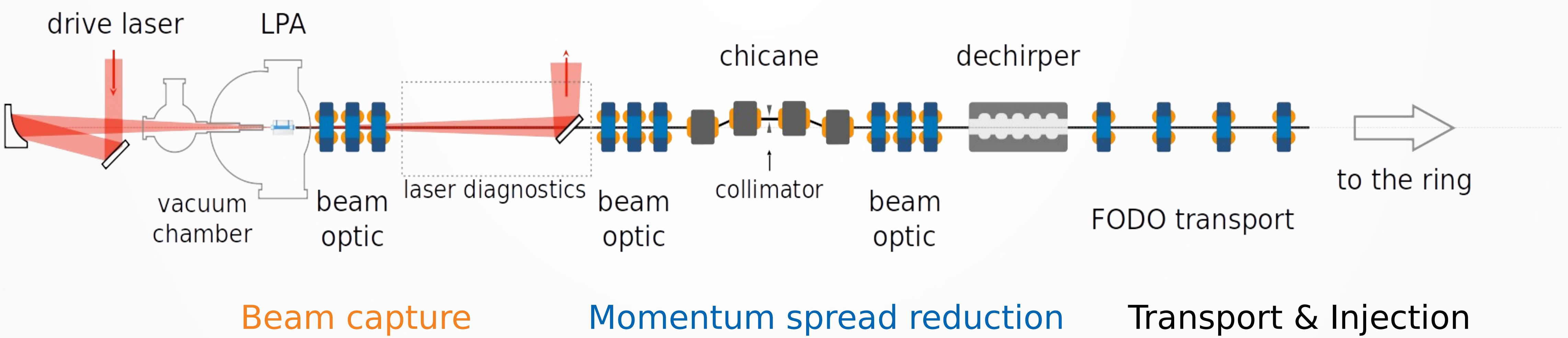
Simulations and considerations for the beamline design

Sergey Antipov **PIP4 Roadmap Meeting** **08.12.20**

Many thanks **I. Agapov, R. Brinkmann, A. Ferran Pousa,**
A. Martinez de la Ossa, M. Thevenet;
F. Lemery, M. Koerfer, A. Maier, F. Mayet, S. Tomin,
P. Winkler, I. Zagarodnov;
S. Antipov (EuclidLabs), S. Baturin (NIU), R. Bruce (CERN)

Focus on a 500 MeV prototype beamline scalable to 6 GeV



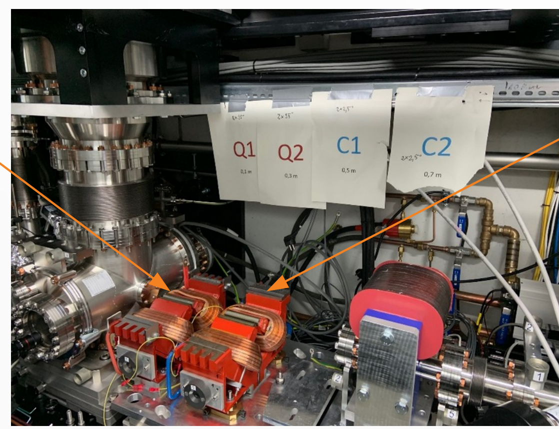
Simulated beam parameters

Energy	**6 GeV**	**500 MeV**
Bunch charge	100 pC	100 pC
Norm. rms emit: x, y	6.5, 2.2 mm-mrad	5.0, 1.7 mm-mrad
Momentum spread, rms	1%	2%
Bunch length, rms	3.2 μm	0.5 μm
Hor. Twiss (α,β,γ)	0.049, 17.6 mm, 0.057 mm^{-1}	-0.74, 8.4 mm, 0.18 mm^{-1}
Vert. Twiss (α,β,γ)	-0.006, 18.3 mm, 0.055 mm^{-1}	-0.27, 3.5 mm, 0.31 mm^{-1}

Beam capture is feasible with conventional EM quadrupoles

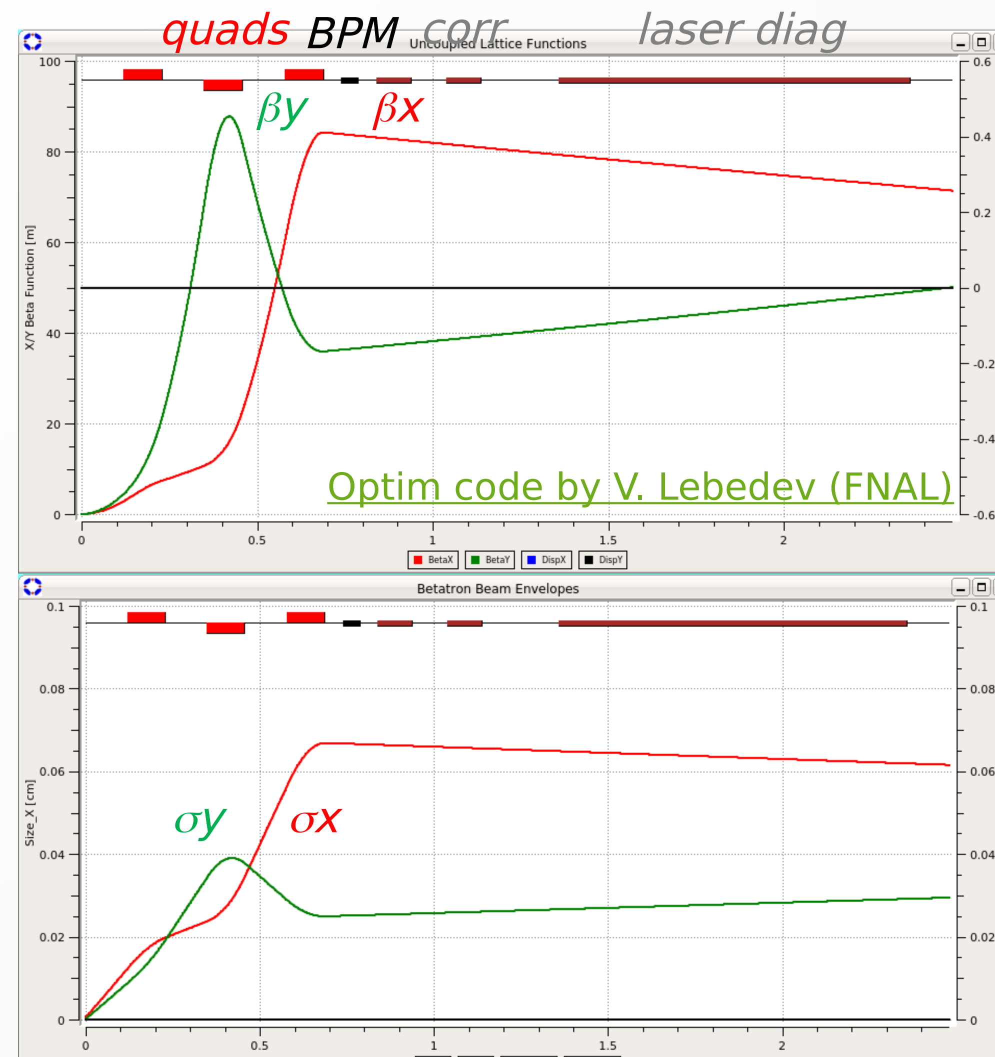
- Permanent and EM quads considered
- Old LUX doublet – capture up to 450 MeV

$G = 90$ T/m
$l_{eff} = 11$ cm
gap = 22 mm



$G = 150$ T/m
$l_{eff} = 11$ cm
gap = 12 mm

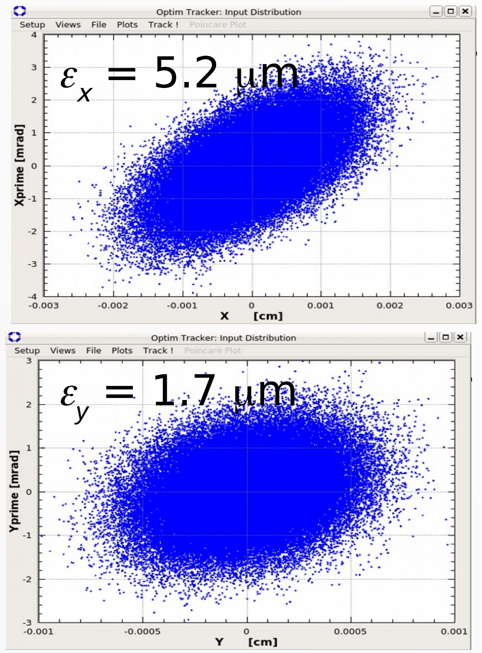
- Propose EQM triplet:
  - $G < 80$ T/m, $l_{eff} = 11$ cm, gap = 22 mm
  - Max $\sigma < 1$ mm
  - Max $\beta < 100$ m



SC is small at 500 MeV: $\delta Q_{SC}/L \sim 0.02$/m

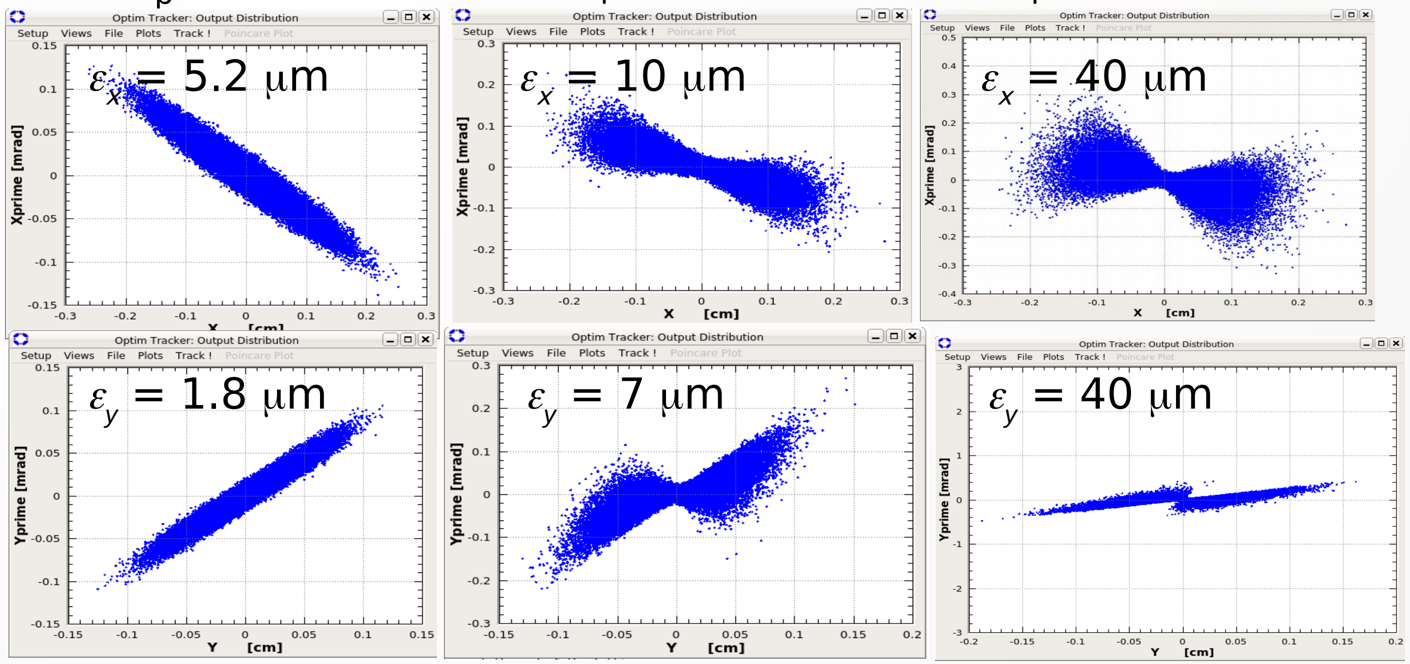
Limiting chromatic emittance blow-up: σ_p within 1%, divergence below 100 mrad

Initial



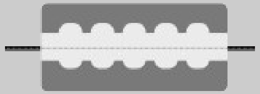
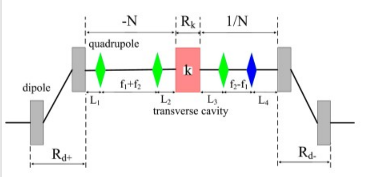
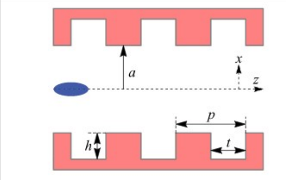
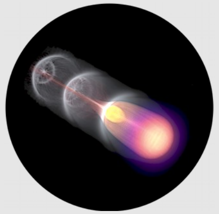
After the capture triplet

$\sigma_p = 10^{-3}$ | $\sigma_p = 10^{-2}$ | $\sigma_p = 2.6 \times 10^{-2}$

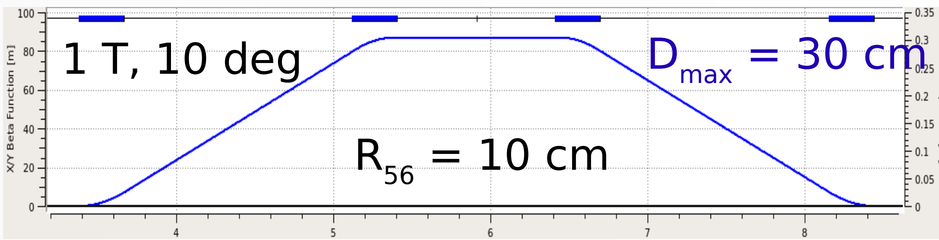


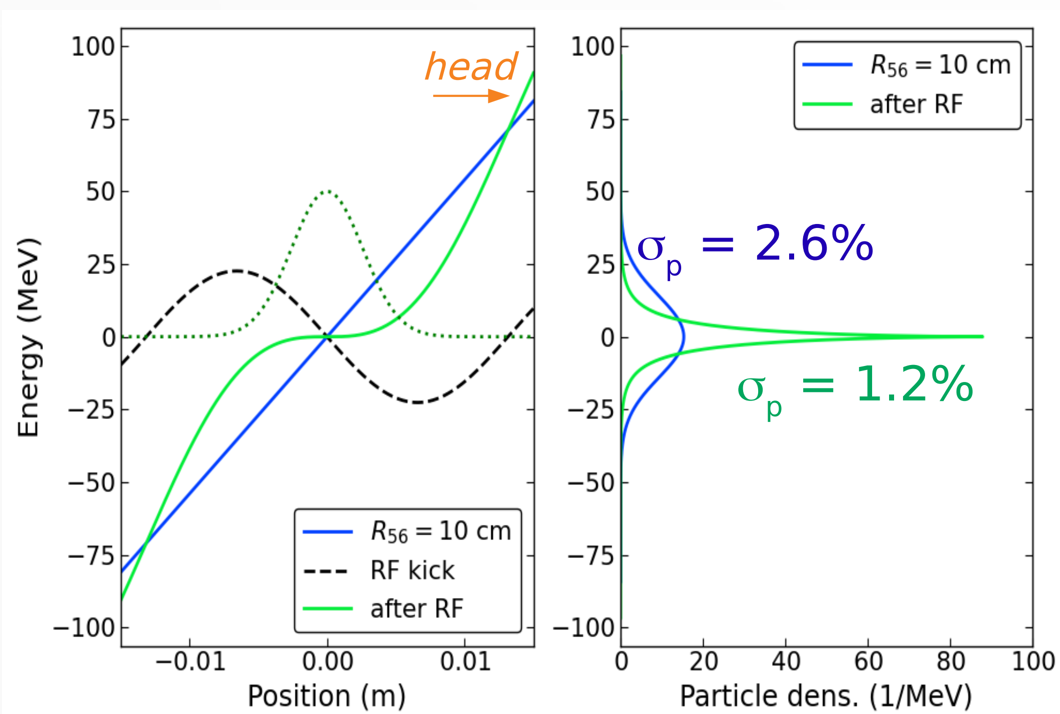
Particle tracking in Optim (10^5 macropart)

Reducing energy spread

	Method	Pros	Cons
Active	X-Band RF 	Readily available Spread + jitter compensation	Power consumption
Active	Emittance exchange 	Lower power consumption	Require a special chicane Marginal gain
Passive	Diel/Corrug dechirper 	No extra power	Require a special chicane
Passive	Plasma dechirper 	No extra power Minimum space	Require a special chicane Require tight re-focusing Head-tail betatron phase adv

0.1% rms momentum spread can be reached with an X-Band RF dechirper





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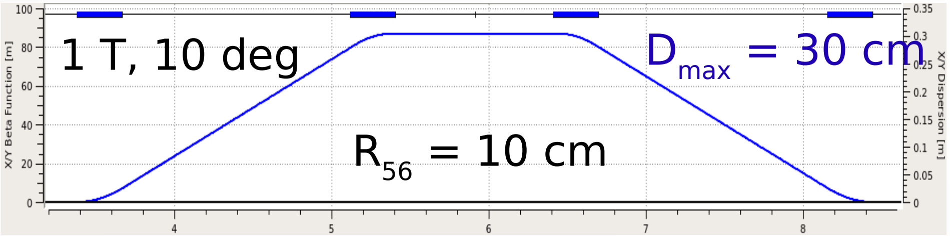
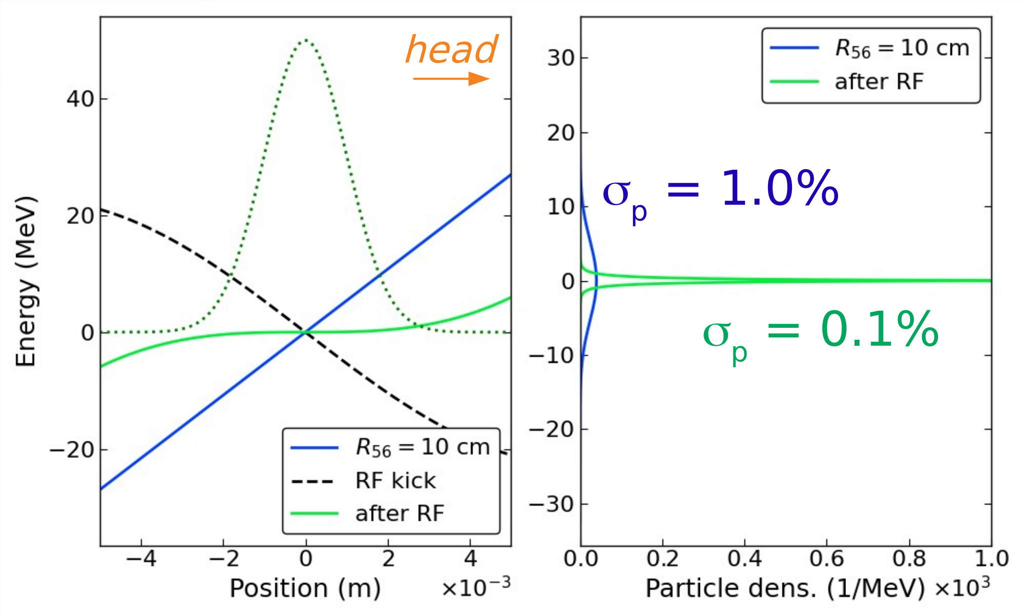
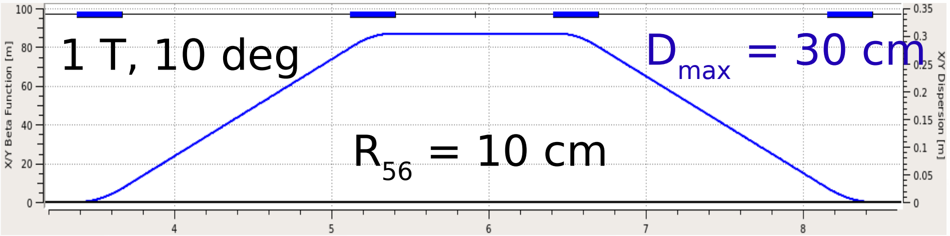
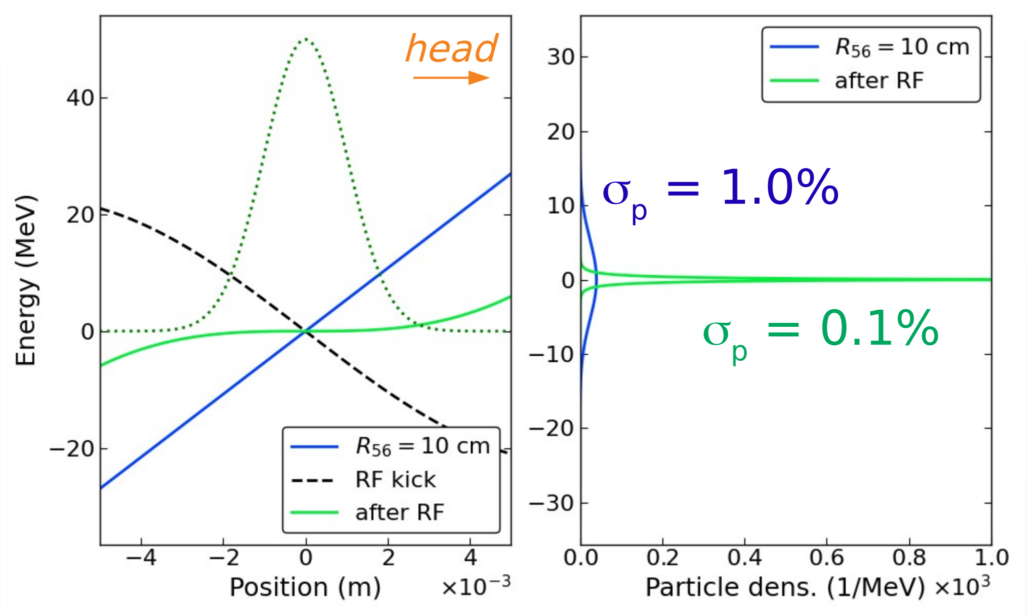




0.1% rms momentum spread can be reached with an X-Band RF dechirper

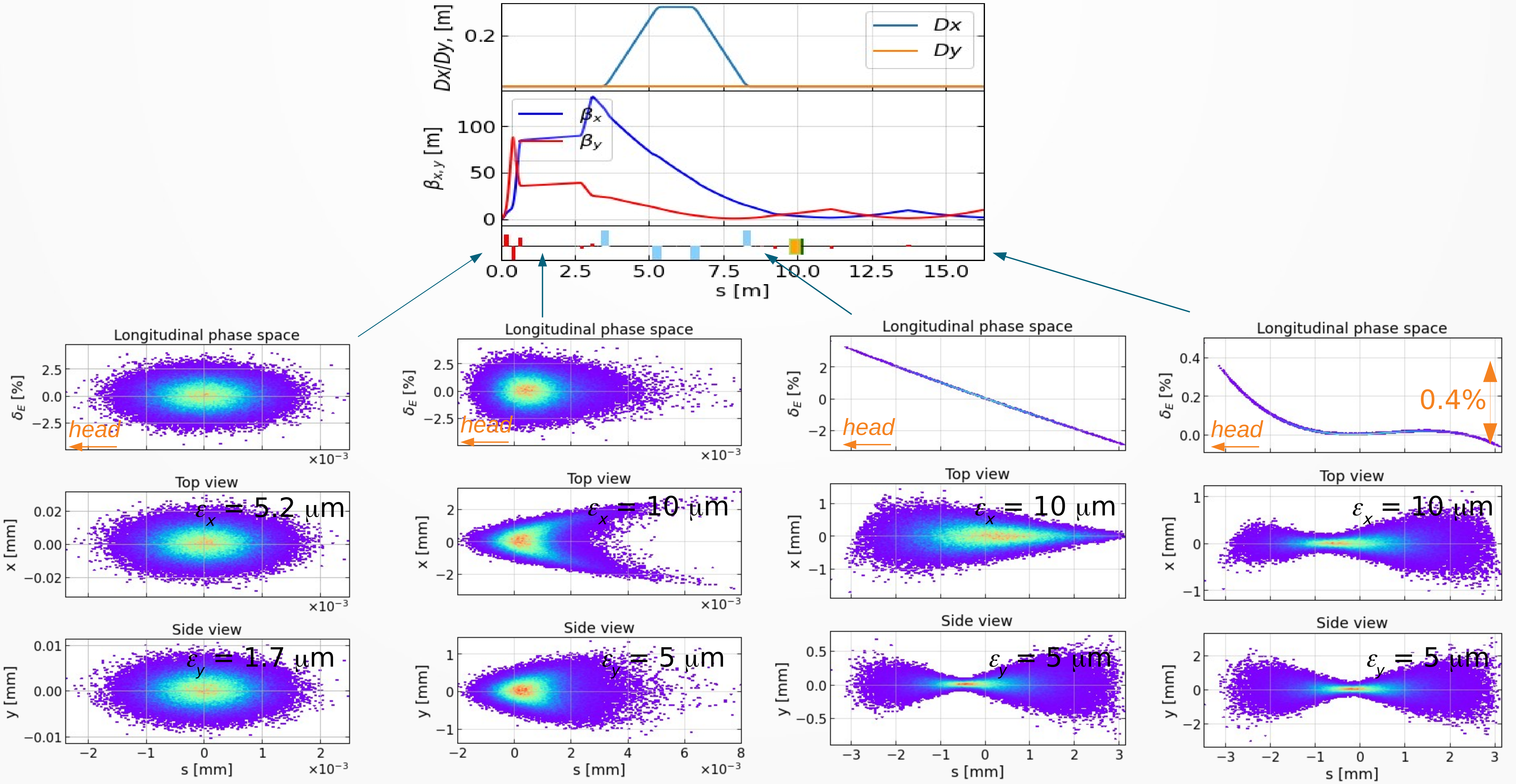


σ_p	R_{56}	V_{RF}	L (60 MV/m)
1.0%	10 cm	22 MV	37 cm
2.6%	3 cm	73 MV	1.2 m

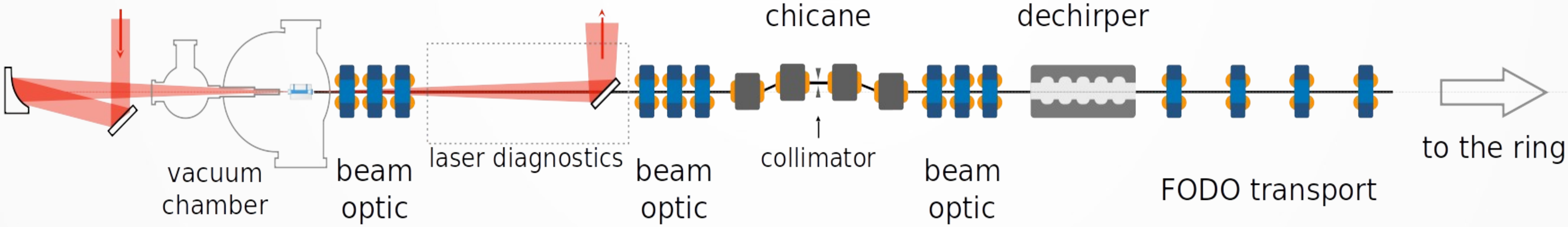


- The chicane can be used for momentum cleaning
  - Cleaning threshold = 3%
  - Half-gap = 9 mm

Tracking simulation: 500 MeV



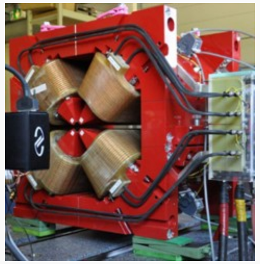
Scaling 500 MeV → 6 GeV



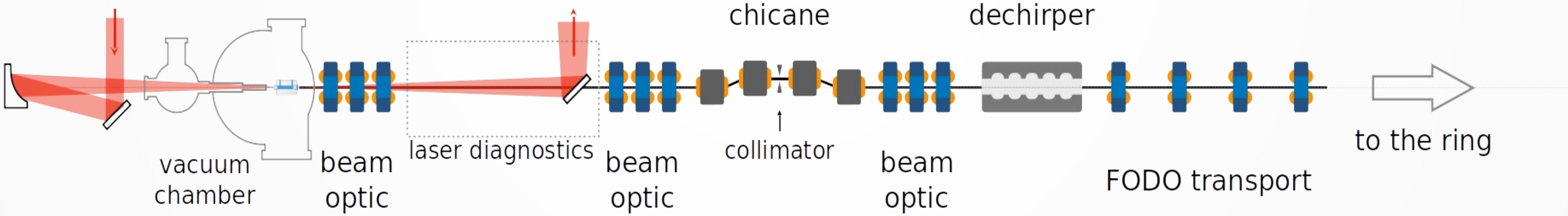
Beam capture

- ✔ Possible with conventional quads
- ✔ Chromatic emittance increase limited for $\sigma_p < 1\%$, div. < 0.2 mrad

ESRF-EBS Quad:
G = 100 T/m
r_0 = 12.5 m
L = 50 cm



Scaling 500 MeV → 6 GeV



Beam capture

- ✔ Possible with conventional quads
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Momentum spread reduction

- ✔ 300 MeV of X-Band RF voltage, 5% of the total beam energy

  Active length: about 5 m
  Cost estimate: 10M euro

- ◆ CSR could be an issue:
  W' ~ 3 MV/m in the first dipole for a 200 pC bunch

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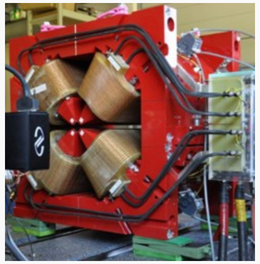
L = 50 cm



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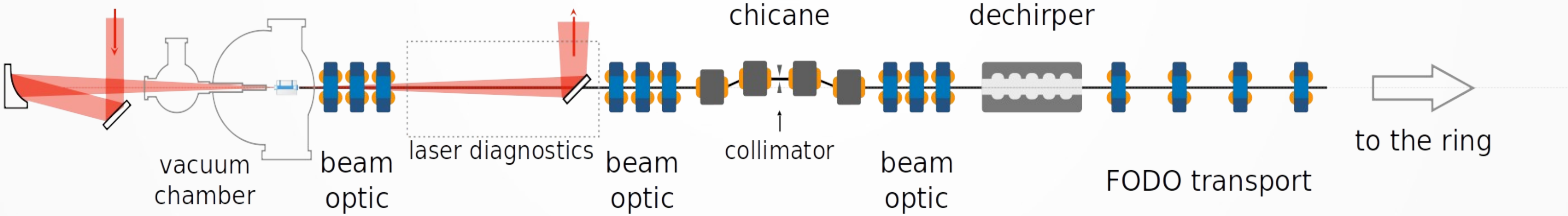

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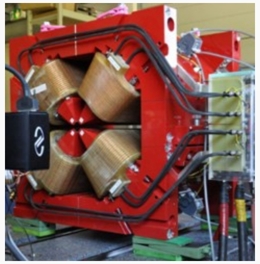

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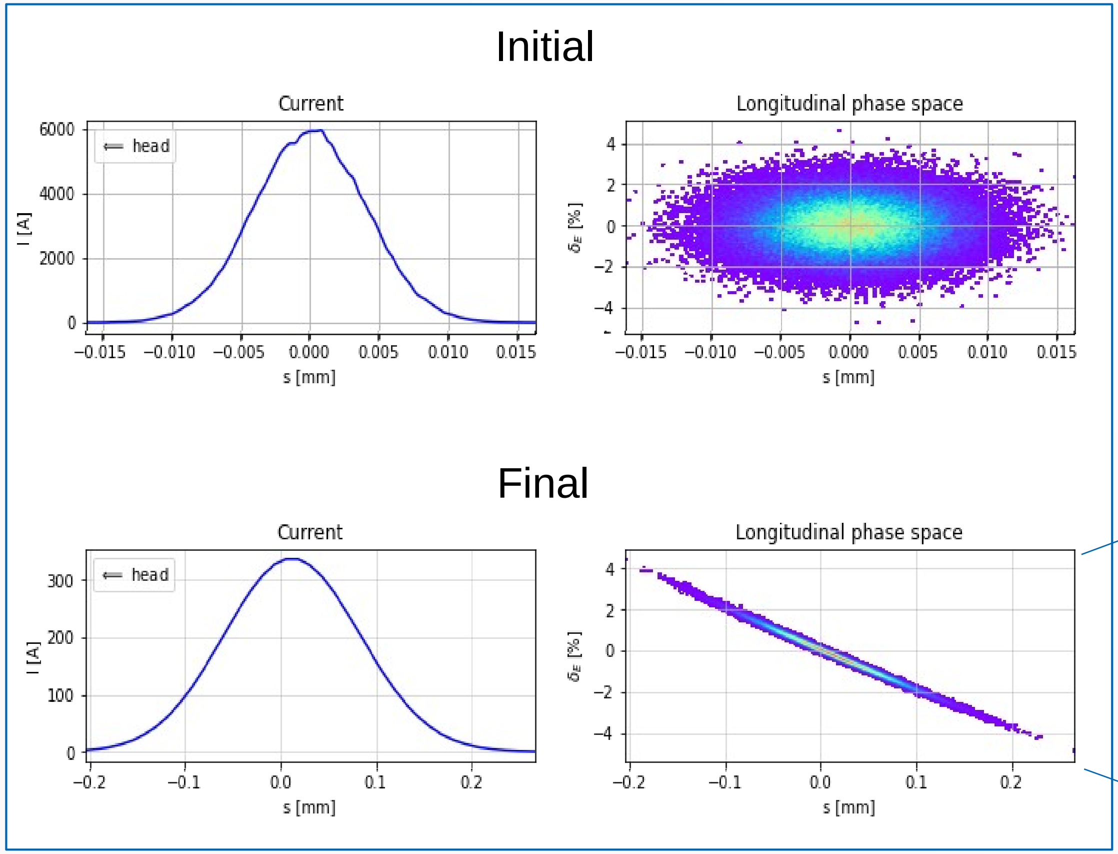
  W’ ~ 3 MV/m in the first dipole for a 200 pC bunch

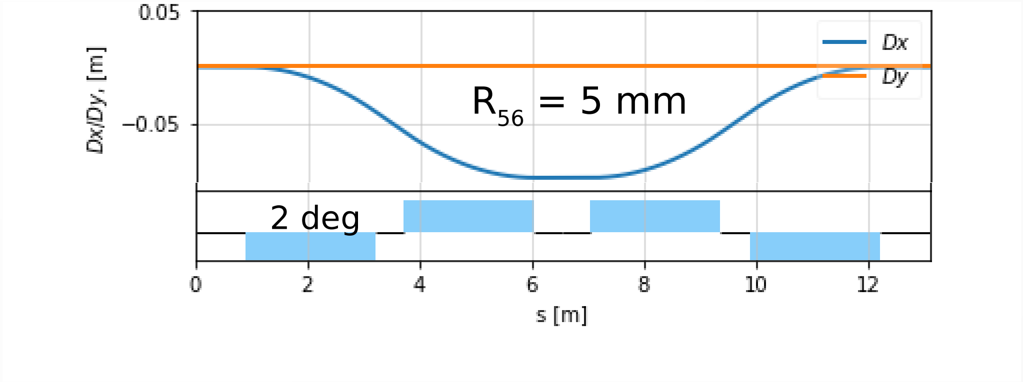
Transport & Injection

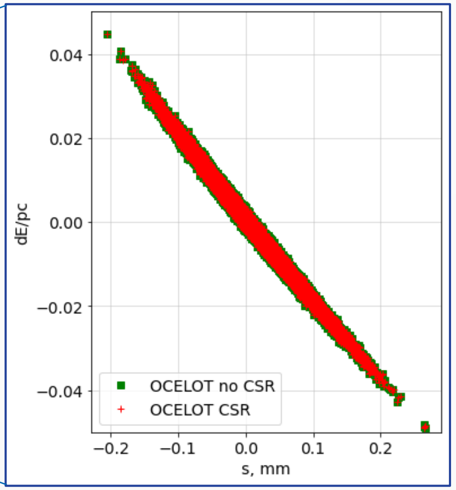
- ✔ Feasible with conventional technology
- ✔ Overall footprint: within 50 m

Limiting CSR in the chicane

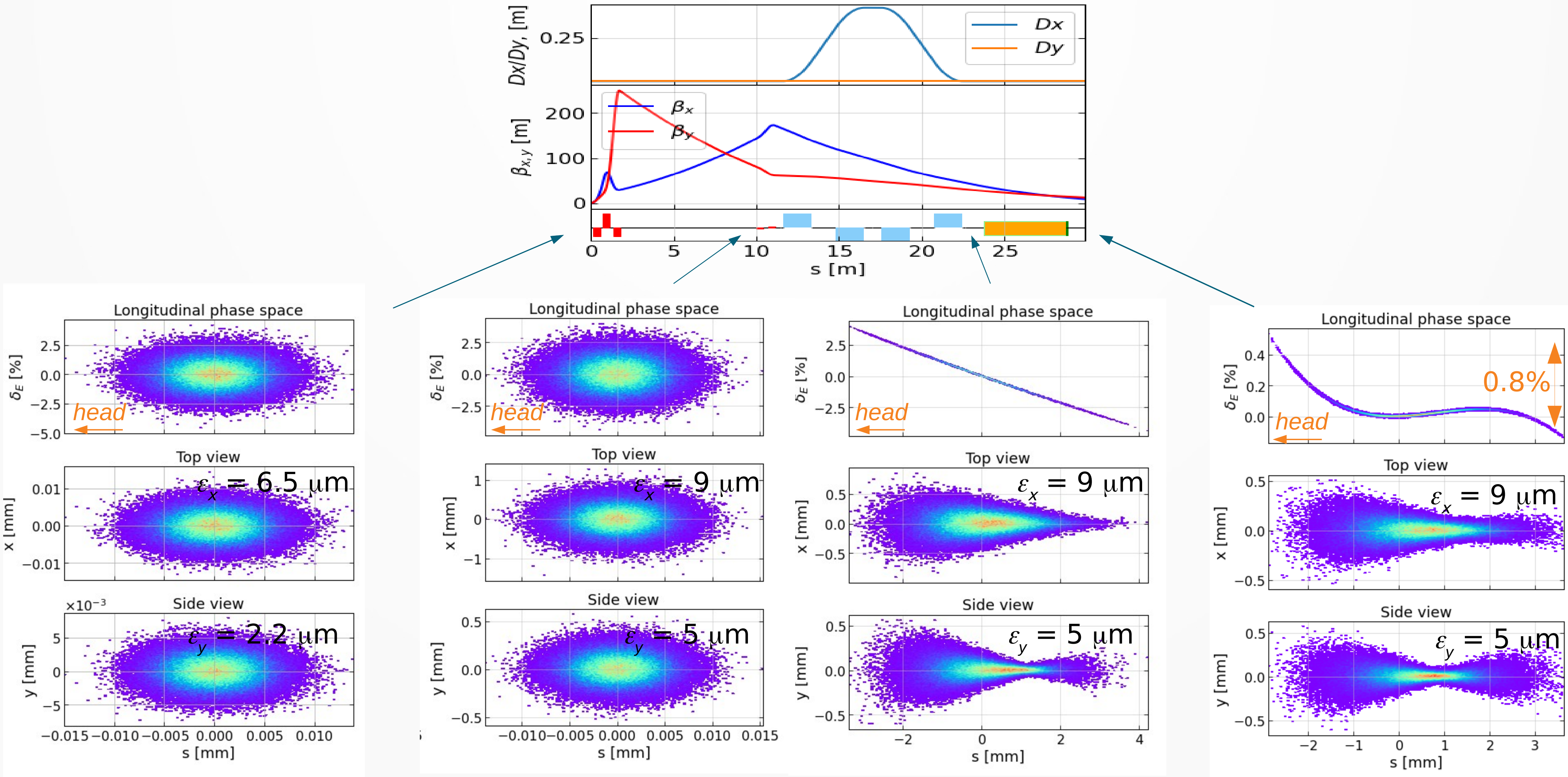
- Not an issue for 500 MeV, but could be significant for 6 GeV
- Mitigated if the bunch is pre-stretched to 50 μm rms with a weak chicane





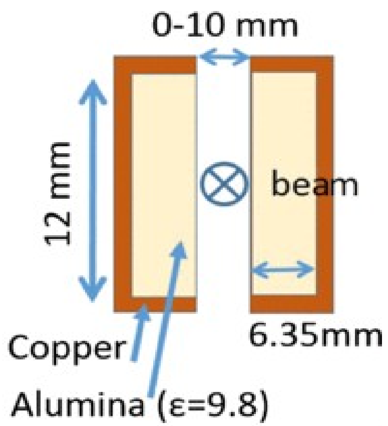


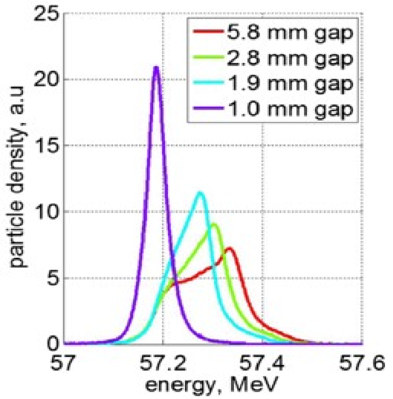
Tracking simulation: 6 GeV



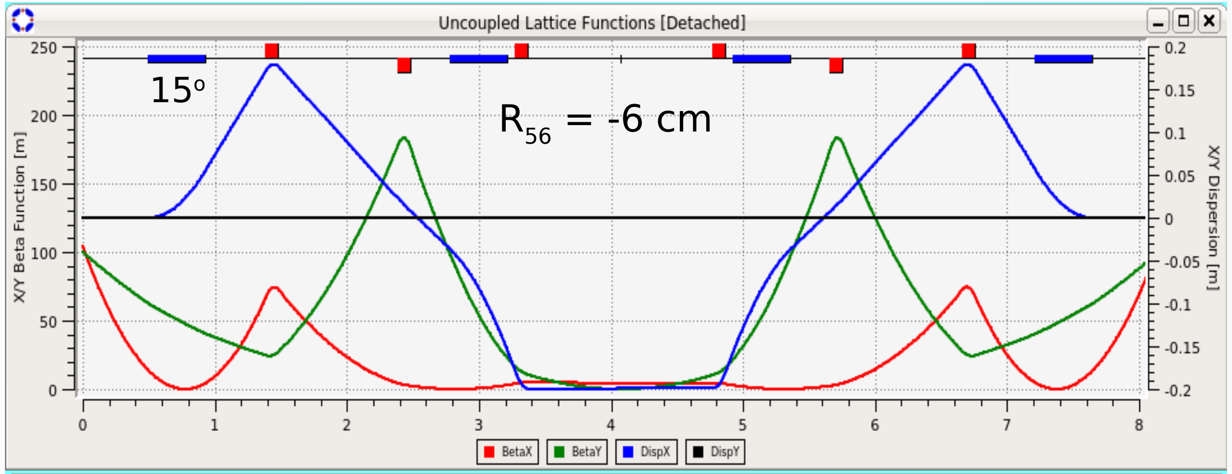
To use a passive structure one needs a negative R_{56} chicane

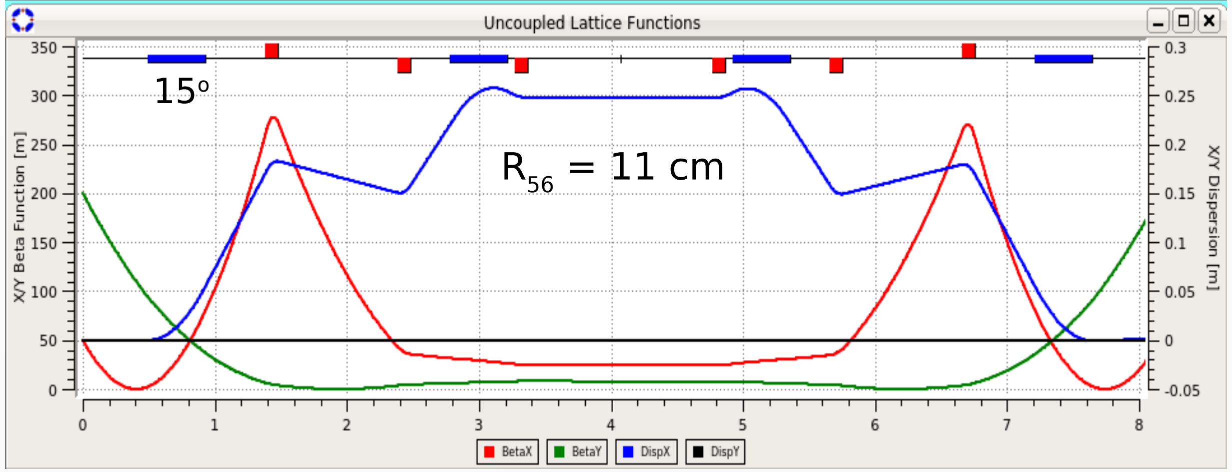
Energy spread reduction with a tunable dielectric dechirper





S. P. Antipov *et al.*, PRL 112, 114801 (2014)



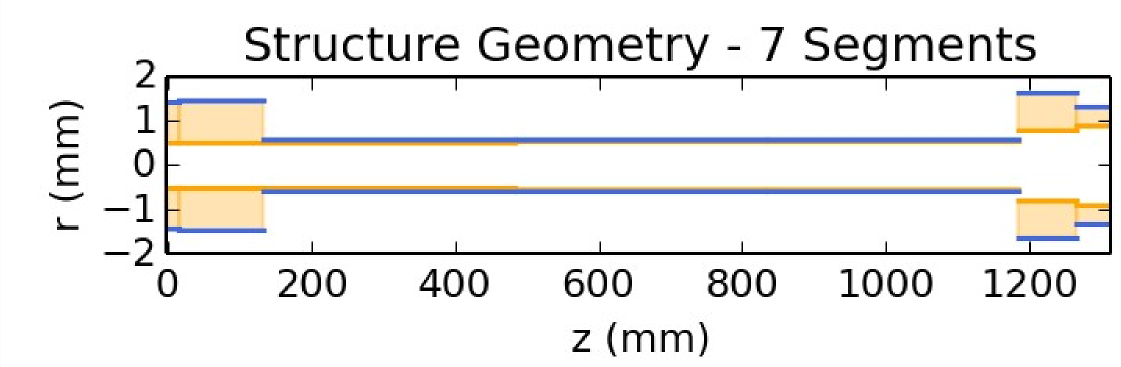


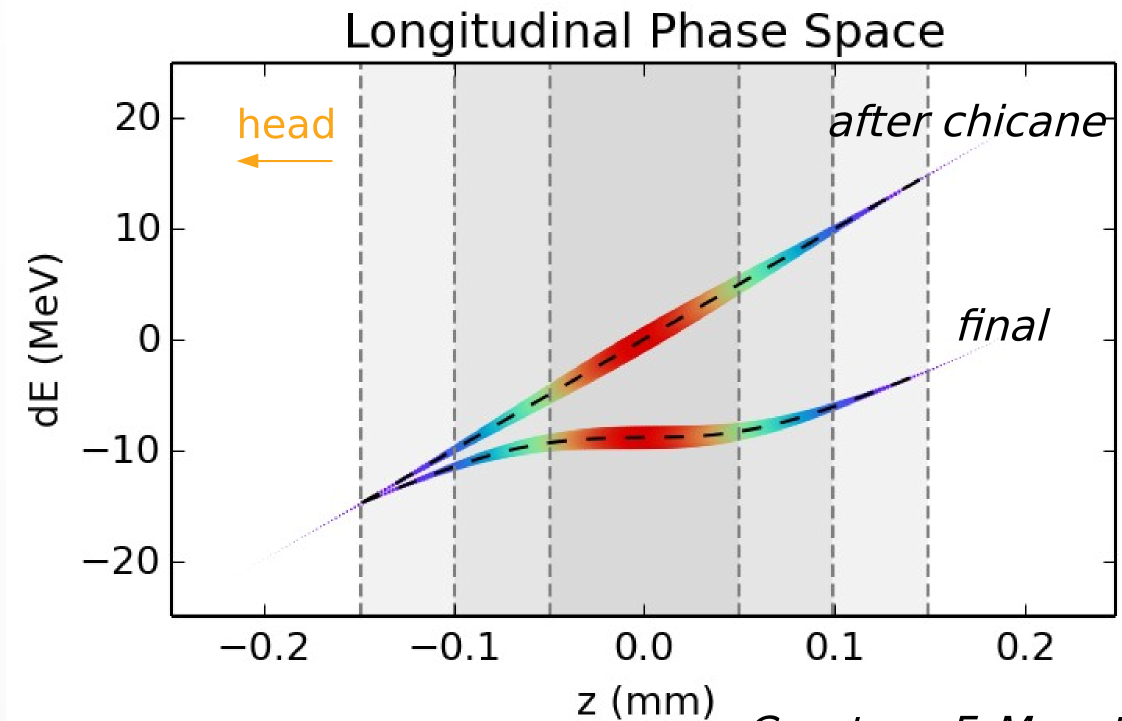
Energy spread compensation using tailored dielectric structures

Longitudinal phase space synthesis with tailored 3D-printable dielectric-lined waveguides

F. Mayet,* R. Assmann, and F. Lemery†
DESY, Notkestrasse 85, 22607 Hamburg, Germany
(Dated: September 28, 2020)

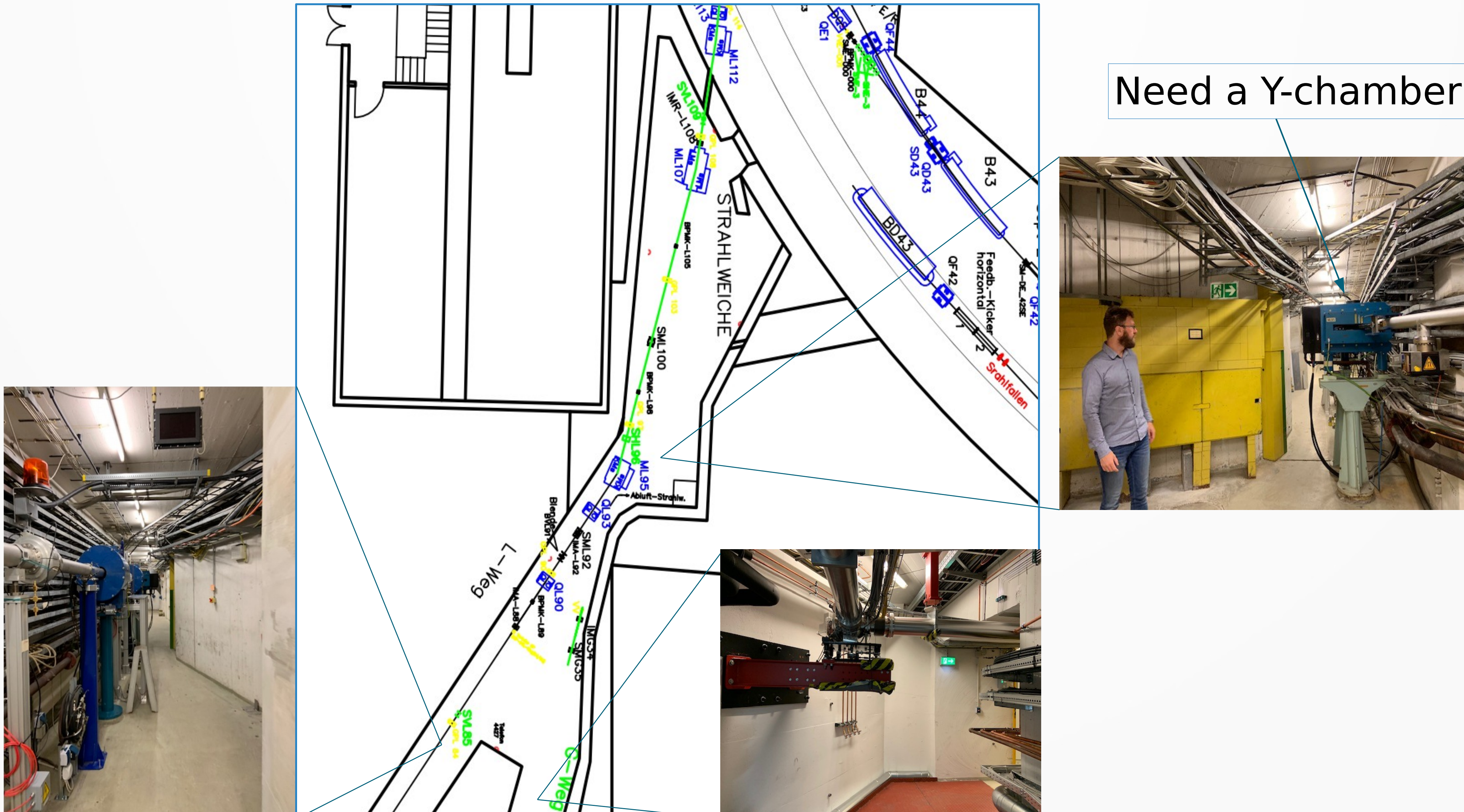
Longitudinal phase space manipulation is a critical and necessary component for advanced acceleration concepts, radiation sources and improving performances of X-ray free electron lasers. Here we present a simple and versatile method to semi-arbitrarily shape the longitudinal phase space of a charged bunch by using wakefields generated in tailored dielectric-lined waveguides. We apply the concept in simulation and provide examples for radiation generation and bunch compression. We finally discuss the manufacturing capabilities of a modern 3D printer and investigate how printing limitations, as well as the shape of the input LPS affect the performance of the device.





Courtesy F. Mayet

How would it look like on the ground?



Injection of an LPA beam into a storage ring is feasible

- Beam capture can be done with existing technology
  - Magnet designs are readily available, positive experimental experience at LUX
  - Acceptable chromatic emittance increase with simulated LPA beam parameters: RMS energy spread of 1%, divergence < 1 mrad

- Energy spread can be reduced to 0.1%
  - Using a chicane + X-band RF
  - Momentum collimation in the chicane
  - Passive structure (dielectric or corrugated) can compensate a part of the energy spread

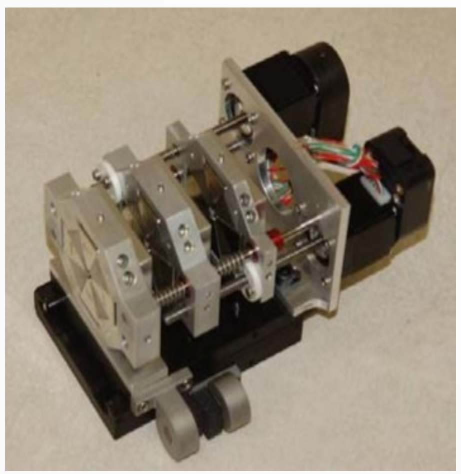
- An injection line can be shared with a conventional linac
  - 500 MeV prototype can be installed in the LUX tunnel
  - Utilize existing infrastructure to inject into DESY-II
  - MEA: Beamline magnets – dipoles and quadrupoles are available

Thank you

Questions?

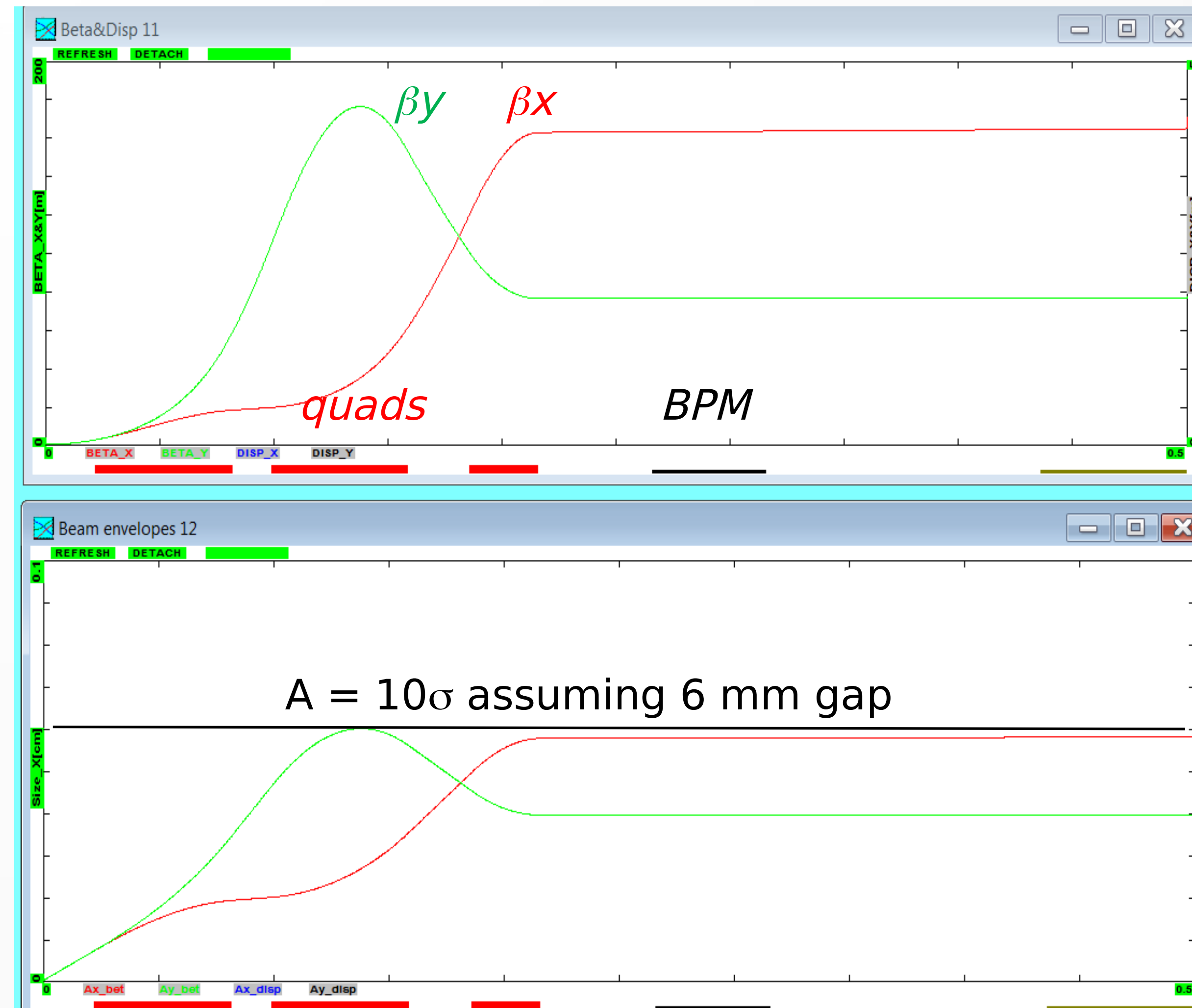
Beam capture with PQMs

- SLAC PQM Triplet:
  G up to 560 T/m, *R* = 3 mm



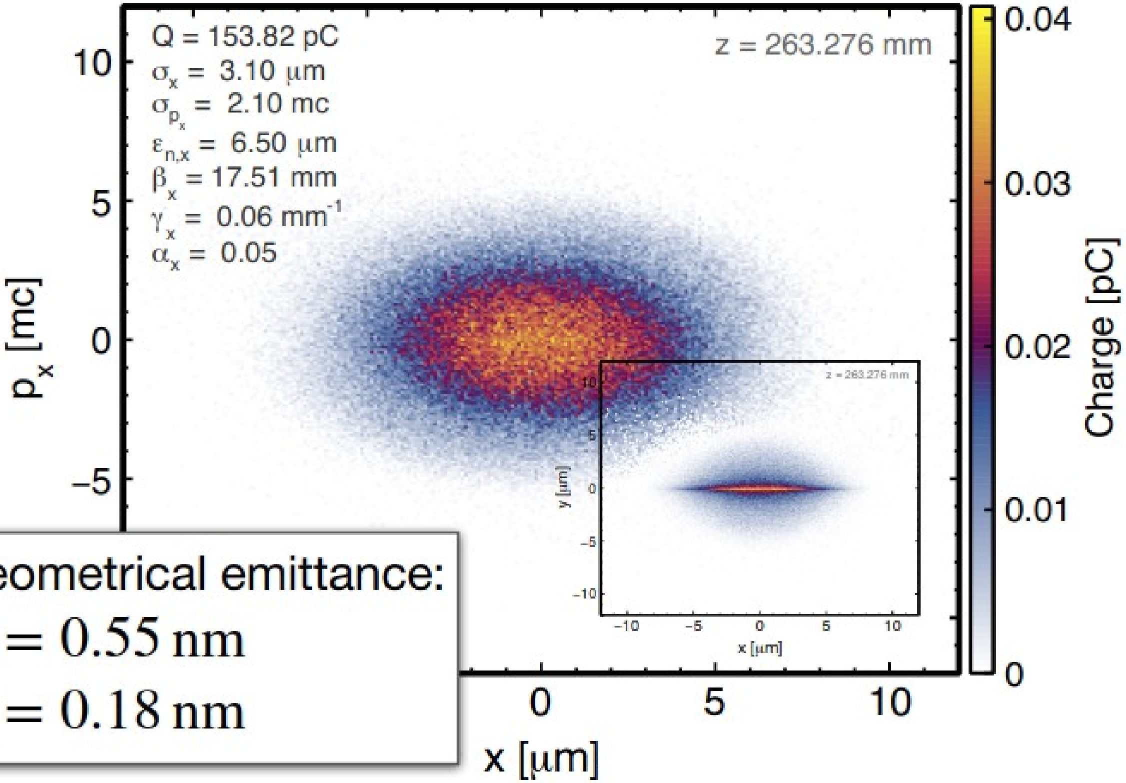
S. Sears et al., SLAC-PUB-12422

- Assume *G* = 530 T/m, *R* = 3 mm
  - Max β: 180 m
  - Max σ: 0.06 mm



PIP4: LPA simulation with 345 TW (27 J)

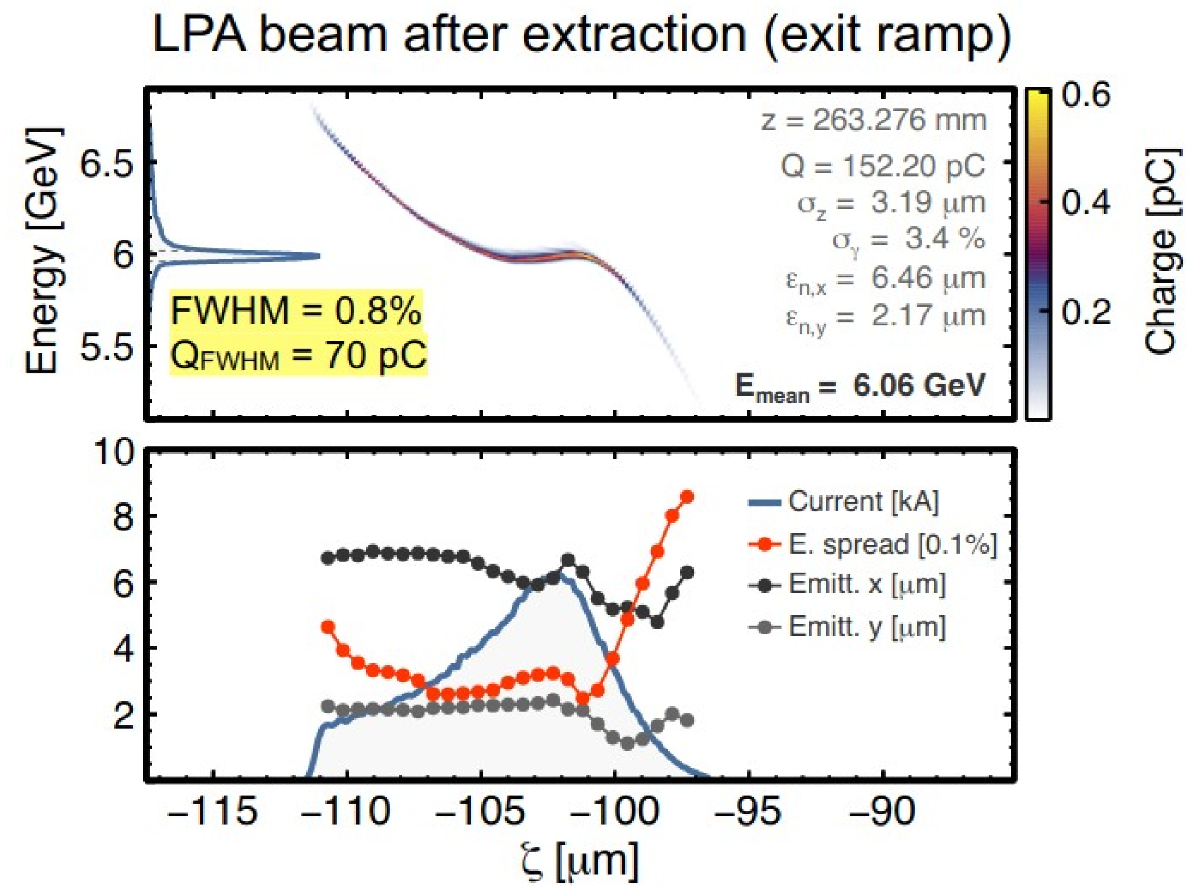
6 GeV bunch after exit plasma ramp



Geometrical emittance:

$\varepsilon_x = 0.55\,\mathrm{nm}$

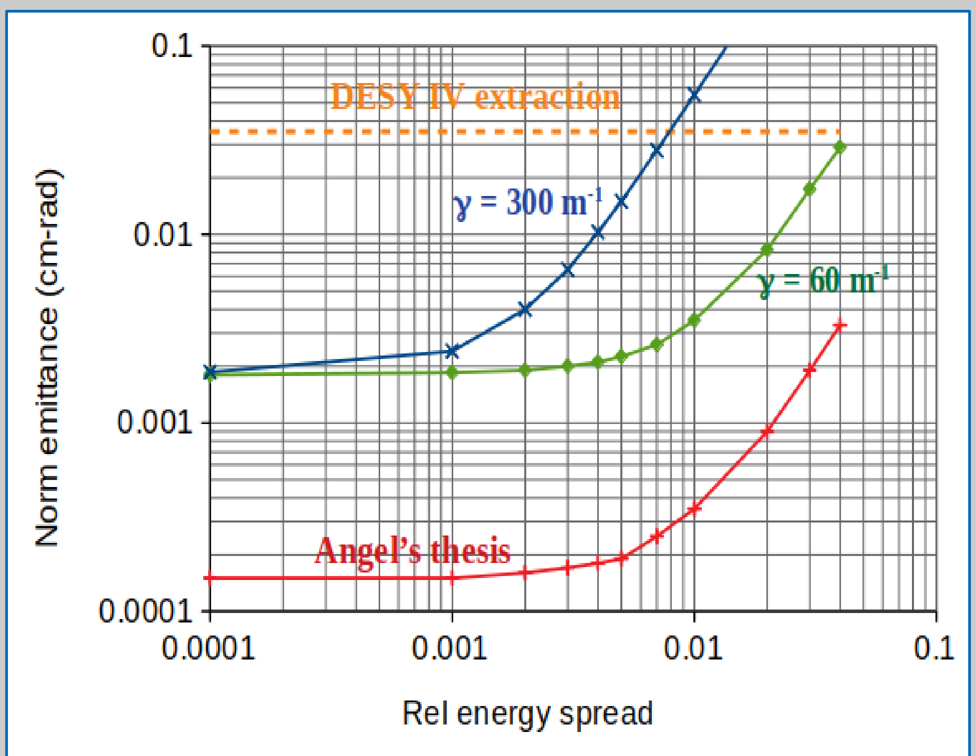
$\varepsilon_y = 0.18\,\mathrm{nm}$



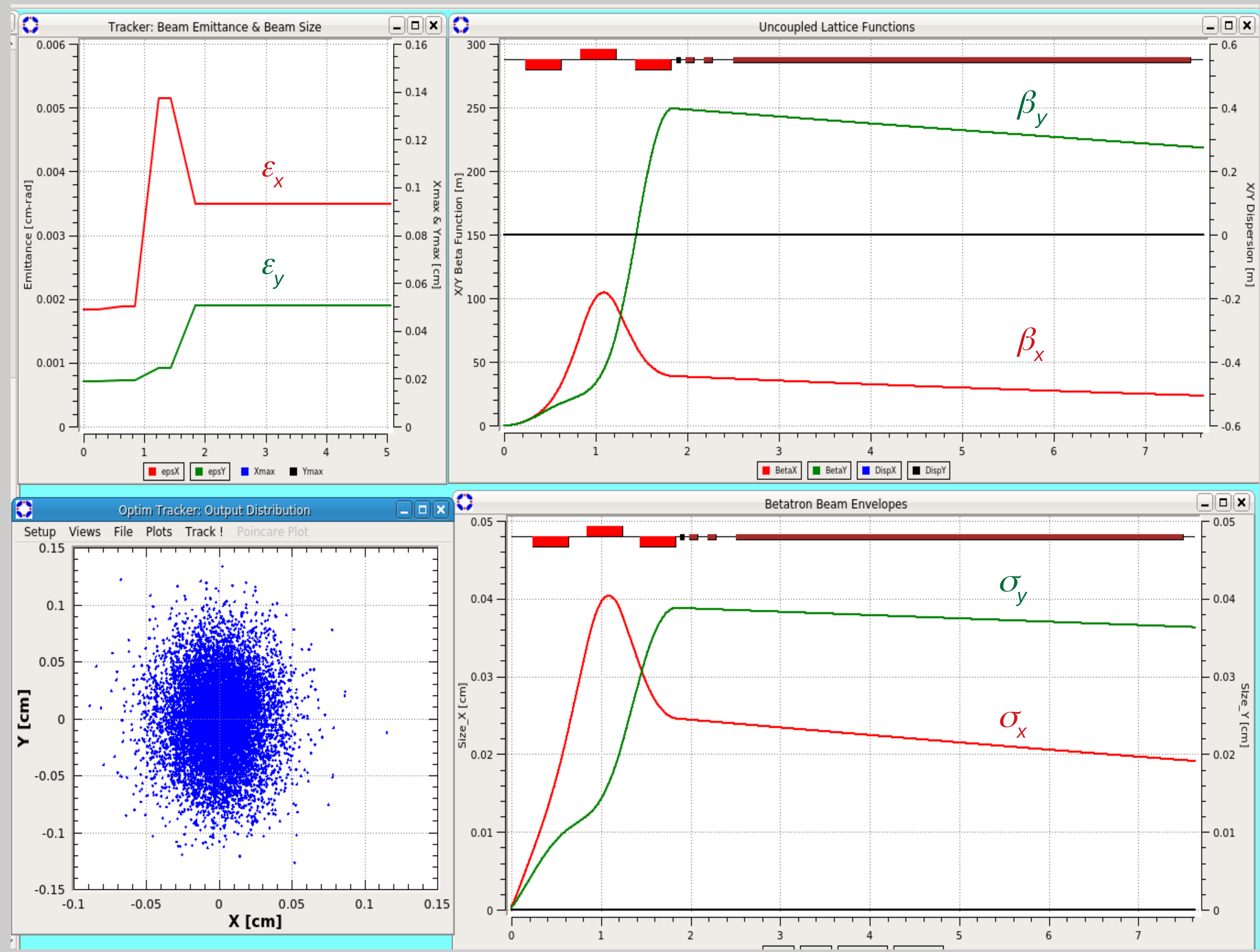

```
charge = 153.901 pC
energy = 6059.416 MeV. rel. spread = 3.569 %
tau    = 25.002 fs. -> current (charge / tau) = 6.156 kA
emitx = 6.530 um. betax = 17.587 mm. gammax = 0.057 mm-1. alphax =  0.049. divx = 0.177 mrad
emity = 2.174 um. betay = 18.309 mm. gammay = 0.055 mm-1. alphay = -0.006. divy = 0.100 mrad
```

6 GeV capture seems feasible with an rms energy spread of 1%

Quad length	40 cm
Quad gradient	< 110 T/m
5 sigma radius	< 2 mm
Chromatic emittance increase (σ_p = 1%)	x2



Lattice parameters and tracking in *Optim*

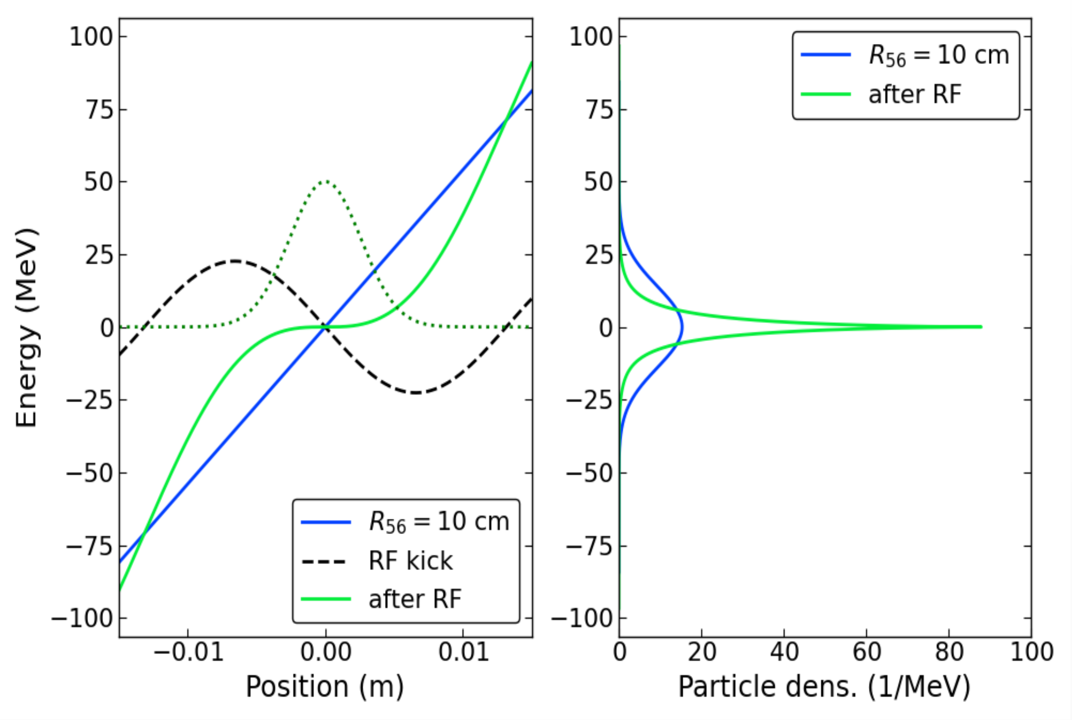


Considerations on momentum collimation

- Control emittance and prevent downstream losses in case of failures
- The total power is 600 W (6 GeV, steady state) – not negligible but still quite small
- To collimate efficiently electrons should interact as quickly as possible
  - Short radiation length and
  - High stopping power.
- Material of choice: copper or tungsten
  - Single stage
  - With cooling

X-band RF inefficient at σ_p > 1%

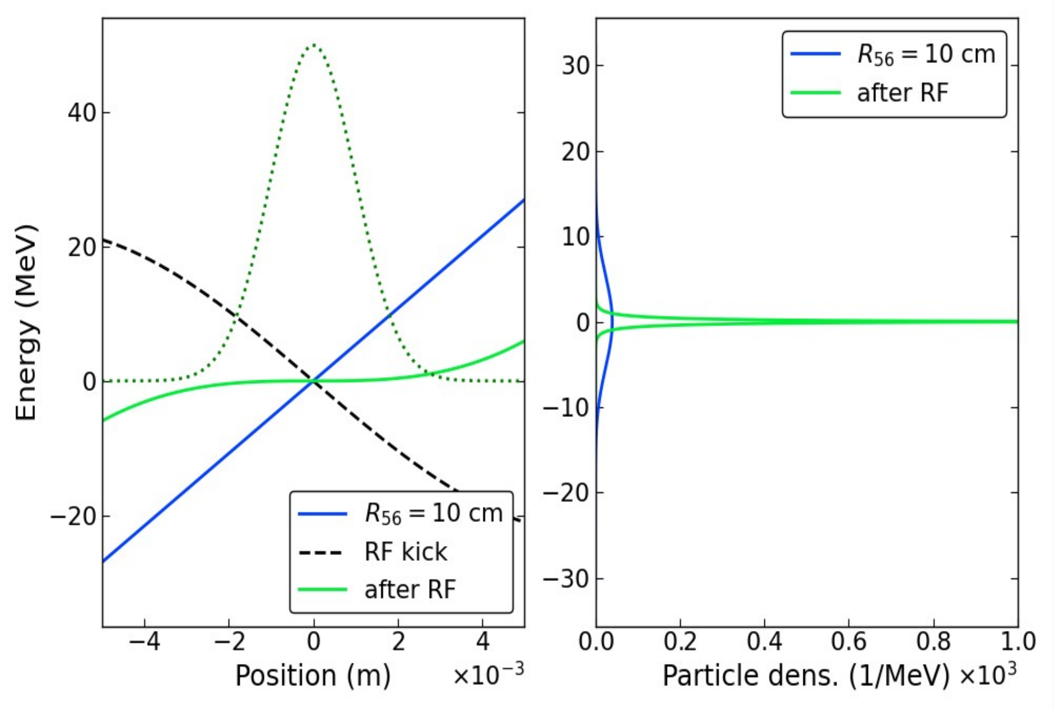
σ_p = 2.6%



Final rms spread 1.3%

Need lower R_{56} and higher RF voltage

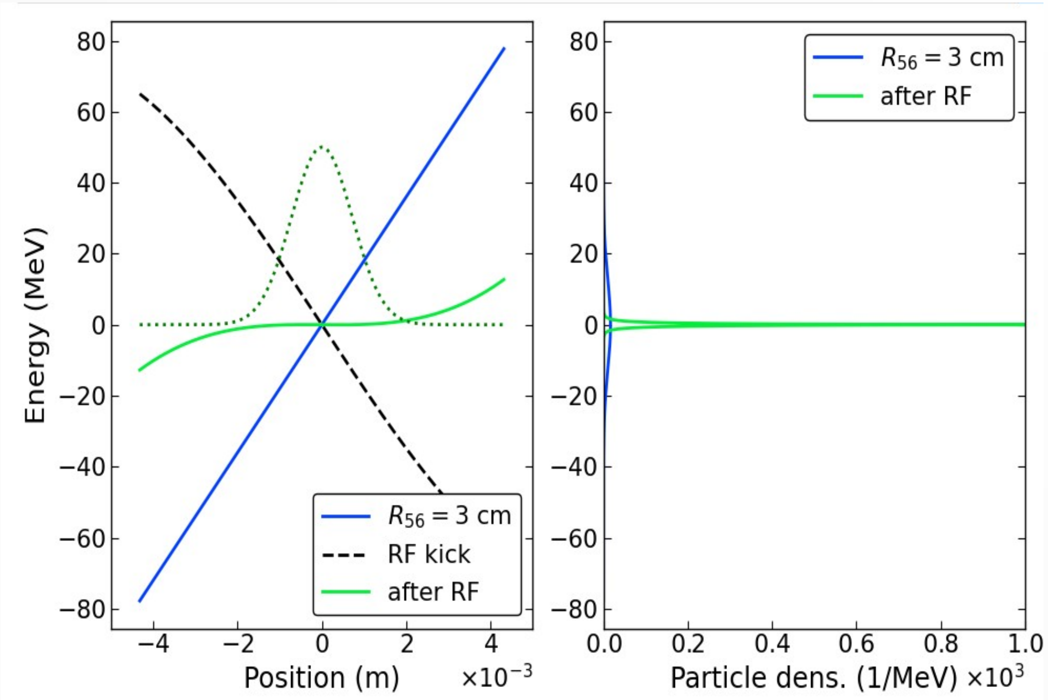
σ_p = 1.0%



Final rms spread 0.1%

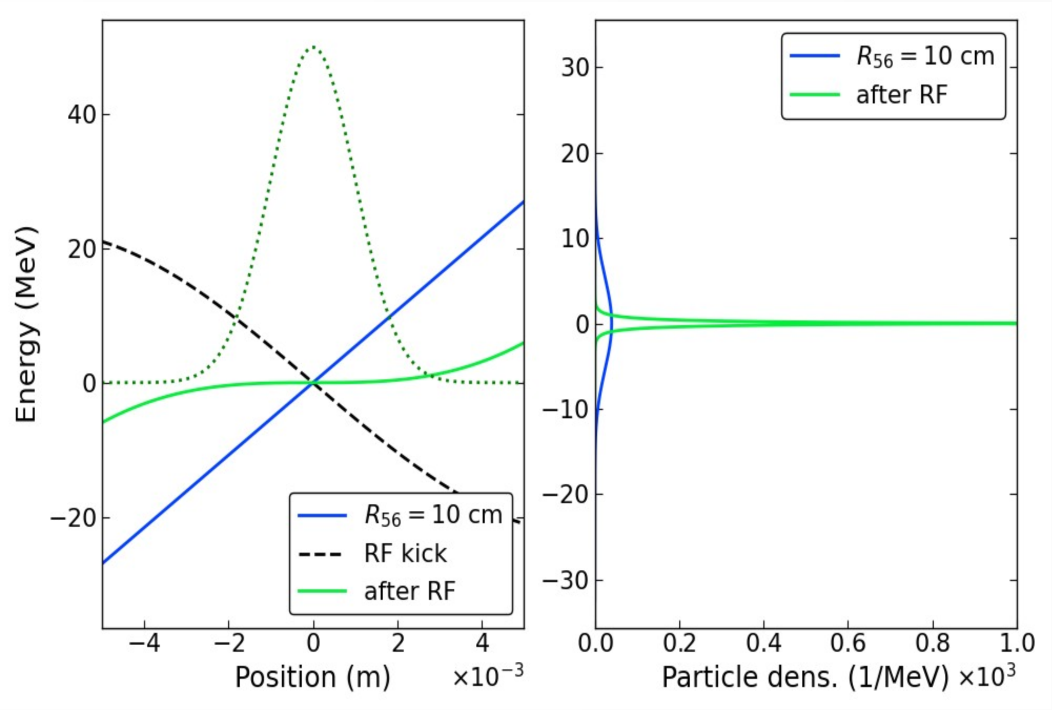
X-band RF inefficient at $\sigma_p > 1\%$

σ_p = 2.6% R_{56} = 3 cm, V_{RF} = 75 MV



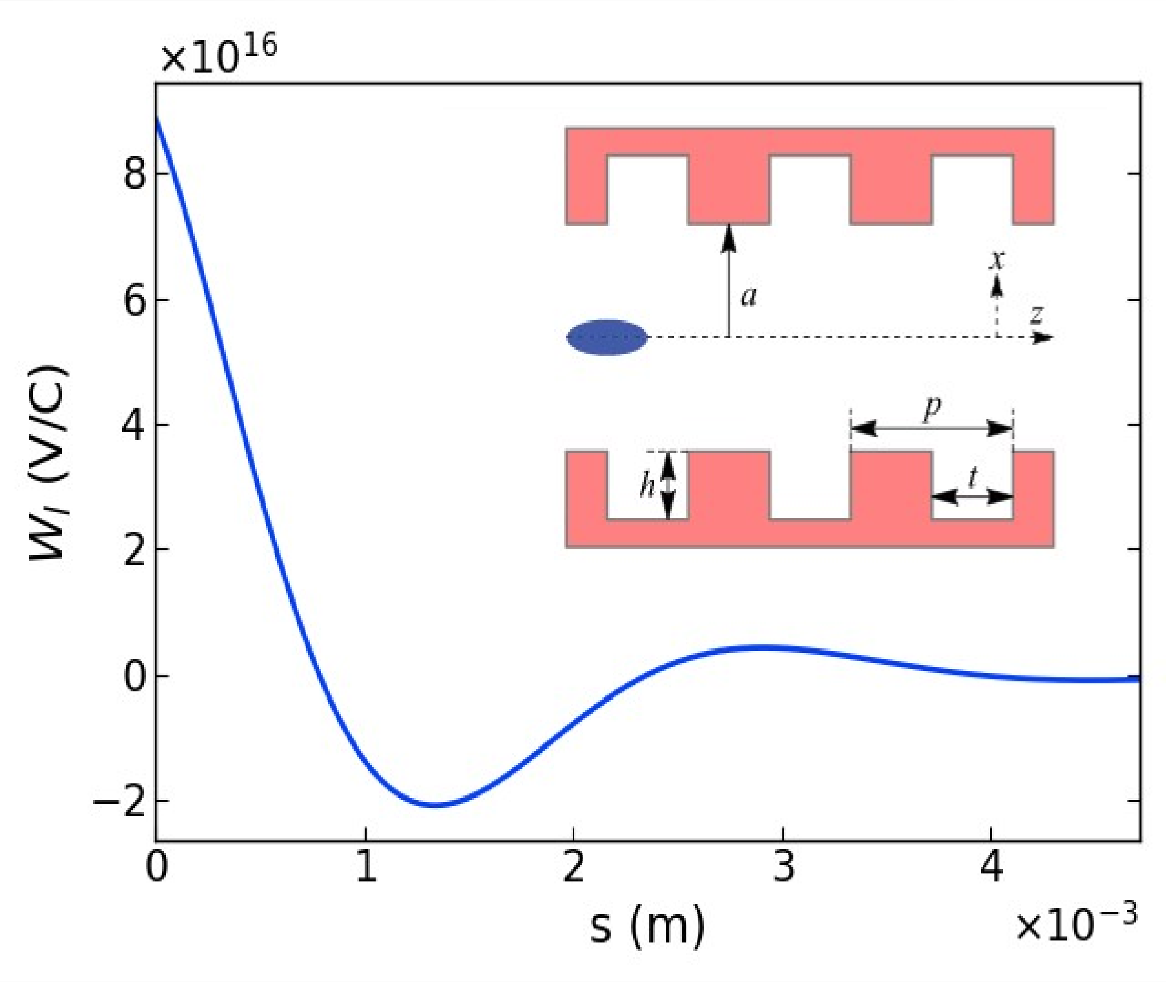
Final rms spread 0.1%

σ_p = 1.0% R_{56} = 10 cm, V_{RF} = 22 MV



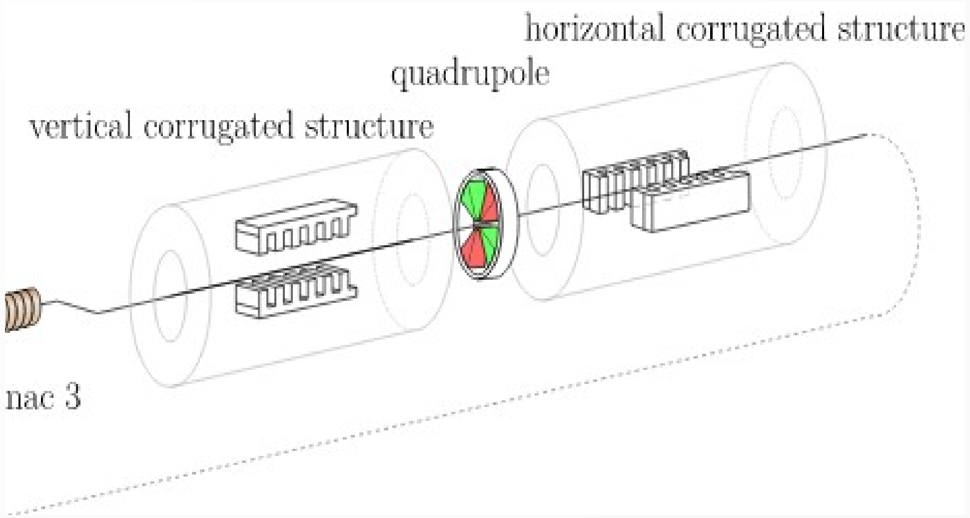
Final rms spread 0.1%

Conventional dechirping: Corrugated pipe



Phys. Rev. Accel. Beams **20**, 104403 (2017)

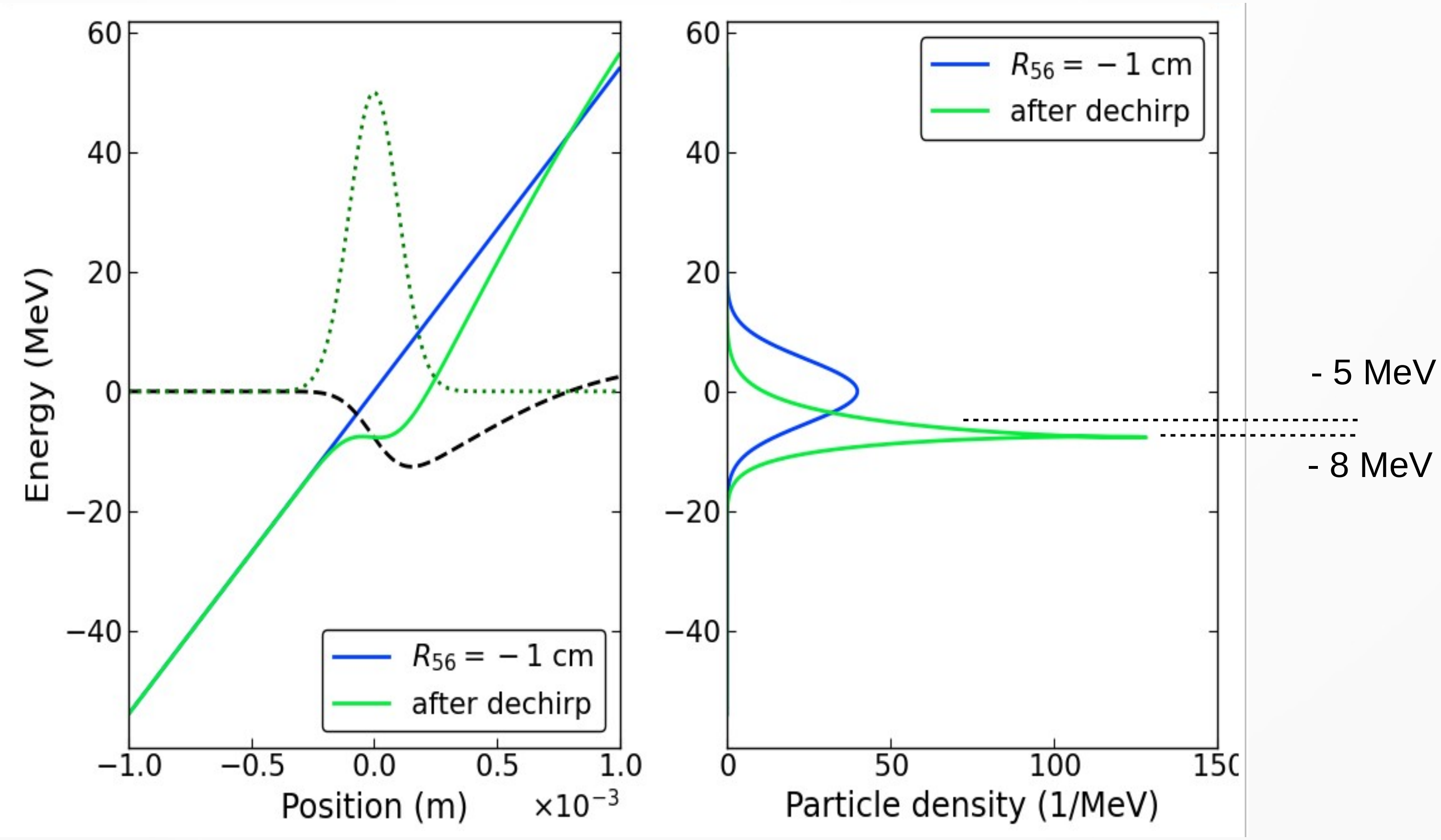
Gap, *g*	Period, *p*	Depth, *h*	Length
1 mm	1 mm	0.5 mm	2 x 1 m



Two structures at 90° minimize transverse kicks

Conventional dechirping: Corrugated pipe

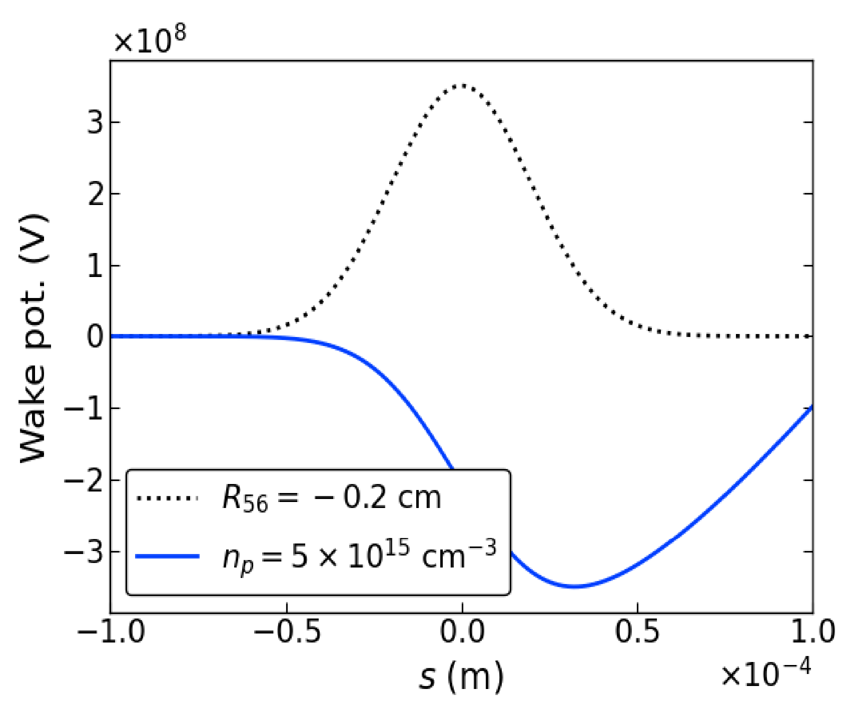
Assuming **1%** rms energy spread

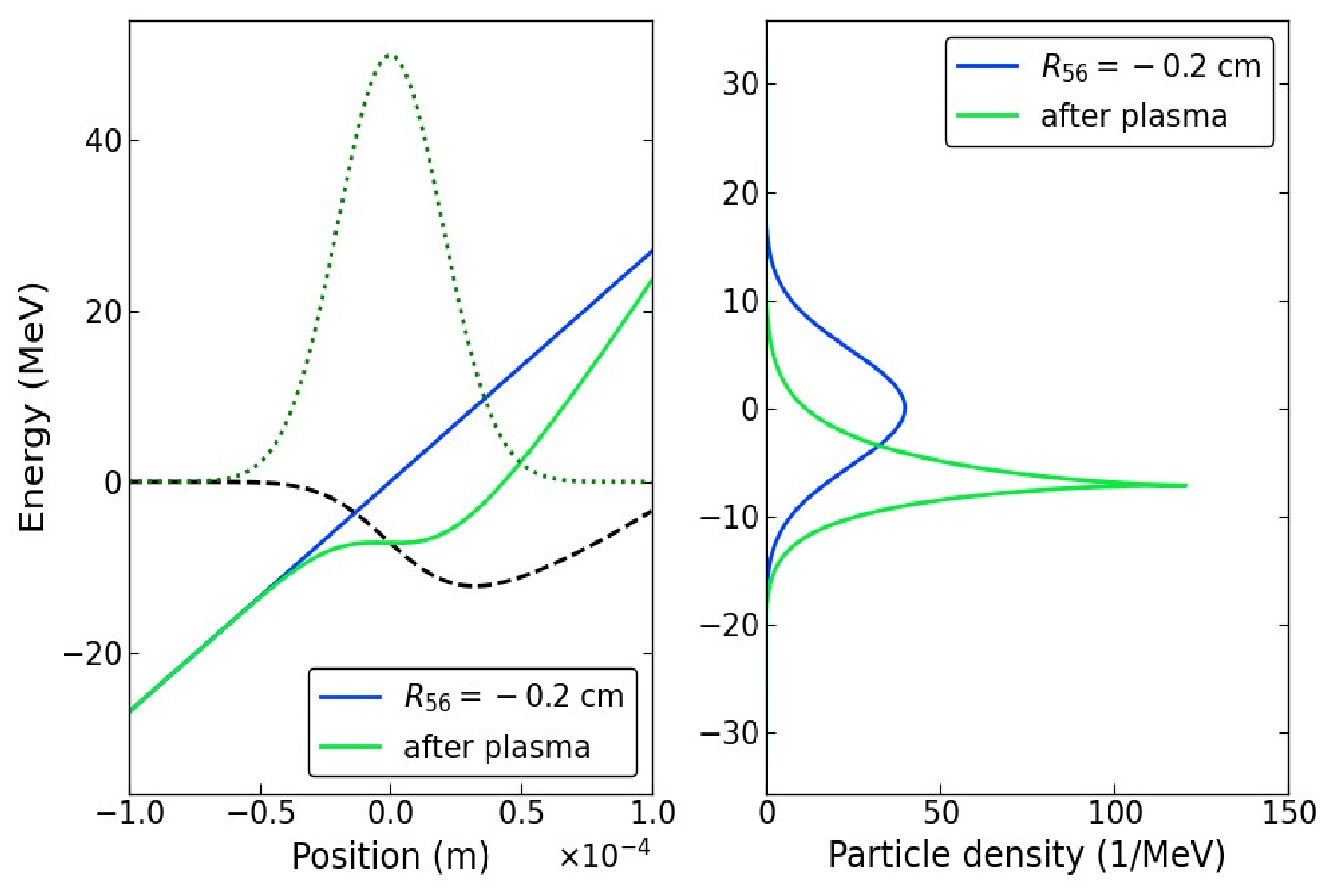


Hard to achieve effective dechirping for large energy spreads

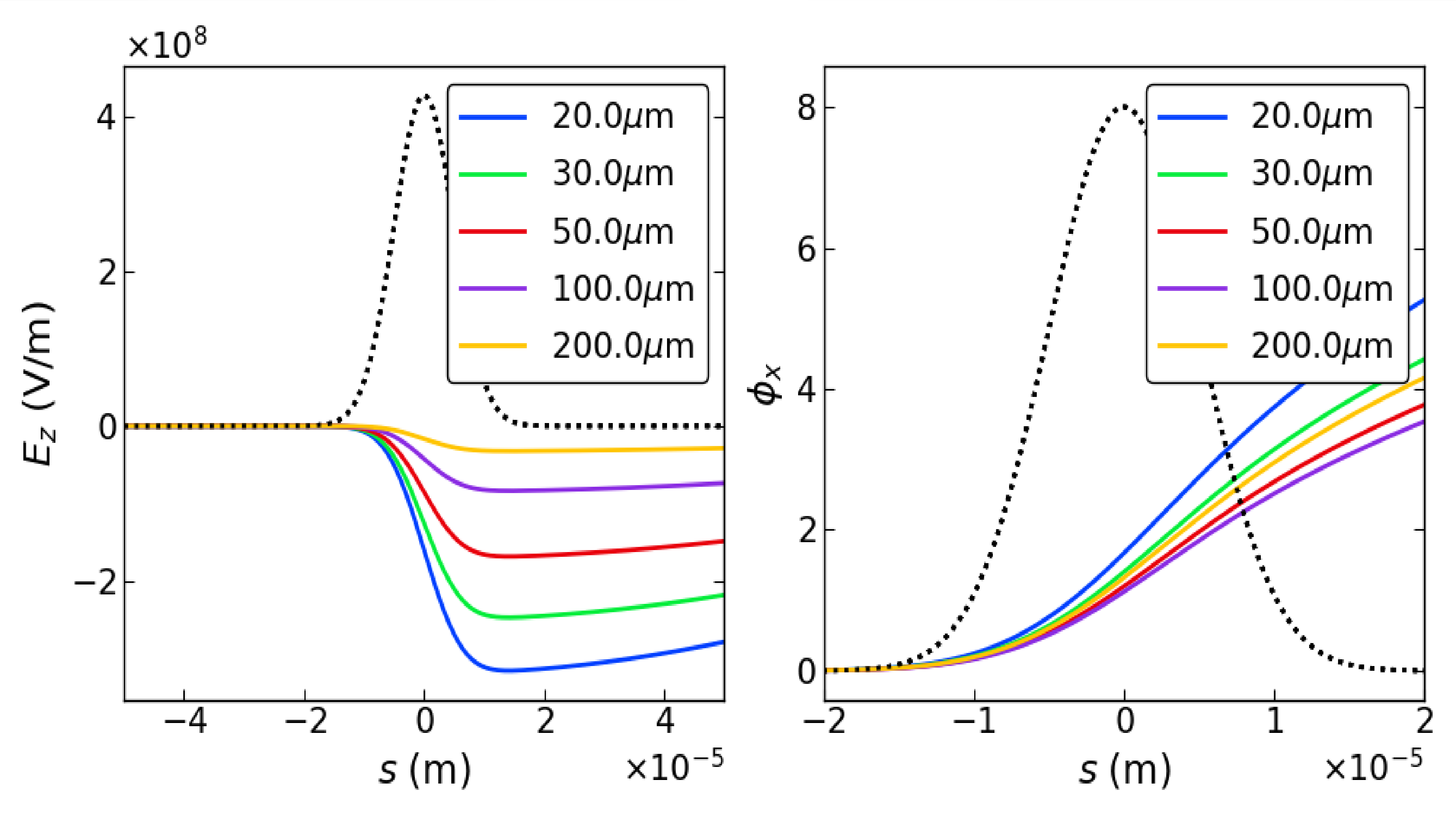
Plasma dechirping: significant gain over a short length

Plasma density: 5x10^{15} cm^{-3}
Cell length: 35 mm length



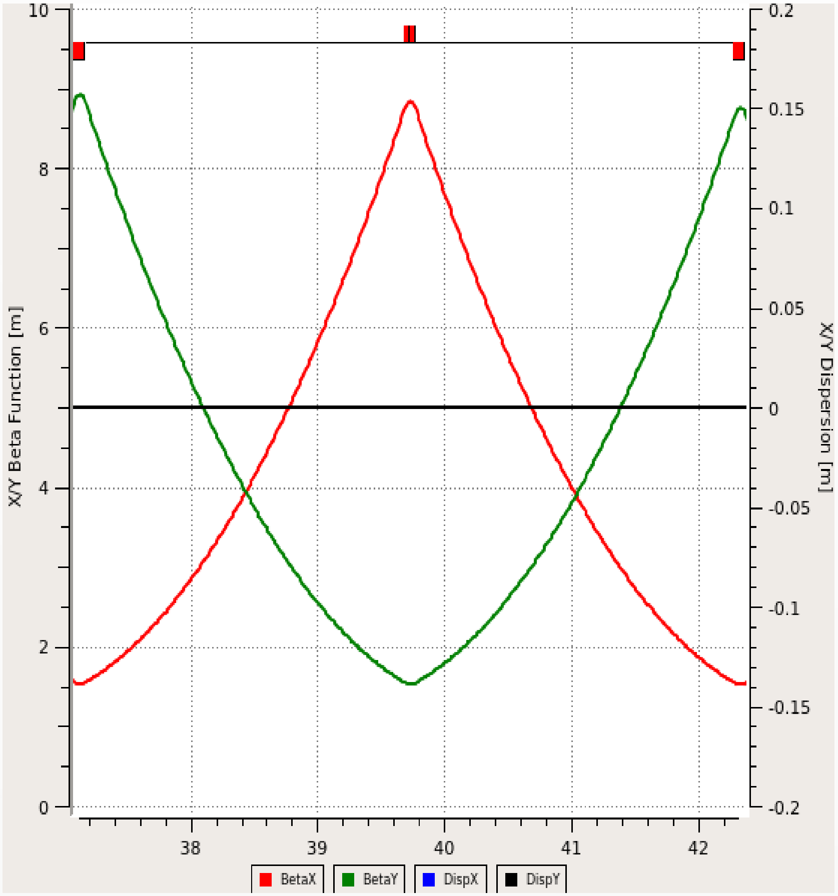


Large head-tail betatron phase advance might spoil emittance



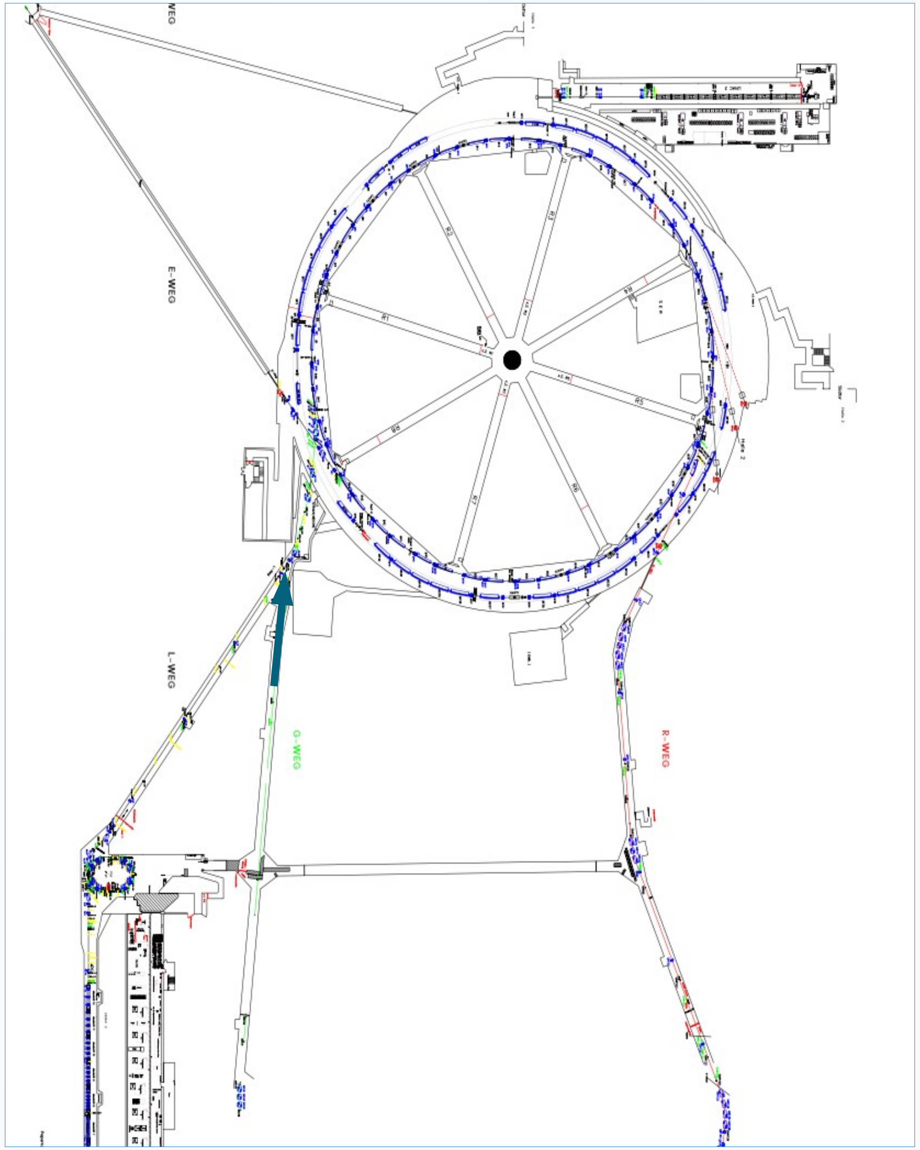
FODO Transport: 500 MeV

- G = 1 kG/cm, L_{FODO} = 5 m, ϕ_{FODO} = 90 deg

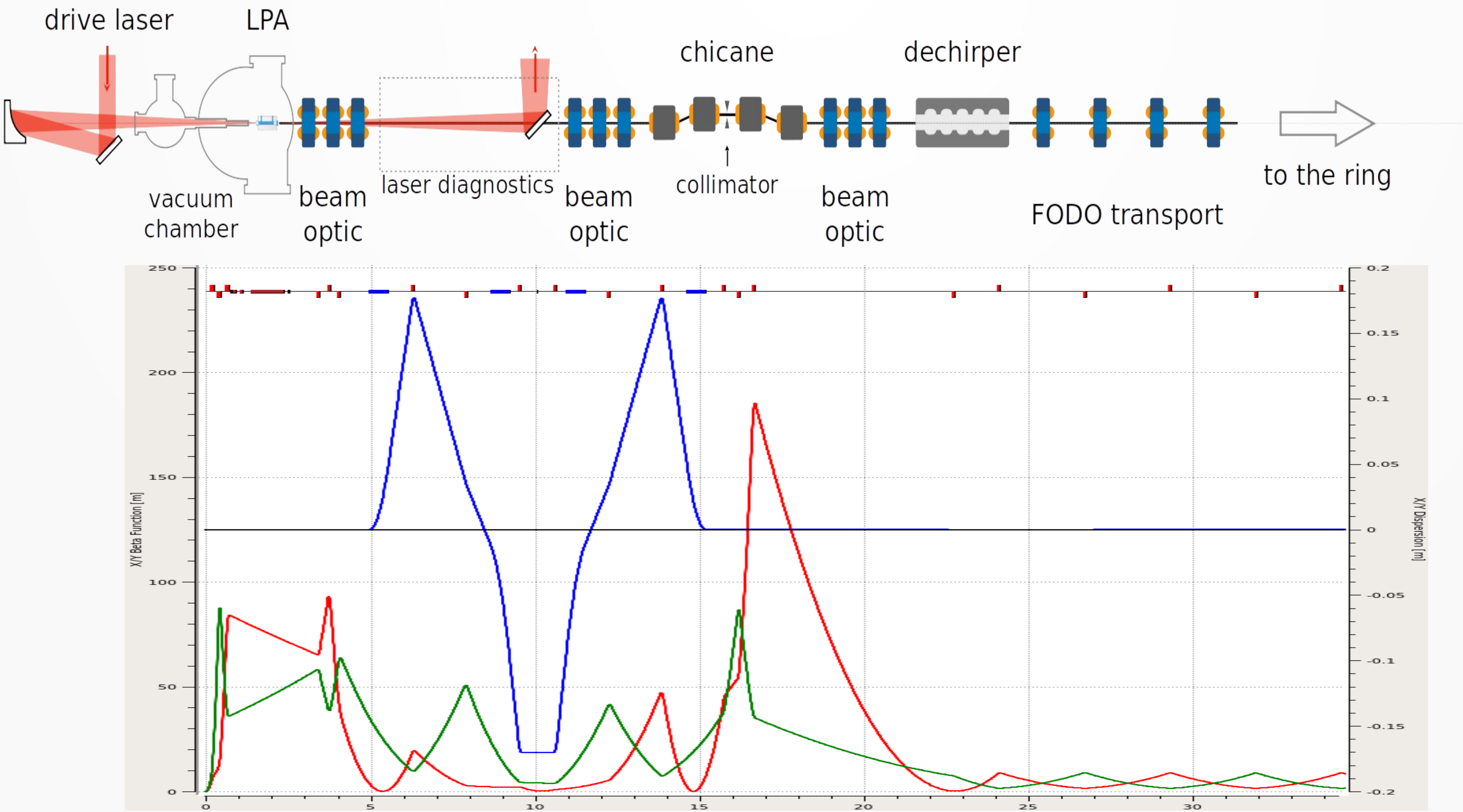


Injection: Re-using an existing system

- Consider G-Weg an optimal location for the prototype
- There is an existing conventional electron linac with an injection system
- Need a large aperture dipole with Y-chamber
  - The magnet is already in the tunnel (ML95)
- Some magnets are available for the beamline
  - HERA Injector quads EL-Type
    - 17 available
    - Fit for all the quads but the triplet
  - HERA dipole correctors CV/CH Type
    - Fit for chicane dipoles
  - Need to be refurbished



Overall view with adjustable chicane



HERA Injector quadrupole EL-Type

- 17 available, fit for all the quads except the triplet

Technische Daten		
Nennstrom	390	A
Spulen (Anzahl, Querschnitt)	4 (236)	mm^2
Leiterquerschnitt (Cu)	59 (9 x 9 ; ø 5.2)	mm^2
Windungszahl n/Spule	19	
Magnetwiderstand bei 20°C	22	mΩ
Induktivität		mH
Frequenz	DC	
Max. Stromdichte	6.6	A/mm^2
Verlustleistung	3.7	kW
Anzahl der Kühlkreise	1	
Kühlwassermenge	1.1	l/min
Δt Kühlwasser max.	50	°C
Differenzdruck	6	bar
Prüfdruck der Spulen	20	bar
Prüfspannung der Spulen	3	kV (eff.)
Feldgradient	45	T/m
Aperturradius	20	mm
Eisenlänge	300	mm
Magnetlänge (eff.)	320	mm
Gesamtlänge	395	mm
Gesamtgewicht	430	kg
Spulengewicht (pro Spule)	11	kg
Hersteller Fertigungszeichnung	Siemens – (Deutschland)	
Hersteller Eisenjoch/Spule	Siemens – (Deutschland)	
Bearbeitet: A.Jantzen-Stenzel	Geändert:	
MEA Tel. 8998–3271 / 3327