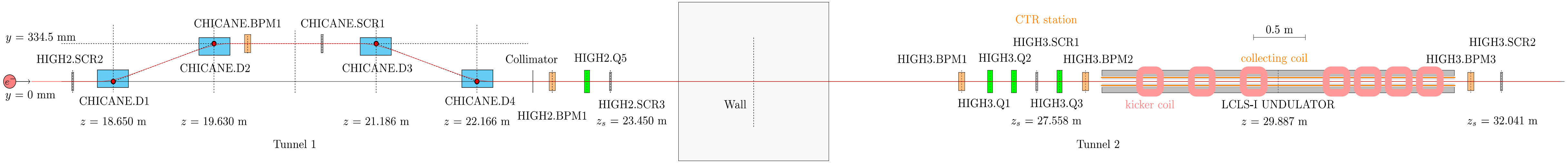
Summary of PITZ BC commissioning studies

PITZ Physics Seminar (PPS)



Ekkachai Kongmon

PITZ , 21 September 2023

HELMHOLTZ

Outline

PITZ Bunch Compressor

Beam trajectory simulation

Dispersion studies

Beam matching

PITZ Bunch Compressor

PITZ magnetic bunch compressor

Specifications	Details
LCLS-I undulator	
Type	planar hybrid (NdFeB)
K-value	3.585 (3.49)
Support diameter / length	30 cm / 3.4 m
Vacuum chamber size	11 mm x 5 mm
Period length (λ_u)	30 mm
Periods / a module	113 periods
e-beam	
Beam momentum	17 – 22 MeV/c
Transvers rms beam size (σ_x, σ_y) (Gaussian beam)	1 mm
e-beam peak current (I)	~200 – 400 A
Bunch charge	2 nC
Radiation	
Radiation wave length	~100 μm (~ 17 MeV/c)

1D Model for FELs

$$\rho = \left[\frac{I}{\gamma^3 I_A}\frac{\lambda_u^2}{2\pi\sigma_x\sigma_y}\frac{(K\times[JJ])^2}{32\pi}\right]^{1/3}$$

$$[JJ] = J_0(\xi) - J_1(\xi) \qquad \xi = \frac{K^2}{2(2+K^2)}$$

Maximum relative energy spread for the compression cases (δ) < $\rho \approx$ **1 %**

$$\Delta z = \boldsymbol{R_{56}}\delta_p$$

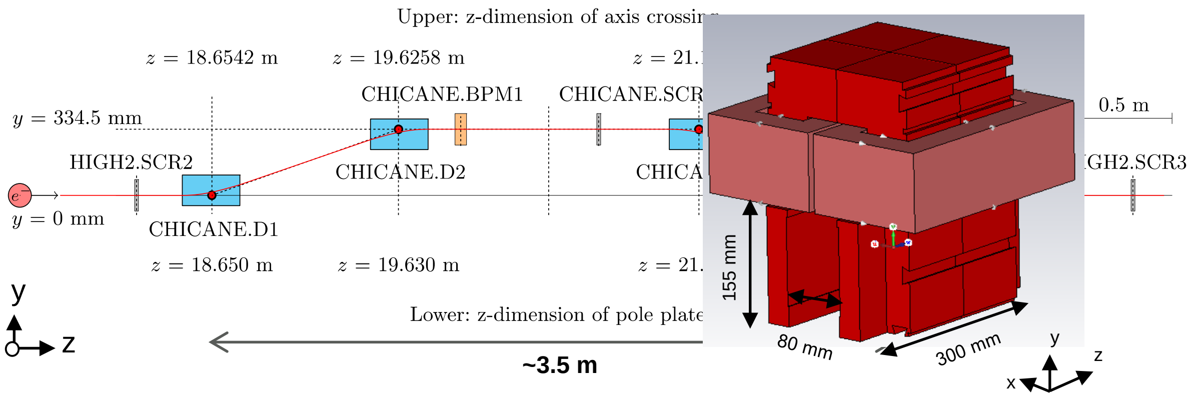
$$\delta \approx 1\,\%$$

$$\Delta z = 0.18\ cm\ (6\ ps)$$

$$R_{56} = 0.180\ m$$

Used to define geometry of the BC

Setup of the BC



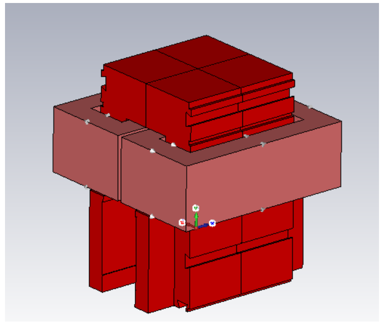
- Designed beam trajectory from **hard edge model** (modified from HERA dipoles)
- Vertical bending direction
- Bending angle : 19 deg.
- $R_{56} \approx -2\theta_0^2\{(L_{12} + \frac{2}{3}L_B)\}$ → ~ 0.198 m

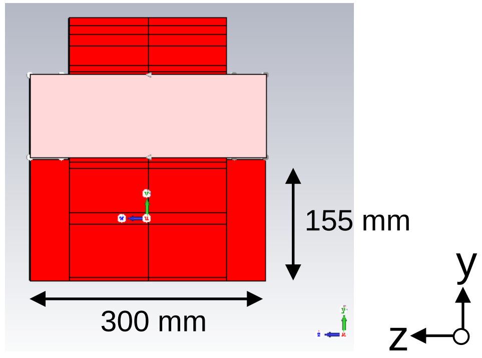
Concept → match R56 between beam and BC

Beam transportation

Chicane magnet

Magnetic field, simulation vs. measurement



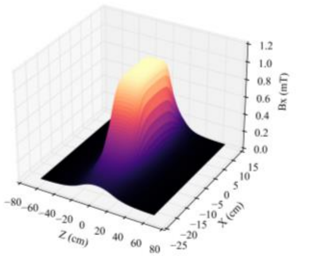


Parameters

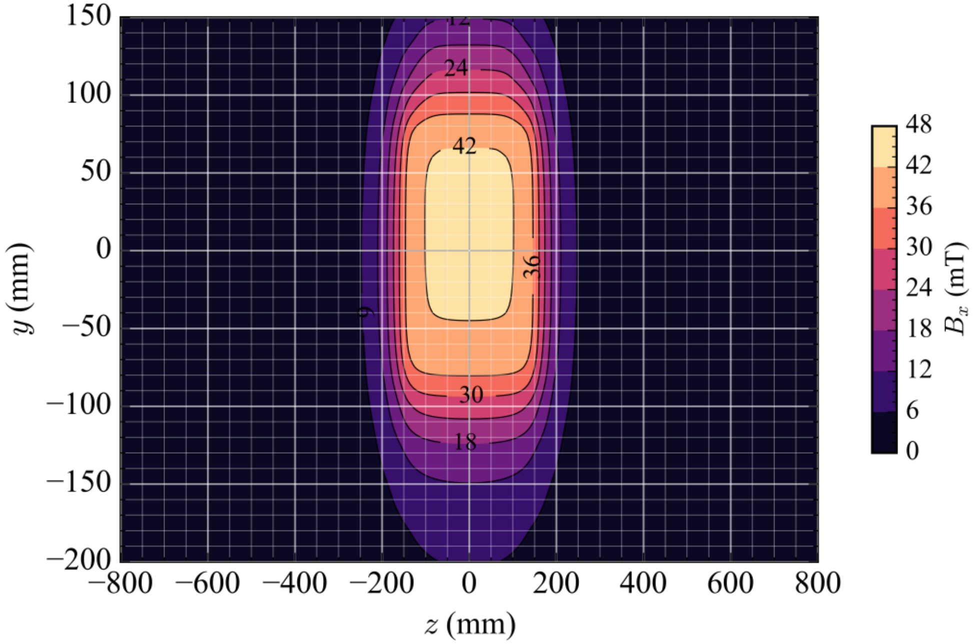
Applied current : 1 A
Number of coil turns : 1332 turns per coil
Maximum magnetic field in x-direction (Bx) at (x, y) = (0,0) along z-direction : 0.04235 T

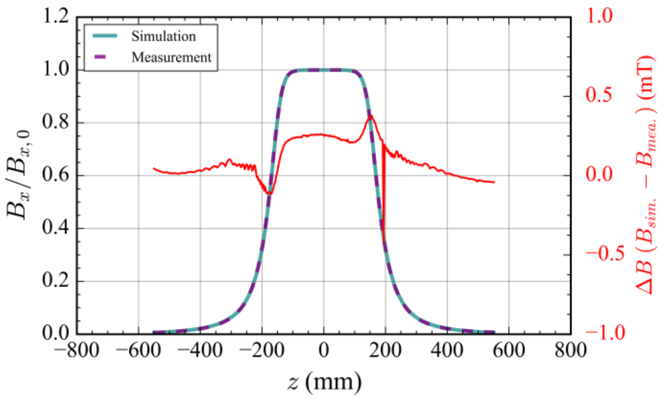
Export 3D magnetic field (dimensions)
D1 and D4 z : -850, 850, y : -70, 350 step 4 mm, x : -30, 30step 1
D2 and D3 z : -860, 860, y : -224, 100 step 4 mm, x : -30, 30 step 1

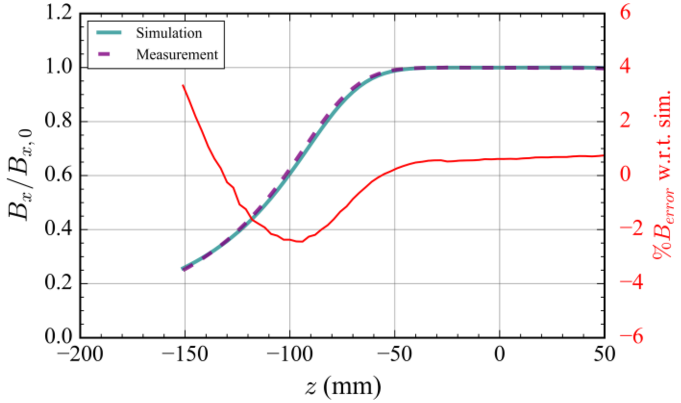
1 V.s = 1 T.m^2 From CST (V.s/m^2 = T)



Plane: x = 0





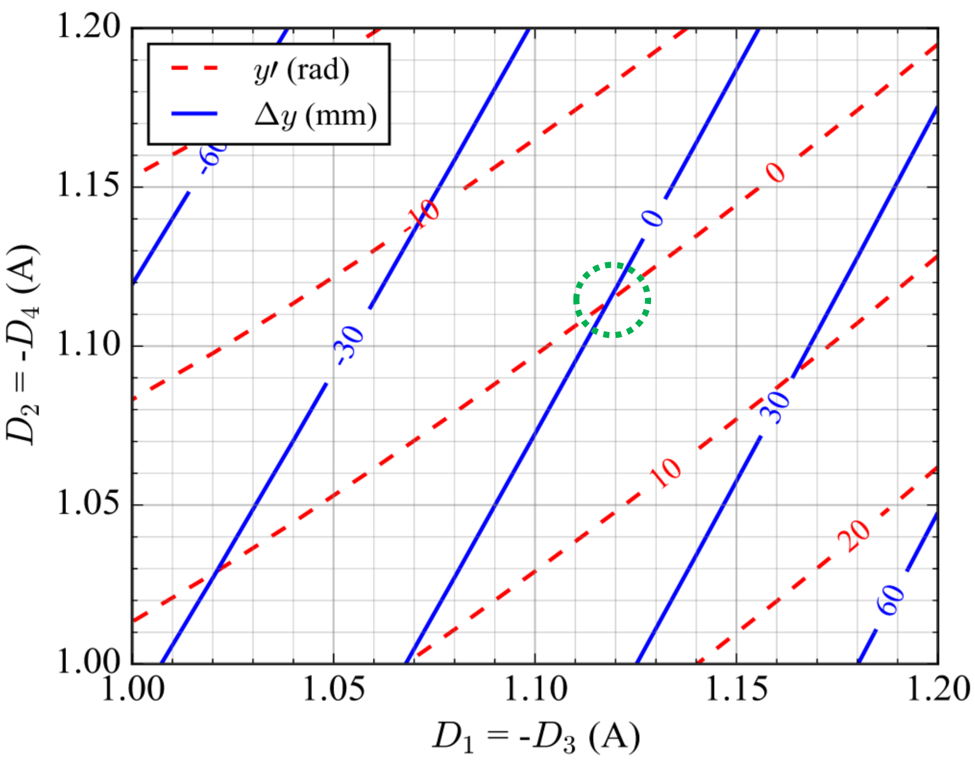


Beam trajectory simulations

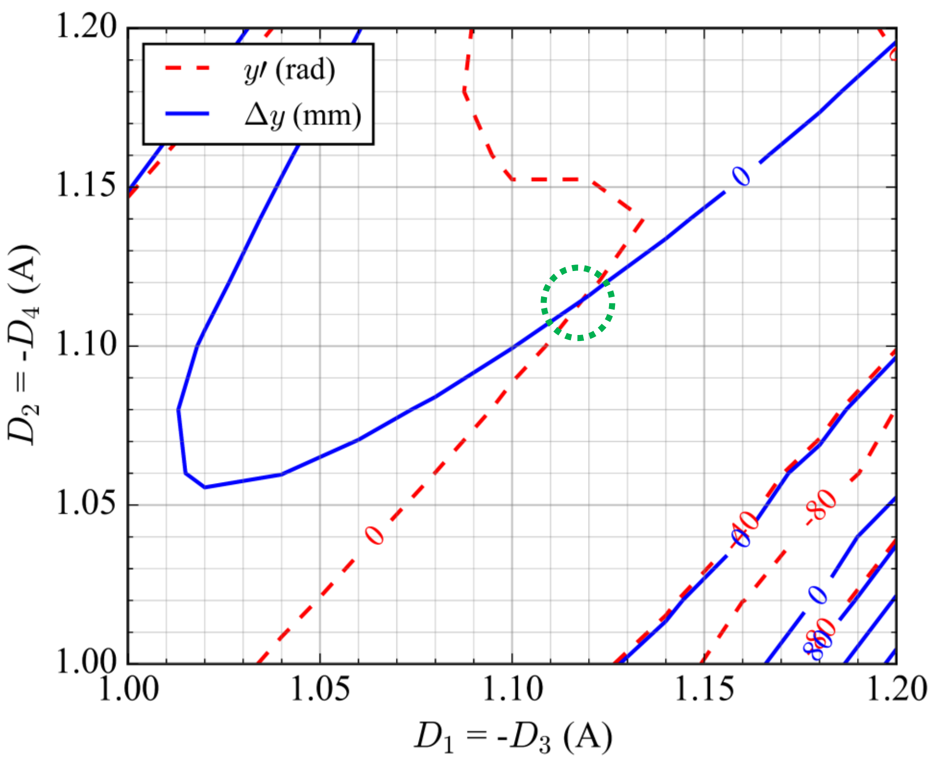
D1 = D3 and D2 = D4

- Average beam momentum : 17 MeV/c
- Bunch charge : **250 pC**

At Center of BC

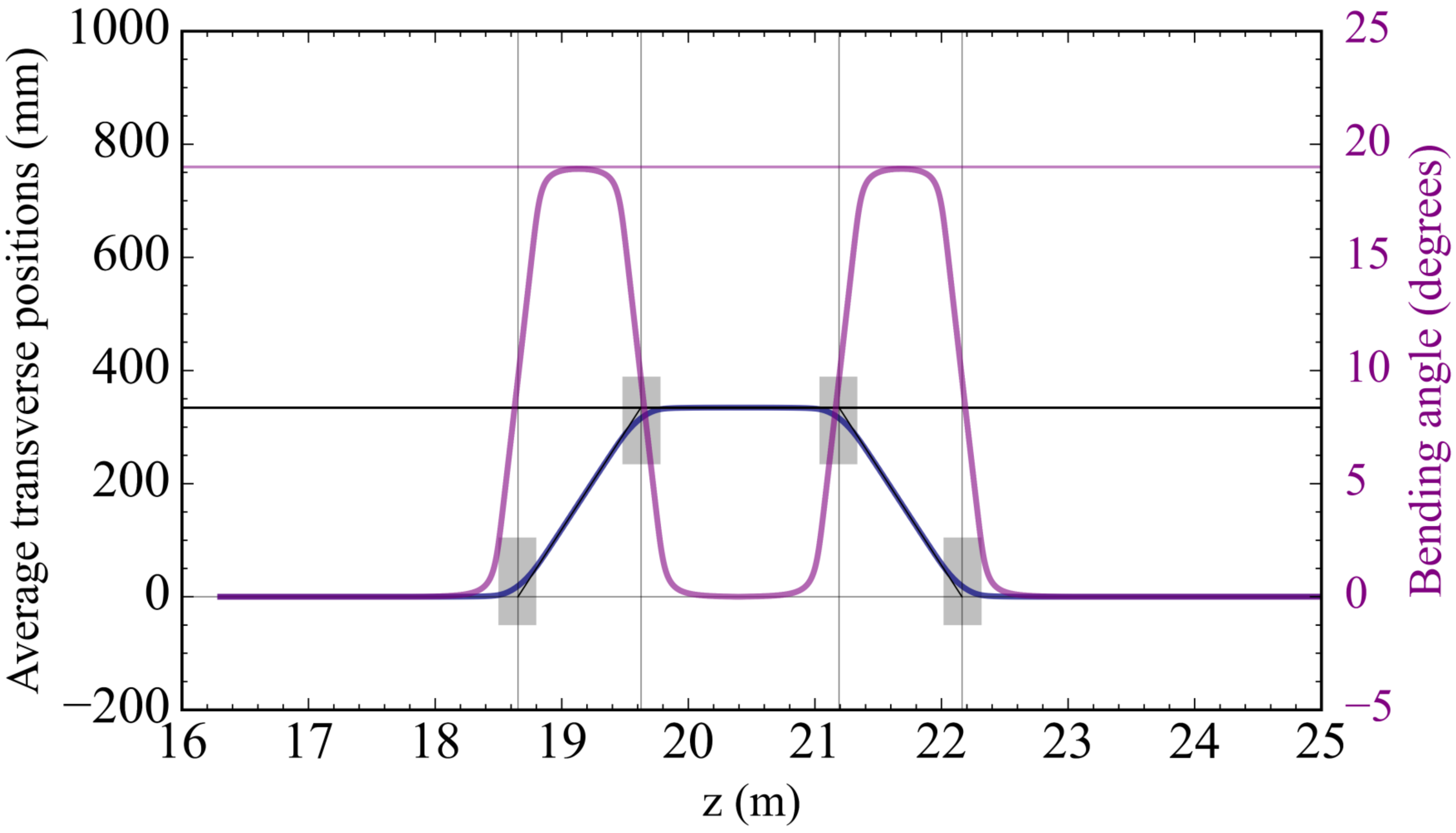


After BC



Beam trajectory simulations

2D scan current with the condition D1 = D4 and D2 = D3



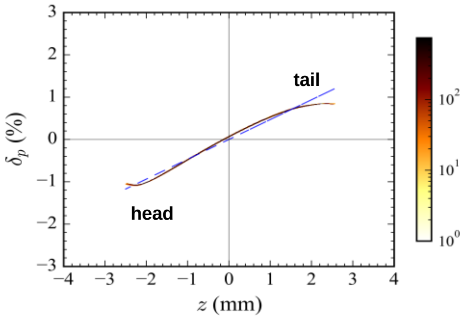
Dispersion studies

Dispersion studies

PITZ magnetic bunch compressor

Electron properties

- Positive chirp
- Energy spread < 1 %



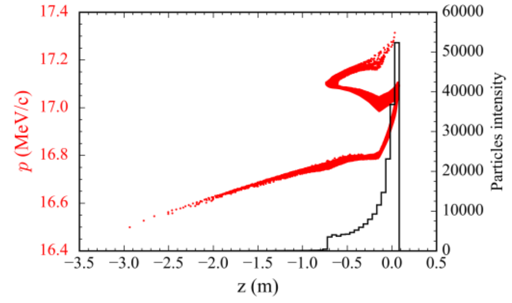
Compression factor

$$C = (1 + h_i R_{56})^{-1}$$

Full-compression $C \rightarrow \infty$

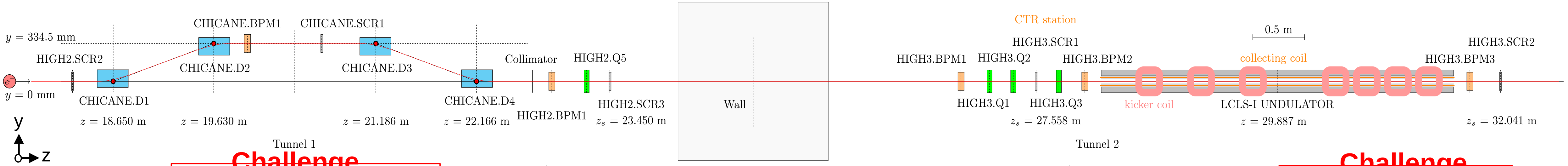
$$R_{56} = -\frac{1}{h_i} = -\frac{1}{slope}$$

Bunch charge 250 pC



Peak currents

- Before : 53.066 A
- After : 265.148 A



Challenge
19 deg. bending angle

~5 m

Challenge
Vacuum chamber size : 11 mm x 5 mm

Objective beam parameters for electron beam transportation

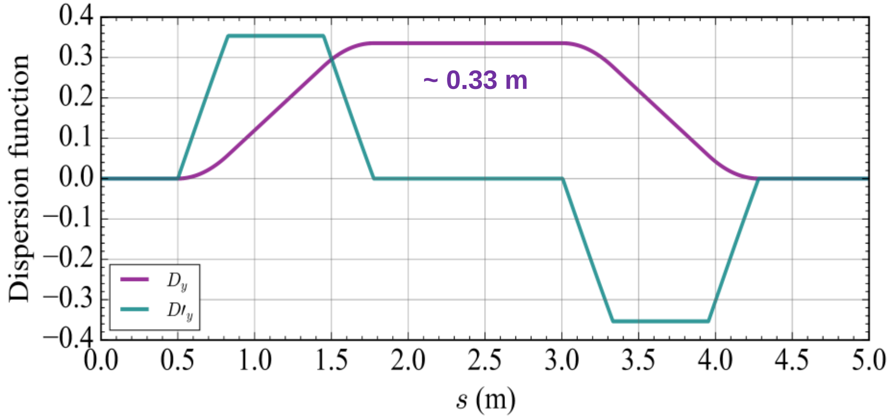
- Dispersion
  - → Zero and constant dispersions after BC
  - → Constant dispersions between D2 and D3
- On-axis trajectory
- Emittance !!!!!!

Drift space between D1 and D2

$$D_2 = D_1 + \lambda D_1'$$

$$D_1' = \sin(\theta)$$

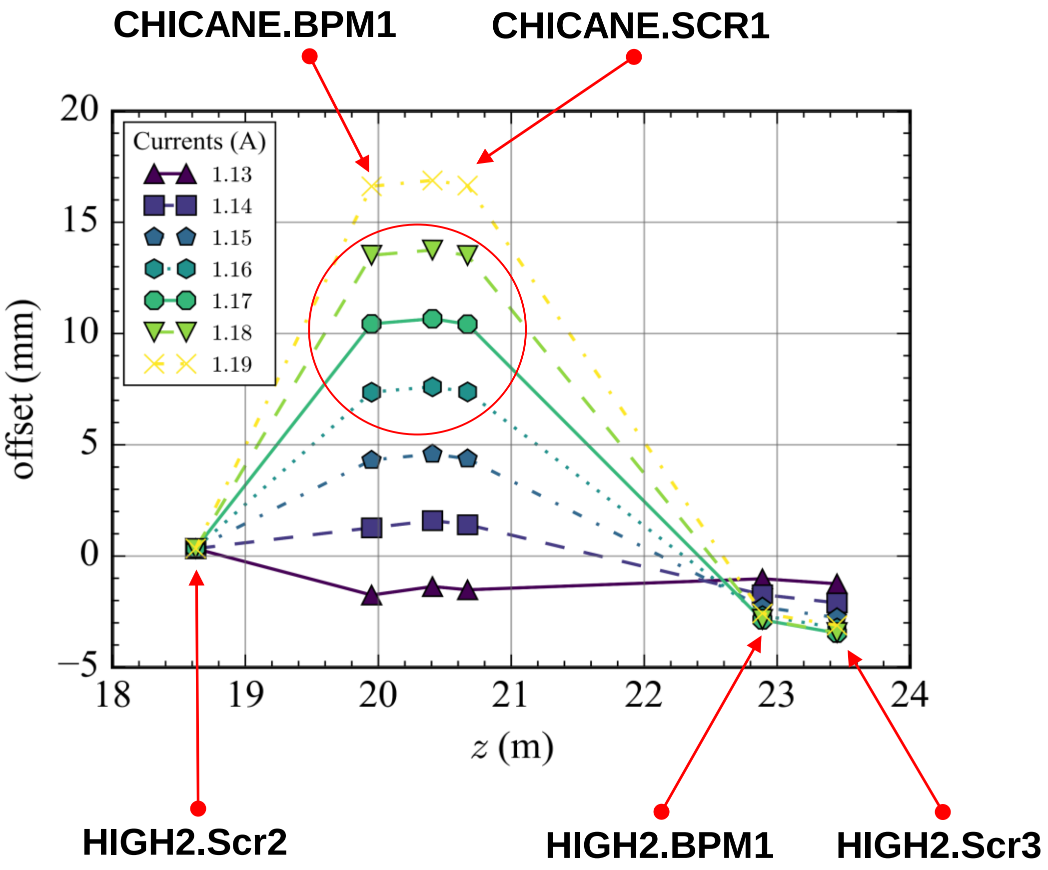
Bending angle

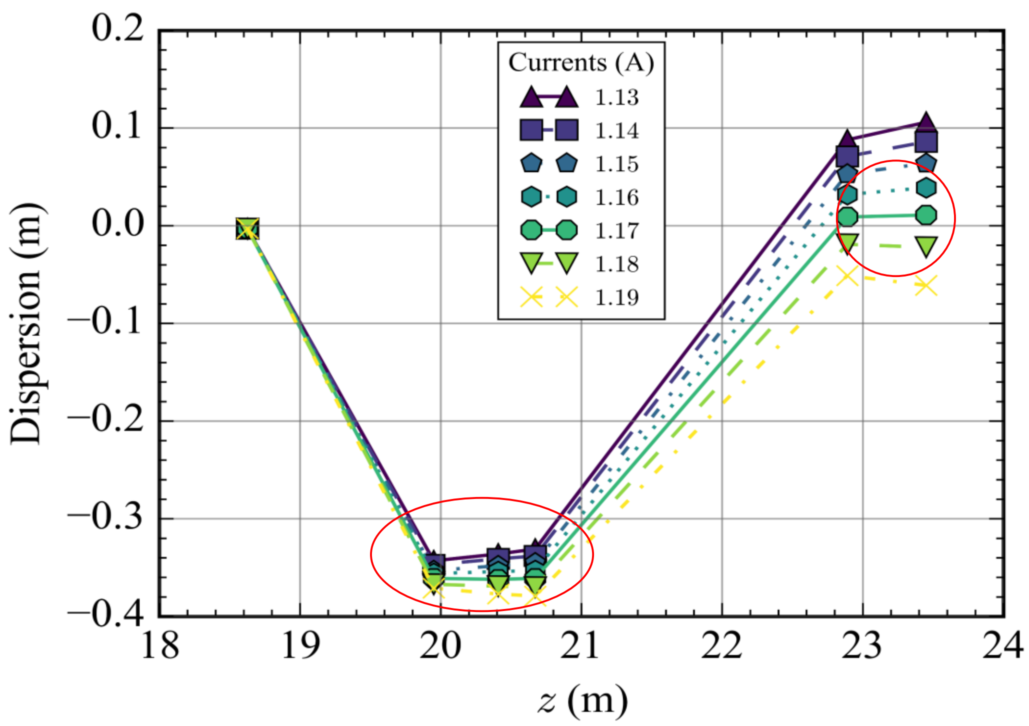


Dispersion studies

Dispersion simulation for identical currents cases

$$D(z) = \frac{< x_{i,B}(z) > - < x_{i,A}(z) >}{\delta}$$





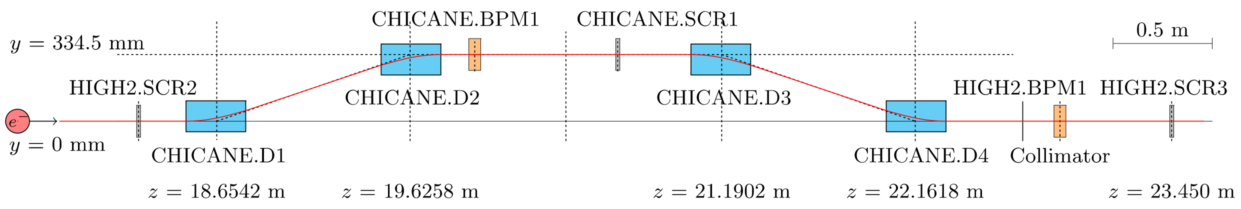
Zero dispersion after chicane → positive offset at chicane arm (between D2 and D3)

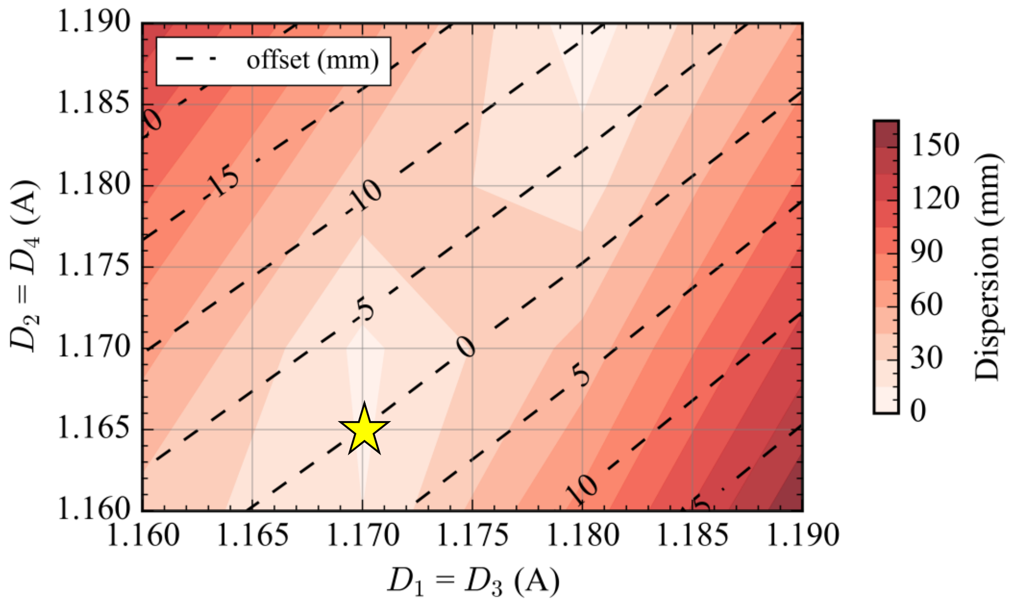
Dispersion studies

Symmetric currents method

Beam pipe radius : 30 mm

D1 = D3, D2 = D4

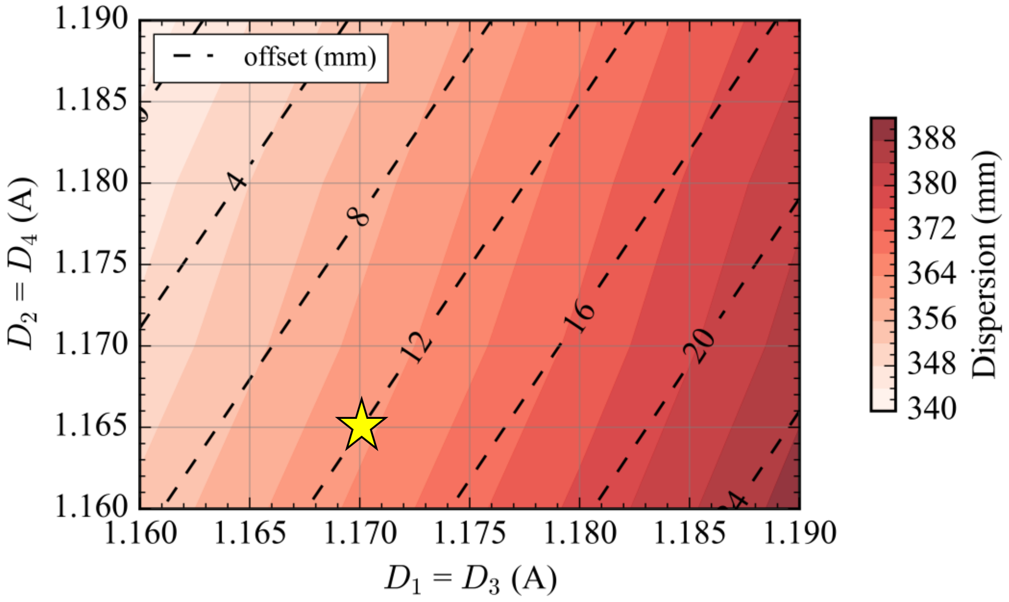




HIGH2.Scr3

→ Zero dispersion after BC

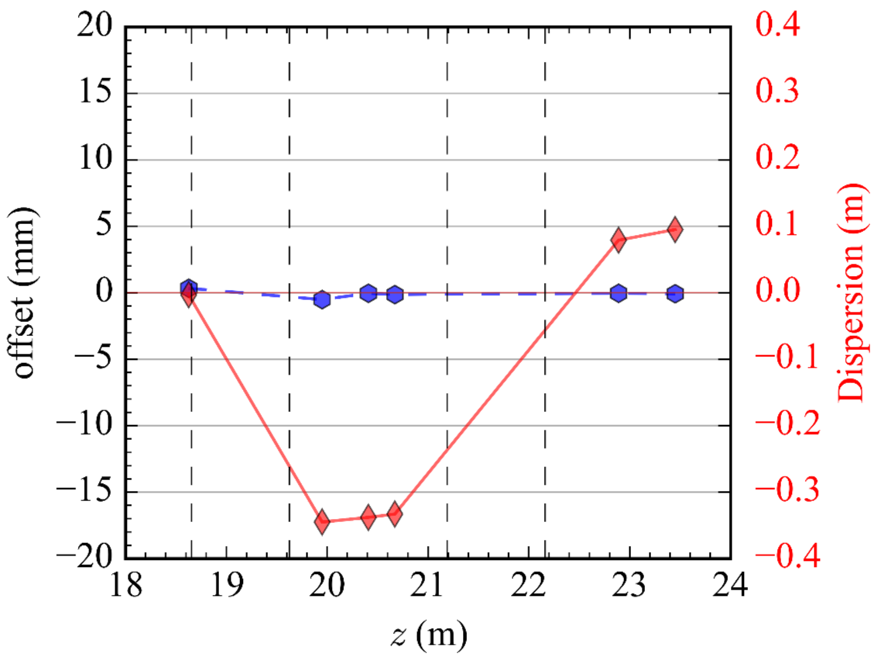
→ ~ 12 mm offset between D2 and D3



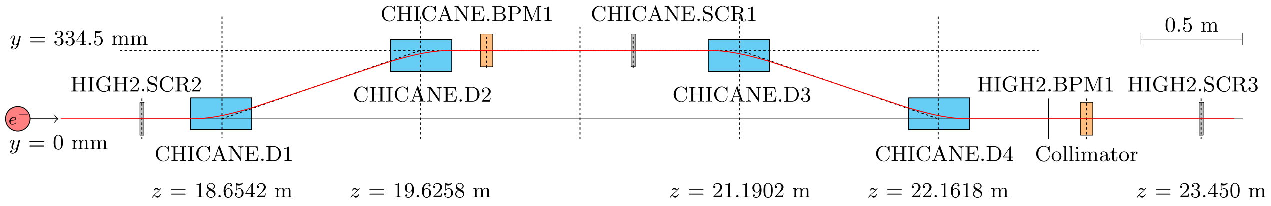
CHICANE.SCR1

Dispersion studies

Independent currents method



er BC



Vertical offset between D2 and D3 $\leq$ 10 mm

Dispersion at HIGH2.SCR3 $\leq$ 0.02 m

Vertical angle at HIGH2.SCR3 $\leq$ 0.5 mrad

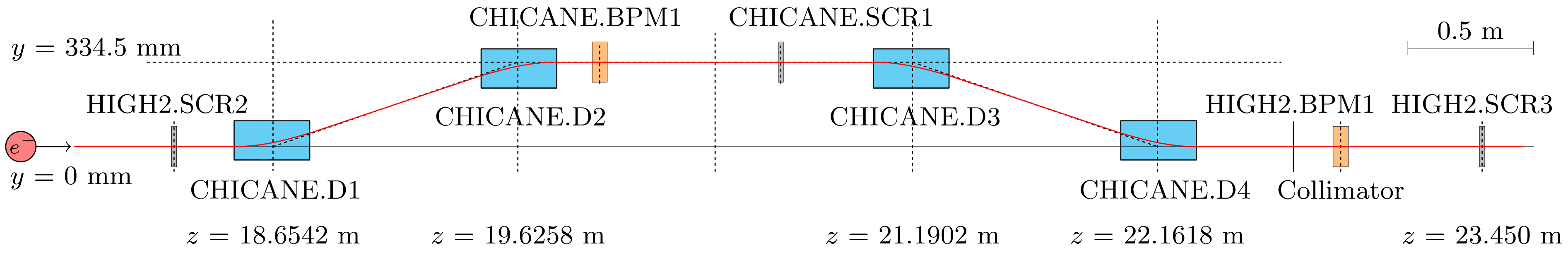
Offset at HIGH2.Scr3 $\leq$ 1 mm

Screen	Position(m)	D1(A)	D2(A)	D3(A)	D4(A)	Offset (mm)	Dispersion (m)
Chicane.BPM1	19.950					8.663	0.358
Center D2 and D3	20.408					9.431	0.358
Chicane.Scr1	20.671	1.163	1.159	1.163	1.163	9.500	0.356
HIGH2.BPM1	22.889					0.990	0.020
HIGH2.Scr3	23.450					0.951	0.020

Dispersion studies

Dispersion measurements

- Beam momentum: ~17 MeV/c
- Bunch charge : 250 pC



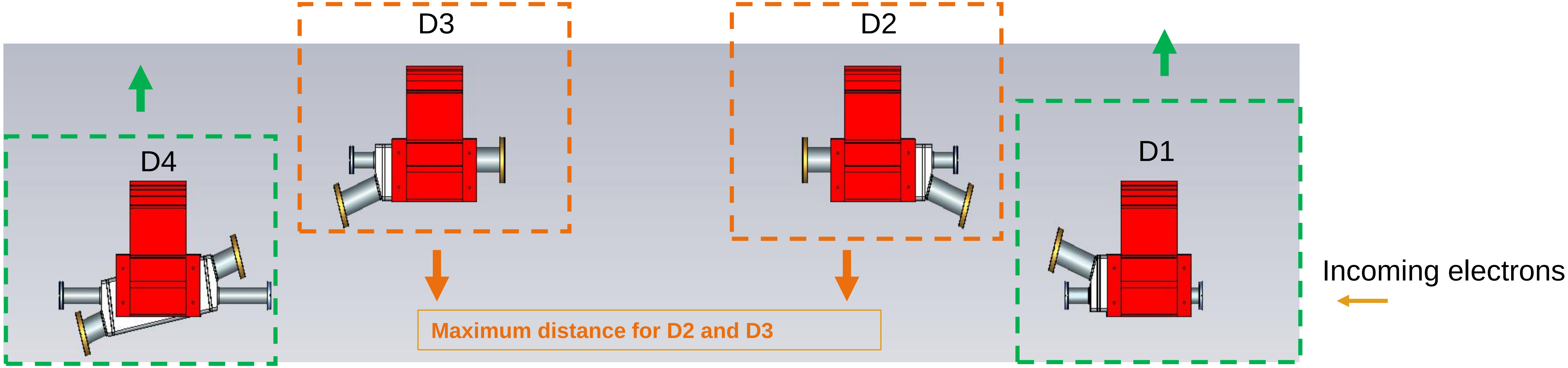
Measurement parameters	Symmetric currents method (D1 = -D3, -D2 = D4)	Independent currents method (Fixed offset, scan D3 and D4 tuning)
Dispersion after chicane	~ 0.00 m	~ 0.03 m (minimum)
Beam angle after chicane	~ 7 mrad	~ 1 mrad
Beam offset chicane arm	~ 12 mm	~ 8.5 mm

Moving BC dipoles

For correcting dispersion

Move D2 and D3 **downward** → corrected dispersion and beam transverse offset between D2 and D3

Move D1 and D4 **upward** → corrected dispersion and **beam transverse offset** after D4



Moving BC dipoles

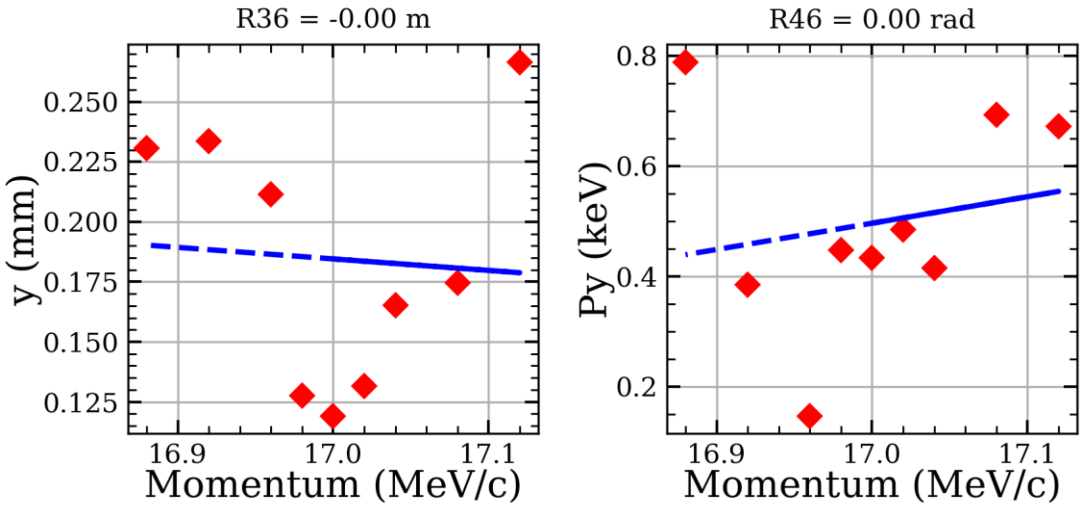
Independent currents method

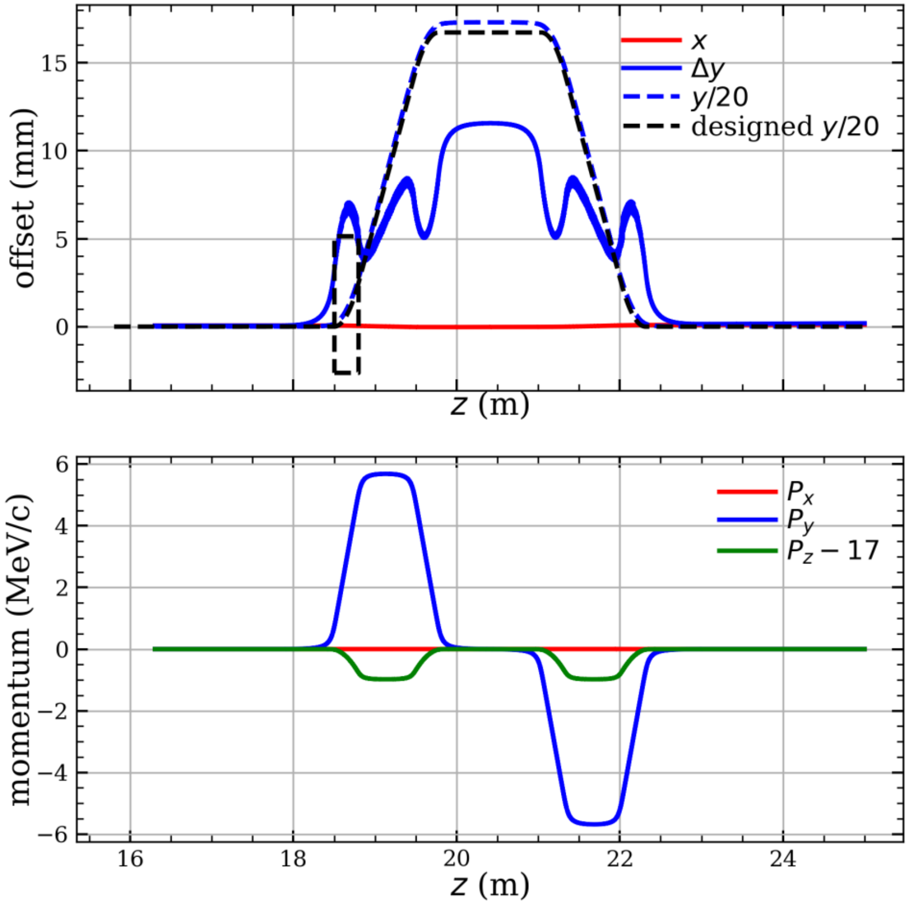
Courtesy X.-K. Li

Dispersion *before* moving dipole magnets in the vertical direction
D1 = D4 = 0 mm
D2 = D3 = 0 mm

Using method D1 = D4 and D2 = D3

D1, D2, D3, D4 = [-1.1714, 1.1693, 1.1693, -1.1714] A





Moving BC dipoles

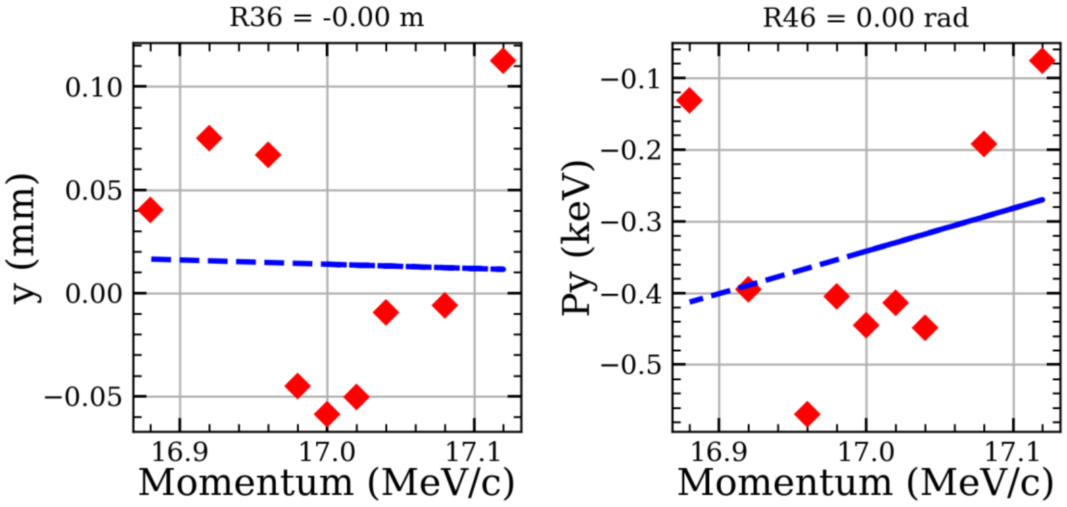
Independent currents method

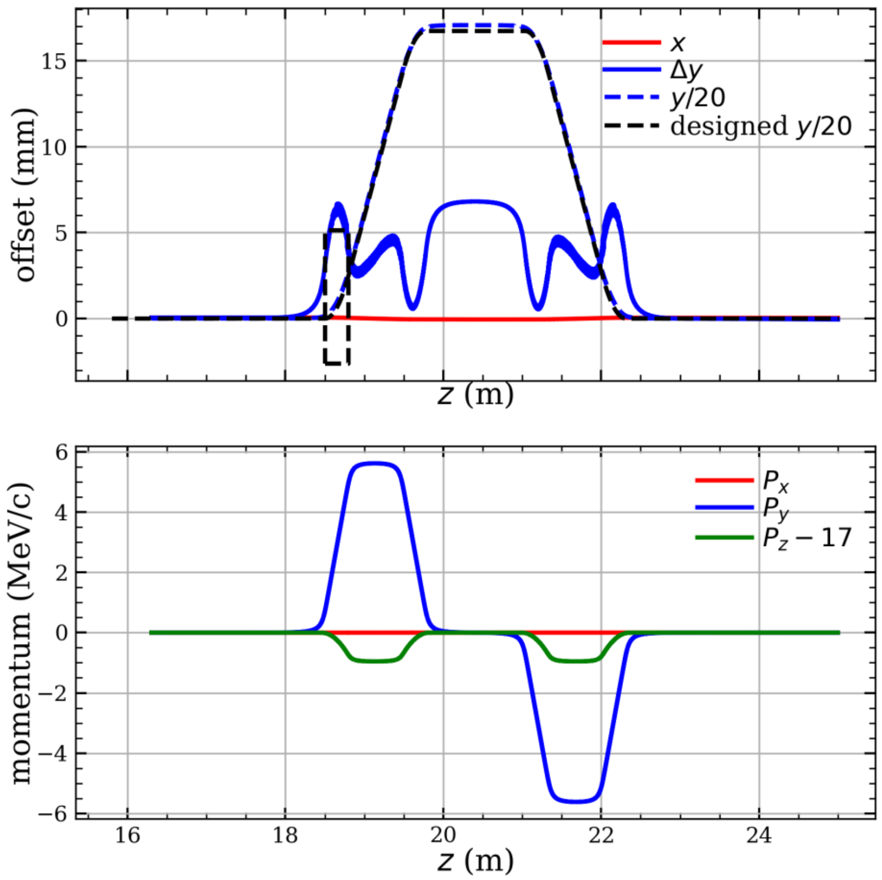
Courtesy X.-K. Li

Dispersion *after* moving dipole magnets in the vertical direction
D1 = D4 = + 6 mm
D2 = D3 = -3.5 mm

Using method D1 = D4 and D2 = D3

D1, D2, D3, D4 = [-1.1560,   1.1552, 1.1552, -1.1560]





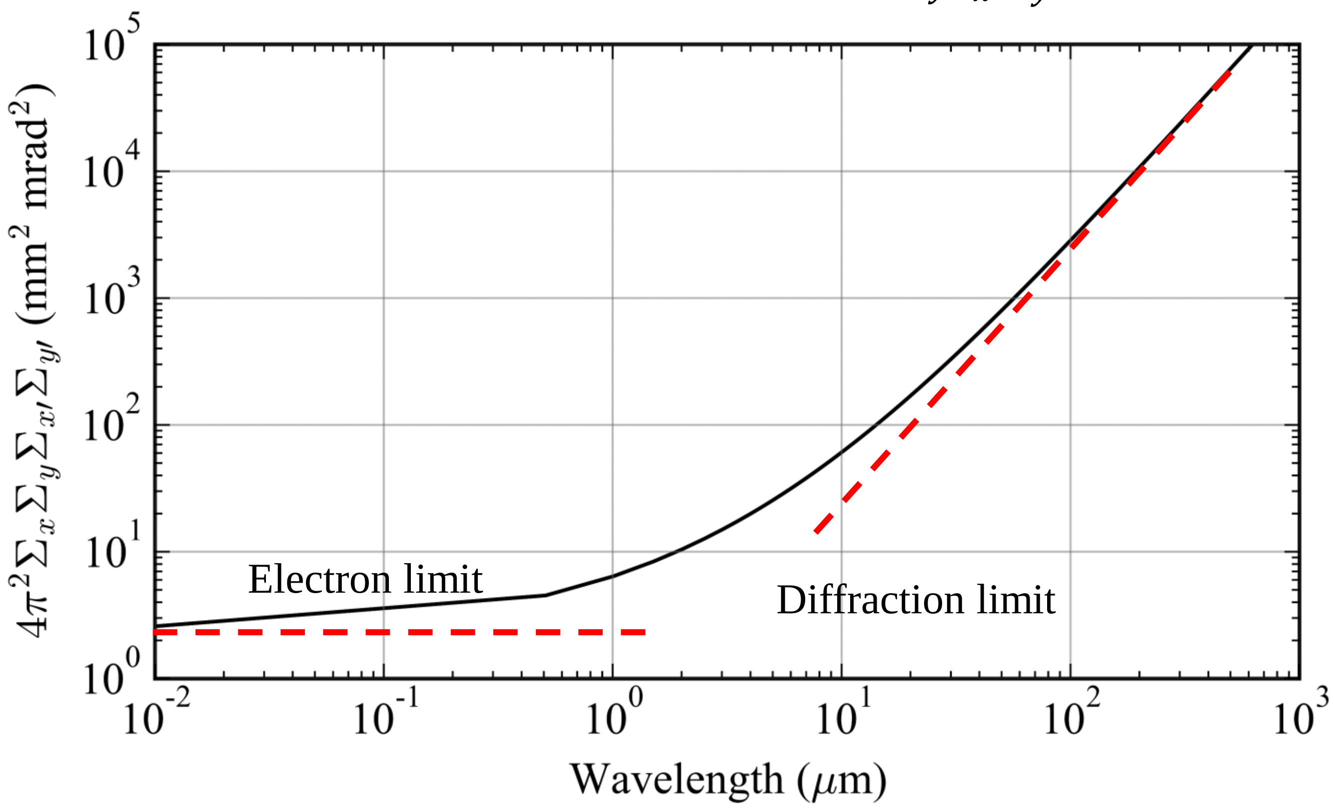
Beam matching

Beam matching

Diffraction limit

$$\mathfrak{B} = \frac{\dot{N}_{ph}}{4\pi^2 \Sigma_x \Sigma_y \Sigma_{x'} \Sigma_{y'} \frac{d\omega}{\omega}}$$

Phase space volume → $4\pi^2 \Sigma_x \Sigma_y \Sigma_{x'} \Sigma_{y'}$

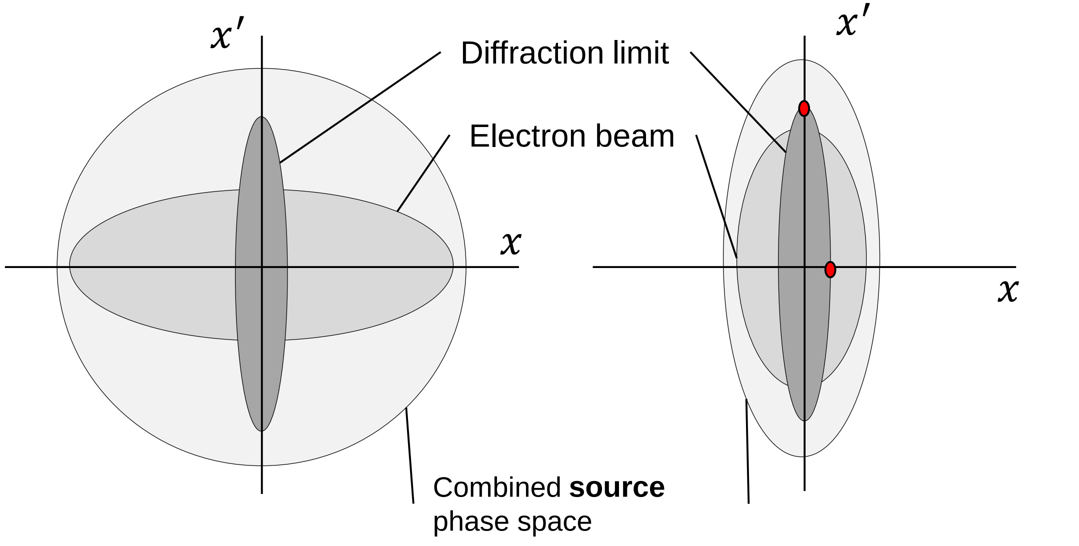


!!! No advantage to gain when $\sigma_r \gg \sigma_{x,y}$ and $\sigma_{r'} \gg \sigma_{x'y'}$

E.g., matching condition for **LCLS-I** undulator at **PITZ**

$$\sigma_{b,x} = 0.65\ mm, \sigma_{b,y} = 0.25\ mm$$
$$\sigma'_{b,x} = 0.33\ mrad, \sigma'_{b,y} = 1.20\ mrad$$

Undulator length (L) = 3.4 m Radiation wavelength (λ) = 100 μm



Beam emittance much be smaller than the diffraction limit

$$\epsilon_{x,y} \leq \frac{\lambda}{4\pi}$$

It is easier to achieve this condition for long wavelength

Beam matching

Finding optimum “beta”

$$\lambda_r = 100\ \mu m$$ **THz**

$$\epsilon_{ph,x,y} = 8\ mm.mrad$$

(Diffraction limited emittance)

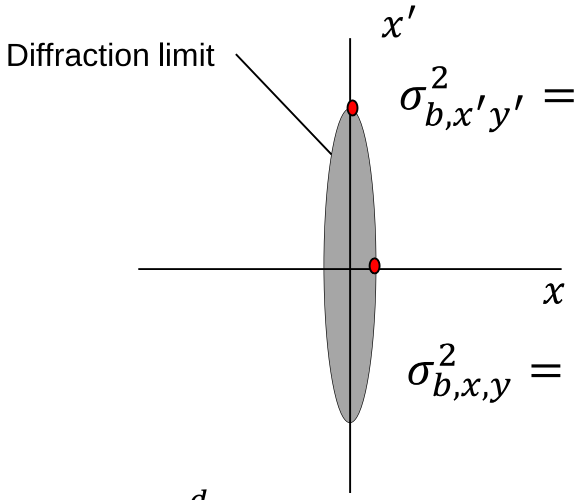
Finding the optimum focusing for optimum matching

$$\sigma_{b,x,y}^2 = \epsilon_{x,y}\beta_{x,y} \text{ and } \sigma_{b,x'y'}^2 = \frac{\epsilon_{x,y}}{\beta_{x,y}}$$

After including **diffraction limit**

$$\sigma_{tot,x}\sigma_{tot,x'} = \sqrt{\epsilon_x\beta_x + \sigma_r^2}\sqrt{\frac{\epsilon_x}{\beta_x} + \sigma_{r'}^2}$$

Betatron function at the **source point**



$$\sigma_{b,x'y'}^2 = \frac{\epsilon_{x,y}}{\beta_{x,y}}$$

$$\sigma_{b,x,y}^2 = \epsilon_{x,y}\beta_{x,y}$$

Minimum at $\left(\frac{d}{\beta_x}\sigma_{tot,x}\sigma_{tot,x'} = 0\right)$

$$\beta_x = \frac{\sigma_r}{\sigma_{r'}} = \frac{L}{4\pi} \rightarrow 0.27\ \text{m}$$

LCLS-I undulator length $(L) = 3.4\ m$

Similarly for y $$\beta_y = \frac{\sigma_r}{\sigma_{r'}} = \frac{L}{4\pi} \rightarrow 0.27\ \text{m}$$

Beam matching

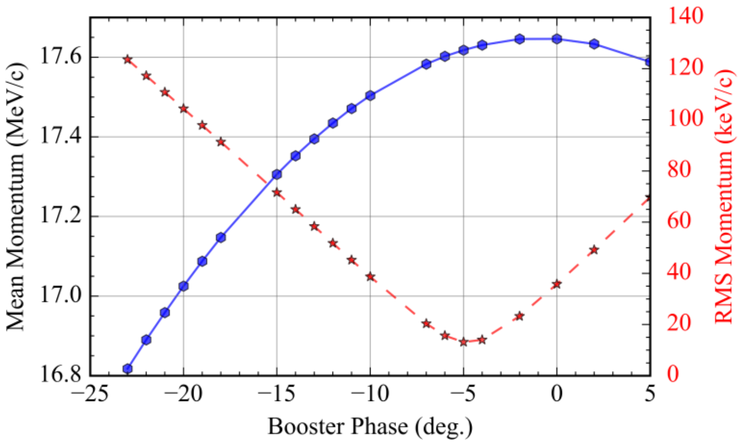
Beam transportation

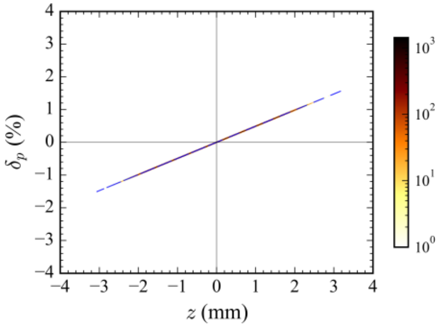
Beam momentum 17 MeV/c

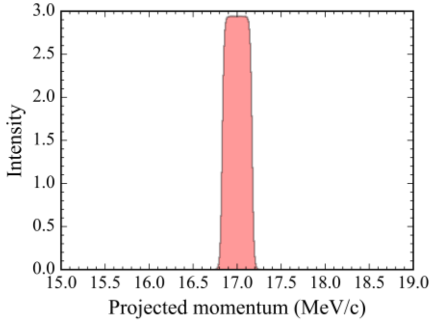
Beam with **chirp**

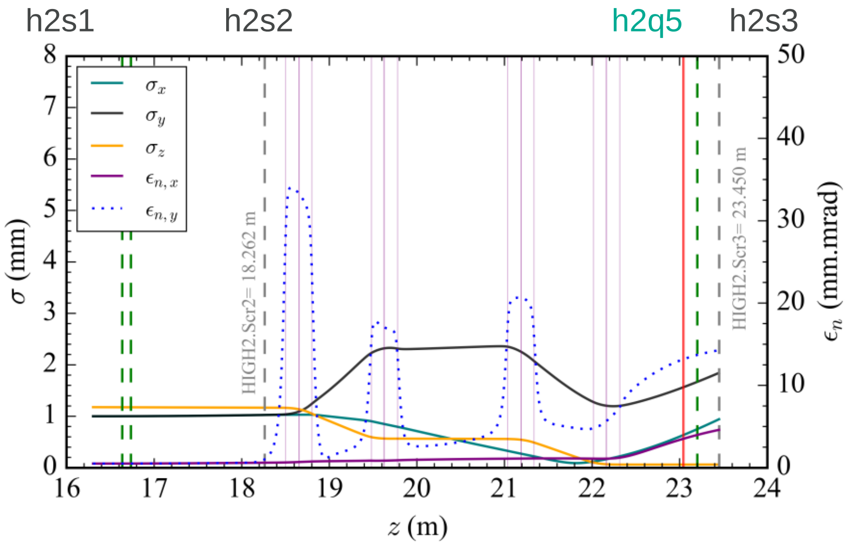
Energy spread 0.6%

Bunch charge 250 pC







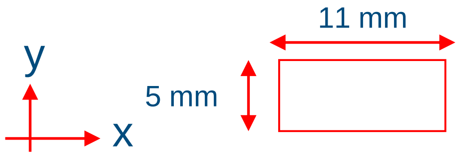


Matching parameters (transverse phase space)

- Twiss-parameters : $\beta_x,\ \beta_y, \alpha_x, \alpha_y$
- Transverse beam emittance : ϵ_x, ϵ_y

Challenges

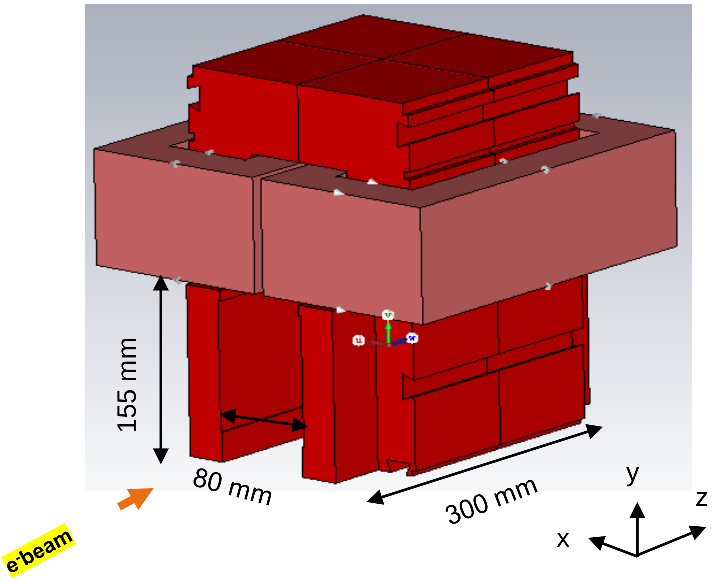
- Only one quadrupole to focus beam after BC
- Increasing of the transverse emittance (vertical) after BC
- Strong space charge force field due to low energy electron beam, compressed beam, and high bunch charge (up to 1.5 nC for SASE)
- Match beam to small vertical pipe of an undulator magnet

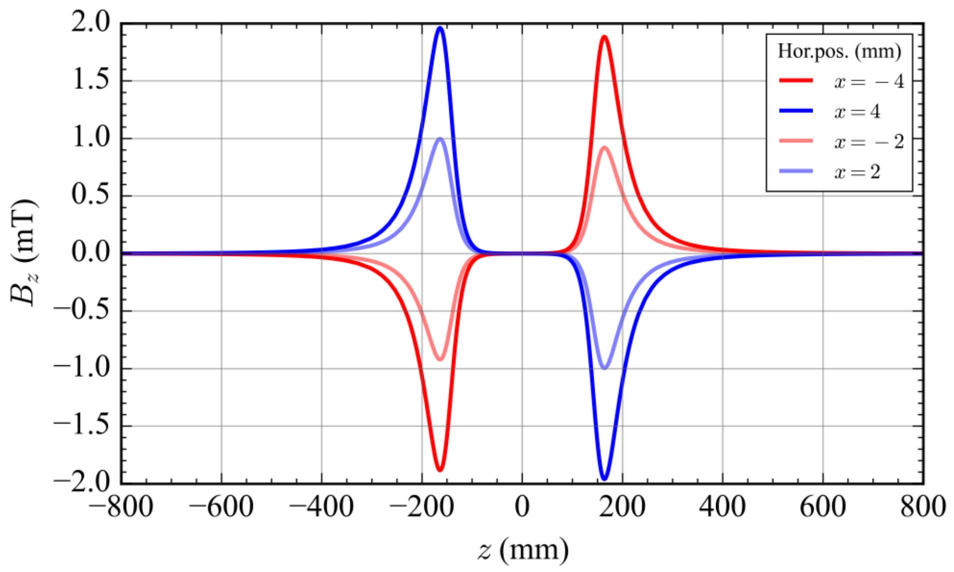


Undulator chamber cross-section

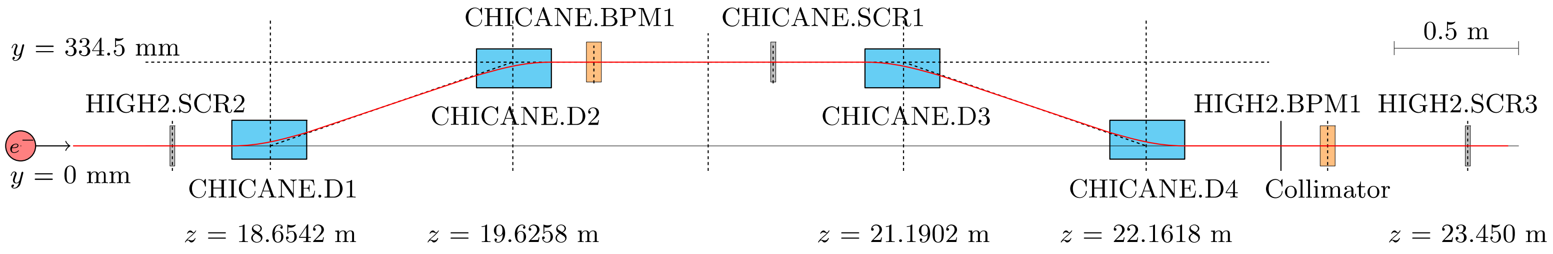
Beam matching

Edge focusing effect





19 degrees bending angle
+
Rectangular Bending magnet

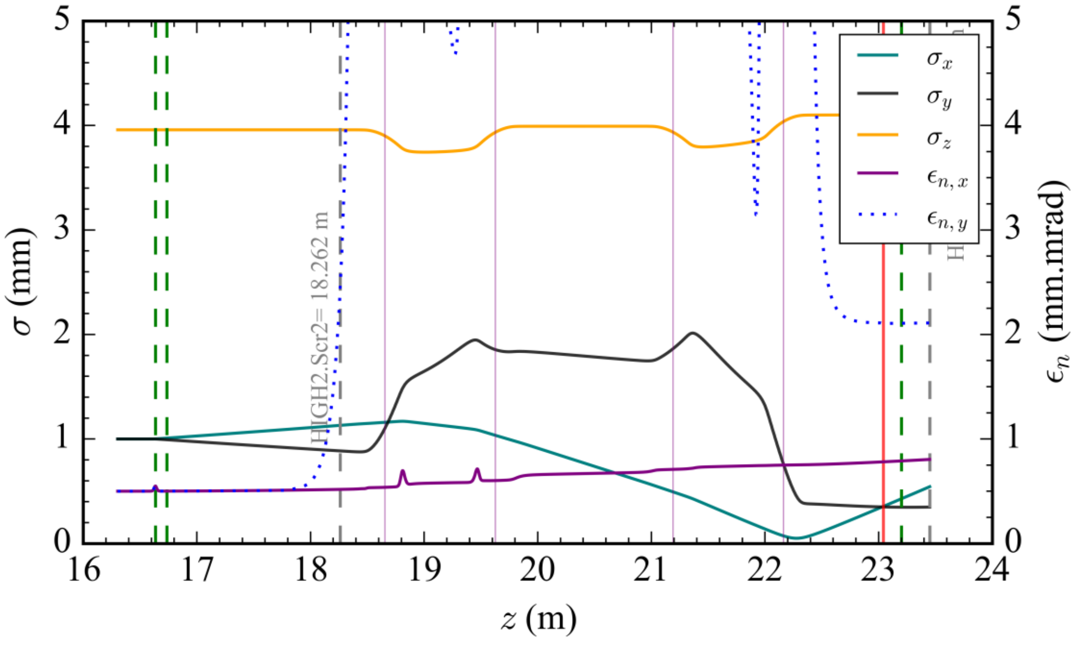


Beam matching

Edge focusing effect

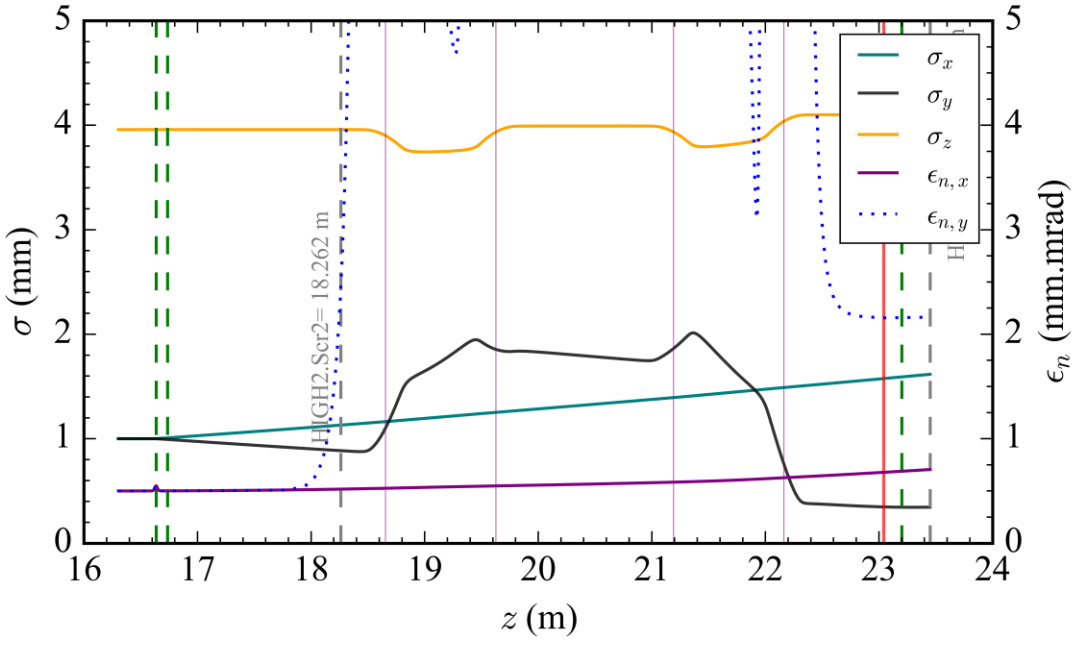
Magnetic field only Bx → ‘3DBNKF25X’

Before move dipole D2 and D3, h2Q1 focusing in y by 0.1 T/m



Bx, By, Bz

Before move dipole D2 and D3, h2Q1 focusing in y by 0.1 T/m

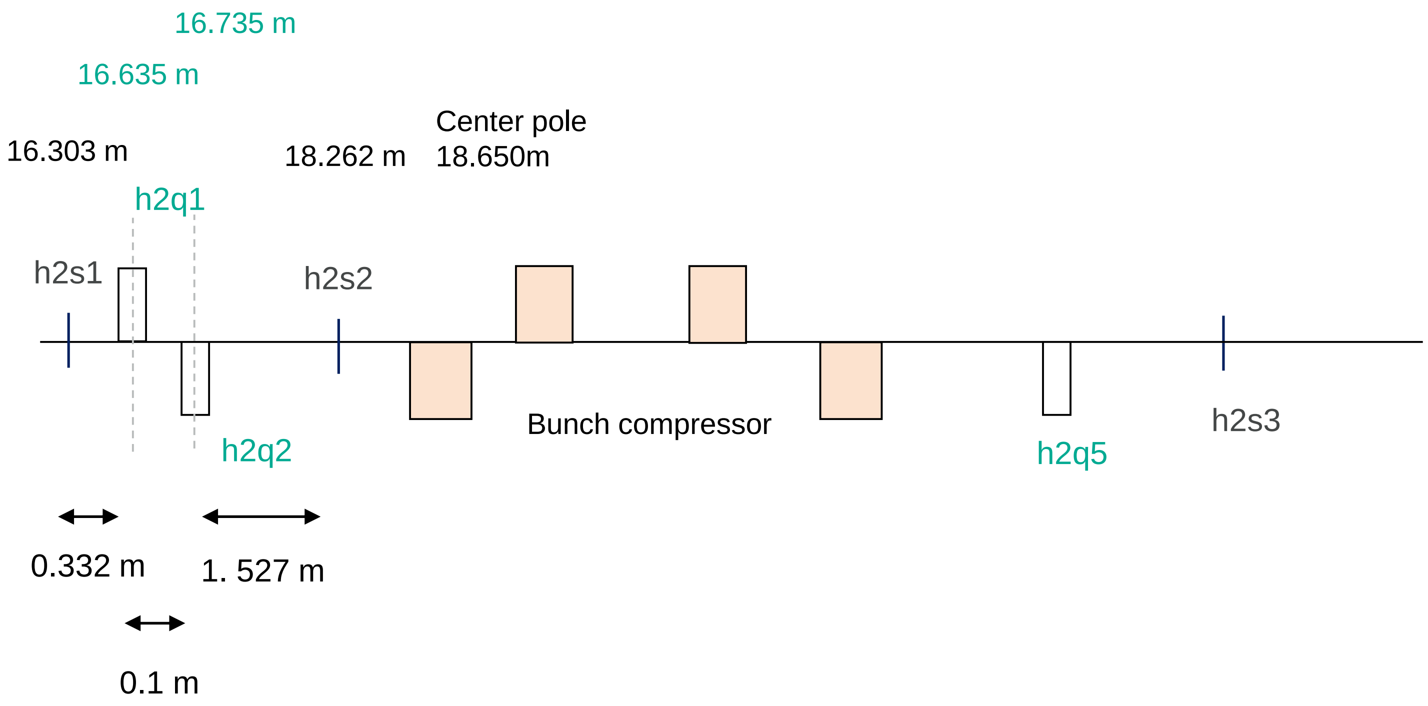


Bx only

Beam matching

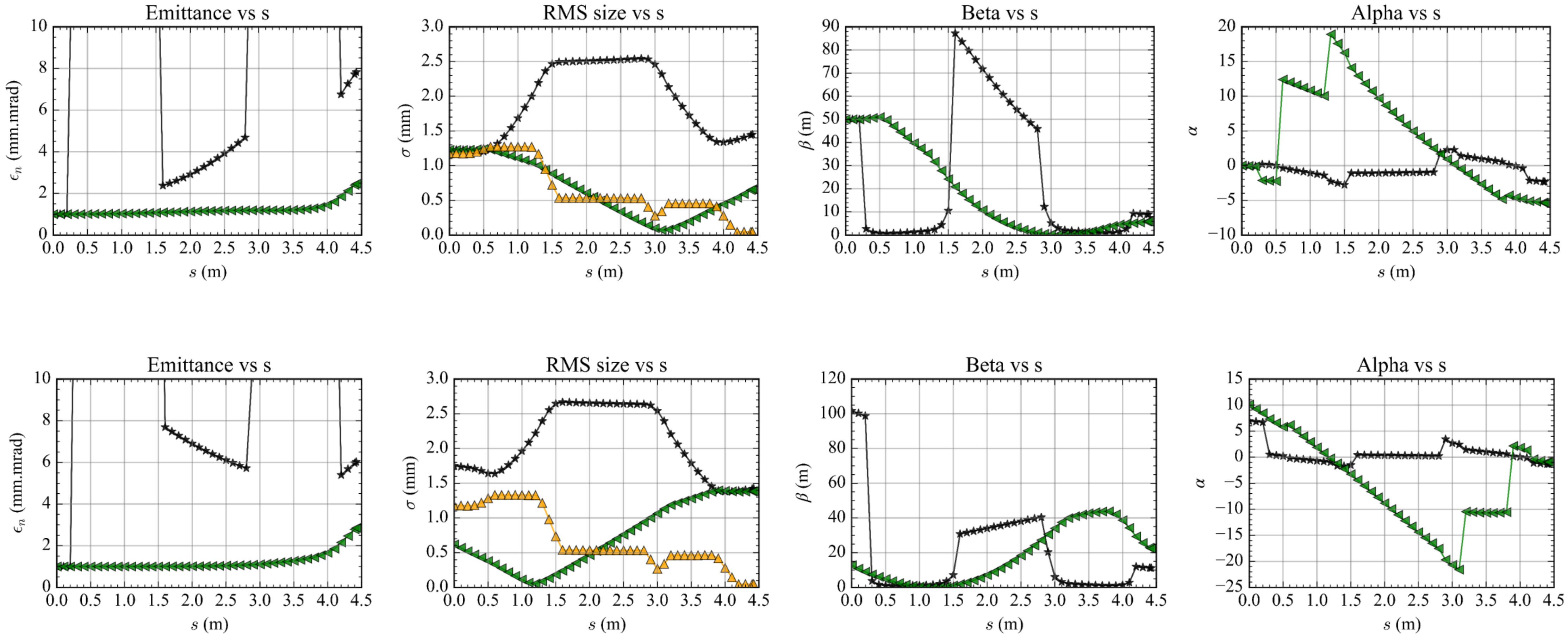
Setup BC (Chicane) → beam dynamics

- Average beam momentum : 17 MeV/c
- Bunch charge : 50 pC, **250 pC**, 1.5 nC
- MMMG phase and ~ -20 deg. w.r.t. MMMG phase



Beam matching

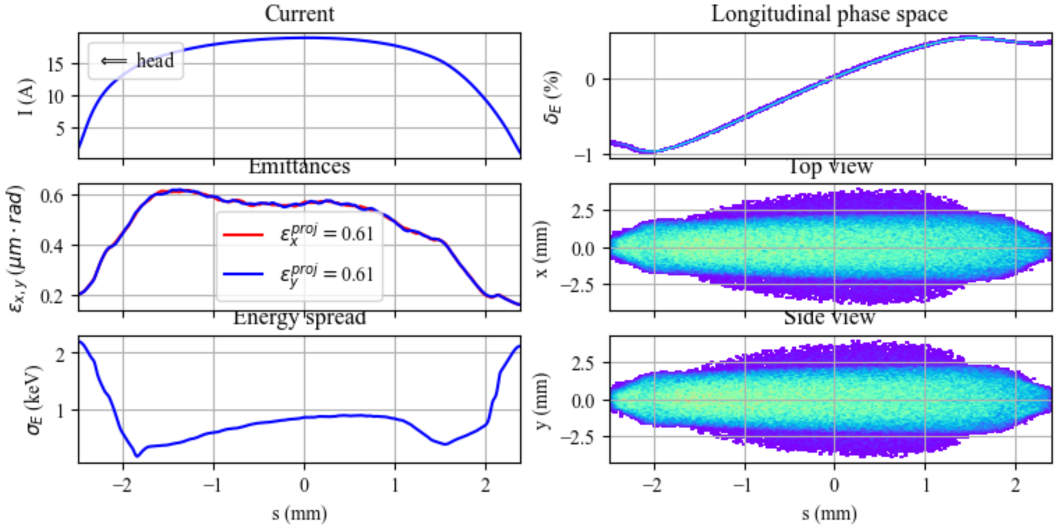
Beam dynamics simulation using OCELOT



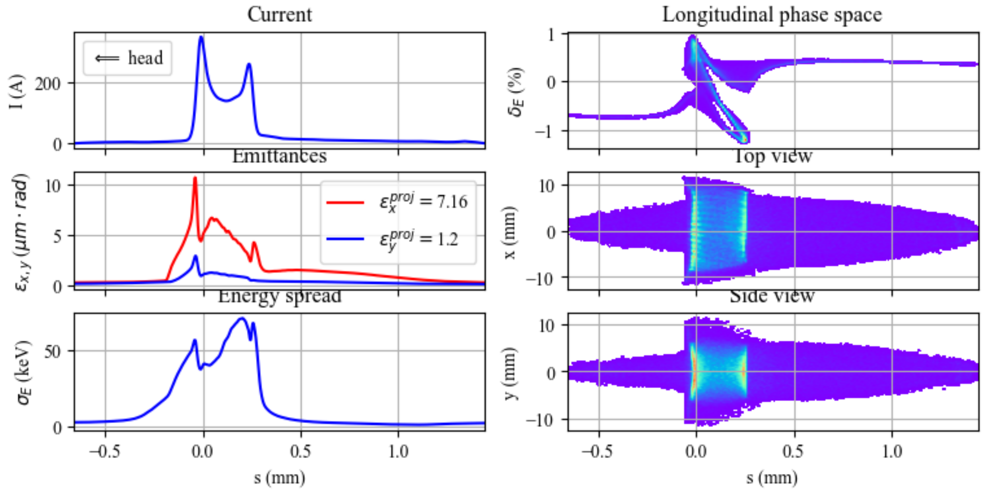
Beam matching

Beam from photocathode

Before BC at HIGH2.Scr2



After compression from BC



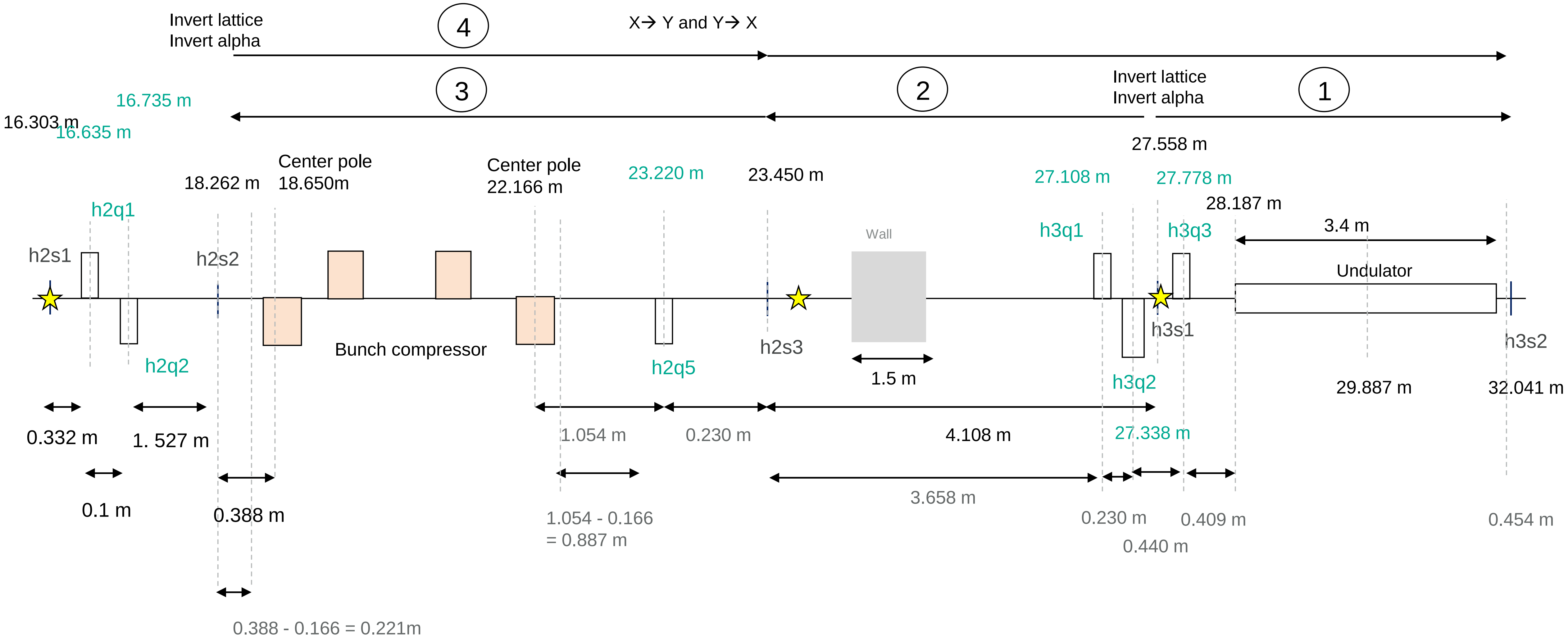
6-D transportation matrix

$$\vec{\chi} = [x, x', y, y', z, \ \Delta p/p_0]^T$$

- Average beam momentum : 17 MeV/c
- Bunch charge : **250 pC**
- ~ -20 deg. w.r.t. MMMG phase

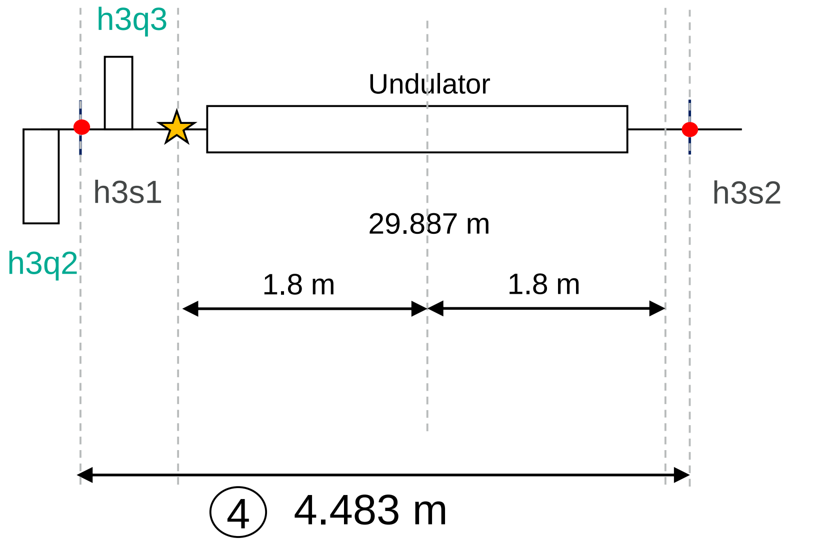
Beam matching

Motivation, Initial beam setup



Beam matching

Finding Twiss-parameters before undulator magnet



Simulation setup

- Using ASTRA + 3D magnetic field of undulator magnet
- Optimized parameters
- Beam momentum 17 MeV/c, Bunch charge 250 pC
  - Transverse beam size $F_x = |\sigma_{xf} - \sigma_{xi}| \rightarrow 0$ $F_y = |\sigma_{yf} - \sigma_{yi}| \rightarrow 0$
  - Correlation

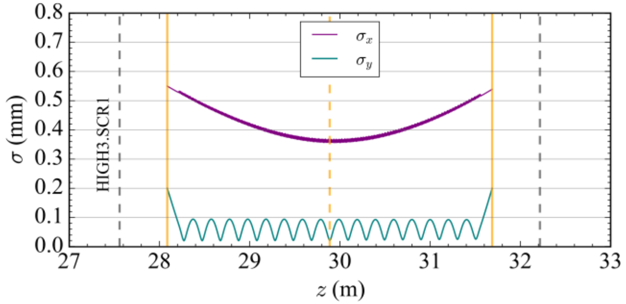
$$\sigma_x^2 = \frac{\beta_x \epsilon_{n,x}}{\beta\gamma}$$

$$cor_{px} = -\frac{\alpha_x}{\beta_x[m]}\sigma_x[mm]$$

Fixed transverse emittance !

Norm. emit_x, Norm. emit_y = 1, 1 mm.mrad

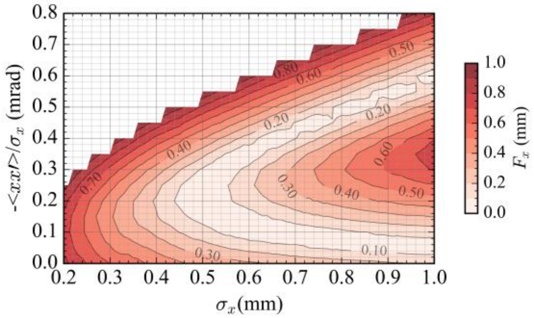
xrms, yrms, corpx, corpy = 0.55, **0.20**, 0.18, **1.0**

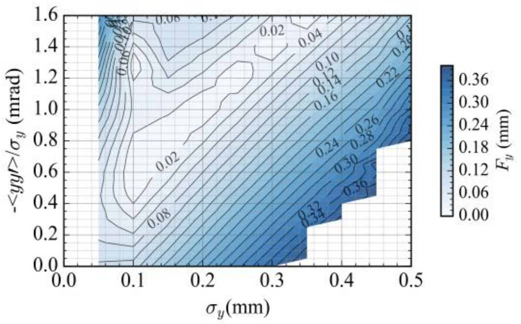


- Xemit = Yemit = 1 um
- Std_x = 0.55 mm
- Std_y = 0.15 mm
- Xx'/std_x = 0.25 mrad
- Yy'/std_y = 0.8 mrad

→

- Beta_x = 10 m
- Beta_y = 0.75 m
- Alpha_x = 4.6→6 m
- Alpha_y = 4 m



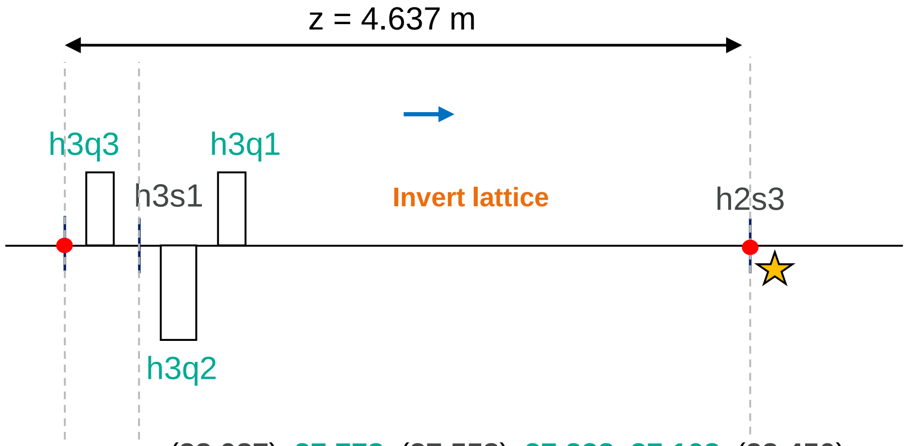


Beam matching

Edge focusing effect

Invert the lattice

Invert alphas

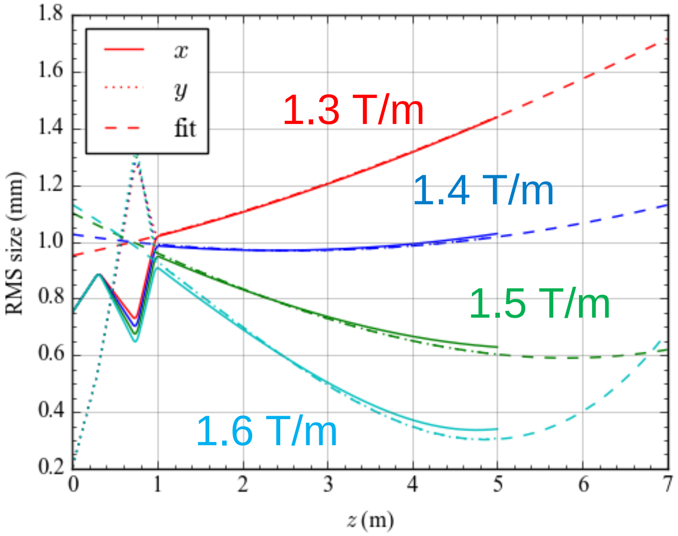


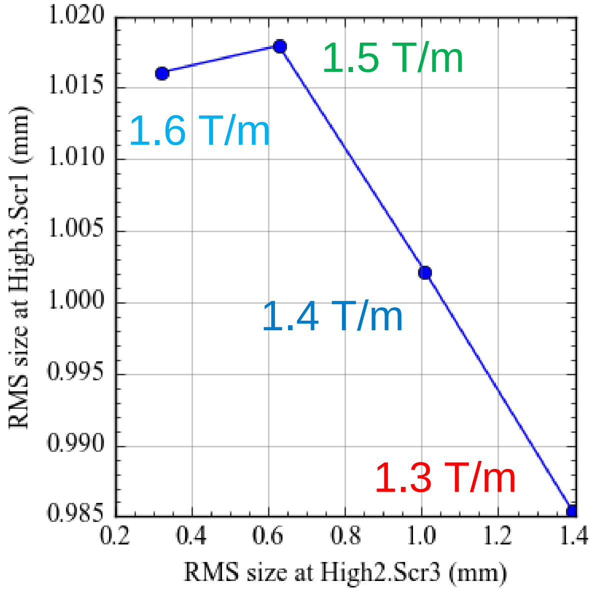
(28.087), **27.778**, (27.558), **27.338**, **27.108**, (23.450)

Positions in beamline

(0), **0.309**, (0.529), **0.749**, **0.979**, (4.637)

Positions in simulation **backward tracking**



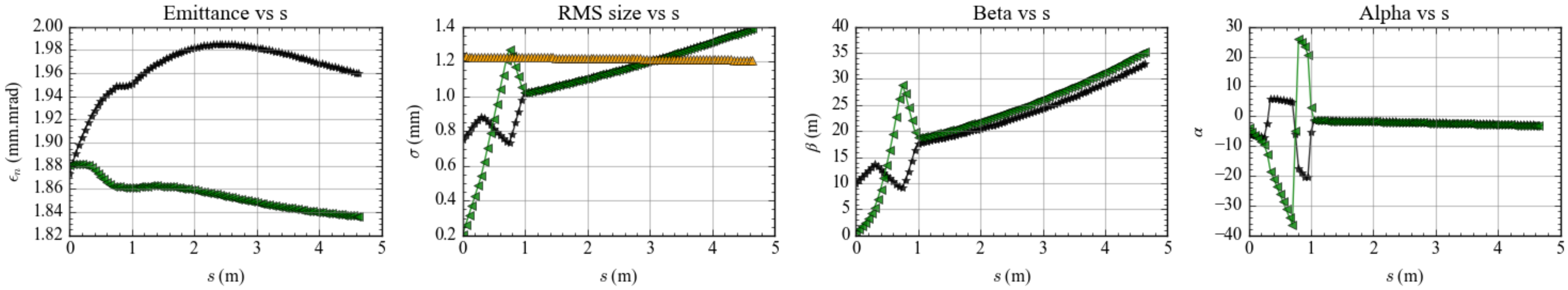


Backward tracking using OCELOT

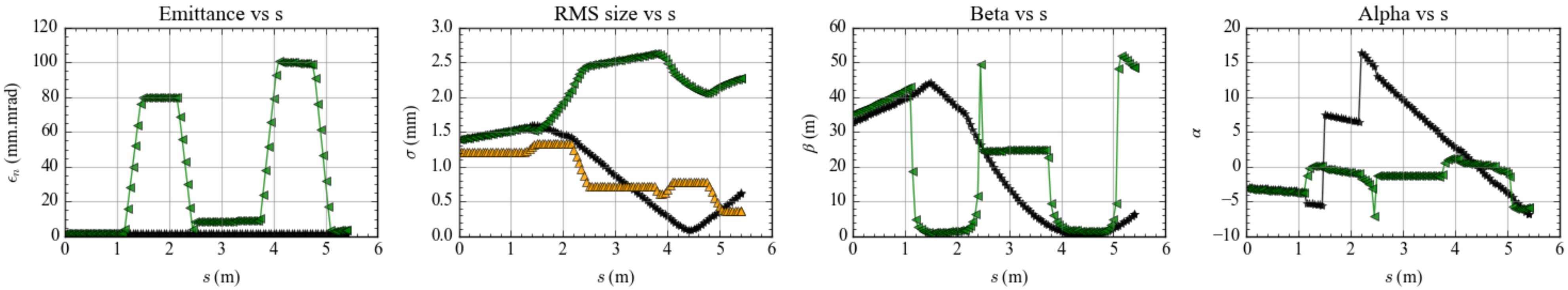
Tracking to the end off the BC, switch x and y axis and tracking further to BC entrance

1st Iteration, HIGH3.Q3 = 1.3 T/m

Green color→ Vertical **Black color**→ Horizontal



X ← → Y

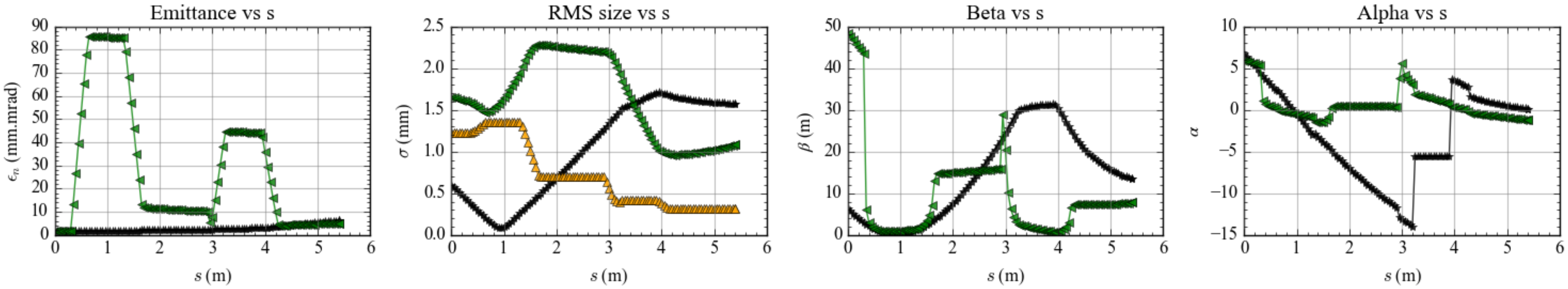


Forward tracking using OCELOT

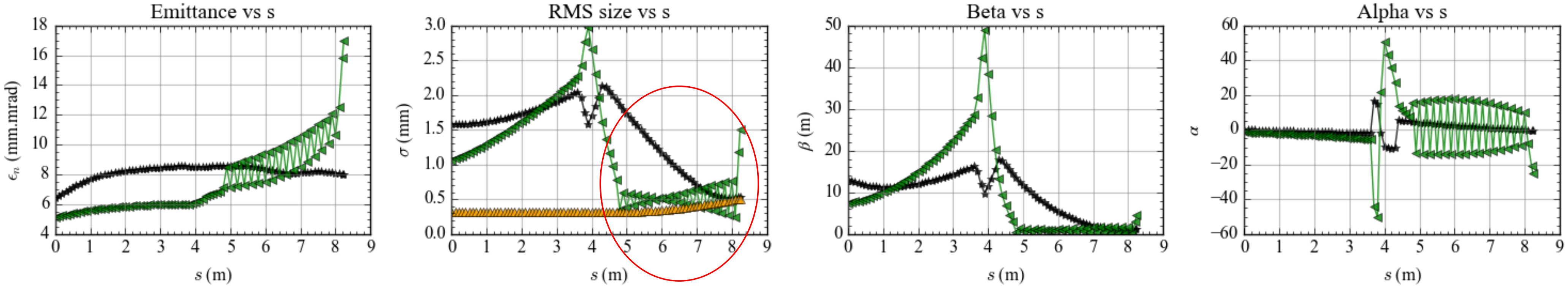
Invert alpha (twiss-parameter), tracking beam the end of the undulator magnet

Green color→ Vertical **Black color**→ Horizontal

1st Iteration, HIGH3.Q3 = 1.3 T/m



X ← → Y



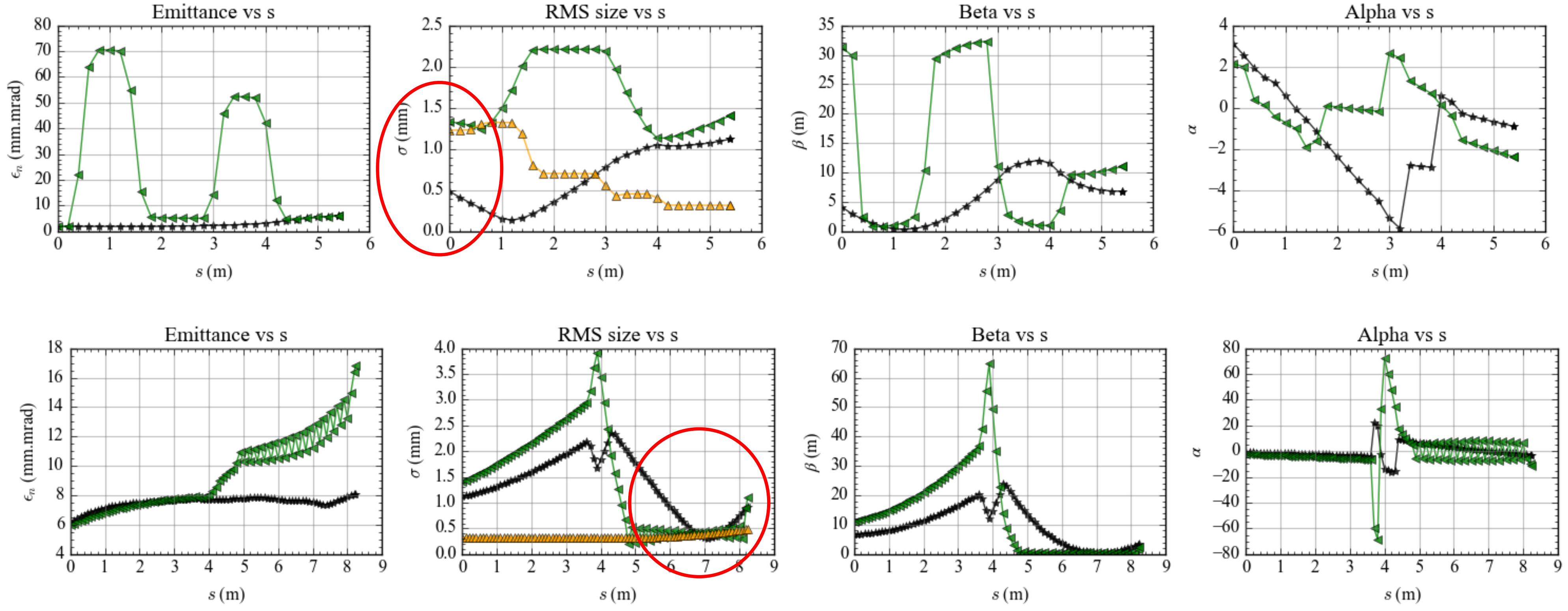
2nd Iteration

Forward tracking to the end of the undulator magnet (using beam from S2E simulation)

1st Iteration, HIGH3.Q3 = 1.3 T/m

2nd Iteration, HIGH3.Q3 = 1.5 T/m

X ← → Y



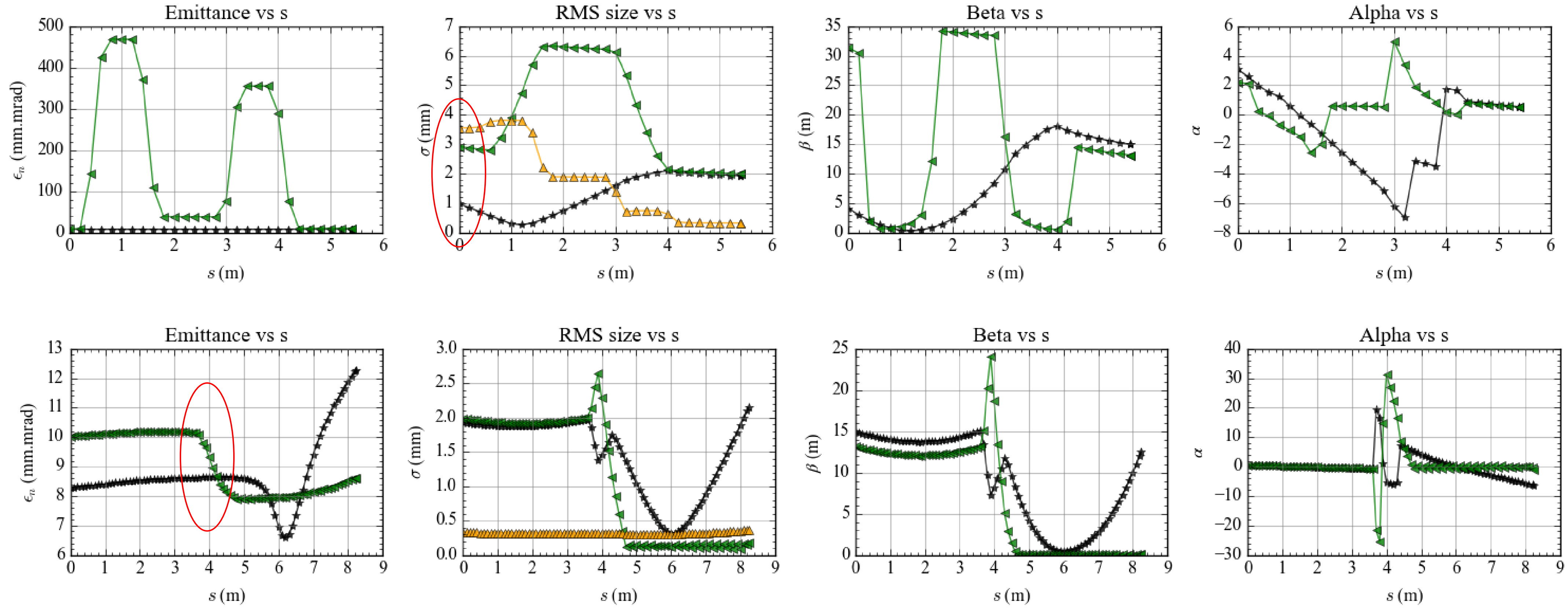
2nd Iteration

Forward tracking to the end of the undulator magnet (using beam from backward tracking)

1st Iteration, HIGH3.Q3 = 1.3 T/m

2nd Iteration, HIGH3.Q3 = 1.5 T/m

X ← → Y



Achievement and Outlook

PITZ and my self

- Dispersion procedure
- Startup procedure for beam matching from BC to undulator magnet
- Beam dynamics in the BC

- Machine operation
- Simulation
- 1 LPR paper from IPAC23
- … 1 paper from beam matching and super-radiant radiation

Next…

- Python script for beam matching (in October)
- MATLAB script for beam matching (in November)

Thank you for your attention