Proton Optics for the Large Hadron electron Collider for alternating e-p and p-p Operation

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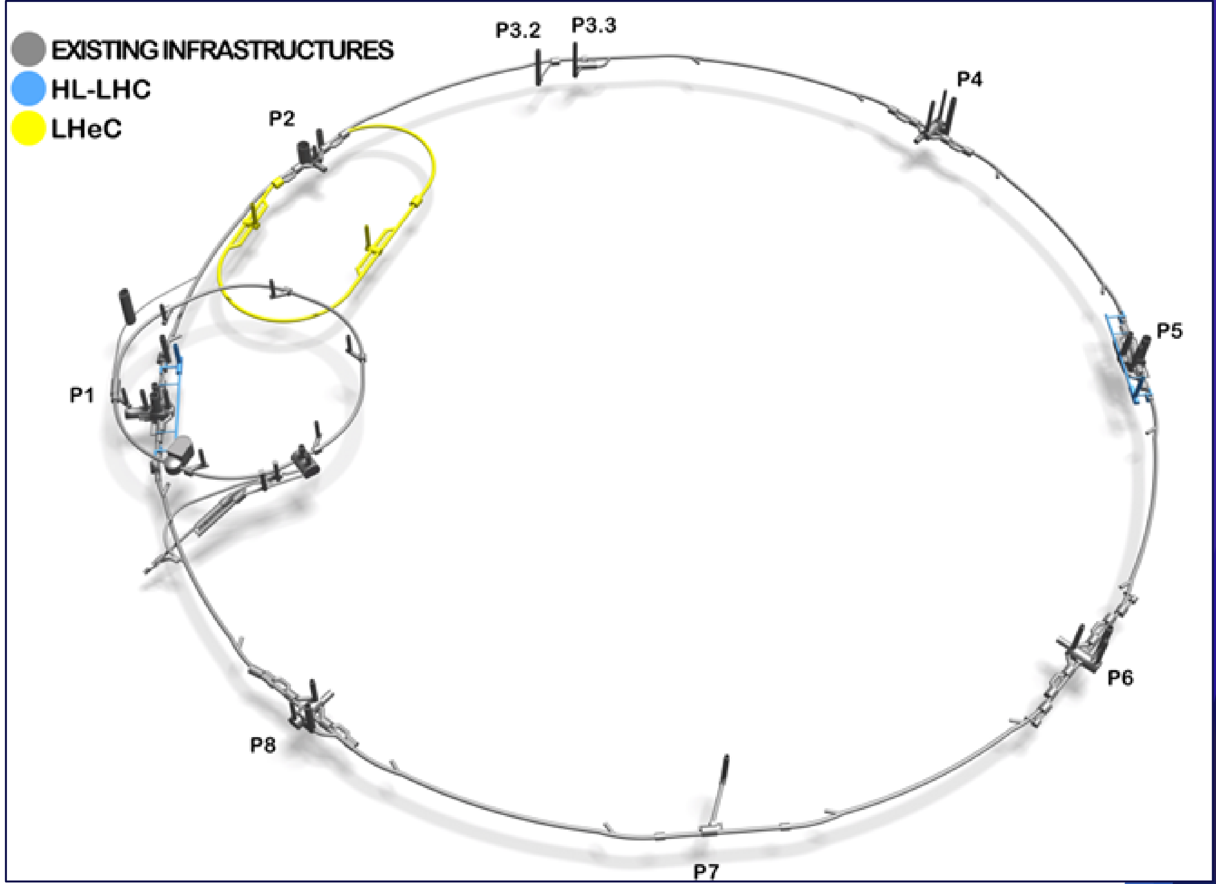
The Large Hadron electron Collider (LHeC)

- 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
- This would enable deep inelastic scattering e-p experiments in IP2 with concurrent p-p operation with the other LHC experiments, and alternating operation with ALICE in IP2

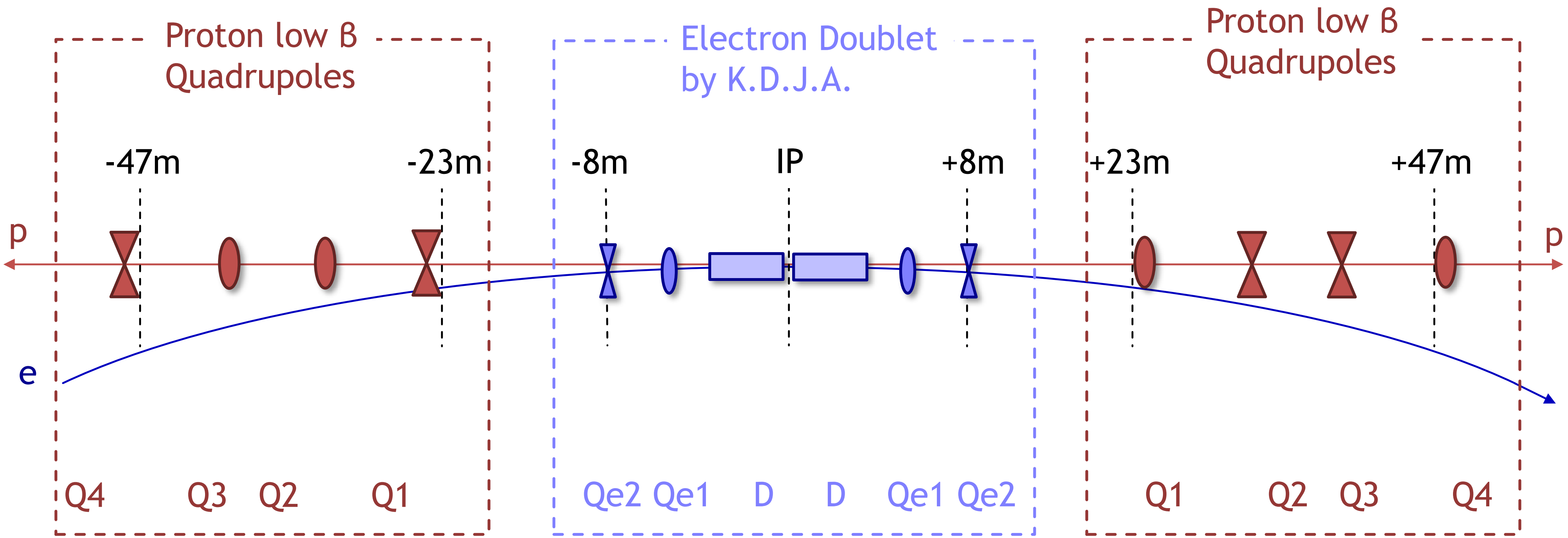


Create a three beam optics in P2, enabling e-p collisions and one spectator proton beam passing by

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

LHeC Design Report

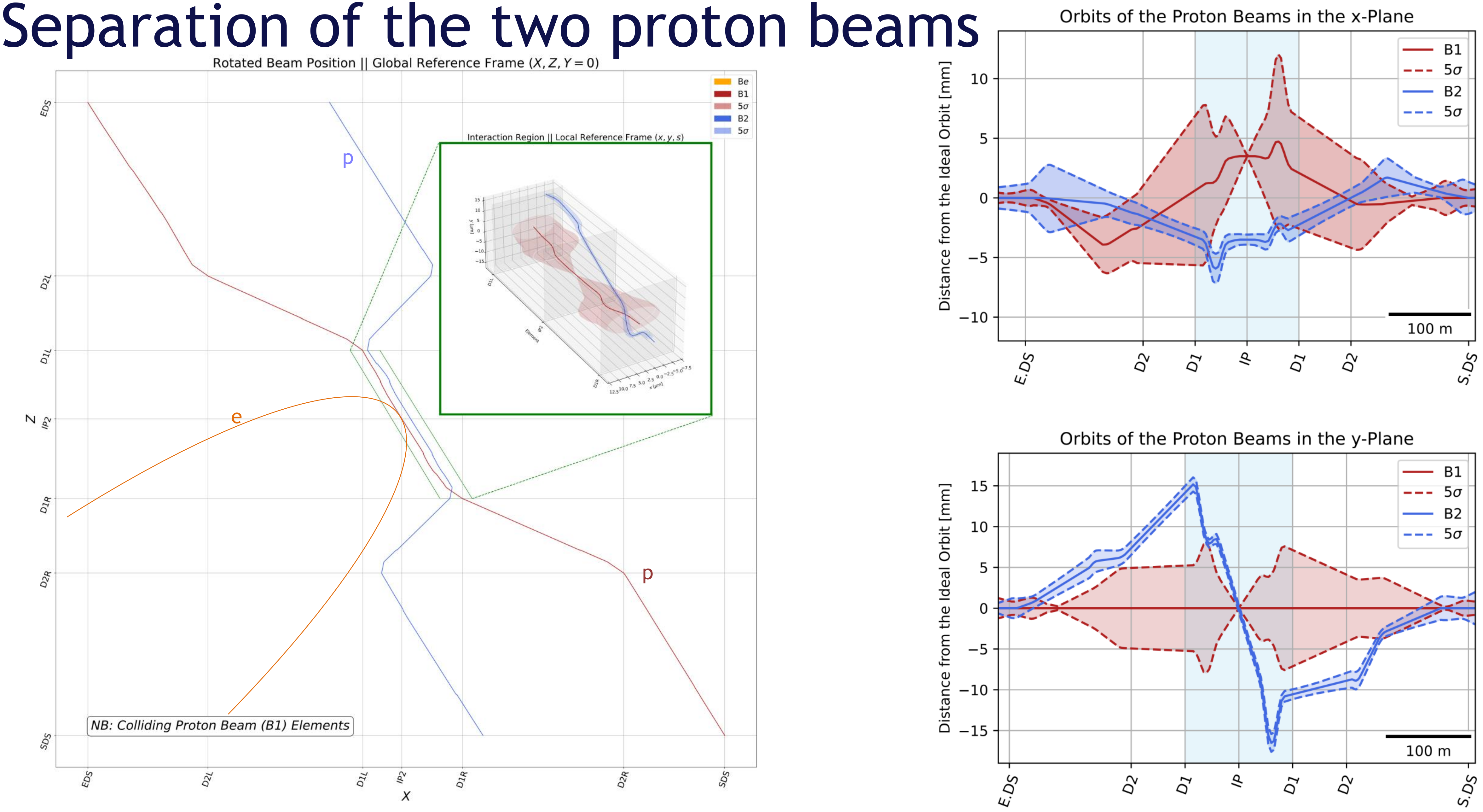
The LHeC interaction region:



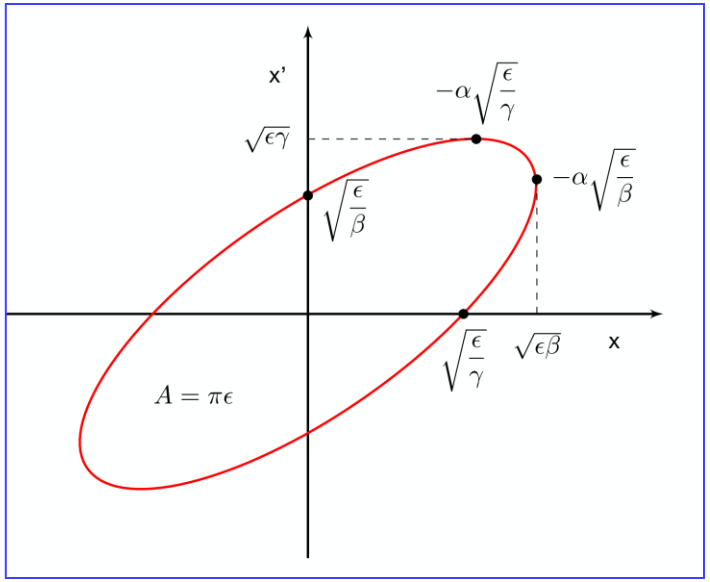
Create a three beam optics, with e-p collisions and one proton beam passing by

[PhD thesis K.D. J. André]()

Separation of the two proton beams



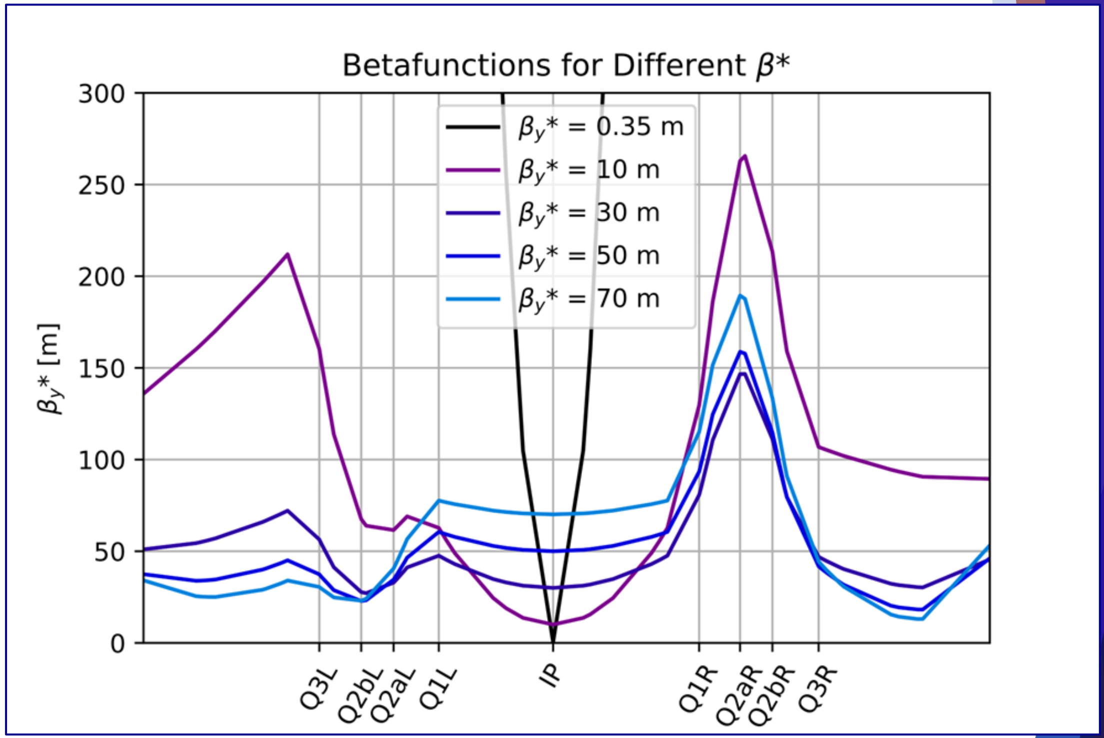
3D plot: M. Smith



Phase space diagram [4]

Mini-beta Insertion

Due to Liouville's theorem the phase space of the beam is conserved ➡ blowup of the betafunction before the IP



- Betafunction at a distance l before a symmetry point ß*:

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

- Find optimal β^*: $\frac{d\beta(s)}{d\beta^*} = 1 - \frac{l^2}{\beta^{*2}} = 0$
- This gives the smallest beta at a distance l for: $\beta^* = l$

➡ The focusing magnets before the IP need the biggest aperture

Asymmetric proton beam optics

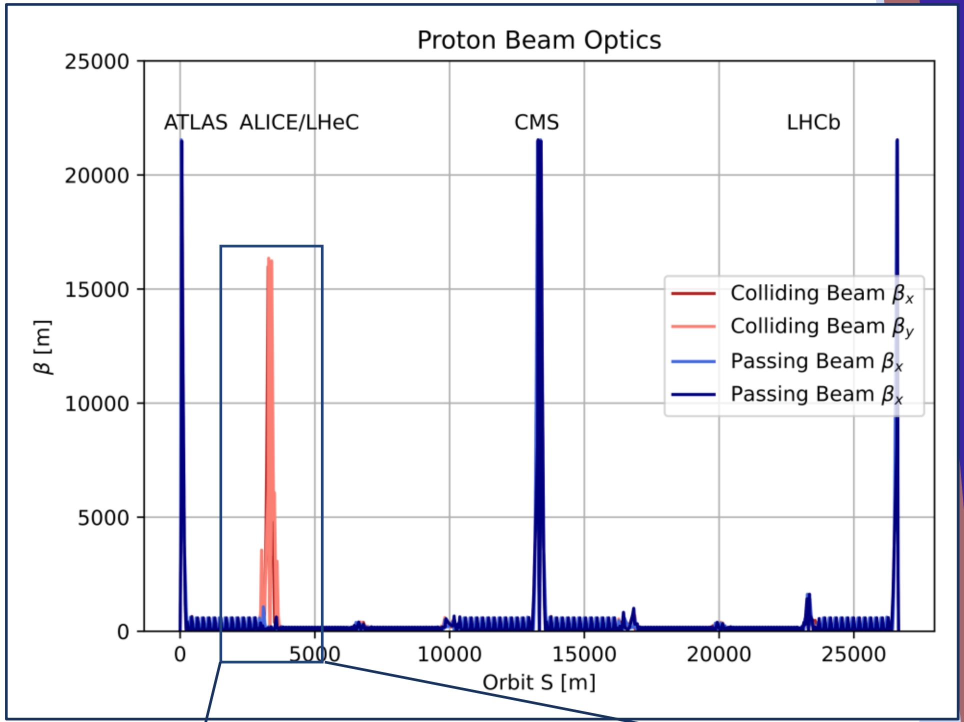
- Relax the non-colliding proton beam to maximize the distance between the proton beams in the shared aperture

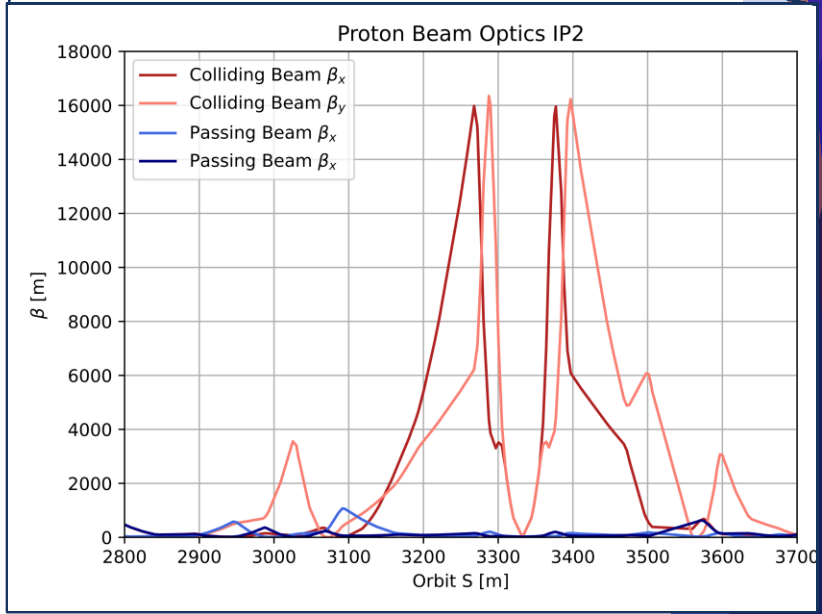
$$\beta(l) = \beta^* + \frac{l^2}{\beta^*}$$

- This enables e-p collisions with a ß* of 0.2m and thus a luminosity of $2.5 \cdot 10^{33} cm^{-2} s^{-1}$
- A new triplet was installed for this design

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

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

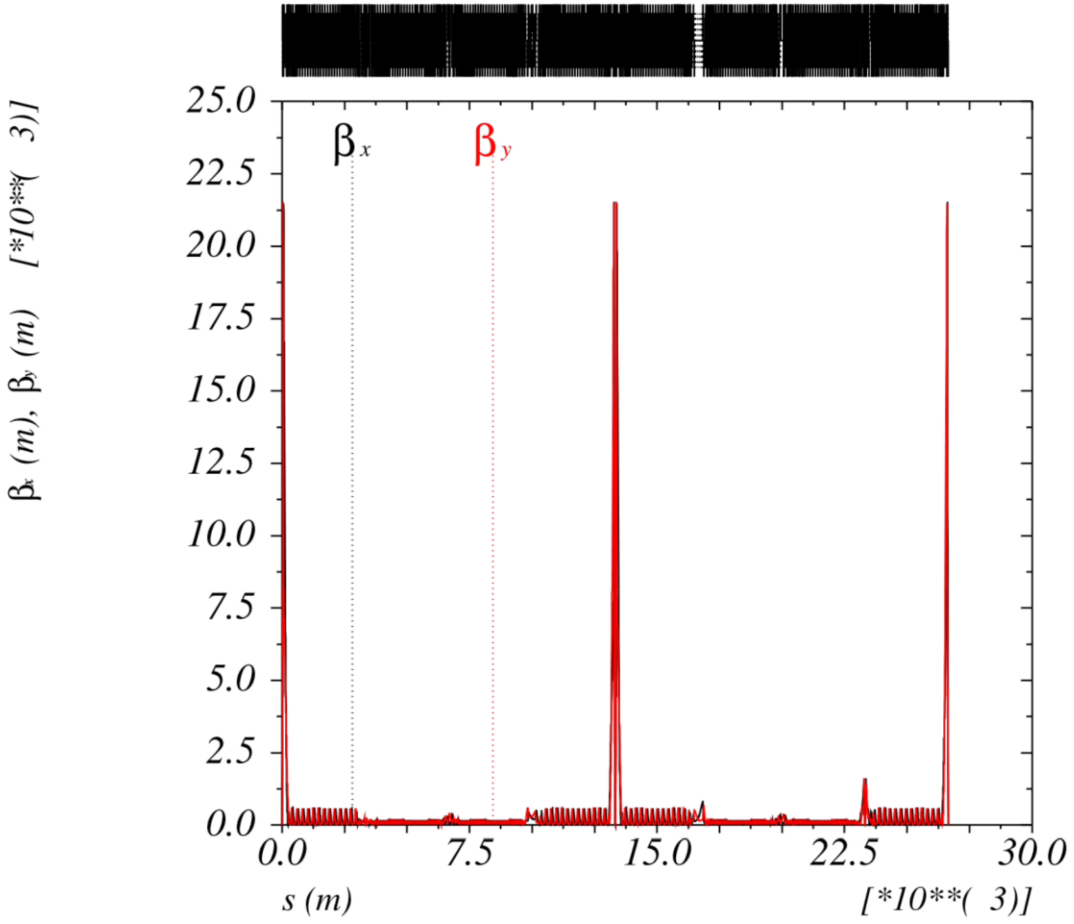




Betafunction of the Achromatic Telescopic Squeeze Optics [2]

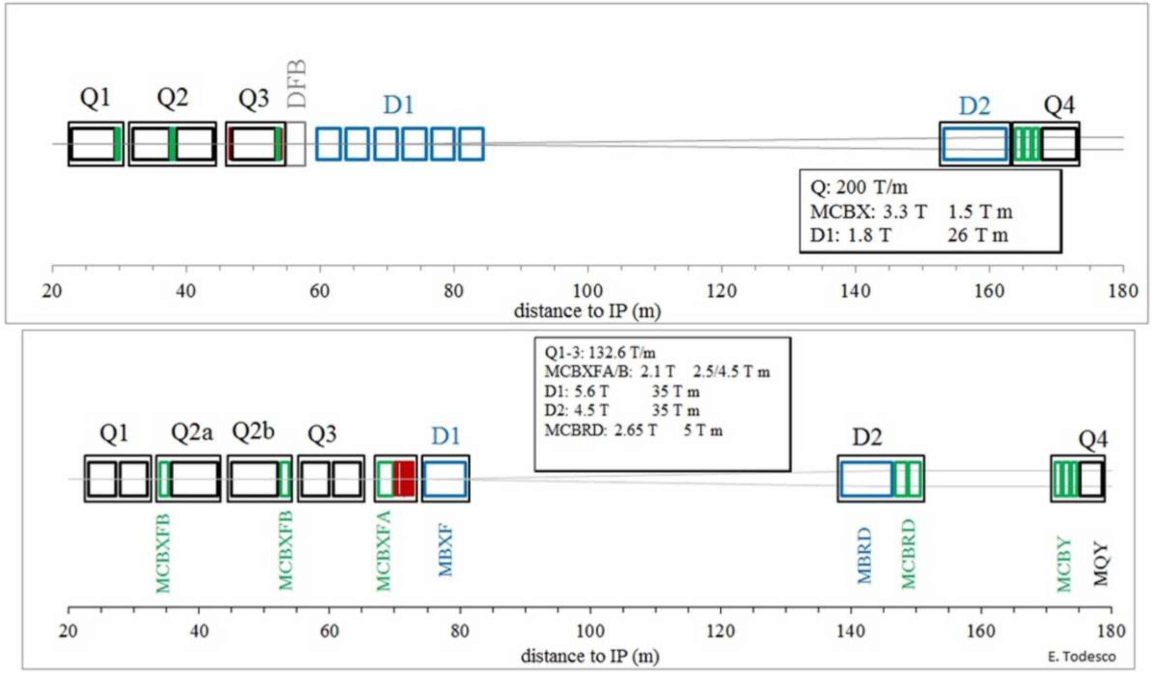
1. Squeeze to ß*=30cm in IP1 and IP5
2. Telescopic Squeeze from adjacent IRs to ß*=15cm

- 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



HL-LHC Upgrade

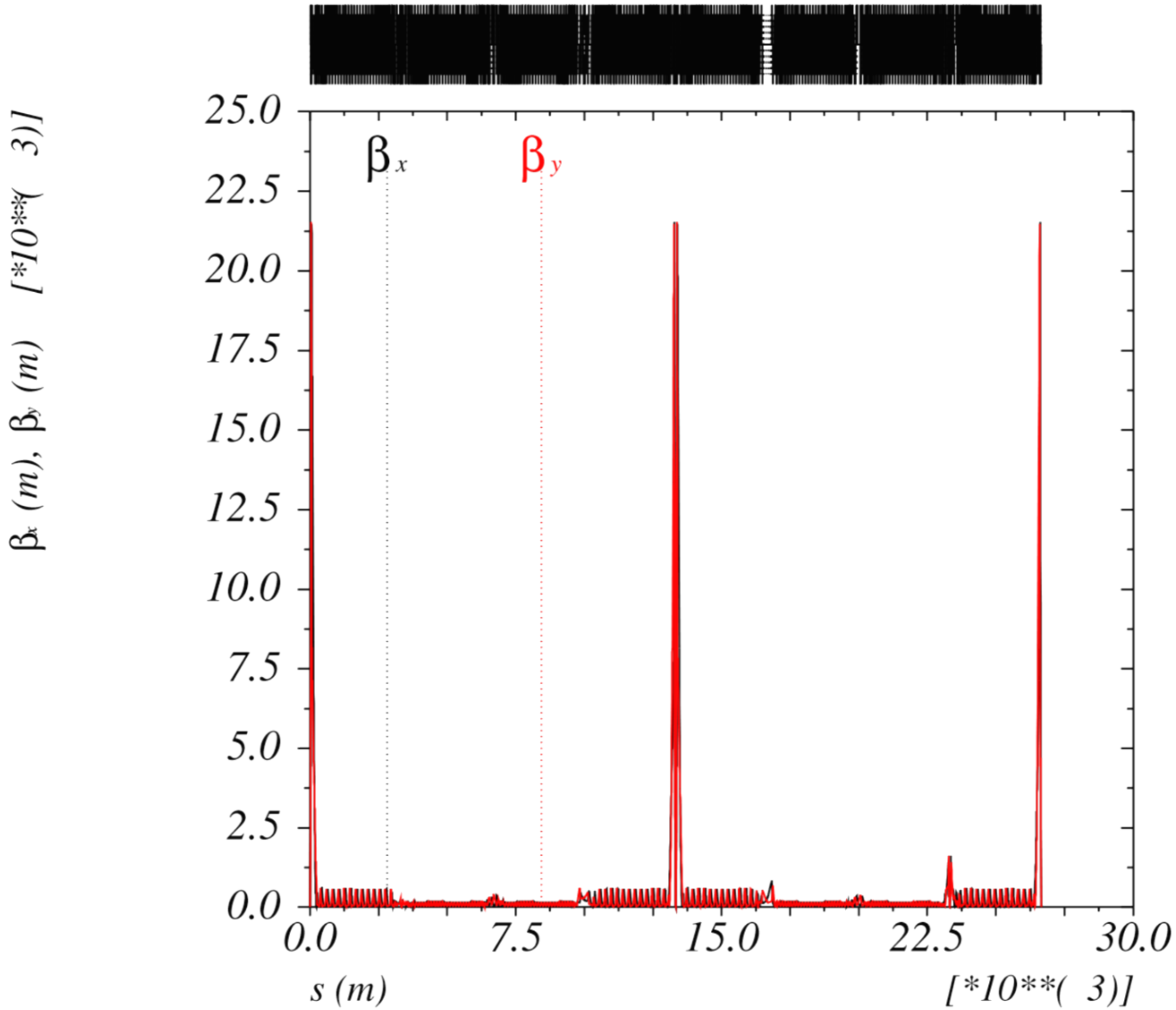
- Final focusing system is changed from NbTi to Nb3Sn
- D1 magnet superconducting
- crab cavities are inserted in IR 1 and IR 5
- Q4 is moved relative to the IP



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

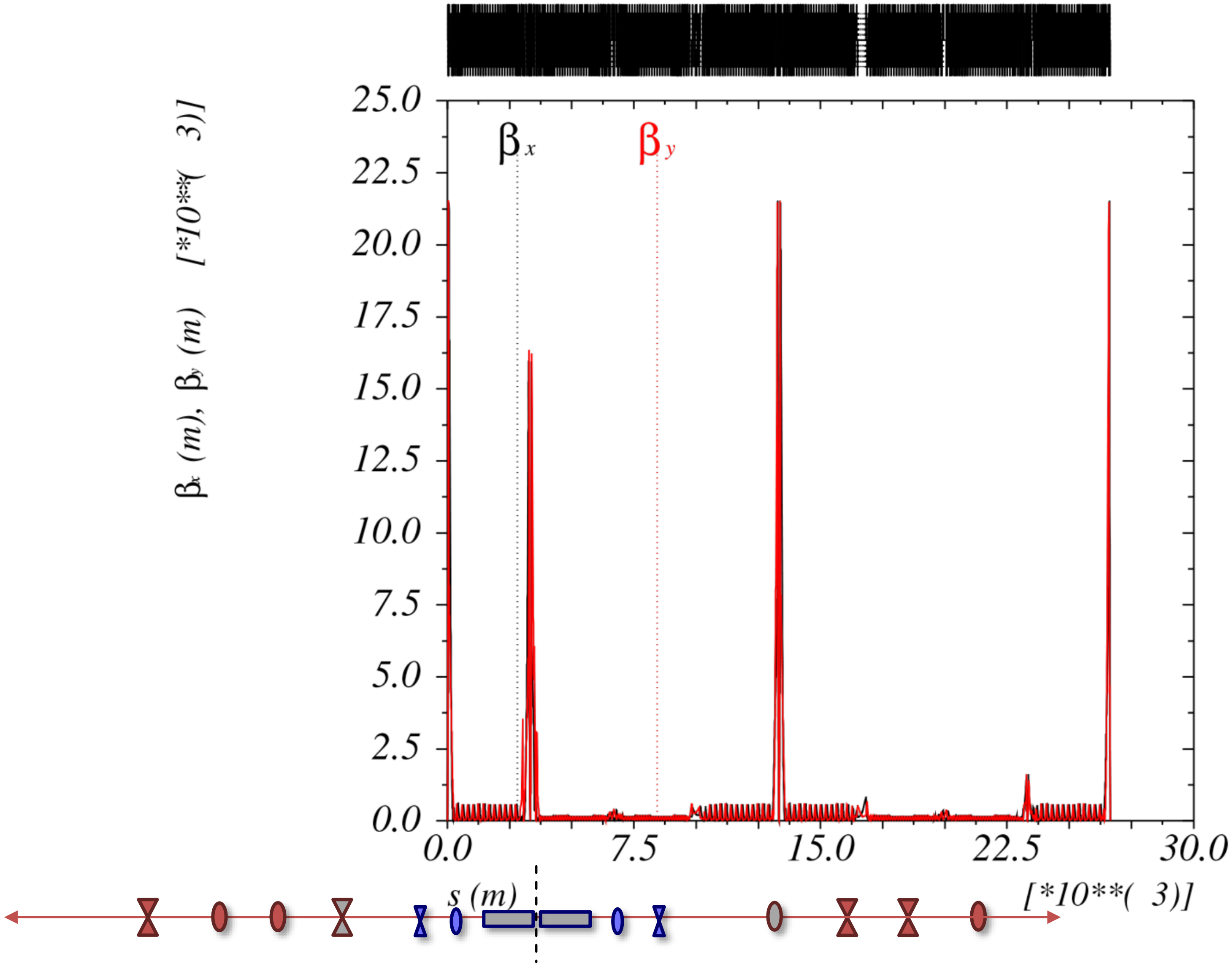
Implement this triplet in IR2 -> Gain of aperture!

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



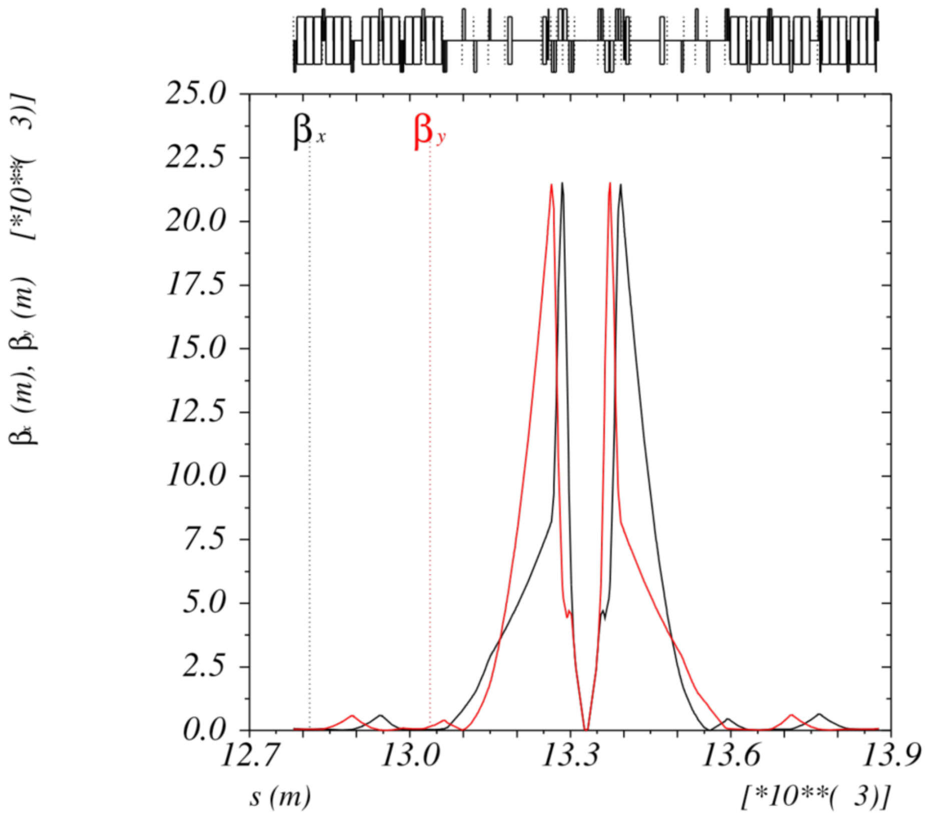
Normal HL-LHC collision Optics with ATS squeeze

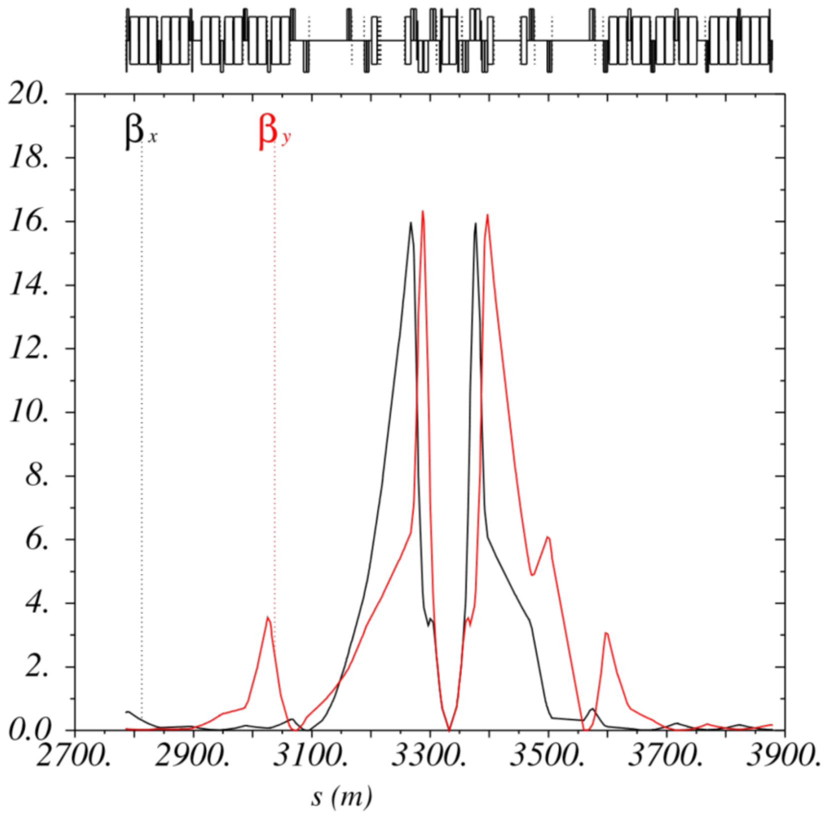
Focusing of the e-p collision proton beam in IP2



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

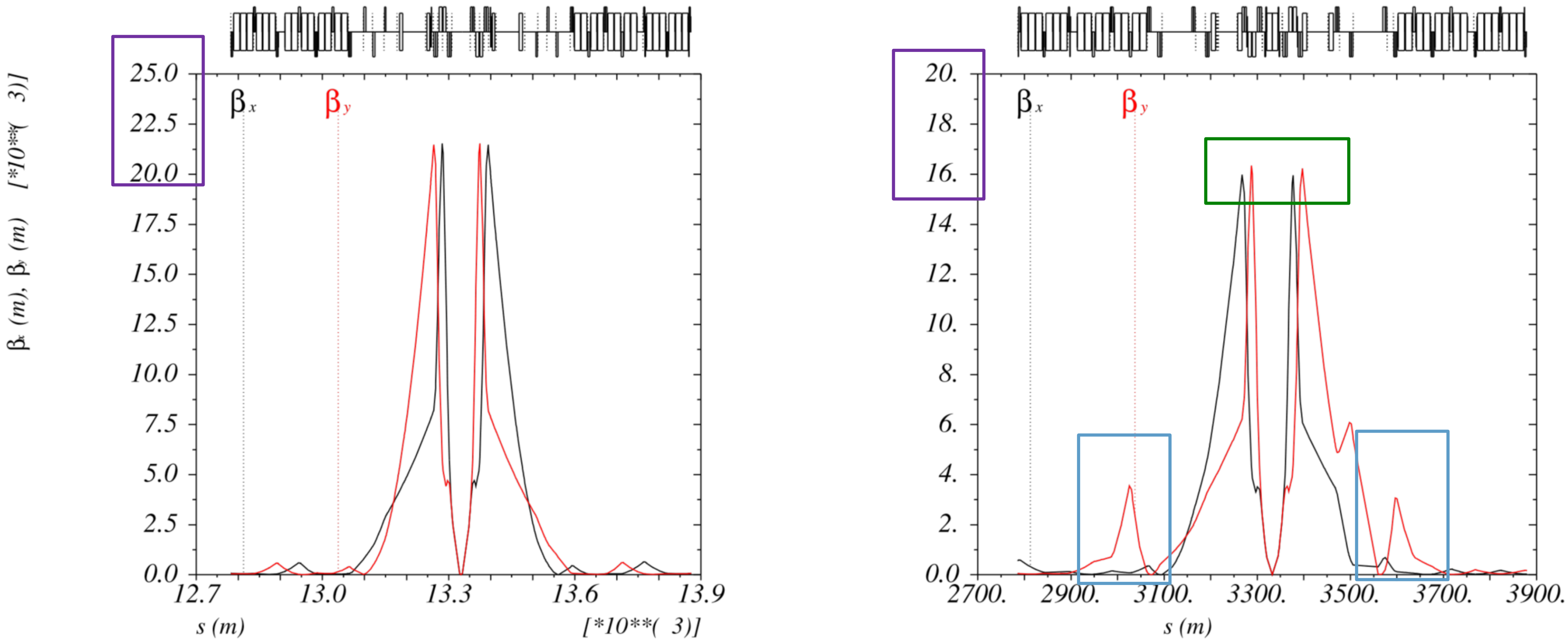
Comparison IR1/5 and IR2 squeeze





Comparison IR1/5 and IR2 squeeze

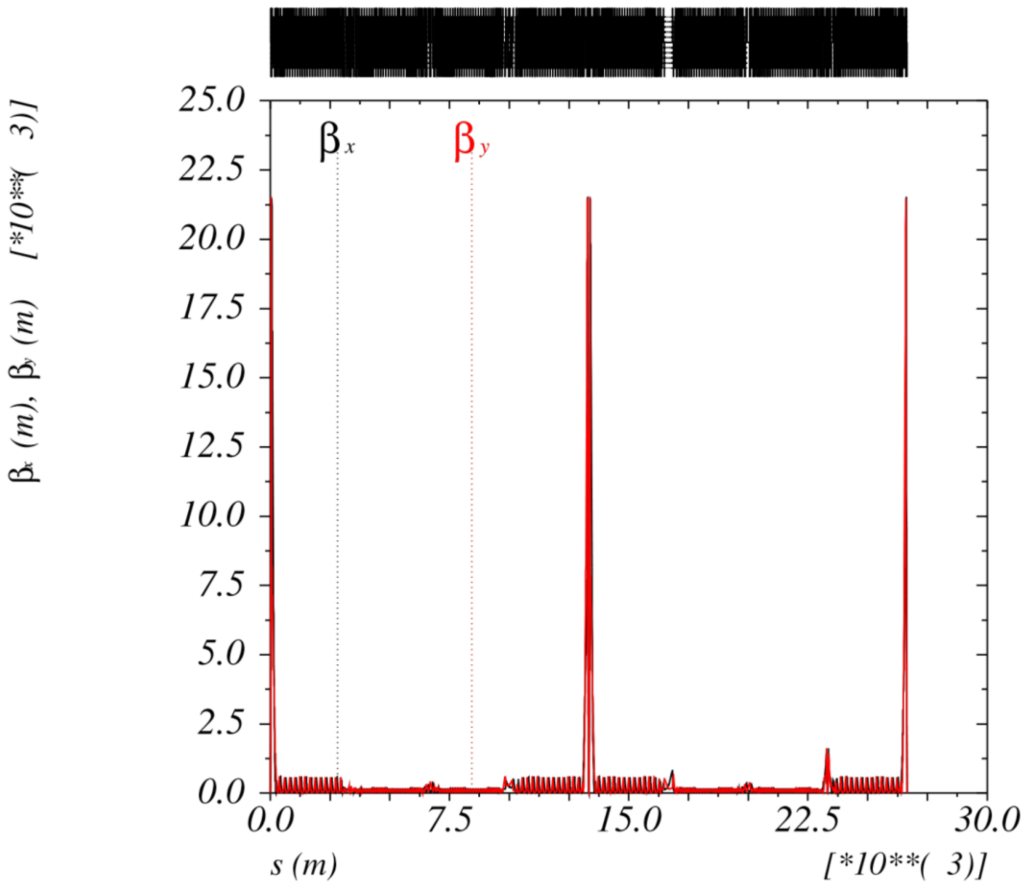
Slight asymmetry: probably caused by the electron IR



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.

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:

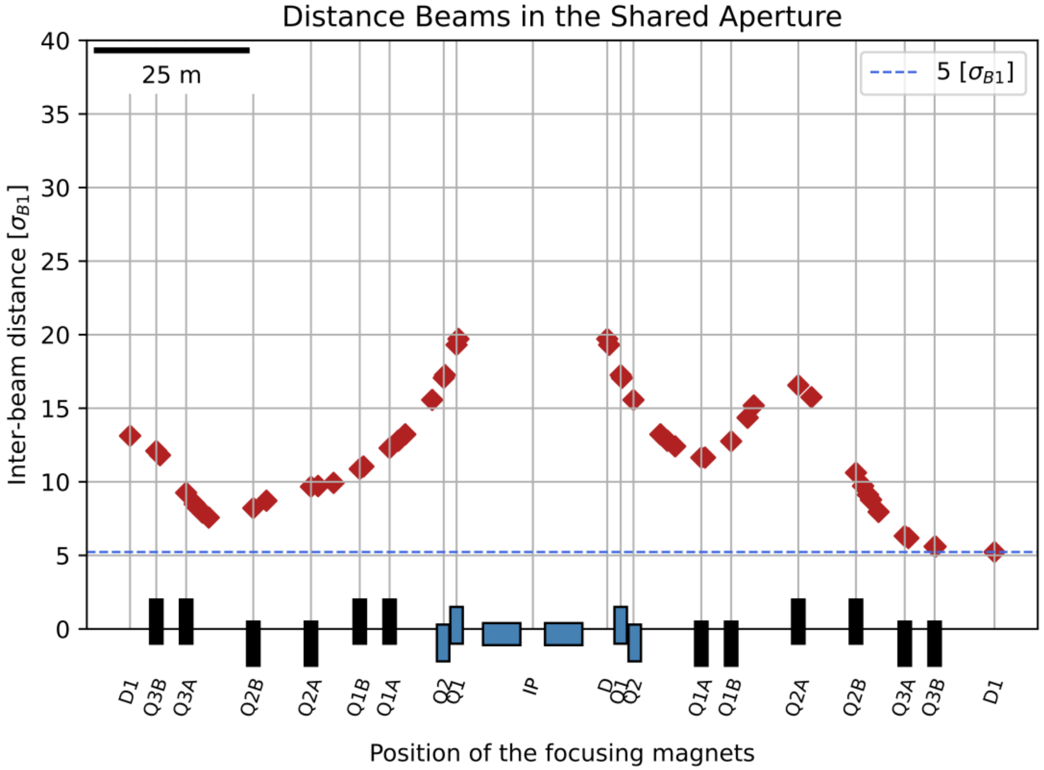
ß$_1$* [m]	0.2	0.25	0.3	0.35
ß$_2$* [m]	18-24	18-24	18-24	18-24
Luminosity [$cm^{-2} s^{-1}$]	2.5×10^{33}	2.0×10^{33}	1.67×10^{33}	1.4×10^{33}

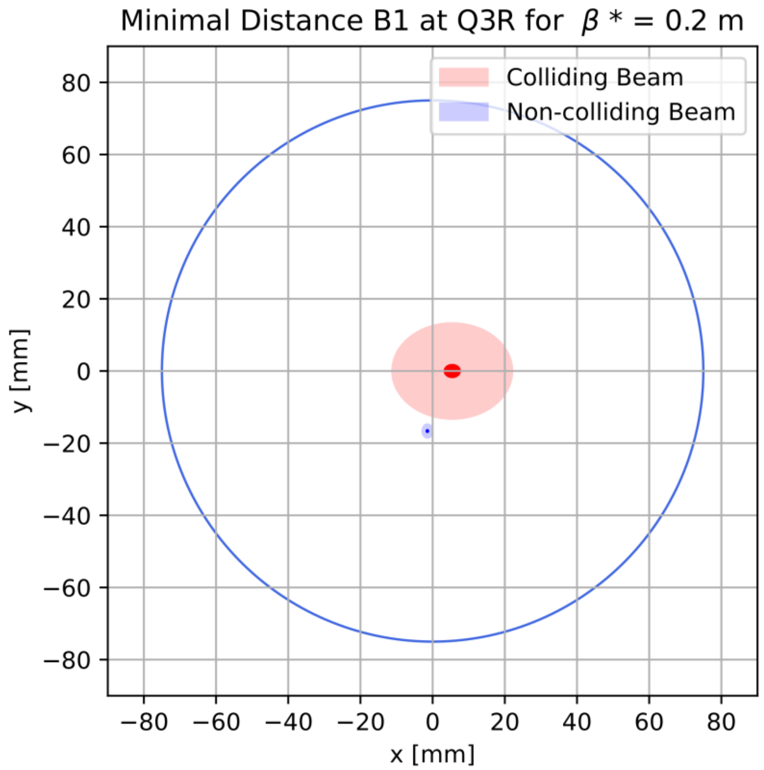
- The corresponding module can be called additionally to the HL-LHC sequence
- The highest luminosity exceeds the first design goal in the LHeC Design Report

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

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

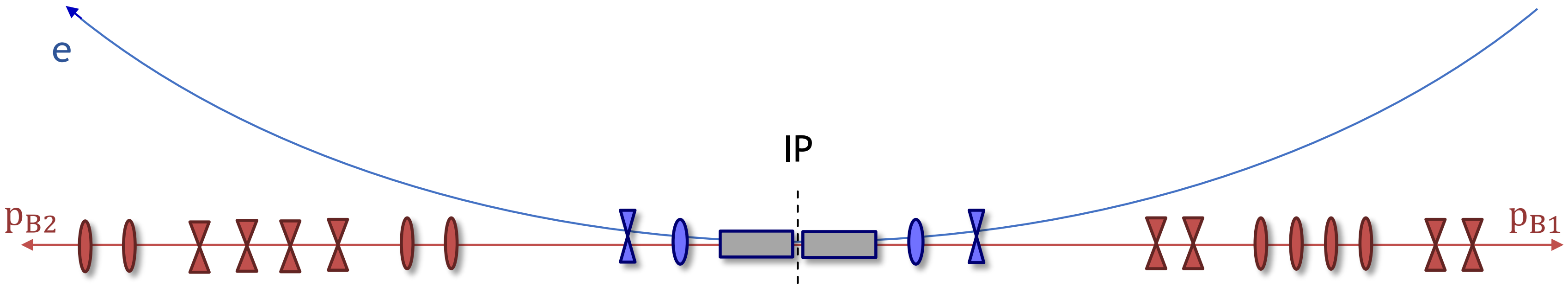




Cross section of the magnet in which the two proton beams get closest

Summary & Outlook

- The local impact of an optimized electron IR on the proton beam orbit and optics can be corrected in the HL-LHC
- Several modular proton optics have been developed by using the arcs and additional insertions to match optics, the tune and the chromaticity
- They enable 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
- These are the first LHeC optics to enable alternate operation with the ALICE experiment/upgrade
- **Outlook:** Tracking simulations to investigate the impact of the proton beams and the electron beam on each other



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”

Thank you for your attention.

Background Slides

Theoretical Background

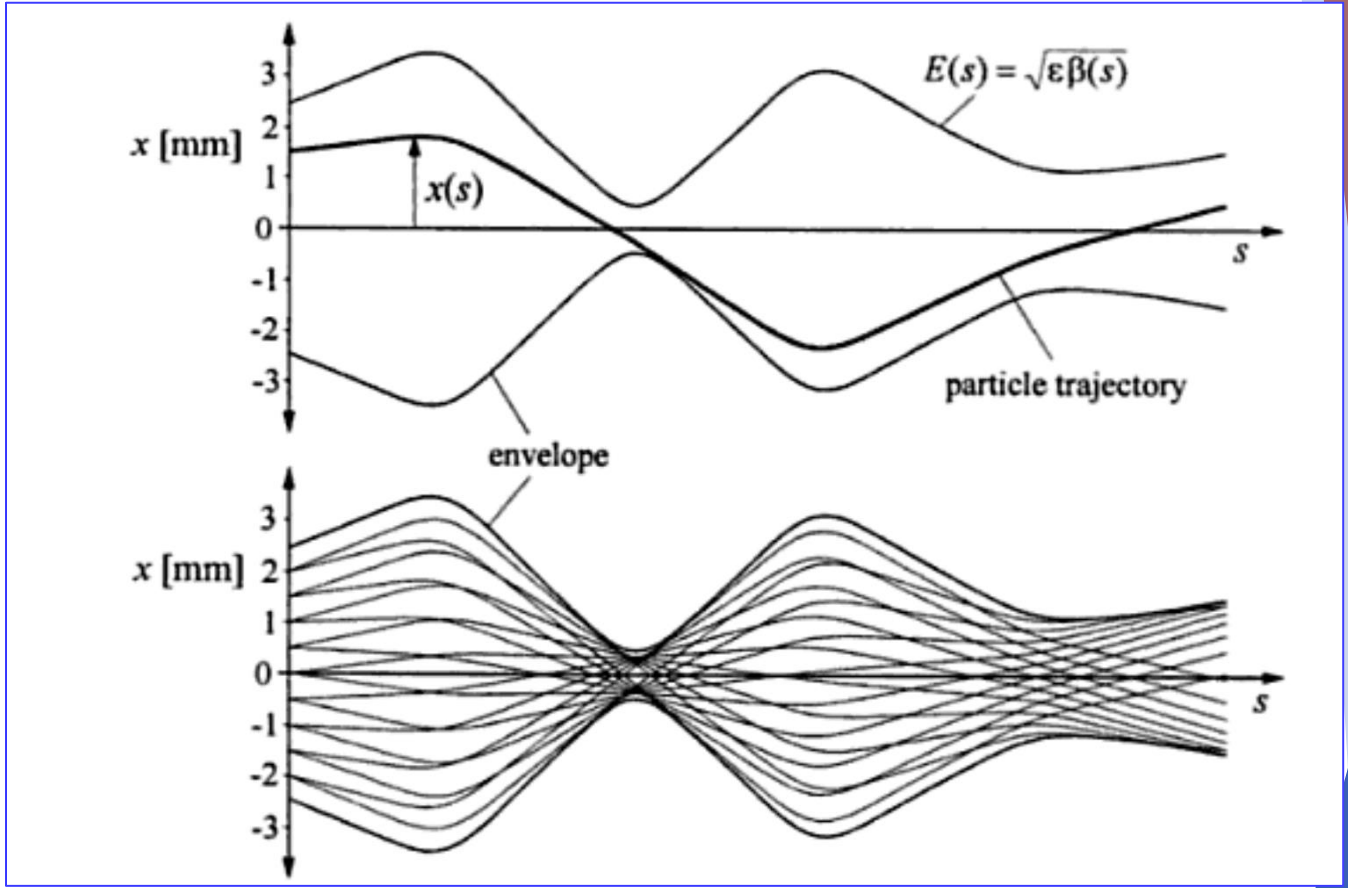
Recap: Beam Envelope

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

- During their travel on the trajectory s, the particles perform betatron oscillations
- The beam envelope for many particles and many turns is defined as:

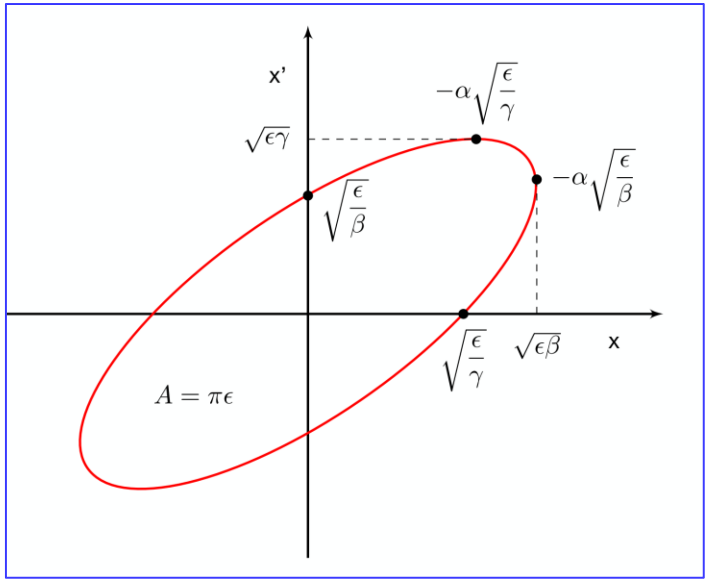
$$E(s) = \sqrt{\varepsilon\beta(s)} = 1\sigma_u \qquad u = x, y$$

- ε is the energy dependent emittance
- β(s) defines the betafunction, which depends on the beam optics defining the beam size at a certain position s



Beam envelope, K. Wille

Mini-beta Insertion



Phase space diagram [4]

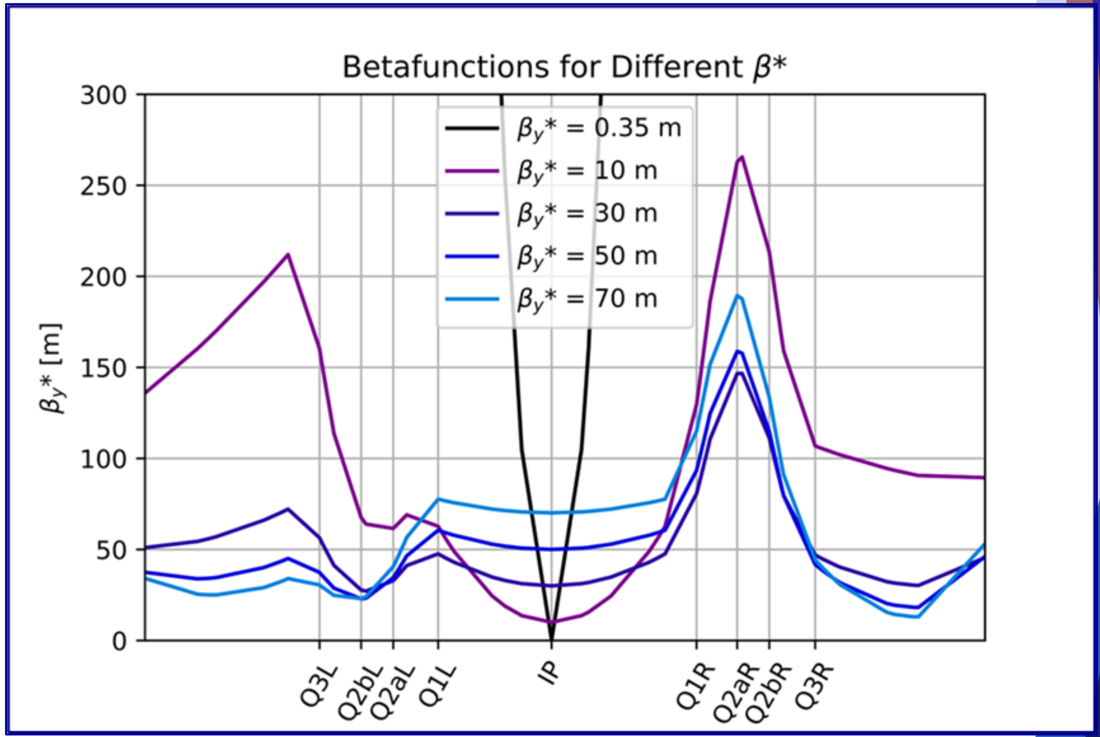
Due to Liouville's theorem the phase space of the beam is conserved ➡ blowup of the betafunction before the IP

- Betafunction at a distance l before a symmetry point ß*:

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

- Find optimal β^*: $\frac{d\beta(s)}{d\beta^*} = 1 - \frac{l^2}{\beta^{*2}} = 0$

- Smallest beta at a distance l for: $\beta^* = l$



➡ The focusing magnets before the IP need the biggest aperture

How does this affect our collider?

- The beam-size is defined as: $1\sigma_u(s) = \sqrt{\varepsilon\beta(s)} = \sqrt{\varepsilon\beta^*}$ at the IP with u=x,y

- Using the formula for the betafunction in a drift: $\beta(l) = \beta^* + \frac{l^2}{\beta^*}$

- For the FCC- hh collider with β^*= 0 .3 and L* = 40m this yields: $\beta(40) = 0.3m + \frac{40m^2}{0.3m}$= 5333.56m

- How far can we go in betastar with a drift of 15m?

$\beta(20) = \beta^* + \frac{20m^2}{\beta^*}$= 5333.64m ⇒ $\beta^* = 0.074m$

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

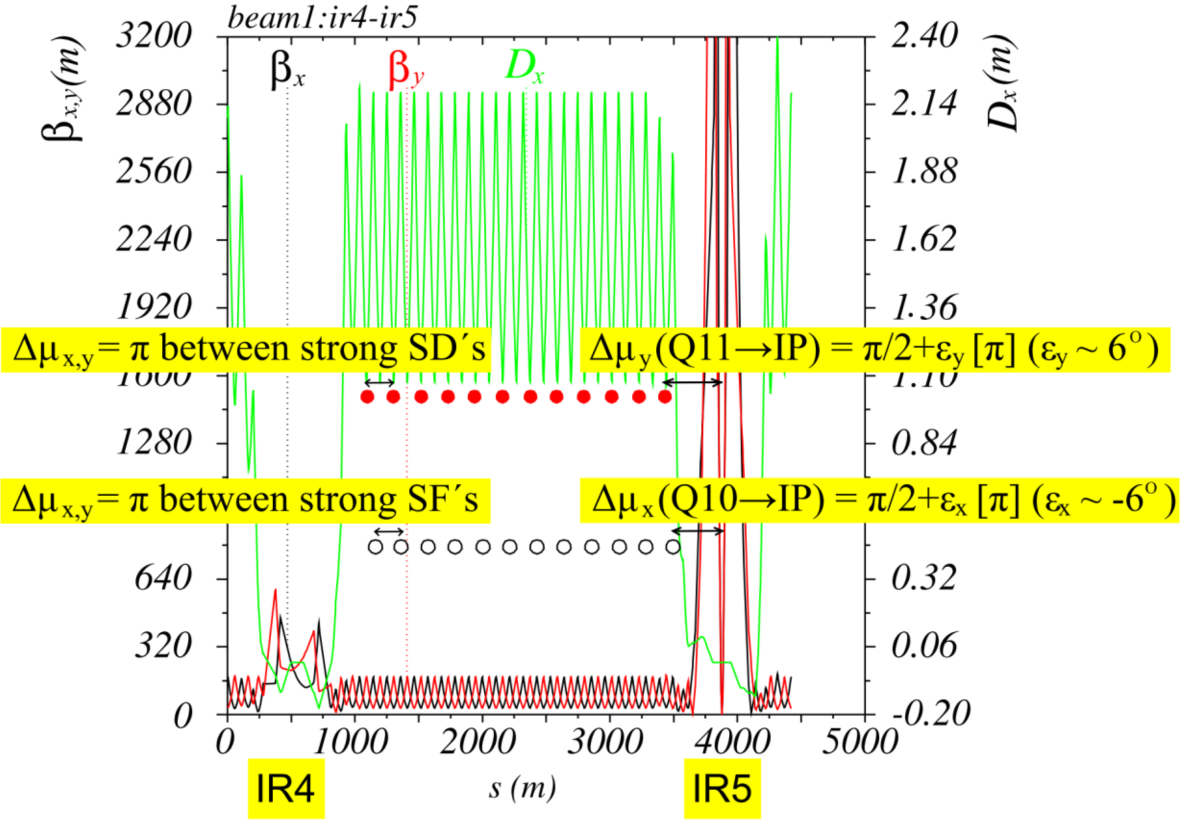
ATS Optics

Betafunction of the Achromatic Telescopic Squeeze Optics

- The chromaticity increases with the strength of the quadrupoles :

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

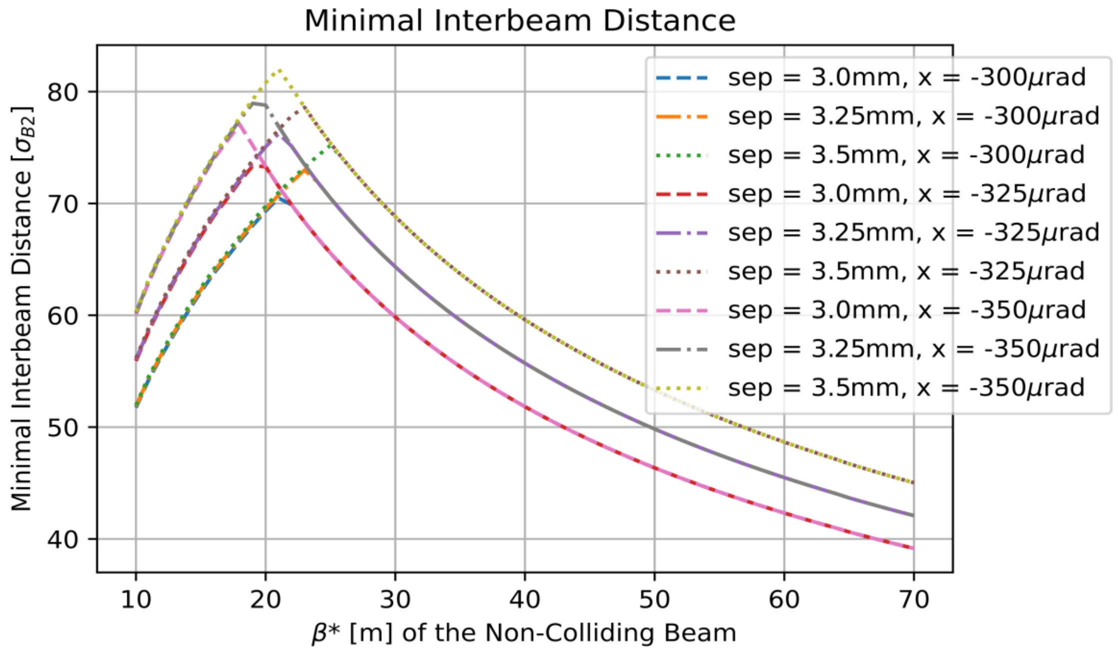
- Highest at points of high betafuntion!
- Limitation on ß*!
- Increase effectivity of sextupoles by introducing a beta-beat to have high betas at the position of the sextupoles -> increase their effectivity!

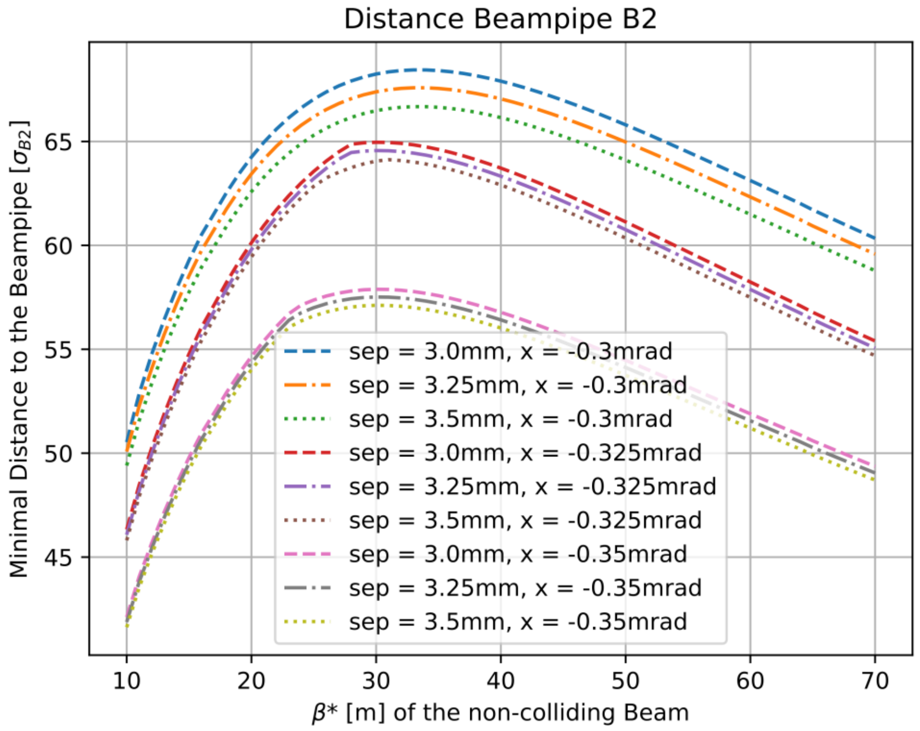


Betafunction before IP5 with position of the sextupoles [2] and optics to have a high betafunction here

Optimization of previous Optics

Parameter Optimization for the two proton beams [3]

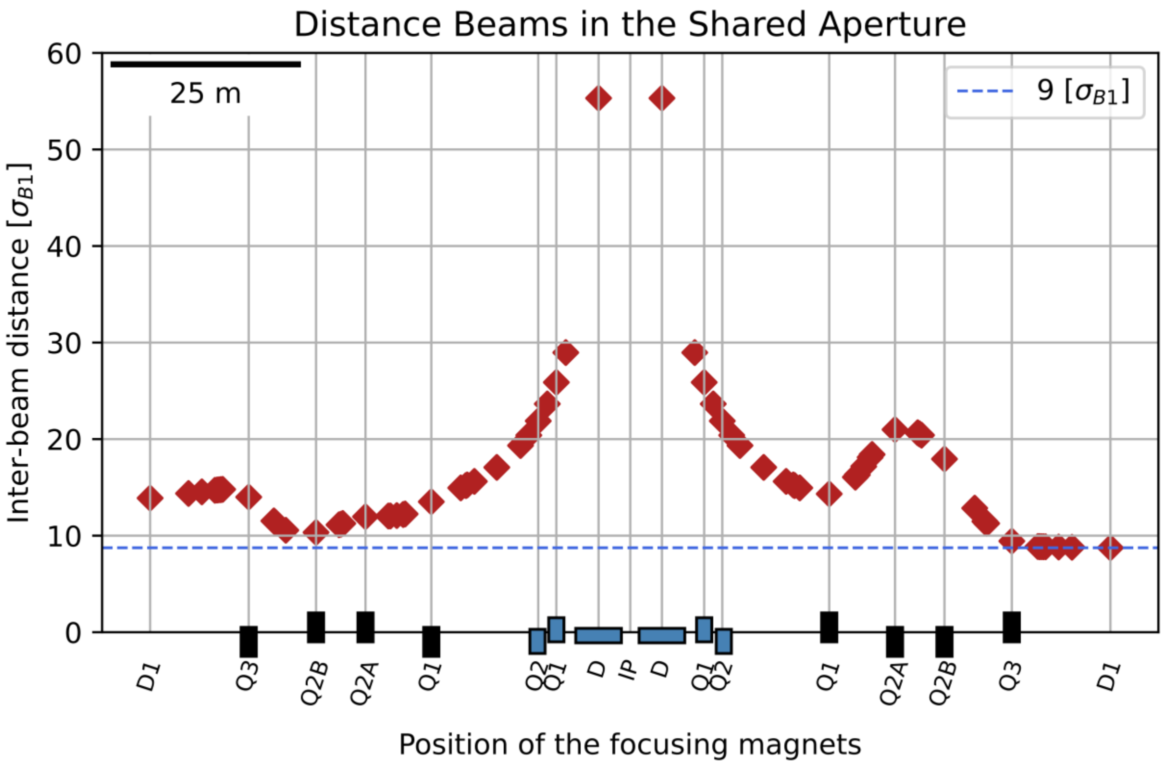




Maximise the distance between the two proton beams in the shared aperture by changing the optical parameters: β^*_{B1} and β^*_{B2} as well as the orbit parameters: the crossing angle x and the separation bump sep

β^*_{B1}	0.35	m
β^*_{B2}	10 to 70	m
x	-300, -325, -350	μrad
sep	3.0, 3.25, 3.5	mm

Distance of the two proton beams in the shared aperture



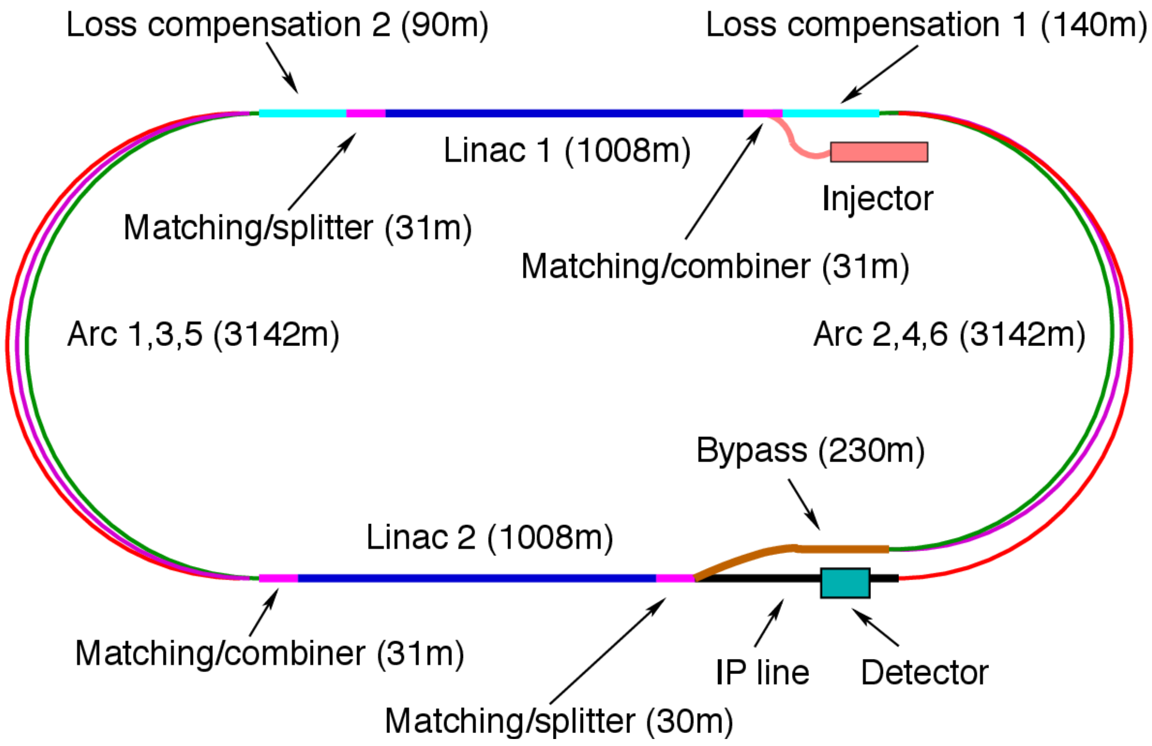
- The two proton beams can be separated by at least 9σ (in σ of the colliding proton beam) in the shared aperture
- This enables e-p collisions with a ß* of 0.35m and thus a luminosity of $1.4 \cdot 10^{33} cm^{-2} s^{-1}$
- This design enables concurrent operation of the LHeC with the other experiments at collision optics
- It enables alternate operation with the ALICE experiment

β^*_{B1}	0.35	m
β^*_{B2}	10 to 70	m
x	-300, -325, -350	µrad
sep	3.0, 3.25, 3.5	mm

On Energy Recovery Linacs

The energy recovery linac (ERL)

- The electrons are accelerated over three turns to 60GeV
- $C \approx \frac{1}{3} C_{LHC} \approx \frac{1}{10} C_{FCC} \approx 9\text{km}$



Schematic Layout of the energy recovery linear accelerator. Courtesy to K.D.J. André [2].

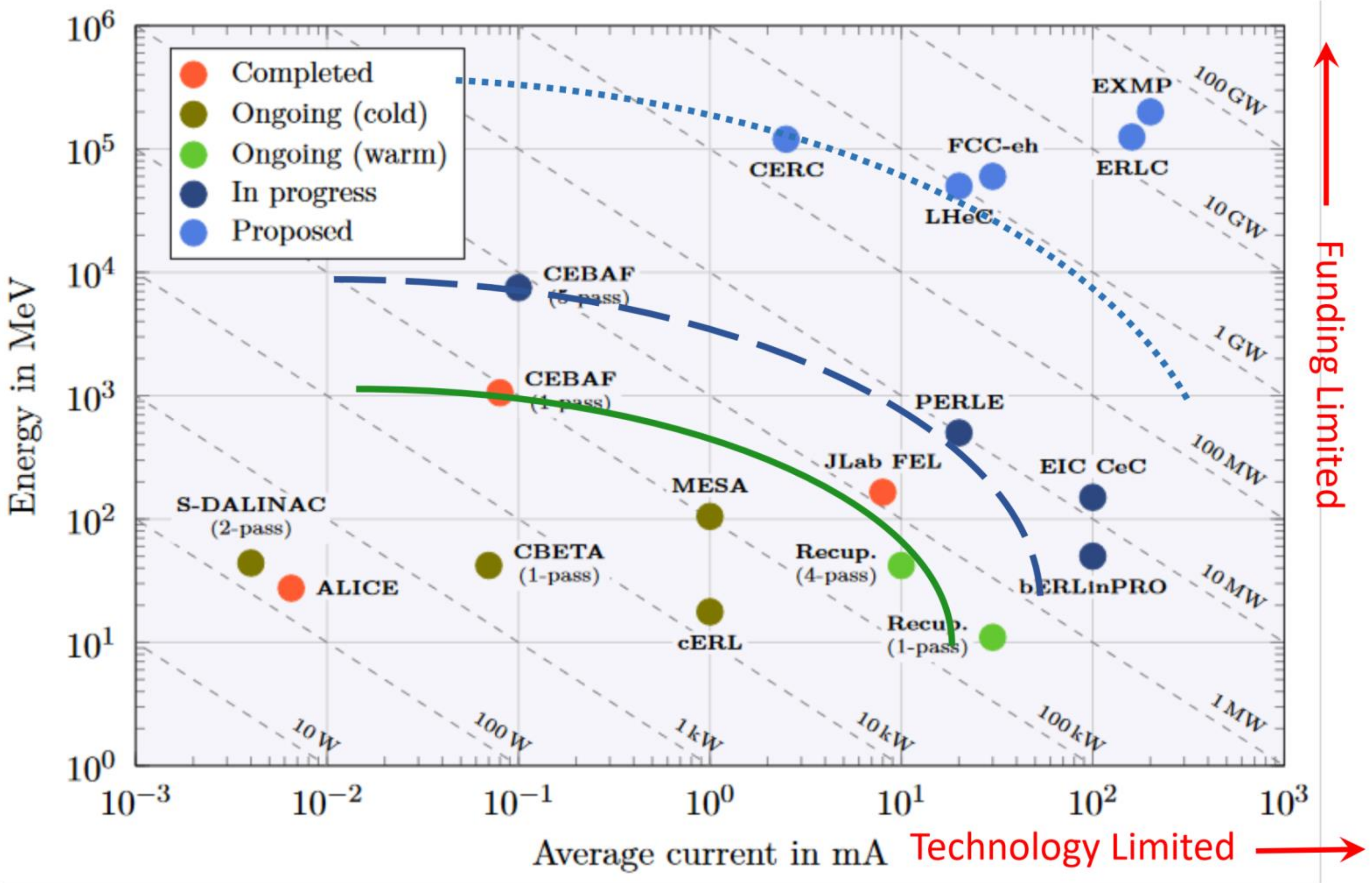
Parameter	Unit	Electron	Proton
Beam energy	GeV	60	50000
Beam current	mA	20.0	640.0
Bunch population	10^{10}	3.1	10.0
Normalised emittance at IP	mm.mrad	20.0	2.2
Betatron function at IP	cm	7.3	30.0
Beam size at IP	µm	3.5	
RMS bunch length σ_z	cm	0.06	8.00
Installed RF voltage	GV	21.2	48×10^{-3}
Beam-beam parameter ξ	10^{-4}	1.1×10^{4}	1.7
Luminosity	$cm^{-2}.s^{-1}$	7.9×10^{33}	

Table with the main parameters of the FCC-eh [2].

- The remaining electrons have a phase advance of 180° when entering the linac again
- 97.92% of the energy can be recovered

- The development of ERLs has been recognized as one of the five main axis of accelerators R&D in support of the European Strategy for Particle Physics (ESPP).
- The ERL Roadmap Panel, chaired by Max Klein and Andrew Hutton, has done a tremendous job with broad and active participation. **PERLE & bERLinPro projects** were recognized as one of the "essential pillars of the ERL development," with milestones to be achieved by the next ESPP in 2026.

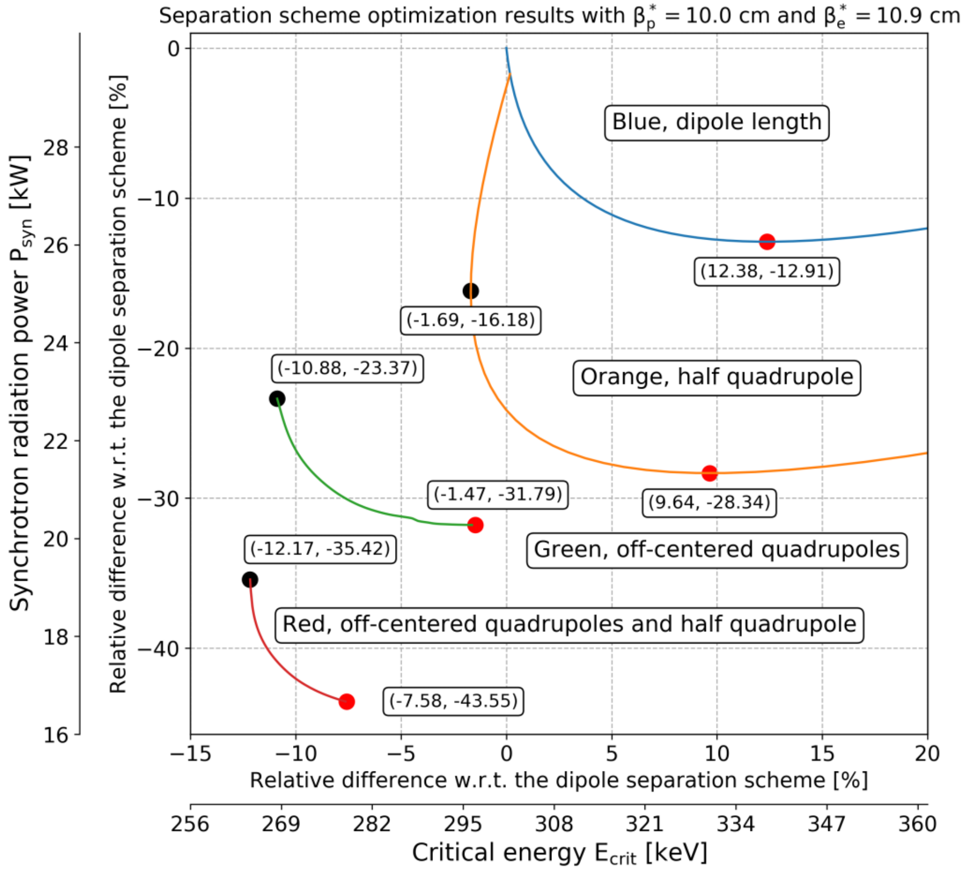
ESPP R&D Accelerator RoadMap:
https://arxiv.org/ftp/arxiv/papers/2201/2201.07895.pdf



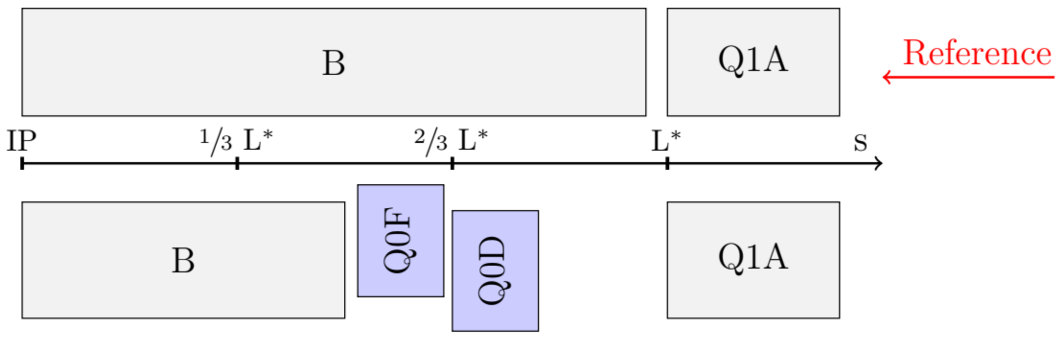
Walid Kaabi, “PERLE: a novel facility for ERL development and applications in multi-turn configuration and high-power regime”, IPAC 2023

Optimization Scheme for the electrons

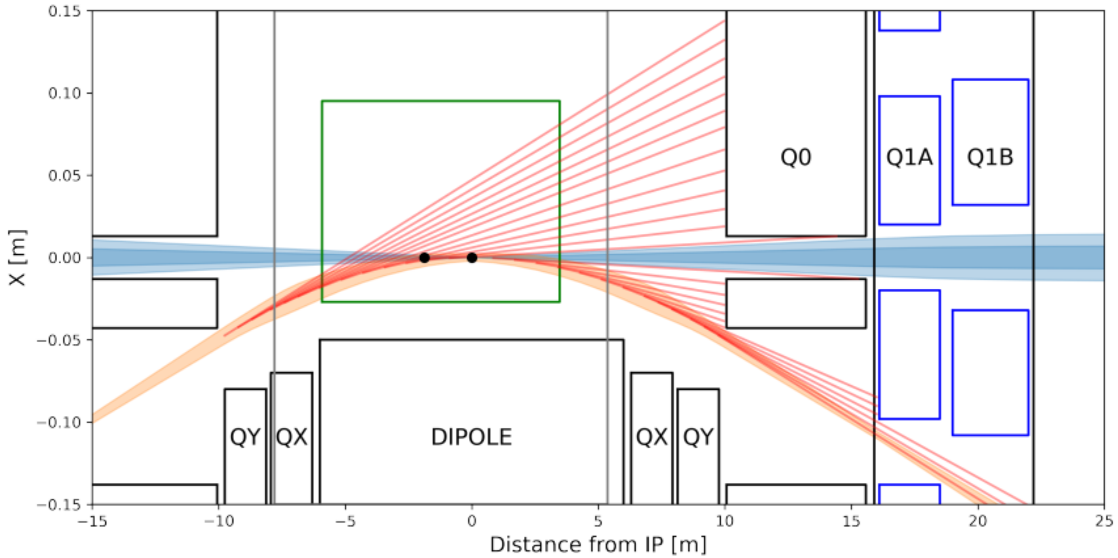
Courtesy K.D.J. André [2]



Optimizations for different focusing schemes of the LHeC

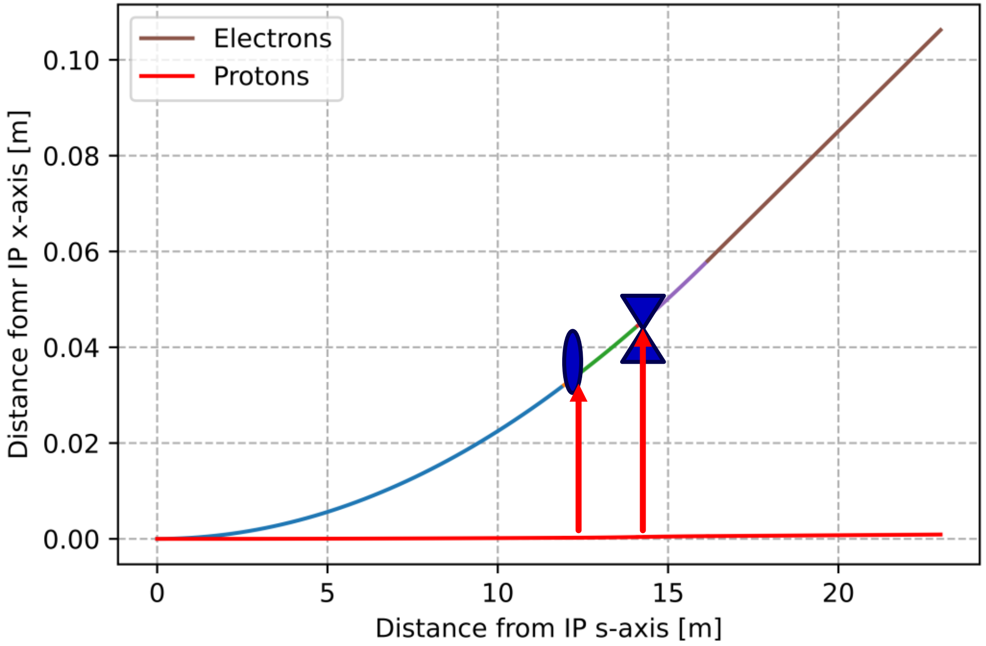


Chosen interaction region for the FCC-eh

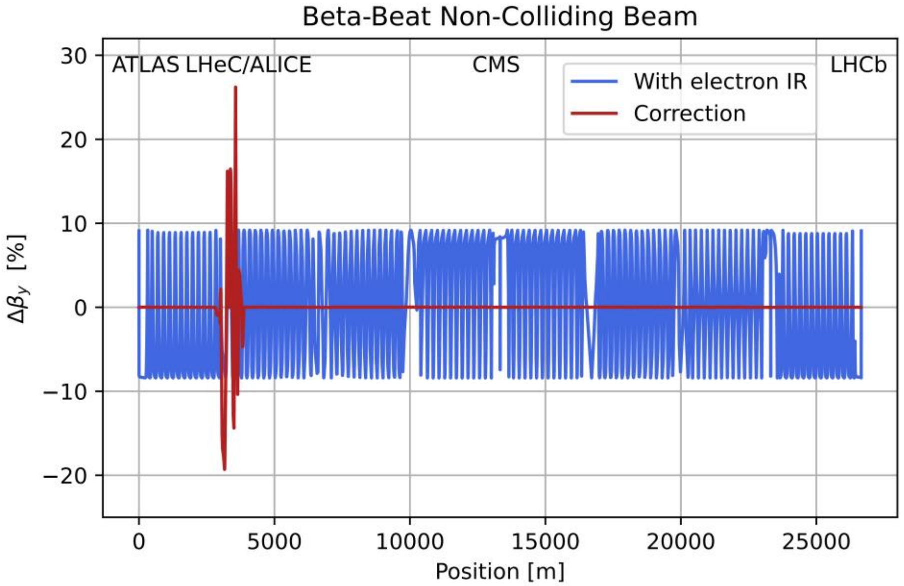


Synchrotron radiation at the IP of the LHeC

Electron doublet influence on the proton optics



- The electron doublet is slightly offset to use the feed-down effect, to get an additional dipole effect
- The impact on the proton beam dynamics has been corrected
- The field at the position of the protons inside the quadrupoles needs to be investigated



On the FCC-eh Collider

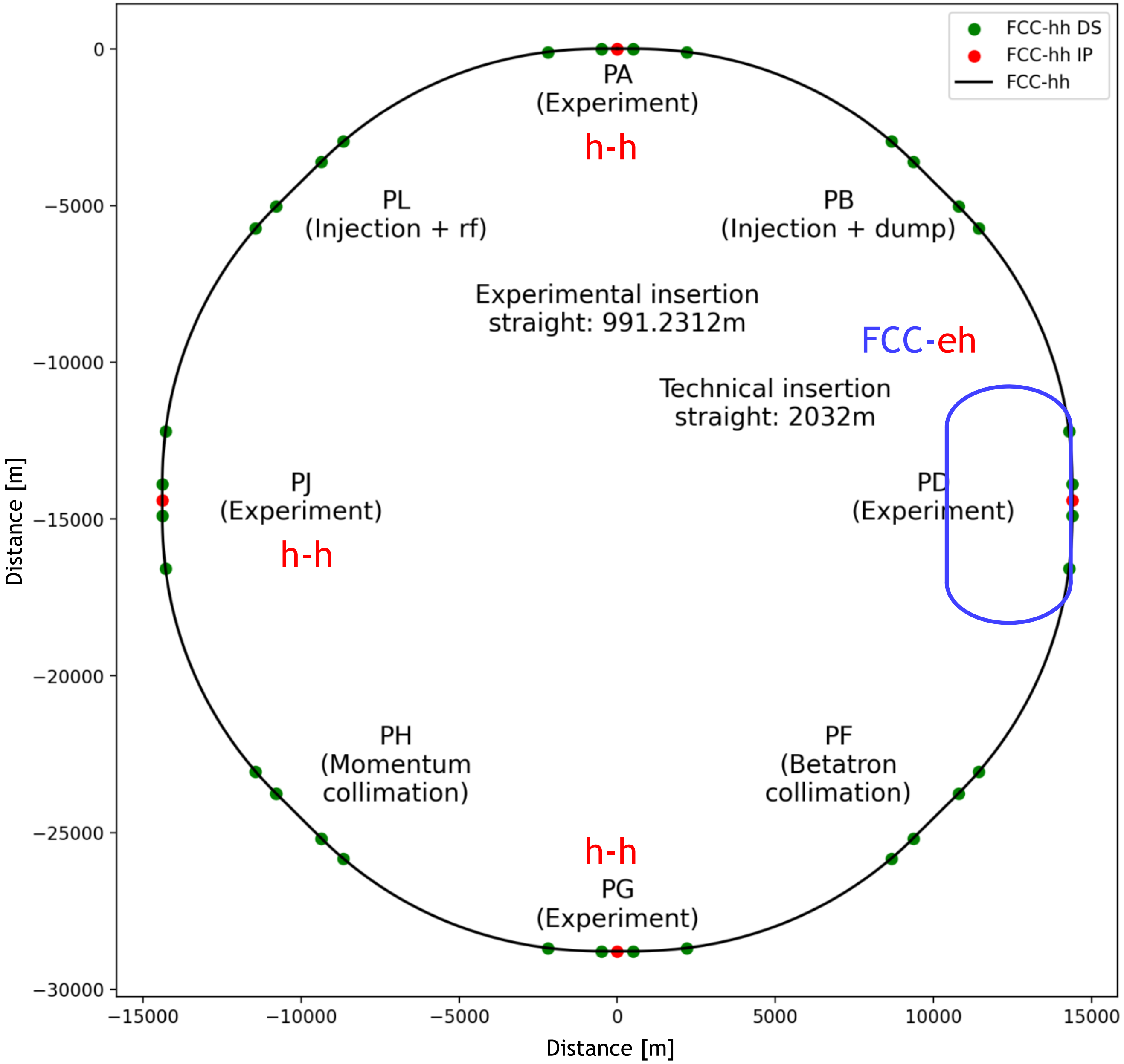
The FCC-eh Collider

- New layout of the FCC-hh collider:

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

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

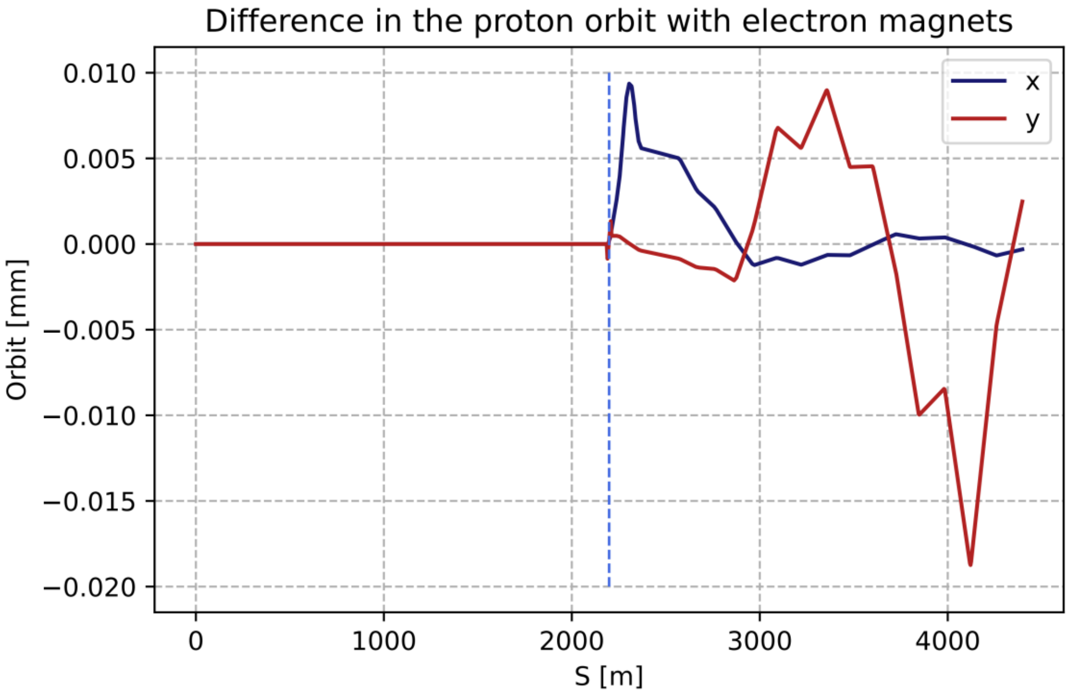
- High precision microscope for inner hadron structure
- Deep inelastic scattering physics
- Collisions of 50TeV protons with 60GeV electrons
- Center of mass energy: $\sqrt{s} = 3.5\ \mathrm{TeV}$
- Peak Luminosity: $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$



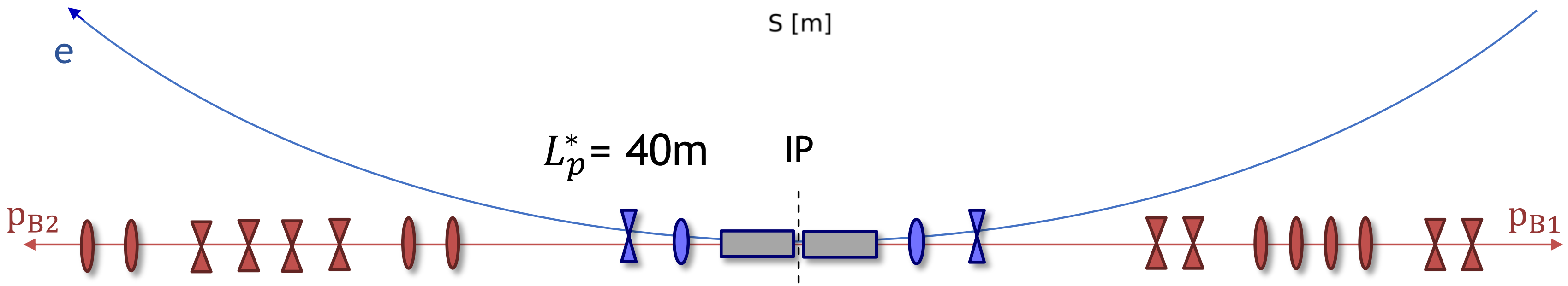
Possible layout of the FCC [1]

The electron interaction region (optimized by K.D.J André)

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

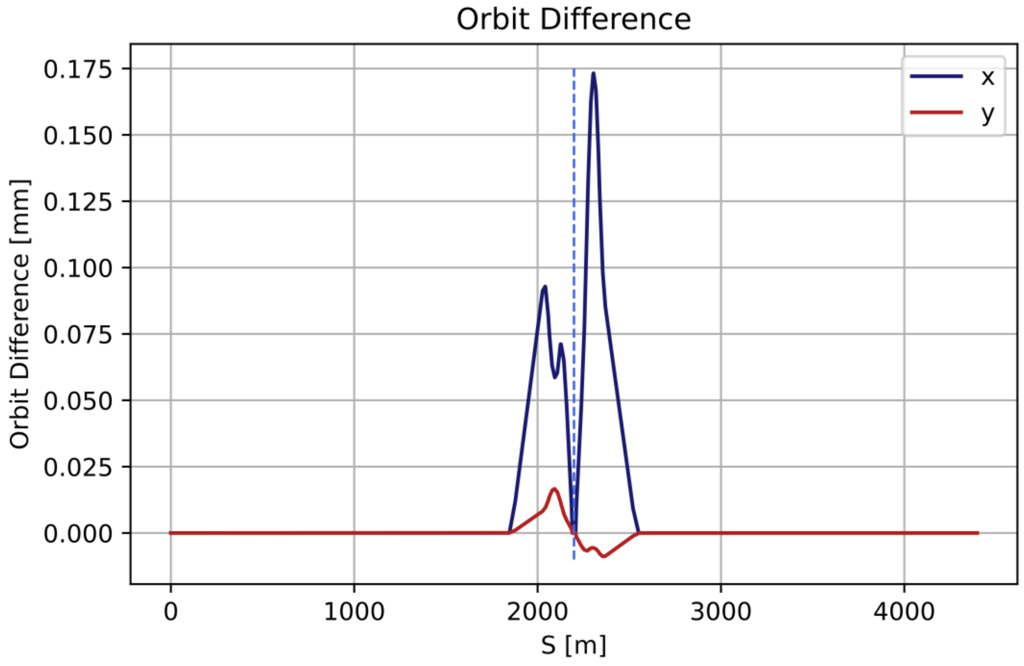


Impact of the electron magnets on the proton orbits (B1). The blue line marks the position of the IP.



Impact of the electron IR on the proton beam dynamics

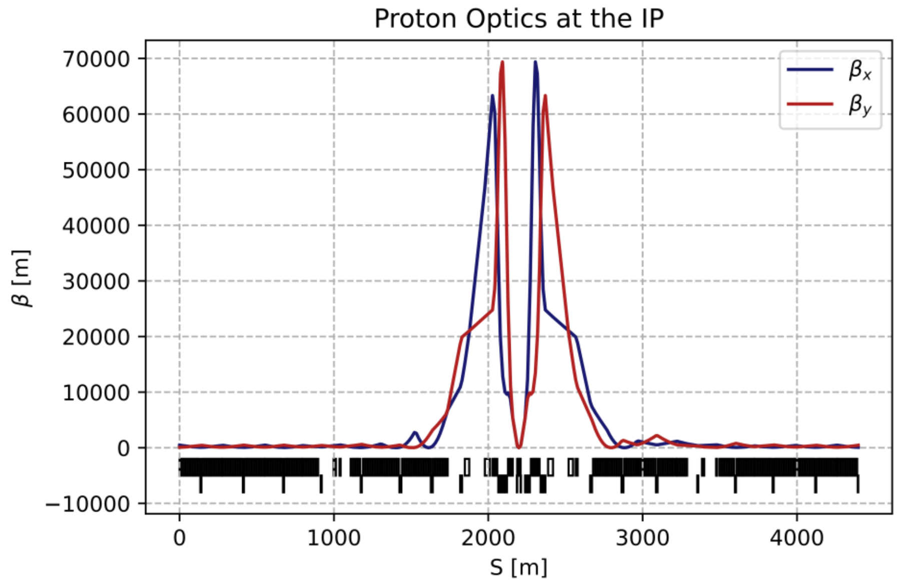
Local correction of the proton orbit:

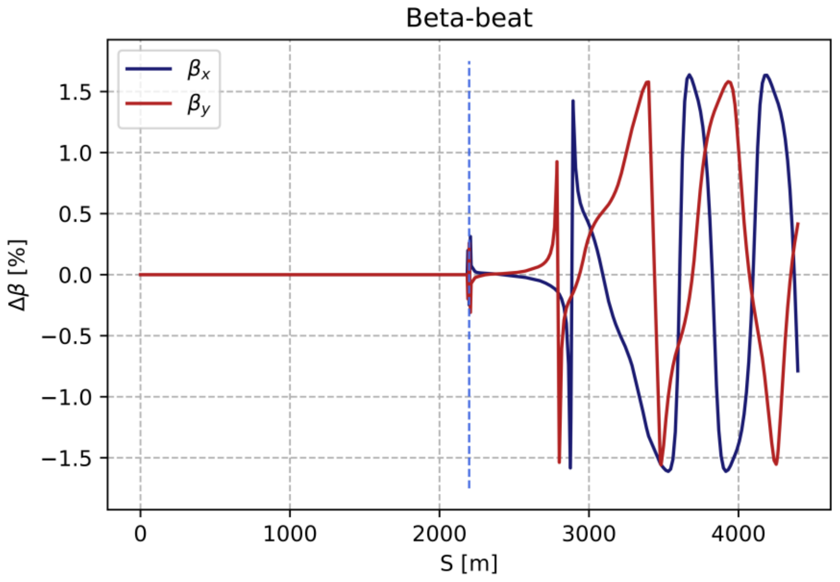


Introduction of a beta-beat of about 1.5% in the proton optics. They are corrected locally at the dispersion suppressors.

Scaling:

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





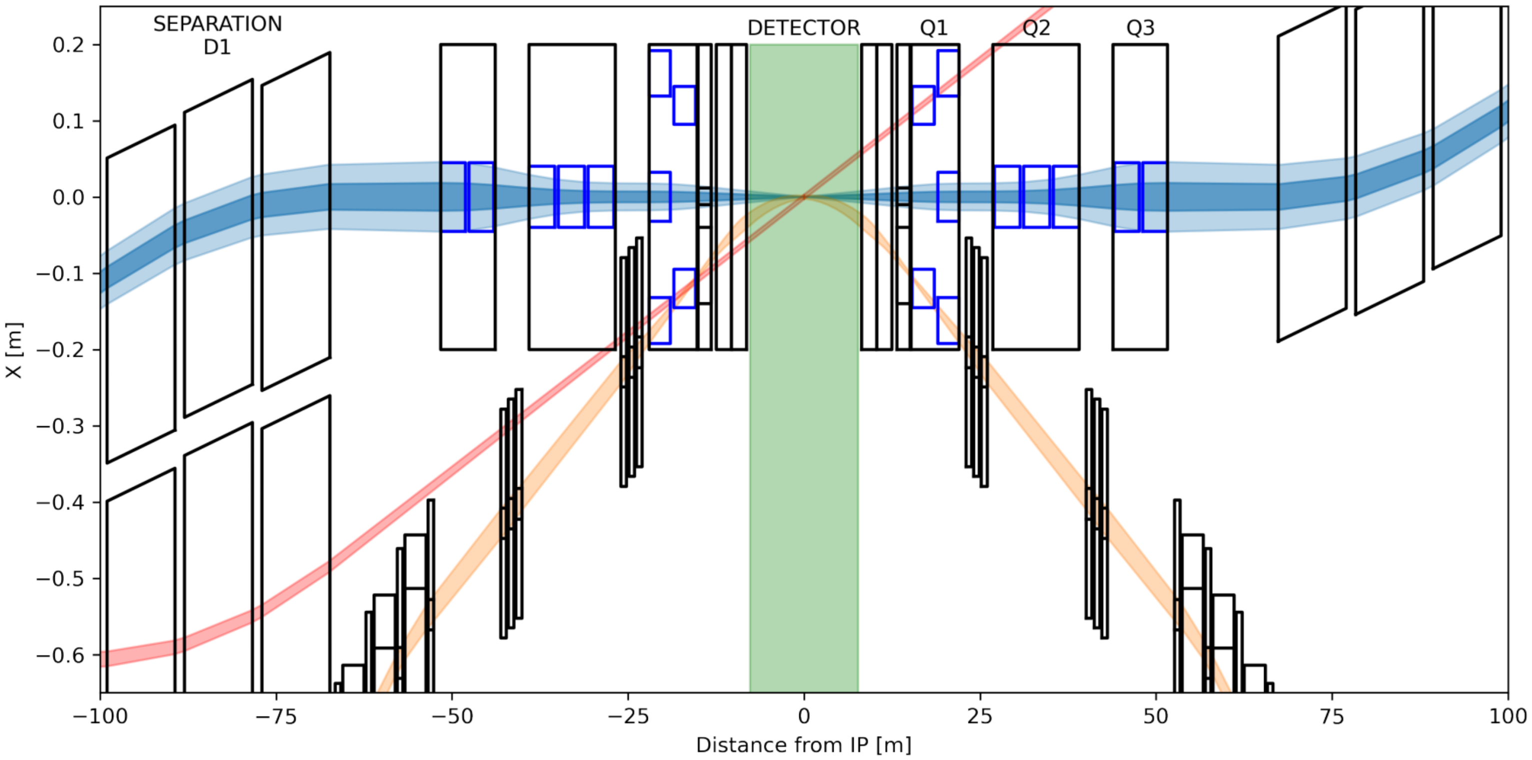
Both effects can be corrected.

Option 1: only e-p interaction in this IP

- **Separate apertures for the proton beams**
- Shift the IP position by ¼ of the bunch distance
- The spectating proton beam crosses with a strong angle (~7mrad)
- L* can be lowered and optimized for the e-p data acquisition
- Lower L* allows a lower ß*

$$L = \frac{N_1 \cdot N_2 \cdot n \cdot f}{4\pi\sigma_x\sigma_y} \sim \frac{1}{\beta^*}$$

Luminosity for round beams



Schematic of an optional LHeC interaction region. Courtesy to K.D.J. André [2]

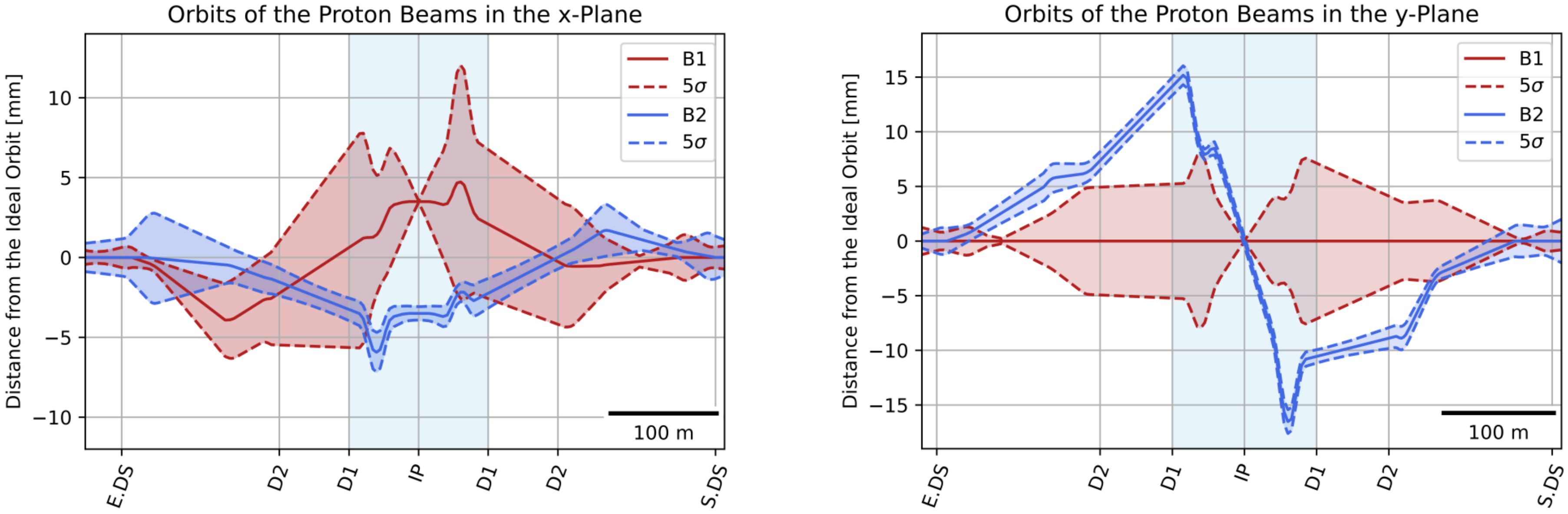
Colliding proton beam | Non-colliding proton beam | Electron beam

Drawback: no h-h collision possible in this IP

Option 2: e-p and p-p interaction alternate in this IP

- The two proton beams **share the same aperture**
- Separation of the two proton beams with the use of orbit bumps
- Further separation in the shared aperture with the use of asymmetric optics for the protons

Separation of 9σ



Schematic of an optional LHeC separation scheme [3]