Tracking simulations for cERL-FEL: Compare results of SAD, ELEGANT and GPT

Demin Zhou

Accelerator laboratory, KEK

Acknowledgements:

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

M. Shimada, Y. Tanimoto

cERL-FEL meeting, Sep. 24, 2020

Outline

- **Simulation of CSR, LSC and TSC effects using SAD**

  *** Use new magnet layout (Daihon20200607, Thanks to N. Nakamura and M. Shimada)**

  Nakamura-san's lattice: RF phase 79 deg, R56@arc=0.217
  Shimada-san's lattice: RF phase 90 deg, R56@arc=0.

  *** Use Gaussian fitted beam sizes for LSC/TSC effects**

- **Comparison of ELEGANT, SAD and GPT simulations**
- **Models for LSC and TSC**
- **Summary**
- **To-Do list**

1. Introduction

ELEGANT files (Nakamura-san):

beam line: fel_SAD.lte

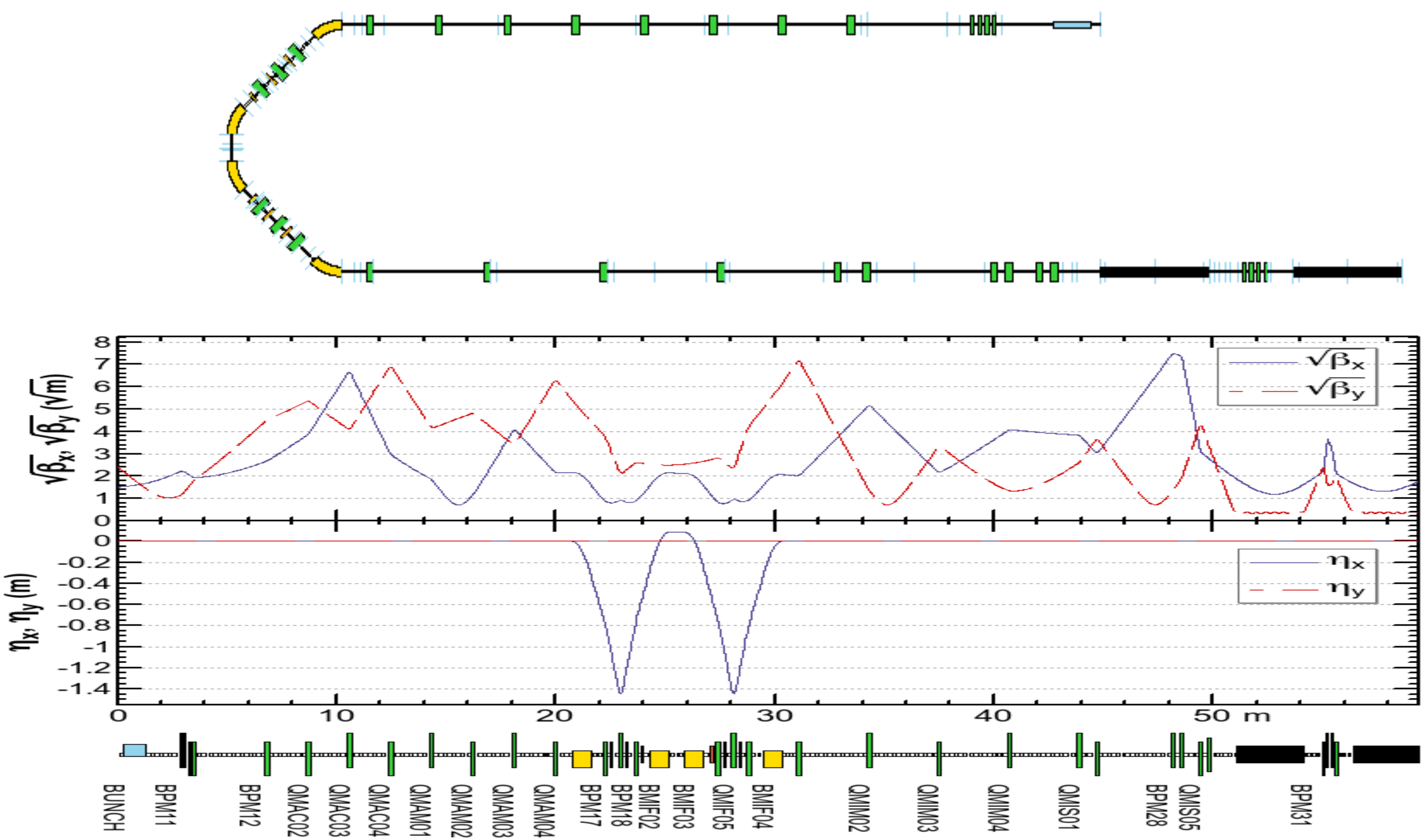
run setup: fel_arcR56_-0.1m_ML2ph_0deg.ele (Use old file)

beam initial distribution: 5MeV_2ps_500k_new.sdds (# of particles: 5e5)

! p_central = 19.582453 (elegant)

MOMENTUM = 10.0066 MEV; ! SAD

Arc R_{56} = 0.217 m



w/o TSC

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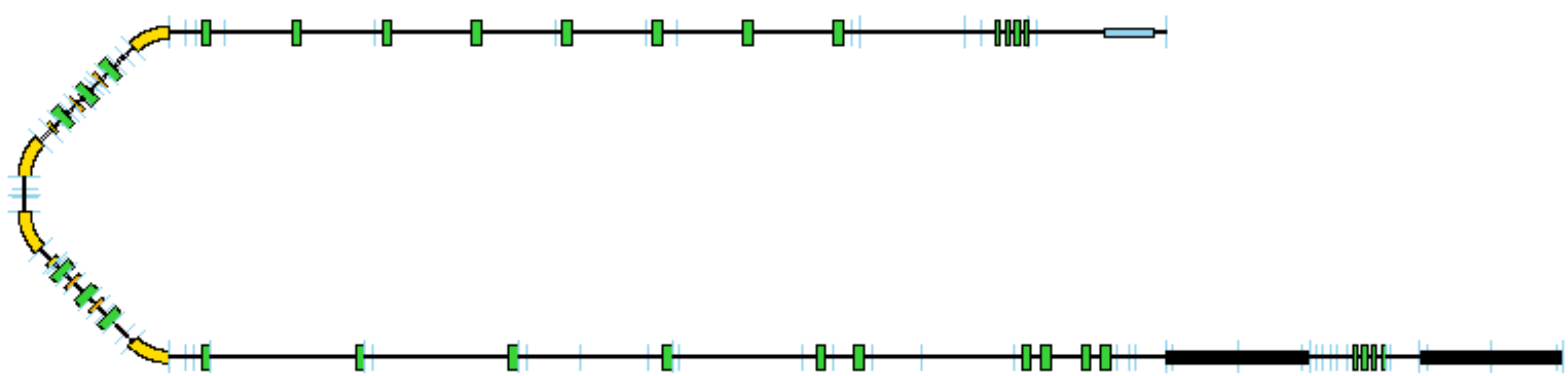

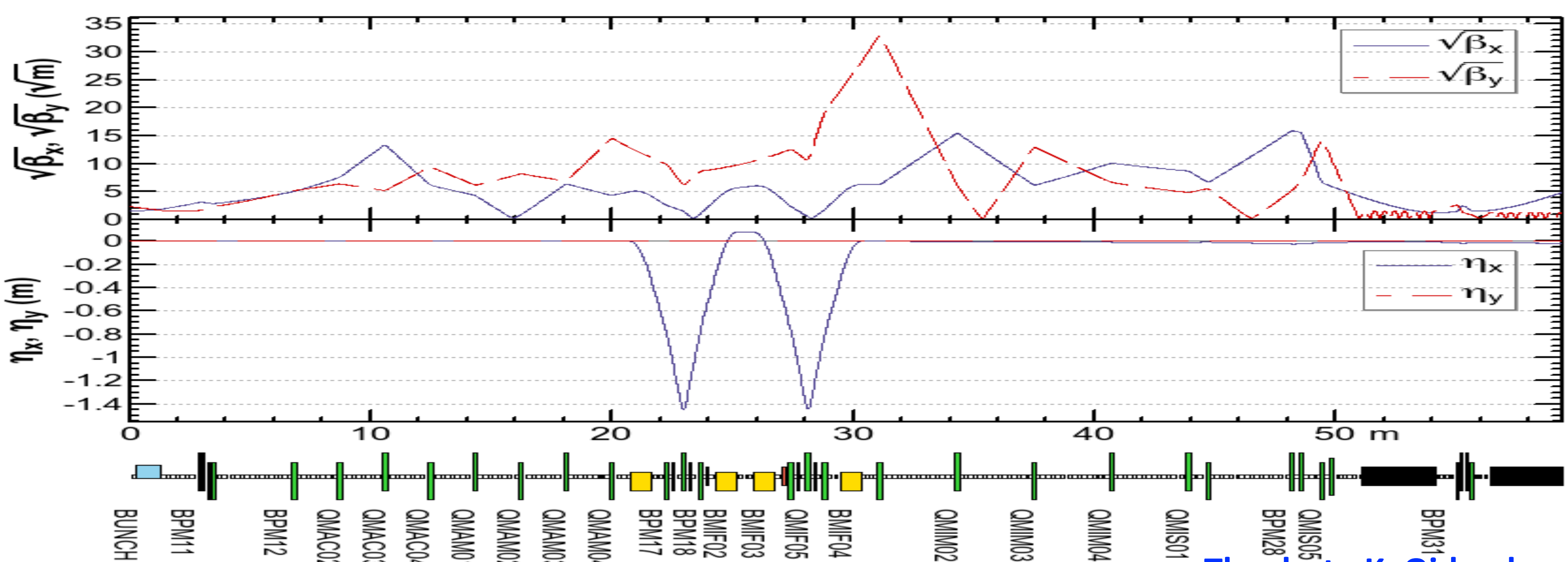

w/ TSC (WSPAC)

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

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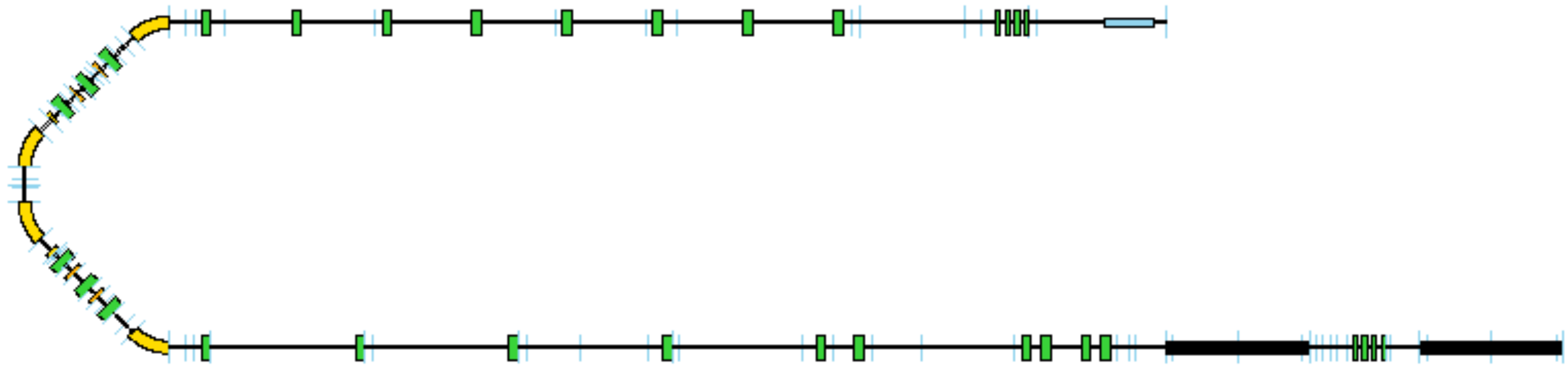

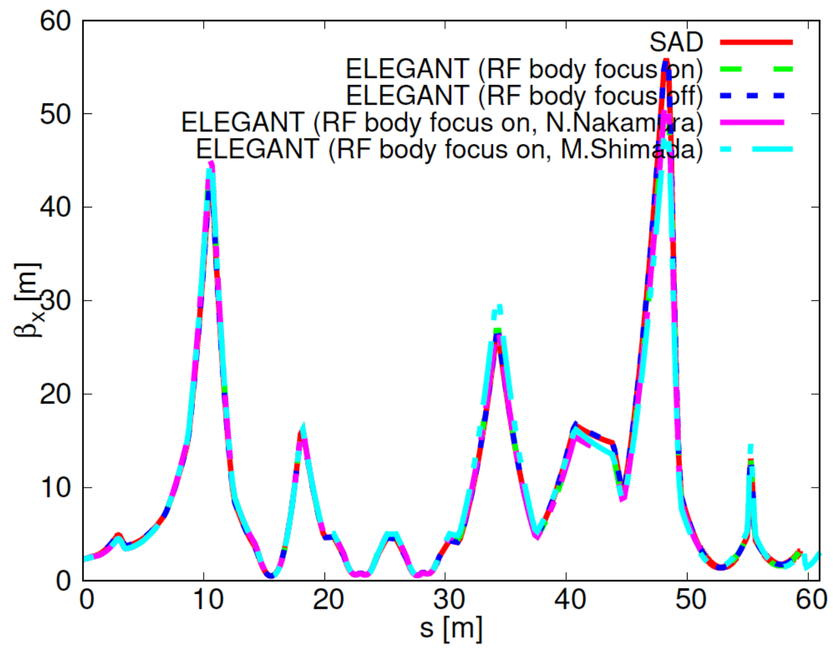

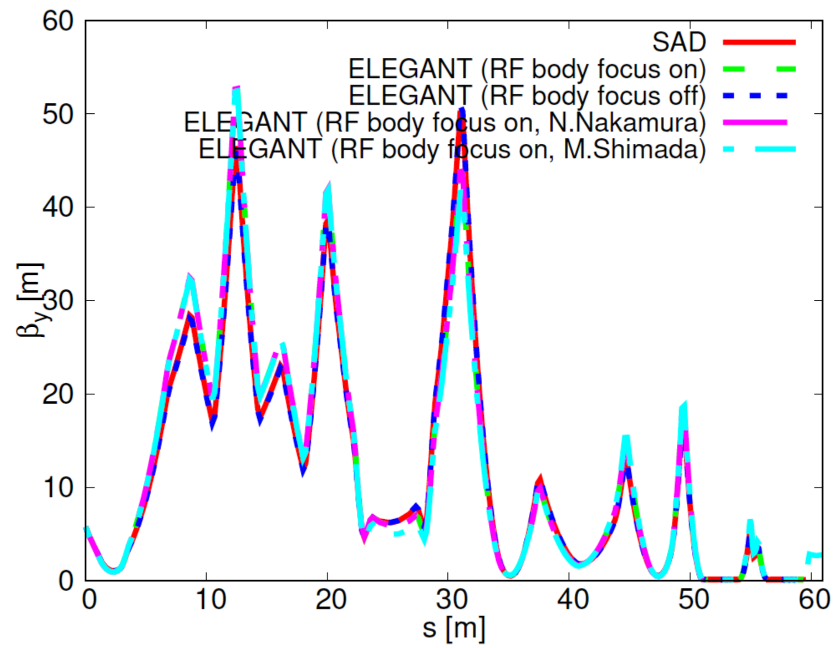

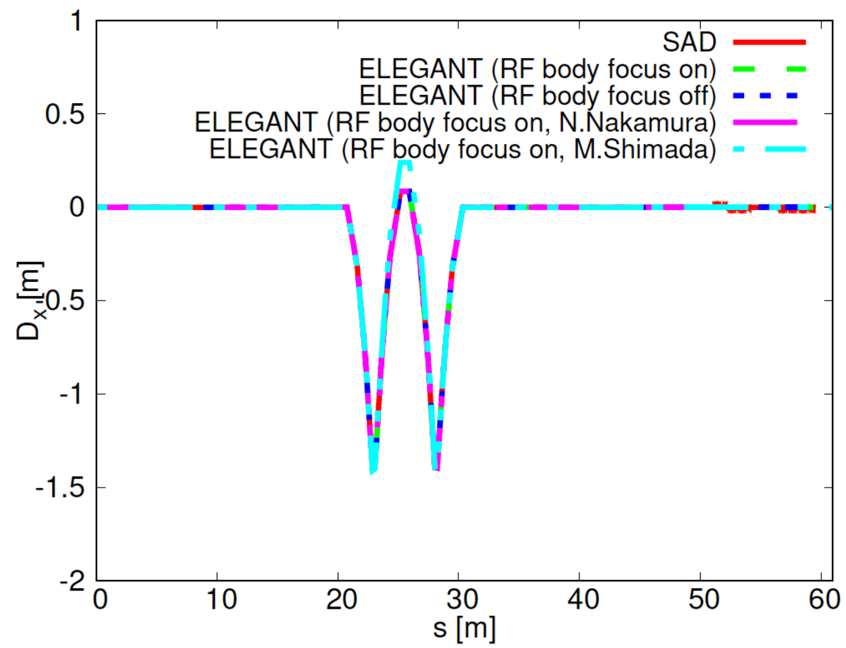

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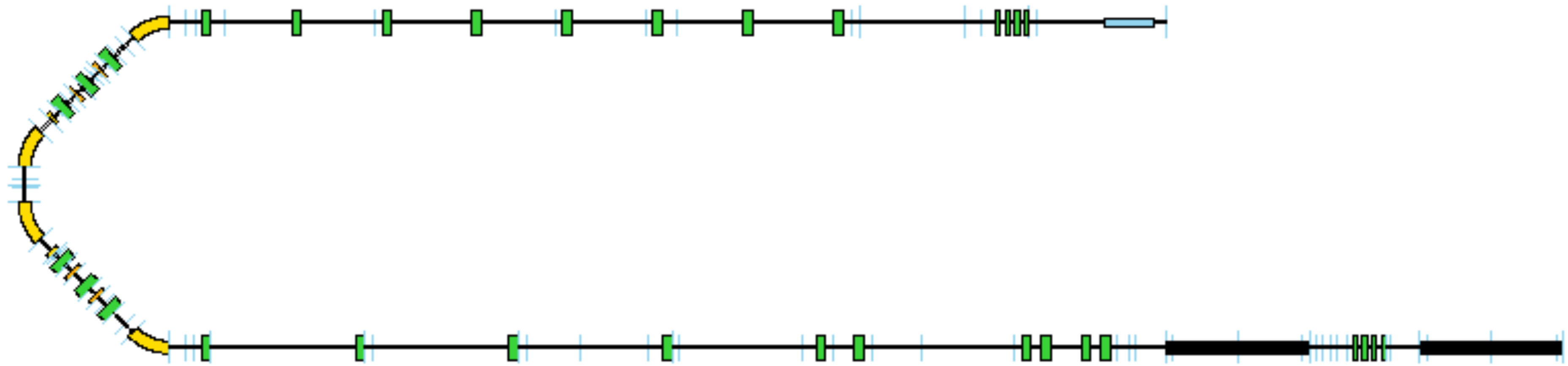
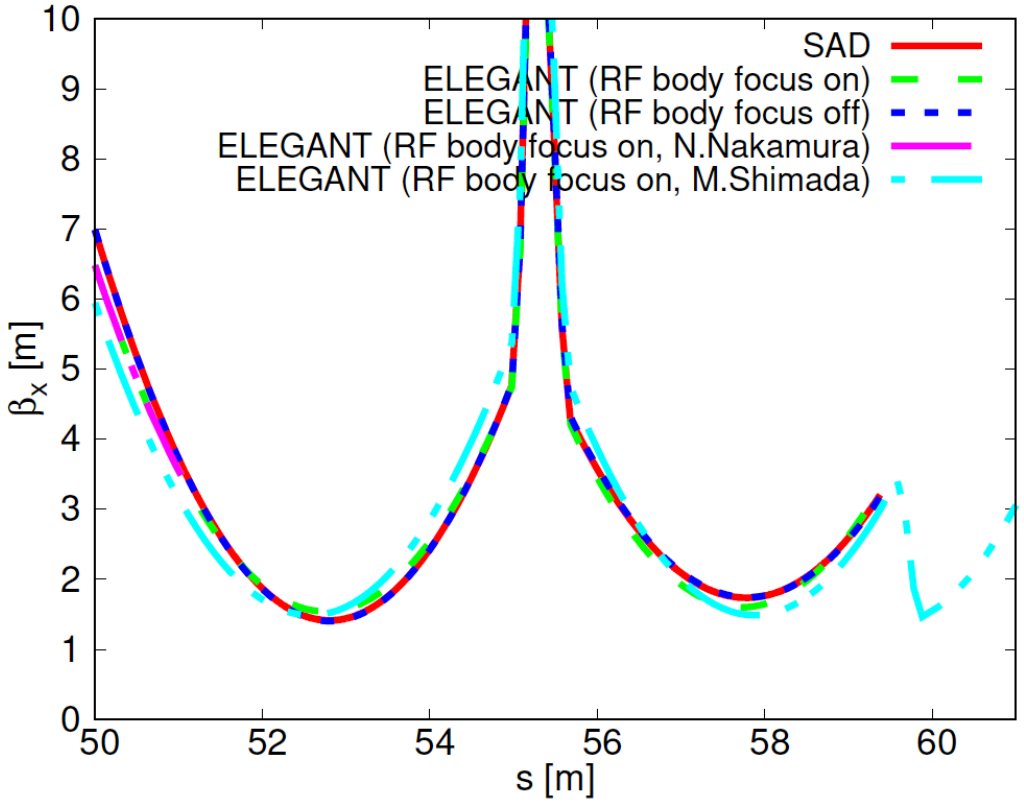
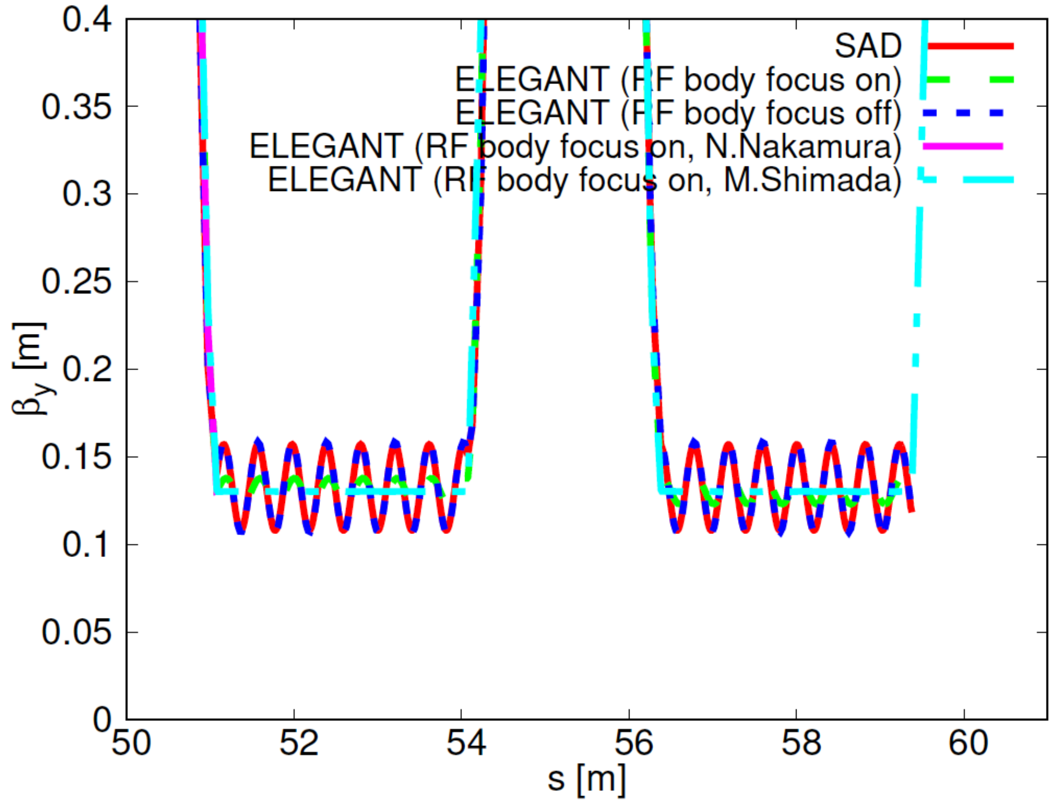






2. Tracking simulations

Simulation of CSR, LSC and TSC effects

rms energy spread:

* CSR is remarkable in the arc

* LSC is most important

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

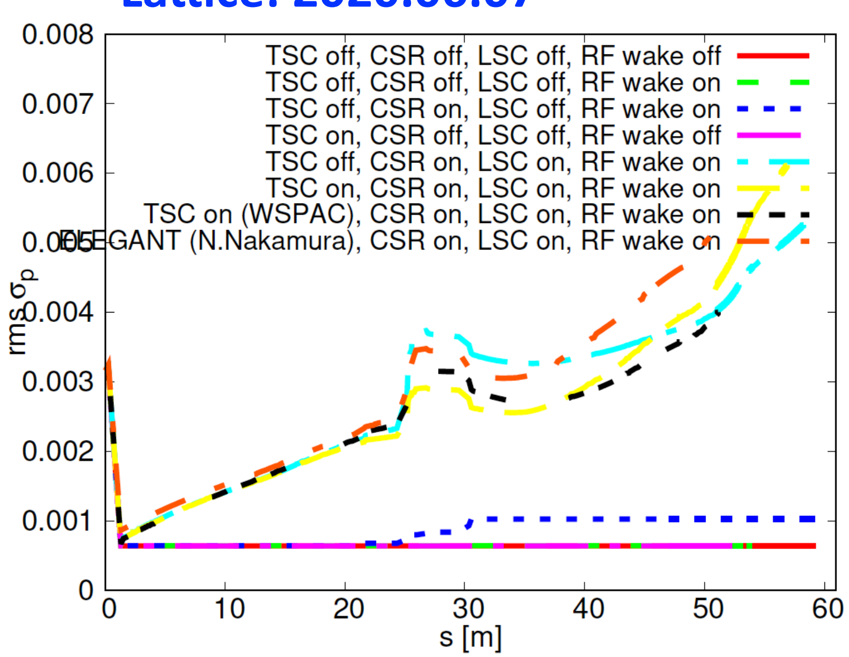
1) The s-dependent energy spreads simulated by SAD and GPT are remarkably different. It might be related to LSC model:

* SAD (and ELEGANT): 1D LSC model (overestimate LSC effects)
* GPT: 3D LSC model (consider x/y dependence of LSC force)

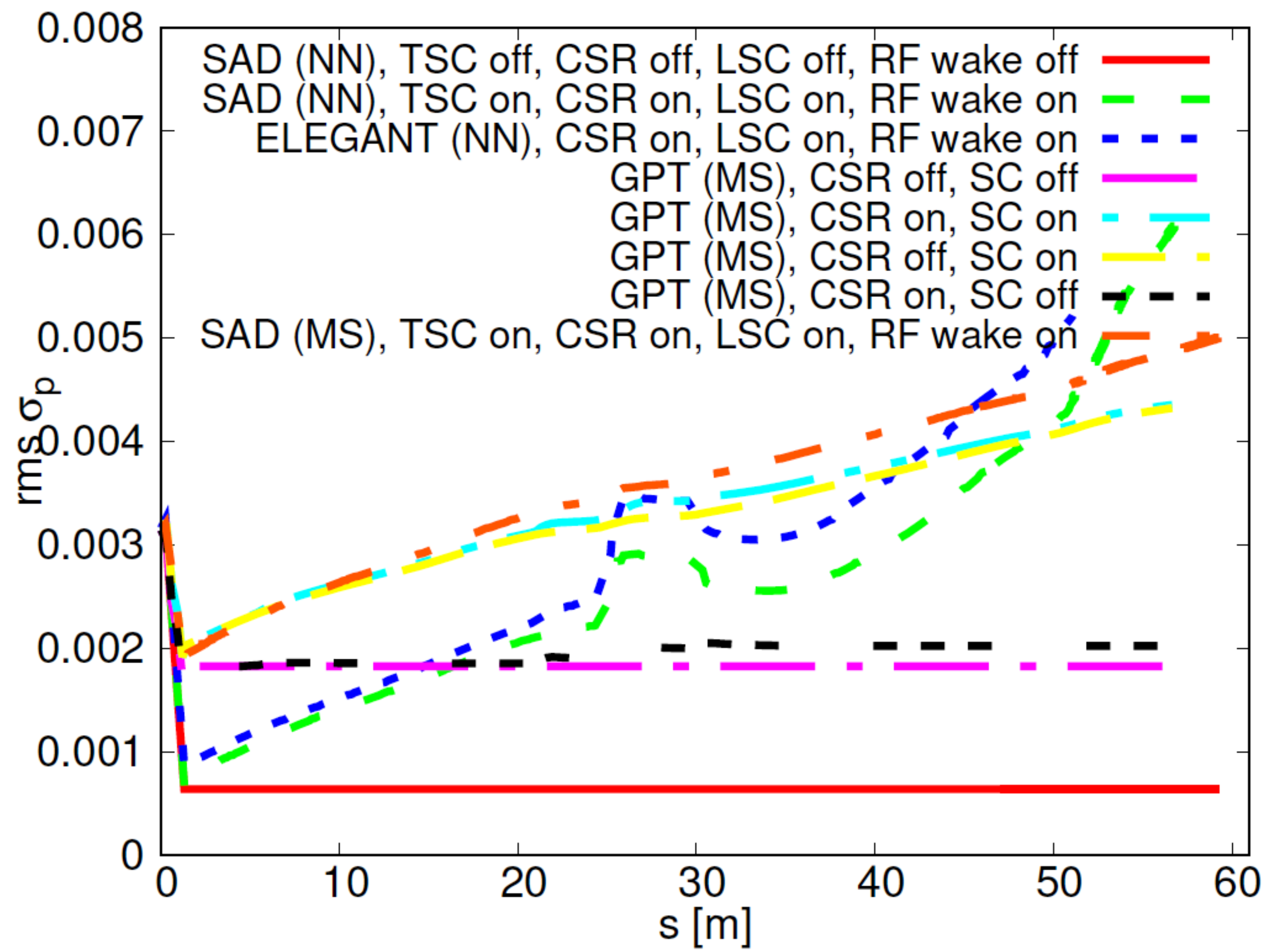
2) The difference between SAD and ELEGANT:

* SAD: 3D TSC with Gaussian distribution in x-y plane
* ELEGANT: TSC is not available
* Without TSC, the CSR models in the arc are different

Lattice: 2020.06.07



From D. Zhou's talk in cERL-FEL meeting, Aug. 27, 2020



2. Tracking simulations

Simulation of CSR, LSC and TSC effects

rms bunch length:

* Bunch length is coupled to energy spread

* TSC plays a role (Mechanism: LSC depends on transverse beam sizes)

1) The s-dependent rms bunch length simulated by SAD and GPT are remarkably different. It might be related to LSC model:

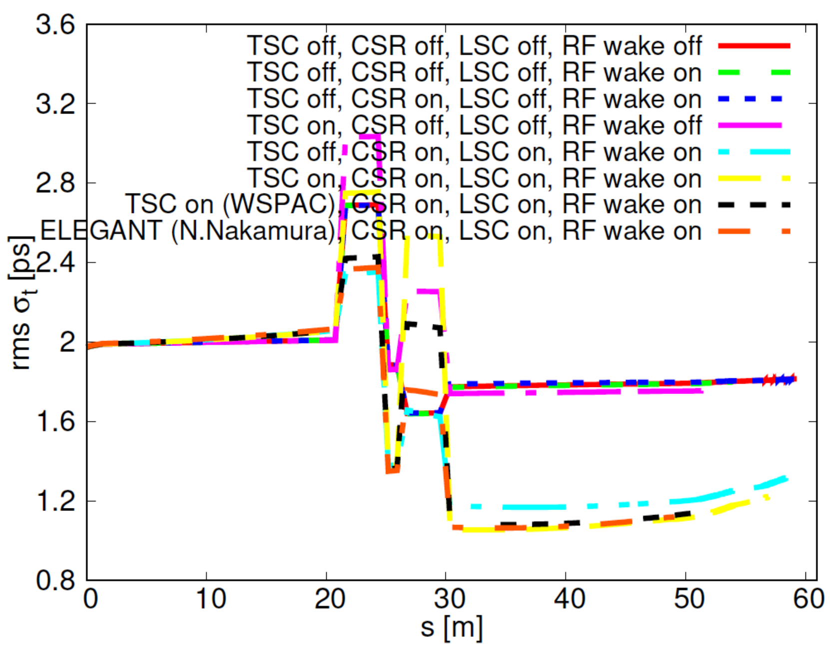
- * SAD (and ELEGANT): 1D LSC model (overestimate LSC effects)
- * GPT: 3D LSC model (consider x/y dependence of LSC force)

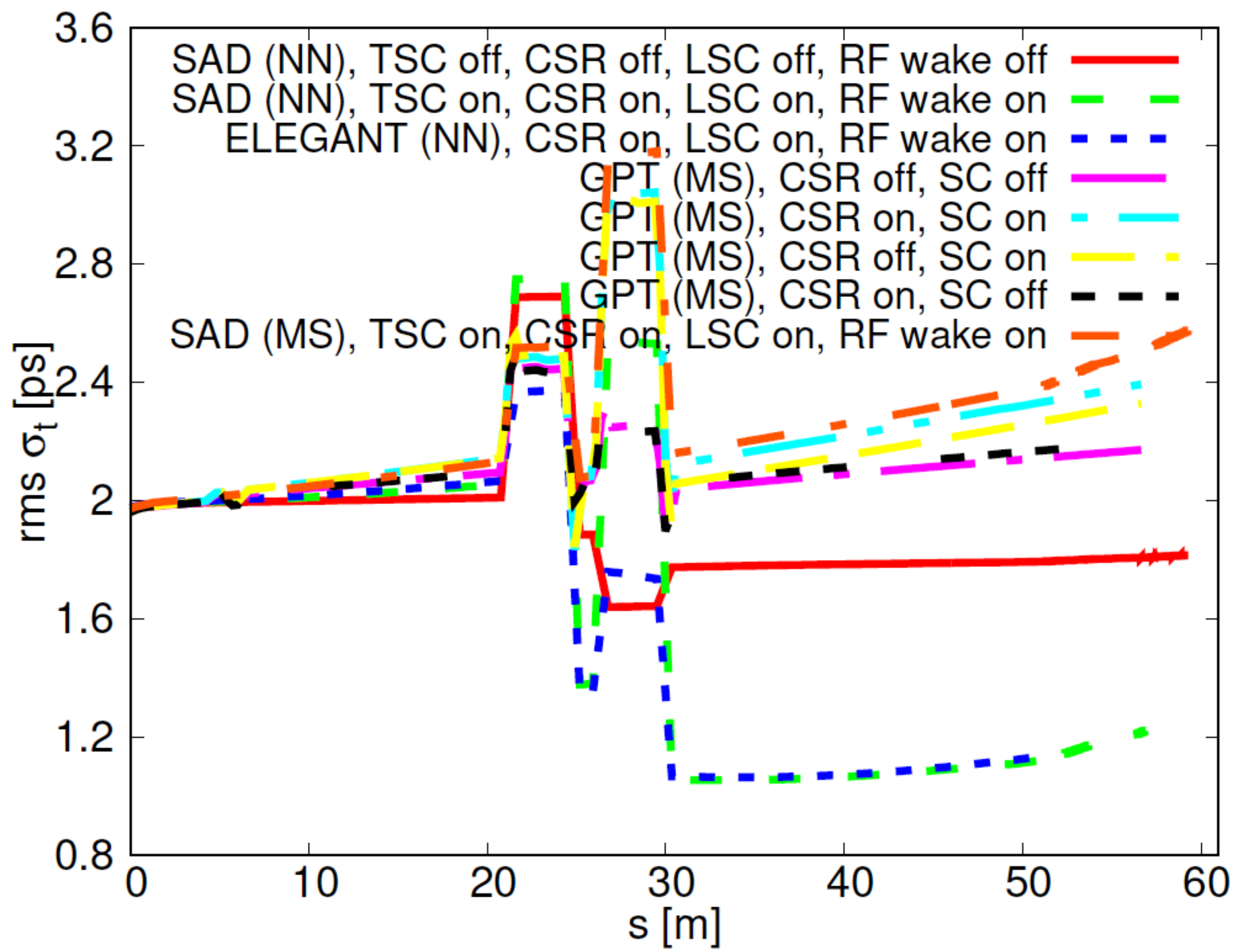
2) The difference between SAD and ELEGANT:

* SAD: 3D TSC with Gaussian distribution in x-y plane

- * ELEGANT: TSC is not available
- * Without TSC, the CSR models in the arc are different

Lattice: 2020.06.07





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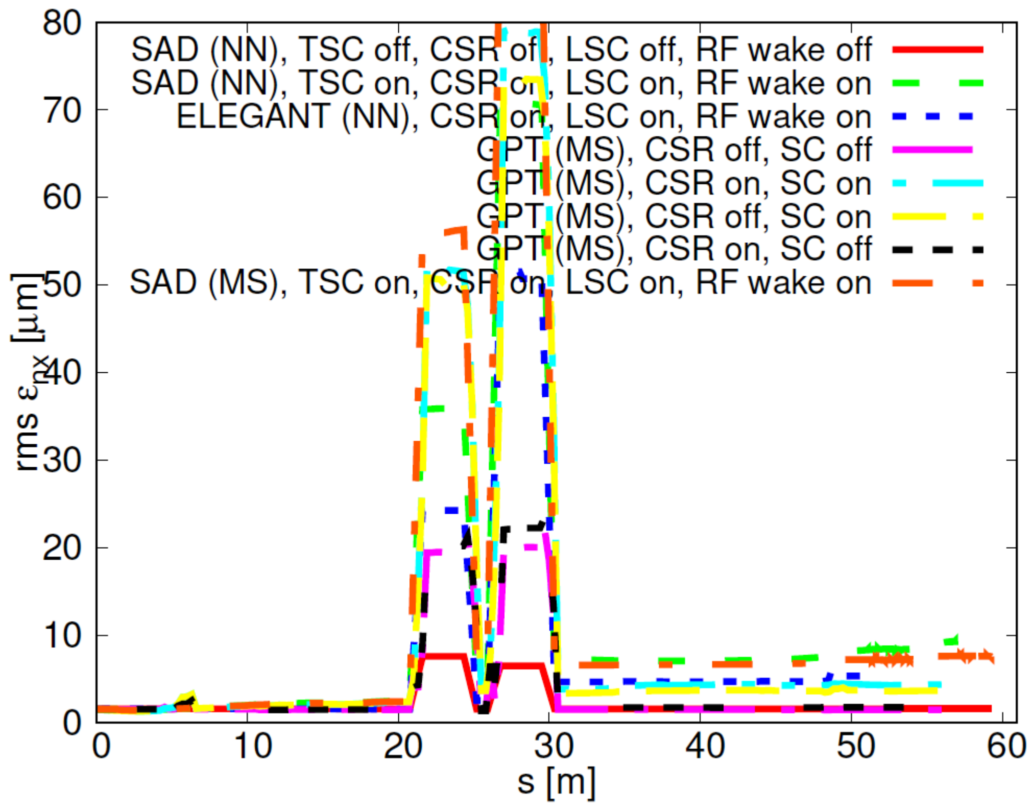
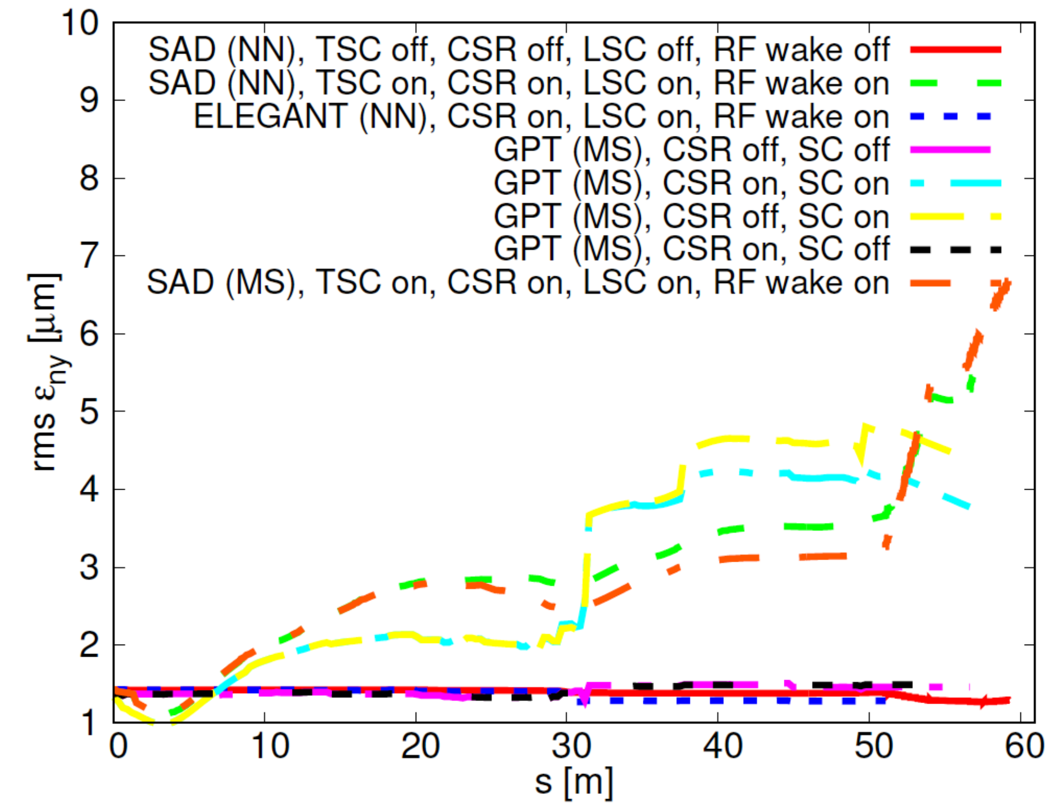
2. Tracking simulations

Simulation of CSR, LSC and TSC effects





Horizontal emittance (normalized):

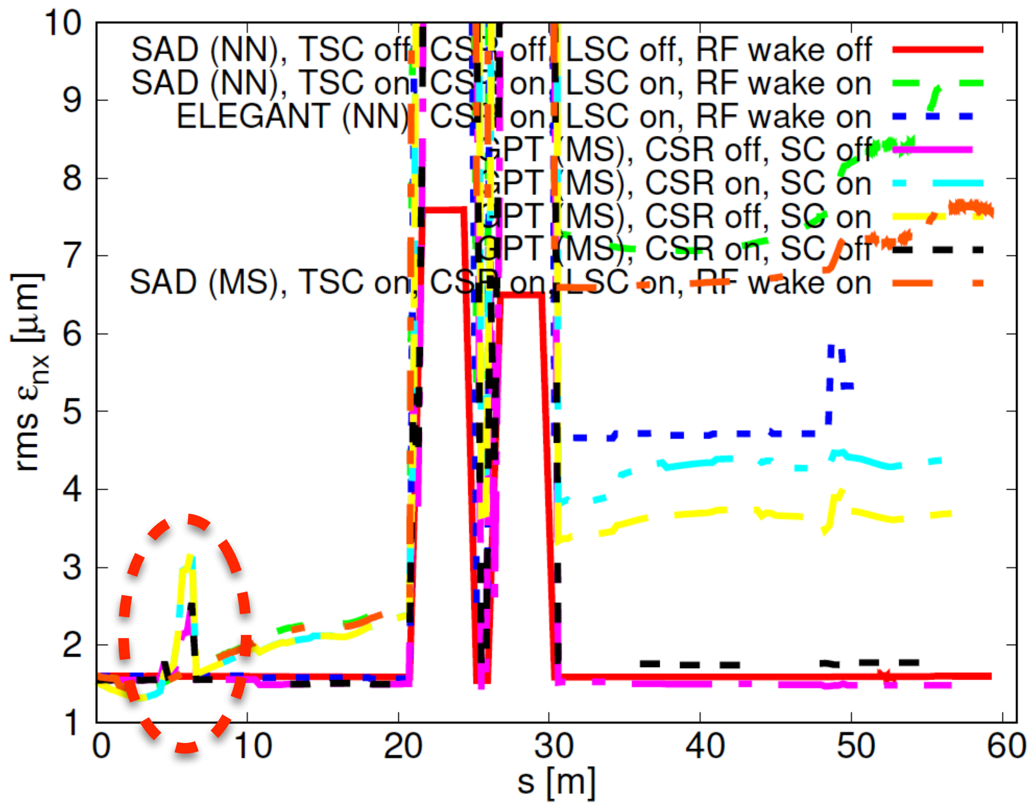
* Hor. emittance is coupled to long. because of non-zero dispersion in the arc section
* GPT: small bump around s=6 m. Why? Is it the chicane?
* Discrepancy between SAD and GPT could be attributed to LSC (but need to be checked)

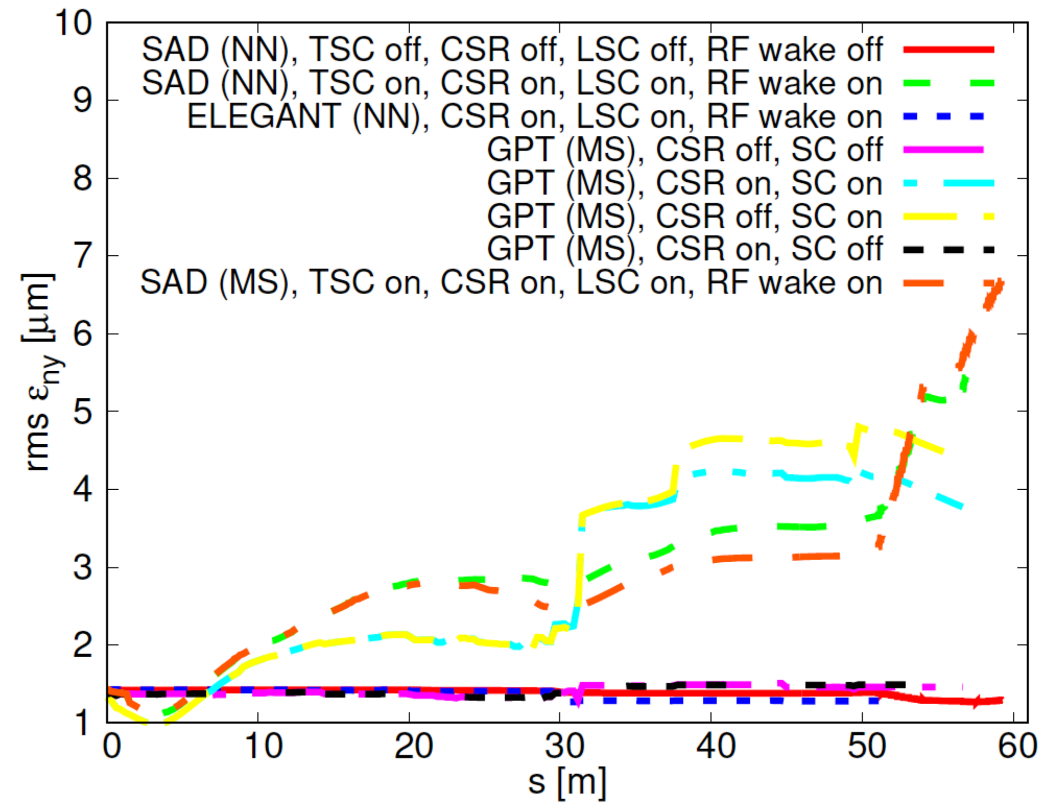
Vertical emittance (normalized):

* Small change along the beam line w/o TSC
* TSC makes big difference (reasonable?) (Both SAD and GPT show strong emittance growth)
* SAD and GPT show different behavior, especially in the arc => Need to be checked
* Mechanism still to be understood

2. Tracking simulations

Simulation of CSR, LSC and TSC effects





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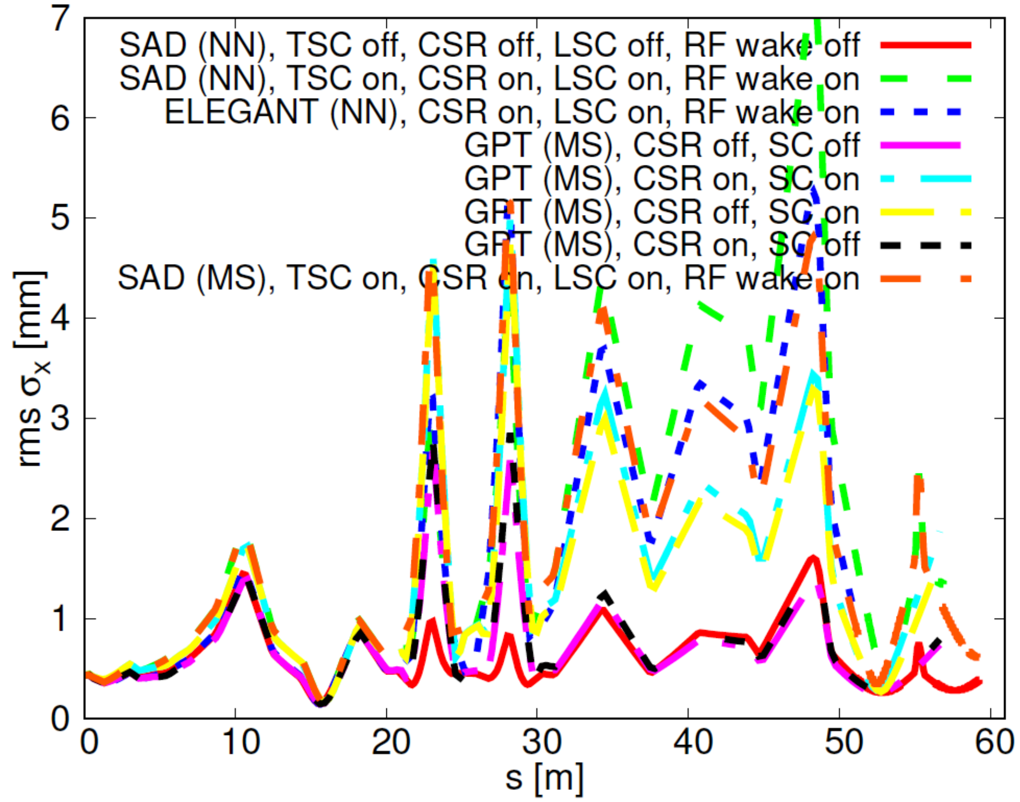
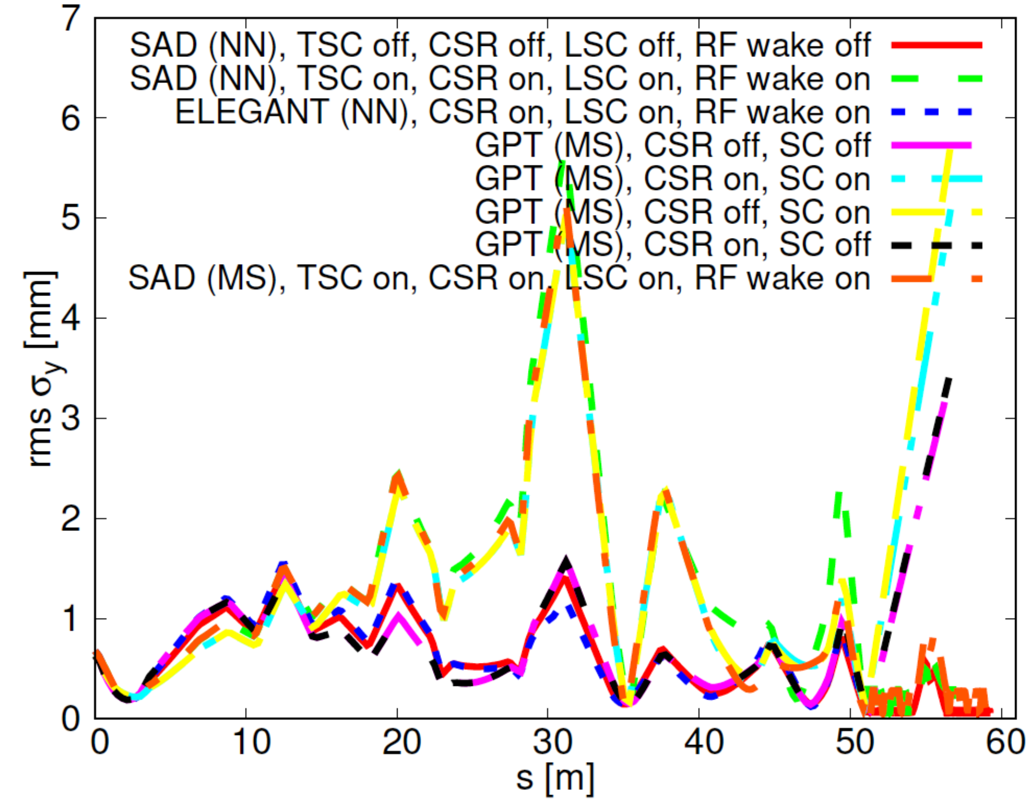
2. Tracking simulations

Simulation of CSR, LSC and TSC effects using SAD





Horizontal rms beam size:

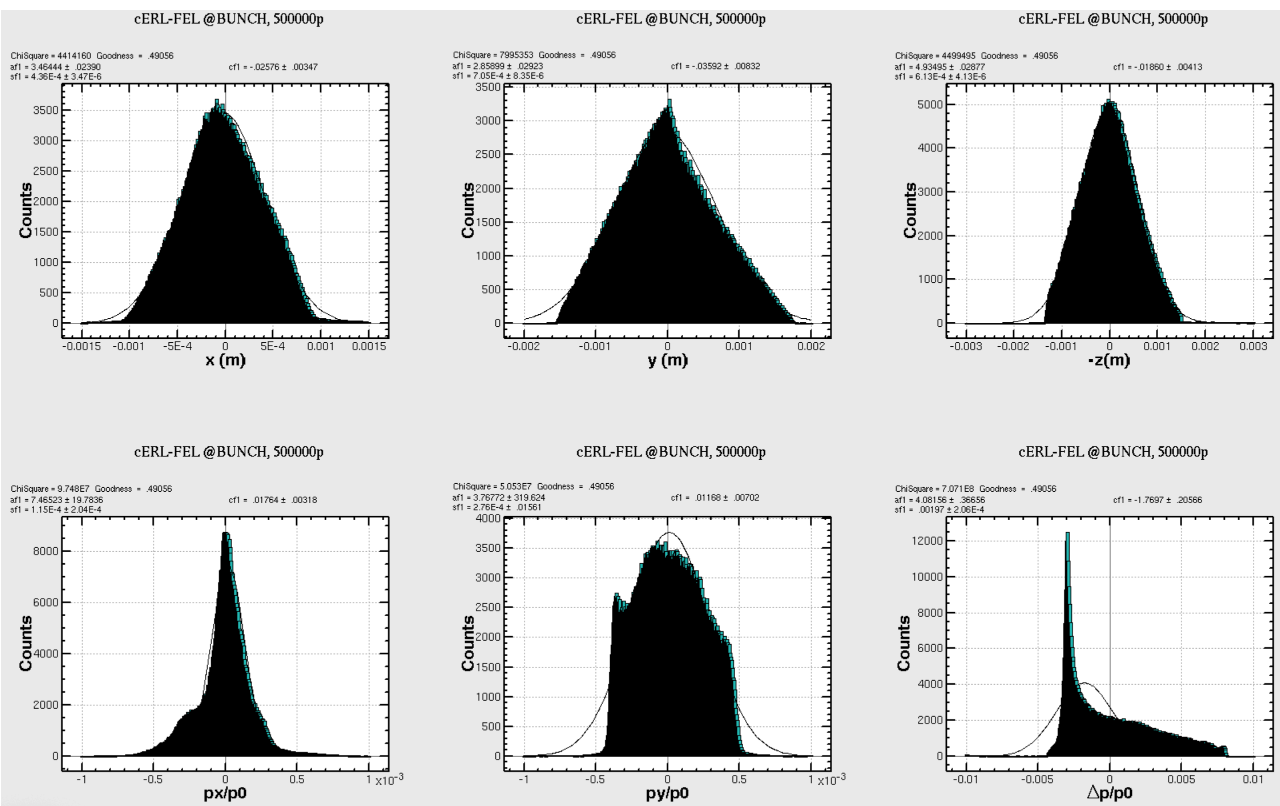
* Hor. beam size is coupled to longitudinal because of dispersion and energy spread
* TSC is less important than LSC?

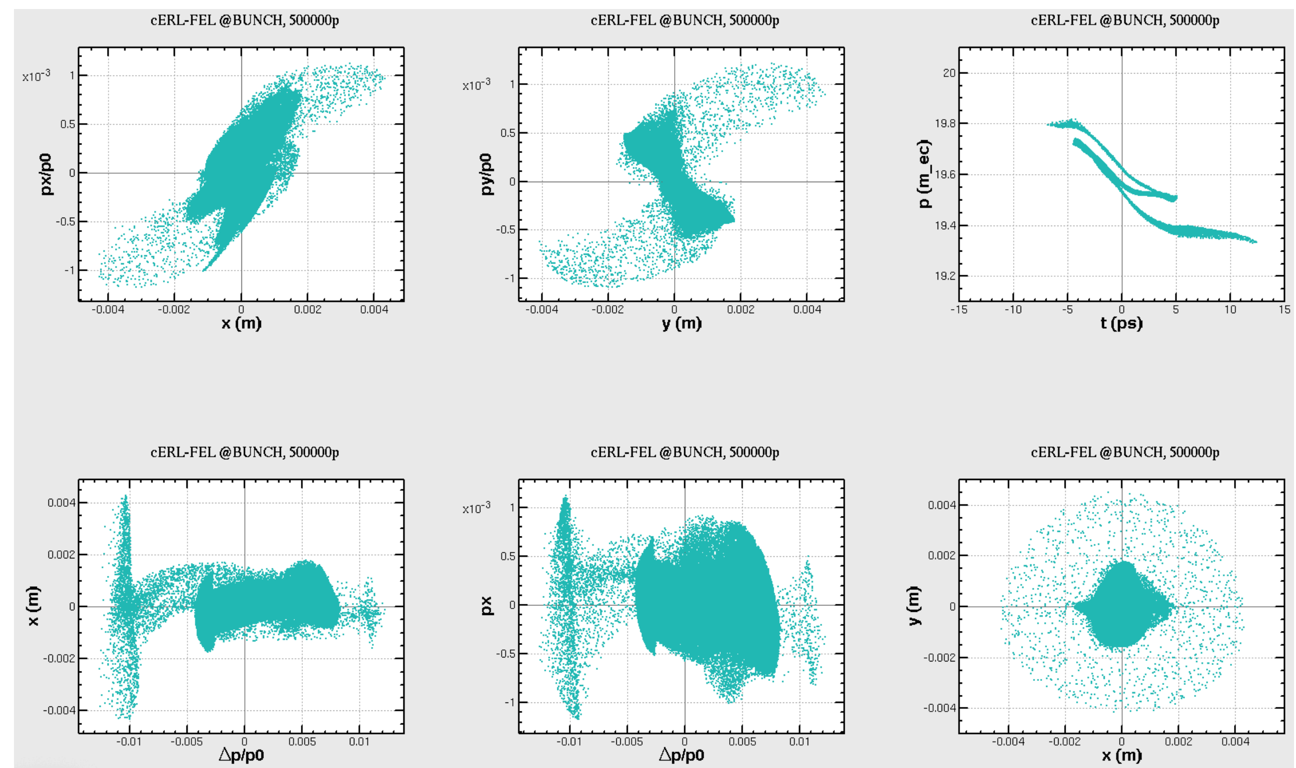
Vertical rms beam size:

* Almost independent w/o TSC
* Reasonable: No coupling between Y and Z/X
* SAD and GPT show similar behavior. TSC is important

2. Tracking simulations

Simulation with RF wake, CSR, and LSC effects using SAD
Beam distribution at POINTD:
SAD, ELEGANT and GPT: should be the same



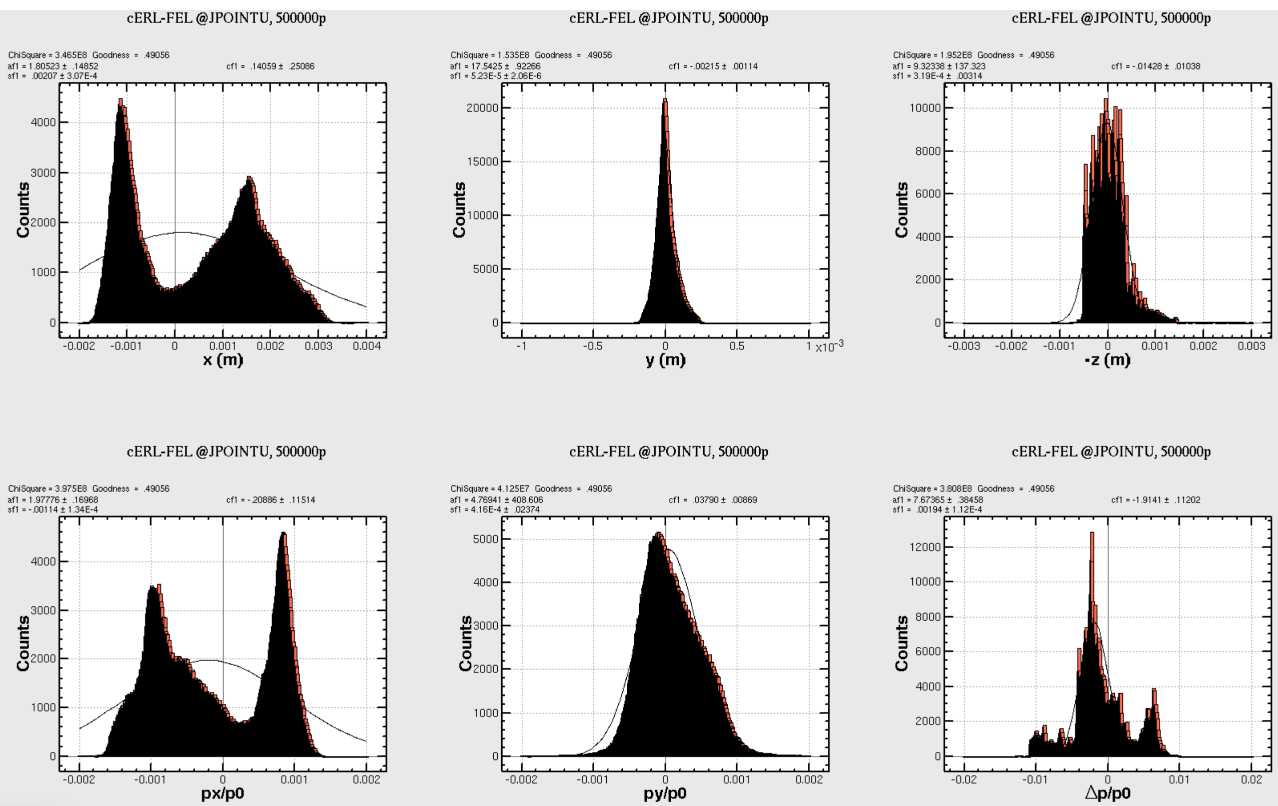


2. Tracking simulations

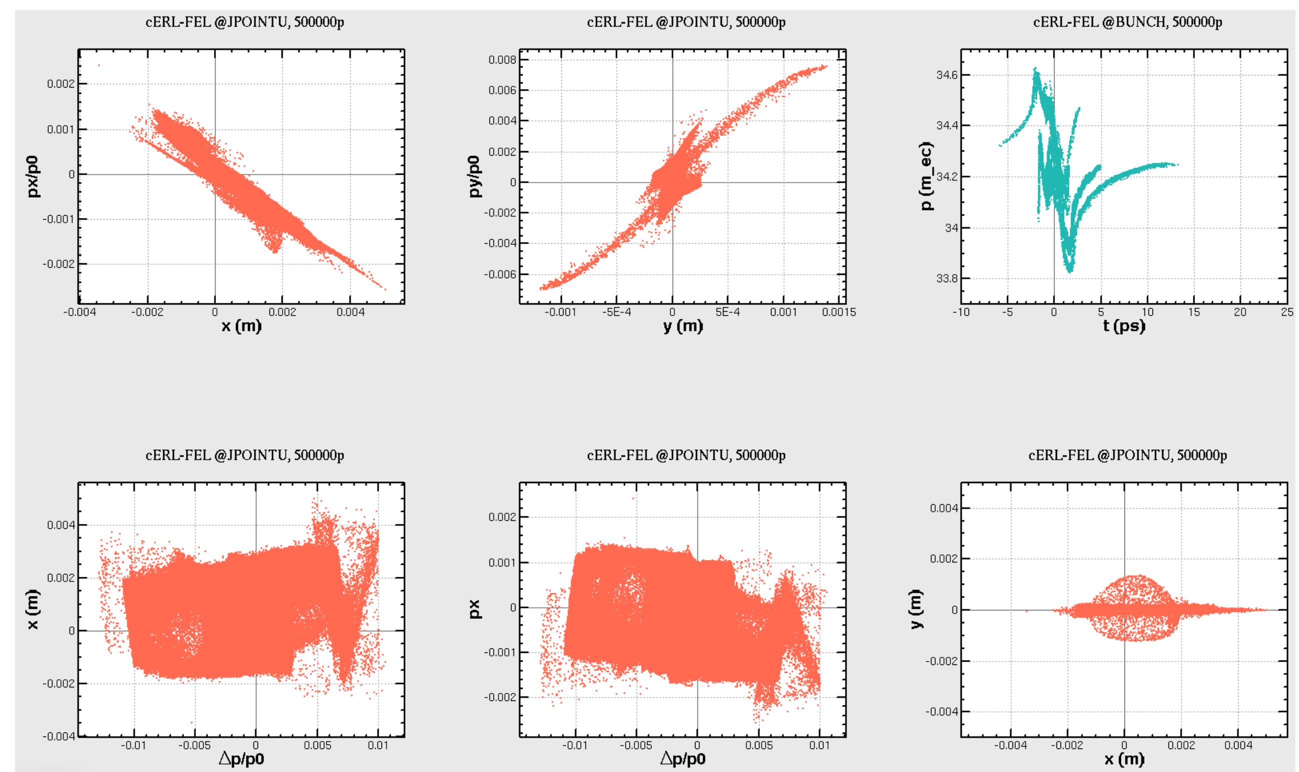
Simulation with RF wake, CSR, and LSC effects using SAD

Beam distribution at POINTU:

512 bins in z-direction for RF wake, CSR, and LSC



Nakamura-san's lattice (without TSC)

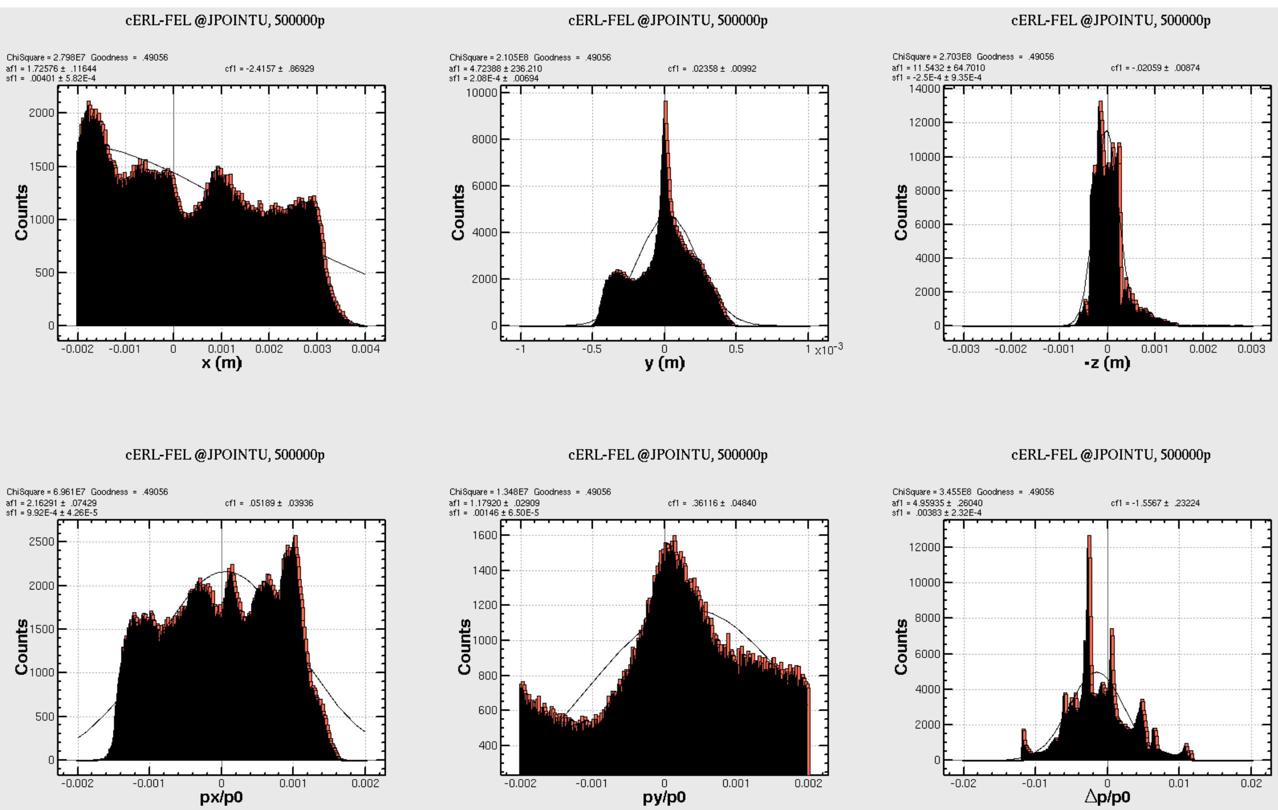


SAD simulation:

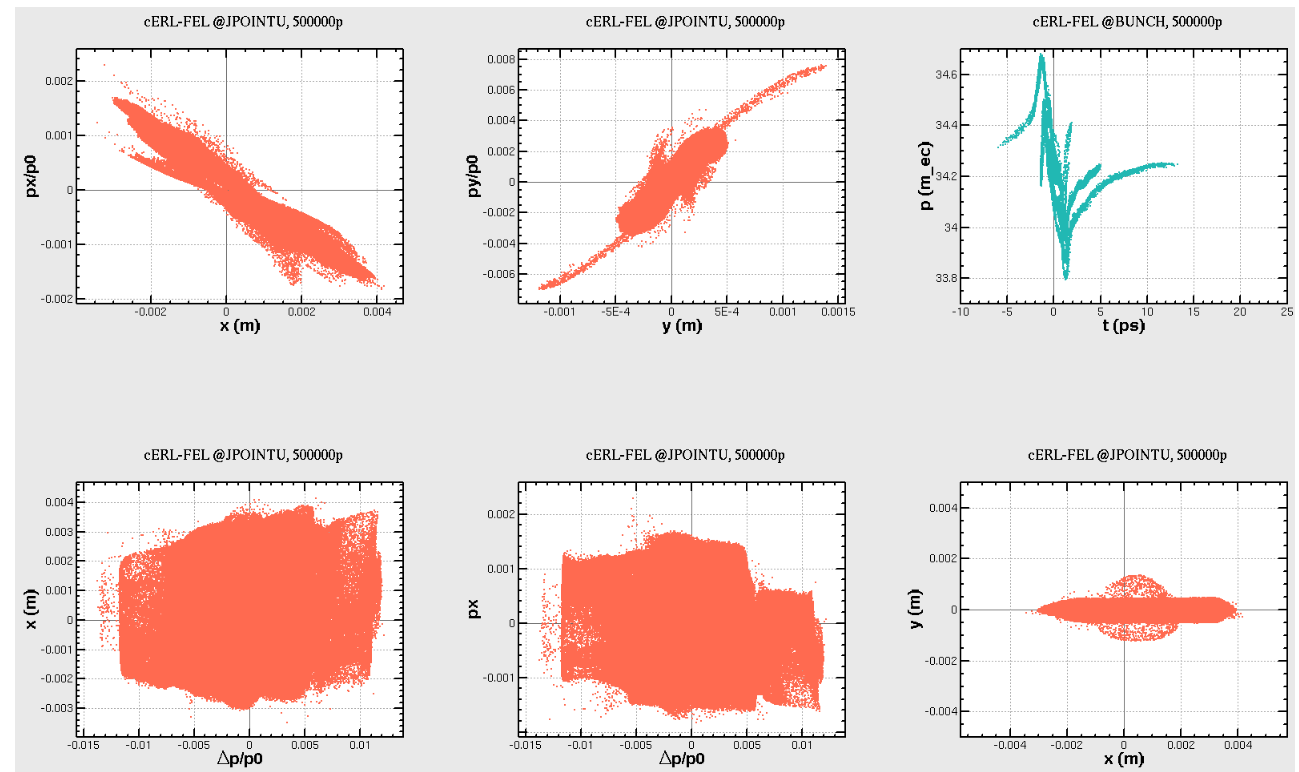
The SC forces are calculated using Gaussian fitted σx and σy, and arbitrary density (histogram) in z direction.

2. Tracking simulations

Simulation with RF wake, CSR, and LSC effects using SAD + TSC
Beam distribution at POINTU:
512 bins in z-direction for RF wake, CSR, and LSC + TSC



Nakamura-san's lattice (with TSC)



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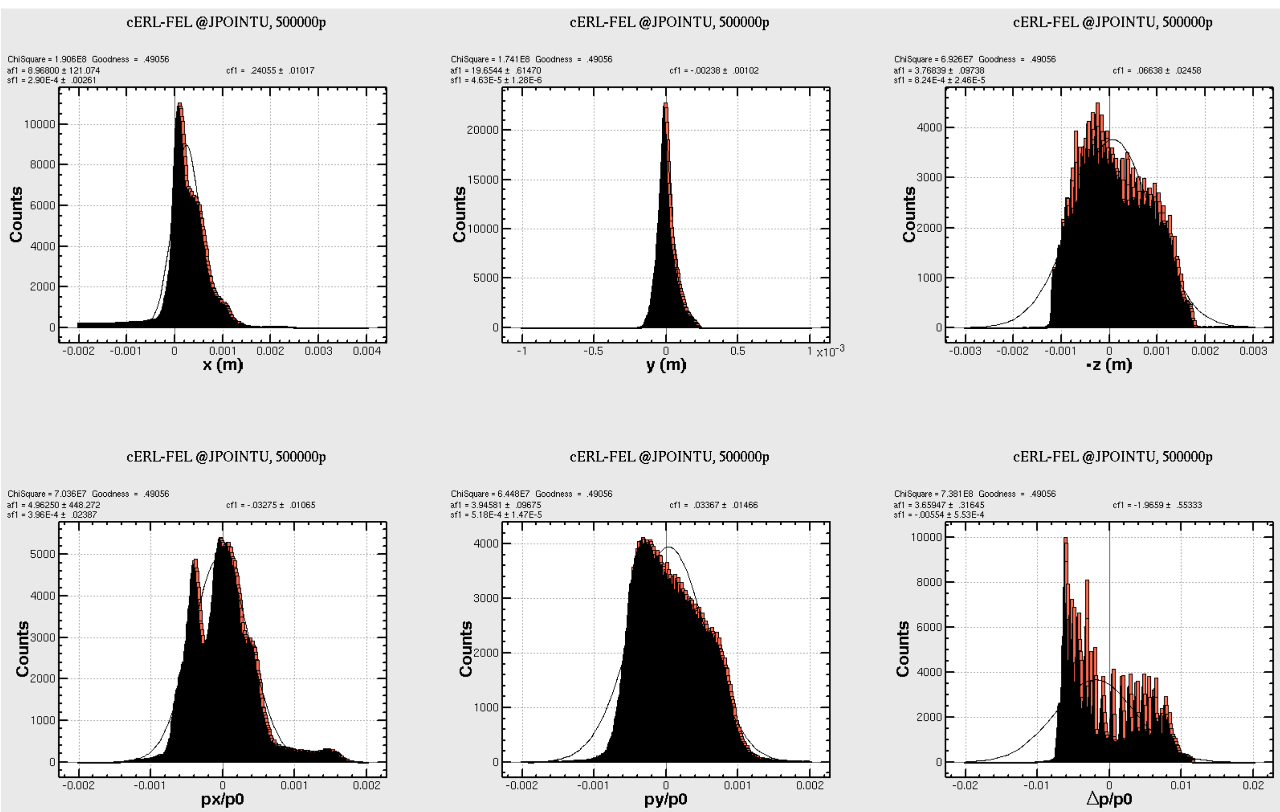
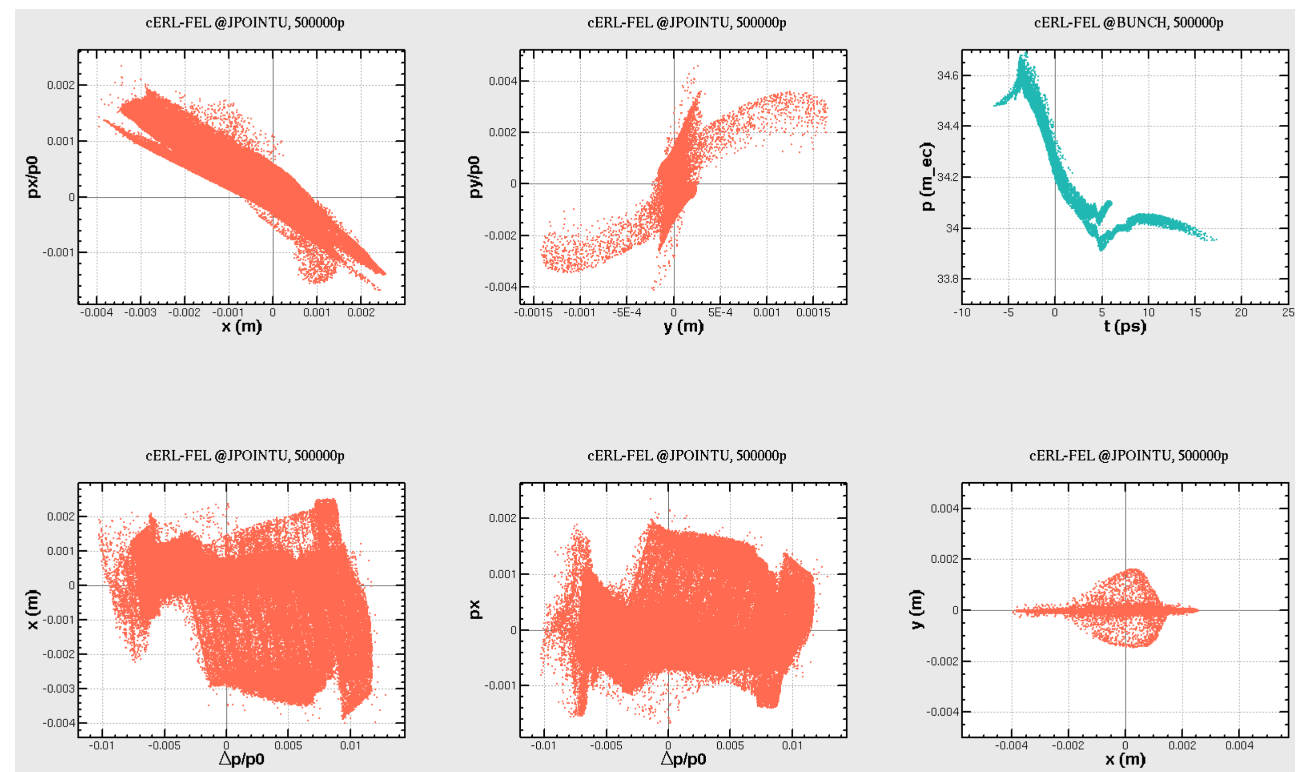
Simulation with RF wake, CSR, and LSC effects using SAD
Beam distribution at POINTU:
512 bins in z-direction for RF wake, CSR, and LSC



Shimada-san's lattice (without TSC)



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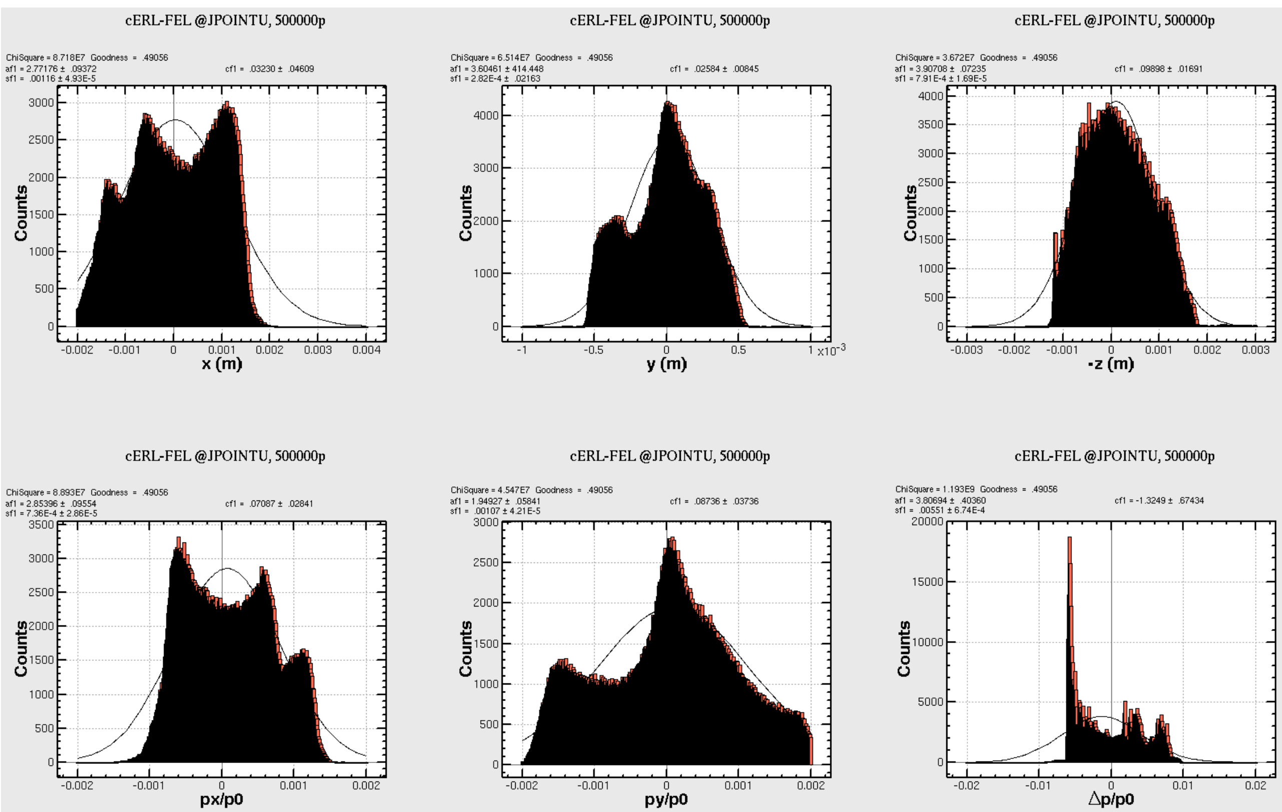
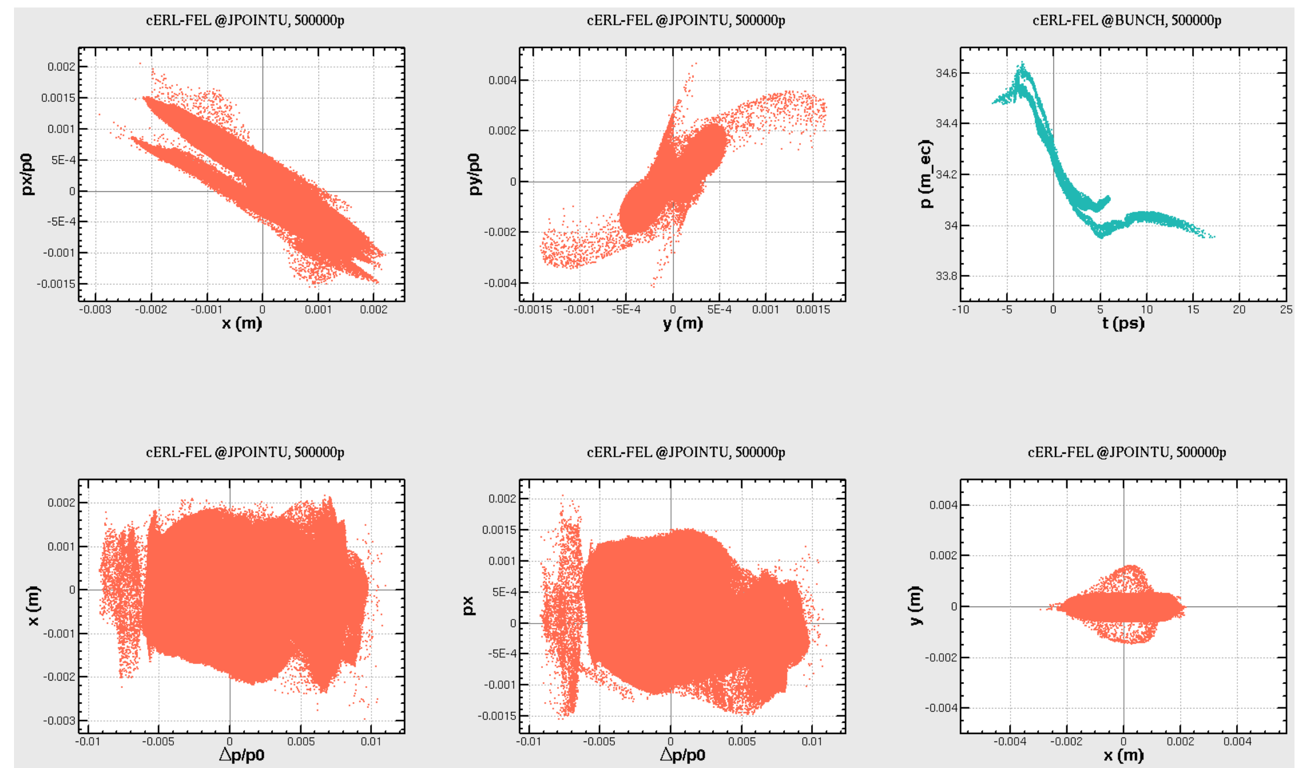
Beam distribution at POINTU:

512 bins in z-direction for RF wake, CSR, and LSC + TSC



Shimada-san's lattice (with TSC)

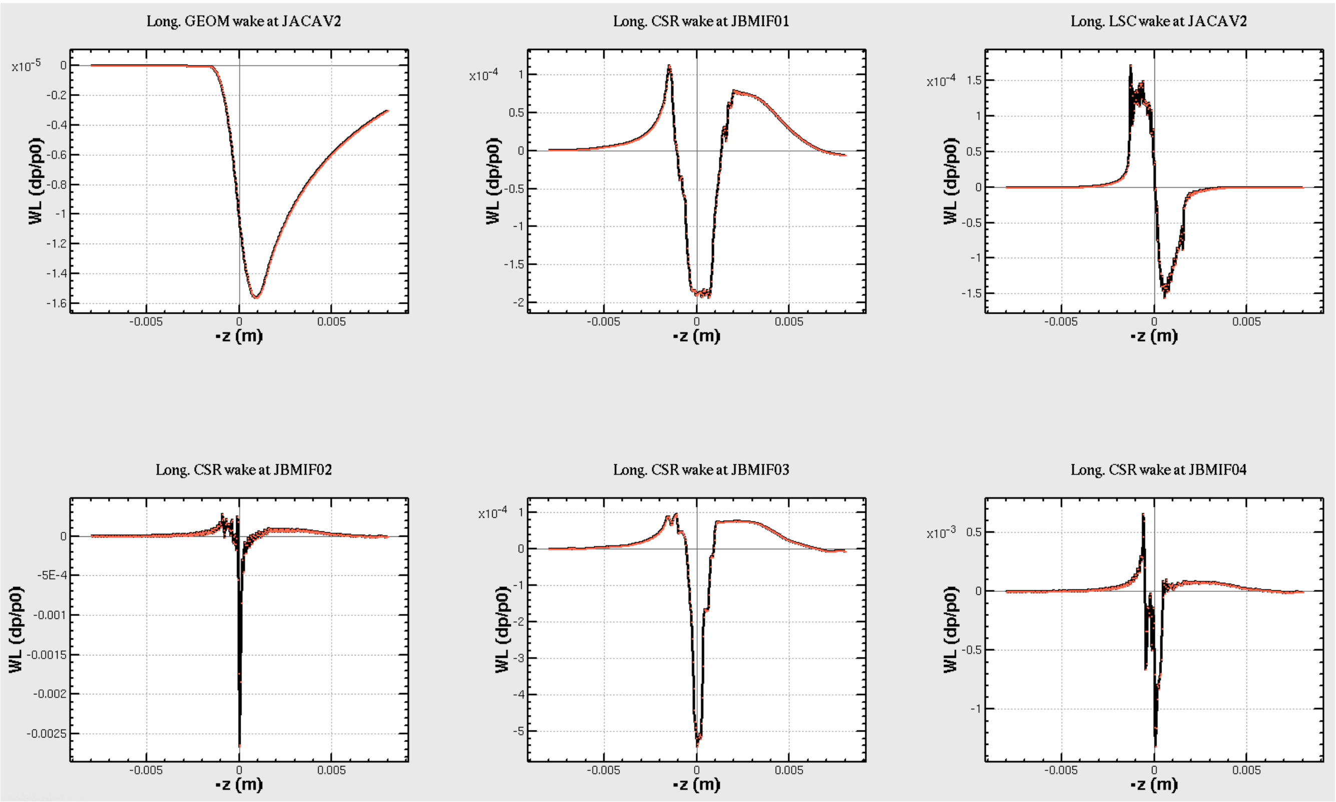


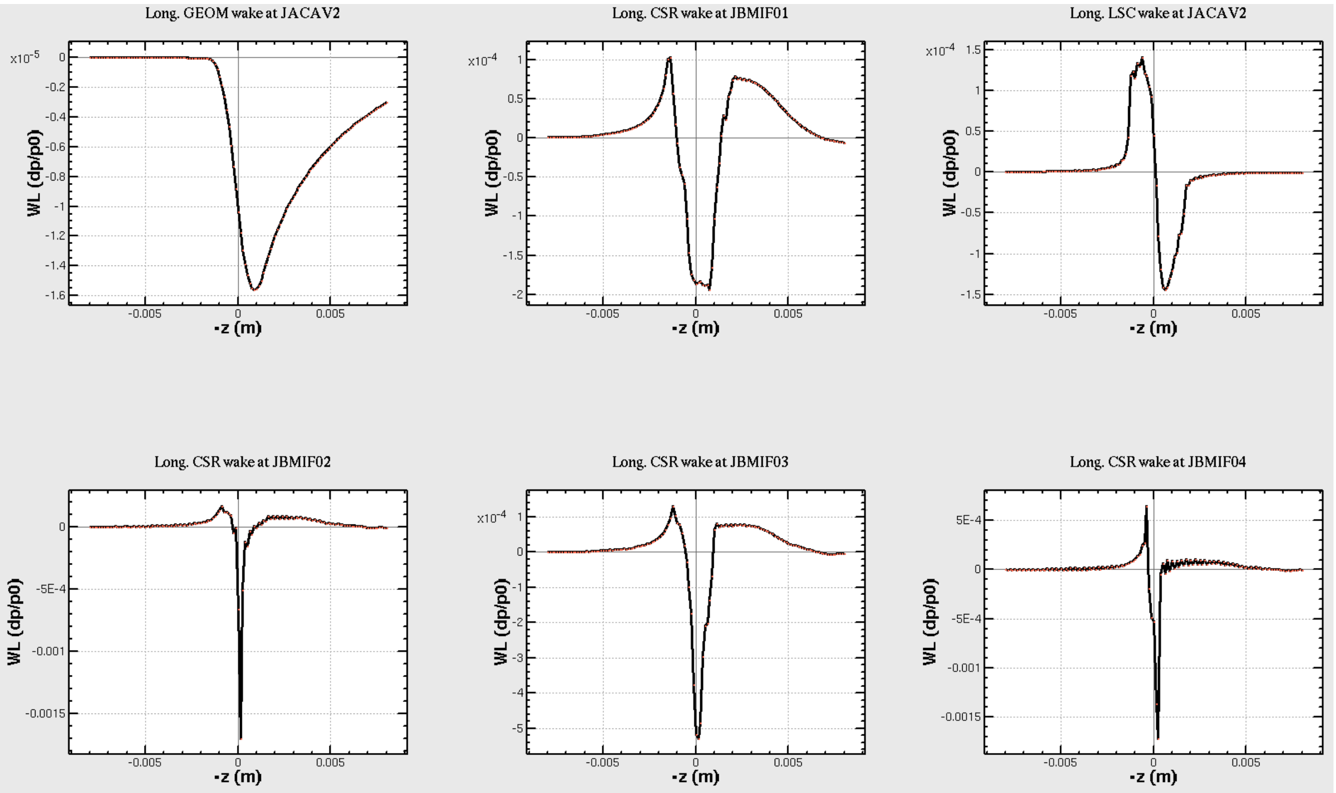
SAD simulation:

The SC forces are calculated using Gaussian fitted σx and σy, and arbitrary density (histogram) in z direction.

2. Tracking simulations

Simulation with RF wake, CSR, and LSC effects using SAD
Wake fields:
512(Left) and 128(Right) bins in z-direction for RF wake, CSR and LSC





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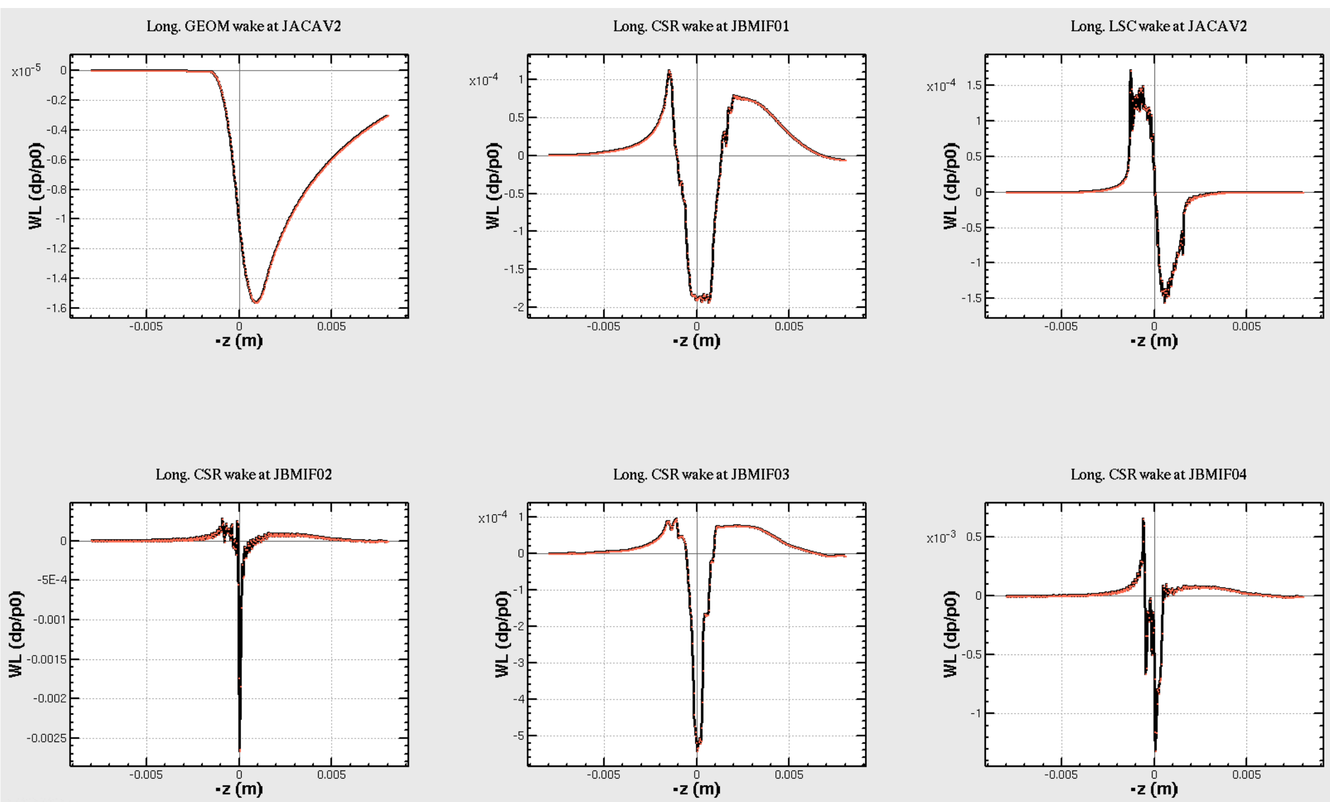
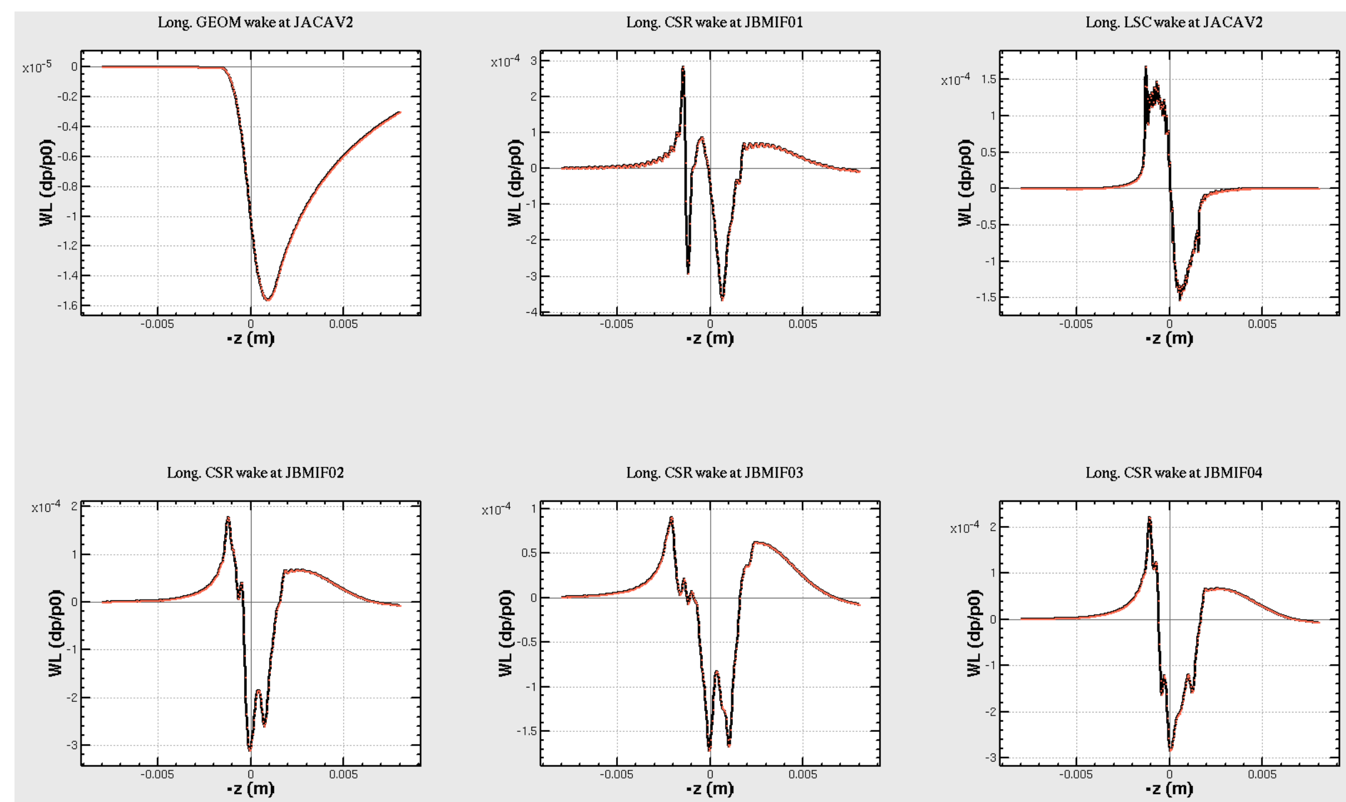
512 bins in z-direction for RF wake, CSR and LSC

Nakamura-san's lattice



Shimada-san's lattice (with TSC)



2. Tracking simulations

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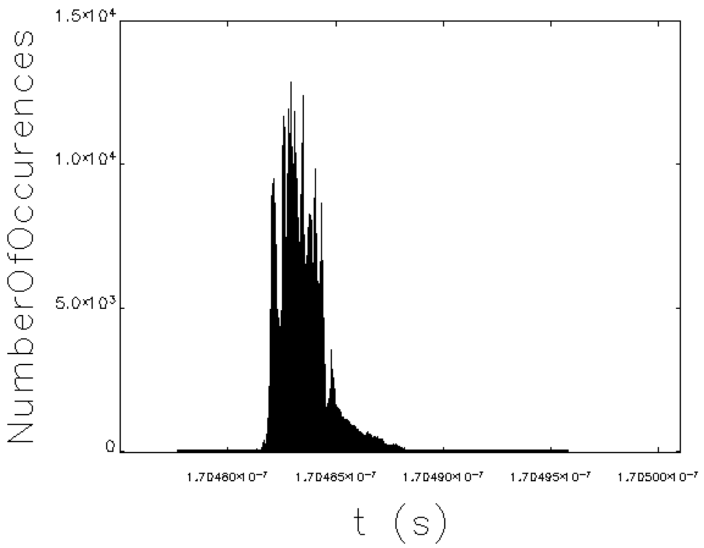
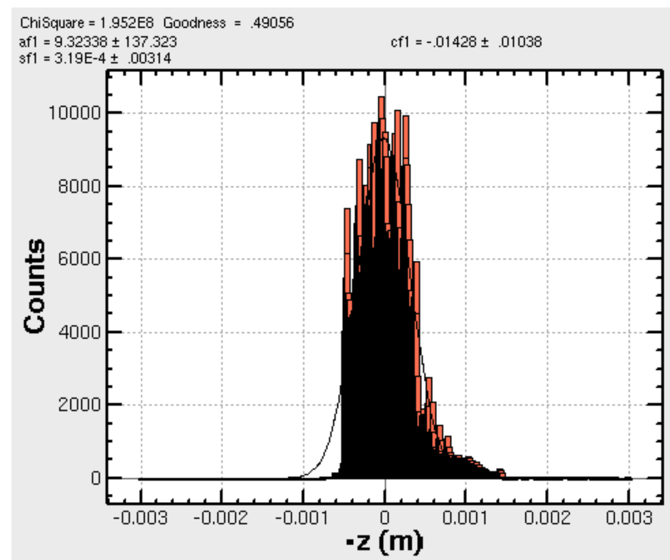
Beam distribution at POINTU:

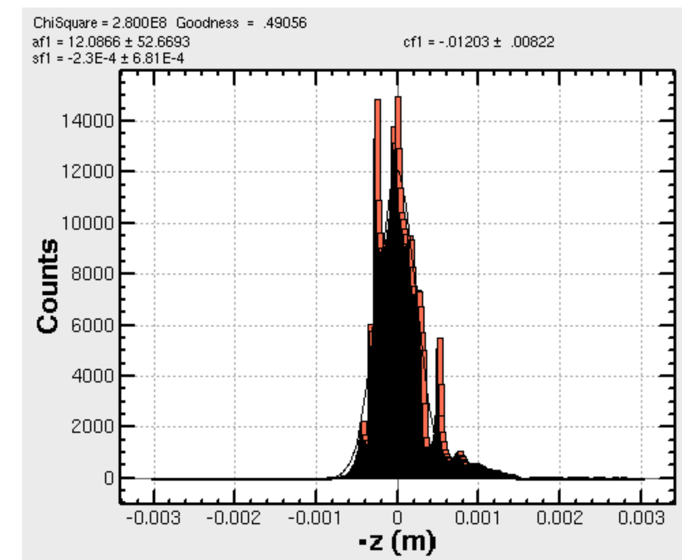
ELEGANT
From N. Nakamura

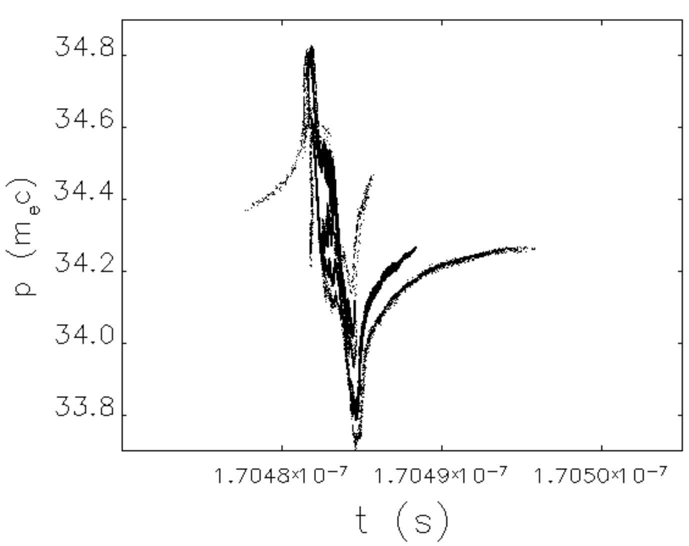


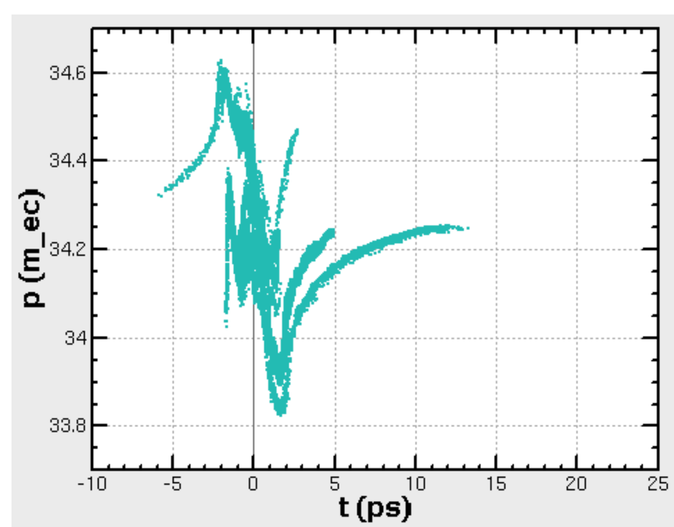
SAD (512 bins)

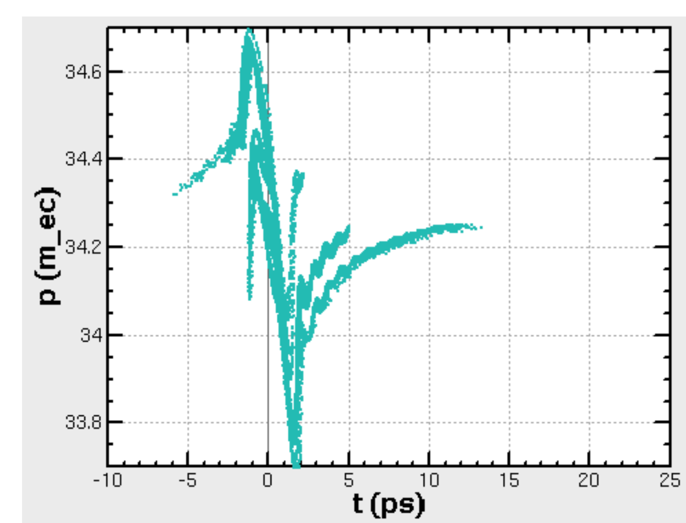


SAD (128 bins)









SAD simulation: The SC forces are calculated using Gaussian fitted σx and σy, and arbitrary density (histogram) in z direction.
ELEGANT simulation: The SC forces are calculated using rms σx and σy and arbitrary density (histogram) in z direction.
CSR model is also different: SAD uses data from CSRZ code, ELEGANT use Stupakov's 1D model

3. Models for LSC and TSC

1D LSC impedance model:

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

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:

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

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

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

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

$$\boxed{\begin{aligned} &\gamma\sigma_z \gg \sigma_\perp \\ &\sigma_\perp = \mathrm{Min}[\sigma_x, \sigma_y] \end{aligned}}$$

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

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

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

4. Summary

* All simulations (ELEGANT, SAD, and GPT) show that LSC dominates the collective effects in cERL-FEL, and CSR is not so important (CSR effects depend on the bunch length in the arc)

** If the FEL performance is sensitive to the beam distribution in the longitudinal phase space, efforts should be made to mitigate the LSC effects

* SAD and GPT simulations indicate that TSC is an important source of transverse emittance growth in cERL-FEL (to be confirmed)

** If the FEL performance is not sensitive to transverse emittance growth, we can still conclude that TSC is not an important issue

* There are also discrepancies between SAD and GPT simulations:

** Energy spread and bunch length: Likely related to LSC models [SAD: 1D, GPT: 3D]

** Vertical emittance growth: To be understood [SAD model needs to be checked/improved]

* The LSC and TSC effects can be mitigated by optics matching. 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

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

ELSEVIER

Beam matching with space charge in energy recovery linacs

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ARTICLE INFO

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Momentum compaction
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 (old)

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

* Use latest magnet layout for simulations (2020.04 done, 2020.06.07 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)

5. To-Do list (updated)

* Further benchmark between ELEGANT, GPT, and SAD (to be reviewed?).

** It's better to have the same lattice, the same initial beam distribution
** It's better to simulate SC and CSR effects separately. This will help better understand what's happening inside the arc.

* LSC model to be improved in SAD (also ELEGANT?)

** Currently 1D (same as ELEGANT) is used. Maybe it's not enough since LSC is dominant.

* TSC model to be revisited in SAD

** Scaling factor OK?
** Currently only put TSC kick at the exit of each finite-length element. Maybe not good enough.

* TSC model to be implemented in ELEGANT?

** Both SAD and GPT show TSC can be important (modify the beam distribution in transverse phase space)
** It is easy to model TSC in elegant. SCMULT is already available for storage rings. Need to activate it for linacs. Possible solutions:
*** Send request of modifying ELEGANT source code to Mike Borland
*** Modify ELEGANT source codes by ourself (I think it should not be difficult)

* Optics matching with SC and CSR

** Strategy to be well defined
** Available codes: To be reviewed