e^- Polarization in EIC electron storage ring

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- Assessing needed polarization
- Results for the unperturbed optics
- Results for the perturbed optics
- σ_y^* knob

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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

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

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”.

Optics

Since starting back in 2017 the storage ring optics is still undergoing some adjustments.

This talk optics:

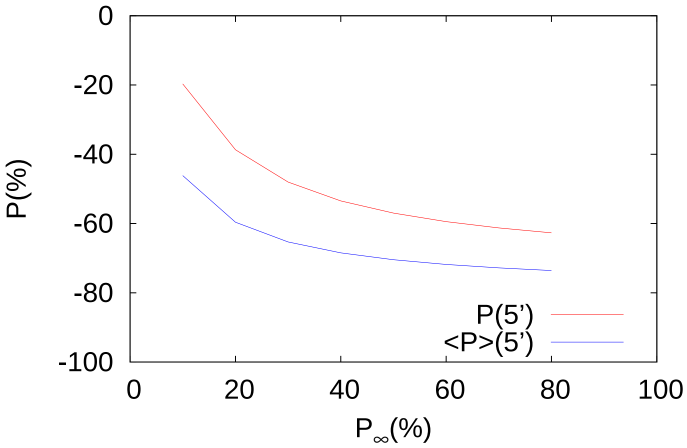
- eRHIC storage ring (esr) optics from December 19 at 18 GeV (Version-5.2)
  - $\boldsymbol{P_{bks}} \simeq$ 82.7 %
  - $\boldsymbol{\tau_{bks}} \simeq$ 35.5 min
- esr optics from at 10 GeV (Version-5.3)
  - $\boldsymbol{P_{bks}} \simeq$ 80.8 %
  - $\boldsymbol{\tau_{bks}} \simeq$ 704 min

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

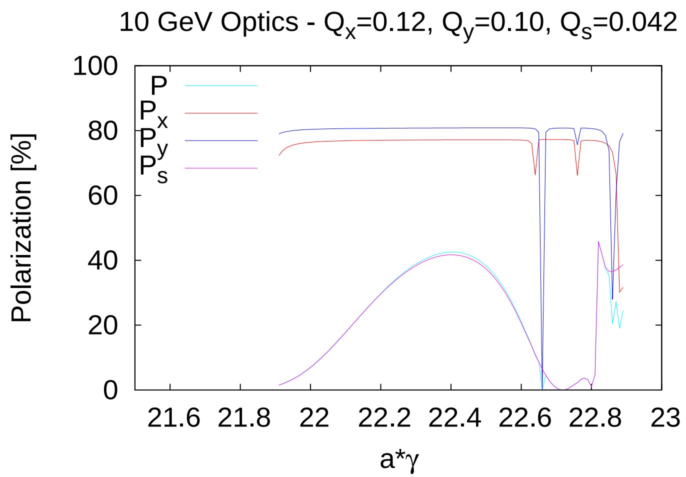
- MADX for computing the optics and simulate mis-alignments.
- SITF (part of SITROS package) for computing polarization in linear spin motion approximation (as SLIM, but it digests thick lenses).
- SITROS Monte Carlo tracking of particles with "big" photons emitted at user chosen dipoles
- first w/o spins for finding equilibrium, thus with spins parallel to $\hat{\boldsymbol{n}}_{\mathbf{0}}$. 2th order orbit description and non-linear spin motion.
  - The diffusion time τ_d is evaluated after some thousands turns and P_∞ evaluated from

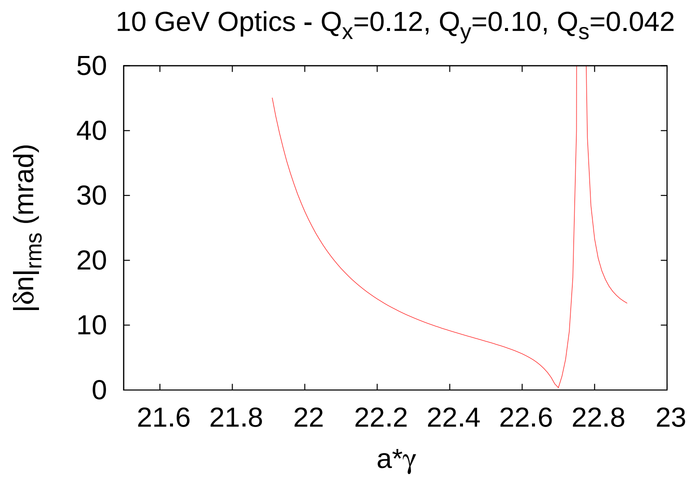
$$\frac{1}{\tau_p} \simeq \frac{1}{\tau_{\mathrm{BKS}}} + \frac{1}{\tau_{\mathrm{d}}} \qquad \text{and} \qquad P_\infty \simeq \frac{\tau_p}{\tau_{\mathrm{BKS}}} P_{\mathrm{BKS}}$$

- Some attempts at using Bmad: it allows for overlapping fields.

Results for the unperturbed machine

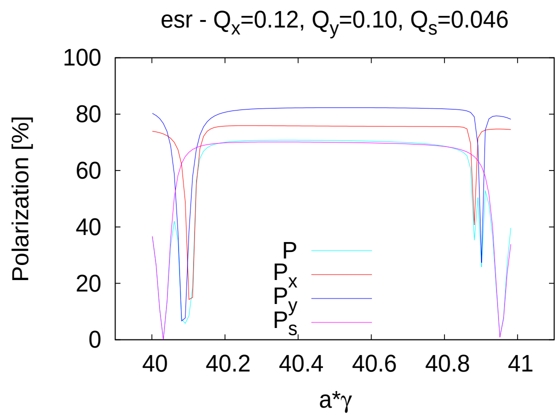
10 GeV esr v-5.3 (SITF)

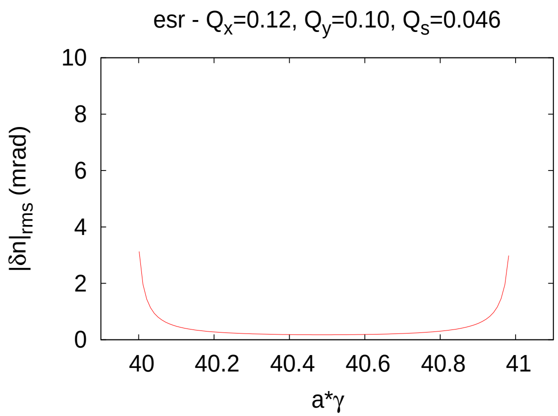




$\Rightarrow$ The relatively low asymptotic polarization should be not a concern at 10 GeV.

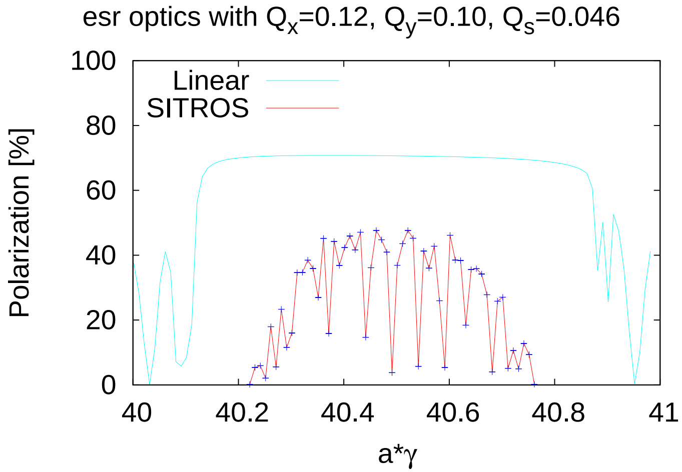
Results for the unperturbed machine: 18 GeV (SITF)





Results for the unperturbed machine: 18 GeV (SITROS)

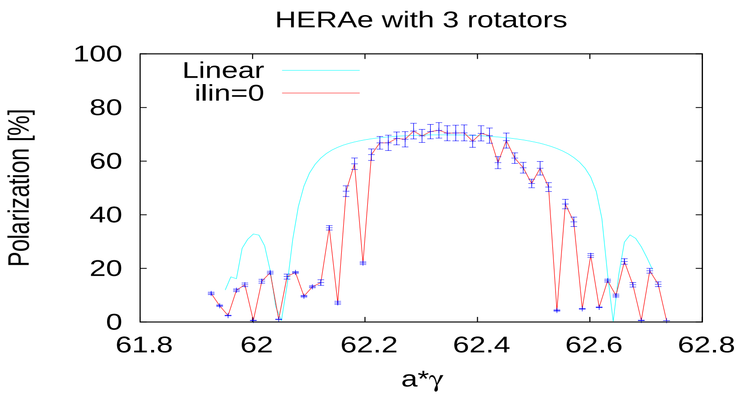
Tunes: Q_x=49.12, Q_y=43.10, Q_s=0.046 (V_{rf}=62.4 MV)



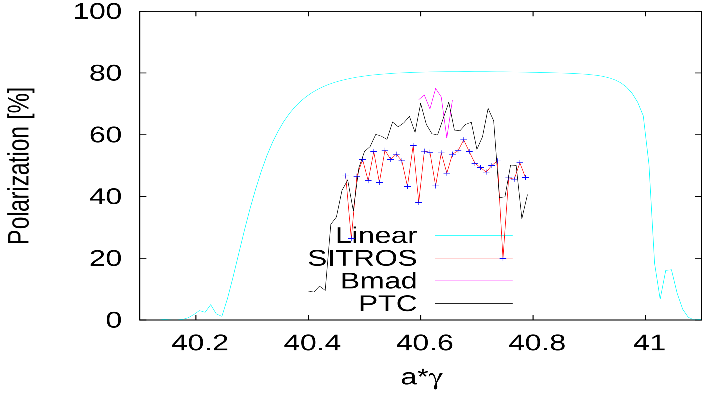
Beam size at IP

	σ_x (mm)	σ_y (μm)	σ_ℓ (mm)
Analytic (SITF)	0.110	0.276	8.434
Tracking (SITROS)	0.106	4.4	8.524

- large equilibrium $\boldsymbol{\sigma_y}$, confirmed by other tracking codes for the ATS version of the lattice;
- unusual large difference between linearized calculation and tracking; confirmed by Bmad and PTC for ATS optics.



Hera-e for comparison



Obsolete ATS optics
(PTC courtesy of Zhe Duan)

However, both are feature only of the *unperturbed* optics.

Machine with misalignments

- 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.

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

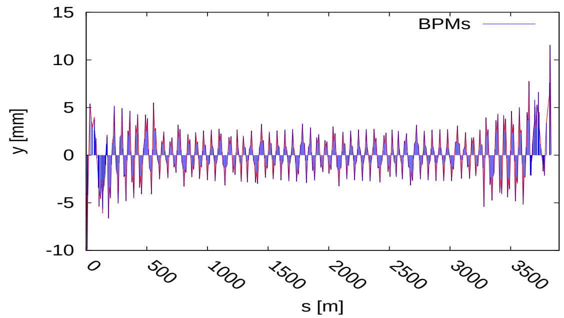
MAD-X fails correcting the orbit! Example with only $\delta y^Q \neq 0$ and sexts off.

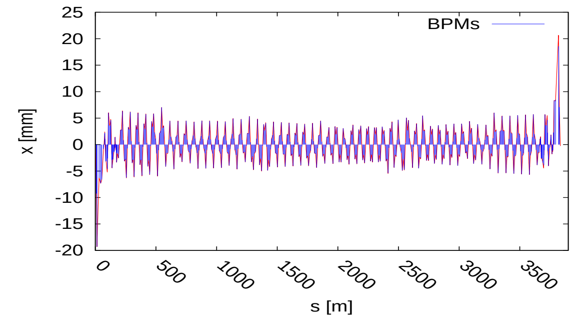
Large discrepancy between what the correction module promises...

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!





Orbit is well sampled

Effect on h-plane with sextupoles off

Separate horizontal and vertical correction inadequate in the rotator sections (38 quads) $\rightarrow$ "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

(*) no iterations, wg_{orb}=1, wg_{disp}=0.

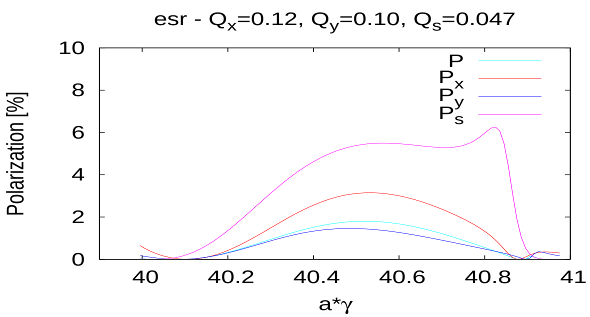
Sextupoles on, no betatron coupling or D_y correction:

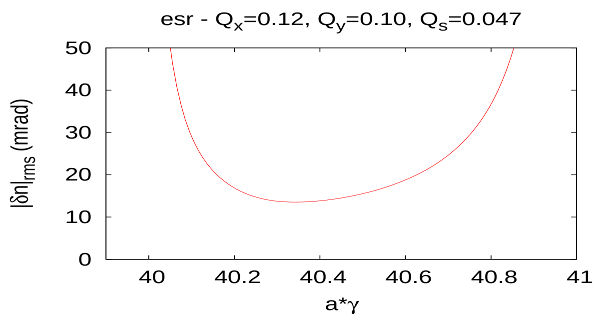
q_x	q_y	x_{rms} (mm)	y_{rms} (mm)	$D_{y,rms}$ (m)	ϵ_x (μm)	ϵ_y (μm)
.3	.2	0.25	0.20	0.036	0.0288	0.0003
.12	.10	0.35	0.36	0.089	0.02529	0.0073(*)

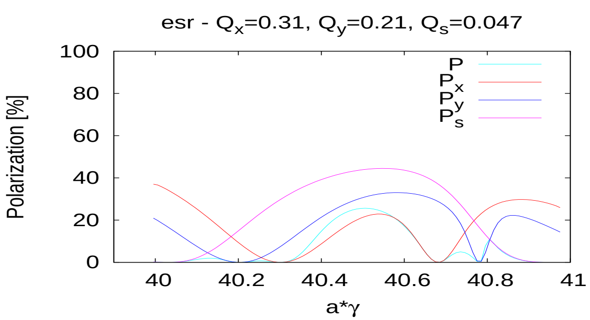
(*) Goal for matching p-beam size: $\approx$ 0.003 μm

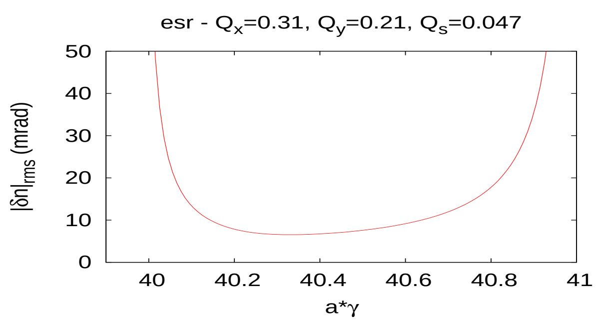
	x_{rms} (mm)	y_{rms} (mm)	$D_{y,rms}$ (m)	ϵ_x (μm)	ϵ_y (μm)
MADX	0.35	0.36	0.089	0.025	0.0073
SITF	0.41	0.38	-	0.024	0.0068

$\rightarrow$ Decent agreement between MADX and SITF.





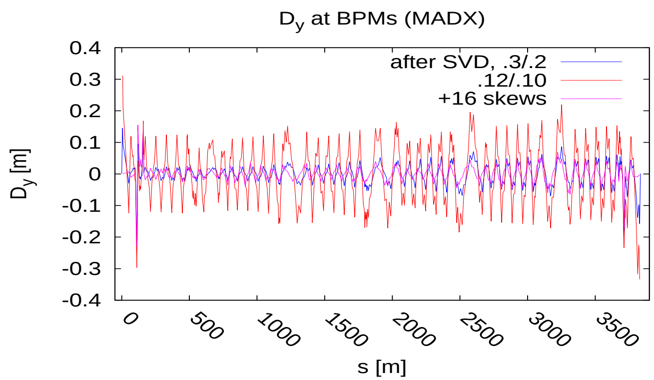


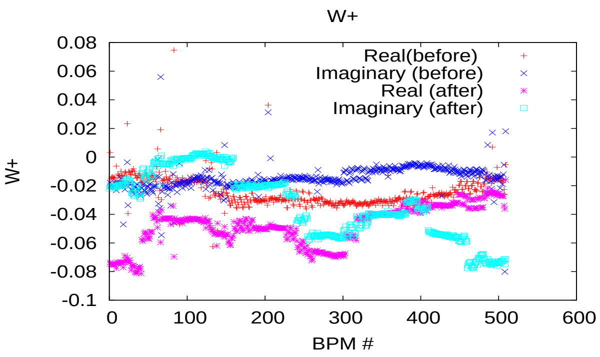


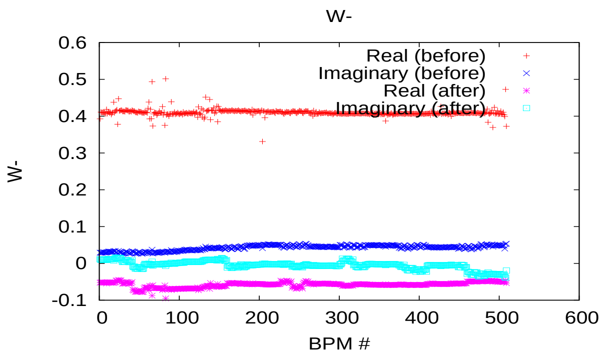
Coupling and dispersion correction with 16 skew quadrupoles.

weights

$\Re(W^-)$	$\Im(W^-)$	$\Re(W^+)$	$\Im(W^+)$	D_y
1	1	0	0	0.5

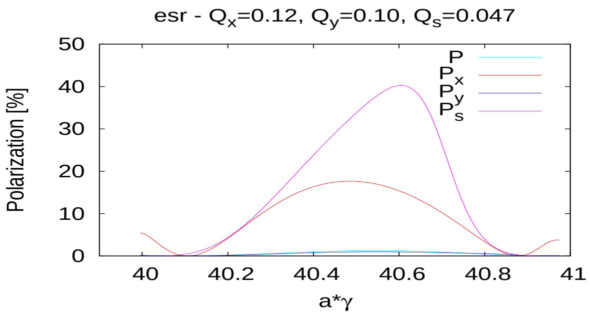


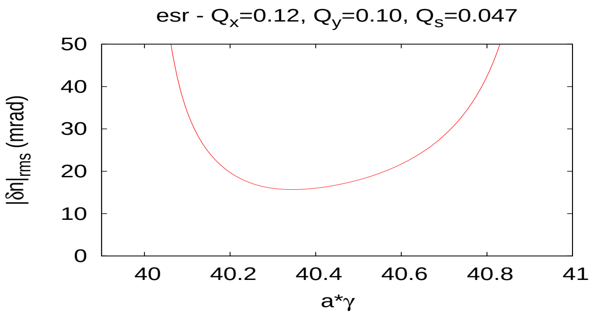




$\rightarrow$ Betatron coupling reduced from 0.014 to 0.002.

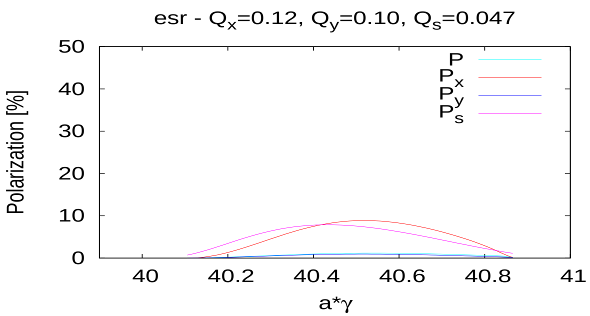
	x_{rms} (mm)	y_{rms} (mm)	$D_{y,rms}$ (m)	ϵ_x (μm)	ϵ_y (μm)
MADX	0.33	0.39	0.030	0.0293	0.0008

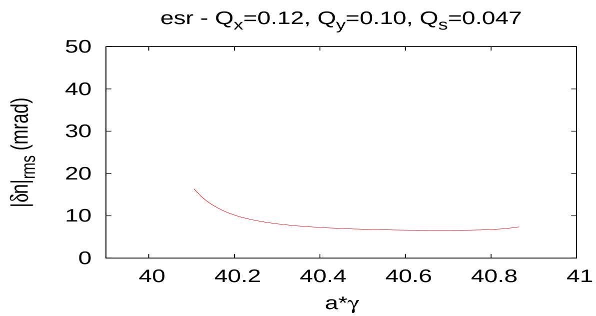

esr - Qx=0.12, Qy=0.10, Qs=0.047
Polarization [%]
P
Px
Py
Ps
a*γ

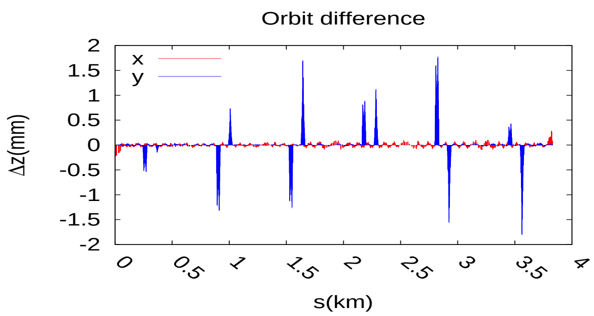

esr - Qx=0.12, Qy=0.10, Qs=0.047
|δn|rms (mrad)
a*γ

Relative large $\hat{\boldsymbol{n}}_0$ distortion. Trying to correct it with harmonic bumps, although it can't be the reason for such a bad result.

New algorithm using ring 6-fold symmetry: 12 harmonic bumps for correcting 4 harmonics keeping the other 8 unchanged.





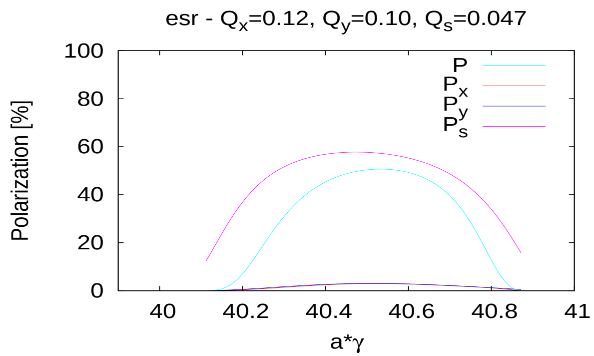


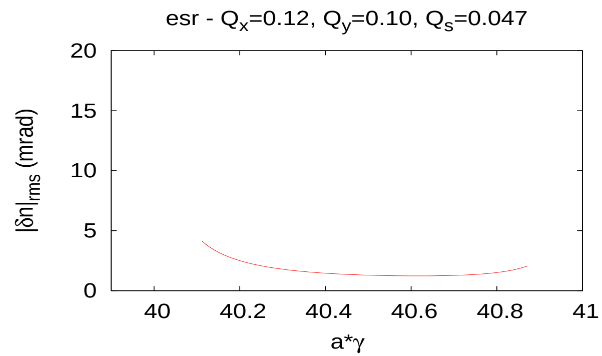
The vertical emittance is increased by the harmonic bumps from 0.8 nm to 2.3 nm.

Conclusion: a more aggressive closed orbit correction is necessary!

	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	.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.



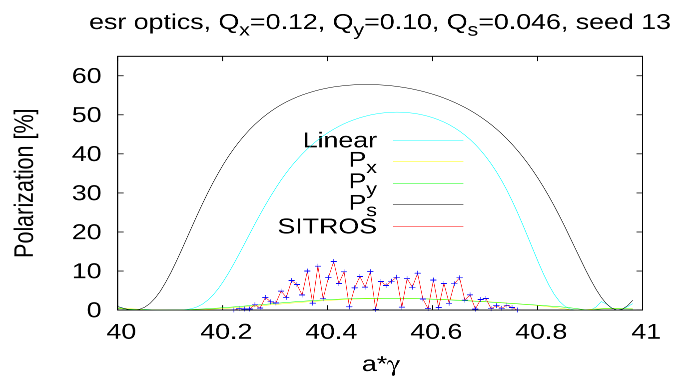


The aggressive orbit correction resulted in larger polarization and smaller $\delta\hat{n}_0$.

Polarization from SITROS tracking, before betatron coupling correction.

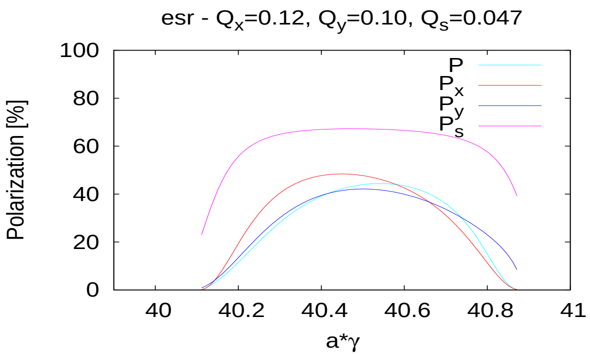
Beam size at IP

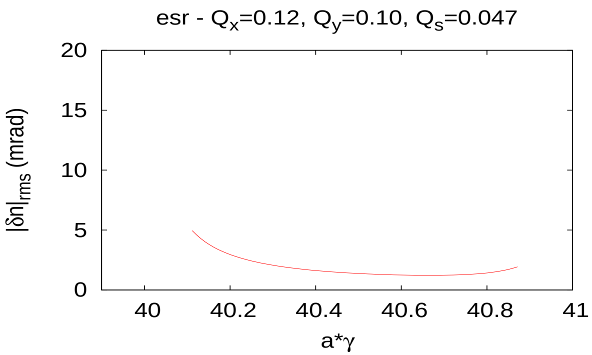
	σ_x (mm)	σ_y (μm)	σ_ℓ (mm)
Analytic	0.096	20.5	8.384
Tracking	0.085	21.3	8.347



Polarization is larger then $P_{x,y}$, but still small → betatron coupling must be corrected!

16 skew quadrupoles used for correcting ΔD_y and betatron coupling from 0.017 to 0.0018.



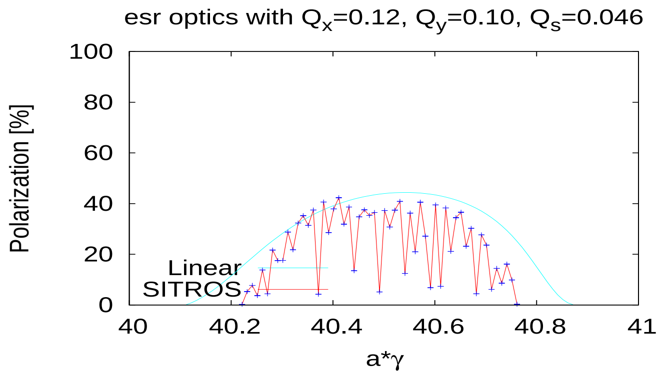


P_x and P_y greatly increased.

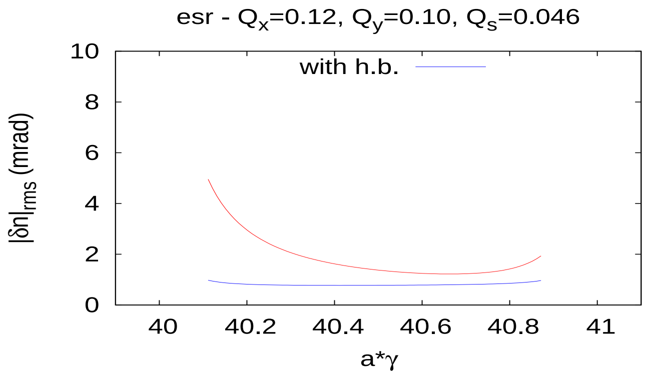
Non linear polarization calculation.

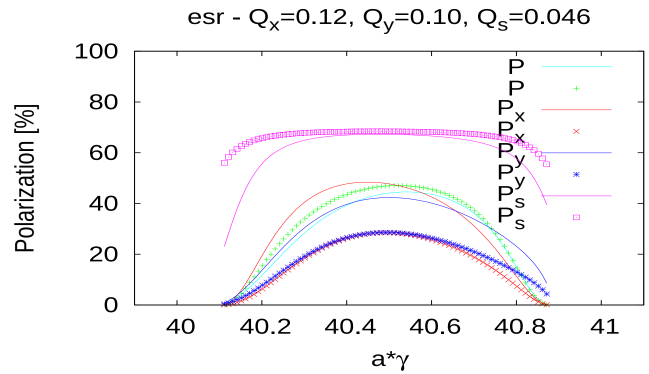
Beam size at IP

	σ_x (mm)	σ_y (μm)	σ_ℓ (mm)
Analytic	0.111	3.285	8.383
Tracking	0.105	4.409	8.345



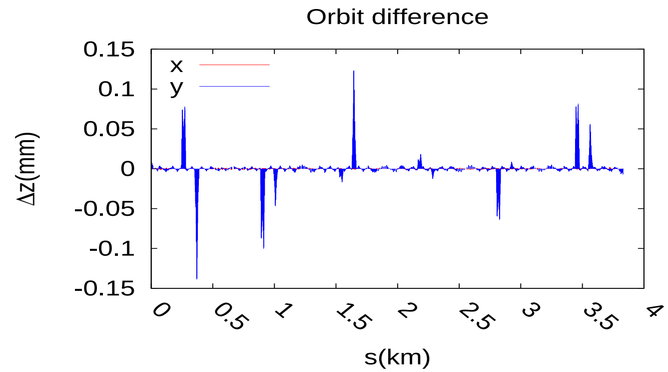
The already small $\hat{\boldsymbol{n}}_0$ can be further reduced by harmonic bumps.





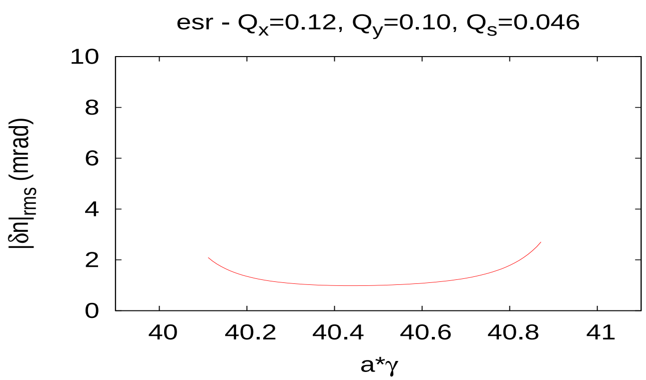
The solid lines refer to the case w/o bumps. $\boldsymbol{P_s}$ increases, but $\boldsymbol{P_x}$ and $\boldsymbol{P_y}$ decrease, likely due to the coupling introduced by the vertical bumps in the sextupoles.

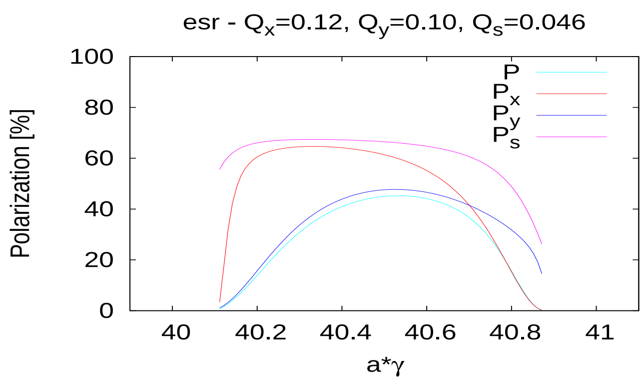
Correcting $\hat{\boldsymbol{n}}_{\mathbf{0}}$ *first*. Vertical orbit difference:



The betatron coupling is now 0.0196 (it was 0.017 after orbit correction).

Corrected in two iterations down to 0.0001.



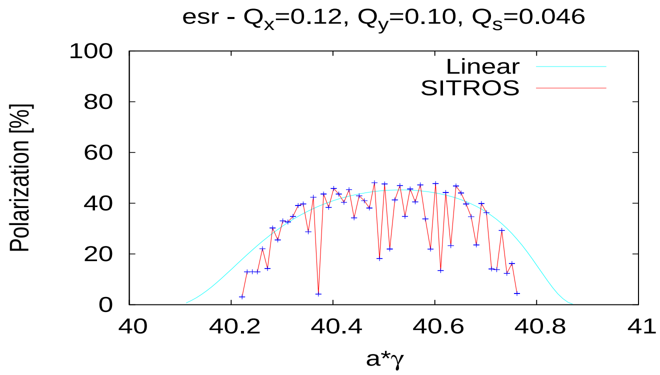


Emittances: ϵ_x=0.0278 μm and ϵ_y=30.4 pm. Goal: $\epsilon_y \approx 3$ nm.

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 about 100 times too small for matching p-beam vertical size.

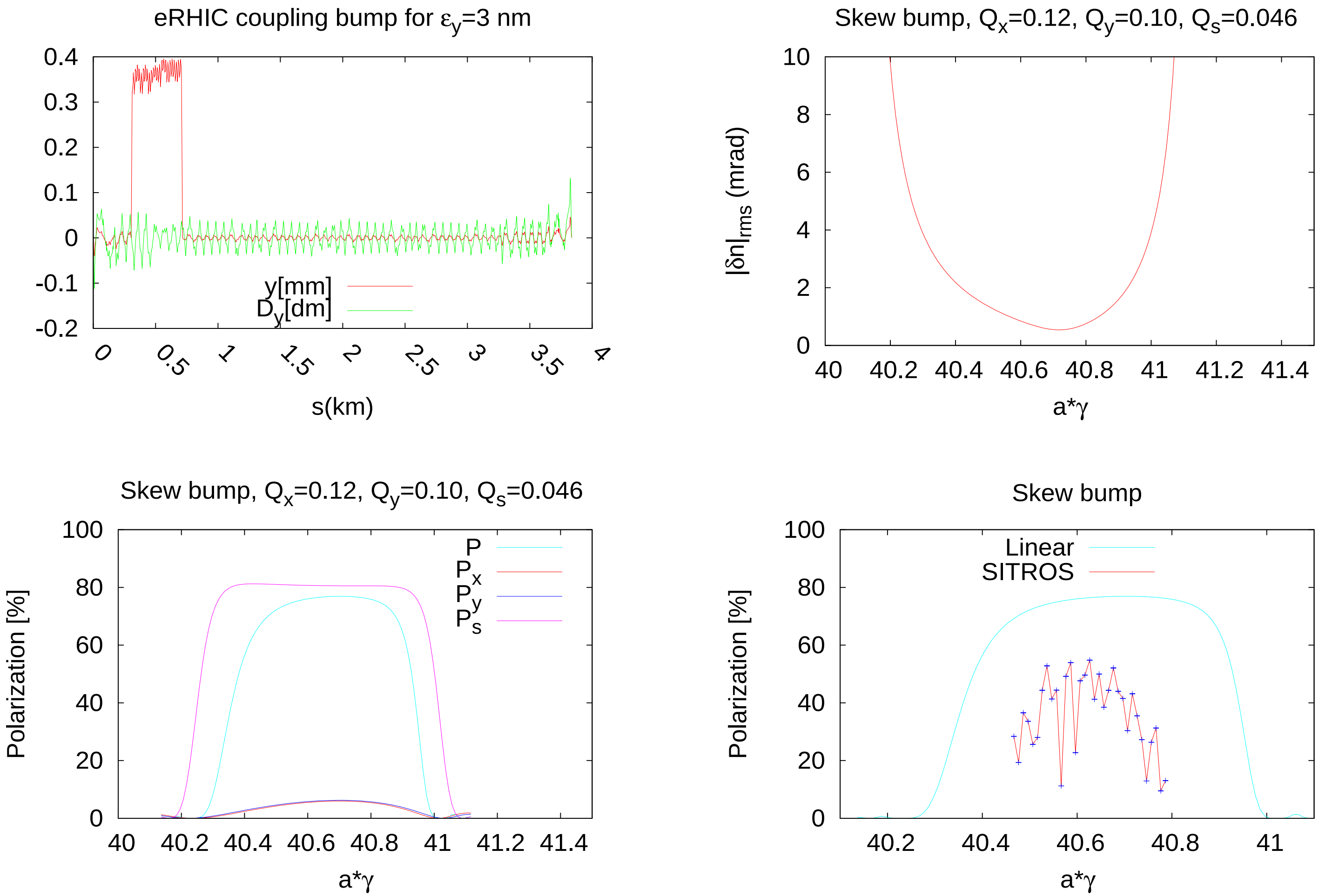
Matching e^-/p sizes at IP

For increasing the beam size at the IP we may try

- adding a long vertical bump trough the sextupoles,
- or 2 pairs of skew quads around the IP.

ϵ_y knob

Long bump in arc sextupoles increases ϵ_y through betatron coupling. It seemed working for the ATS optics: $\hat{n}_0$ almost unperturbed, small orbit excursion.

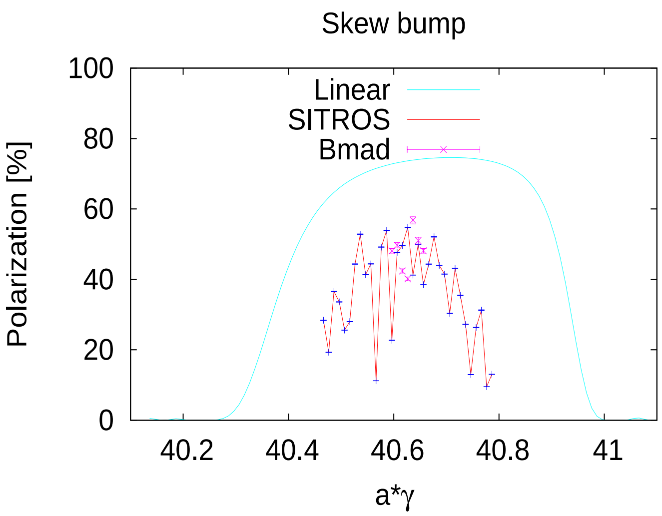


Beam size at IP

	σ_x (μm)	σ_y (μm)	σ_ℓ (mm)	ϵ_y (nm)
SITF	105.0	22.6	6.98	3.1
SITROS tracking	101.3	26.1 (*)	6.95	-

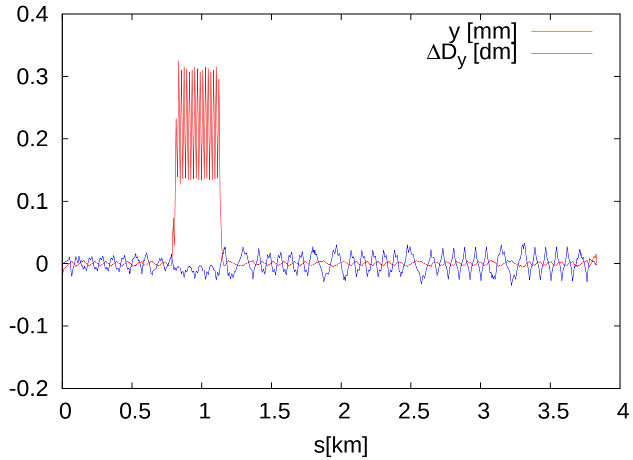
(*) Much larger than needed, but polarization large.

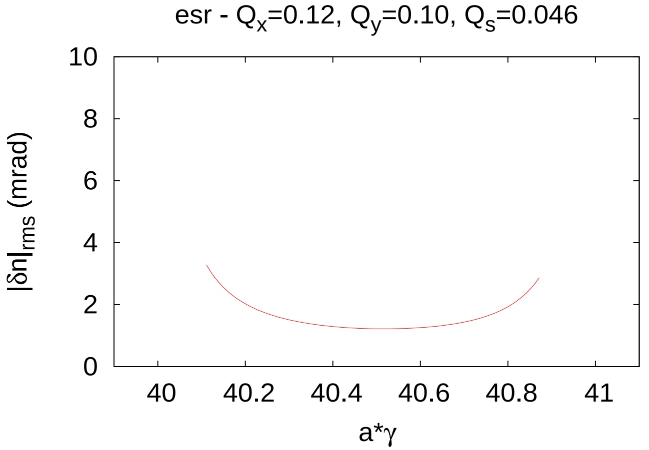
SITROS results of large $\boldsymbol{P}$, despite $\boldsymbol{P_{x,y}} \simeq 0$, were confirmed by Bmad, although not in the details.

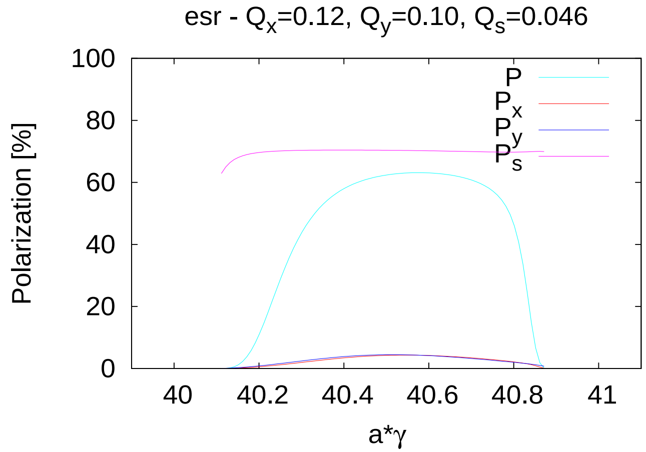


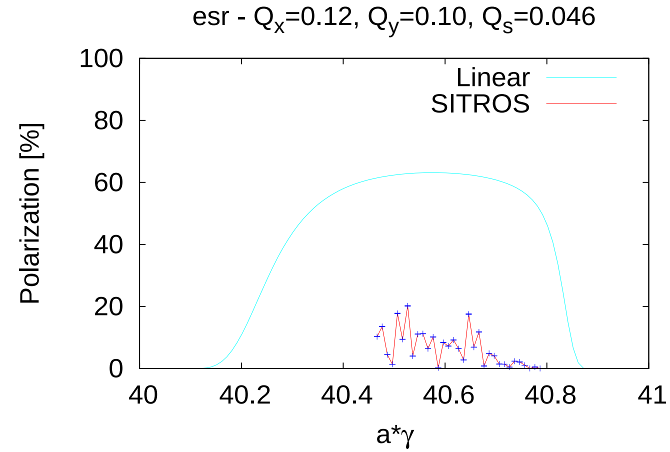
Those promising results are not confirmed by the esr v5.2 optics, despite a more effective bump.

For ϵ_y= 3 nm (unperturbed machine):



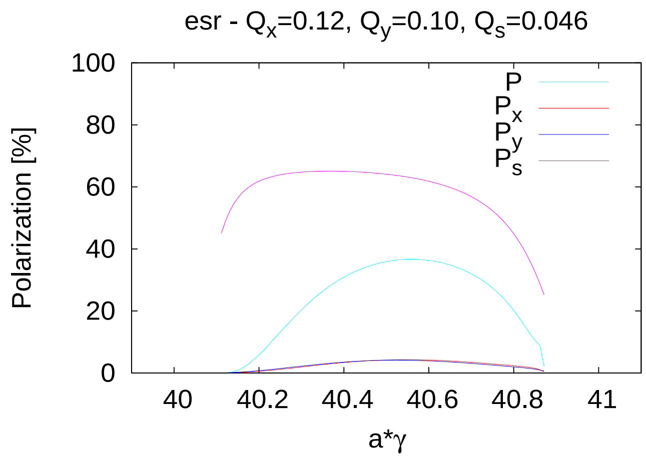


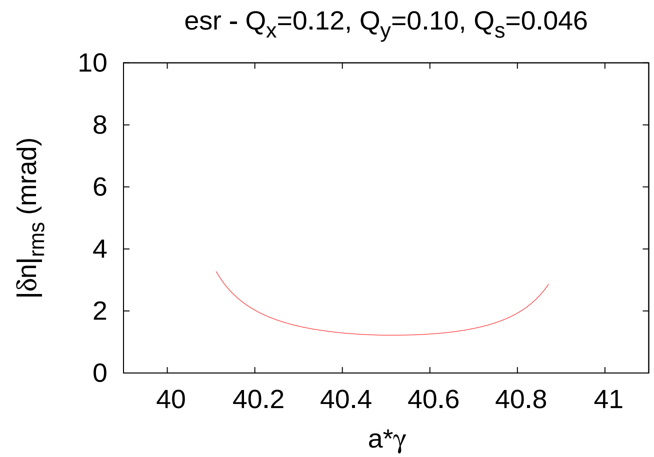


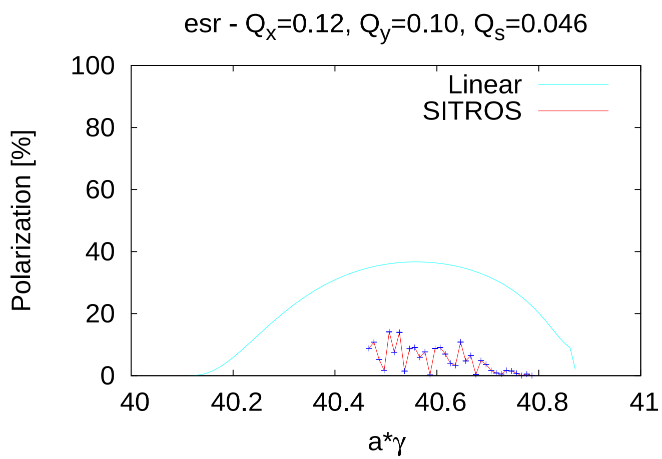


SITROS polarization is larger than P_x and P_y, but still too small.

For the perturbed machine with all corrections and long bump in addition:







Beam size at IP

	σ_x (μm)	σ_y (μm)	σ_ℓ (mm)	ϵ_y (nm)
SITF	100.2	16.7	8.538	3.2
SITROS tracking	93.8	15.8	8.572	-

The long bump is no more an option.

σ_y^* knob

The e^- beam σ_y^* may be *locally* increased by 2 pairs of skew quadrupoles around the IP. From Willeke and Ripken (DESY 88-114)

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

With the option "RIPKEN=true", MADX Twiss computes β_{xI}, β_{xII}, β_{yI} and β_{yII}.

For ϵ_y=3.3 nm, the wished σ_y is $\sigma_y = \sqrt{\beta_y \epsilon_y} = \sqrt{0.09 \times 3.3 \times 10^{-9}} = 17.2\ \mu\text{m}$ (β_y unperturbed vertical β at IP).

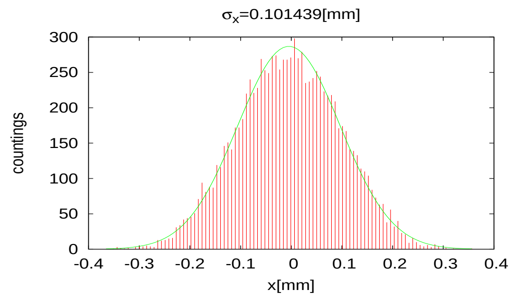
The strength of the "leading" skew quad is changed in MADX until $y_{max} \approx 17\ \mu$m is reached.

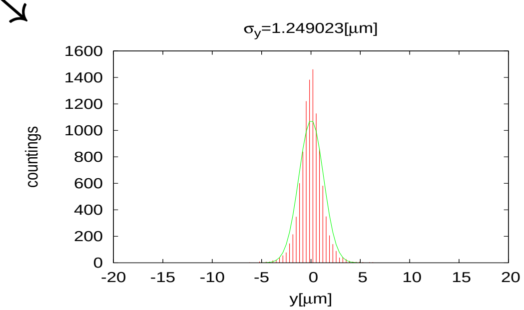
	s [m]	ℓ [m]	K [m^{-2}]
SKQA	-4.4	0.010	0.45
SKQB	-1.0	0.010	-1.98
SKQC	1.0	0.010	1.98
SKQD	4.4	0.010	-0.45

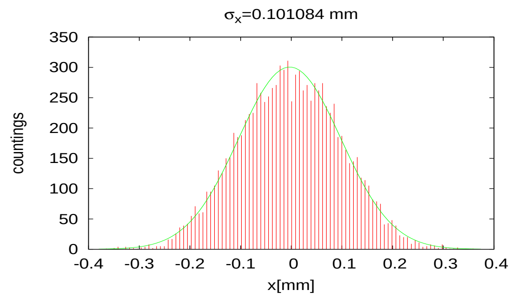
Effect of σ_y^* knob from tracking

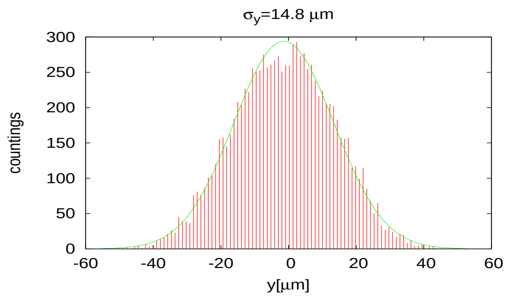
SITROS tracking of 10000 particles for a distorted ATS optics.

↙ no skews ↘



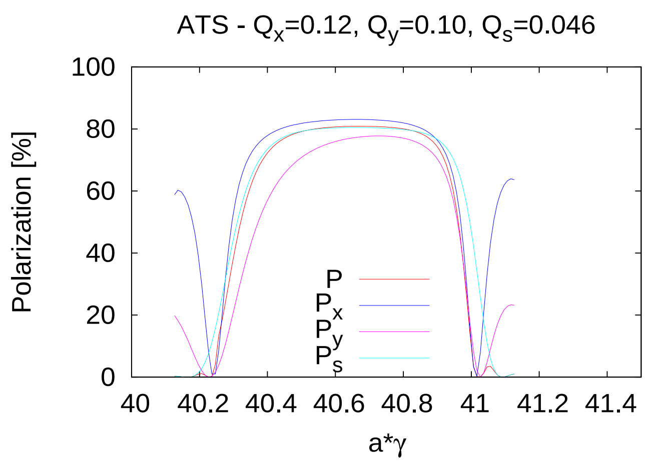


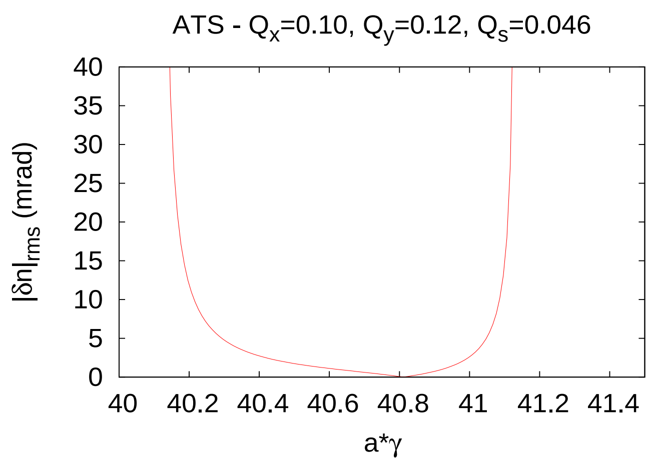


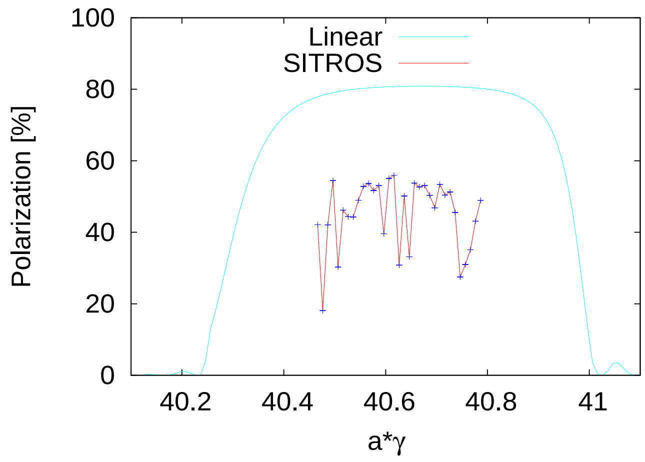


↖ with skews ↗

Polarization with 2 pairs of skews for $\boldsymbol{\sigma_y}$=21 $\boldsymbol{\mu}$m (ATS, perturbed):



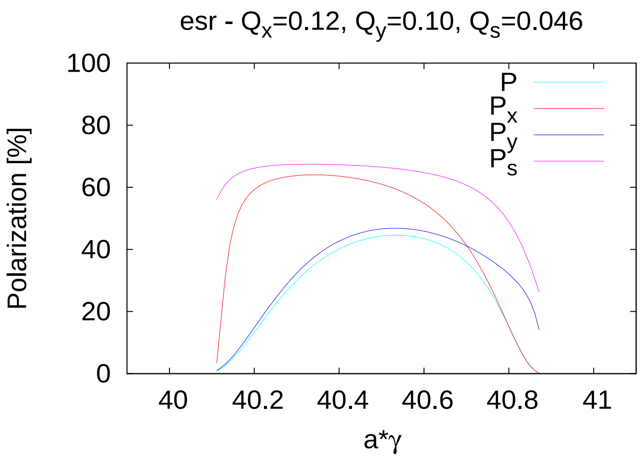


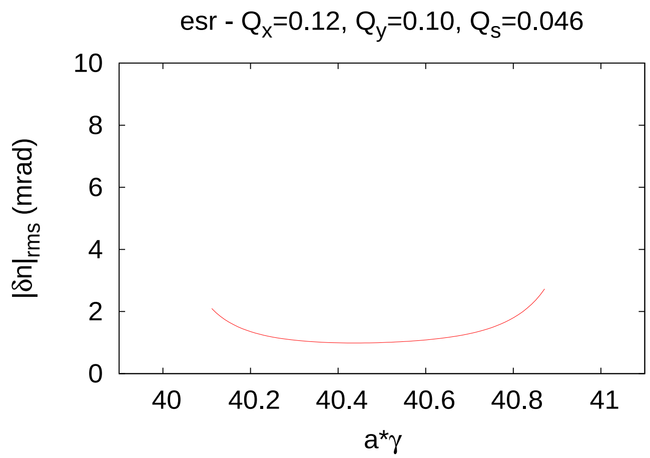


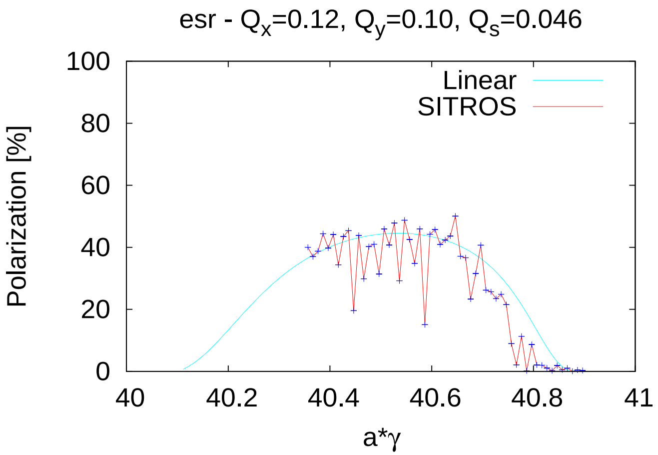
Beam size at IP with 2 pairs of skews (ATS)

	$\boldsymbol{\sigma_x}$ [$\boldsymbol{\mu}$m]	$\boldsymbol{\sigma_y}$ [$\boldsymbol{\mu}$m]	$\boldsymbol{\sigma_\ell}$ [mm]
analytical (SITF)	121	17.6	6.97
SITROS	143	21.1	6.98

For the esr perturbed machine with "local coupling bump" in addition:







Beam size at IP with errors and 2 pairs of skews (esr)

	σ_x (μm)	σ_y (μm)	σ_ℓ (mm)	ϵ_y (nm)
SITF	111.8	16.2	8.541	0.031
SITROS tracking	106.6	16.0	8.572	-

Summary

- In presence of (conservative) errors, polarization of $\approx$ 40%-45% seems achievable.
  - The orbit must be very carefully corrected, which leads to a small vertical beam size at the IP (some tens of pm).
- Matching the $\boldsymbol{p}$ vertical beam size:
  - excitation of vertical emittance through uncompensated spurious vertical dispersion or through global betatron coupling lead to very low polarization.
    - It may be still an option if the required $\boldsymbol{\sigma_y^*}$ is small.
  - 2 pairs of skew quadrupoles for "transferring" some horizontal emittance into the vertical plan at the IP seems the better way.
    In practice could be embedded into the experimental solenoid compensation scheme.

THANKS!