Tracking simulations for cERL-FEL with TSC using SAD

Demin Zhou

Accelerator laboratory, KEK

Acknowledgements:

N. Iida, R. Kato, T. Miyajima, N. Nakamura, K. Oide,

M. Shimada, Y. Tanimoto

cERL-FEL meeting, Aug. 06, 2020

Outline

- ➤ Simulation of CSR, LSC and TSC effects using SAD
  - * Use new magnet layout
  - * Use Gaussian fitted beam sizes for LSC/TSC effects
- ➤ Models for LSC and TSC
- ➤ Summary
- ➤ To-Do list

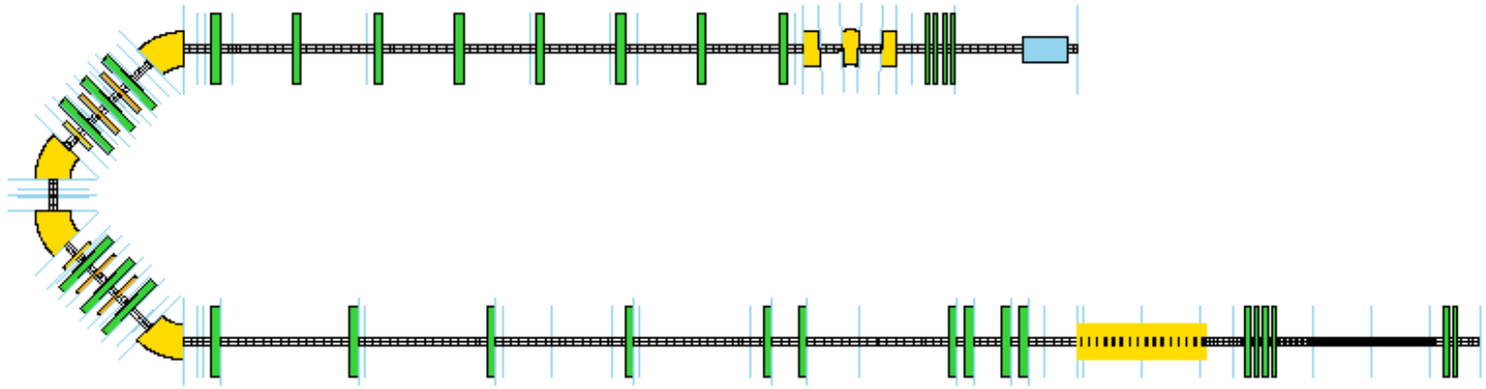
1. Introduction

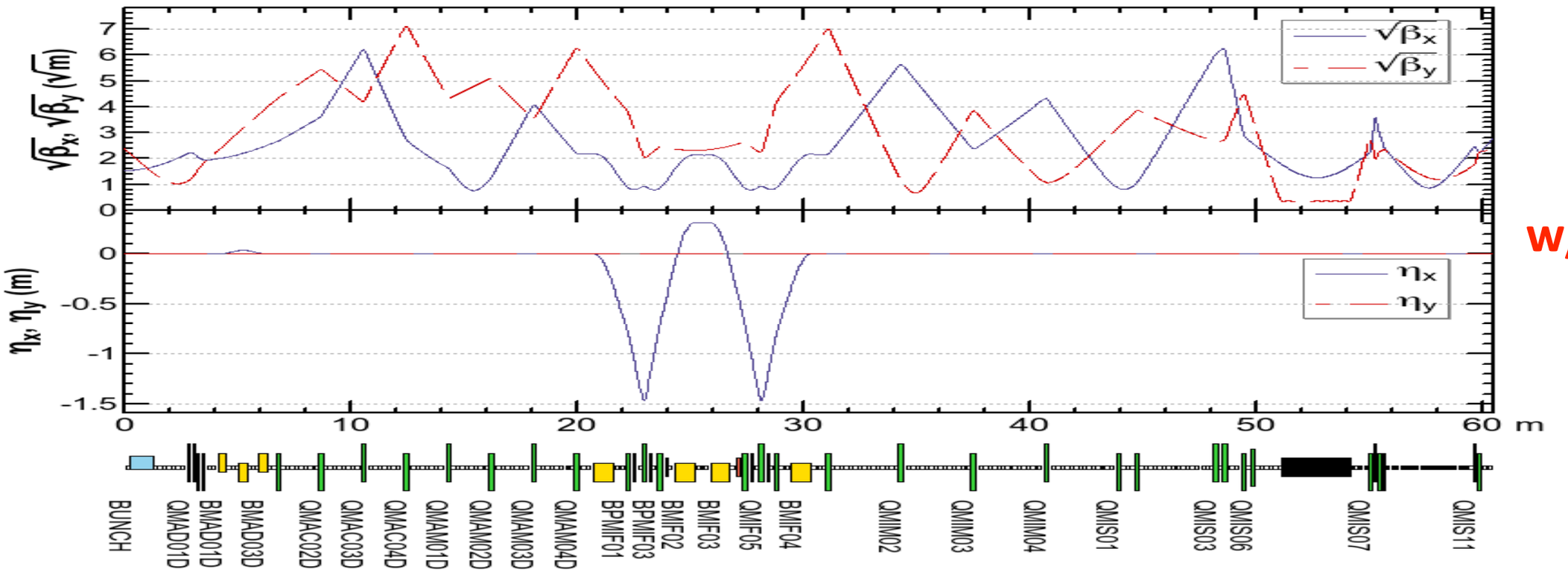
! p_central = 19.582453 (elegant)
MOMENTUM = 10.0066 MEV; ! SAD

Arc R_{56} = -0.1 m

ELEGANT files (Nakamura-san):

beam line: fel_arcR56_-0.1m_ML2ph_0deg.lte
run setup: fel_arcR56_-0.1m_ML2ph_0deg.ele
beam initial distribution: 5MeV_2ps_100k_new.sdds (# of particles: 1e5)





w/o TSC

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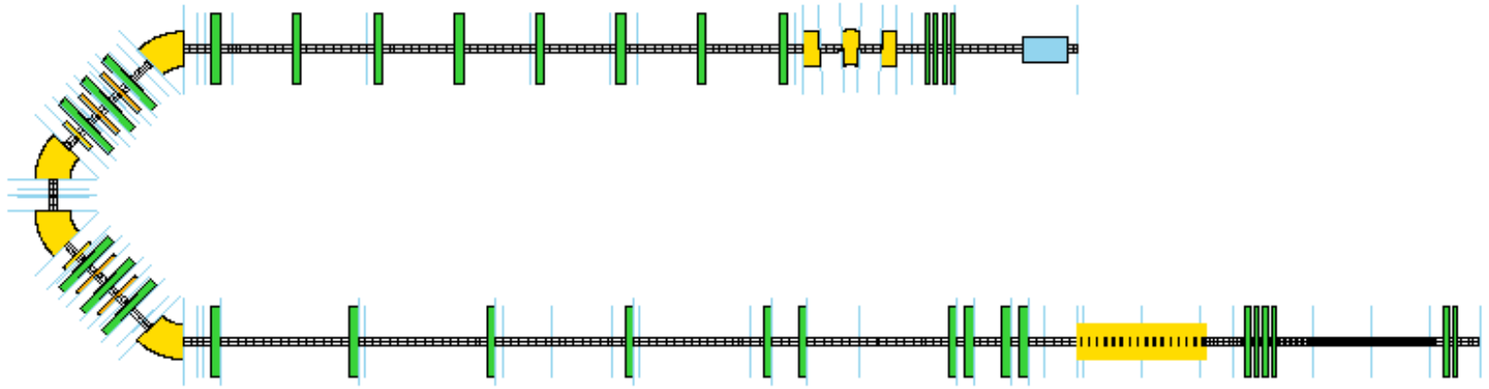

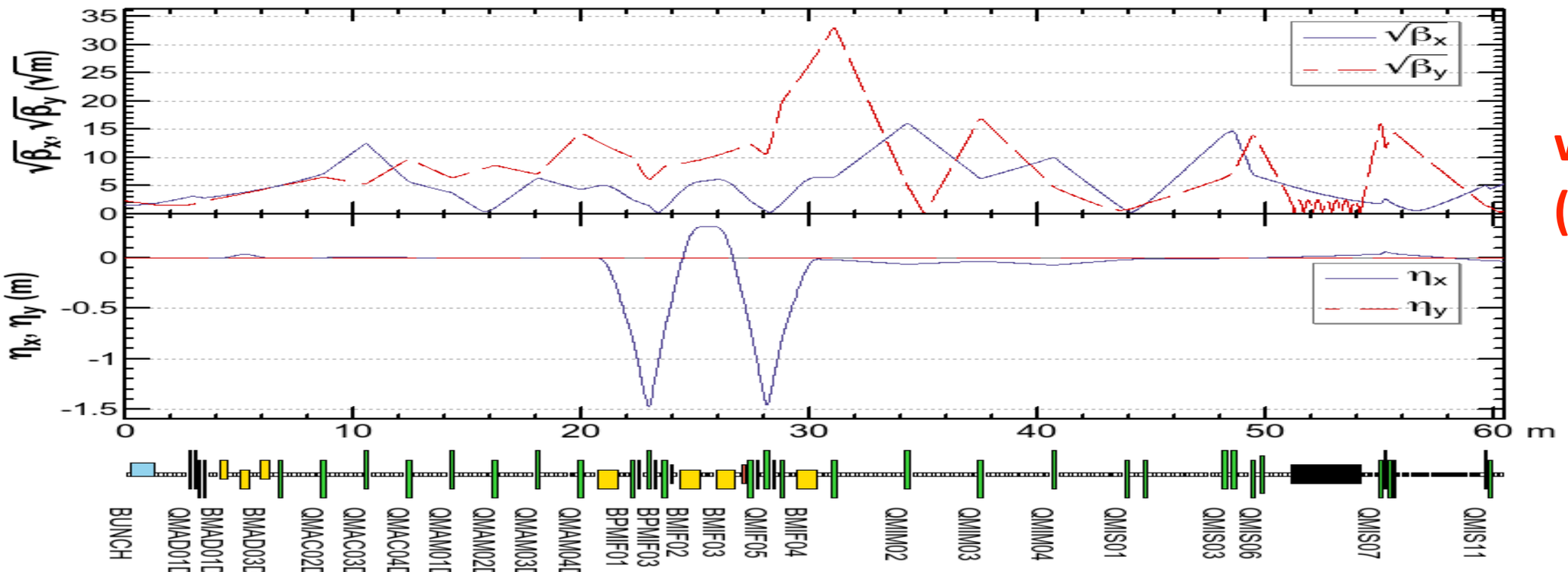

w/ TSC (WSPAC)

Thanks to K. Oide: devel version of SAD: https://github.com/KatsOide/SAD.git

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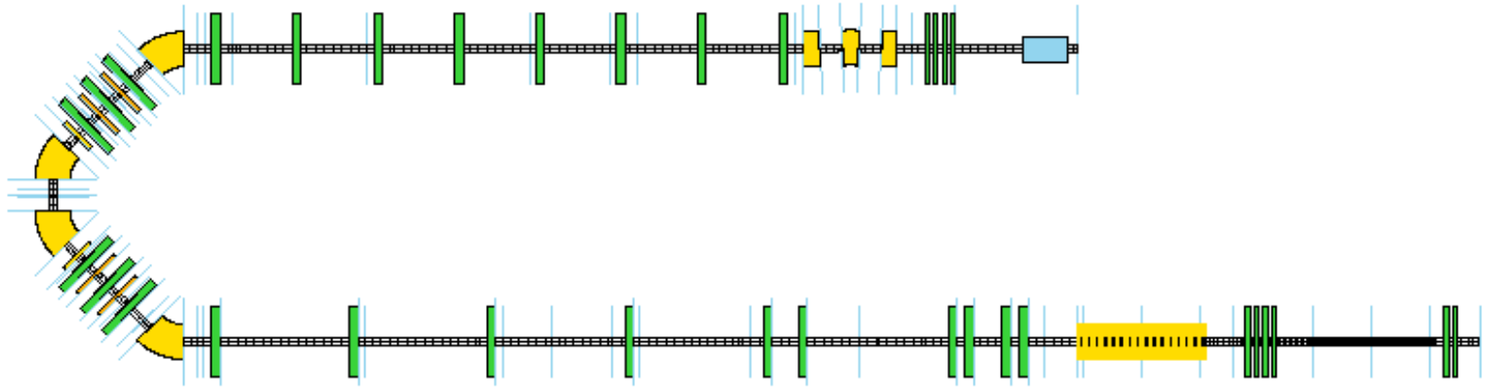

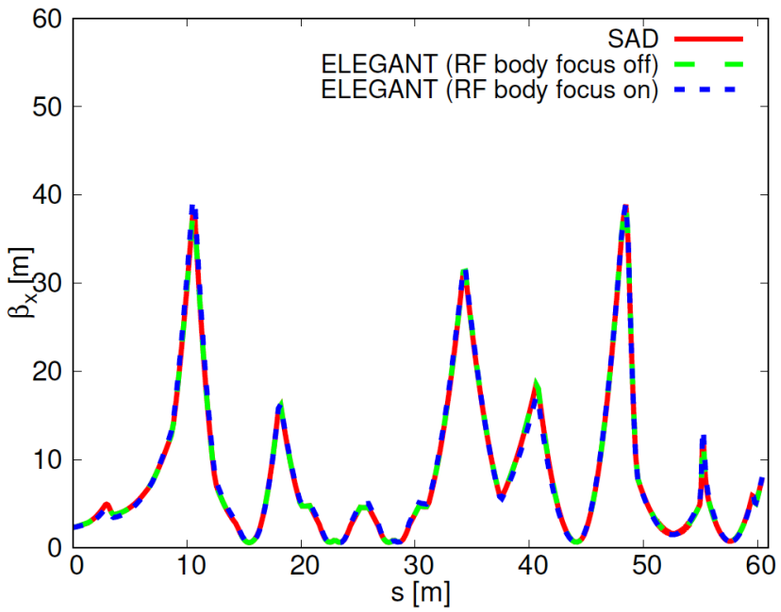

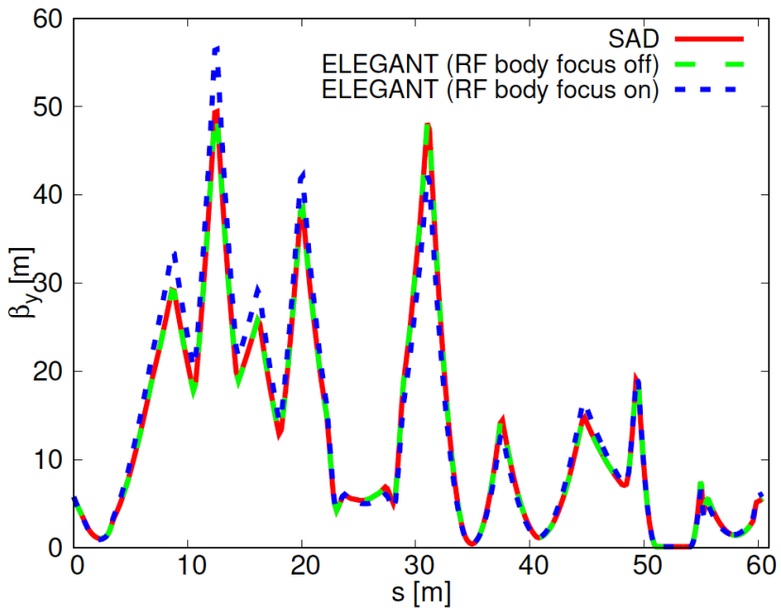

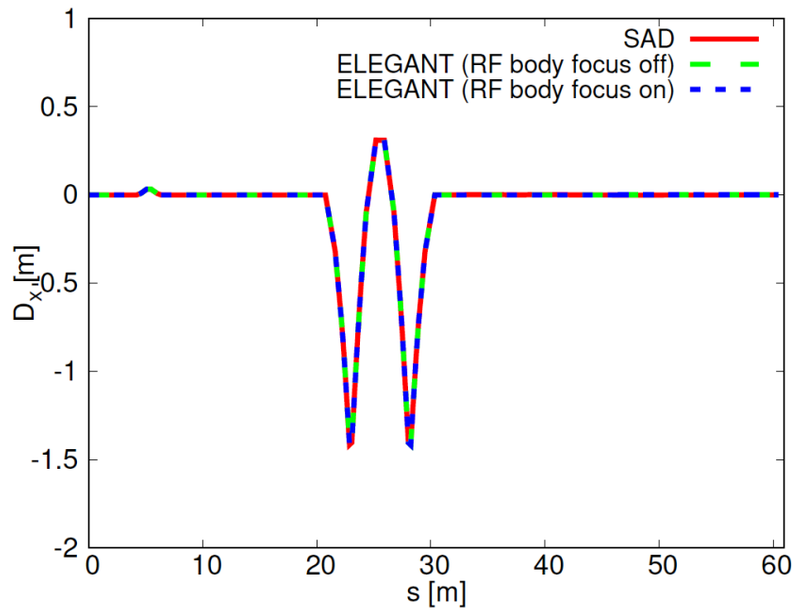

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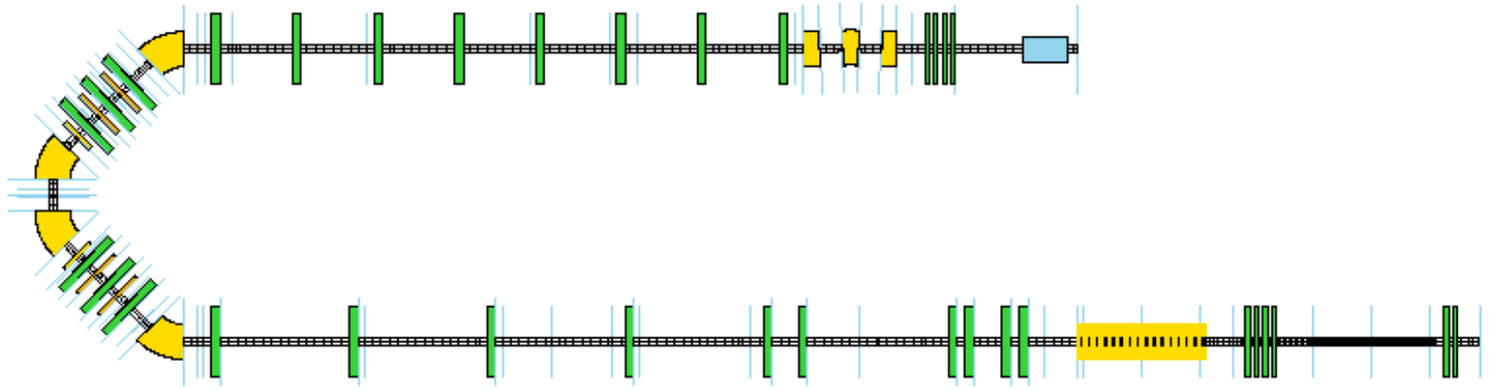
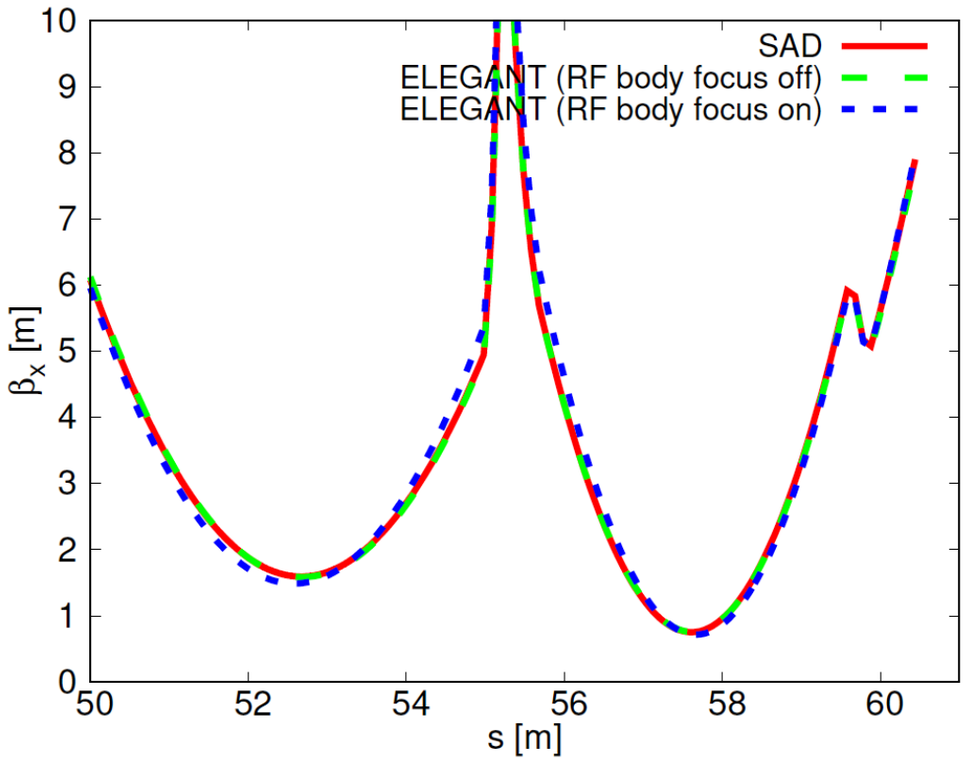
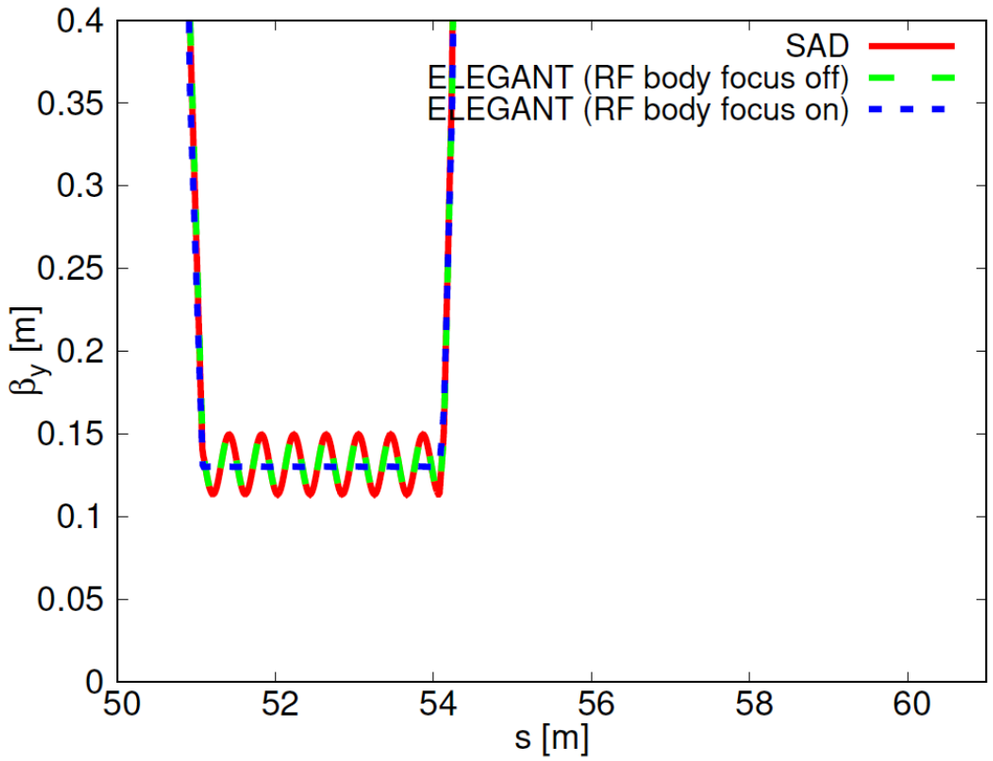






2. Tracking simulations

Simulation of CSR, LSC and TSC effects using SAD

rms energy spread:

*** CSR is remarkable in the arc**

*** LSC is most important**

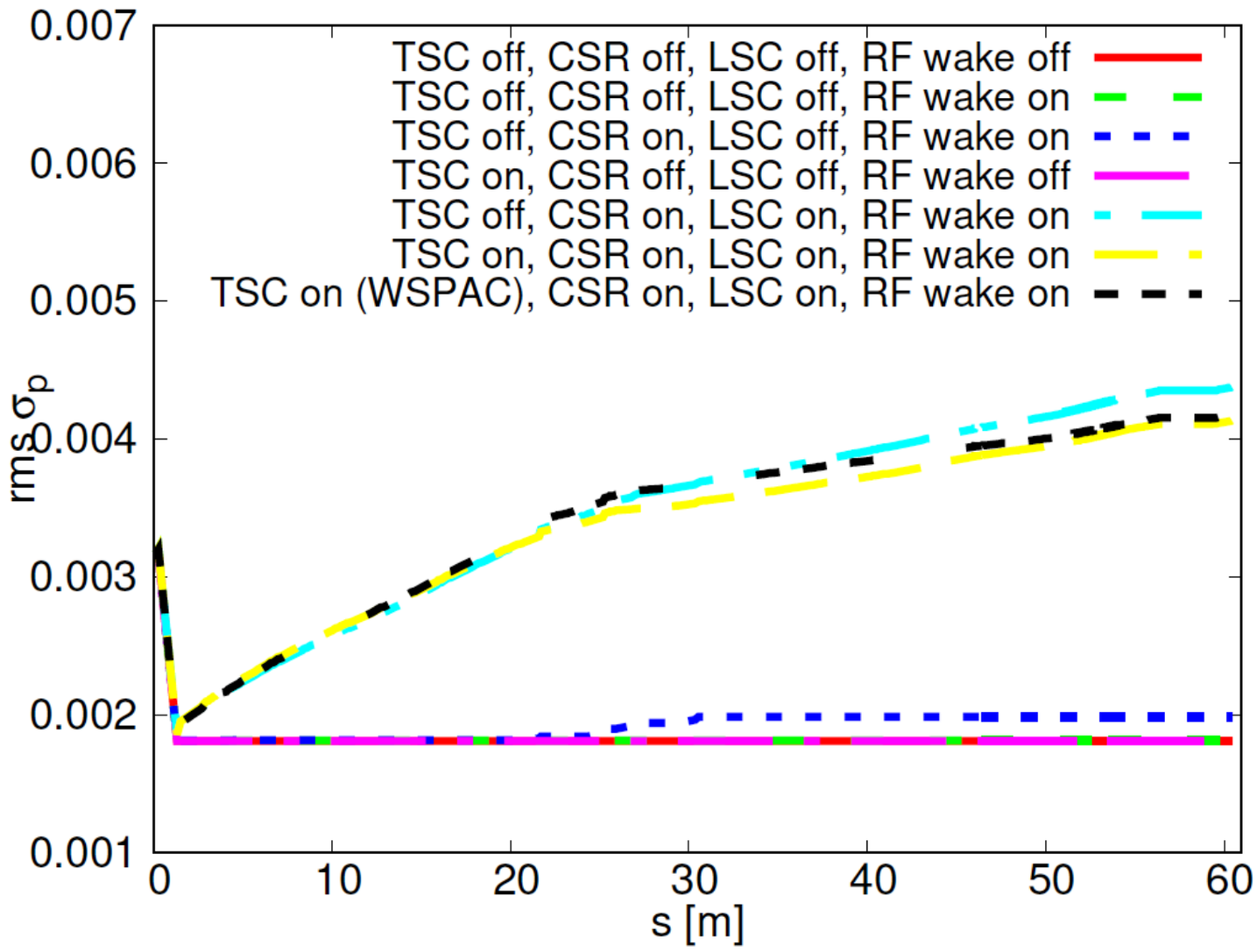
*** TSC is also remarkable (Mechanism: LSC depends on transverse beam sizes)**

Tracking with WSPAC using SAD:

*** Weak-strong model**

*** Nonlinear space-charge force with 3D Gaussian distribution**

*** Beam sizes given by optics with initial emittances and Twiss functions**



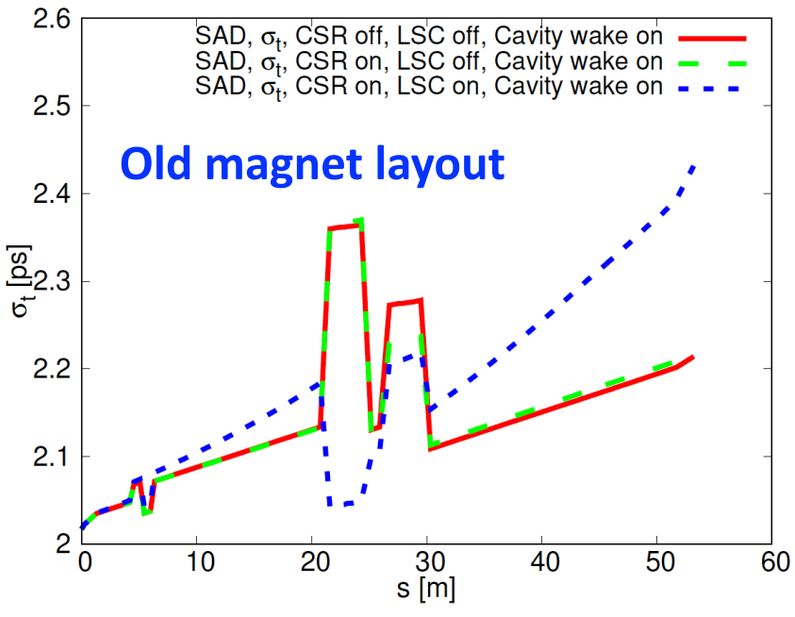
2. Tracking simulations

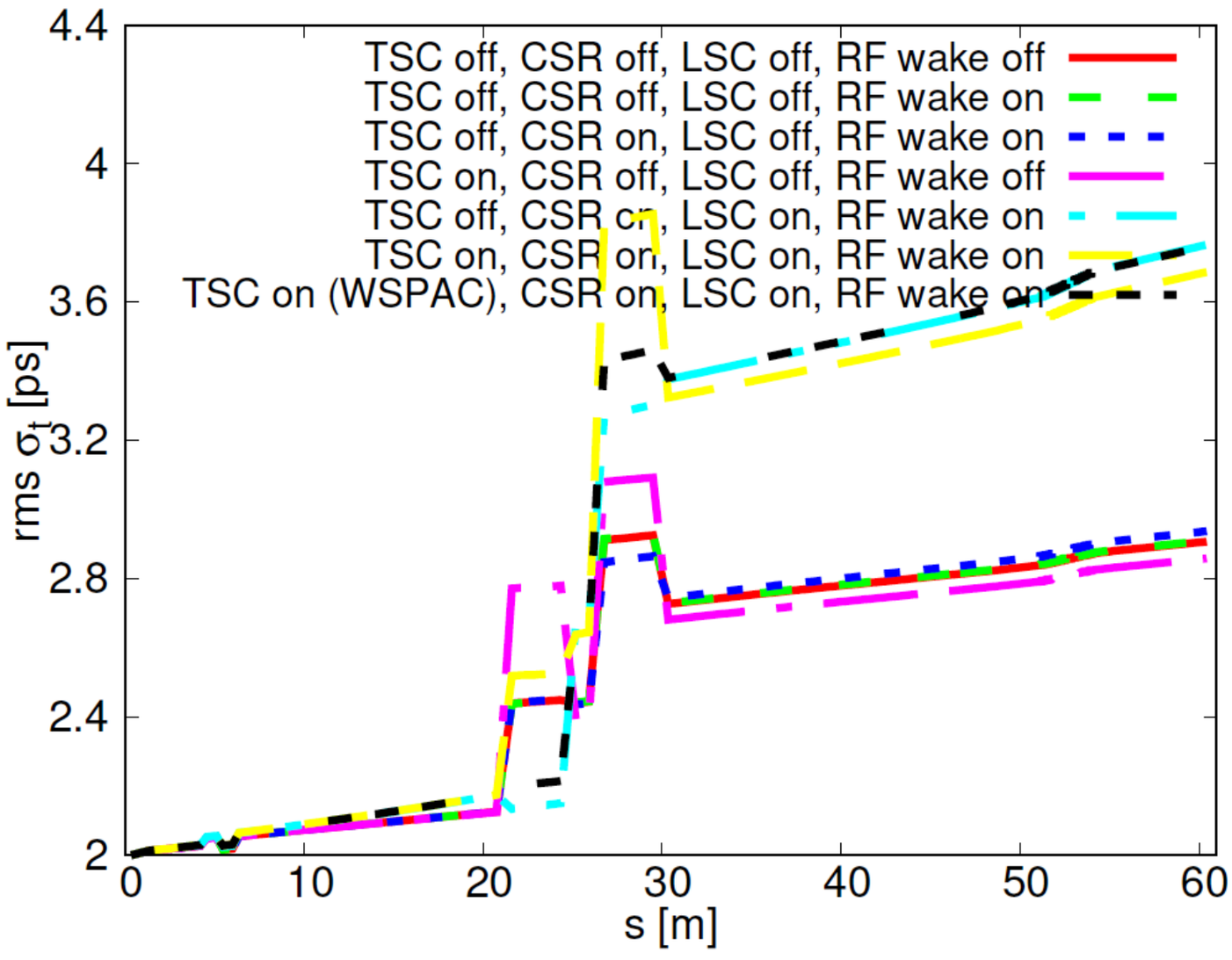
Simulation of CSR, LSC and TSC effects using SAD

rms bunch length:

* Bunch length is coupled to energy spread
* TSC plays a role (Mechanism: LSC depends on transverse beam sizes)

Comment:
R56 is the main reason for different behavior of s-dependent bunch length?

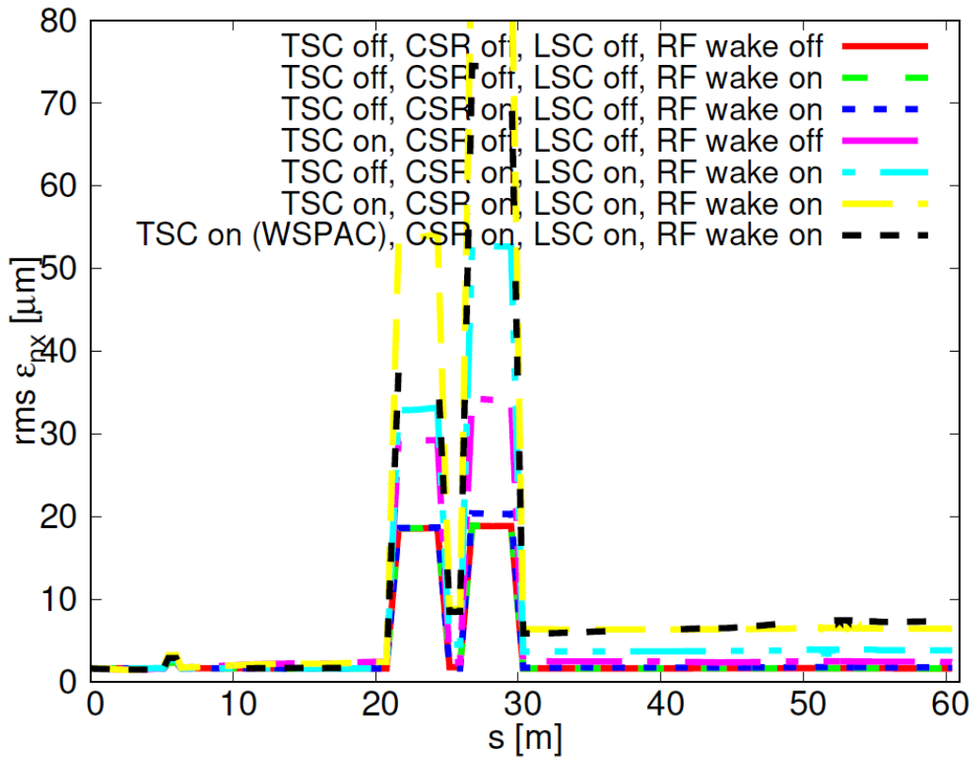


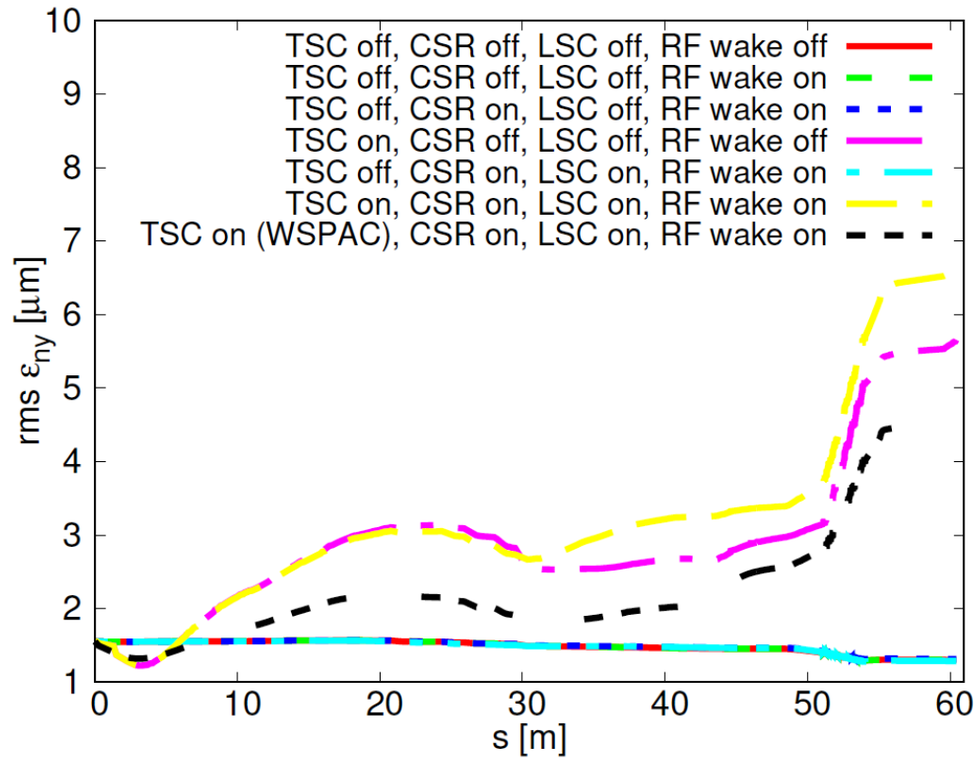


From D. Zhou's talk in cERL-FEL meeting, May 26, 2020

2. Tracking simulations

Simulation of CSR, LSC and TSC effects using SAD



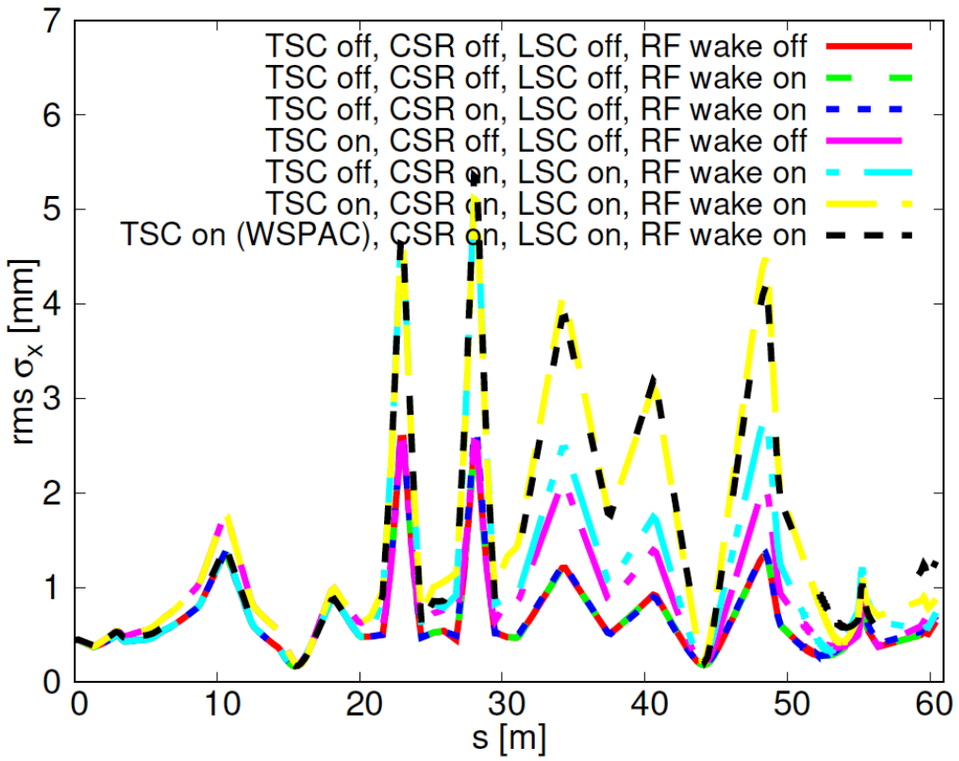


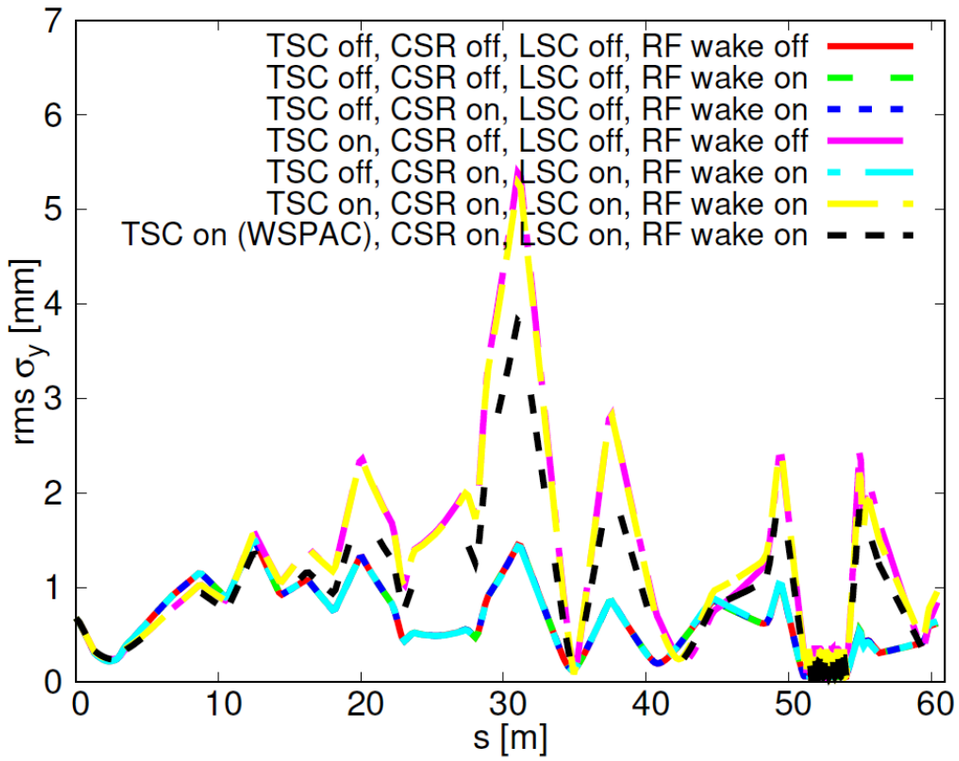
Horizontal emittance (normalized):
*** Hor. emittance is coupled to long. because of non-zero dispersion in the arc section**

Vertical emittance (normalized):
*** Small change along the beam line w/o TSC**
*** TSC makes big difference (reasonable?)**
*** Mechanism to be understood**

2. Tracking simulations

Simulation of CSR, LSC and TSC effects using SAD





Horizontal rms beam size:

*** Hor. beam size is coupled to longitudinal because of dispersion and energy spread**

*** TSC is important**

Vertical rms beam size:

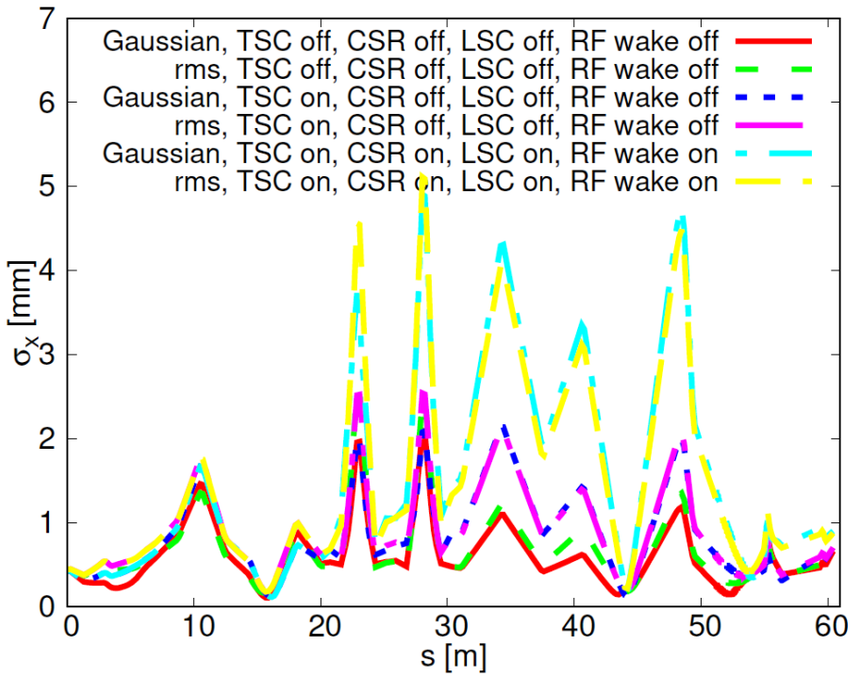
*** Almost independent w/o TSC**

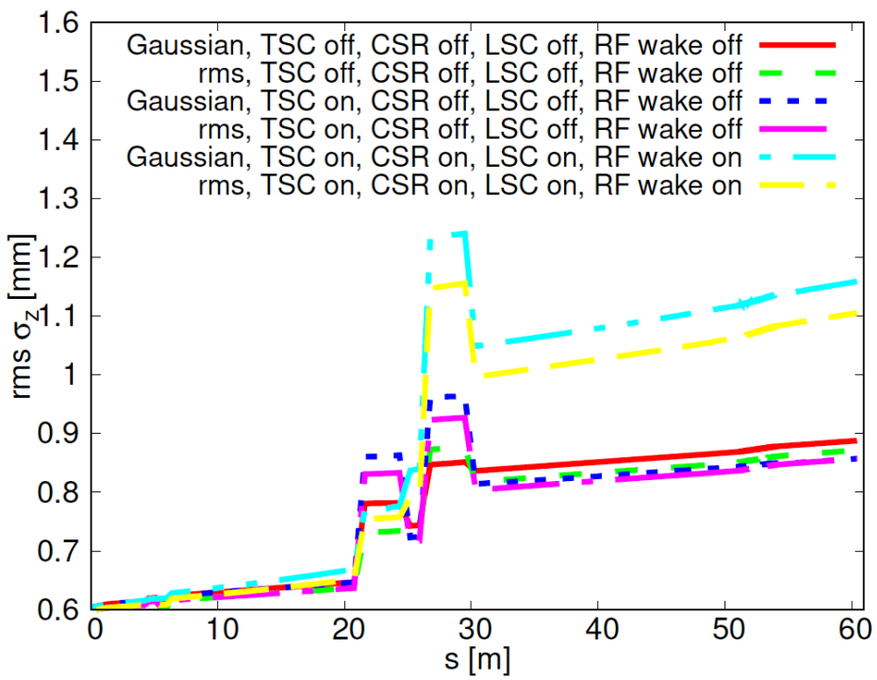
*** Reasonable: No coupling between Y and Z/X**

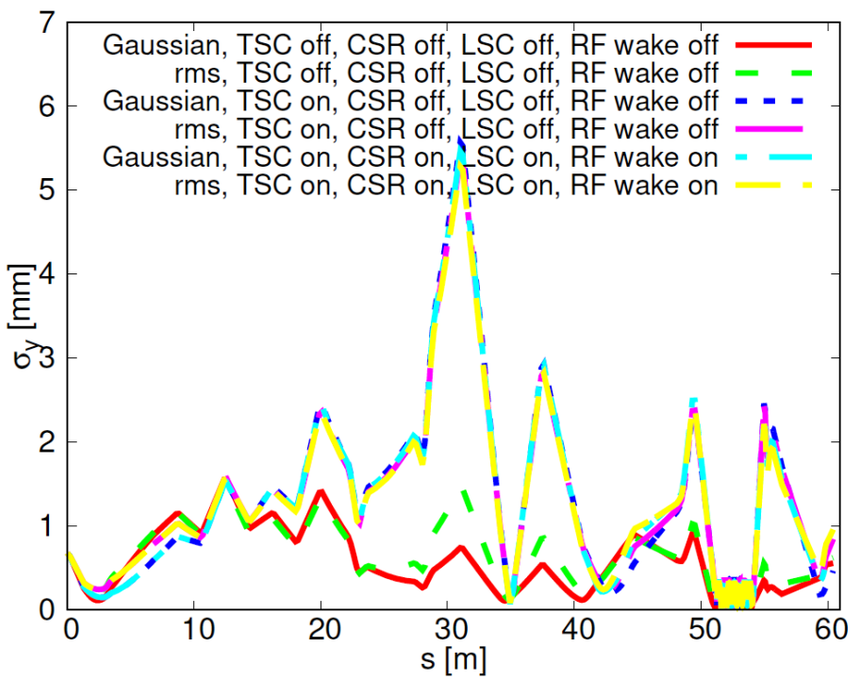
*** TSC is important**

2. Tracking simulations

Simulation of CSR, LSC and TSC effects using SAD
rms vs. Gaussian fitted beam sizes







3. Models for LSC and TSC

1D LSC impedance model:

$$\frac{Z_{\rm LSC}(k)}{L} = \frac{iZ_0}{\pi k r_b^2}\left[1 - \frac{kr_b}{\gamma}K_1\left(\frac{kr_b}{\gamma}\right)\right] \qquad r_b = 1.747(\sigma_x + \sigma_y)/2$$

Z. Huang et al., Phys. Rev. ST Accel. Beams 7 074401 (2004)
M. Venturini, Phys. Rev. ST Accel. Beams 11 034401 (2008)

3D TSC impedance model:

$$\frac{W_{\rm x}(x,y,z) - iW_{\rm y}(x,y,z)}{L} = \frac{-iZ_0 c}{2\pi\gamma^2}\psi(z)\frac{\sqrt{\pi}}{2(\sigma_x^2 - \sigma_y^2)}\left[w(a+ib) - e^{-B}w(ar + i\frac{b}{r})\right]$$

$$a = \frac{x}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}} \qquad b = \frac{y}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}} \qquad r = \frac{\sigma_y}{\sigma_x}$$

$$B = a^2(1-r^2) + b^2(\frac{1}{r^2} - 1) = \frac{x^2}{2\sigma_x^2} + \frac{y^2}{2\sigma_y^2}$$

ψ(z): Longitudinal density. For Gaussian distribution:

$$\psi(z) = \frac{1}{\sqrt{2\pi}\sigma_z}e^{-\frac{z^2}{2\sigma_z^2}}$$

Application conditions:
Assume σx and σy are z-independent inside the bunch, and:

$$\gamma\sigma_z \gg \sigma_\perp$$

$$\sigma_\perp = {\rm Min}[\sigma_x, \sigma_y]$$

A. Xiao et al., PAC'07, also FERMILAB-CONF-07-702-AD

4. Summary

*** SAD simulations indicate that LSC and TSC are equally important sources of transverse emittance growth in cERL-FEL**

*** A full 3D self-consistent simulation (GPT is a good choice) is necessary to benchmark SAD simulations**

*** If emittance growth due to SC is proved to be true, then optics matching with SC is necessary in cERL-FEL. This was investigated in A. Khan's work (A. Khan et al., NIMA 948 (2019) 162822)**

Nuclear Inst. and Methods in Physics Research, A 948 (2019) 162822

Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/nima

Beam matching with space charge in energy recovery linacs

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ARTICLE INFO

Keywords:
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Space charge

ABSTRACT

Matching with space charge of an Energy-Recovery Linac (ERL) arc into the subsequent RF structure is essential to preserve beam quality. We show how to match beam envelopes and dispersion along the bends and recirculation arcs of an ERL, including space charge forces, in order to adjust the beam to the parameters of the subsequent RF structure. For a qualitative analysis, we show that one can use a beam matrix approach together with the smooth focusing approximation but with longitudinal–transverse coupling. It is also shown that the space-charge-modified dispersion plays a key role for the adjustment of the momentum compaction R_{56} required for both the isochronous and the non-isochronous recirculation mode of an ERL. In this work, a simple coupled transverse–longitudinal beam matrix approach for matching with space charge is employed and compared with particle tracking simulations using ELEGANT. As an example case, we use the 5 MeV low-energy, 180° injection arc, which also works as a bunch compressor, and matched to the subsequent first RF structure of the projected multi-turn Mainz Energy-recovering Superconducting Accelerator (MESA).

5. To-Do list

* Further benchmark between ELEGANT and SAD (almost done?).
Benchmark with GPT (to be done)

* Use latest magnet layout for simulations (2020.04 done, 2020.06 to be done)

* Longitudinal space charge (LSC) impedance: Simple 1D model (ELEGANT model, implemented) and my model (w/o chamber shielding, done; include chamber shielding, to be tested)

  ** Replaced rms σ_x and σ_y by Gaussian fitted ones for the input parameters of LSC impedance (ELEGANT model) (done, NO big difference)

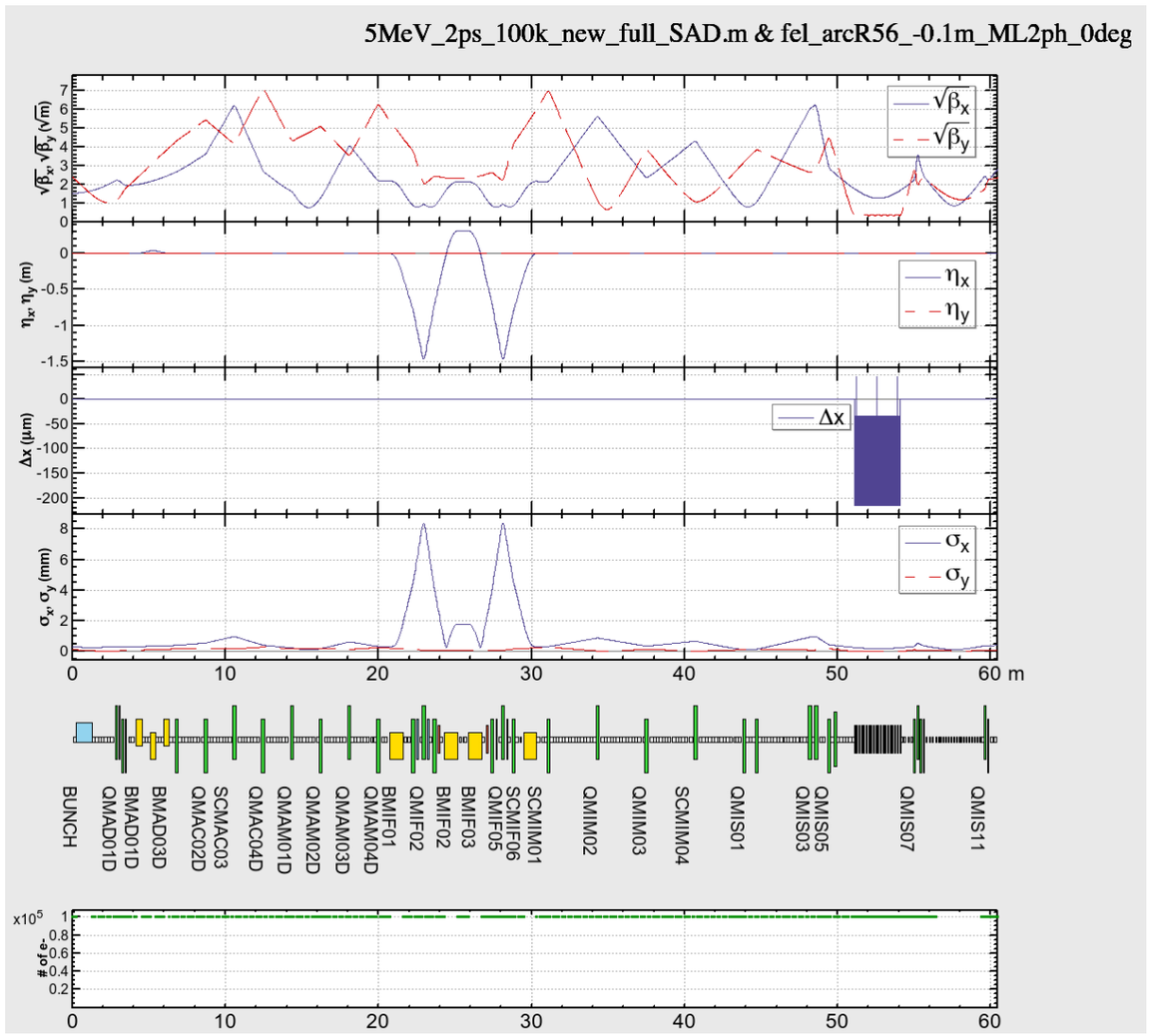
  ** 3D LSC model might be necessary

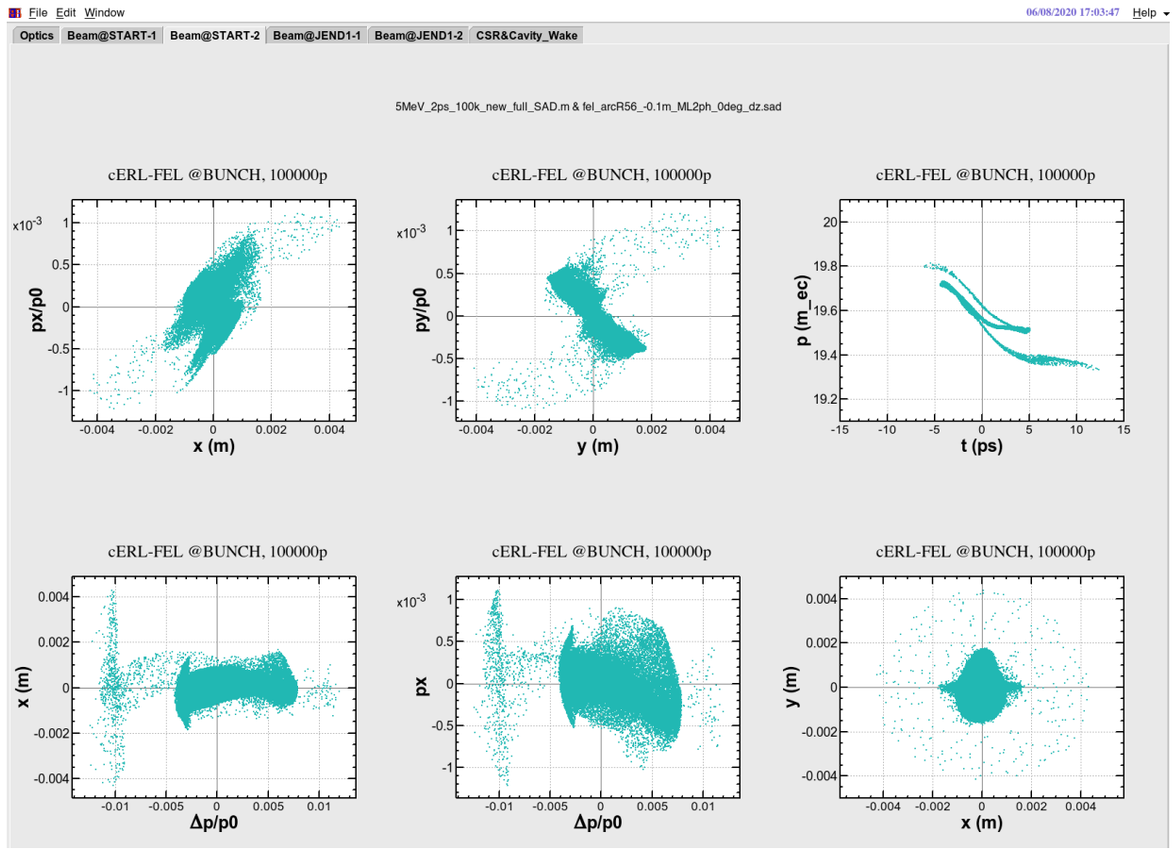
* Transverse space charge (TSC) effects (done, important in cERL-FEL?)

* "Interference" of CSR and space charge (both LSC and TSC) in dipole magnets (to be revisited, in dipoles transverse beam sizes change quickly along s)

Backup

CSR on, LSC on, Cavity wake on, Gaussian fit on





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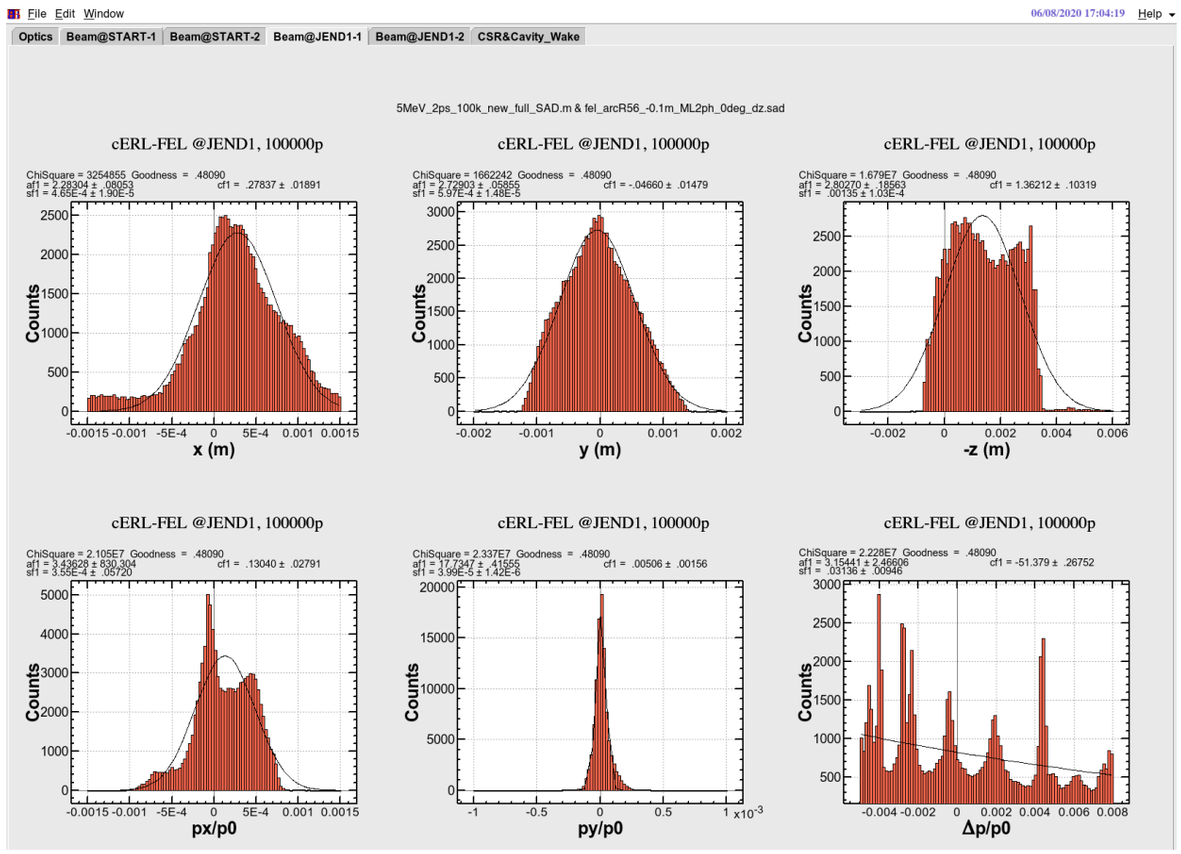
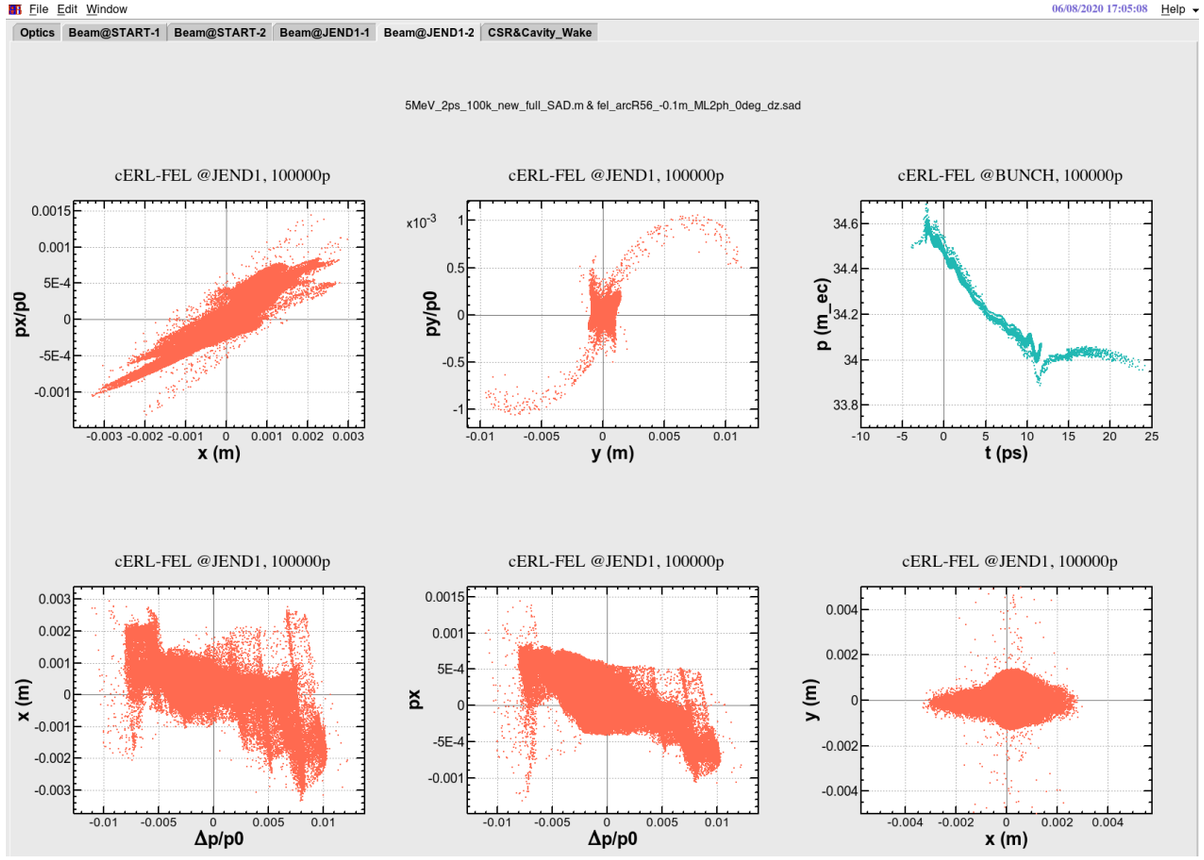
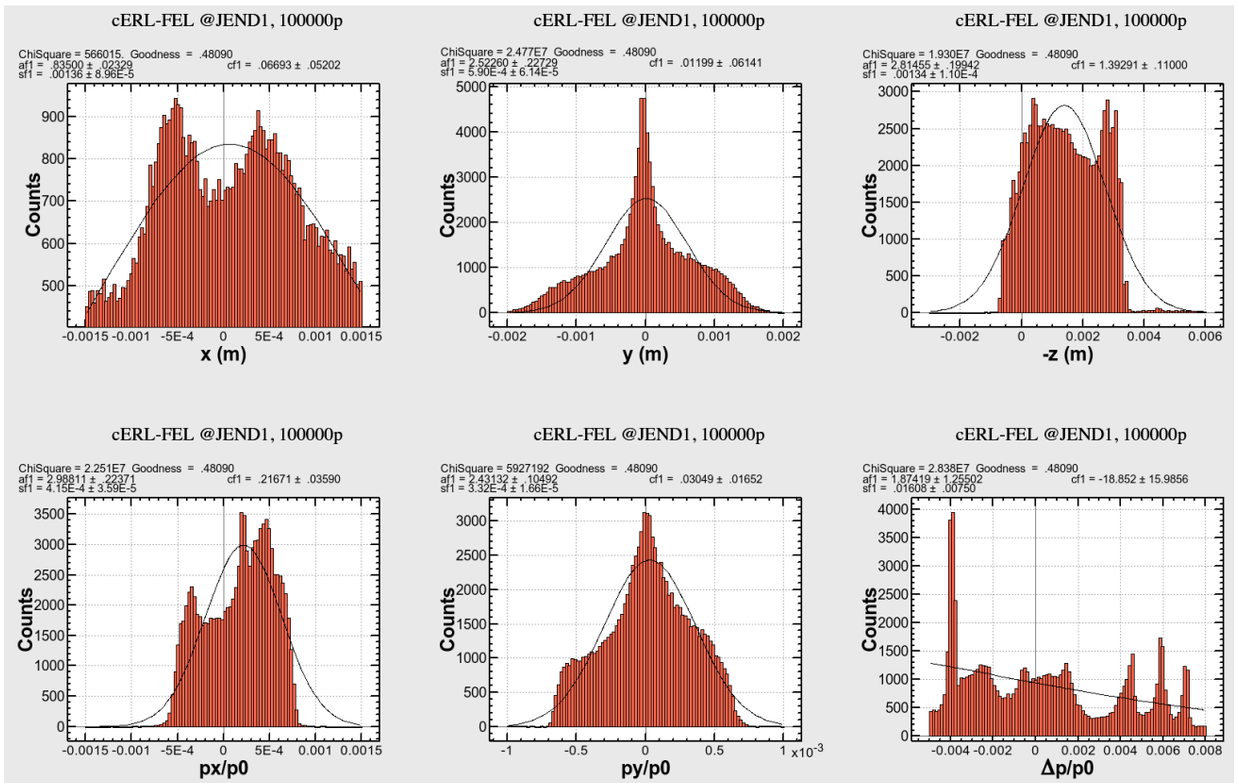
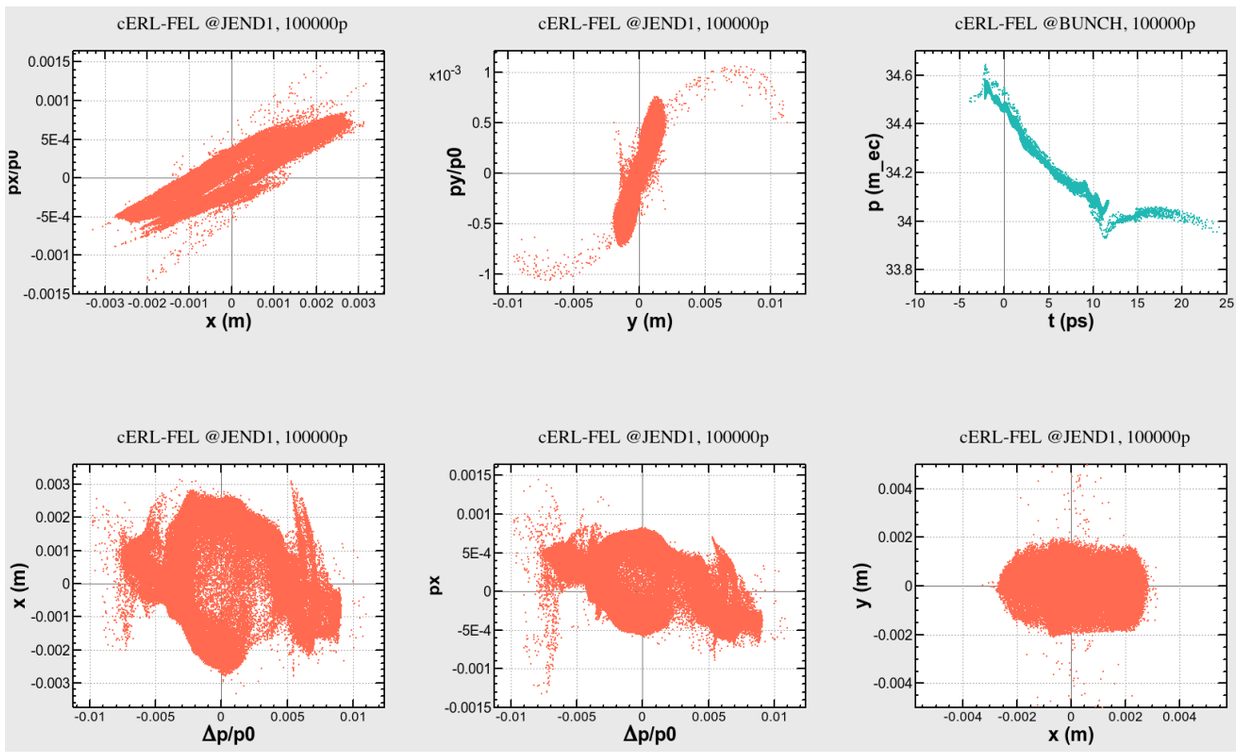




Backup

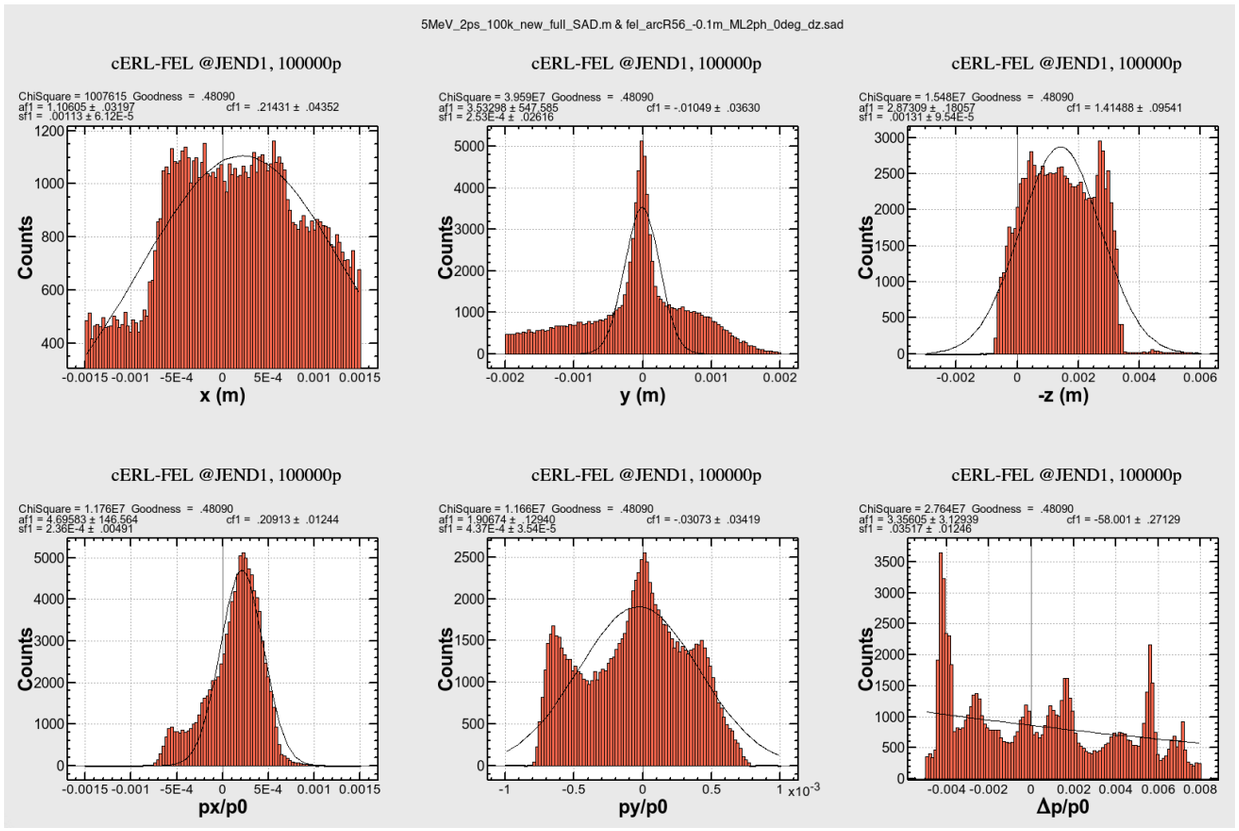
CSR on, LSC on, Cavity wake on, Gaussian fit on, TSC on (WSPAC)

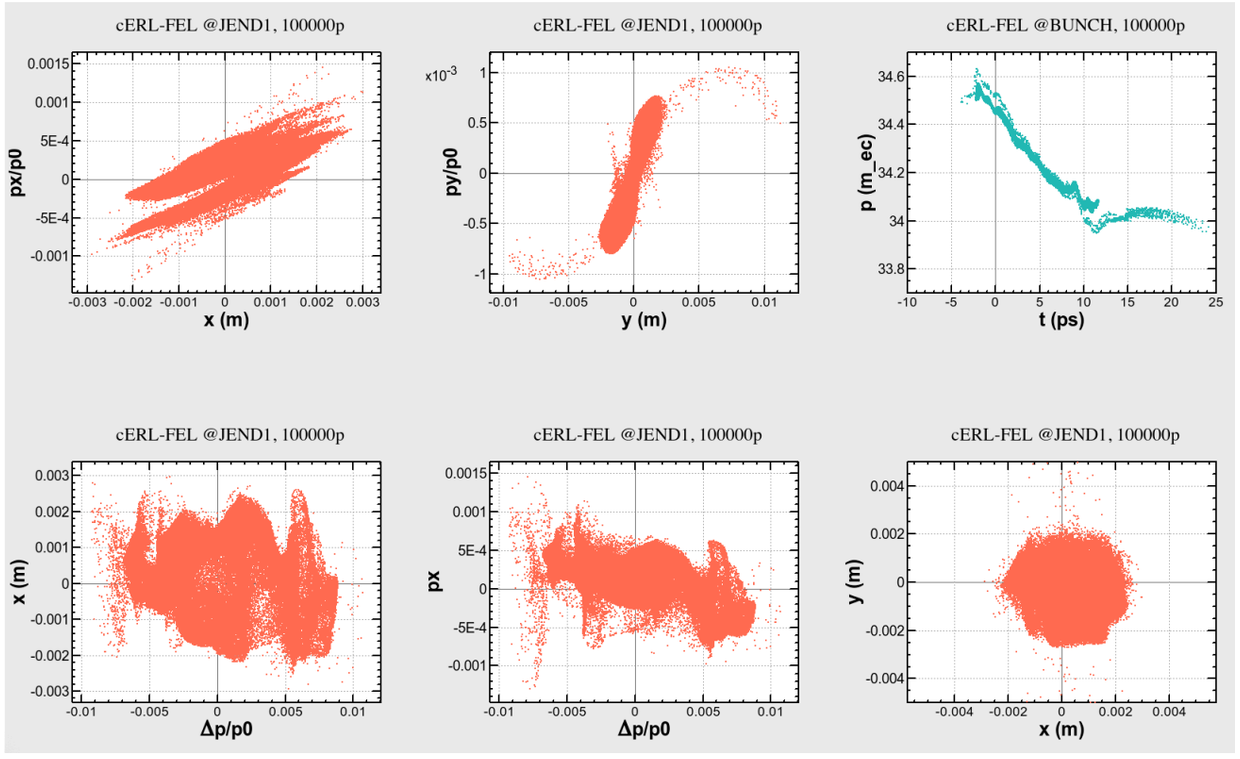




Backup

CSR on, LSC on, Cavity wake on, Gaussian fit on, TSC on (My model)





Backup

CSR on, LSC on, Cavity wake on, Gaussian fit on