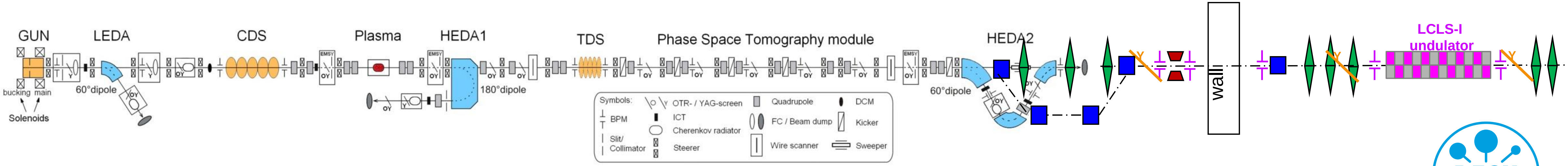
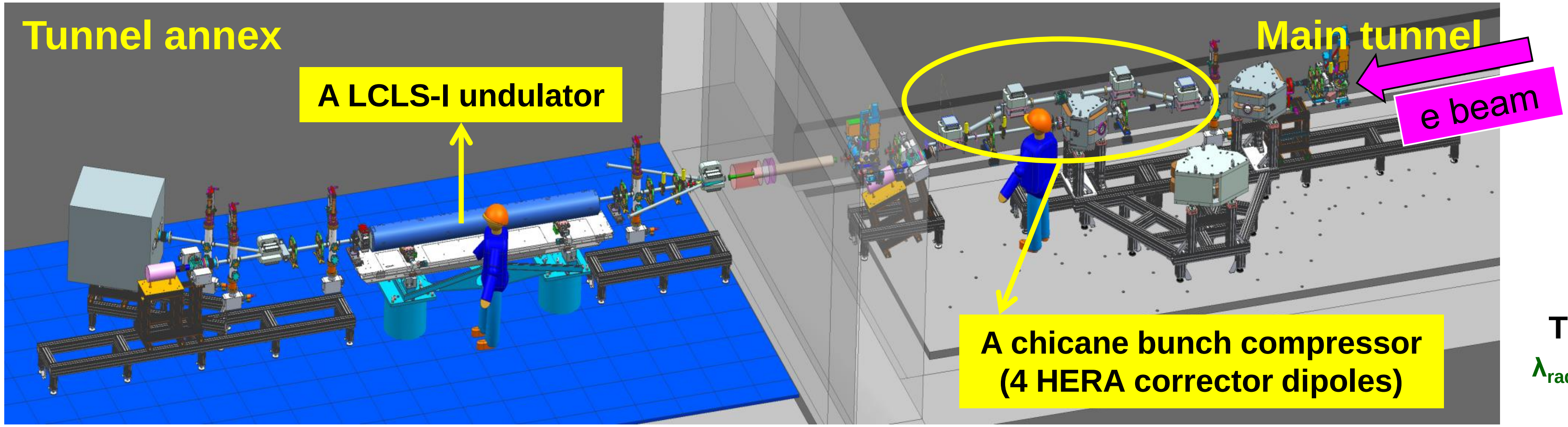
Start-to-end and CSR Simulation of Bunch Compressor for the PITZ THz SASE FEL Experiment

Anusorn Lueangaramwong from group PITZ
Meeting at DESY in Hamburg 10.03.2020



Plan of Proof-of-Principle Experiments for THz FEL at PITZ

The proposed extension for the proof-of-principle experiments for THz FEL at PITZ



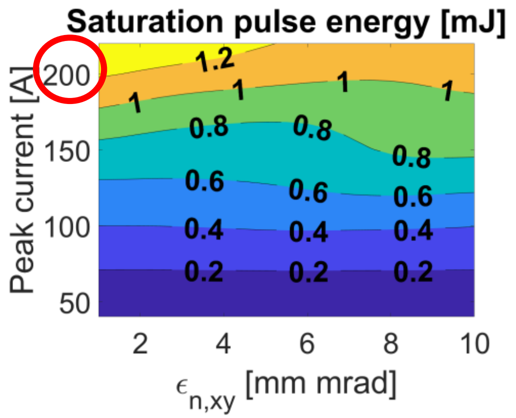
- High peak current and long bunch beams for high-gain FELs (SASE and seeding)
- Ultra-short bunch beams for coherent THz radiation (undulator, transition and diffraction)
- **A bunch compressor (BC)** is needed for beam manipulations

Estimations of FEL parameter space:

λ_{rad} = 100 mm , a helical undulator (λ_u = 40mm)

Genesis 1.3 code, a model Gaussian bunch

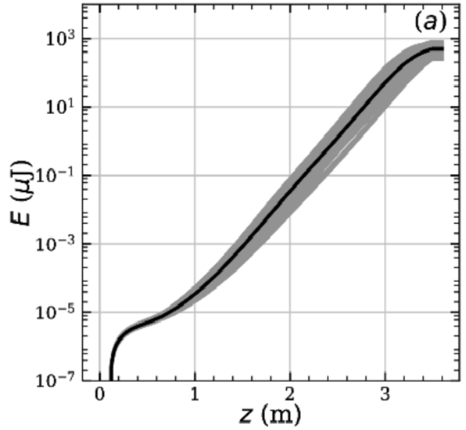
(P. Boonpornprasert, UHH PhD thesis, 2020)


Saturation pulse energy [mJ]

The gain curve from S2E simulations:

λ_{rad} = 100 mm, a LCLS-I undulator (λ_u = 30 mm)

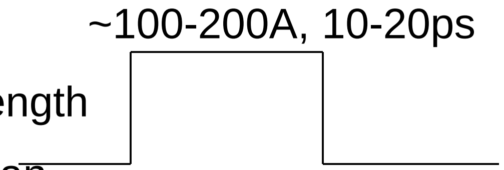
(X. K. Li et. al., TUPRB018, IPAC2019)



Bunch Compressor Study

To investigate performance of our chicane design

- To optimize for SASE
  - high averaged currents, longer than cooperation length
  - high charge <4nC, longitudinal flat-top and Gaussian



- To support tuning seeded FEL (by Photocathode laser pulse modulation)
- To optimize for Super radiant
  - short bunch length
  - relatively low charge 10pC-1nC, longitudinal Gaussian
- To optimize for low-q sub-ps high-repetition application
  - <1pC

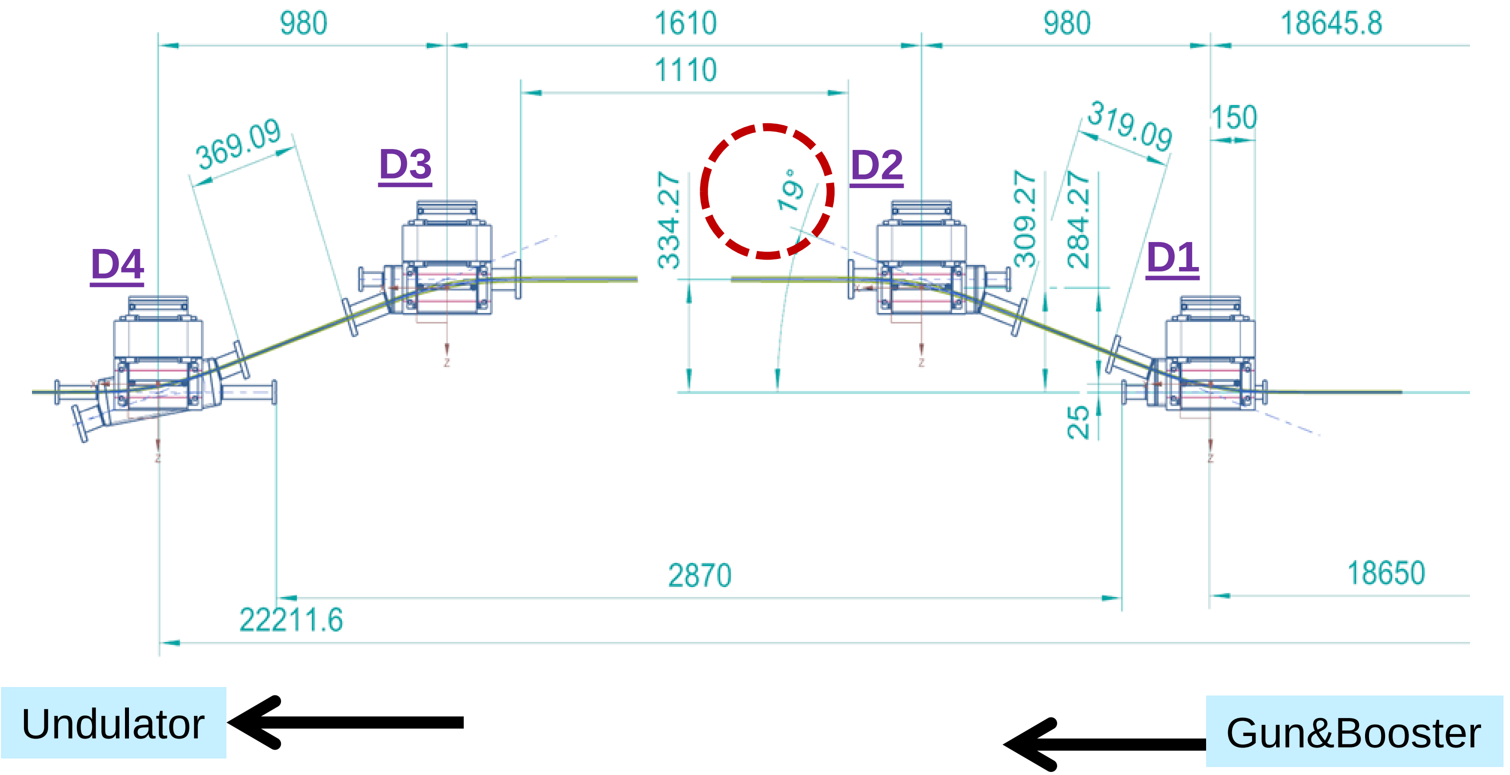
Study with Simulations

performance of the bunch compressor design

- When considering
  - CSR effect
  - Space charge effect
  - Use of B-field profile
  - Charge ~ up to few nC

- Simulations
  - Scan charge up to 4 nC
  - Use distributions based on PITZ beam – optimized with booster phase

Layout of PITZ Bunch Compressor (R56 = -0.218m)



6-22MeV/c
working on **17MeV/c**

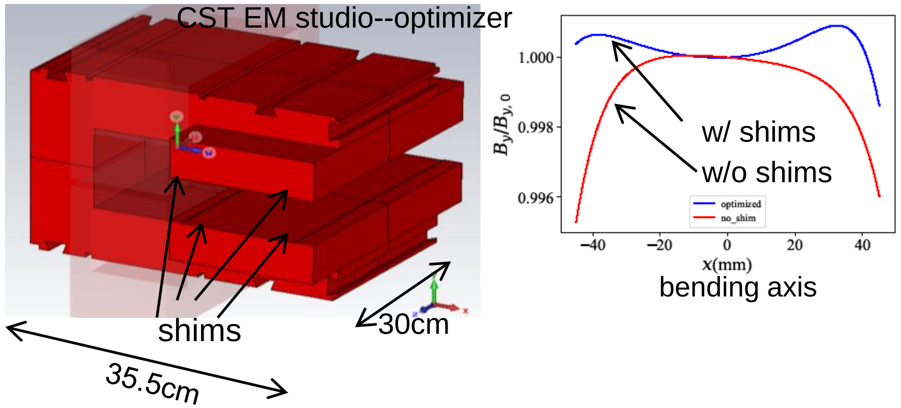
Simulation Programs

for CSR effect

Our Requirements

- Fringe field (we import field profile from CST EM studio)
- Space charge effect (we have low E beam ~ 17 MeV)

old HERA magnet with new pole shoe



Programs (so far we know)

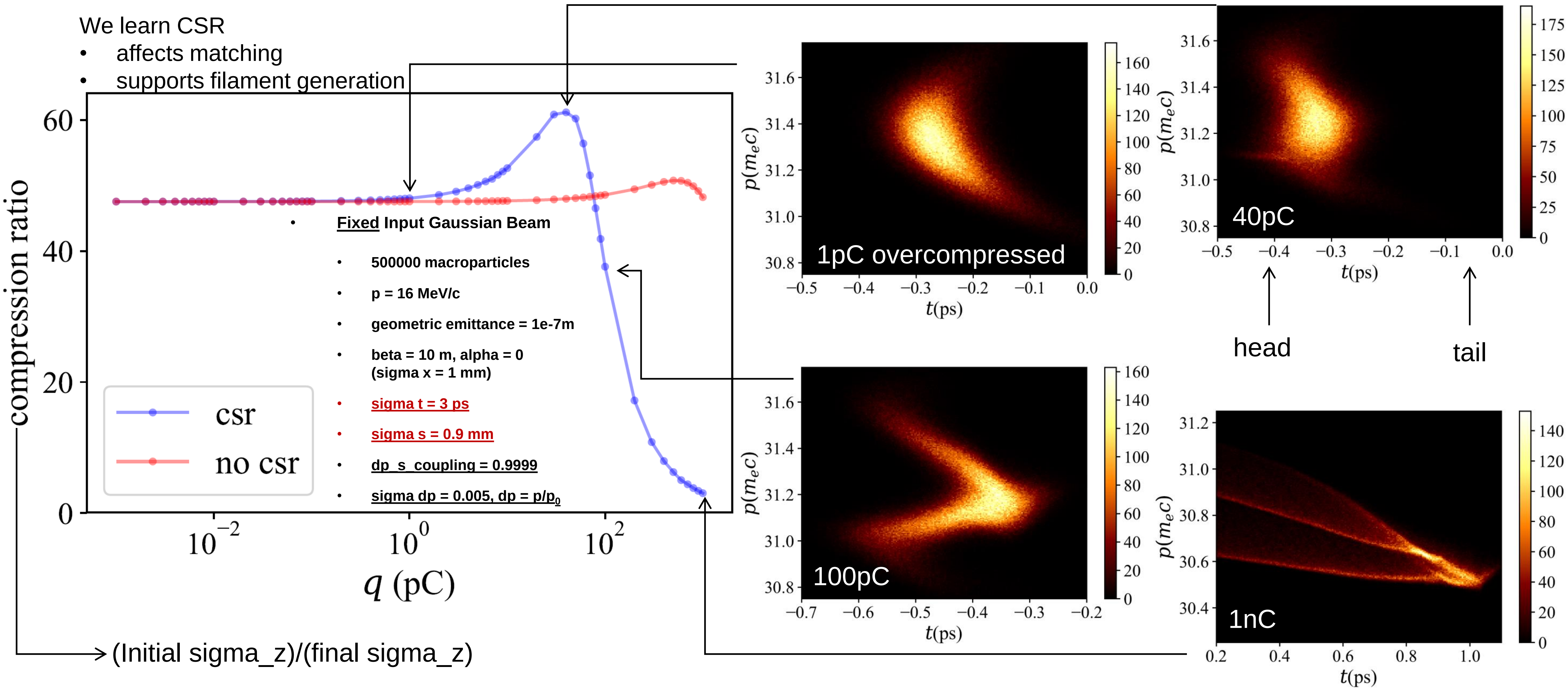
- according to their manuals

program	track dim	csr	sp charge	import B field	fringe field
ASTRA	3d	no?	yes	3d on "cavity"	w/ import file
IMPACT-T	**3d**	**yes**	**yes**	**1d**	**Enge function**
OCELOT	3d	Yes(1d)	Yes(3d)	no	no
xtrack	3d	Yes(1d)	yes (3d)	no	no

Preliminary Study w/ IMPACT-T: Bunch Charge Scan

Evolution of filaments with Input Gaussian Beam (fixed chirp, not optimized, not matched)

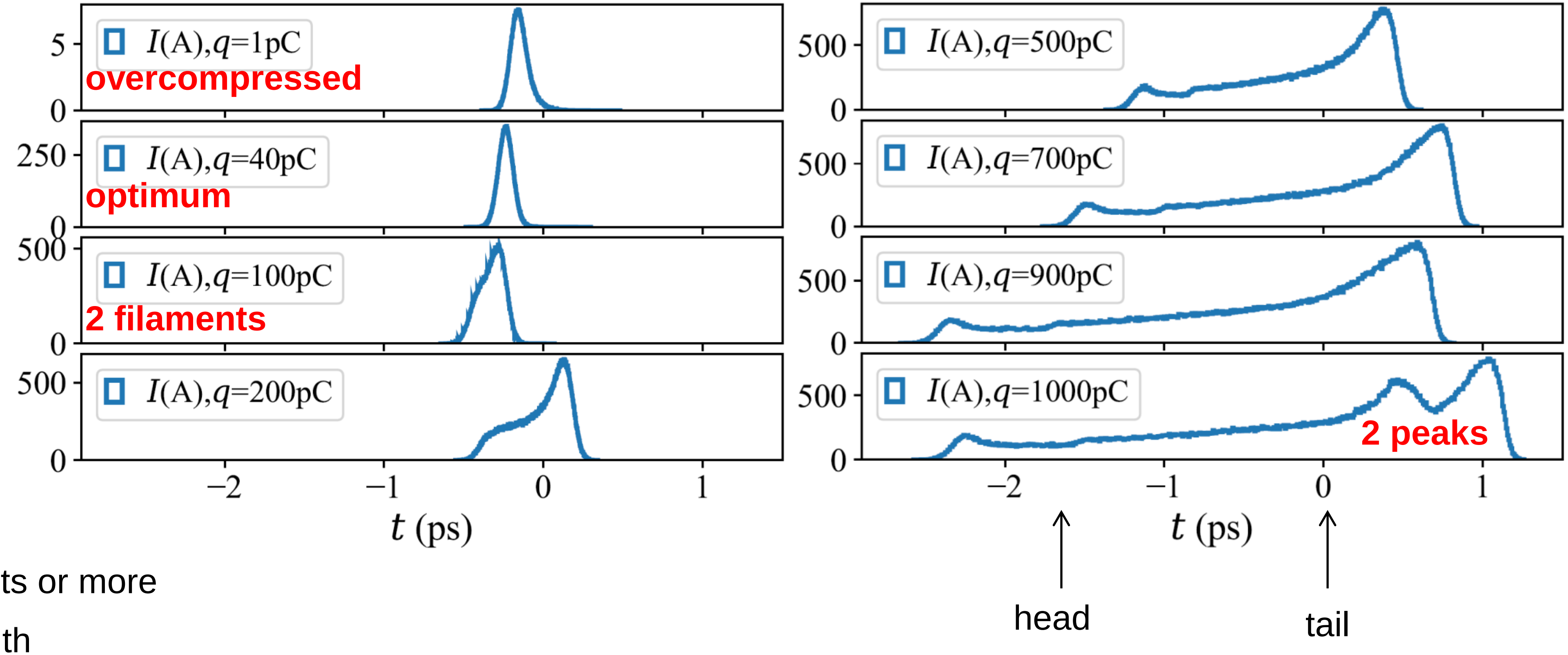
We learn CSR
- affects matching
- supports filament generation



- **Fixed Input Gaussian Beam**
  - **500000 macroparticles**
  - **p = 16 MeV/c**
  - **geometric emittance = 1e-7m**
  - **beta = 10 m, alpha = 0 (sigma x = 1 mm)**
  - **sigma t = 3 ps**
  - **sigma s = 0.9 mm**
  - **dp_s_coupling = 0.9999**
  - **sigma dp = 0.005, dp = p/p_0**

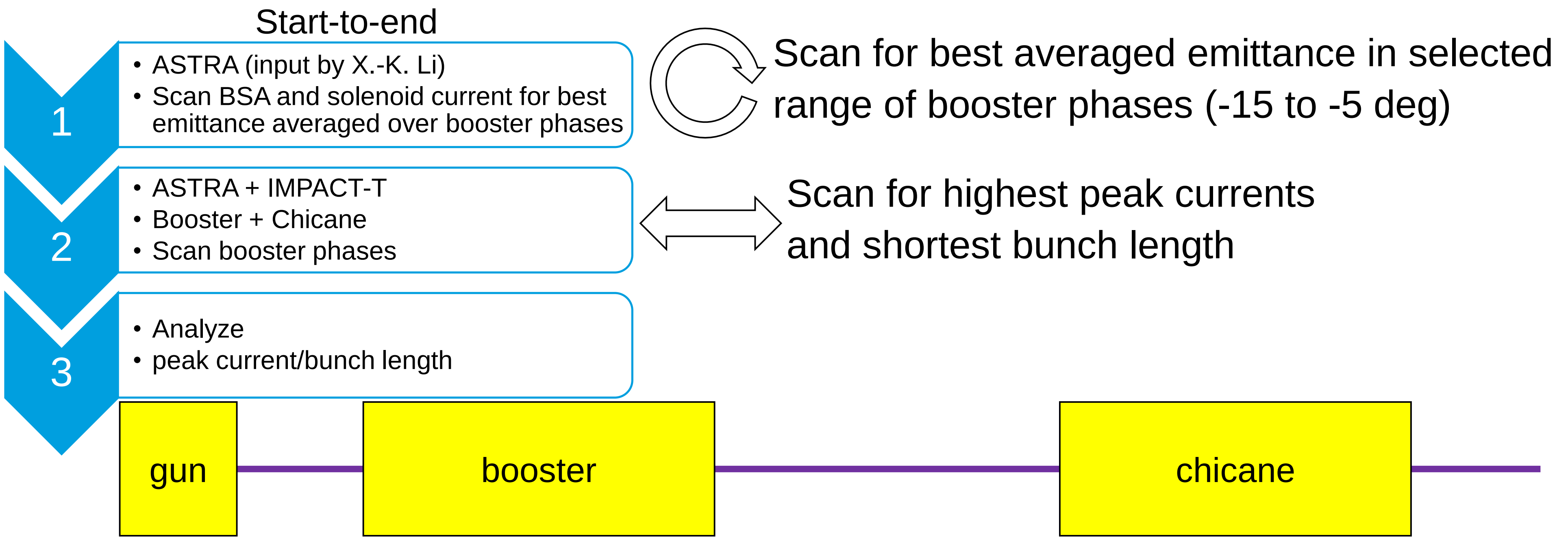
Preliminary Study w/ IMPACT-T: Bunch Charge Scan (cont.)

profiles



- Charge > 100 pC
  - forming 2 filaments or more
  - larger bunch length
- Charge ~1nC
  - forming 2 peaks in profile

Start-to-end Programs



Start-to-end

1
- ASTRA (input by X.-K. Li)
- Scan BSA and solenoid current for best emittance averaged over booster phases

Scan for best averaged emittance in selected range of booster phases (-15 to -5 deg)

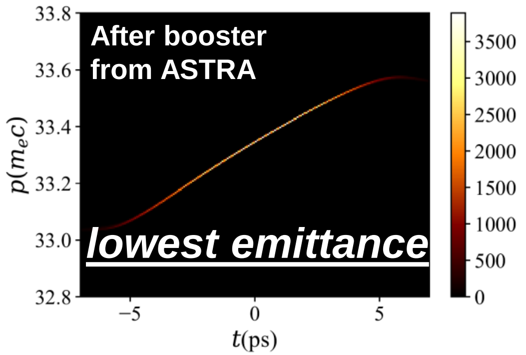
2
- ASTRA + IMPACT-T
- Booster + Chicane
- Scan booster phases

Scan for highest peak currents and shortest bunch length

3
- Analyze
- peak current/bunch length

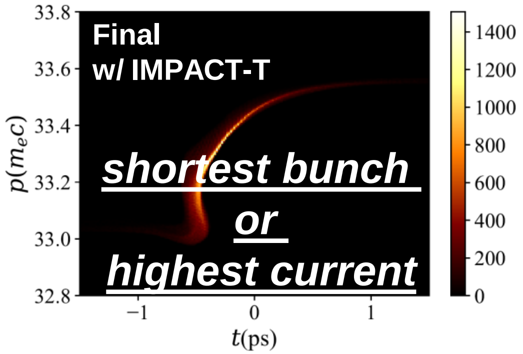
Guassian & flat-top

1 scan solenoid current and BSA (initial sig_x) and again solenoid current



After booster from ASTRA

lowest emittance



Final w/ IMPACT-T

shortest bunch or highest current

2 scan ***booster phase***

Step1: Beam Input

For ASTRA

- Gaussian Beam
  - LE = 0.55e-3, dist_pz = 'i',
  - Dist_z = 'g',
    sig_clock = 6e-3/2.355,ns
  - Dist_x = 'r', sig_x = BSA/4,
  - Dist_y = 'r', sig_y = BSA/4,

- Flat-top Beam
  - LE = 0.55e-3, dist_pz = 'i',
  - Dist_z = 'plateau',
    Lt = 16.e-3, rt = 2.e-3,ns
  - Dist_x = 'r', sig_x = BSA/4,
  - Dist_y = 'r', sig_y = BSA/4,

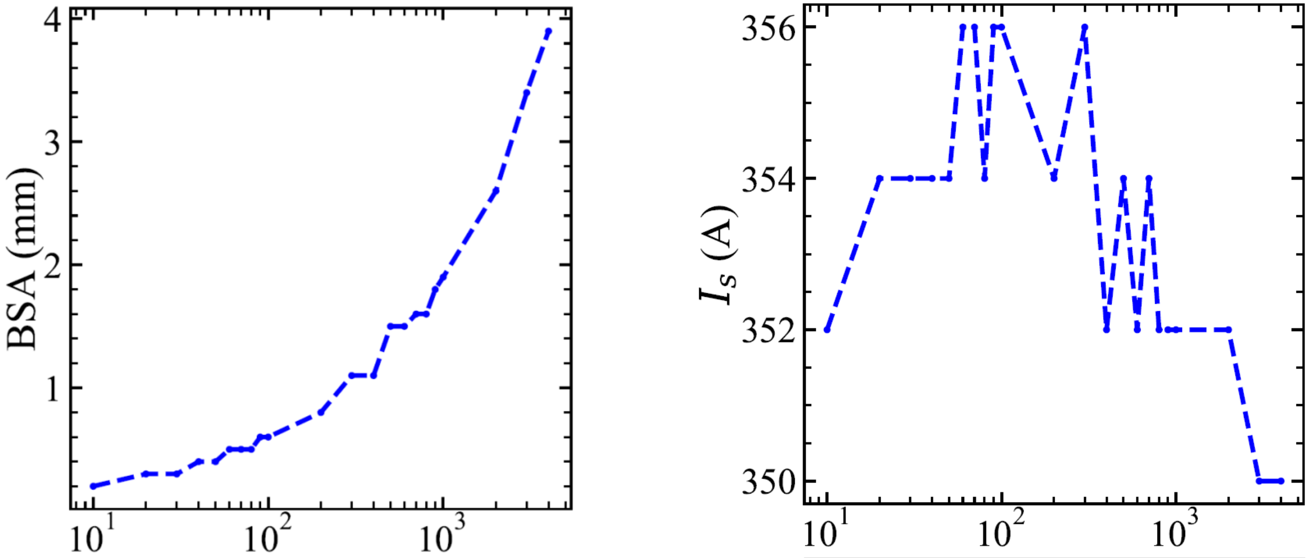
Best case
Flatop ~20-25ps
from MBI laser

or Short Gaussian ~2ps

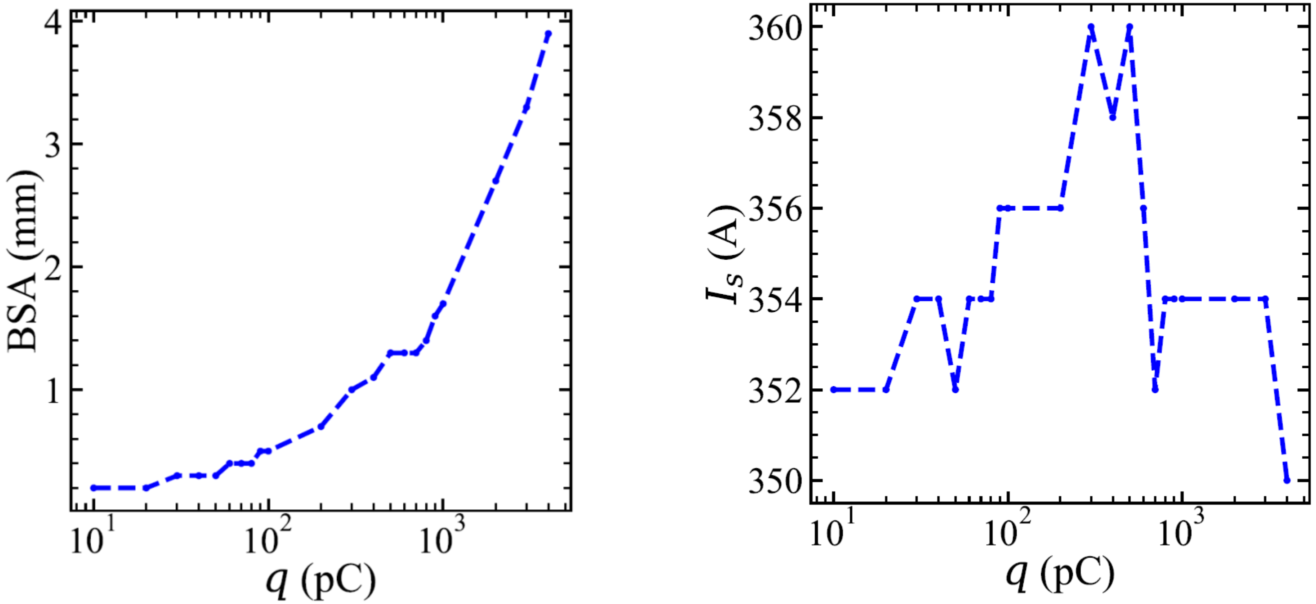
Step1: ASTRA scan, Finding working points for next step

Obtain our conditions (low emittance)

- Gaussian Beam



- Flat-top Beam



Note:

- scan BSA, solenoid current

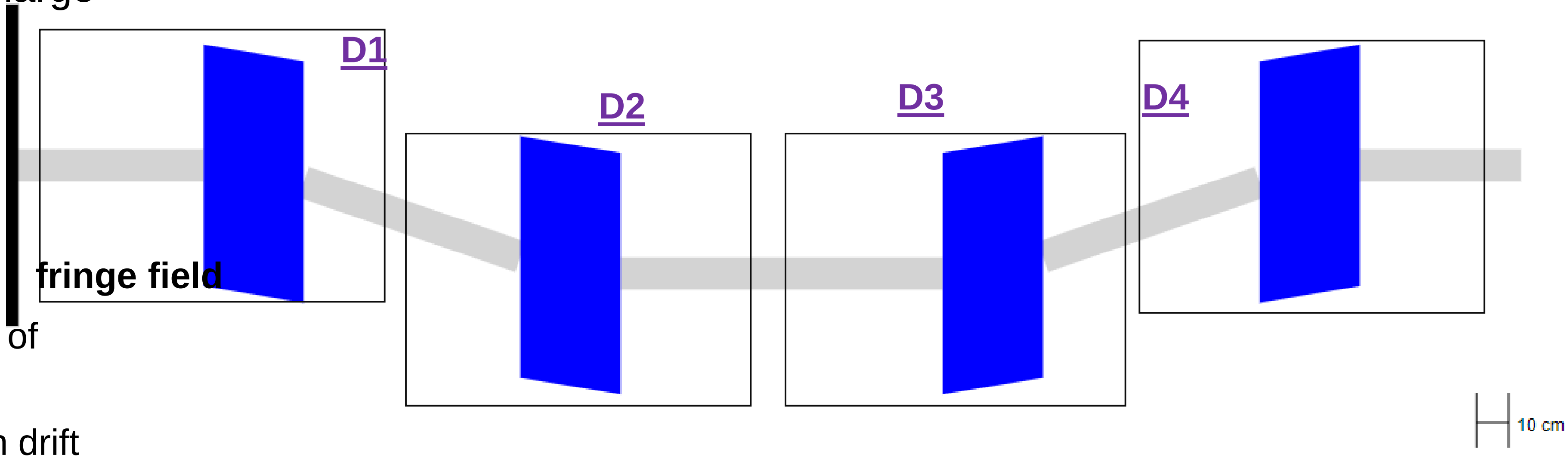
- fixed laser duration, etc.

- for each charges

Step2: IMPACT-T setup

For fast scan

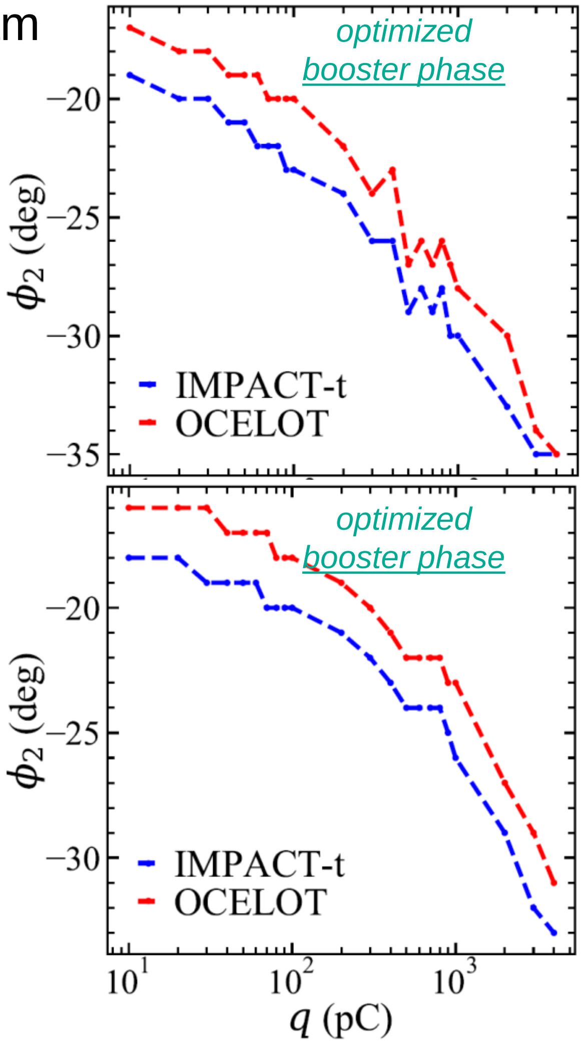
- Include 2D or 3D space charge
  - **x = bending axis**
  - Grid 64x64x64
  - Time step = 1e-13 s
- Use Fringe field element
  - extended to the maximum of ~0.5m from dipole edge
  - allow calculation of CSR in drift between dipoles
- Only includes longitudinal CSR effects
  - Already subtracts the short-range space-charge effect
- Does not include shielding and wake effect

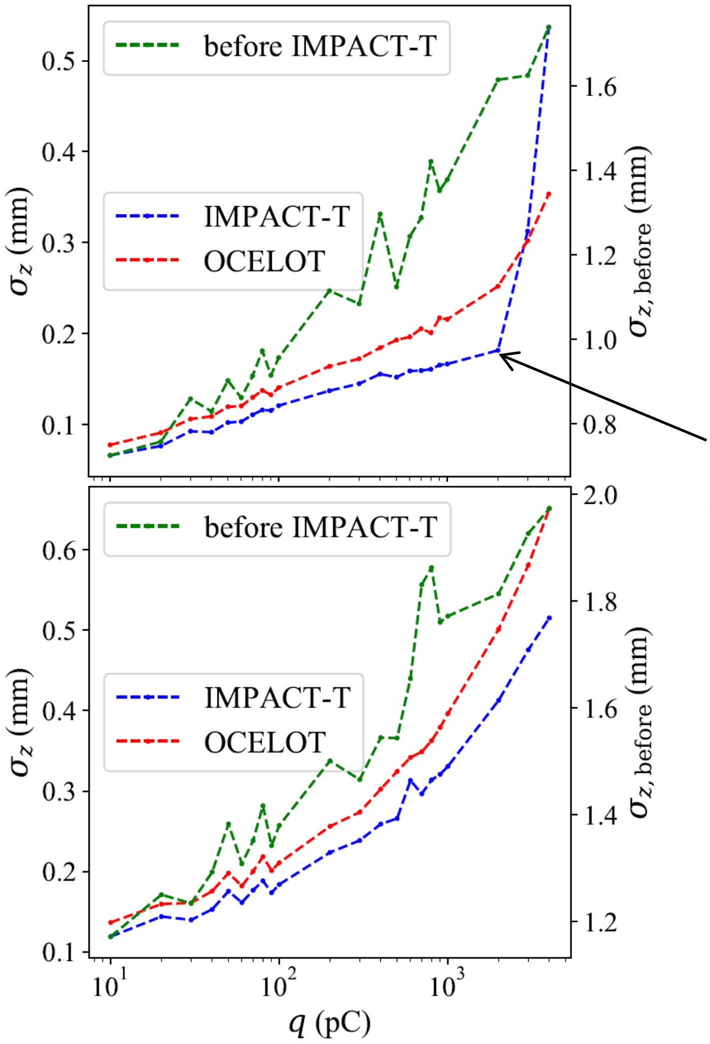


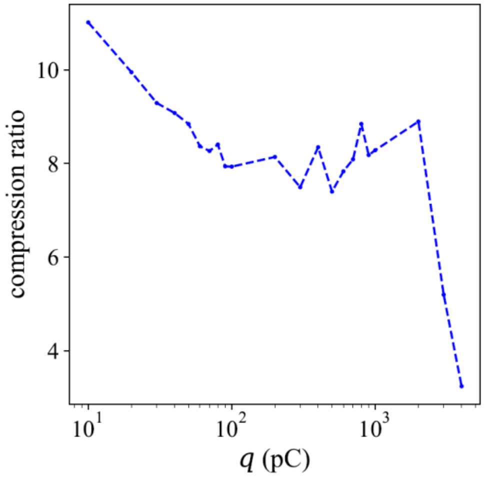
Step2: Scan for shortest bunch length

- Gaussian Beam

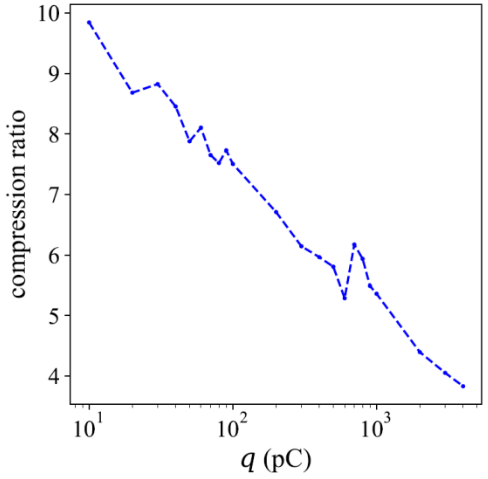
- Flat-top Beam







S2E optimization could allow compression at high charges



Note: last 2 points (Gaussian) is out of range

Step3: Analyze for highest peak currents (IMPACT-T)

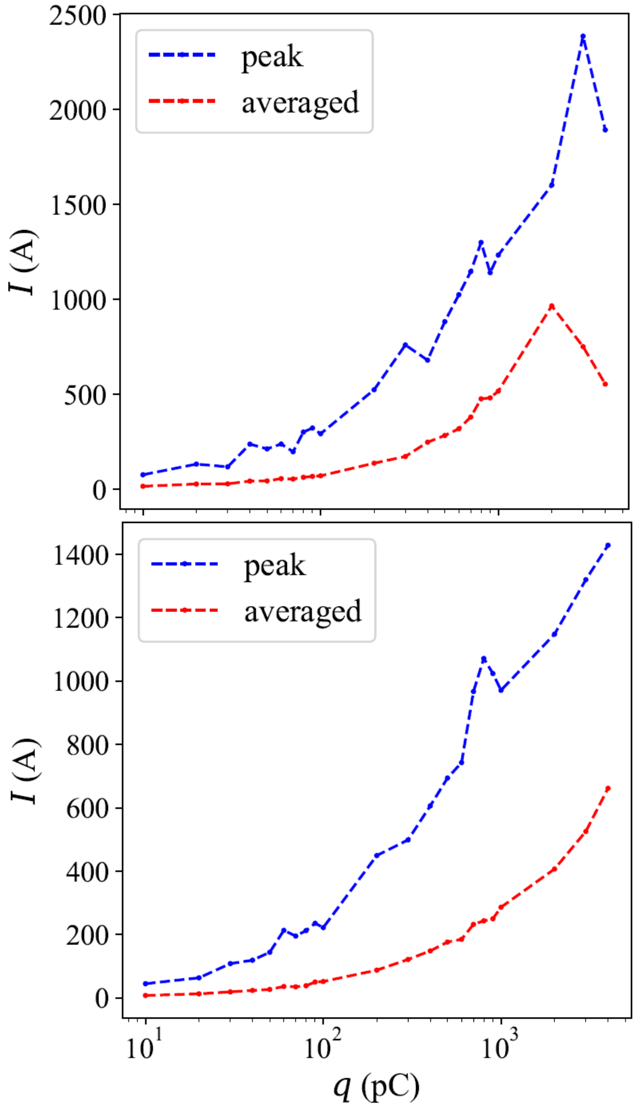
Histogram w/ 64 bins (+/-1.5std)

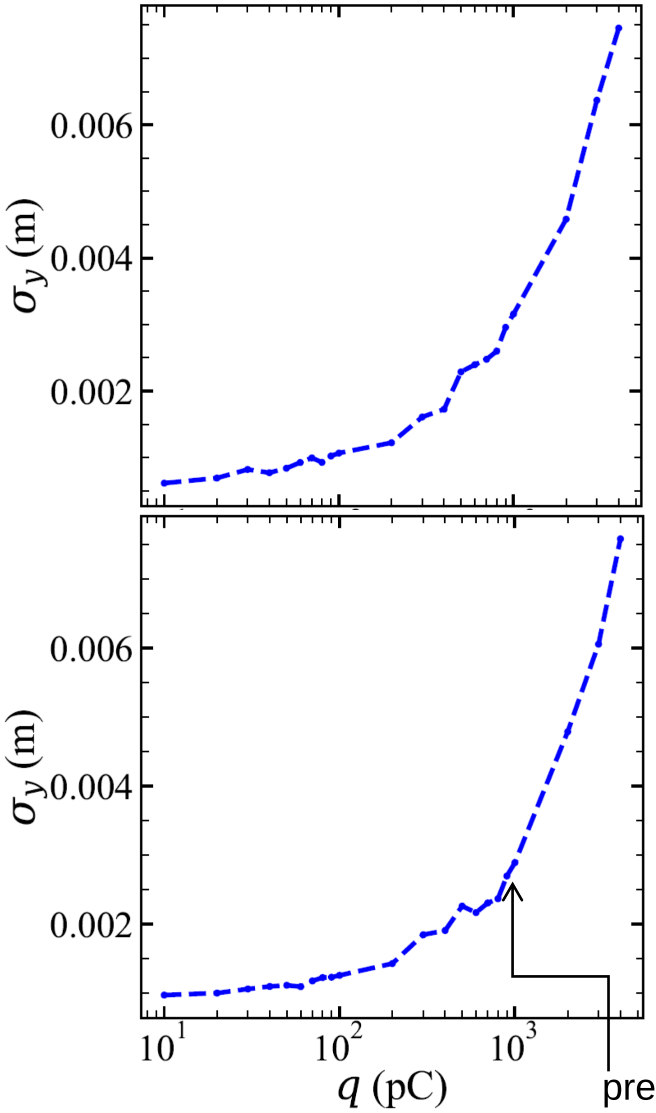
- Gaussian Beam

@ optimized booster phase for shortest bunch length

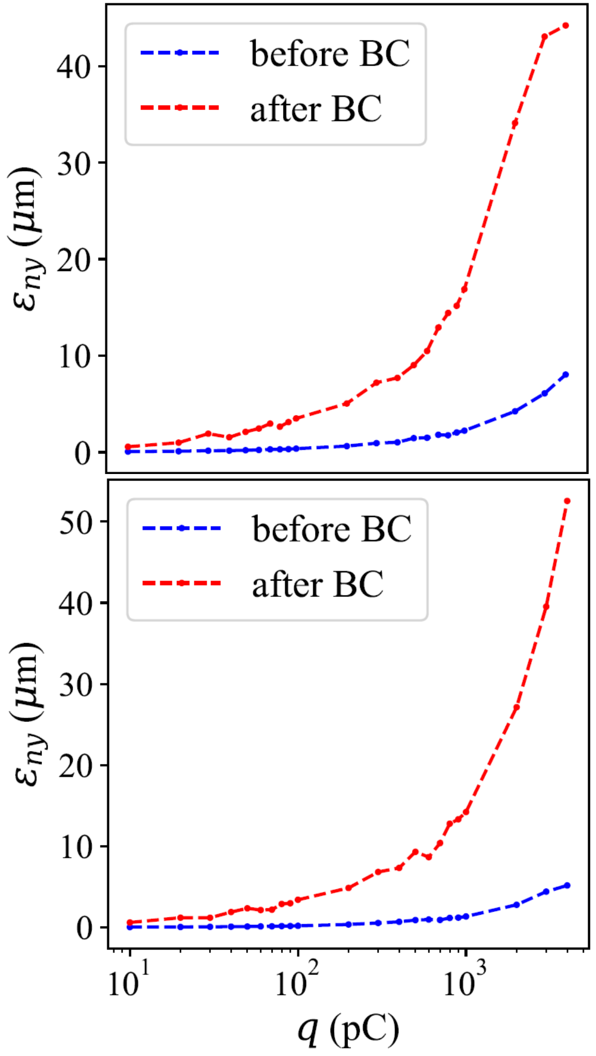
- Flat-top Beam

@ optimized booster phase for shortest bunch length





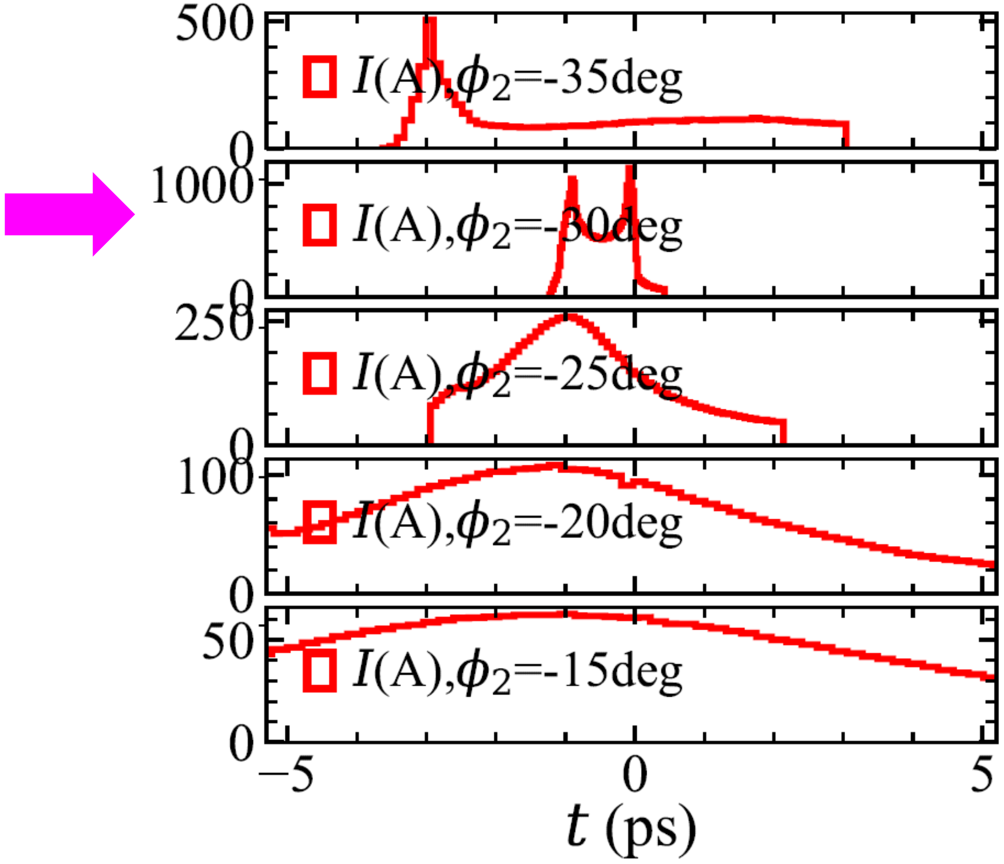
previuosly ~ 0.0025 m @ 1nC
S2E doesn't improve this



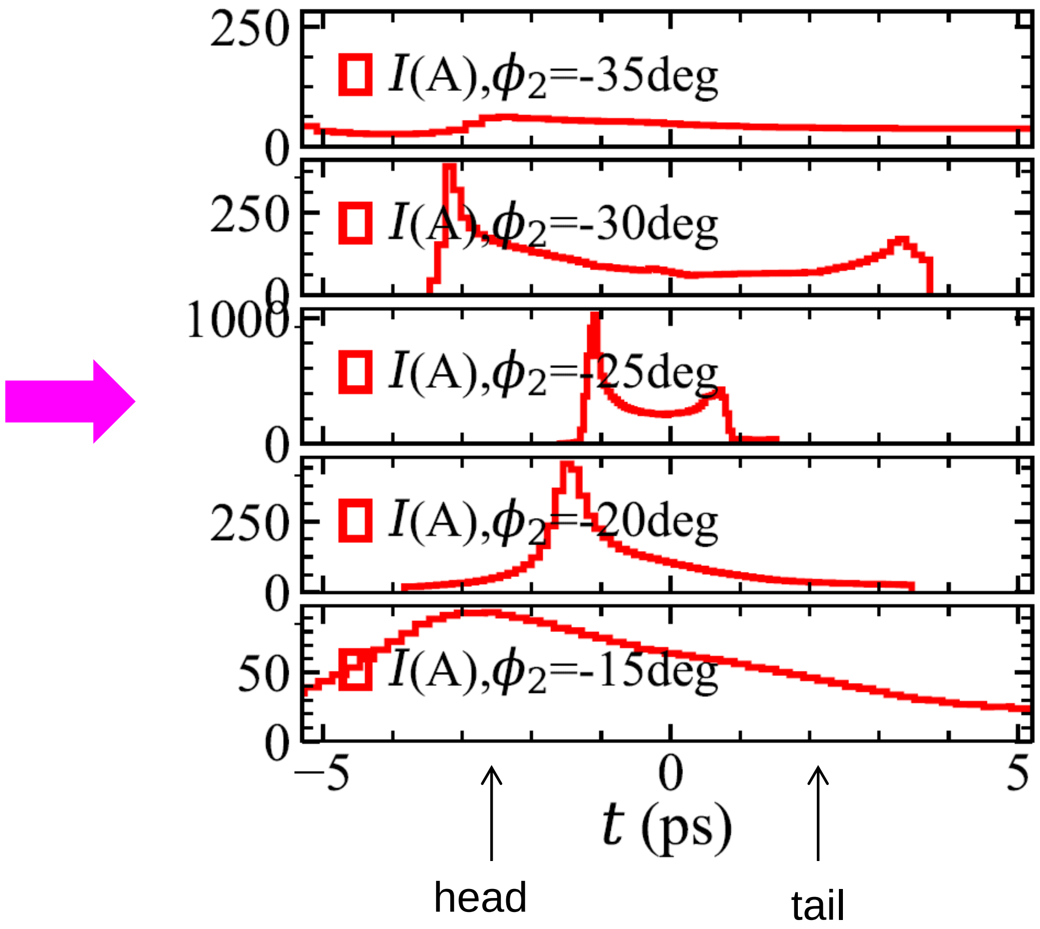
Booster phase scan @900pC

Current profile

- Gaussian Beam



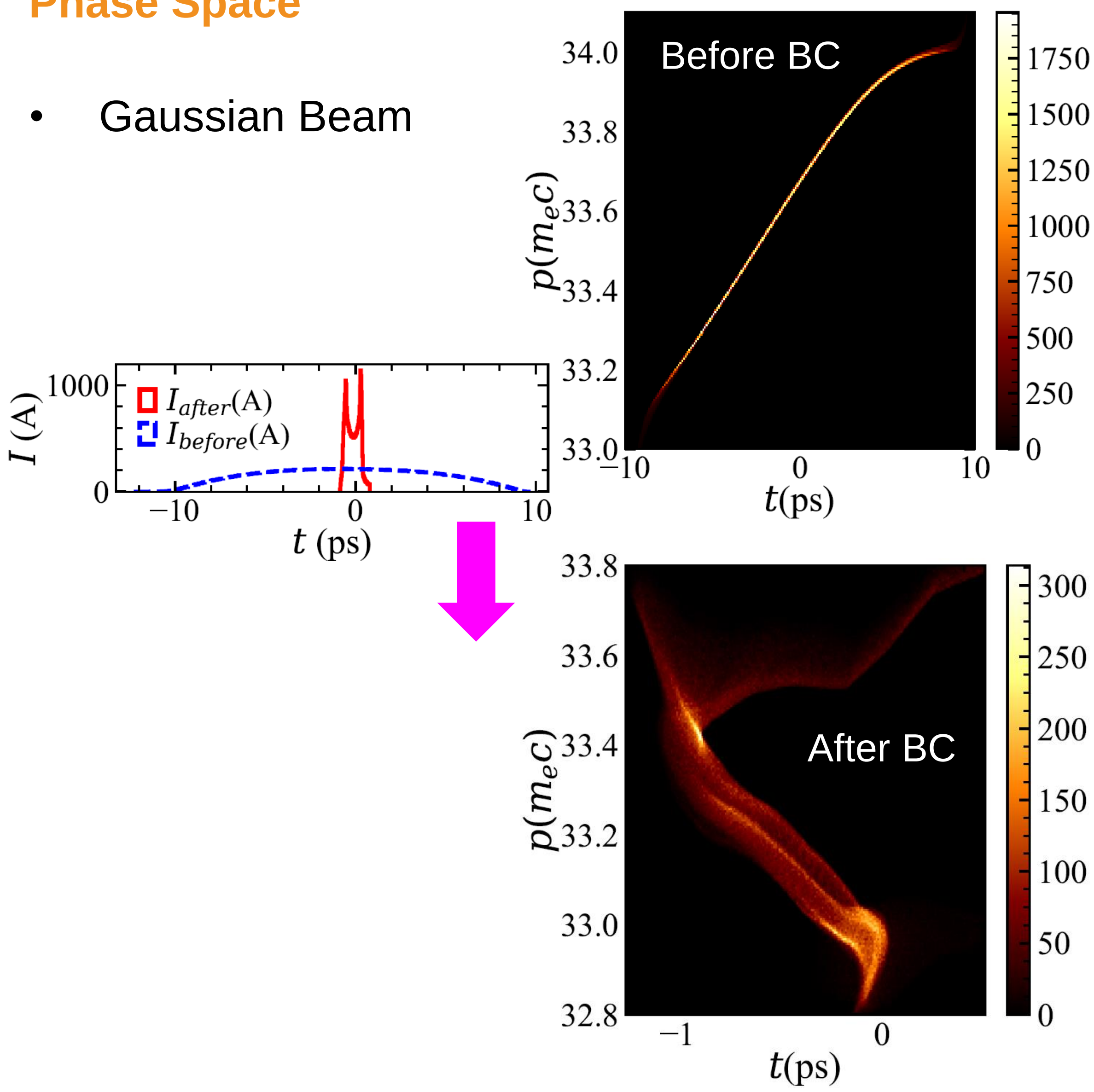
- Flat-top Beam



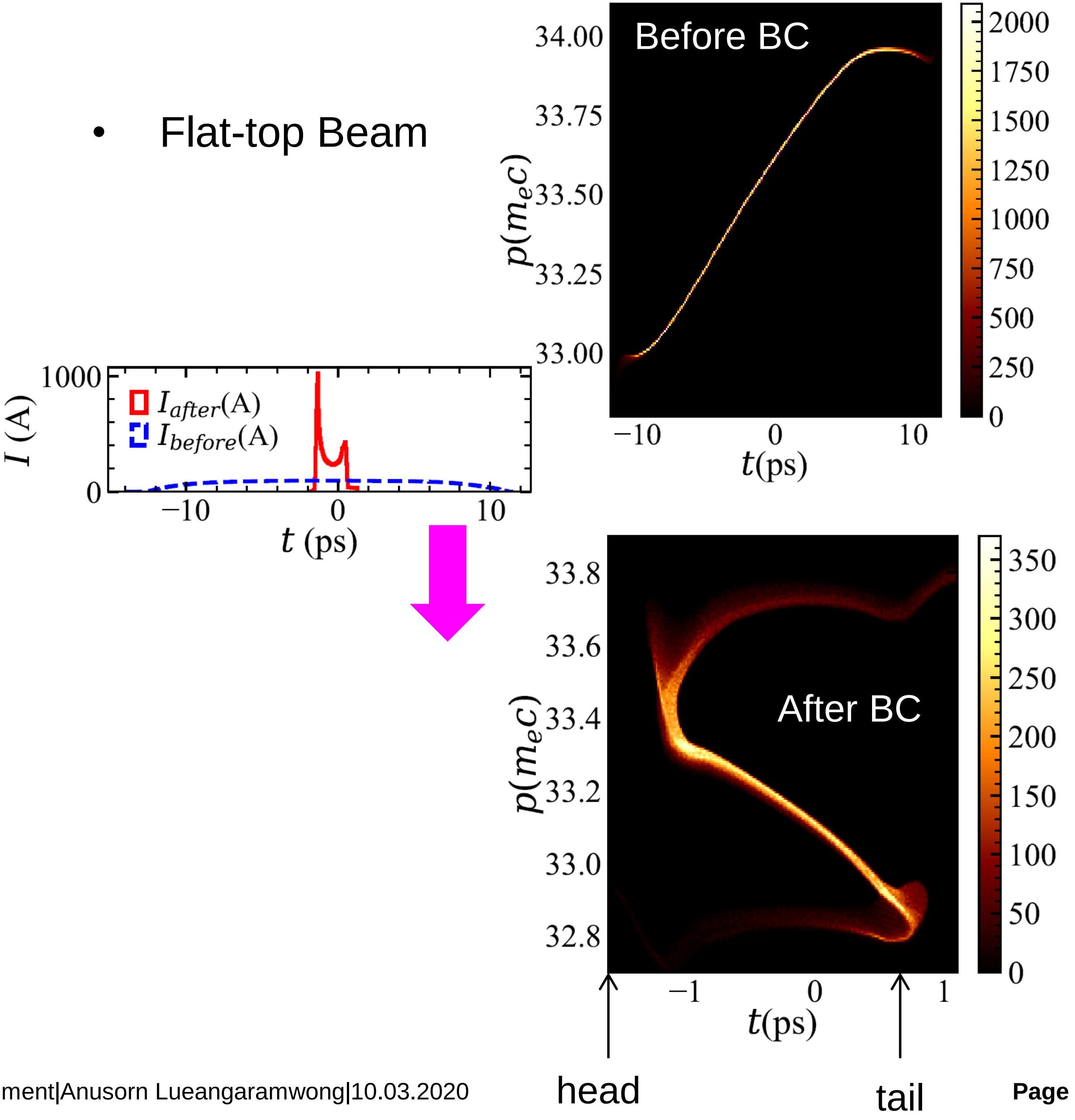
Shortest Bunch Length @900pC

Phase Space

- Gaussian Beam



- Flat-top Beam



Summary + Discussion

- PITZ BC to achieve high current/short bunch for various applications
- Start-to-end program is used to investigate performance of our chicane design when including CSR effect
- To optimize SASE (on going)
  - ~1kA w/ rms bunch length ~ 0.17mm or 0.6ps (for 0.9nC), can be too short
  - Emittance growth due to CSR limits use of high charge
- To optimize for Super radiant
  - Shorter bunch length at lower charge (~100um from 100pC)

- Next:
  - post BC propagation
  - analyze with new goal function for optimized current profiles to SASE FEL
  - repeat with OCELOT
  - check shielding and wake effect

Questions

- What is a proper compressed profile?
  - for SASE FELs
  - for Super radiant THz radiation
  - for sub-ps application
- How stable is the compression (further propagation)
- Microbunching instability (no signature so far?)
- Transverse emittance degradation
- RF torelence

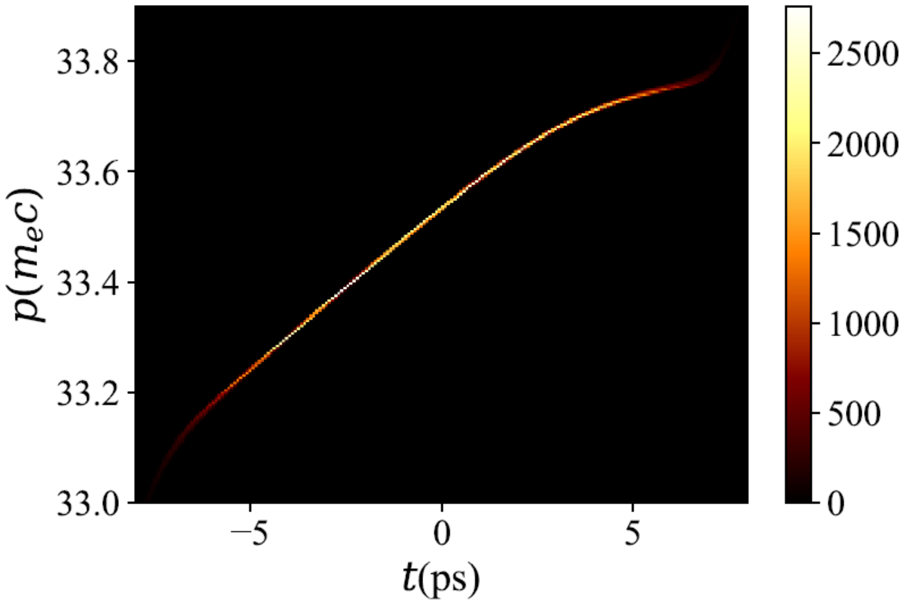
Acknowledgement

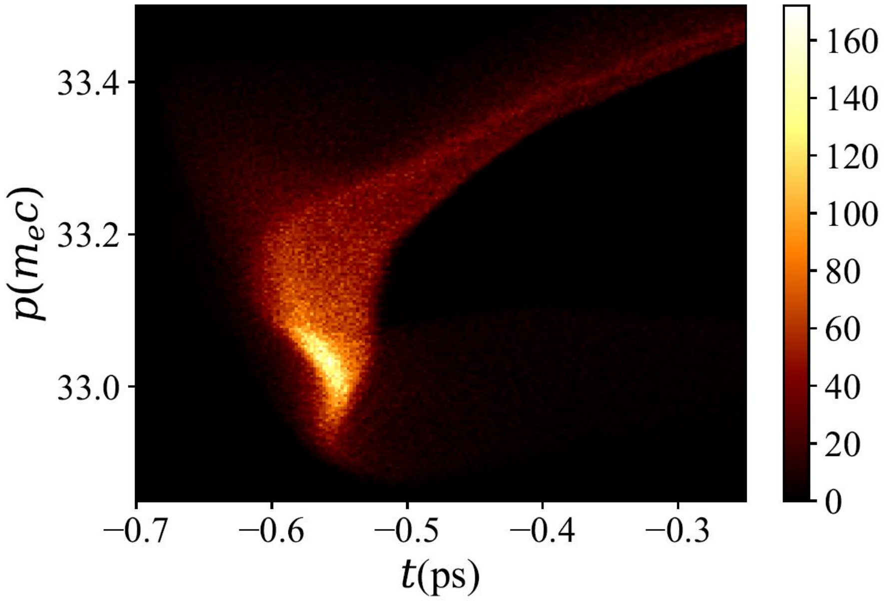
- X. Li : ASTRA scripts and FEL calculation
- P. Boonpornprasert : FEL radiation calculation
- H. Shaker : Original BC design & help with CSRtrack/OCELOT

Further Analysis : maximum peak current/averaged current

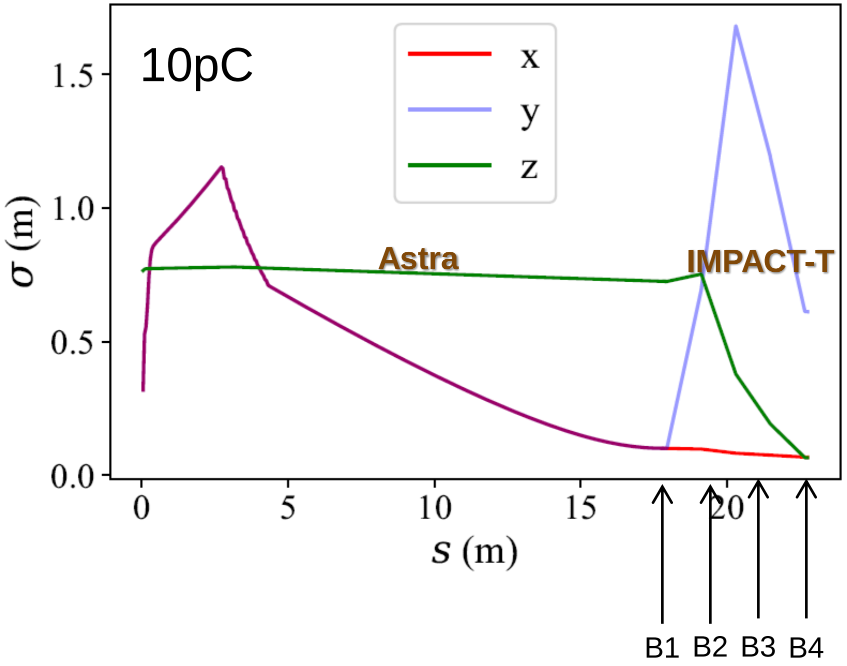
instead using peak current for shortest bunch in the booster phase scan

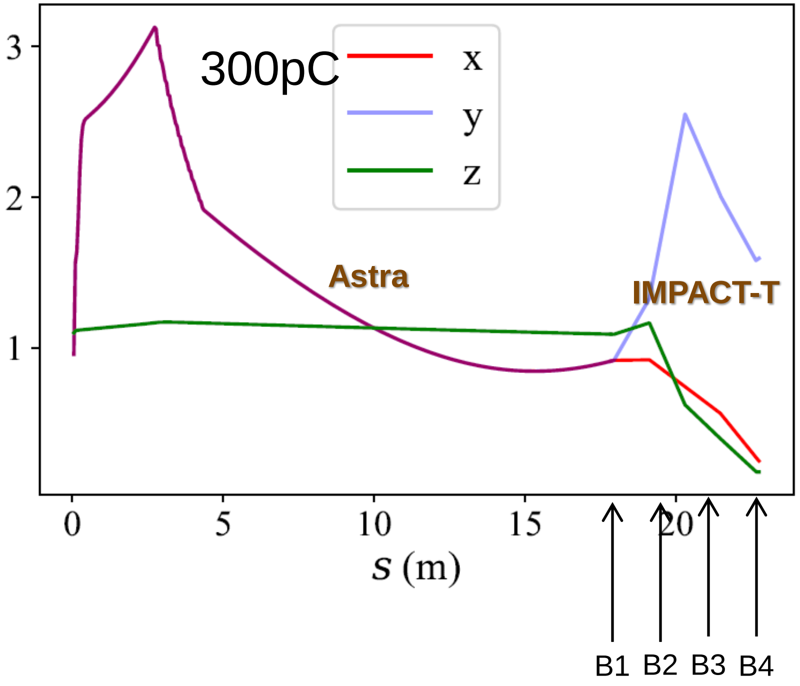
- Case of Gaussian Q-300.0pC phase=-25.00deg
  - Obtain ~1.5kA

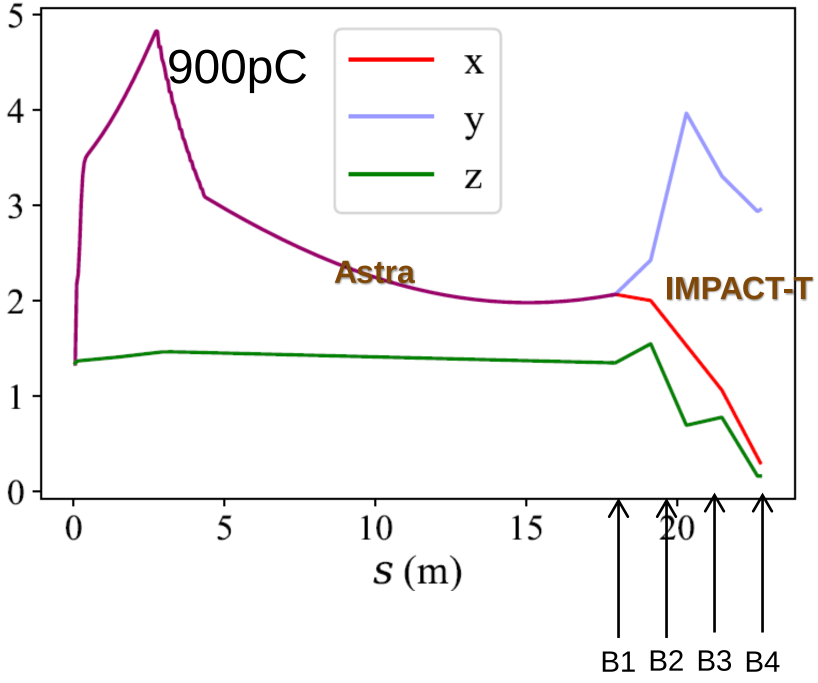




Evolution of Beam Size

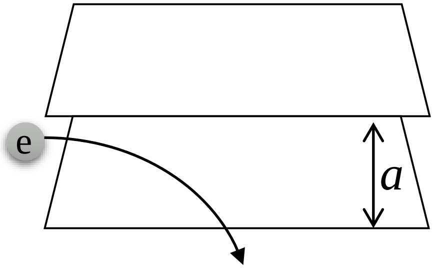






Shielding effect: 2 infinite shielding plate

electron orbit midway between the infinite plates (a = gap)

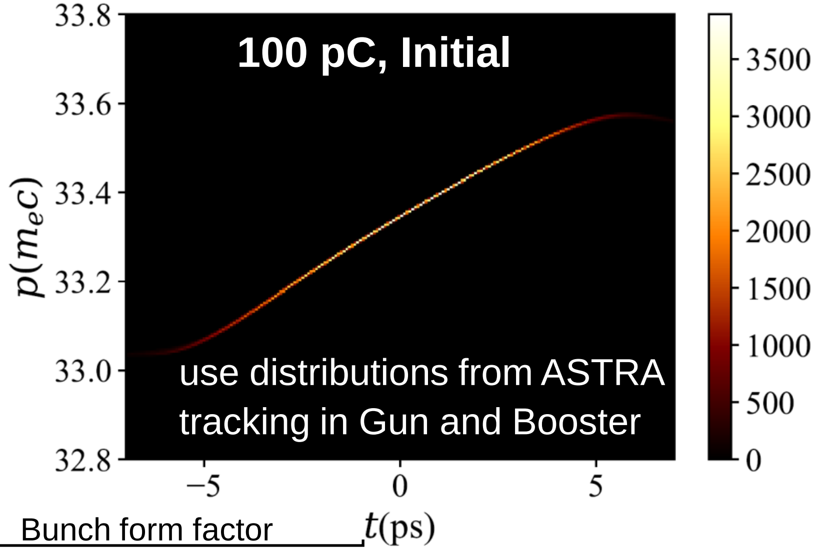


Koschik, Alexander & Caspers, Fritz & Métral, Elias & Vos, Lucien & Zotter, Bruno. (2019). Transverse Resistive Wall Impedance and Wake Function with "Inductive Bypass".

$$P_{\mathrm{coh}}{}^{(0)} = N^2 \sum P_n{}^{(0)} f_n. \quad P_n{}^{(0)} = (n\omega e^2/R)\left[2\beta^2 J_{2n}{}'(2n\beta) - (1-\beta^2)\int_0^{2n\beta} J_{2n}(x)dx\right]$$

$$P_{\mathrm{coh}}{}^{(\infty)} = N^2 \sum P_n{}^{(\infty)} f_n. \quad P_n{}^{(\infty)} = (n\omega e^2/R)(4\pi R/a)\mathrm{Re}\Big\{\sum_{j=1,3,\ldots}^{\infty}\big[-H_n{}^{(1)}J_n + \tfrac{1}{2}\beta^2(H_{n-1}{}^{(1)}J_{n-1} + H_{n+1}{}^{(1)}J_{n+1})\big]\Big\}$$

$$\gamma_{nj}R = [(n\beta)^2 - (j\pi R/a)^2]^{\frac{1}{2}}$$



use distributions from ASTRA tracking in Gun and Booster

Bunch form factor