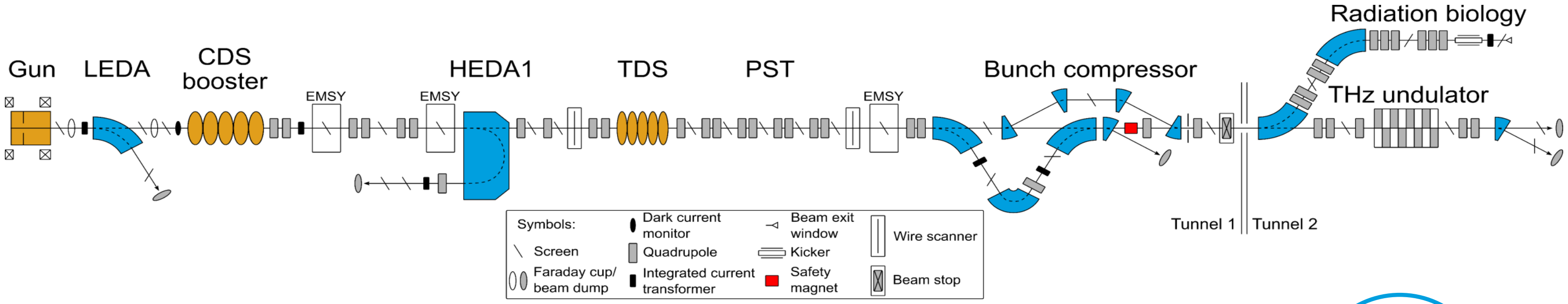
Beam Dynamics Simulation and Optimization of an Electron Beam for Magnetic Bunch Compressor Commissioning at PITZ

PPS 16 March 2023



Ekkachai Kongmon

PITZ, 16 March 2023

HELMHOLTZ

Outline of the presentation

Introduction

- Bunch compressor
- PITZ accelerator
- PITZ Bunch Compressor
  - 1D Models for FELs
  - Designed trajectory

Beam trajectory simulation

- Set up simulation
- Optimization of magnetic chicane current

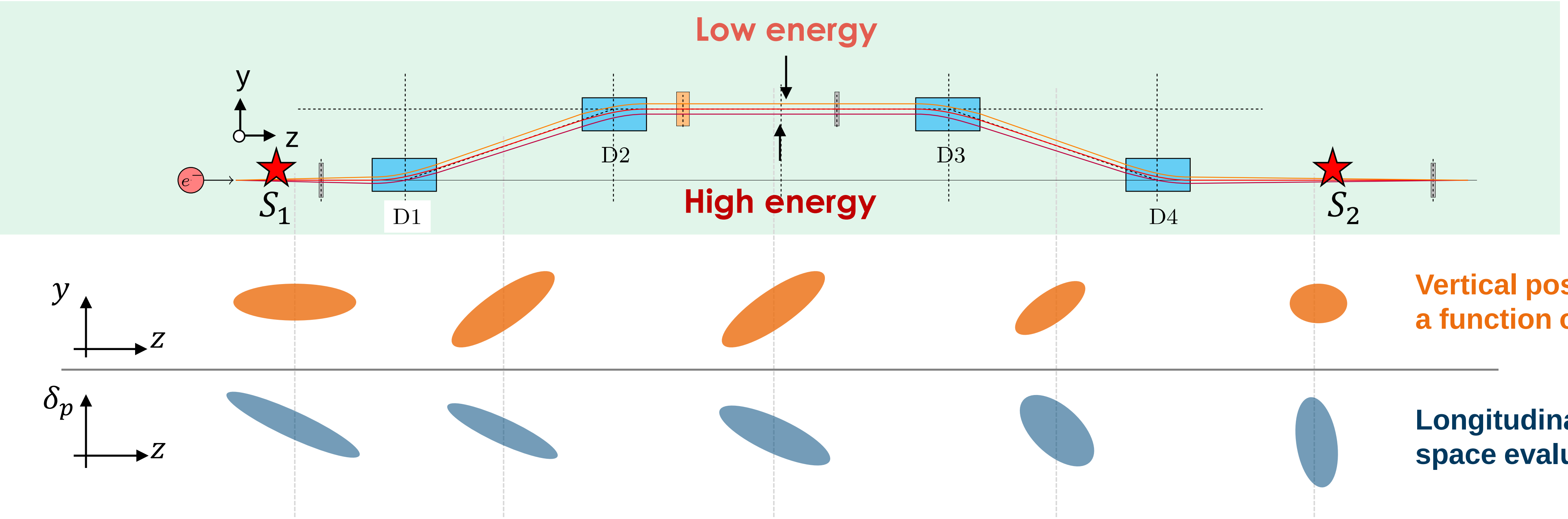
Beam dynamics simulation

- Using the optimized case from trajectory

Summary and Future work

Bunch Compressor

Bunch compression in magnetic chicane



Vertical position as a function of z

Longitudinal phase space evaluation

$$\vec{\chi}(S_2) = R \times \vec{\chi}(S_1)$$

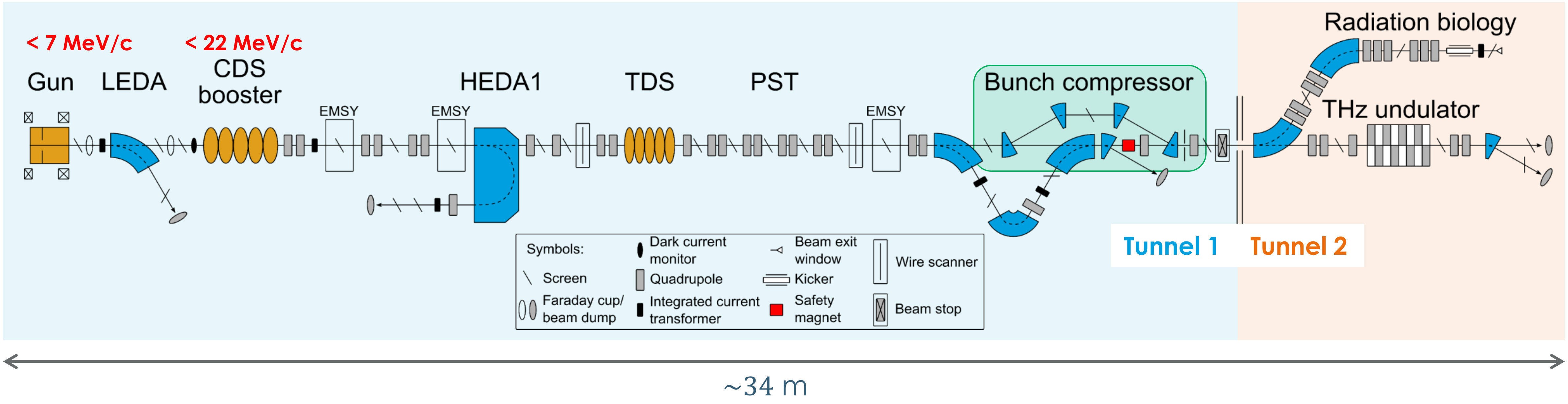
$$\begin{pmatrix} x_f \\ x'_f \\ y_f \\ y'_f \\ z_f \\ \delta_{p,f} \end{pmatrix} = \begin{pmatrix} R_{11} & R_{12} & 0 & 0 & 0 & 0 \\ R_{21} & R_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & R_{33} & R_{34} & 0 & R_{36} \\ 0 & 0 & R_{43} & R_{44} & 0 & R_{46} \\ R_{51} & R_{52} & 0 & 0 & 1 & R_{56} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_i \\ x'_i \\ y_i \\ y'_i \\ z_i \\ \delta_{p,i} \end{pmatrix}$$

$$z_f = \cancel{R_{51} x_i + R_{52} x'_i} + z_i + R_{56}\delta_p$$

$$z_f(S_2) = z_i(S_1) + \boldsymbol{R_{56}}\delta_p$$

PITZ Accelerator

PITZ Bunch compressor



Production and optimization of the high brighness THz radiation, called free-electron laser (FEL)

- SASE (bunch length longer 5 ps → peak current 200 – 400 A for 2 – 4 nC)
- Seeded
- Super-radiant

FLASH beamline for biology application

- Irradiation biology

PITZ Bunch Compressor

1D Model for FELs

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 A
Bunch charge	4 nC
Radiation	
Radiation wave length	~100 μm (~ 17 MeV/c)

Pirece parameter

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

$$[JJ] = J_0(\xi) - J_1(\xi)$$

$$\xi = \frac{K^2}{2(2+K^2)}$$

Beam requirements

1. Electron beam **relative energy spread (δ) should be smaller than Pirece parameter (ρ)**
2. Geometric emittance of an electro beam ($\varepsilon_\perp$) should be smaller than radiation emittance (ε_r), $\varepsilon_r = \lambda_r / 4\pi$

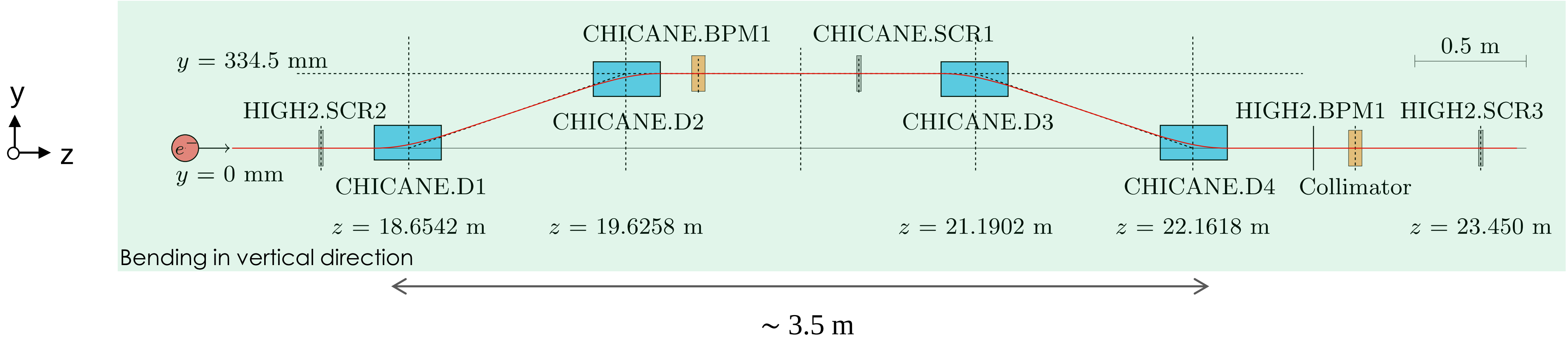
ρ = 0.015 for 17 MeV/c

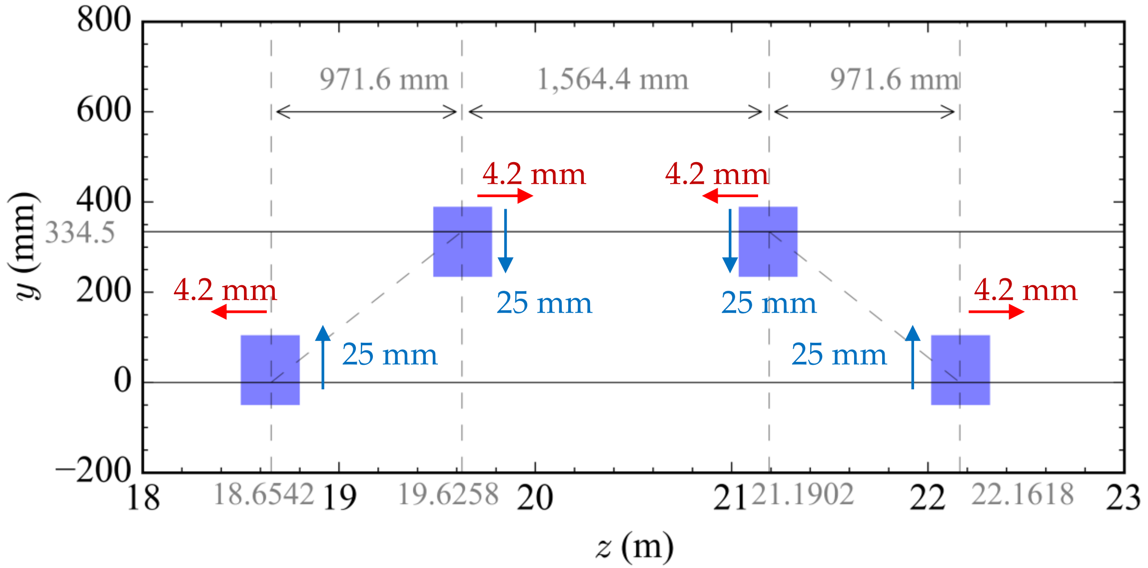
= 0.013 for 22 MeV/c

Maximum relative energy spread (δ) $< \rho \approx 1$ %

PITZ Bunch Compressor

Designed beam trajectory from hard edge model





Parameters	Value
Beding angle	19 degrees
Bending radius	904.67 mm
Distance D1→ D2 (L_{12})	680 mm
Pole length (L_B)	300 mm

$$R_{56} \approx 0.198\, m$$

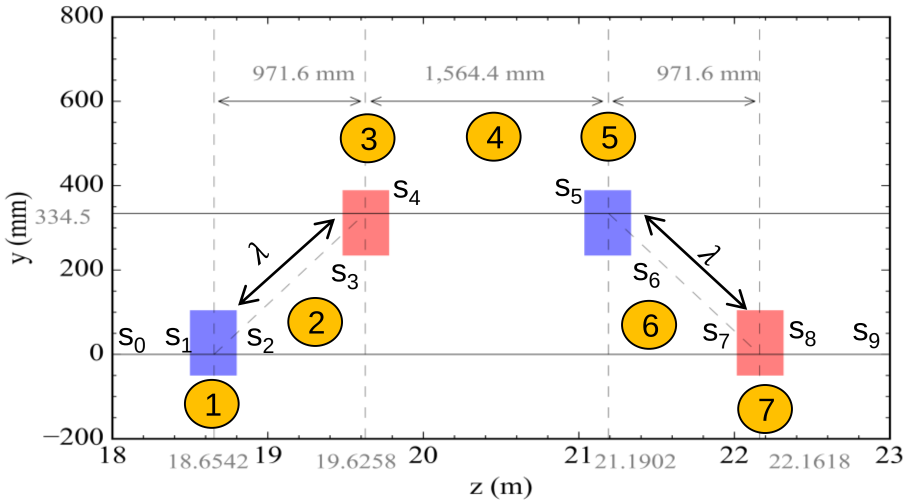
$$R_{56} \approx -2\theta_0^2\{(L_{12} + \frac{2}{3}L_B)\}$$

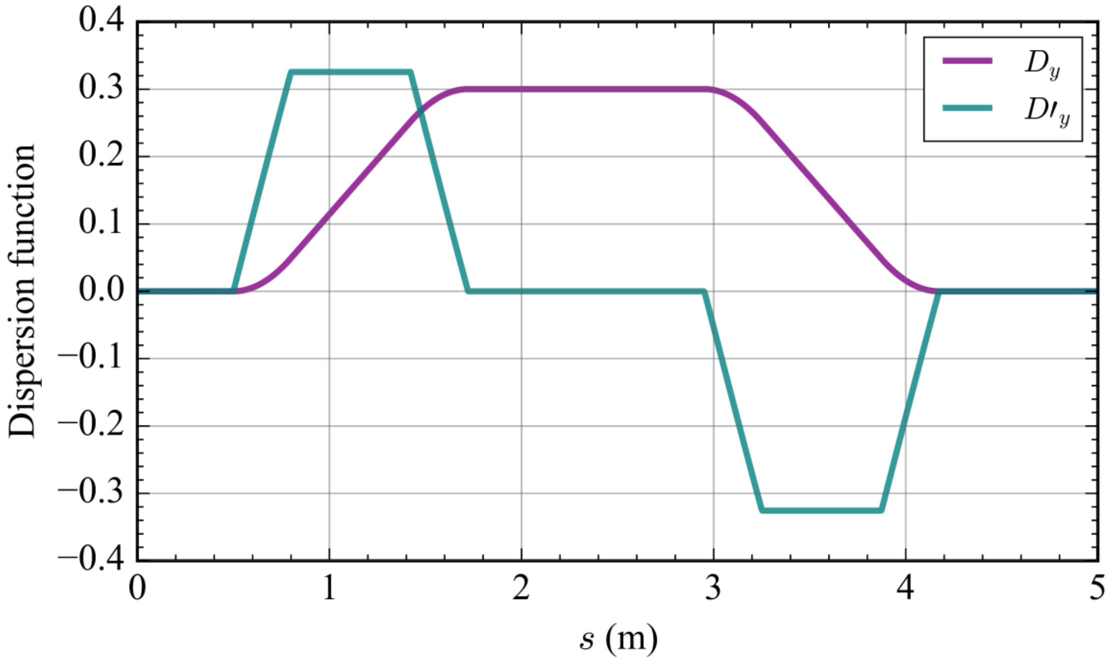
PITZ Bunch Compressor

Dispersion function of the hard edge dipole

Dispersion function	$S_0 \rightarrow S_1$	$S_1 \rightarrow S_2$
D_1	0	$R(1-\cos(\frac{s-s_1}{R}))$
D_1'	0	$\sin(\frac{s-s_1}{R})$

1. 1^{st} dipole D_1 and D_1'
2. Drift space $\boldsymbol{D_2} = D_1 + \lambda D_1'$, $D_2' = D_1'$
3. 2^{nd} dipole $\boldsymbol{D_3} = D_2 - D_1$, $D_3' = D_2' - D_1' = 0$
4. Drift space $\boldsymbol{D'} = 0$
5. 3^{rd} dipole $\boldsymbol{D_4} = D_3 - D_1$, $D_4' = -D_1'$
6. Drift space $\boldsymbol{D_5} = D_4 + \lambda D_4' = -D_1$, $D_5' = D_4' = -D_1'$
7. 4^{th} dipole $\boldsymbol{D_6} = D_5 + D_1 = 0$, $D_6' = D_5' + D_1' = 0$





Simulation of an electron beam for trajectory tool development of the magnetic Bunch Compressor (BC)

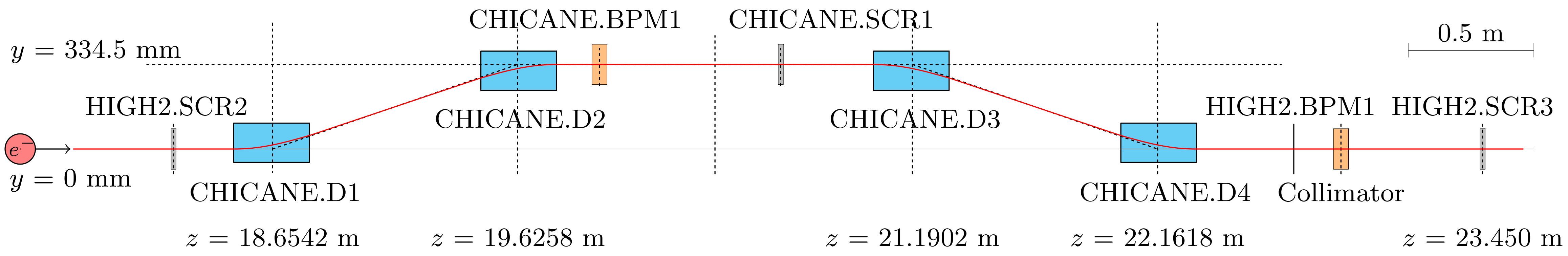
To find the optimum current of all dipole magnets for electron beam transportation throughout the BC.

- **For high charge transportation.**
- **For compression phase.**

- **Vertical offset from the center of vacuum tube.**
- **Dispersion (R_{36})**

Beam Trajectory Simulation

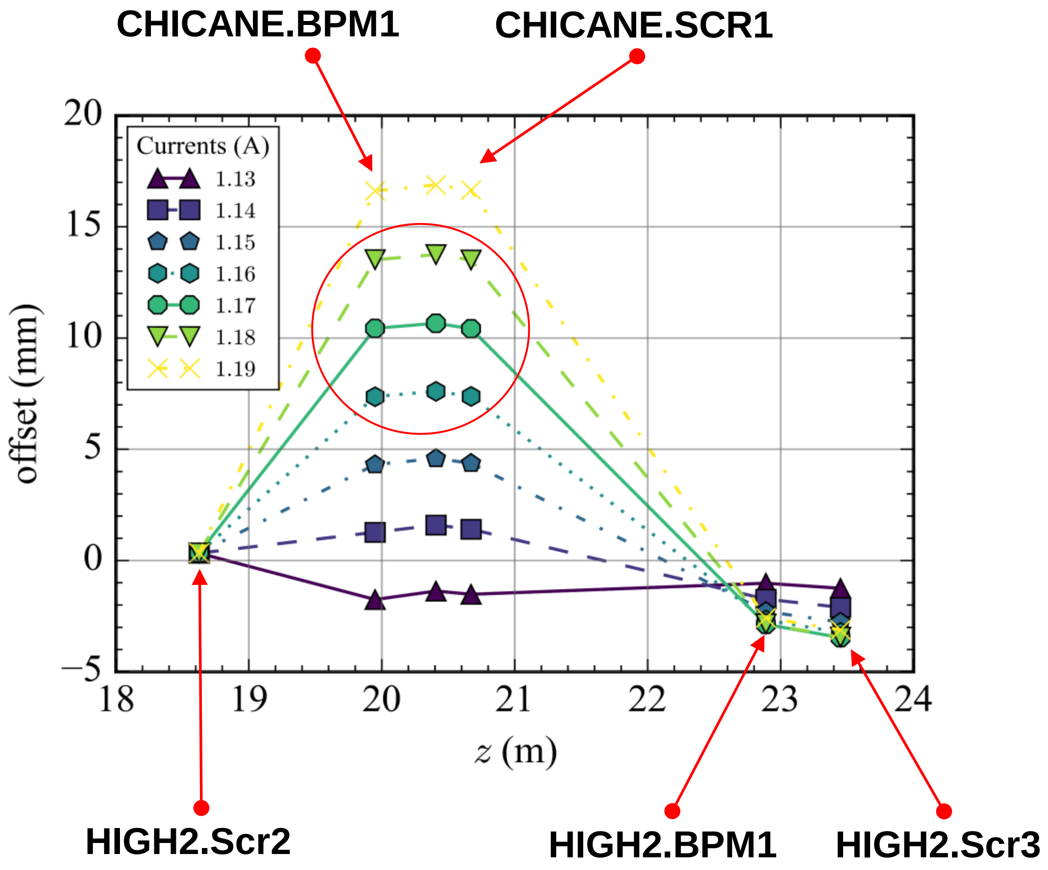
Initial parameters and set up



Beam momentum	**17** MeV/c
Dipole field	**3D field from CST**
Dipole current	Positive for D1 and D4 Negative for D2 and D3

Beam Trajectory Simulation

Dispersion function for identical currents cases



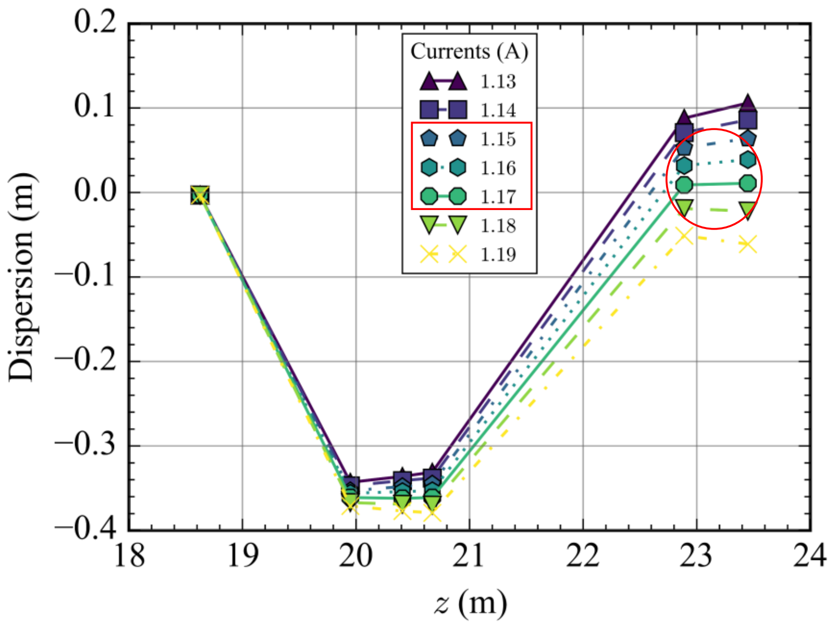
Parameters

Dispersion at HIGH2.Scr3

Offset at HIGH2.Scr3

Vertical angle at HIGH2.Scr3

Offset center between D2 and D3

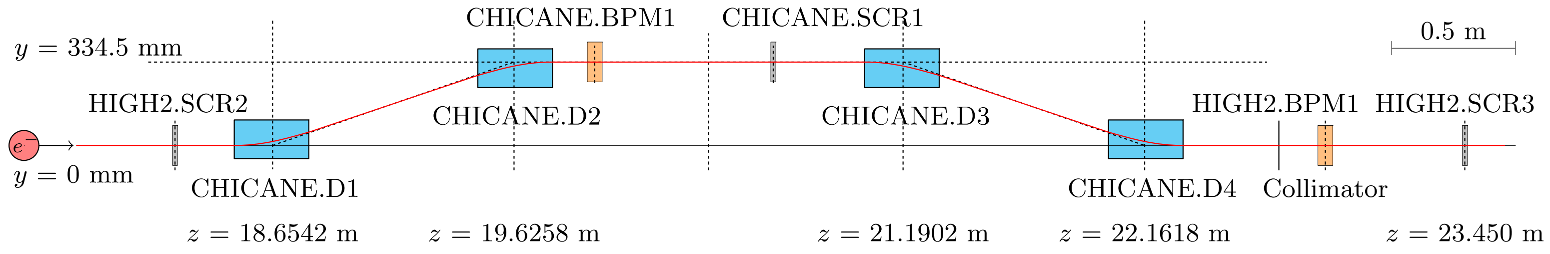


Beam momentum : 17 MeV/c

Beam Trajectory Simulation

Minimization with the 1 mA step of the dipole currents

Goal parameters	Value
Dispersion at HIGH2.SCR3	≤ 0.02 m
Offset at HIGH2.SCR3	≤ 1 mm
Vertical angle at HIGH2.ScCR3	≤ 0.5 mrad
Vertical offset D2 and D3	≤10 mm



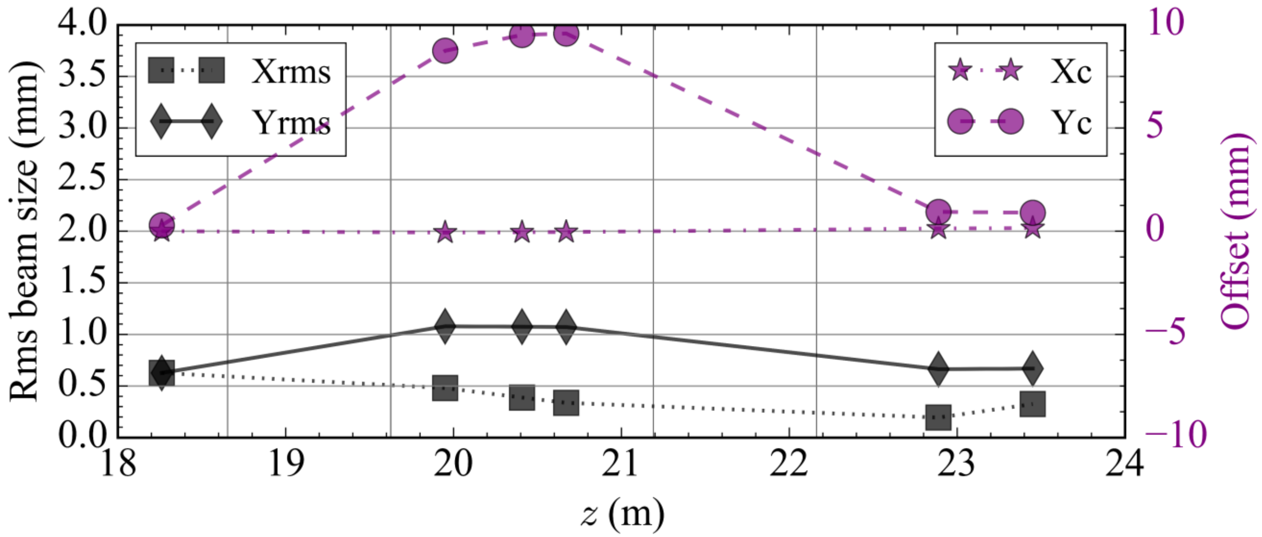
Vacuum tube between Dipole2 and Dipole3 is **NW63CF** type, which has the **inner radius of 30 mm.**

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

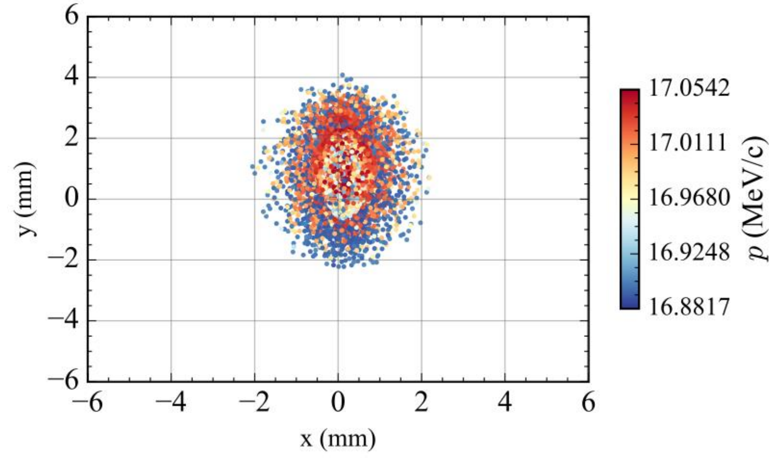
Beam dynamics simulations

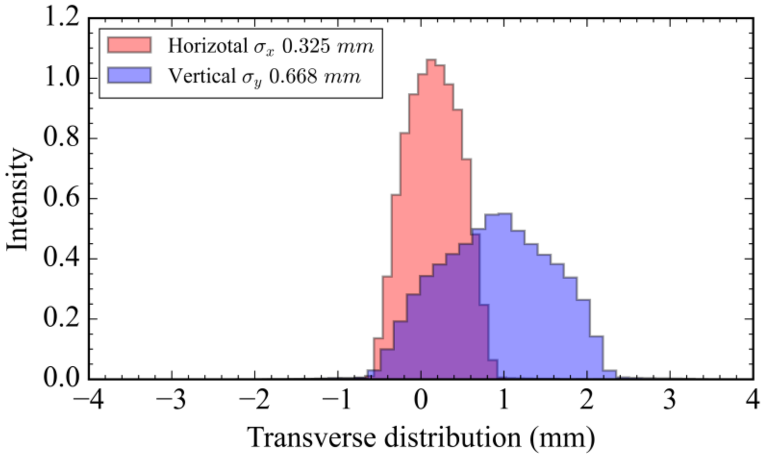
Bunch charge : 200 pC, Including space charge force field.

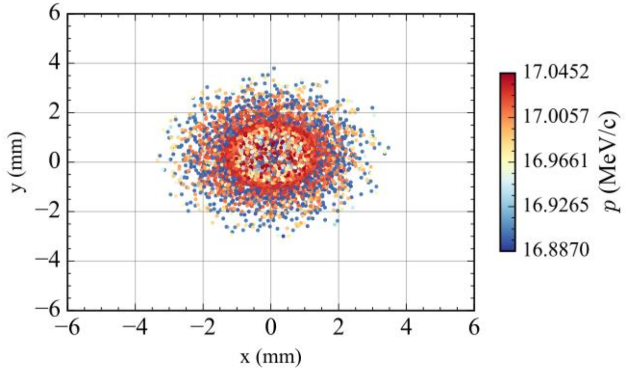
*** Using minimum momentum spread phase**

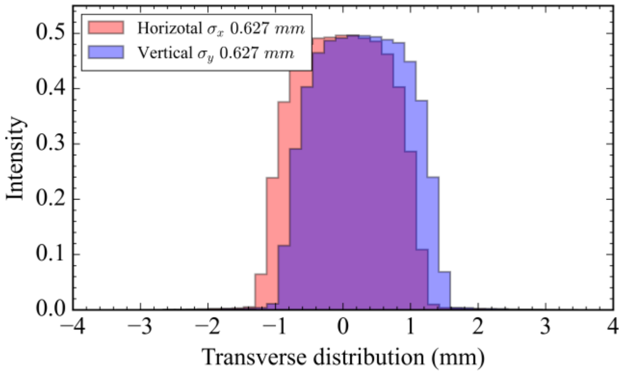


Beam after chicane (HIGH2.SCR3)







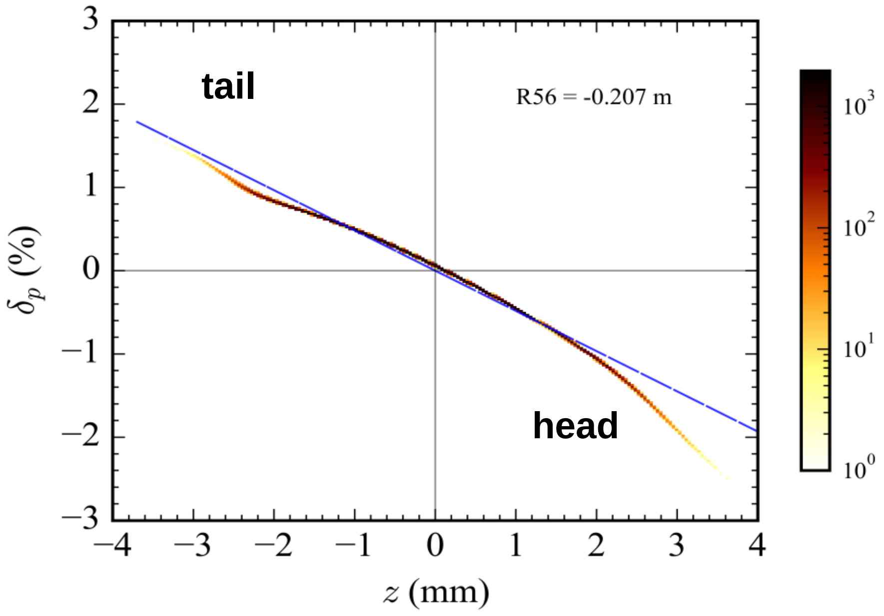


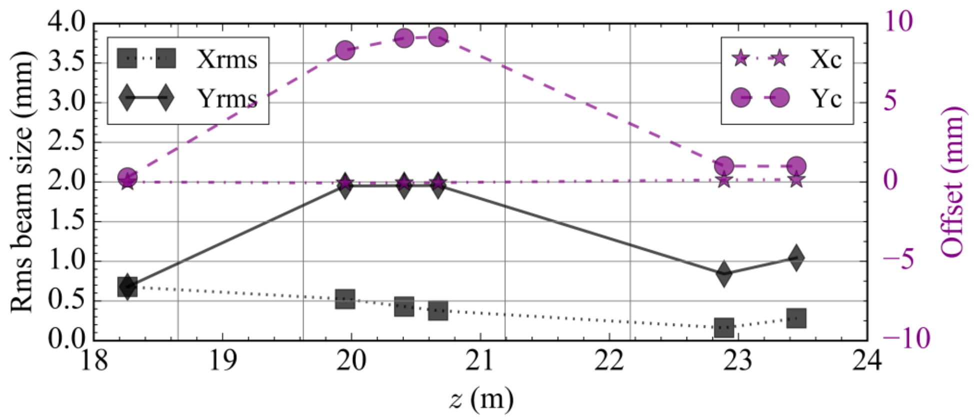
Beam before chicane (HIGH2.SCR2)

Beam dynamics simulations

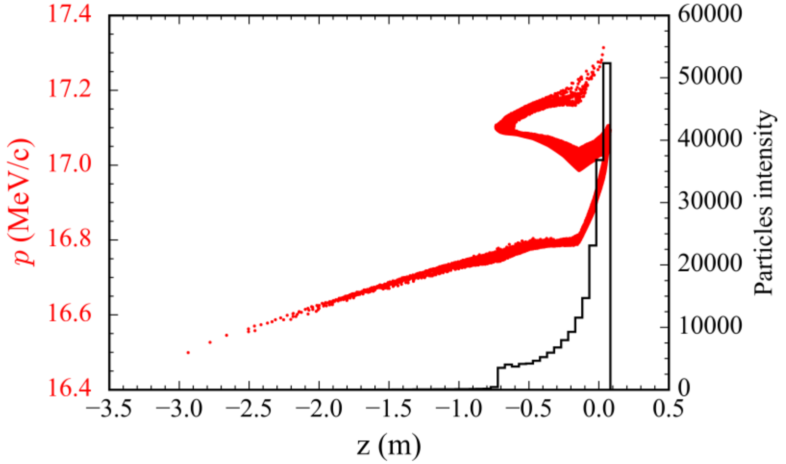
Using optimum phase for electron beam compression

Booster Phase : -20 deg. From MMMG phase





Beam after chicane (HIGH2.SCR3)



Compression factor

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

full-compression $C \to \infty$

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

Peak currents

Before : 53.066 A

After :265.148 A

* In experiment the full compression phase can be measured by measuring the radiated energy from CTR.

Summary and Discussion

1. **To reach the minimum dispersion after chicane, we can’t transport the beam along the on-axis (designed) trajectory.**

2. **Maximize parameters → to find the optimum currents for all dipoles**
   - **At the arm of chicane : Chicane.BPM1, Chicane.Scr1**

     → Vertical offset = + 10 mm.

   - **After chicane: HIGH2.BPM1, HIGH2.Scr3**

     → Vertical offset = |1 |mm

     → Vertical angle = 1 mrad

     → Dispersion = 0.02 m

Future works

1. **Using the optimization method to transport electron beam with the compression phase and high charge.**
   - Booster phases : 0, -5, -10, -15, -20, -25 degrees.
   - Bunch charge : 50, 200, 500, 1000, 2000, 4000 pC.
2. **Including the CSR effect for high bunch charge beam transportation (> 200 pC).**
3. **Study compression conditions for SASE, seeded, super radiant FELs techniques.**
4. **Beam matching**
   - Booster to chicane
   - Chicane to undulator
5. **Study on THz FEL production by including magnetic bunch compressor to the process.**

Thank you for your attention