Preliminary results of 5 nC beam simulation for radiation application in the tunnel annex

Xiangkun Li, PPS, August 20 2020,

Outline

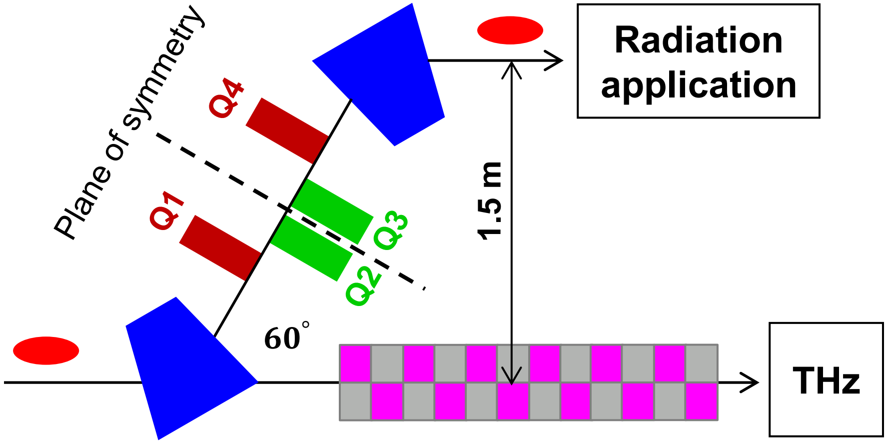
- Introduction
- Injector optimization
- Beam transport in the dogleg
- Discussion
- Summary

Introduction

Background

- A second beamline parallel to the THz SASE FEL in the tunnel annex is being considered for radiation application

Parameter	Value	Unit
Charge	**5**	nC
Bunch length	**30 - 100**	ps
Beam size	**?**	mm
Momentum	**~20**	MeV/c



- Currently start-to-end simulation is undergoing to check if such a beam could be produced there with our photo-injector and how the beam will look like

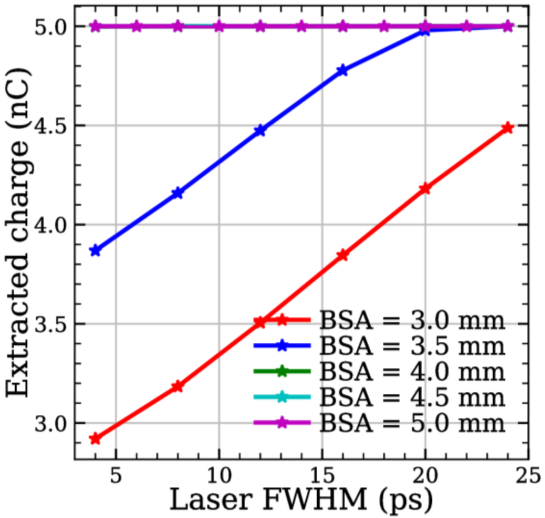
Introduction

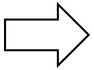
Consideration on the simulation

- To relax space charge at 5 nC
  - Larger laser spot size with higher gun gradient of **60 MV/m**
- Controllable bunch length (30 to 100 ps FWHM)
  - Relatively long laser pulse at emission
  - Positive and linear energy chirp ← gun and booster phases
- Solenoid optimization for best emittance and easier transport
- Achromatic design of dogleg (R16=R26=0) ?

Injector optimization
Laser profile scan

- Gun gradient 60 MV/m, MMMG phase
- Laser is uniform transversely and flattop longitudinally



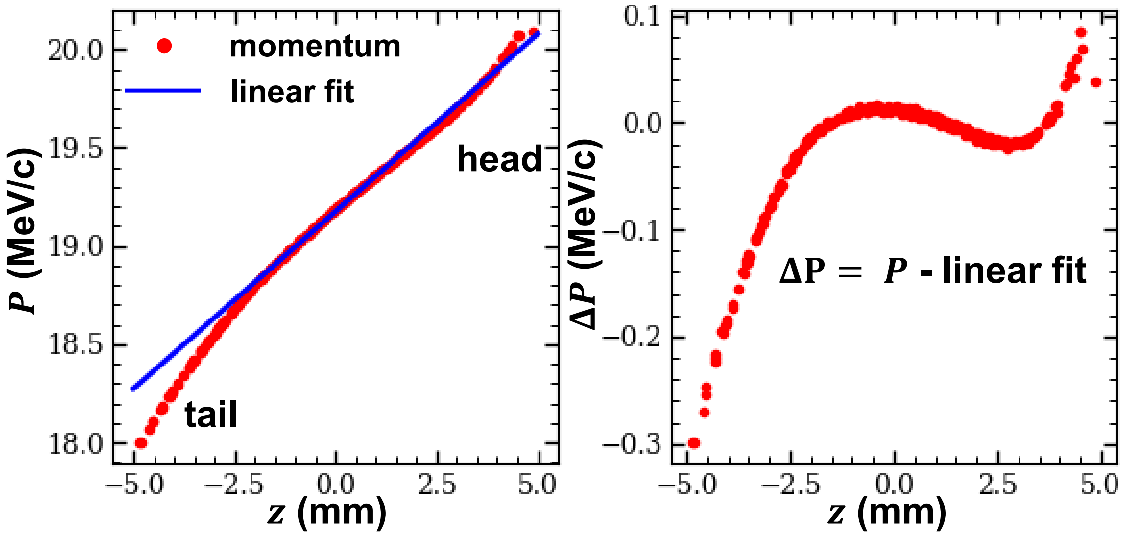


BSA 4 mm
FWHM 16 ps

Injector optimization

Gun and booster phase scan

- A linear energy chirp is preferred for bunch length manipulation later
- Definition of chirp and higher order momentum spread

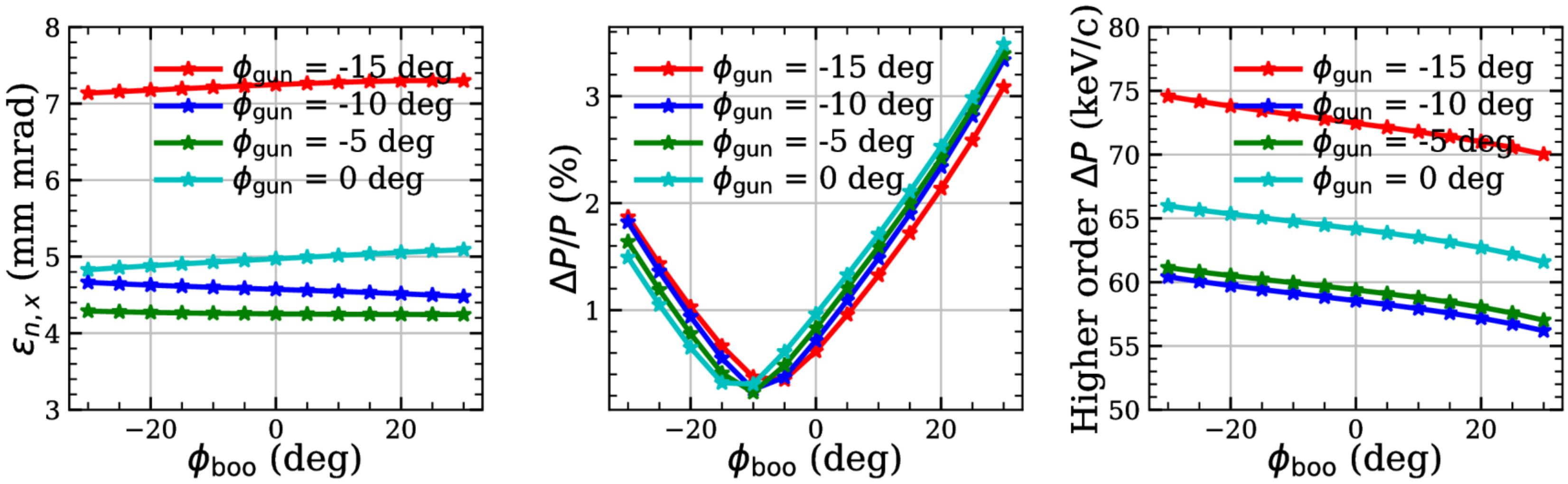


positive chirp => stretching longitudinally in the chicane

Injector optimization

Gun and booster phase scan

- A linear energy chirp is preferred for bunch length manipulation later



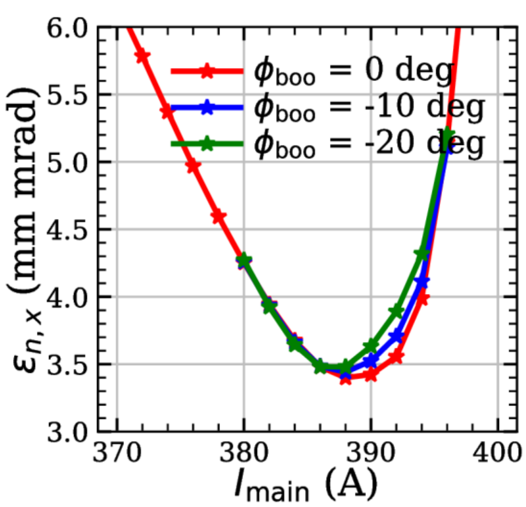
Norm. emittance **Momentum spread** **Higher order momentum spread**

- Gun phase: -5 degree => better emittance and smaller higher order energy spread;
- Booster phase: -20 (negative chirp), -10 (minimum spread), 0 (positive chirp)

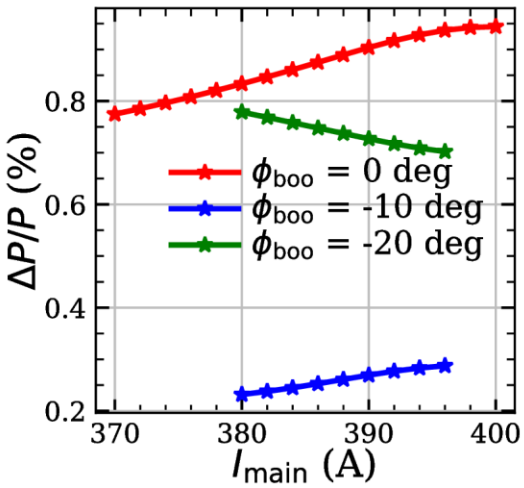
Injector optimization

Solenoid current scan

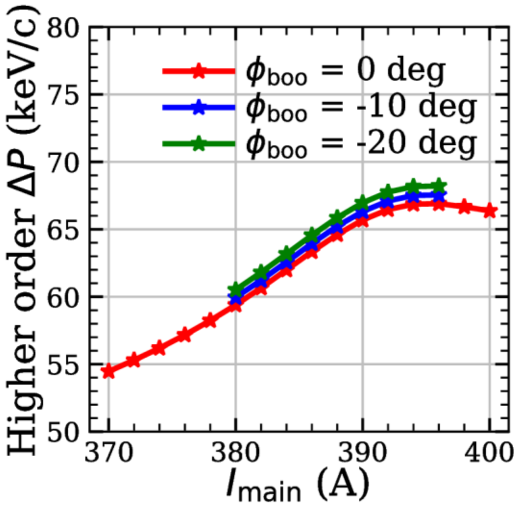
- The best solenoid current is around 388 A for all three booster phases



Norm. emittance



Momentum spread

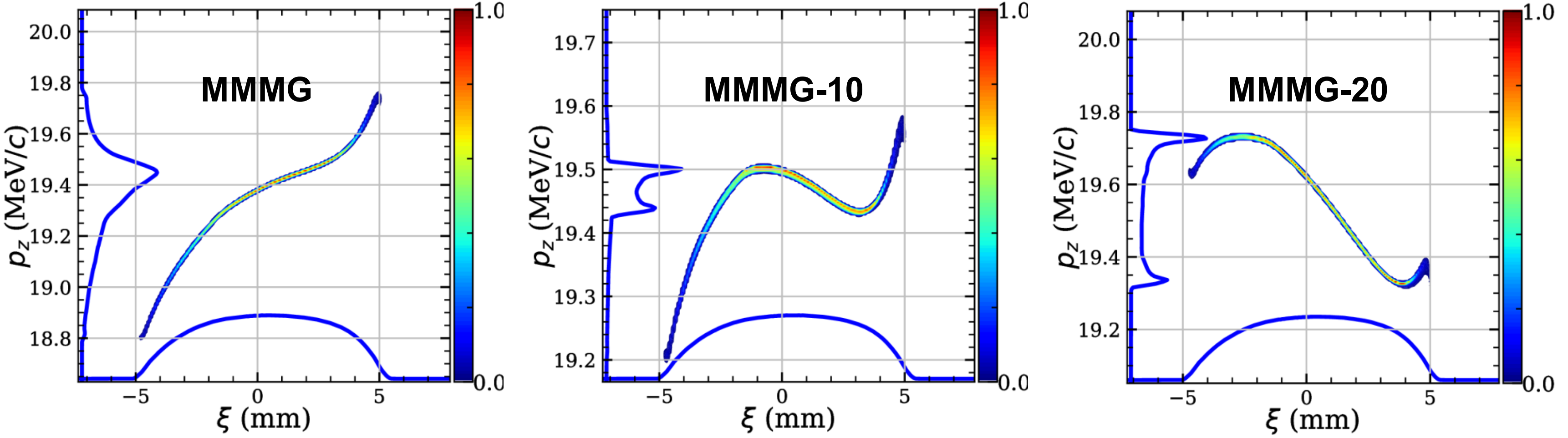


Higher order momentum spread

Injector optimization

Longitudinal phase space at the best solenoid current

- Chirp vs booster phase at EMSY1

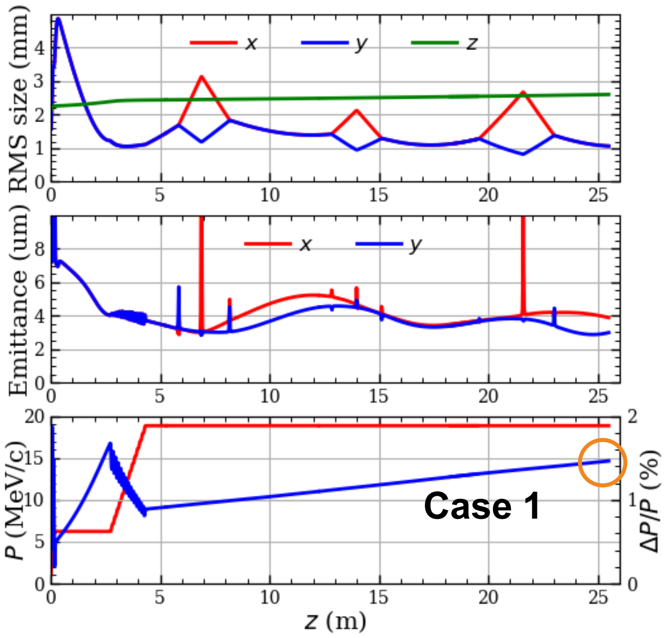


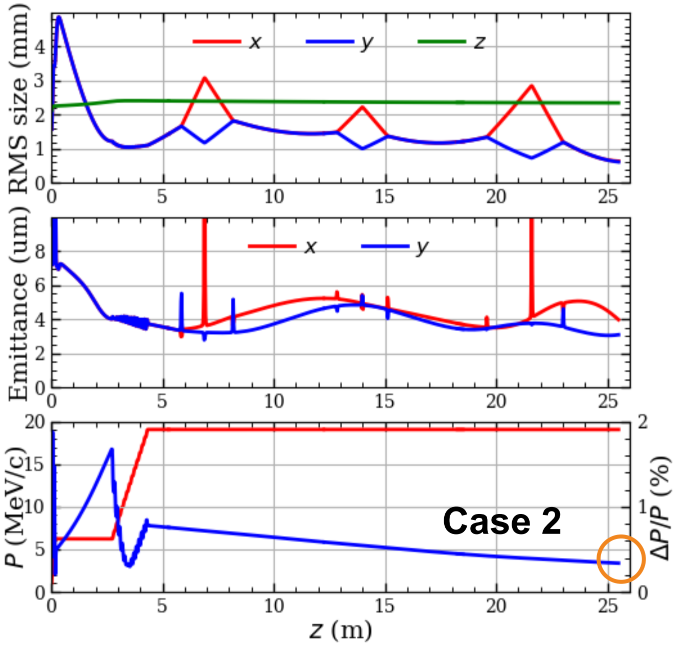
Case 1 **Case 2**

Injector optimization

Beam transport to the dogleg entrance

- Three triplets are used to focus the beam down to the dogleg entrance (z=26 m)
- The main difference is that the **momentum spread** is large (~1.5 %) at the dogleg for **Case1** but reaches the minimum (~ 0.3%) for **Case 2**

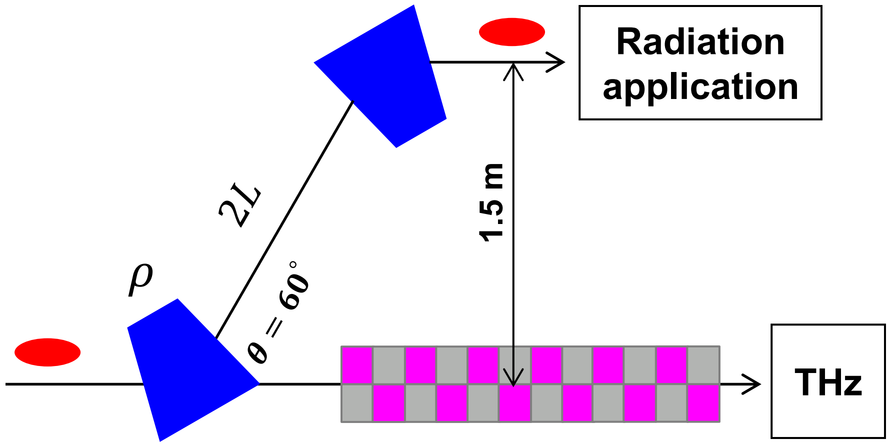




Beam transport in the dogleg (Case 1)

With only the dipoles

Parameter	Value	Unit
Angle, θ	**60**	degree
Radius, ρ	**0.4**	m
Gap	50	mm
Translation	1.5	m



$$\begin{bmatrix} x \\ x' \\ \dfrac{\delta p}{p} \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} x_0 \\ x_0{}' \\ \left(\dfrac{\delta p}{p}\right)_0 \end{bmatrix},$$

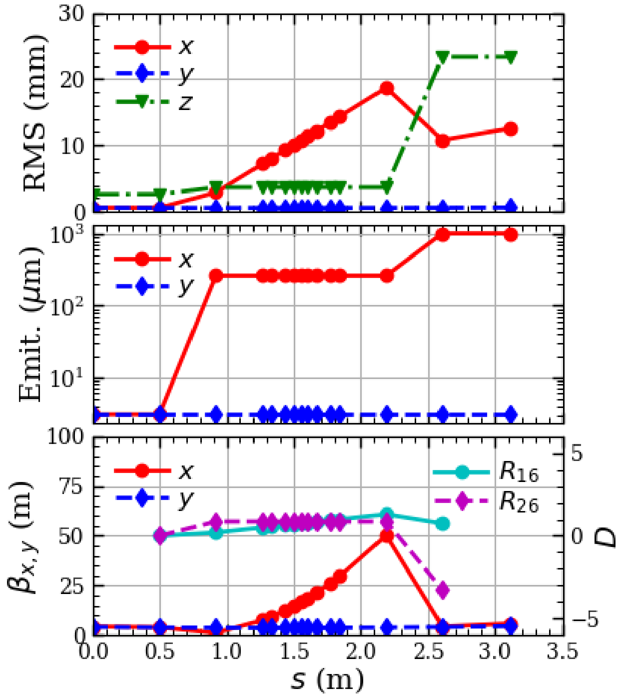
$$M_{13} = 2[L\sin\theta + \rho(1-\cos\theta)]\cos\theta \neq 0$$

$$M_{23} = \frac{2[L\sin\theta + \rho(1-\cos\theta)]\sin\theta}{\rho} \neq 0$$

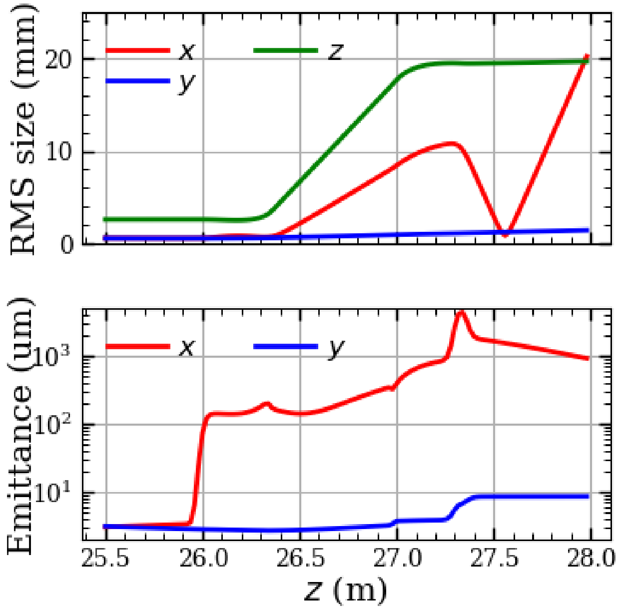
Beam transport in the dogleg (Case 1)

With only the dipoles

- The transverse beam size and emittance, the bunch length have increased



Transport with first-order transfer matrix



Cartesian CS in Astra

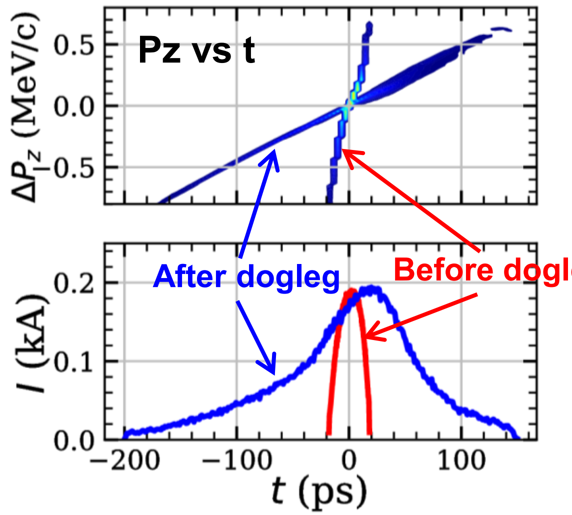
Astra simulation with SC

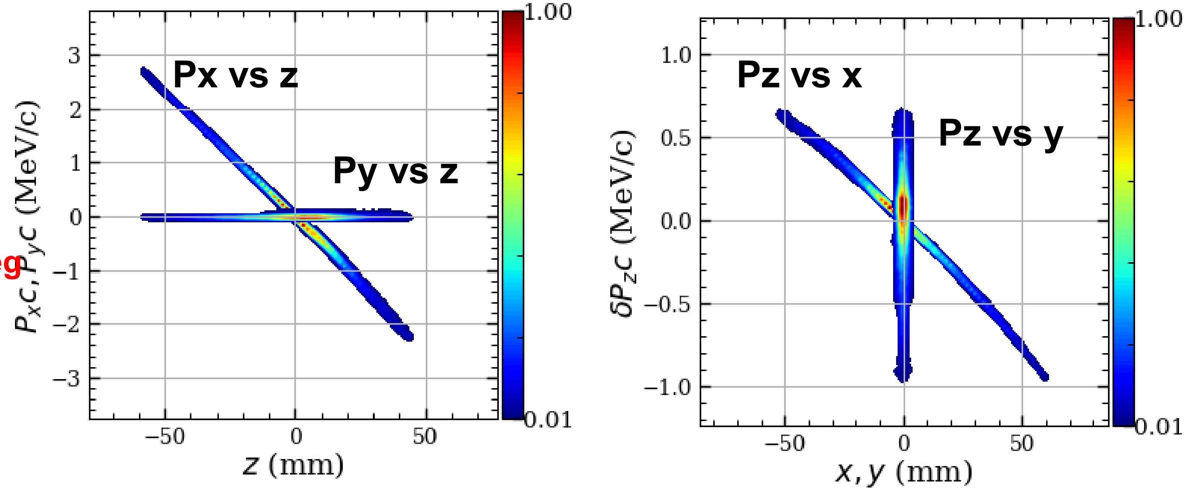
Beam transport in the dogleg (Case 1)

With only the dipoles

- The bunch is stretched after dogleg (28.5 ps -> 105 ps FWHM), but with P_x correlated along the bunch (z) and P_z correlated across the bunch (x) in the deflection plane

  => huge emittance and rapid growth of beam size





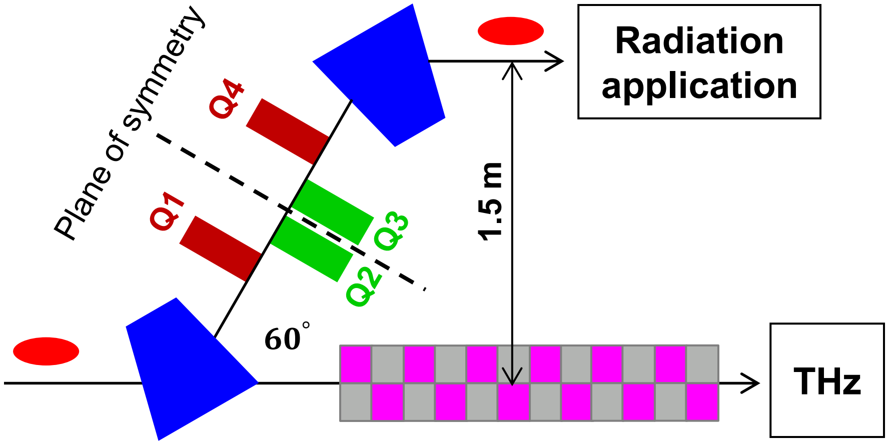
Horizontal and longitudinal correlation after dogleg

Beam transport in the dogleg (Case 1)

Insertion of quadrupoles between dipoles

- Q1 and Q4: removing the dispersion and focusing the beam horizontally
- Q2 and Q3: focusing the beam vertically

Parameter	Value	Unit
Angle	**60**	degree
Radius	**0.4**	m
Gap	50	mm
Translation	1.5	m



Beam transport in the dogleg (Case 1)

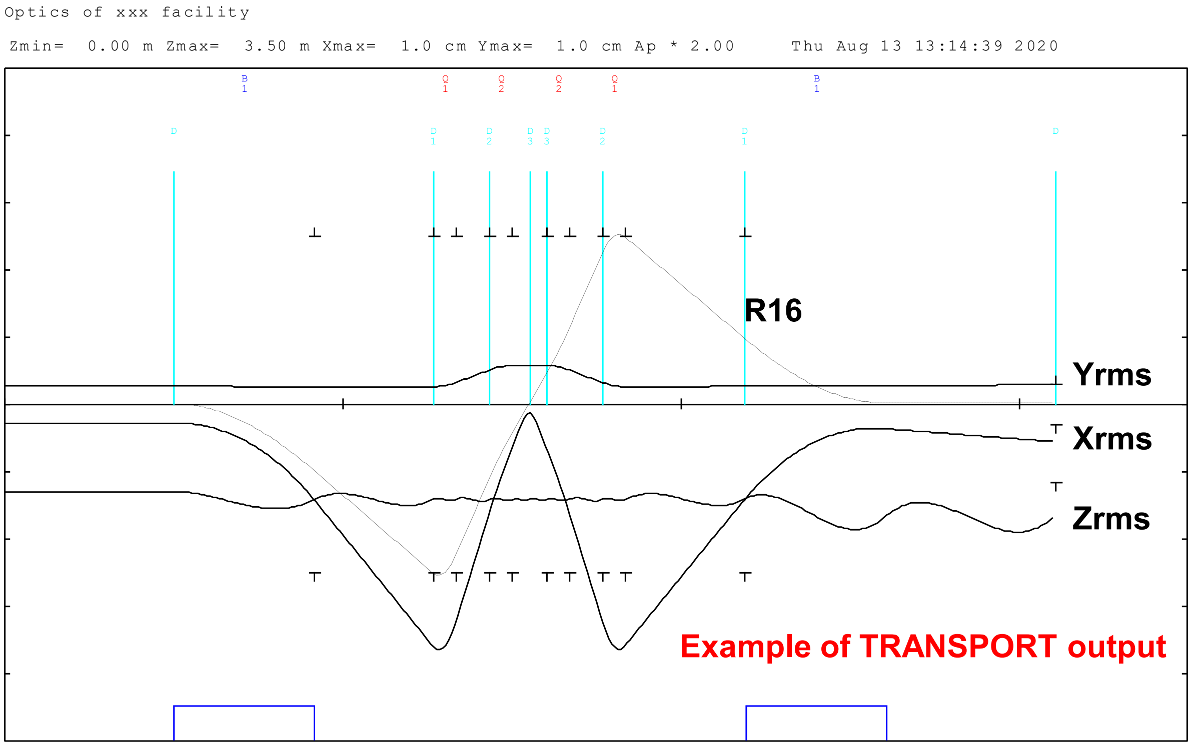
Insertion of quadrupoles between dipoles

Optimized with TRANSPORT:

Method:
Use beam matrix and transfer matrix + random search

Constraint:
Q1 = Q4, Q2 = Q3
Translation = 1.5 m

Goal:
R16 = R26 = 0 (Achromatic)
Matched beam size and emittance at the dogleg exit

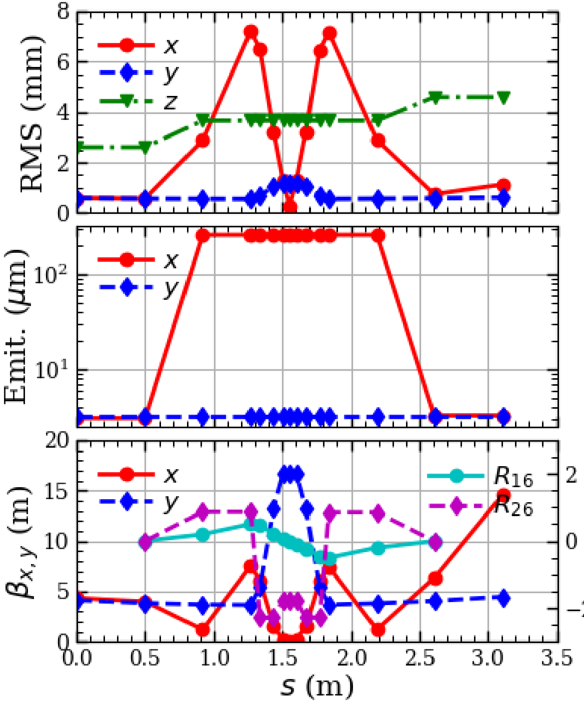


http://aea.web.psi.ch/Urs_Rohrer/MyWeb/trancomp.htm

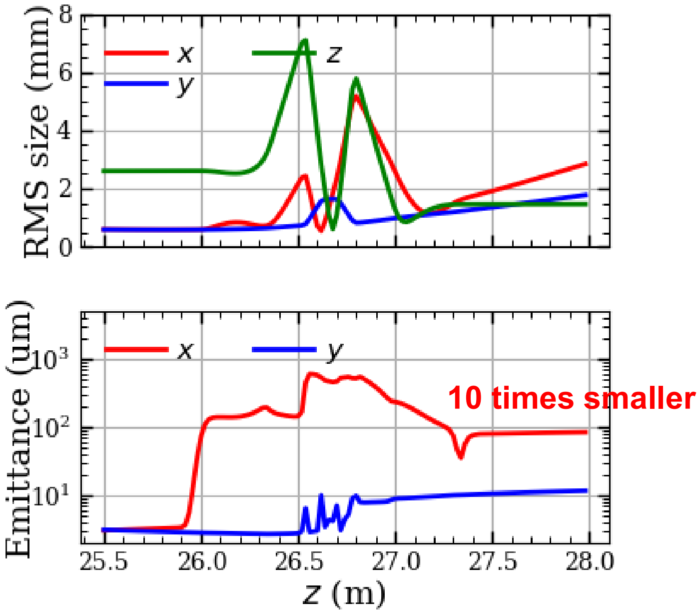
Beam transport in the dogleg (Case 1)

Insertion of quadrupoles between dipoles

- The beam sizes are maintained after the dogleg



Transport with first-order transfer matrix

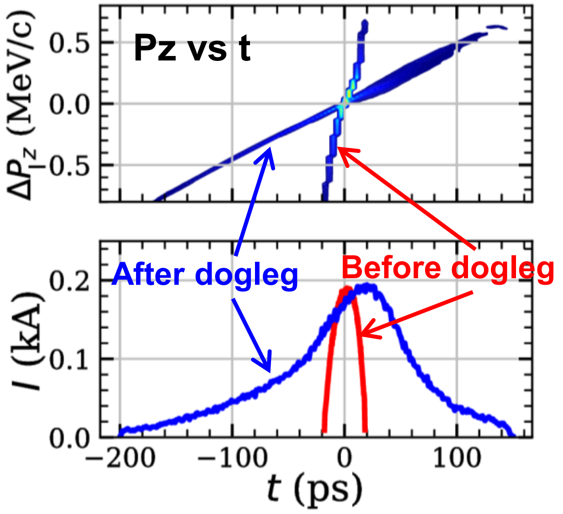


Astra simulation with SC

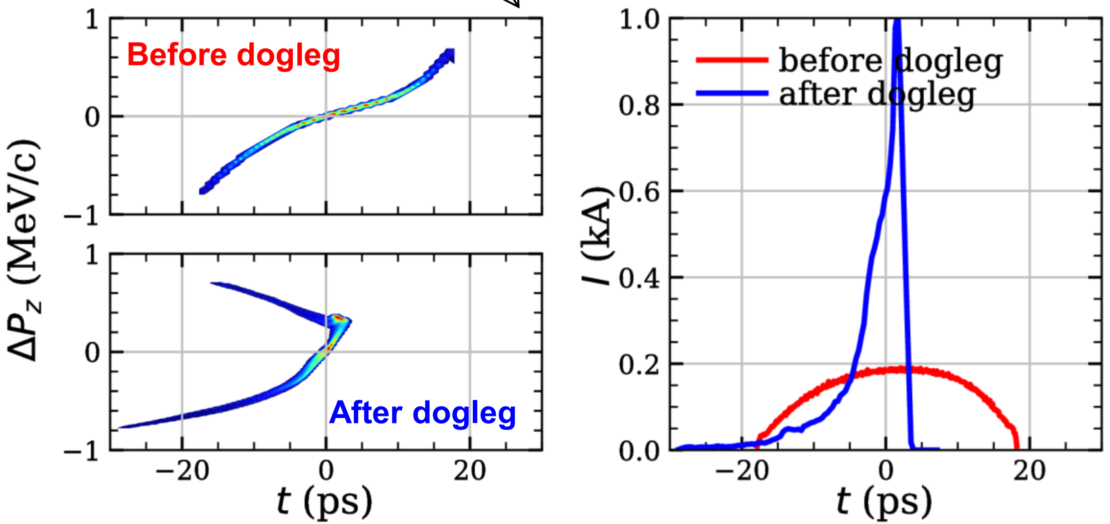
Beam transport in the dogleg (Case 1)

Insertion of quadrupoles between dipoles

- Longitudinal phase space before and after dogleg



LP with only dipoles



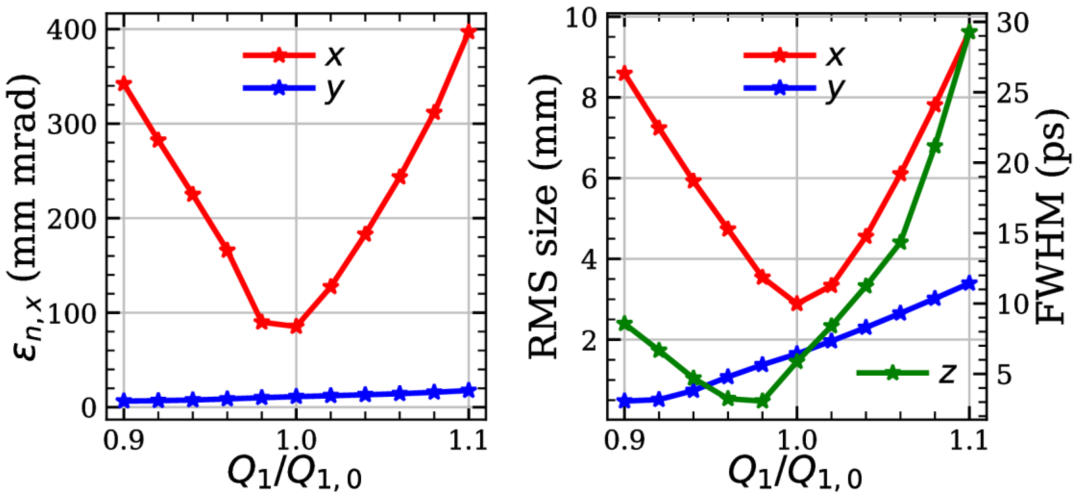
Longitudinal phase space

Bunch profile

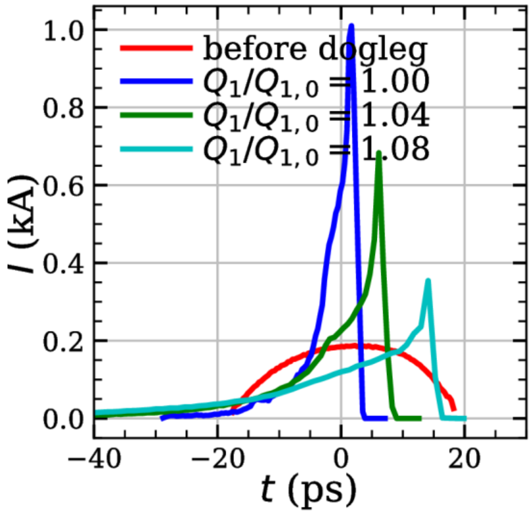
Beam transport in the dogleg (Case 1)

Insertion of quadrupoles between dipoles

- Tuning the first and last quadrupole gradients simultaneously



Beam parameters 0.7 m downstream the 2nd dipole



Long. profiles

Beam transport in the dogleg (Case 1)

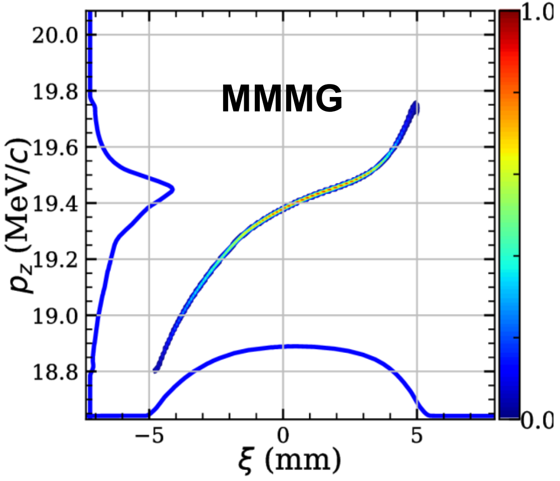
Summary

- The dispersion results in a huge emittance and a rapid growth of beam size in the horizontal (deflection) plane; meanwhile the bunch is stretched
- The dispersion can be almost removed by introducing a symmetric focusing optics; but cannot be got rid of due to the relatively large energy spread
  - The emittance is about one order of magnitude smaller
  - The bunch length can be tuned by the quad gradient only in a small range
- The optimized quadrupole gradient needs an max. excitation current of ~ 15 A
  - Derived from High1.Q5 calibration -> ~0.65 T/m/A

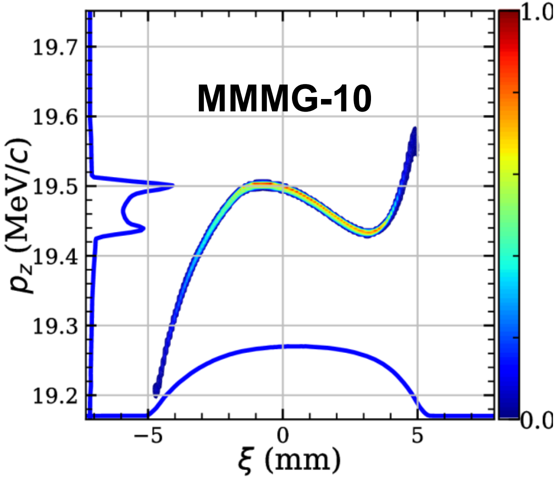
Injector optimization

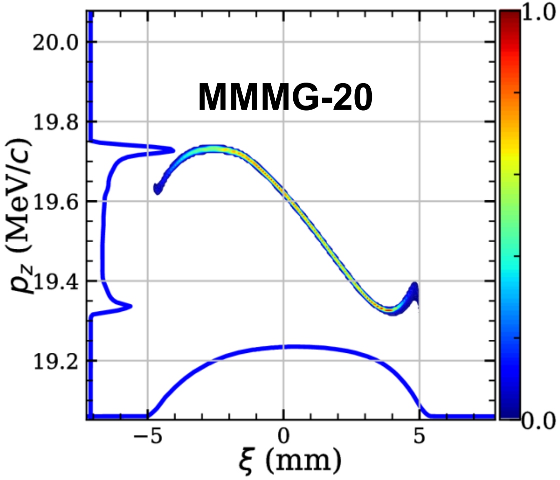
Longitudinal phase space at the best solenoid current

- Chirp vs booster phase at EMSY1



Case 1



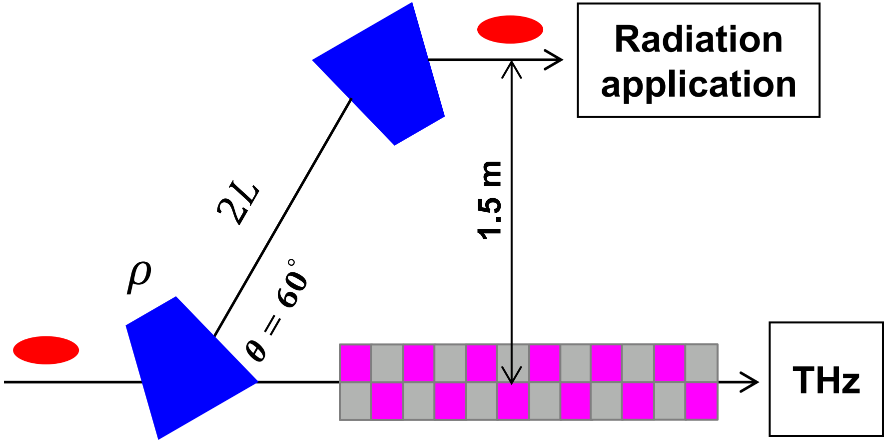


Case 2

Beam transport in the dogleg (Case 2)

With only the dipoles

Parameter	Value	Unit
Angle, θ	**60**	degree
Radius, ρ	**0.4**	m
Gap	50	mm
Translation	1.5	m



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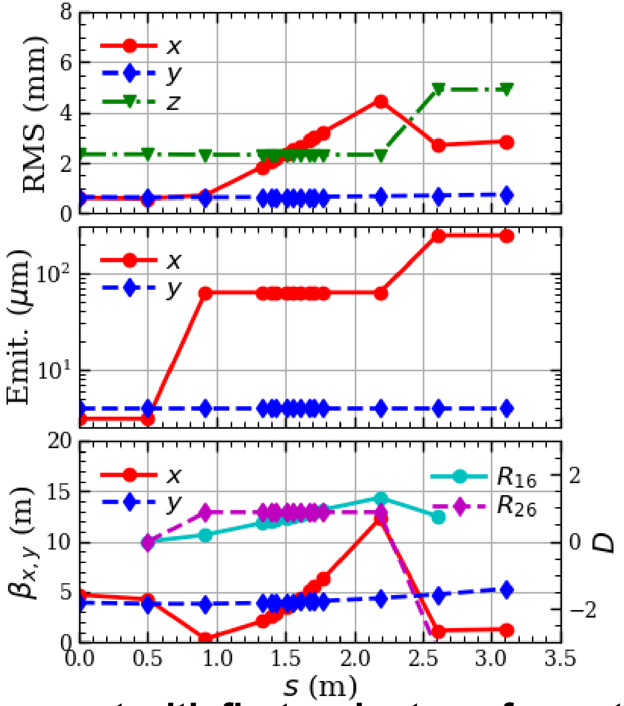
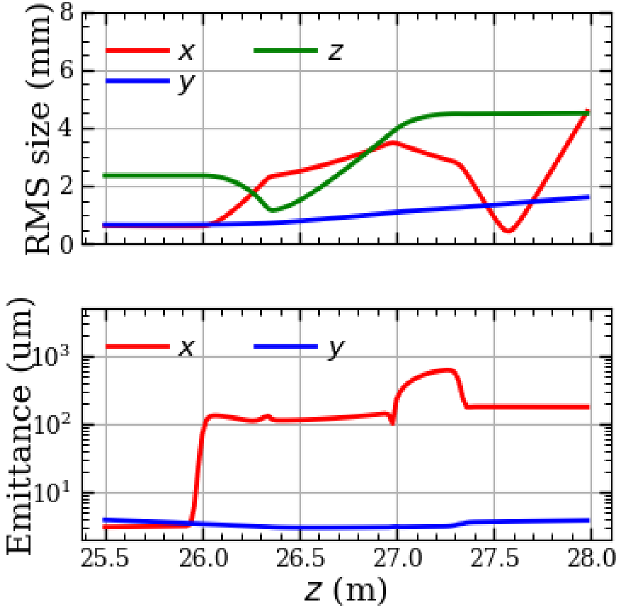
Beam transport in the dogleg (Case 2)

With only the dipoles



Transport with first-order transfer matrix



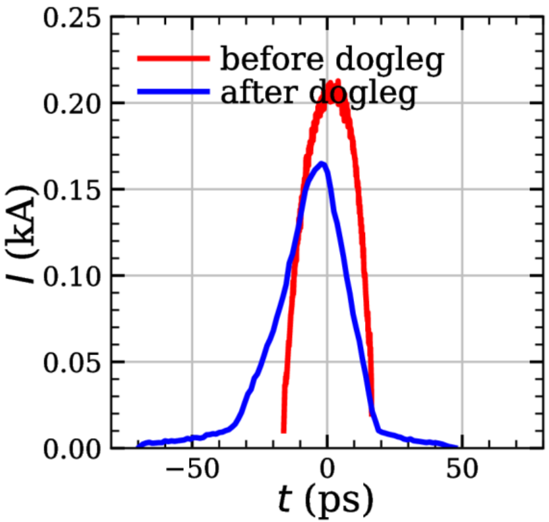
Astra simulation with SC

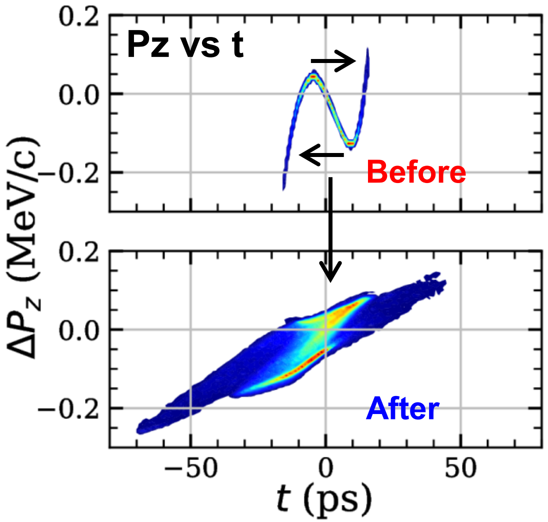
x10 smaller than Case 1

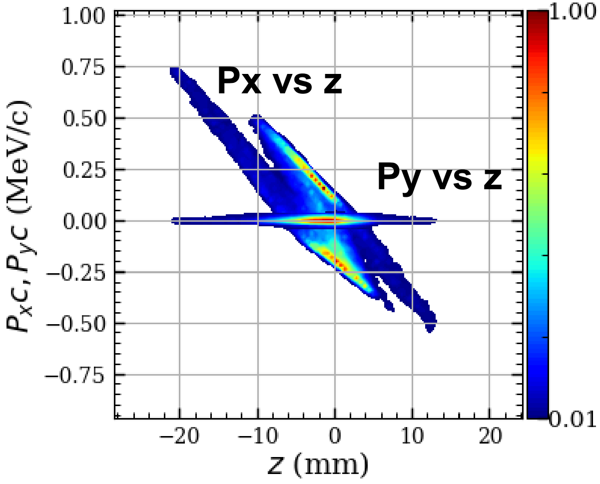
Beam transport in the dogleg (Case 2)

With only the dipoles

- The bunch is over-compressed in the dogleg; the divergence is big in the deflection plane, resulting in big emittance and rapid growth of beam size







x-z correlation after dogleg

Beam transport in the dogleg (Case 2)

Insertion of quadrupoles between dipoles

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Parameter	Value	Unit
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Gap	50	mm
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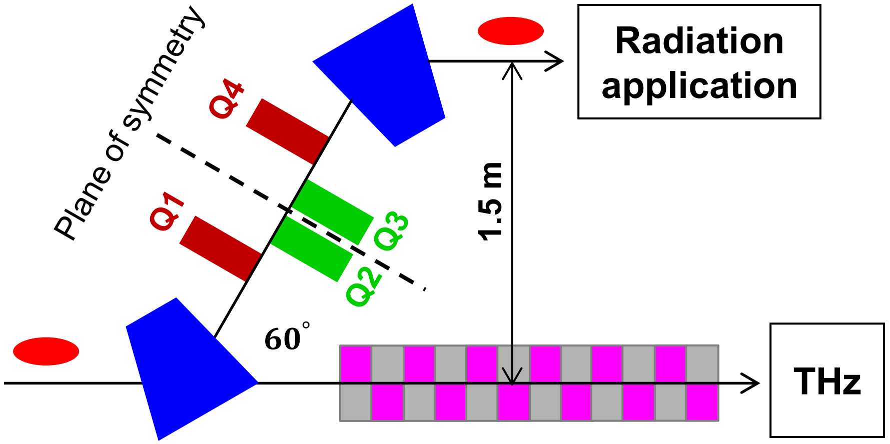


Beam transport in the dogleg (Case 2)

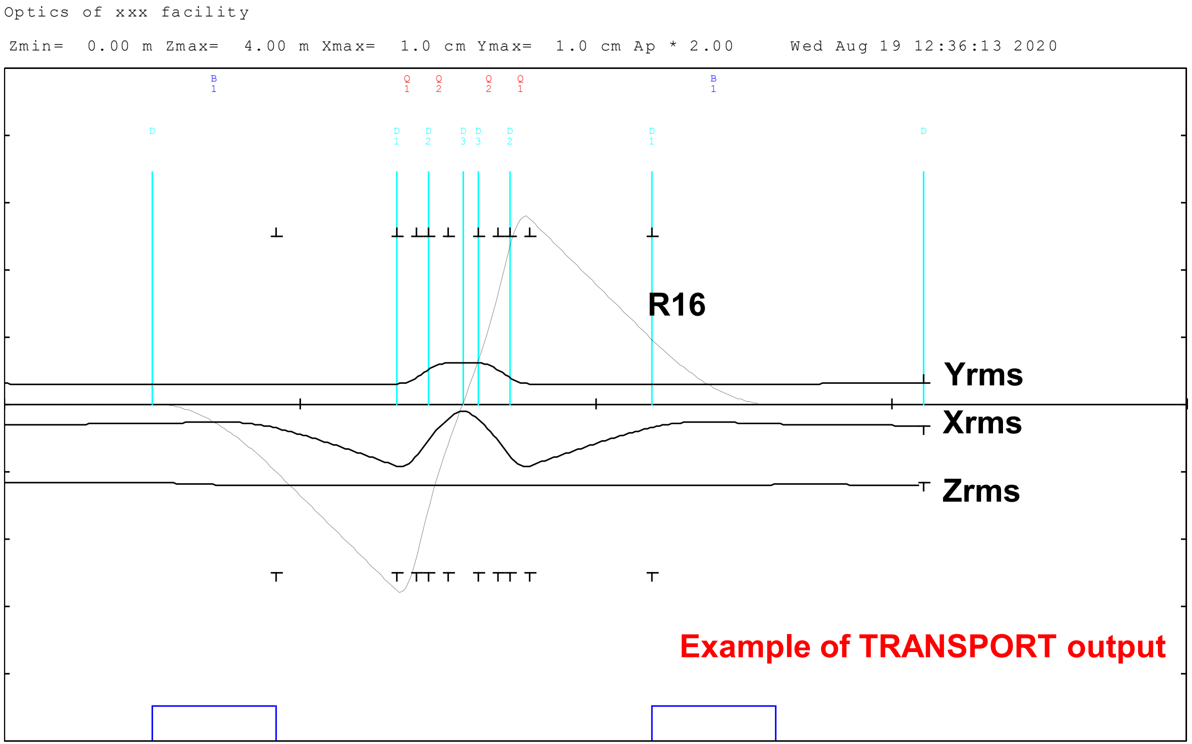
Insertion of quadrupoles between dipoles

Optimized with TRANSPORT:

Method:
Use beam matrix and transfer matrix + random search

Constraint:
Q1 = Q4, Q2 = Q3
Translation = 1.5 m

Goal:
R16 = R26 = 0 (Achromatic)
Matched beam size and emittance at the dogleg exit



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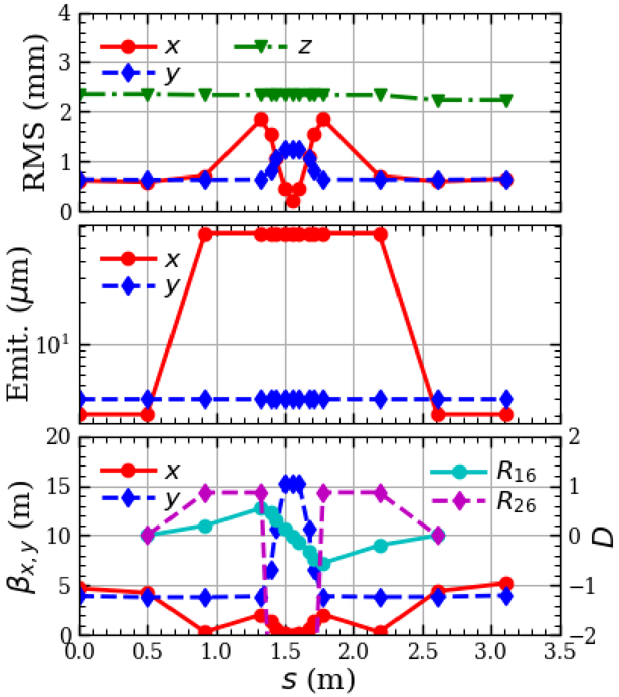
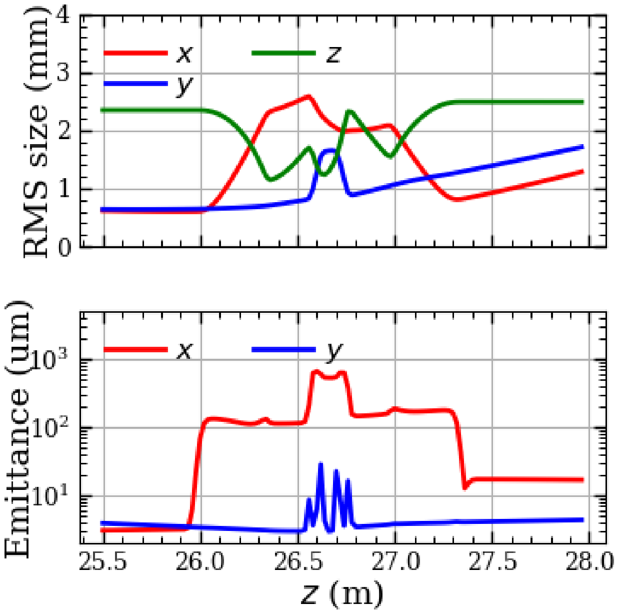
Beam transport in the dogleg (Case 2)

Insertion of quadrupoles between dipoles

- The beam sizes and emittances are maintained after the dogleg



Transport with first-order transfer matrix

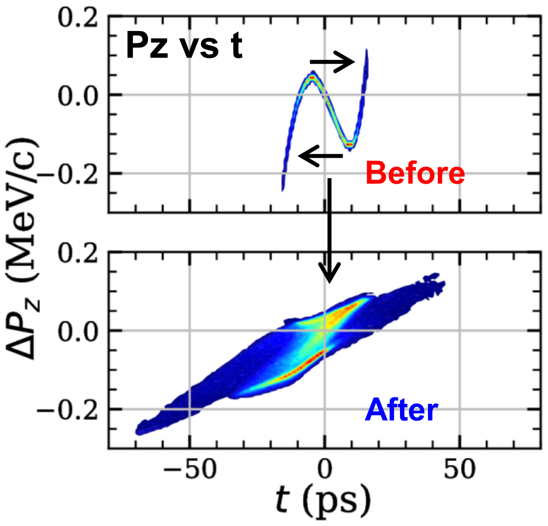


Astra simulation with SC

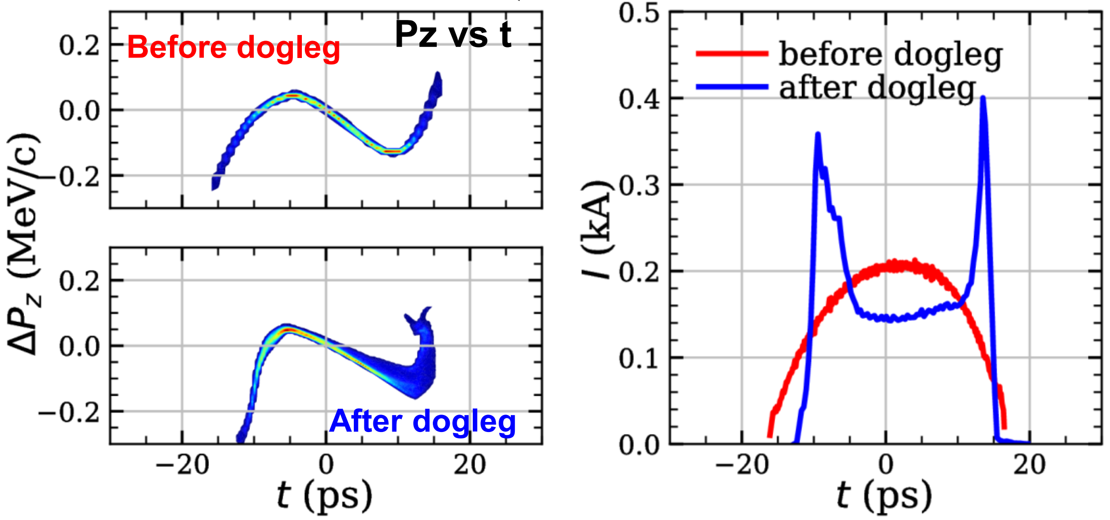
Beam transport in the dogleg (Case 2)

Insertion of quadrupoles between dipoles

- Longitudinal phase space before and after dogleg



LP with only dipoles



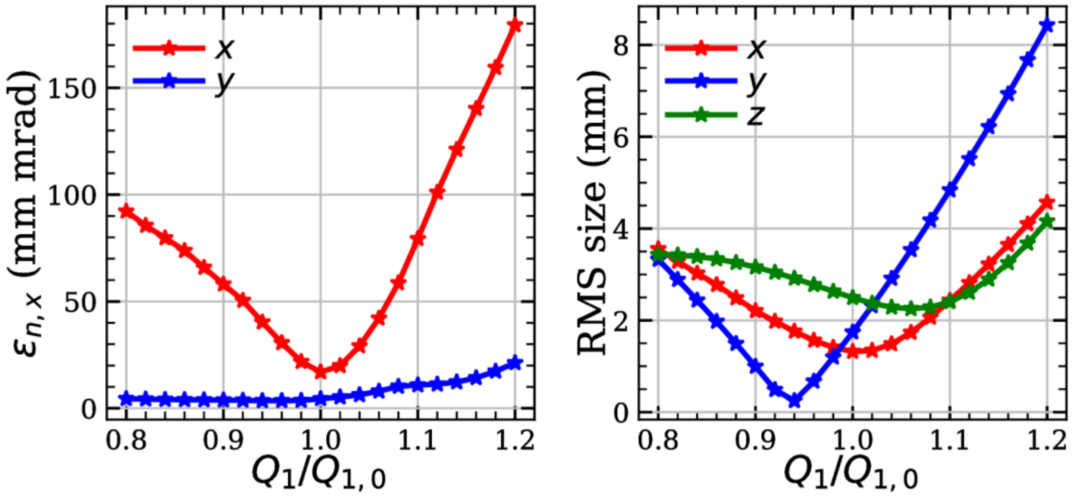
Longitudinal phase space

Bunch profile

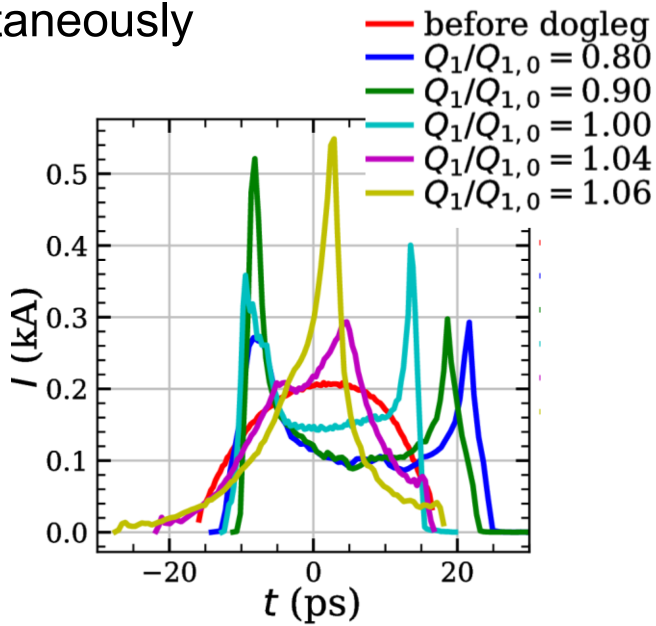
Beam transport in the dogleg (Case 2)

Insertion of quadrupoles between dipoles

- Tuning the first and last quadrupole gradients simultaneously



Beam parameters 0.7 m downstream the 2nd dipole



Long. profile

The shape is held up to $Q_1/Q_{1,0} = 1.02$

Beam transport in the dogleg (Case 2)

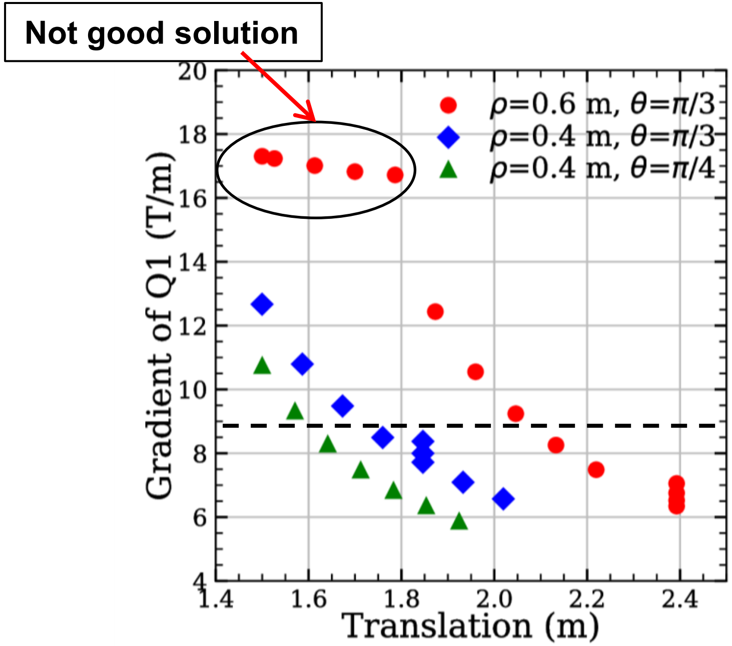
Summary

- The dispersion also results in a big emittance and a growth of beam size in the horizontal (deflection) plane; meanwhile the bunch is over-compressed
  - The emittance is x10 smaller than that for Case 1, thanks to smaller energy spread
- The dispersion can be removed by introducing a symmetric focusing optics
  - The emittance is only 10-20 um, x5 smaller than Case 1
  - The bunch length can be tuned by the quad gradient also in a small range
- The optimized quadrupole gradient needs an max. excitation current of ~ 19.5 A
  - Derived from High1.Q5 calibration -> ~0.65 T/m/A

Discussion

Limit of quadrupole gradient

- With TRANSPORT, the gradients of the quadrupoles have been optimized against the drift length between dipoles (or translation), the bending radius and angle

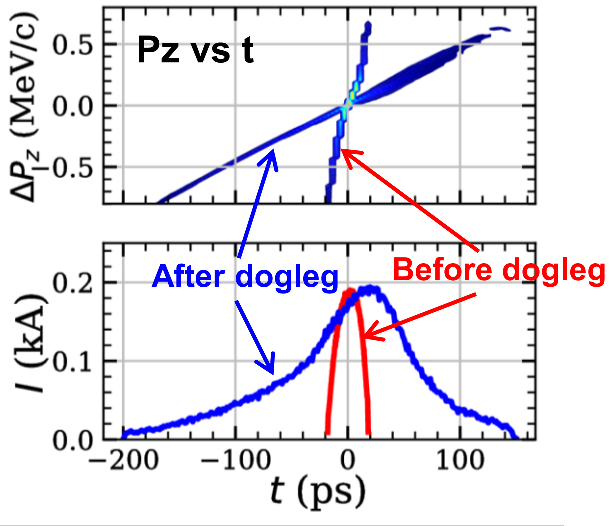


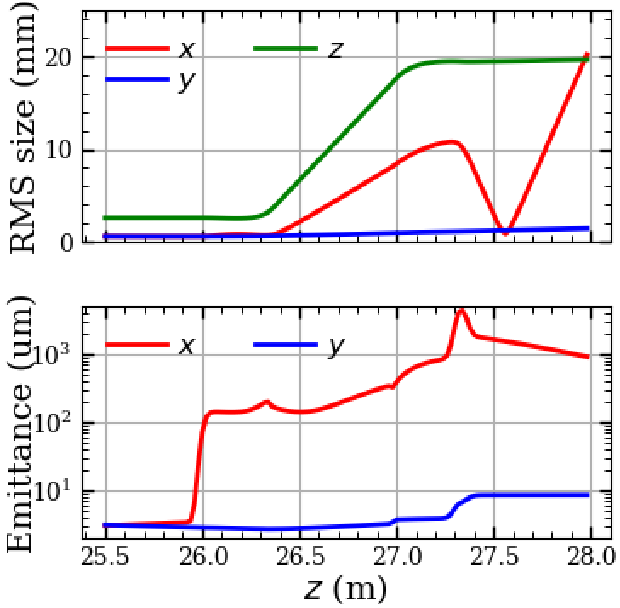
Dashed lines correspond to the gradient from an excitation current of 12 A

Discussion

If the transverse beam emittance and size are not important

- Then prepare the radiation experiment right after the 2nd dipole (or after two quads with a short drift length); only two dipoles are necessary with the bunch length controlled by the booster phase but with <u>bad control transversely</u>





Maximize R56 while minimizing R16 and R26 against bending angle and radius and the translation

Summary

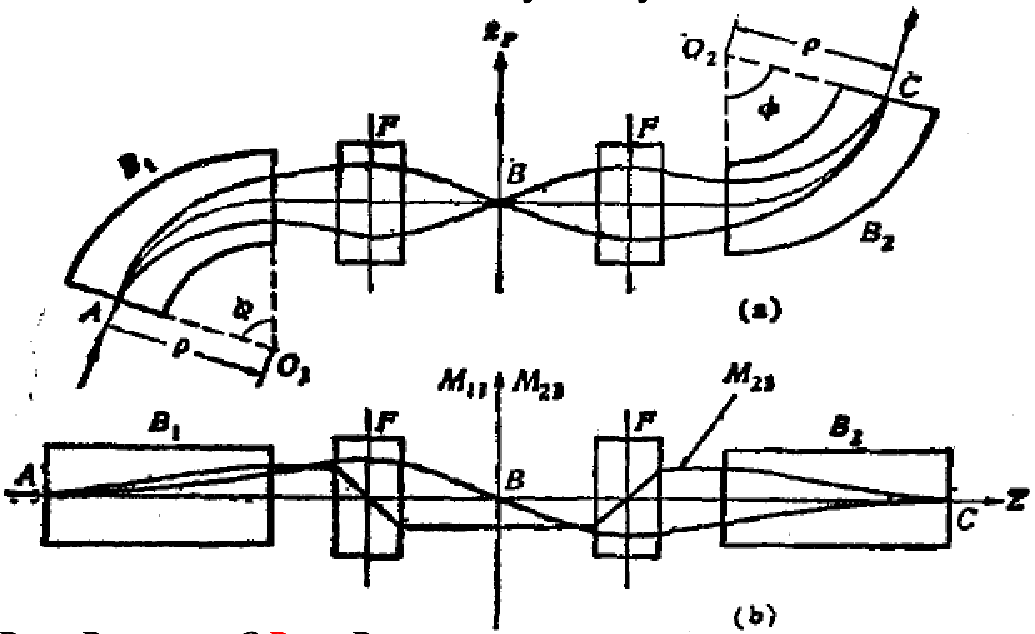
- Start-to-end simulations have been carried out in the context of radiation application at PITZ with the specified heavy charge of 5 nC
- Attention was paid on the beam transport in the dogleg for two types of electron bunches (positive and negative energy chirps)
  - For a dispersive dogleg with just two dipoles, the bunch length can be well controlled by tuning the booster phase thus the chirp, but with a poor beam quality in the deflection plane
  - For an achromatic dogleg, the bunch length can be only tuned in a small range, but the beam quality can be maintained in the deflection plane, especially when the energy spread is small
- For further simulations, more specifications on the beam quality and more space for the dogleg would be helpful

Backup

Backup

Achromatic condition

Plane of symmetry



$$D_x(A \to B) = \begin{pmatrix} D_{x11} & D_{x12} & D_{x13} \\ D_{x21} & D_{x22} & D_{x23} \\ 0 & 0 & 1 \end{pmatrix}$$

$$M_x(A \to C) = \begin{pmatrix} 1 + 2D_{x12}D_{x21} & 2D_{x12}D_{x22} & 2D_{x13}D_{x22} \\ 2D_{x11}D_{x21} & 1 + 2D_{x12}D_{x21} & 2D_{x13}D_{x21} \\ 0 & 0 & 1 \end{pmatrix}$$

$$M_{x13} = M_{x23} = 0 \Rightarrow \boldsymbol{D_{x13} = 0}$$

Achromatic!