Simulations for FCC-ee beam self-polarization

E. Gianfelice (Fermilab)

VYDIO December 14, 2017

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

- Program for coupling functions $\boldsymbol{w}^{\pm}$ correction brought back in operation and modified for new 45 GeV optics.
- More systematic investigation of effect of single errors: work ongoing.

The new 45 GeV optics with smaller $\boldsymbol{\beta}_{\boldsymbol{y}}^{*}$

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

Reminder

Previous optics with “reasonable” errors

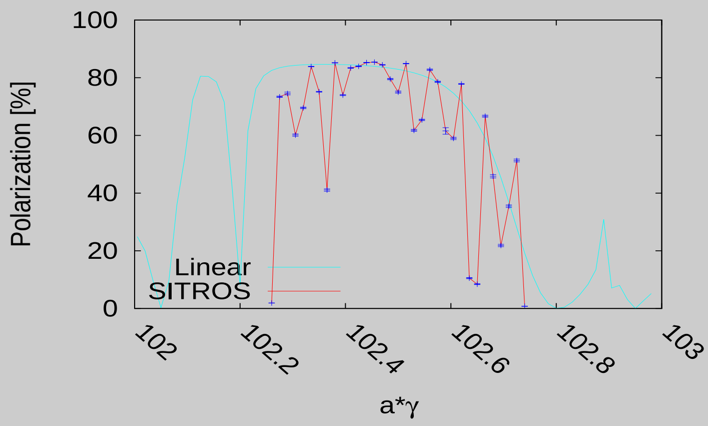
- 8 doublet quads
  - δx^q_{rms}=δy^q_{rms}=50 μm
  - 50 μrad roll angle
- all other quads
  - δx^q_{rms}=δy^q_{rms}=100 μm
  - 100 μrad roll angle
- 3148 BPMs *coupled* to near-by-quadrupole.

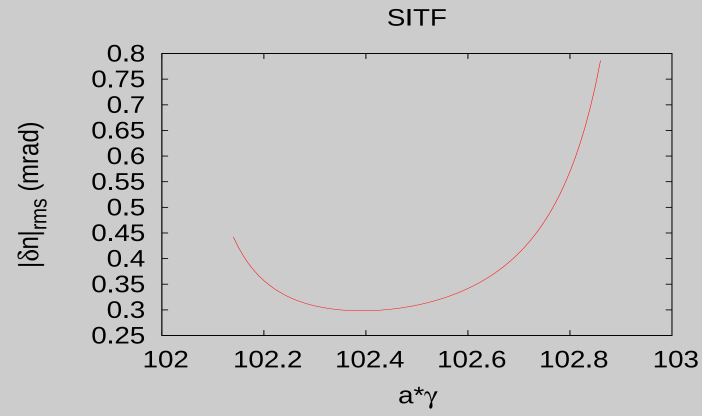
Orbit corrected with 1574 CHs +1586 CVs (one particular seed) down to

- x_{rms}= 75 μm w/o BPMs errors $\longrightarrow$ 92 μm with BPMs offset&tilt
- y_{rms}= 41 μm w/o BPMs errors $\longrightarrow$ 57 μm with BPMs offset&tilt

For a particular machine realization (no statistics)

a) machine stable with errors in the quads only, $|\boldsymbol{C^-}| \simeq 0.015$ and $\boldsymbol{D_y^{rms}} \simeq 7$ mm





b) stable but large coupling ($|\boldsymbol{C^-}|$=0.074) and emittance ($\boldsymbol{\epsilon_x} \simeq 140$ pm, $\boldsymbol{\epsilon_y} \simeq 17$ pm at 45 GeV) with BPMs offset and tilt;

c) Twiss failure with calibration errors as small as 0.1% (?).

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.

[a] errors added in 10 steps

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

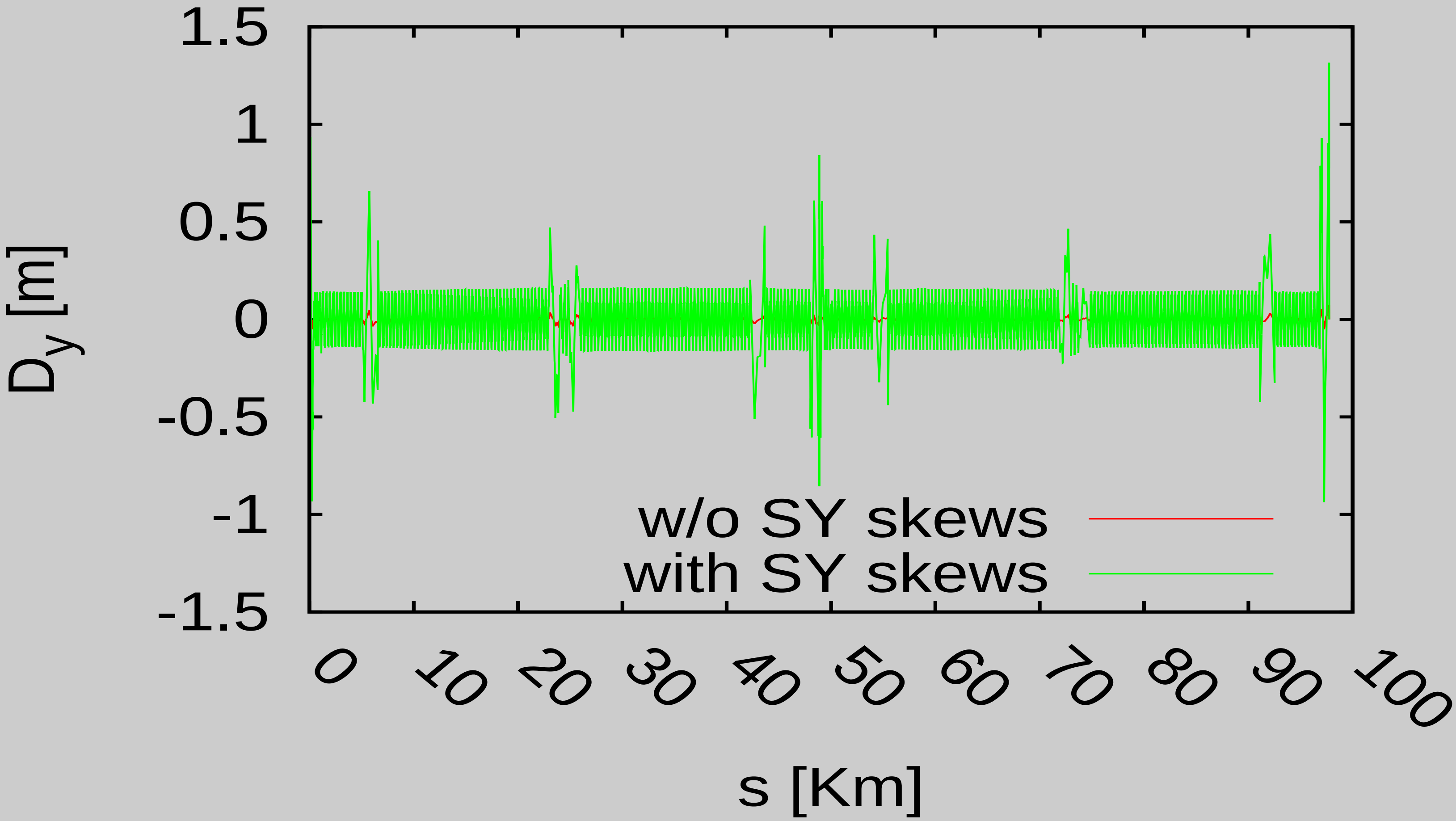
	IR Quads	IR BPMs	other Quads	other BPMs
δx (μm)	0	0	50	50
δy (μm)	0	0	50	50
$\delta\theta$ (μrad)	0	0	50	50
calibration	-	0	-	1%

- The coupling is due mainly to the SYs: with them off it is $|C^-| < 0.002$
- they also compensate each other so that it is not possible to switch them off individually.

$\rightsquigarrow$ 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 $K = -S \times \ell \times y$ it is possible to reach $|C^-| \simeq 0.0009$, but indeed vertical dispersion increases.

[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.

New optics: IR

Adding errors to QC1R1.1 for an otherwise *undistorted* machine : most challenging is the vertical displacement.

Twiss failure with $\boldsymbol{\delta^Q y}$=10 $\boldsymbol{\mu}$m by switching on the SY sextupoles with beam offsets of $\simeq \pm 0.6$ mm at SYs.

It is necessary to improve the correction. I have already a BPM in the center of each SY and I have a vertical corrector at 0.1 m from QC1R1.1

By adding a second vertical corrector just after the QC1R1.1 it is possible to reach $\boldsymbol{\delta^Q y}$=100 $\boldsymbol{\mu}$m with beam offsets at the SYs of $\simeq \pm 0.3$ mm.

In the real machine one would resort to dipole (and skew quad) windings for a fully local correction (as in HERA-e after luminosity upgrade). But neither MADX or SITROS can digest overlapping elements.

So for the IR quads there is a “cure” but we can’t propose it for all the quads...

Simulation with MADX: ignoring the IR quads errors seems too crude. Adding a second corrector or move it closer may be the solution w/o investing time in BMAD.

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%

IP1 Right (seed=17): stable, $|C^-|$ ≃0.014 SYs on, *unchanged* when off: this coupling come from the quads tilt itself! It can be conveniently corrected by skew quad windings because D_x=0. Using 5 skew quad multipoles it is reduced to 0.008, no better... For the moment I try the distributed correction.

IP1 Left (seed=19): stable, $|C^-| < 0.002$ SYs on.

IP2 Left (seed=15): stable, $|C^-|$ ≃0.011 SYs on *unchanged* when off.

IP2 Right (seed=21): stable, $|C^-|$ ≃0.012 SYs on.

All other quads (seed=13): stable, $|C^-| < 0.002$ SYs on.

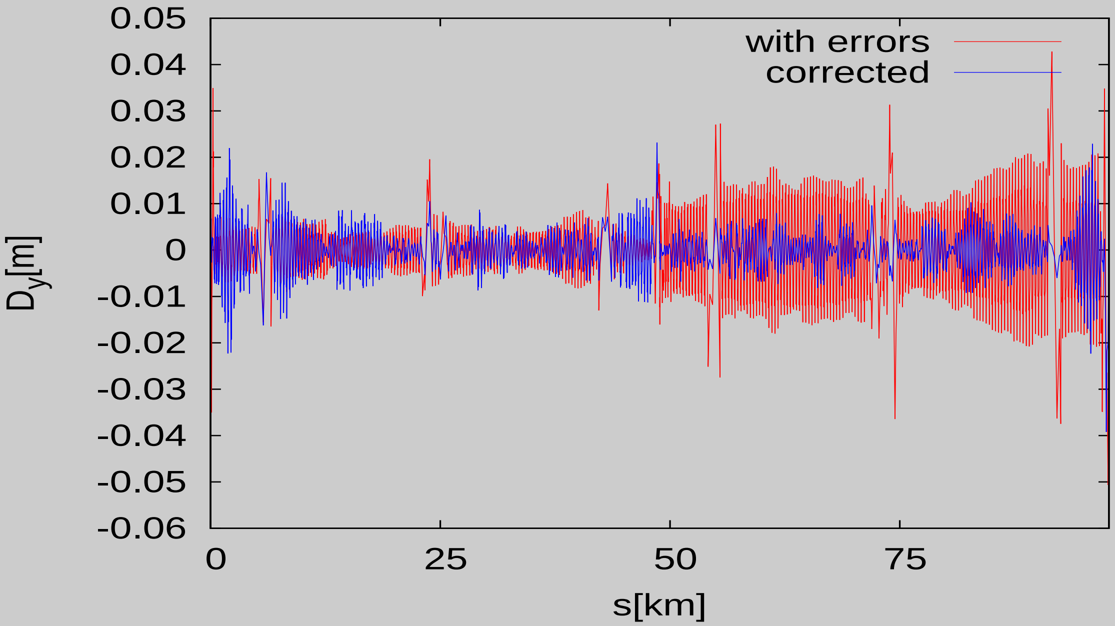
Put all together : stable machine with $|C^-|$ ≃0.018.

	D^y_{rms}	ϵ_x	ϵ_y	ϵ_ℓ
	mm	nm	pm	μm
unp.	0	0.255	0.0000	1.259
errs+corrs	11.4	0.254	2.937	1.237

with V=96 MV

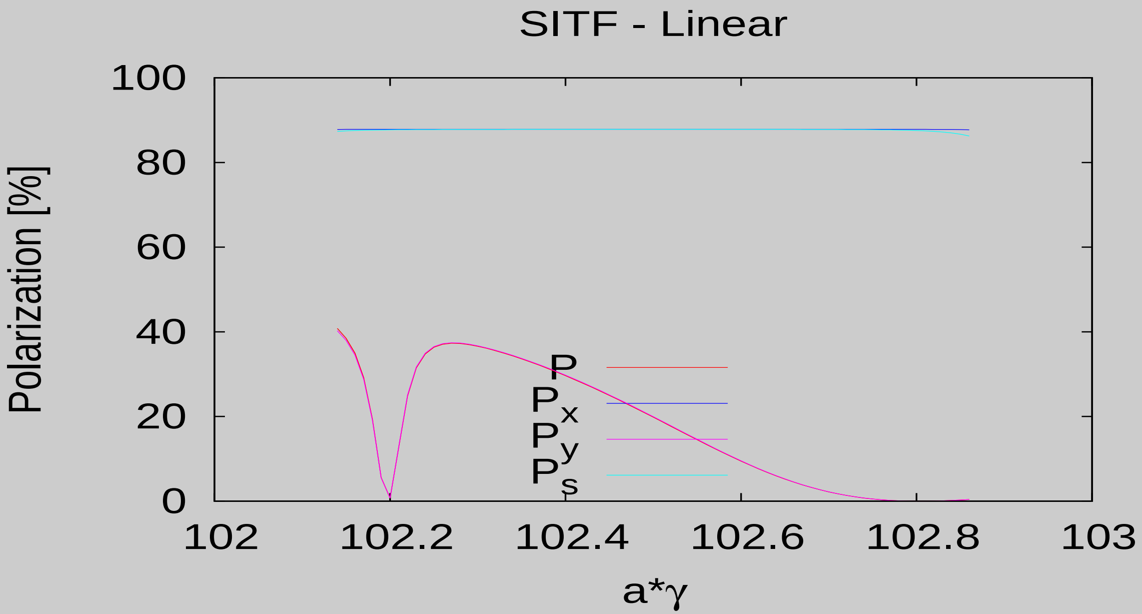
Use 290 skews for correcting coupling and vertical dispersion

	D^y_{rms}	ϵ_x	ϵ_y	$\|C^-\|$ (TBT)
	mm	nm	pm	a.u.
errs+corrs	11.4	0.254	2.937	0.0207
errs+corrs +skews (1 iter)	4.0	0.255	0.265	0.0013



But problems:

- When the wigglers are on ϵ_y increases: $\epsilon_y/\epsilon_x \simeq$0.4%! A hint that the vertical dispersion is "too" large.
- (Linear) Polarization largely limited by vertical motion to $\simeq$35% ($|\delta\hat{n}_0|_{rms} \simeq$0.15 mrad)



Switching wigglers off ($\rightarrow \epsilon_y$=0.265 pm) does not improve polarization!

Arcs: change strategy

Vertical dispersion increases when moving to "polarization tunes"

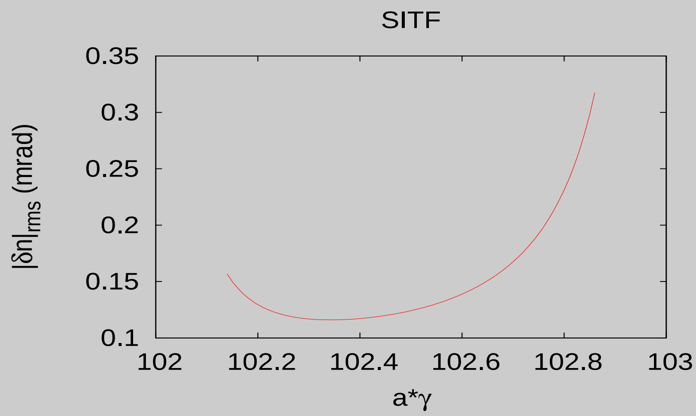
- Switch to .1/.2 tunes and turn on sextupoles at the end of the orbit correction and re-correct orbit (if stable...)

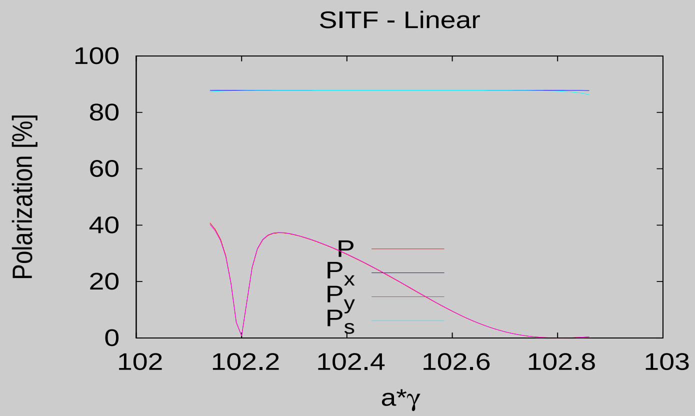
	IR Quads	IR BPMs	other Quads	other BPMs
δx (μm)	0	0	50	50
δy (μm)	0	0	50	50
$\delta\theta$ (μrad)	0	0	50	50
calibration	-	0	-	1%

- 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.

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





No improvement wrt to the case including errors in the IR quads!

Back to theory. In linear approximation

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

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

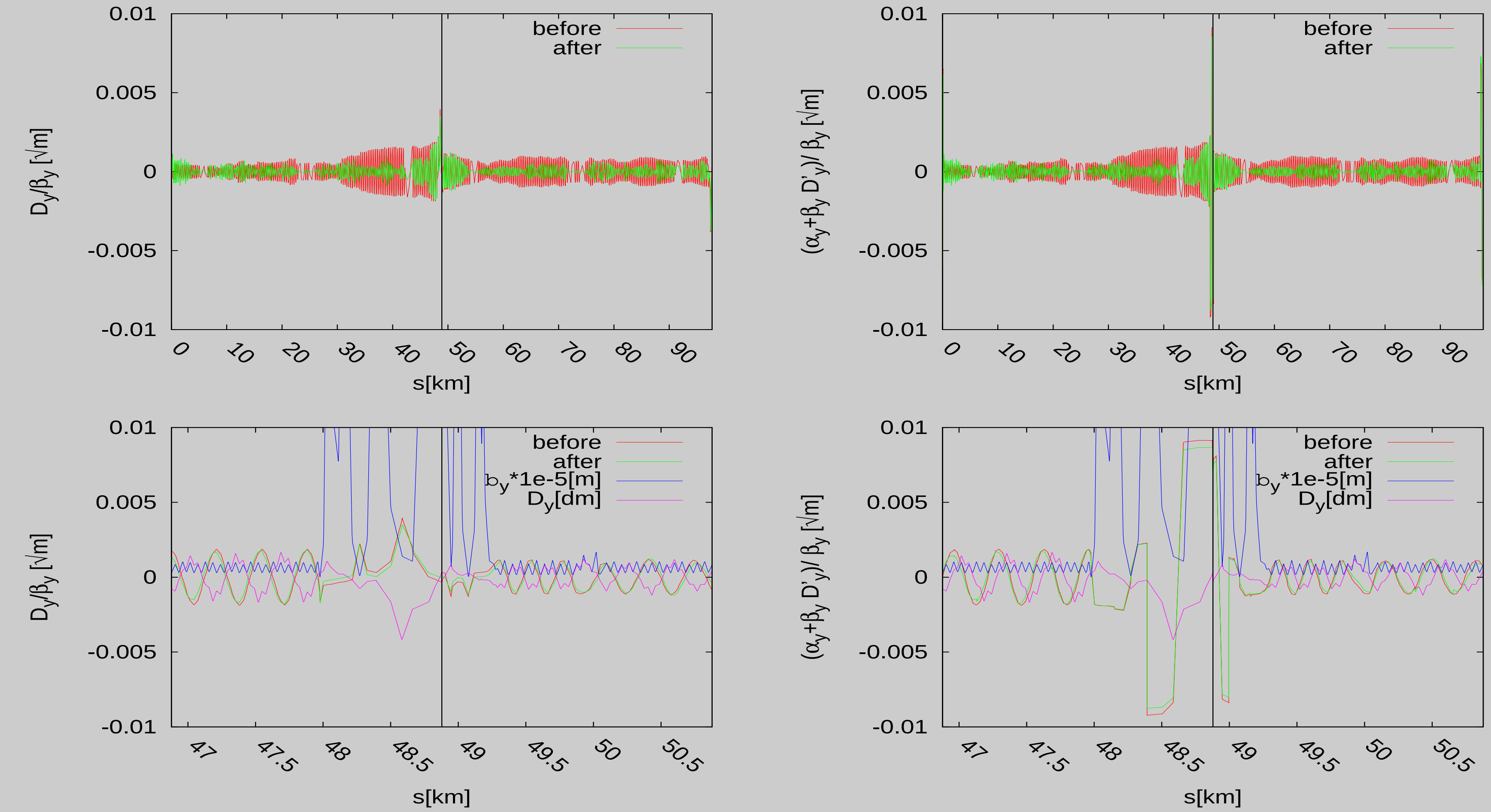
$$\Delta_{\pm s} = (1 + a\gamma)\frac{e^{\pm i\mu_s}}{e^{2i\pi(\nu \pm Q_s)} - 1}\; J_s$$

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

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

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

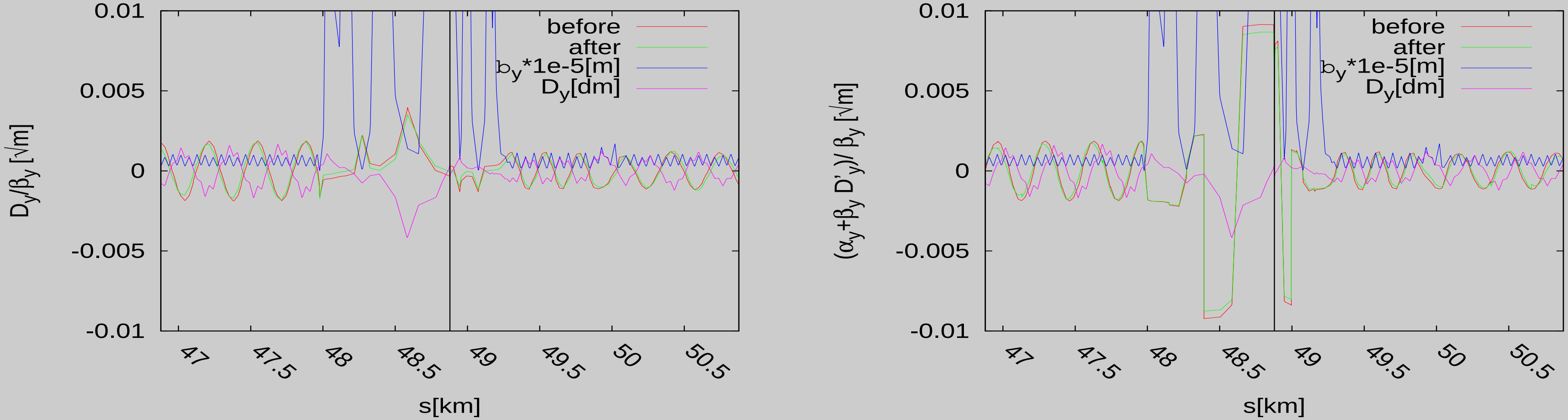
Plotting the factor $\frac{[-D_y \pm i(\alpha_y D + \beta D'_y)]}{\sqrt{\beta_y}}$ which multiplies $J_{\pm y}$



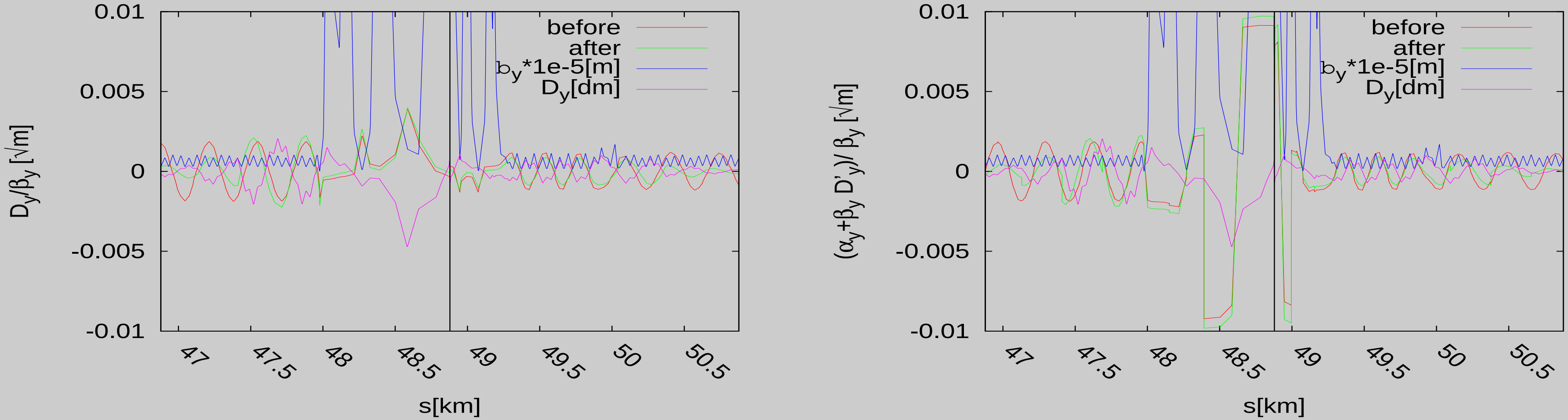
Hypothesis: the factor $\frac{[-D_y \pm i(\alpha_y D + \beta D'_y)]}{\sqrt{\beta_y}} D_y$ must be better controled!

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

Correcting coupling and $\boldsymbol{D_y}$



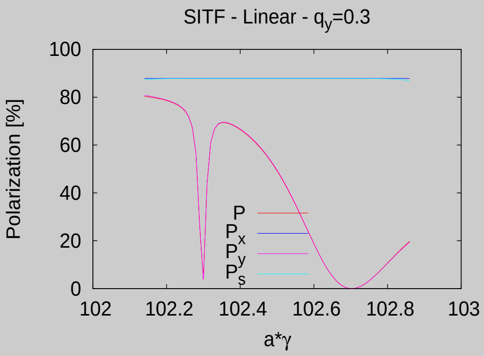
Correcting only $\boldsymbol{D_y}$

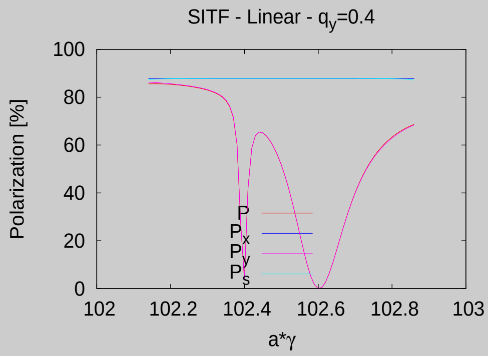


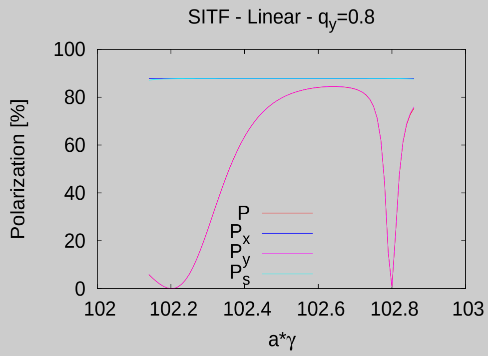
Indeed no improvement of the factor.

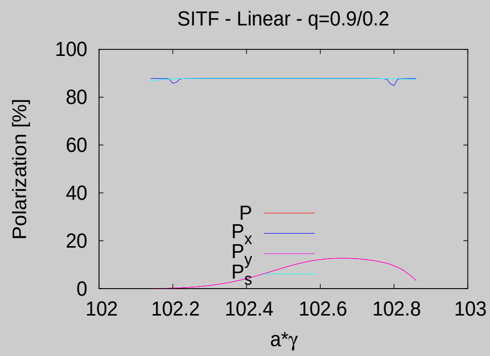
Swopping tunes: $\boldsymbol{P_y} \to 0$

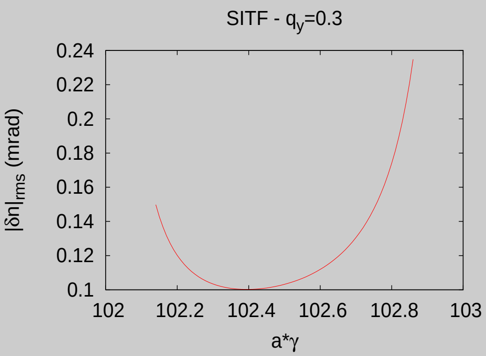
Increasing $\boldsymbol{Q_y}$ to .3 helped!

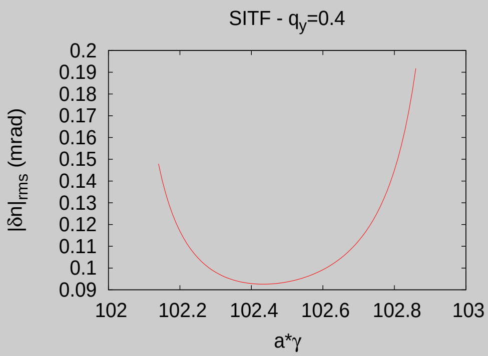


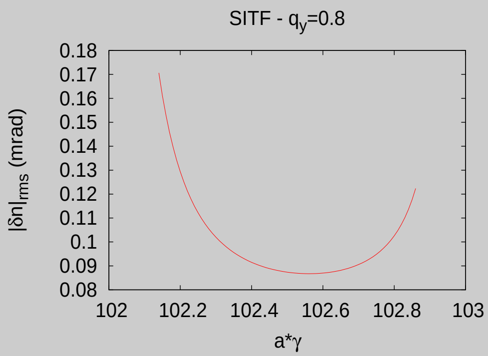


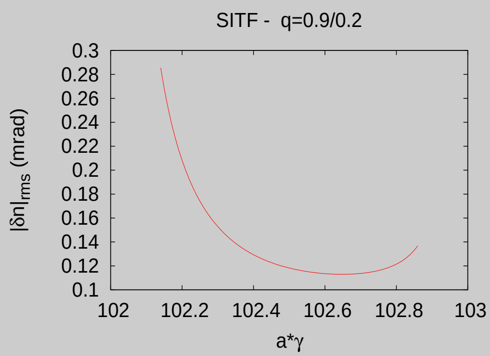




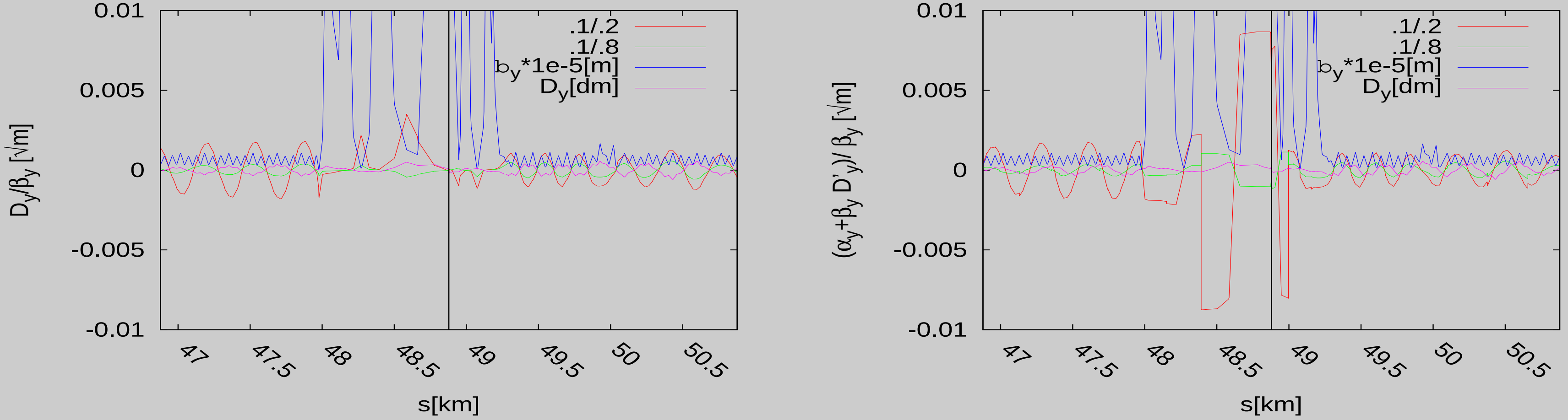








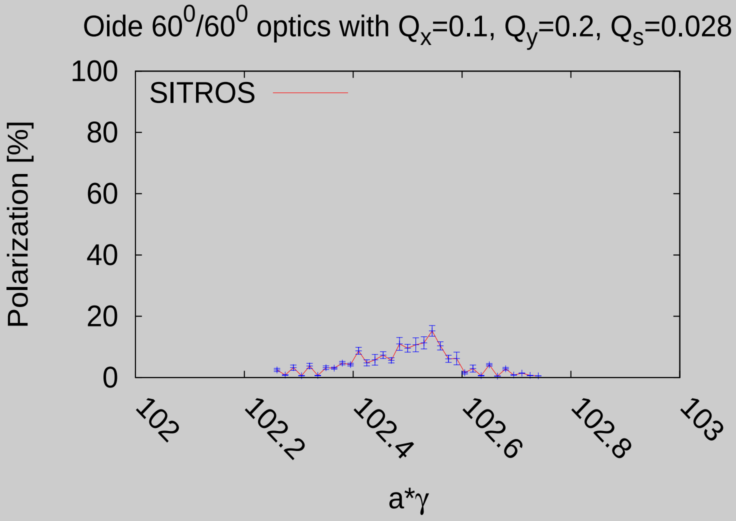
0.1/0.8



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

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

- .1/.8
  - "NaN" after $\simeq$ 3000 turns (confirmed by MADX-PTC tracking)
- .1/.2
  - Beam equilibrium found but ϵ_x=1.25 nm, ϵ_y=57.8 pm and little polarization...



A new problem?

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 ($\simeq 2\ \tau_x$)

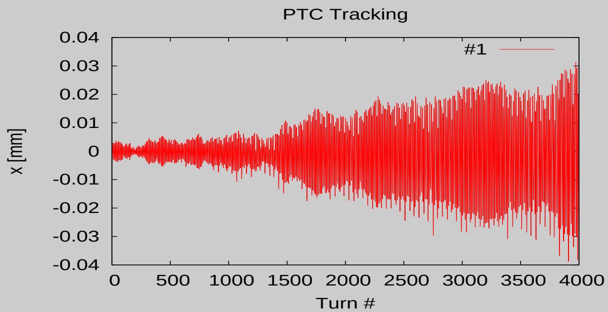
Hints from Tobias:

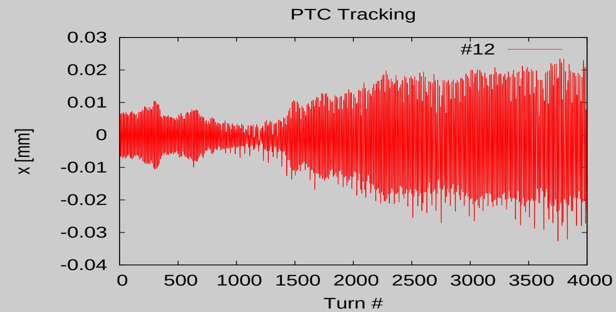
- PTC does not compute the synchronous phase
- sign convention is opposite to MADX

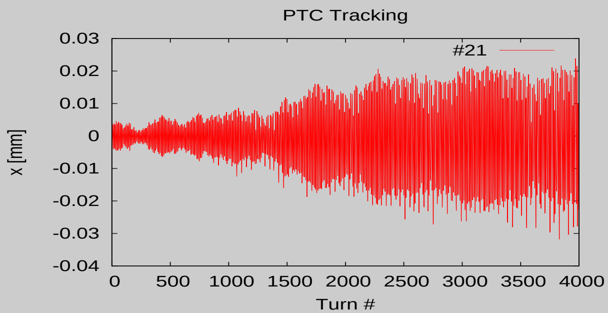
Used commands

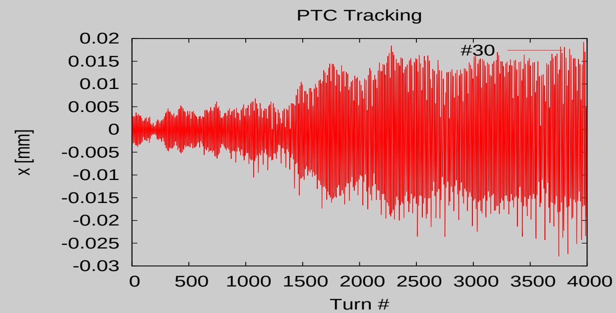
```
!compute synchronous phase
 match, sequence=L000013;
  vary, name = LAGCA1, step=1.0E-6;
  constraint, sequence=L000013, range = #E, T=0;
  jacobian, calls=30, tolerance=1.E-22, strategy=3;
 endmatch;

 !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;
```

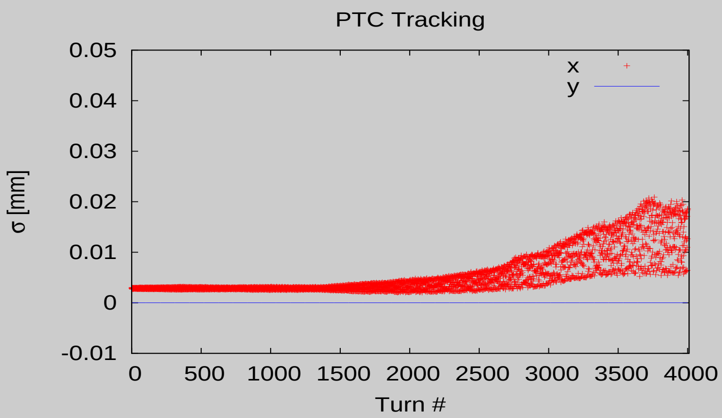
Ideal machine, tunes: .1/.2/.024







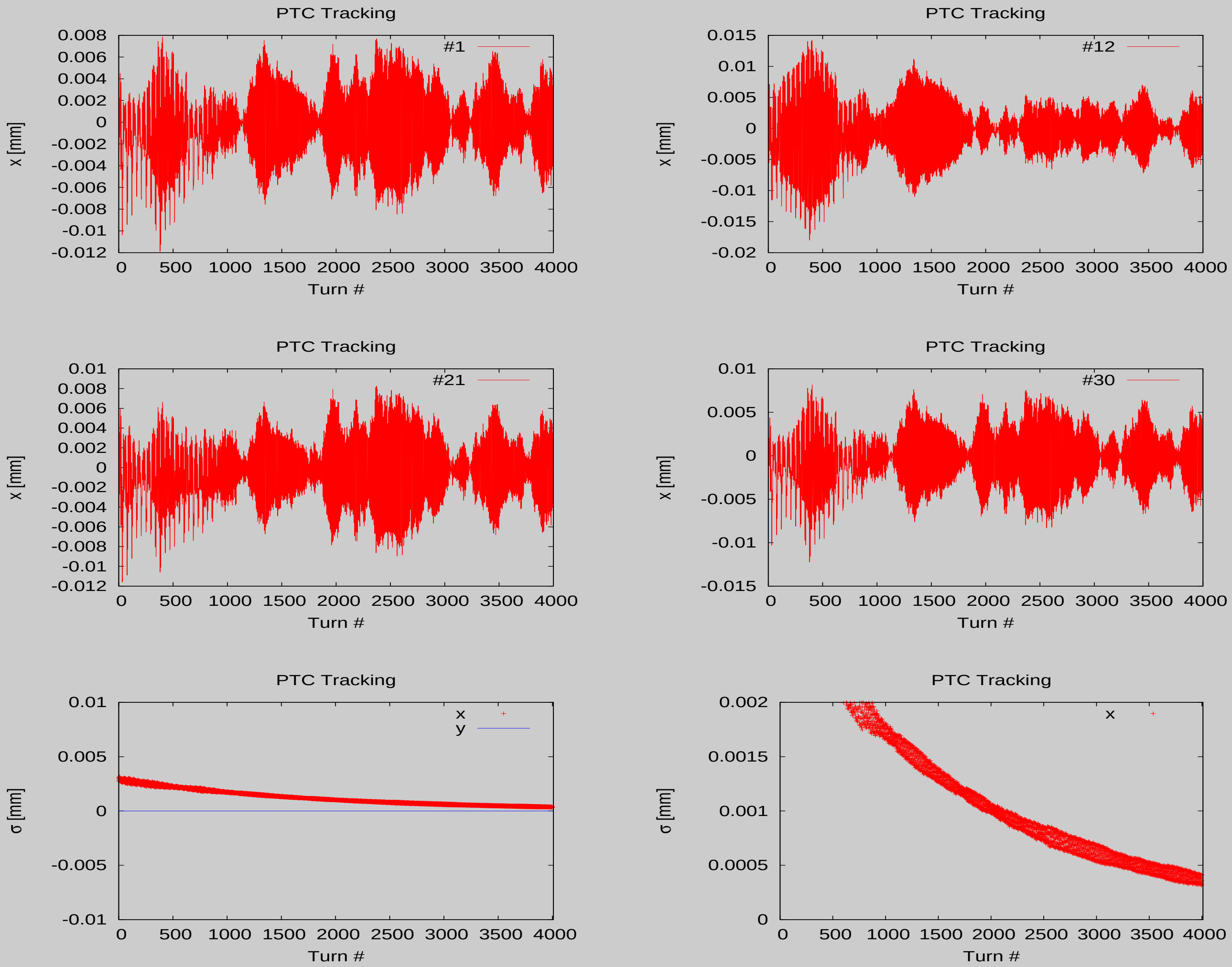




$\boldsymbol{\sigma_x} \simeq 13\ \boldsymbol{\mu}\text{m} \rightarrow \boldsymbol{\epsilon_x} = 1.1$ nm

in agreement with SITROS !

Repeat using “ptc_setswitch”



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