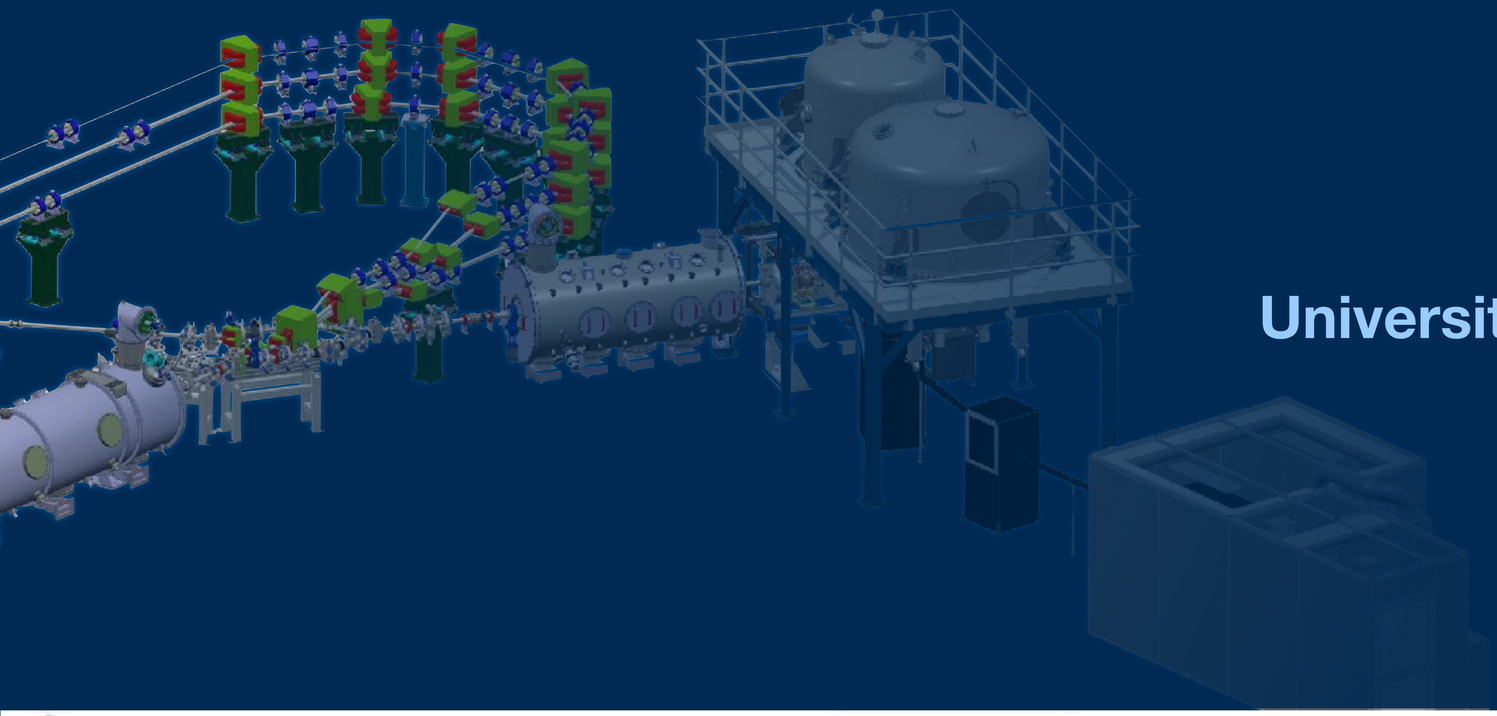
Powerful Energy Recovery LINAC for Experiments (PERLE) at IJCLab



Alex Fomin

Université Paris-Saclay, CNRS/IN2P3, IJCLab

On behalf of the PERLE Collaboration

Outline

Introduction

- ERL concept
- Main objectives of PERLE
- Project status

Optics matching & solution search

- Single- and three-turn configurations
- Common section: basic solution and extra freedom
- Systematic search for matching solutions
- Compact merger: constraints and space-charge compensation
- Turnaround loops: Top / Mid / Bot

New optics flexibility & diagnostics

- Straight section:
  transverse and longitudinal phase control
- Mirror Diagnostic Line:
  longitudinal phase-space measurement

Summary





Why ERLs ?

Linear colliders:

✓ **excellent beam quality (fresh beam)**

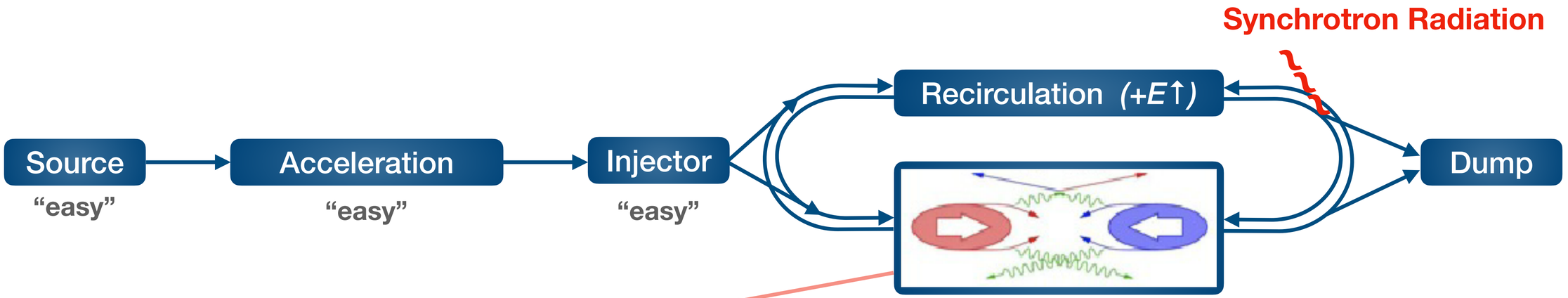
✗ low luminosity (single pass)



Linear colliders: ✓ excellent beam quality (fresh beam) ✗ low luminosity (single pass)

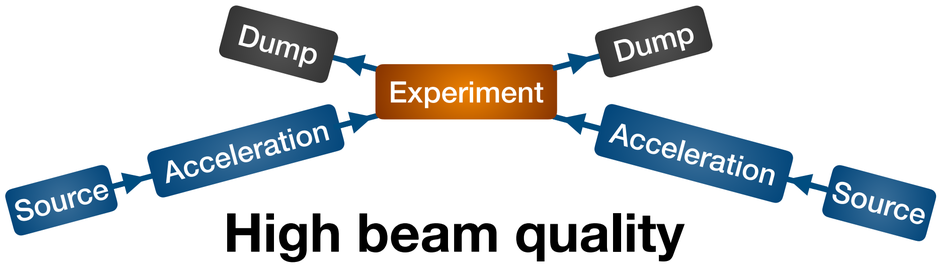


Storage rings: ✓ better luminosity ✗ e^- beams degradation due to collisions



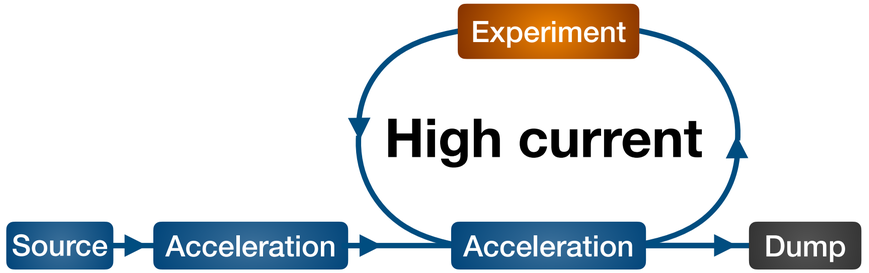
Beamstrahlung: ***LEP:*** ***30 min,*** $L_0 = 10^{32}\ cm^{-2}s^{-1}$ ***vs*** ***LHC:*** ***10 hours,*** $\langle L_0 \rangle \sim 10^{34}\ cm^{-2}s^{-1}$

Linear colliders

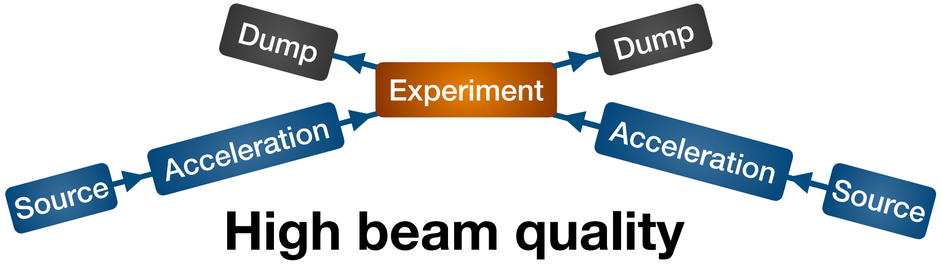


High beam quality

Circular colliders

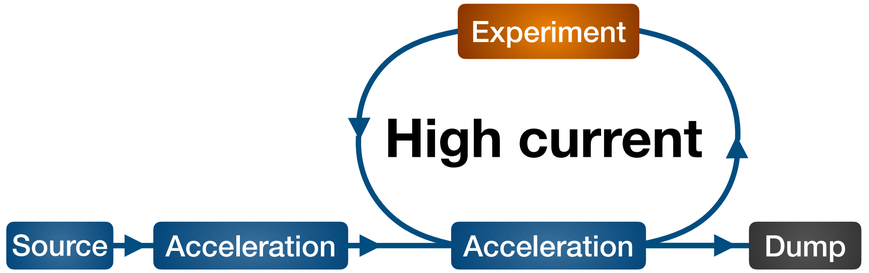


Linear colliders



High beam quality

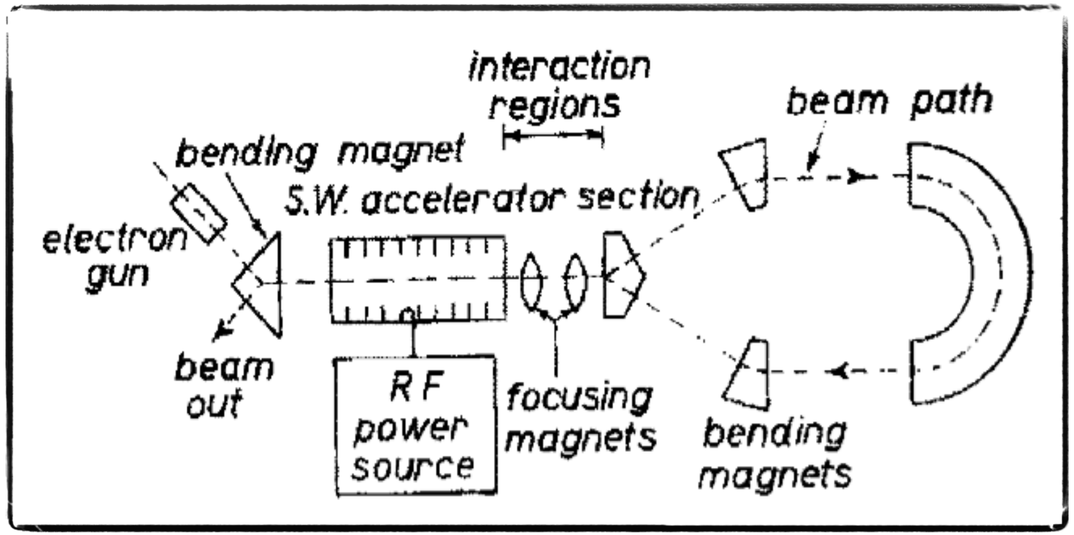
Circular colliders



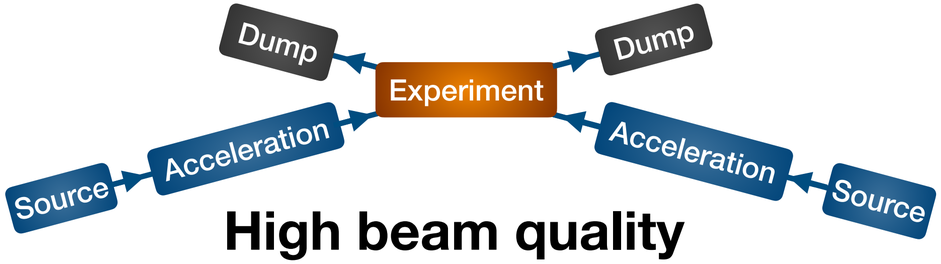
Energy Recovery Linac

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.

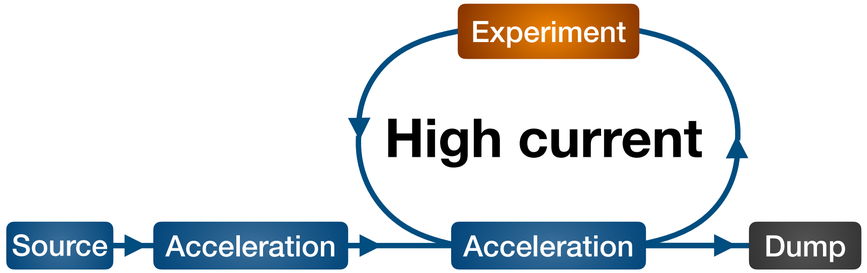


Linear colliders



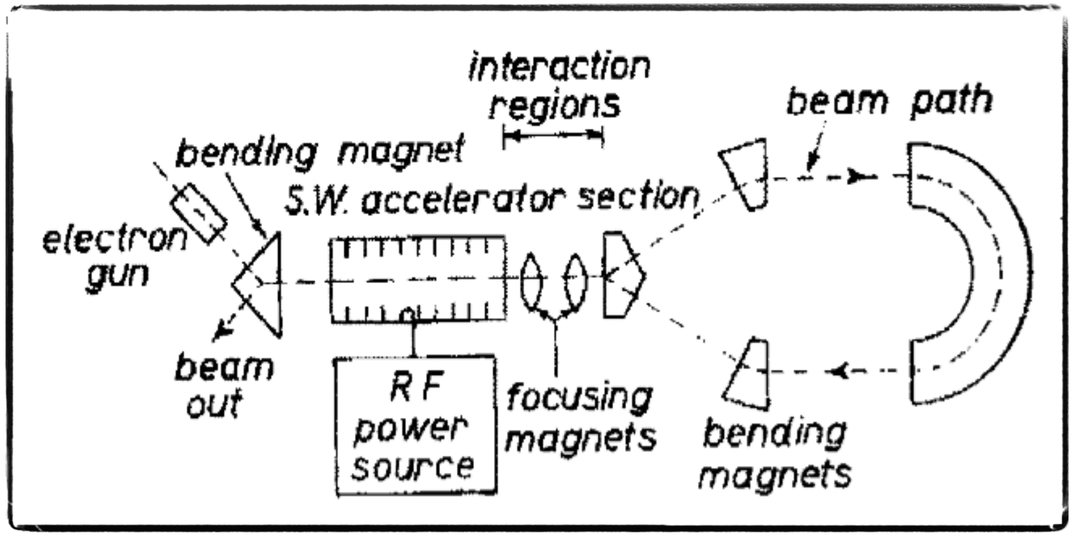
High beam quality

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Energy Recovery Linac

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



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

Applications:

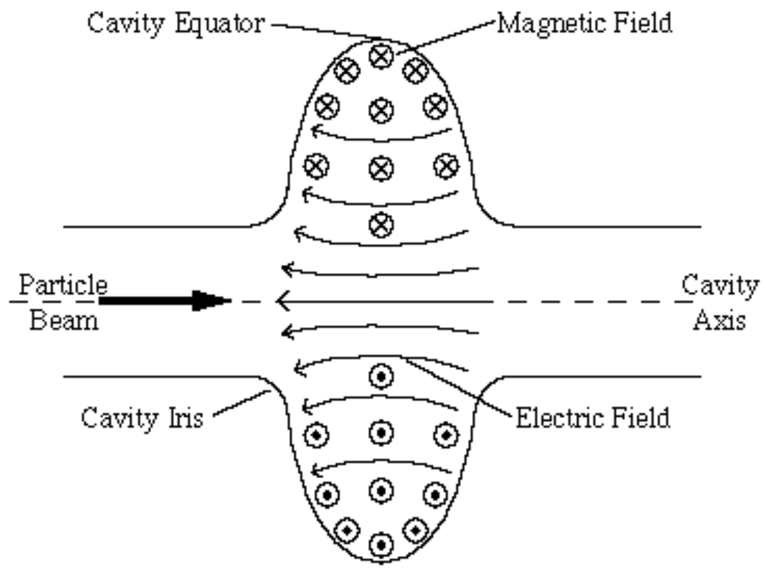
- FELs
- Lepton colliders
- Nuclear physics

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.

How does Energy Recovery works

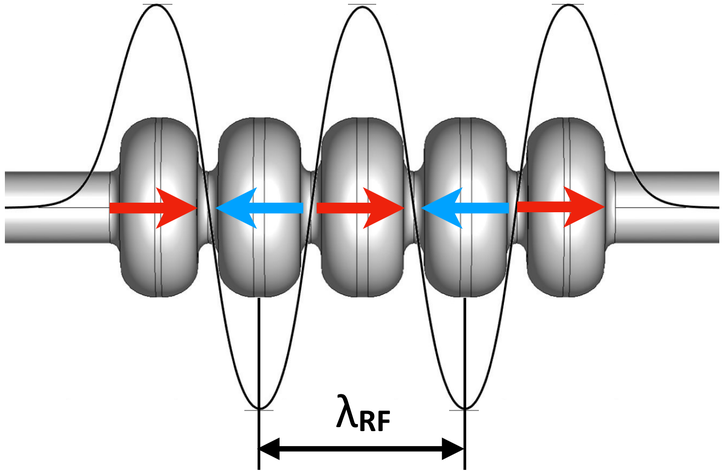
Acceleration in an RF cavity via Standing Wave

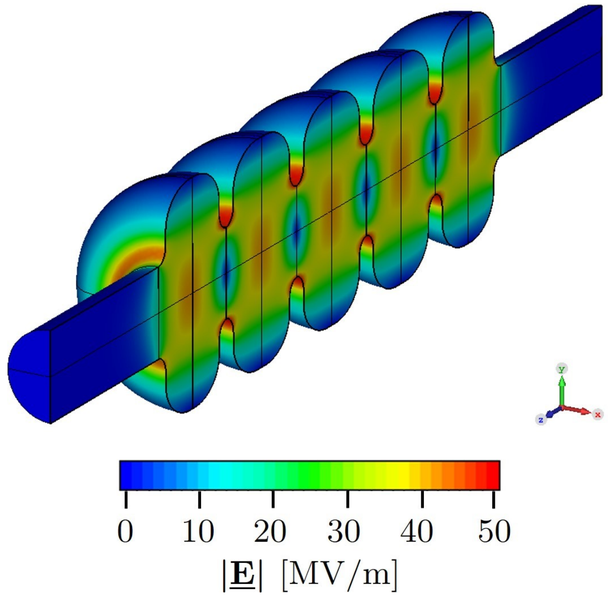


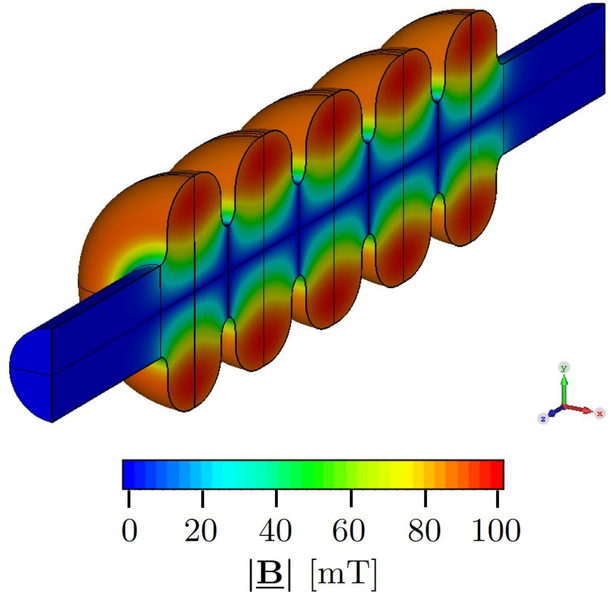
RF cavity — a metal resonator that sustains a standing E-M wave:

- electric field — aligned along the beam axis to accelerate particles
- magnetic field — circulates around that axis

Accelerating and decelerating field in the cavity





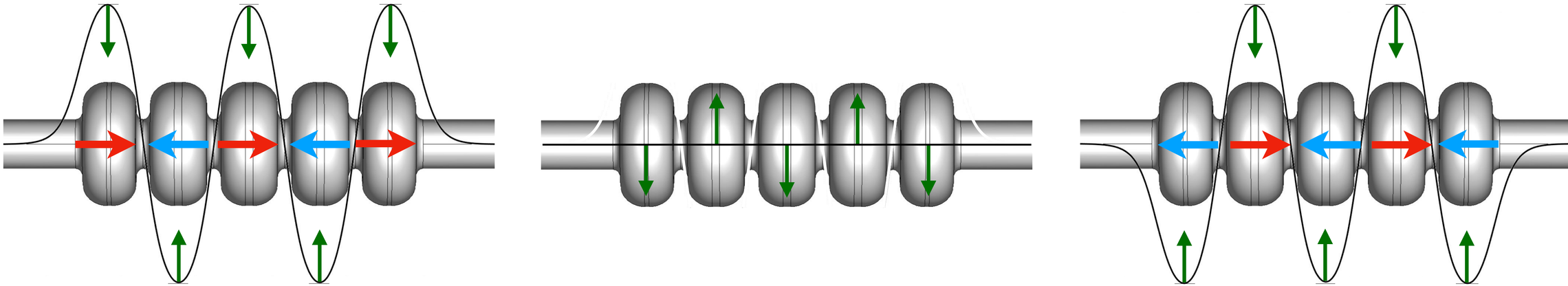


λ_{RF} — wave length ($\lambda_{RF} = c / f_{RF}$) can be from **~1mm** to **~1m**

Acceleration in an RF cavity via Standing Wave

$E(z, t) = E(z)\cos(\omega t) \quad \omega t \equiv \phi$

$\phi = 0$ $\phi = \pi/2$ $\phi = \pi$



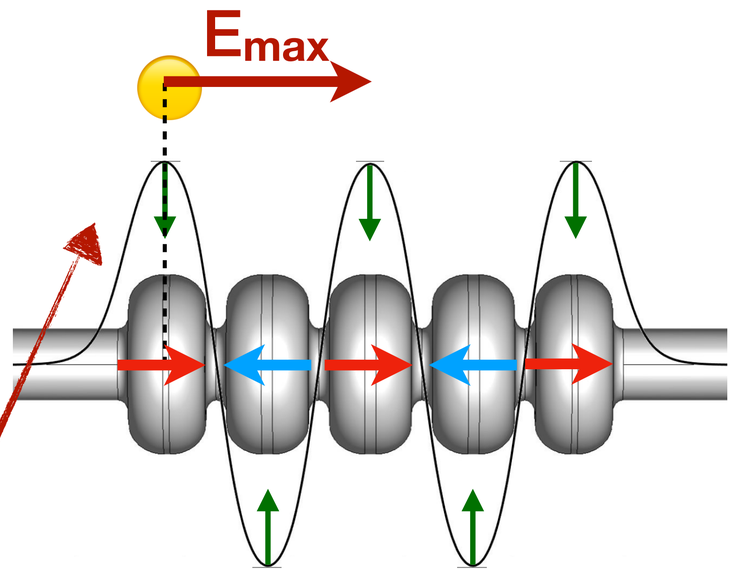
$E = E_{max}$ $E = 0$ $E = E_{max}$

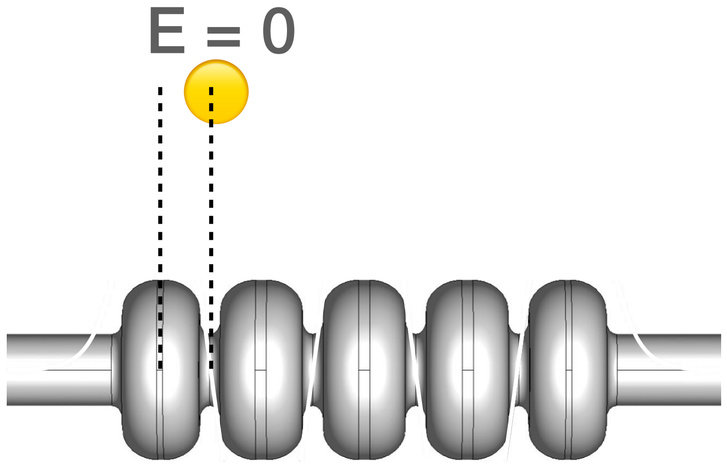
Acceleration in an RF cavity via Standing Wave

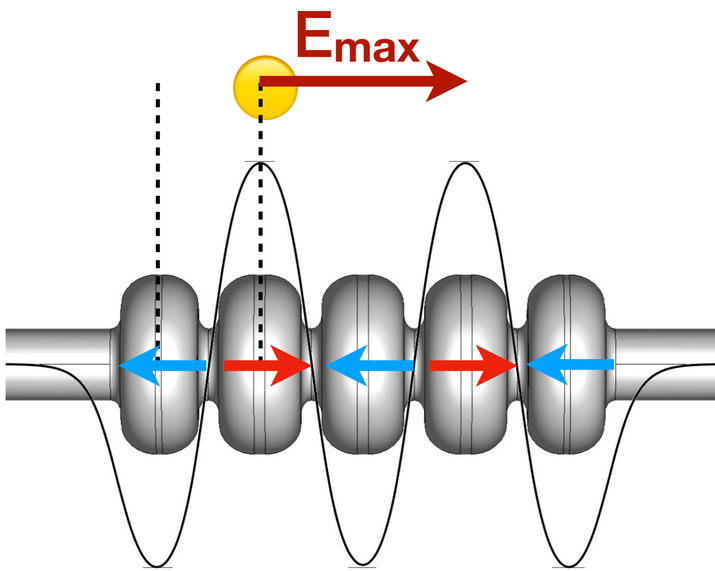
$E(z, t) = E(z)\cos(\omega t)$ $\omega t \equiv \phi$

$\phi = 0$ $\phi = \pi/2$ $\phi = \pi$

$z_0 = 0$







Acceleration on crest

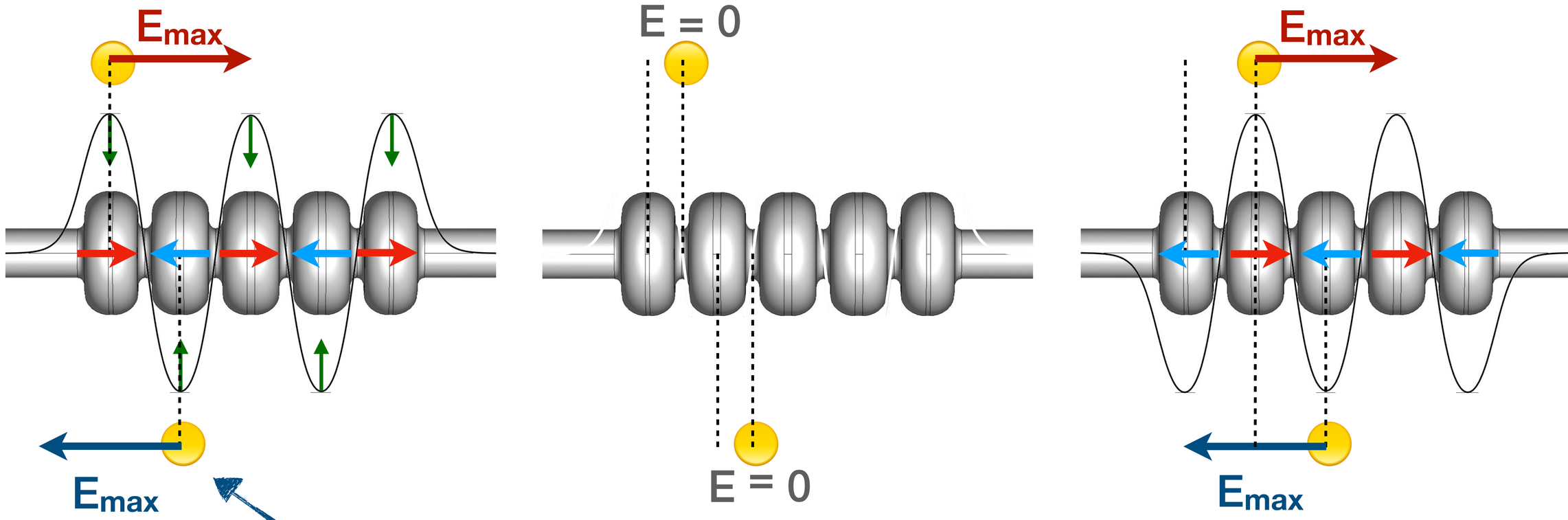
Acceleration in an RF cavity via Standing Wave

$E(z, t) = E(z)\cos(\omega t)$ $\omega t \equiv \phi$

$\phi = 0$ $\phi = \pi/2$ $\phi = \pi$

$z_0 = 0$

$z_0 = \lambda_{RF}/2$



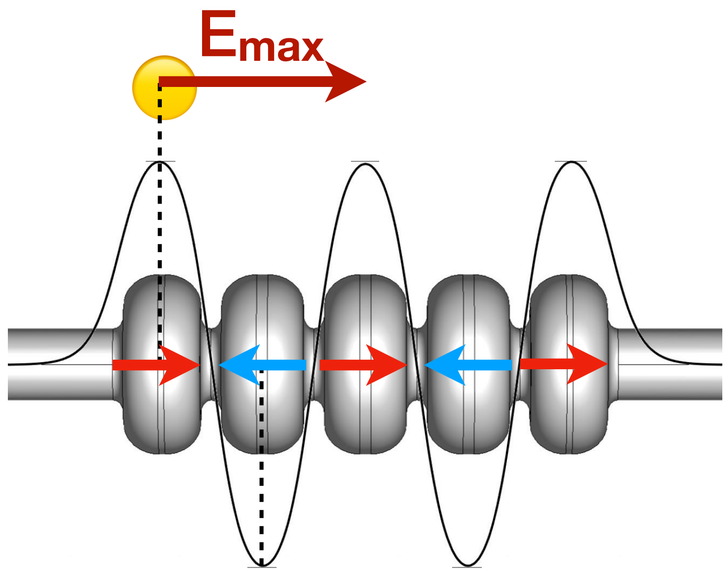
deceleration

$\lambda_{RF} = c / f_{RF} \approx 3\ 10^8$ m/c / 800 MHz = 37.5cm

Acceleration in an RF cavity via Standing Wave

RF cavity — a metal resonator that sustains a standing E-M wave

$z_0 = 0$



$z_0 = \lambda_{RF}/2$

Emax

deceleration

Lorentz equation:

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B} = \vec{F_E} + \vec{F_B}$$

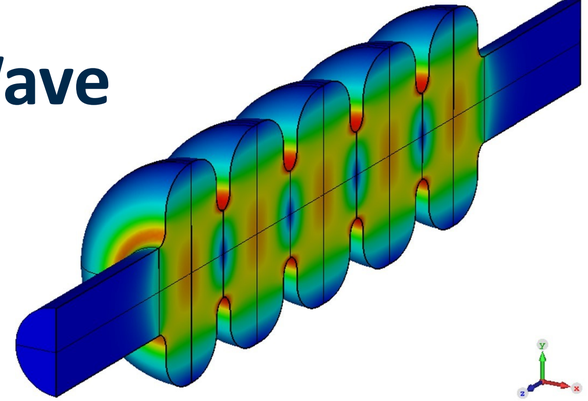
Acceleration — work of the electromagnetic Force

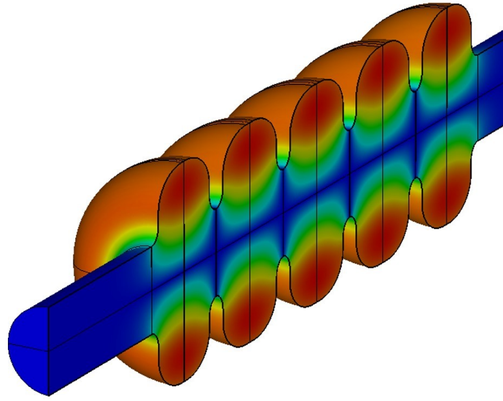
$$\Delta W = \int_{t_{in}}^{t_{out}} \delta W \, dt, \qquad \delta W = \vec{F}_{\text{elec}} \cdot \vec{v} \, dt = q\vec{E} \cdot \vec{v} \, dt$$

the goal of PERLE: $P = \Delta E \, I = 250 \text{ MeV } 20 \text{ mA} = \mathbf{5 \text{ MW}}$

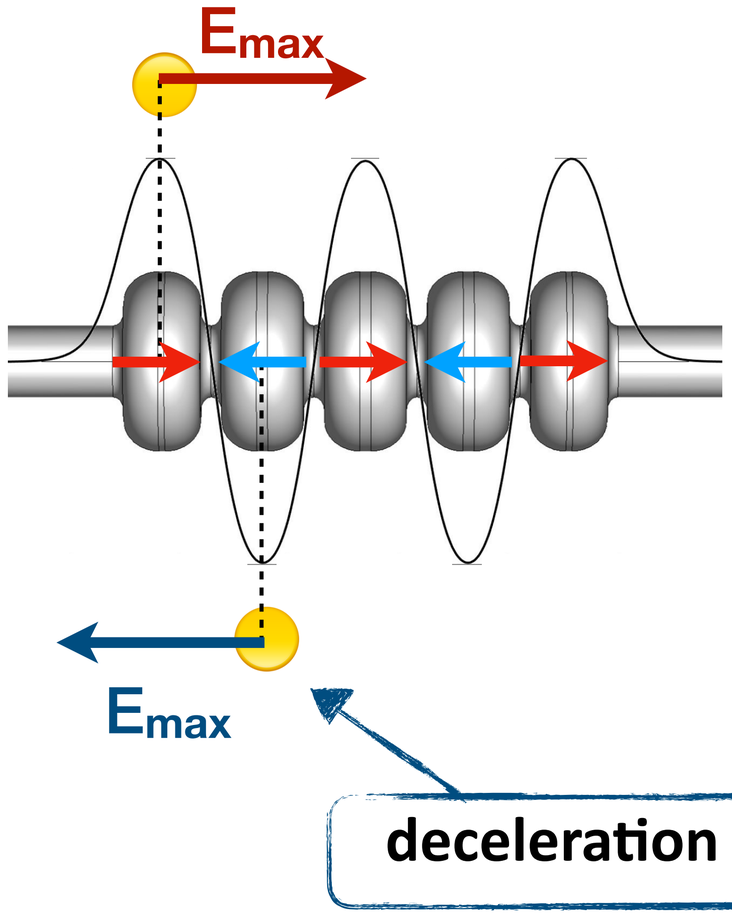
Acceleration in an RF cavity via Standing Wave

RF cavity — a metal resonator that sustains a standing E-M wave





$z_0 = 0$



$z_0 = \lambda_{RF}/2$

deceleration

Acceleration — work of the electromagnetic Force

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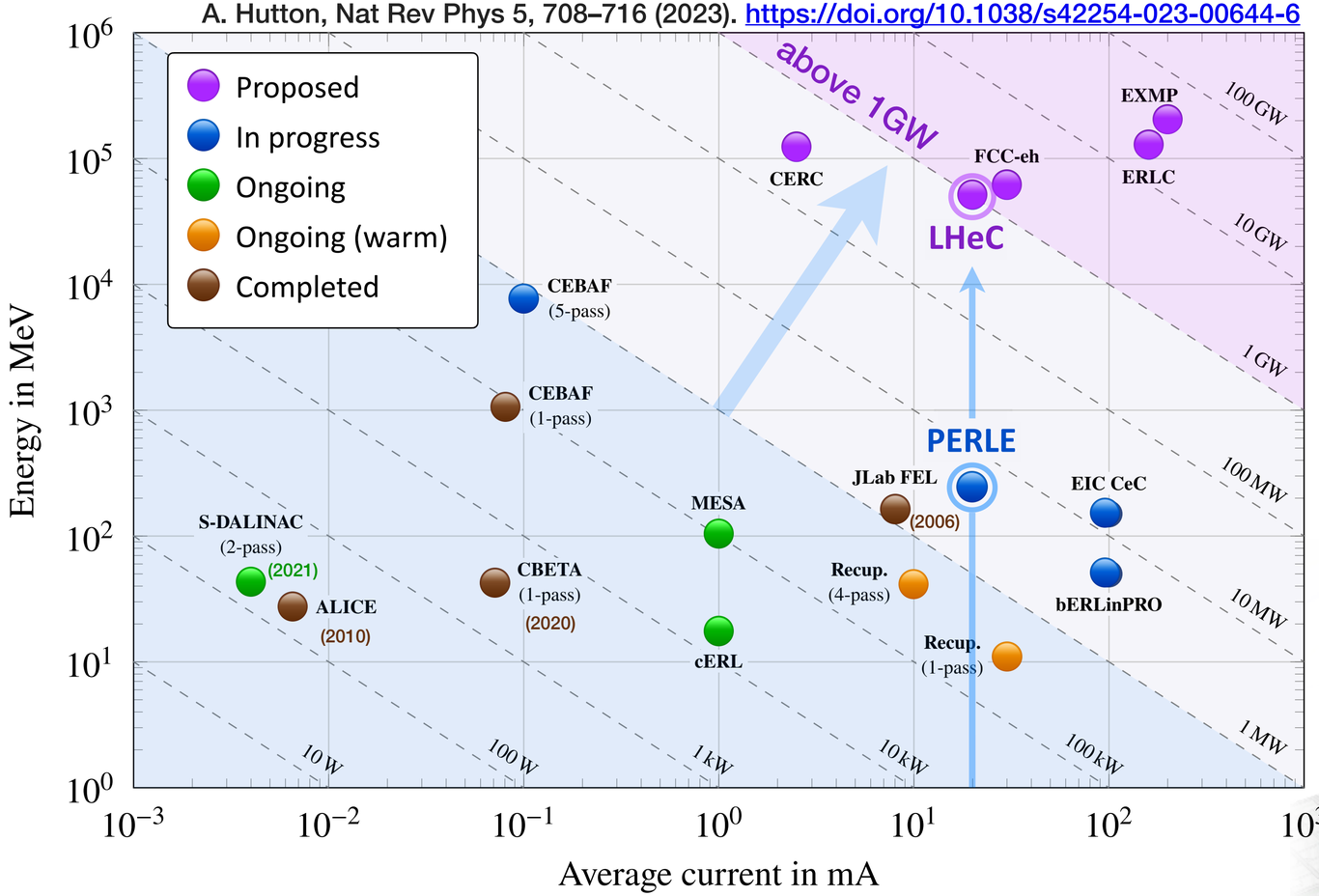
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Bunch energy → Wake fields → E-M wave

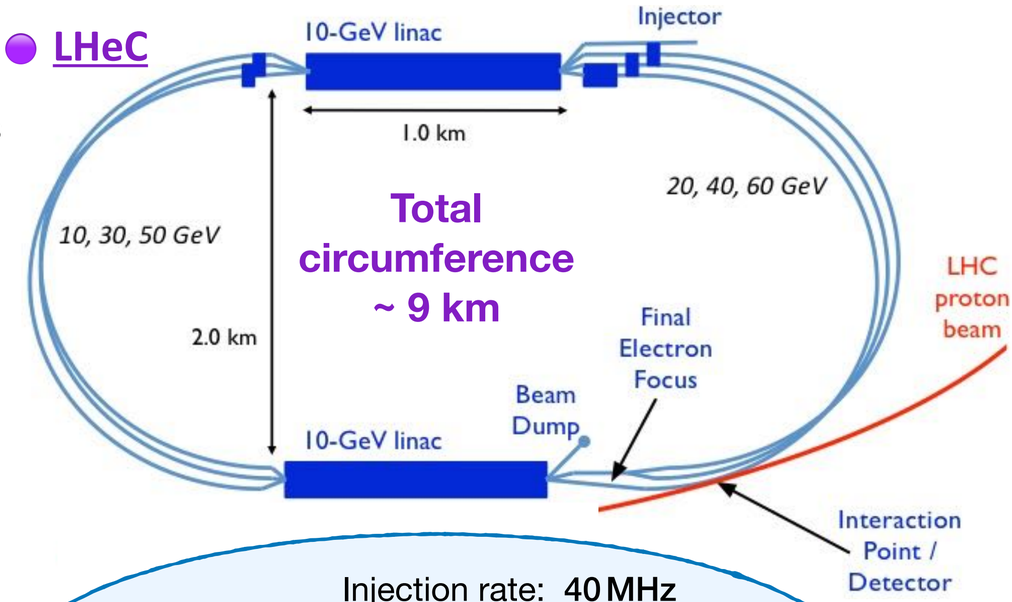
PERLE main objectives:

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



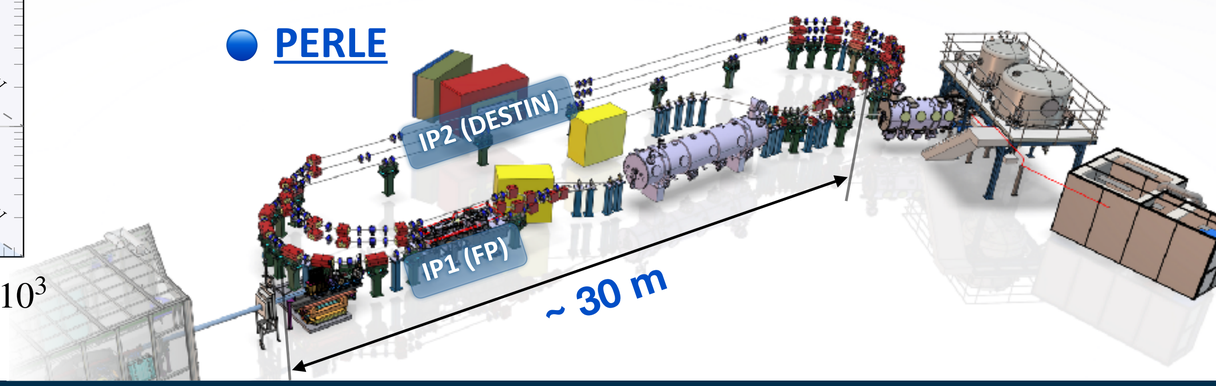
LHeC



The same bunch parameters

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

PERLE



PERLE — Powerful Energy Recovery LINAC for Experiments

06.2012 — First Idea (Erk Jensen and Rama Calaga)

Test Facility → ERL injector of LHeC ERL

08.2012 — First Lattice Design (Alex Bogacz)

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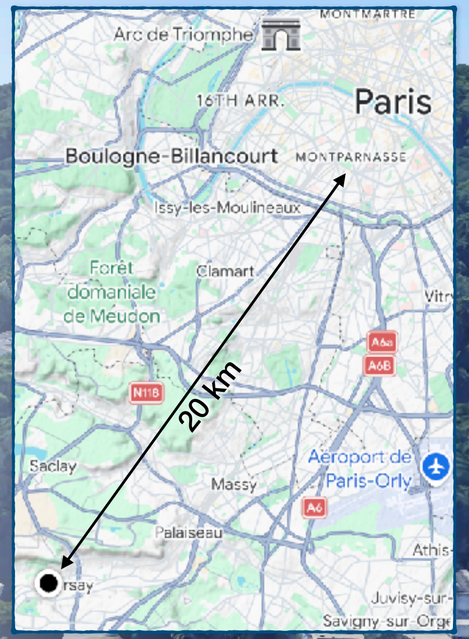
06.2015 — Powerful ERL for Experiments

10.2016 — PERLE at Orsay (Achille Stocchi and Max Klein)

05.2017 — Conceptual Design Report

Implantation in IGLOO building







PERLE status

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03.2024 — Start of building phase

04.2026 — HV conditioning up to 350 kV (ongoing)

- WEP5090 (R. Roux)

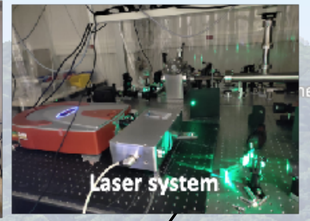
04.2026 — CsK_2Sb synthesized, QE = 6.5%

- THP2102 (M. De Vos)
- THP2104 (M. Baylac)

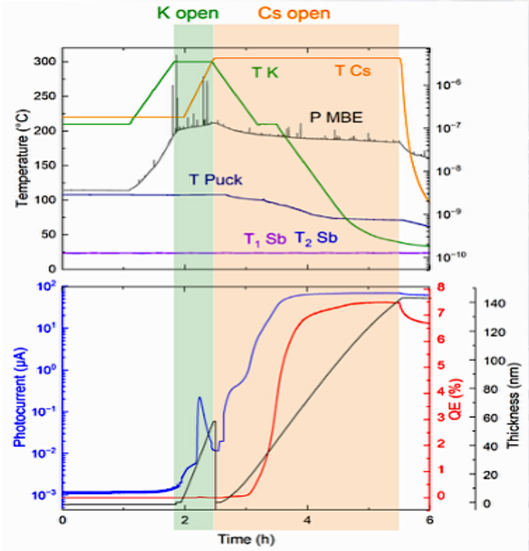














This work received government funding managed by the Agence Nationale de la Recheche (ANR) in the France 2030 framework - reference ANR-24-RRII-0001

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🔗 WEP5090 (R. Roux)

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🔗 THP2102 (M. De Vos)

11.05.2026 First Electrons !!!

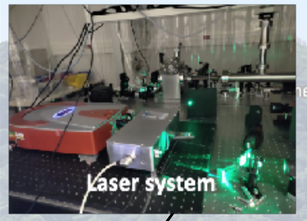
🔗 THP2104 (M. Baylac)

Next day — 2.5 mA (in the Faraday cup)

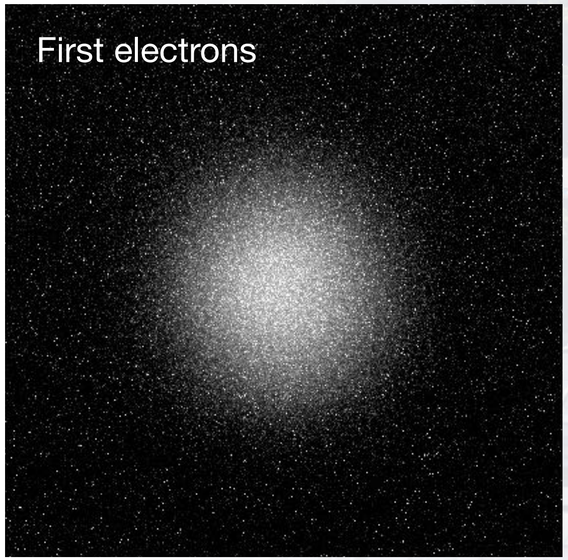














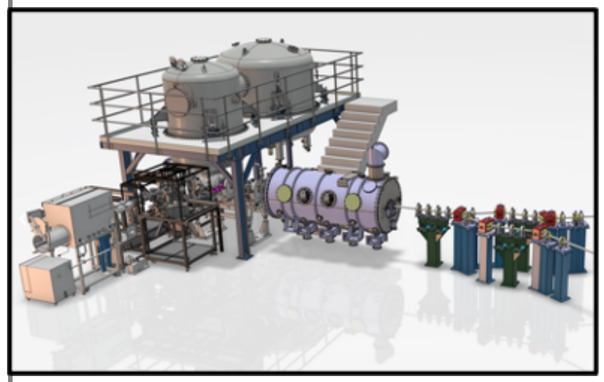
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PERLE in a nutshell

Main target parameters:

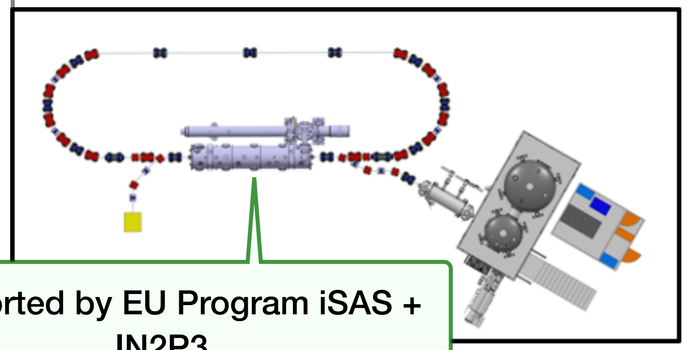
Injection energy	7 MeV
Electron beam energy	250 MeV
Normalised Emittance	6 mm mrad
Average beam current	20 mA
Bunch charge	500 pC
Bunch length	3 mm
Bunch spacing	25 ns
RF frequency	801.58 MHz
Duty factor	CW

Phase 1: Injector Line



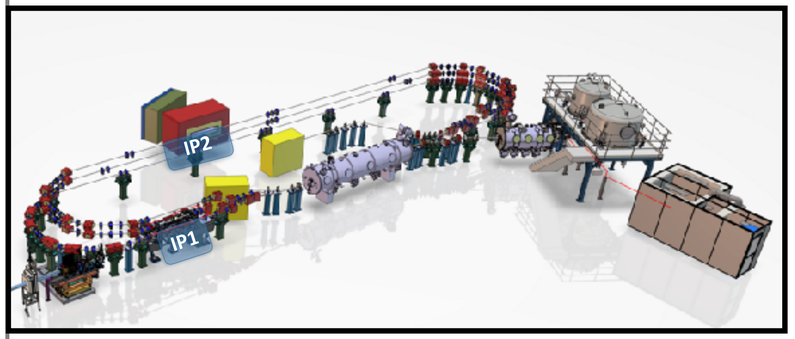
Supported by National Program France 2030 / ANR

Phase 2: PERLE Single Turn



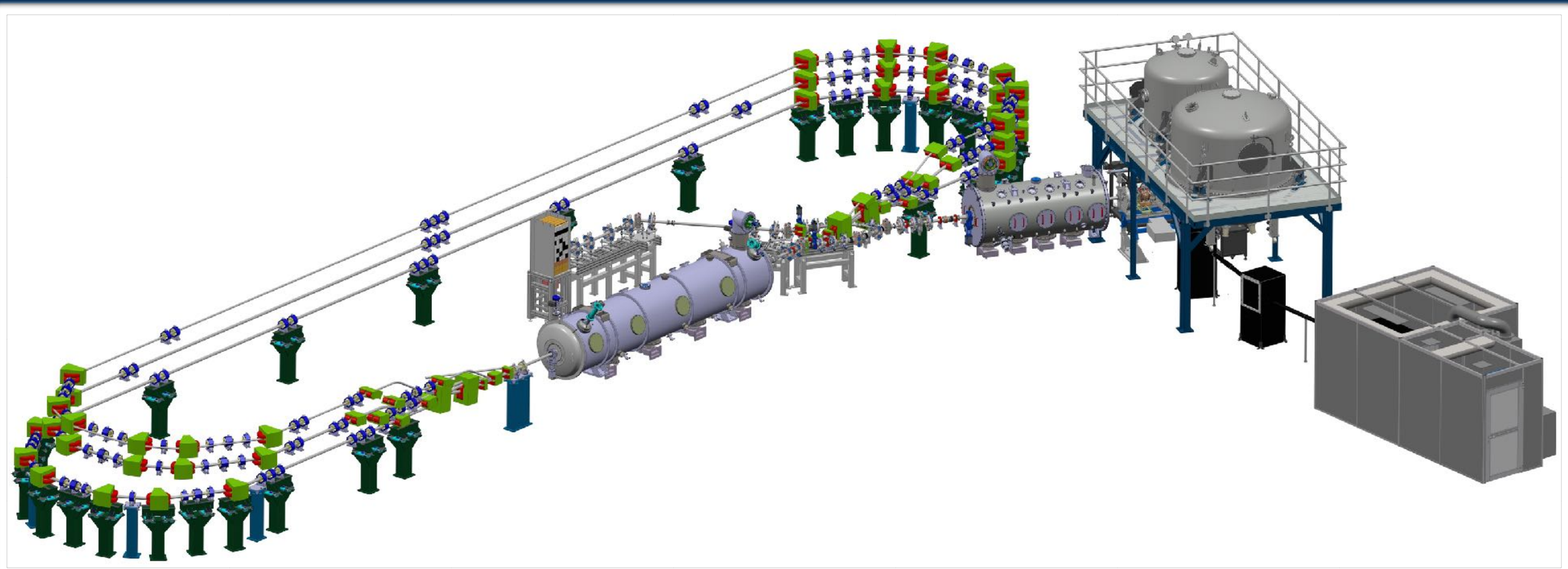
Supported by EU Program iSAS + IN2P3

Phase 3: PERLE 250 MeV

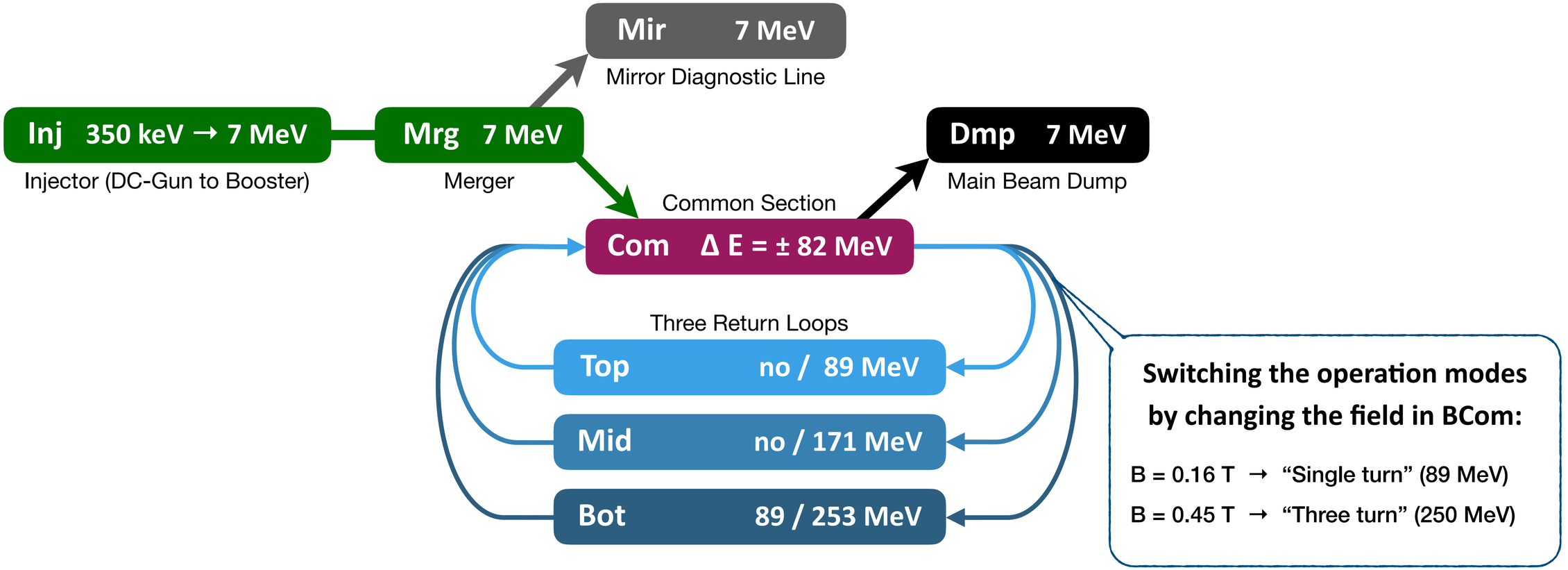


TDR and Prototyping Phase

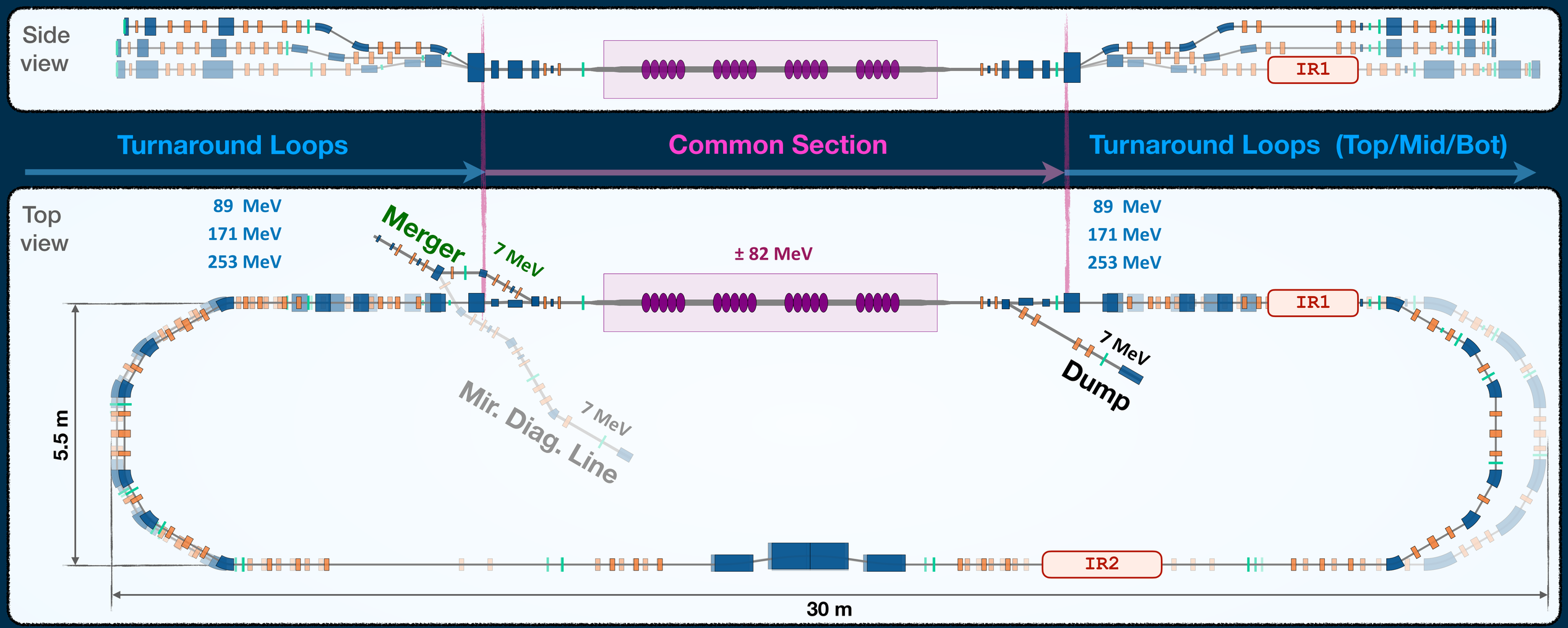
2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031



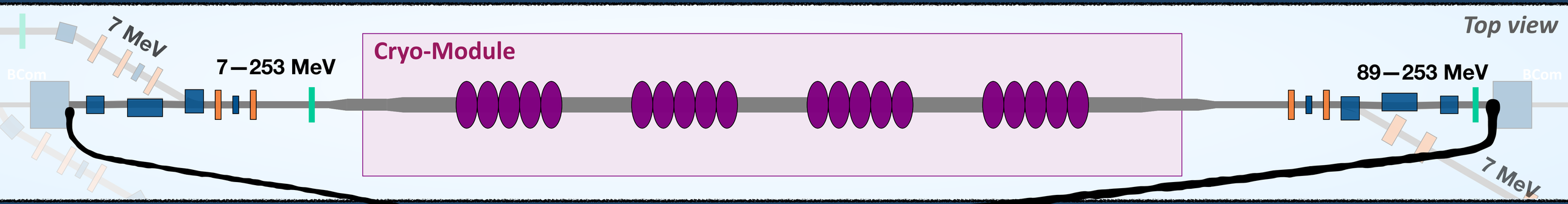
Single Turn & Three Turn configurations

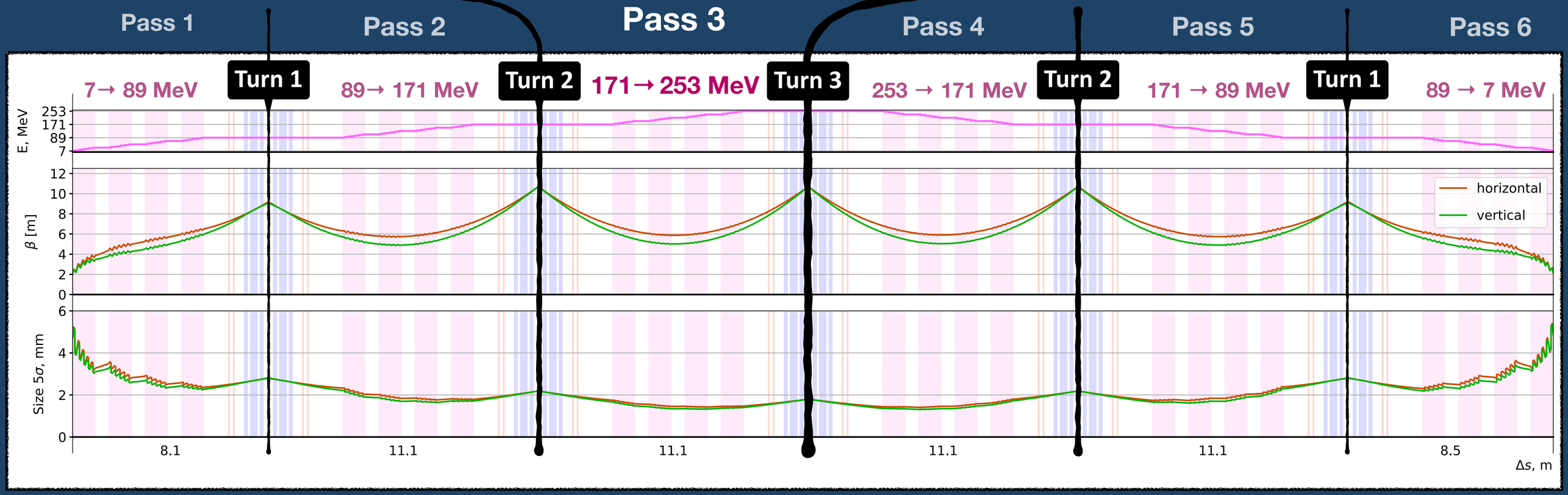


Three Turn configuration layout — 6 passes (↑↑↑↓↓↓)

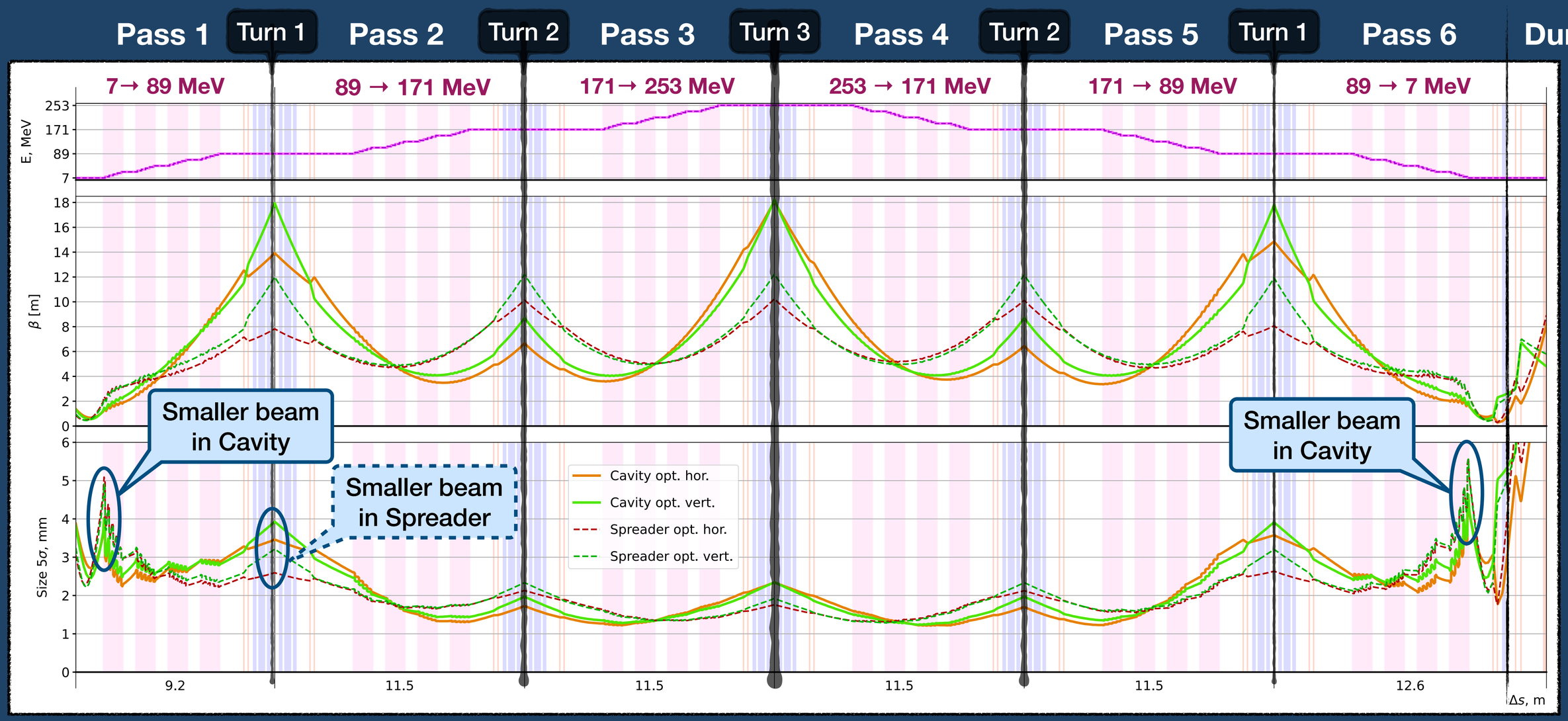


Optics matching. Turn = twiss reflection. Common section - basic solution



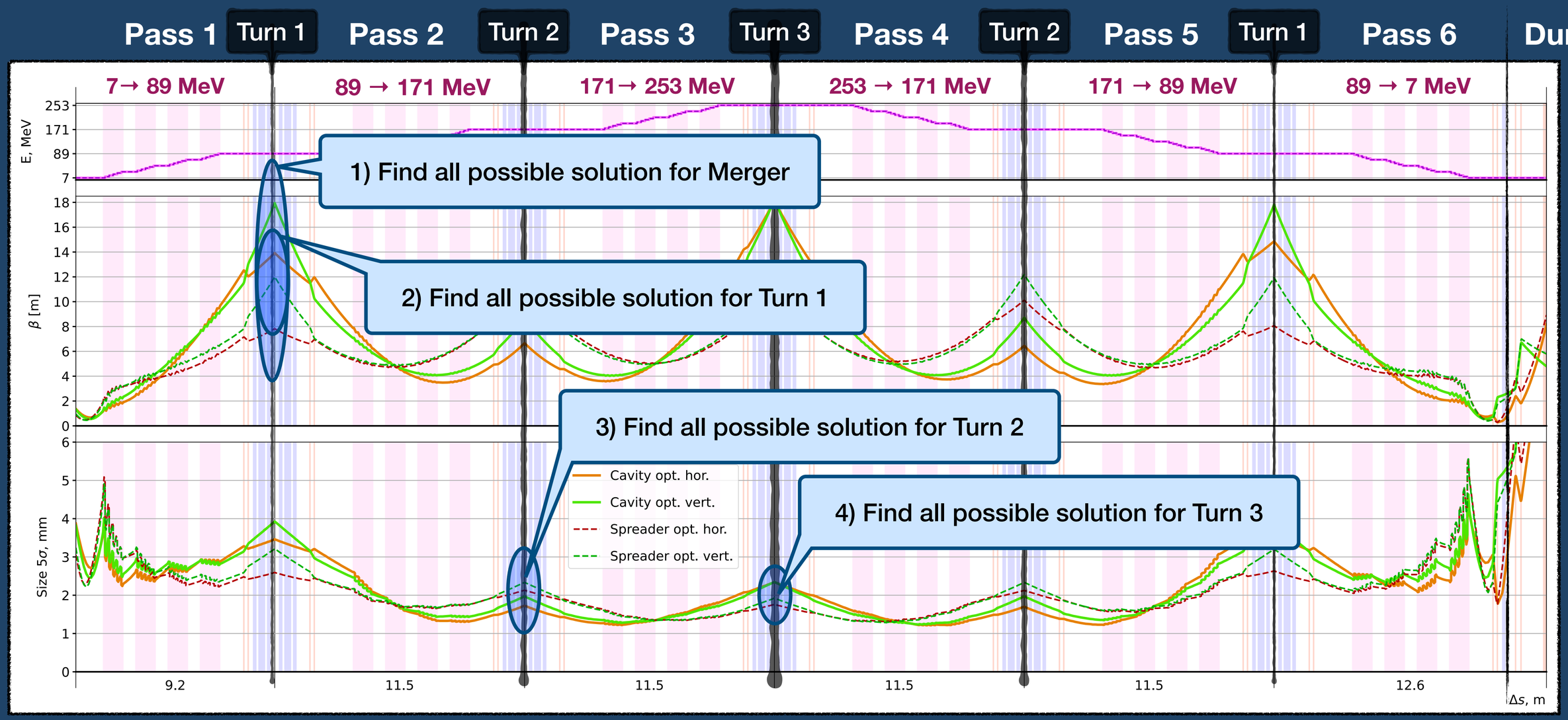


Optics matching. Turn = twiss reflection. Common section - extra freedom



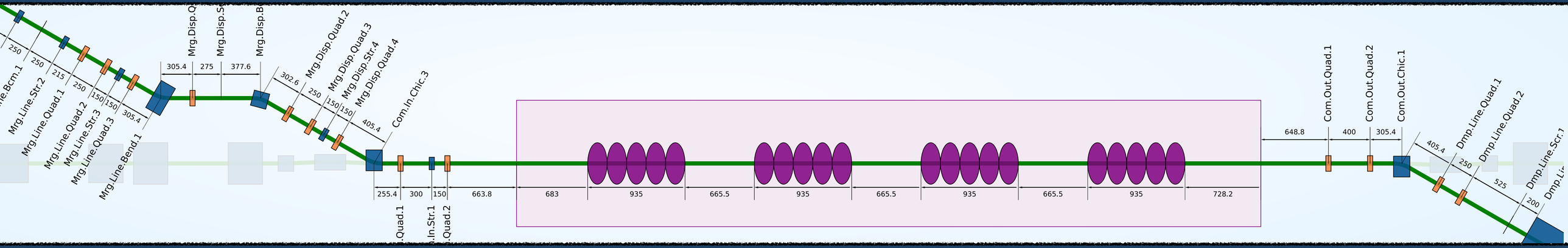
Tuning the twiss parameters at injection → beam size optimisation in the Cavities or in the Spreader

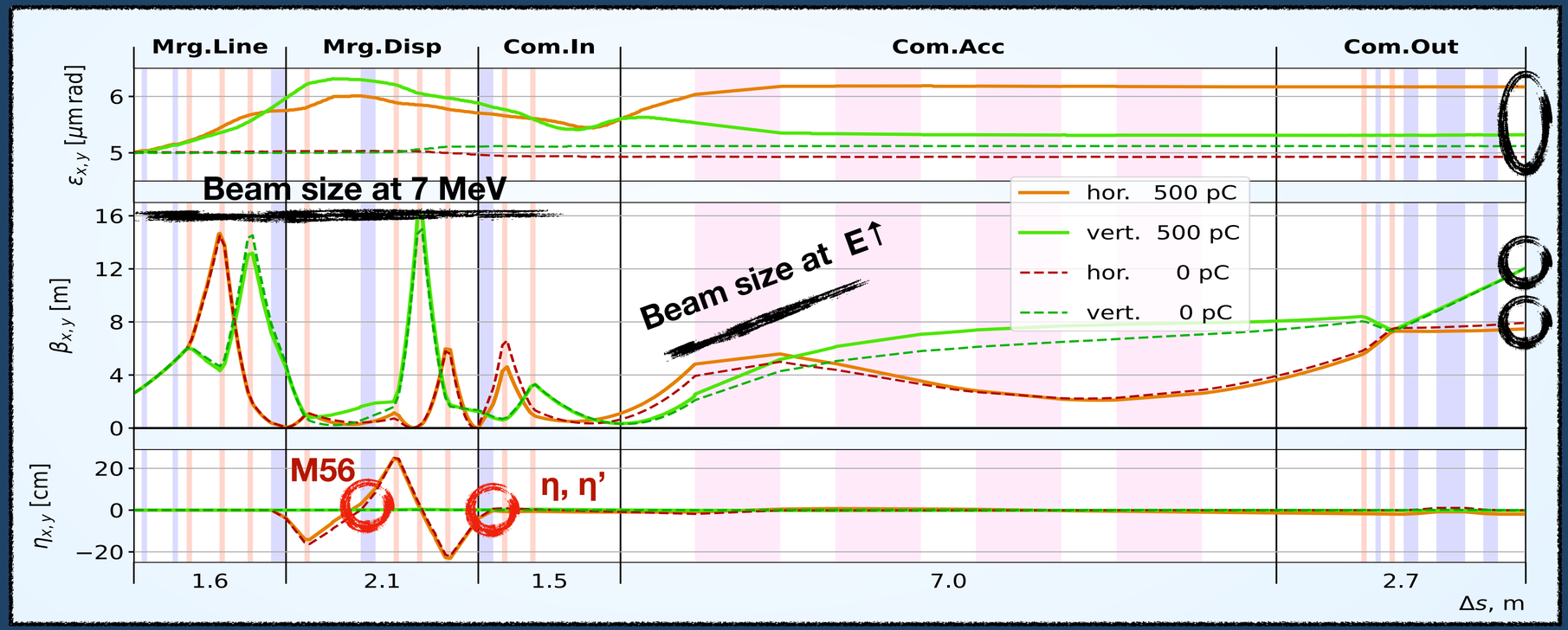
Optics matching. Turn = twiss reflection. Search for all solutions



Find all possible solution (with necessary constrains) for Merger, Turns 1, 2 and 3

Optics matching. 3-dipole merger. Space-charge compensation





Merger space-charge dominated

(> 100 pC @ 7 MeV)

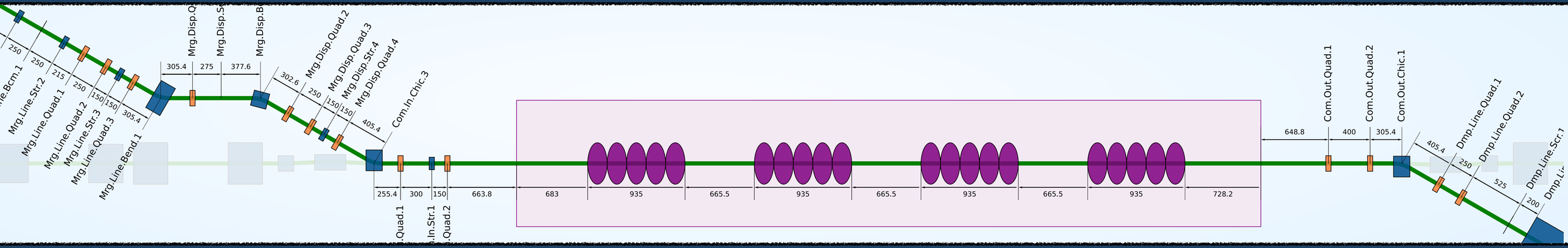
Matching with tracking Bmad ~1h

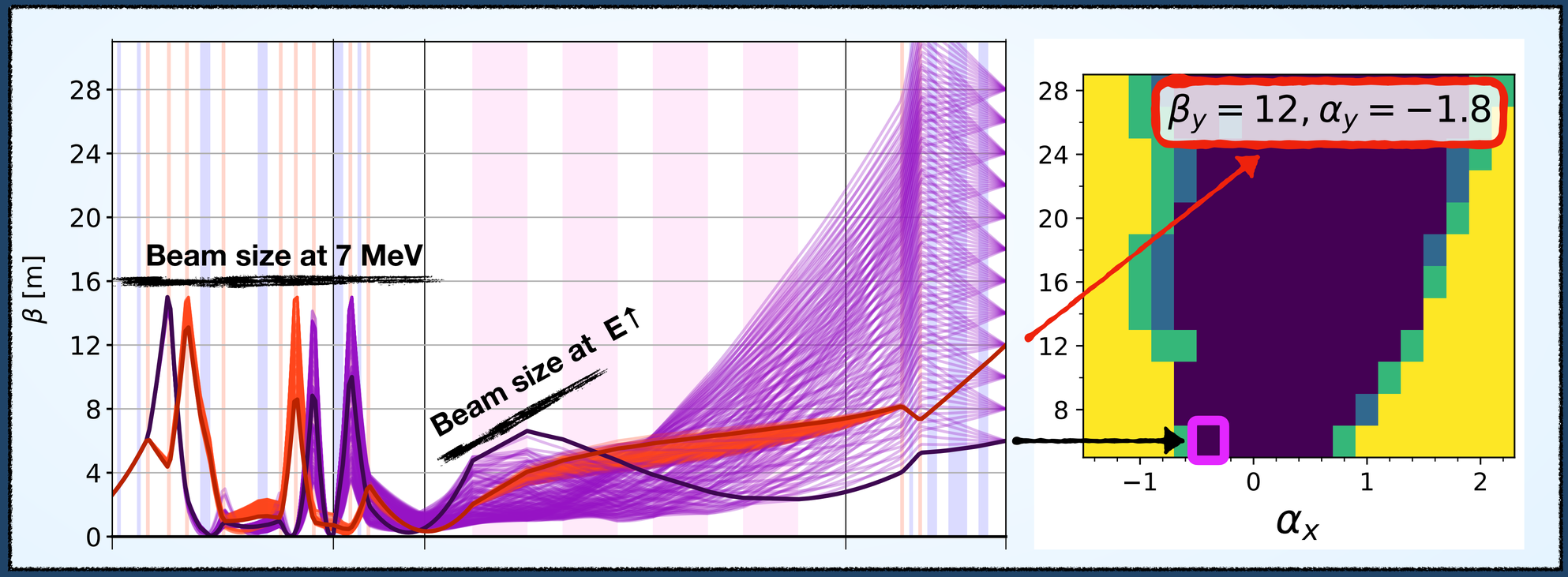
|G| ↑ ~ 9 % in four quads

G correction < 3 % in the rest five

Symmetric quads in Com.Out

Optics matching. Merger + 1st acceleration. Solution search





Solution search

Beam size + disp. + M56

+

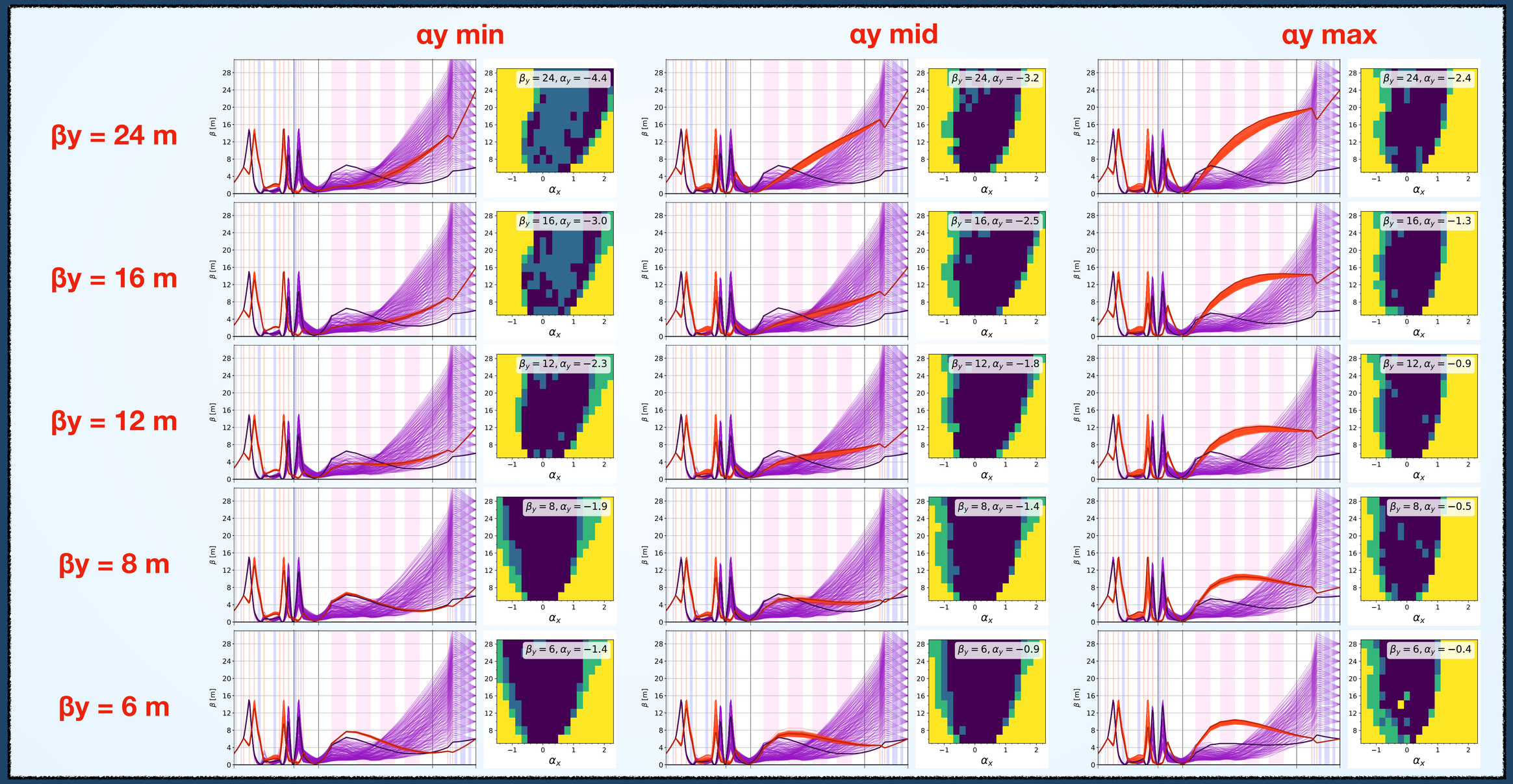
Scanning final twiss:

βx, βy, αx, αy

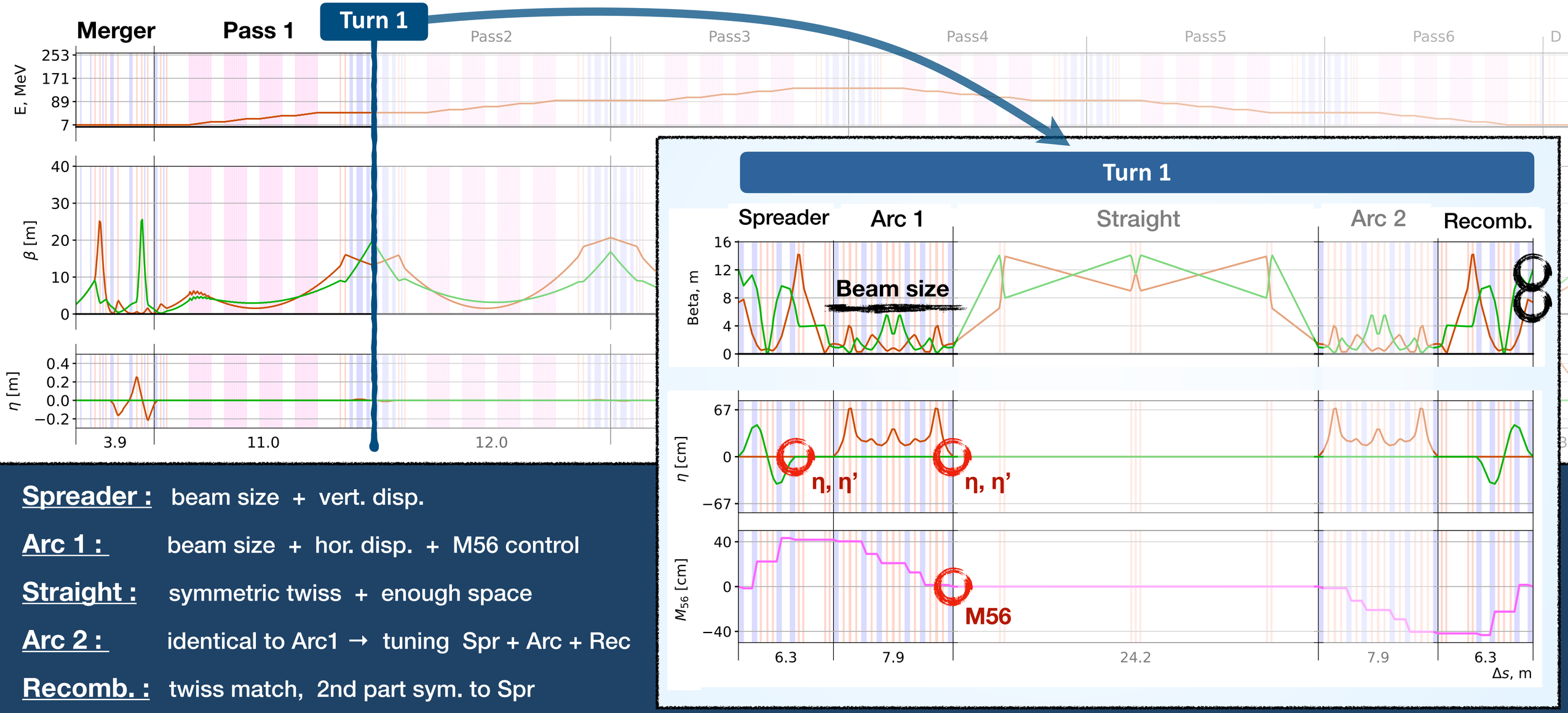
Multiple pass scan:

using neighbor init. tune

Optics matching. Merger + 1st acceleration. Solution search (4D)



Optics matching. Turn 1 (Spreader + Arc 1 + Recombiner)



Spreader : beam size + vert. disp.

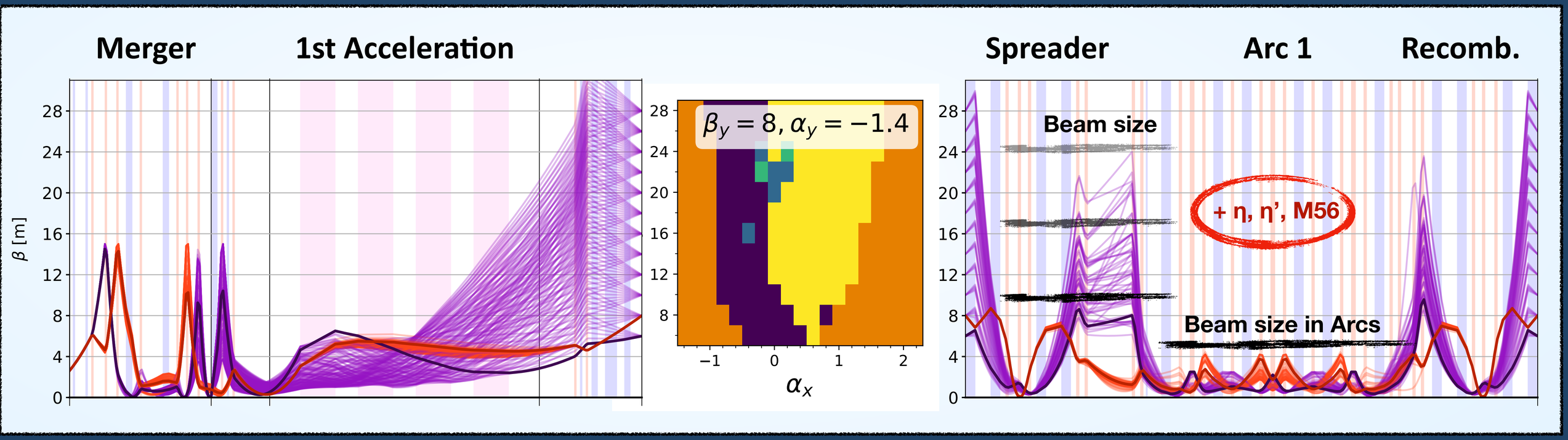
Arc 1 : beam size + hor. disp. + M56 control

Straight : symmetric twiss + enough space

Arc 2 : identical to Arc1 → tuning Spr + Arc + Rec

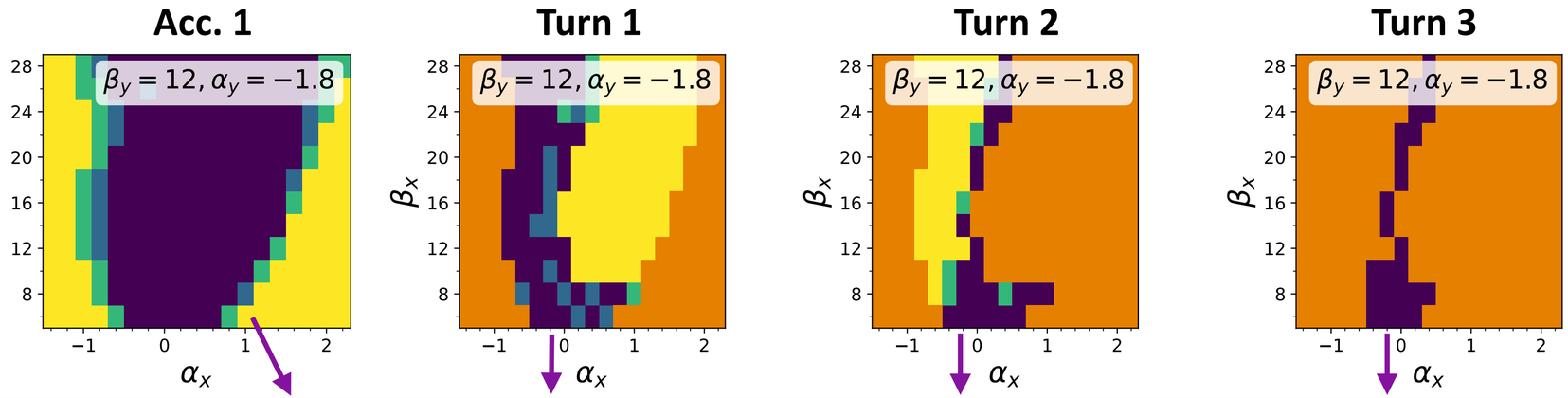
Recomb. : twiss match, 2nd part sym. to Spr

Optics matching. First turnaround loop (Top). Solution search



Low β solutions are prioritized

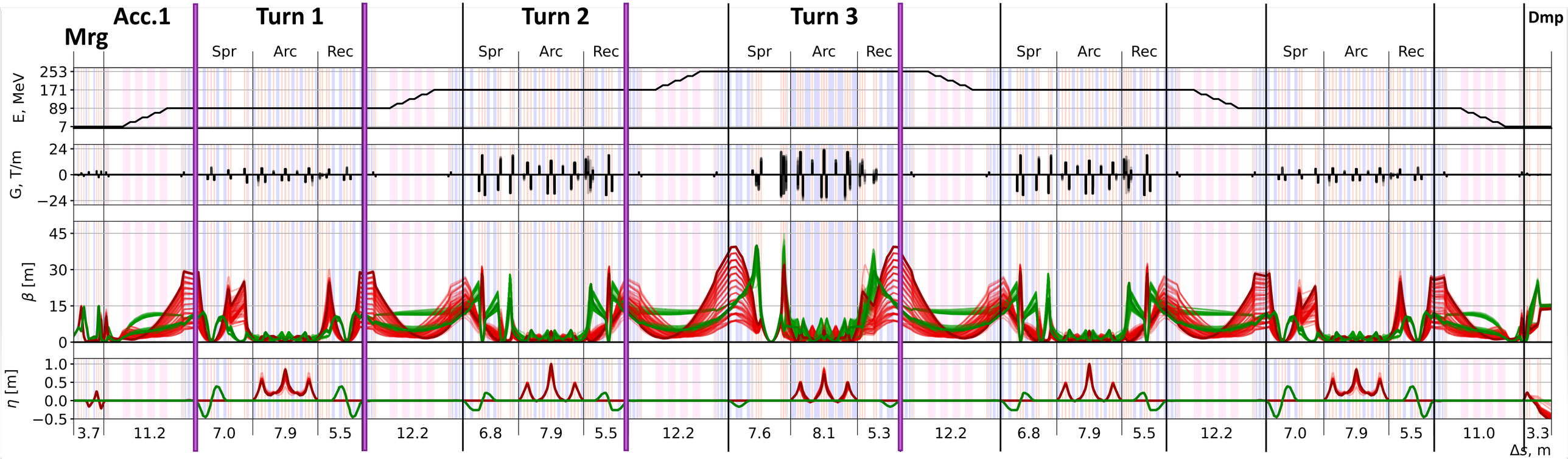
Optics matching. All turnaround loops Top / Mid / Bot



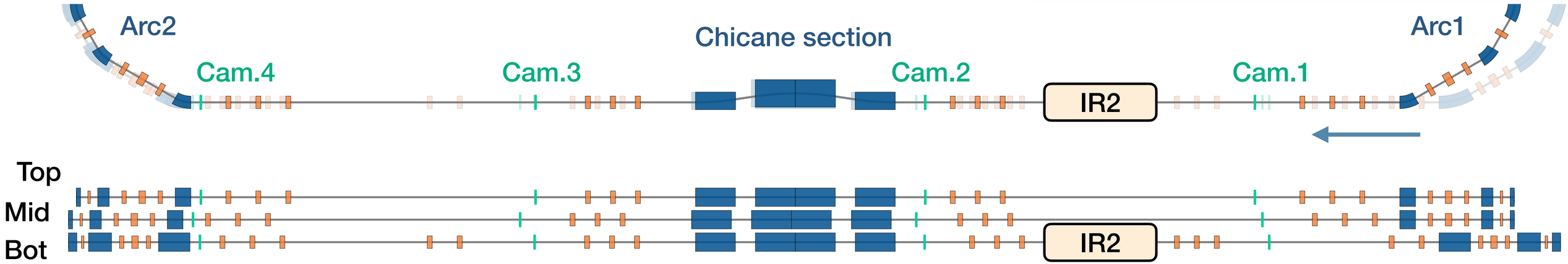
Optics matched with simple scheme

Spreader + Arc 1 + Recombiner

- Symmetric twiss
- Closed dispersion and M56
- Minimal beam size

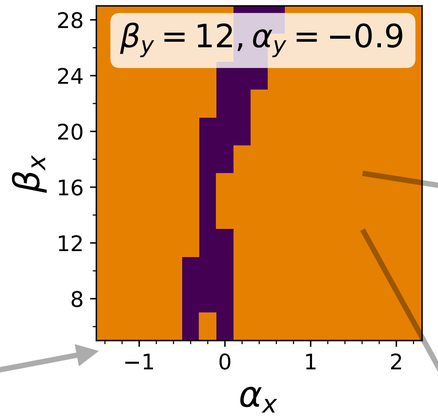


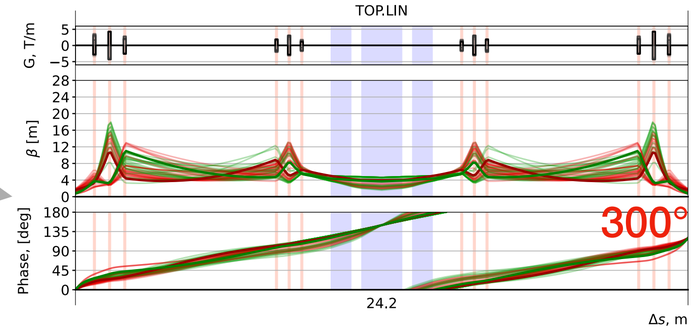
Straight Line section. Transverse and longitudinal phase control

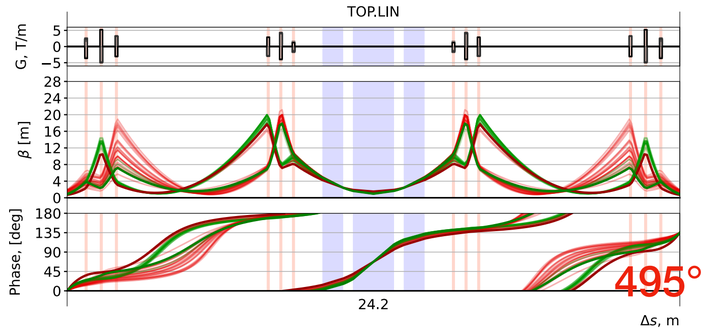


Structure

- **Top.Lin** (89 MeV) : symmetric, 4 quadruple triplets → **12 quads**
- **Mid.Lin** (171 MeV) : symmetric, 4 quadruple triplets → **12 quads**
- **Bot.Lin** (89, 253 MeV) : 2 + 3 + 3 + 3 + 2 + 3 → **16 quads**
- **All Lines** : chicane sections + 4 screens → **9 dipoles** + **16 screen**



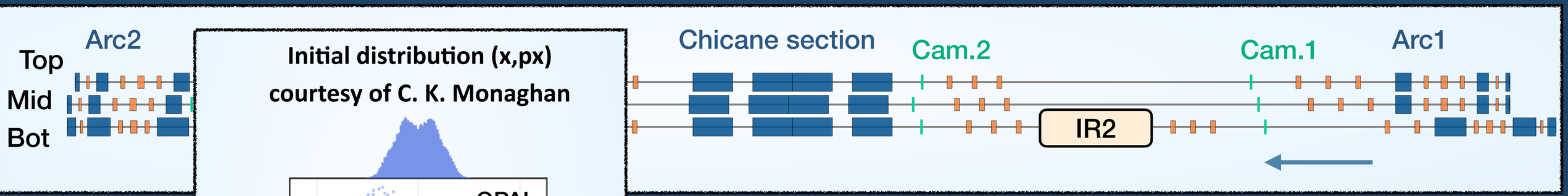


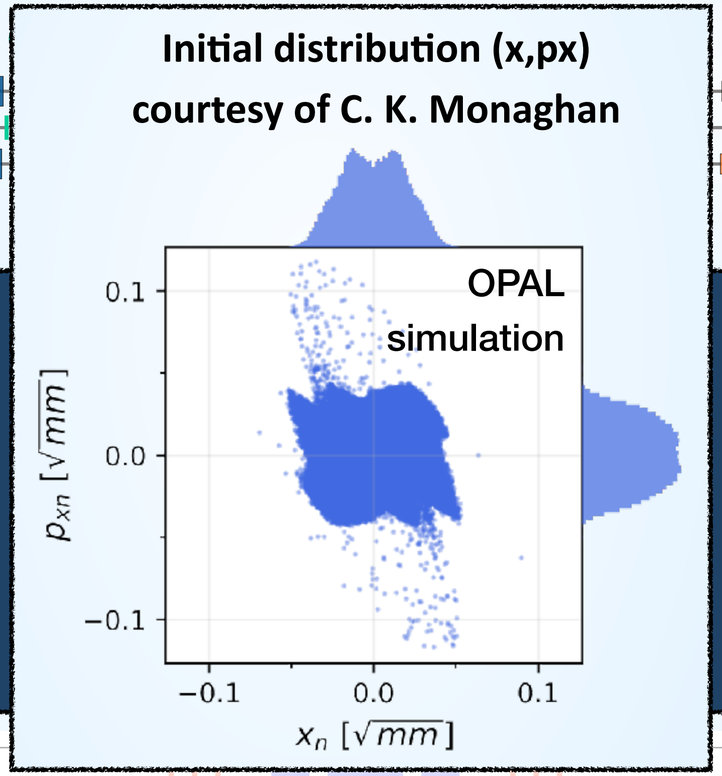


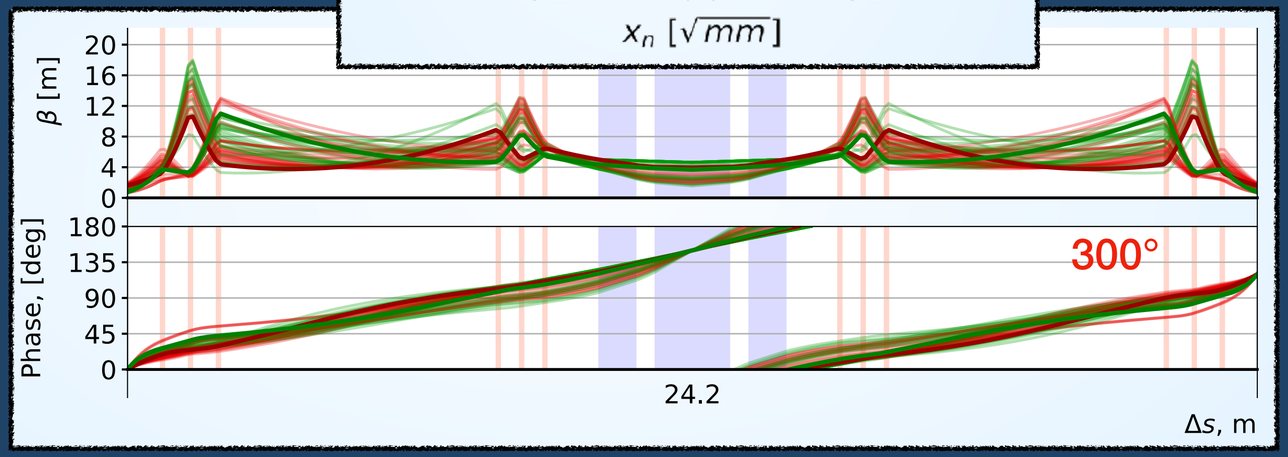
Capabilities:

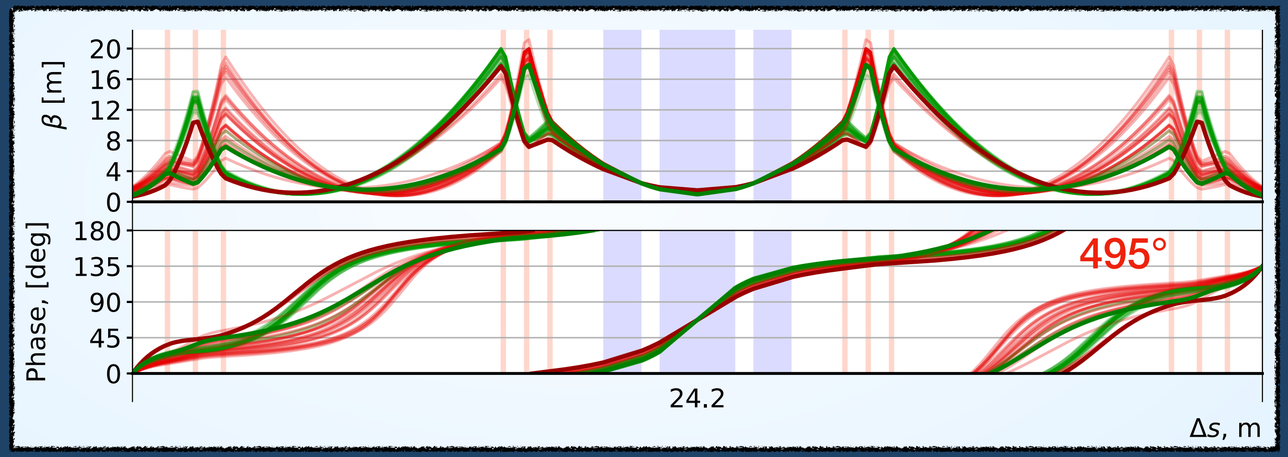
- Flexible matching for **all valid compact-section optics solutions**
- **Transverse phase control : full 180° rotation in x/y planes** → beam **tomography** + best **transmission**
- **Longitudinal phase control : ± 20° (± 20.8 mm)** → optimization for **transmission and experiments**

Straight Line section. Transverse phase control : full 180° rotation in x/y planes

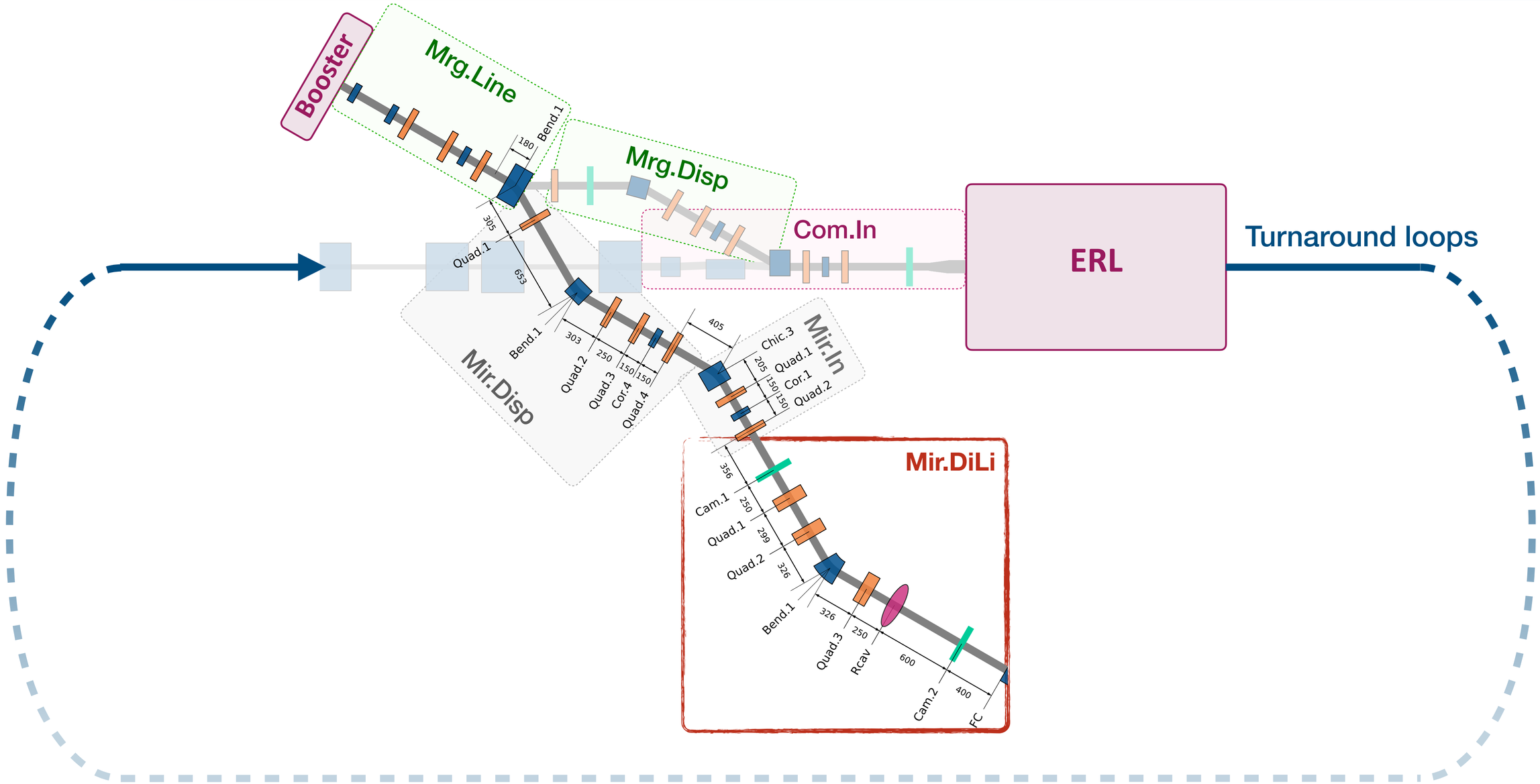




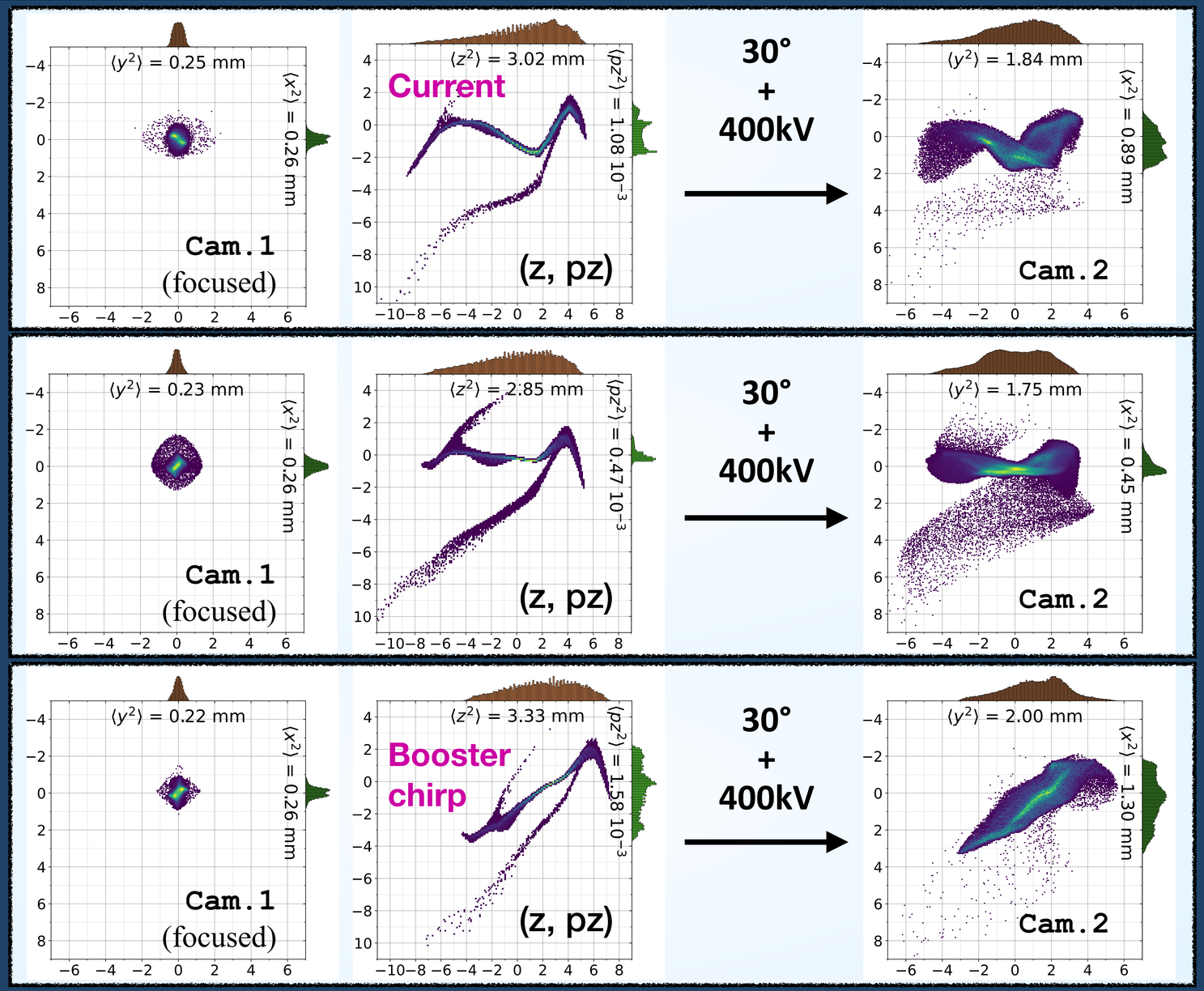


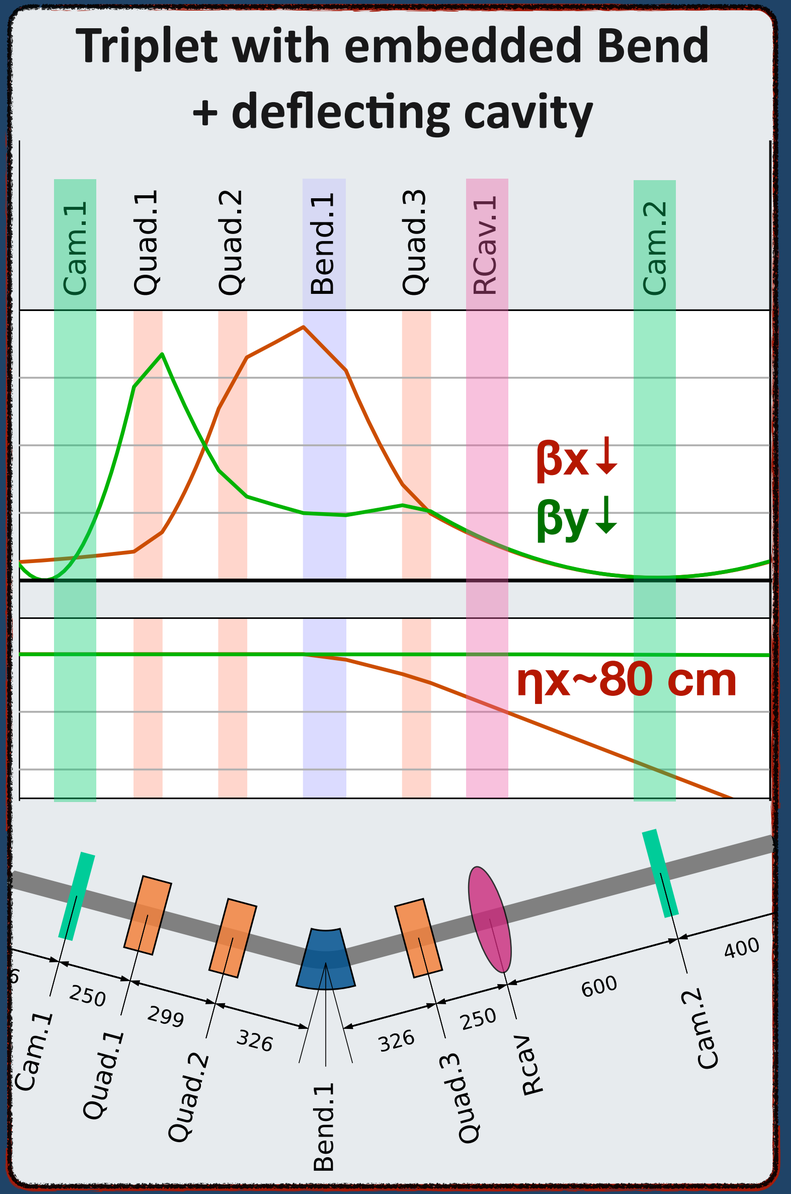


Mirror Diagnostic Line — Longitudinal Phase-Space Measurement



Mirror Diagnostic Line — Longitudinal Phase-Space Measurement





Conclusions

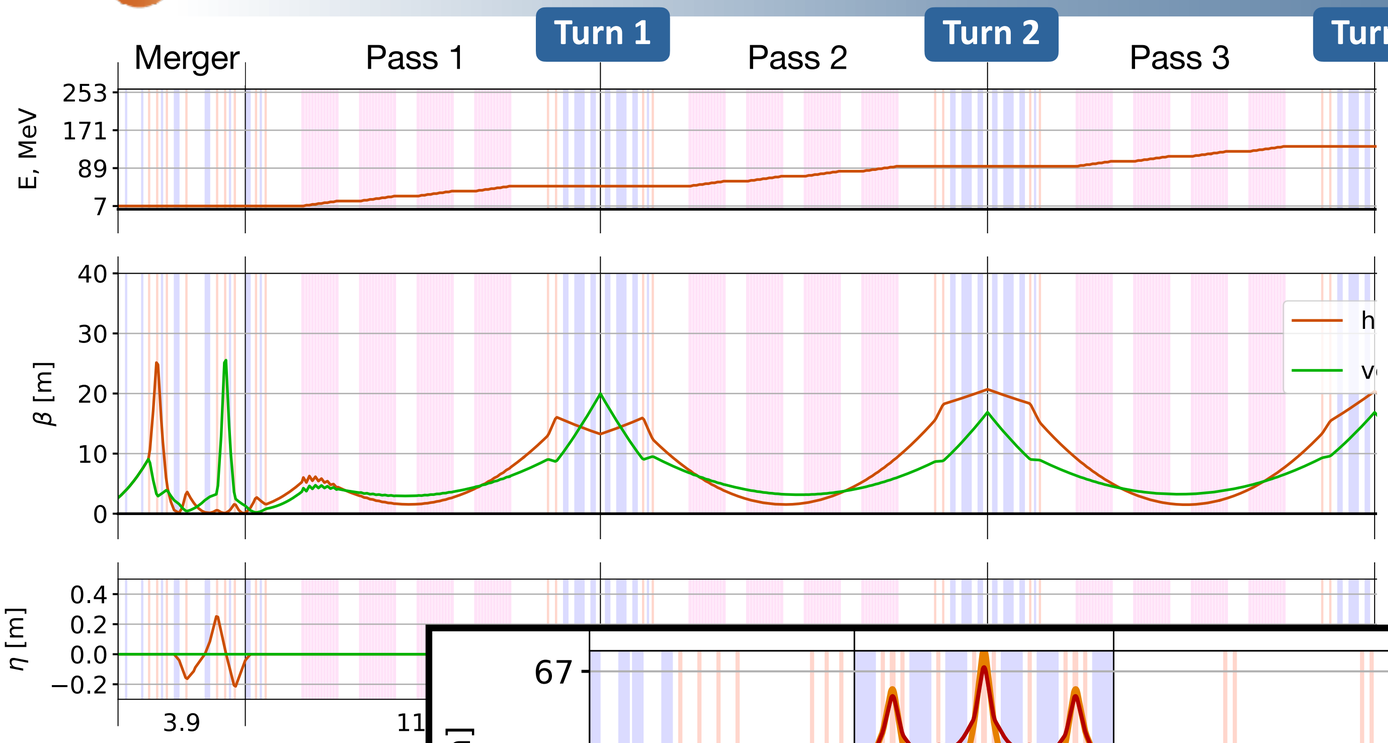
- **Multiple optics solutions** found for the space-constrained sections
- Flexible **straight sections** provide transverse and longitudinal **phase-advance control**
- Mirror Diagnostic Line enables **longitudinal phase-space measurements** without enlarging the merger
- Combined flexibility and diagnostics support **commissioning** and **optimisation** of the PERLE lattice

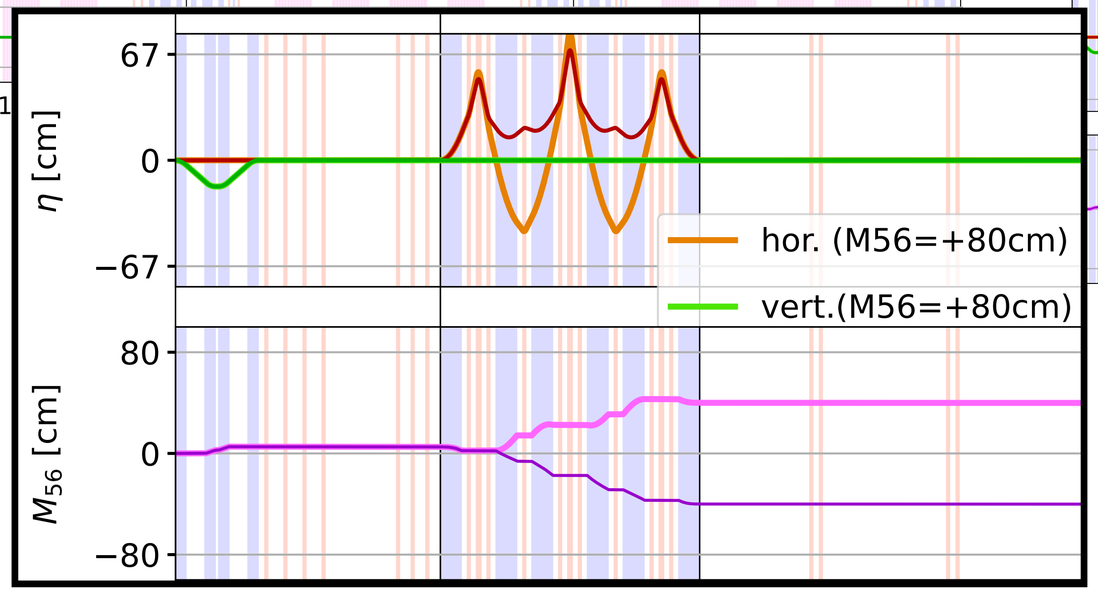
Conclusions

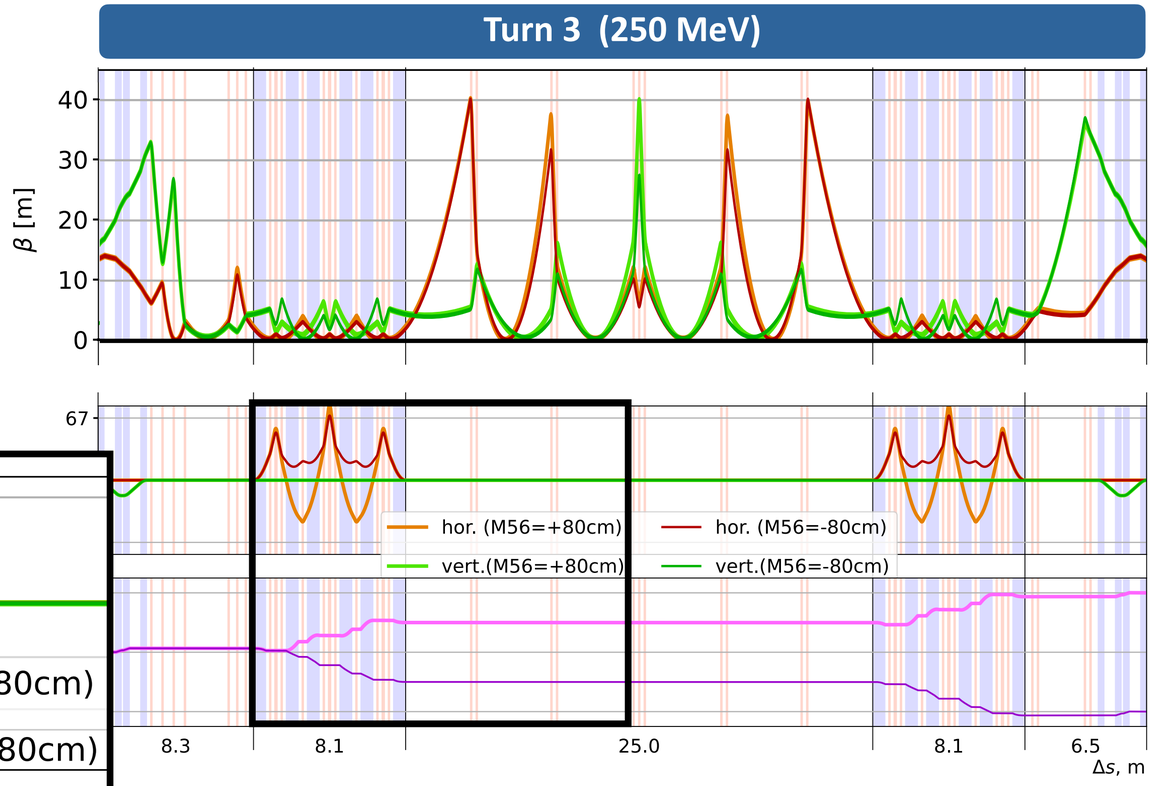
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- Combined flexibility and diagnostics support **commissioning** and **optimisation** of the PERLE lattice

Thank you!

PERLE Optics: Multi-turn tuning







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

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