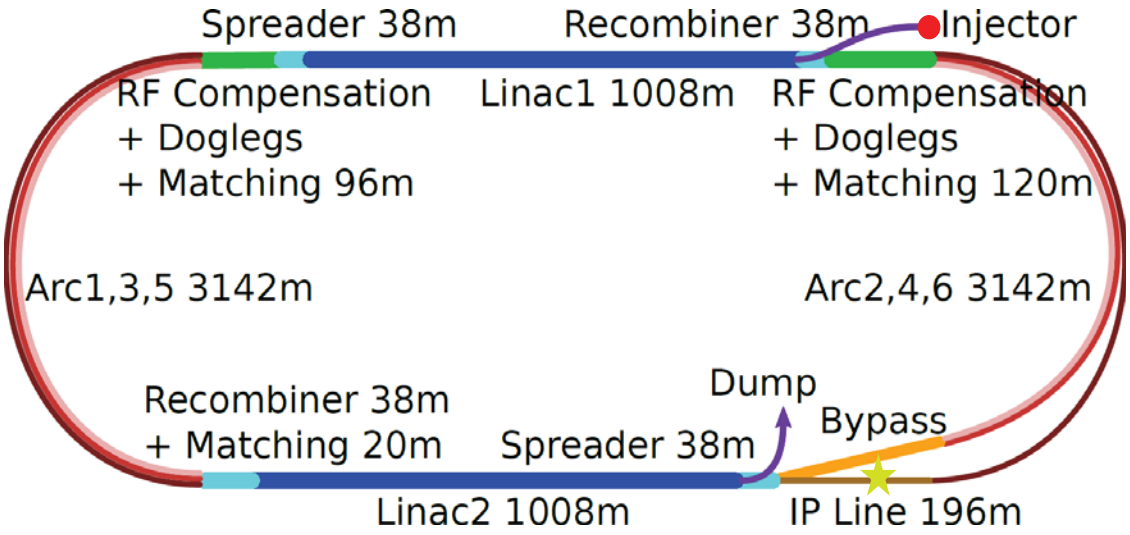
ERL – Design and Beam Dynamics Issues

Alex Bogacz – Jefferson Lab

Dario Pellegrini – EPF Lausanne/CERN

Andrea Latina and Daniel Schulte – CERN

60 GeV ERL Recirculator Complex



RECIRCULATOR COMPLEX

- 0.5 Gev injector
- Two SCRF linacs (20 GeV per pass)
- Six 180° arcs, each arc 1 km radius
- Re-accelerating stations
- Switching stations
- Matching optics
- Extraction dump at 0.5 GeV

TOTAL CIRCUMFERENCE ~ 8.9 km

10^{34} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60
Luminosity [10^{33}cm^{-2}s^{-1}]	16	16
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	2.5	20
Beta Function $\beta^*_{x,y}$ [m]	0.05	0.10
rms Beam size $\sigma^*_{x,y}$ [μm]	4	4
rms Beam divergence $\sigma'_{x,y}$ [μrad]	80	40
Average Beam Current [mA]	1112	25 delivered 150 in linacs
Bunch Spacing [ns]	25	25
Bunch Population	$2.2*10^{11}$	$4*10^9$
Bunch charge [nC]	35	0.64

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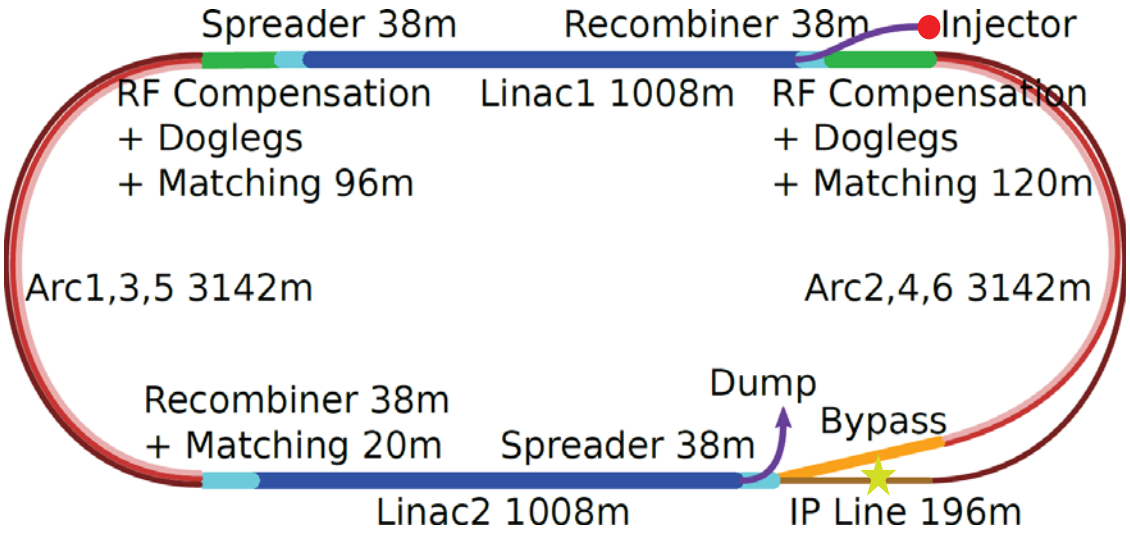

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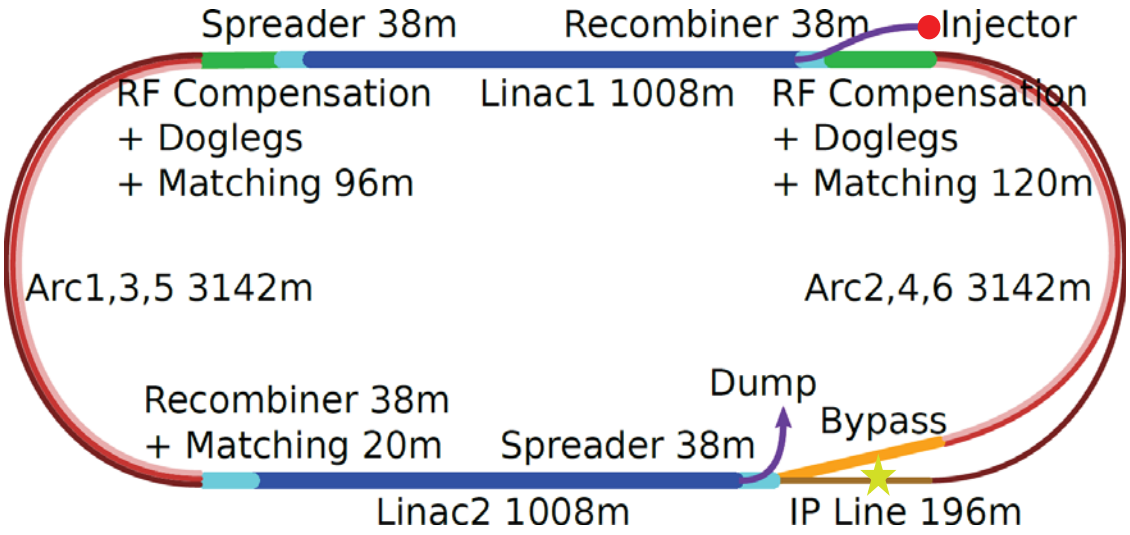

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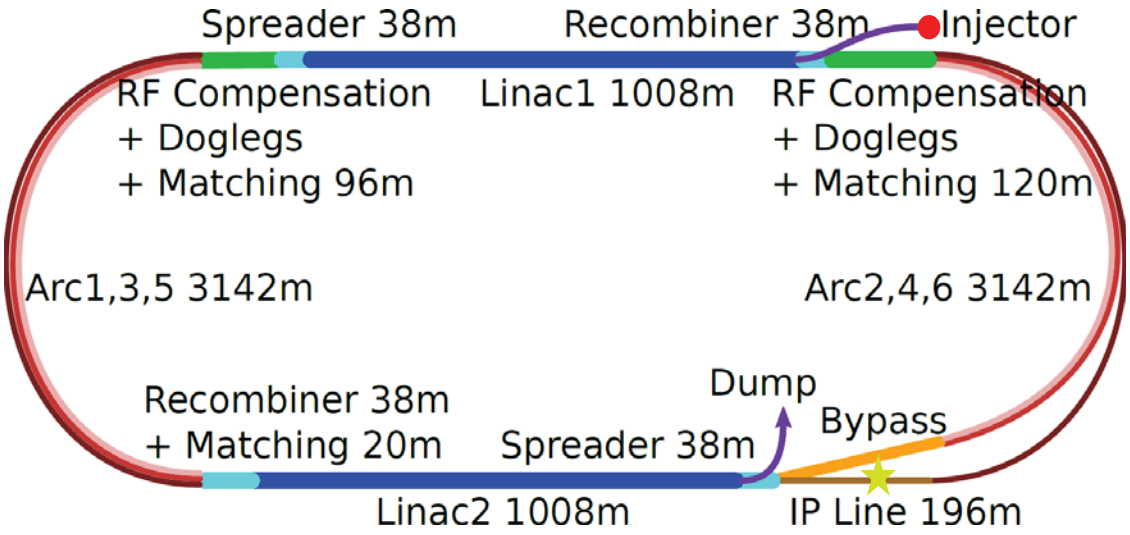

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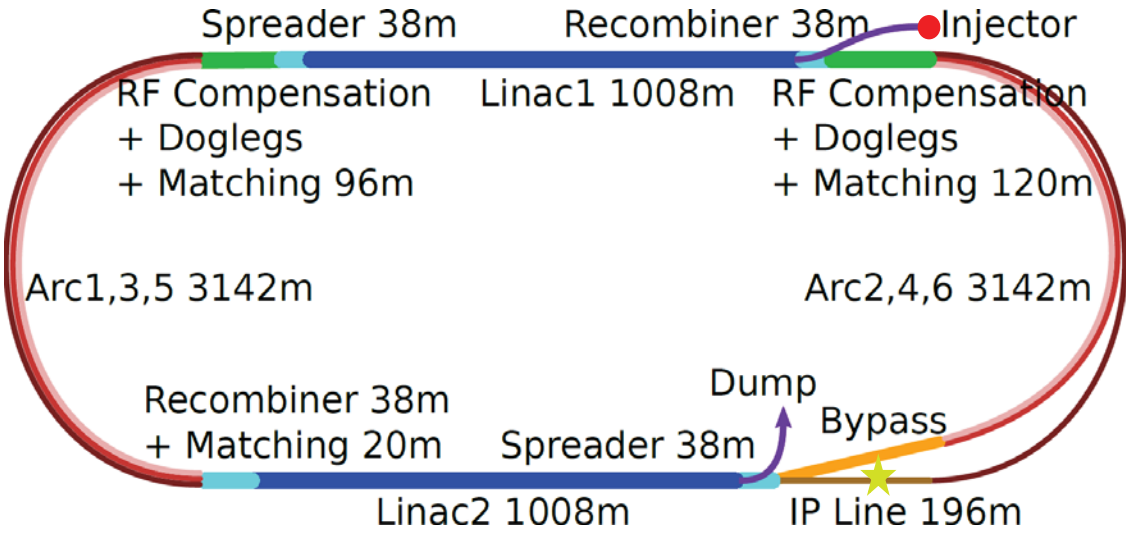

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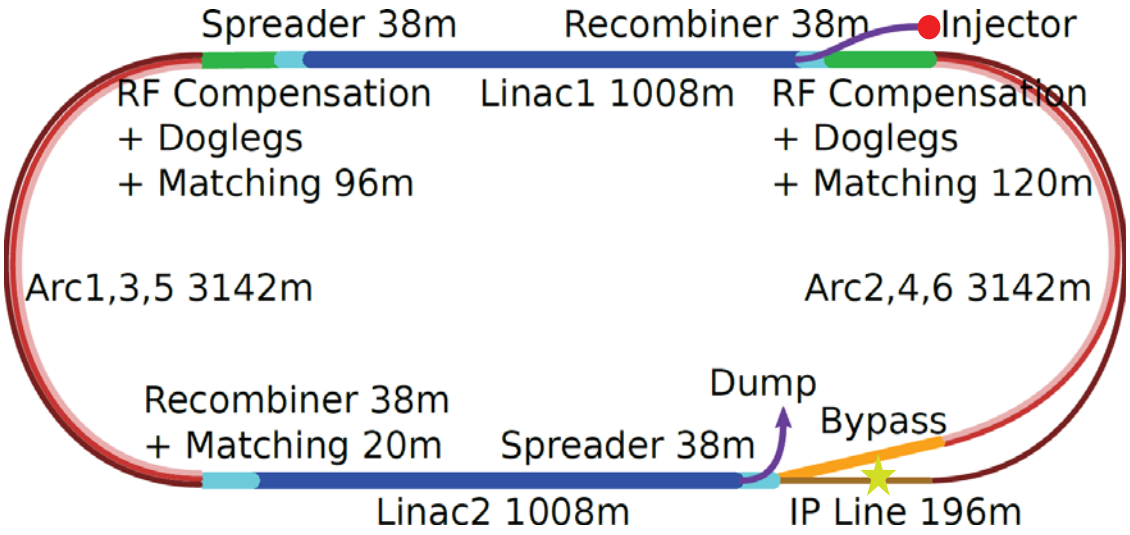

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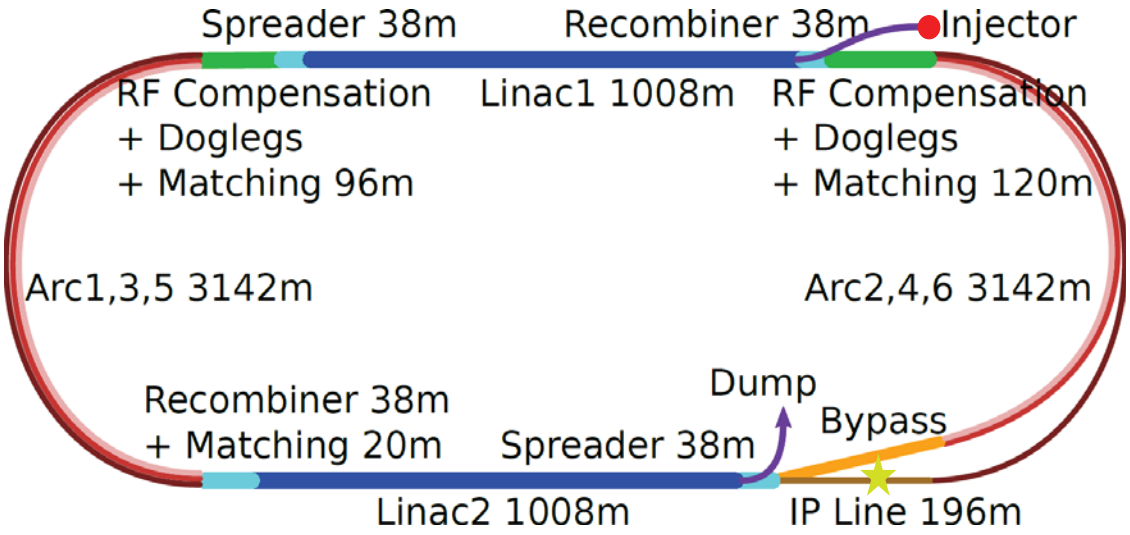

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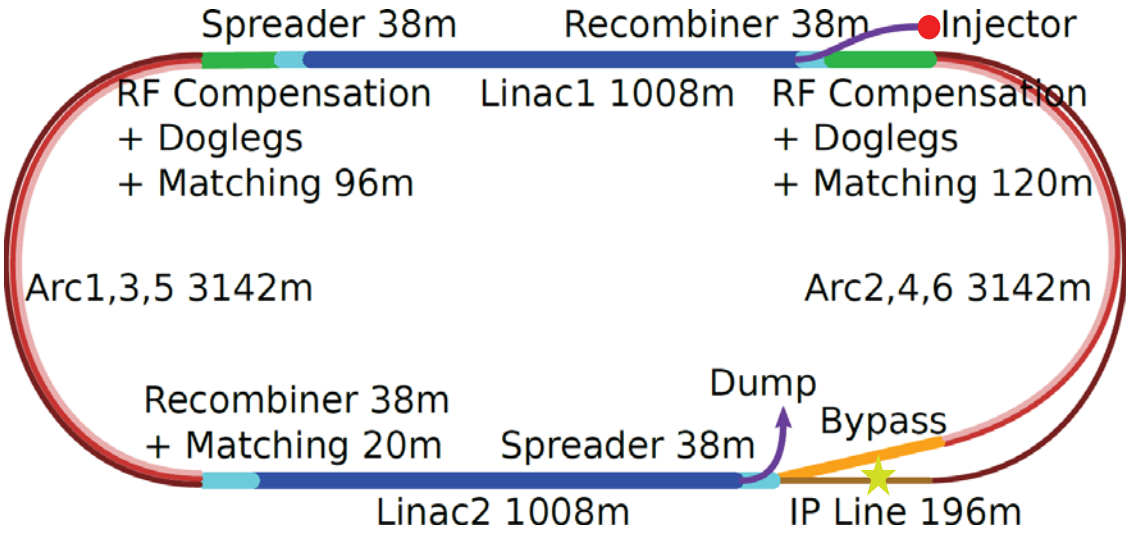

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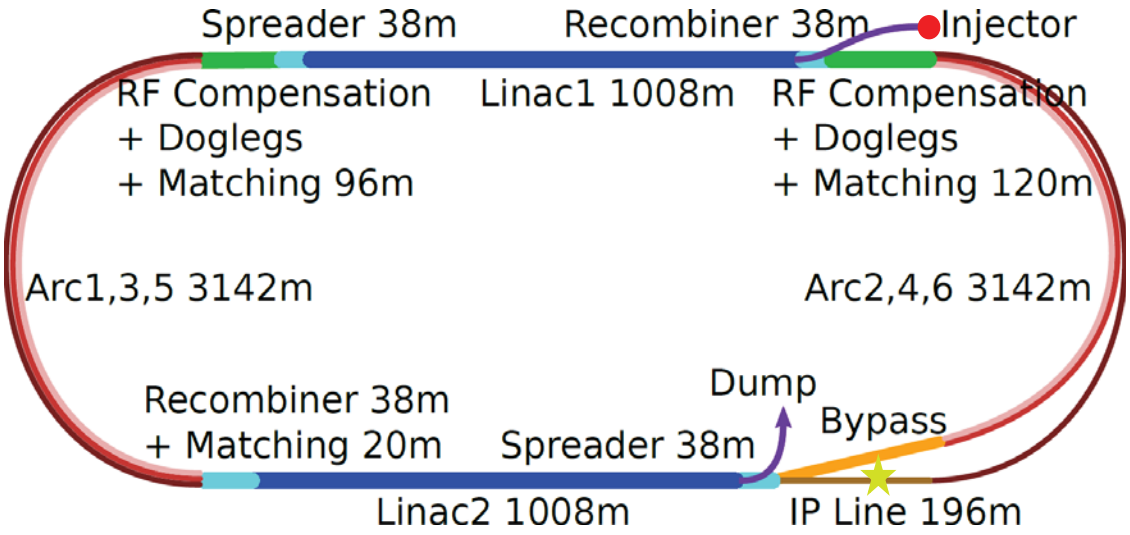

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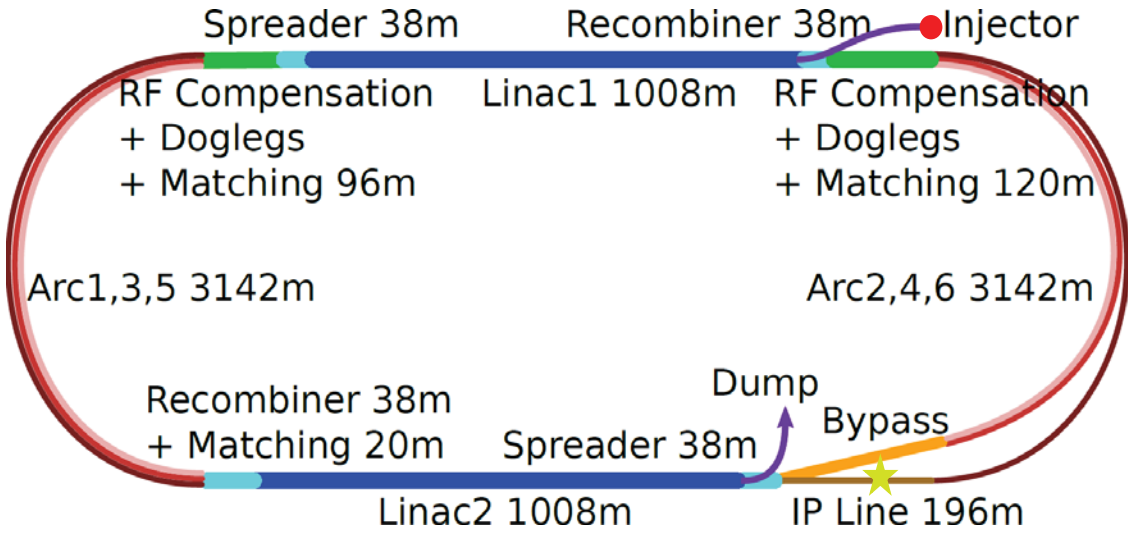

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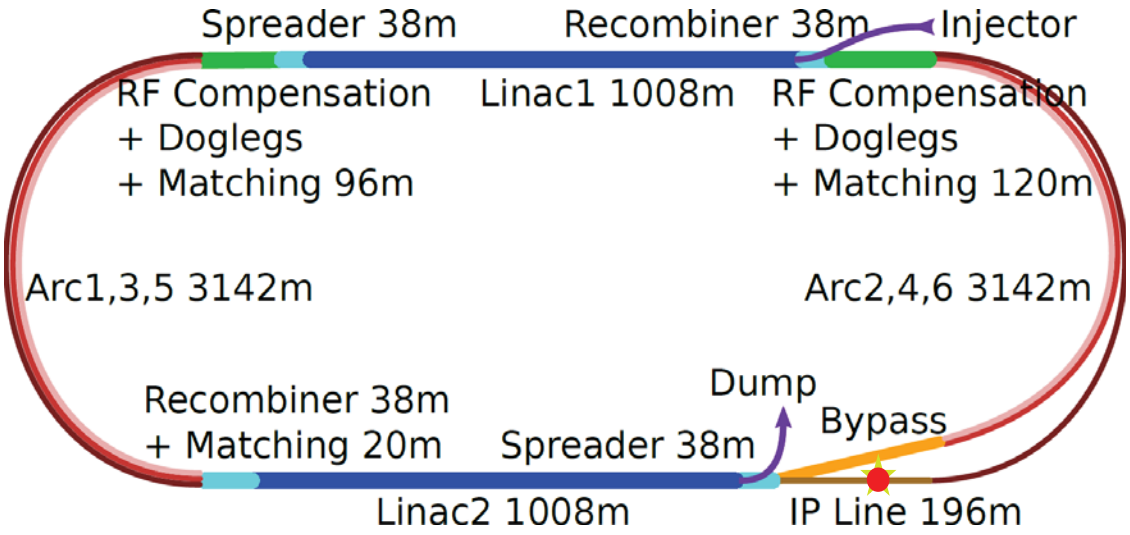

Arc6: $\Delta s = \lambda/2$

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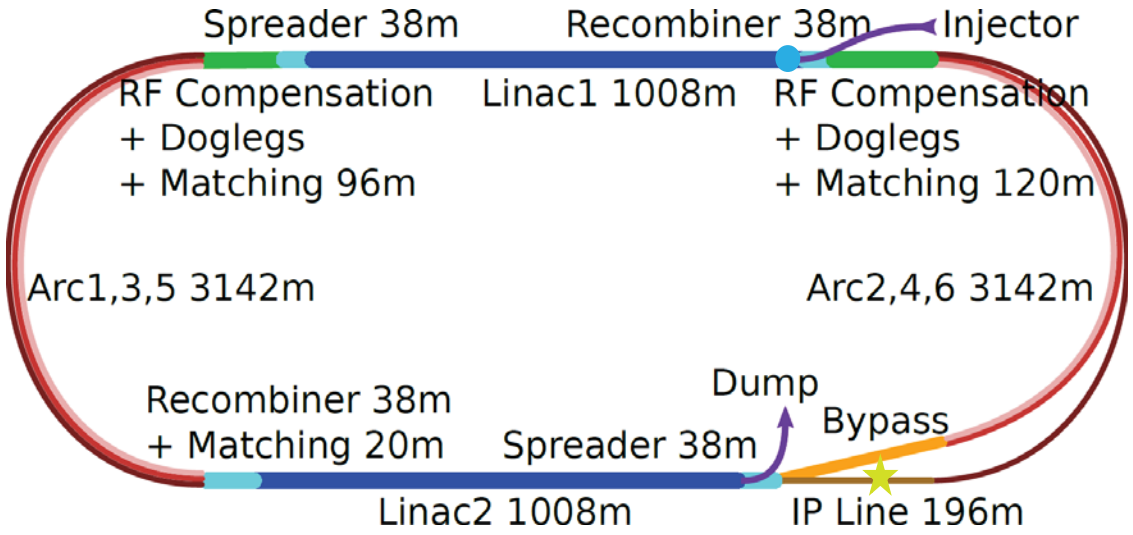

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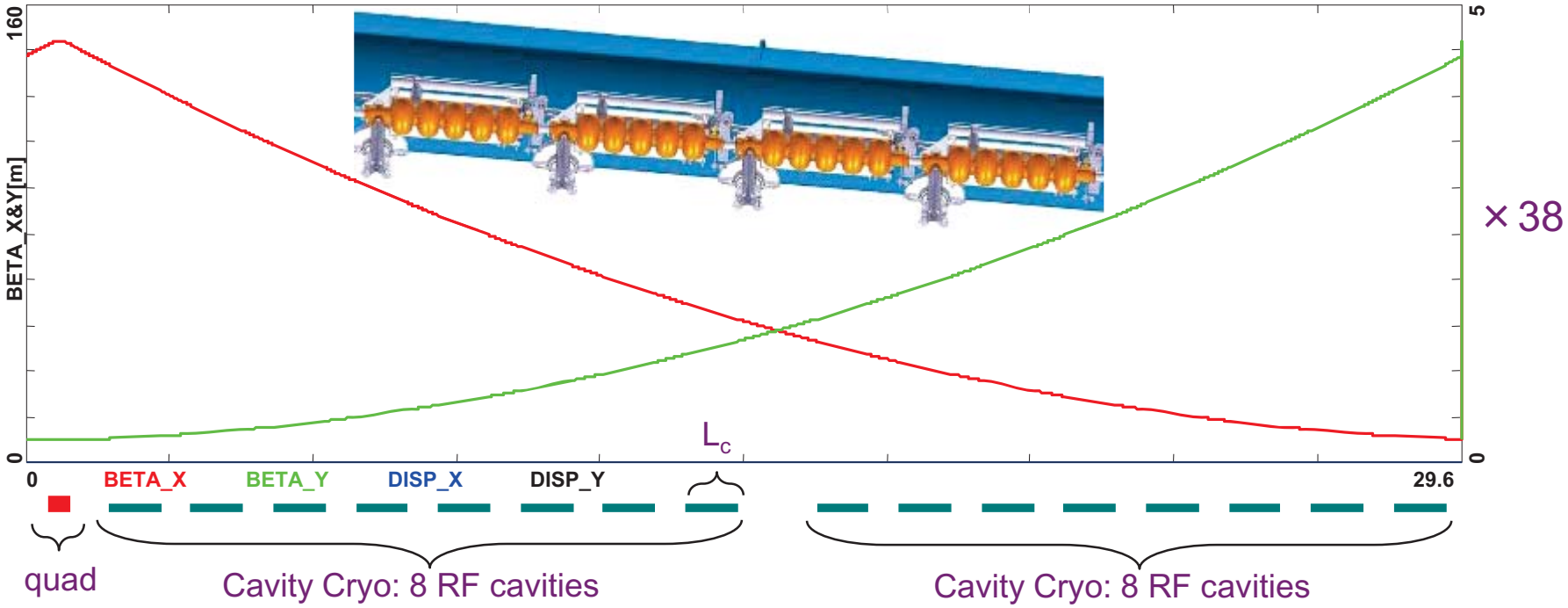
Cryo Unit Layout/Optics – Half-Cell 130^0 FODO



802 MHz RF, 5-cell cavity:

λ = 37.38 cm

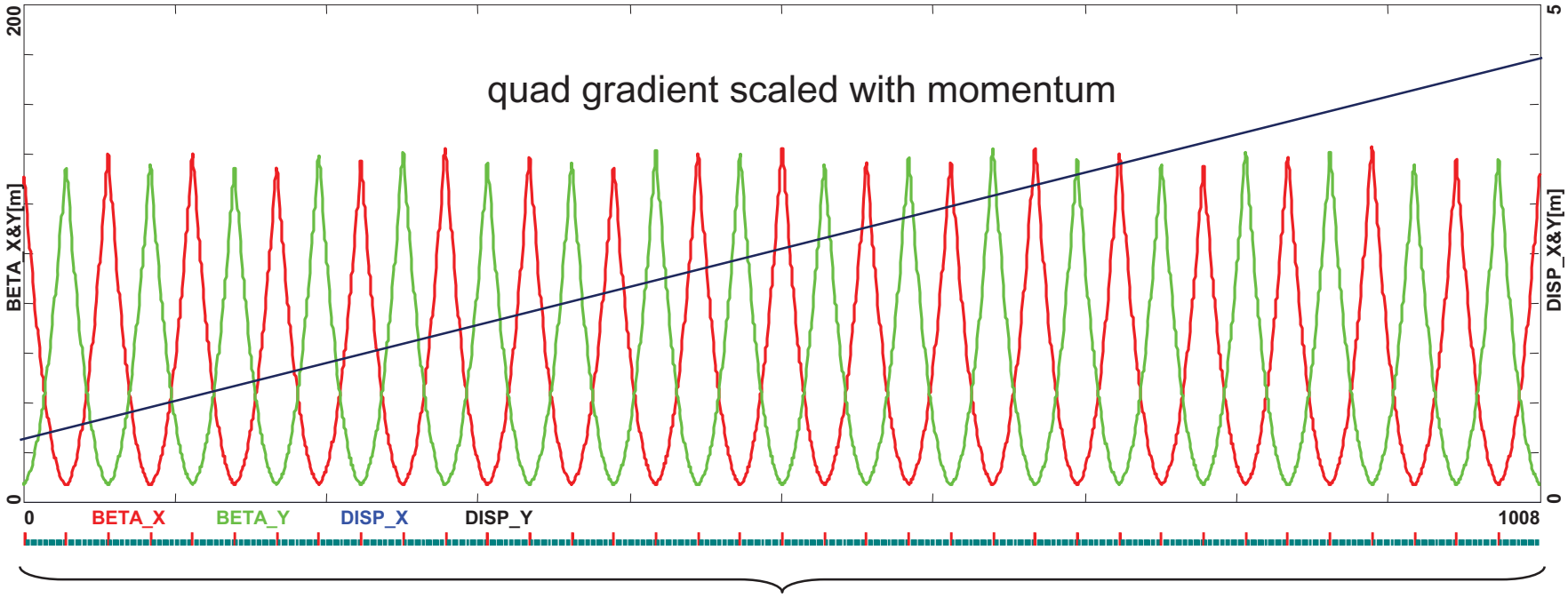
$L_c = 5\lambda/2 = 93.45$ cm

Grad = 18 MeV/m (16.8 MeV per cavity)

ΔE= 269.14 MV per Cryo Unit

10 GeV Linac Optics - Focusing Profile

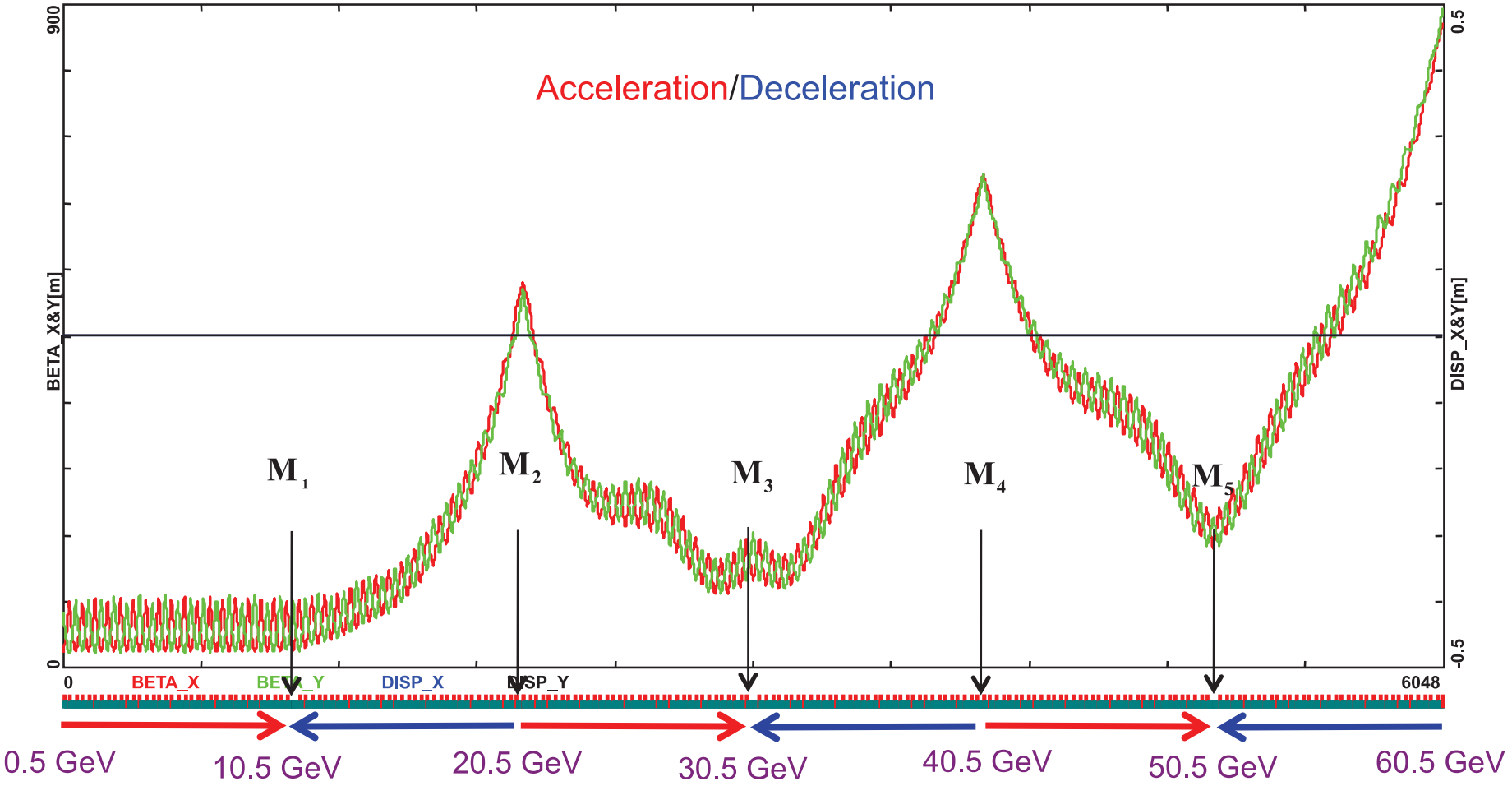
E = 0.5 – 10.5 GeV



19 FODO cells (19 × 2 × 16 = 608 RF cavities)

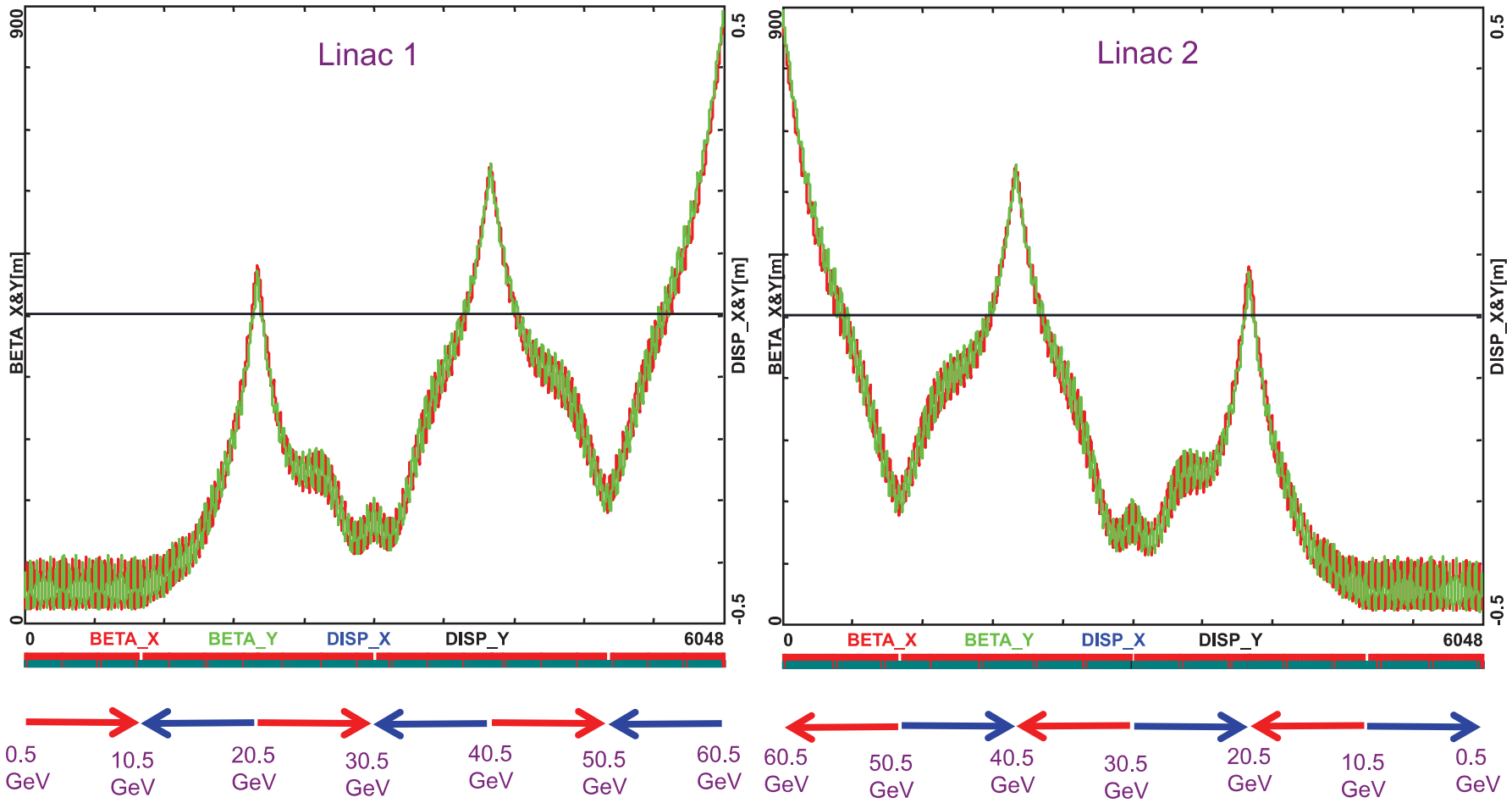
$$\left\langle \frac{\beta}{E} \right\rangle = \left(\frac{1}{L} \int \frac{\beta}{E}\, ds \right)_{\min}$$

Linac 1 – Multi-pass ER Optics

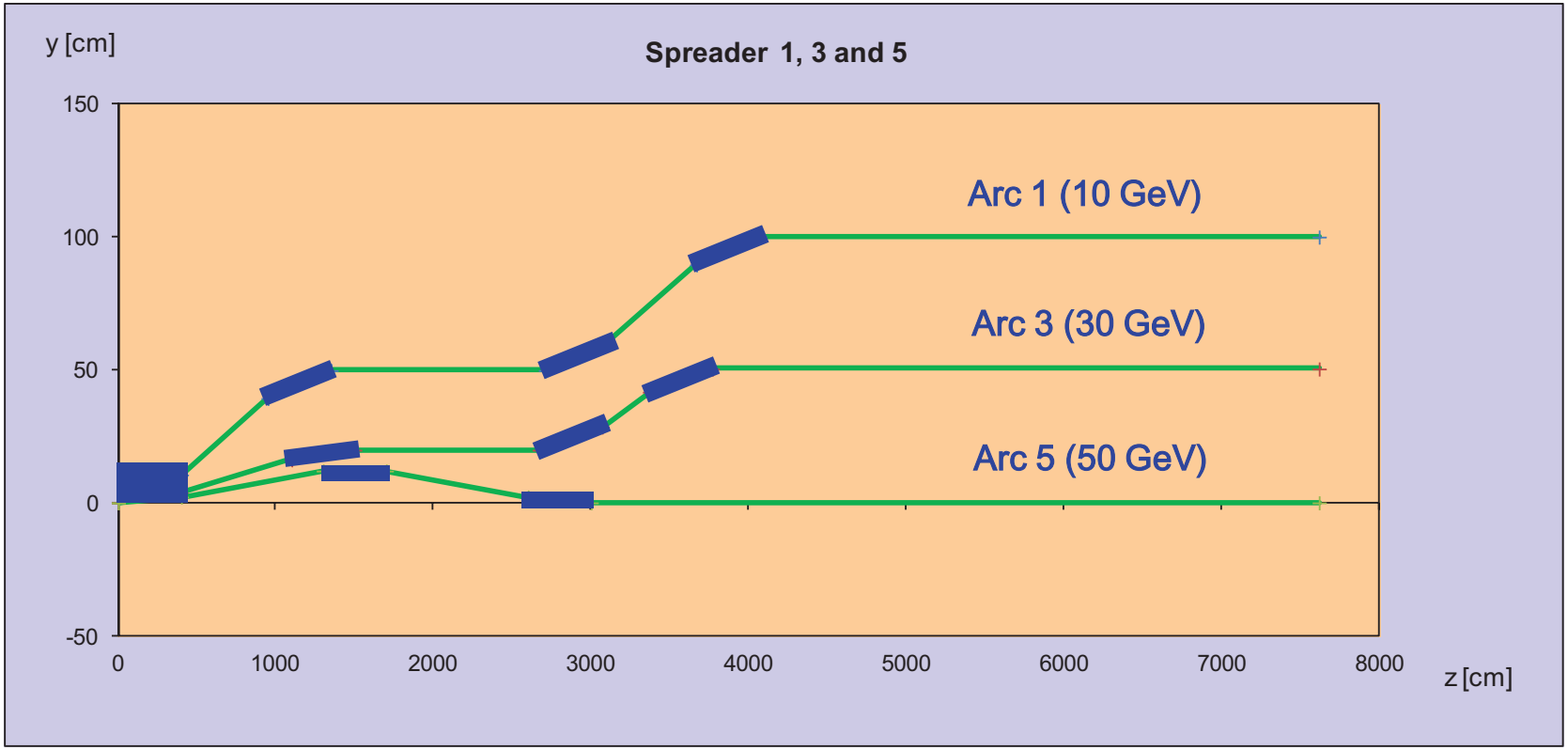


Linac 1 and 2 – Multi-pass ER Optics

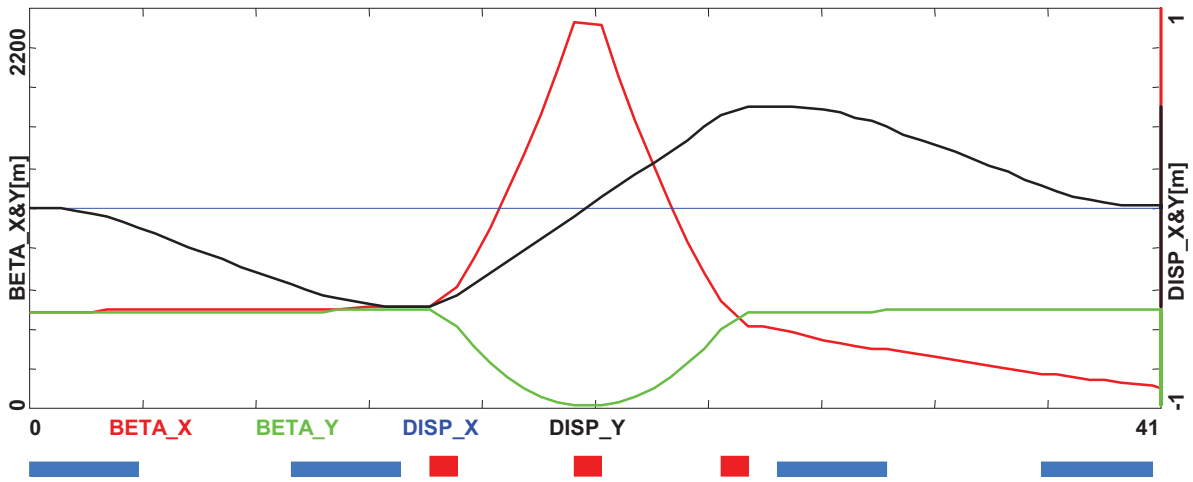
Acceleration/Deceleration



Vertical Separation of Arcs



Vertical Spreaders (20 GeV) – Optics



Bends (4):

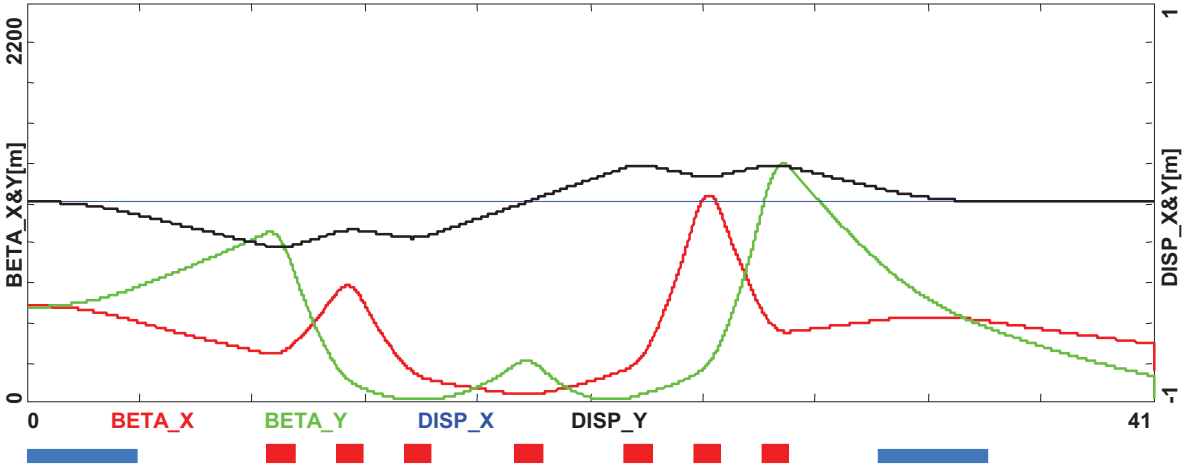
$ang= 3 deg.

$Lb=400 cm

$B=0.9 Tesla

Quads (3):

$G=14 Tesla/m



Bends (2):

$ang= 1.86 deg
$Lb=400 cm

$B=0.54 Tesla

Quads (7):

$G=22-43 Tesla/m

Arc Optics – Emittance preserving FMC cell

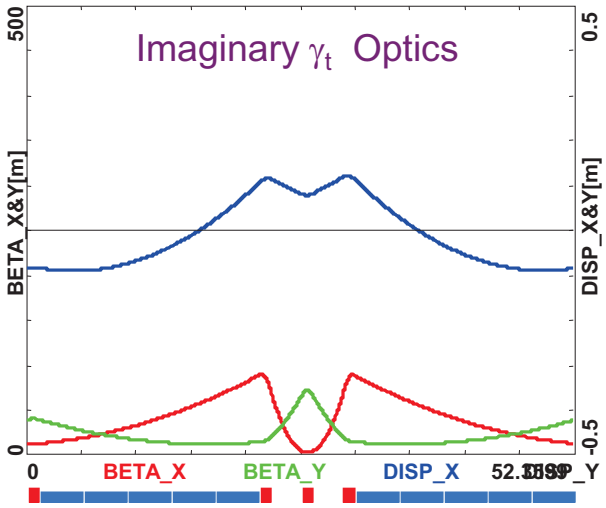
- Emittance dilution due to quantum excitations:

$$\Delta\varepsilon_x^N = \frac{55\, r_0}{48\sqrt{3}}\frac{\hbar c}{mc^2}\gamma^6 I_5$$

$$I_5 = \int_0^L \frac{H}{|\rho|^3} ds = \frac{\theta\langle H\rangle}{\rho^2}$$

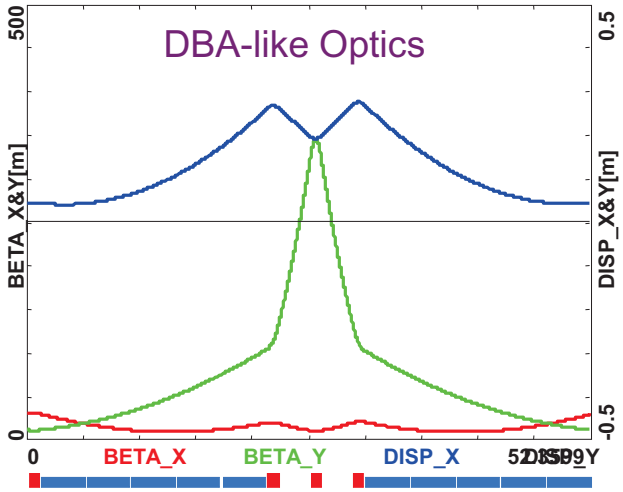
$$H = \gamma D^2 + 2\alpha DD' + \beta D'^2$$

Arc 1 , Arc2



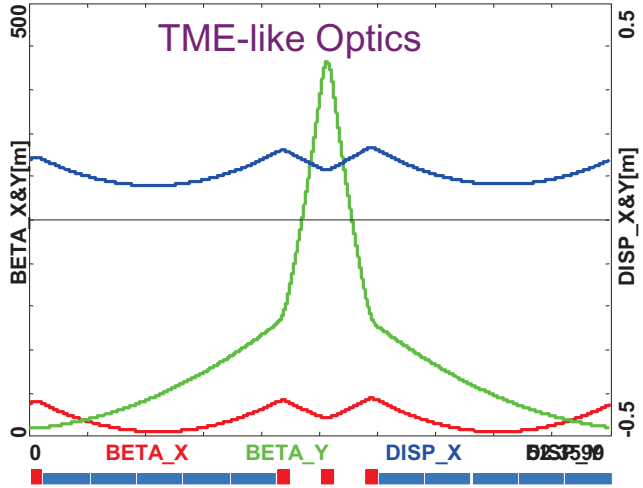
$$\langle H\rangle = 8.8 \times 10^{-3}\ m$$

Arc 3, Arc 4



$$\langle H\rangle = 2.2 \times 10^{-3}\ m$$

Arc5, Arc 6



$$\langle H\rangle = 1.2 \times 10^{-3}\ m$$

factor of 20 smaller than FODO

total emittance increase in Arc 1- 5: $\Delta\varepsilon_x^N$ = 4.9 μm rad

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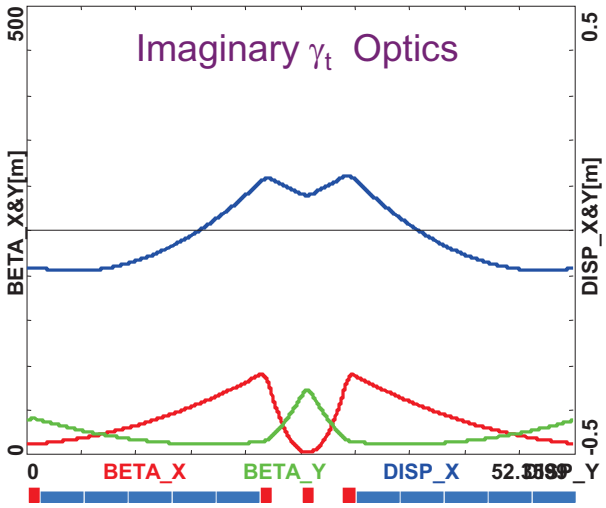

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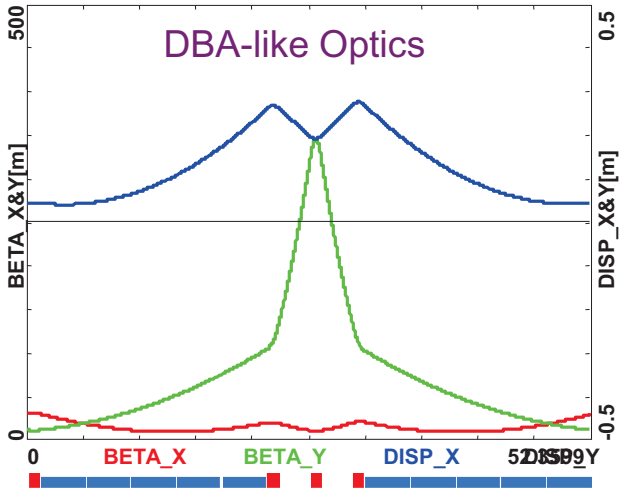

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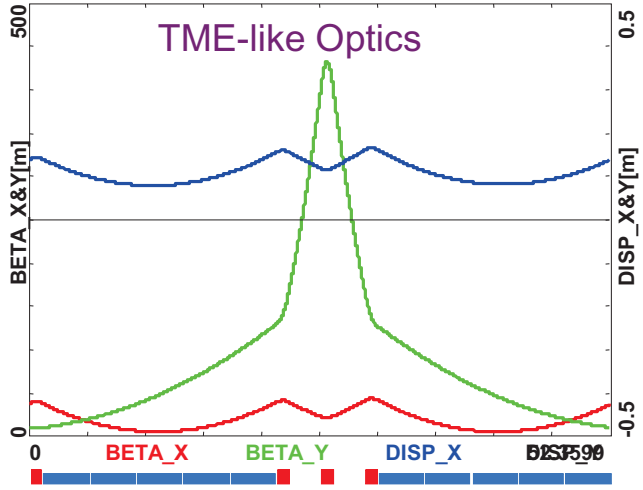

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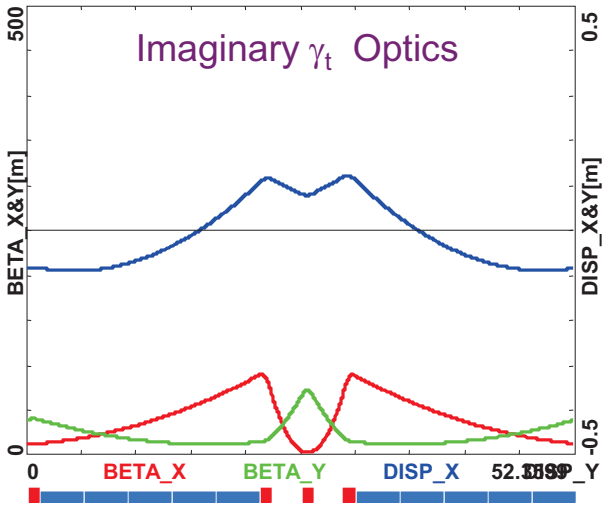
$$I_5 = \int_0^L \frac{H}{|\rho|^3} ds = \frac{\theta\langle H\rangle}{\rho^2}$$

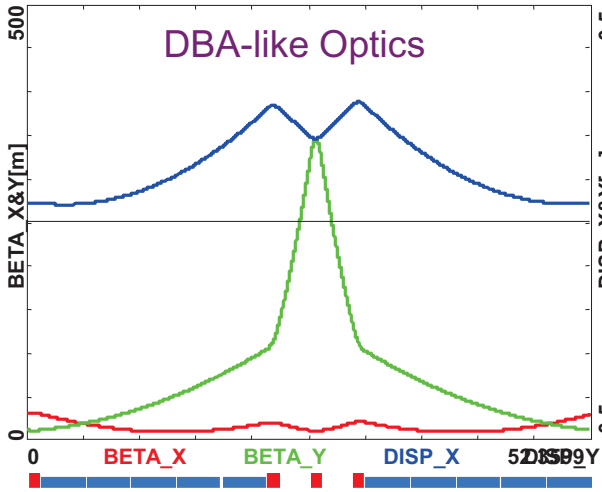
$$H = \gamma D^2 + 2\alpha DD' + \beta D'^2$$

Arc 1 , Arc2



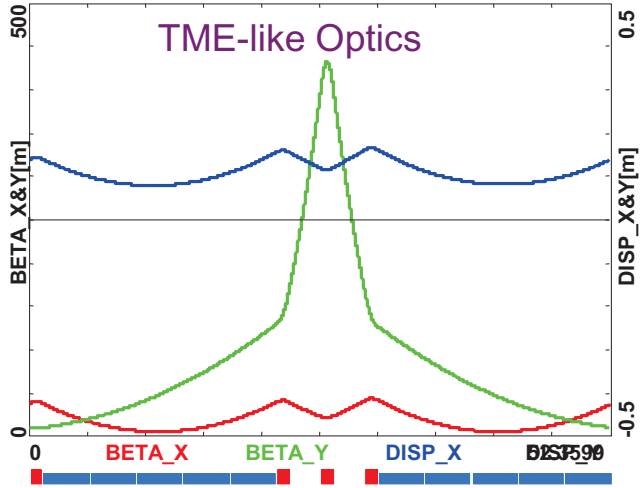
$$\langle H\rangle = 8.8 \times 10^{-3}\ m$$

Arc 3, Arc 4



$$\langle H\rangle = 2.2 \times 10^{-3}\ m$$

Arc5, Arc 6

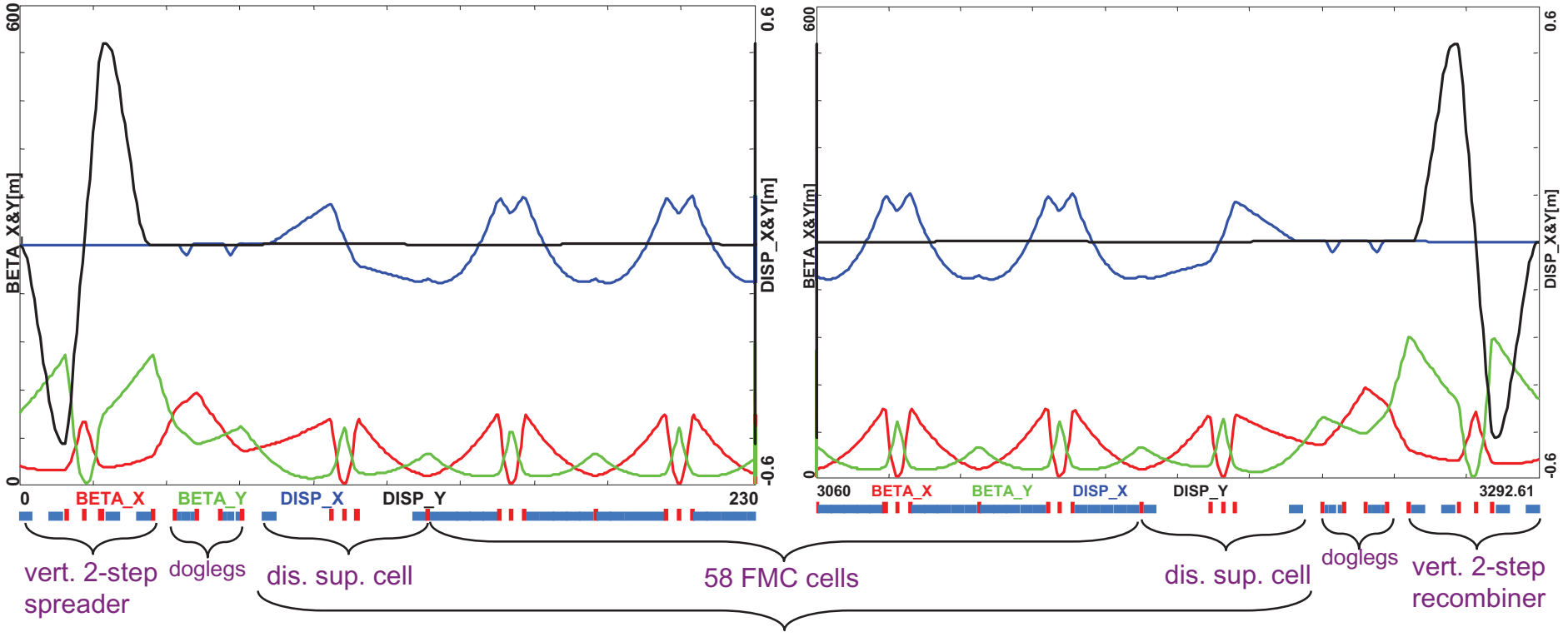


$$\langle H\rangle = 1.2 \times 10^{-3}\ m$$

factor of 20 smaller than FODO

total emittance increase in Arc 1- 5: $\Delta\varepsilon_x^N$ = 4.9 μm rad

Arc 1 Optics (10 GeV)

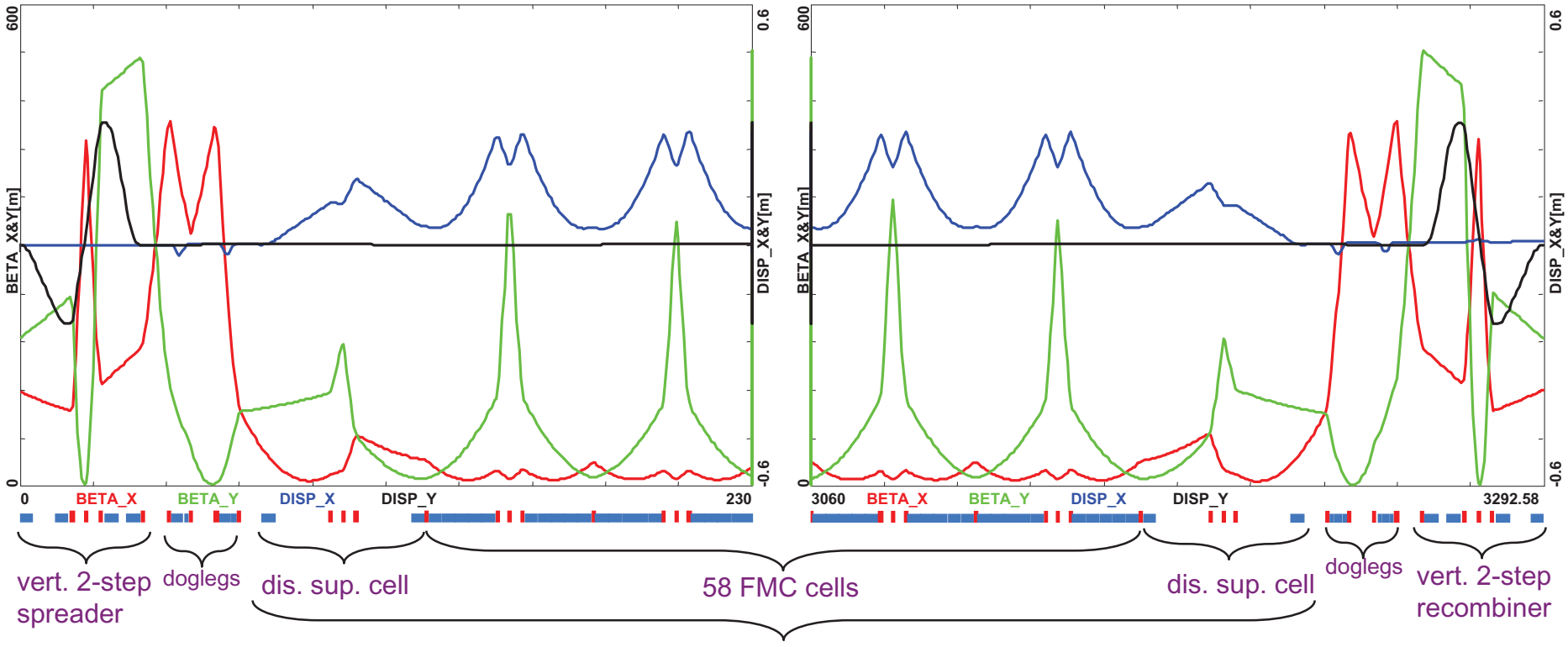


Arc dipoles:

$Lb=400 cm

$B=0.47 kGauss

Arc 3 Optics (30 GeV)

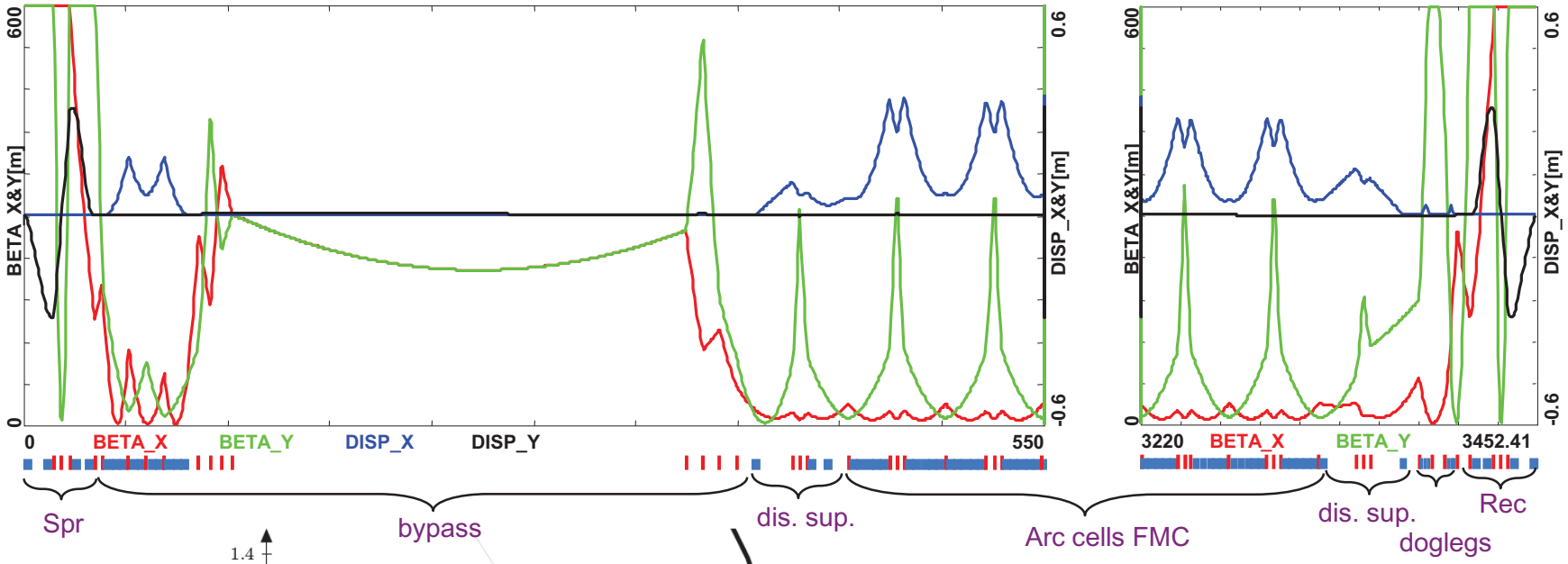


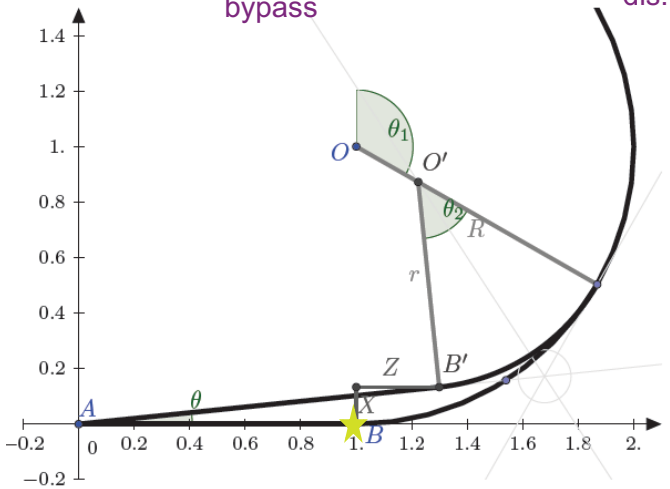
Arc dipoles:

$Lb=400 cm

$B=1.37 kGauss

Arc 4 (with bypass) Optics (40 GeV)





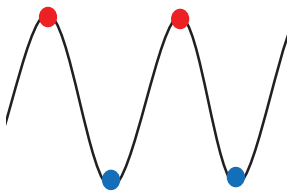
$$X = R + (R - r)\cos(\theta_1) + r\cos(\theta_1 + \theta_2)$$
$$Z = (R - r)\sin(\theta_1) + r\sin(\theta_1 + \theta_2)$$

SR Energy Loss and RF Compensation

turn no	E [GeV]	ΔE [MeV]	Cryomodules
1	10.4	0.7	0
2	20.3	9.9	0
3	30.3	48.5	1
4	40.2	151	1
5	50.1	365	3
6	60.0	751	6
7	50.1	365	3
8	40.2	151	1
9	30.3	48.5	1
10	20.3	9.9	0
11	10.4	0.7	0
dump	0.5	0.0	

Frequency	1604 MHz
Gradient	30 MV/m
Design	9 cells
Cells length	841 mm
Structure length	<1 m
Cavity per cryomodule	6
Cryomodule length	~6 m
Cryomodule voltage	150 MV

802 MHz RF



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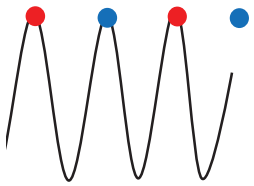

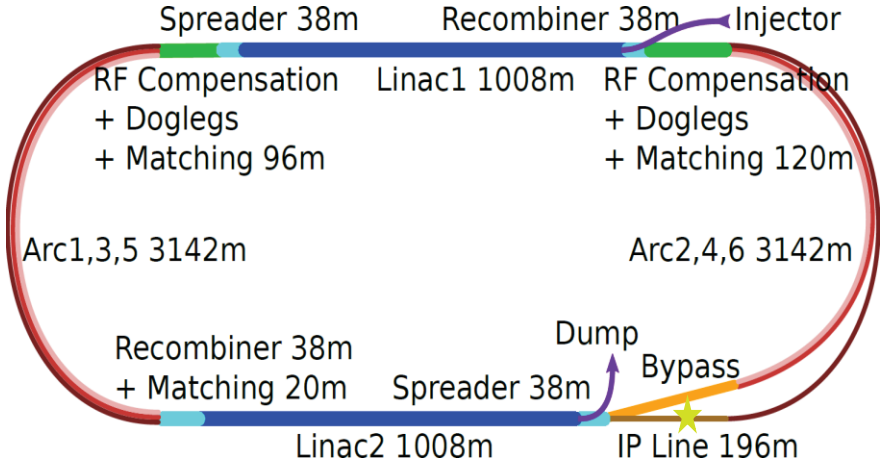

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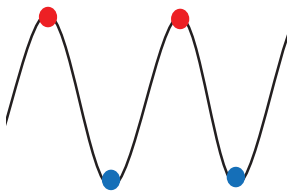

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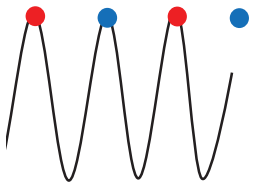

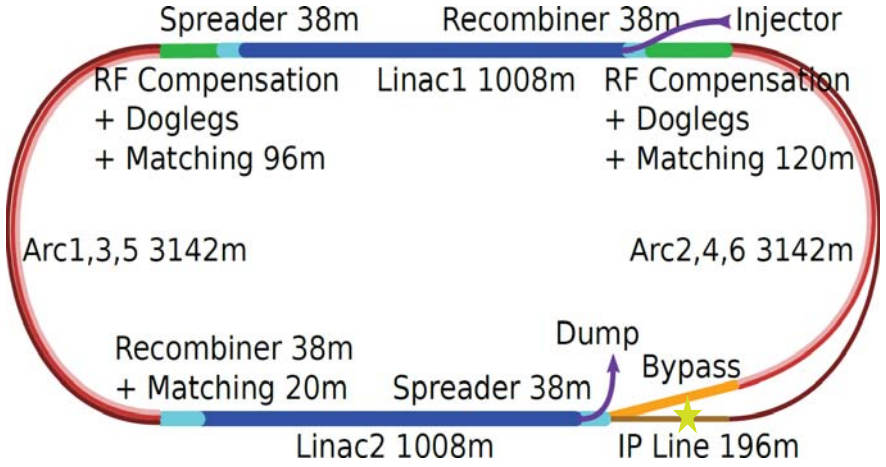

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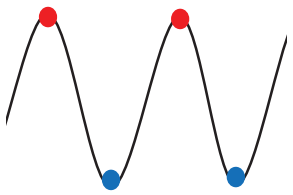

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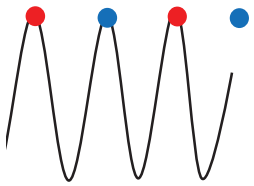

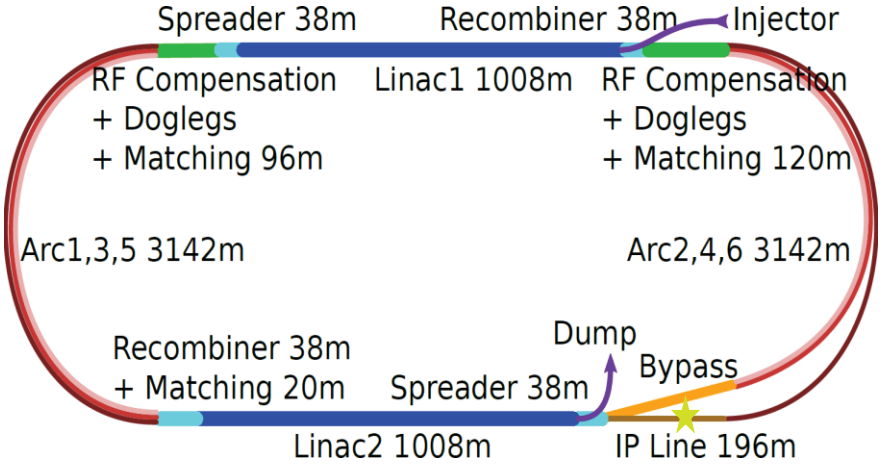

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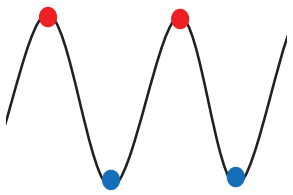

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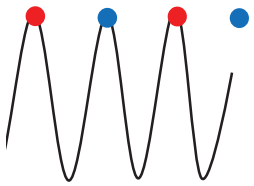
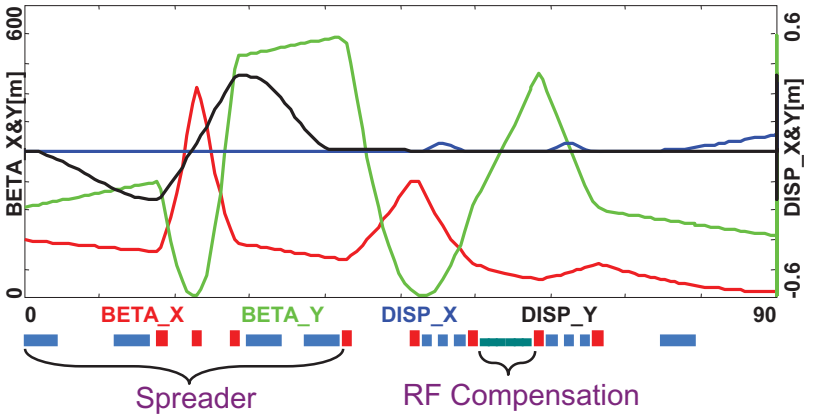




ERL Design – Summary

- Multi-pass linac Optics in ER mode
  - Choice of linac RF and Optics – 802 MHz SRF and 130^0 FODO
  - Linear lattice: 3-pass ‘up’ + 3-pass ‘down’
- Arc Optics Choice – Emittance preserving lattices
  - Quasi-isochronous lattices
  - Flexible Momentum Compaction Optics
  - Balanced emittance dilution & momentum compaction
- Complete Racetrack Lattice Architecture
  - Vertical switchyard
  - Matching sections & path-length correcting ‘doglegs’
  - Bypasses around the IR
  - SR Compensation with second harmonics RF

Tracking Simulations in the LHeC Recirculating Lattice

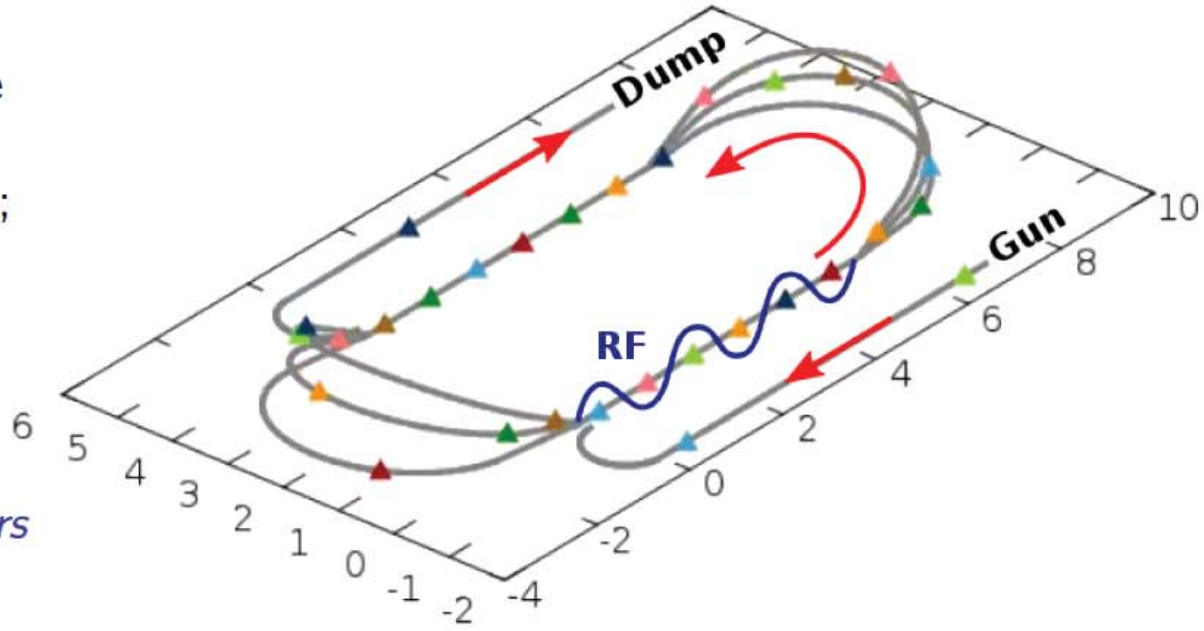
Overview

- The tool: PLACET2;
- End-to-end optics parameters;
- Synchrotron Radiation effect;
- Recombination Pattern and Long-Range Wakefields;
- Impact of Cavities misalignments.

PLACET2

New version of the tracking code PLACET equipped with the *recirculation module*.
Allows to simulate the propagation of many bunches in recirculating lattices.

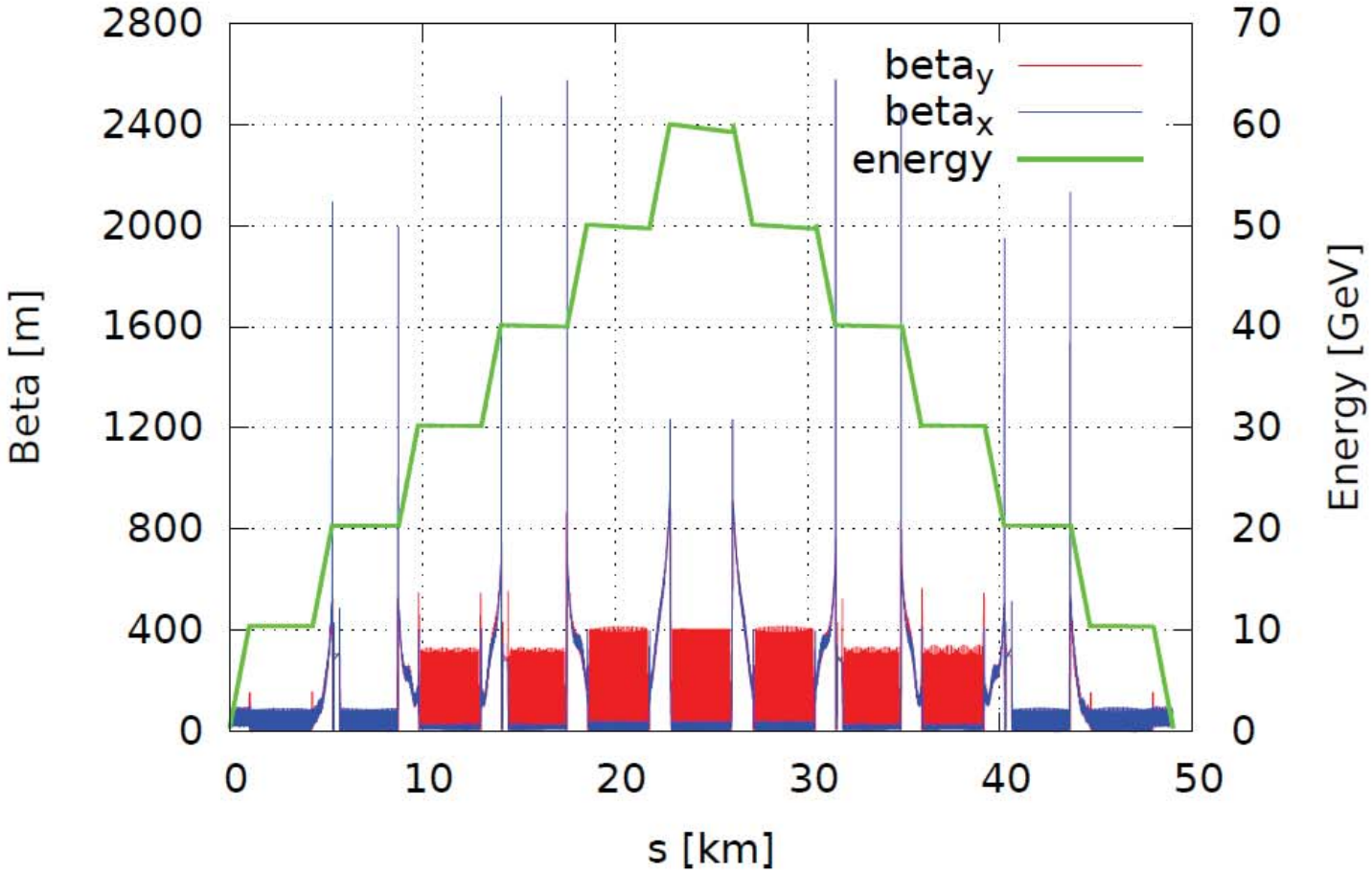
- description of multiple *beamlines* as standard sequences of elements;
- creation of *links* between them with runtime-evaluated routing criteria;
- new elements: *injectors* and *dumps*.



Each beamline sees the correct sequence of bunches even when the train is recombined → Can compute *multibunch effects*.
Parallel tracking implemented over different beamlines.

End-to-end Optics

PLACET2 extracts the optics parameters from the particle distribution. A test bunch is followed from the injector to the dump. Basic validation of the setup.



Notable: the energy loss due to synchrotron radiation in Arc 6, the different average β in the arcs, the recovery of the mismatch generated in the linacs.

Synchrotron Radiation

Has an important impact on the operation of the machines:

- Heavy *energy losses* (750 MeV in Arc 6 at 60 GeV): introduction of compensating sections, reduction of the energy recovery efficency.

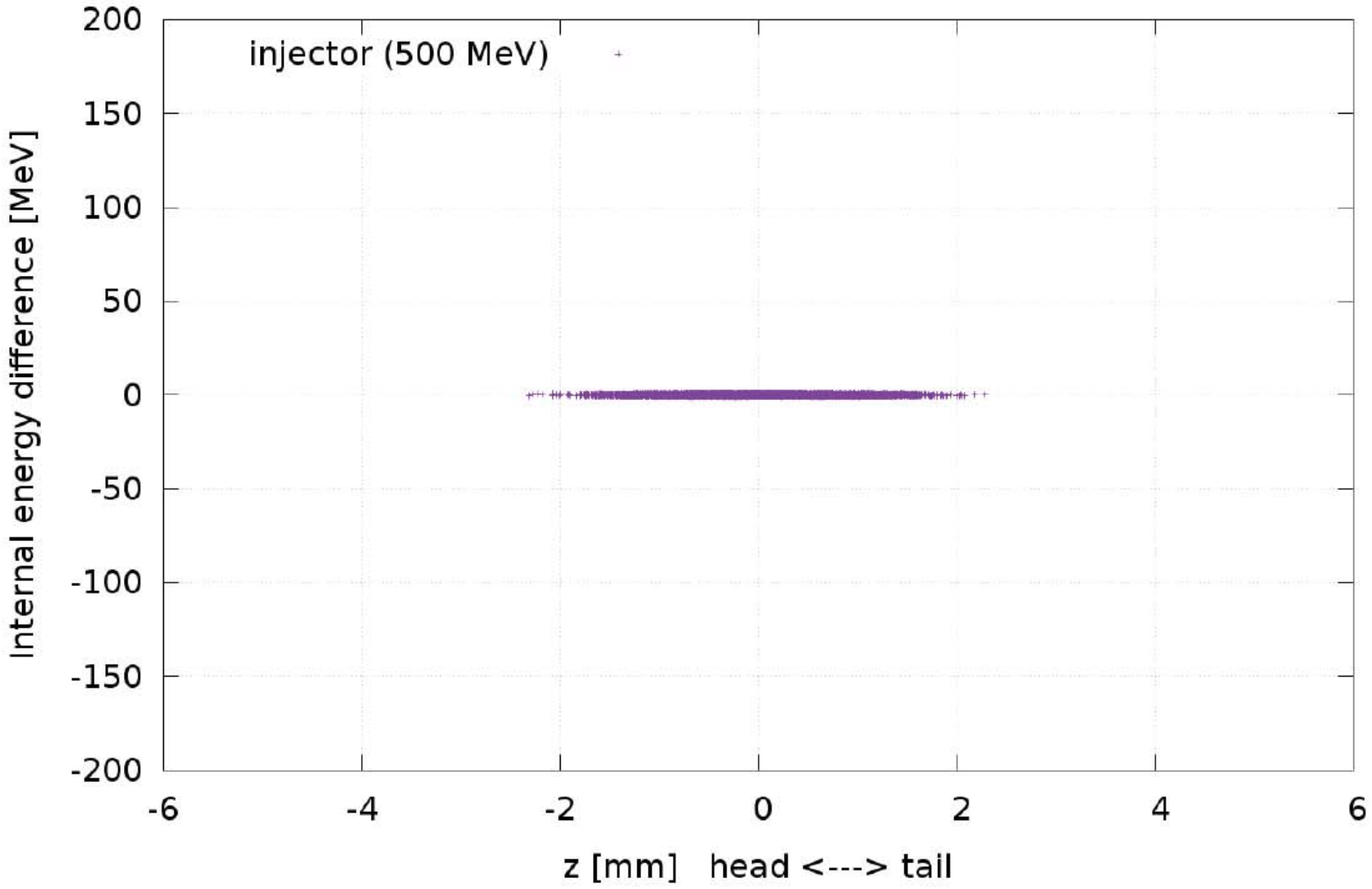
$\rightarrow$ Impact evaluated in the early design phase.

- *Quantum excitation* increases the emittance and the energy spread, what is the quality of the beam at collision? Can we complete the deceleration and reach the dump?

$\rightarrow$ Requires tracking studies.

Synchrotron Radiation

Evolution of the Longitudinal Phase Space



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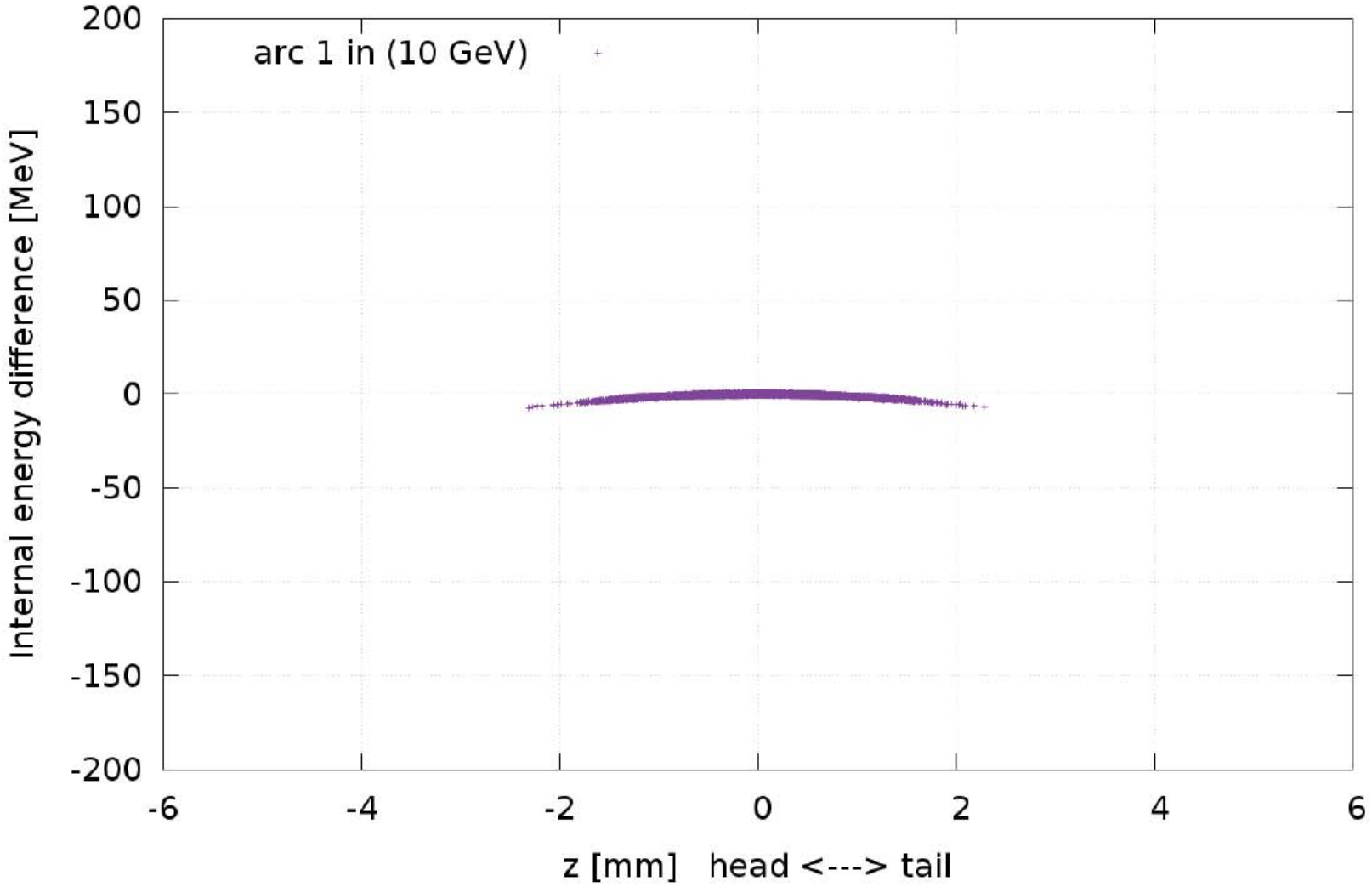

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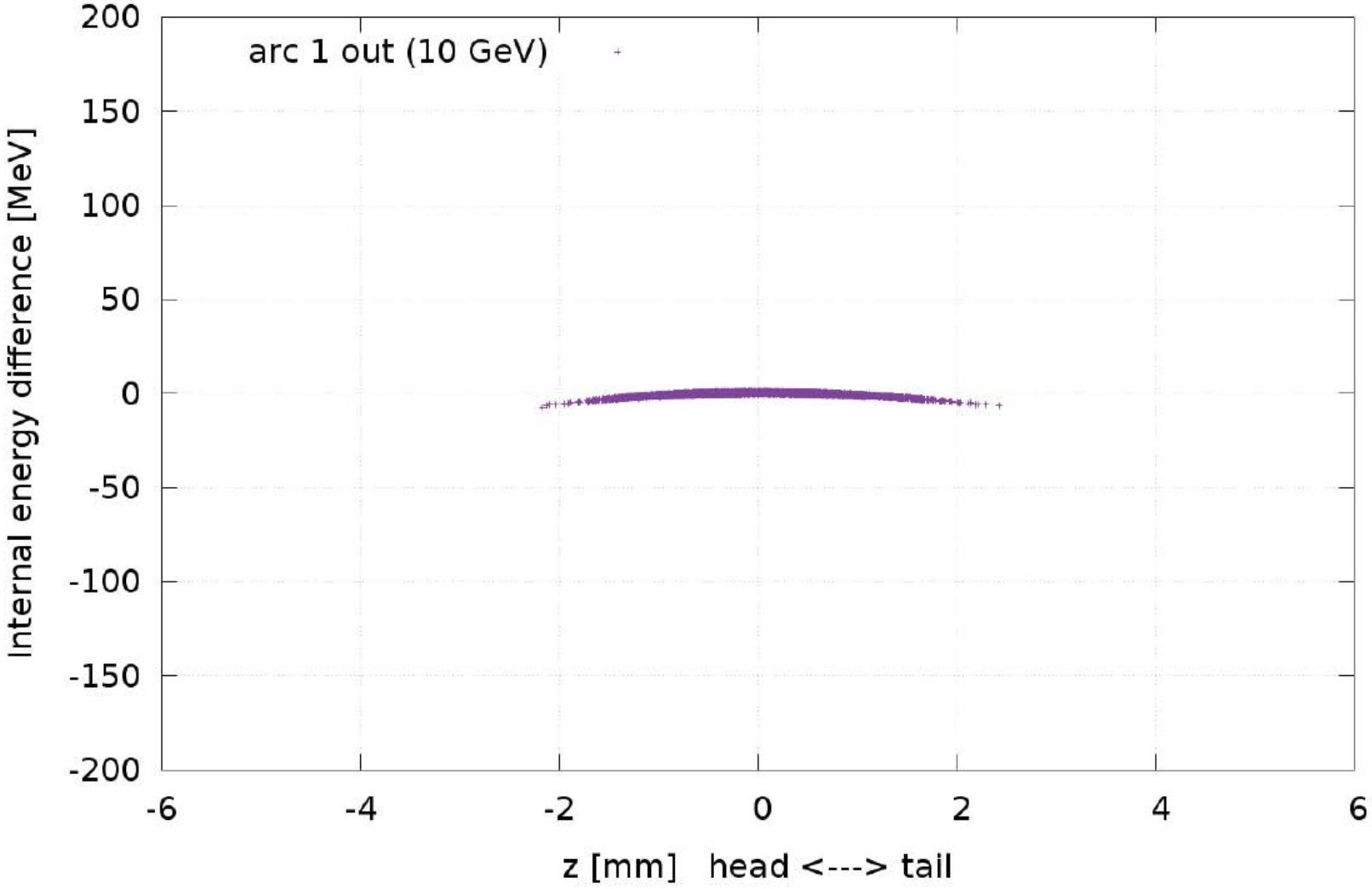

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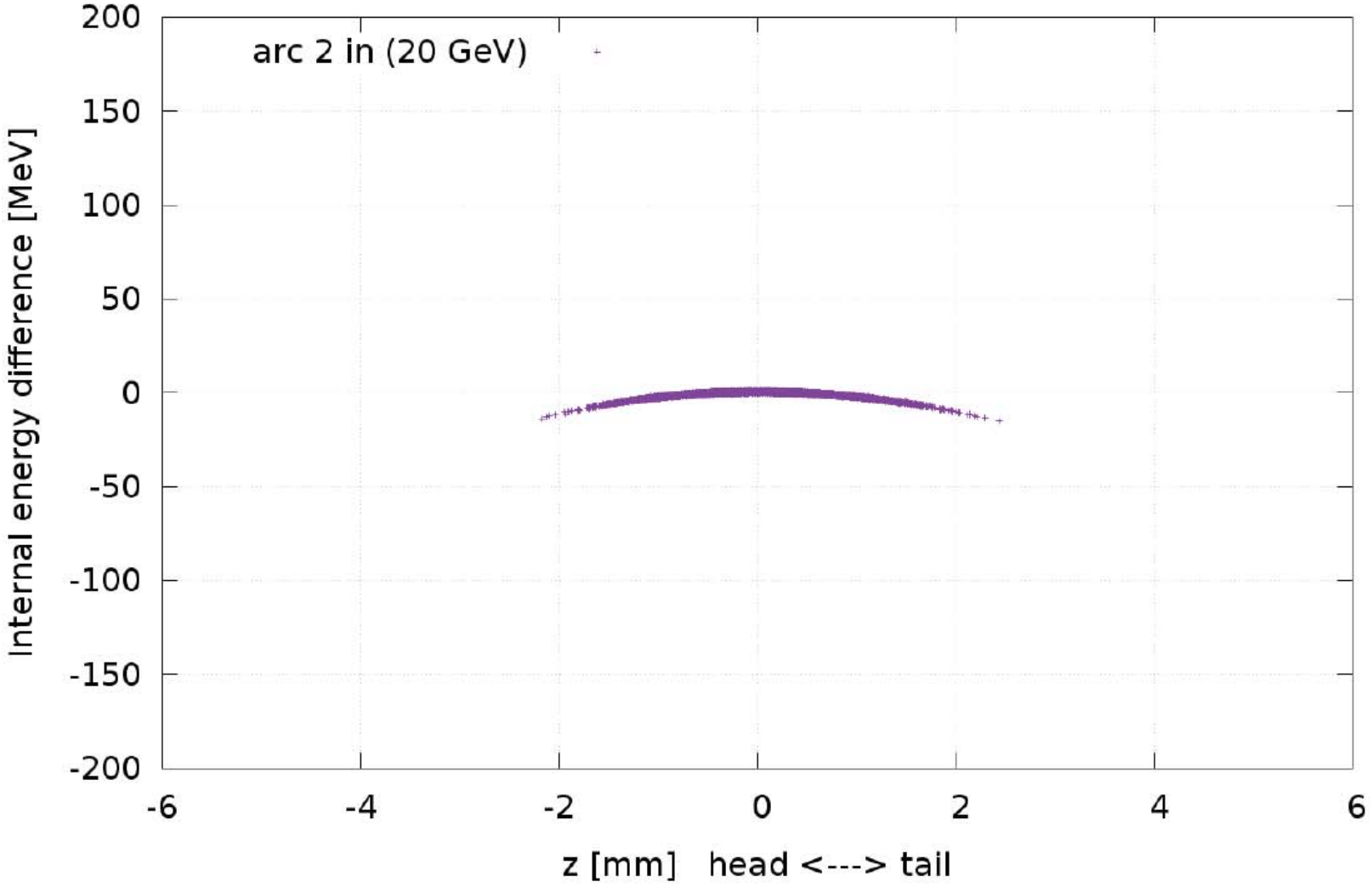

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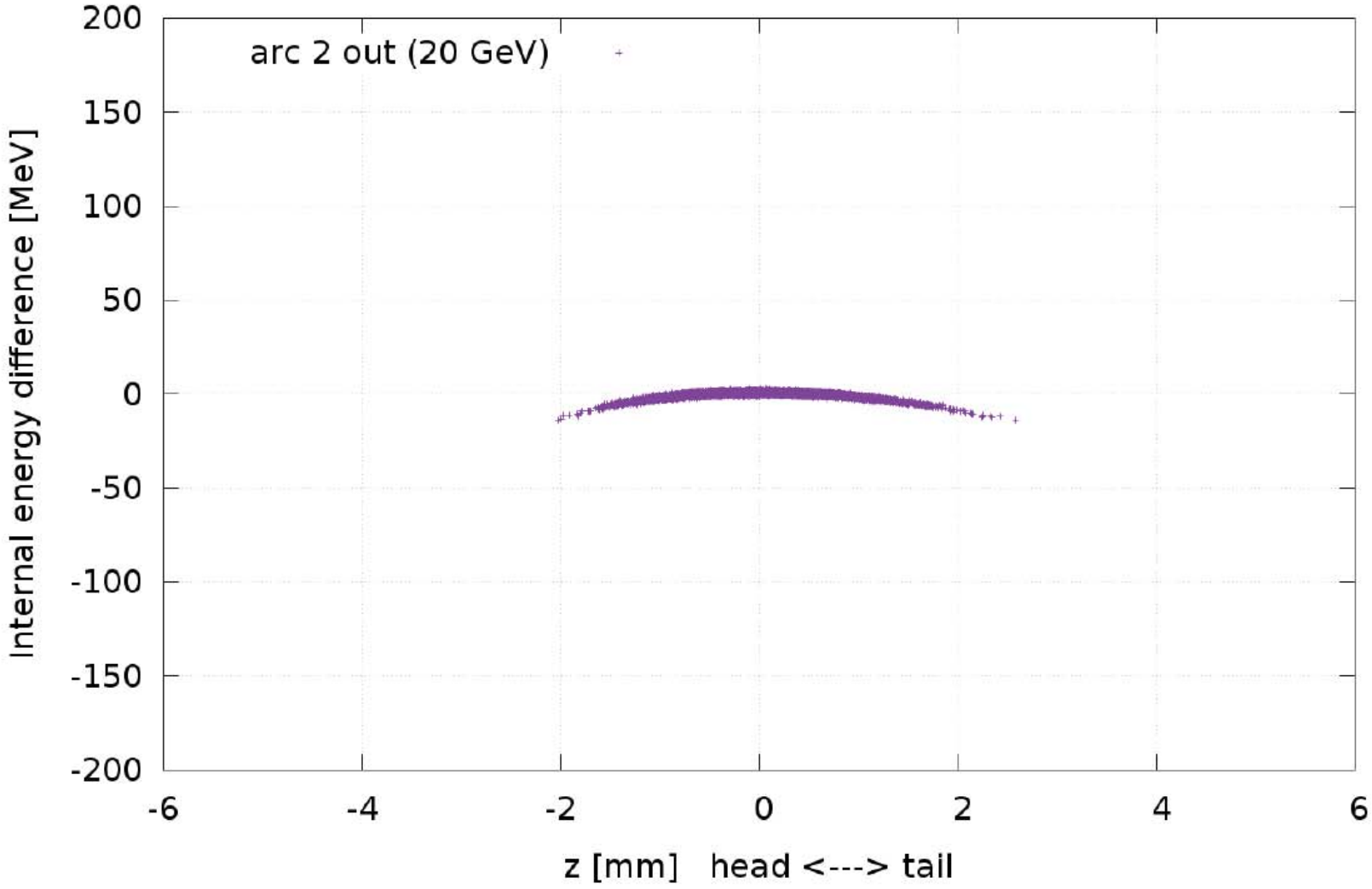

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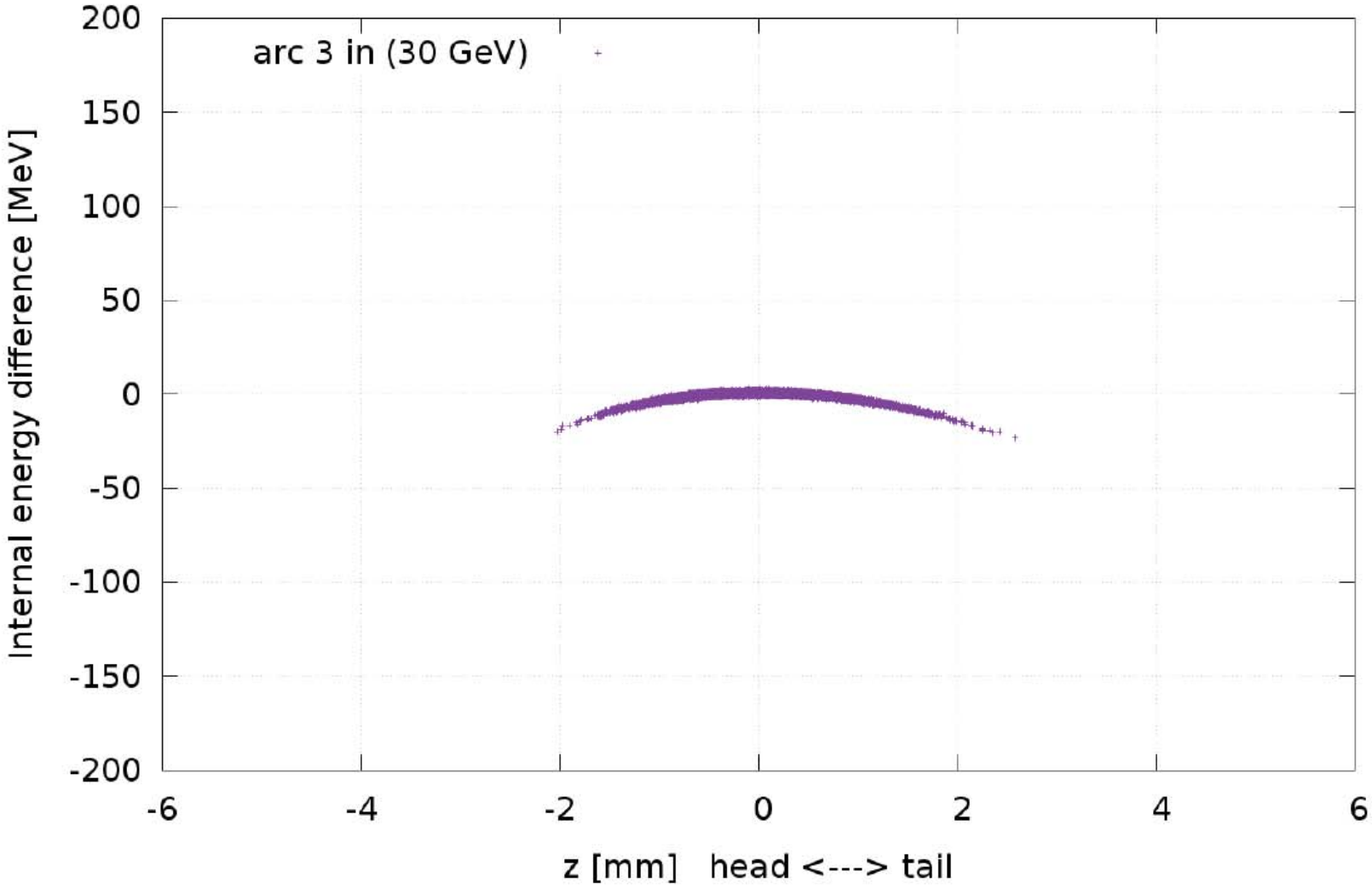

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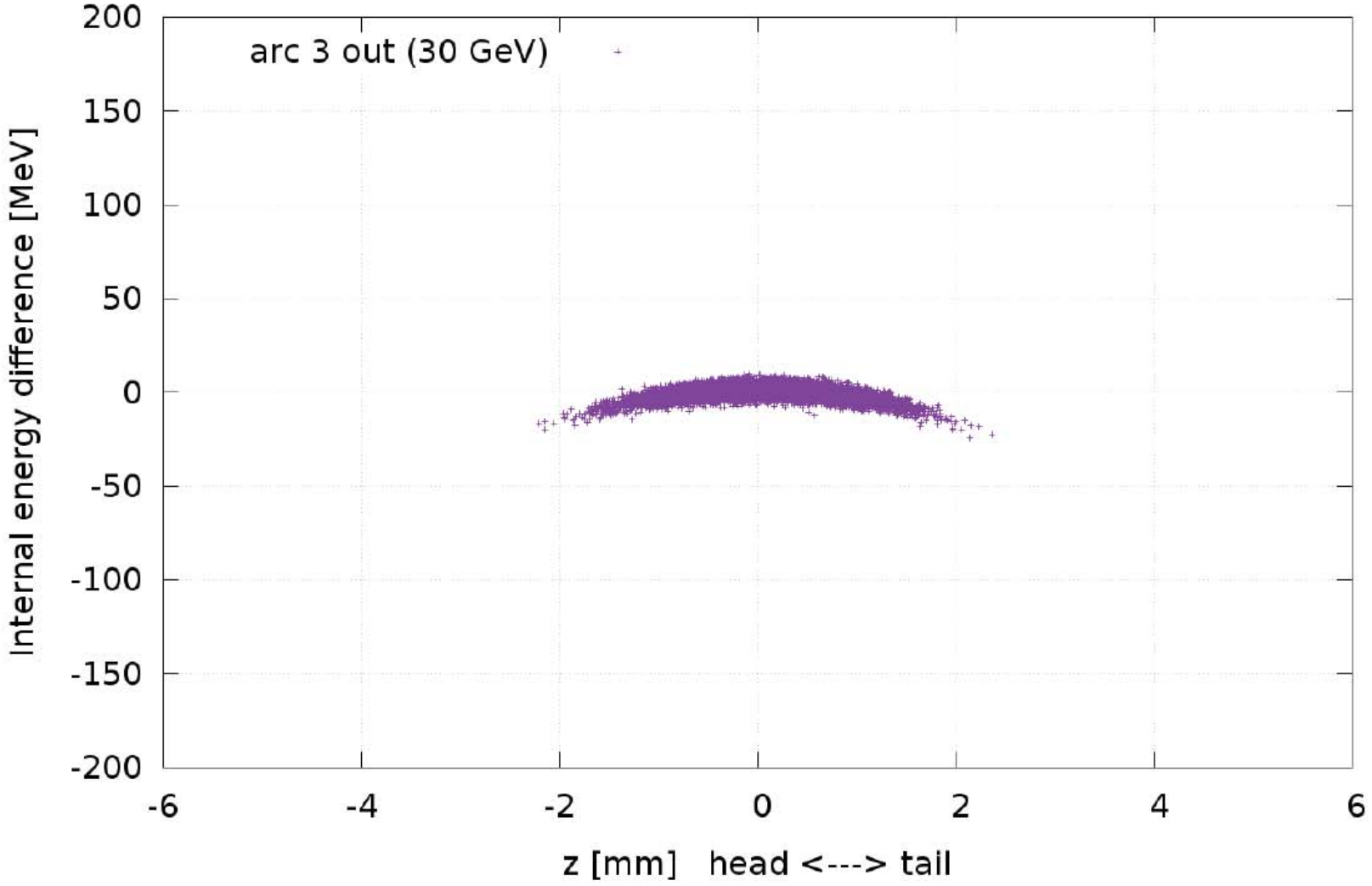

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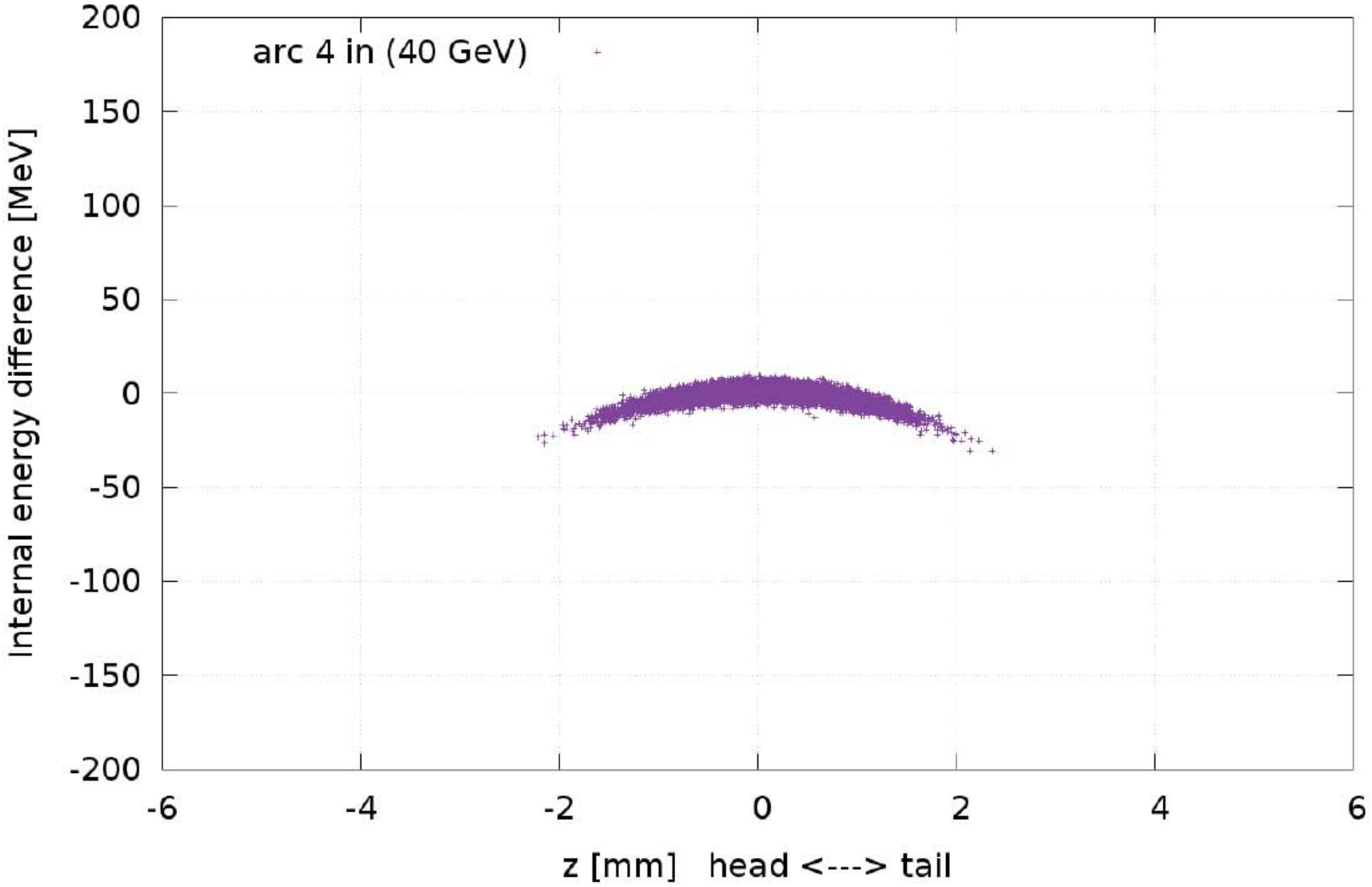

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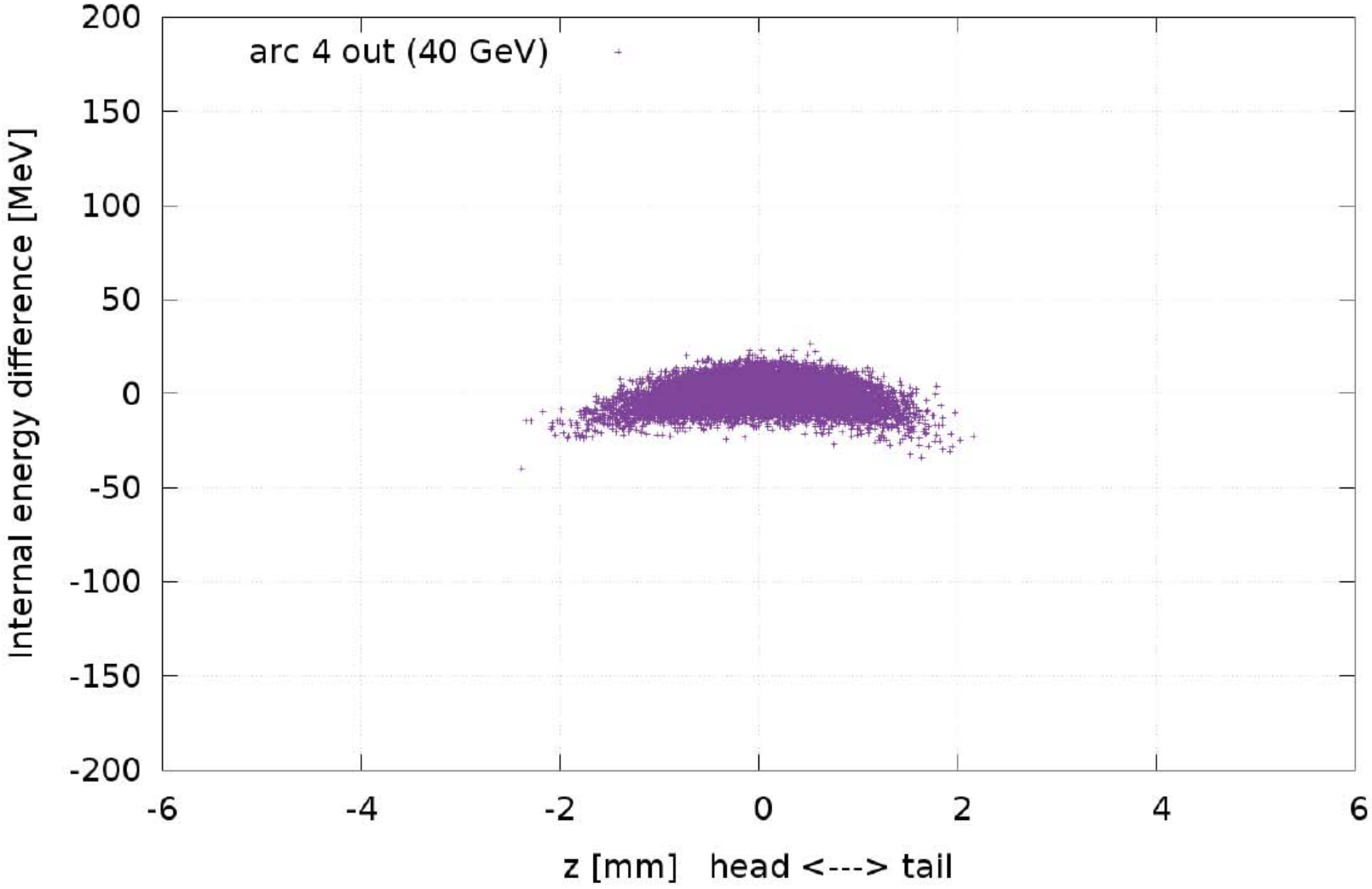

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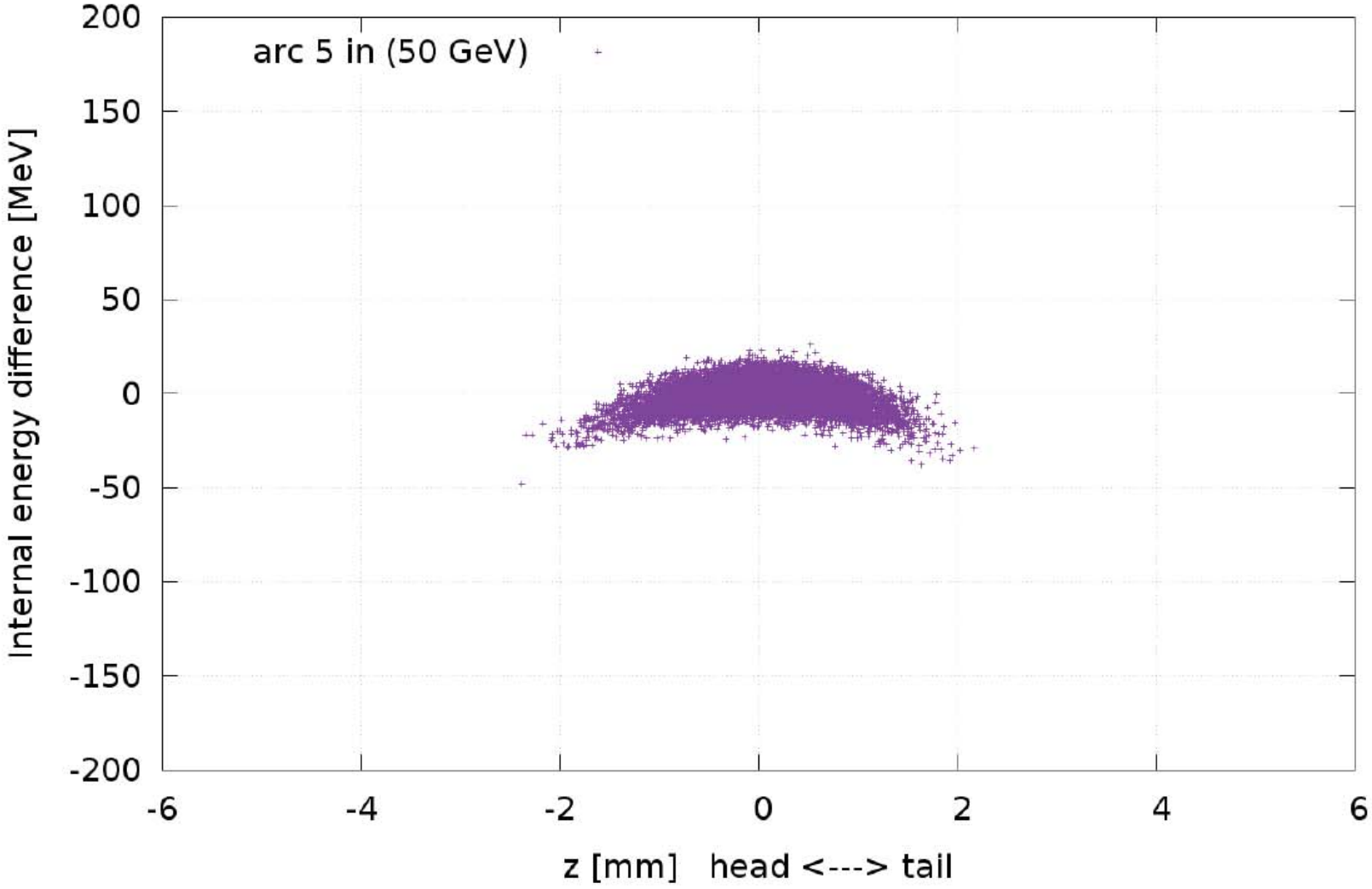

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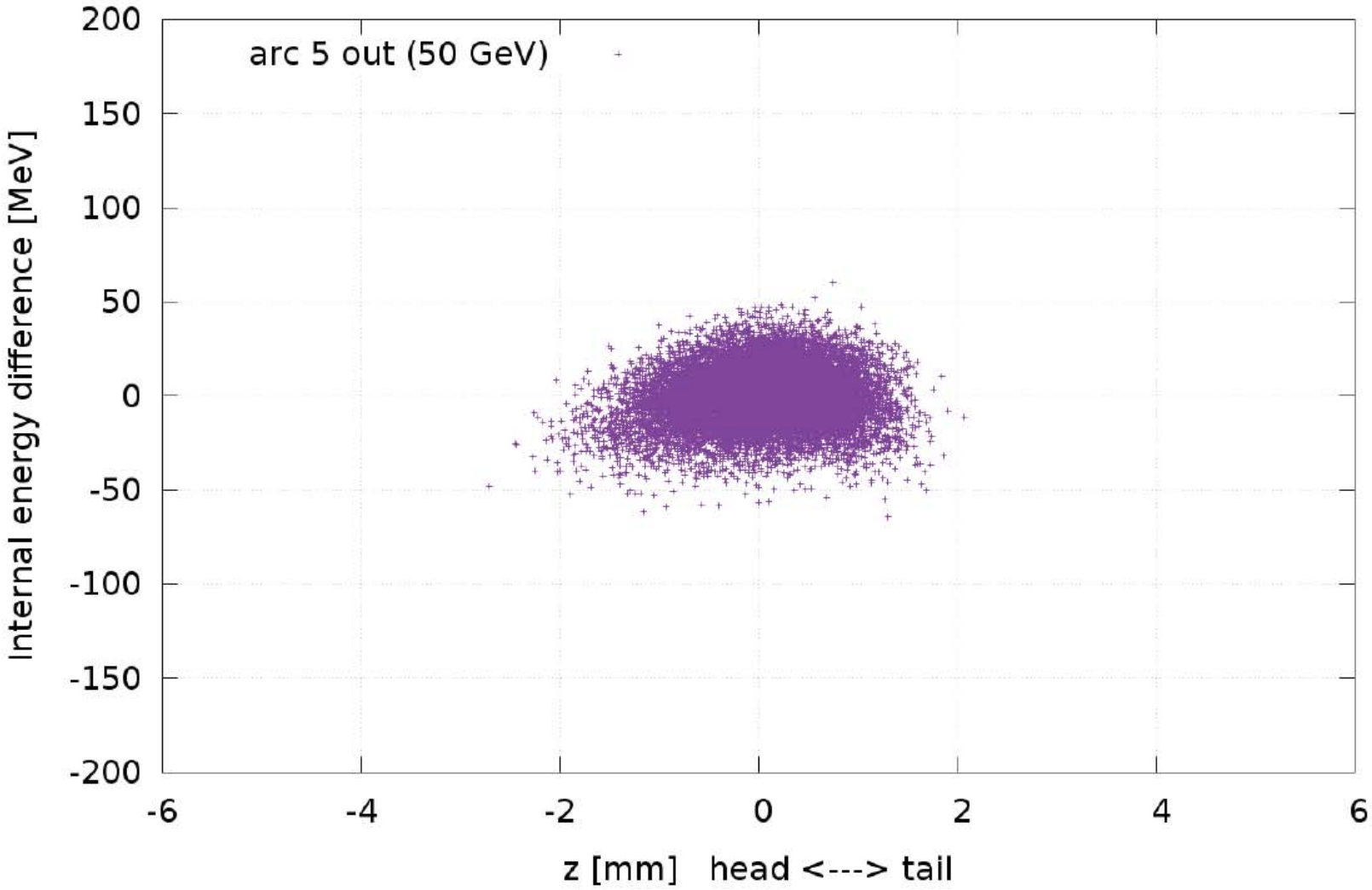

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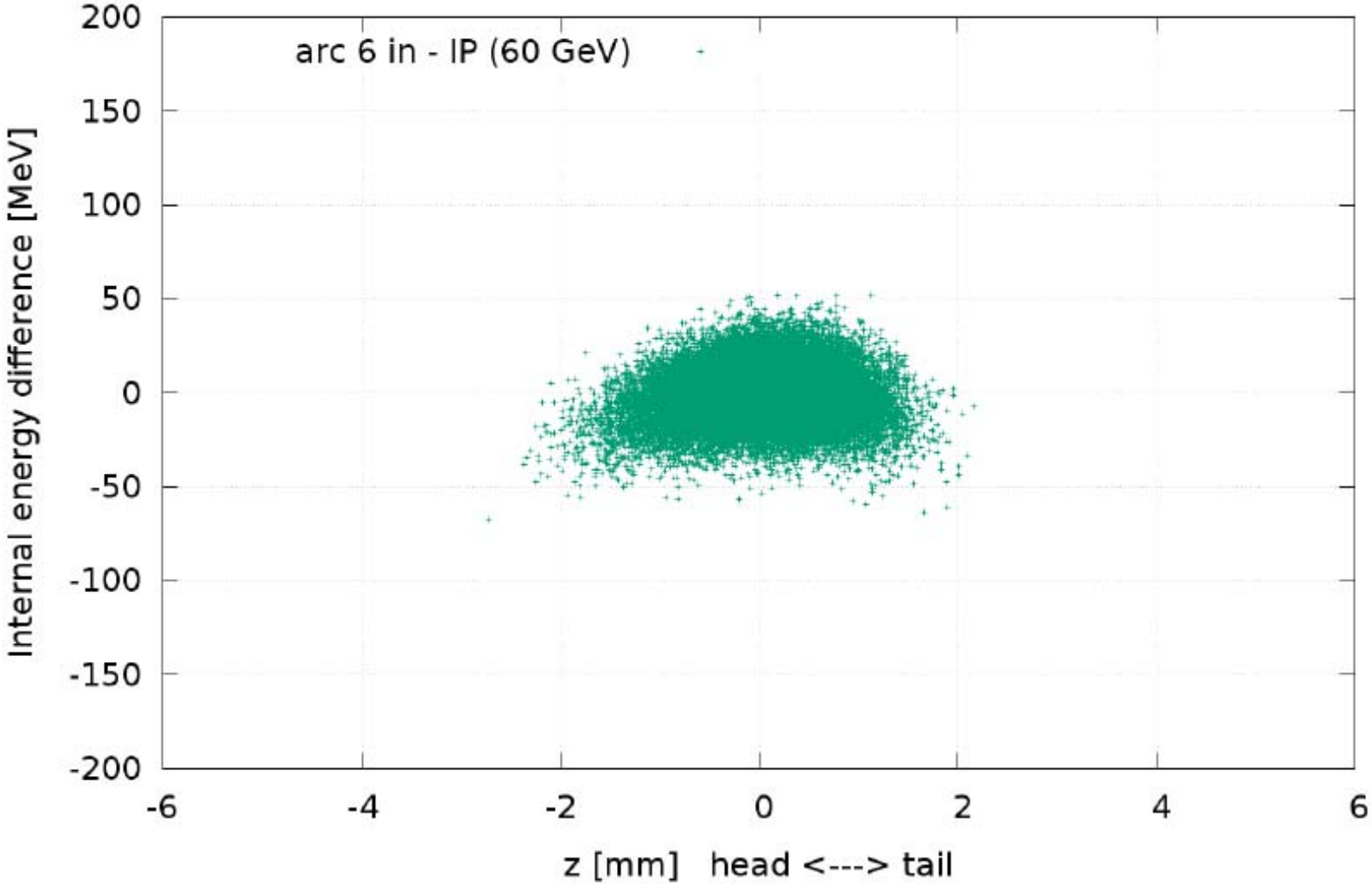

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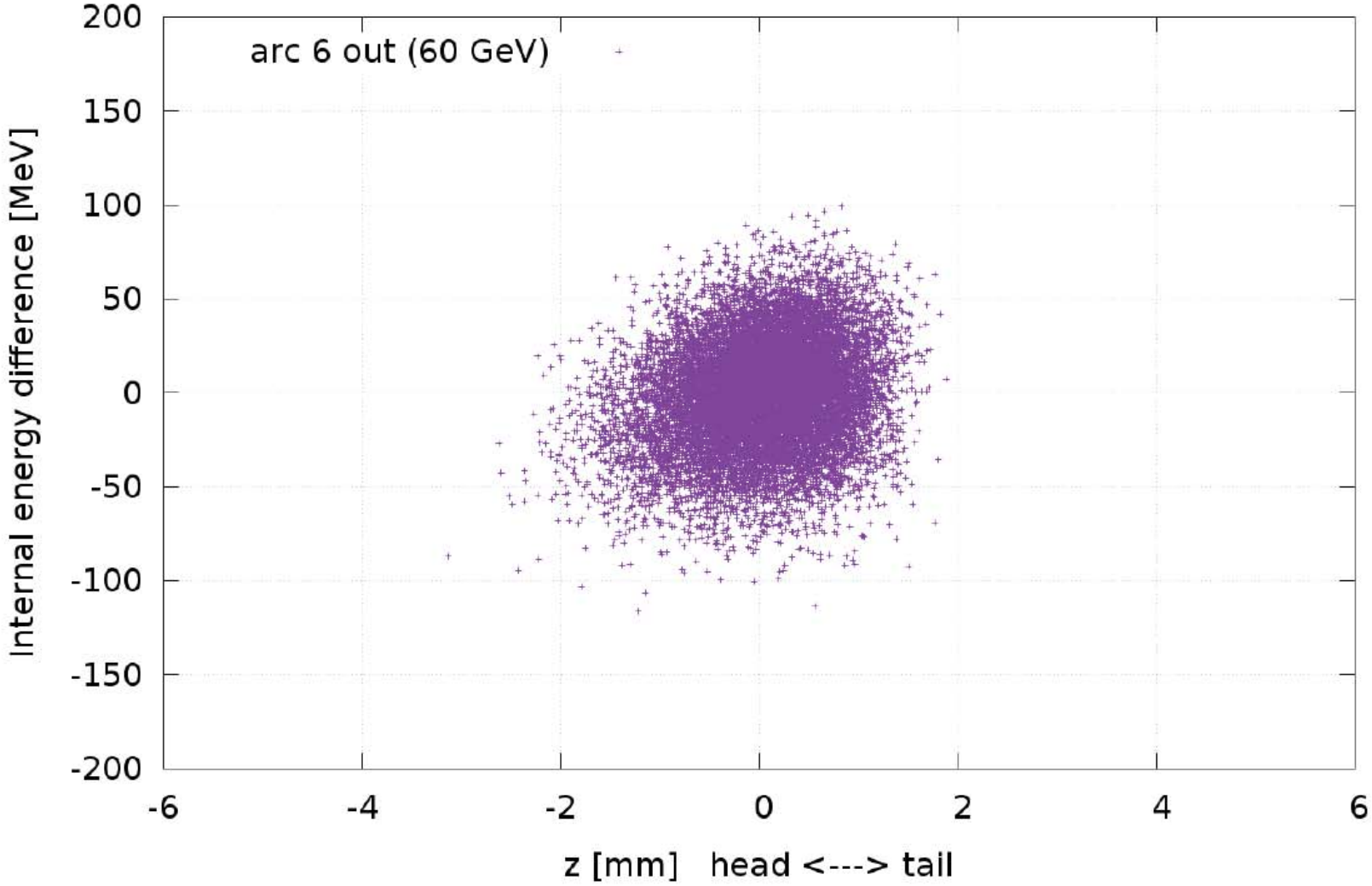

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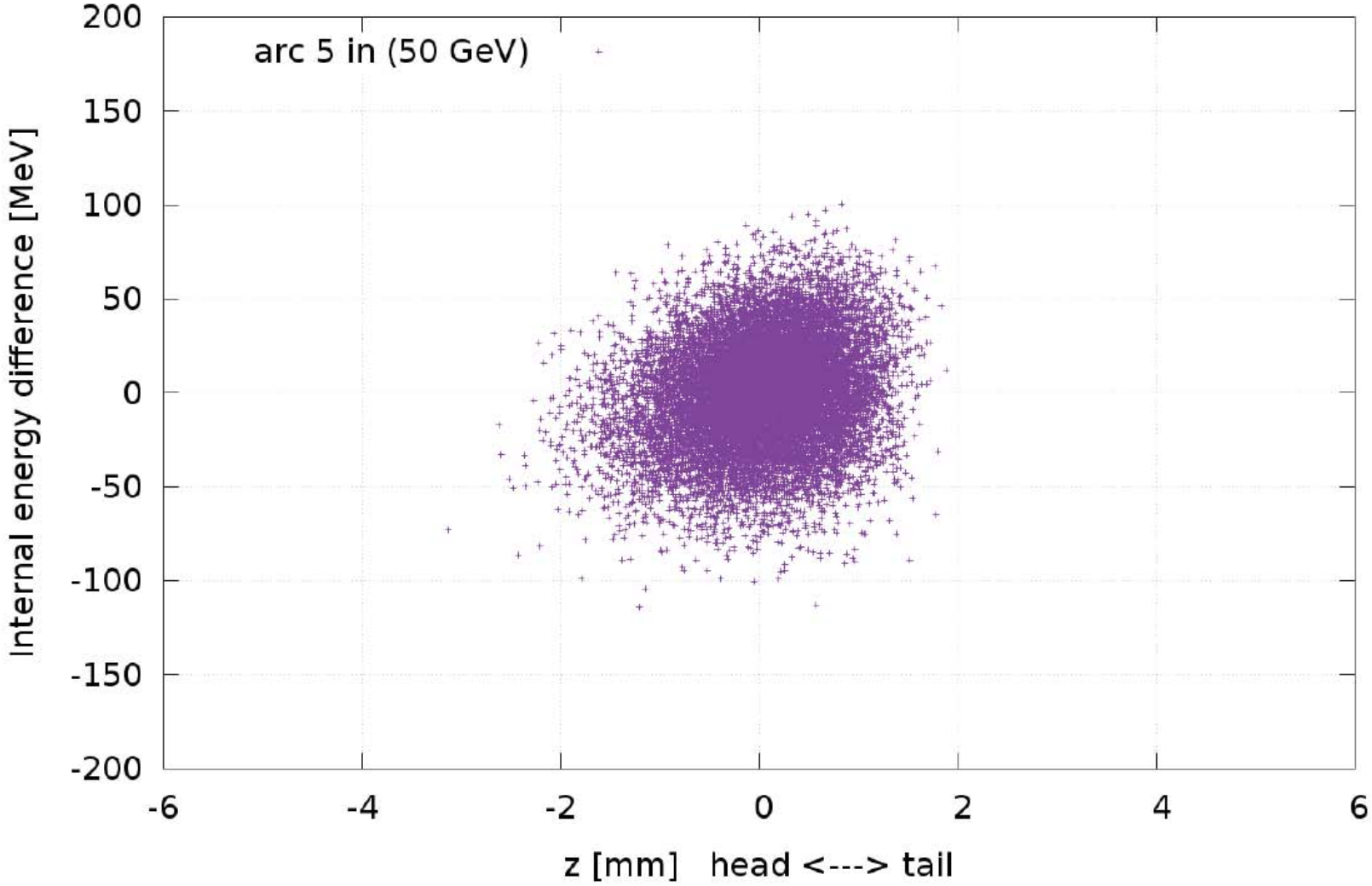

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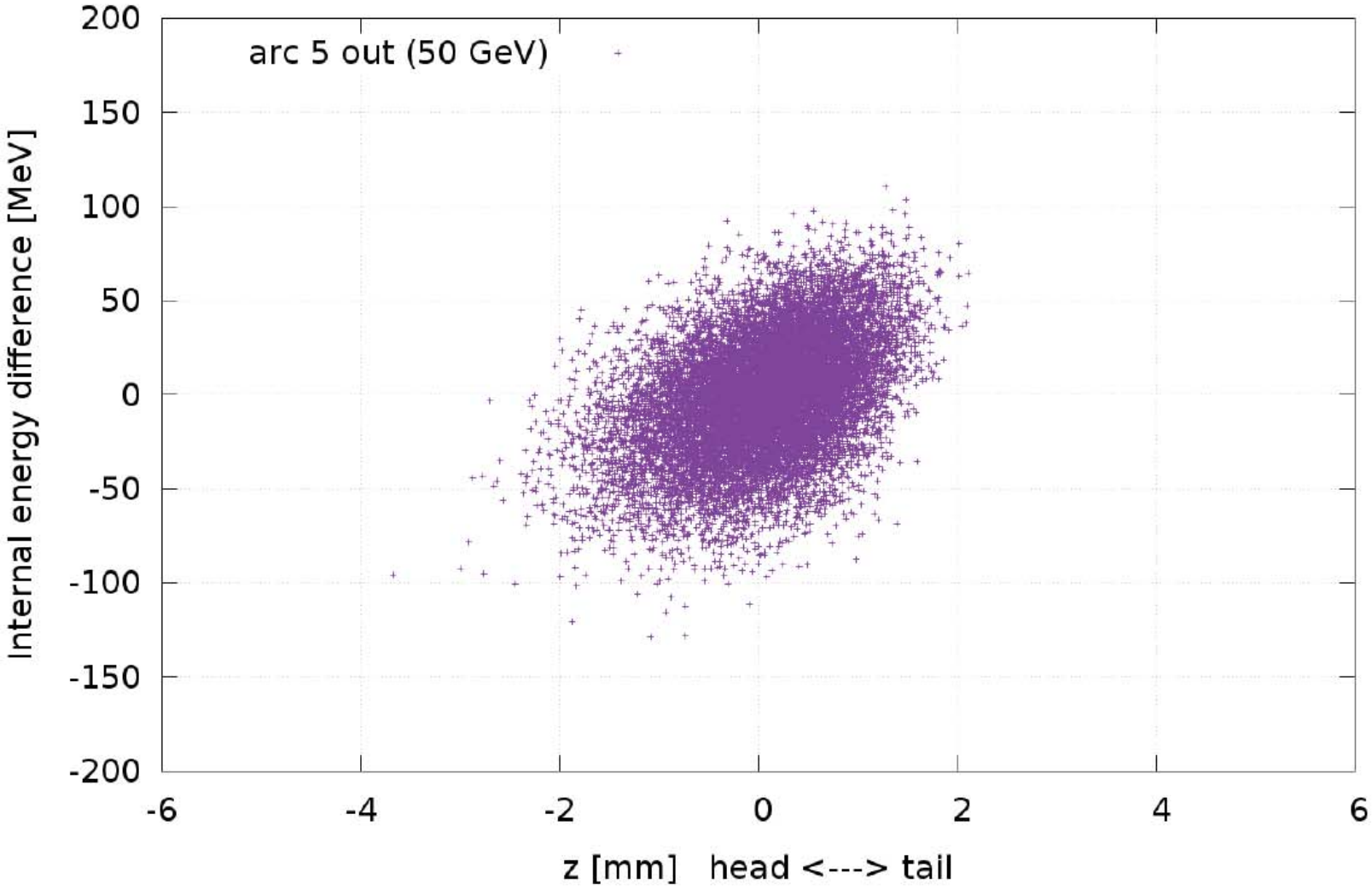

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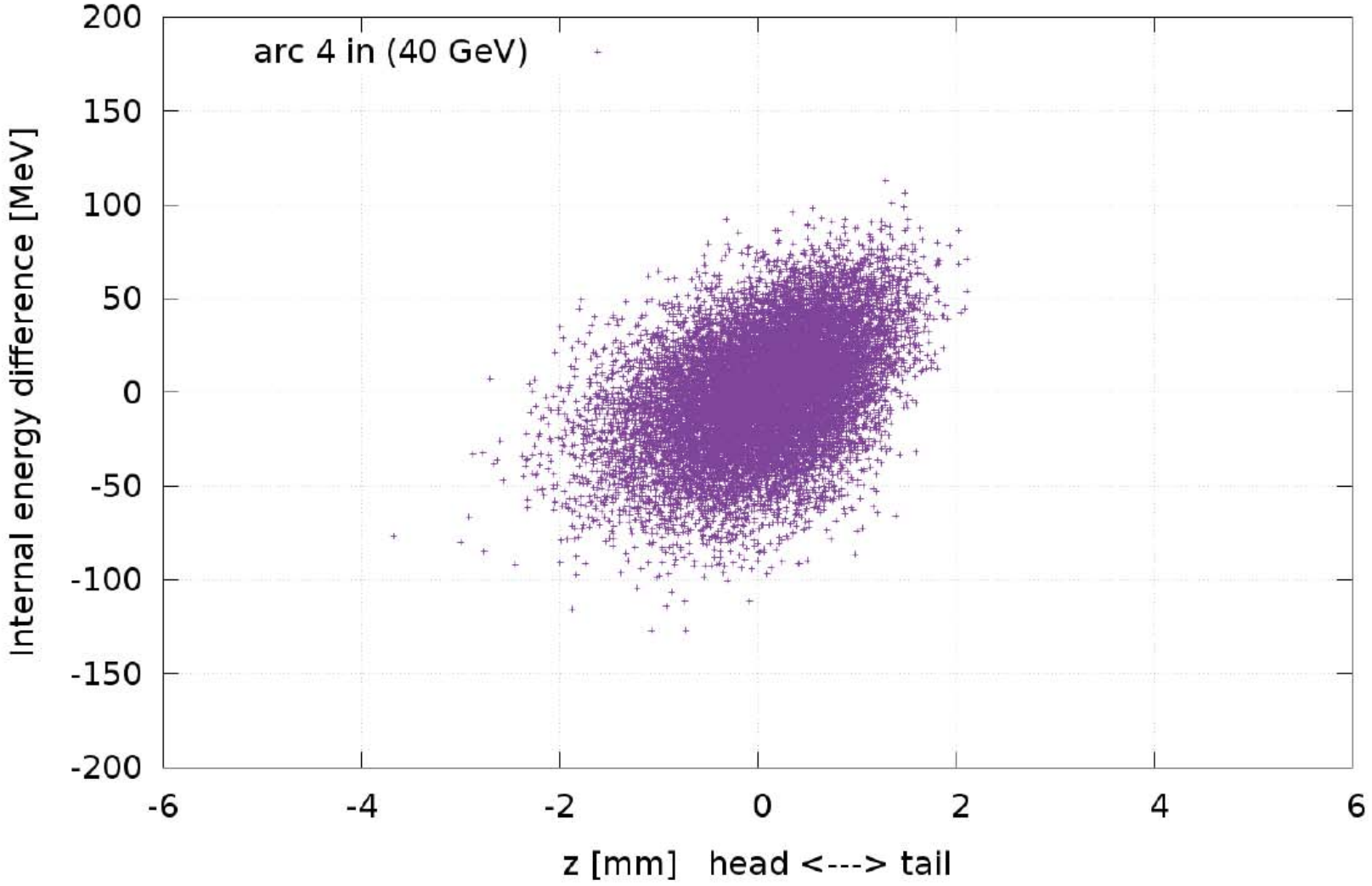

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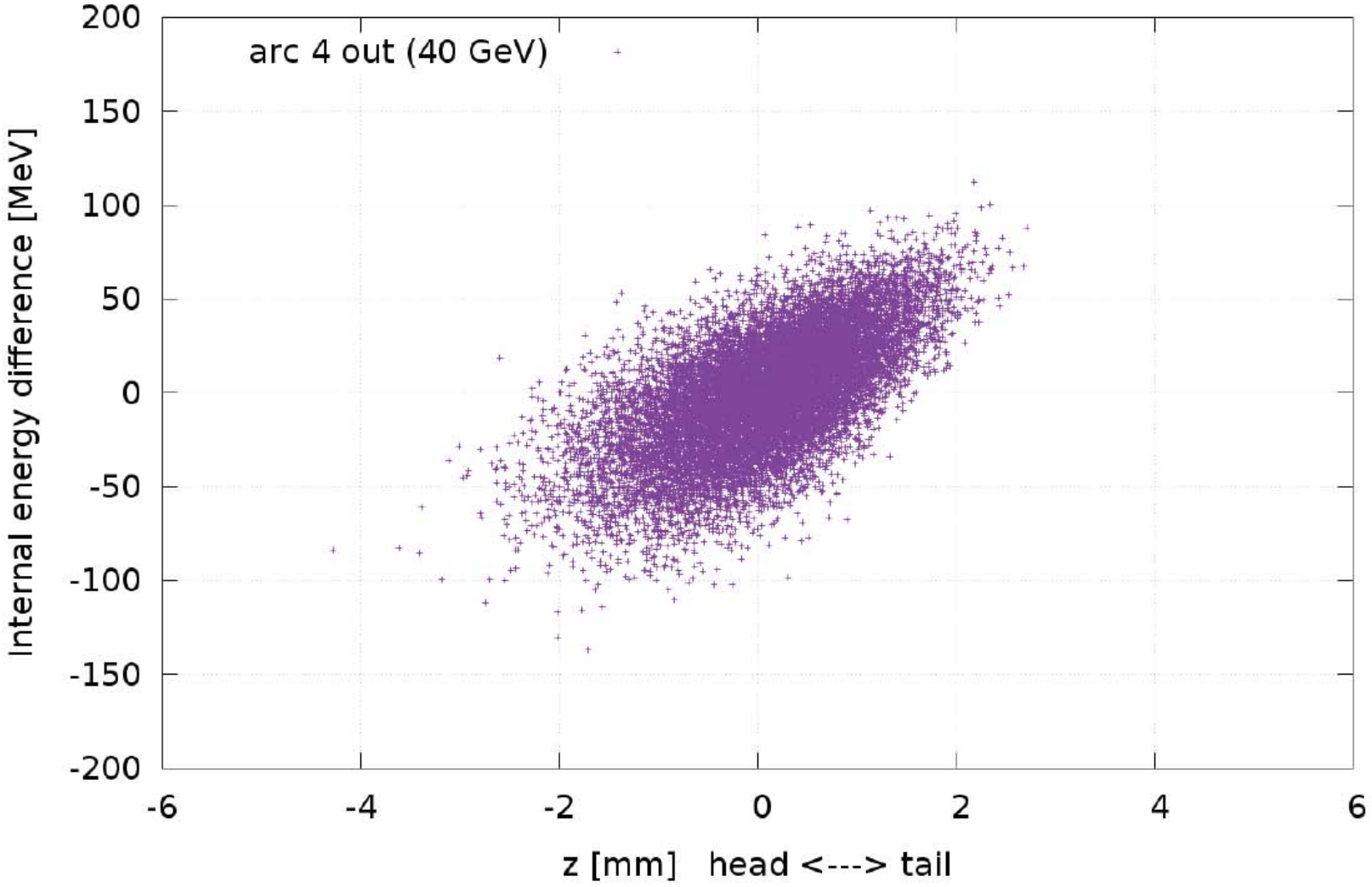

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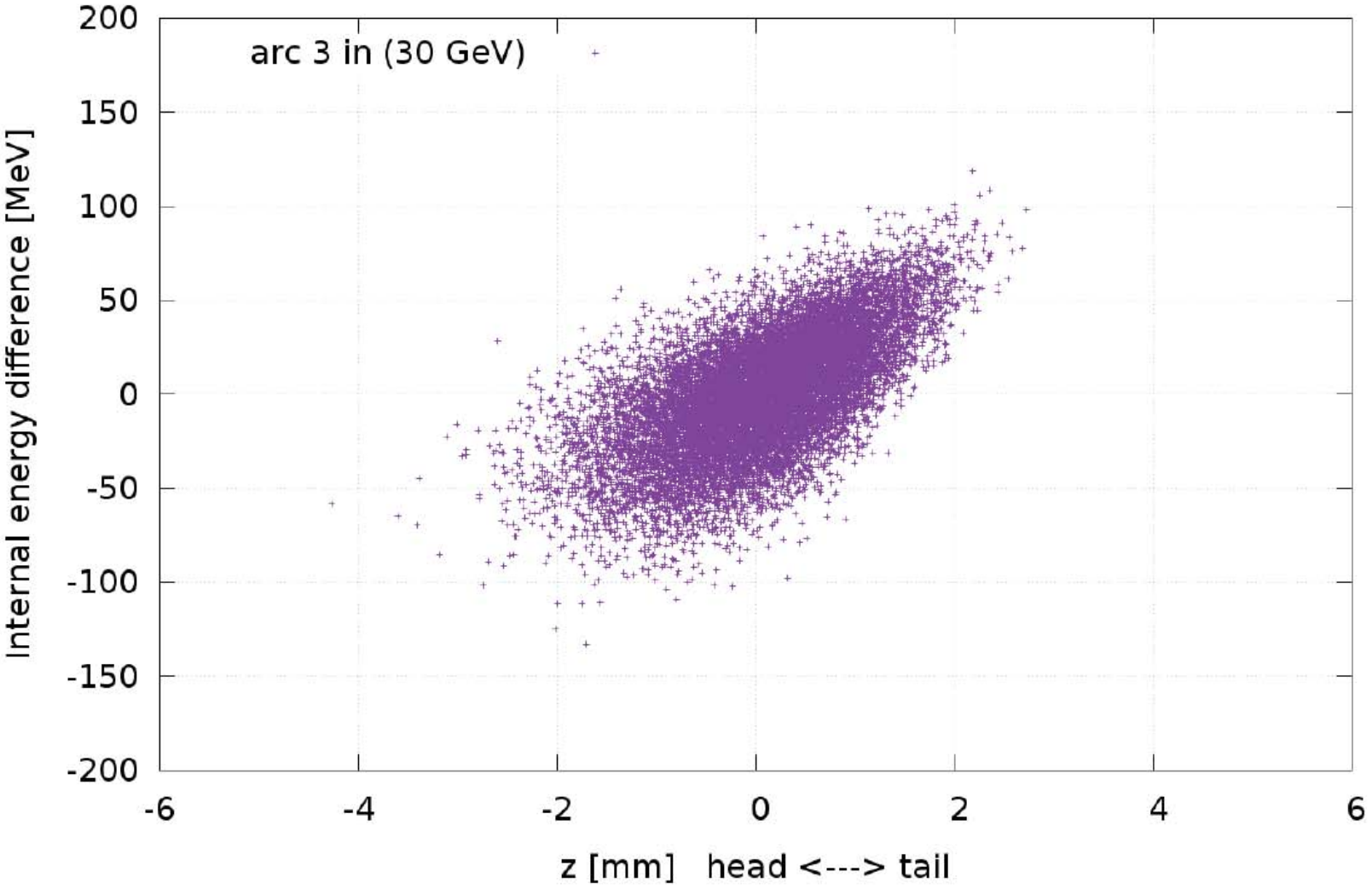

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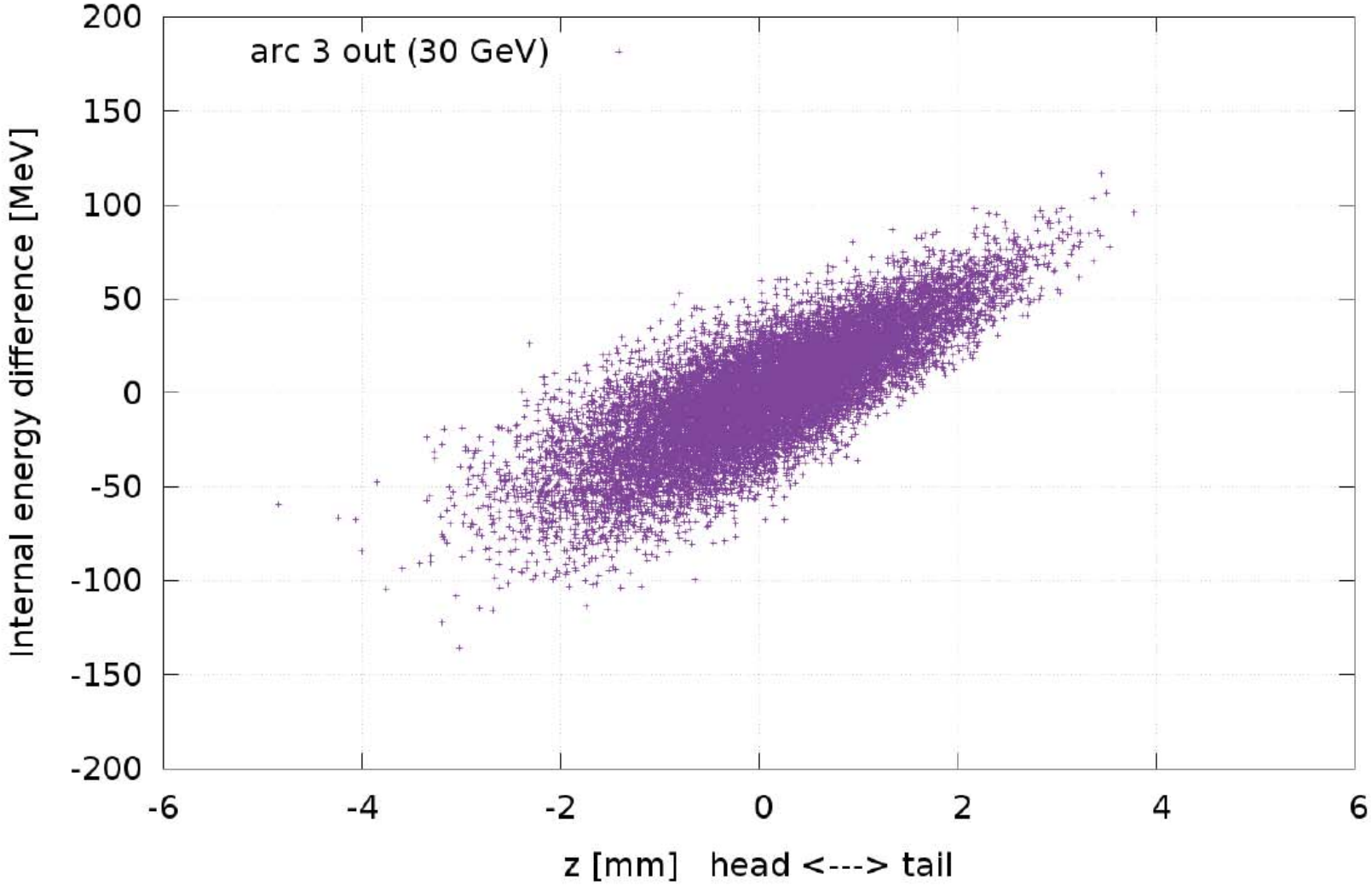

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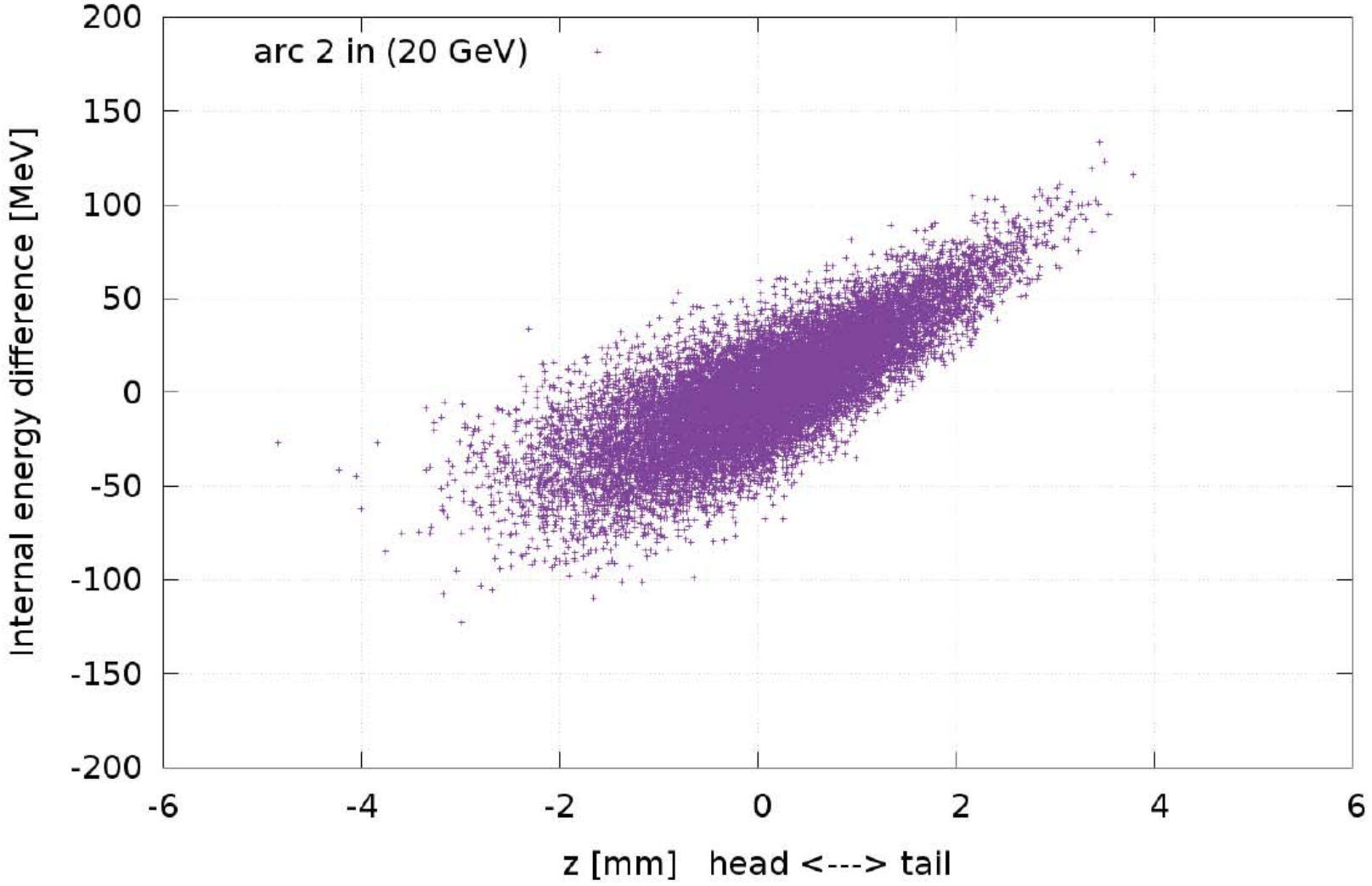

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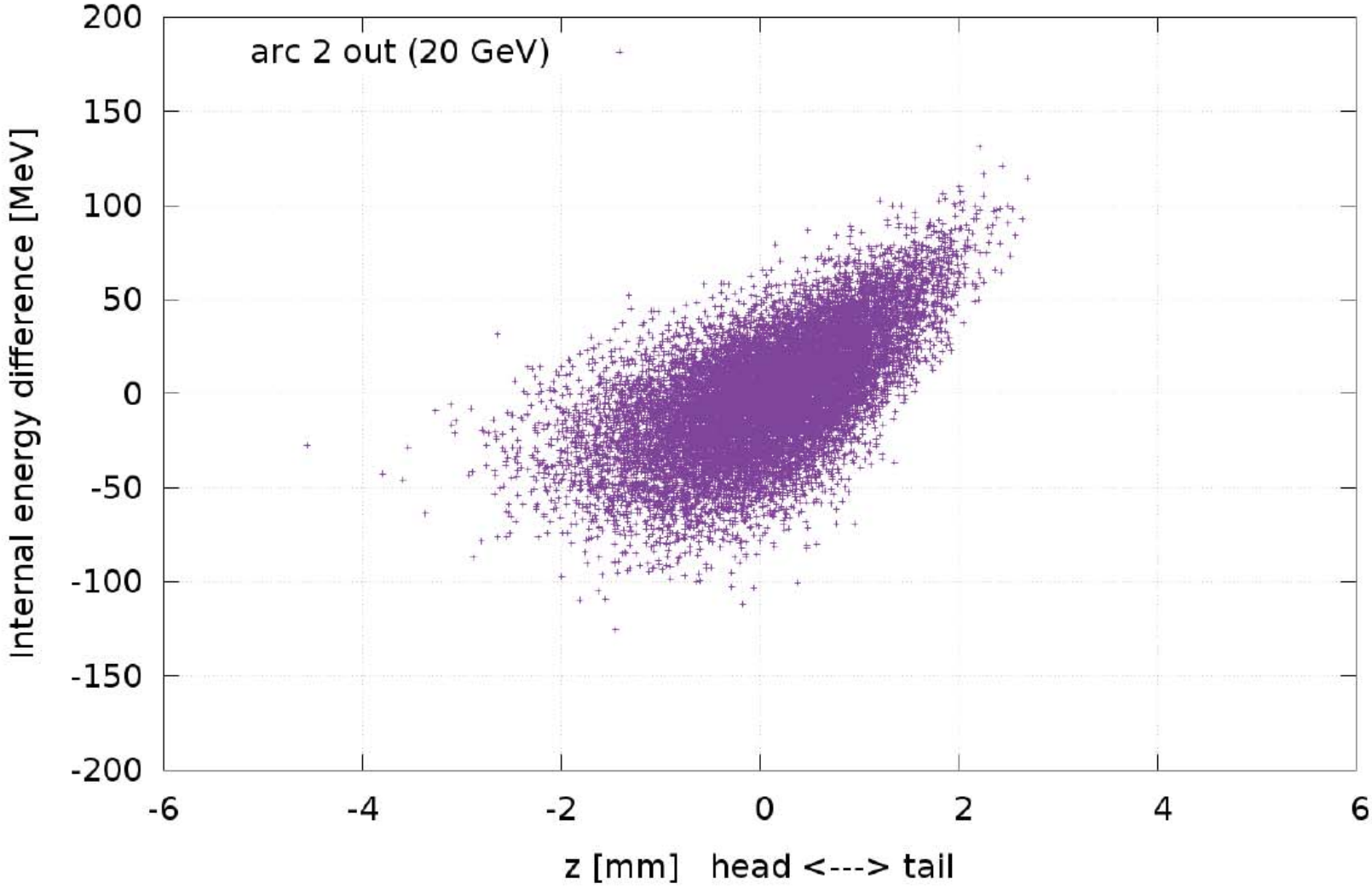

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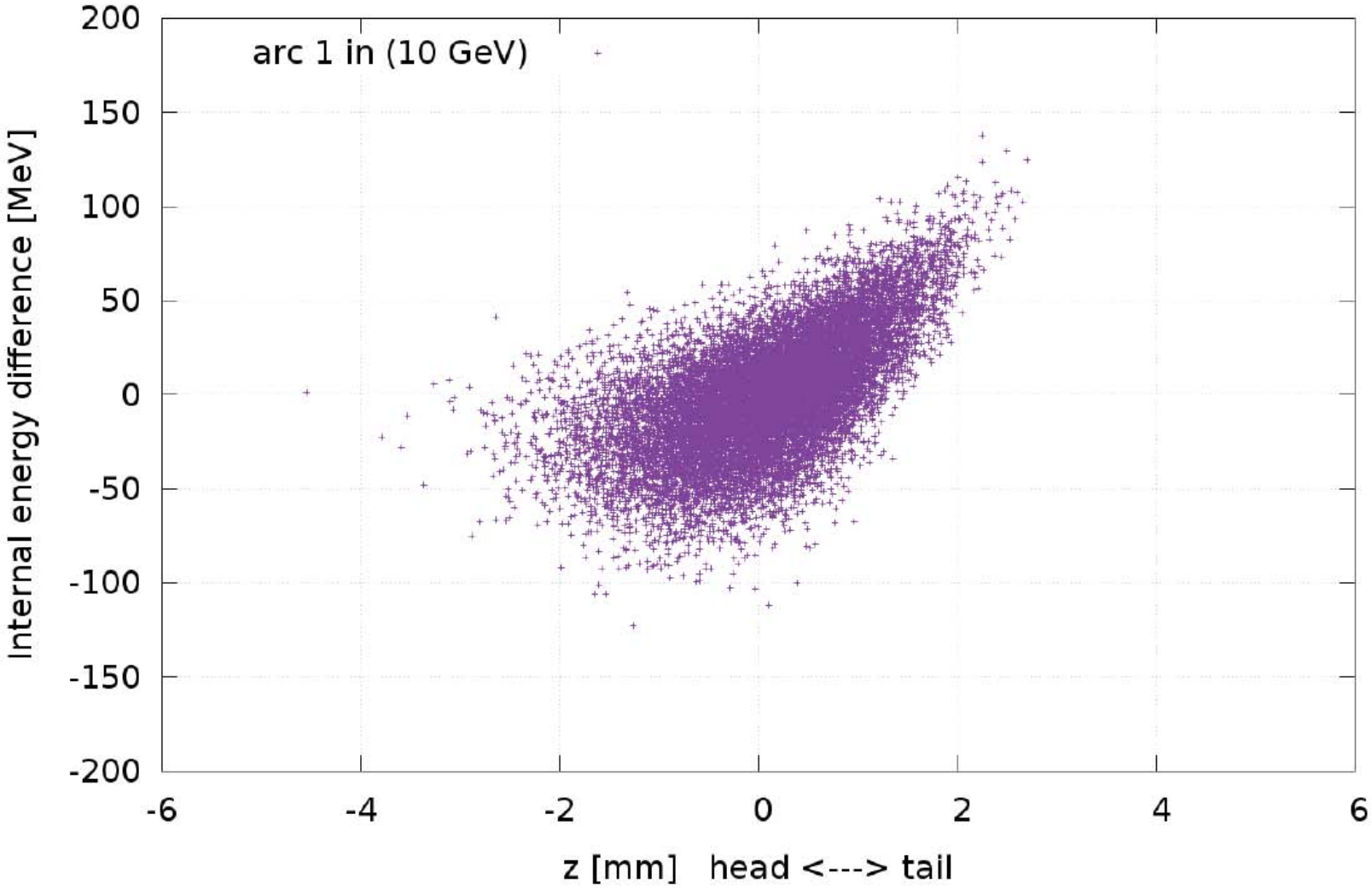

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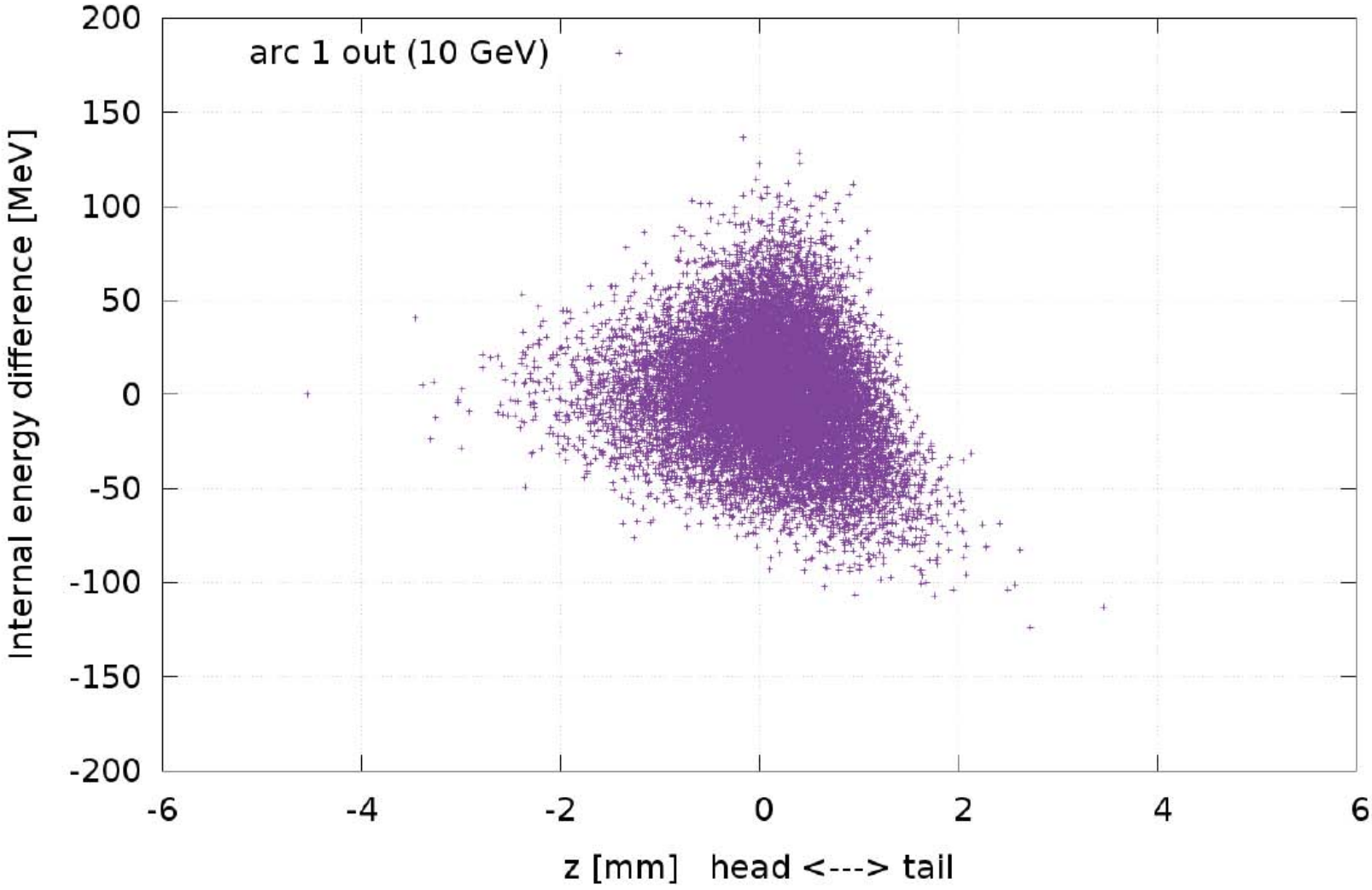

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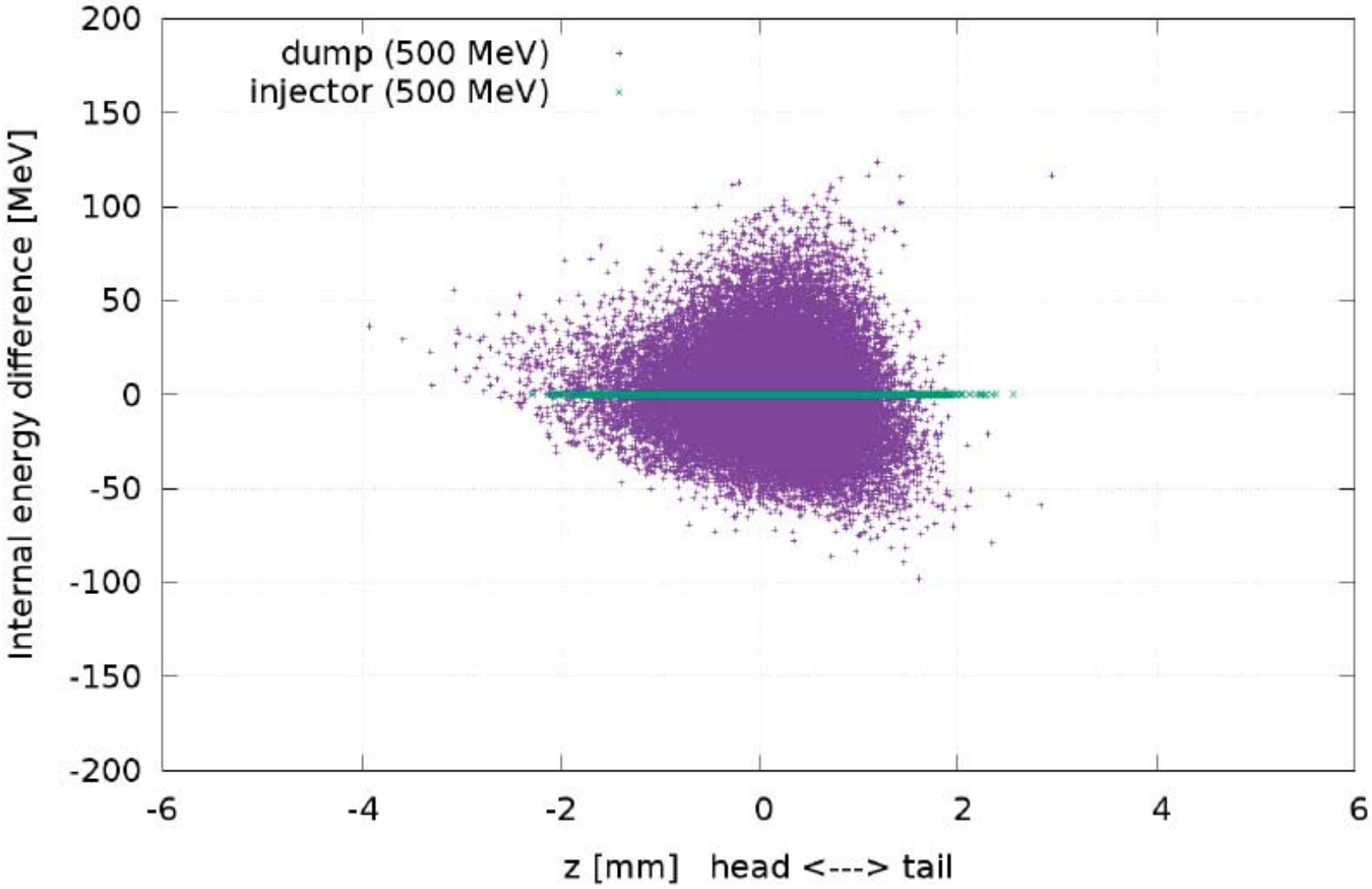
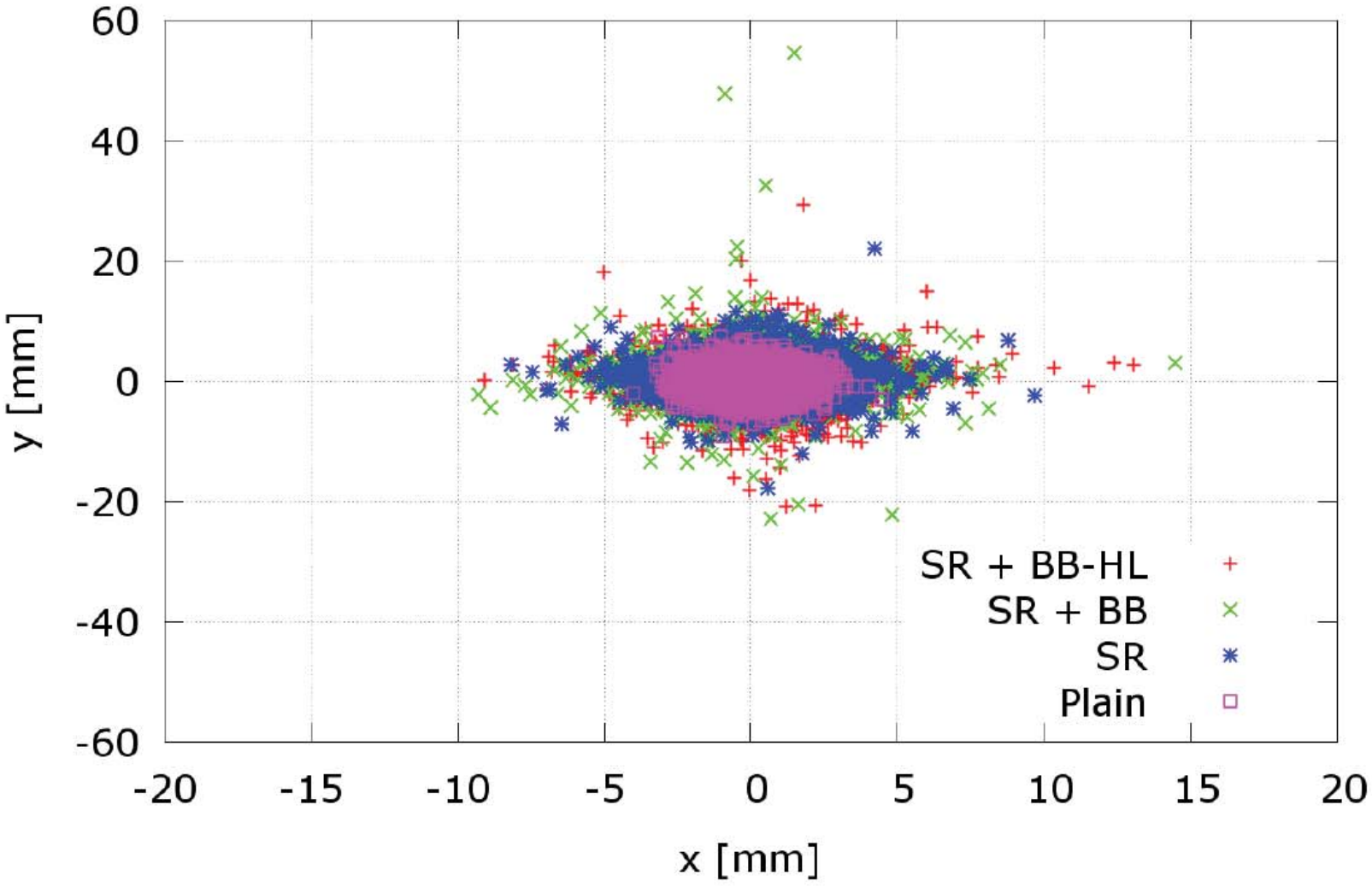


Synchrotron Radiation and Beam-Beam

Transverse Plane at Dump



Aperture radius of the SPL cavity is 40 mm.

Long Range Wakefields

- Bunches entering the radio frequency cavities excite higher order modes of oscillation of the field,
- Bunches coming later are kicked by the excited modes, when they come back can establish a positive feedback,
- Dipolar modes are particularly strong, they can amplify the beam jitter and, in the worst case, cause beam loss.

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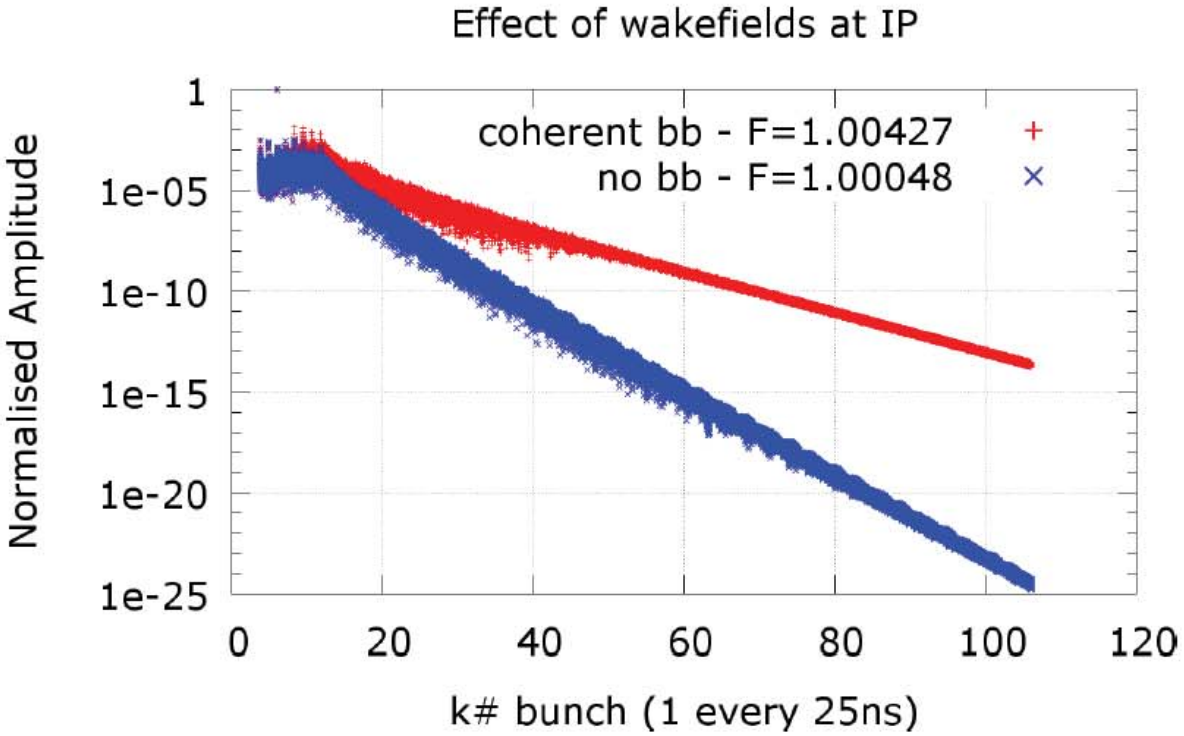
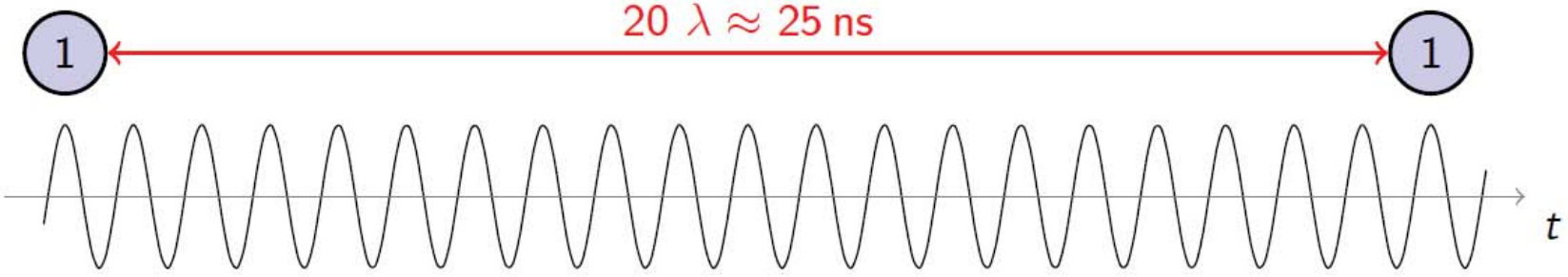


- Fill the machine with perfectly centred (single particle) bunches,
- Inject a bunch with some offset,
- Keep injecting perfect bunches and see how they are perturbed.

Recombination Pattern

Multi-bunch effects are enhanced by the value of $\frac{\beta}{E}$ $\rightarrow$ low energy particles are more susceptible.
The filling of the RF buckets of the LHeC can be controlled tuning the lengths of the arcs $\rightarrow$ maximise the separation between the bunches at first and sixth turn.



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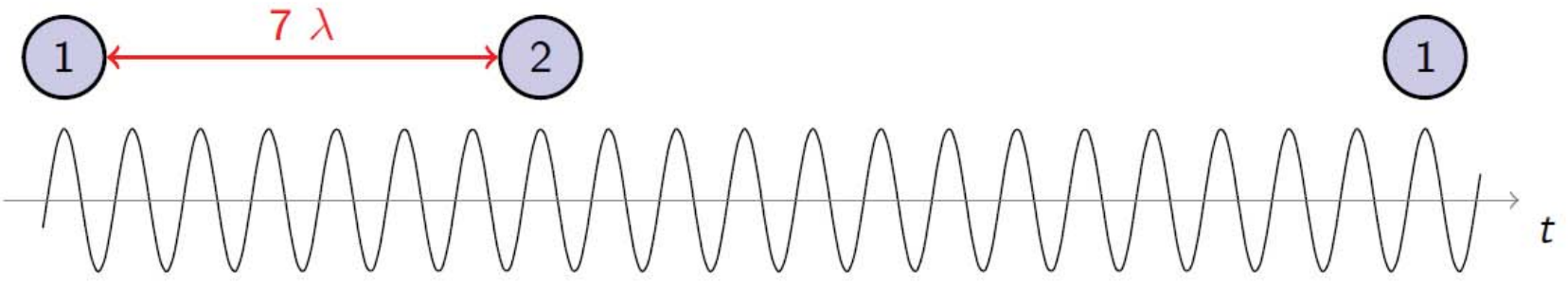

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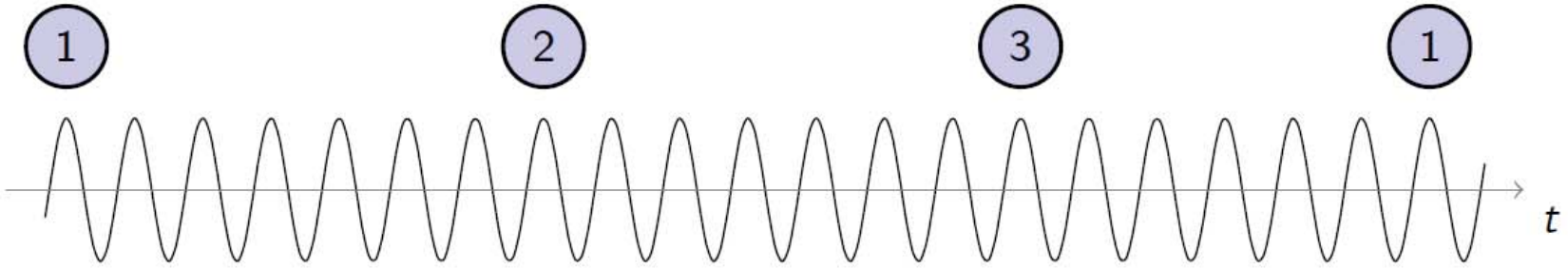

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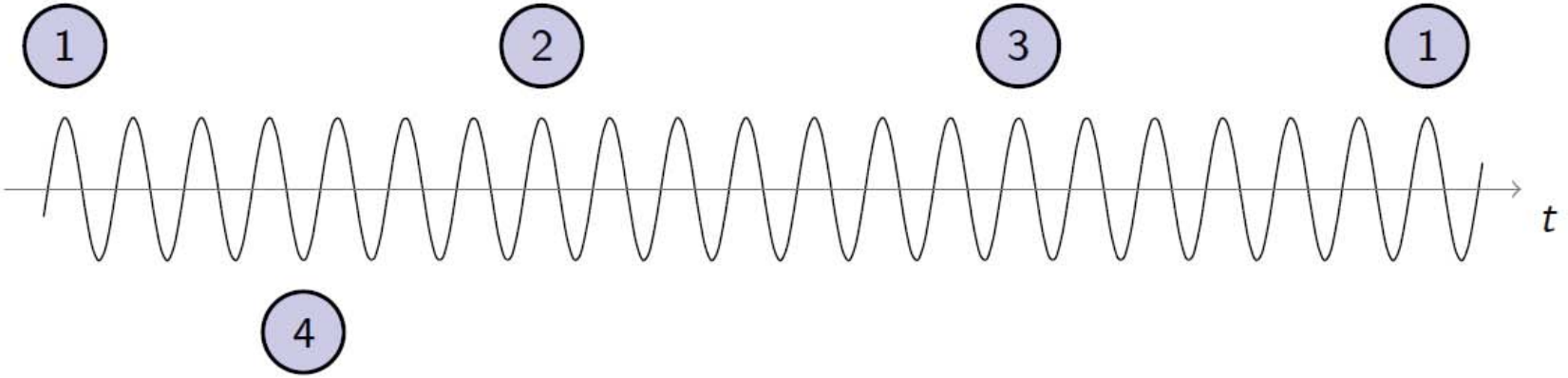

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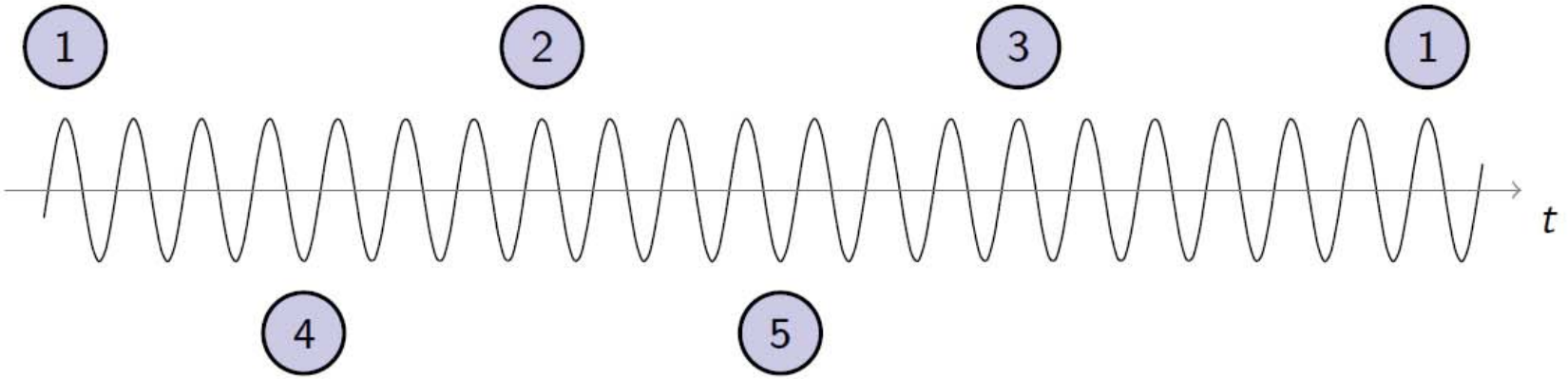

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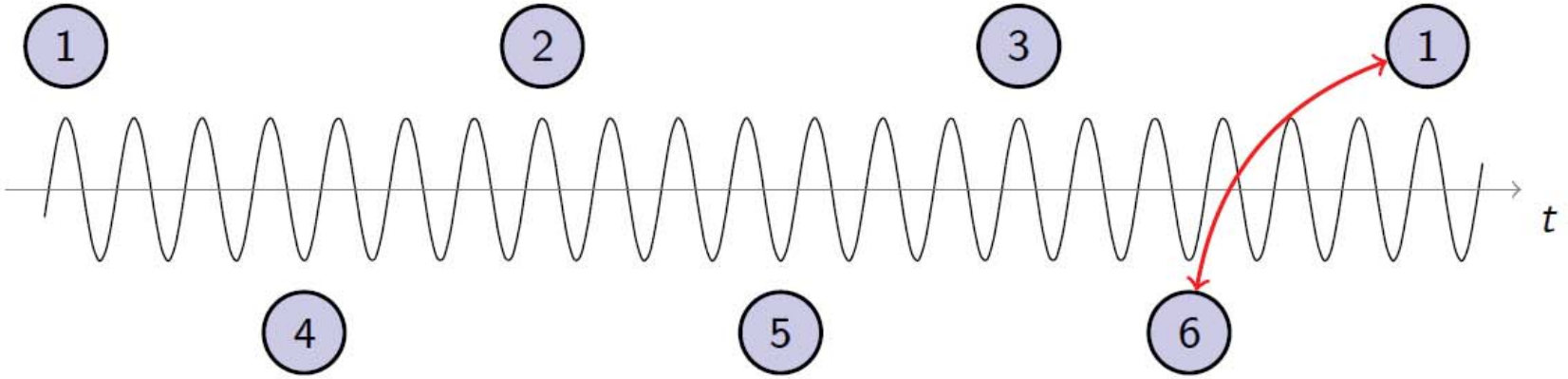

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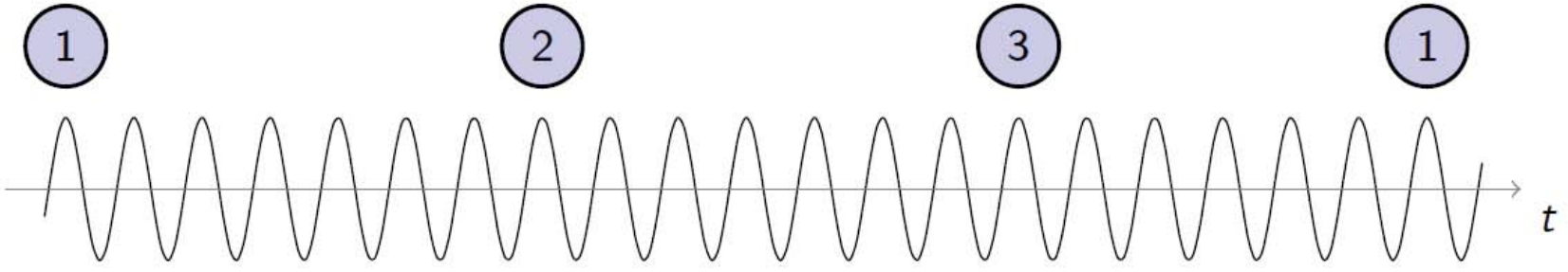

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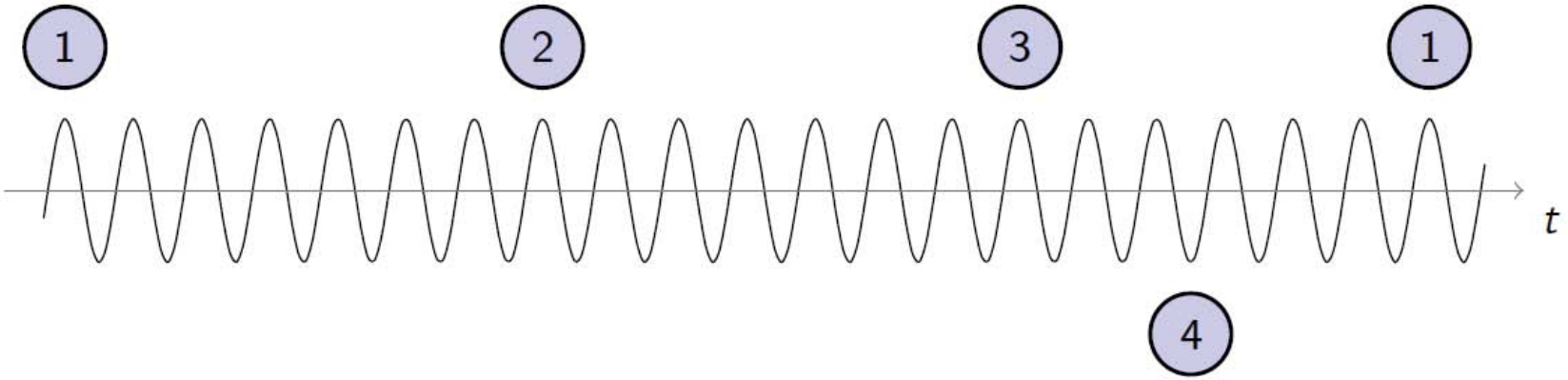

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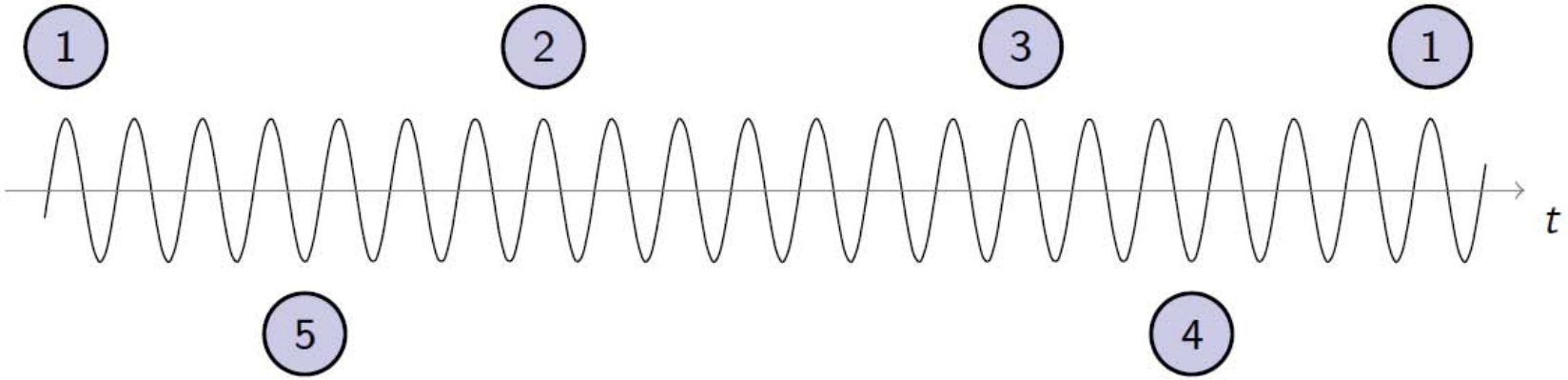

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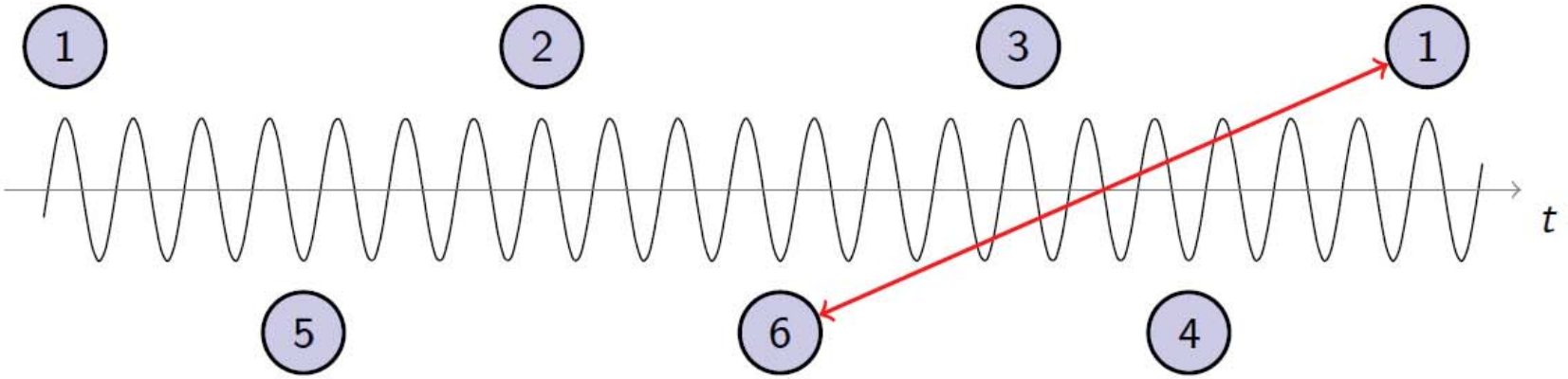
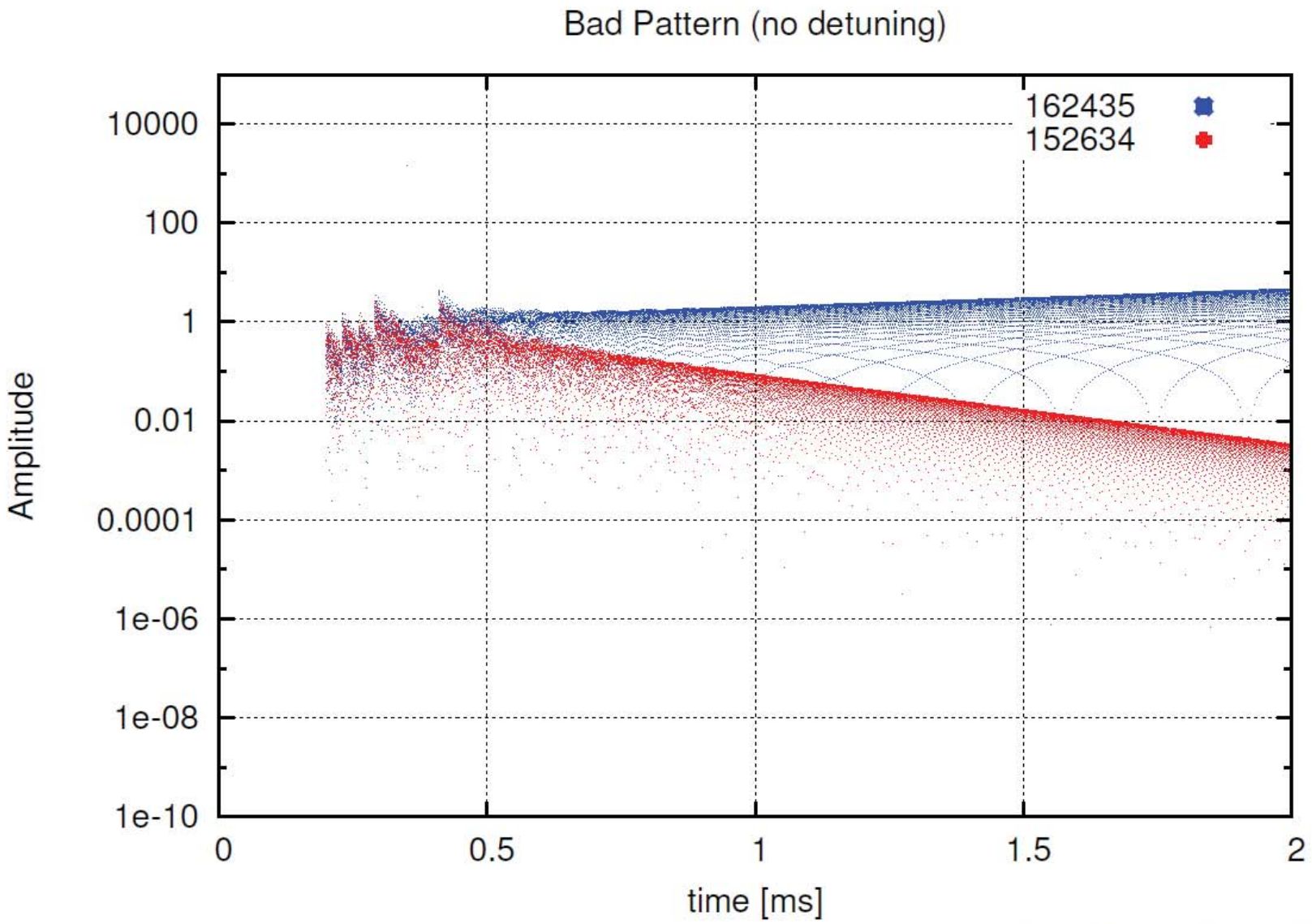


- Pattern 162435 is bad!
- Pattern 152634 is better!

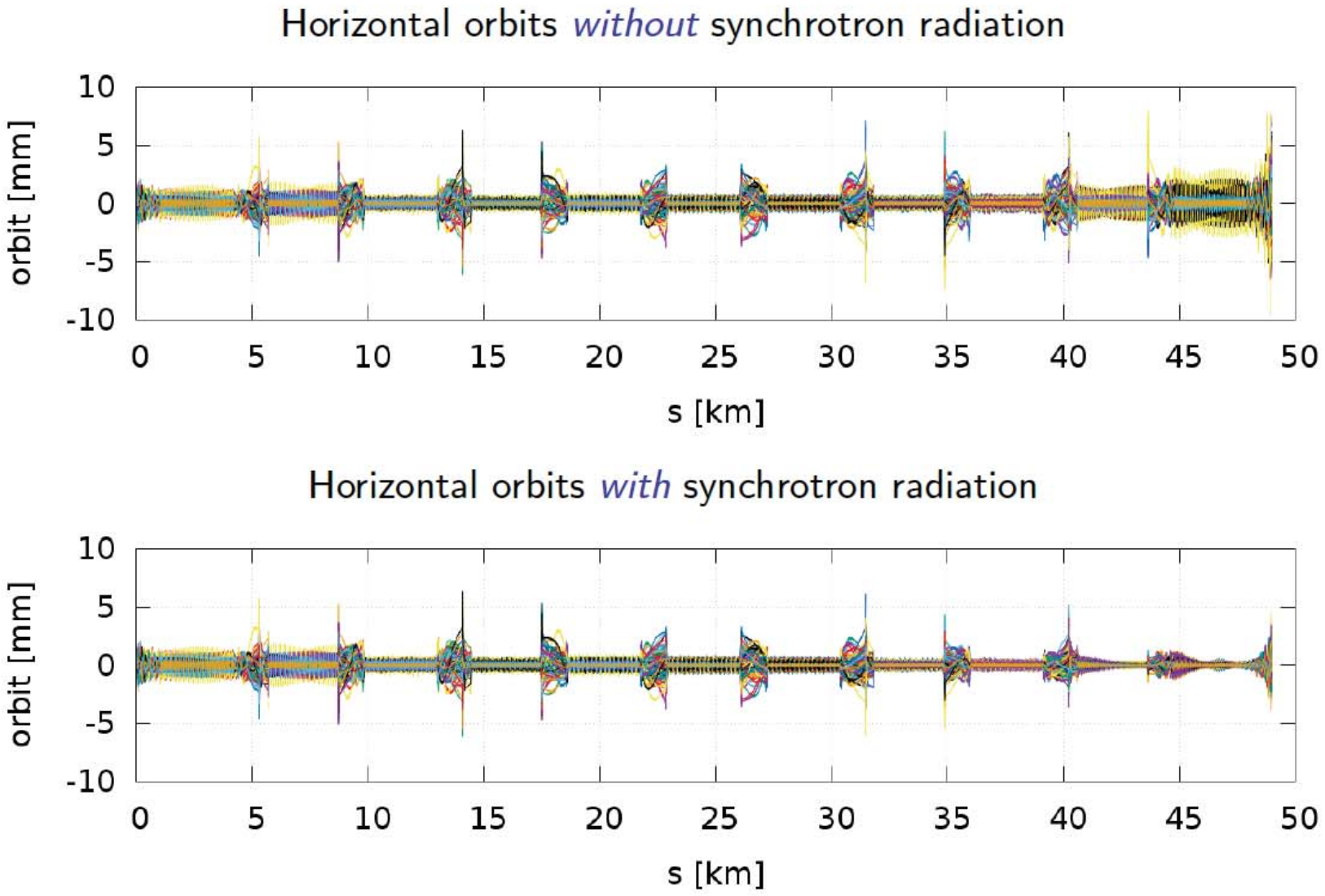
Pattern and Long Range Wakefields

The pattern has an influence on the threshold current



Cavity misalignments

100 uncorrected orbits obtained for 300 μm **misalignments and** 300 μrad **tilts.**



Conclusions

- The LHeC study is progressing both on the **lattice design**:
  - Design of arcs with IR bypasses
  - Optimized Spreaders/Recombiners
  - Addition of SR compensation sections
- and on the **beam dynamics** simulations:
  - PLACET2 is in good state of development and is being productive
  - Impact of Synchrotron Radiation
  - Recombination Pattern and Long Range Wakefields
  - Cavities misalignments
- Next major steps:
  - Complete the lattice integration with the interaction region
  - Simulation of the ion cloud effect

Thanks for your attention!

and special thanks to:

Frank Zimmermann

Oliver Brüning

and

Max Klein

http://lhec.web.cern.ch