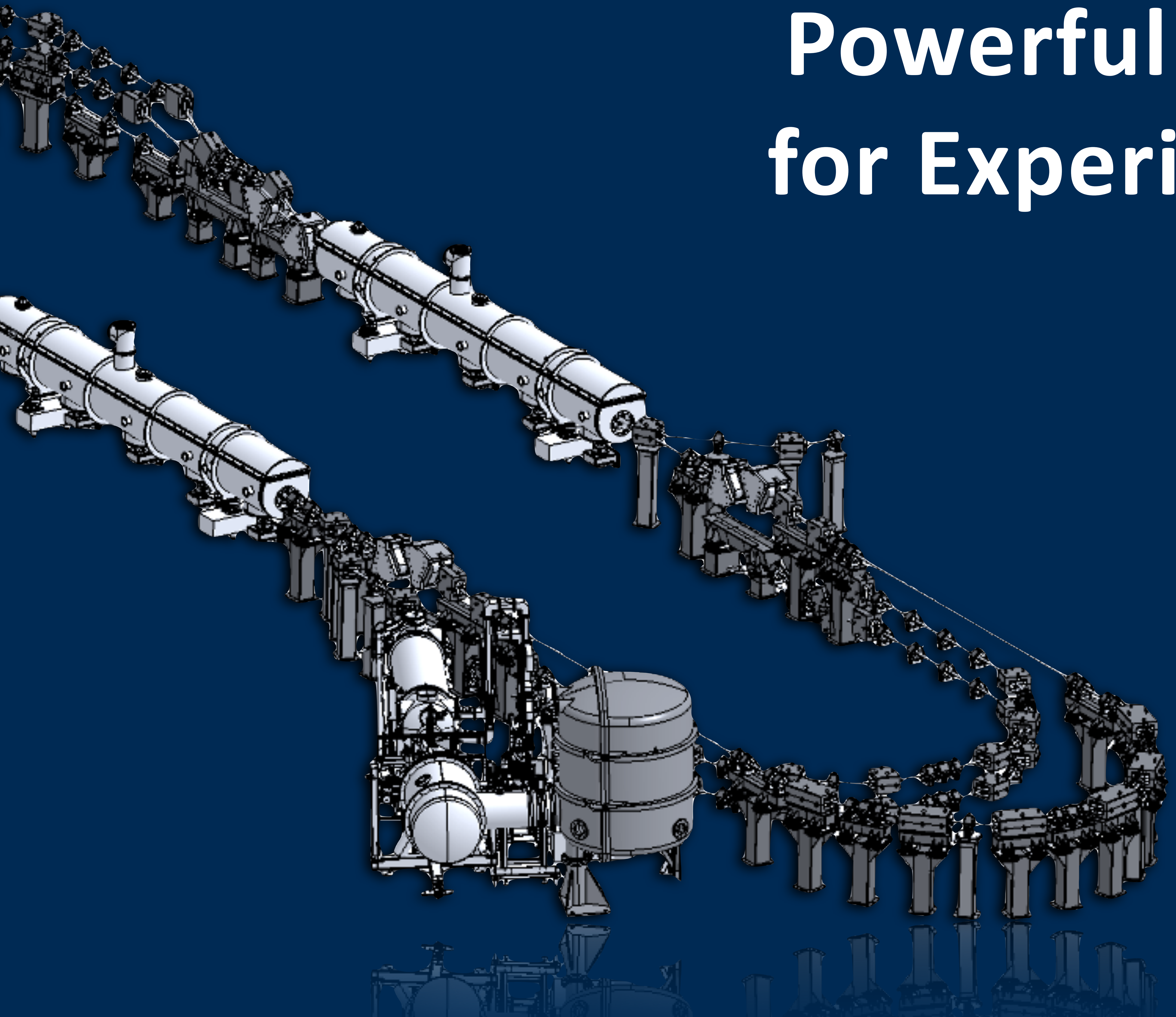
French-Ukrainian Workshop 2025 (IJCLab, Orsay, France 10-12/06/2025) https://indico.ijclab.in2p3.fr/event/11849/



Powerful Energy Recovery LINAC for Experiments (PERLE) at IJCLab

Alex Fomin

on behalf of PERLE collaboration

université PARIS-SACLAY

cnrs

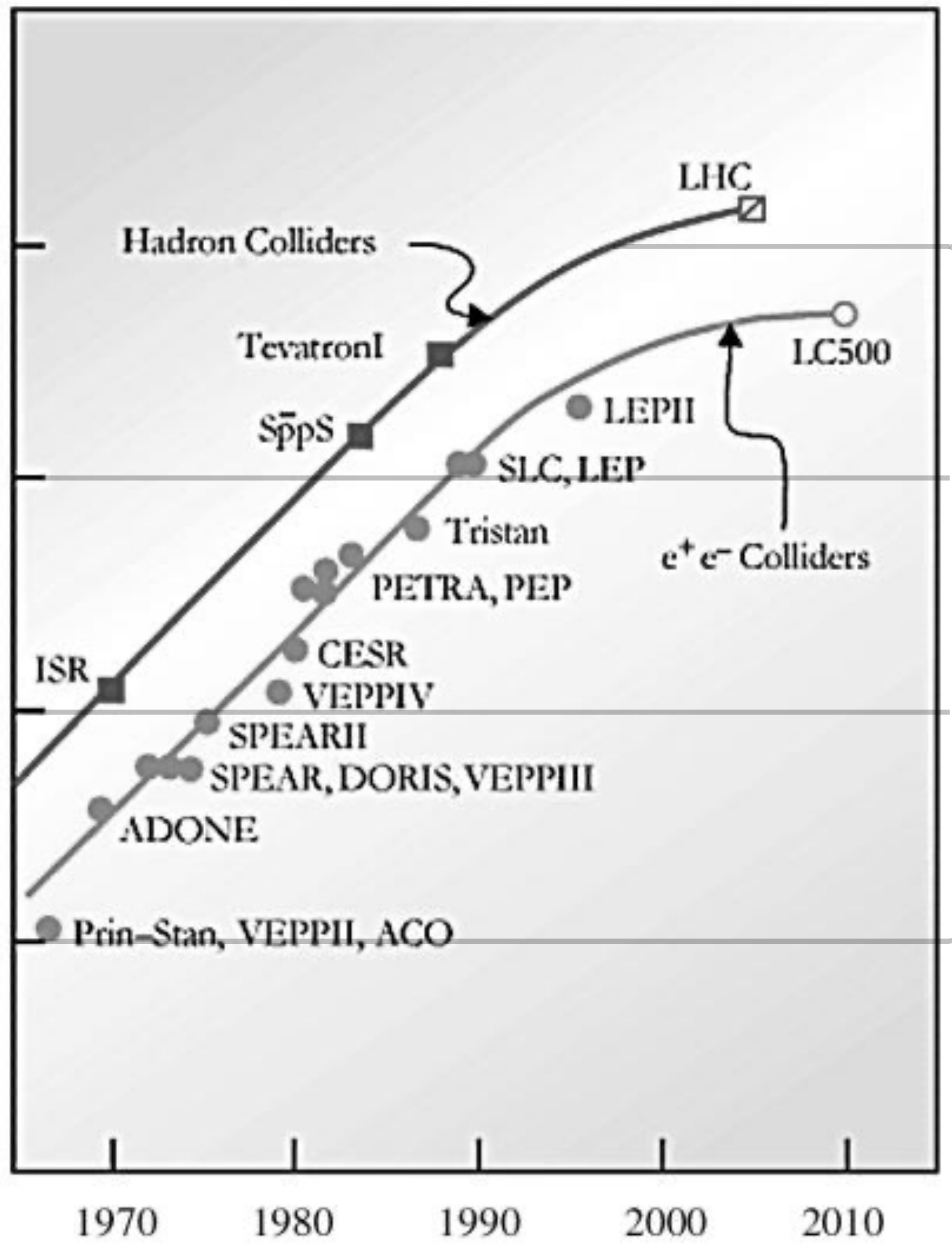
IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

Accelerators evolution: the Livingston chart

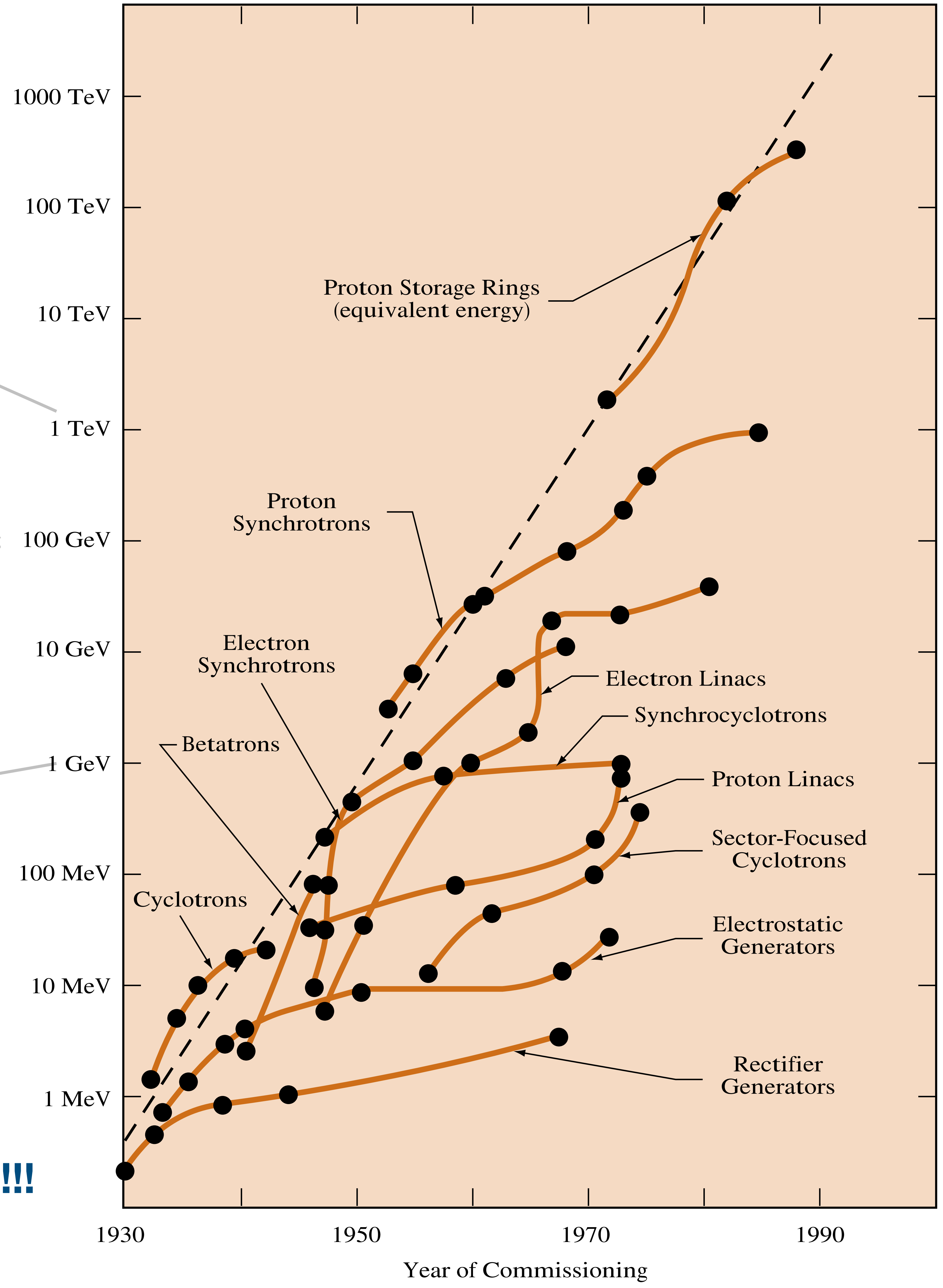
The Livingston chart shows, in a very striking way, how the succession of new ideas and new technologies has relentlessly pushed up accelerator beam energies over five decades at the rate of over one and a half orders of magnitude per decade.

Accelerators are the biggest scientific instruments human mankind has built

- Large size (~ 30 km footprint)
- High cost (~ billion Euro)
- Needs lots of electricity
- Technology pushed to its limits
- ~ 20-30 years to make one
- Global co-ordination



slac.stanford.edu/pubs/beamline/27/1/27-1-panofsky.pdf



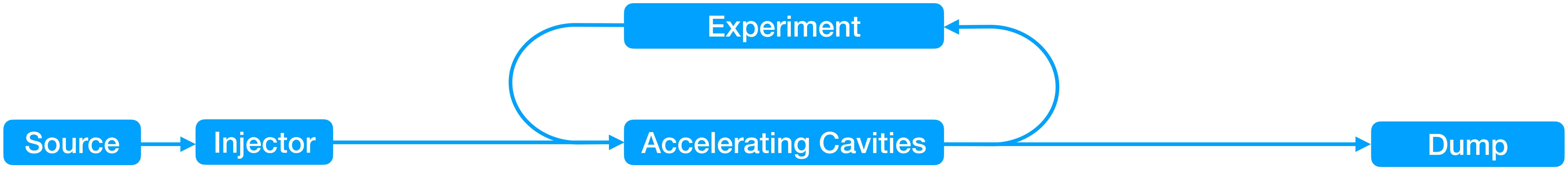
The future holds many challenges for the accelerator engineers.

All this effort justified by the chance to discover new particles, forces, properties of matter !!!

Energy Recovery Linacs (ERL)

Accelerating two beams, colliding them, and then dumping them is extremely inefficient.

Storage rings work fine for protons and ions (LHC fill can last for 30+ hours), but not for electrons (fast beam degradation due to collisions).



Energy Recovery Linacs (ERL)

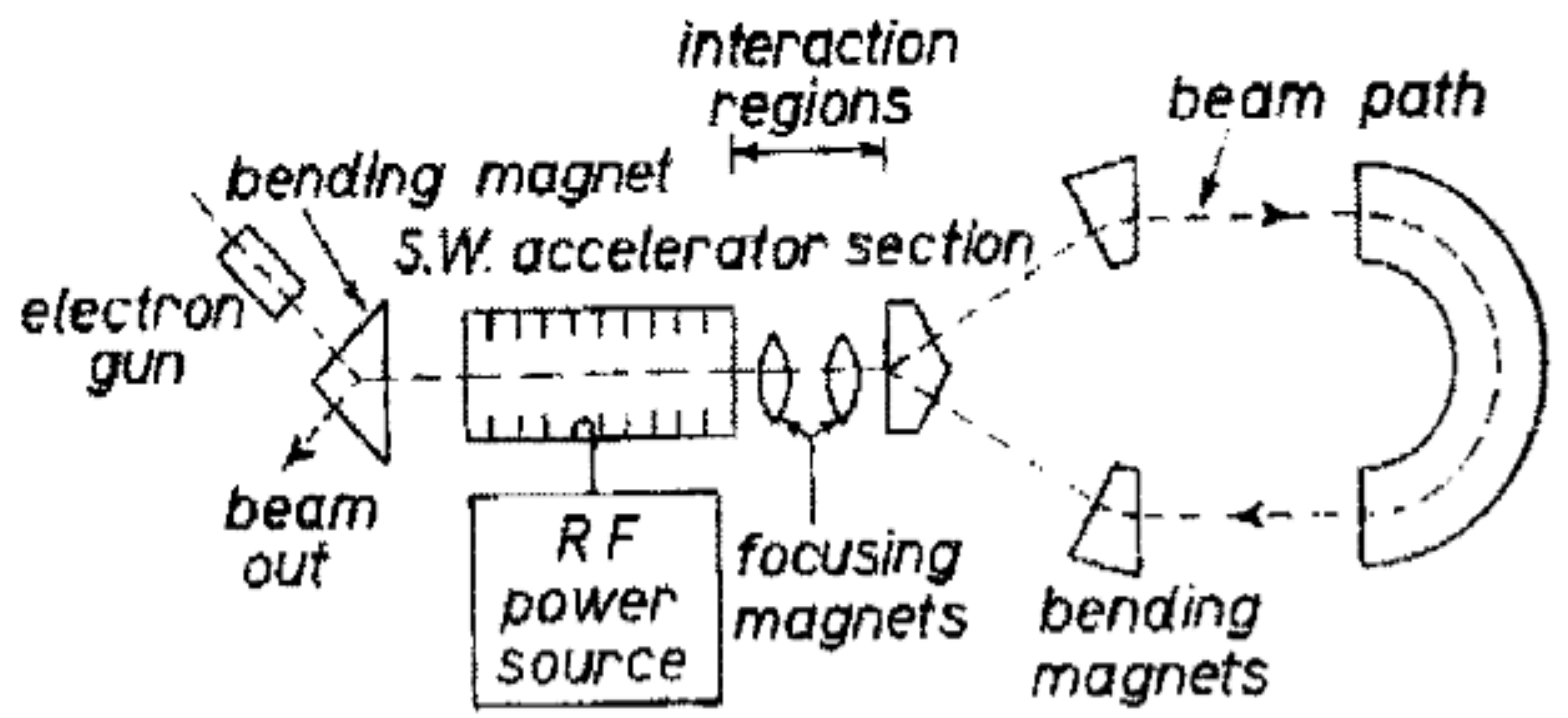
Accelerating two beams, colliding them, and then dumping them is extremely inefficient.

In 1965 Maury Tigner proposed idea of an energy-recovery linac

- to enhance the current in a collider for high-energy physics
- recover the energy of the beams in the same cavities in which they were accelerated, then the machine efficiency could be greatly increased
- the design of the final dump also becomes much simpler

No ERL machine for 30 years! Why?

Maury Tigner, A Possible Apparatus for Electron Clashing-Beam Experiments, N.Cim 10(1965)1228



Recirculation lattice to recycle kinetic beam energy of a decelerating beam for acceleration of a newly injected low energy beam. Avoid synchrotron loss initiated emittance growth as in storage rings. Minimize power consumption (by an order of magnitude) and dump at E_{inj}

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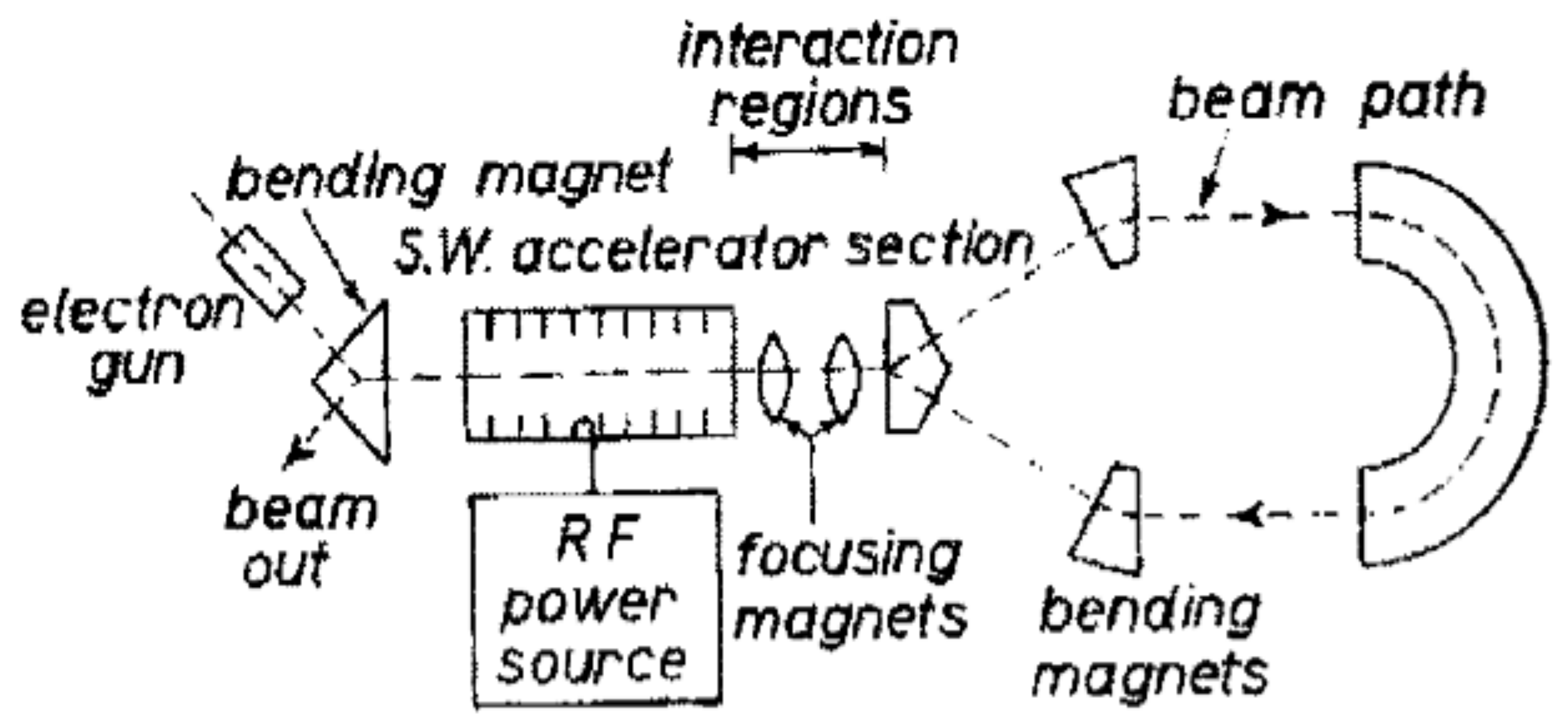
The implementation of an efficient solution relied on the development of reliable superconducting radio frequency (SRF) accelerating cavities. These were developed over the next decade.

Maury Tigner, A Possible Apparatus for Electron Clashing-Beam Experiments, N.Cim 10(1965)1228



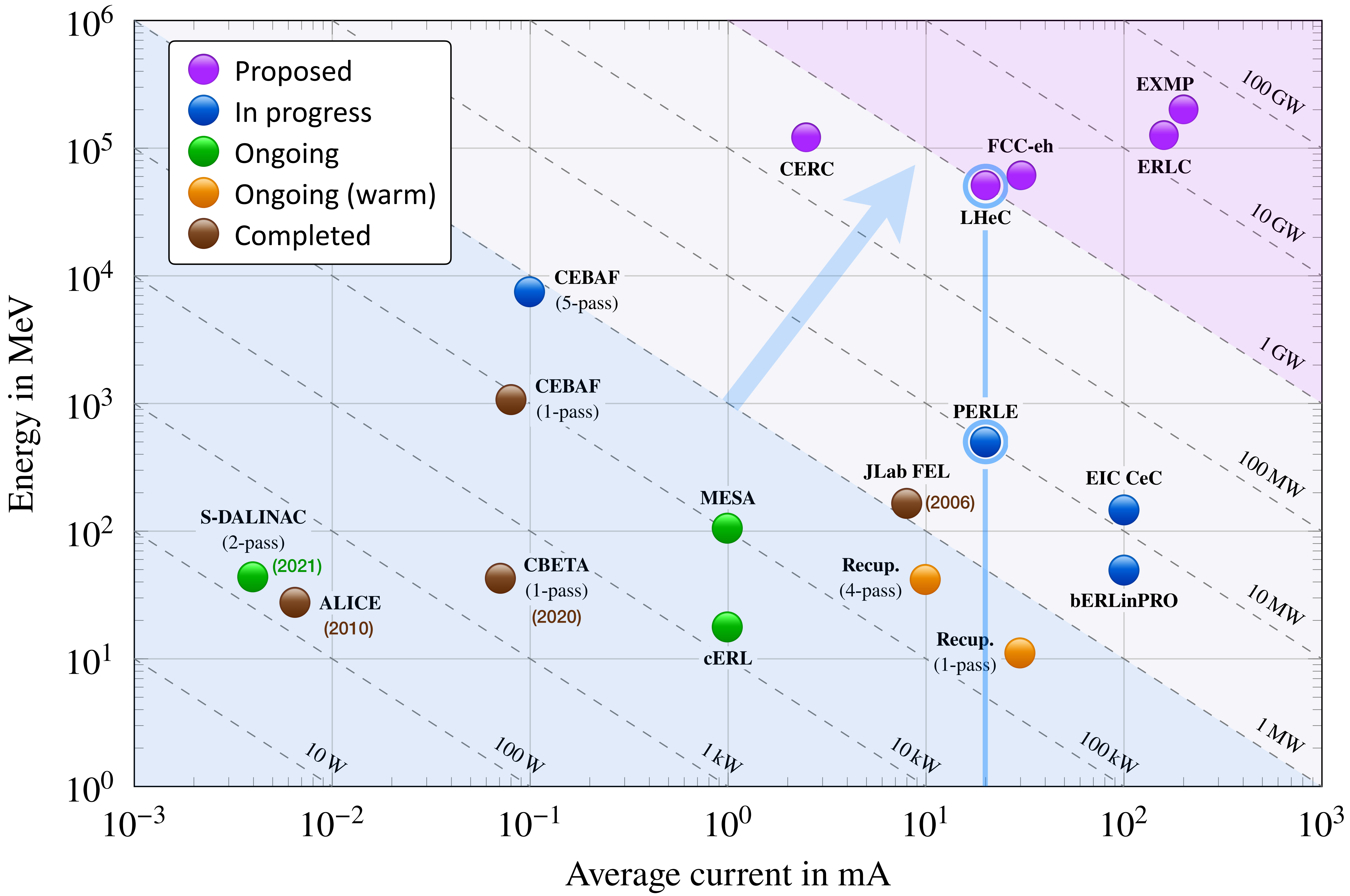
Recirculation lattice to recycle kinetic beam energy of a decelerating beam for acceleration of a newly injected low energy beam. Avoid synchrotron loss initiated emittance growth as in storage rings. Minimize power consumption (by an order of magnitude) and dump at E_{inj}

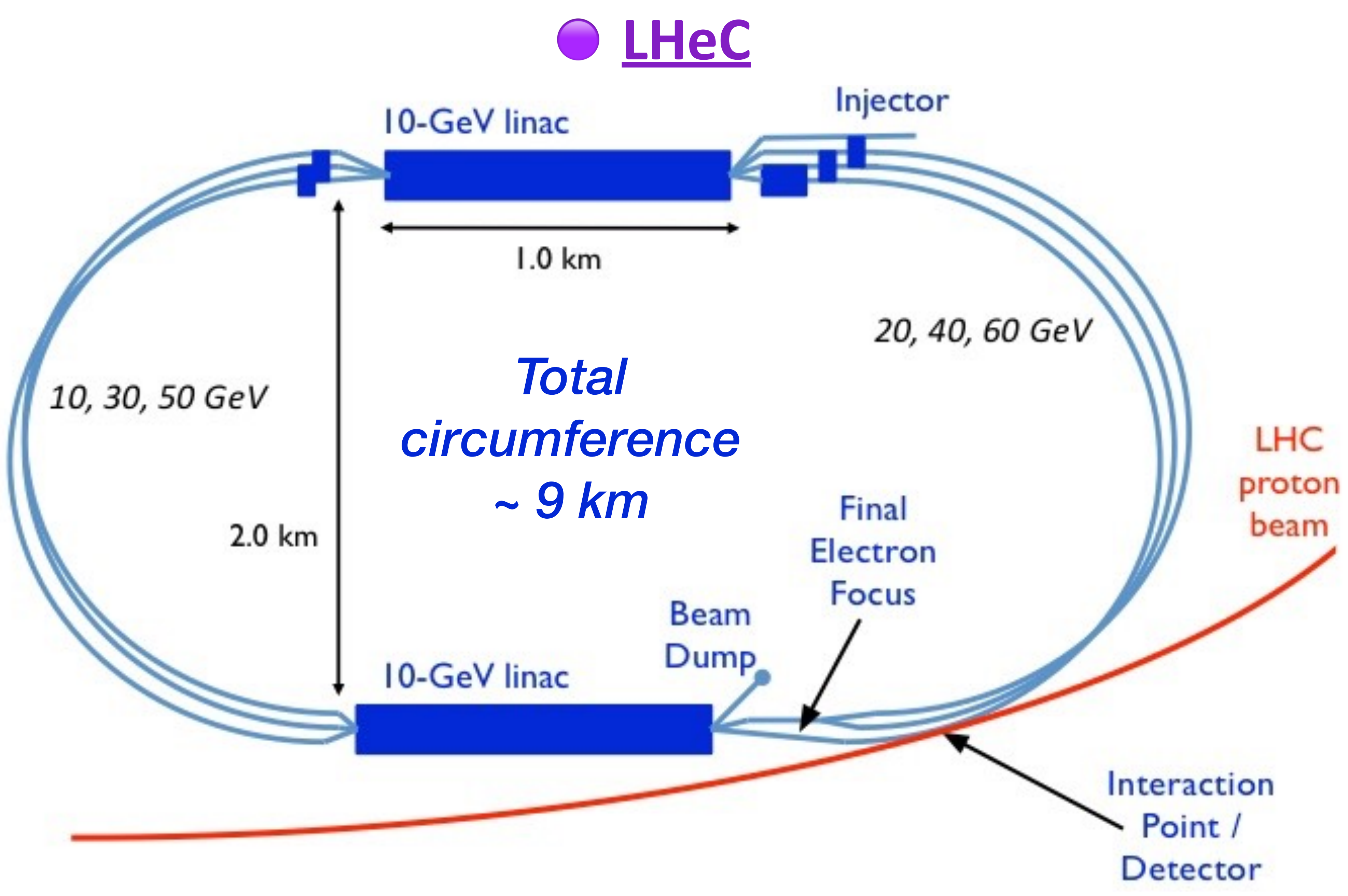
"There will be no future large-scale science project without an energy management component, an incentive for energy efficiency and energy recovery among the major objectives"

Frédérick Bordry, Director for Accelerators and Technology at CERN (2019)

Energy Recovery Linacs (ERL)

Proven accelerator technology, pushing for higher energy and beam current reaching in view of collider applications above 1GW.





PERLE has the same bunch parameters as LHeC

Injection rate: **40 MHz** (every **25 ns**)

Target current: **20 mA**

Bunch charge: **500 pC** (3×10^{9} e^{-})

RF cavities: **801 MHz**

PERLE Timeline

06.2012 — First Idea

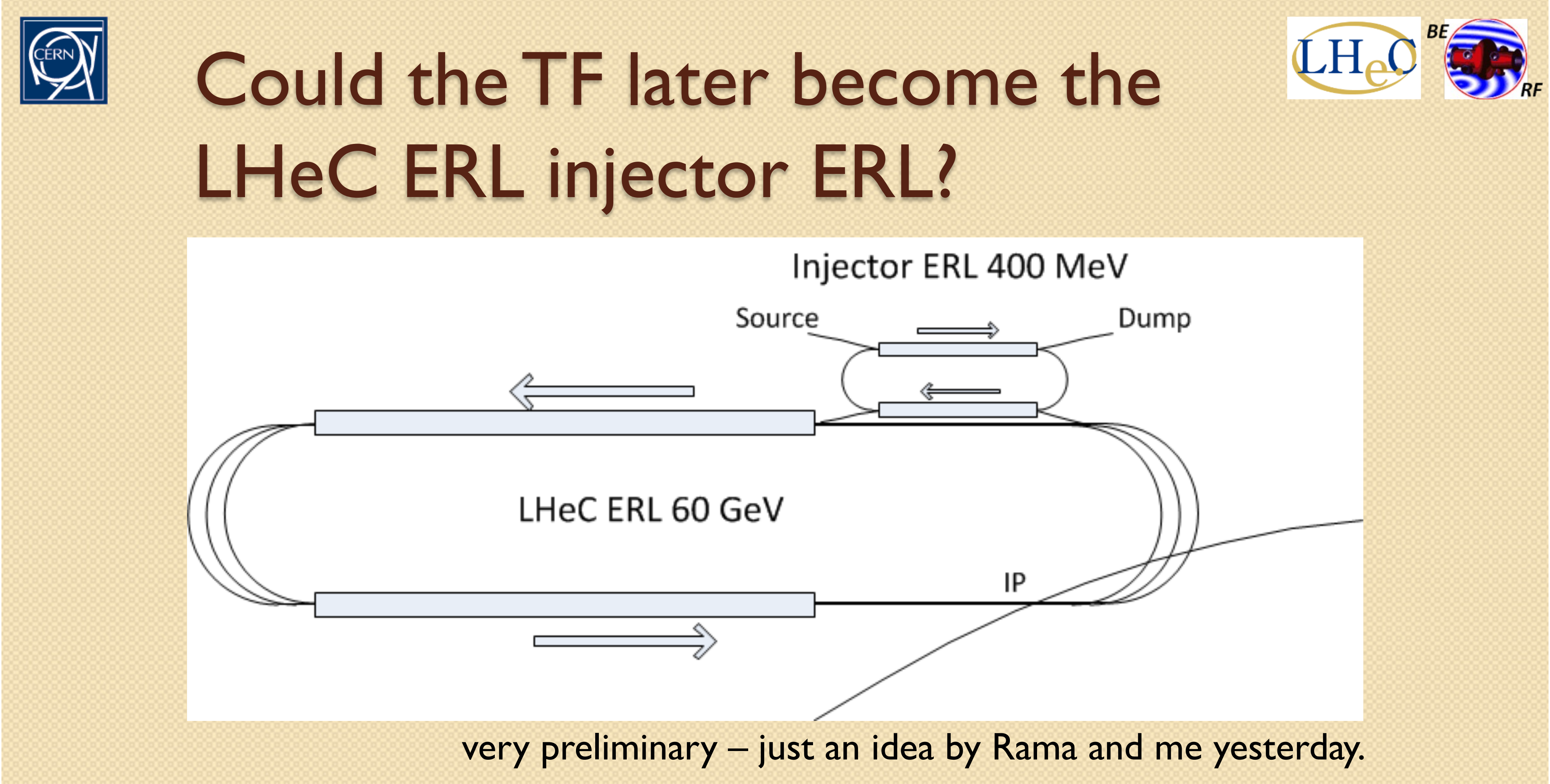
Erk Jensen: Workshop on the LHeC (CERN)

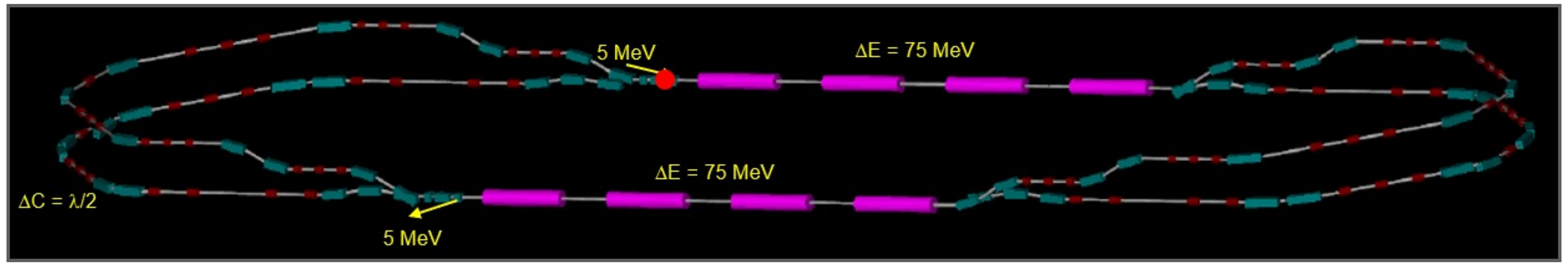
08.2012 — First Lattice Design

Alex Bogacz: after discussion with Erk Jensen

06.2015 — Name PERLE

Erk Jensen: LHeC Workshop (CERN)





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06.2015 — Name PERLE

Erk Jensen: LHeC Workshop (CERN)

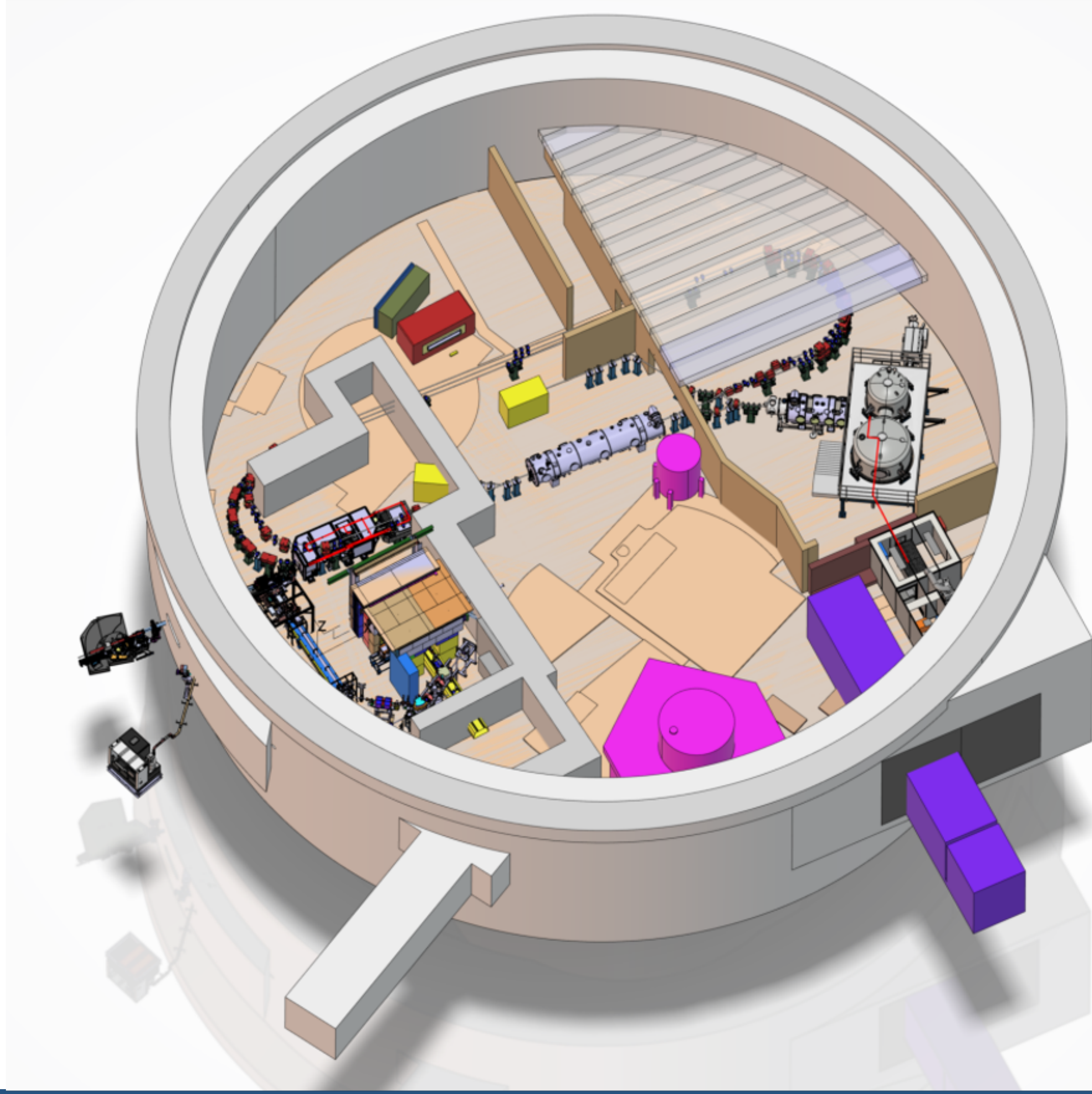
10.2016 — Meeting on PERLE at Orsay

Max Klein: Workshop on the LHeC (Switzerland)

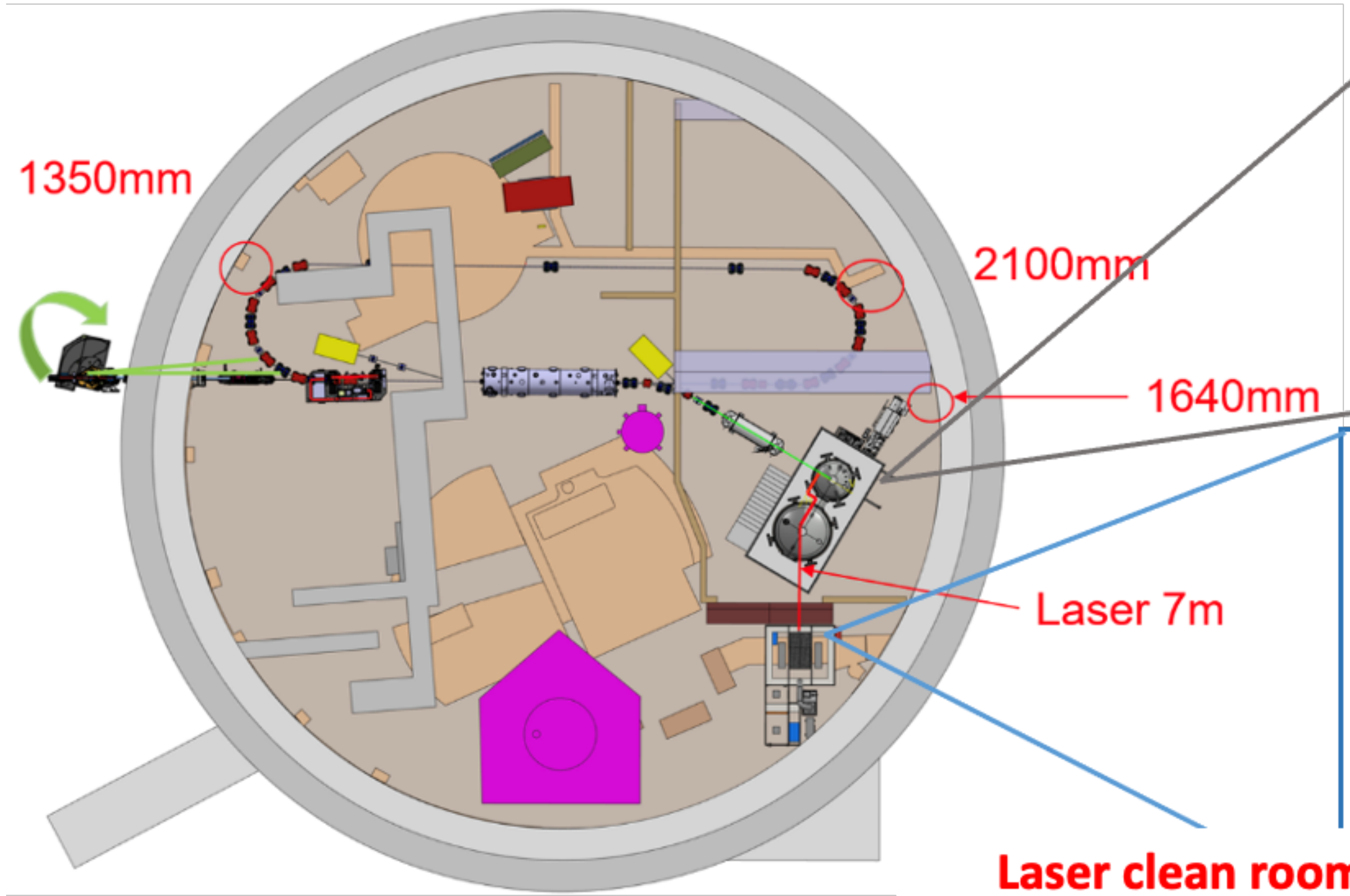
05.2017 — Conceptual Design Report

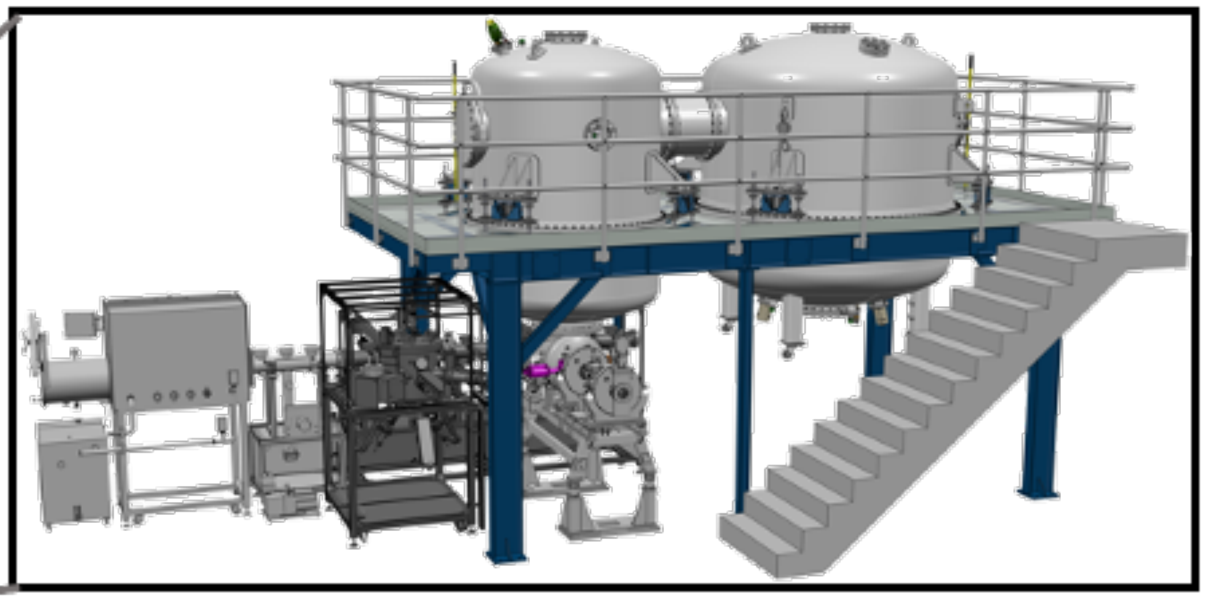
This year — Technical Design Report

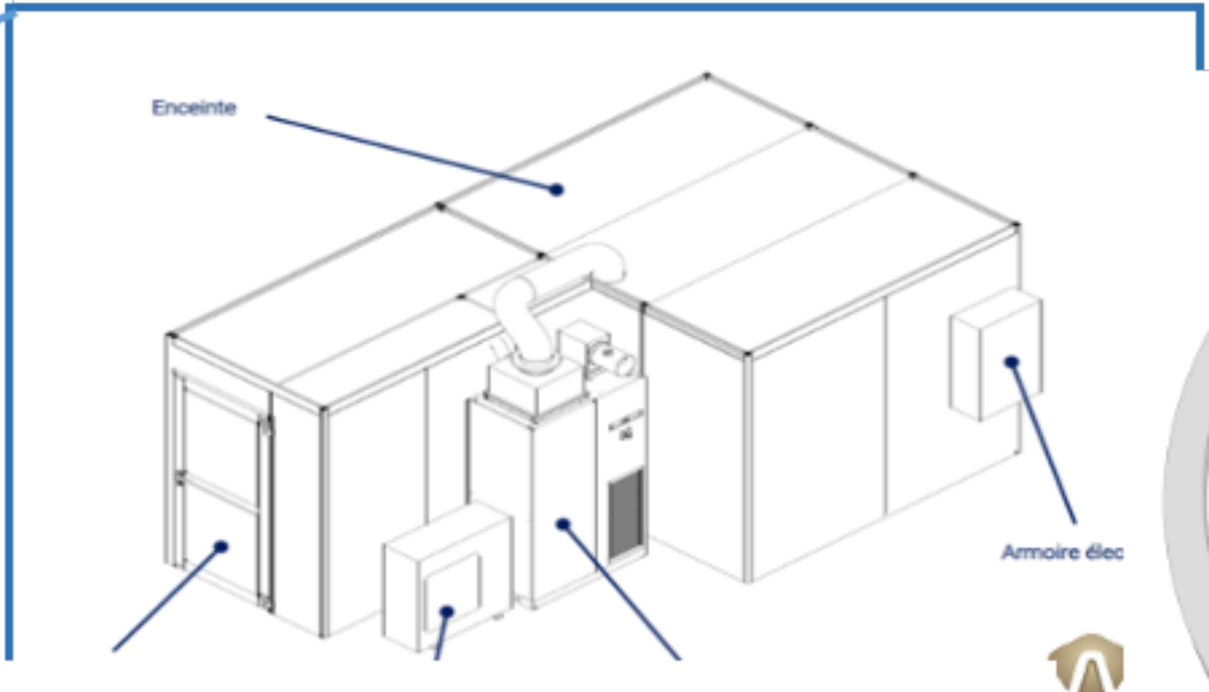
Implantation in IGLOO being finalised



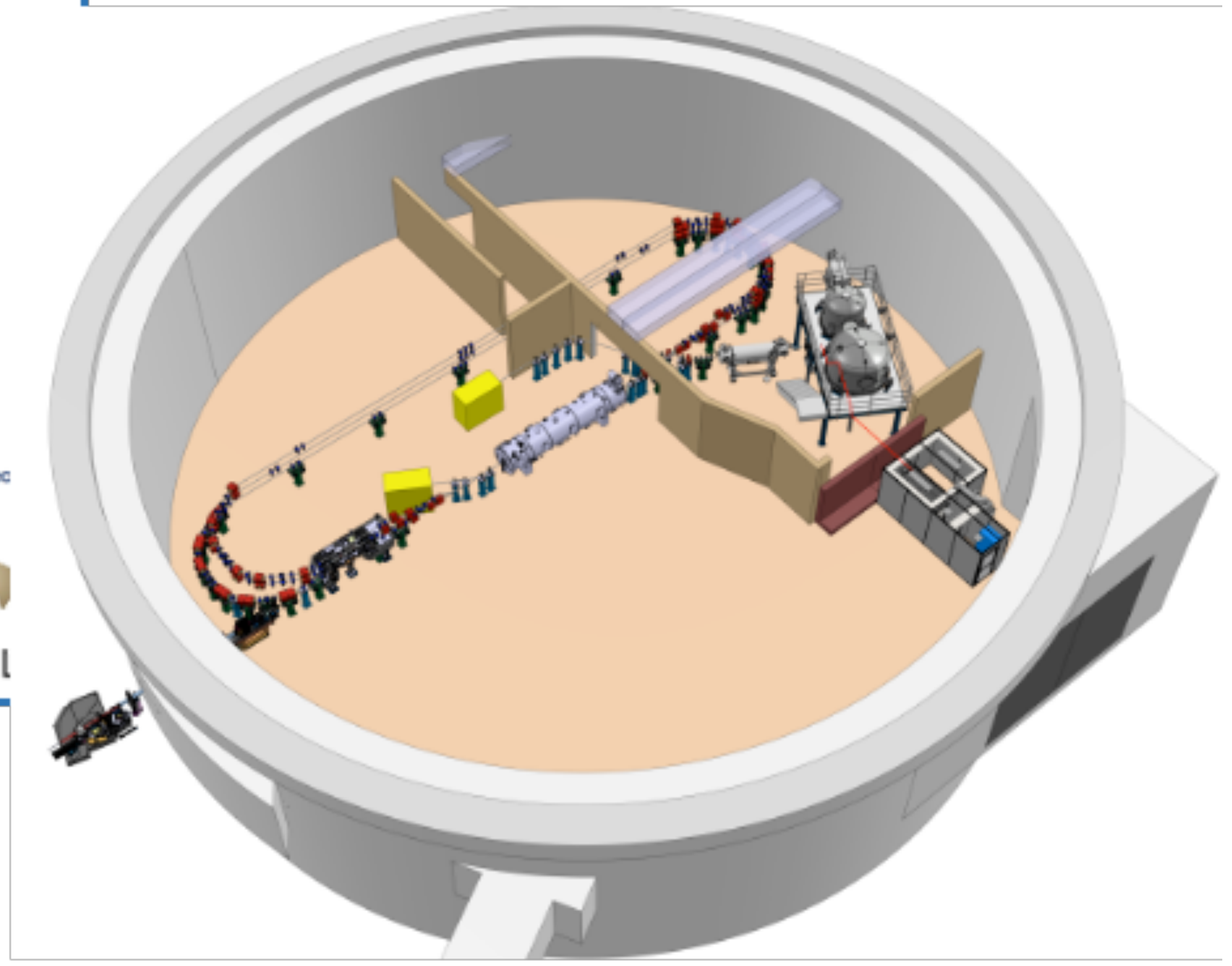
PERLE Timeline





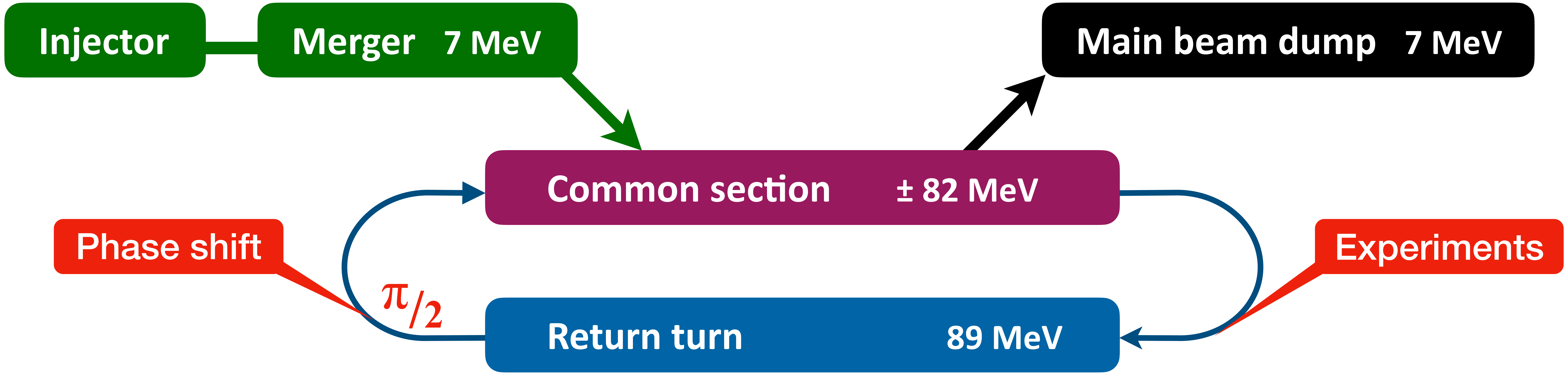


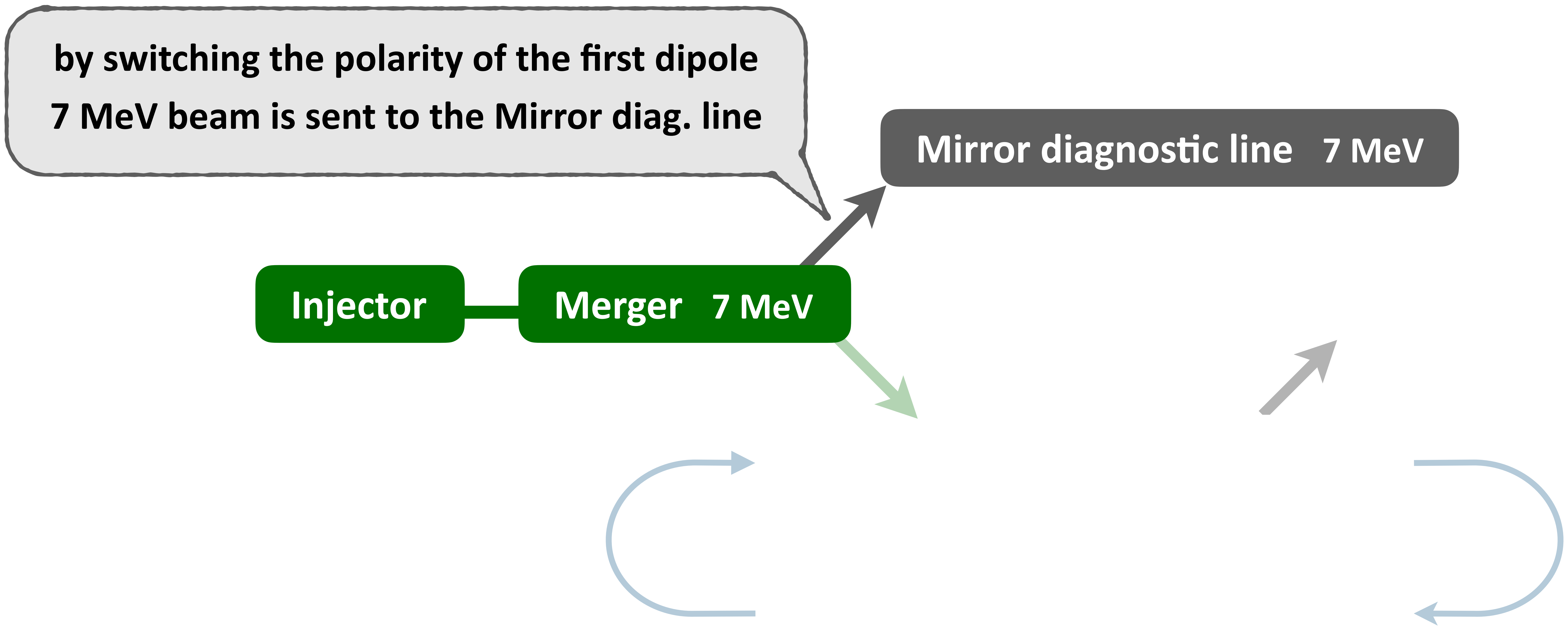
Laser clean room: delivered in June 2024

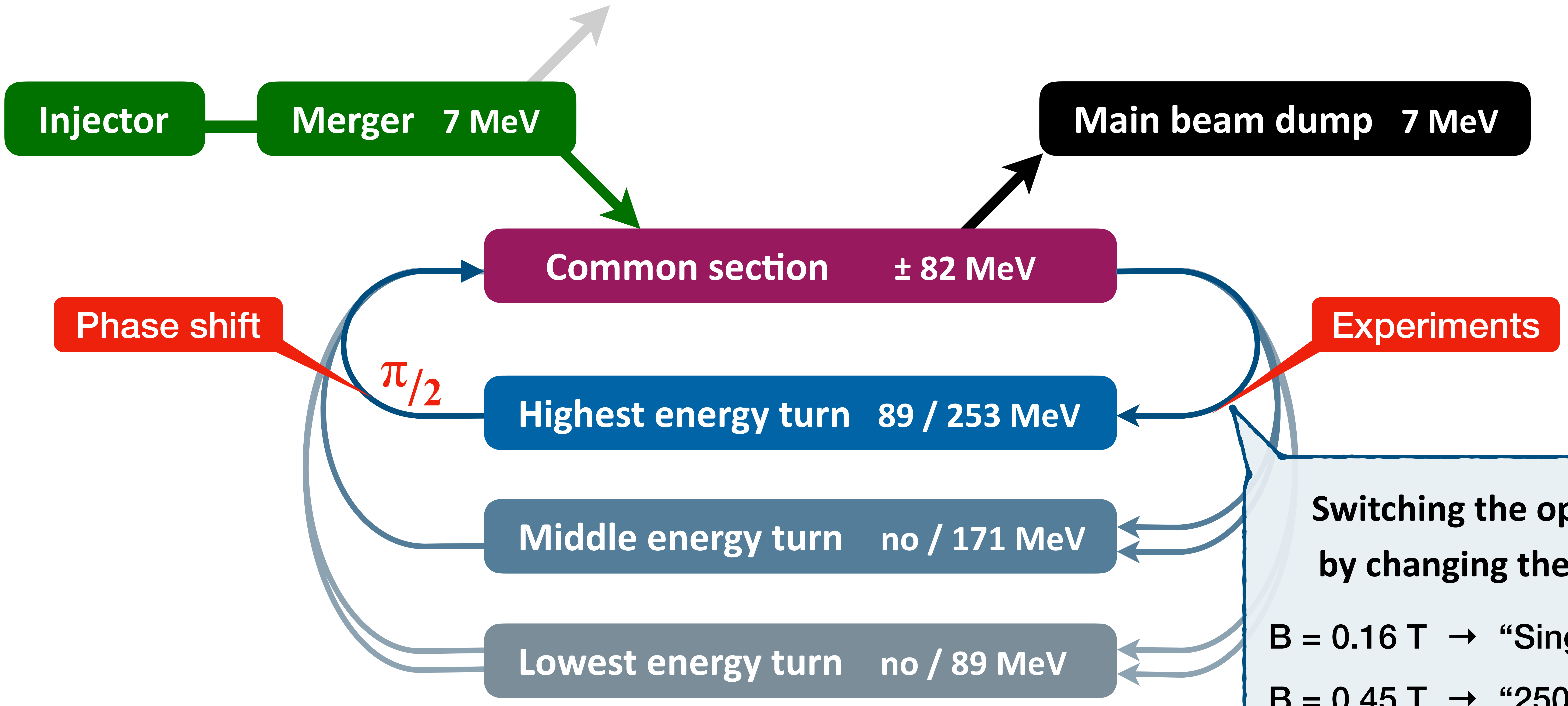


Implantation in igloo being finalized

Lattice design


Injector
Merger 7 MeV
Main beam dump 7 MeV
Common section ± 82 MeV
Phase shift
π/2
Experiments
Return turn 89 MeV


by switching the polarity of the first dipole
7 MeV beam is sent to the Mirror diag. line
Mirror diagnostic line 7 MeV
Injector
Merger 7 MeV

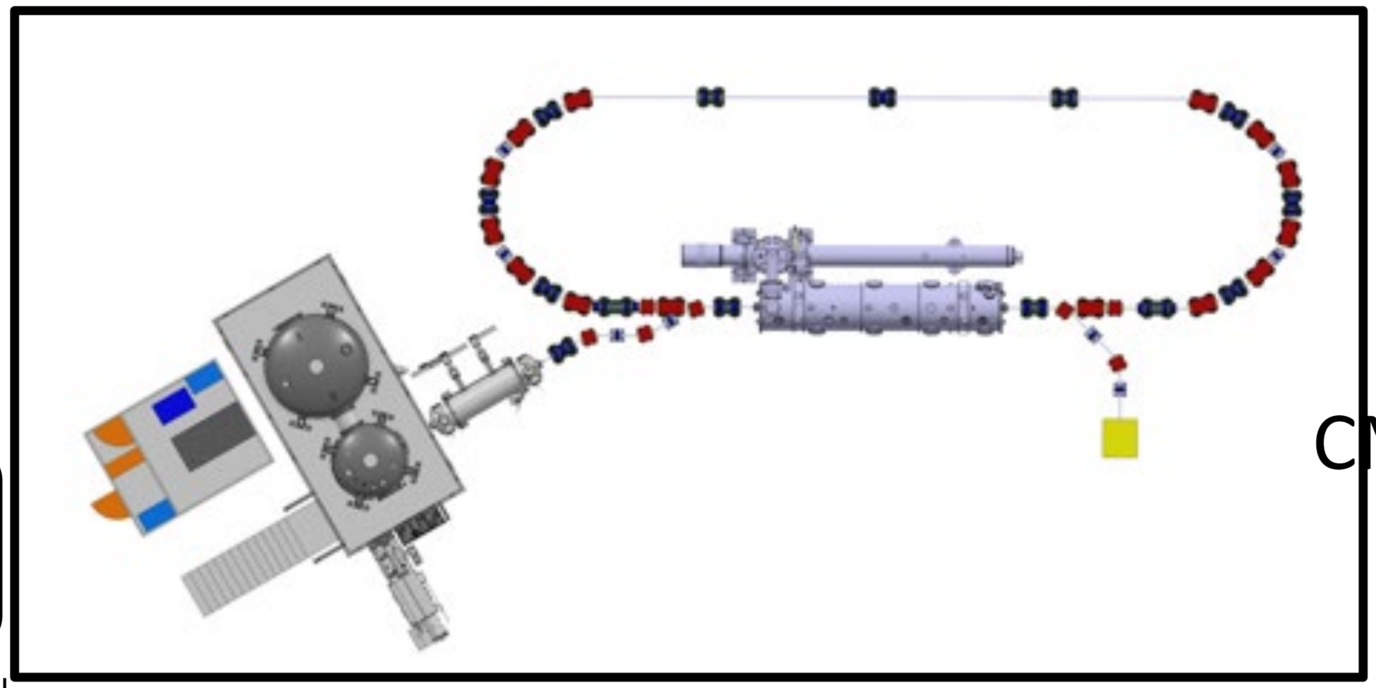


Switching the operation modes by changing the field in BCom:

B = 0.16 T → "Single turn" (89 MeV)

B = 0.45 T → "250 MeV"

PERLE Timeline



"Partially" FUNDED!

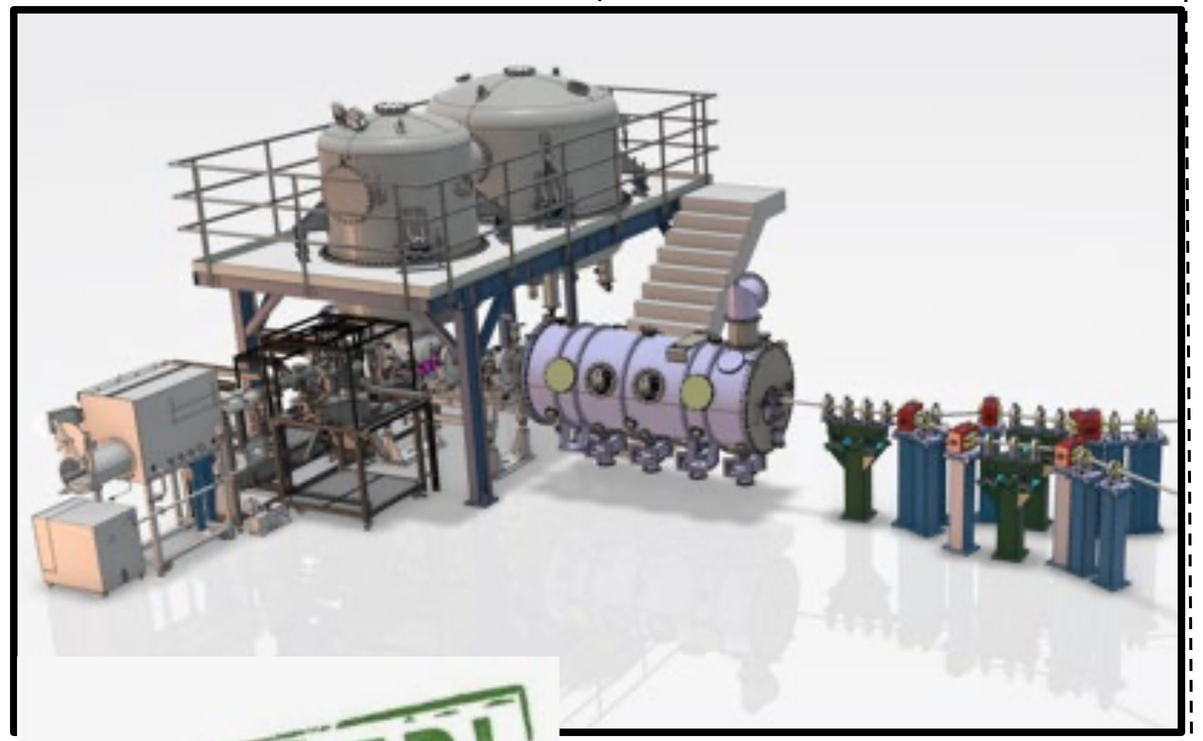
CM funded by EU Program iSAS
+ Matching funds (IN2P3)

TDR and prototyping

Phase 2: PERLE 1 tour

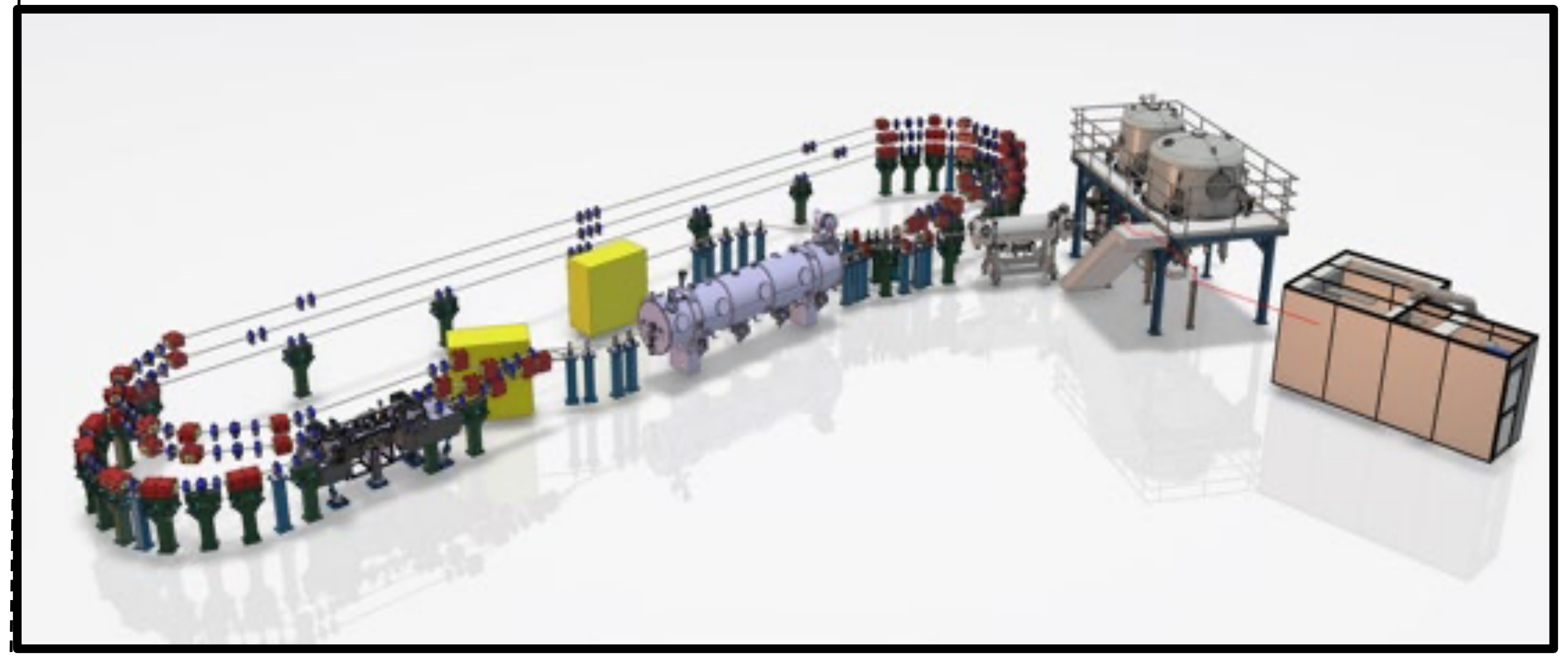
Phase 1: Injection line

Phase 3: PERLE 250 MeV



FUNDED!

By CNRS National Program RI2

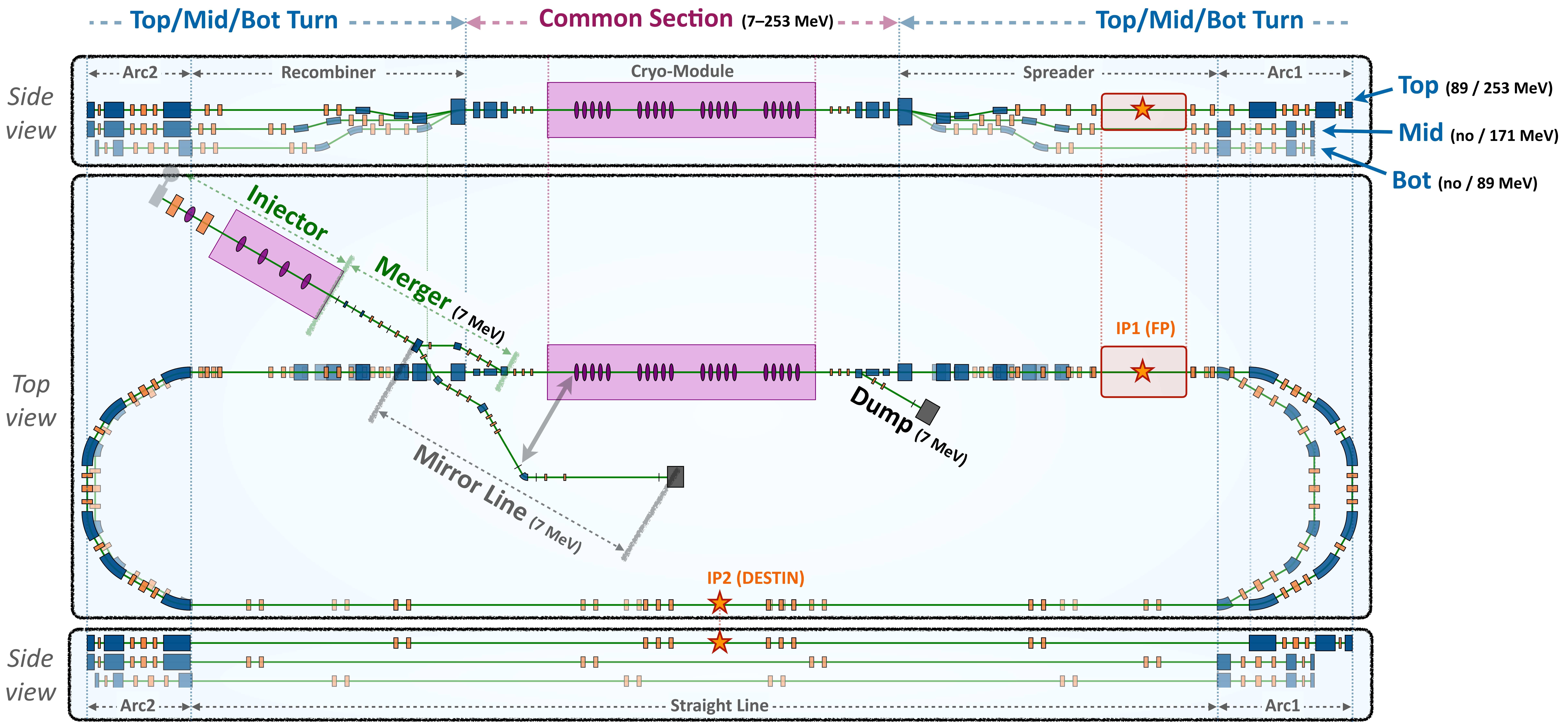


Extra funding needed for 6 arcs configuration

2022	2023	2024	2025	2026	2027	2028	2029	2030	2031

Phase 4: PERLE 500 MeV

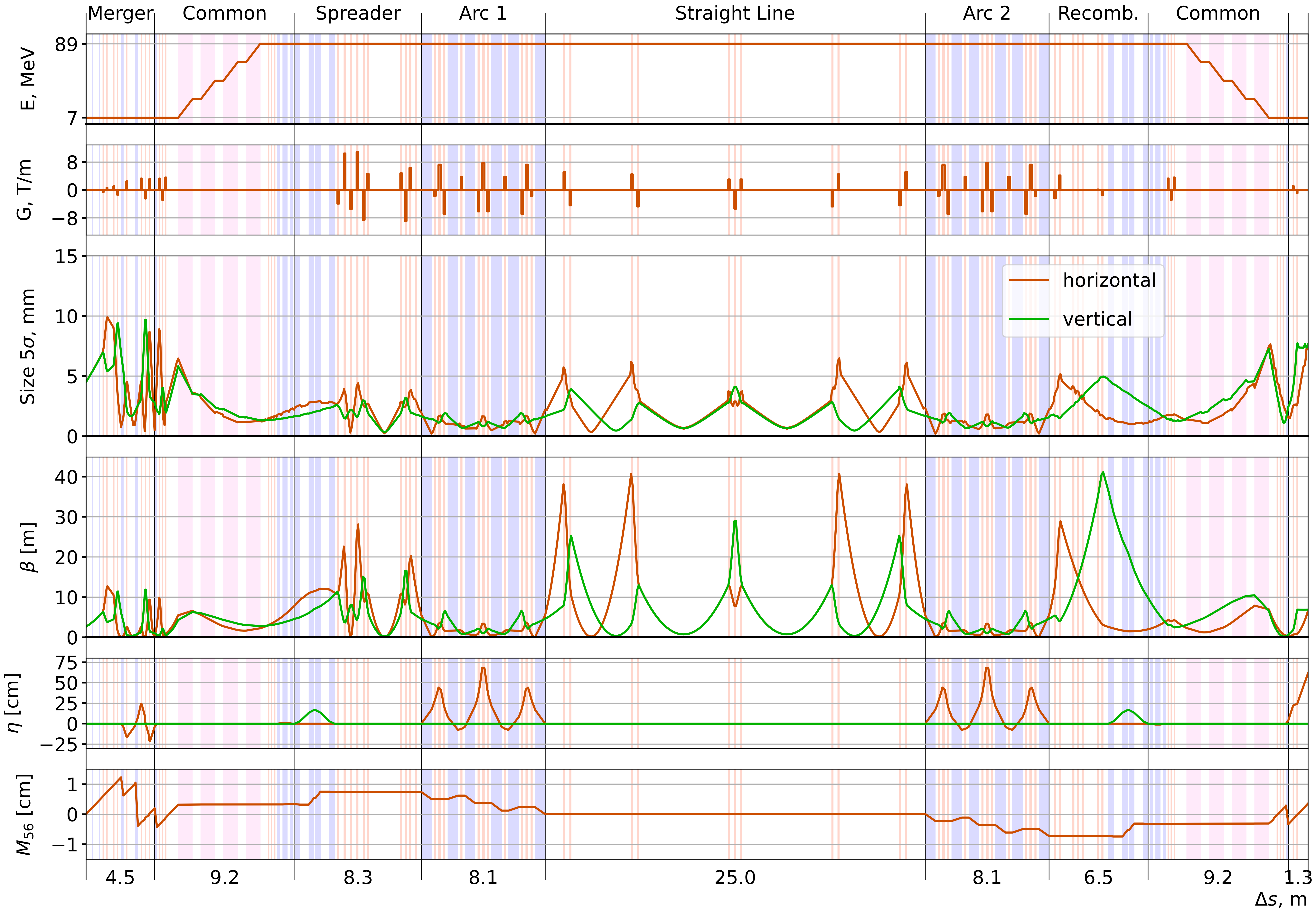
PERLE Lattice 250 MeV version



Lattice design. 250 MeV & 500 MeV versions

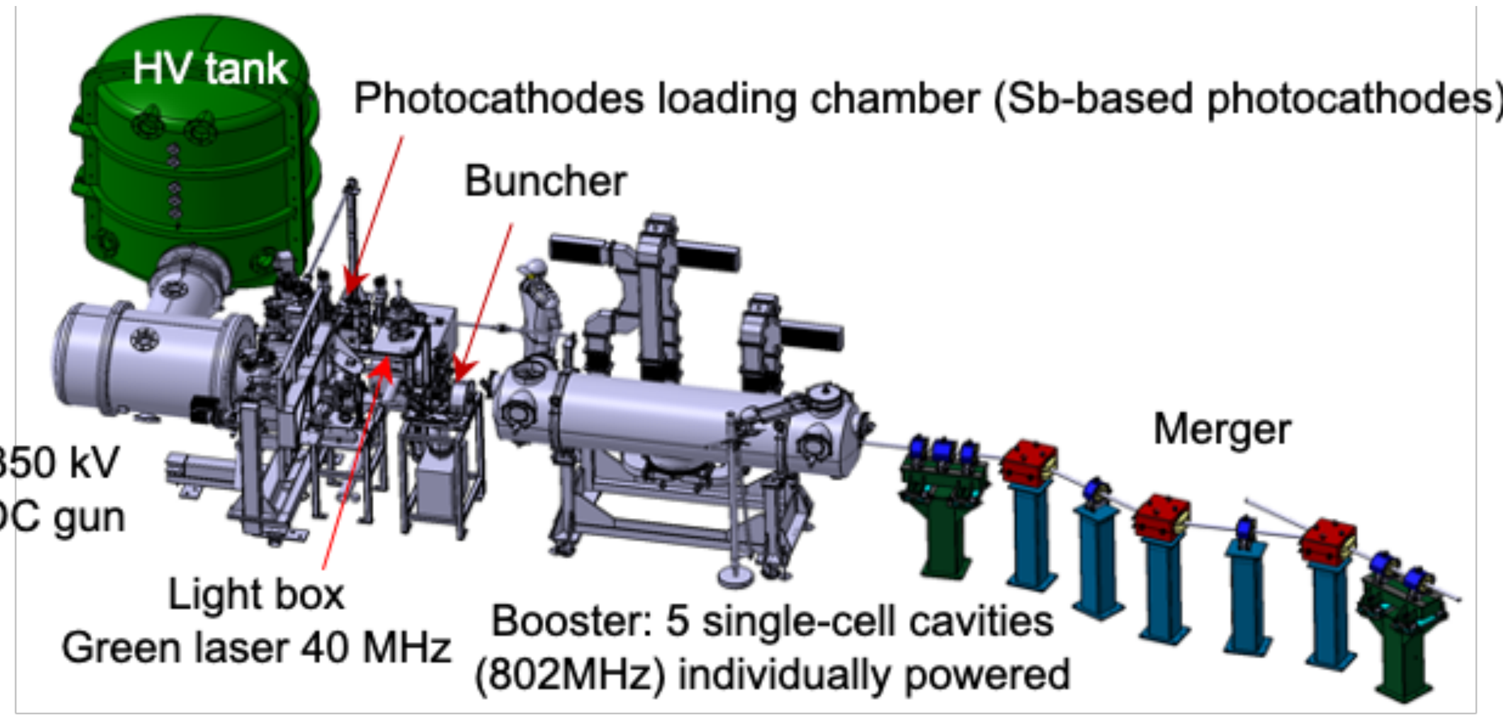
All main elements should be reused in 500 MeV version of PERLE

PERLE Optics: from Merger to Dump (“Single turn” version)



PERLE Optics: from Injection to Dump (250 MeV version)

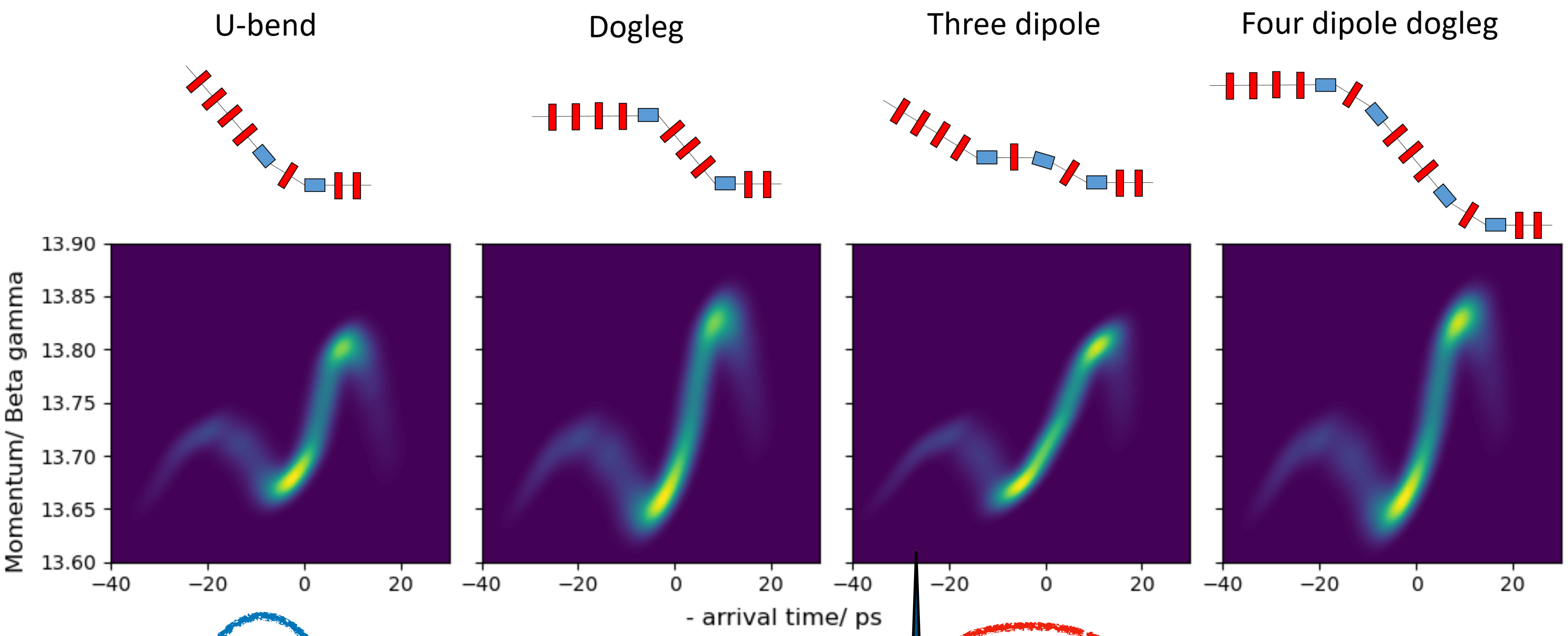
Beam Dynamics



A conceptual design of the PERLE injector was made within a collaboration between AsTeC-Daresbury, UoL and IJCLab.

(PhD of B. Hounsell)

Four merger schemes

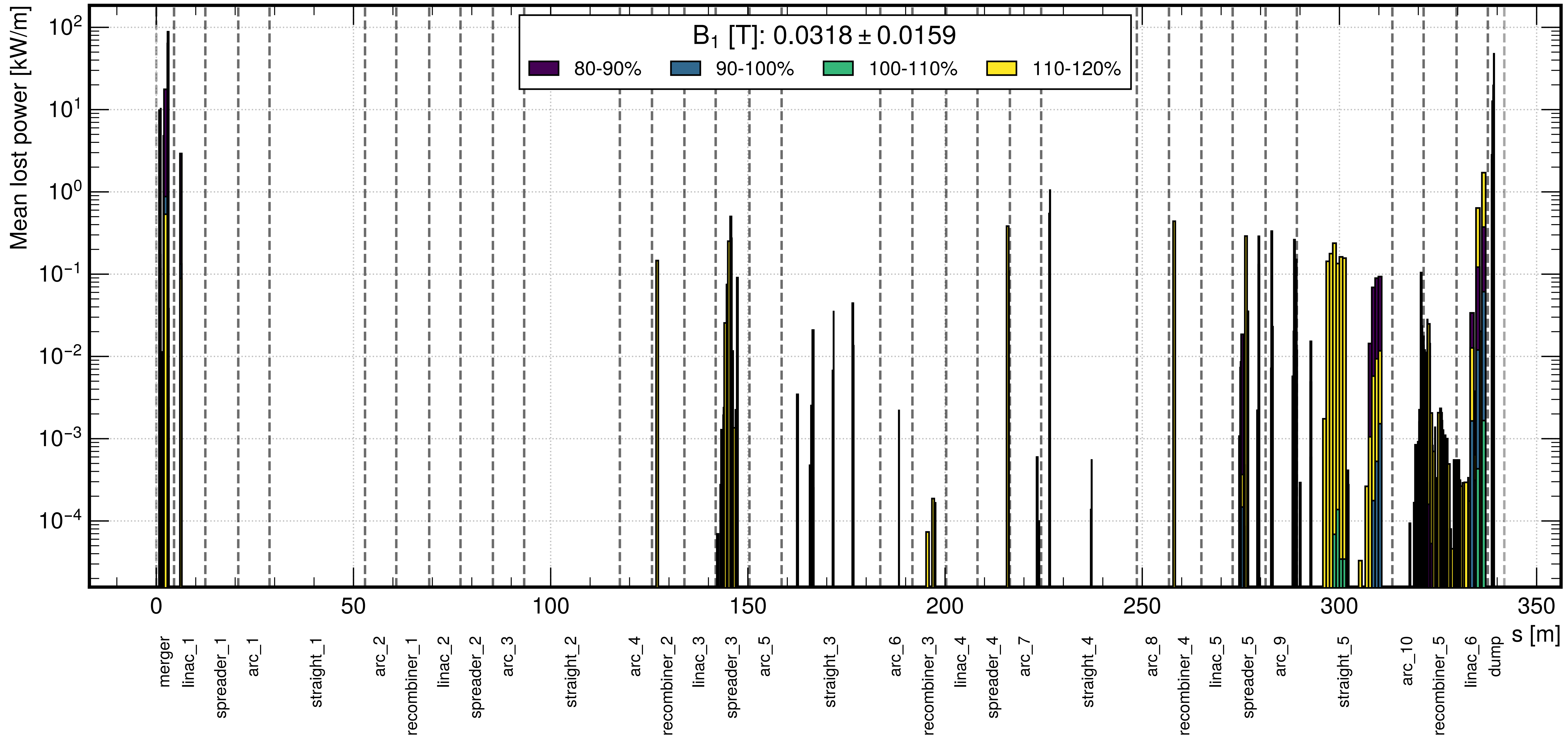


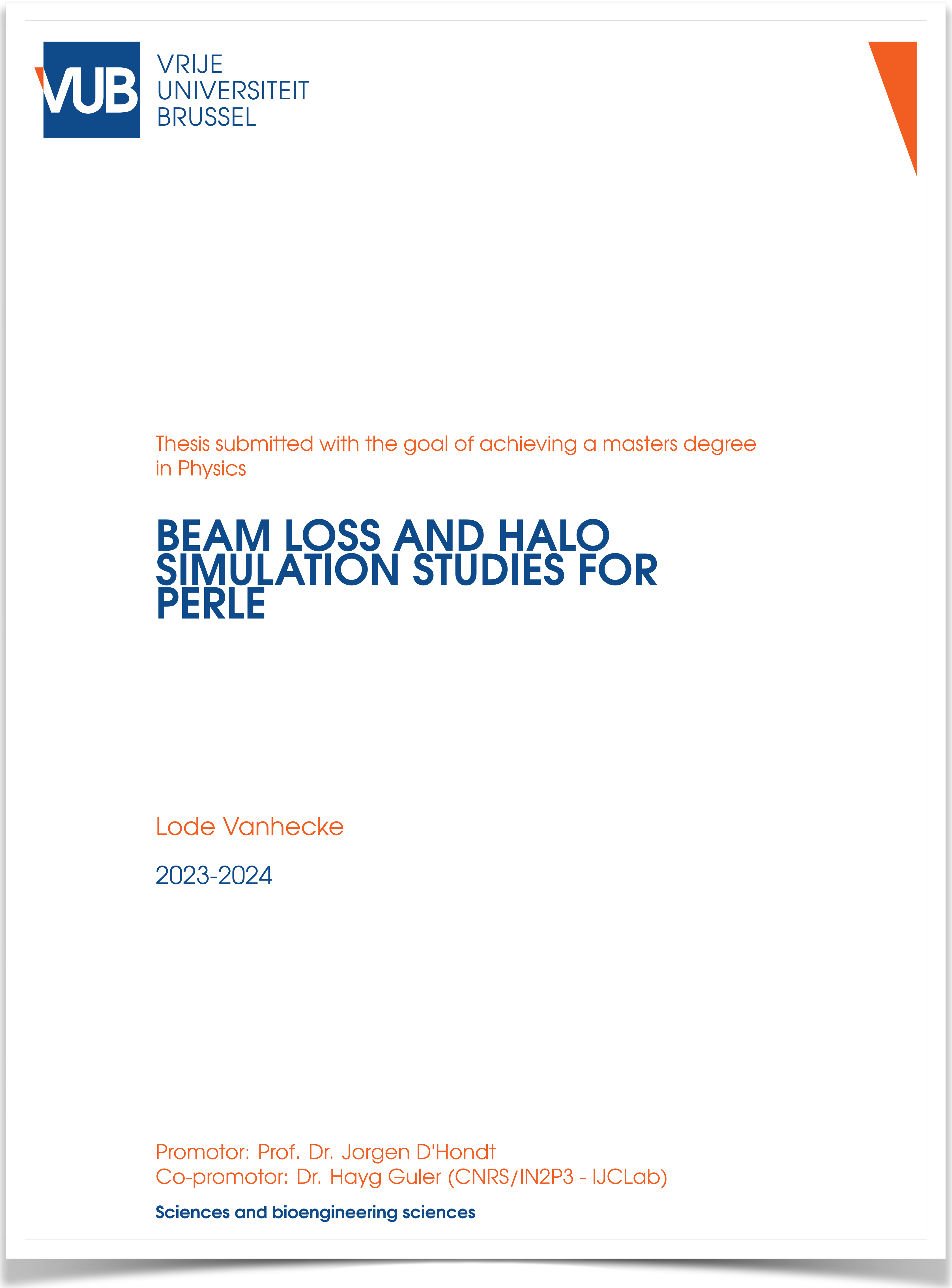
	U-bend	Dogleg	Three dipole	Four dipole dogleg	Spec
εx/ mm·mrad	4.3	5.2	5.9	4.7	< 6
εy/ mm·mrad	4.4	4.5	3.2	7.0	< 6
Mismatch factor	0.014	0.72	0.05	0.11	0
R56/ m	0.023	0.0185	-0.155	0.031	0

Initially preferred scheme

CBETA choice

- Effect of field errors and laser offset in the injector on the losses in ERL
- Simulation ASTRA + BMAD
- 5% field errors → significant losses
- major losses found in the merger — layout should be optimised



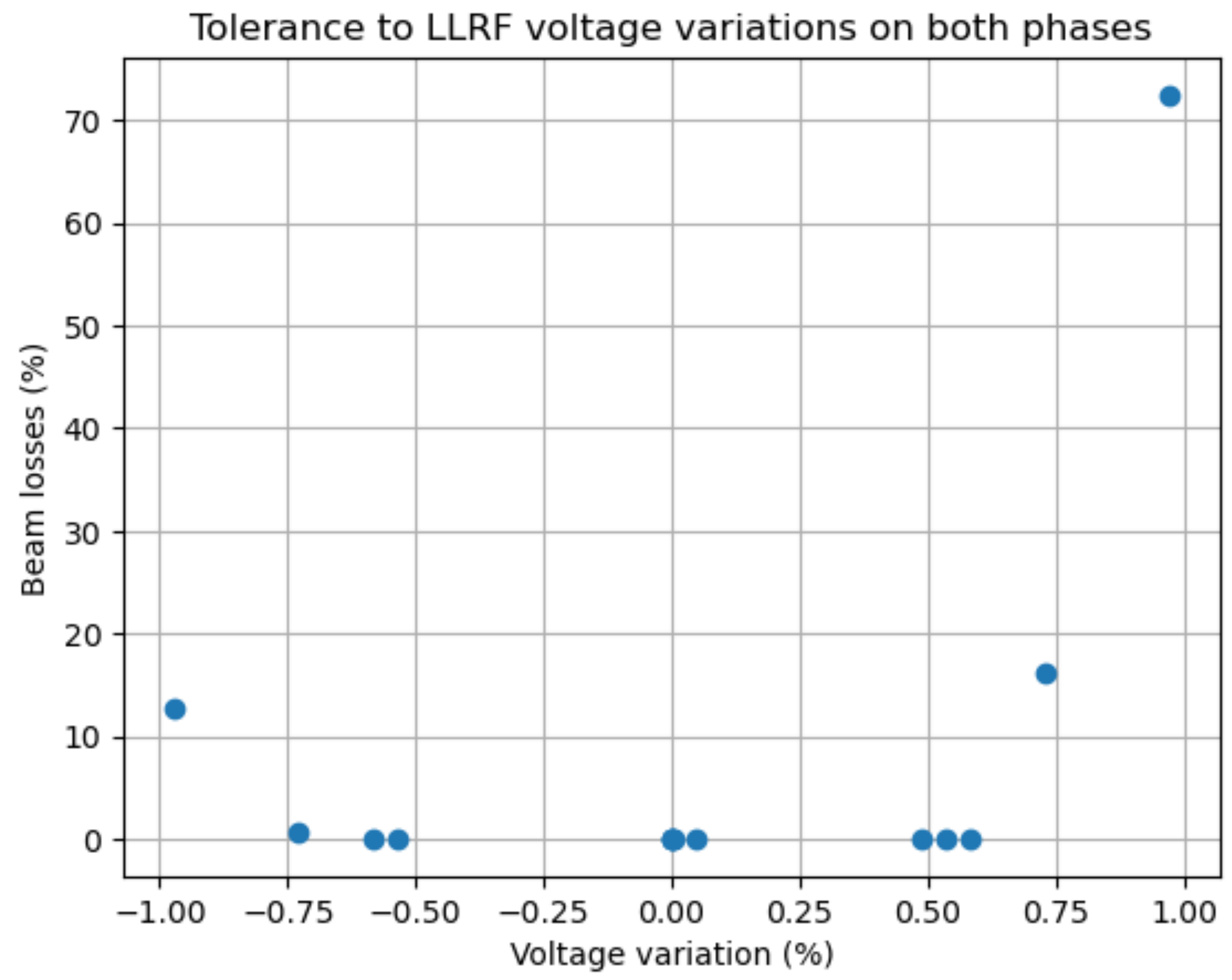


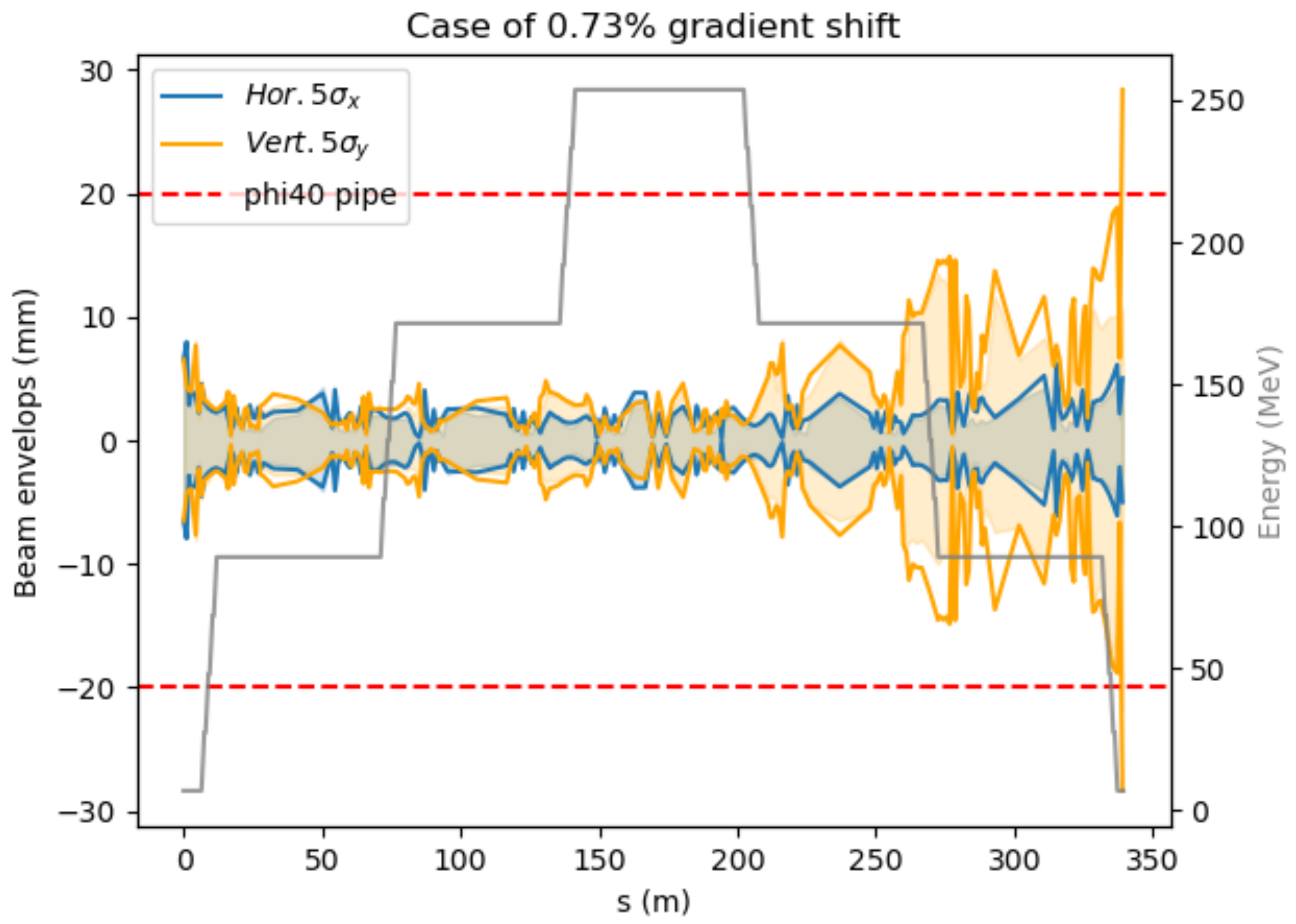
Sensitivity to cavity power supply instabilities (J. Michaud)

Cavity voltage variations

- BMAD simulation
- Acceptance is ±0,5% (≈ 120 kV)

  (worst case scenario: 4 cavities detuned)

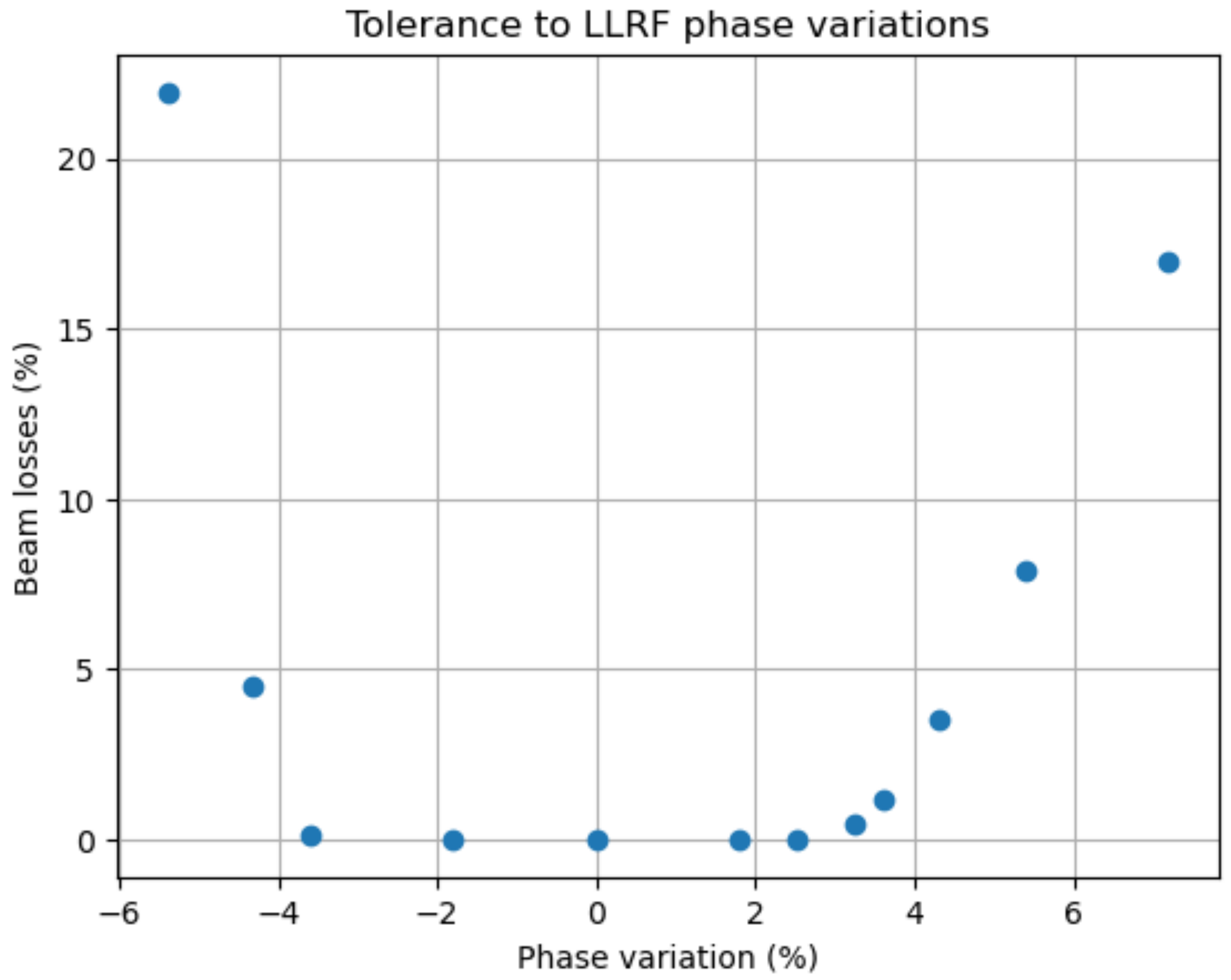


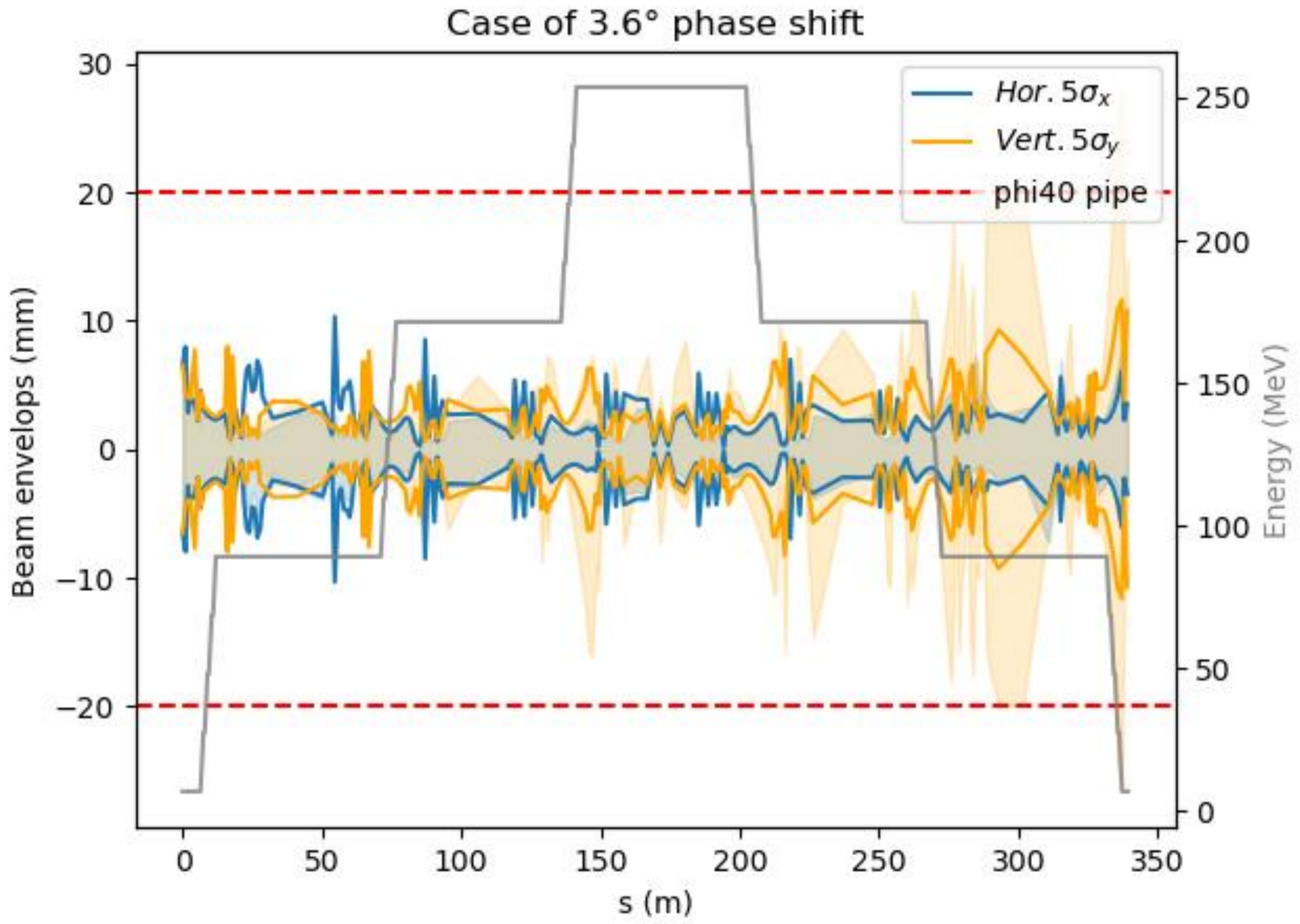


LLRF phase variations

- Acceptance is ±2,5 degrees for all cavities

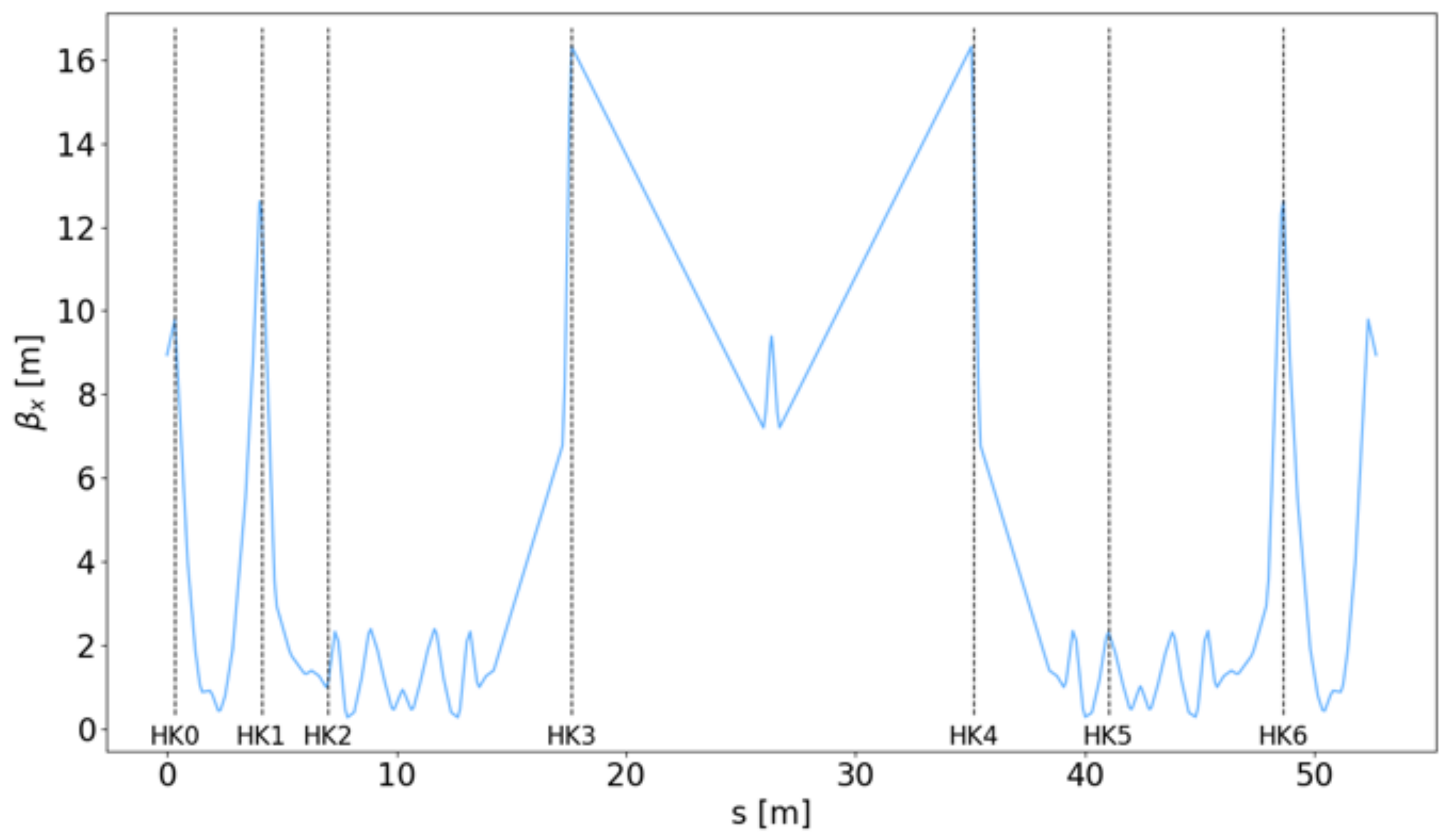
  (worst case scenario: 4 cavities detuned)

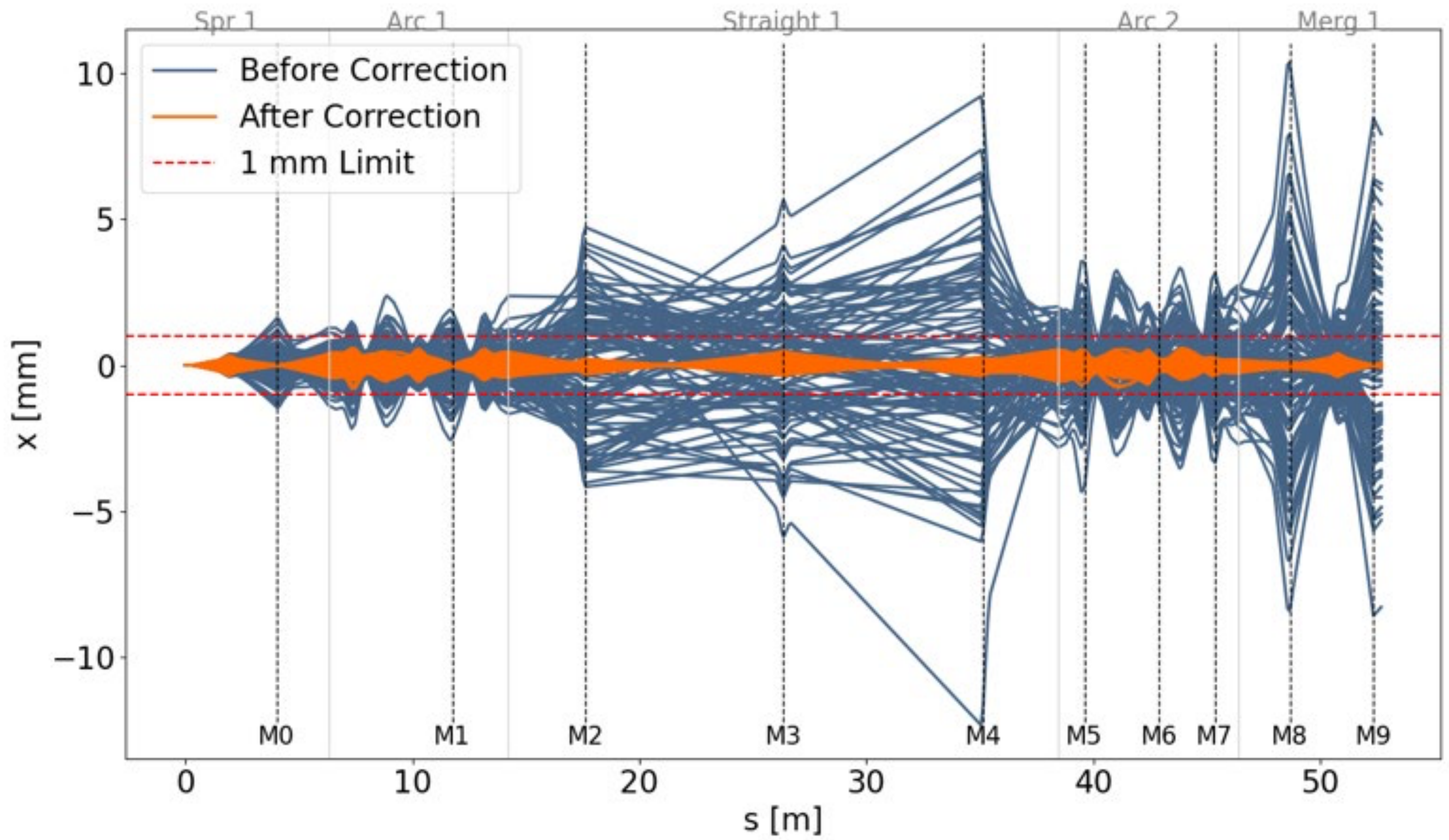




Optics Misalignments Studies (R. Abukeshek)

- Recalculating the optics of Turn 1 with all (45) quadrupoles misaligned: Misalignment affects the dispersion in both planes. No effect on Beta function.
- Gradually adding kicker-Monitor pair and observe the next places to mount the BPMs. In each step, the value of the previous HK_n are fixed from the previous optimization and introduced directly to the lattice



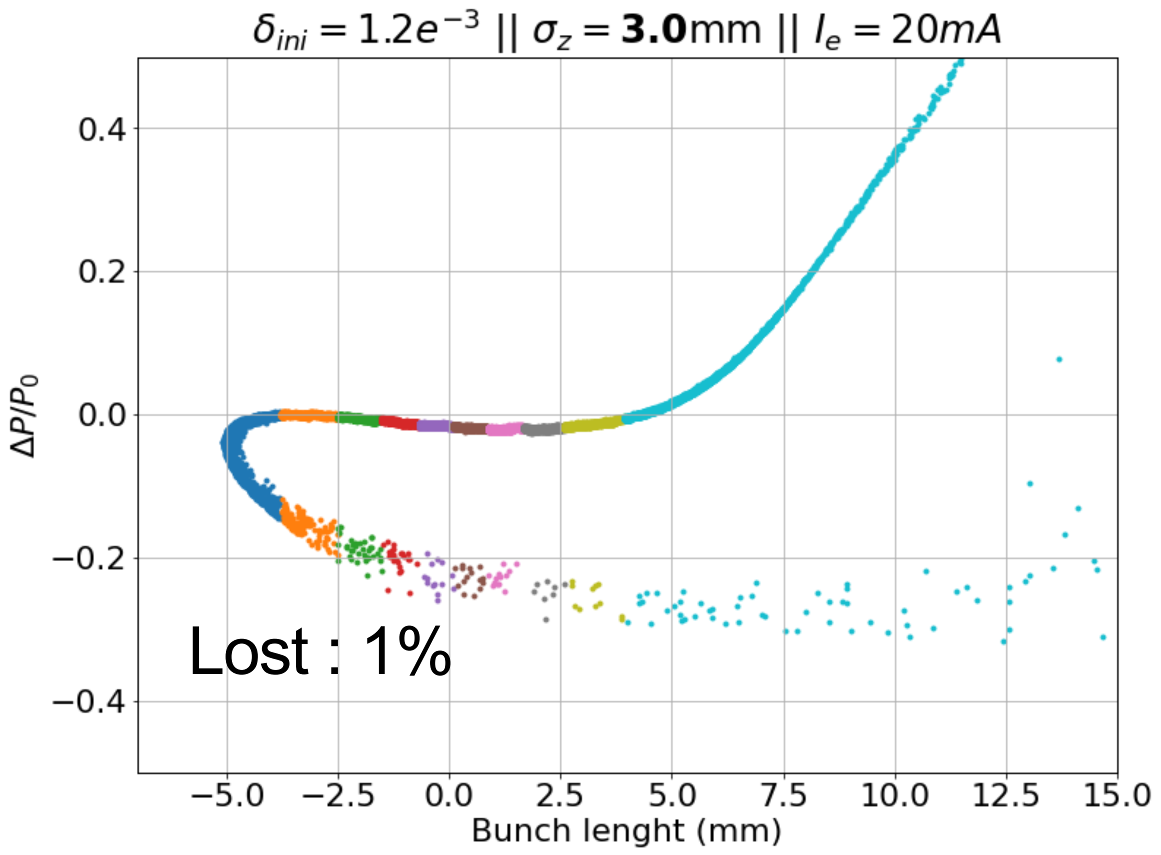


- positions of all kickers & monitors for the 1st turn are found: 7 kickers and 10 BPMs are needed.

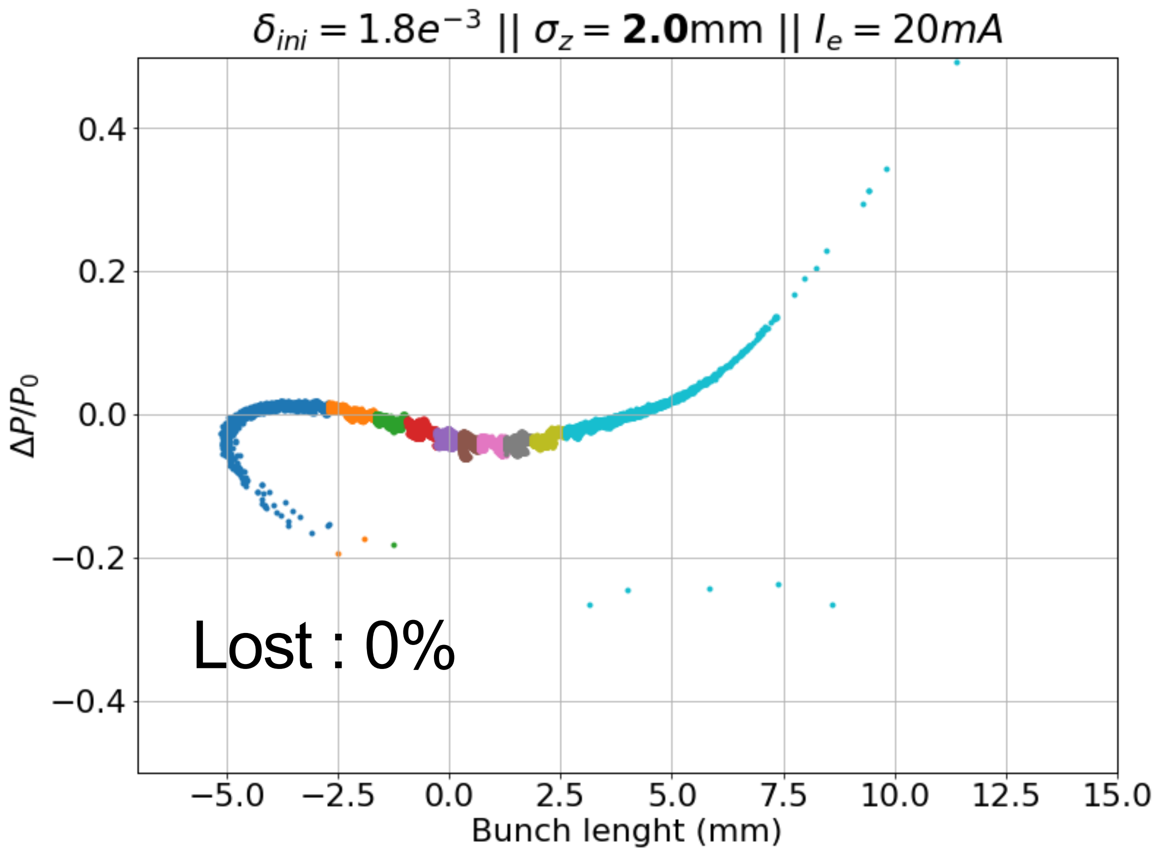
Simulation of 100 beam orbits along the 1st pass of PERLE (**blue**) and corrections (**orange**)

RF curvature vs CSR (work by K. André and J. Michaud)

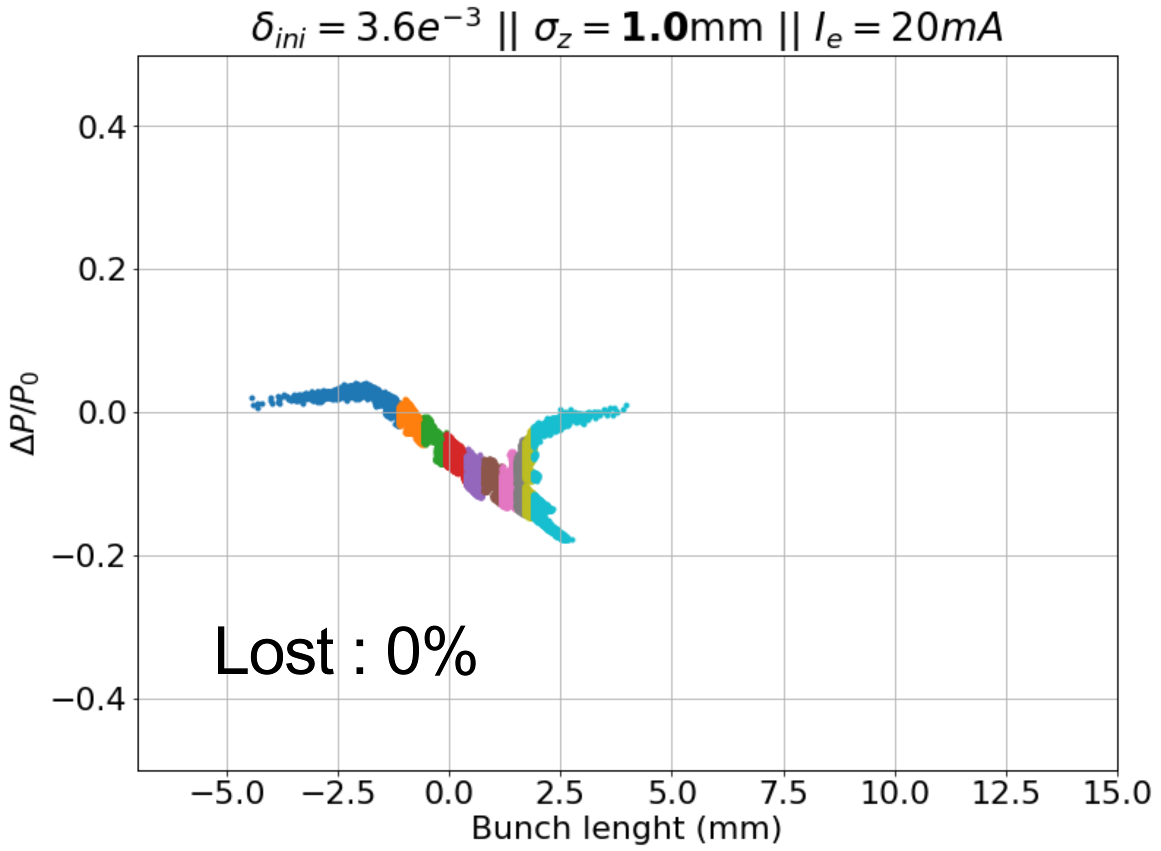
3 mm bunch length



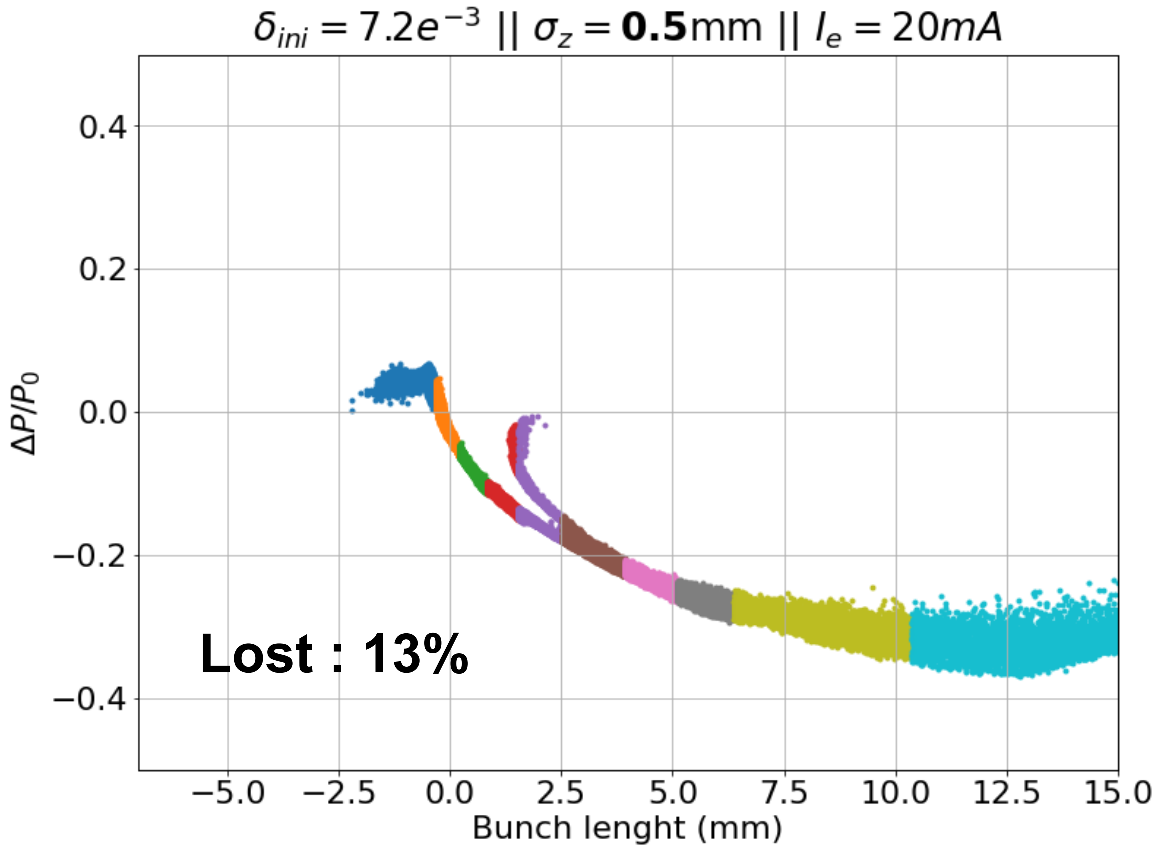
2 mm bunch length



1 mm bunch length



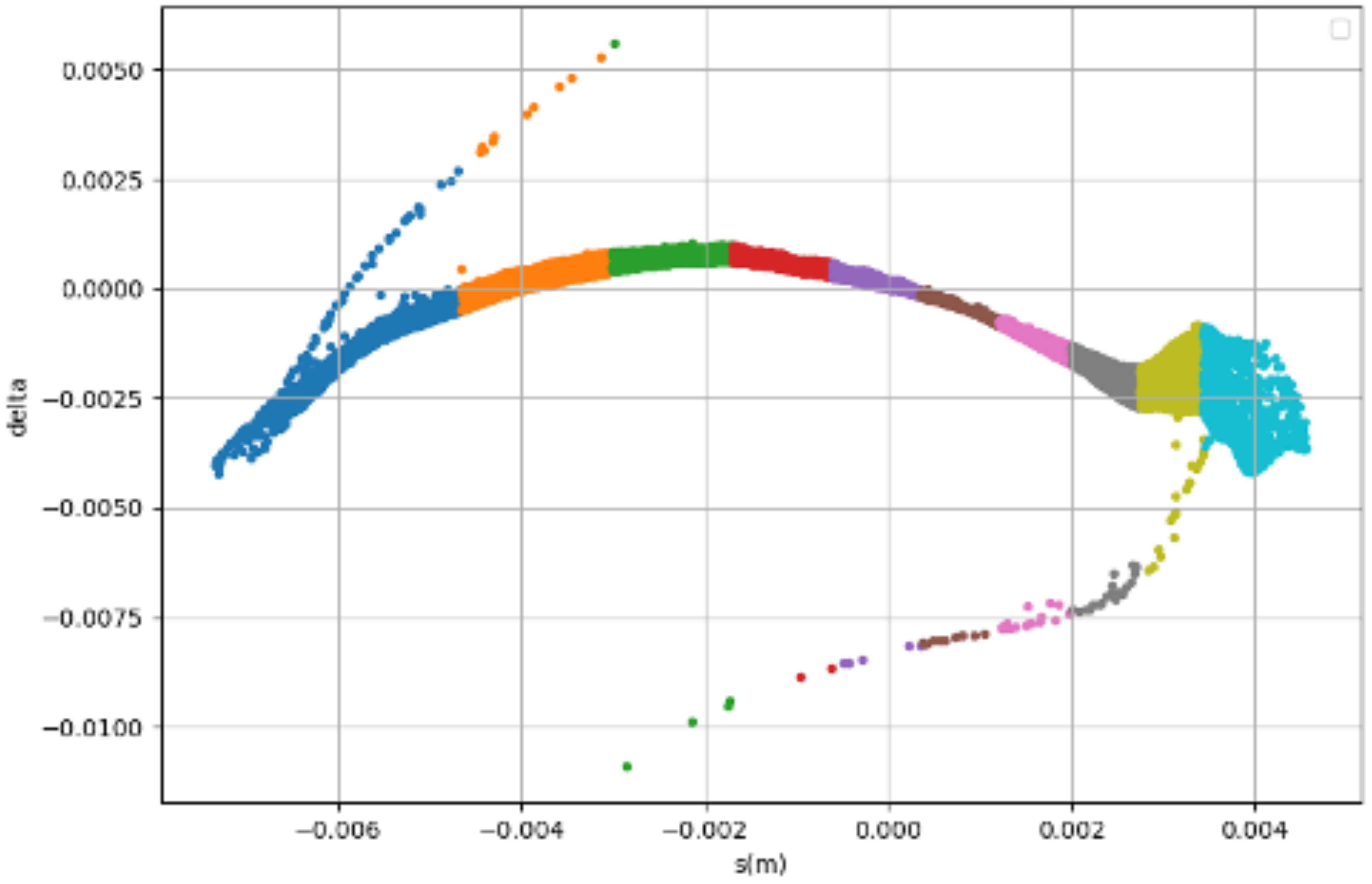
0,5 mm bunch length



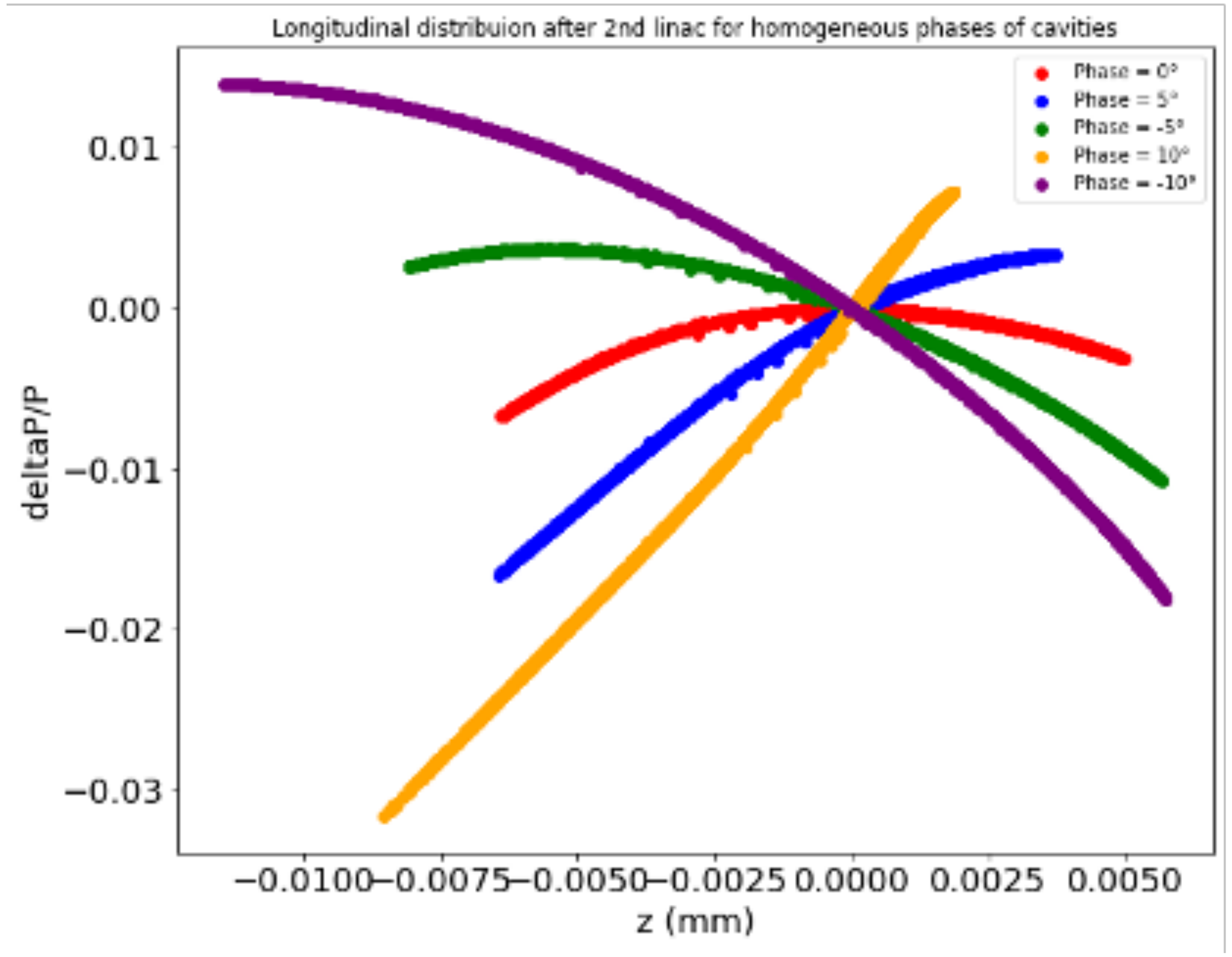
RF curvature dominated

CSR dominated

Initial longitudinal distribution at the exit of the booster



Phases in the cavities can be used to linearise the longitudinal distribution



$\phi_0 = 0°$: parabolic shape (on crest)

$\phi_0 = 5°$: start linearizing (~debunching)

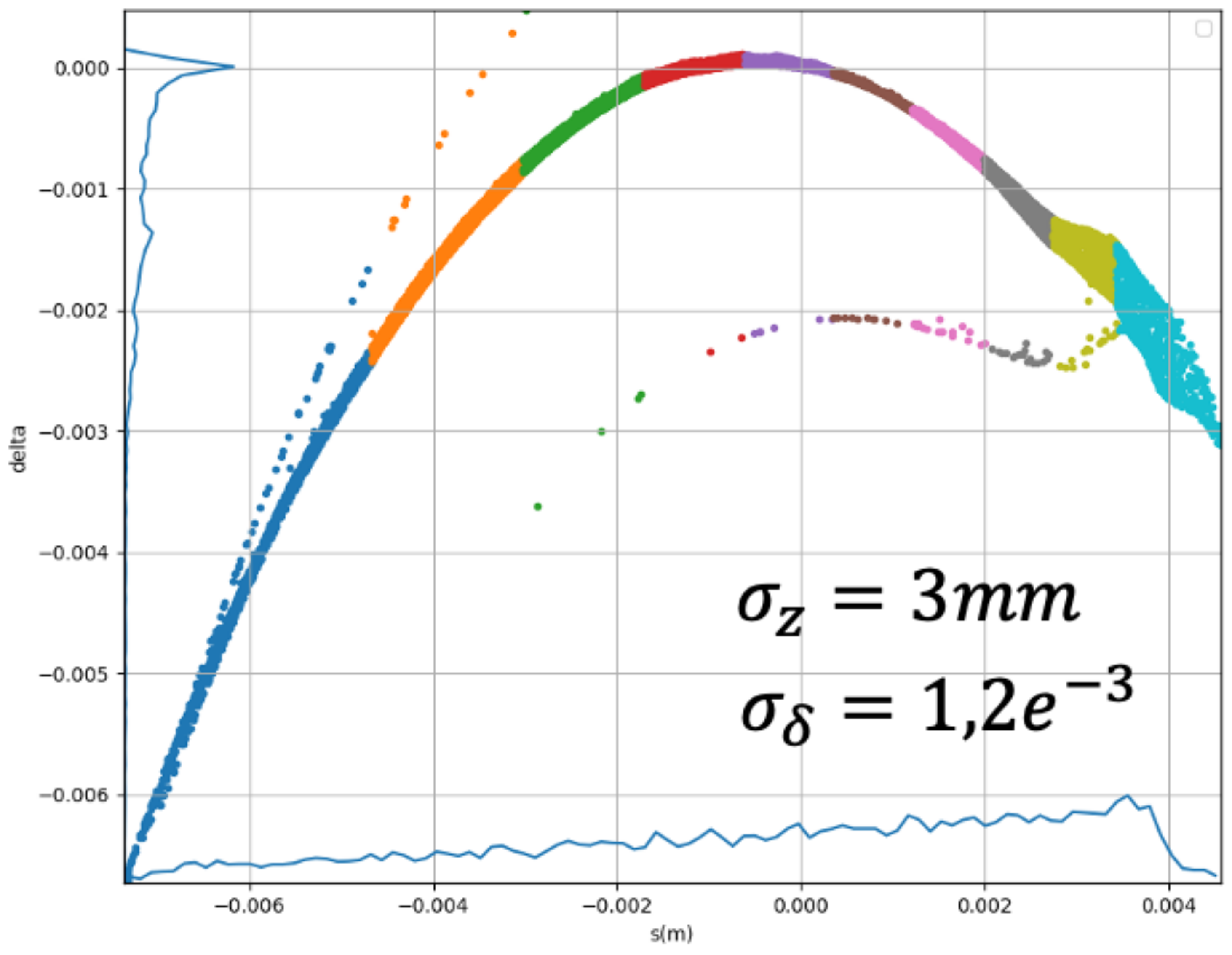
$\phi_0 = 10°$: fully linear

$\phi_0 = -5°$: start linearizing (~bunching)

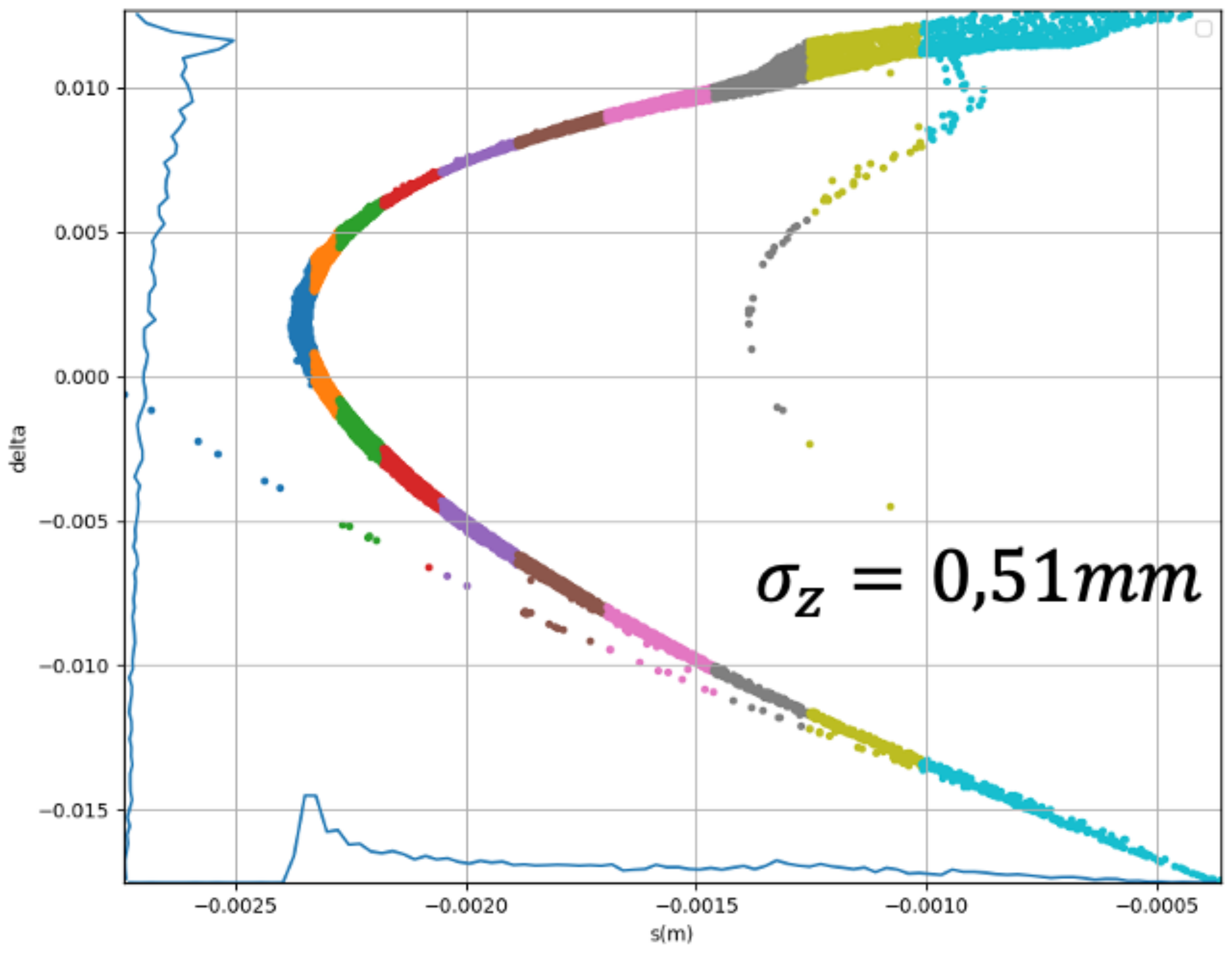
$\phi_0 = -10°$: almost linear

Manipulation of longitudinal phase space (J. Michaud)

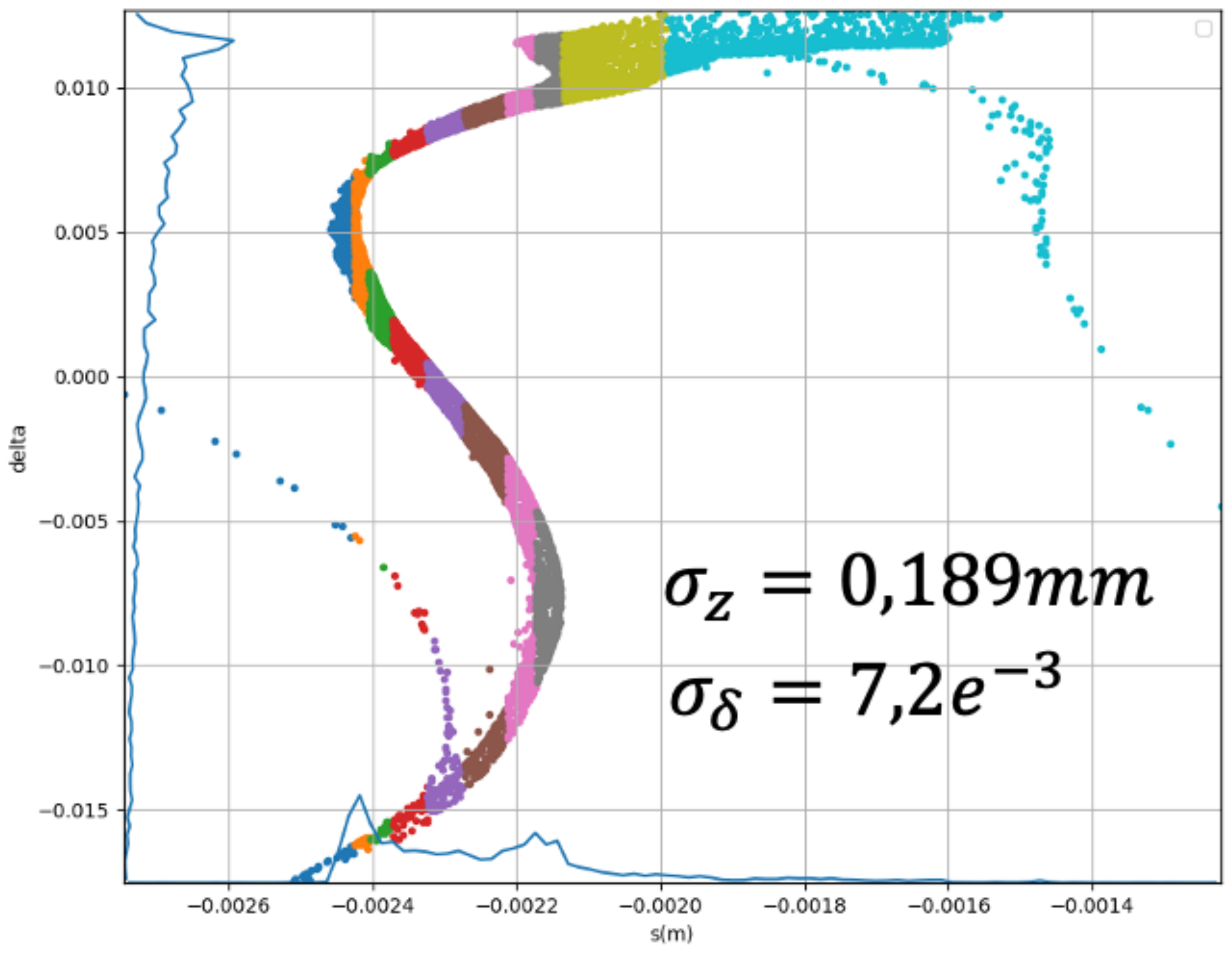
Bunch longitudinal distribution at IP-FP



Bunch compression with R56 = -0.4 m

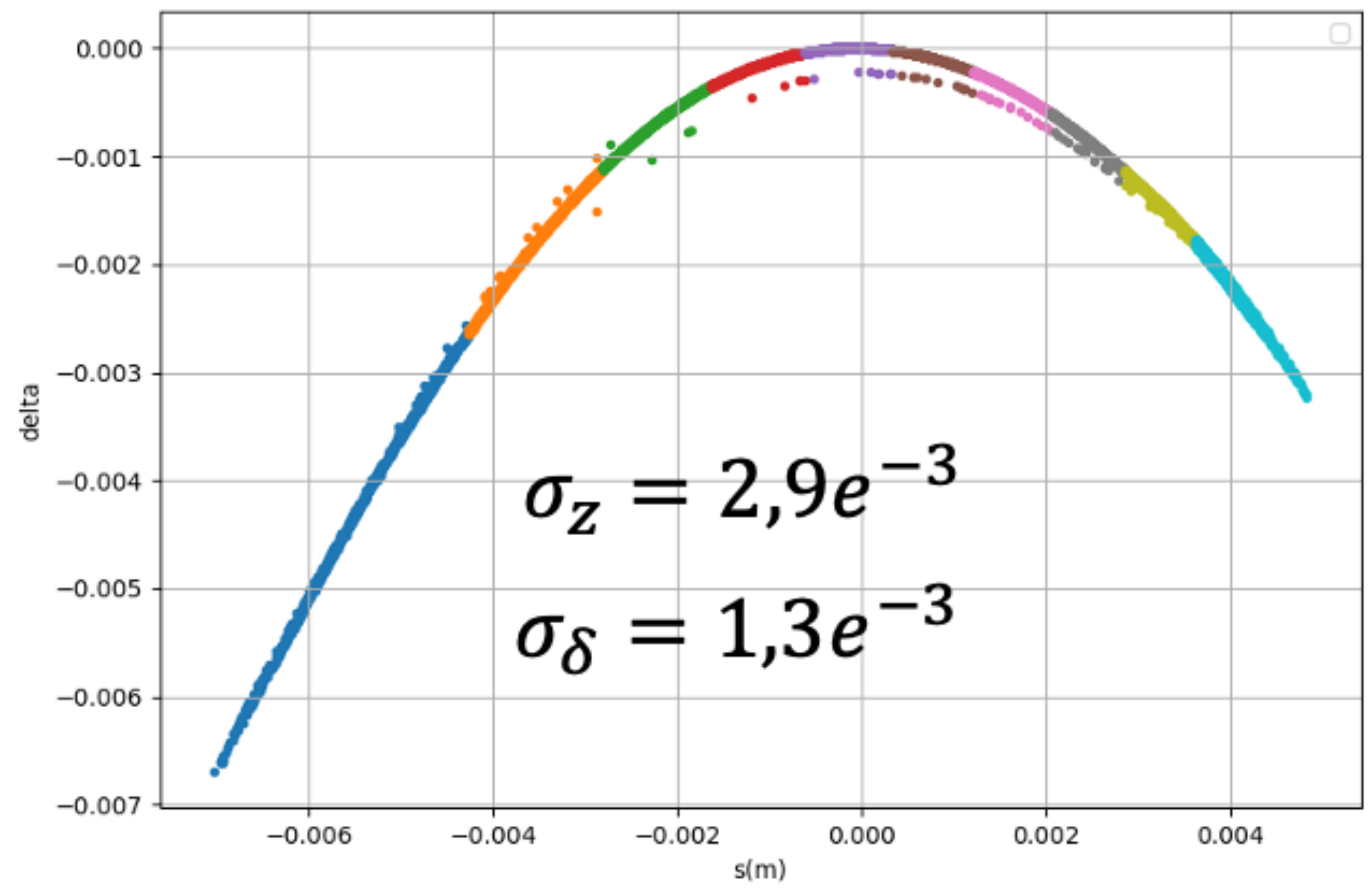


Higher order compression with R566 = 7

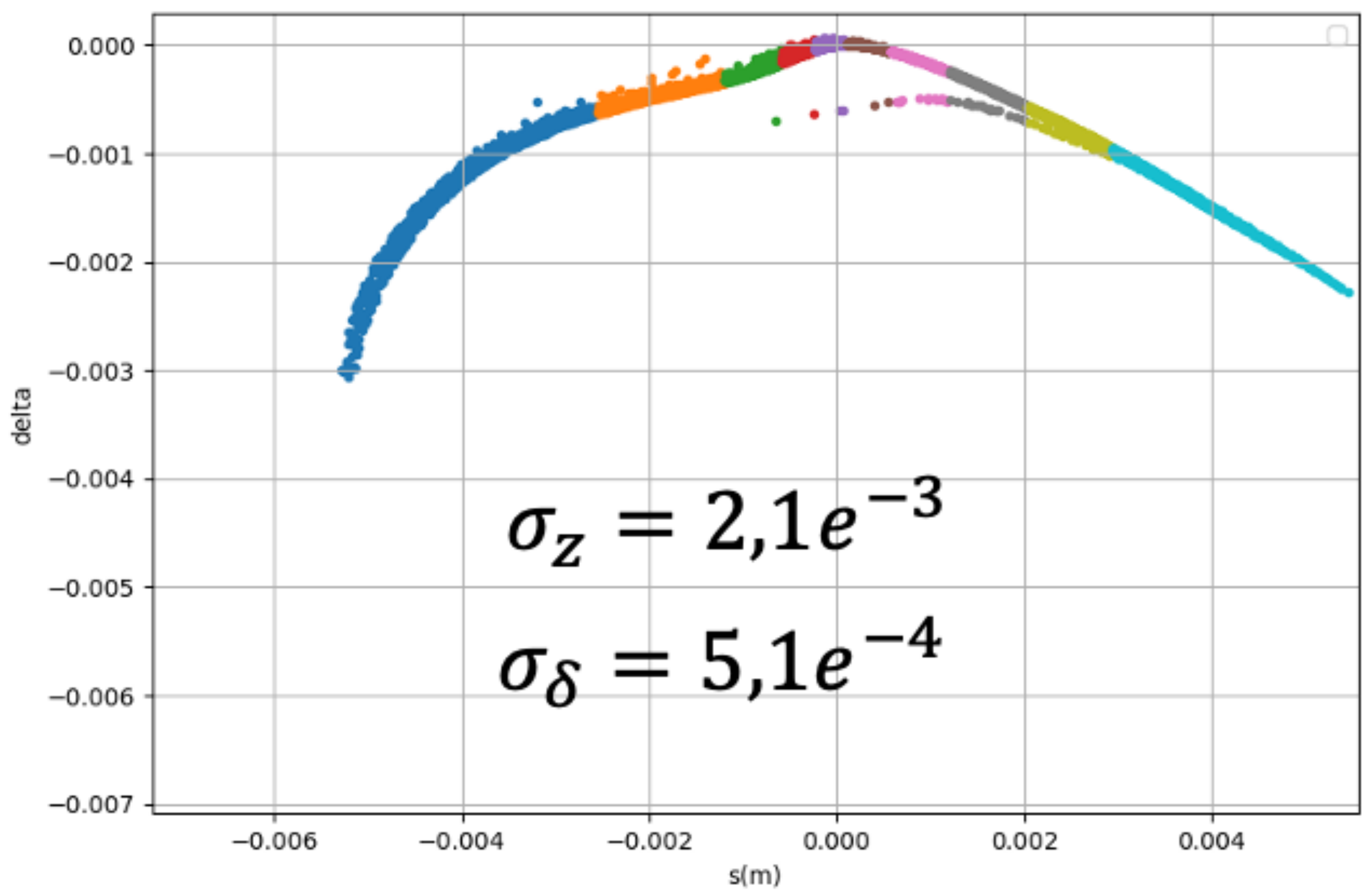


Example of energy spread minimisation (J. Michaud)

No longitudinal match



With energy spread compression



	R56	R566	Phase
Pass 1	-0,05	-8	7
Pass 2	-0,8	-8	-11
Pass 3			-2

→ 0,6 MeV
→ 1,5 MeV
→ 0,05 MeV

1° ≈ 1mm path correction
Max : 18mm

Thank you !