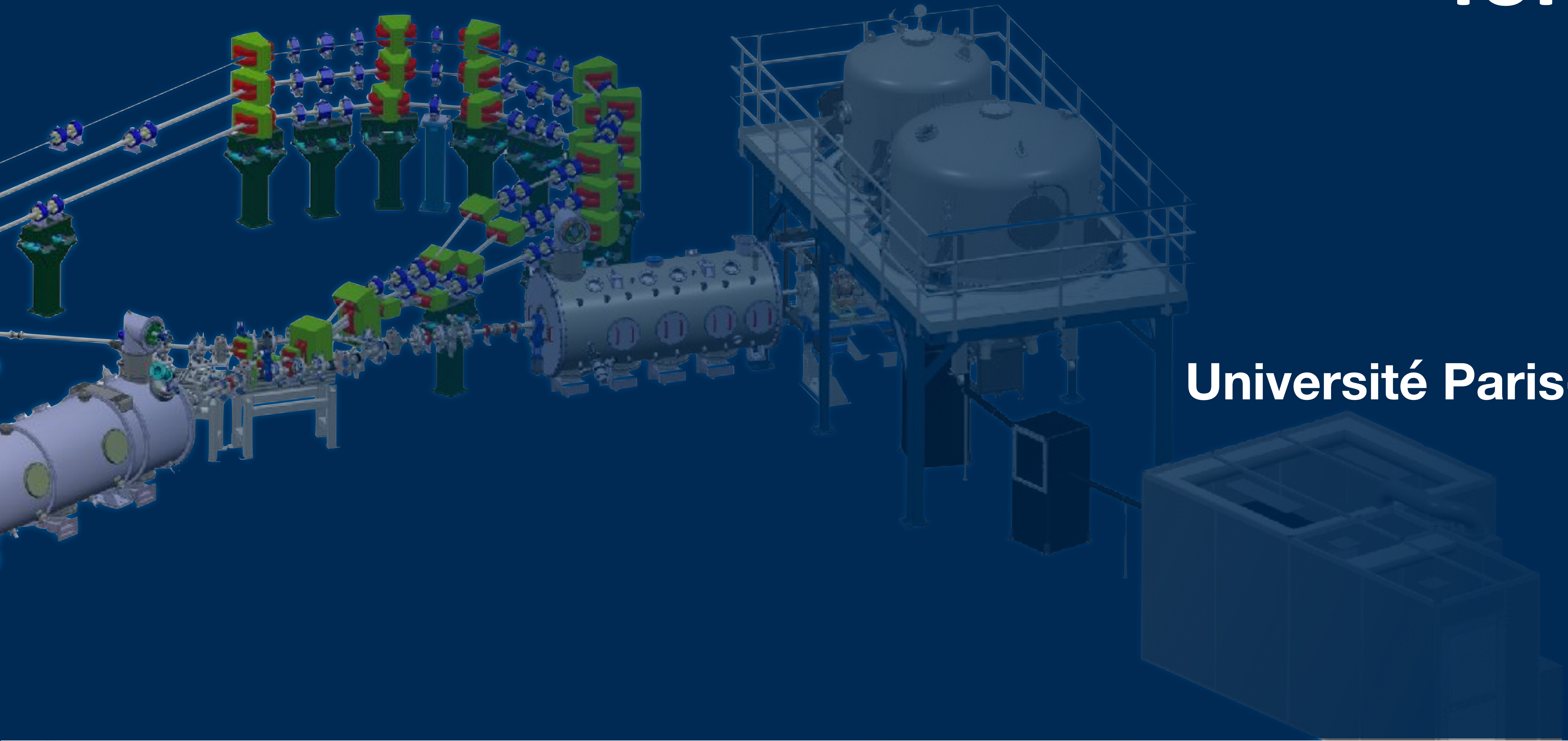
Beam Dynamics Challenges and Optics Developments for the PERLE Multi-Turn ERL



Dr. Alex Fomin

Université Paris-Saclay, CNRS/IN2P3, IJCLab (Orsay, France)

On behalf of the PERLE Collaboration

Outline

Introduction

- ERL concept
- Main objectives of PERLE
- Project status

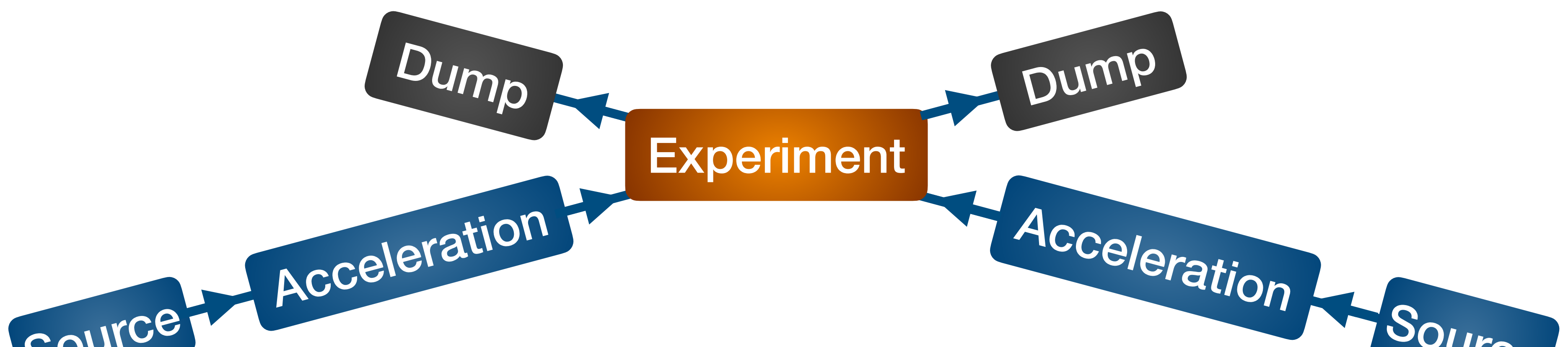
Lattice design & optics

- Single and multi turn operation
- Merger special design

Beam dynamics studies

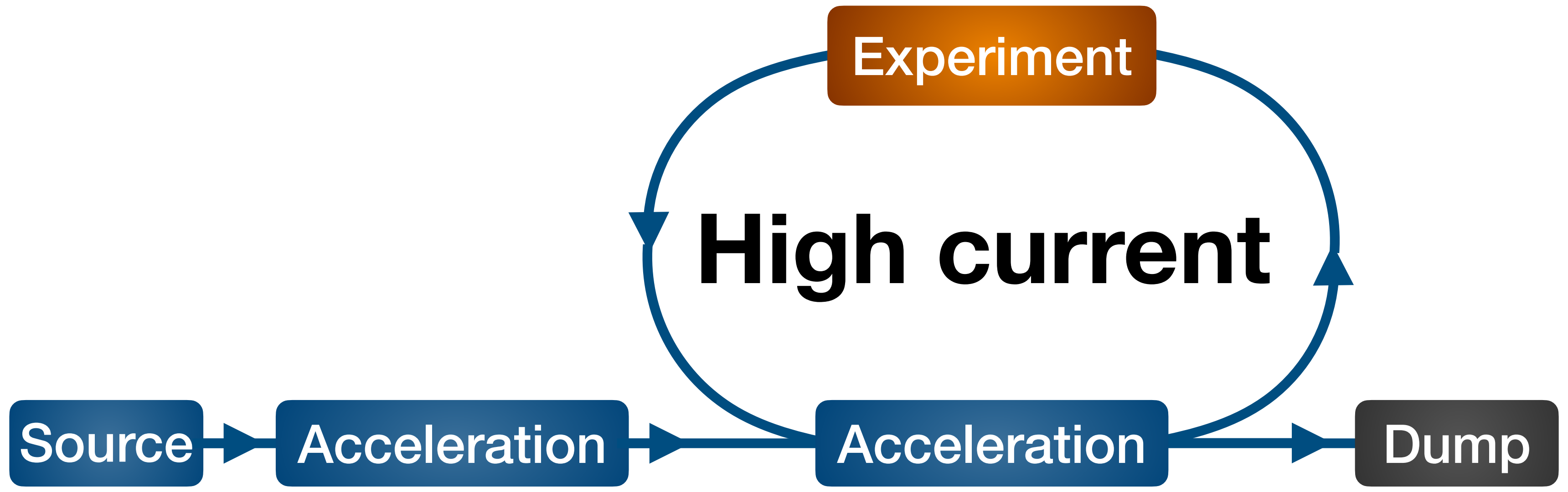
- Optimal bunch length
- Longitudinal matching
- Misalignments studies
- Effect of non linear fields
- Halo cleaning and collimation

Linear colliders



High beam quality

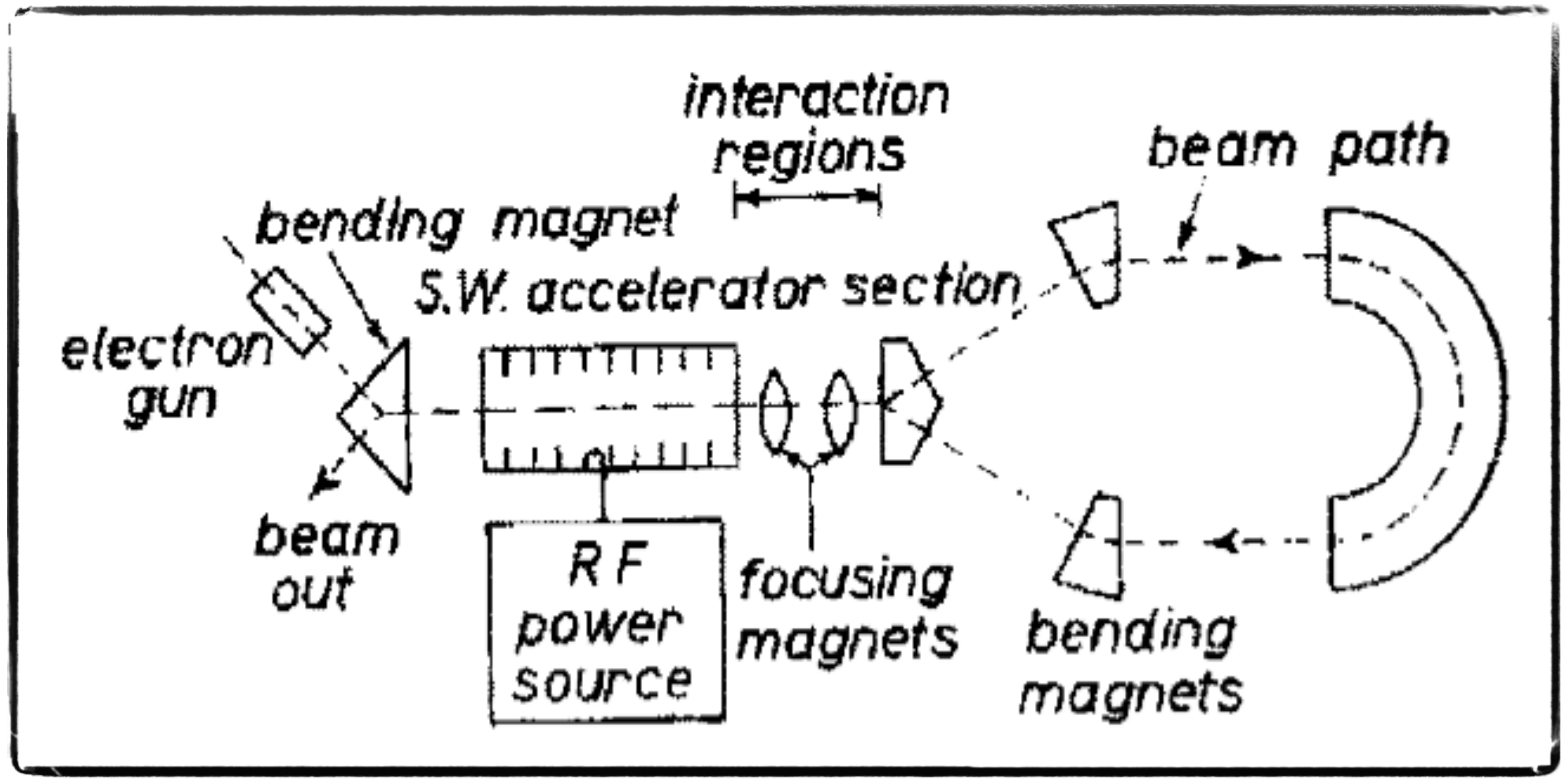
Circular colliders



Energy Recovery Linac

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

…to recycle kinetic beam energy
of a decelerating beam for acceleration
of a newly injected low energy beam.



Applications:

- FELs
- Lepton colliders
- Nuclear physics

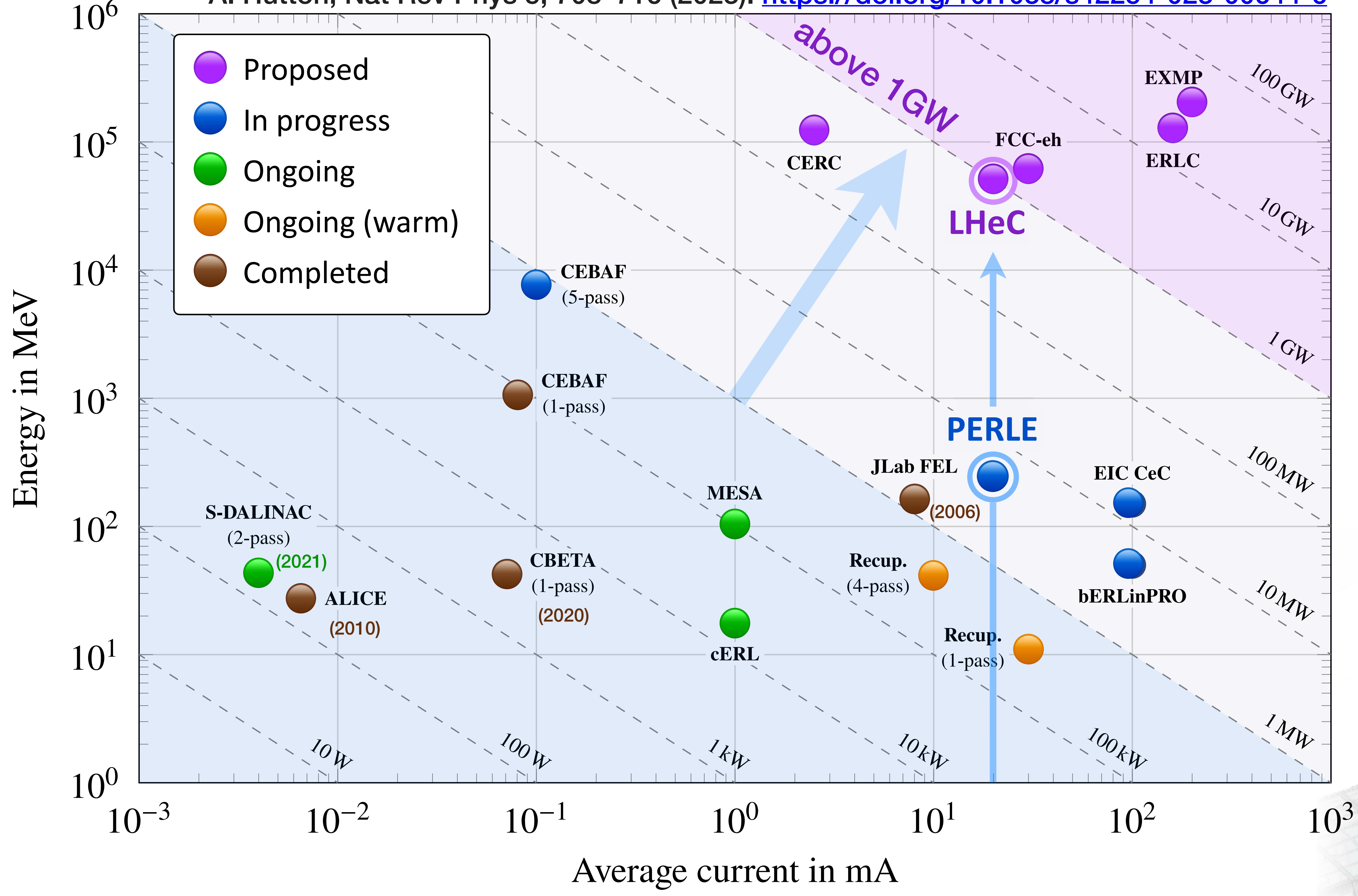
Update of the European Strategy for Particle Physics (2020) :

"The energy efficiency of present and future accelerators … should remain an area requiring constant attention."
A detailed plan … for the "saving and re-use of energy" should be part of the approval process for any major projects.

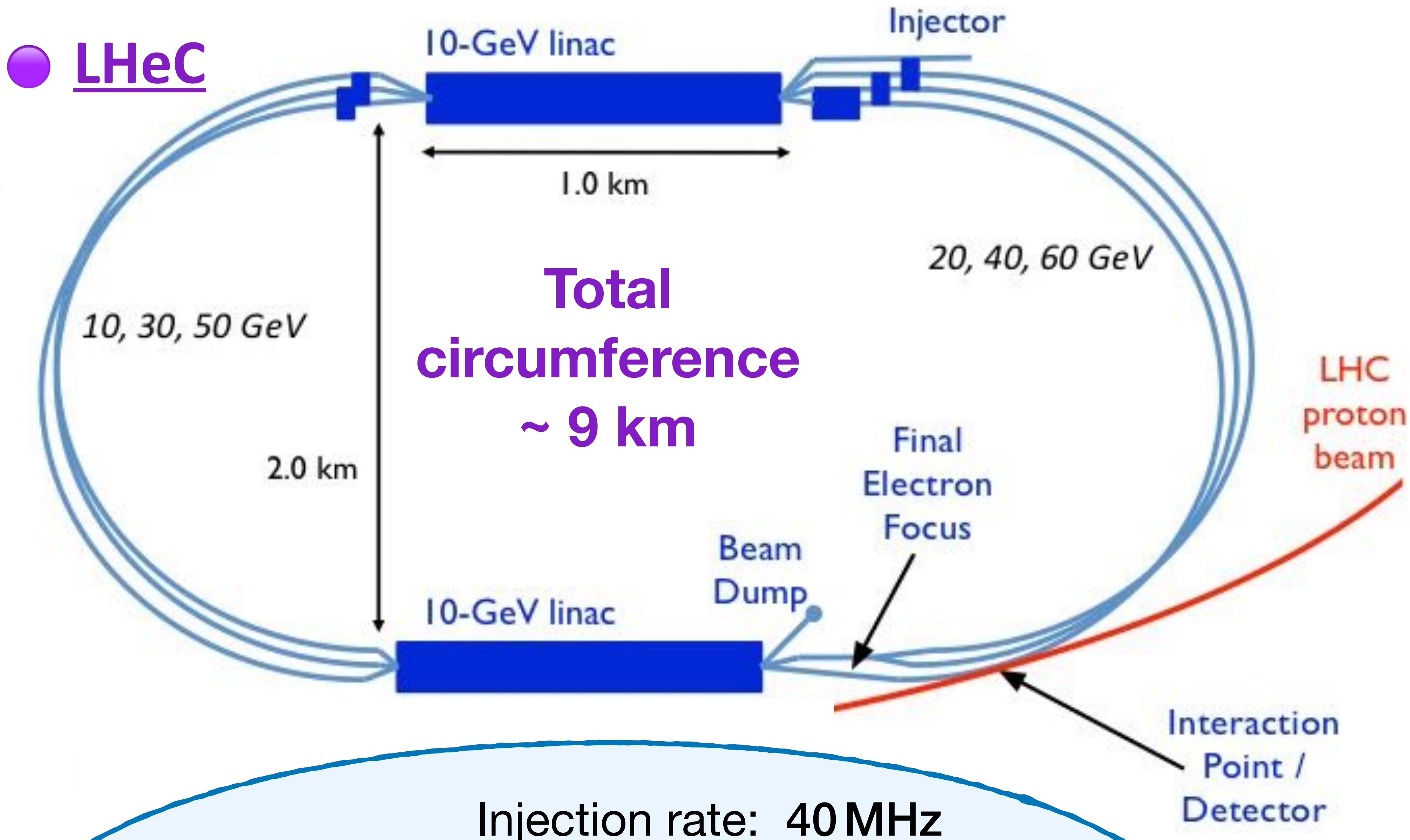
PERLE main objectives:

1. **Demonstrate multi-turn and high current operation**
2. **Validation of technical choices:** DC electron gun, 800 MHz SRF, non-invasive diagnostics
3. **Host experiments:** Fabry–Perot inverse Compton source, DESTIN (inelastic eA scattering)

A. Hutton, Nat Rev Phys 5, 708–716 (2023). https://doi.org/10.1038/s42254-023-00644-6



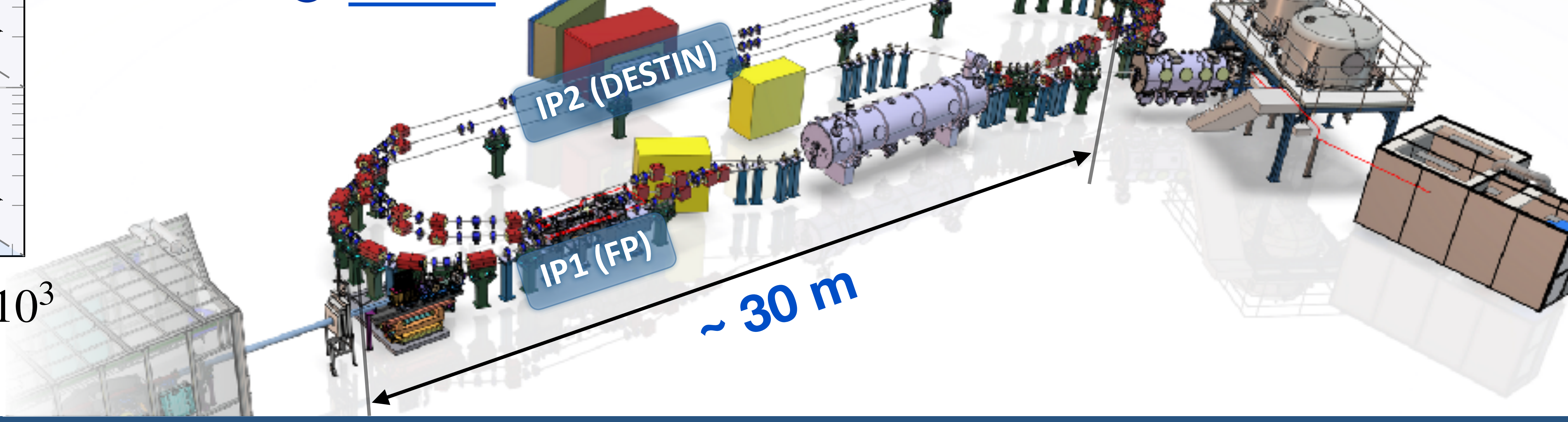
LHeC



The same bunch parameters

- Injection rate: 40 MHz
- Bunch charge: 500 pC
- Target current: 20 mA
- RF cavities: 801 MHz

PERLE



06.2012 — First Idea (Erk Jensen and Rama Calaga)

Test Facility → ERL injector of LHeC ERL

08.2012 — First Lattice Design (Alex Bogacz)

06.2015 — Powerful ERL for Experiments

PERLE — Powerful Energy Recovery LINAC for Experiments

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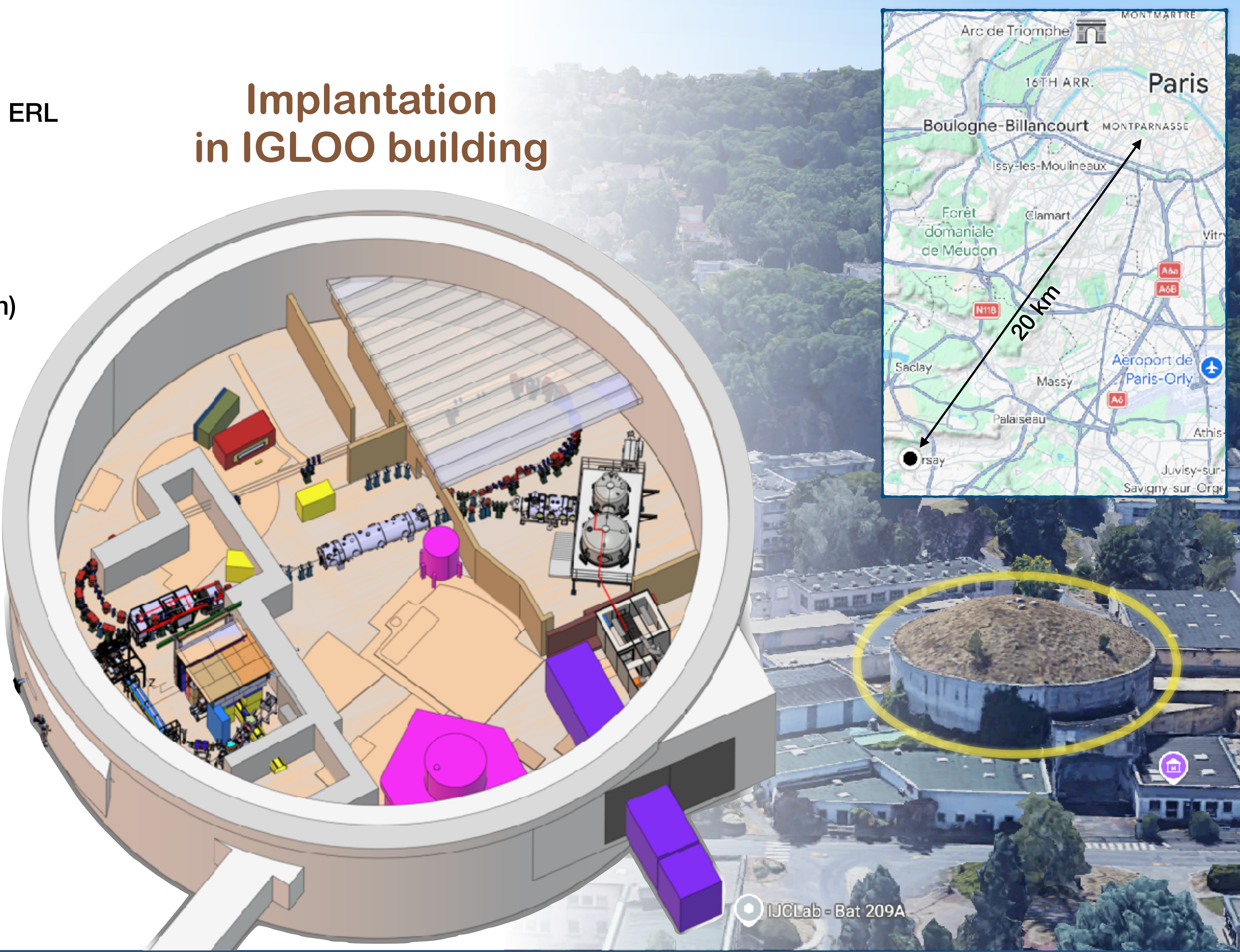
05.2017 — Conceptual Design Report

Implantation in IGLOO building



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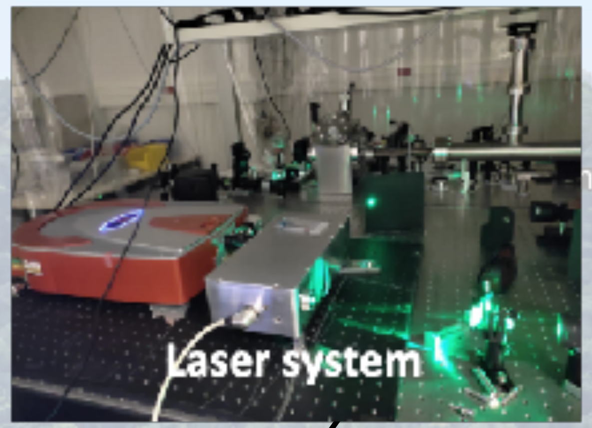
04.2026 — HV conditioning up to 350 kV (ongoing)

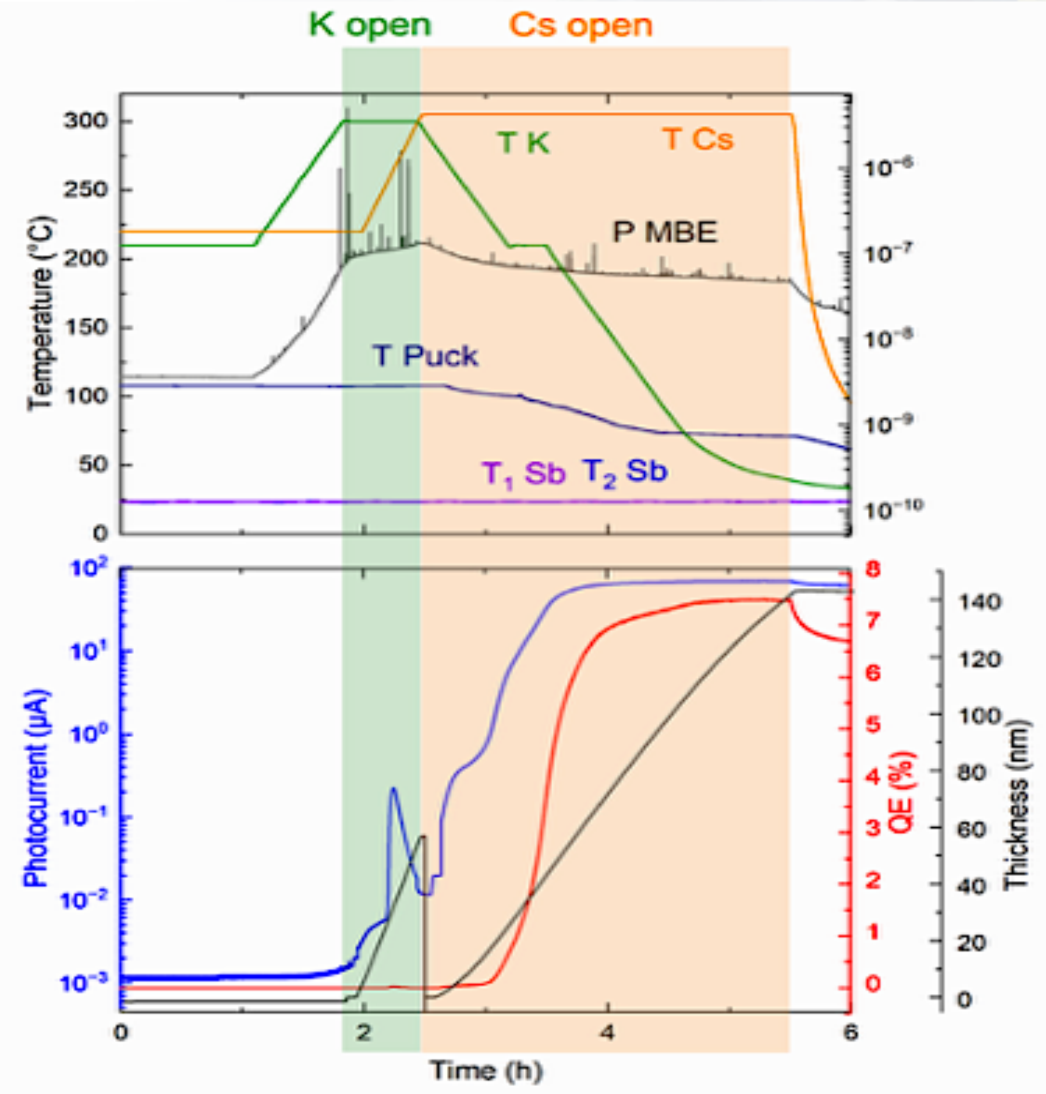
🔗 WEP5090 (R. Roux)

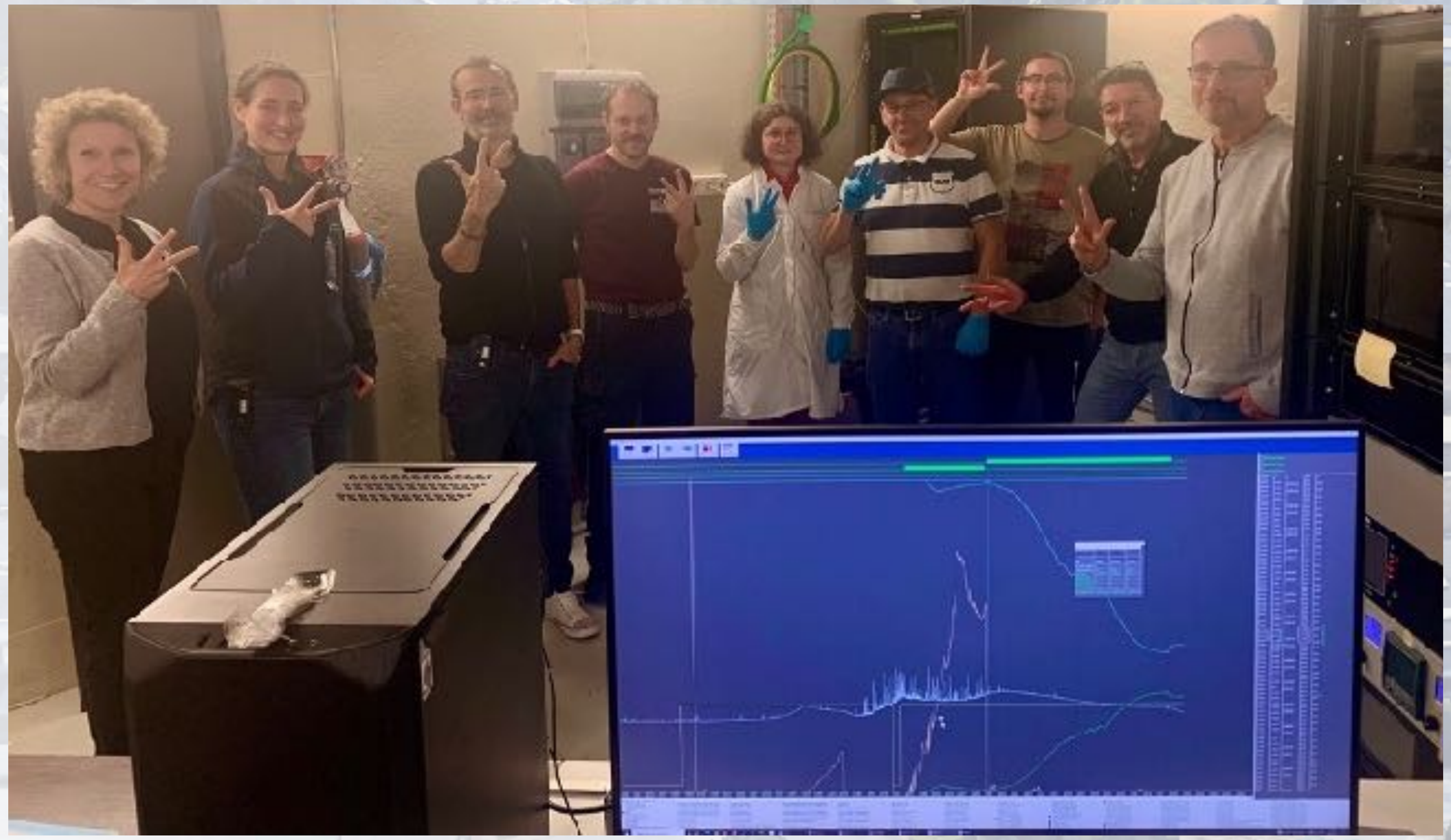
04.2026 — CsK_2Sb synthesized, QE = 6.5%

🔗 THP2102 (M. De Vos)

🔗 THP2104 (M. Baylac)







This work received government funding managed by the Agence Nationale de la Recheche (ANR) in the France 2030 framework - reference ANR-24-RRII-0001

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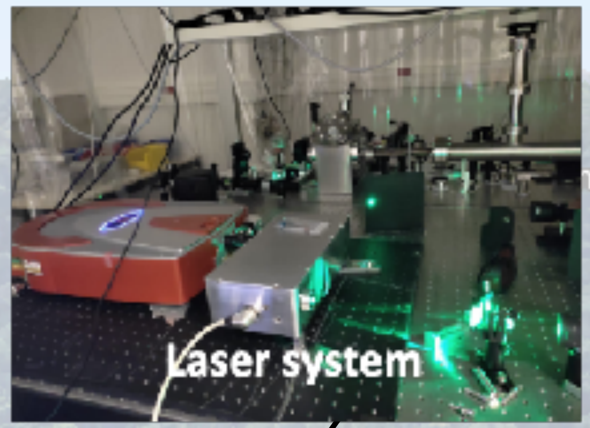
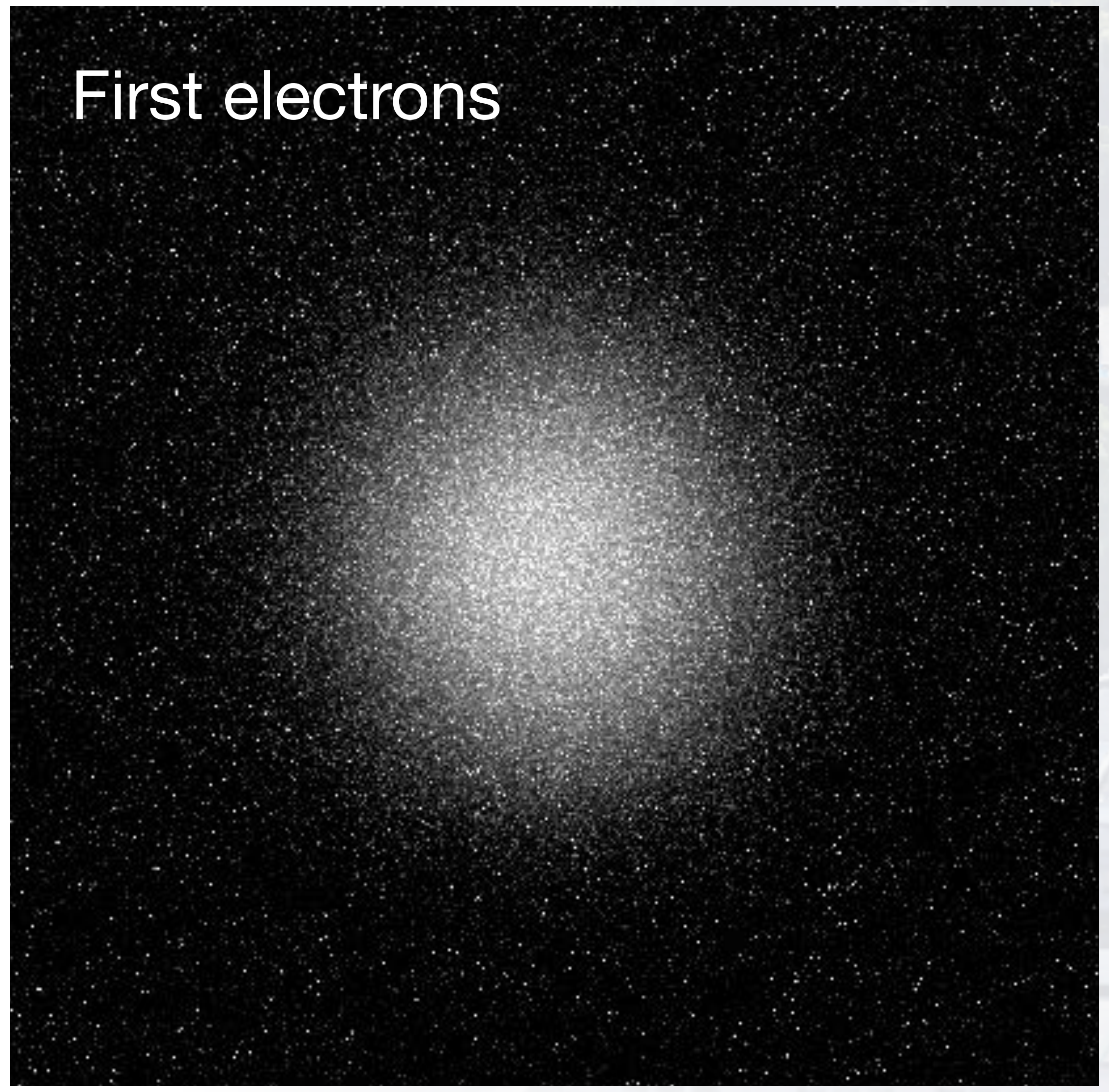
11.05.2026 First Electrons !!!

🔗 THP2104 (M. Baylac)

Next day — 2.5 mA (in the Faraday cup)





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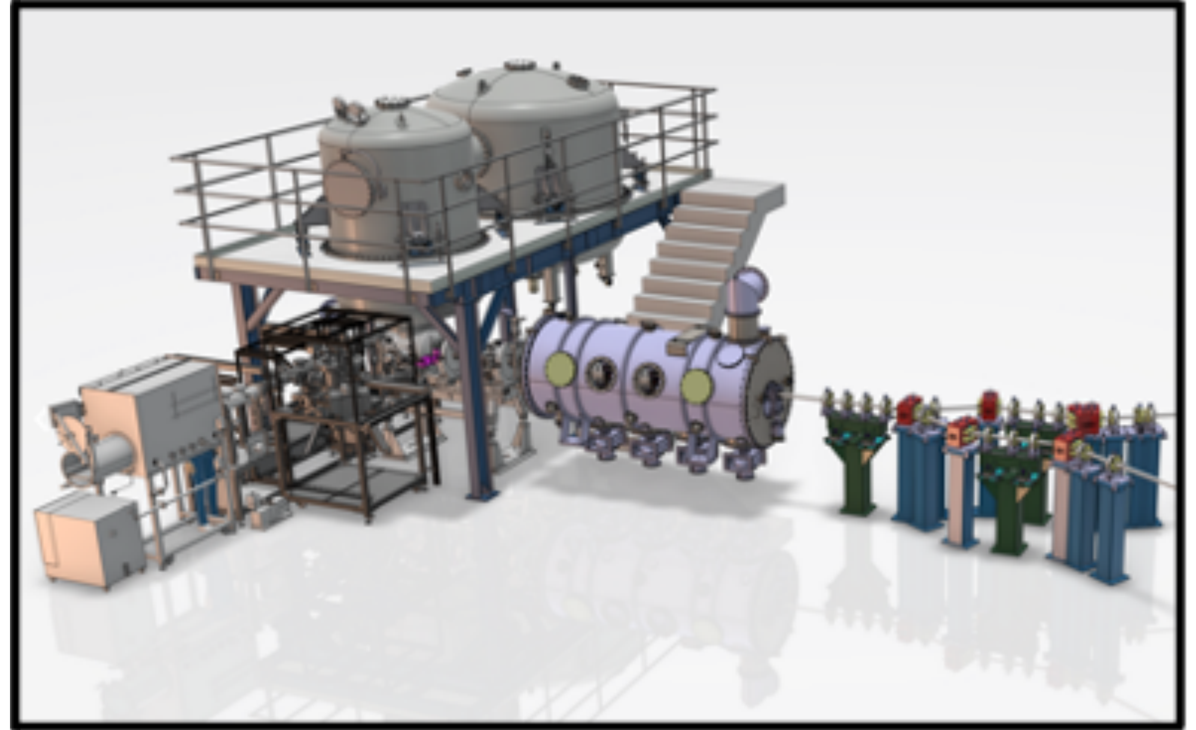
PERLE in a nutshell

Main target parameters:

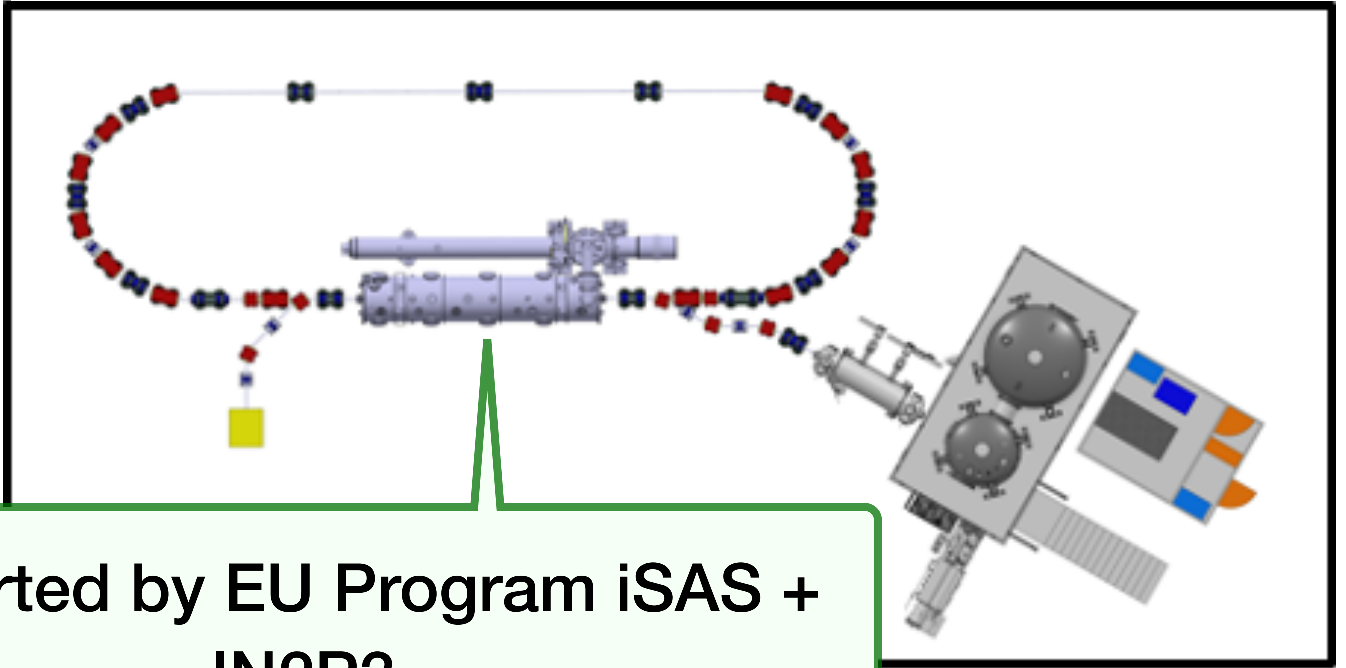
Injection energy	7 MeV
Electron beam energy	250 MeV
Normalised Emittance	6 mm mrad
Average beam current	20 mA
Bunch charge	500 pC
Bunch length	3 mm
Bunch spacing	25 ns
RF frequency	801.58 MHz
Duty factor	CW

Phase 1: Injector Line



Supported by National Program France 2030 / ANR

Phase 2: PERLE Single Turn



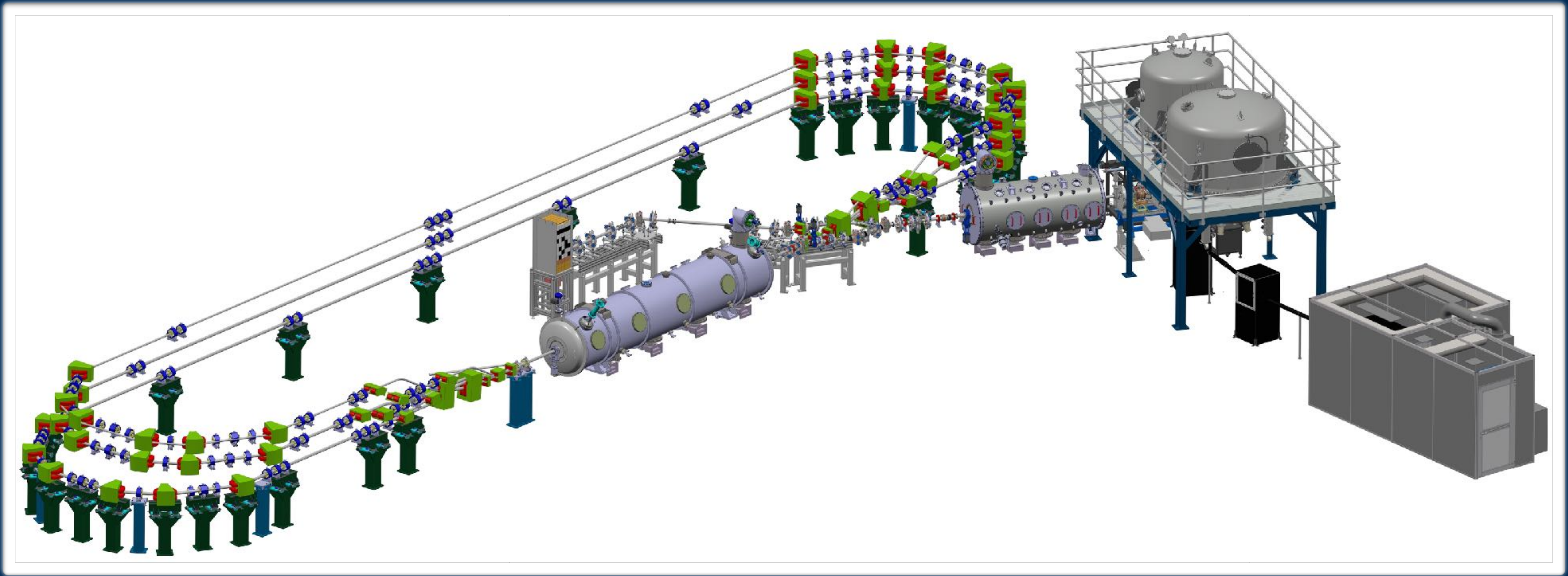
Supported by EU Program iSAS + IN2P3

Phase 3: PERLE 250 MeV

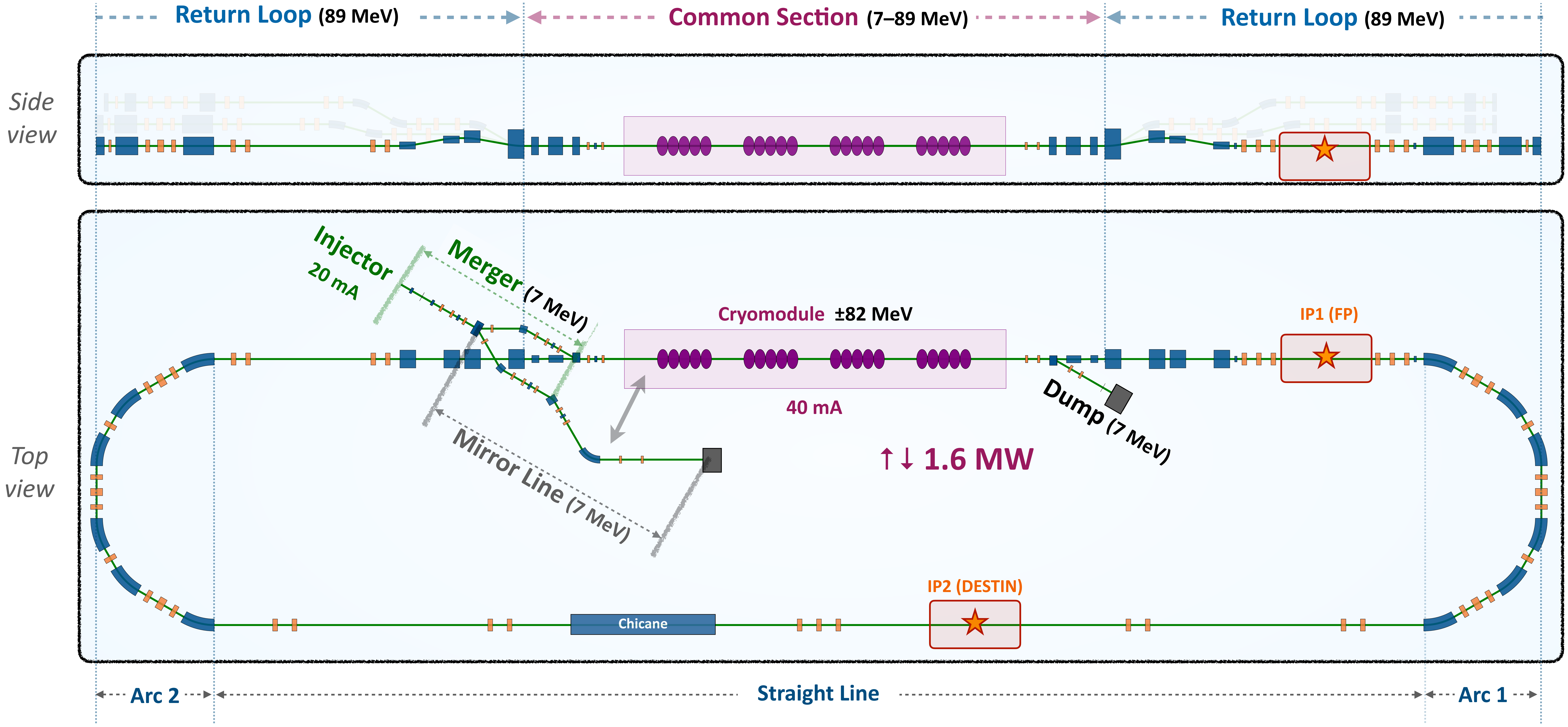
TDR and Prototyping Phase

2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031

Lattice design & Optics

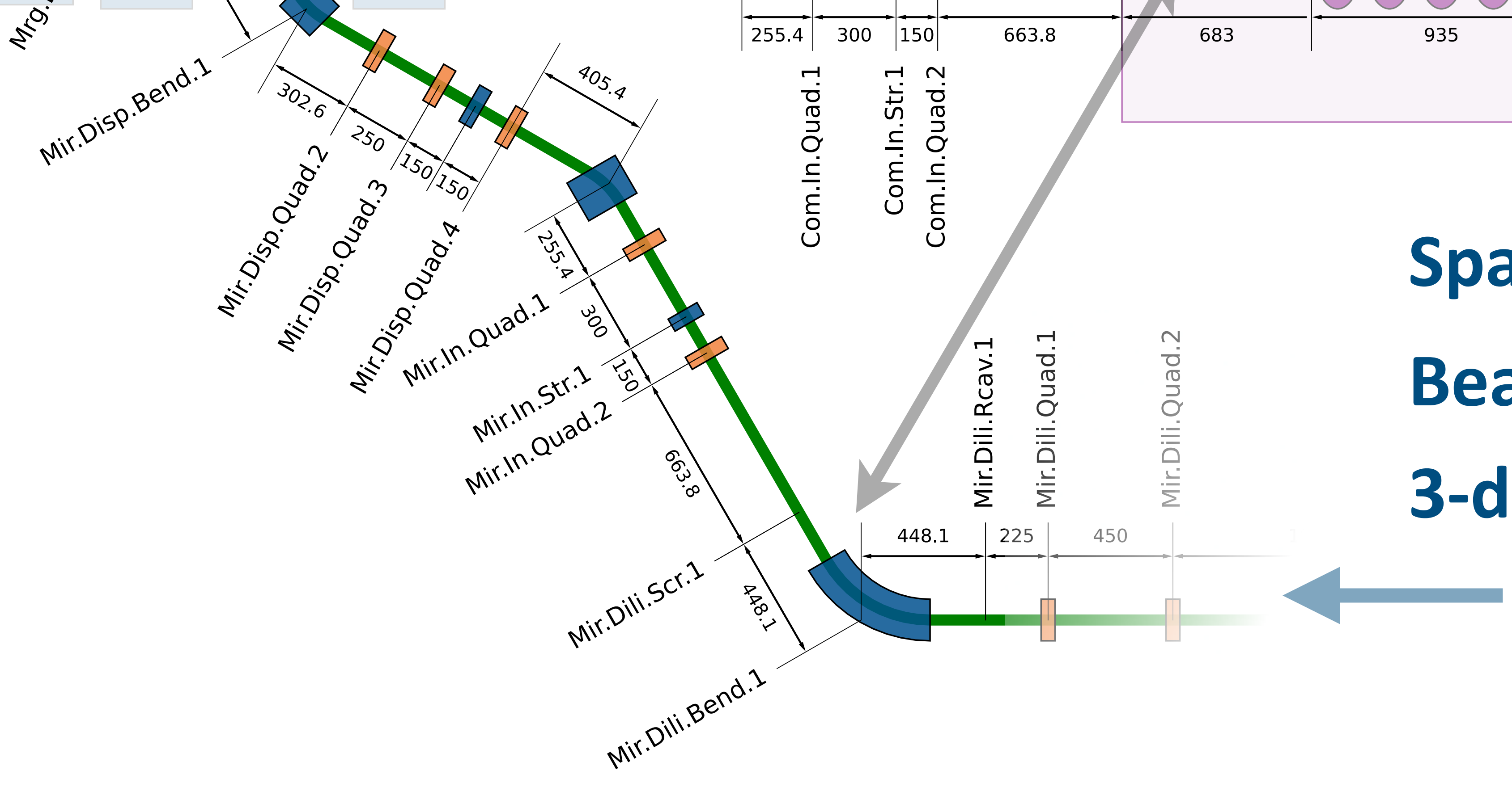


PERLE — Single Turn 2 passes (↑↓)



PERLE — 250 MeV 6 passes (↑↑↑↓↓↓) + 2 Return Loops

PERLE Lattice. Mirror Diagnostic Line (7 MeV)



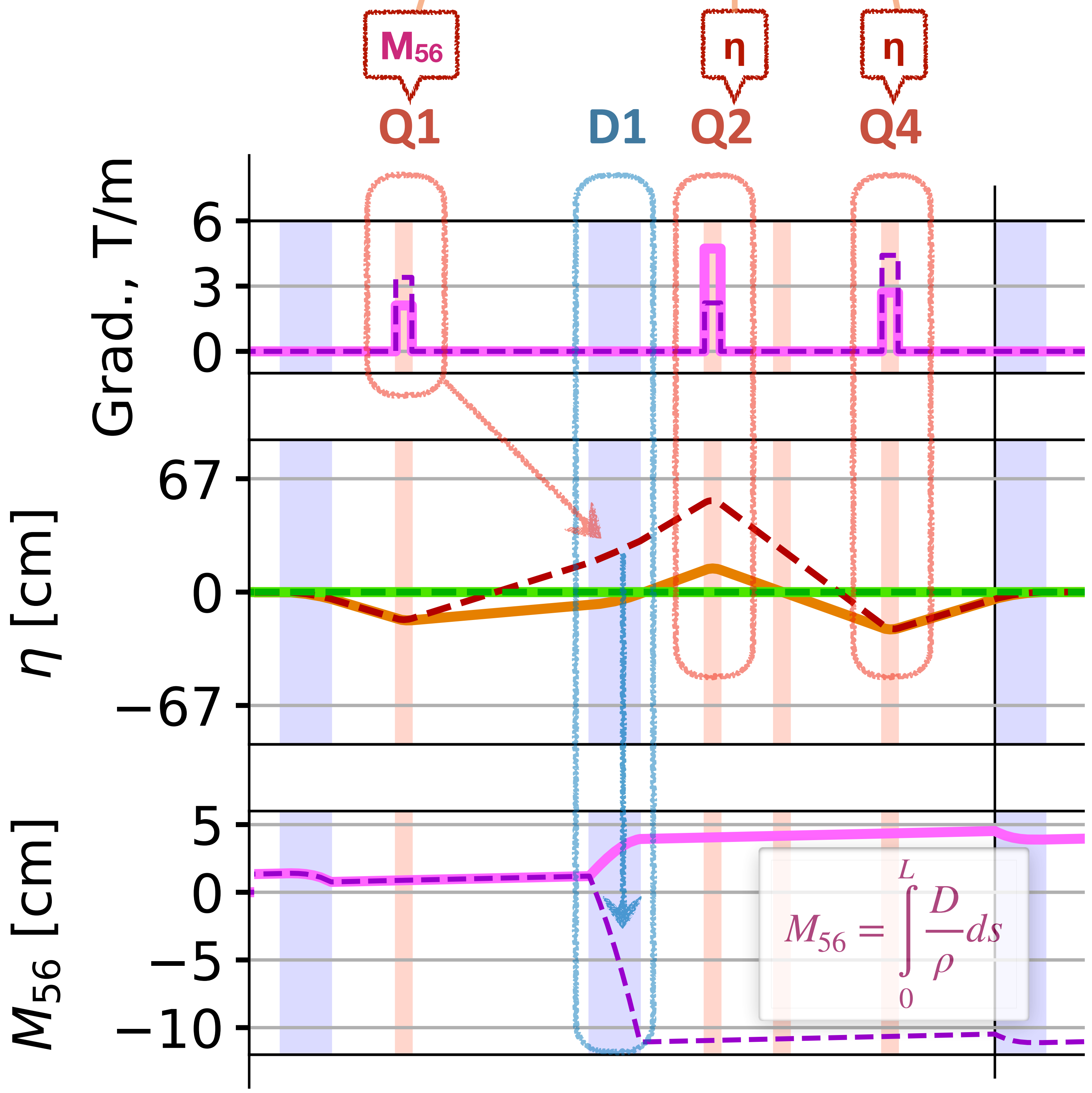
Space-charge dominated injector at 7 MeV and >100 pC: goal: 500 pC

Beam characterization priority: longitudinal phase space

3-dipole merger:

- Mirror diagnostic line
- CBETA-like
- Non-invasive LPS measurement
- Trade-off: large M56 growth

PERLE Lattice. 3-dipole merger and M56 control



Space-charge dominated injector at 7 MeV and >100 pC: goal: 500 pC

Beam characterization priority: longitudinal phase space

3-dipole merger:

- Mirror diagnostic line
- CBETA-like
- Non-invasive LPS measurement
- Trade-off: large M56 growth
- Remedy: singlet–triplet scheme for longitudinal control

Optics roles:

- Q1: dispersion in middle dipole → M56
- Q2, Q4: close dispersion bump
- Q3: beam-size control

Application: longitudinal matching 🔗 **WEP5006 (J. Issa)**

Single Turn operation (89 MeV) BMAD optimization

Single Turn operation (89 MeV) BMAD optimization (emittance vs halo)

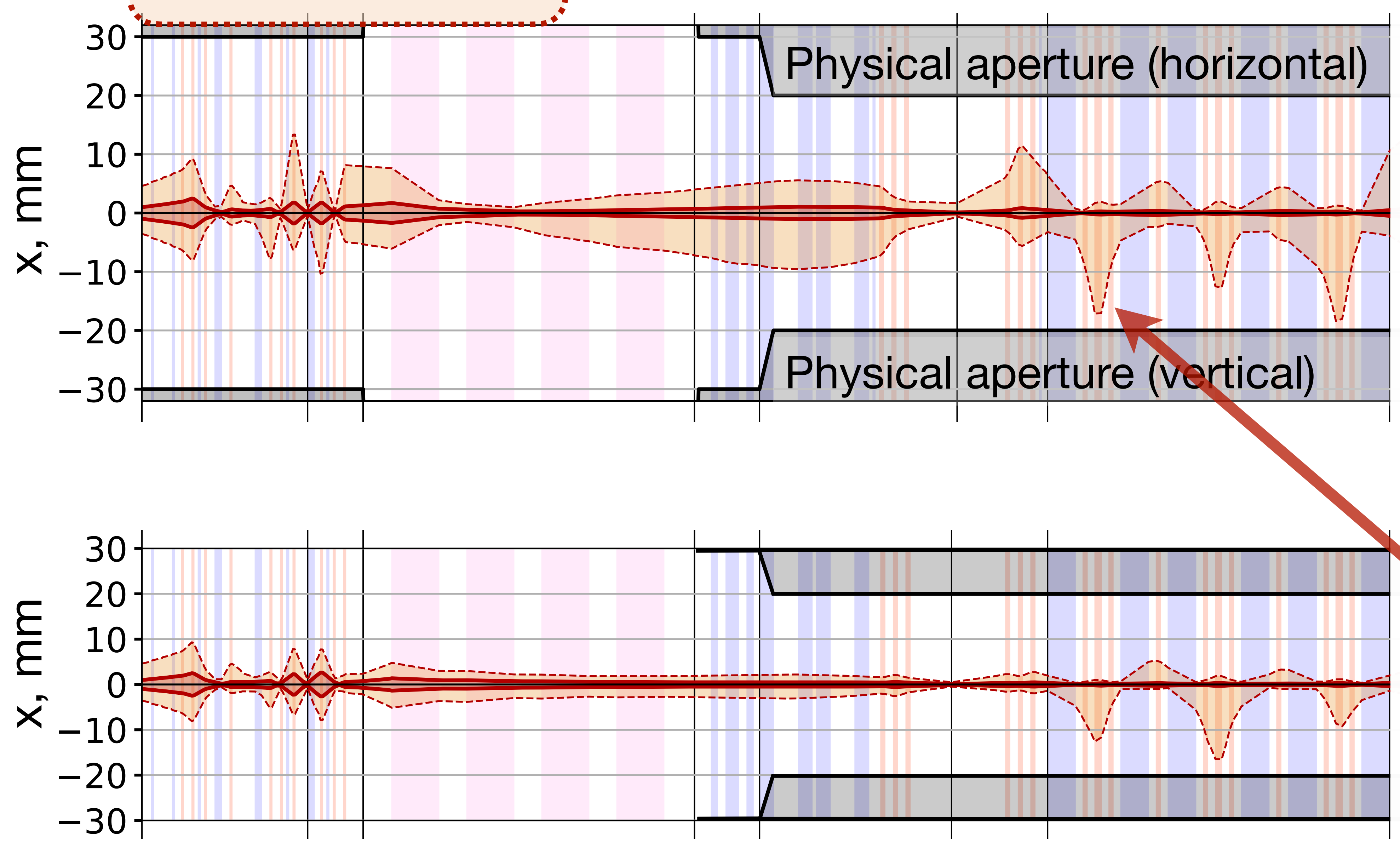
Because of space charge, the matching becomes a trade-off: minimize emittance growth, or minimize halo formation — but not perfectly both at once

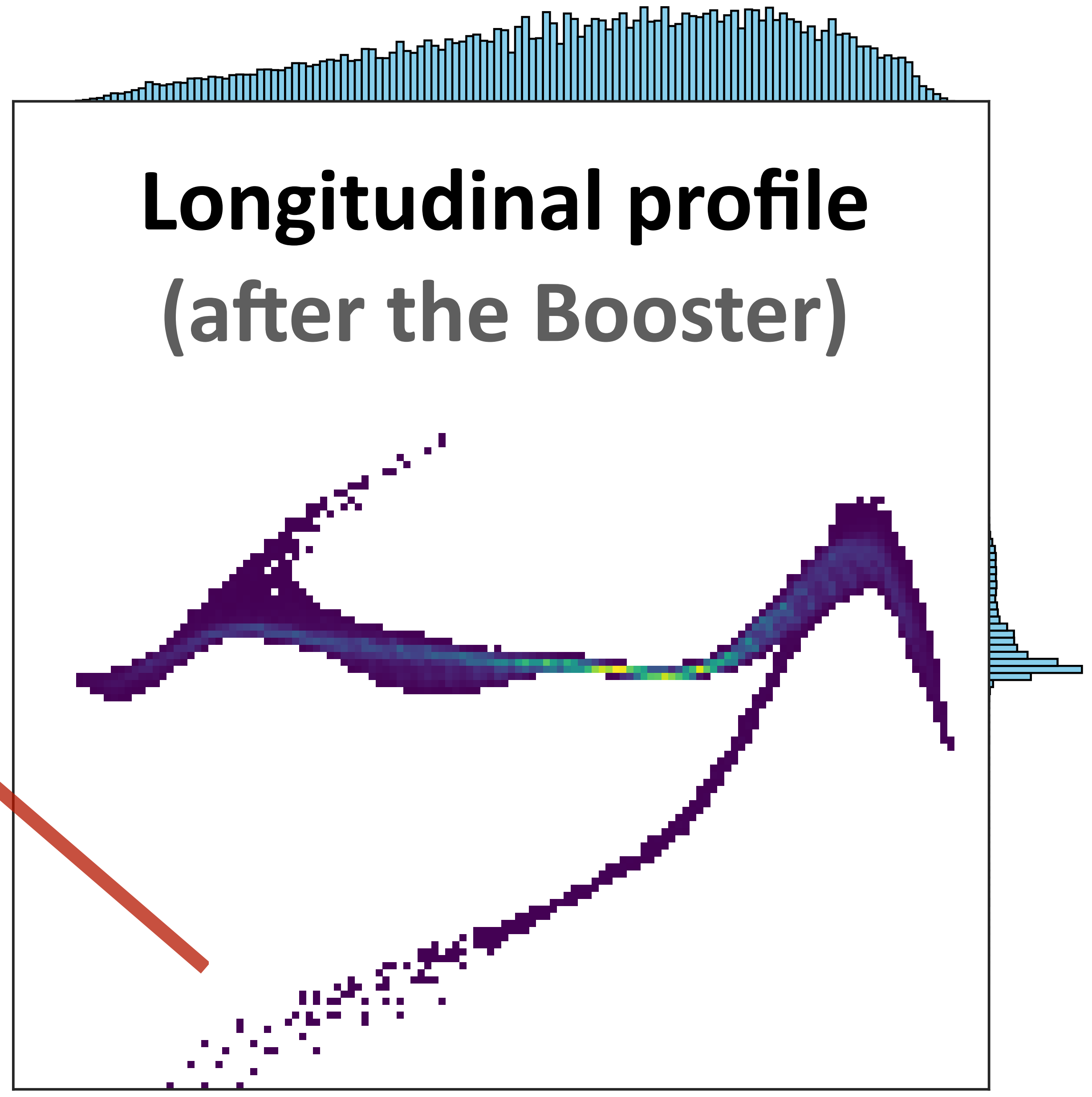
Single Turn operation (89 MeV) BMAD optimization (emittance vs halo)

Single Turn operation (89 MeV) BMAD optimization (emittance vs halo)

Space charge dominated region (>100 pC)

→ BMAD Optimization using tracking (Beam core vs halo size)

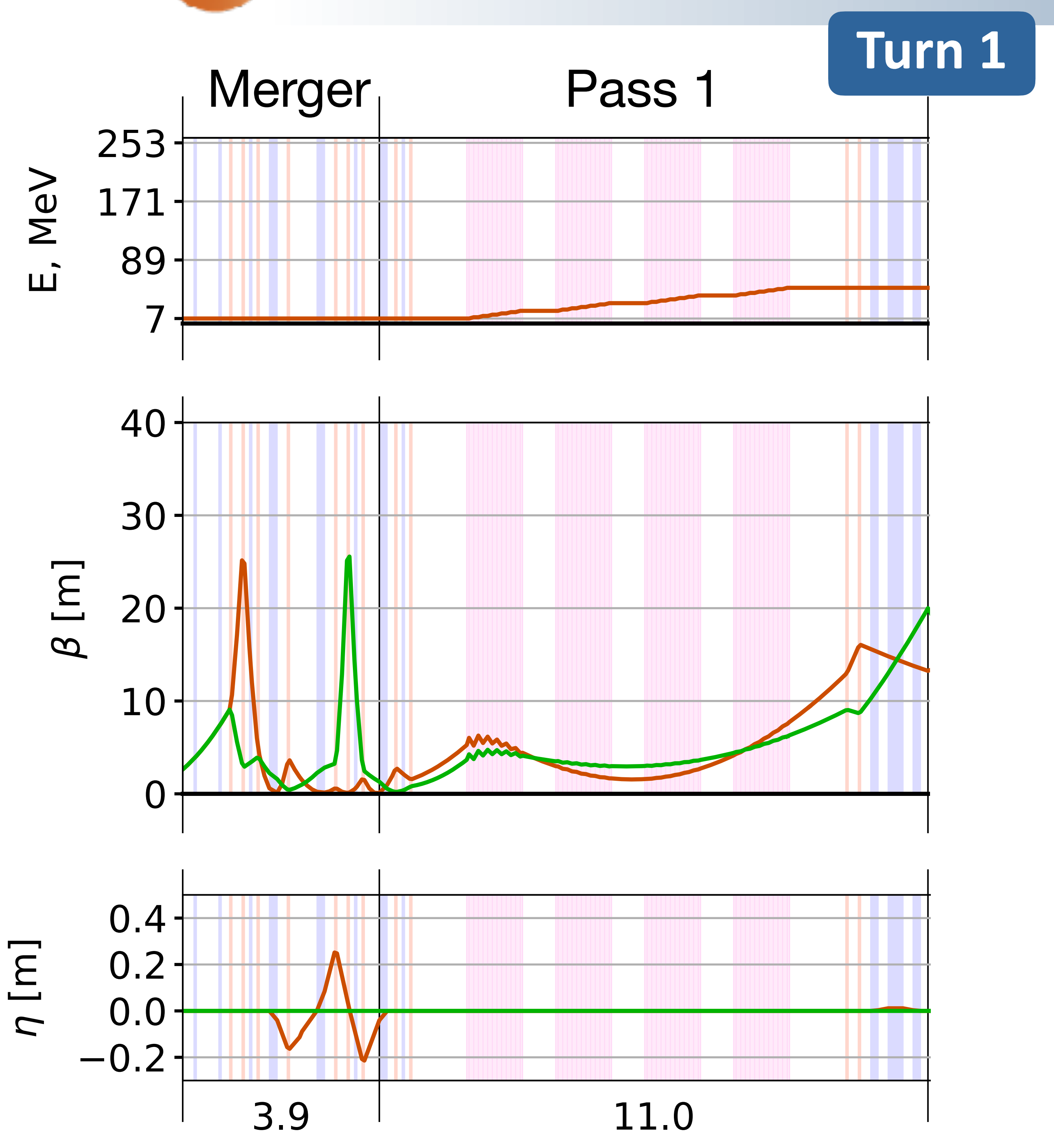


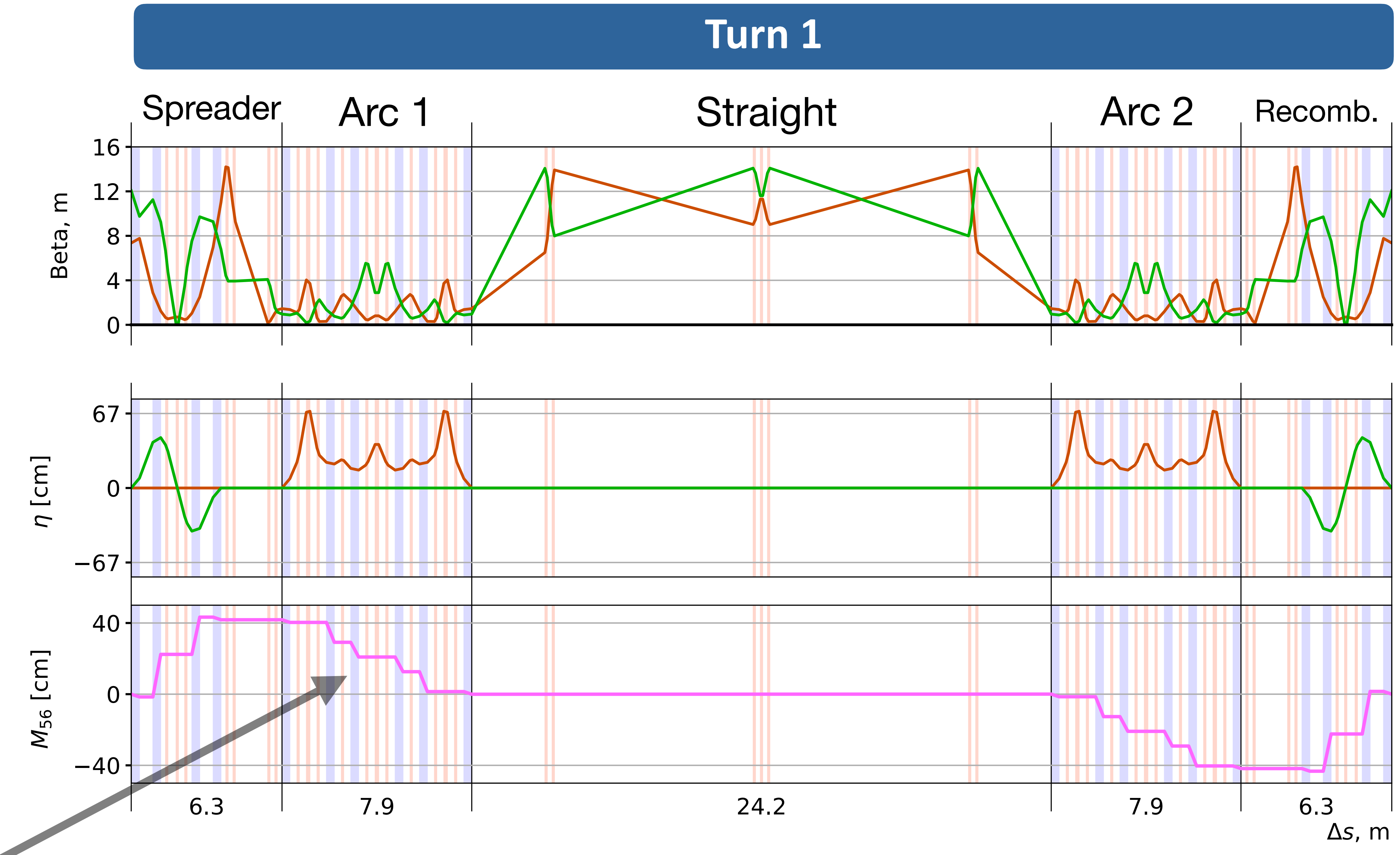


In the dispersive region, the halo reveals the off-momentum tail of the bunch

Mitigation strategy:
collimation in the merger
🔗 WEP5064 (A. Cieplak)

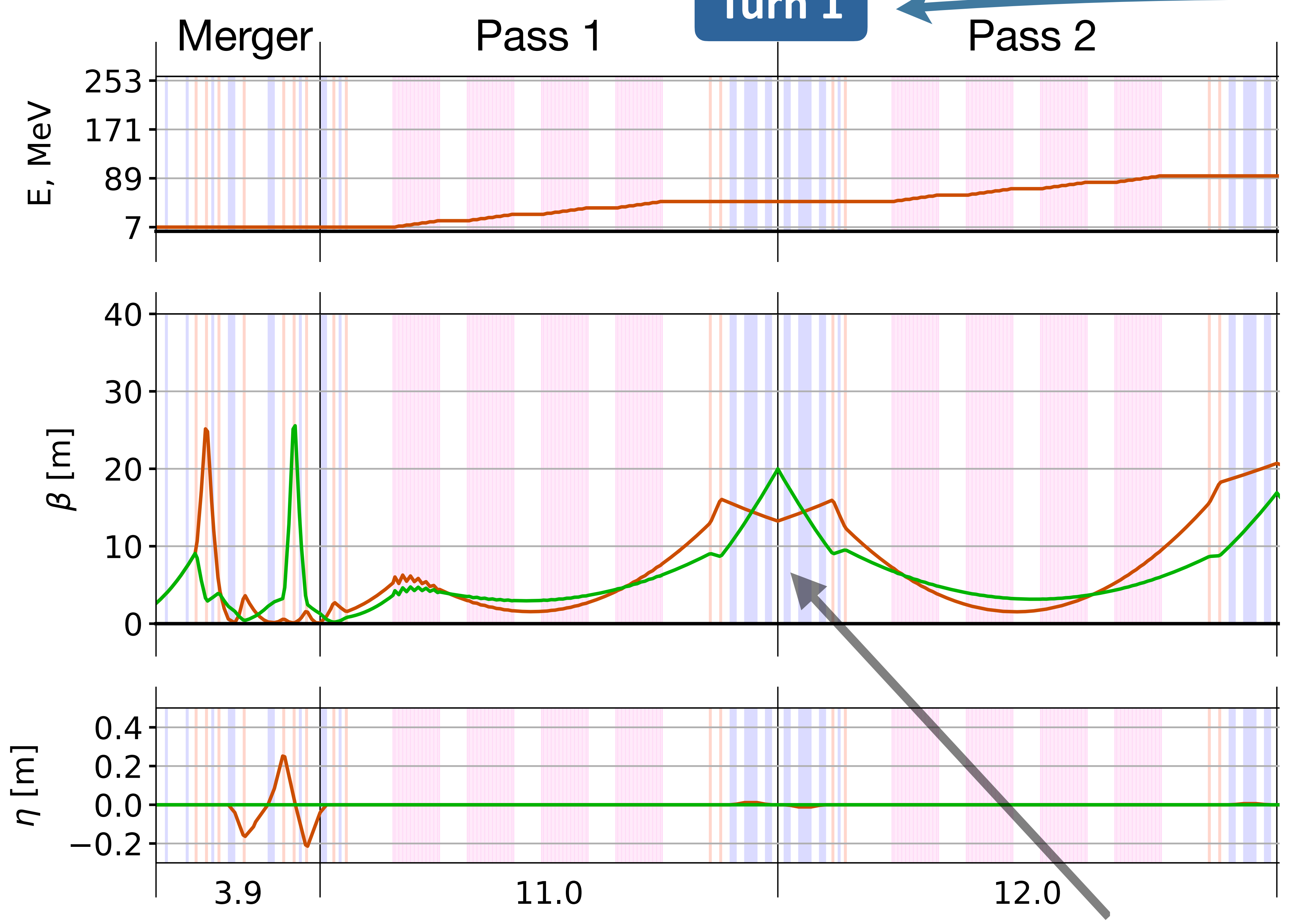
PERLE Optics: Multi-turn tuning



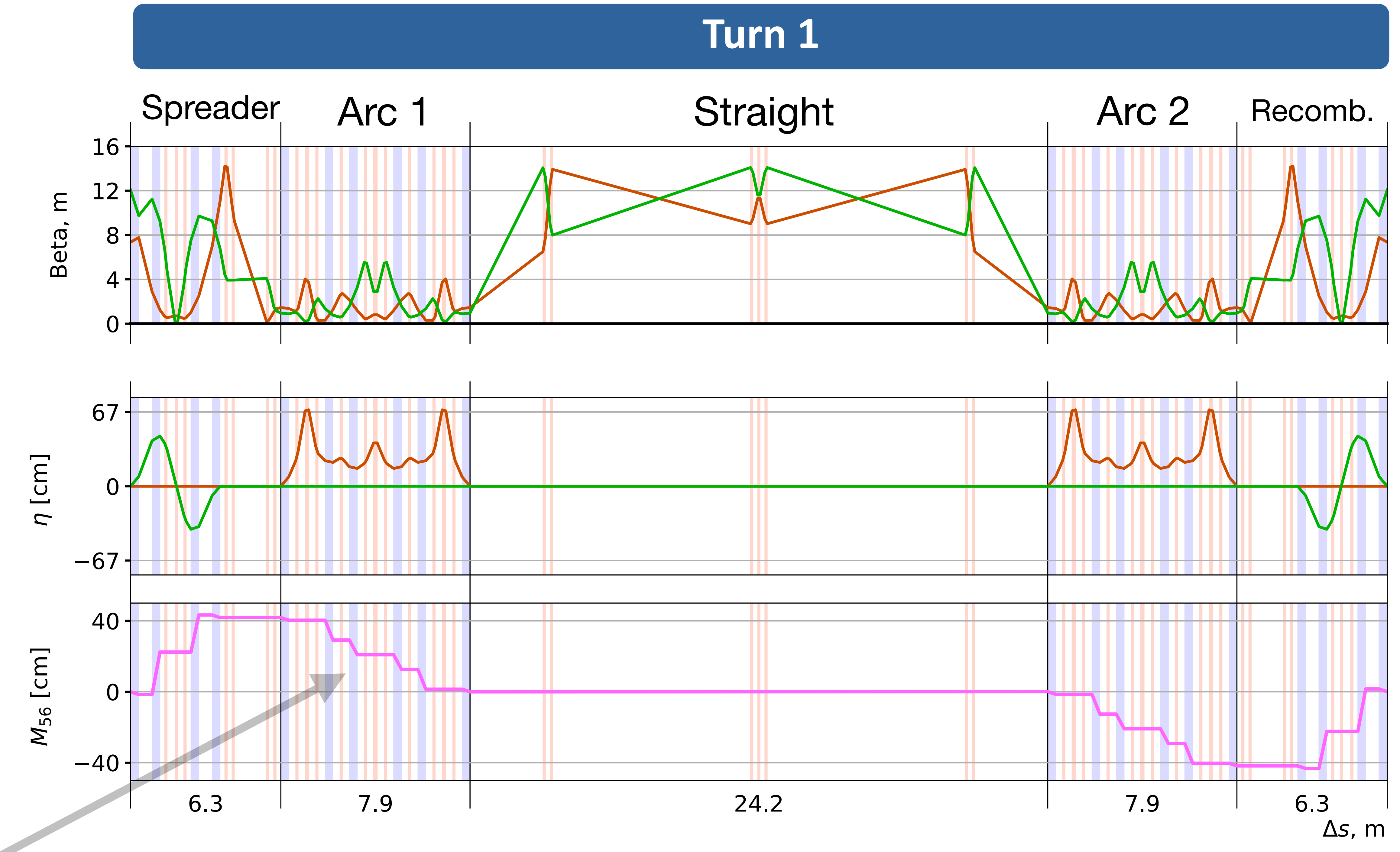


In the arc, **M56** is another tuning knob: we can close the spreader-induced bump, improve transport, and match the longitudinal phase space at the IPs

PERLE Optics: Multi-turn tuning



Return passes use the same lattice → **mirror Twiss**



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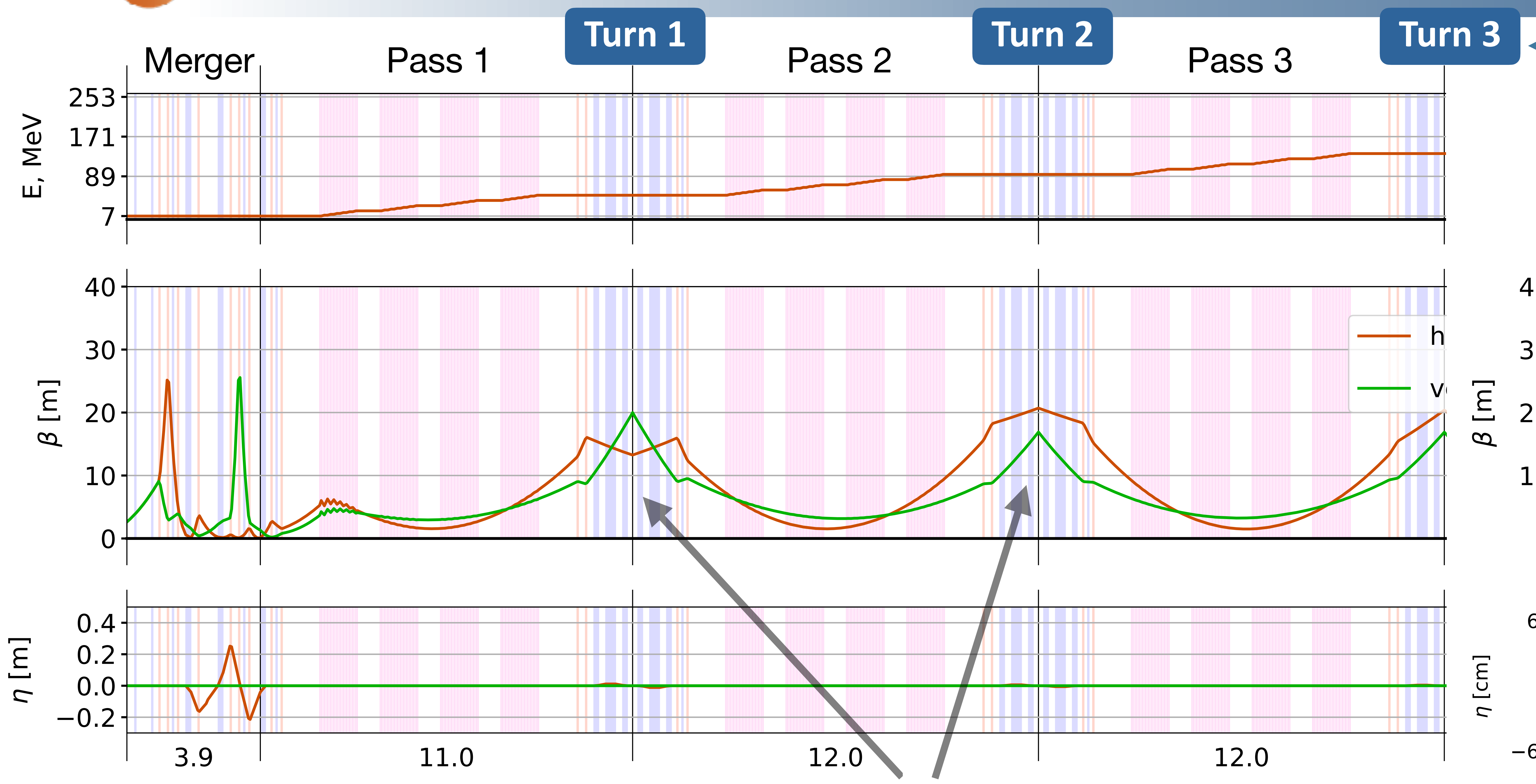

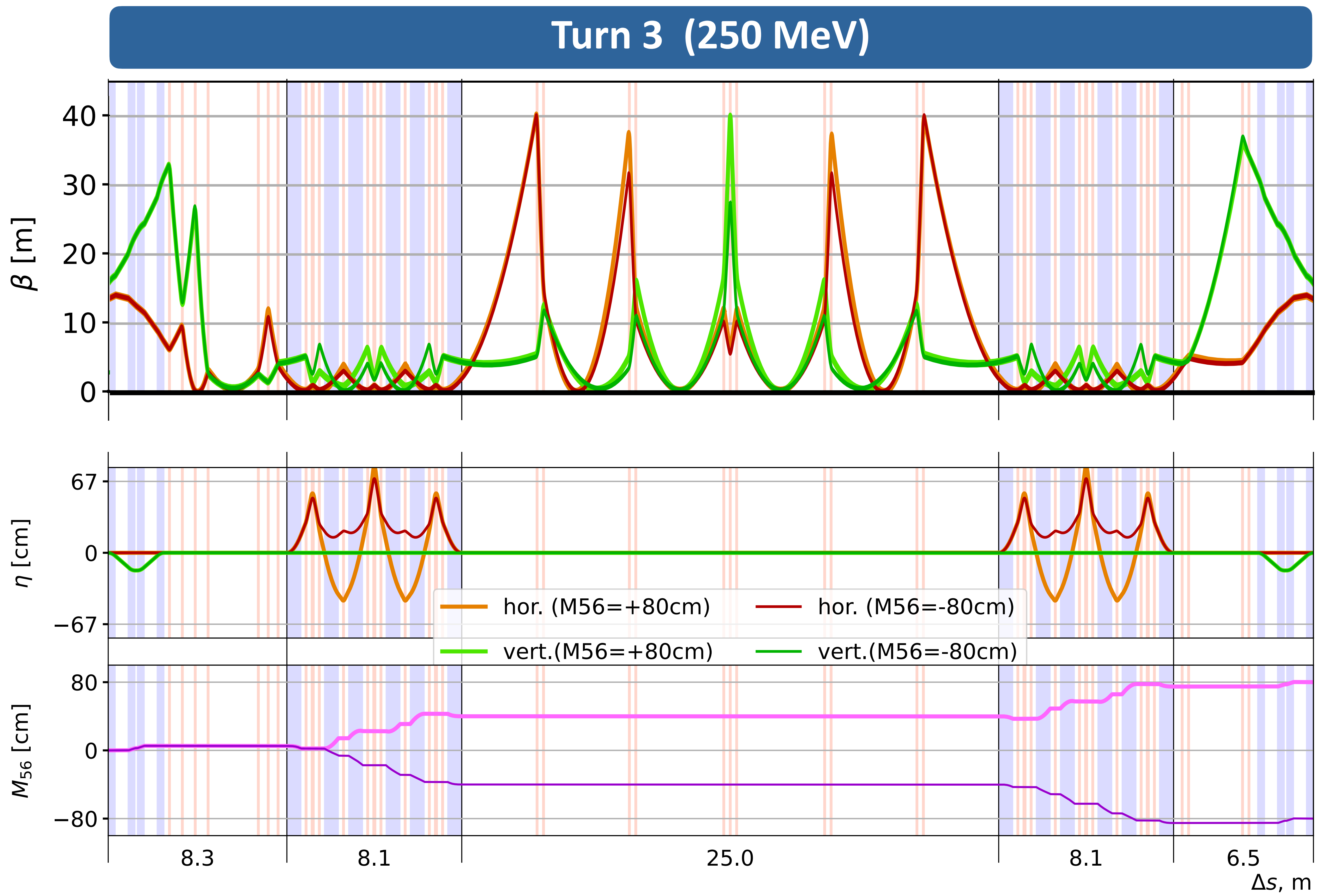

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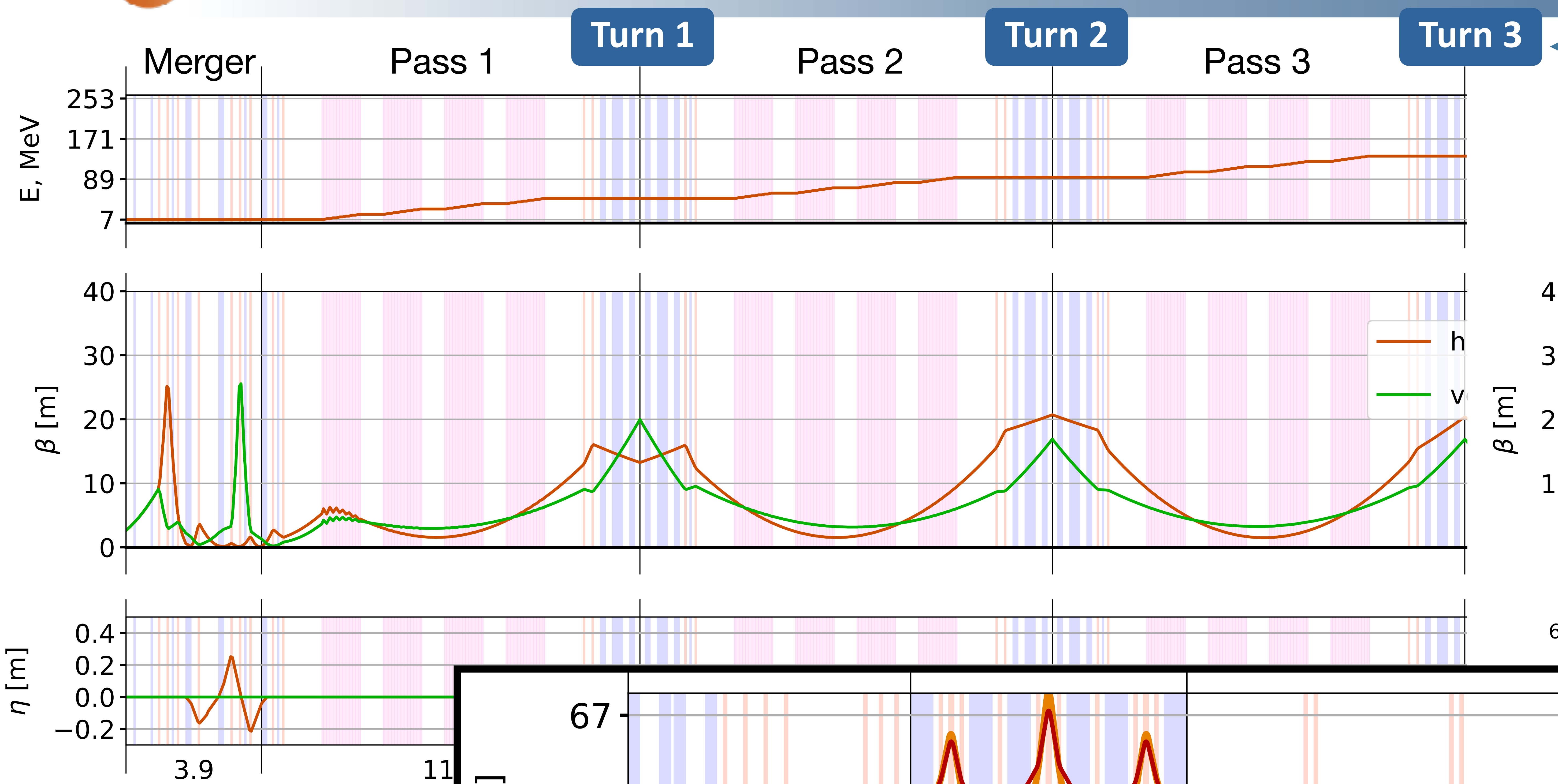
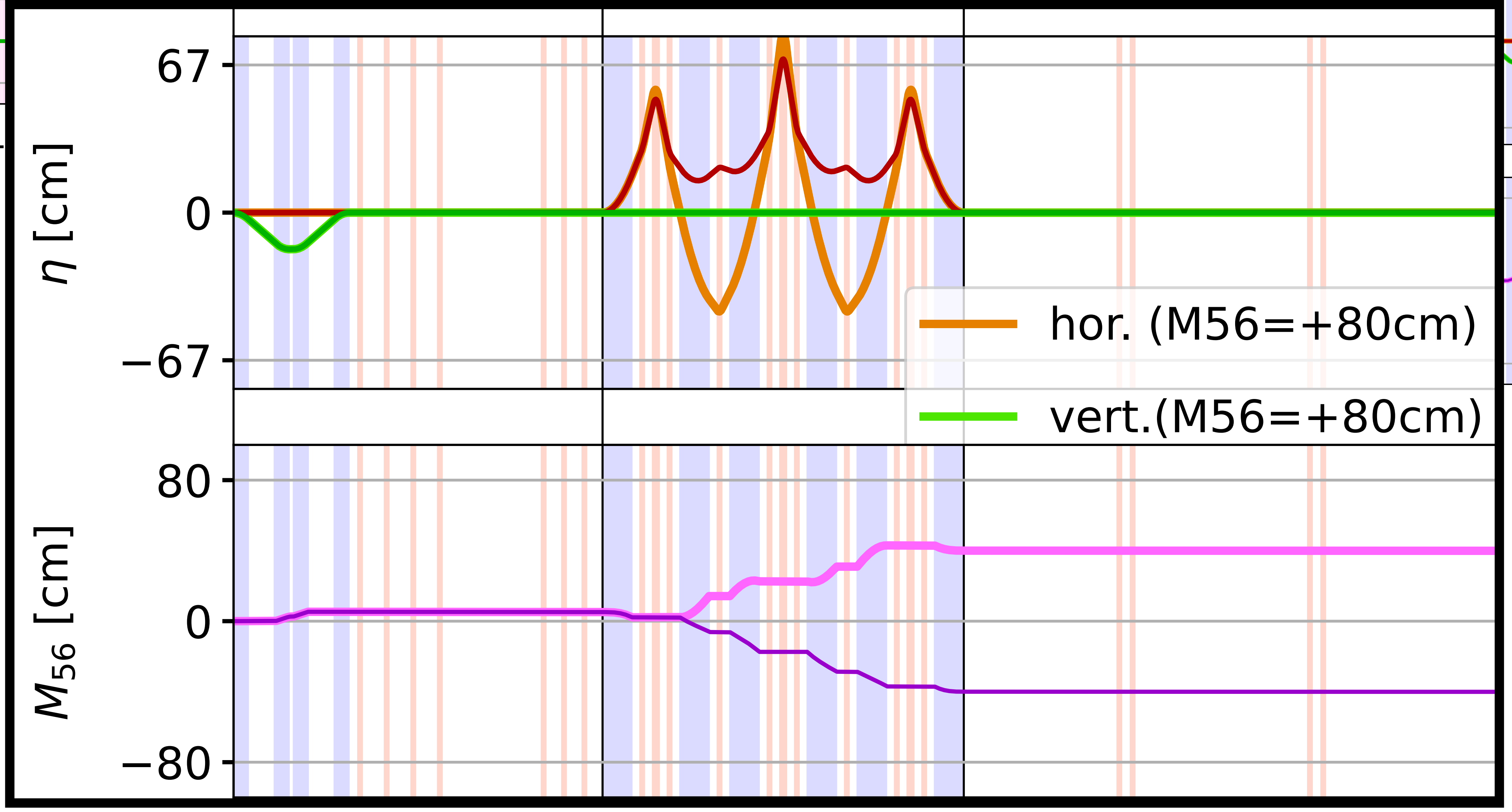
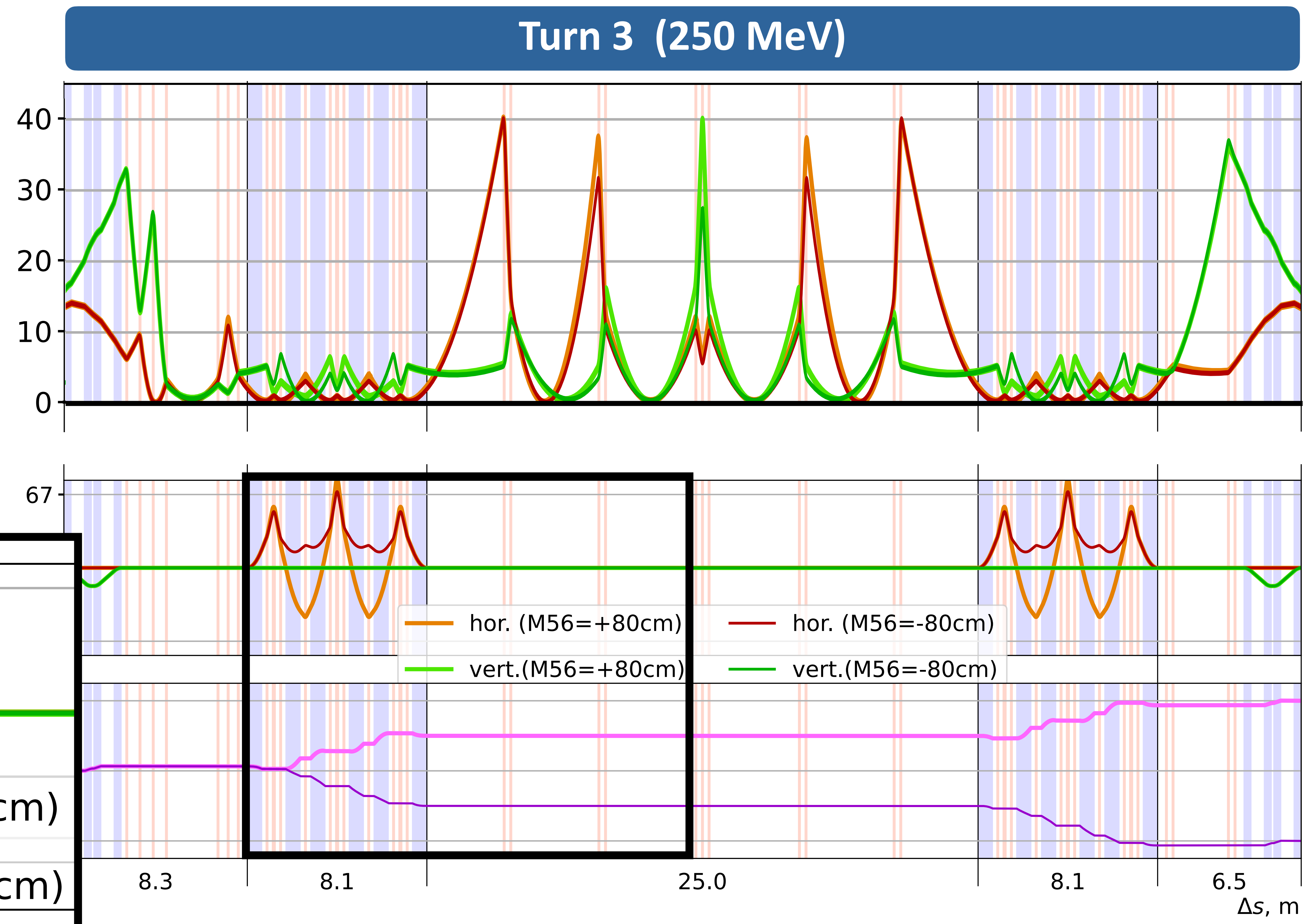






$$M_{56} = \int_0^L \frac{D}{\rho} ds$$

➡ Tuning M56 in the Arcs with minor change of beam properties or introduce a local bump of M56 = ± 80 cm

PERLE Optics: Multi-turn tuning

Return passes use the **same lattice in reverse order → mirror Twiss**

Small deviations from the ideal symmetry can be used for **fine tuning**.

Multiple optics solutions exist, trading beam size between the merger, linac entrance, and spreader/recombiner sections.

Beam dynamics studies

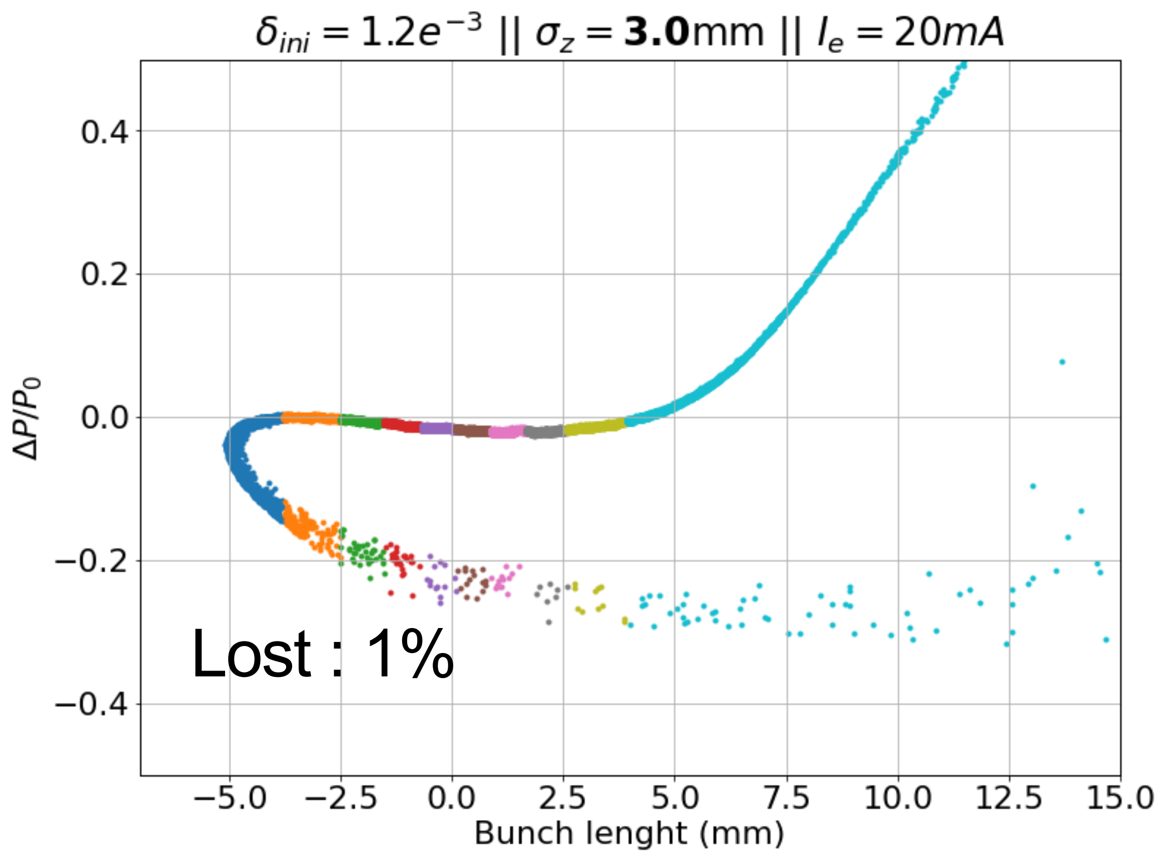
Longitudinal beam dynamics — Optimal bunch length

DOI: 10.1103/PhysRevAccelBeams.27.031603

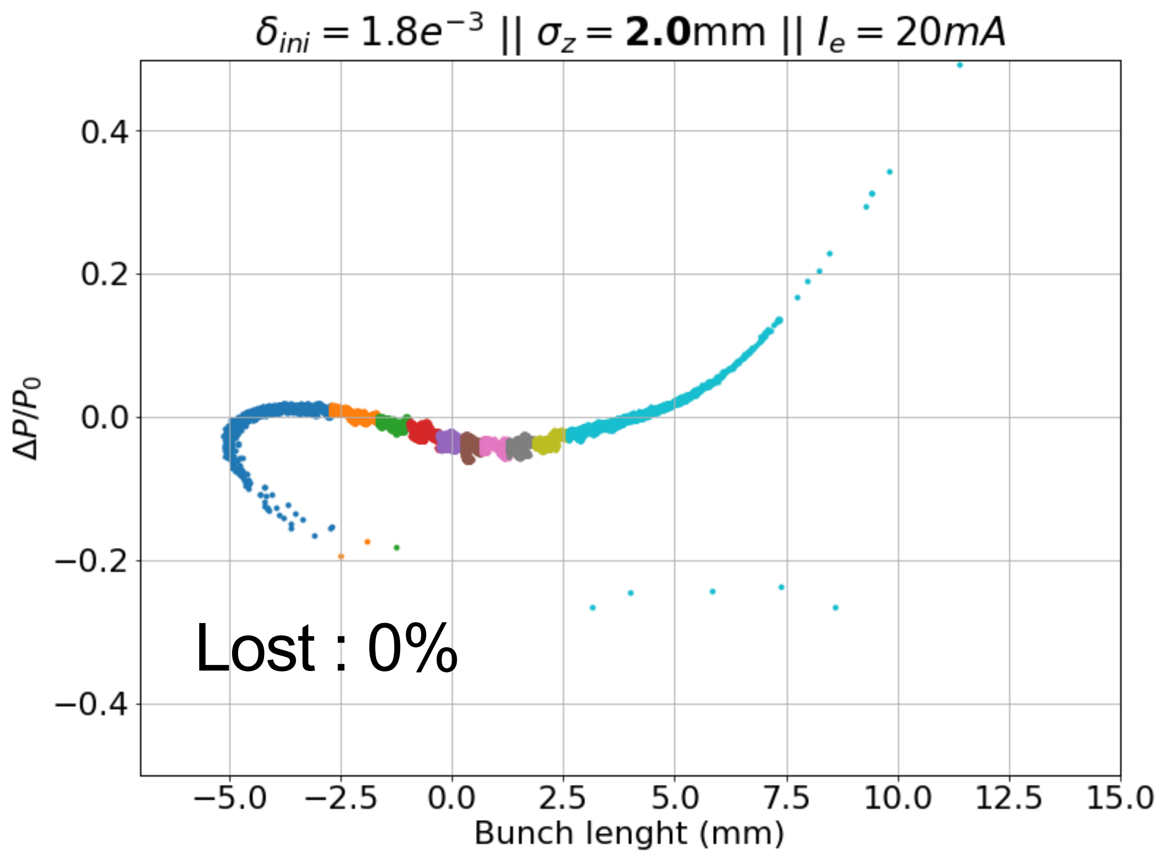
The optimal bunch length is a compromise between RF nonlinearity and CSR effects.

Tracking throughout the full machine using PLACET2 and BMAD (courtesy of K. André and J. Michaud)

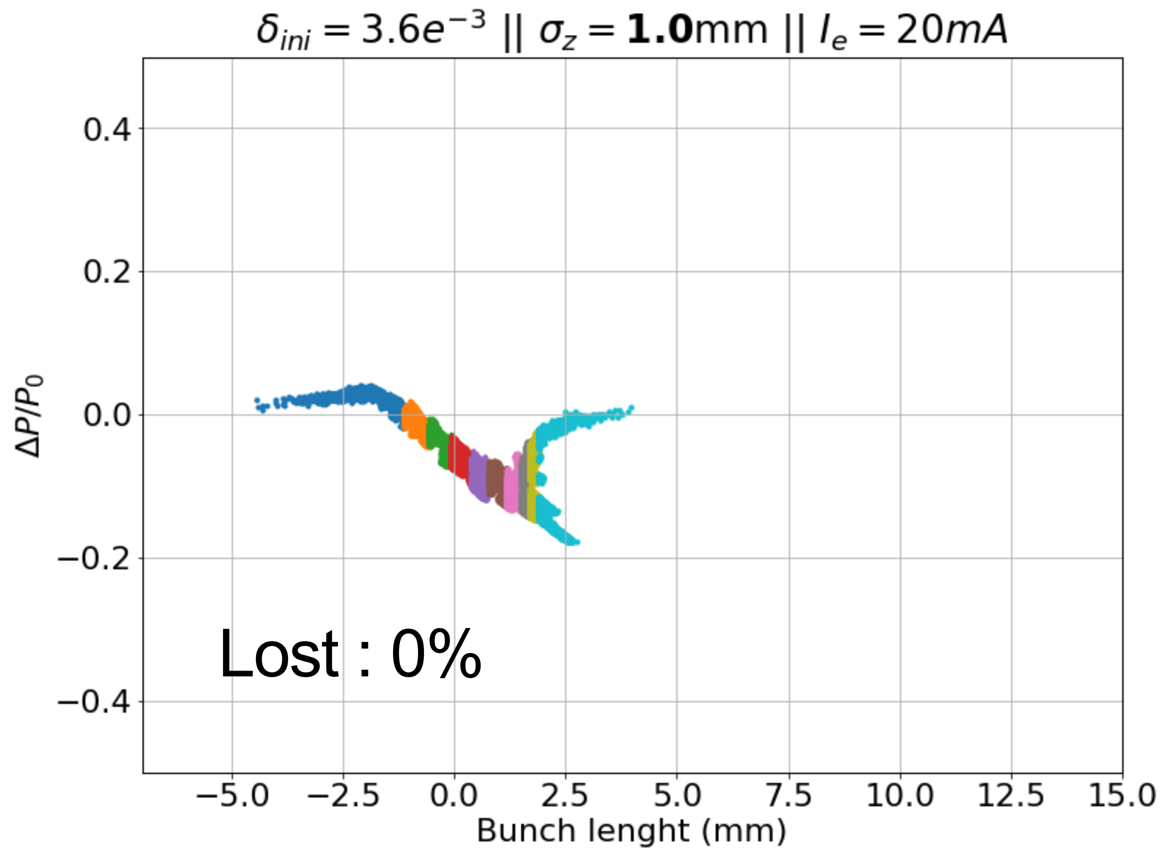
3 mm bunch length



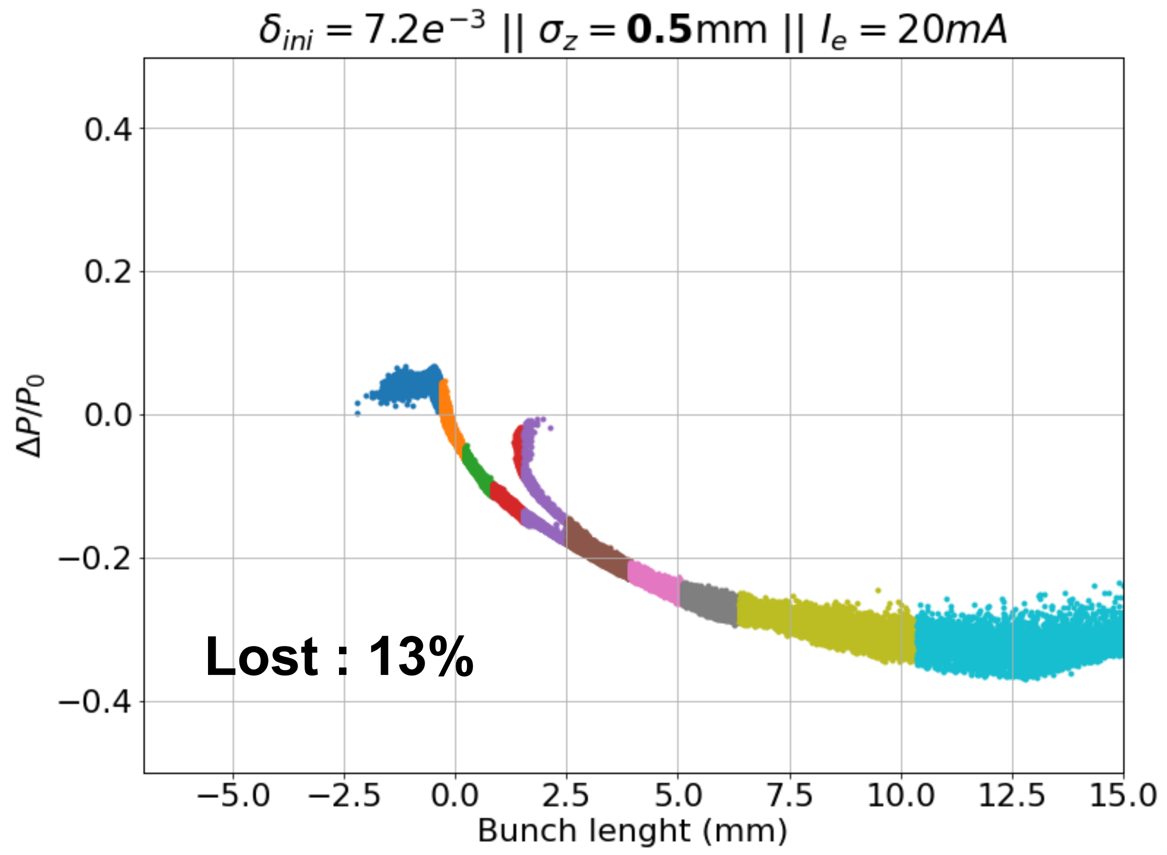
2 mm bunch length



1 mm bunch length



0,5 mm bunch length



RF curvature dominated

CSR dominated

Longitudinal matching for PERLE

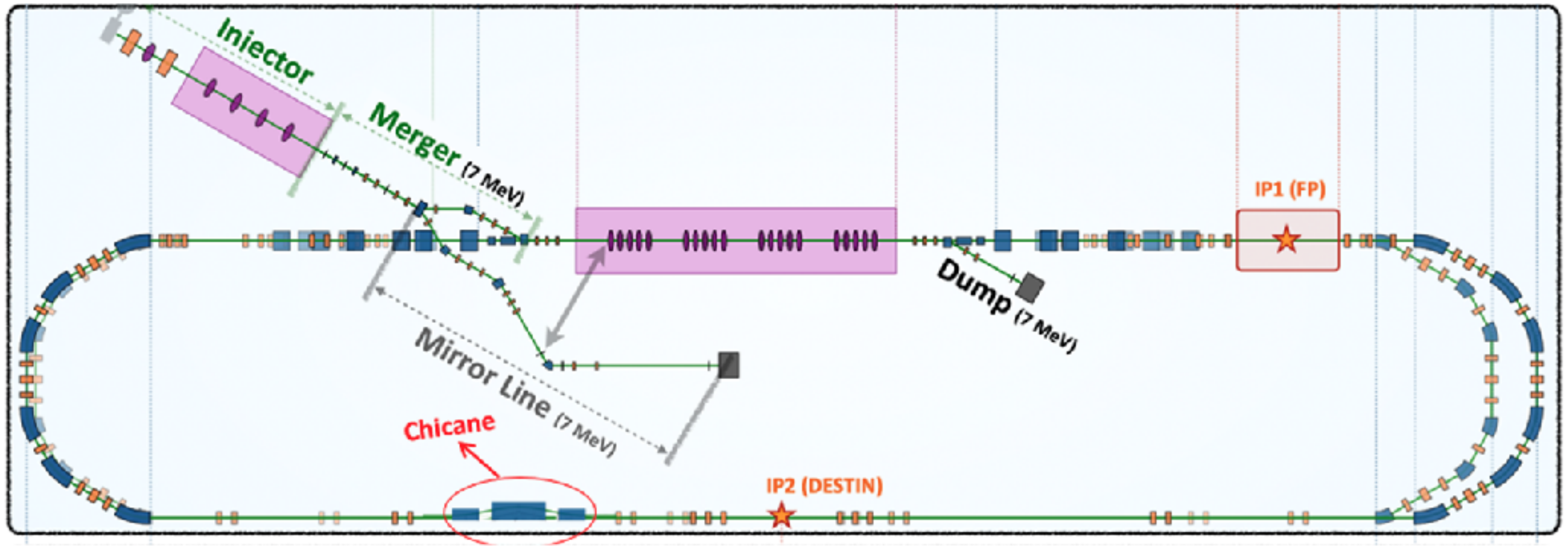
WEP5006 (J. Issa)

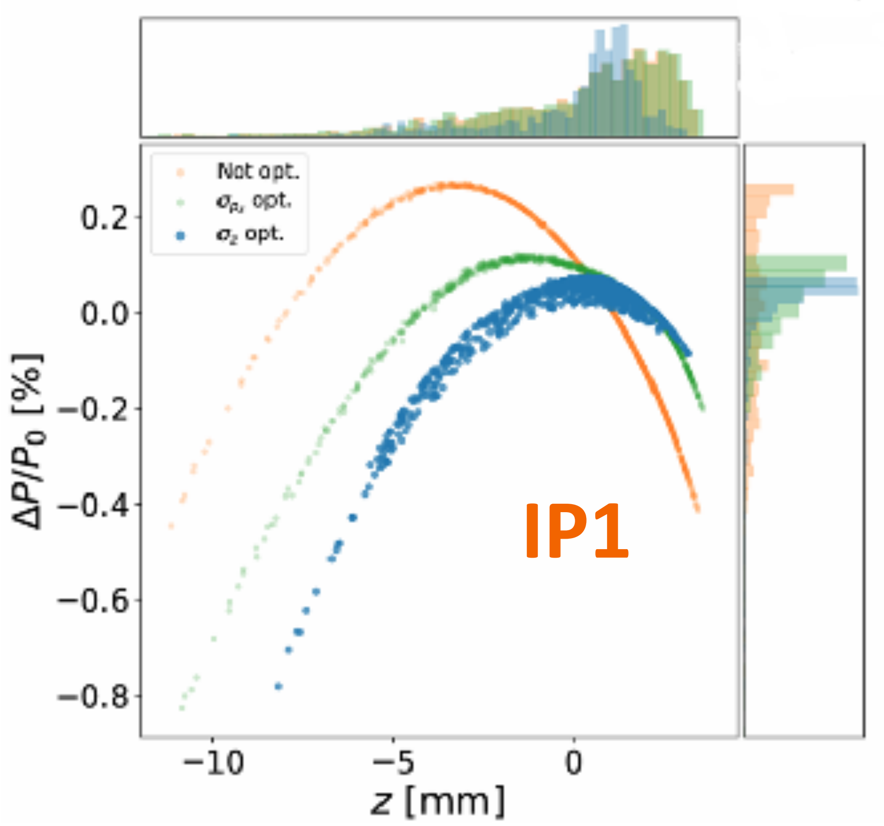
Longitudinal matching and control is important for:

- Experiments requirements IP1 and IP2
- Beam stability and losses
- Energy recovery efficiency

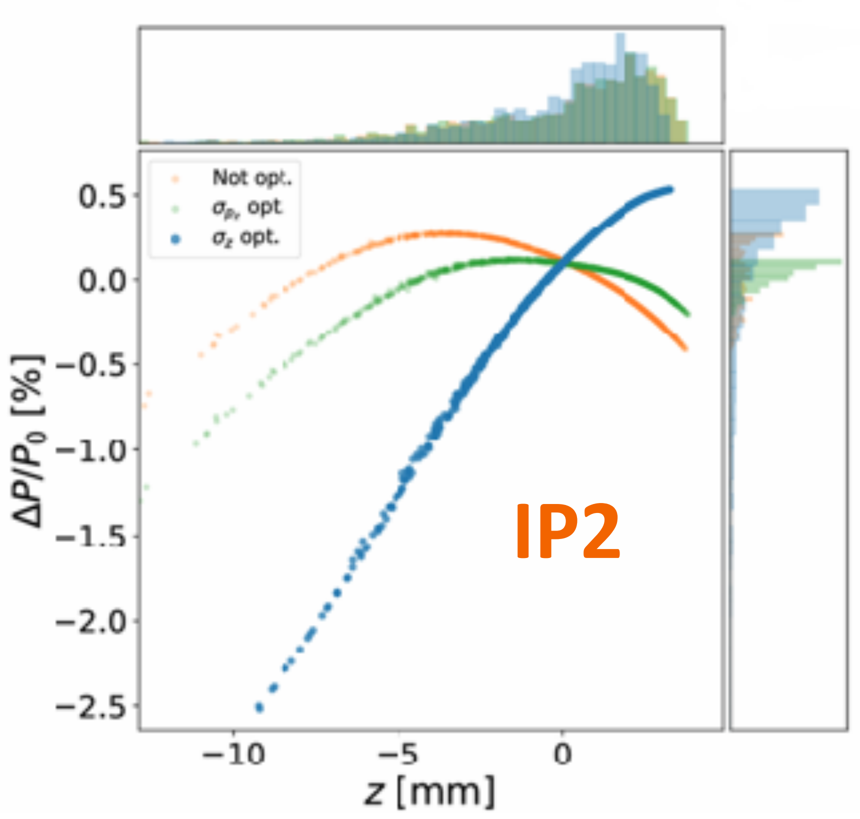
Tools that we can use:

- Quads for longitudinal dispersion (R56) tuning (Merger & Arcs)
- Path length chicane for phase tuning (One for each turn !)
- Sextupoles for T566, octupoles…





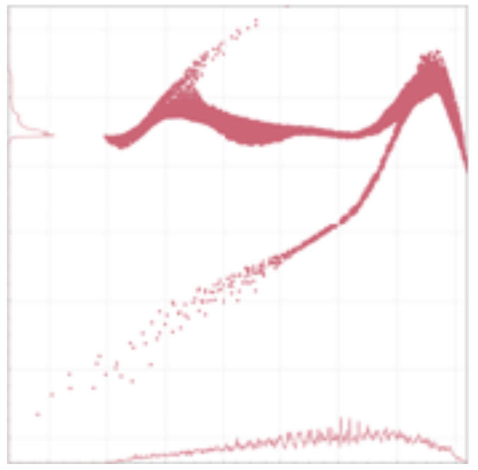
σ_z: 2.89mm → 2.13mm
σ_{pz}: 0.2% → 0.17%



σ_z: 3mm → 2.73mm
σ_{pz}: 0.2% → 0.17%

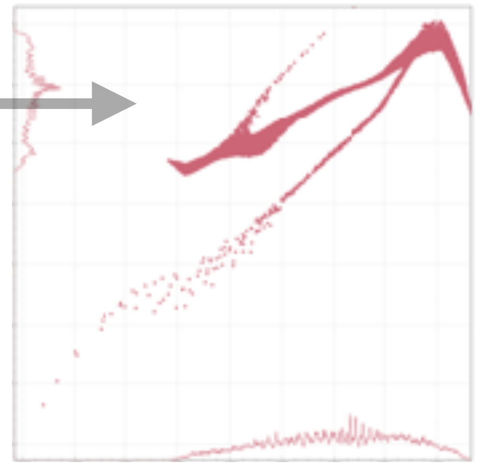
Current studies:

- BMAD simulation with absolute time tracking
- RF field maps (fundamental mode only)
- Path length chicane optimized



Preliminary results:

- Chirped distribution from booster is helpful
- Single Turn configuration not optimal for energy spread
- Multi-pass configuration is ideal for longitudinal matching



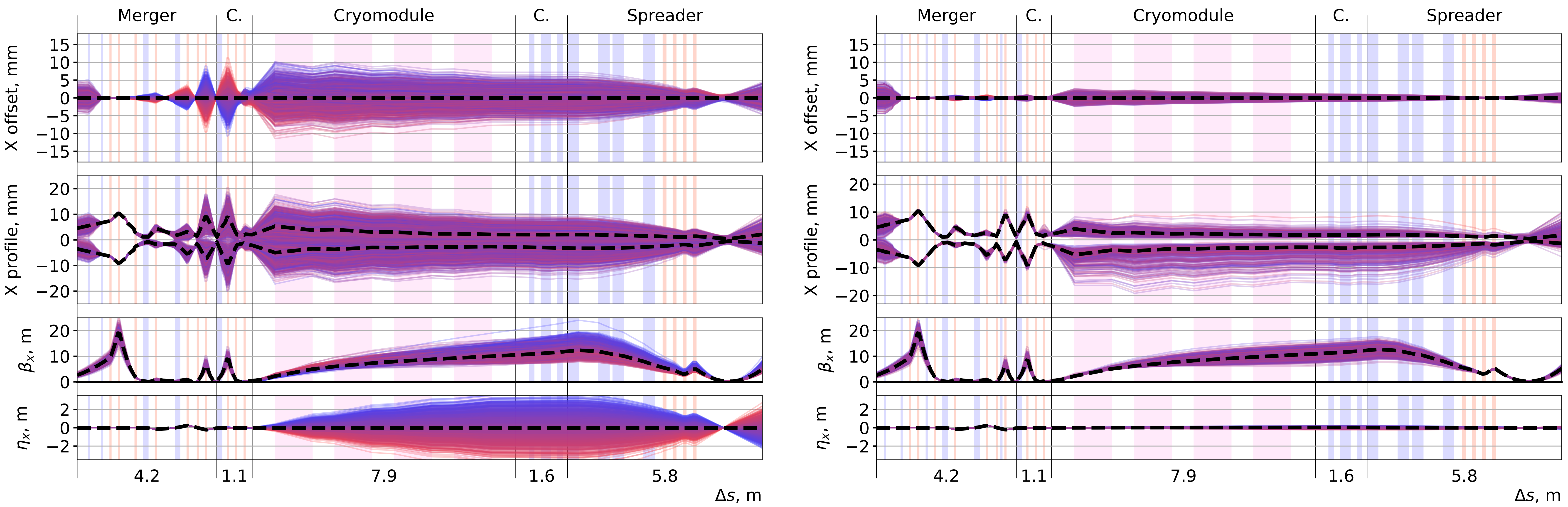
Merger: cavities and quadrupole static misalignments & correction

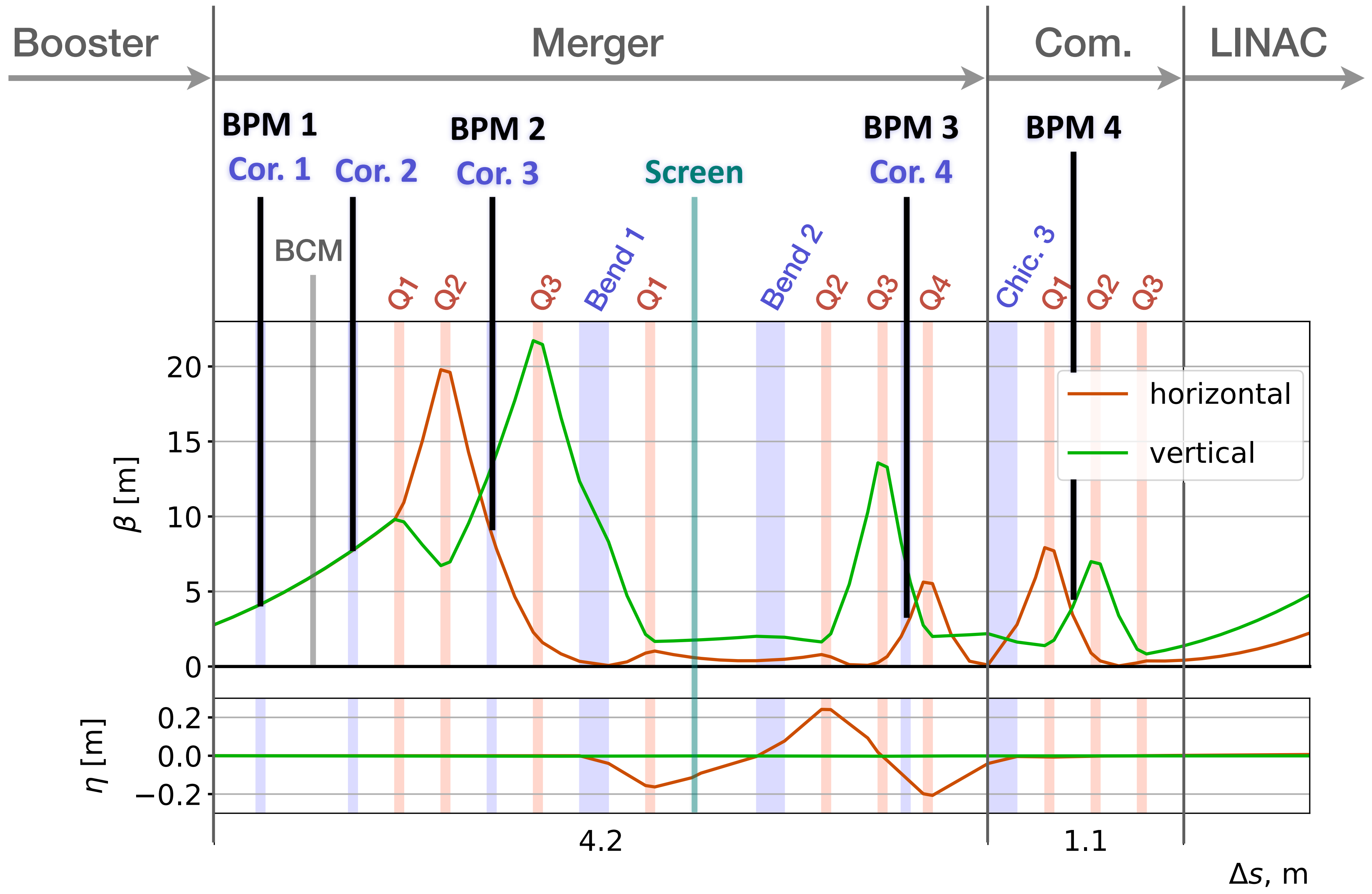
Booster cavities static misalignments:

normal distribution: $\sigma_{x,y,z}$ = 1 mm, σ_{tilt} = 0.1°

Merger quadrupoles static misalignments:

normal distribution: $\sigma_{x,y}$ = 0.1 mm





Two-step trajectory correction — minimalistic scheme:

1. Booster correction: BMPs 1&2, Correctors 1&2
2. Quadrupole correction: using BMPs 3&4, Correctors 3&4

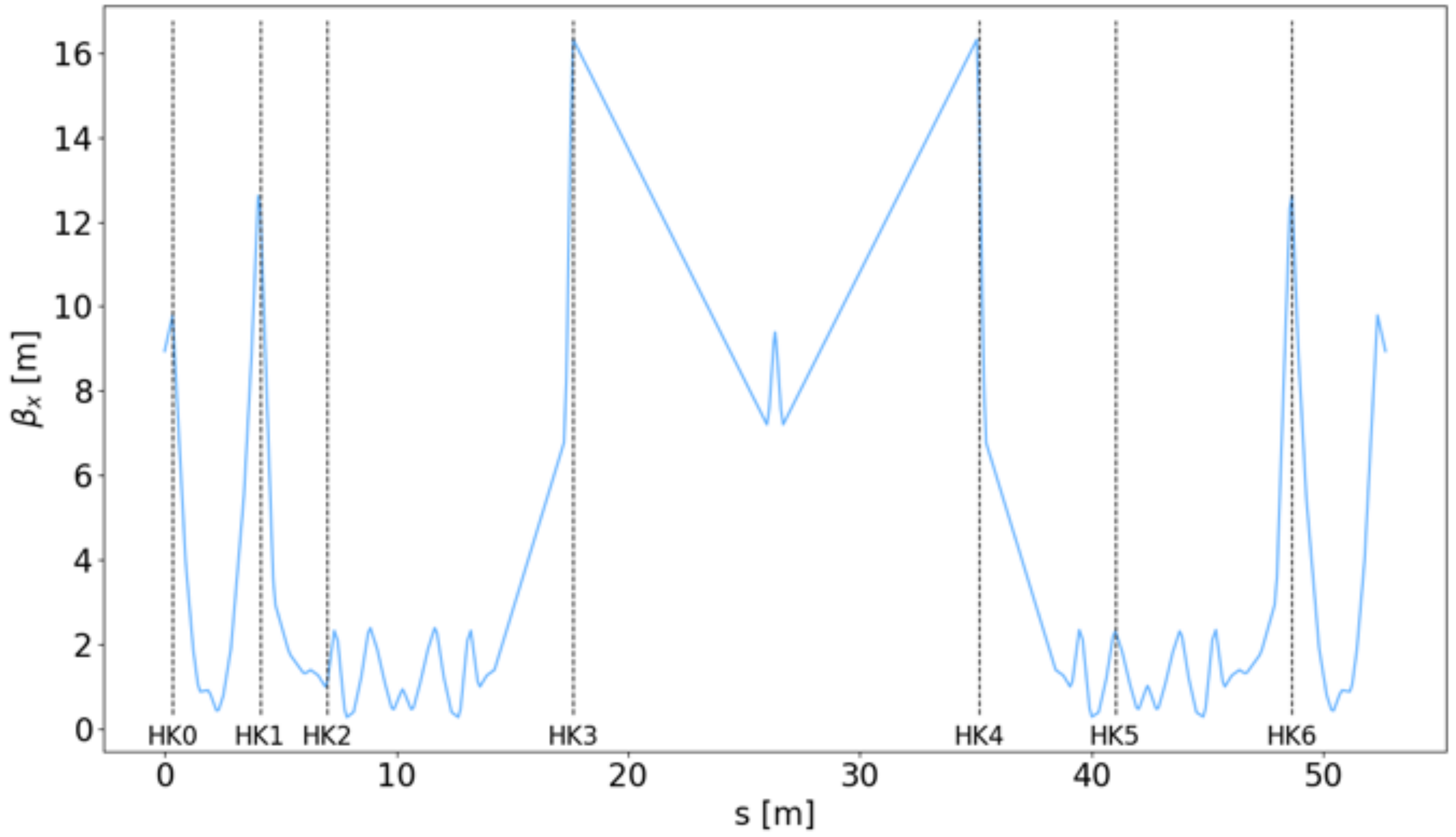
Result:

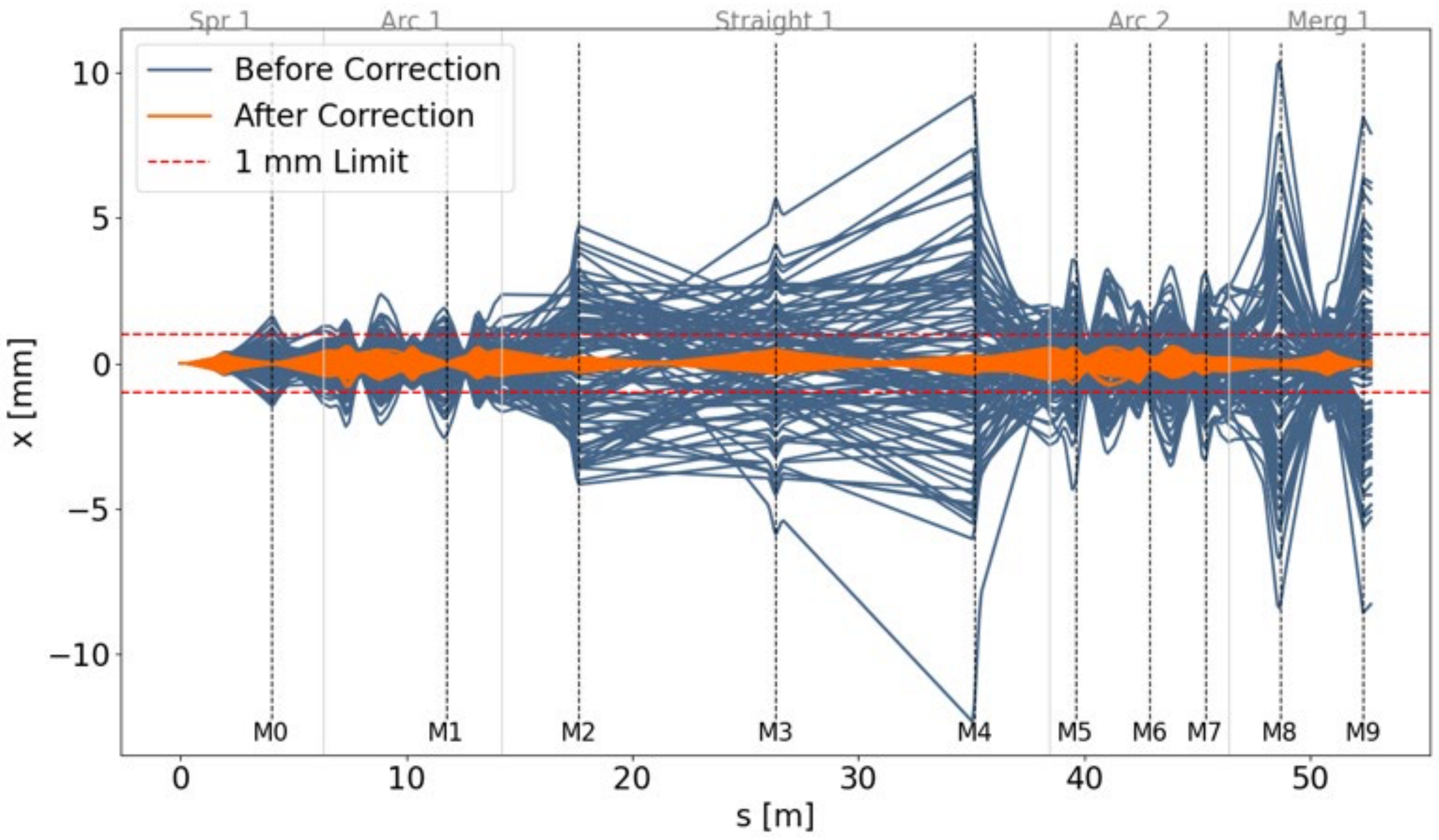
- loss-free passage through the linac
- No dispersion, trajectory offset < 3 mm (17 mm untreated)

First turn: Quadrupole static misalignments

MOP1110 (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**)

Assessing Corrector-Integrated Quadrupoles for PERLE

THP2103 (A. Fomin)

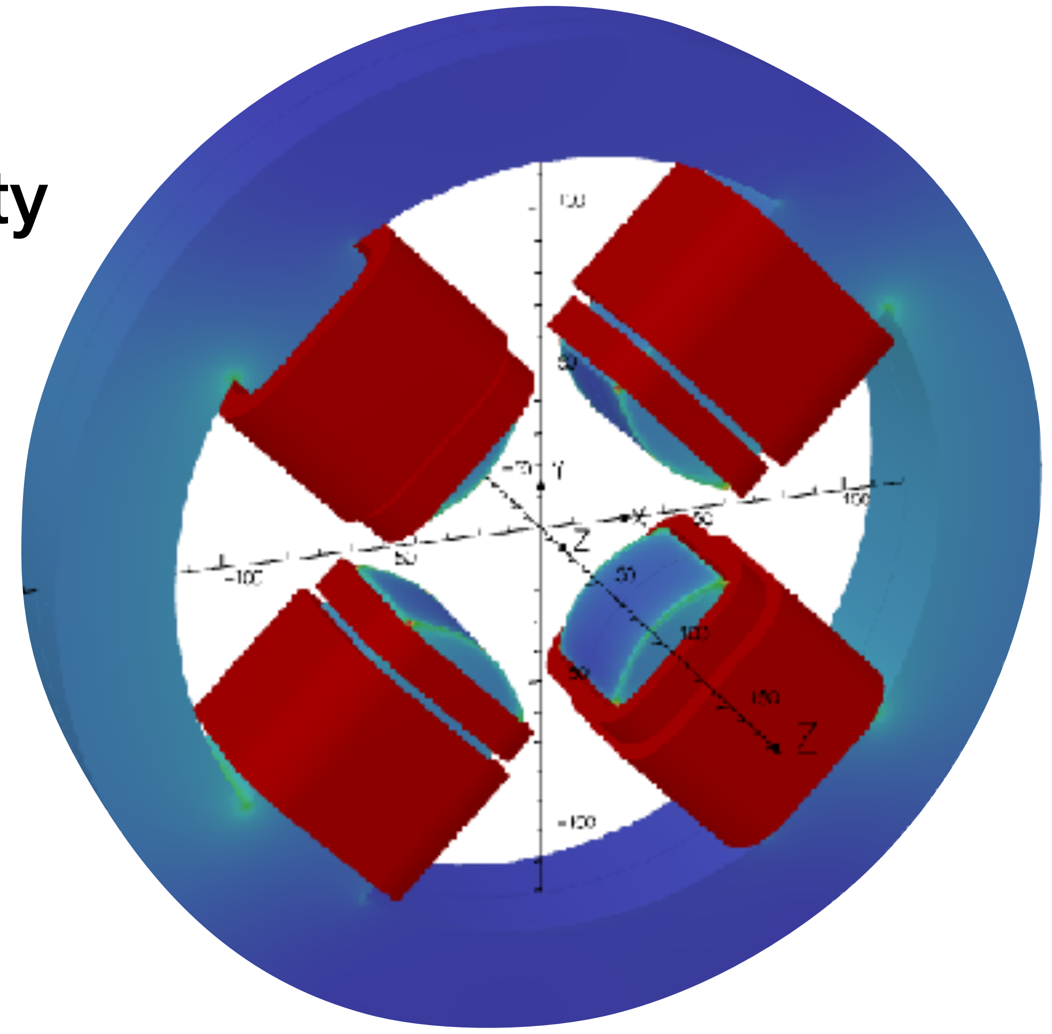
Compact correctors → **nonlinear off-axis fields**

Beam size trade-off: space charge ↔ halo from nonlinearity

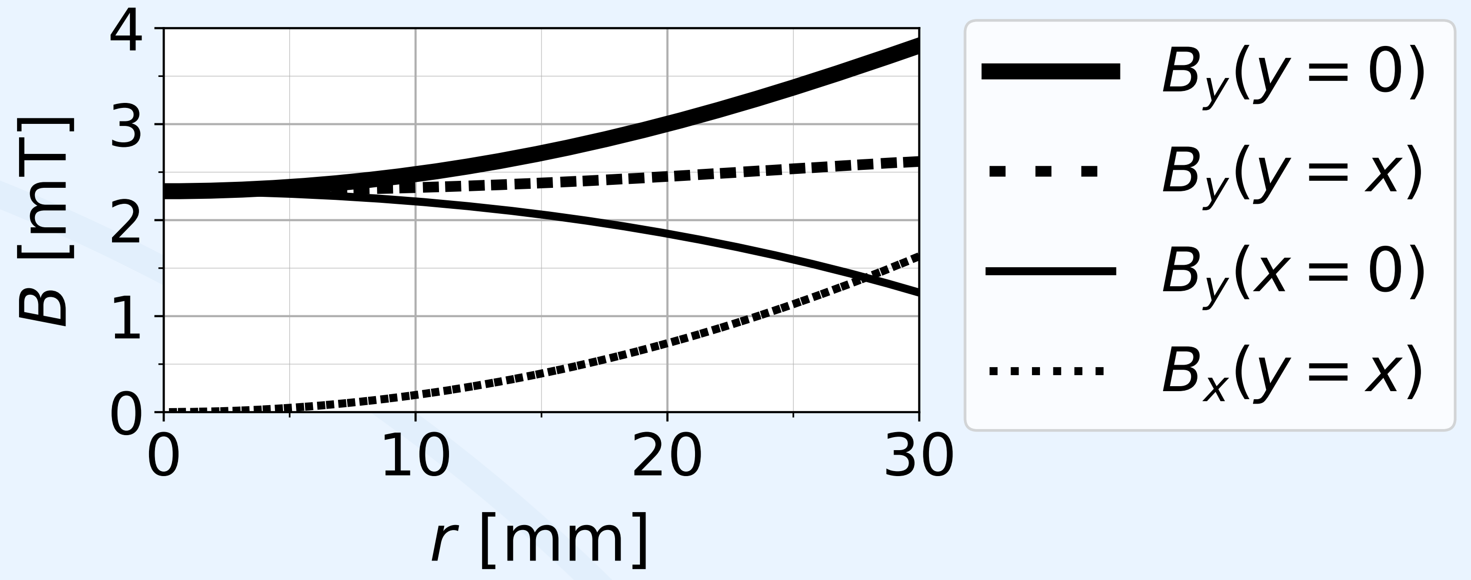
cERL kick maps (measured) → real-field validation

OPERA + BMAD → emittance, steering, halo impact

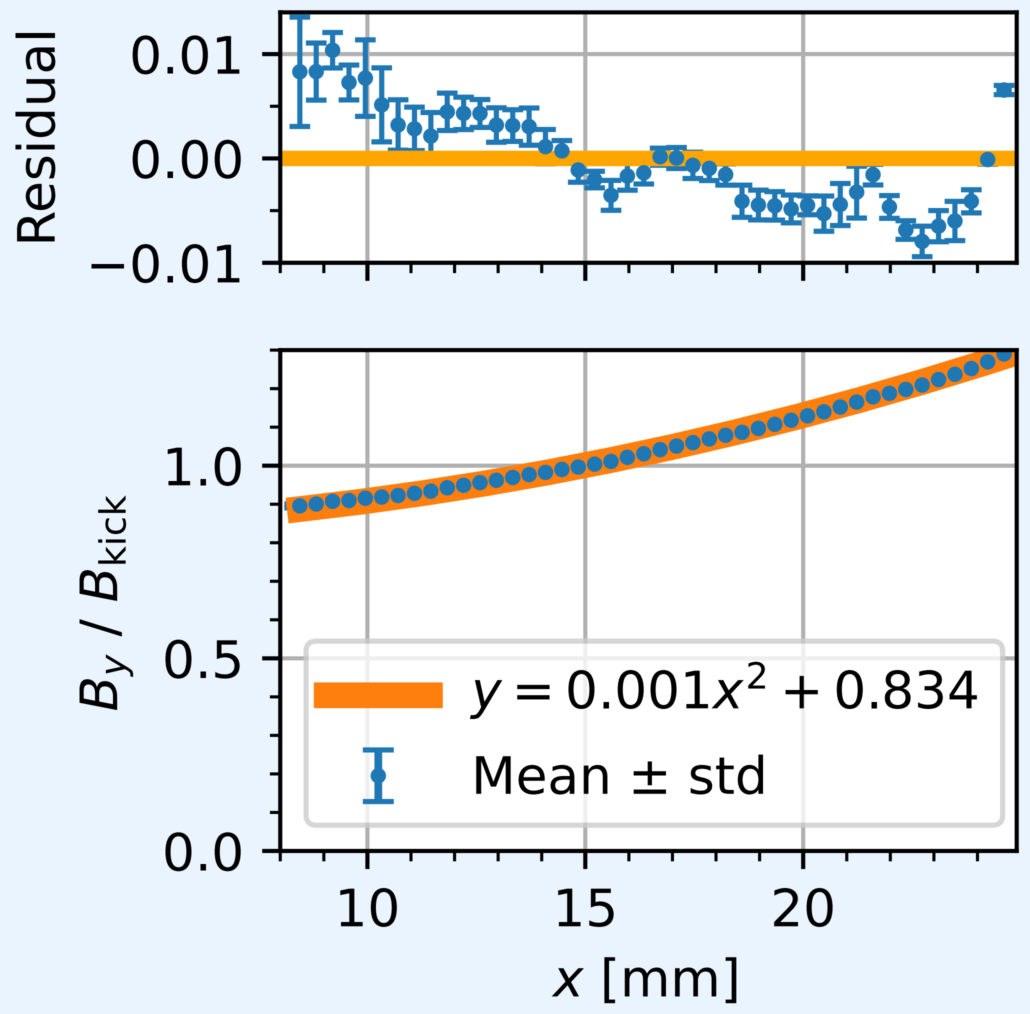
→ Design limits & lattice placement for PERLE

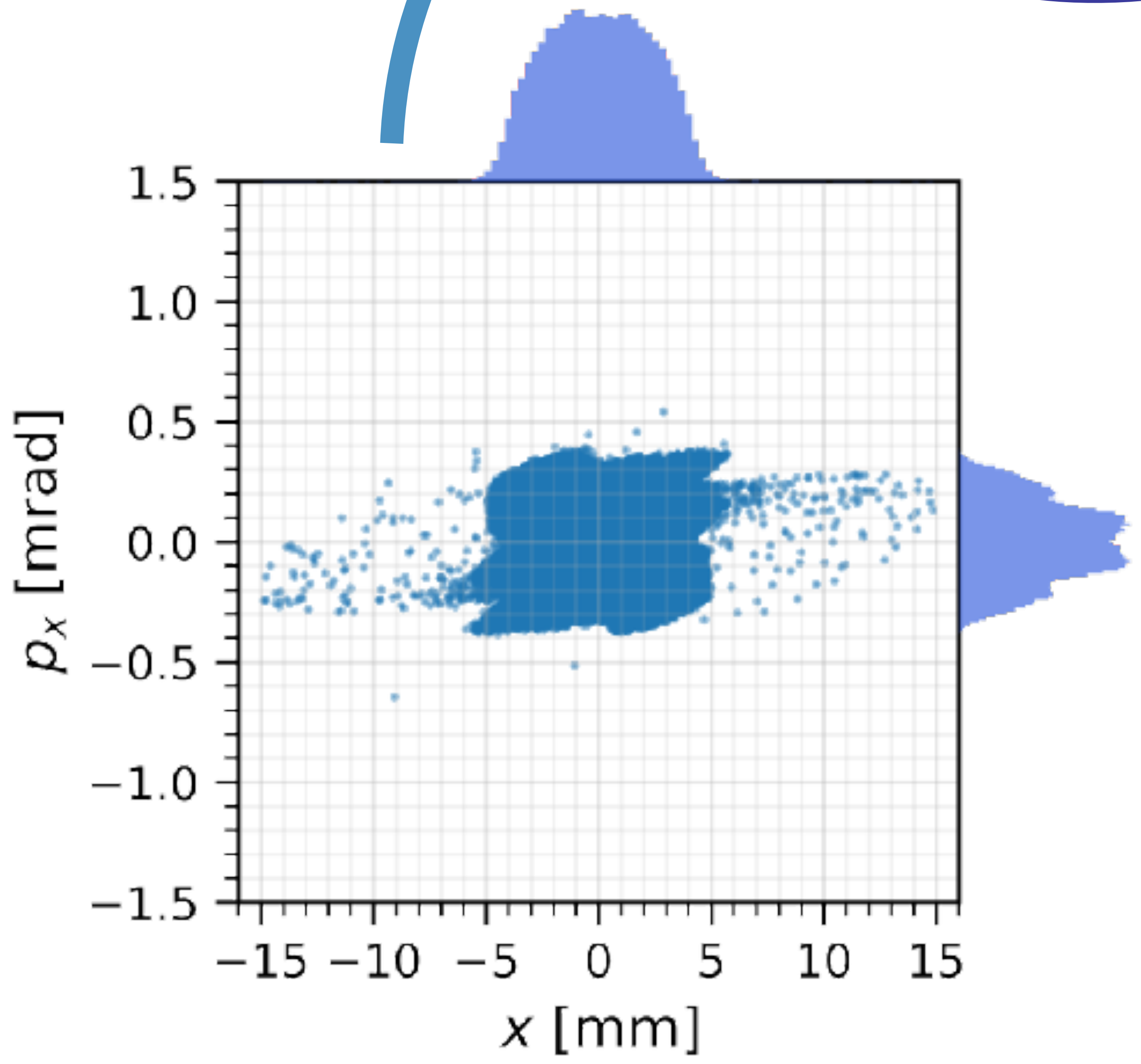


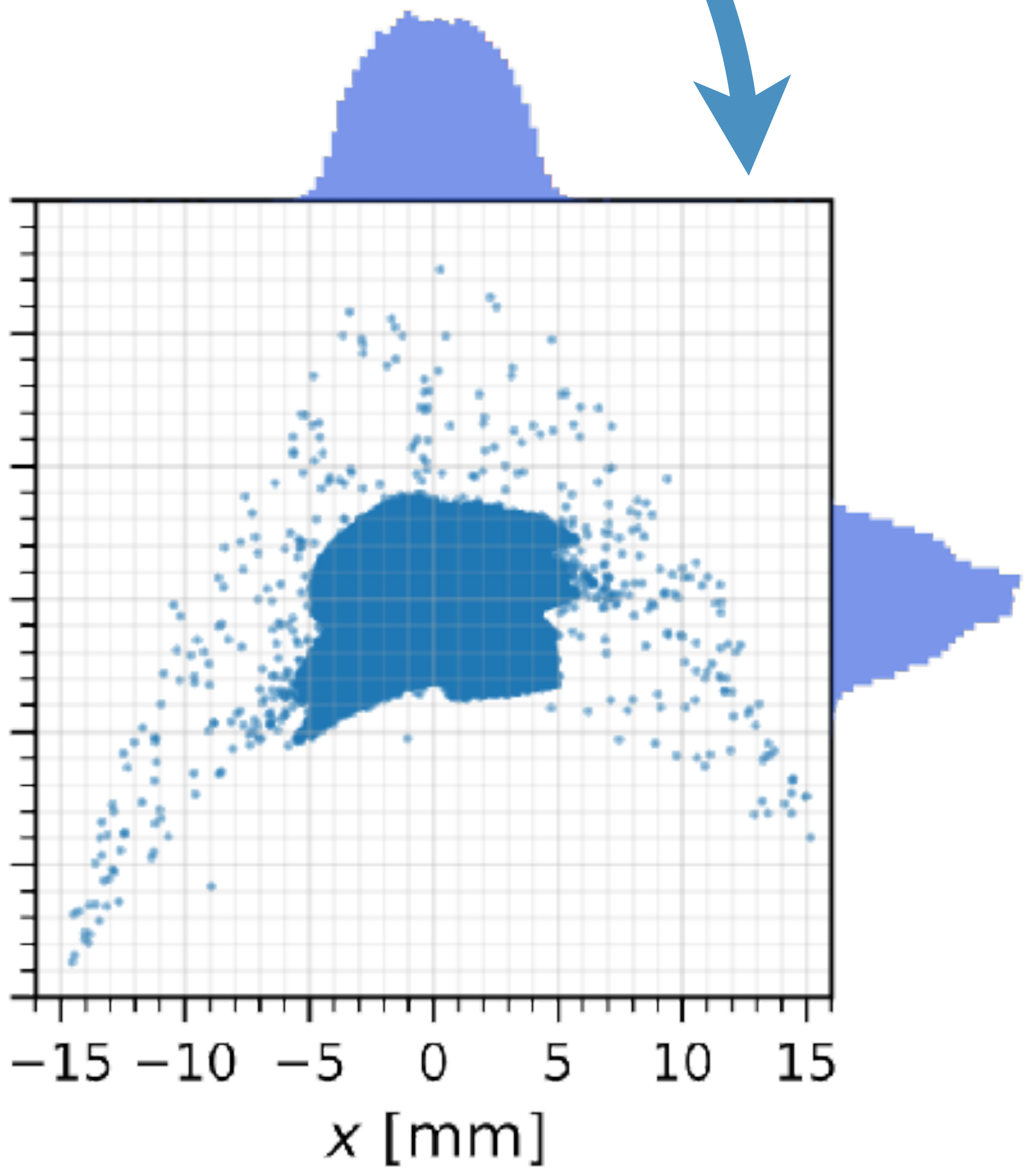
Field nonlinearity (OPERA 3D model)

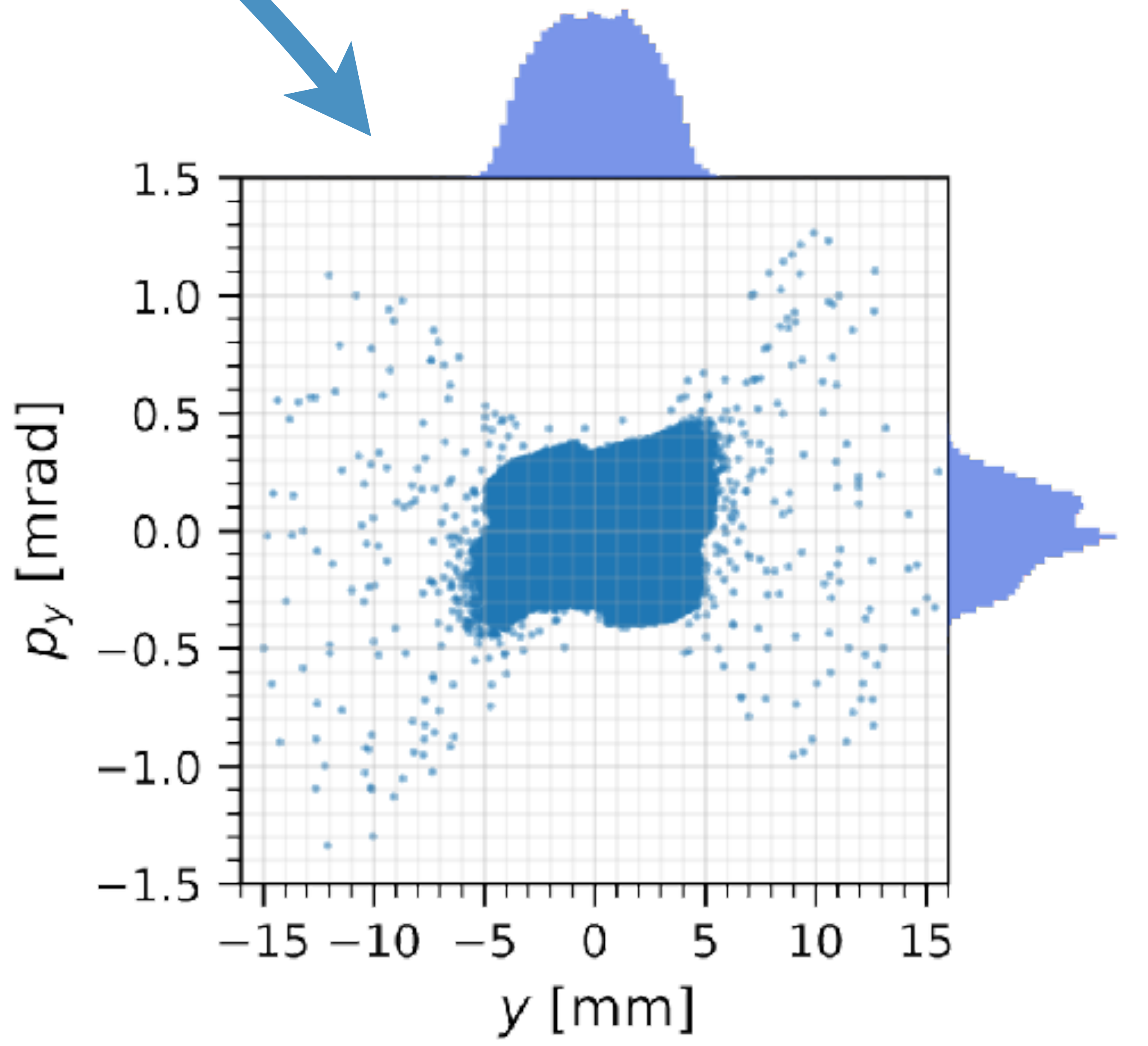


Field nonlinearity (measured)







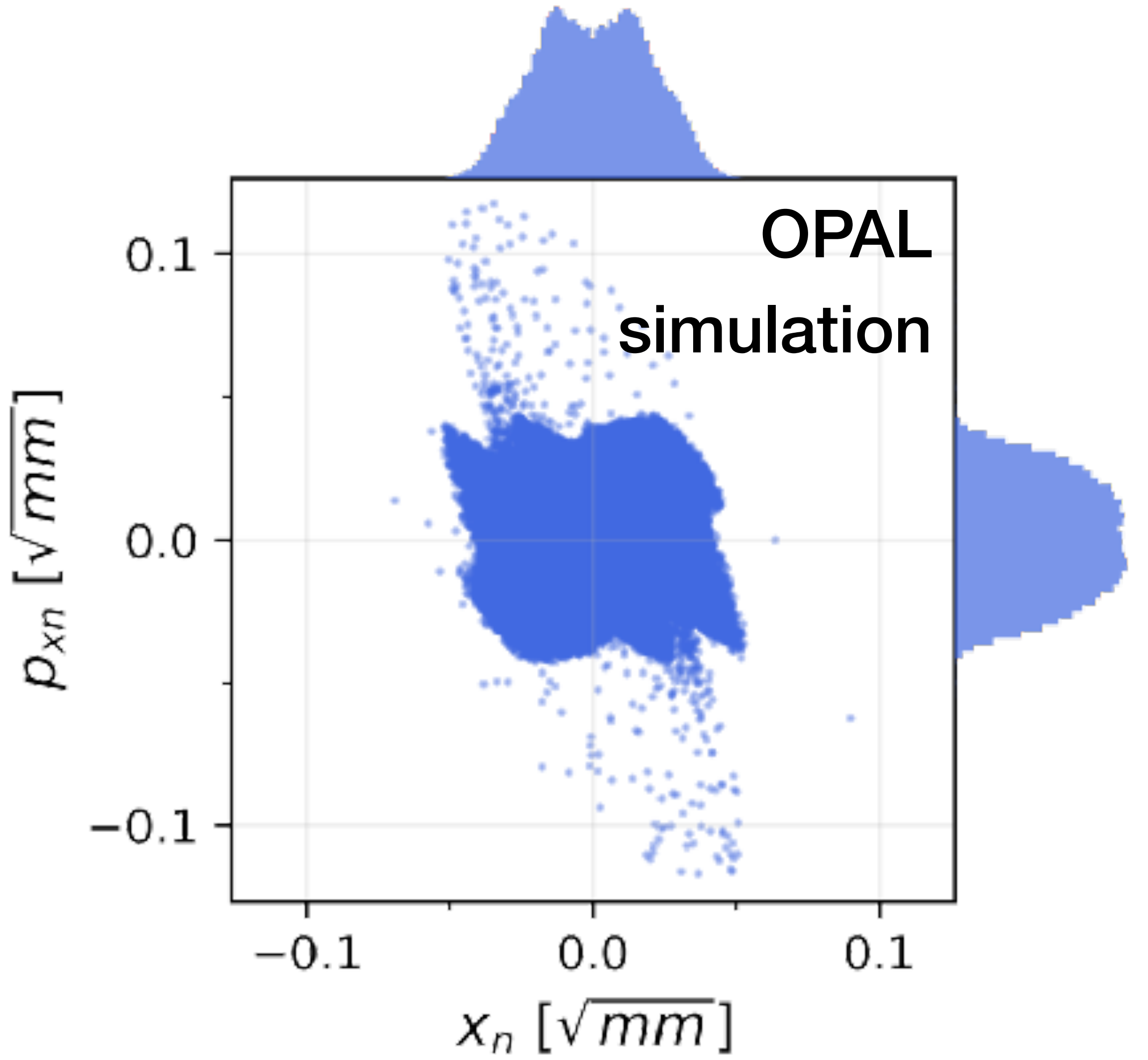


Halo cleaning and collimation at PERLE

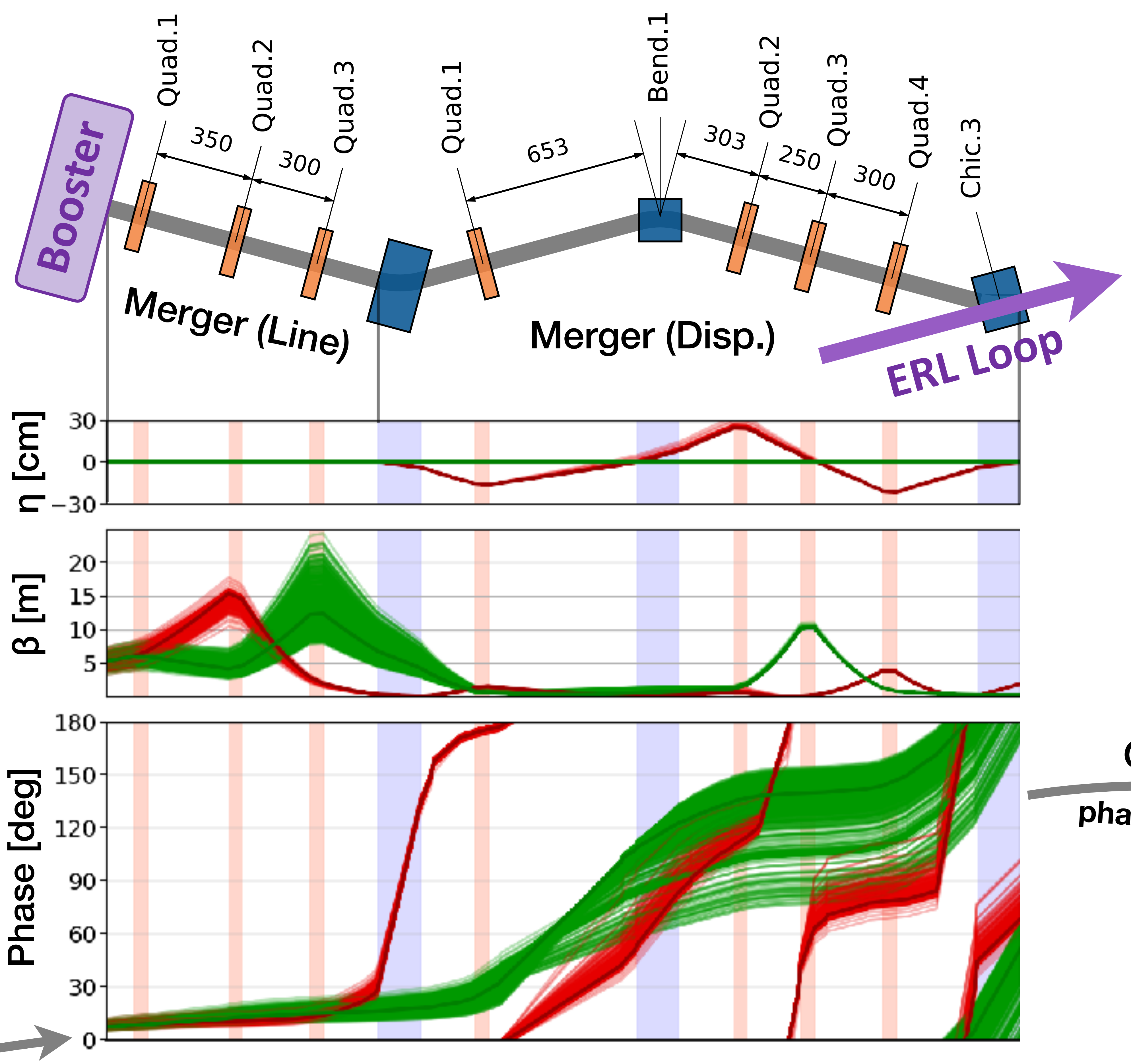
WEP5064 (A. Cieplak)

- Limited dispersion for effective off-momentum collimation
- Dedicated collimation locations identified
- Result: reduced transverse halo factor
- Partial cleaning of the longitudinal halo population

Initial distribution (x,px)
courtesy of C. K. Monaghan



Initial
after the Booster



Initial: $H_x = 0.77$

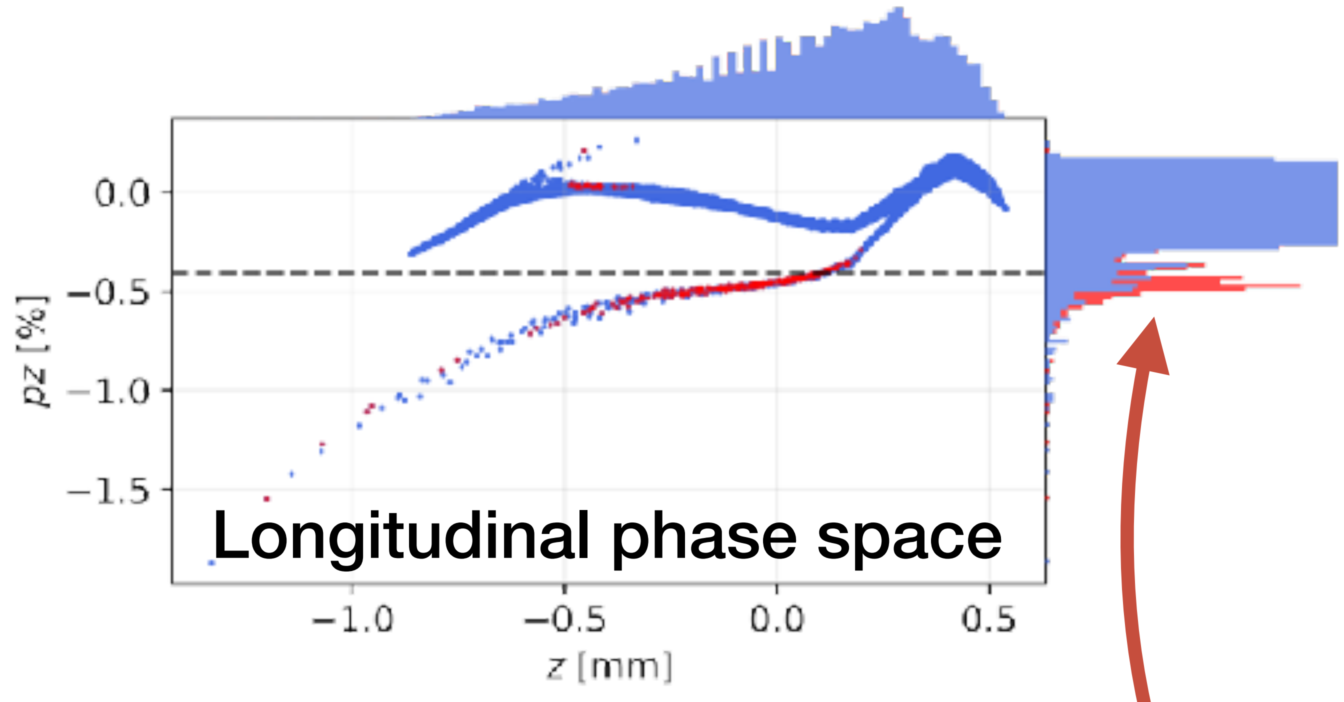
$H_y = 0.74$

$\eta_{\parallel} = 0$

Collimated: $H_x = 0.49$

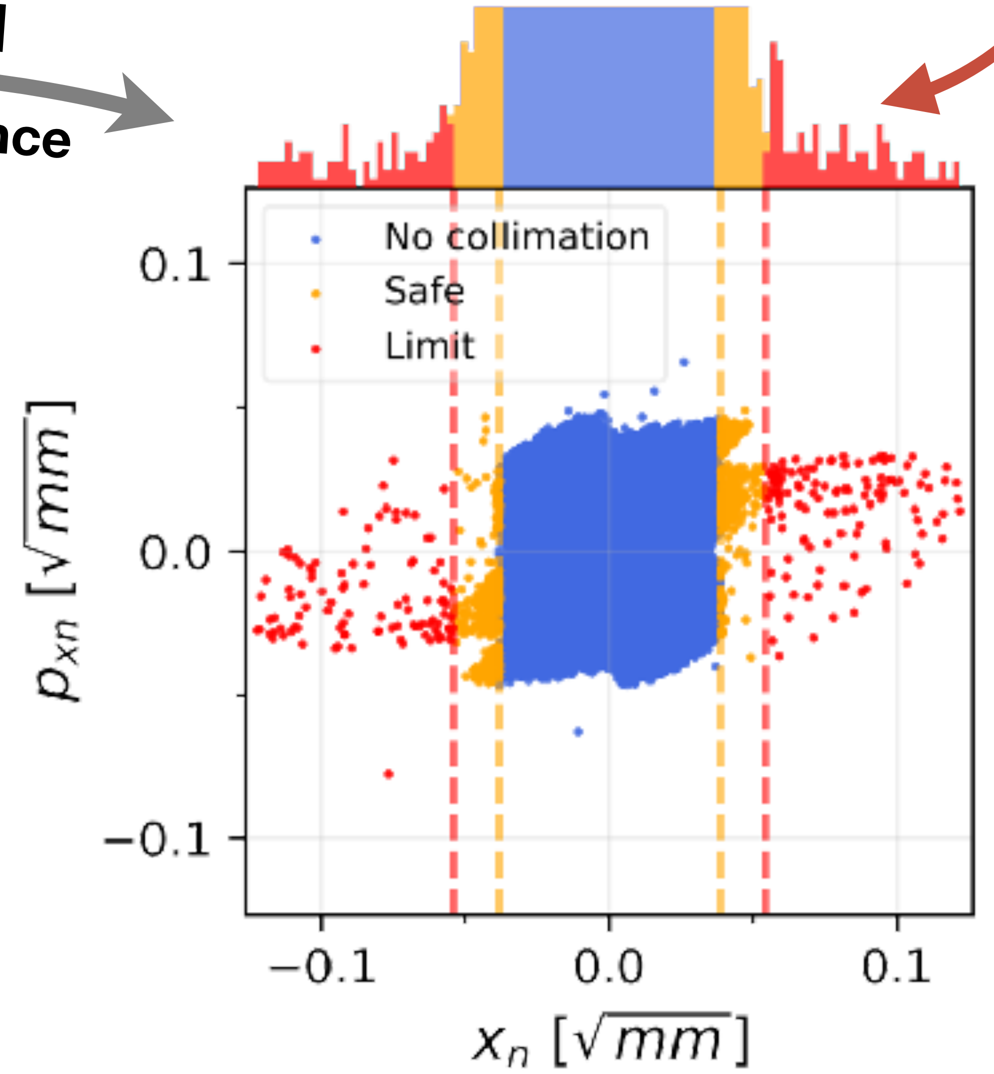
$H_y = 0.47$

$\eta_{\parallel} = 77\,\%$



Correlation between transverse and longitudinal halo

Optimal
phase advance



PERLE project status

04.2026 — HV conditioning up to 350 kV (ongoing) 🔗 WEP5090

04.2026 — CsK_2Sb synthesized, QE = 6.5 % 🔗 THP2102

11.05.2026 First Electrons !!! 2.5 mA (next day in the Faraday cup) 🔗 THP2104

Lattice design & optics

- Single and multi turn operation
- Merger and Arcs with M56 control

Beam dynamics studies

- Longitudinal matching for Single Turn operation ← chirped distribution from the booster + M56 in Merger and Arcs 🔗 WEP5006
- Static misalignments (Booster cavities + Quadrupoles in Merger and 1st turn) → correction scheme 🔗 MOP1110
- Effect of non linear fields 🔗 THP2103
- Halo cleaning and collimation 🔗 WEP5064
- And many other

Thanks for all members of PERLE Collaboration !!!

An-Najah National University: Hadil Abualrob

CERN: Sebastian Calvo, Rama Calaga, Gino Cipolla, Frank Gerigk, Shahnam Gorgi Zadeh, Franck Peauger, Vittorio Parma, Karl Schirm, Calum Sharp, Walter Venturini

ESS-Bilbao: Juan Luis Muñoz

GANIL: Mamadou Faye

IJCLab - IN2P3/CNRS/Université Paris-Saclay: Rasha Abukeshek, Mohammed Ben Abdillah, Sébastien Blivet, Sylvain Brault, Sophie Chance, Arnaud Cieplak, Olivier Dalifard, Victor Dalifard, Mélanie De Vos, Patricia Duchesne, Patxi Duthil, Alex Fomin, Olivier Frossard, Nicolas Gandolfo, Hayg Guler, Janine Issa, Fatematuj Johara, Christophe Joly, Walid Kaabi, Eric Legay, Aurore Lermitage, Samuel Marchal, Aurélien Martens, Bruno Mercier, Julien Michaud, Akira Miyazaki, Daniele Nutarelli, Gilles Olivier, Guillaume Olry, Axel Perez Ruiz, Luc Perrot, Laurent Pinot, Fabien Razafimamonjy, Denis Reynet, Raphael Roux, Hervé Saugnac, Gael Sattonnay, Achille Stocchi, Sandry Wallon, Sébastien Wurth

JLab: Alex Bogacz, Pashupati Dhakal, Rongli Geng, Andrew Hutton, Robert Rimmer, Sadiq Saitiniyazi, Haipeng Wang

Liverpool University - Cockcroft Institute: Angus Jones, Carsten P Welsch, Connor Monaghan, Hao Zhang, Joseph Wolfenden

LPSC - IN2P3/CNRS: Julien Angot, Maud Baylac, Frédéric Bouly, Emmanuel Froidefond, Yolanda Gomez Martinez, Etienne Labussière, Adrien Placais

STFC UKRI: Deepa Angal-Kalinin, Lee Jones, Boris Militsyn, Hywel Owen, Peter Williams

University of Lancaster: Rob Apsimon, Graeme Burt, Amos Dexter, Harry Marks, Ian Bailey

Do NOT Miss !

PERLE Contributions:

Beam Dynamics

- MOP1110 Linear imperfection and orbit correction scheme for the PERLE accelerator (R. Abukeshek)
- WEP5006 Ongoing studies of longitudinal matching for the PERLE accelerator (J. Issa)
- WEP5064 Halo cleaning and collimator optimization at PERLE (A. Cieplak)
- THP2103 Assessing Corrector-Integrated Quadrupoles for PERLE (A. Fomin)

Injection line

- WEP5089 HOM study of the PERLE's booster cavity (R. Roux)
- WEP5090 Status of the PERLE's injector (R. Roux)
- THP2104 High current photogun for the energy recovery linac PERLE (M. Baylac)
- THP2102 High quantum efficiency alkali-antimonide photocathodes for PERLE high current DC gun (M. De Vos)

Sustainability

- MOP7179 Power Balance of the PERLE Energy Recovery Linac (F. Bouly)

RF systems

- MOP7022 Dielectric Characterization of Beam Line Absorber Samples for Next-Generation High Intensity Electron Beam SRF Accelerators (A. P. Ruiz)
- WEP6126 RF coupling choices, power requirements, and their impact on transients in the PERLE energy recovery linac (F. Bouly)
- WEP6146 RF system status for PERLE (F. Bouly)

Diagnostics

- WEP6035 Overview of Beam diagnostics for PERLE (M. B. Abdillah)
- WEP6036 Beam positions monitors for PERLE (M. B. Abdillah)

Thank you

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