Simulations for FCC-ee beam self-polarization

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VYDIO February 5, 2018

Goal since October Workshop: a complete simulation of the effect of misalignements.

Optics: 45 GeV optics with smaller $\boldsymbol{\beta_y^*}$ from September 2017

- 60 deg FODO.
- $\hat{\boldsymbol{\beta}}_{\boldsymbol{y}}$ is smaller but focusing is stronger too.
- As a consequence, the SY sextupoles became stronger.

Reminder from December 14 meeting: two (more) problems encountered i.e.

- Small $\boldsymbol{\epsilon_y}$ and $\boldsymbol{D^y_{rms}}$ is no warranty for high polarization
- Problems by tracking with SITROS and MAD-X PTC

New optics: arcs

Stable machine and $|\boldsymbol{C}^-| \simeq 0$ with [a]

	IR Quads	IR BPMs	other Quads	other BPMs
$\boldsymbol{\delta x}$ ($\boldsymbol{\mu}$m)	0	0	50	0
$\boldsymbol{\delta y}$ ($\boldsymbol{\mu}$m)	0	0	50	0
$\boldsymbol{\delta\theta}$ ($\boldsymbol{\mu}$rad)	0	0	50	0
calibration	-	0	-	0

Trying increasing errors: Twiss failure by switching on the SY sextupoles.

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[a] errors added in 10 steps

New optics: arcs

Stable machine and $|\boldsymbol{C}^-| \simeq 0.007$ with [a]

	IR Quads	IR BPMs	other Quads	other BPMs
$\boldsymbol{\delta x}$ ($\boldsymbol{\mu}$m)	0	0	50	50
$\boldsymbol{\delta y}$ ($\boldsymbol{\mu}$m)	0	0	50	50
$\boldsymbol{\delta \theta}$ ($\boldsymbol{\mu}$rad)	0	0	50	50
calibration	-	0	-	1%

- The coupling is due mainly to the SYs: with them off it is $|\boldsymbol{C}^-| < 0.002$

$\leadsto$ try inserting a thin skew quadrupole in the middle of each SYs for a coupling local correction. This may introduce vertical dispersion.

By powering the 8 SYs skews with $\boldsymbol{K} = -\boldsymbol{S} \times \boldsymbol{\ell} \times \boldsymbol{y}$ it is possible to reach $|\boldsymbol{C}^-| \simeq 0.0009$, but indeed vertical dispersion increases.

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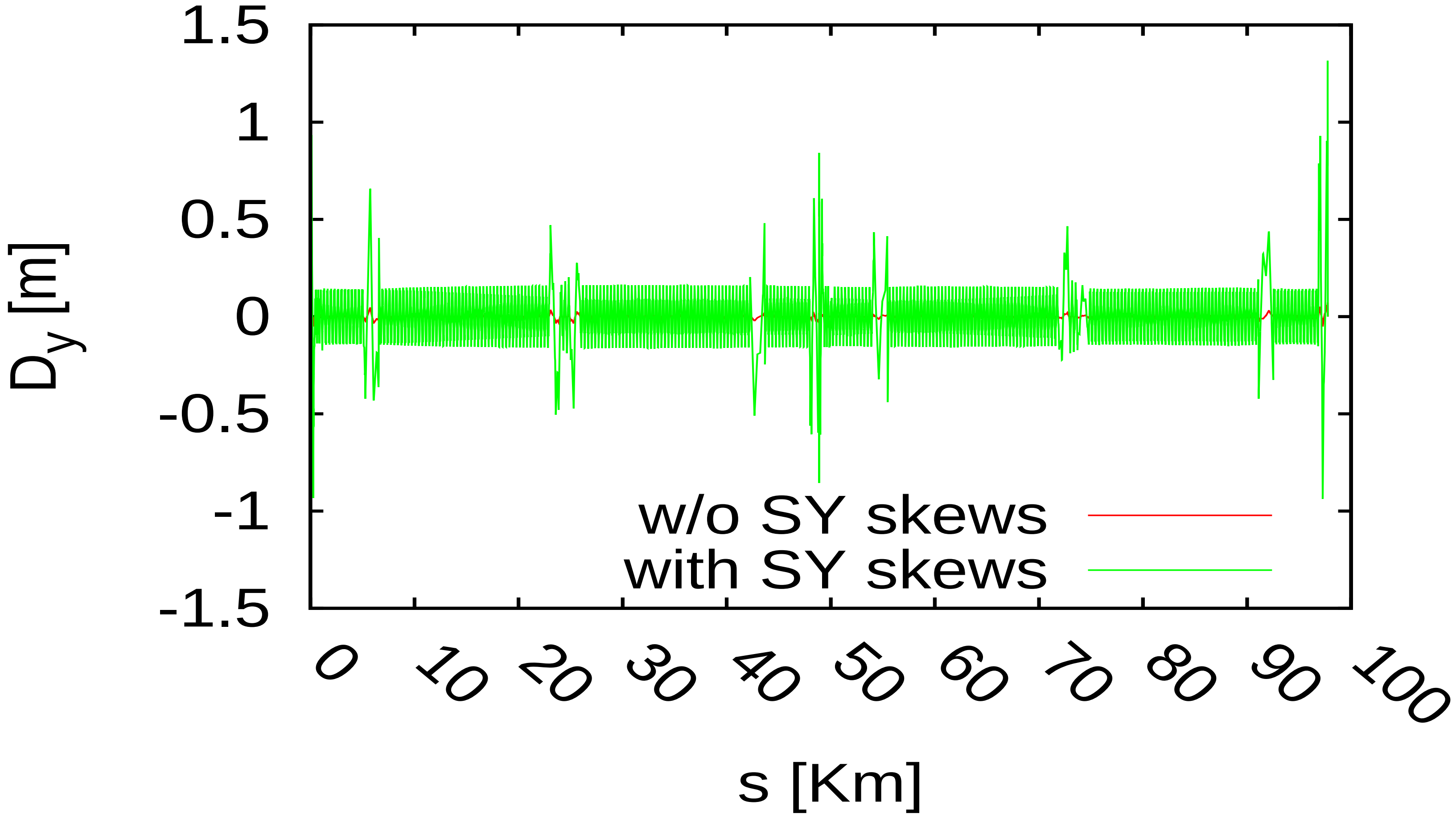
[a] errors added in 10 steps, but calibration errors kept fixed at 1%



$\boldsymbol{D_y}$ rms value increases from 7 mm to 130 mm.

Will be it possible to correct $\boldsymbol{D_y}$ later on by the “distributed” skew quads? For the moment I do not resort to those skews.

Improvements to IR correction

- one vertical corrector 0.05 m long close to each QC1Rn , QC1Ln, QC2Rn, QC2Ln and QT
- one horizontal and one vertical corrector 0.05 m long close to each QC2Rn, QC2Ln and QT

Strategy for inserting errors:

- one IP at a time
- correction by SVD using only the local correctors

	IR Quads	IR BPMs	other Quads	other BPMs
$\boldsymbol{\delta x}$ ($\boldsymbol{\mu}$m)	50	50	0	50
$\boldsymbol{\delta y}$ ($\boldsymbol{\mu}$m)	50	50	0	50
$\boldsymbol{\delta \theta}$ ($\boldsymbol{\mu}$rad)	50	50	0	50
calibration	-	1%	-	1%

Put all together : stable machine with $|\boldsymbol{C}^{-}| \simeq 0.018$.

	$\boldsymbol{D^y_{rms}}$	$\boldsymbol{\epsilon_x}$	$\boldsymbol{\epsilon_y}$	$\boldsymbol{\epsilon_\ell}$
	mm	nm	pm	$\boldsymbol{\mu}$m
unp.	0	0.255	0.0000	1.259
errs+corrs	11.4	0.254	2.937	1.237

with $\boldsymbol{V}$=96 MV

Arcs: change strategy

Vertical dispersion increases when moving to “polarization tunes”

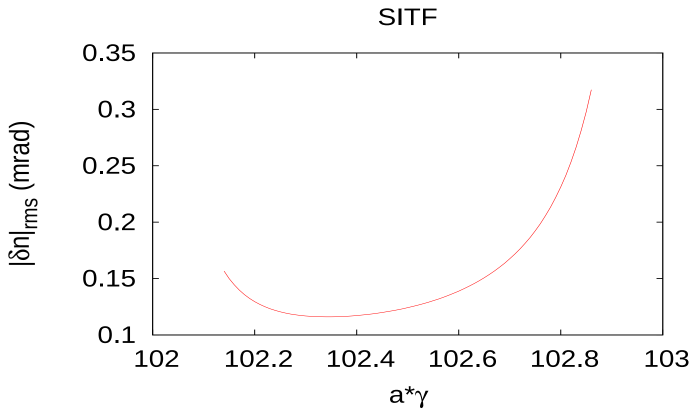
- Switch to .1/.2 tunes and turn on sextupoles at the end of the orbit correction and re-correct orbit (if stable...)

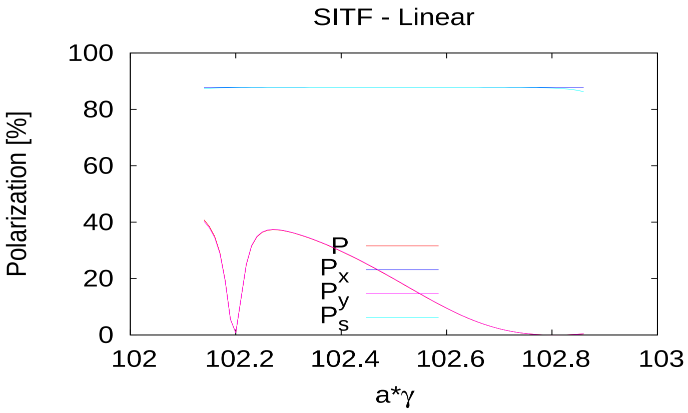
	IR Quads	IR BPMs	other Quads	other BPMs
δx (μm)	0	0	50	50
δy (μm)	0	0	50	50
$\delta \theta$ (μrad)	0	0	50	50
calibration	-	0	-	1%

- Reading back errors and corrections there is discrepancy in the vertical plane (only!)
  - y_{rms}=10 μm $\rightarrow$ 20 μm
  - D^y_{rms}=3.6 mm $\rightarrow$ 5.6 mm
- $|C^-| \simeq 0.003$
- ϵ_y=1.7 pm (with wigglers, no IR errors)

Errors only in the arcs quads. Add coupling/$\boldsymbol{D_y}$ correction with 289 skew quads.

	$\boldsymbol{x_{rms}}$ ($\boldsymbol{\mu}$m)	$\boldsymbol{y_{rms}}$ ($\boldsymbol{\mu}$m)	$\boldsymbol{D^y_{rms}}$ (mm)	$\boldsymbol{\epsilon_x}$ (nm)	$\boldsymbol{\epsilon_y}$ (pm)	$\boldsymbol{\lvert C^- \rvert}$
before	10	20	5.6	0.225	1.752	0.003
after	10	20	3.1	0.225	0.125	0.0005





Back to theory. In linear approximation

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

$$\Delta_{\pm x,\pm y} = (1 + a\gamma)\frac{e^{\mp i\mu_{x,y}}}{e^{2i\pi(\nu\pm Q_{x,y})} - 1}\,\frac{[-D \pm i(\alpha D + \beta D')]_{x,y}}{\sqrt{\beta_{x,y}}}\; J_{x,y}$$

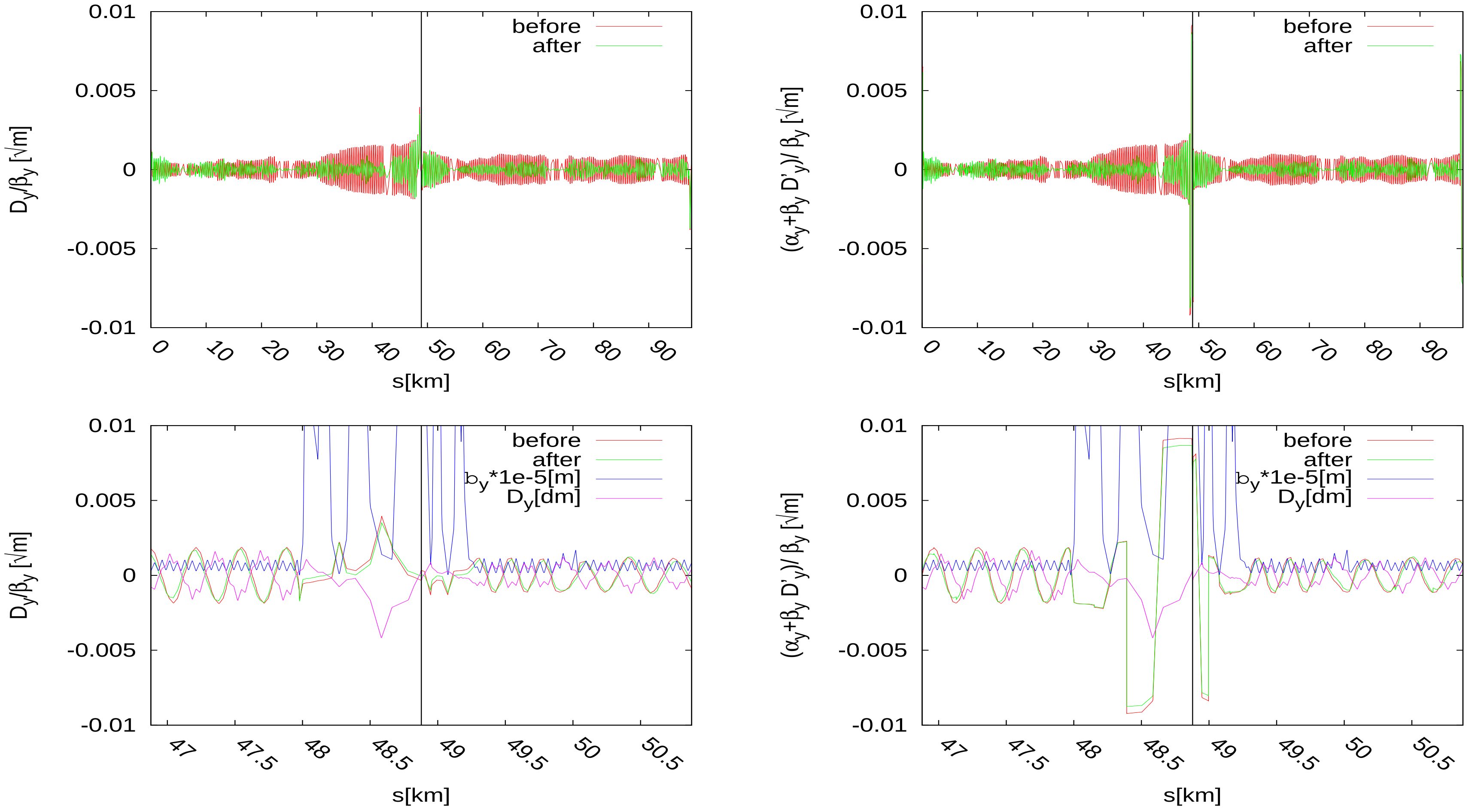
$$\Delta_{\pm s} = (1 + a\gamma)\frac{e^{\pm i\mu_s}}{e^{2i\pi(\nu\pm Q_s)} - 1}\; J_s$$

$$J_{\pm x,\pm y} = \int_s^{s+L} ds'(\hat{m}_0 + i\hat{l}_0)\cdot\left\{\begin{array}{c}\hat{y}\sqrt{\beta_x}\\ \hat{x}\sqrt{\beta_y}\end{array}\right\} K e^{\pm i\mu_{x,y}}$$

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

Why is $\Delta_{\pm y}$ so large? If D_y is too large, why is P_y and not P_s affected?

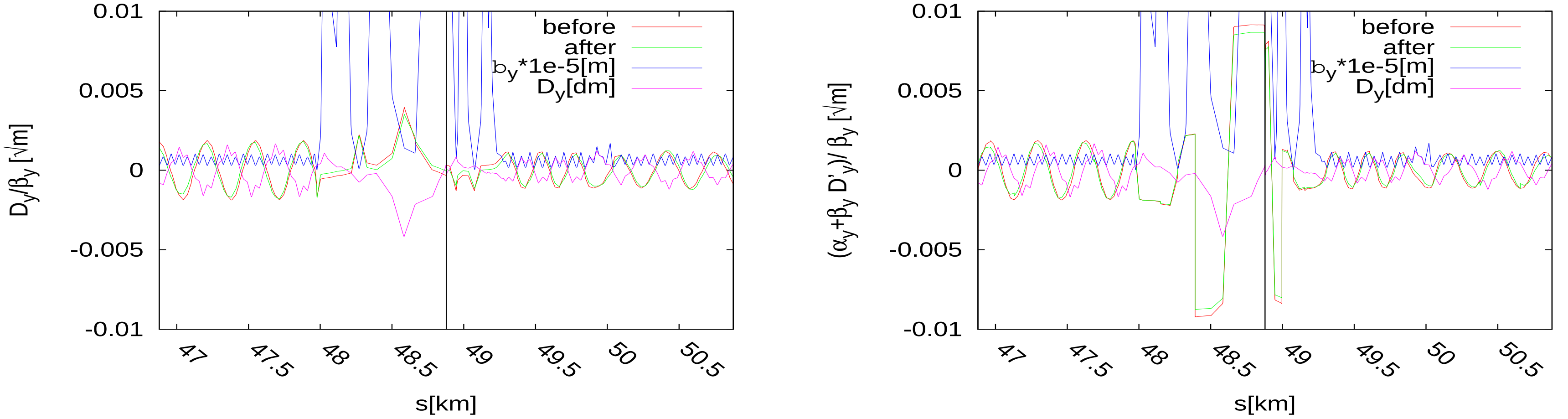
Plotting the factor $\frac{[-D_y \pm i(\alpha_y D + \beta D'_y)]}{\sqrt{\beta_y}}$ which multiplies $J_{\pm y}$



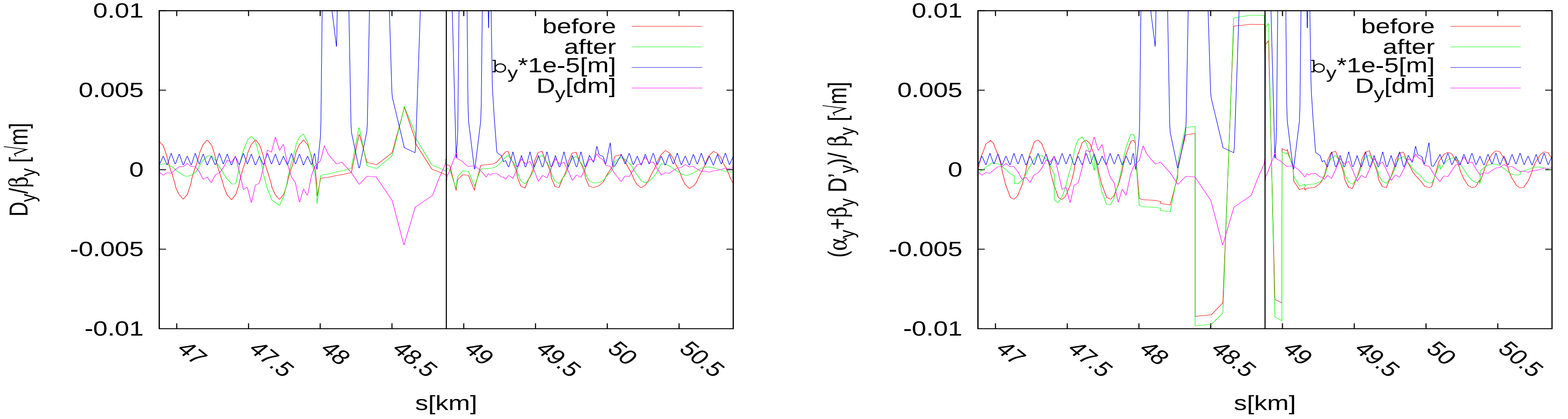
Hypothesis: the factor $\frac{[-D_y \pm i(\alpha_y D + \beta D'_y)]}{\sqrt{\beta_y}} D_y$ must be better controled!

Trying correcting only $\boldsymbol{D_y}$ (2 mm rms): no change on polarization.

Correcting coupling and $\boldsymbol{D_y}$



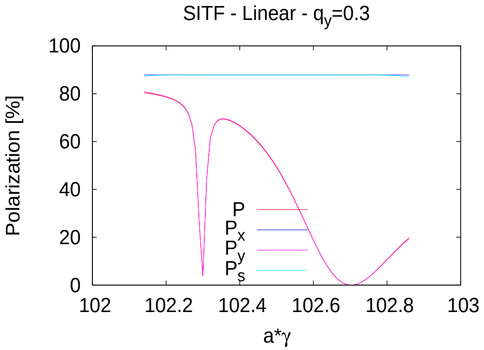
Correcting only $\boldsymbol{D_y}$

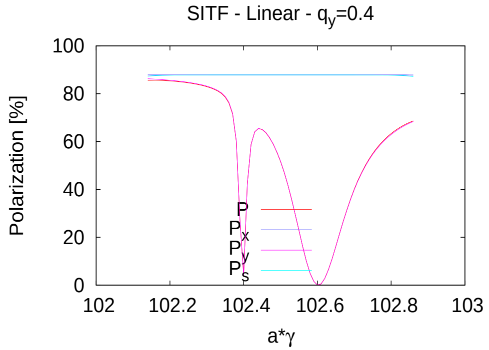


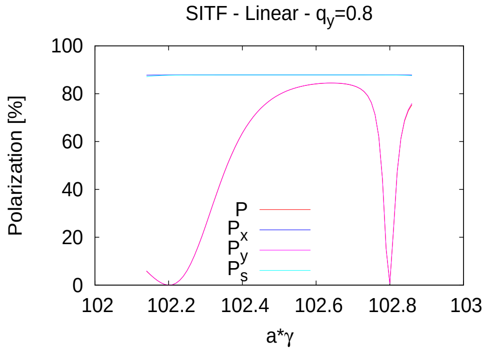
Indeed no improvement of the factor.

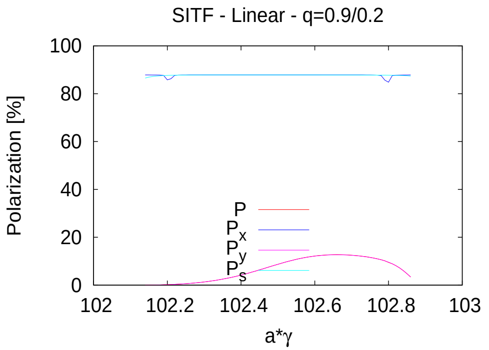
Swopping tunes: $\boldsymbol{P_y} \to 0$

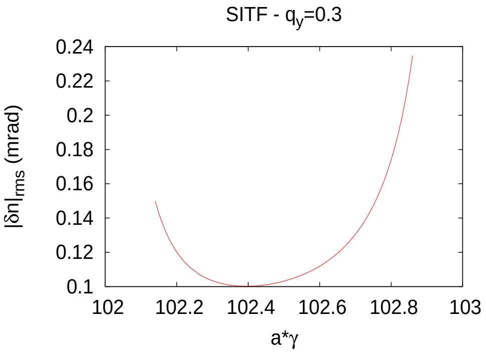
Increasing $\boldsymbol{Q_y}$ to .3 helped!

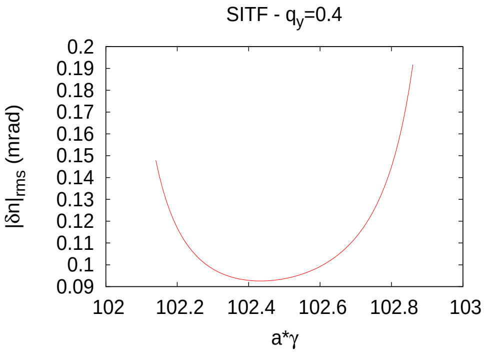


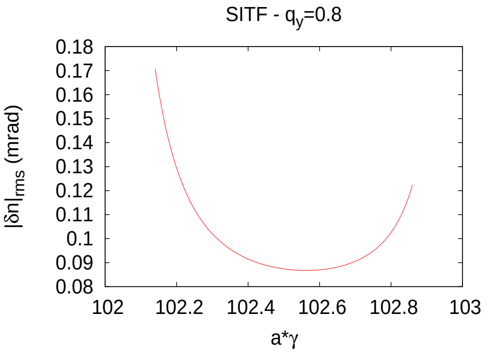


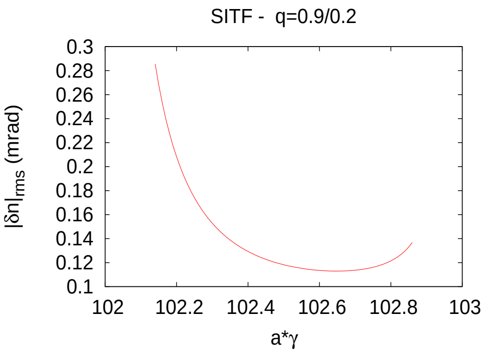




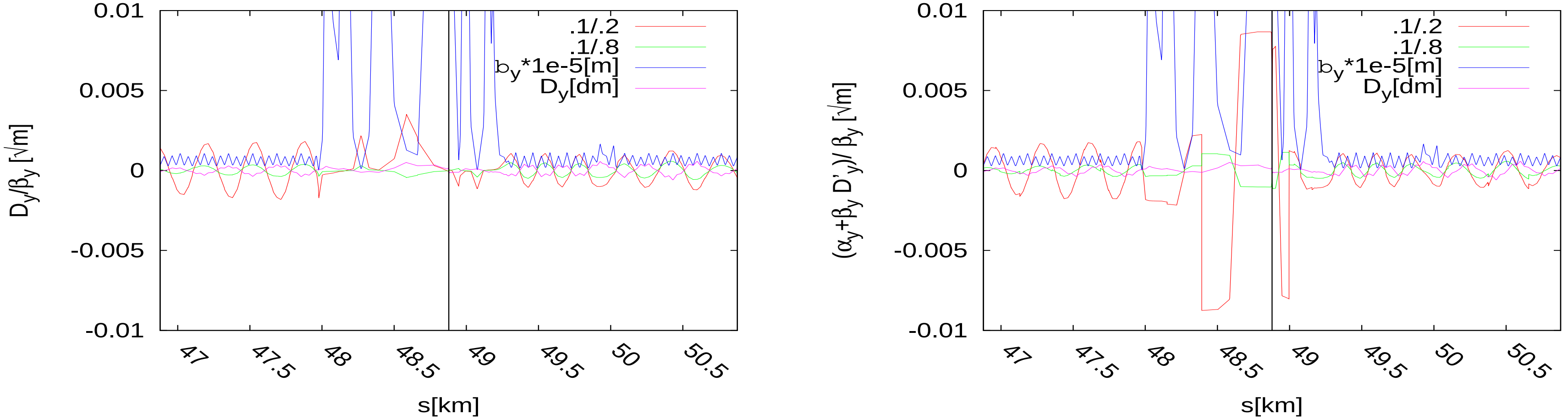








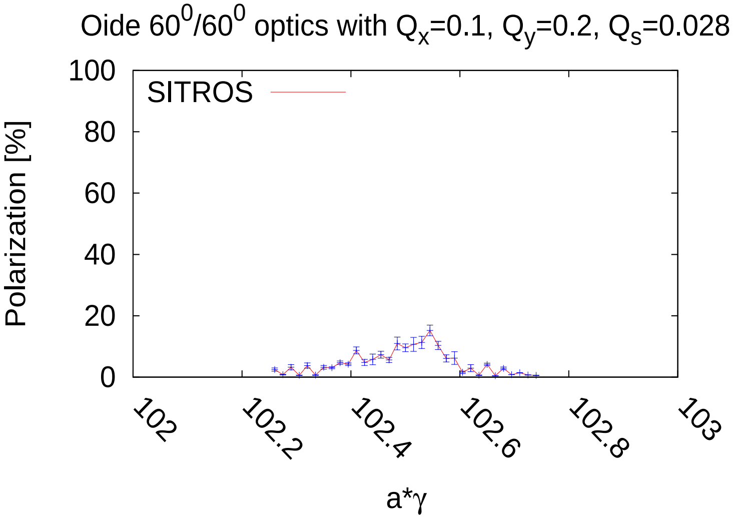
0.1/0.8



Large improvement of the factor → disease understood, a cure must be found!

Running SITROS (w/o wigglers, because bends array dimension exceeded...)

- .1/.8
  - "NaN" after ≃ 3000 turns
- .1/.2
  - Beam equilibrium found but $\boldsymbol{\epsilon_x}$=1.25 nm, $\boldsymbol{\epsilon_y}$=57.8 pm and little polarization...



Tracking problems

Why are the emittances found by SITROS tracking so large?

Repeat tracking for the ideal machine: ϵ_x=1 nm (instead of 0.24 nm), ϵ_y=0

Increase from 300 to 600 particles, no difference.

Increase number of bends for radiation (from 1400 to 2400): ϵ_x=1.1 nm

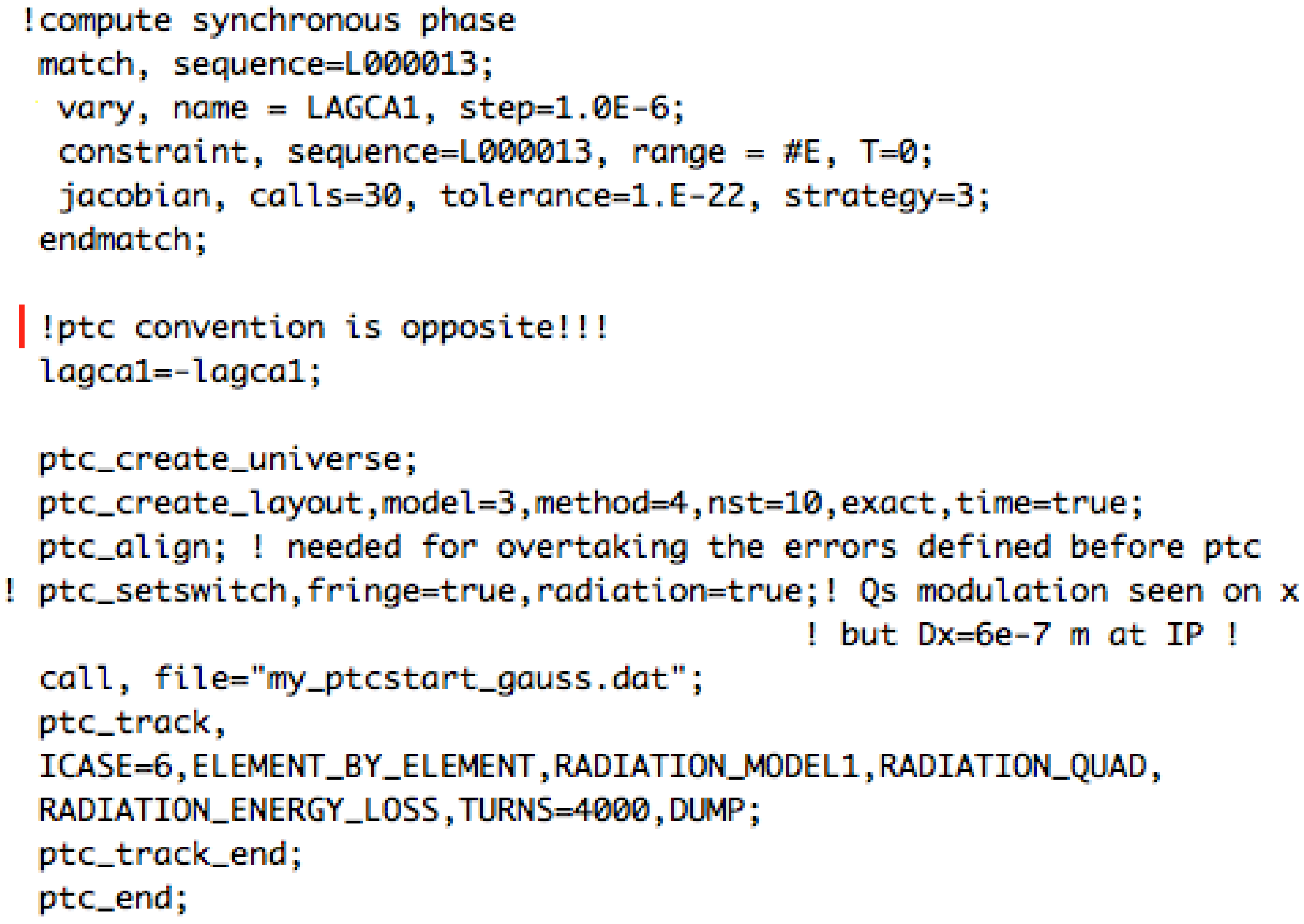
Try tracking with MADX-PTC.

- 40 particles
- 4D Gaussian distribution with 1 σ cut
- 4000 turns ($\simeq 2\ \tau_x$)

Hints from Tobias:

- PTC does not compute the synchronous phase
- sign convention is opposite to MADX

Used commands

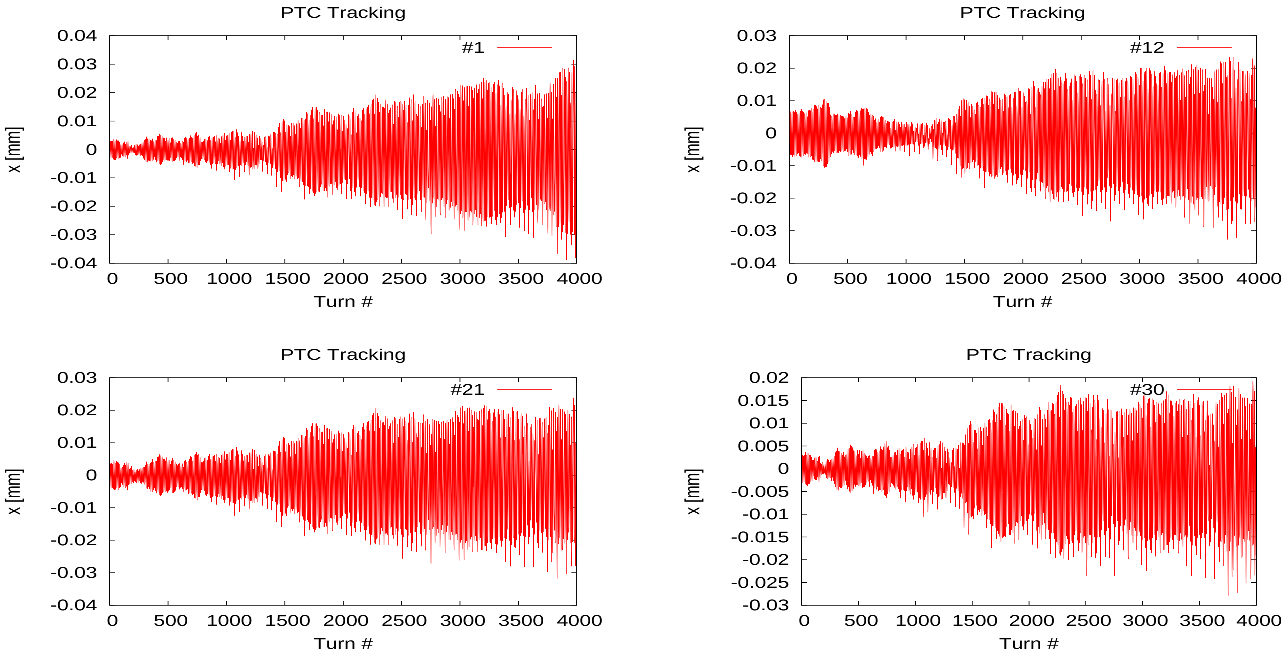


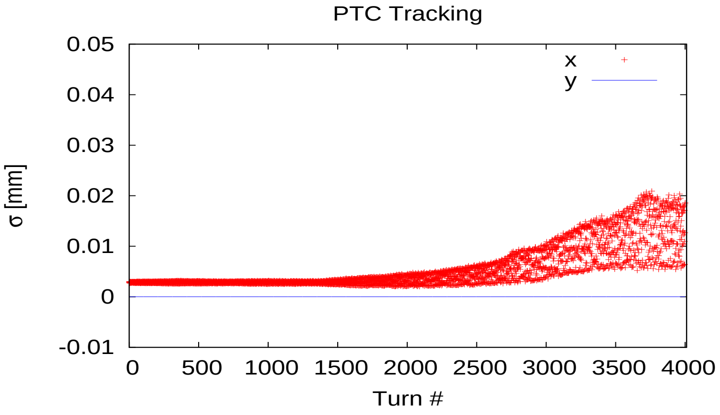
```
 !compute synchronous phase
  match, sequence=L000013;
   vary, name = LAGCA1, step=1.0E-6;
   constraint, sequence=L000013, range = #E, T=0;
   jacobian, calls=30, tolerance=1.E-22, strategy=3;
  endmatch;

  !ptc convention is opposite!!!
  lagca1=-lagca1;

  ptc_create_universe;
  ptc_create_layout,model=3,method=4,nst=10,exact,time=true;
  ptc_align; ! needed for overtaking the errors defined before ptc
! ptc_setswitch,fringe=true,radiation=true;! Qs modulation seen on x
                                          ! but Dx=6e-7 m at IP !
  call, file="my_ptcstart_gauss.dat";
  ptc_track,
  ICASE=6,ELEMENT_BY_ELEMENT,RADIATION_MODEL1,RADIATION_QUAD,
  RADIATION_ENERGY_LOSS,TURNS=4000,DUMP;
  ptc_track_end;
  ptc_end;
```

Ideal machine, tunes: .1/.2/.024

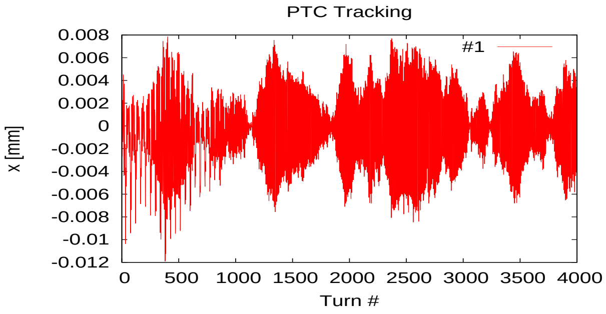


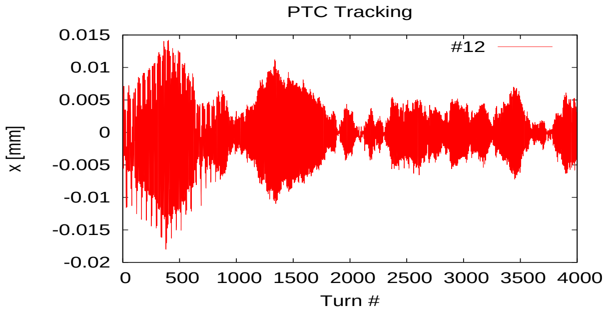


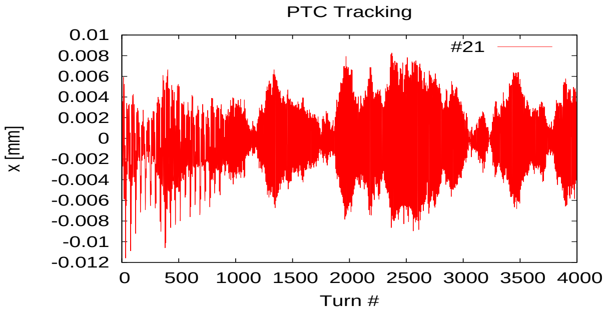
$\boldsymbol{\sigma_x} \simeq 13\ \boldsymbol{\mu}\mathrm{m} \rightarrow \boldsymbol{\epsilon_x}=1.1\ \mathrm{nm}$

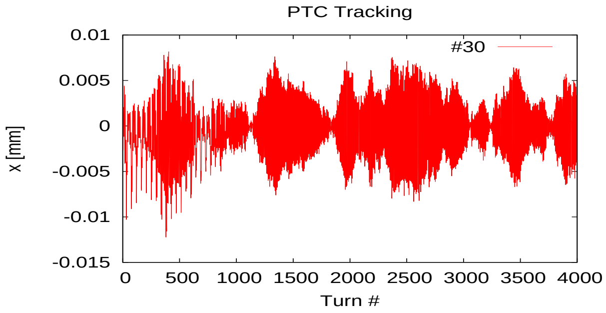
in agreement with SITROS !

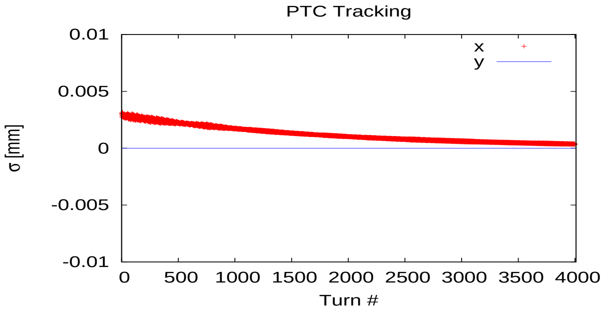
Repeat using “ptc_setswitch”

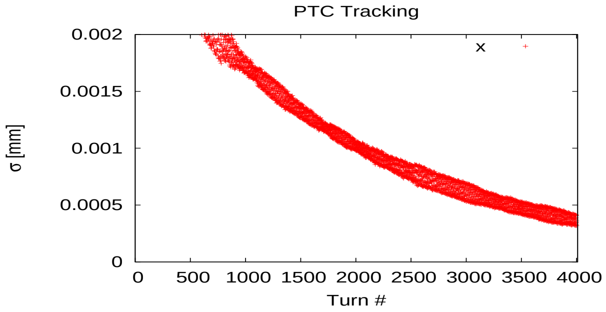








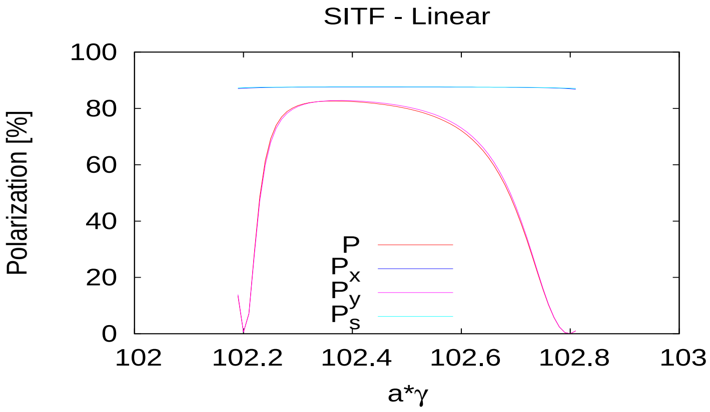


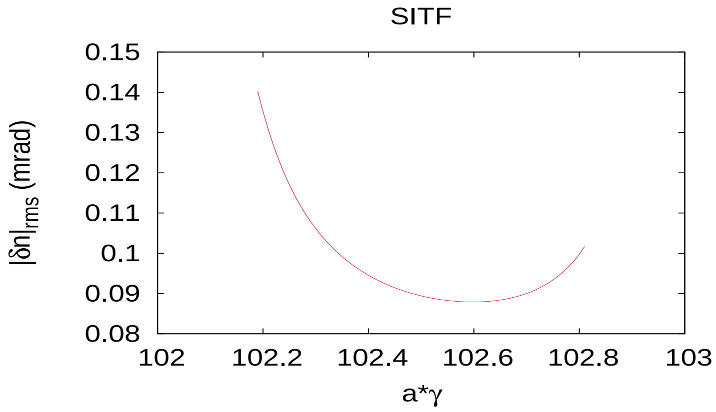


$$\boldsymbol{\sigma_x} \lesssim 0.318\ \boldsymbol{\mu}\text{m} \rightarrow \boldsymbol{\epsilon_x} \lesssim 0.7\ \text{pm}$$

Back to the polarization problem

Tried a different seed: same problem. Found skew quadrupole settings improving $\Delta_\pm$ at expenses of betatron coupling. With .1/.2 tunes:





	x_{rms} (μm)	y_{rms} (μm)	D^y_{rms} (mm)	ϵ_x (nm)	ϵ_y (pm)	$\lvert C^-\rvert$
no skews	41	16	12	0.222	12	0.017
with	40	17	7	0.220	5	0.022

Problems by SITROS tracking: no equilibrium found, particles “lost” because of too large vertical amplitude!

- Decreasing the errors by a factor 3 and eliminating errors on BPMs did not help.
- Equilibrium instead is found for the ring w/o errors.
- Did I introduce a bug in the code?? Verified that reasonable values of equilibrium emittance are obtained with SITROS tracking for the optics prior to the $\boldsymbol{\beta_y^*}$=0.8 mm one and the introduction of 4 more wigglers.