Design of the Interaction Region for Concurrent e-p and p-p Operation

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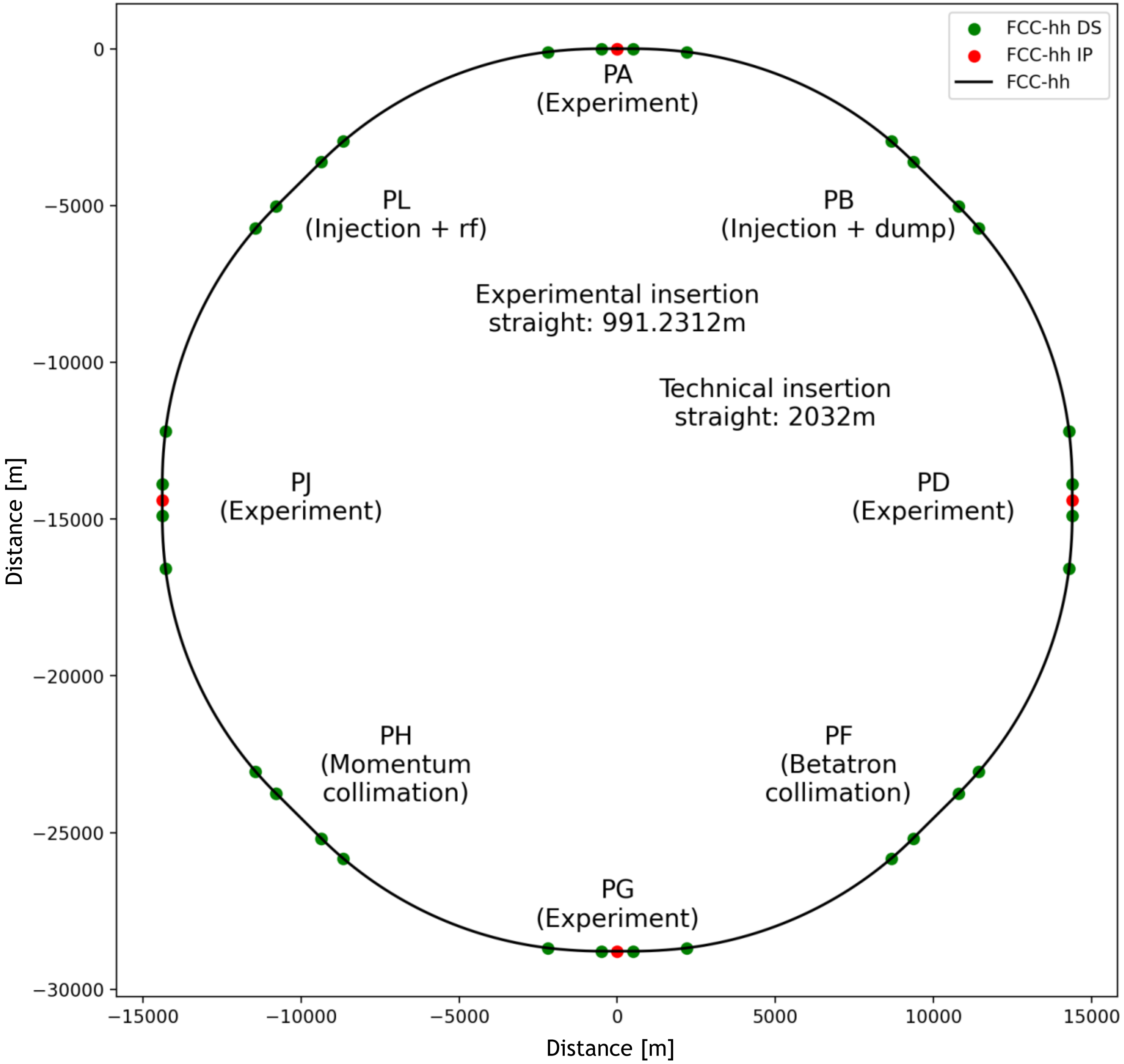
The FCC-eh Collider

- New layout of the FCC-hh collider:

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

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



Possible layout of the FCC [1]

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The FCC-eh Collider

- New layout of the FCC-hh collider:

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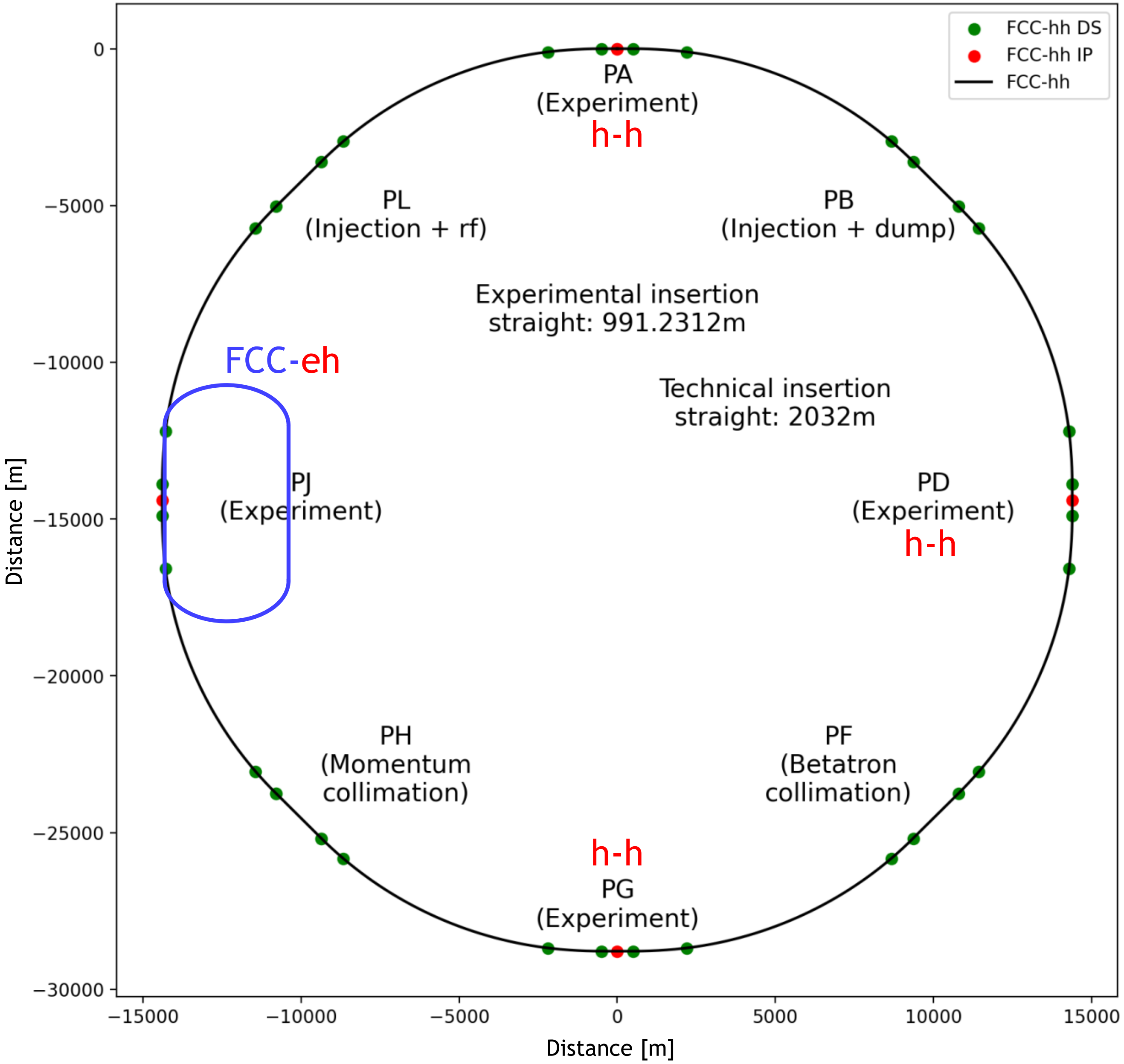
- High precision microscope for inner hadron structure
- Deep inelastic scattering physics
- Collisions of 50TeV protons with 60GeV electrons
- Center of mass energy: $\sqrt{s} = 3.5\ \text{TeV}$
- Peak Luminosity: $10^{34}\text{cm}^{-2}\text{s}^{-1}$



Possible layout of the FCC [1]

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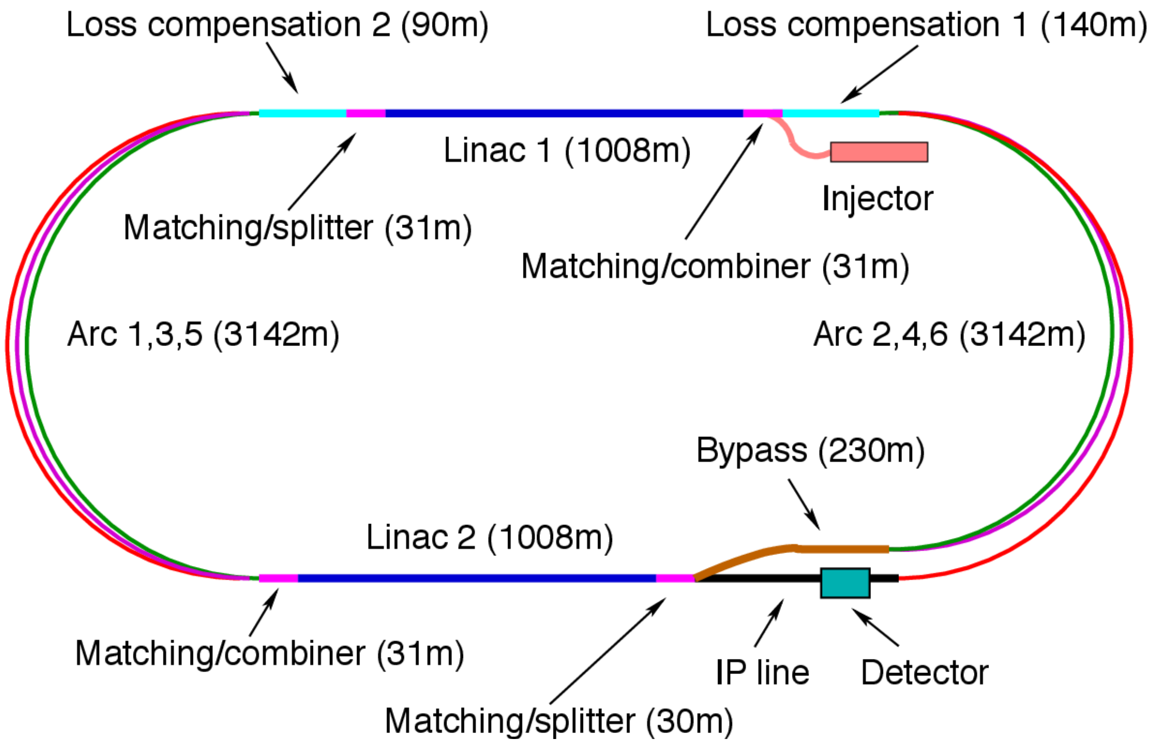
The energy recovery linac (ERL)

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



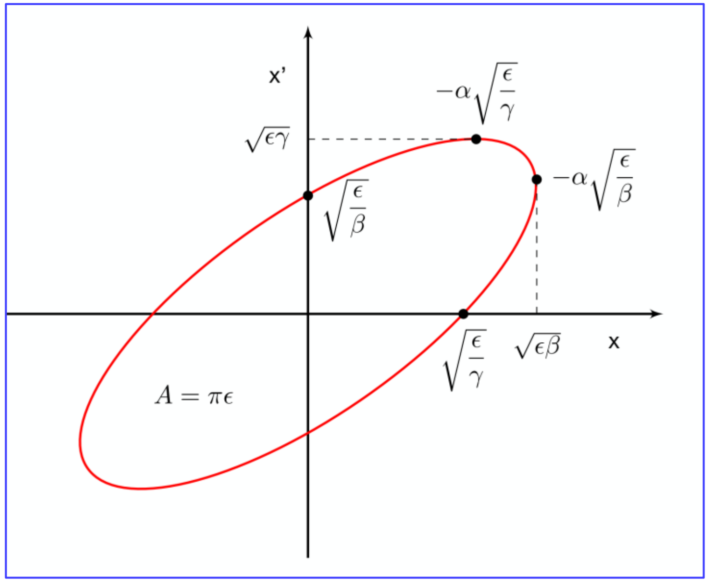
Schematic Layout of the energy recovery linear accelerator. Courtesy to K.D.J. André [2].

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].

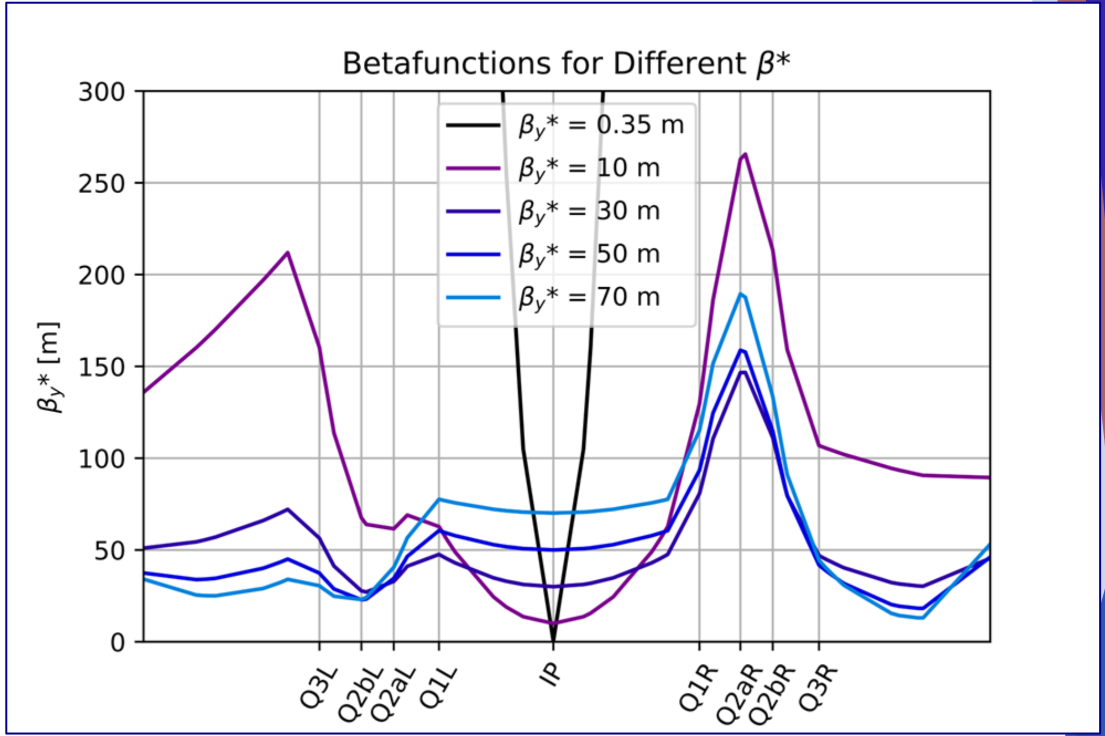
- The remaining electrons have a phase advance of 180° when entering the linac again
- 97.92% of the energy can be recovered

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: $\beta^* = l$

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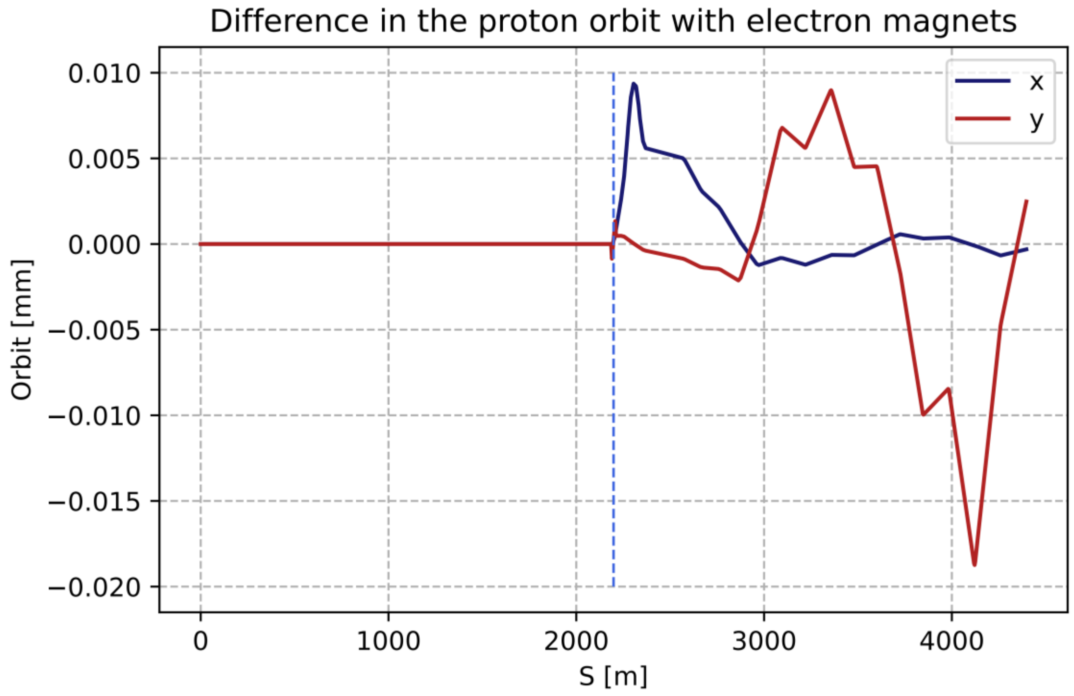
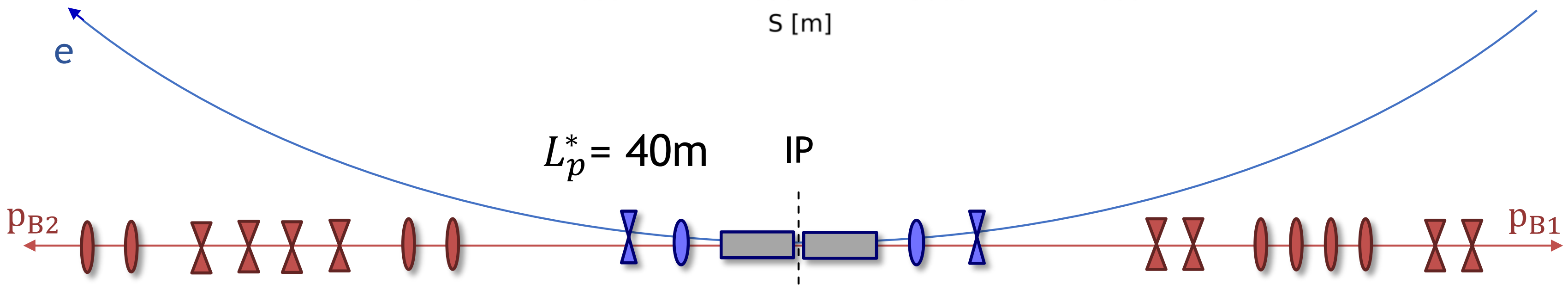
➡ The focusing magnets before the IP need the biggest aperture

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.



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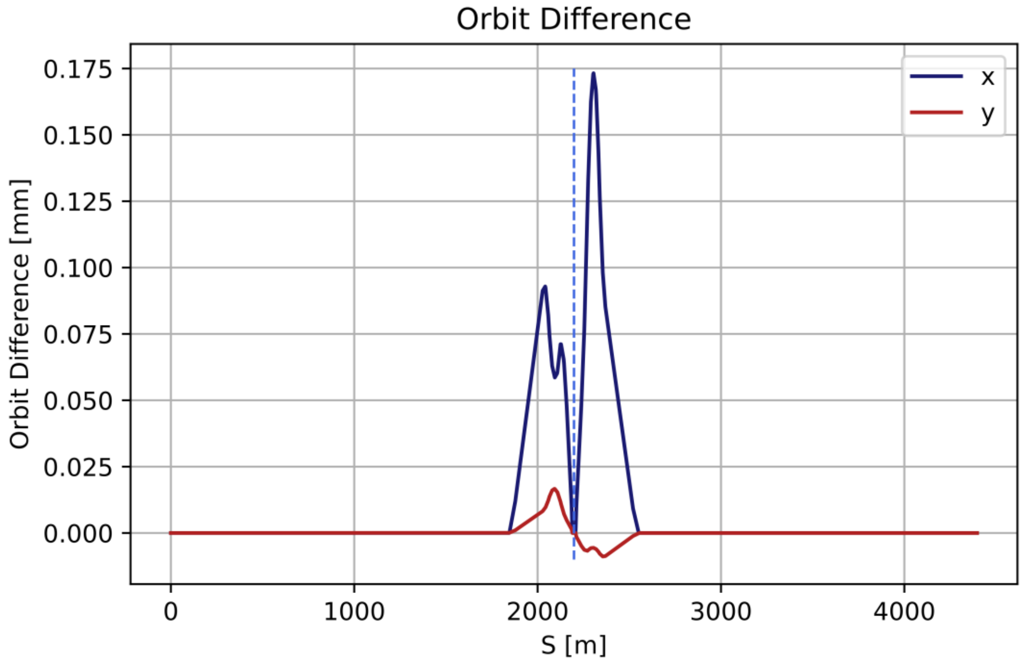
Impact of the electron IR on the proton beam dynamics

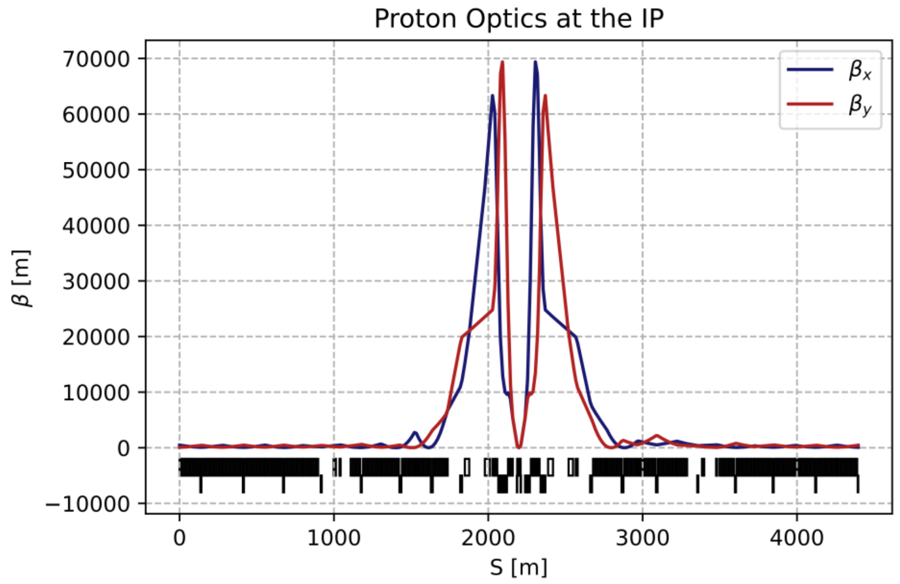
Local correction of the proton orbit:

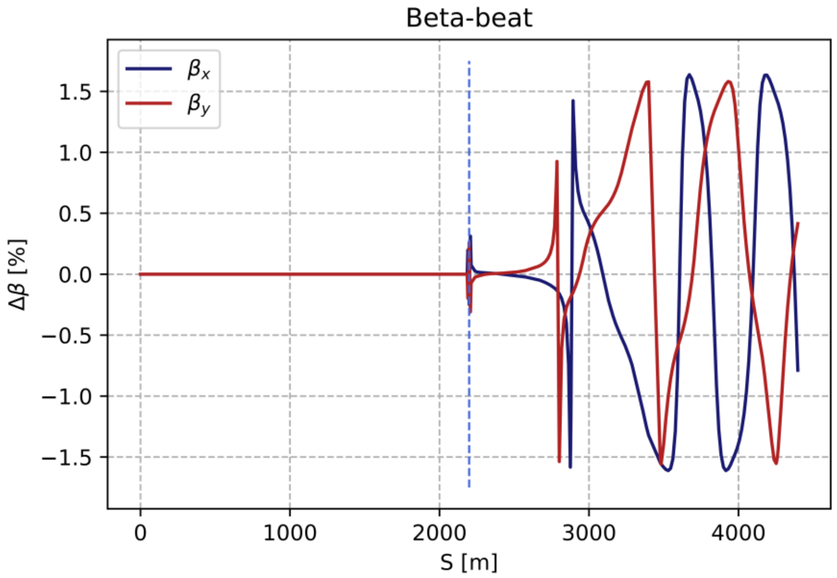


Introduction of a beta-beat of about 1.5% in the proton optics. They are corrected locally at the dispersion suppressors.

Scaling:

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





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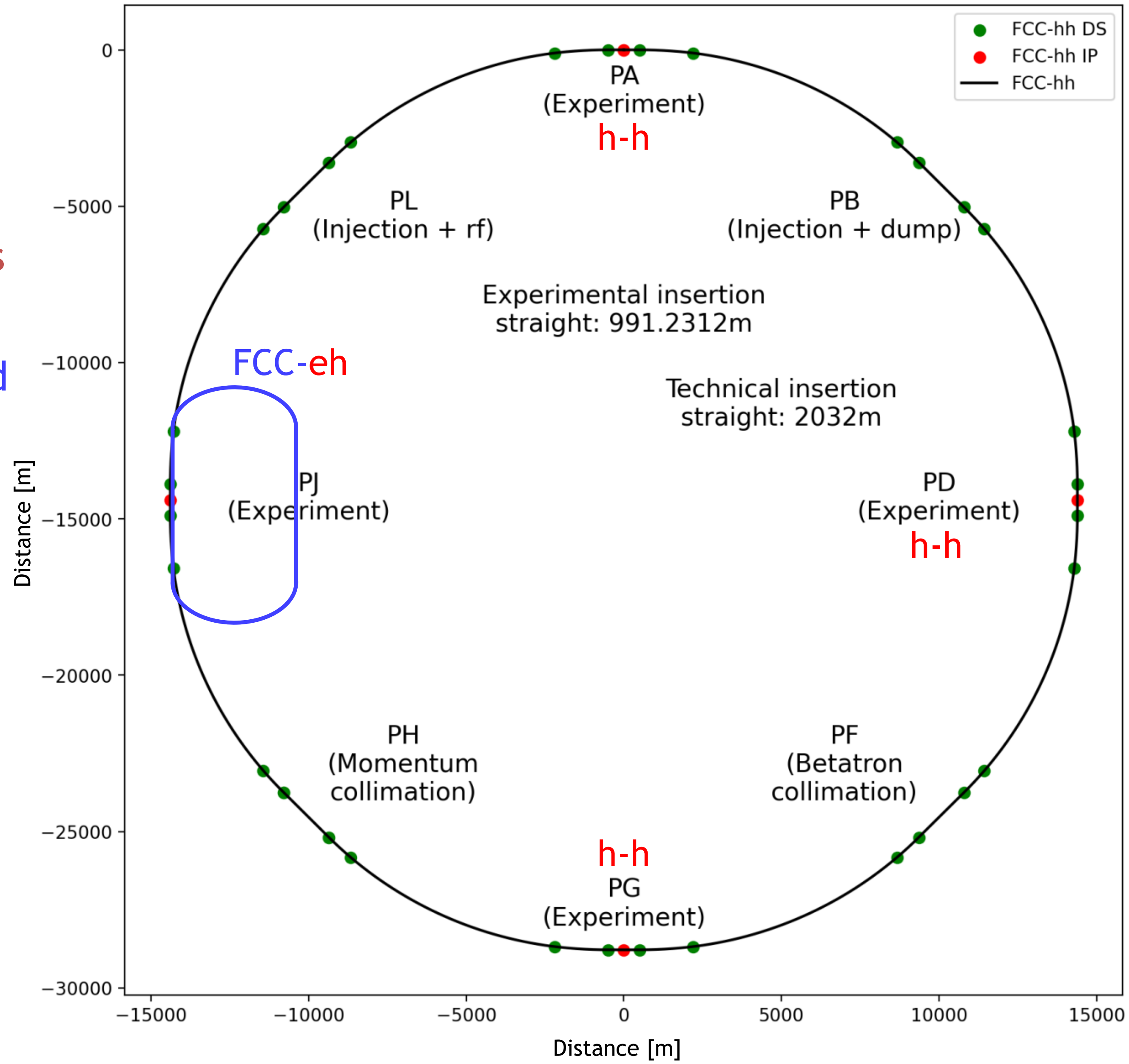
Both effects can be corrected.

Concurrent Operation of e-h and h-h

- Concurrent operation implies 3 beams at the IR
- The two protons need to be separated at the e-p interaction point
- How will this IP be used?



Possible layout of the FCC [1]

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Concurrent Operation of e-h and h-h

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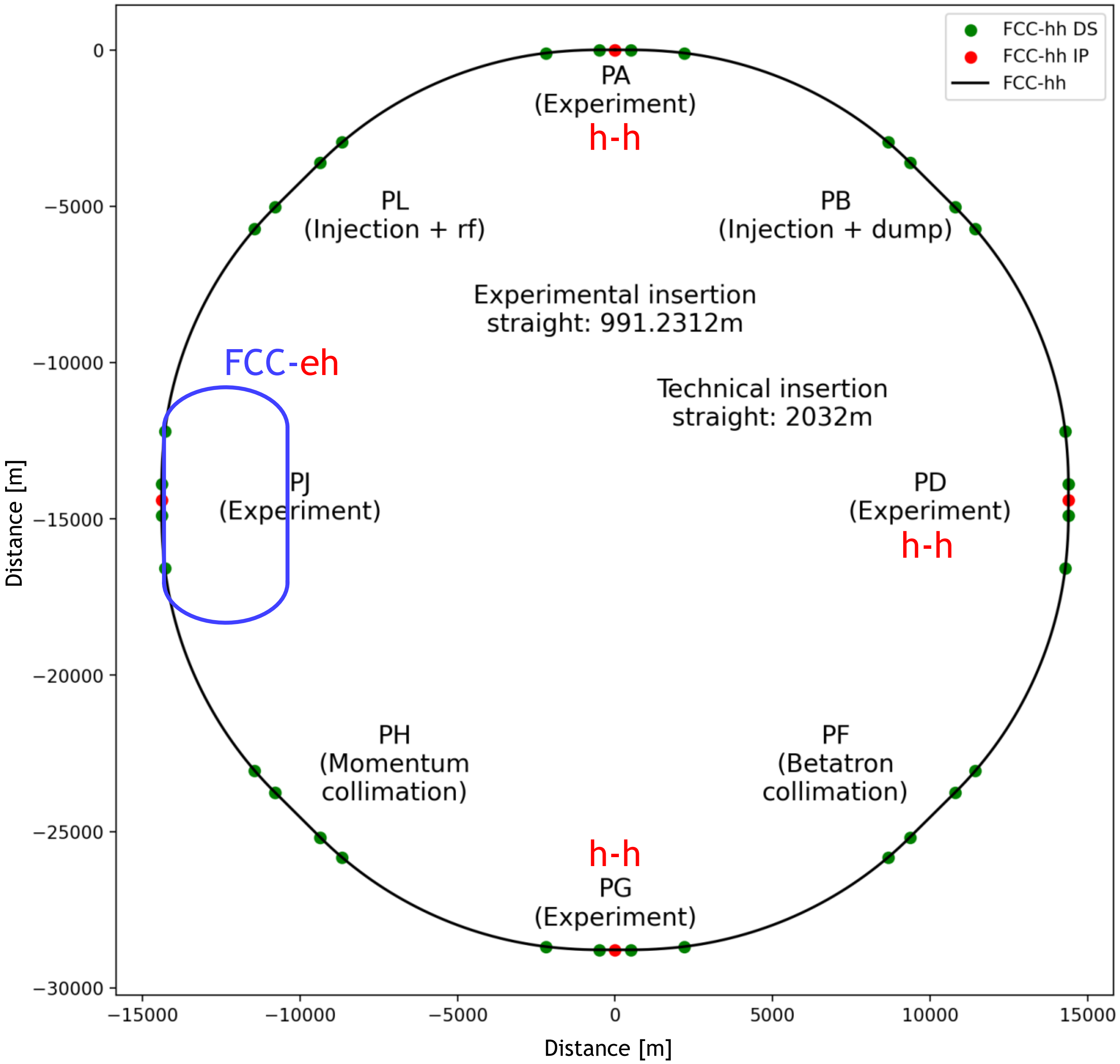
- How will this IP be used?

Option 1: only e-p interaction in this IP

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



Possible layout of the FCC [1]

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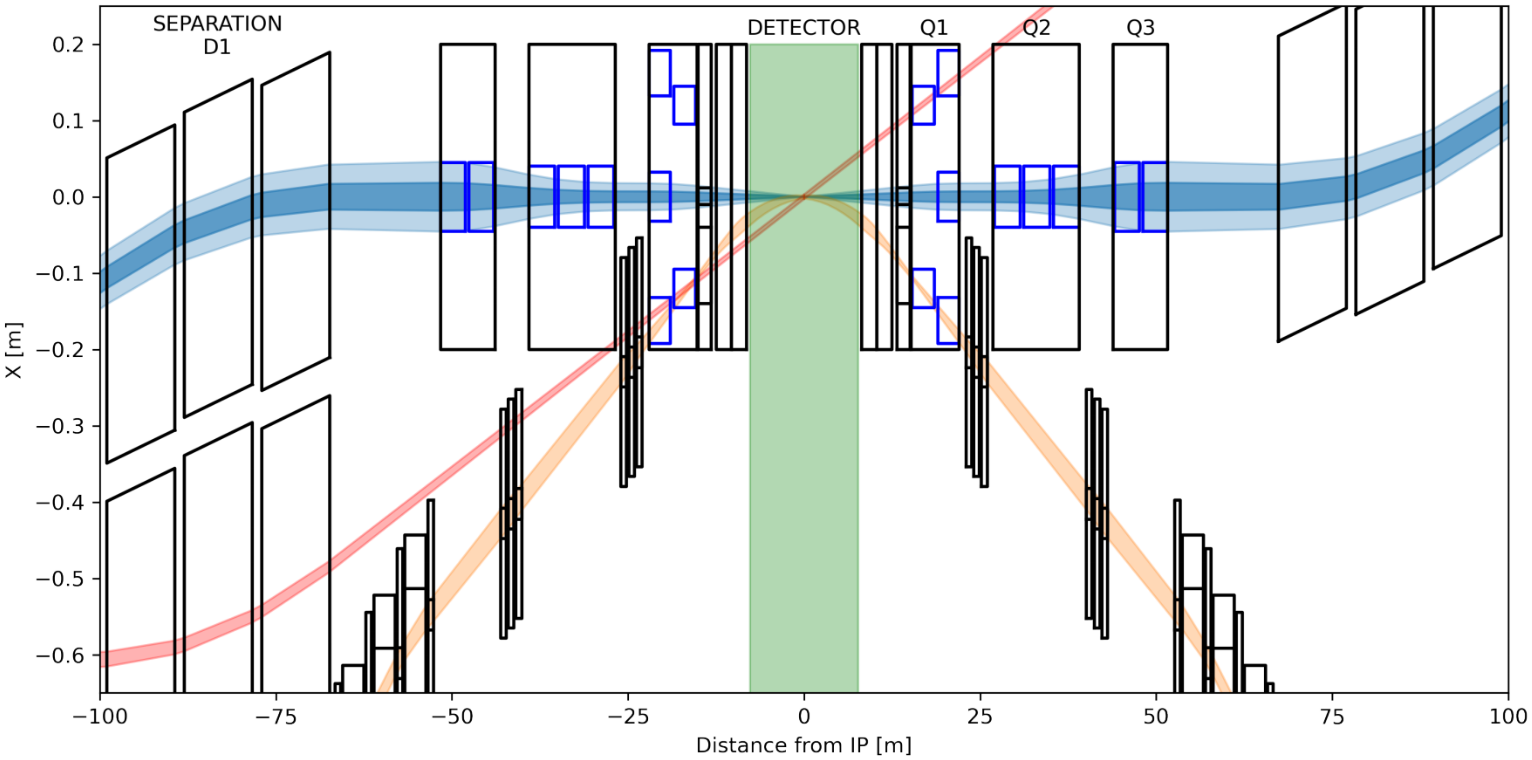
Option 1: only e-p interaction in this IP

- **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

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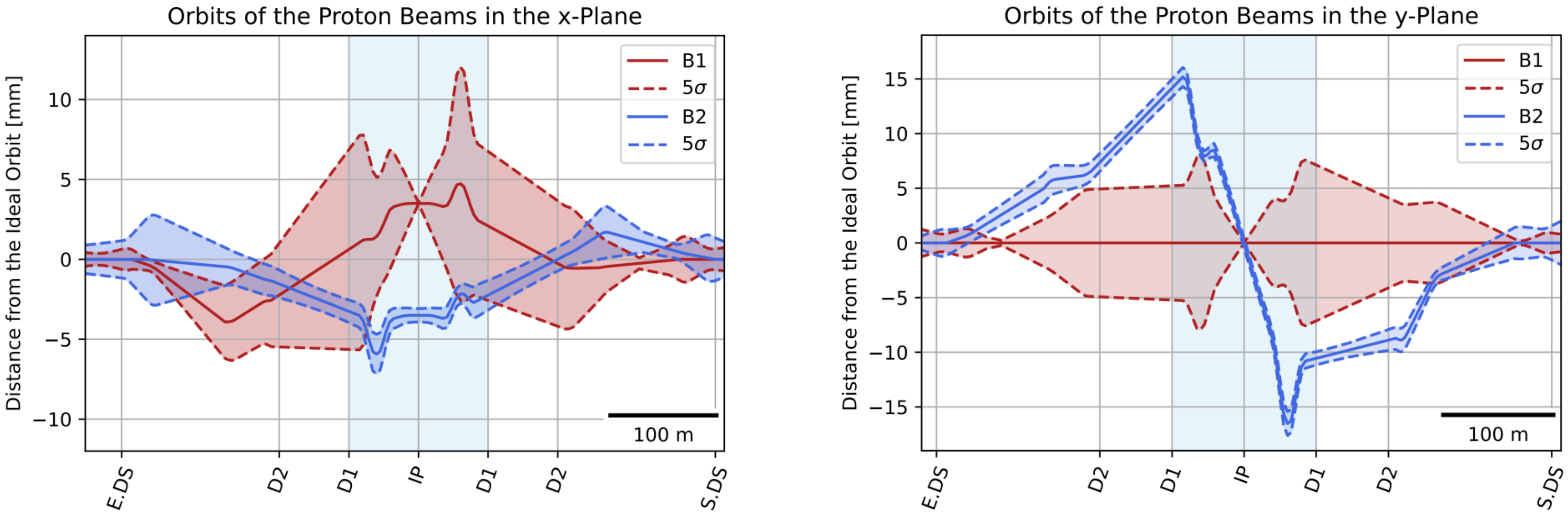
Option 2: e-p and p-p interaction alternate in this IP

- 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]

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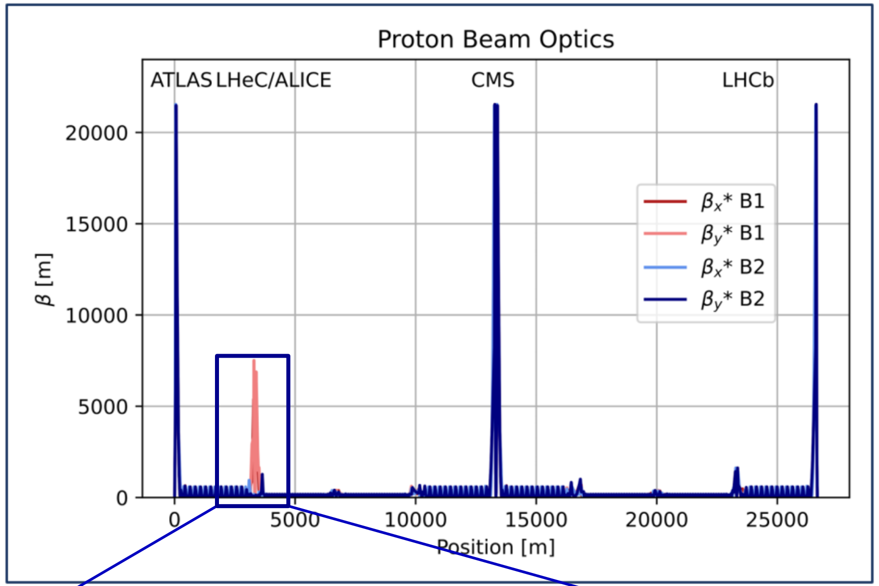
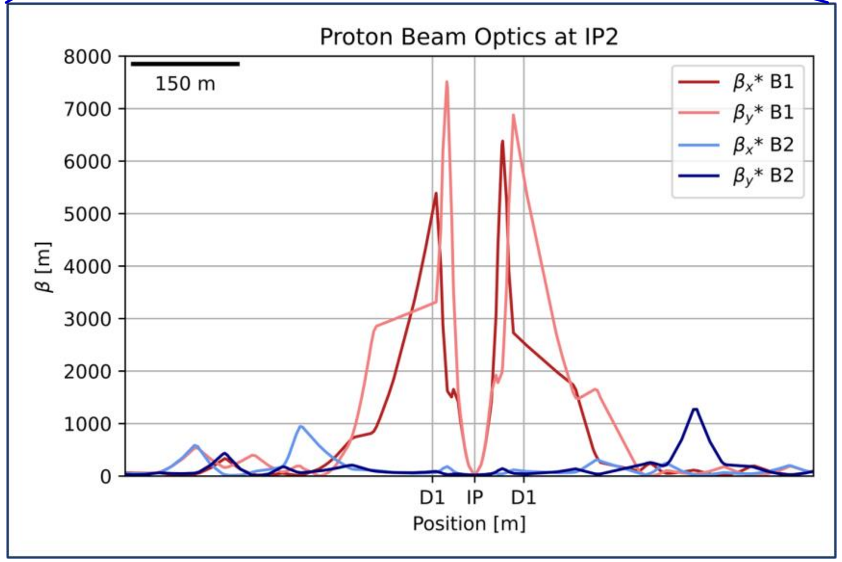
Option 2: e-p and p-p interaction alternate in this IP





Asymmetric proton beam optics for the LHeC.

Betafunction before a drift space of the length l with minimum betafunction ß* :

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

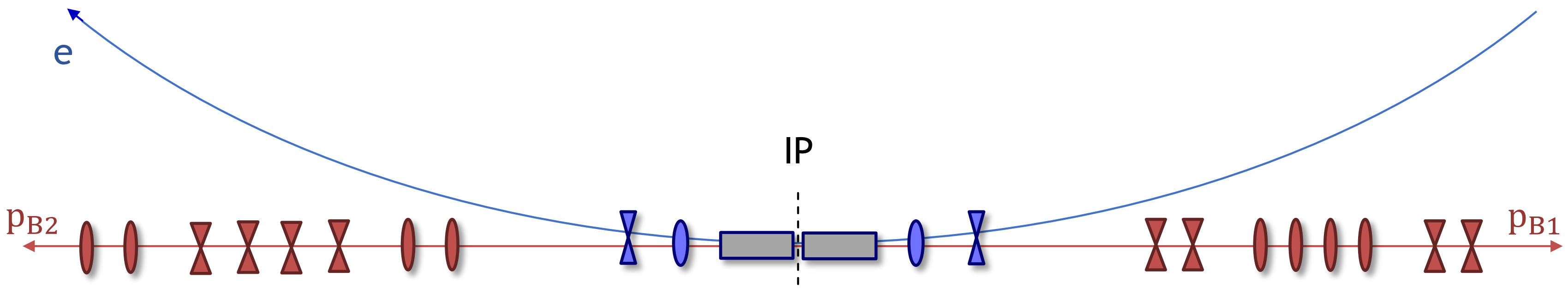
- A high ß* of the spectating proton beam at the IP keeps it at a smaller beam size in the shared aperture
- Use asymmetric proton beam optics to maximize the distance between the beams in the shared aperture
- A low ß* of the colliding beam increases the Luminosity

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

Luminosity for round beams

Summary & Outlook

- An electron interaction region has been optimized to minimize the synchrotron radiation power
- The local impact of the electron magnets on the proton beam orbit and optics can be corrected in the new FCC-hh lattice
- 2 schemes to separate the proton beams have been designed for the LHeC ➡ they can be adapted for the FCC-eh
- **Outlook:** implement both separation schemes into the new h-h lattice
- Tracking simulations to investigate the impact of the proton beams on each other



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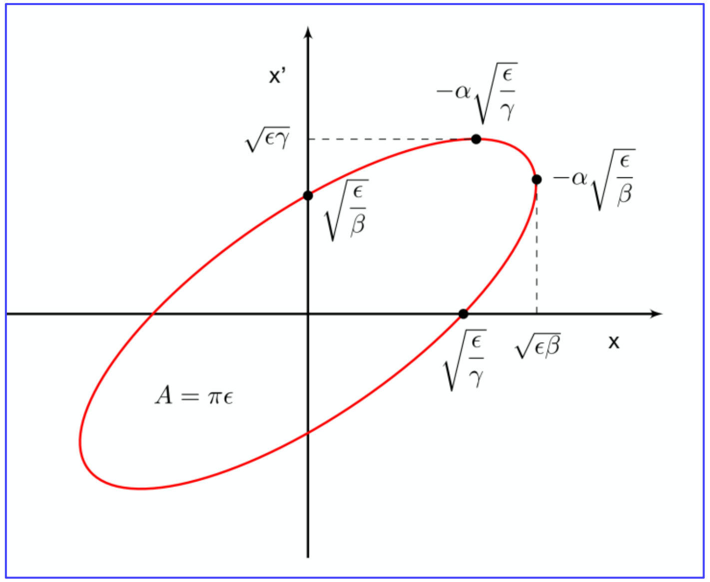
Thank you for your attention.

Background Slides

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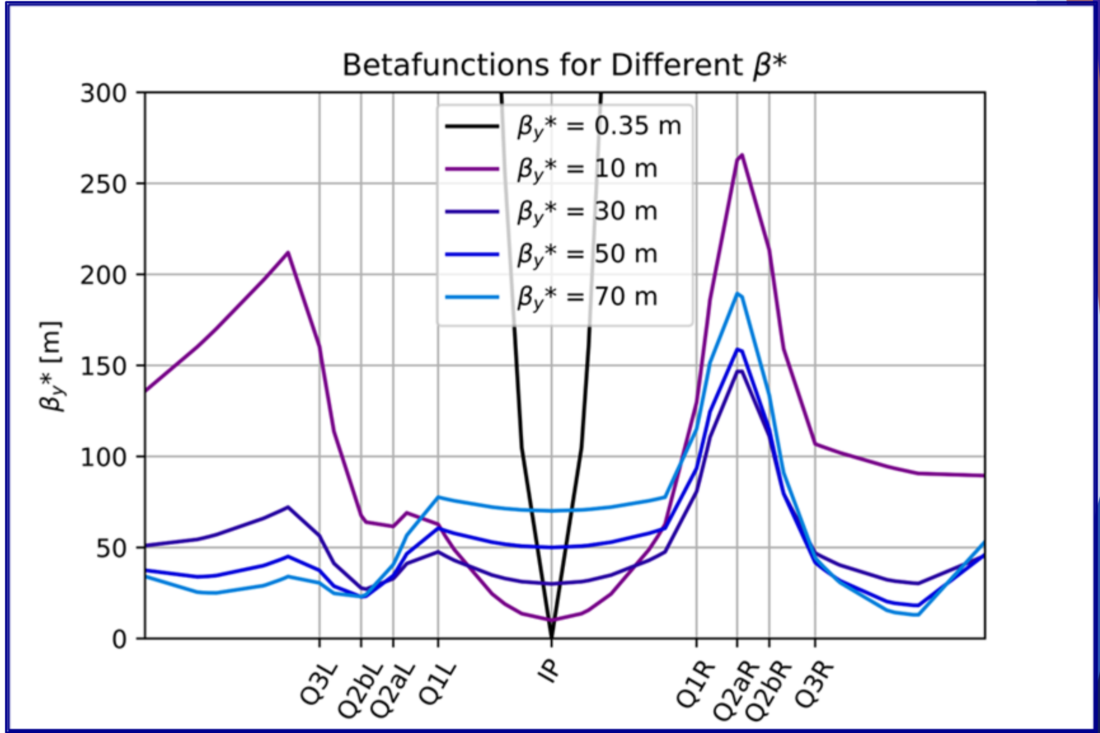
- Smallest beta at a distance l for: $\beta^* = l$



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➡ 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 $\beta^*= 0.3$ 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

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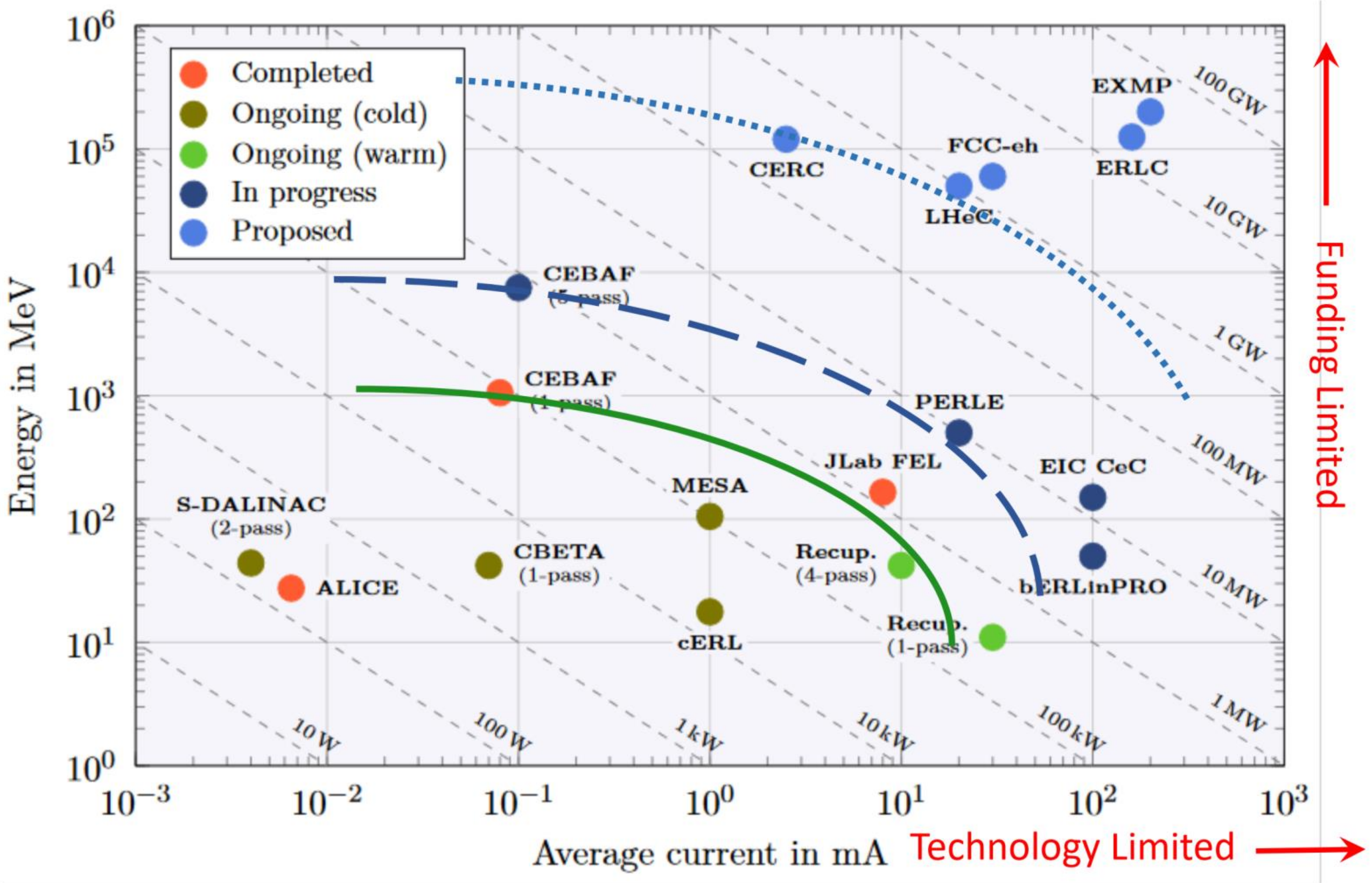
- The development of ERLs has been recognized as one of the five main axis of accelerators R&D in support of the European Strategy for Particle Physics (ESPP).
- The ERL Roadmap Panel, chaired by Max Klein and Andrew Hutton, has done a tremendous job with broad and active participation. **PERLE & bERLinPro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

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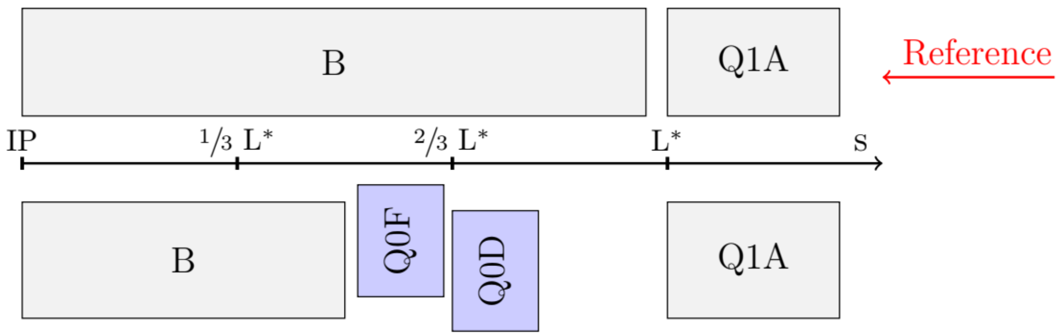
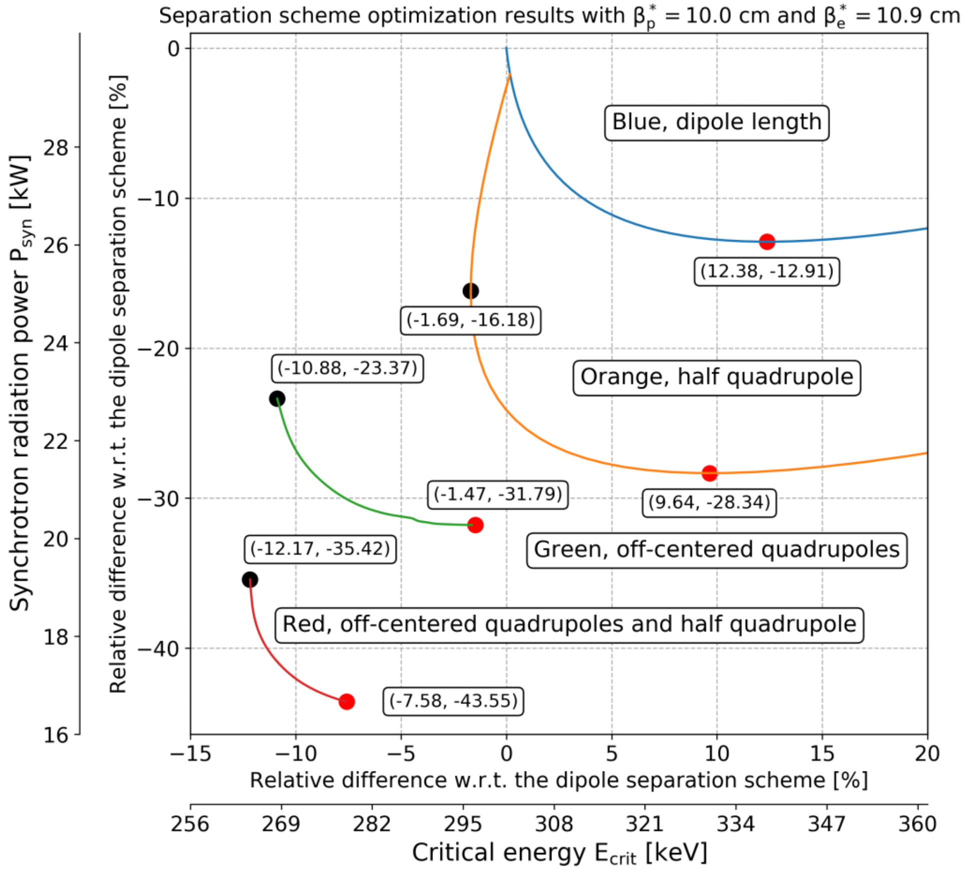
Optimization Scheme for the electrons

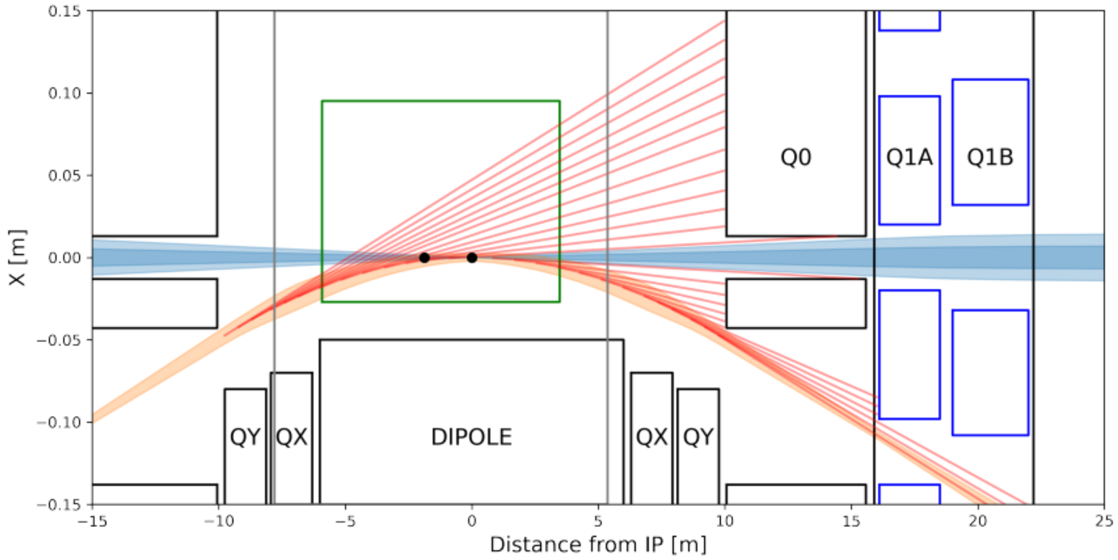
Courtesy K.D.J. André [2]



Chosen interaction region for the FCC-eh



Optimizations for different focusing schemes of the LHeC



Synchrotron radiation at the IP of the LHeC

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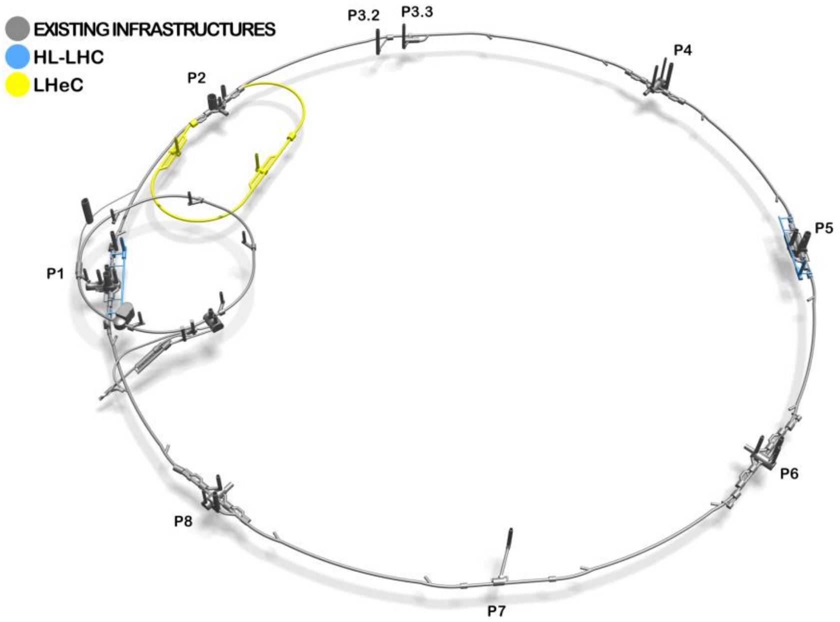
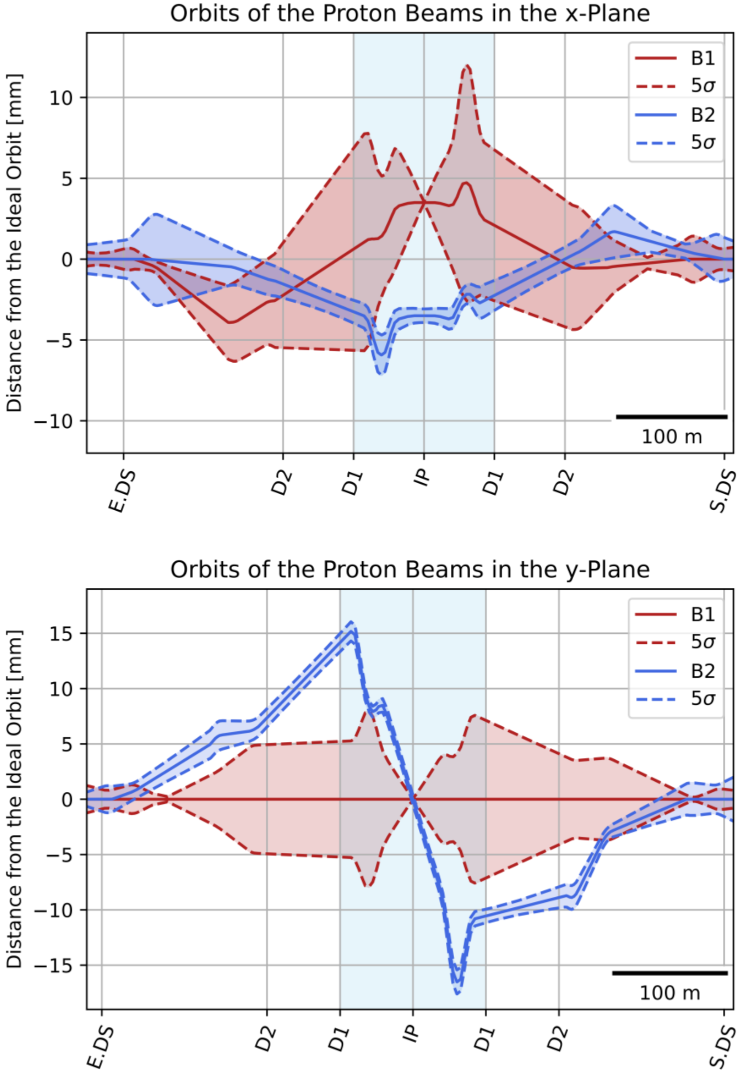
LHeC interaction region for Concurrent e-p and p-p Operation [3]



Possible layout of the LHeC. Showing existing infrastructures in grey, the HL-LHC upgrade in blue and the ERL in yellow. [P. Agostini et al., “The Large Hadron-electron Collider at the HL-LHC,” J. Phys. G: Nucl. Part. Phys., vol. 48, no. 11, p. 110 501, 2021, doi:10.1088/1361-6471/abf3b]



Possible separation scheme of the LHeC [3]

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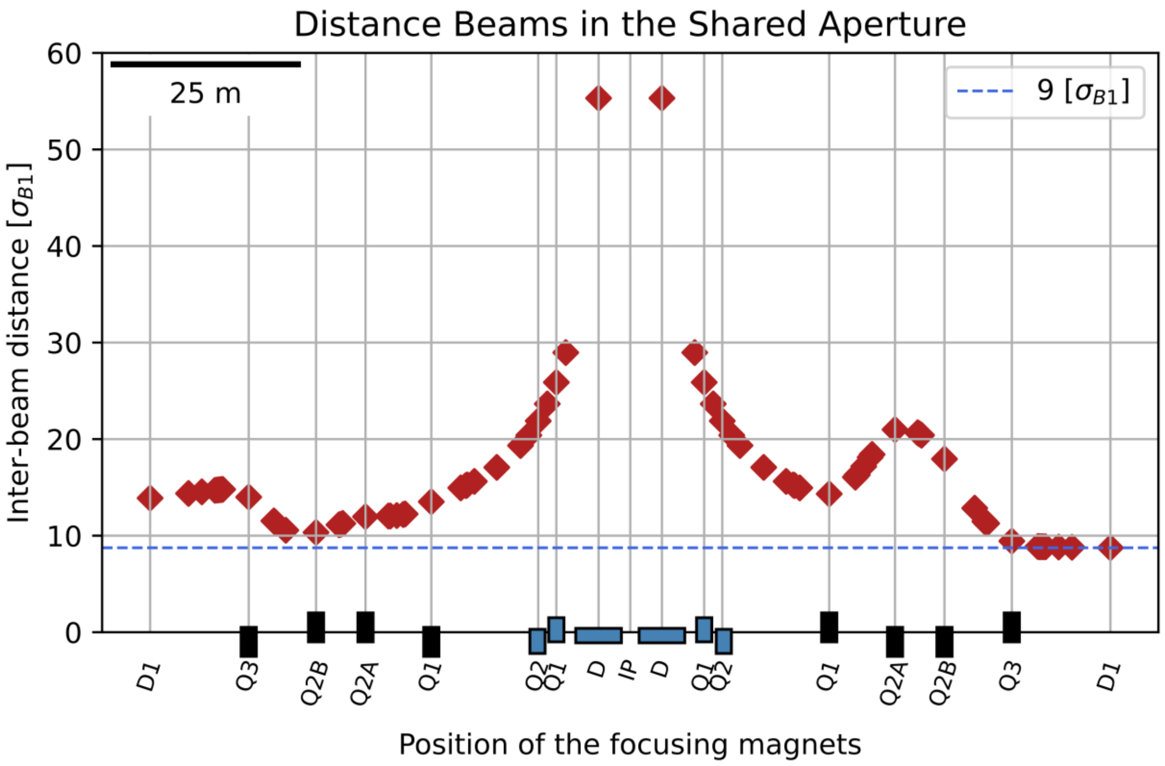
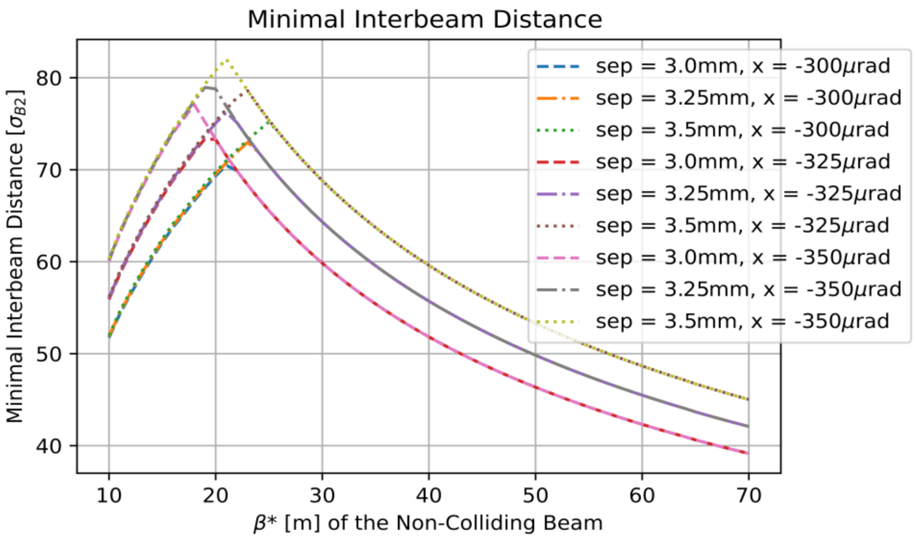
LHeC interaction region for Concurrent e-p and p-p Operation [3]





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

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