Proton Optics for Concurrent Operation of the e-p and p-p Experiments in the HL-LHC

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CERN

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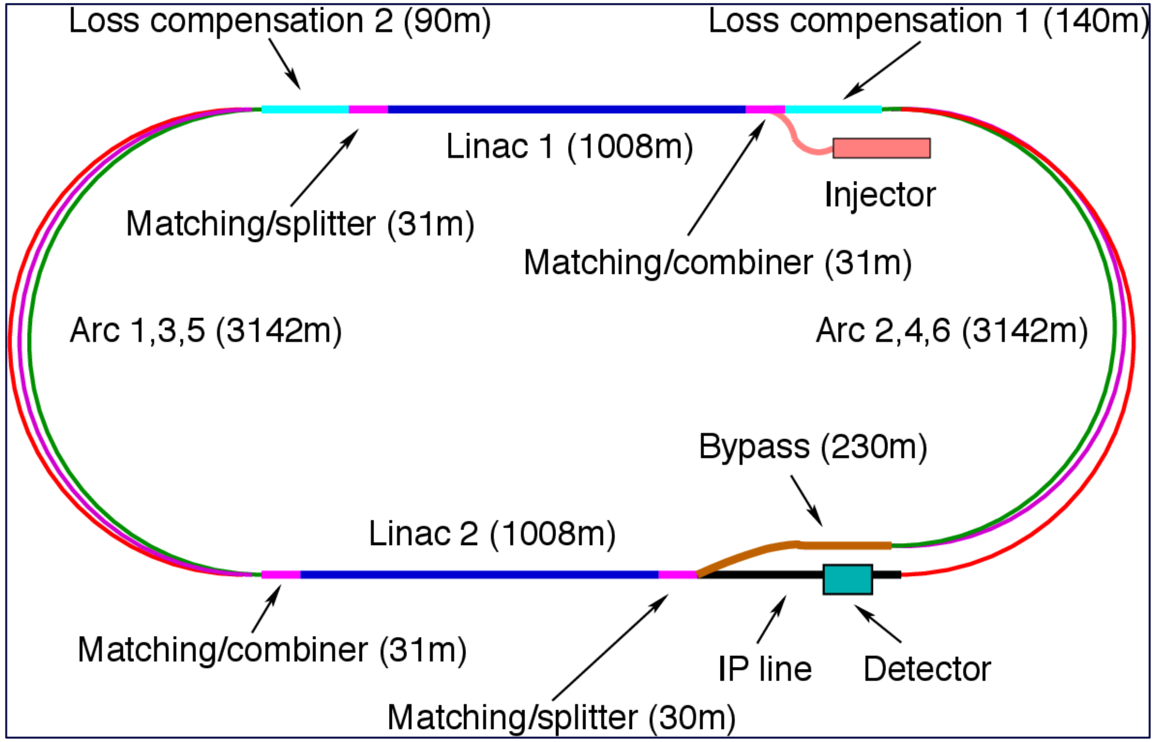
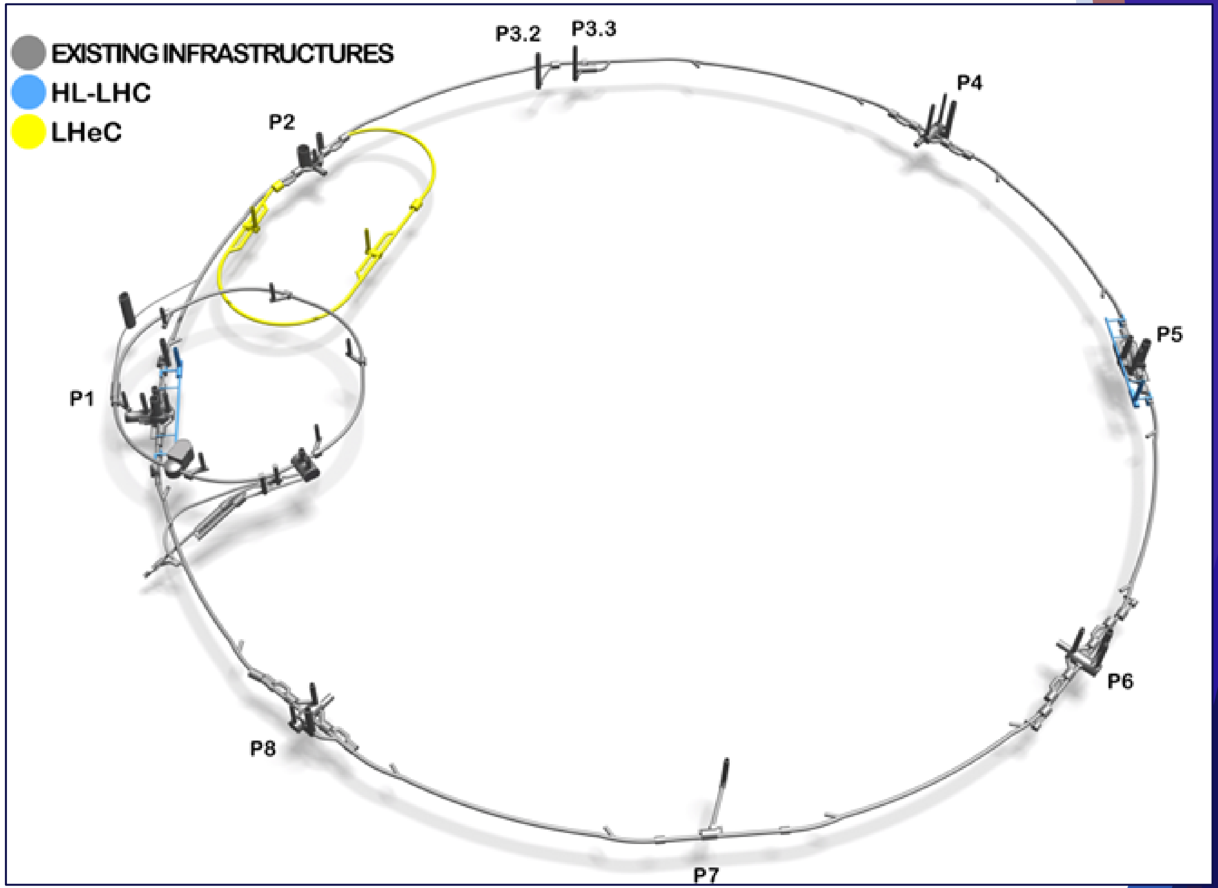
The Large Hadron electron Collider (LHeC)

- Equip the HL-LHC with a tangential energy recovery linac (ERL)
- Realization of collisions of a 7 TeV proton beam with a 50 GeV electron beam -> $\sqrt{s} = 1.2$ TeV

electron acceleration



proton acceleration



LHeC Design Report

Schematic Layout of the energy recovery linear accelerator. Courtesy to K.D.J. André.

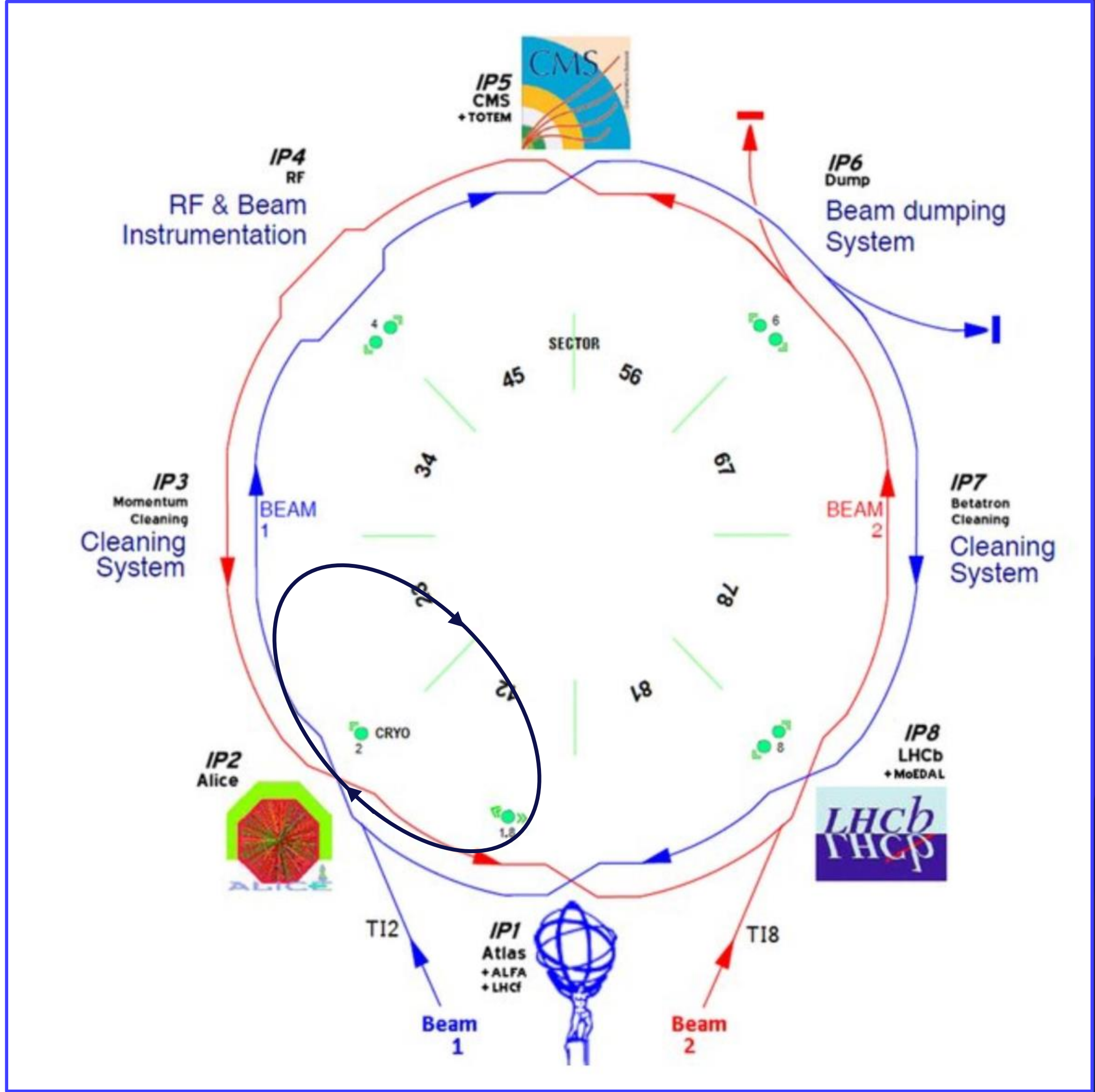
Concurrent Operation with the High-Luminosity experiments

- The ERL enables deep inelastic scattering e-p experiments in point 2
- They run concurrently with p-p operation of the other HL-LHC experiments
- Operation with ALICE alternates

PhD topic:

Operate three beams in point 2, enabling e-p collisions and guide the second proton beam around this interaction point

LHeC as stand-alone experiment: Thesis Emilia Alaniz, Thesis Roman Martin



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Theoretical Background: Beam Envelope

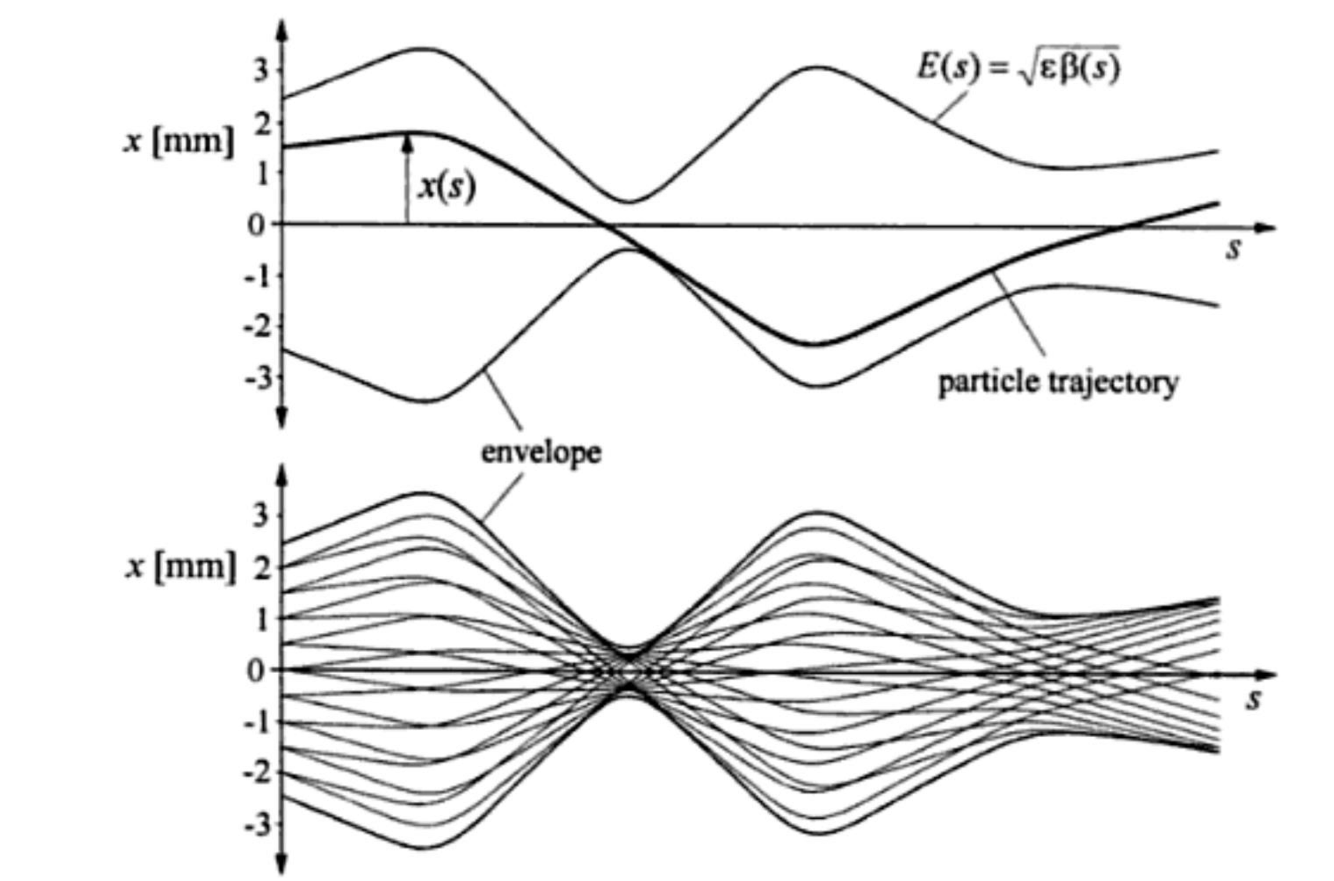
- Single particles perform betatron oscillations around their orbit s
- Many particles performing many turns are wrapped by the beam envelope:

$$E(s) = \sqrt{\varepsilon\beta(s)} = 1\sigma_u \quad with\, u = x, y$$

- ε is the energy dependent emittance
- β(s) defines the beta function, which defines the beam size at a certain position s
- Actual beam size at ATLAS and CMS:

$$\sigma_{x,y} = 16.7\ \mu m$$

$$with\ \varepsilon \sim 10^{-10} m, \quad \beta \sim 1m$$



Beam envelope, K. Wille

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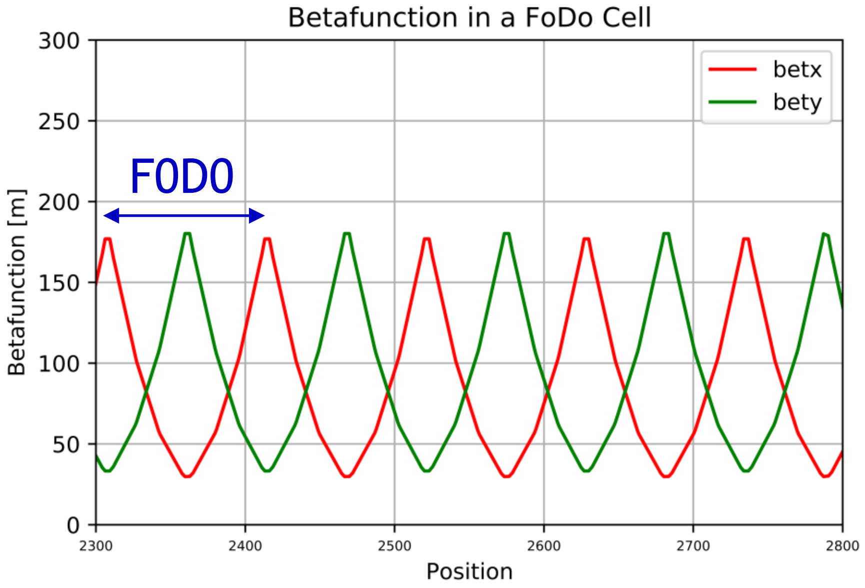
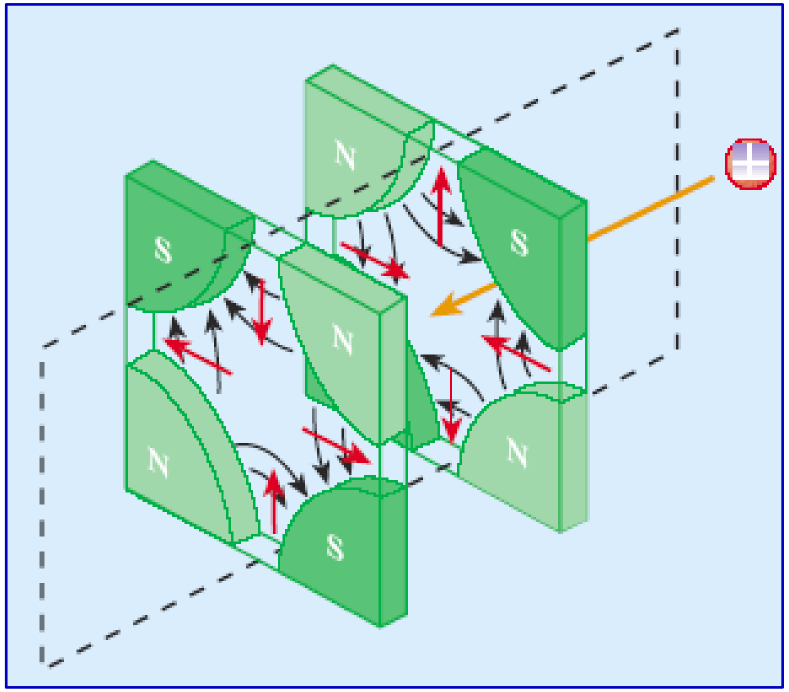
Theoretical Background: FoDo Lattices

- FoDo: Focussing (in the horizontal plane) 0 Defocussing (in the horizontal plane) 0
- The particles are kept around the orbit using a series of quadrupoles in FoDo cells
- The drift spaces can be filled with dipoles, ensuring the bending of the beam!





How is the beam focused inside the detectors before the collision?

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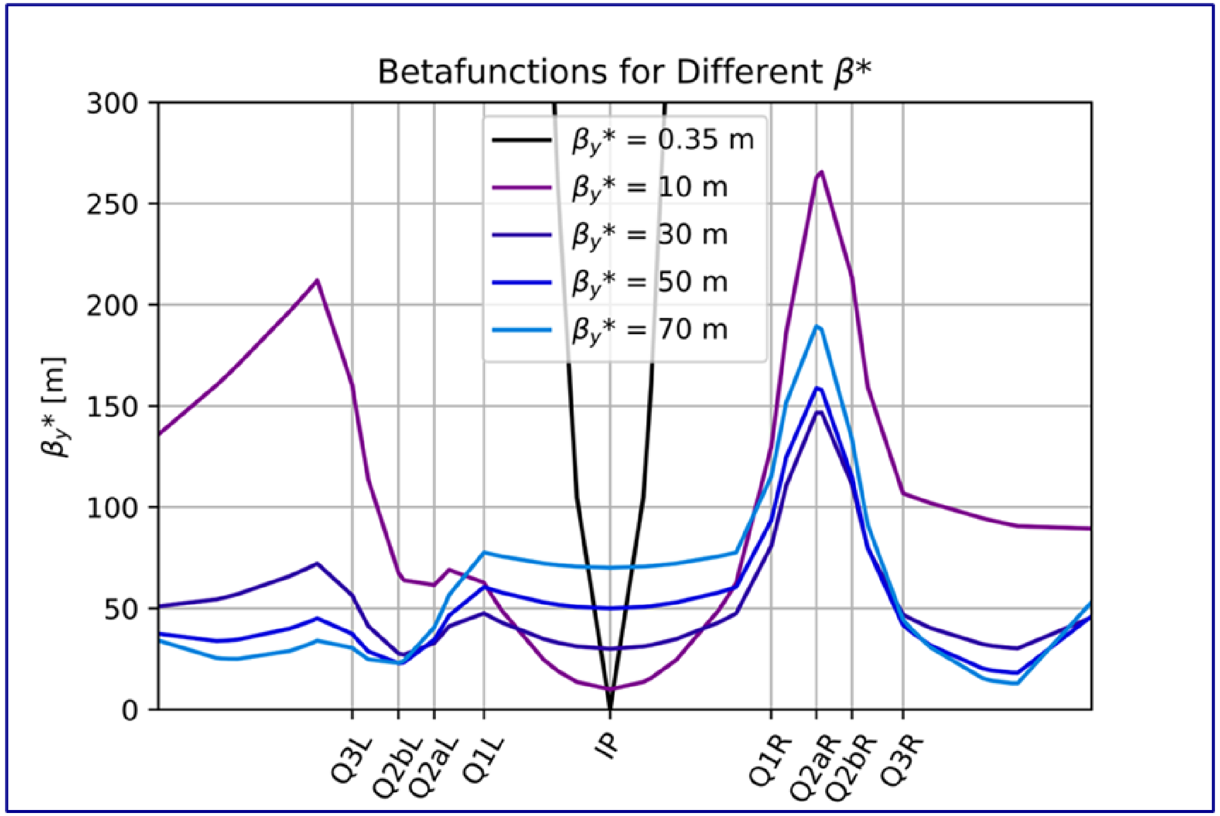
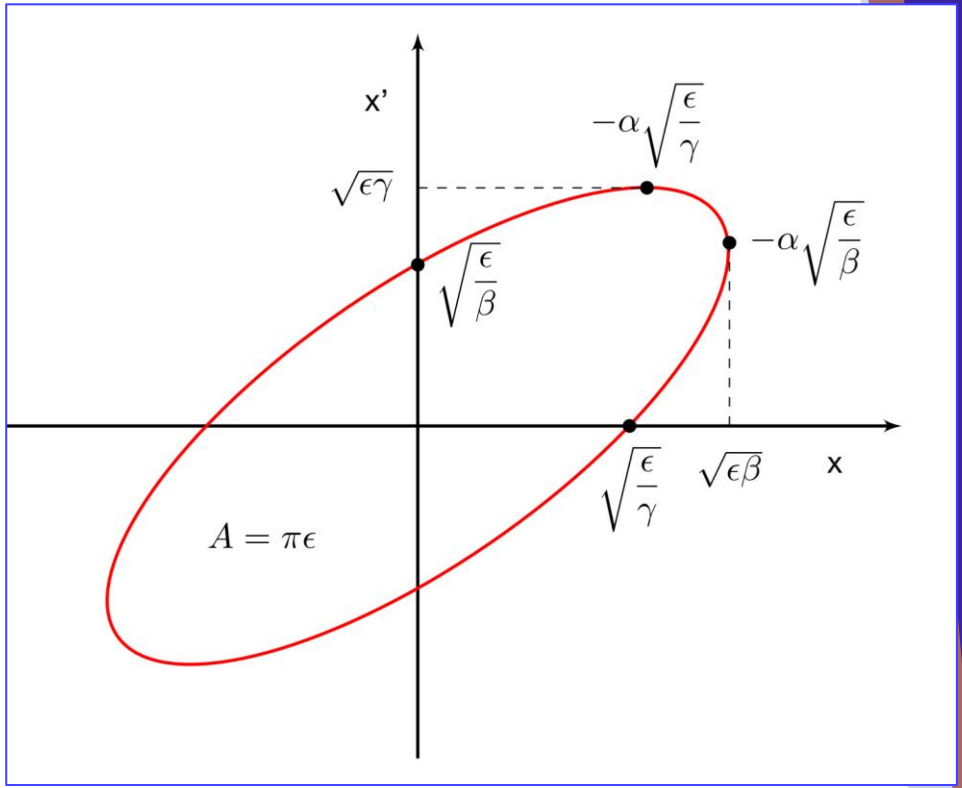
Phase Space Conservation and Liouville's Theorem

- *The phase-space distribution function is constant along the trajectories of the system*
- The area in the phase space is conserved

➡ the smaller the beam size, the bigger the divergence





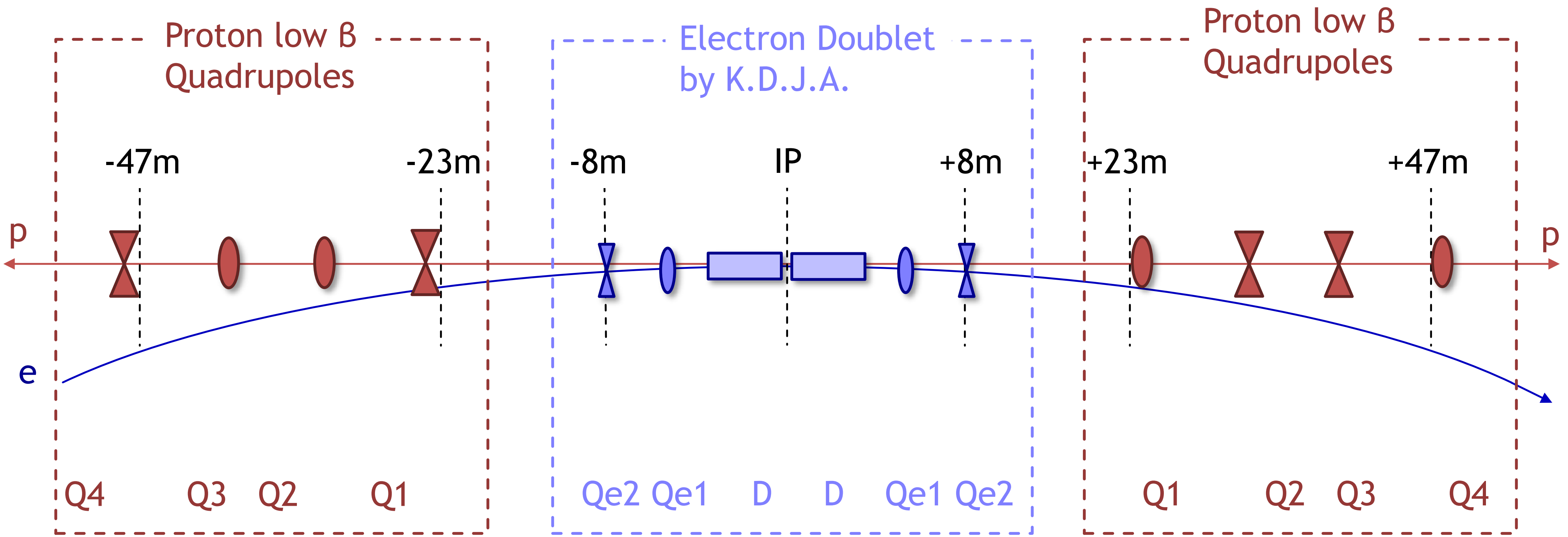
Phase Space Diagram

Betafunction before a drift space of the length l with symmetry point ß*:

$$\beta(l) = \beta^* + \frac{l^2}{\beta^*}$$

The quadrupoles before the IR need the biggest aperture!

The LHeC interaction region:



PhD topic: ➡

Operate three beams in point 2, enabling e-p collisions and guide the second proton beam around this interaction point

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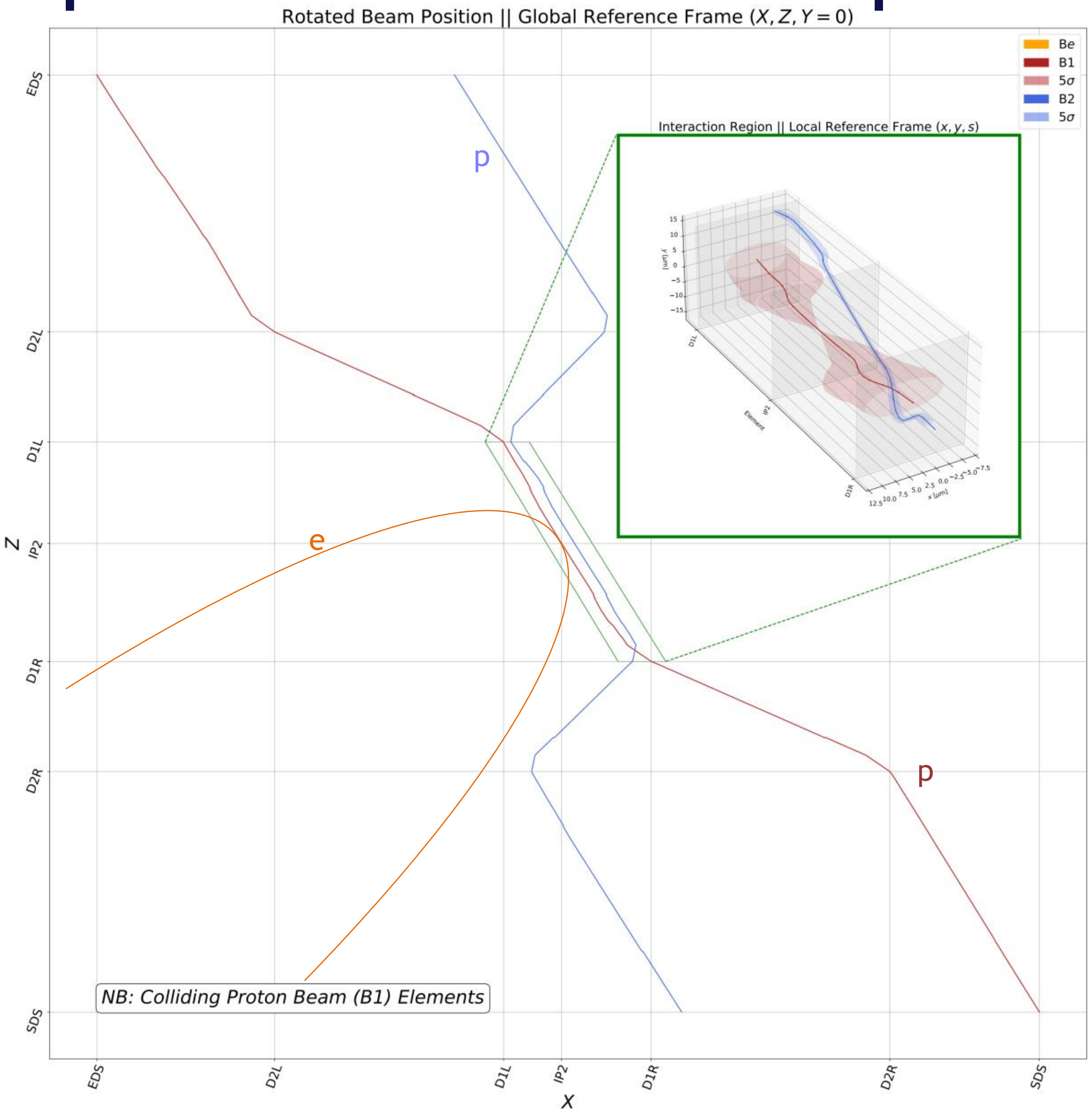
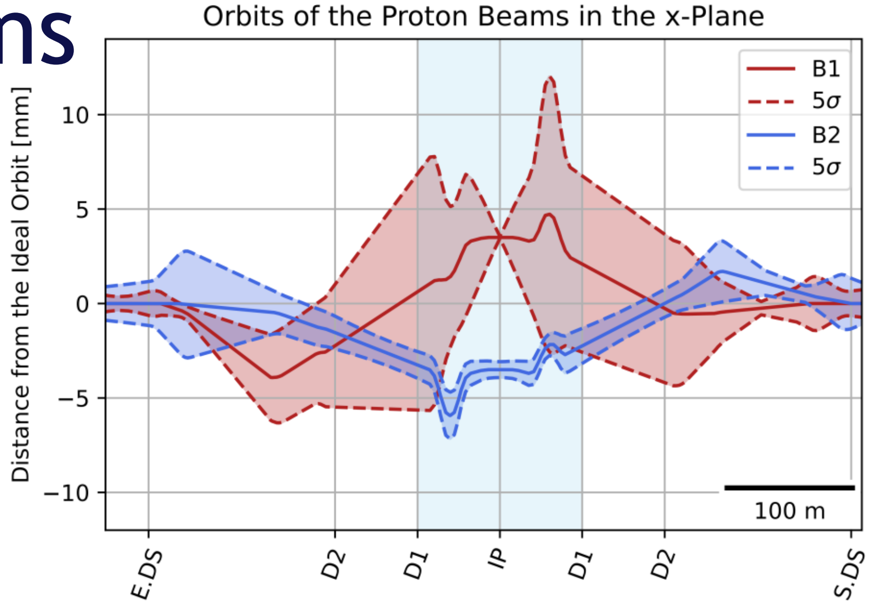
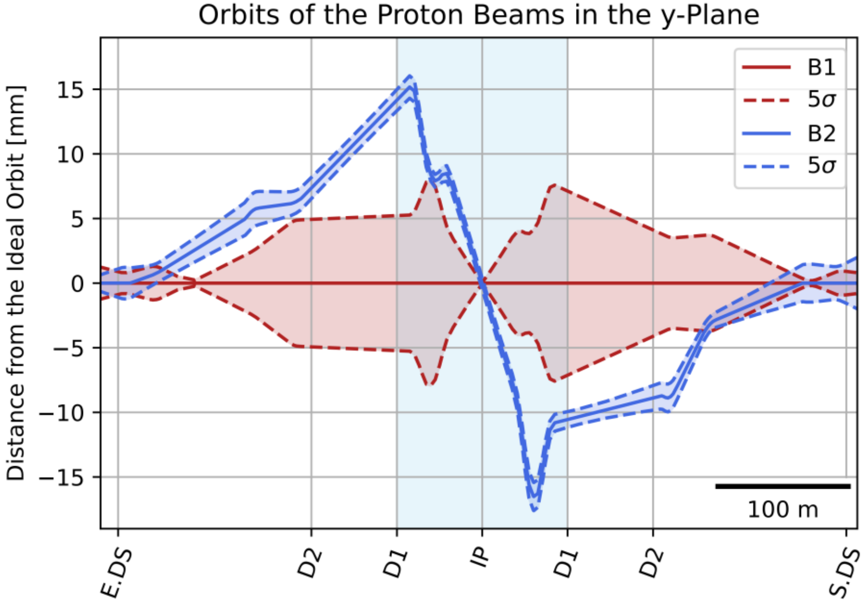
Separation of the two proton beams







3D plot: M. Smith

Asymmetric proton beam optics

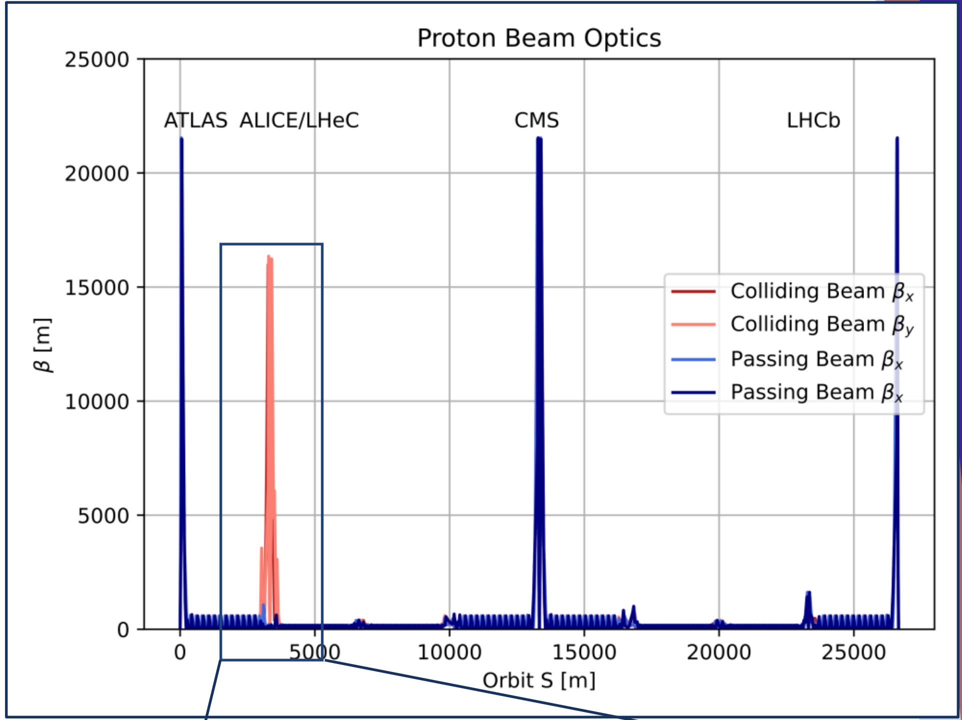
- Relax the non-colliding proton beam to maximize the distance between the proton beams in the shared beampipe

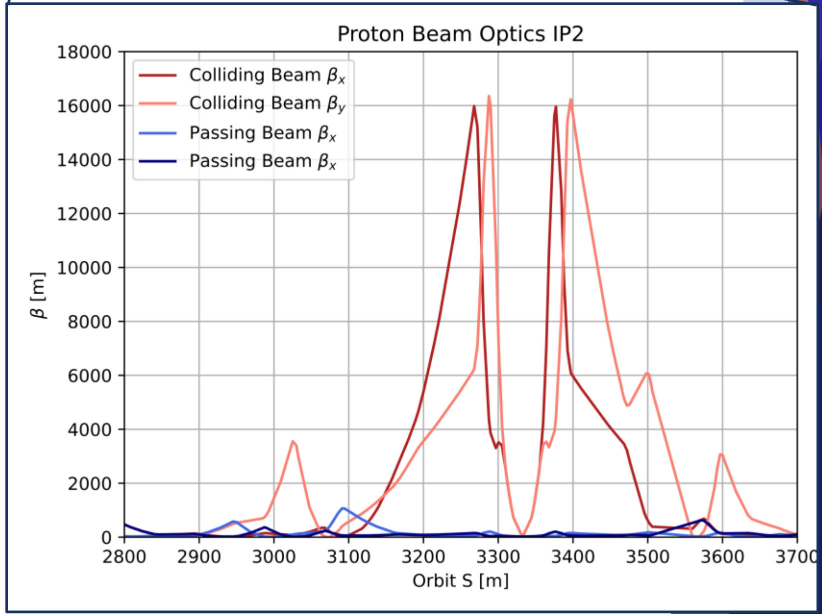
$$\beta(l) = \beta^* + \frac{l^2}{\beta^*}$$

- This enables e-p collisions with a ß* of 0.2m and thus a luminosity of $2.5 \cdot 10^{33} cm^{-2} s^{-1}$

$$L = \frac{N_1 \cdot N_2 \cdot n \cdot f}{4\pi\sigma_x\sigma_y} [cm^{-2}s^{-1}]$$

$$E(s) = \sqrt{\varepsilon\beta(s)} = 1\sigma_{x,y}$$





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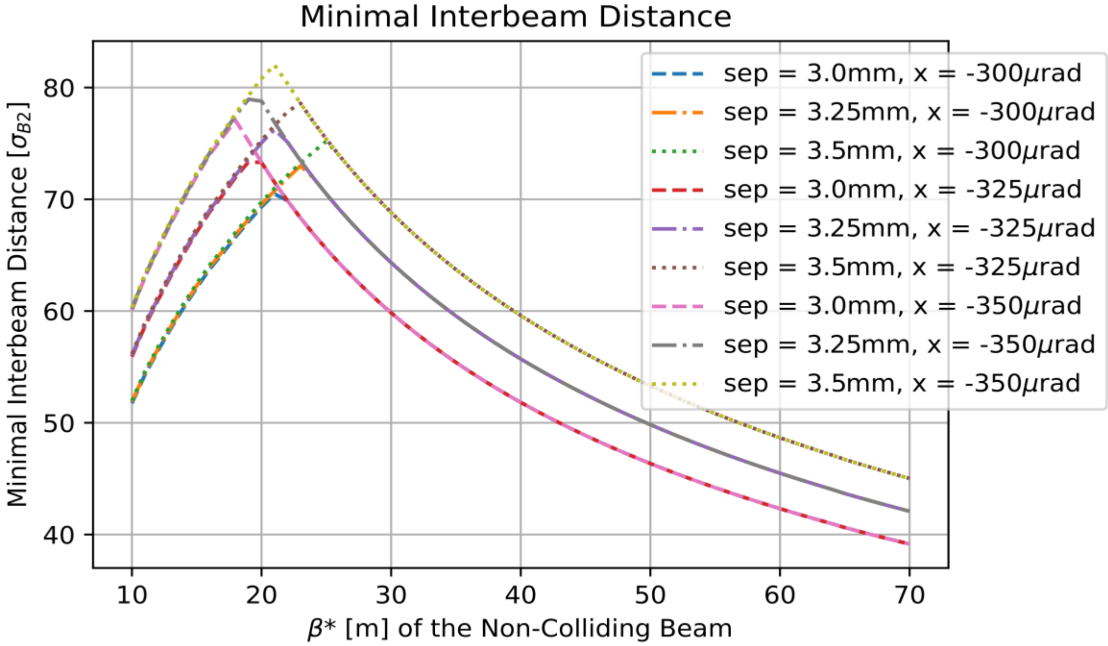
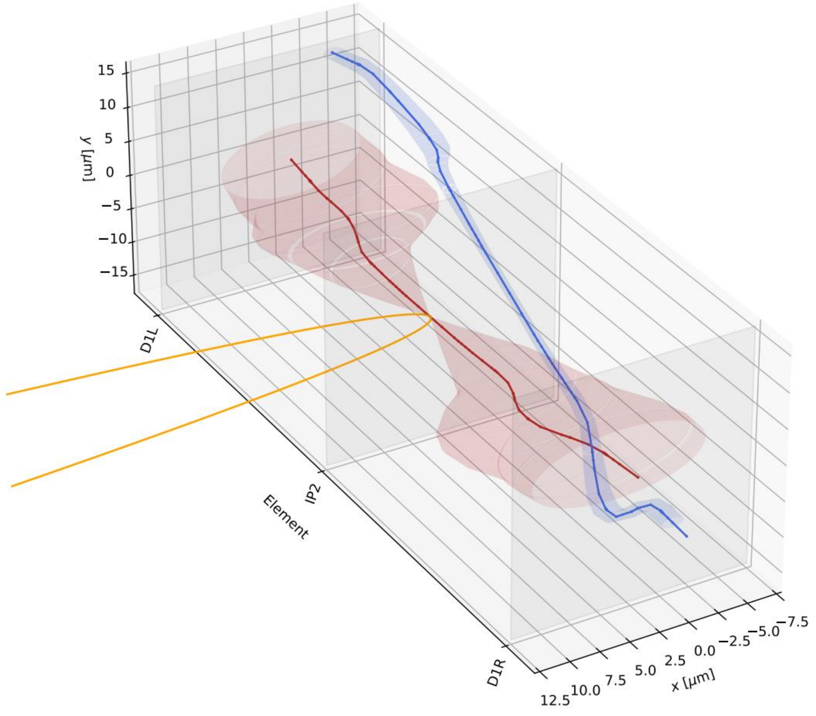
Parameter Optimization for the two proton beams [3]



Aim: maximise the distance between the two proton beams in the shared beampipe



Scanned optical parameters: β^*_{B1} and β^*_{B2}

Scanned orbit parameters: the crossing angle x and the separation bumps sep

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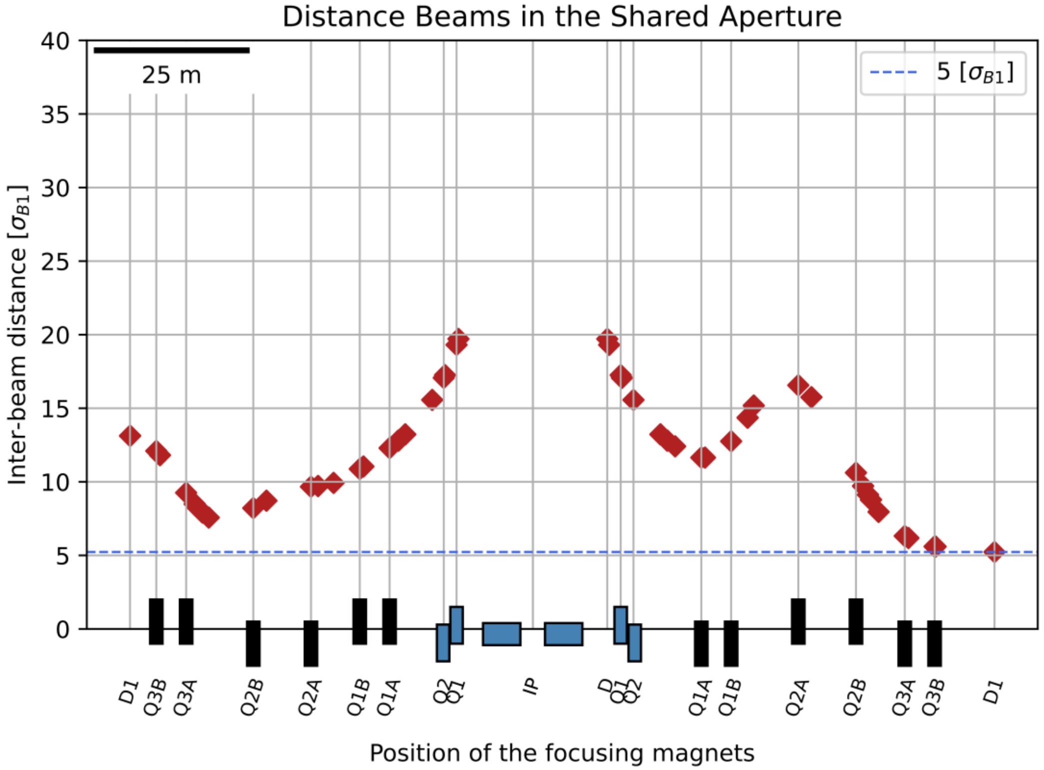
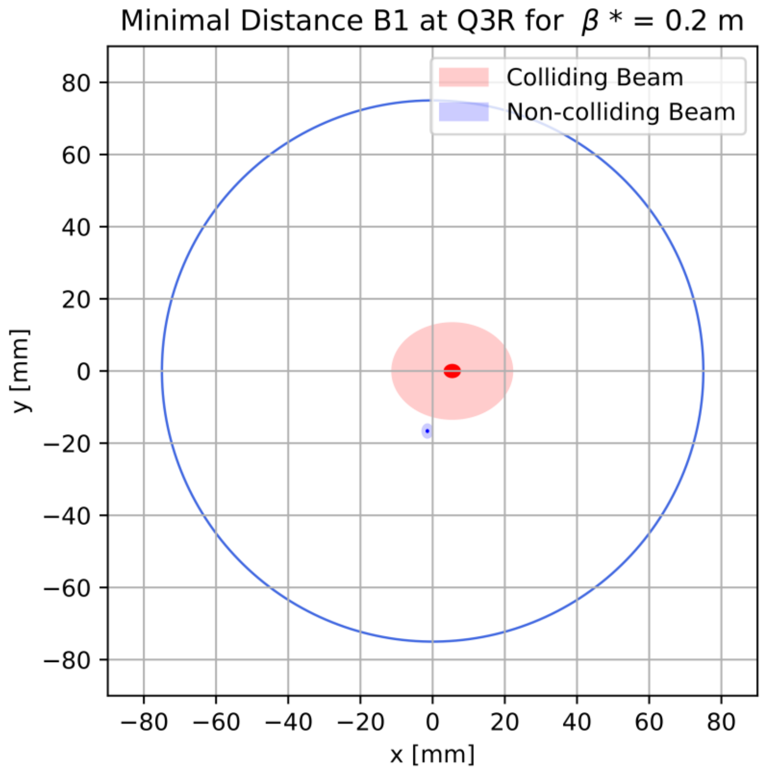
Distance between the two proton beams in the shared aperture

- A minimal distance of 5.6σ between the two proton beams can be assured throughout their shared aperture while reaching the luminosity goal





Cross section of the magnet in which the two proton beams get closest

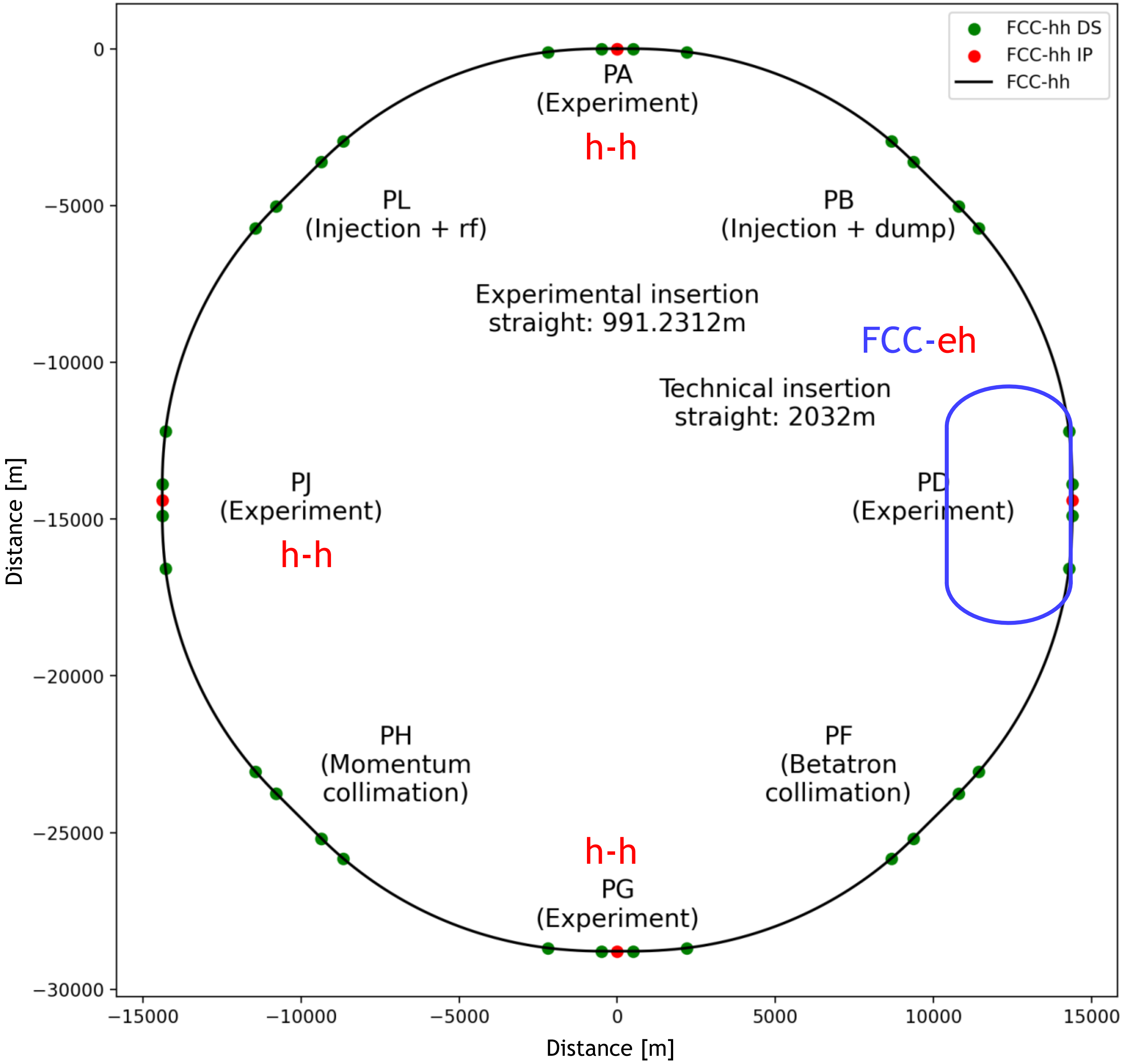
The FCC-eh Collider

- New layout of the FCC-hh collider:

[FCC-hh ring: overview of the new layout](#)

[New FCC-hh ring layout: arc and insertion optics](#)

- High precision microscope for inner hadron structure
- Collisions of 50TeV protons with 60GeV electrons
- Center of mass energy: $\sqrt{s} = 3.5\ \mathrm{TeV}$
- Peak Luminosity: $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$



Possible layout of the FCC [1]

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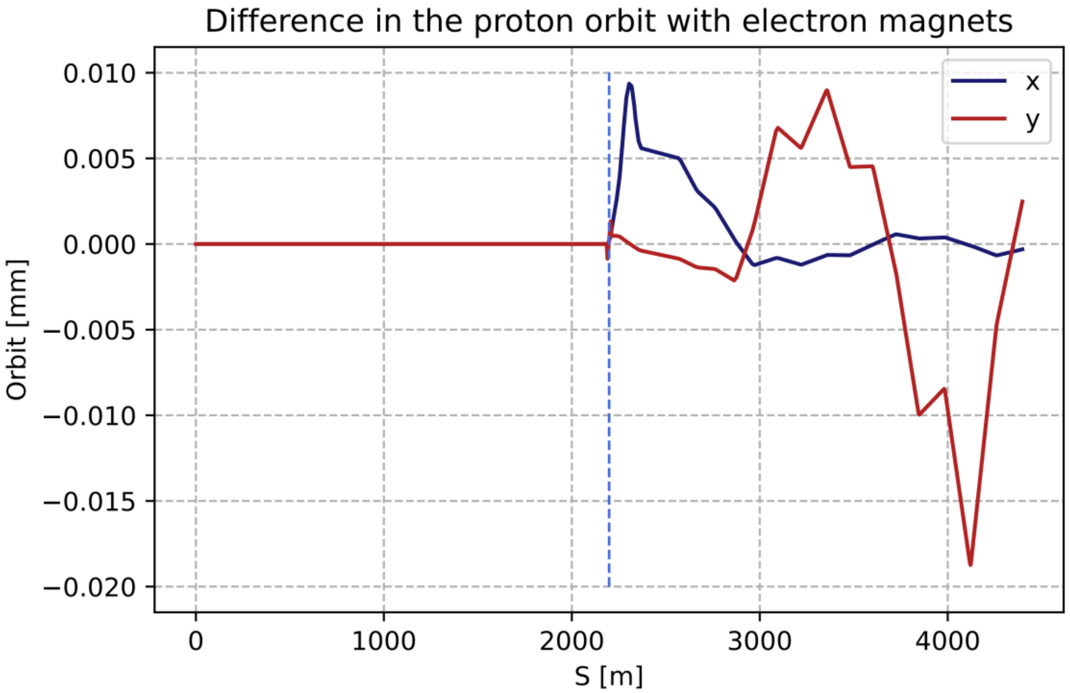
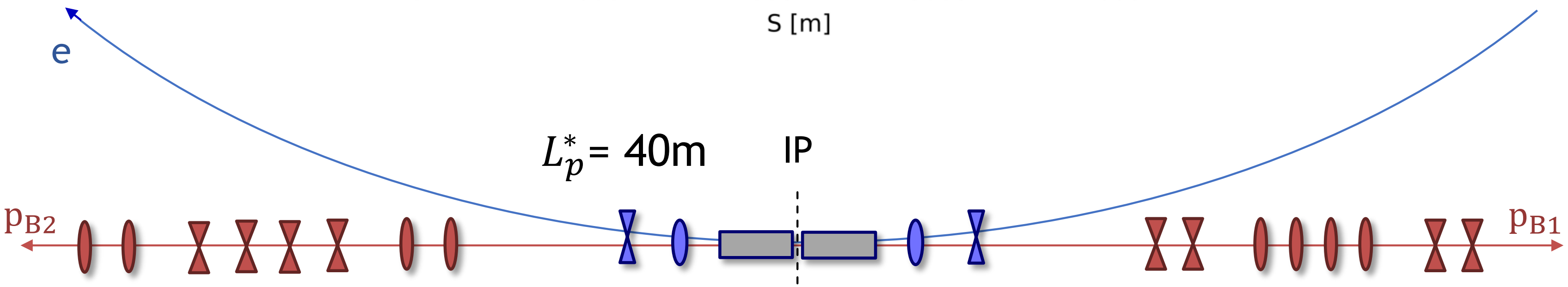
Insertion of the electron interaction region

- Optimized to minimize the synchrotron radiation power
- An electron doublet is used for round electron beams
- Two dipoles are used to bend the electrons
- The protons pass the electron magnets with a scaling factor of $\frac{60\ GeV}{50\ 000\ GeV} \approx 0.0012$



Impact of the electron magnets on the proton orbits (B1). The blue line marks the position of the IP.



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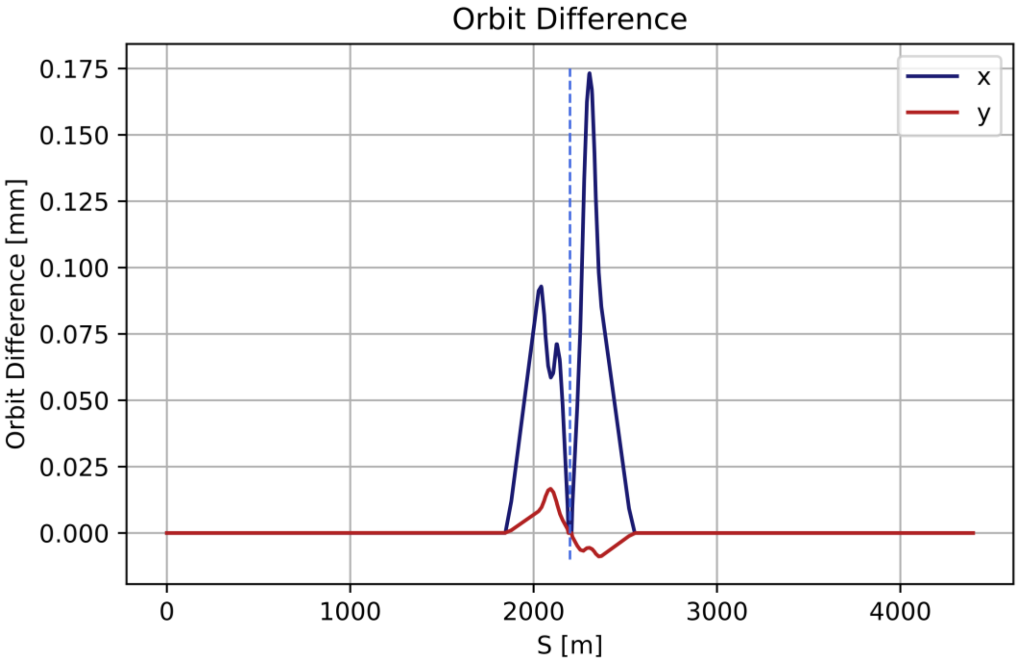
Impact of the electron IR on the proton beam dynamics

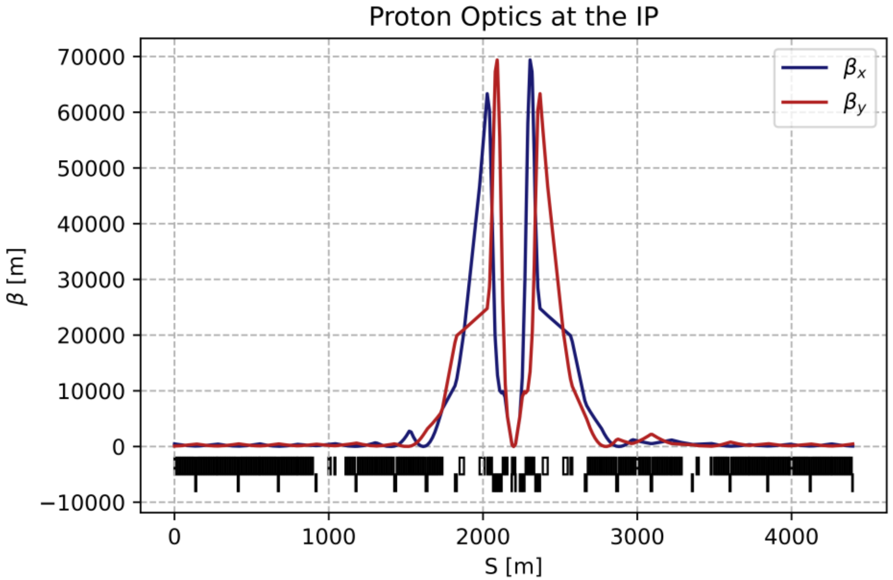
Local correction of the proton orbit:

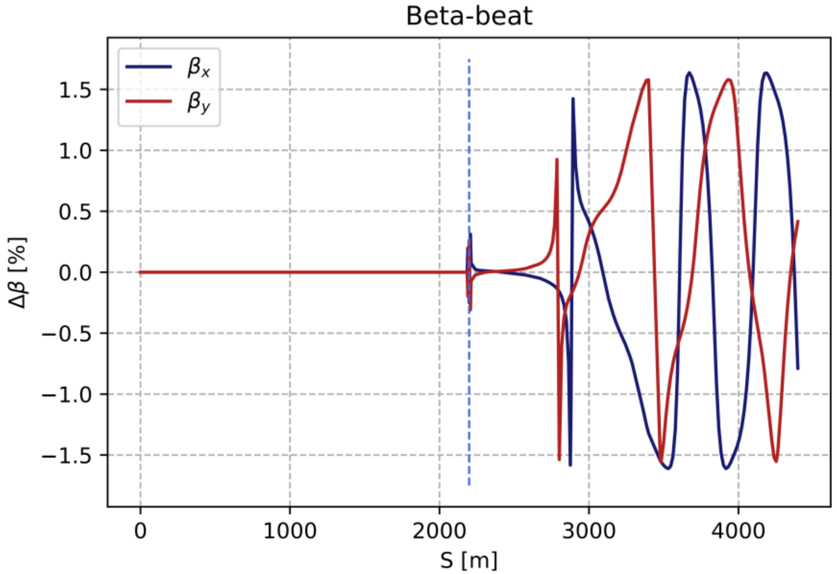


Introduction of a beta-beat of about 1.5% in the proton optics.

Scaling of electron and proton energies:

$$\frac{60\ GeV}{50\ 000\ GeV} \approx 0.0012$$





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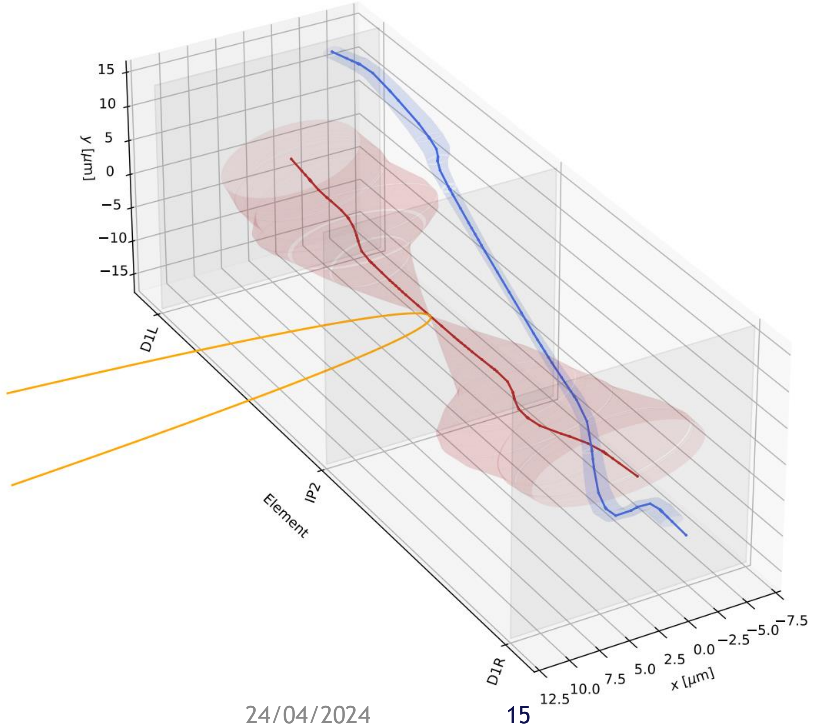
Both effects can be corrected.

Summary

- A n optimized modular e-p interaction region has been be inserted into the HL-LHC lattice
- This enables e-p collisions with a luminosity of up to $2.5 \cdot 10^{33} cm^{-2} s^{-1}$
- The optics enable concurrent operation of the LHeC with the other HL-LHC experiments at collision optics with only small modifications to the LHC lattice
- These are the first LHeC optics to enable alternate operation with the ALICE experiment/upgrade

- An optimized modular IR has been inserted into the updated FCC lattice
- You can build your own LHeC lattice on the LHeC git

THANK YOU.



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Sources

- [1] A. Abramov, W. Bartmann, M. Benedikt, R. Bruce, M. Giovannozzi, G. Perez Segurana, T. Risselada, F. Zimmermann CERN, “Updated FCC-hh layout under thebaseline scenario”, Oral Contribution FCC Scientific Advisory Committee, 28 April 2023
- [2] K. Andre, “Lattice design and beam optics for the energy recovery linac of the large hadron-electron collider,” Ph.D. dissertation, University of Liverpool, 2022, http://livrepository.liverpool.ac.uk/3161486/
- [3] T .von Witzleben, K. D. J. André, R. De Maria, B. Holzer, M. Klein, J. Pretz, M. Smith, “Beam Dynamics for Concurrent Operation LHeC and the HL-LHC”, IPAC 2023
- [4] K. Wille, “Introduction to Accelerator Physics”

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Background Slides

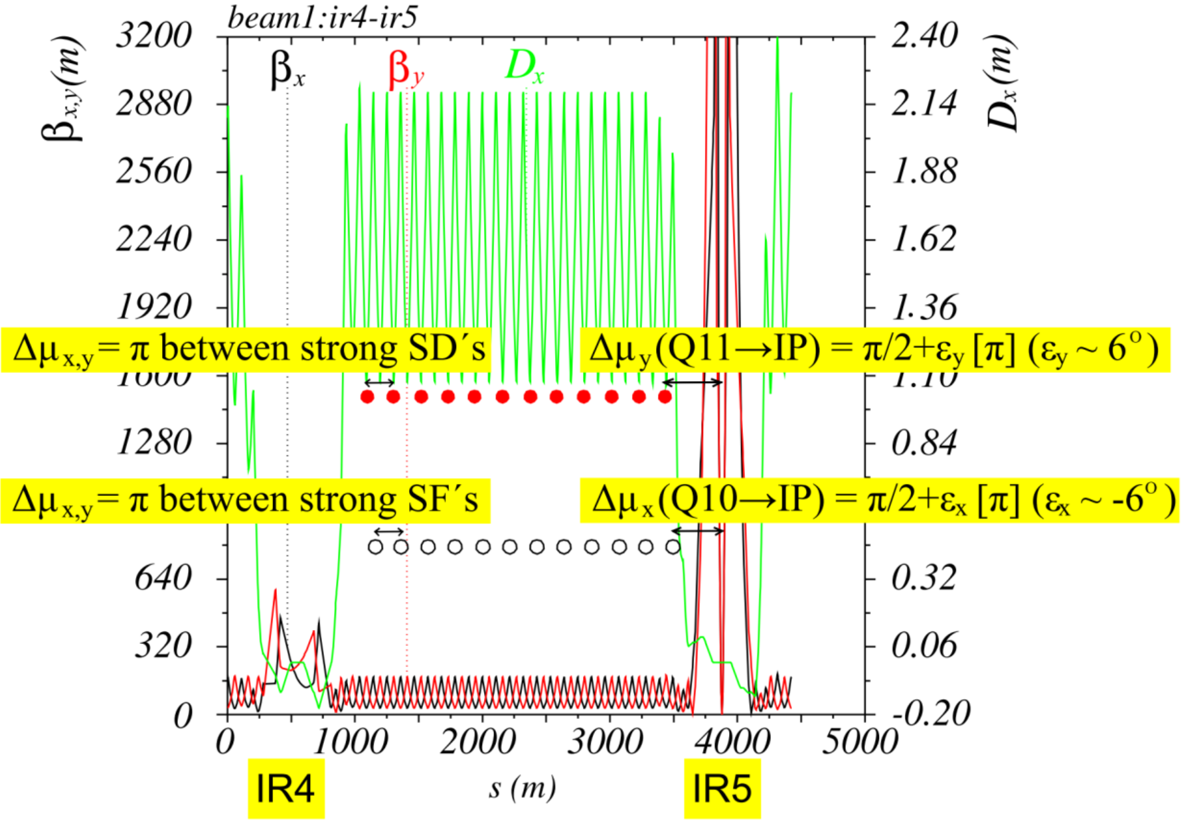
ATS Optics

Betafunction of the Achromatic Telescopic Squeeze Optics

- The chromaticity increases with the strength of the quadrupoles :

$$\xi = \frac{1}{4\pi} \oint k(s)\ \beta(s) ds$$

- Highest at points of high betafuntion!
- Limitation on ß*!
- Increase effectivity of sextupoles by introducing a beta-beat to have high betas at the position of the sextupoles -> increase their effectivity!



Betafunction before IP5 with position of the sextupoles [2] and optics to have a high betafunction here

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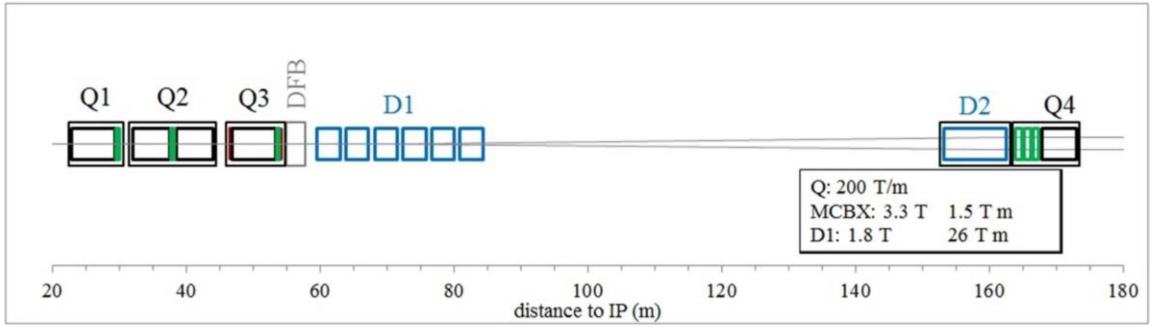
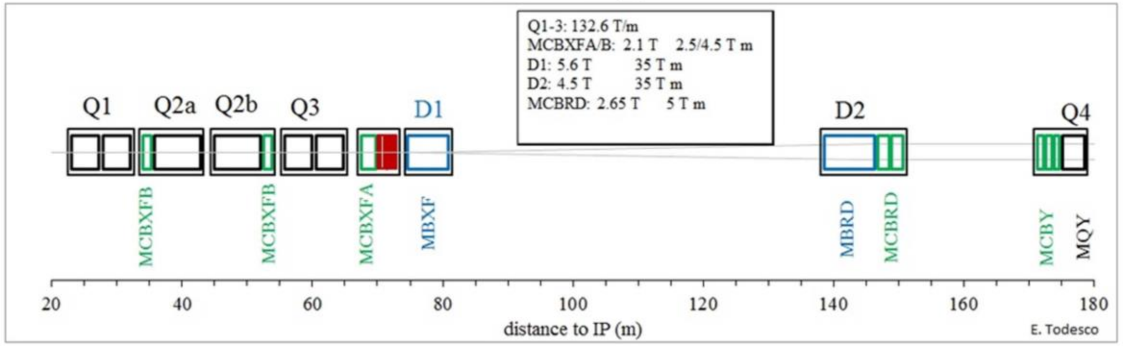
HL-LHC Upgrade

- Final focusing system is changed from NbTi to Nb3Sn
- D1 magnet superconducting
- crab cavities are inserted in IR 1 and IR 5
- Q4 is moved relative to the IP





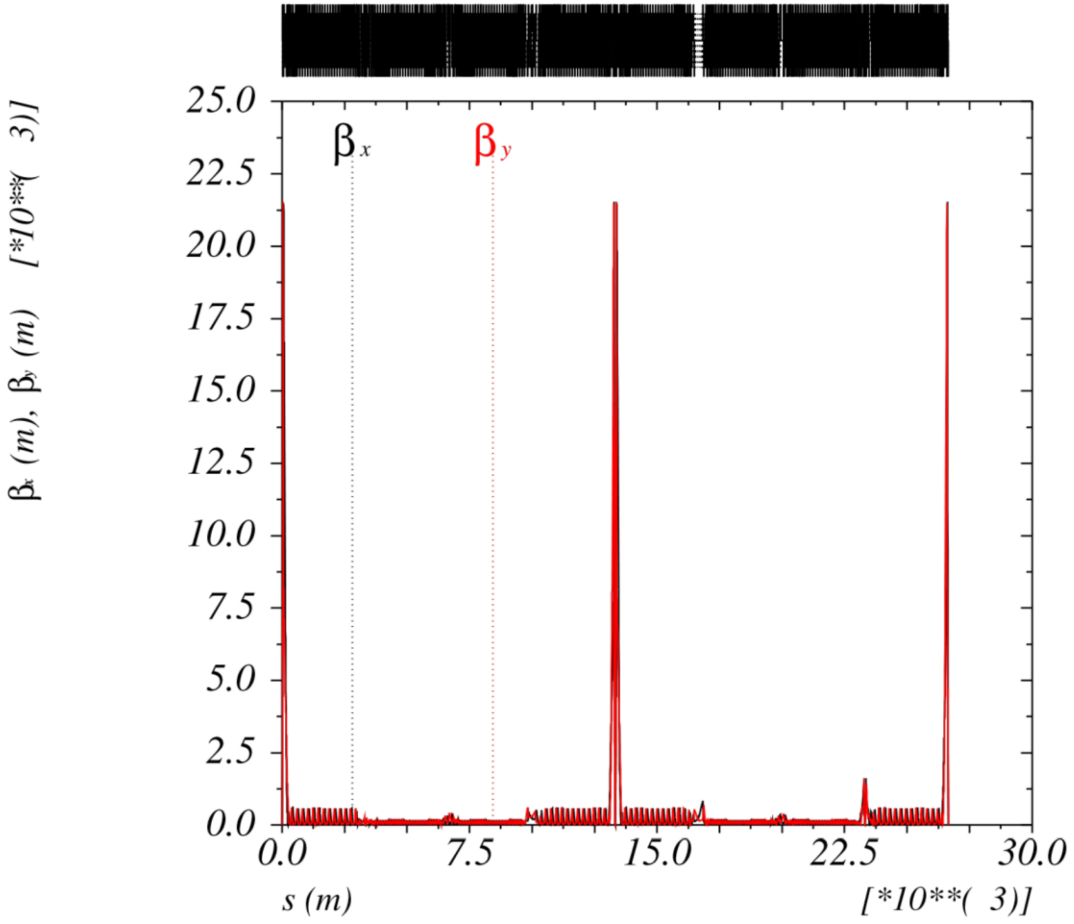
Parameter	Unit	Value HL-LHC	LHC IR1/5 Q1/Q2/Q3
Magnetic field gradient	T/m	132.6	200/205
Magnetic length	m	4.20/7.15	6.3/5.5/6.3
Aperture radius	mm	75	22.2/28.95
Number of turns per pole		50	
Conductor material		Nb_3Sn	NbTi

Implement this triplet in IR2 -> Gain of aperture!

Betafunction of the Achromatic Telescopic Squeeze Optics [2]

1. Squeeze to ß*=30cm in IP1 and IP5
2. Telescopic Squeeze from adjacent IRs to ß*=15cm

- Pre-squeeze with defined phase advances in IR1/IR5
- Telescopic squeeze by only acting on the adjacent matching quadrupoles
- The peak betafunctions in the arcs increase with decreasing ß*
- Introduce a beta-beat to have high betas at the position of the sextupoles -> increase their effectivity!
- The magnets of IP2 are being used for the squeeze in IP1



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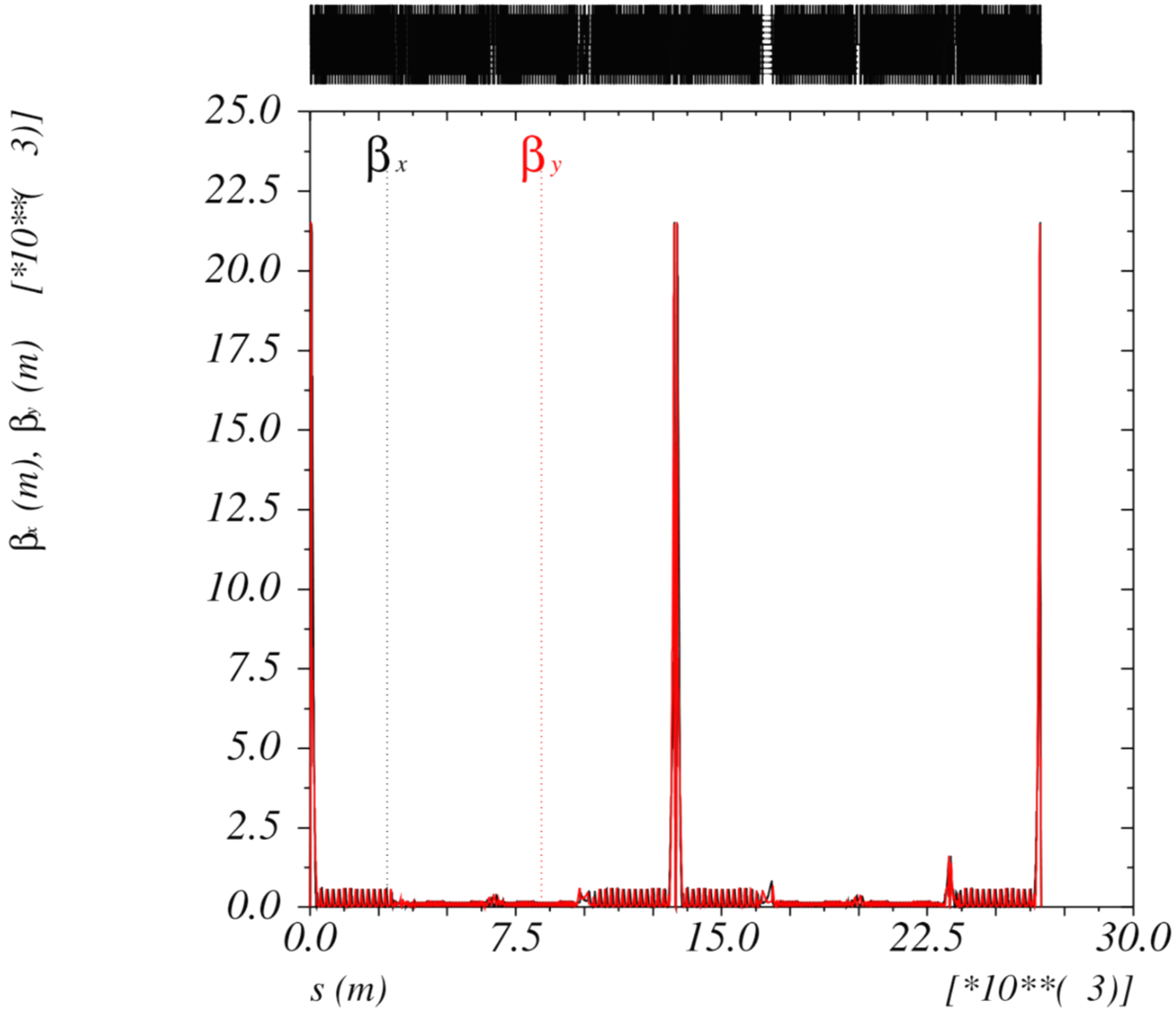
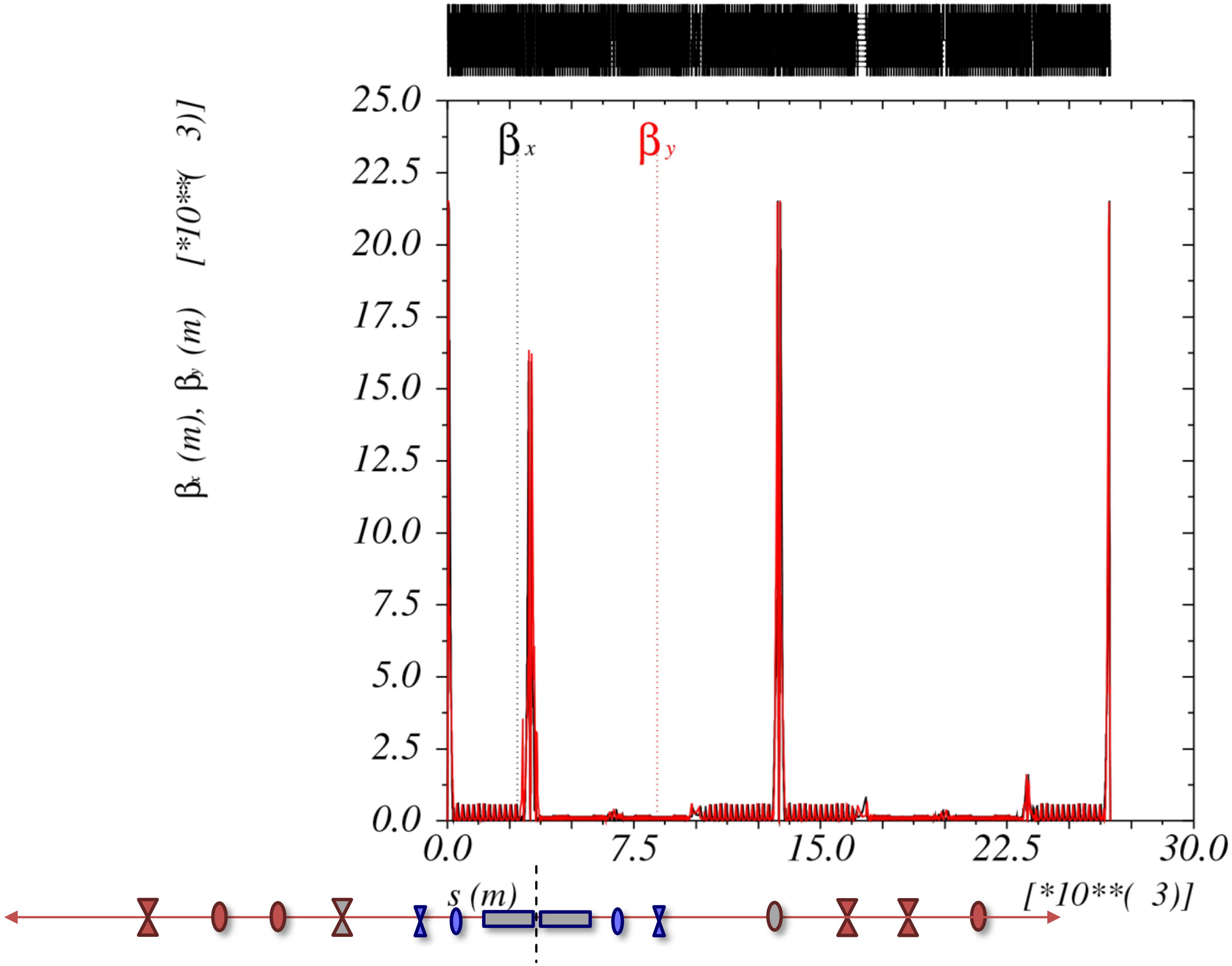
Development of the proton Optics in IP2 for e-p collisions



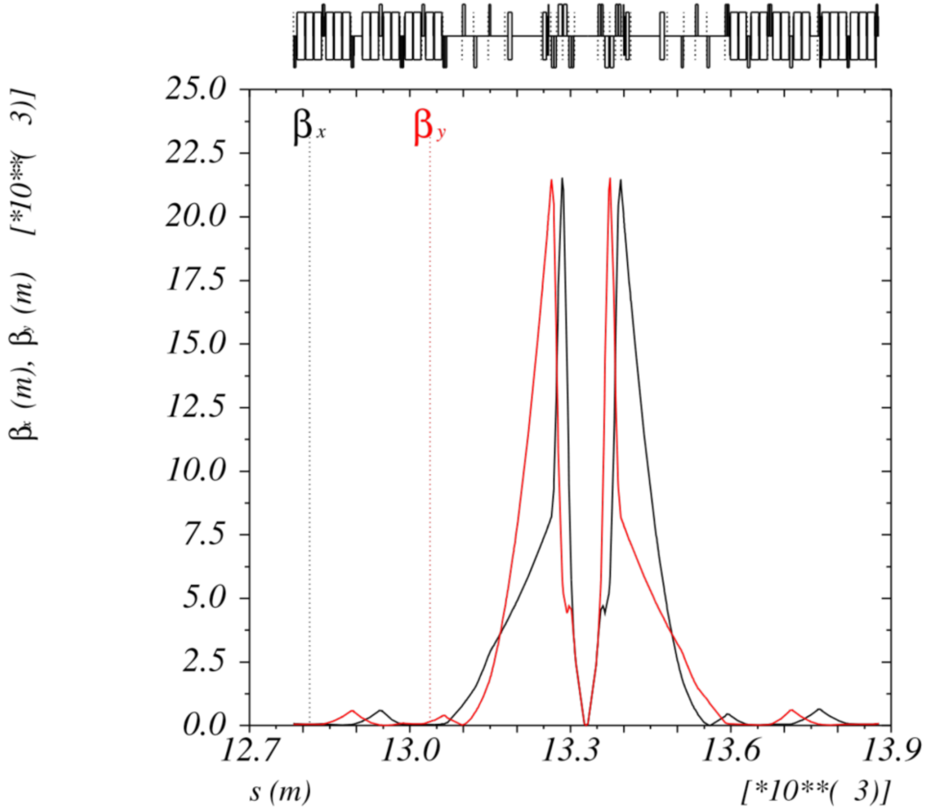
Normal HL-LHC collision Optics with ATS squeeze

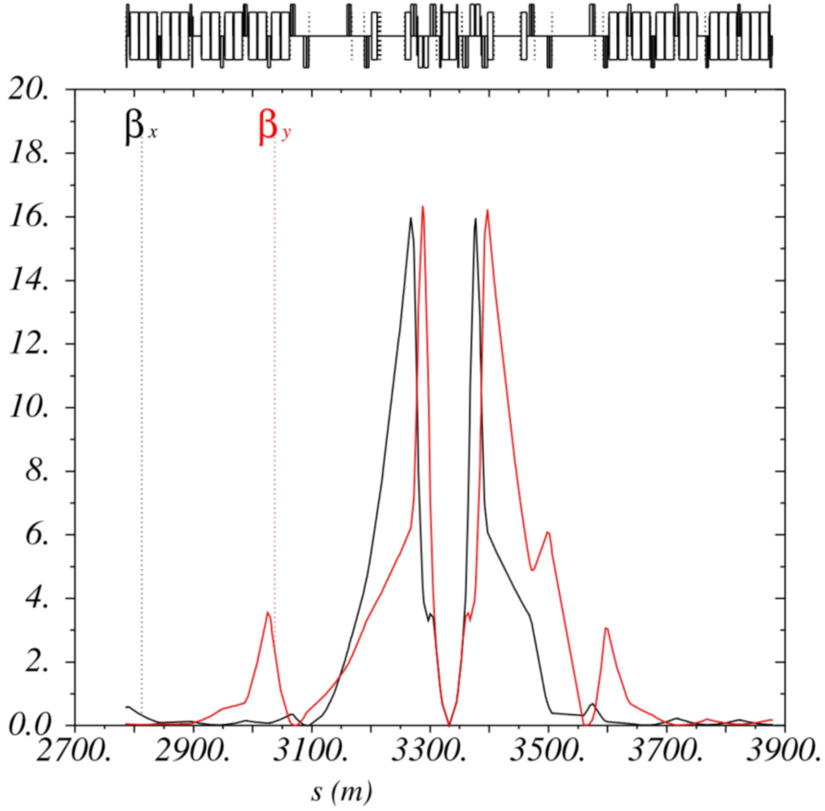
Focusing of the e-p collision proton beam in IP2



1. Introduce electron IR in IP2 and correct optics and orbit
2. Introduce new Nb3Sn triplet and D1 and rematch to the original ß* of 10m
3. Start squeezing ß* in IP2, match the ß*, the α function, and the dispersion
4. Rematch phase advance at IP4
5. Correct chromaticity globally

Comparison IR1/5 and IR2 squeeze





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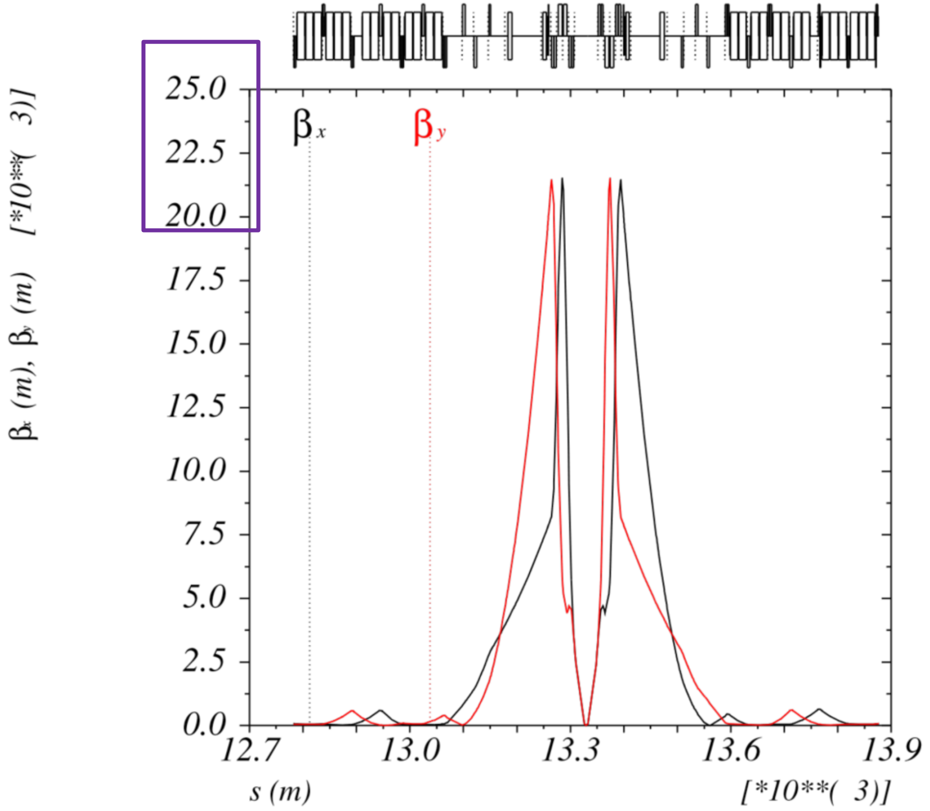
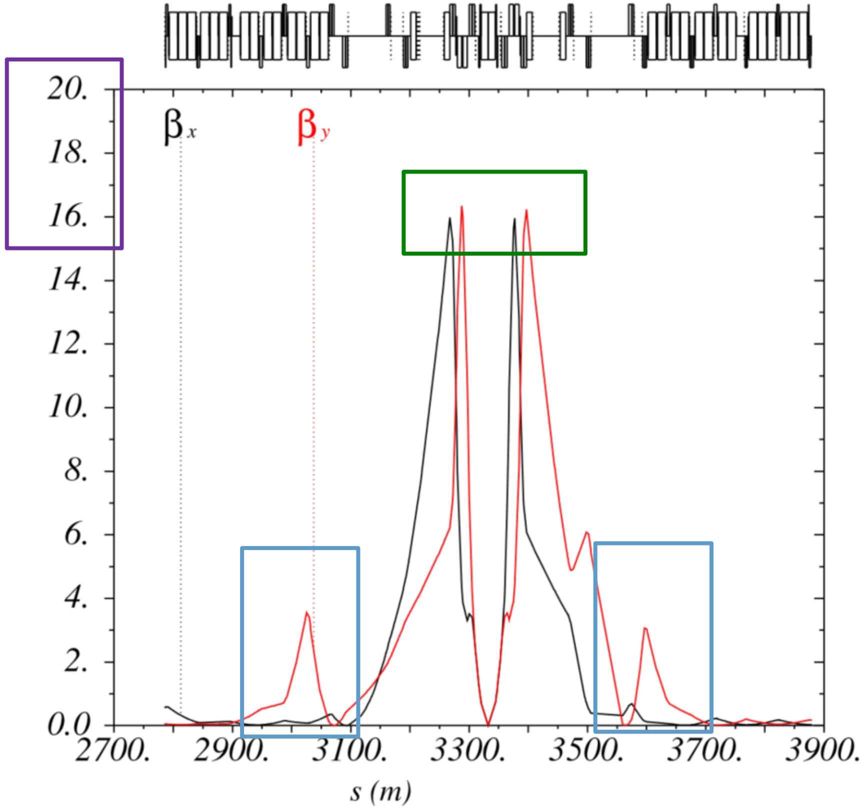
Comparison IR1/5 and IR2 squeeze

Slight asymmetry: probably caused by the electron IR





Height of the betafunctions in the triplet is smaller to make space for the three beams.

Peaks: strength limits of the quadrupoles? Positioning different to IR1 and IR5. Phase advance is not matched here.

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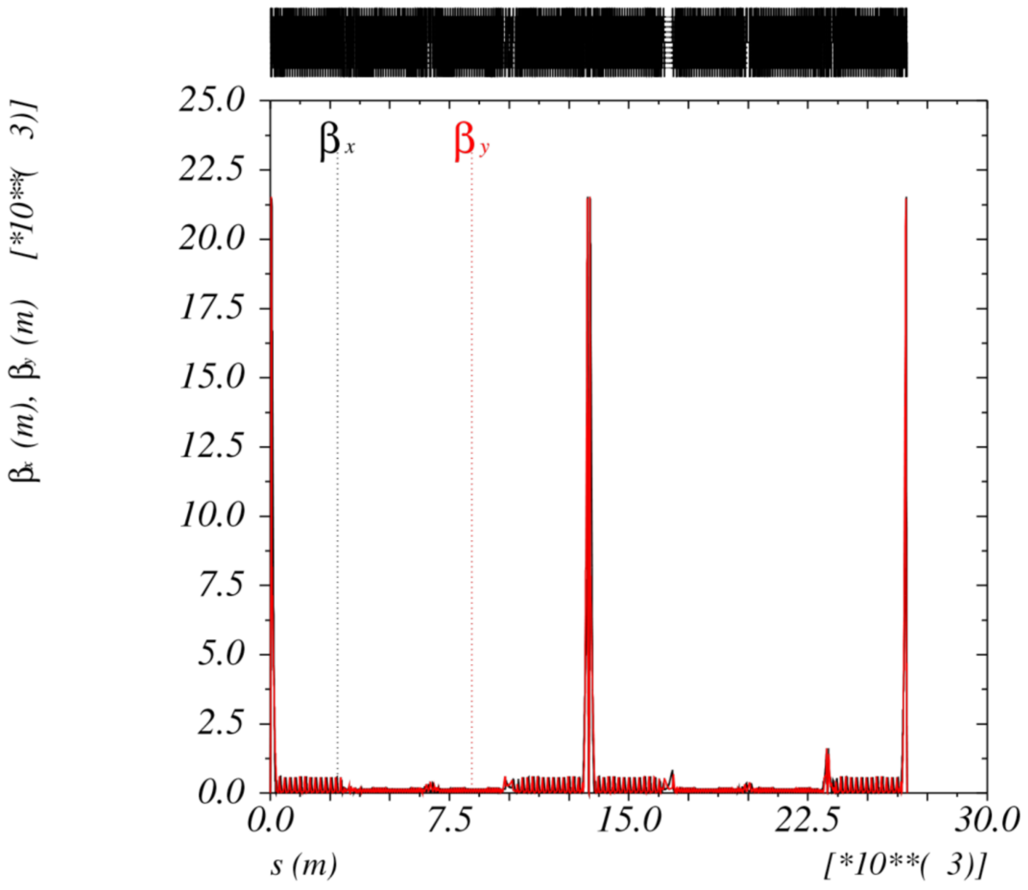
Optics rematch for the spectating proton beam



1. The new triplet and the new D1, as well as the electron IR, are inserted
2. These are locally rematched at IP2, to a ß* of 10m
3. All conditions are locally rematched on the left of IP3
4. The beam is relaxed to ß* values between 18m and 24 m, to stay as small as possible in the shared interaction region
5. The chromaticity is corrected globally

Possible modular optics for both proton beams:

- This matching routine has been performed for the following optics:

ß$_1$* [m]	0.2	0.25	0.3	0.35
ß$_2$* [m]	18-24	18-24	18-24	18-24
Luminosity [$cm^{-2}\,s^{-1}$]	2.5×10^{33}	2.0×10^{33}	1.67×10^{33}	1.4×10^{33}

- The corresponding module can be called additionally to the HL-LHC sequence
- The highest luminosity exceeds the first design goal in the LHeC Design Report

$$L = \frac{N_1 \cdot N_2 \cdot n \cdot f}{4\pi\sigma_x\sigma_y} [cm^{-2}s^{-1}]$$

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