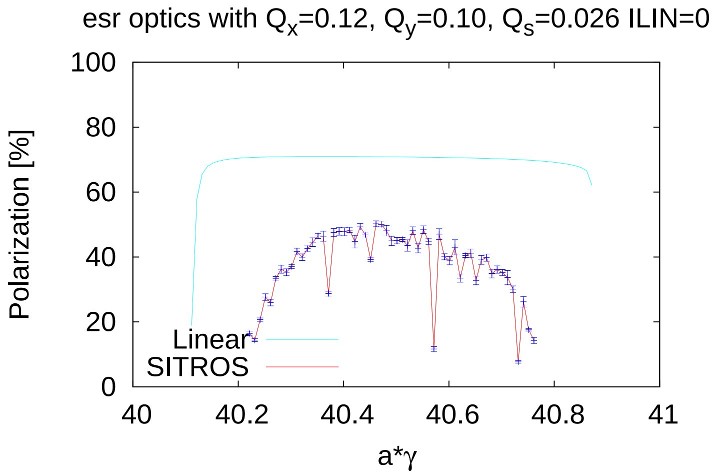


Beam size at IP

	σ_x [mm]	σ_y [μm]	σ_ℓ [mm]
Analytic (SITF)	0.110	0.268	8.649
Tracking (SITROS)	0.074	2.1	8.72

Distance between resonances is ≈ 0.046.

esr optics v5.2 with $\boldsymbol{Q_s}$=0.026



Beam size at IP

	$\boldsymbol{\sigma_x}$ (mm)	$\boldsymbol{\sigma_y}$ ($\boldsymbol{\mu}$m)	$\boldsymbol{\sigma_\ell}$ (mm)
Analytic (SITF)	0.109	0.235	15.307
Tracking (SITROS)	0.164	0.575	15.328

Machine with misalignments

Challenges set by the beam-beam simulations:

- low fractional tunes: .12/.10;
- working point close to linear coupling resonance;
- large vertical beam size at IP:
  - $\boldsymbol{\sigma_y^*} \approx 12\ \boldsymbol{\mu}$m at 18 GeV, ie $\boldsymbol{\epsilon_y} \approx 3$ nm for $\boldsymbol{\beta}^*$=0.048 m.

Correction description

- 546 BPMs (h+v) added close to each quadrupole.
- 2x546 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.

Strategy

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

Assumed quadrupole RMS misalignments

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

Due to coupling, separate horizontal and vertical correction as done in MADX is inadequate in the rotator sections (38 quads)
→ "external" program used for correcting horizontal and vertical orbits (and dispersion if needed) simultaneously.

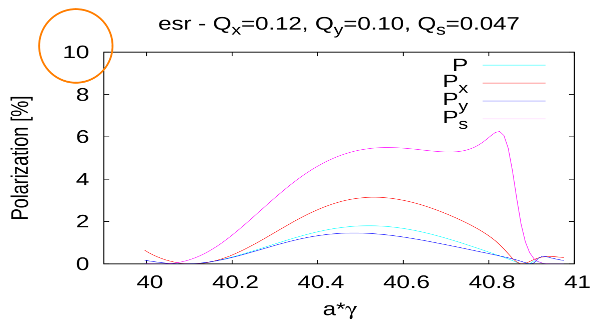
One particular error realization:

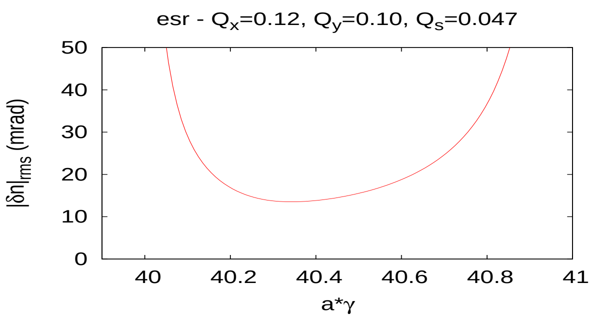
Tunes: .3/.2 — Sextupoles: off

	x_{rms} (mm)	y_{rms} (mm)	$D_{y,rms}$ (m)
errors	4.80	11.6	2.057
SVD	0.25	0.20	0.074

Sextupoles on

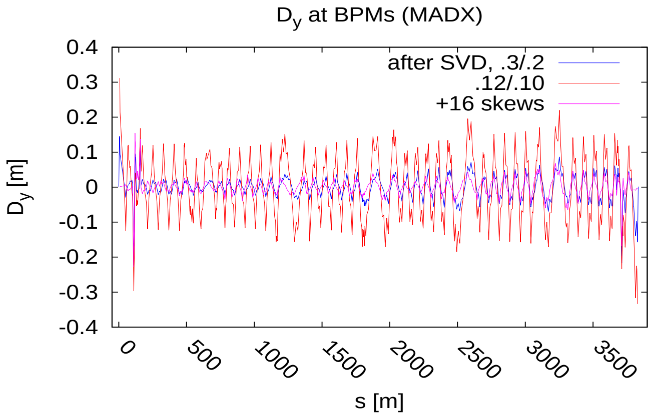
q_x	q_y	x_{rms} (mm)	y_{rms} (mm)	$D_{y,rms}$ (m)	ϵ_x (μm)	ϵ_y (μm)
.3	.2	0.25	0.20	0.036	0.0288	0.0003
.12	.10	0.35	0.36	0.089	0.02529	0.0073



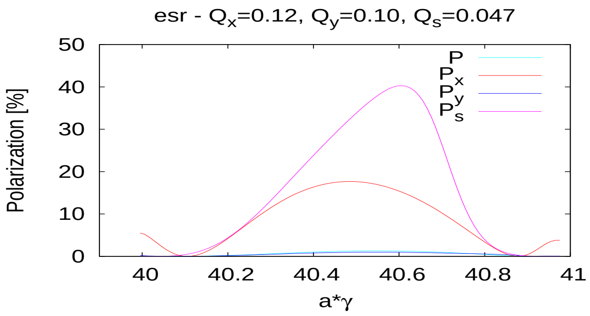


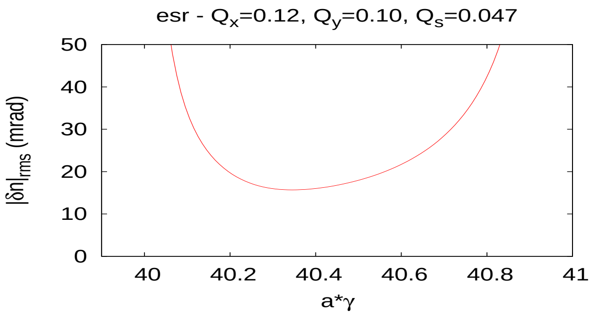
Coupling and spurious vertical dispersion correction with 16 skew quadrupoles.

Minimum tune distance reduced from 0.014 to 0.002.



	x_{rms} (mm)	y_{rms} (mm)	$D_{y,rms}$ (m)	ϵ_x (μm)	ϵ_y (μm)
MADX	0.33	0.39	0.030	0.0293	0.0008





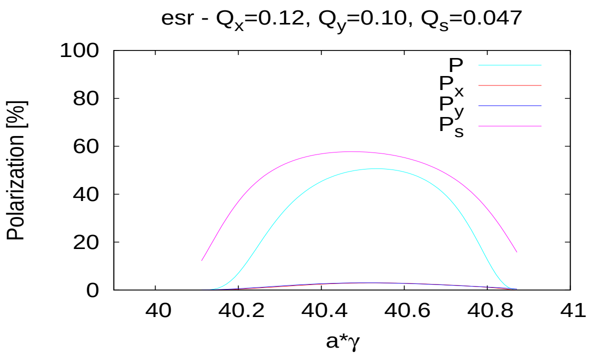
$\longrightarrow$ Still no polarization!

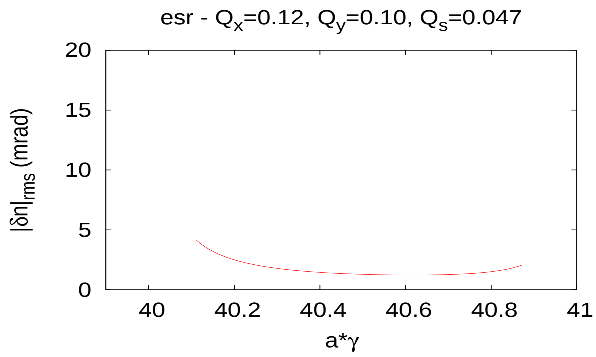
Try a more aggressive closed orbit correction!

	q_x	q_y	x_{rms} (mm)	y_{rms} (mm)	$D_{y,rms}$ (m)	ϵ_x (μm)	ϵ_y (μm)
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 tunes	.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

Resulting betatron coupling: 0.015. $\uparrow$

With no coupling correction large ϵ_y just by setting tunes close to the linear coupling resonance.



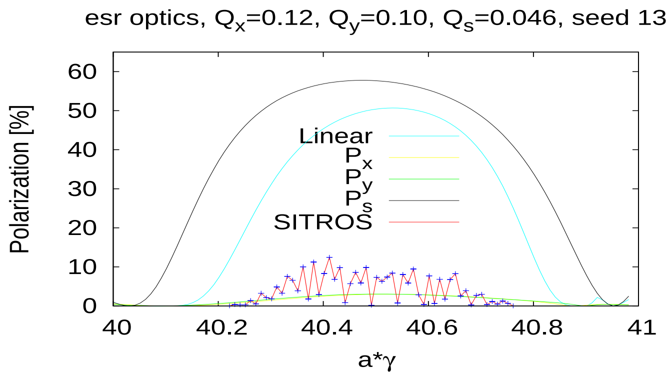


The aggressive orbit correction resulted in a smaller $\delta\hat{n}_0$ and larger polarization. However the low P_x and P_y are worrisome.

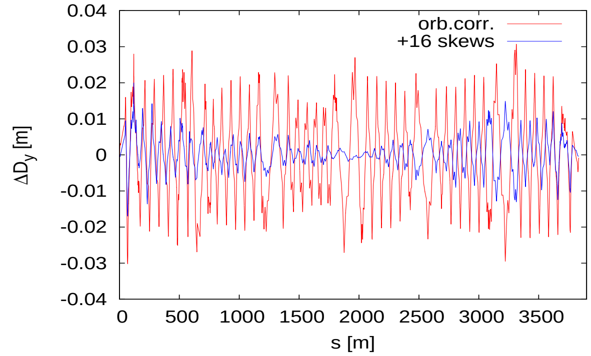
Polarization from SITROS tracking, *before* betatron coupling correction.

Beam size at IP

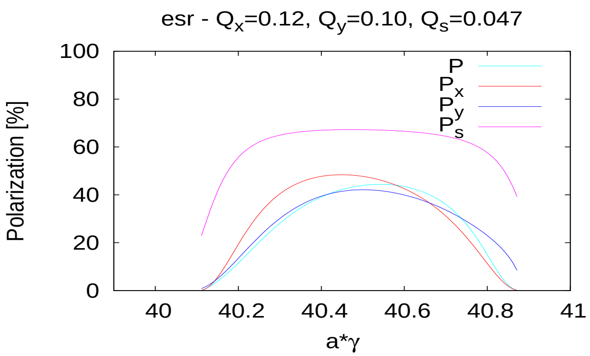
	σ_x (mm)	σ_y (μm)	σ_ℓ (mm)
Analytic	0.096	20.5	8.384
Tracking	0.085	21.3	8.347

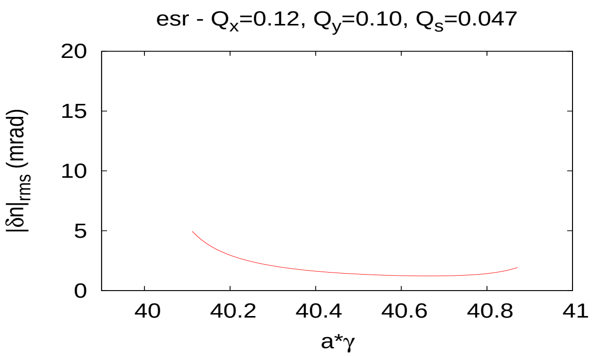


Polarization is larger then $P_{x,y}$, but still small $\rightarrow$ betatron coupling must be corrected!
16 skew quadrupoles used for correcting ΔD_y (from 12 mm rms to 4.5 mm) and betatron coupling (from 0.017 to 0.0018).



After skew quads optimization and $\delta\hat{n}_0$ correction:



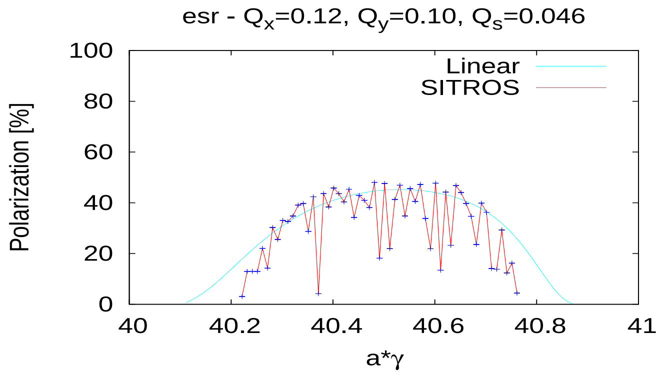


P_x and P_y greatly increased.

Non linear polarization calculation.

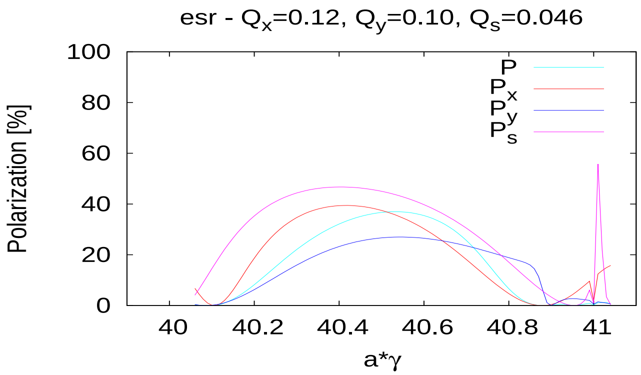
Beam size at IP

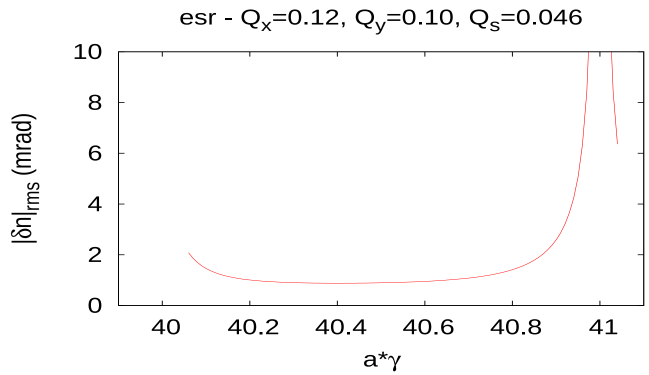
	σ_x (mm)	σ_y (μm)	σ_ℓ (mm)
Analytic	0.111	1.758	8.543
Tracking	0.107	2.044	8.357



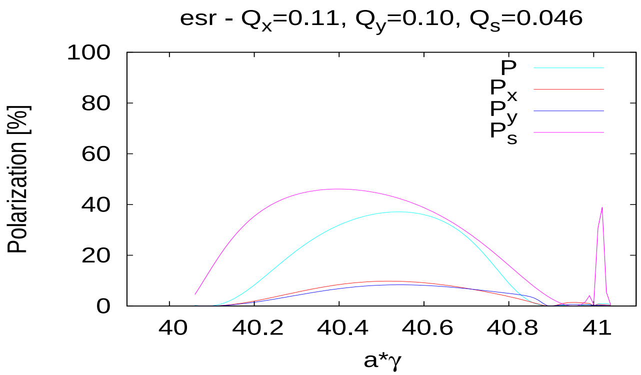
Polarization over 40%, but σ_y is now too small for matching p-beam vertical size.

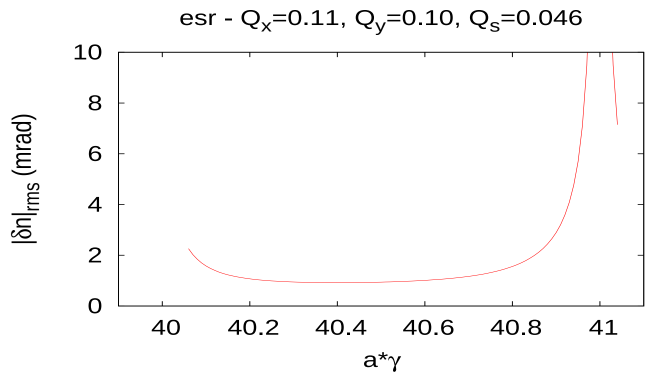
Try a different scheme by using only 2 skew quadrupoles at $D_x \approx 0$ for correcting *only* betatron coupling. Resulting ϵ_y=0.2 nm. $D_{y,rms}$=0.025 m (almost unchanged). Minimum tune distance: 0.008.

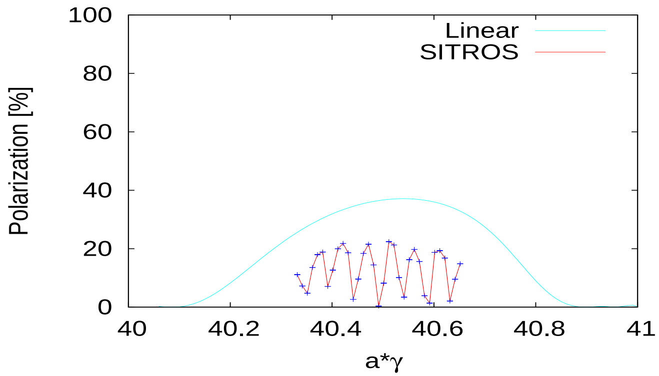




Move tunes much closer for increasing ϵ_y to 1 nm.







Beam size at IP

	σ_x (mm)	σ_y (μm)	σ_ℓ (mm)
Analytic	0.108	9.53	8.483
Tracking	0.087	6.93	8.617

With only 2 quadrupoles global betatron coupling may be corrected, however polarization is low.

Conclusion to get large polarization:

- $\boldsymbol{\Delta D_y}$ must be corrected as well as possible.
- Linear betatron coupling correction is needed.

We are left with the problem of increasing $\boldsymbol{\sigma_y^*}$ w/o destroying polarization.

Linear approximation for spin diffusion (uncoupled motion):

$$\frac{\partial \hat{n}}{\partial \delta}(\vec{u};s) = \vec{d}(s) = \frac{1}{2}\Im\Big\{(\hat{m}_0 + i\hat{l}_0)^* \sum_{k=\pm x,\pm y,\pm s} \Delta_k\Big\}$$

spin basis vectors
in h-plane outside rotators

For synchrotron motion:

$$\Delta_{\pm s}(s) = (1 + a\gamma)\frac{e^{\mp i\mu_s}}{e^{2i\pi(\nu \pm Q_s)} - 1}\; J_s$$

quad strength

$$J_s(s) = \int_s^{s+L} ds'(\hat{m}_0 + i\hat{l}_0)\cdot(\hat{y}D_x + \hat{x}D_y)\, K$$

$\rightarrow$ $\boldsymbol{D_y} \neq 0$ at quadrupole locations is bad!

For vertical betatron motion:

$$\boldsymbol{\Delta}_{\pm y}(s) = (1 + a\gamma)\frac{e^{\mp i\mu_y}}{e^{2i\pi(\nu \pm Q_y)} - 1}\frac{[-D_y \pm i(\alpha_y D_y + \beta_y D'_y)]}{\sqrt{\beta_y}}(s)\;\; J_{\pm y}$$

with

$$J_{\pm y}(s) = \int_s^{s+L} ds'(\hat{m}_0 + i\hat{l}_0)\cdot\hat{x}\sqrt{\beta_y}\, K e^{\pm i\mu_y}$$

$\rightarrow$ $D_y \neq 0$ at location where $J_{\pm y} \neq 0$ (everywhere!) is bad too!

Matching e^-/p sizes at IP

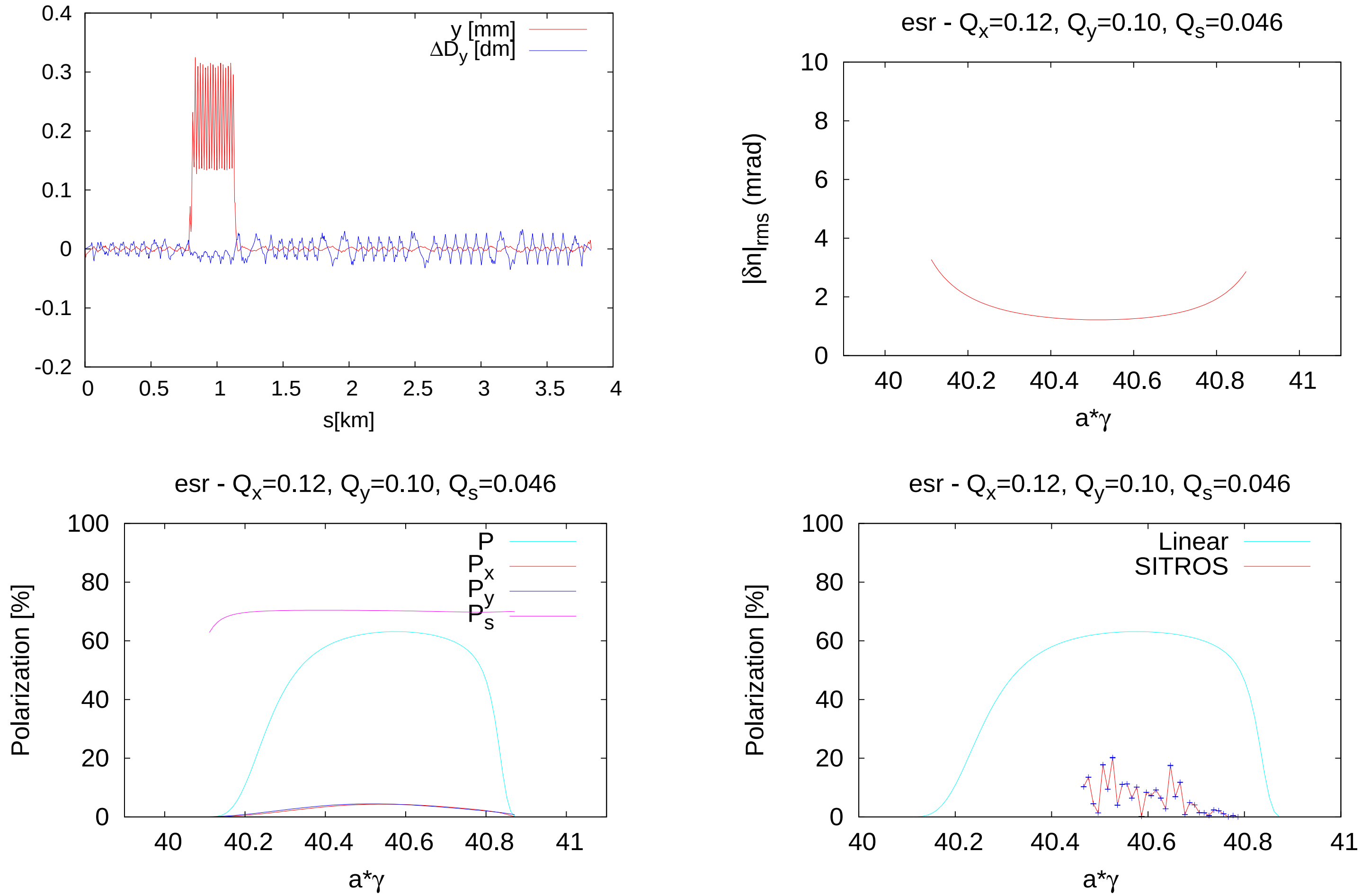
For increasing the beam size at the IP we may try

- adding a long vertical bump trough the arc sextupoles;
- a bump in a straight section without quadrupoles;
- 2 pairs of skew quads around the IP (and variations on the theme).

ϵ_y knob

Long bump in arc sextupoles increases ϵ_y through betatron coupling.

For ϵ_y= 3 nm (unperturbed machine):

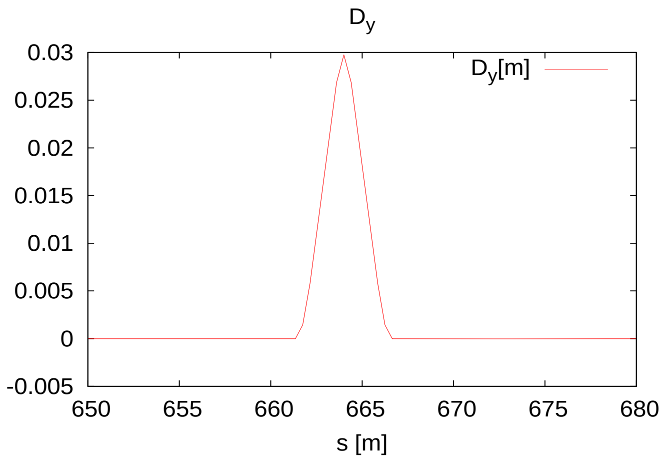


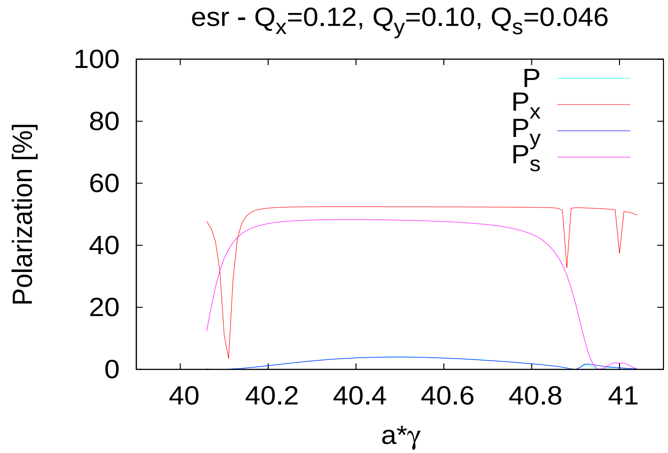
SITROS polarization is larger than P_x and P_y, but still too small.

ϵ_y knob (cont.)

We may try a closed vertical bump with dipoles in a straight section without quadrupoles. They could be located at the crossing points with the p-ring.

3 vertical bending magnets inserted between db2er_8 (653 m) and hq3er_8 (672 m). With 14.5 mrad bending angle at the first dipole it is ϵ_y=2.9 nm (MADX), 1.3 nm (SITF).





- P_{BKS} ≈55.6%: could be improved by
  - using longer dipoles,
  - shaping the optics to get same emittance with weaker fields.
- Polarization is limited by vertical betatron motion. It could be improved by *spin matching*, ie by designing the optics so that $J_{\pm y}(s)$=0 where $D_y \neq$0.

$\boldsymbol{\sigma_y^*}$ knob

The e^- beam $\boldsymbol{\sigma_y^*}$ may be *locally* increased by "borrowing" some horizontal emittance by introducing local coupling at the IP

$$\boldsymbol{y_{rms} = \sqrt{\epsilon_I \beta_{yI} + \epsilon_{II} \beta_{yII}}}$$

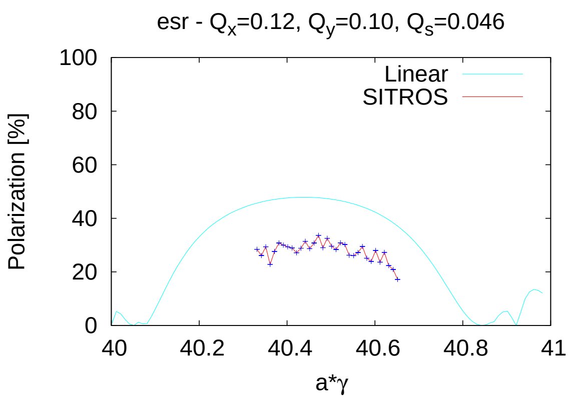
from coupling

- For a goal $\boldsymbol{\epsilon_y}$=3 nm and $\boldsymbol{\beta_y^*}$=0.05 m $\longrightarrow$ wished $\boldsymbol{\sigma_y^*}$ is $\approx$12 $\boldsymbol{\mu}$m.
- With $\boldsymbol{\beta_x^*}$=0.4 m and $\boldsymbol{\epsilon_x}$=0.028 $\boldsymbol{\mu}$m, it must be $\boldsymbol{\beta_{yI}^*}$=0.005 m.

It may be achieved by using 2 pairs of skew quadrupoles around the IP so to keep the rest of the machine uncoupled.

The idea has been refined and integrated into the experiment solenoid compensation scheme by Vasiliy Morozov who added additional constraints (beam ellipse tilt, phases advances etc.).

Unperturbed optics v5.3 with experiment solenoid compensation and $\boldsymbol{\sigma}_{\boldsymbol{y}}^{*}$ knob.



	$\boldsymbol{\sigma_x}$ (mm)	$\boldsymbol{\sigma_y}$ (μm)	$\boldsymbol{\sigma_\ell}$ (mm)
Analytic (SITF)	0.107	10.6	8.728
Tracking (SITROS)	0.087	9.9	8.508

Beam-beam studies are going-on with different $\boldsymbol{e^-}$ working points and $\boldsymbol{\sigma}_{\boldsymbol{y}}^{*}$ values.
The problem of the $\boldsymbol{e^-/p}$ beam size matching is still unsolved!

Summary

- In presence of (conservative) errors, polarization of $\approx$ 40%-45% seems achievable.
  - Orbit, spurious vertical dispersion and betatron coupling must be very carefully corrected, which leads to a small vertical beam size at the IP (some tens of pm).
- Matching the p vertical beam size:
  - excitation of vertical emittance through uncompensated spurious vertical dispersion or through global betatron coupling leads to very low polarization.
    - It may be still an option if the required σ_y^* is small.
  - excitation of vertical emittance through a closed vertical dispersion bump leads to very low polarization too.
    - It may be still an option by optimizing the optics and the dipole fields.
  - Introducing local coupling at the IP for "transferring" some horizontal emittance into the vertical plan seems the better way for polarization but it can spoil the luminosity.

THANKS!