Layout of the Interaction Region for Electron Proton Collisions in the LHeC Collider

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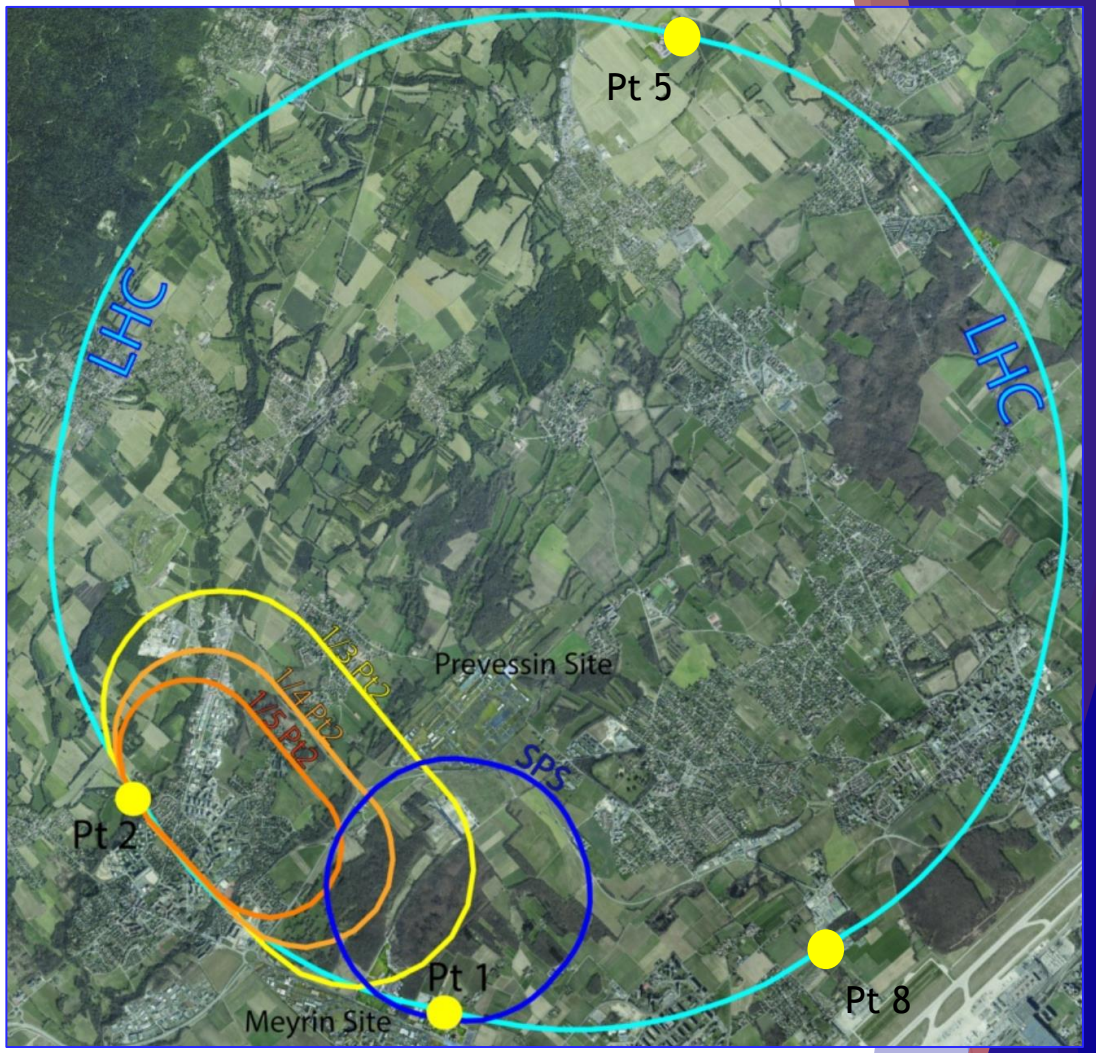
The Large Hadron electron Collider

- Equip the Large Hadron Collider with a tangential energy recovery linac
- 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 experiments at IP2 with concurrent operation with the other experiments

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



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Theoretical Background: Beam Envelope

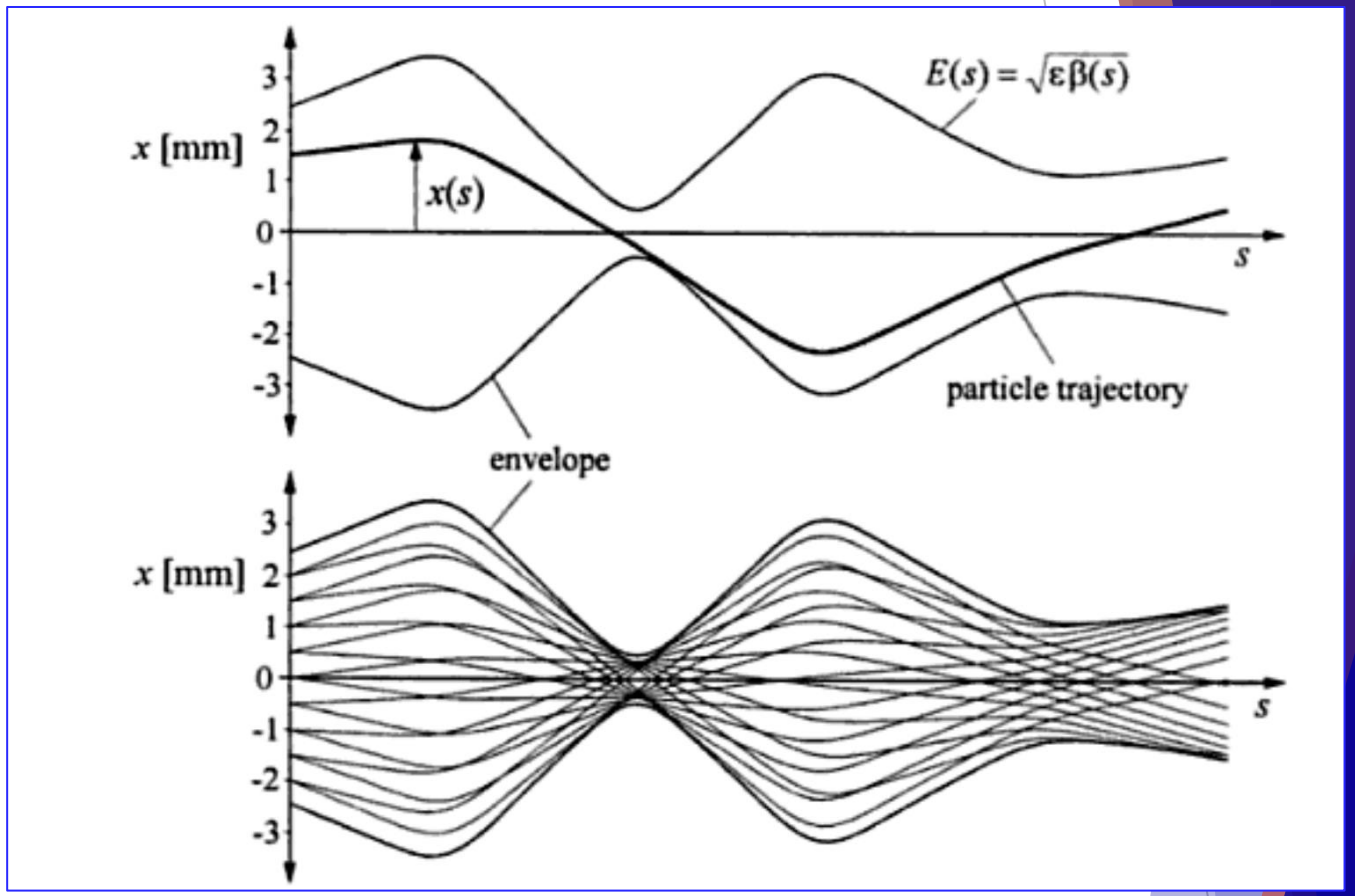
- Single particles perform betatron oscillations around their orbit s
- Many particles performing many turns are wrapped by the beam envelope:

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

- 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:

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

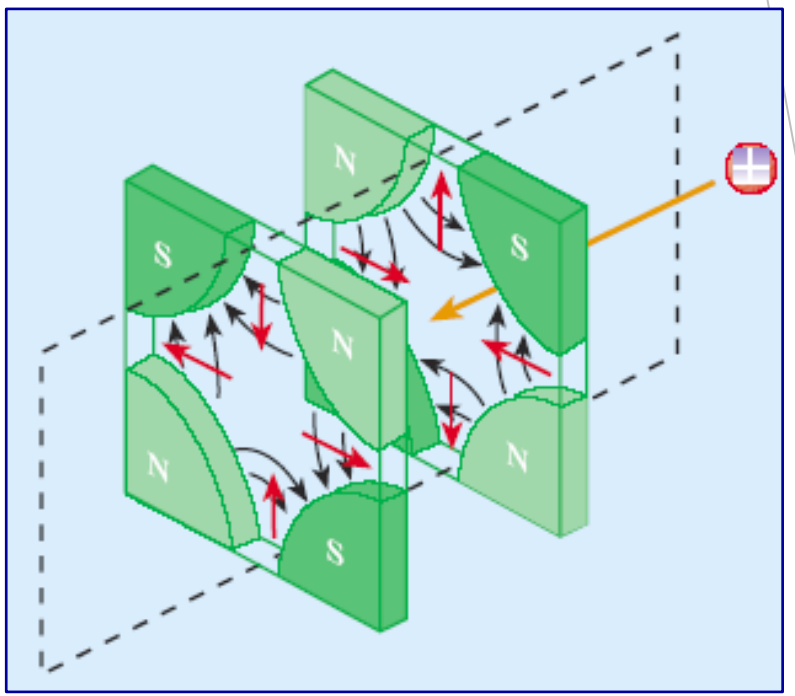
- $with\ \varepsilon \sim 10^{-10}$m $\quad \beta \sim 1\ m$

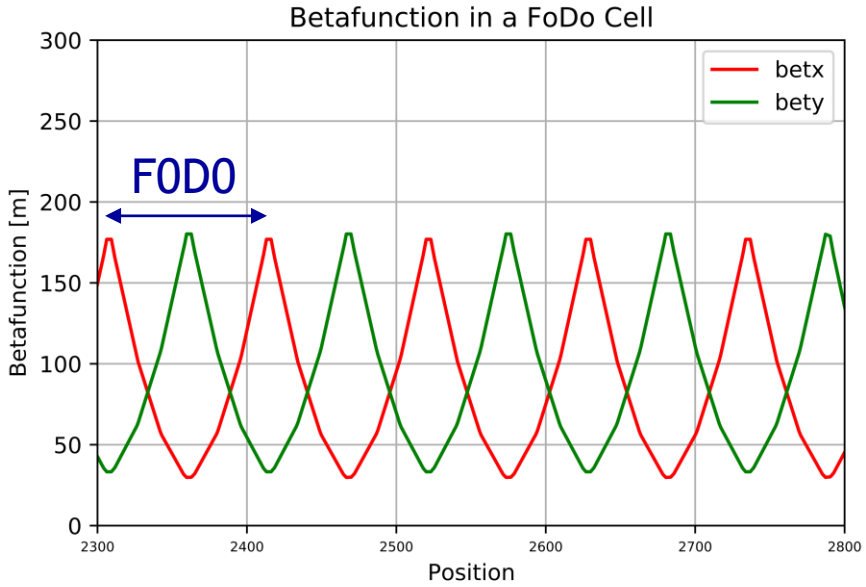


Beam envelope, K. Wille

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 down before the collision?

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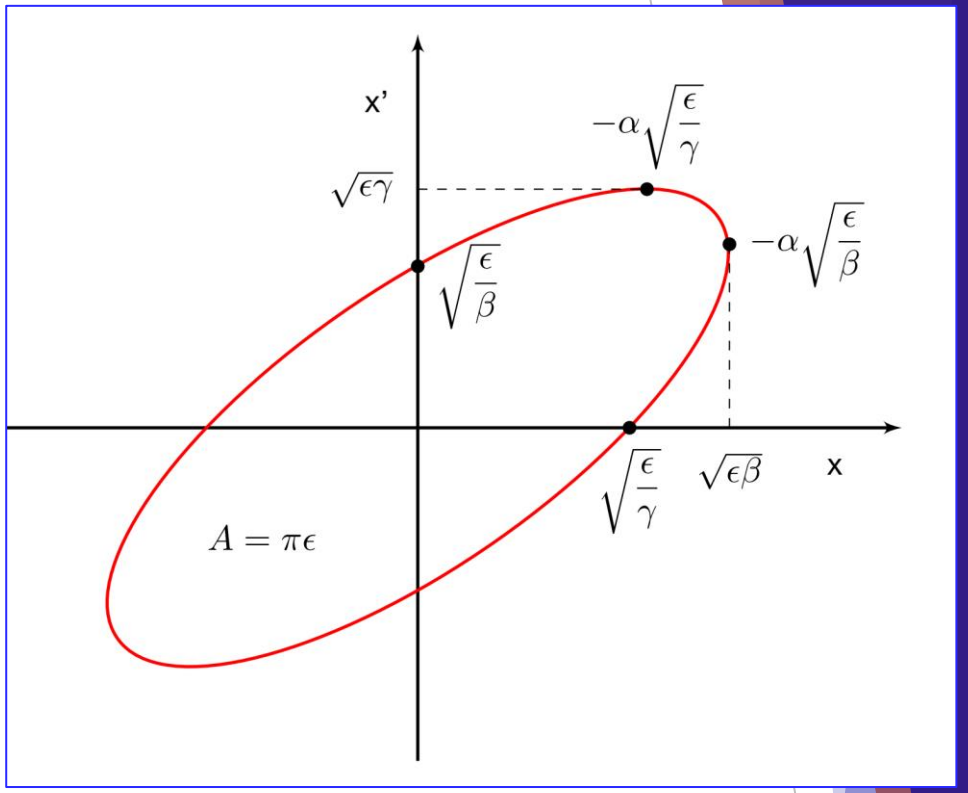
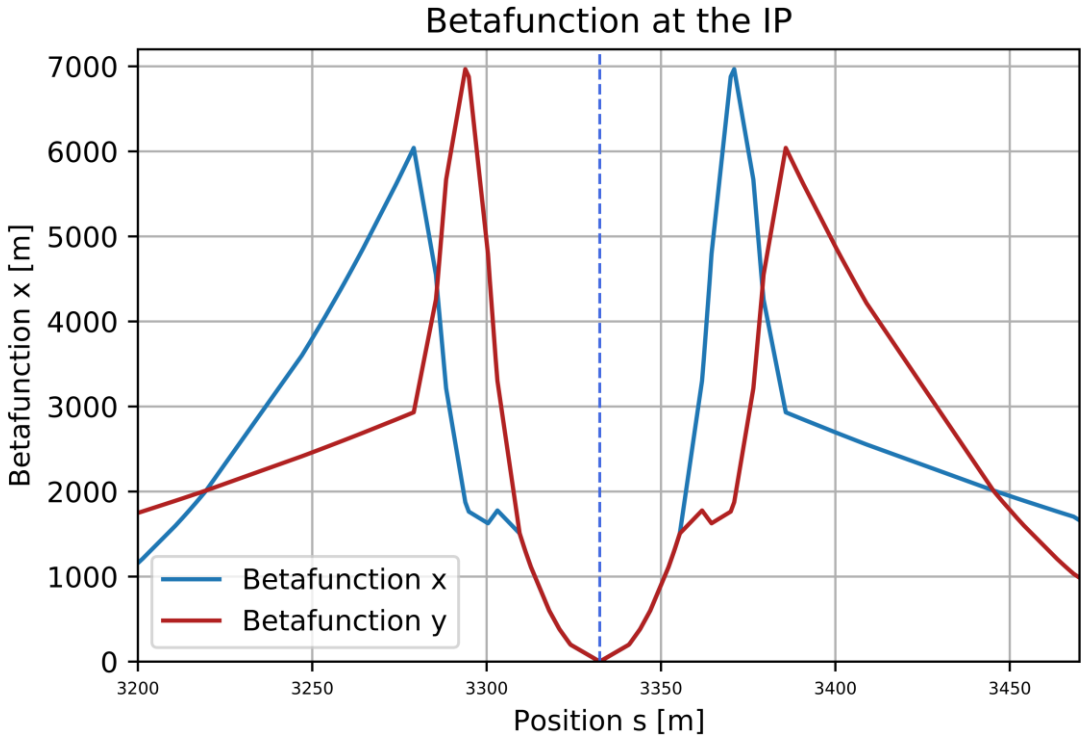
Phase Space Conservation and Liouville's Theorem

- *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

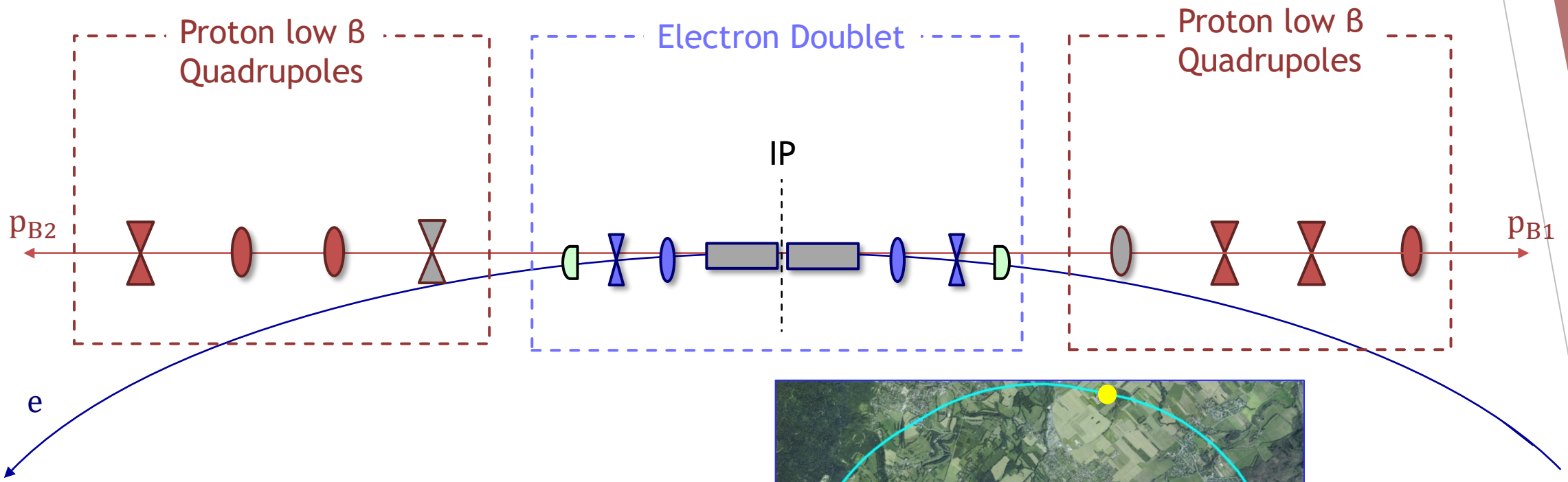


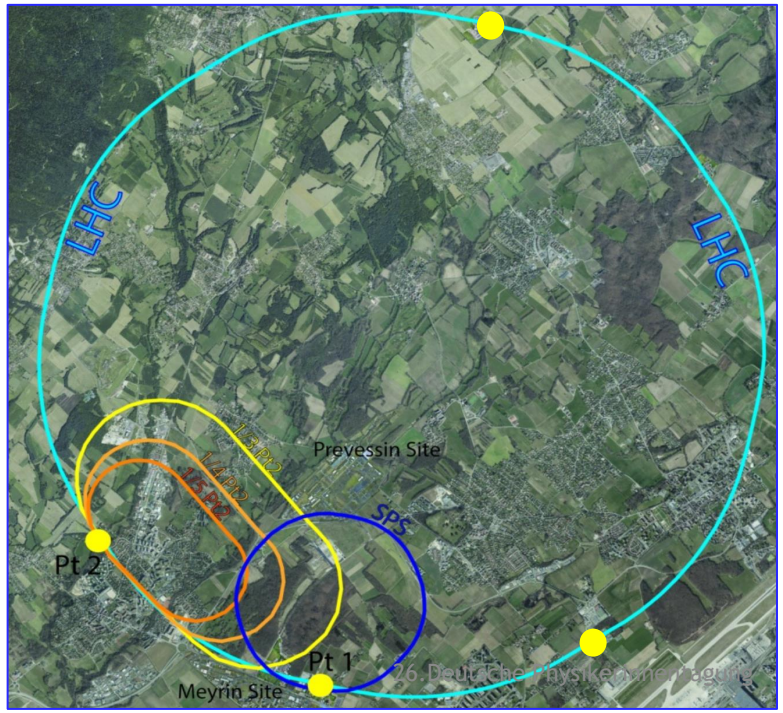
Betafunction before a drift space of the length l with minimum betafunction ß* :

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

The quadrupoles before the IR need the biggest aperture!

The Interaction Region of the LHeC





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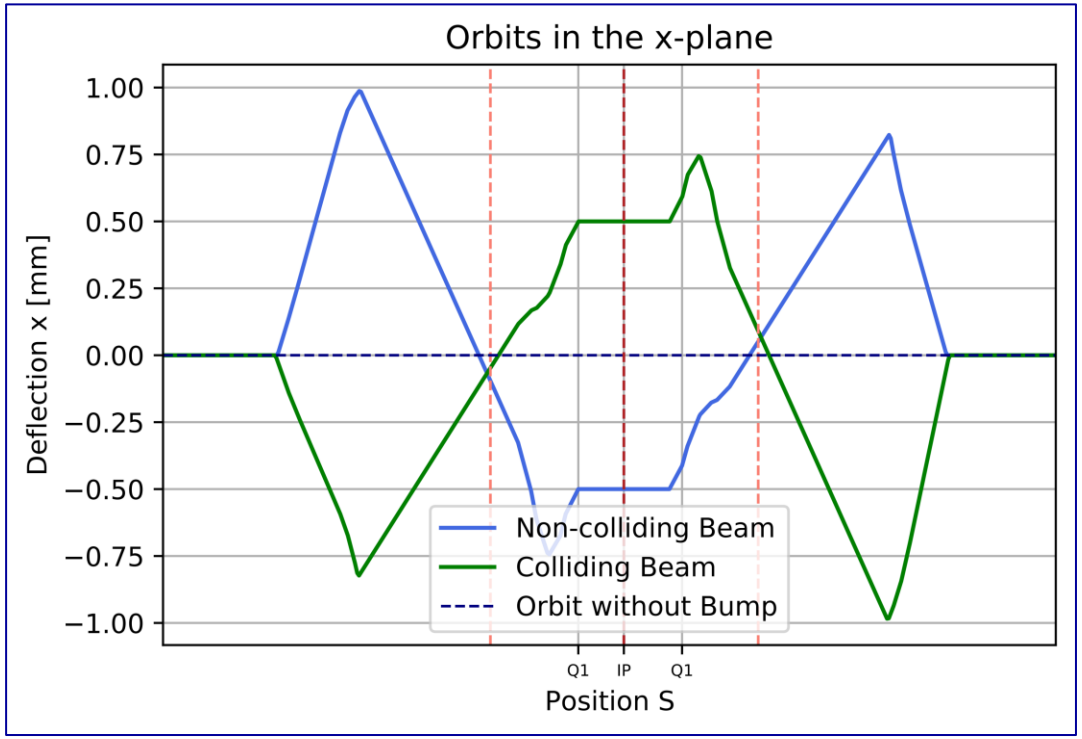
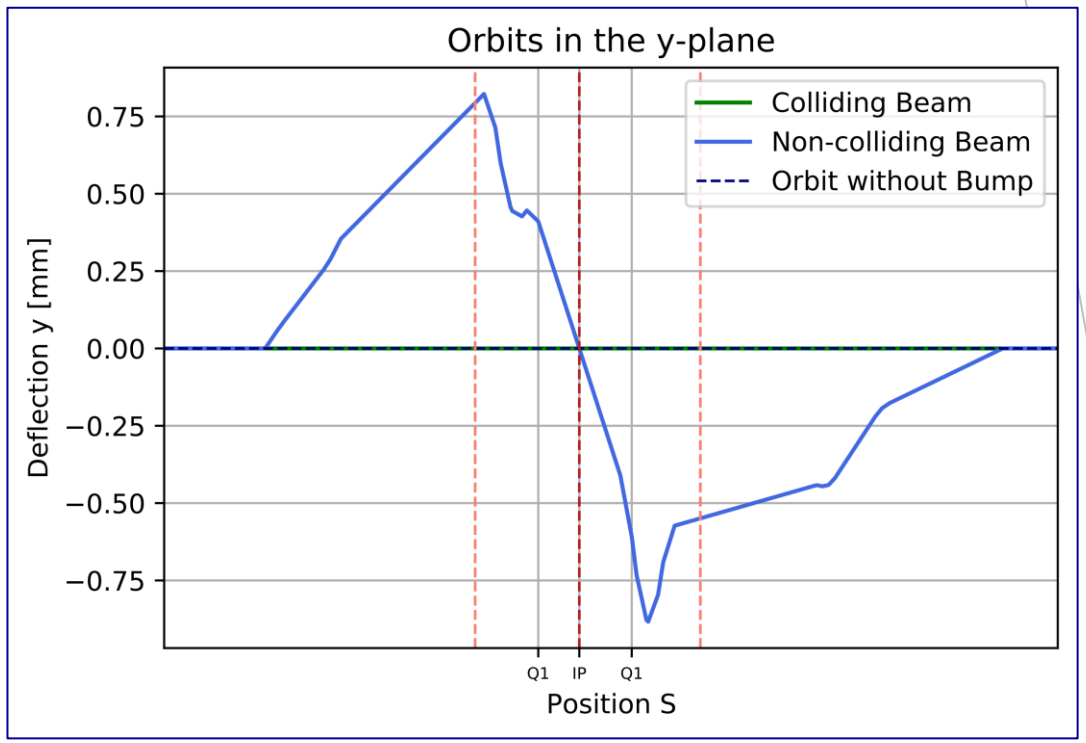
Beam Orbits in the Interaction Region





- Before the interaction region the beams do not share the same beam pipe
- The 2 Proton beams are separated in their shared interaction region with orbit bumps

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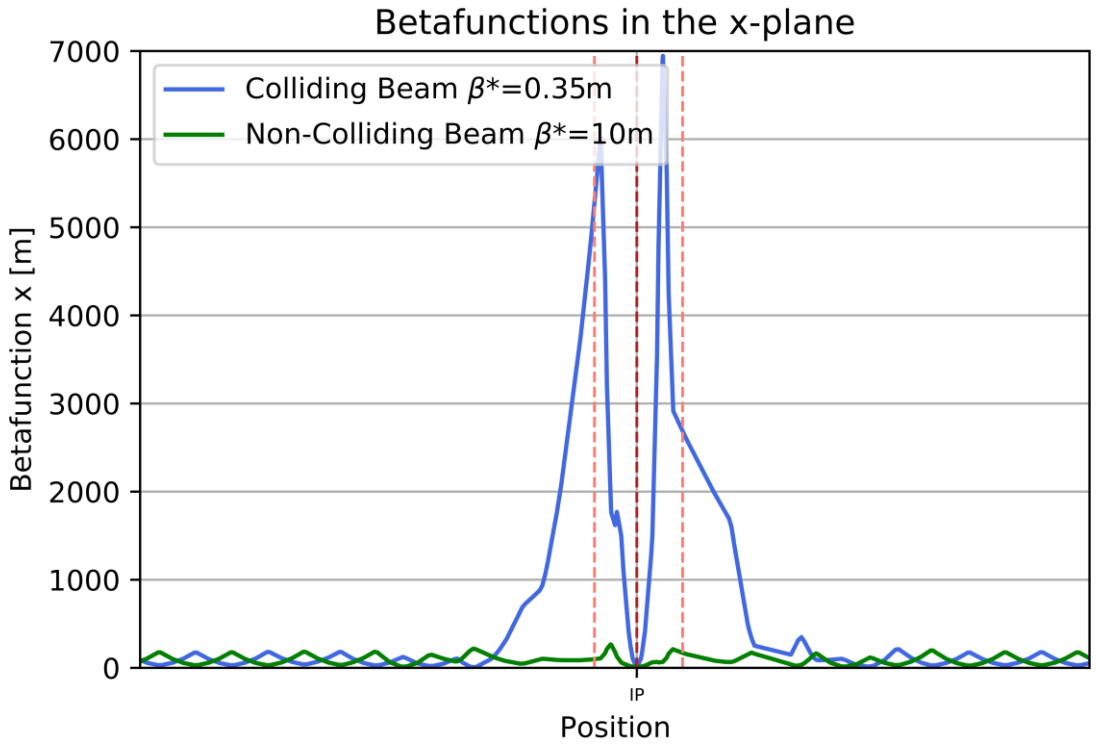
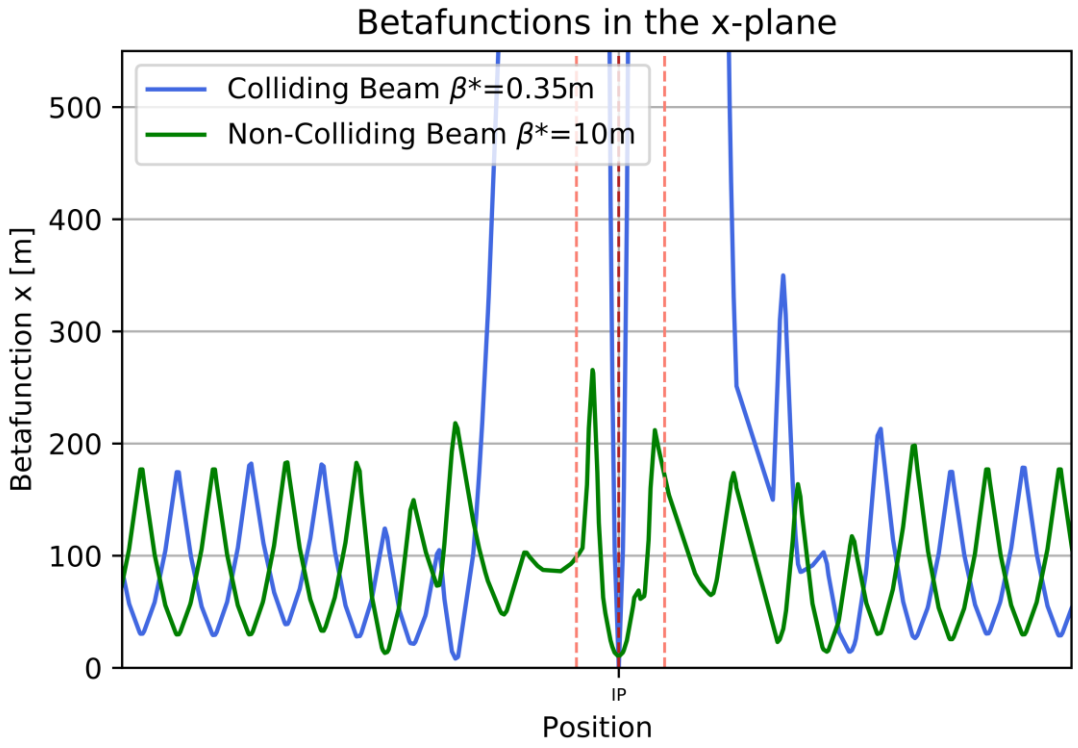
Optics in the Interaction Region

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

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



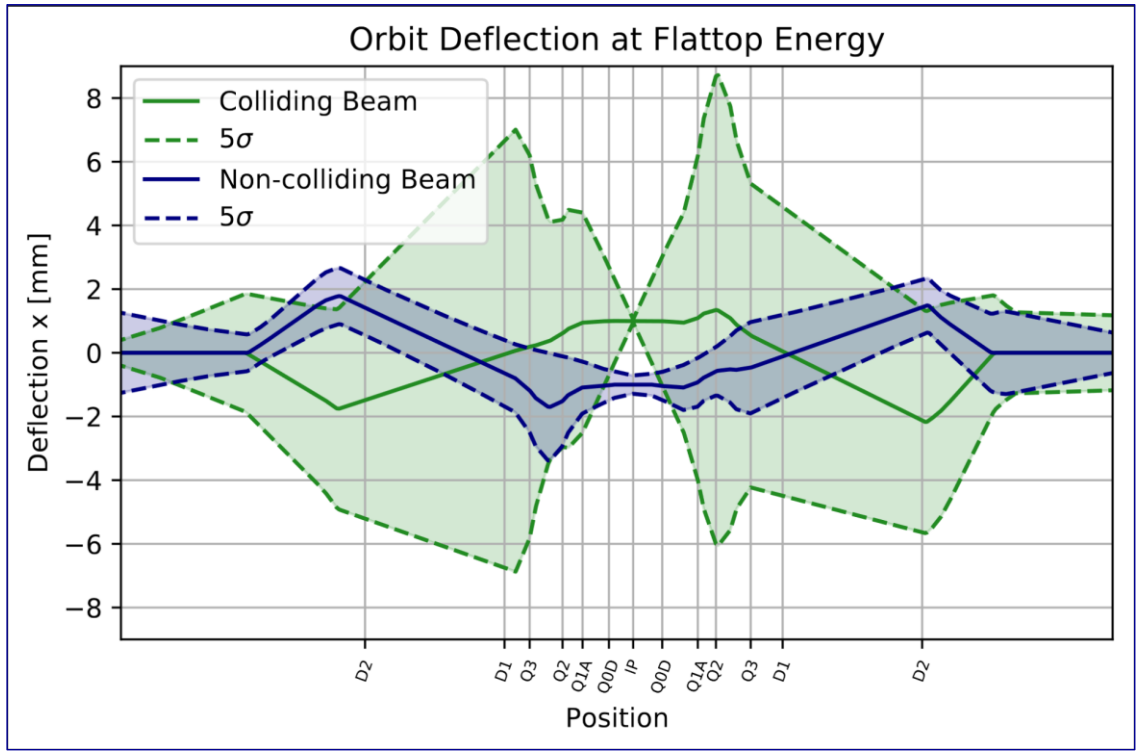


$$E(s) = \sqrt{\varepsilon\beta(s)} = 1\sigma_u$$

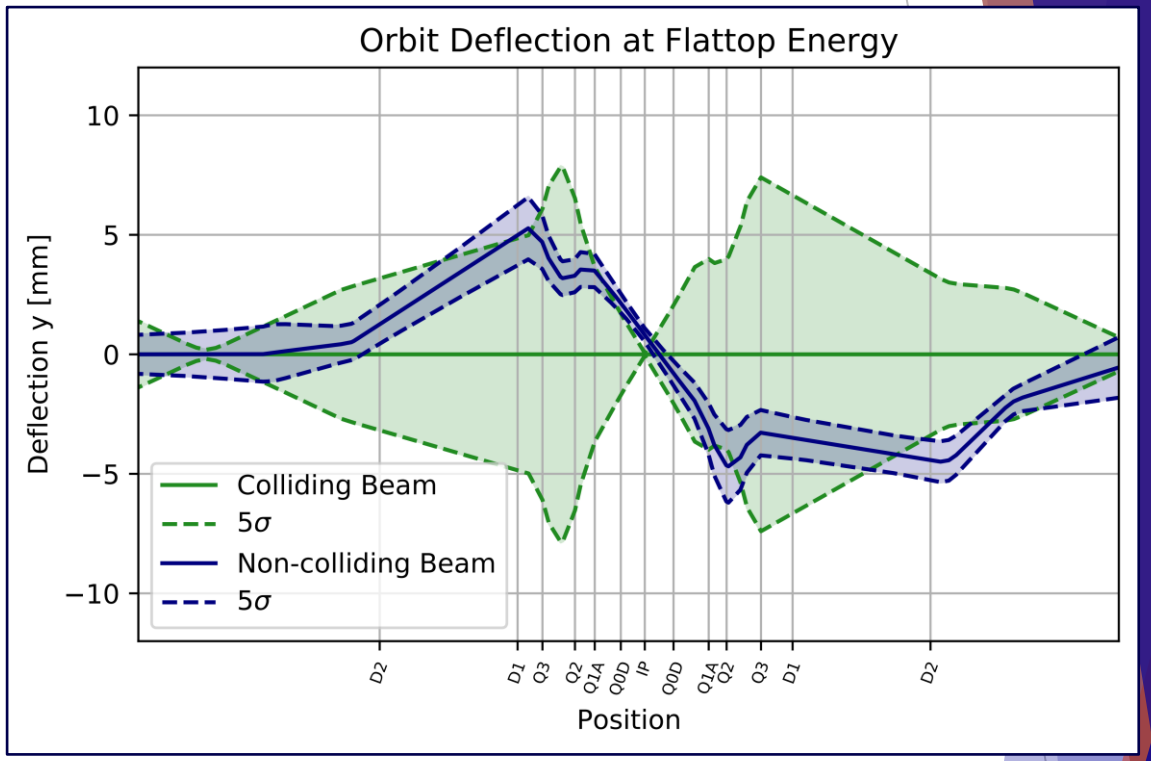
Beam envelope

Proton Beam Orbits and Optics at IP2

x-plane



y-plane



At the IP:

ß*= 0.35m Colliding Beam

ß*= 10m Non-colliding Beam

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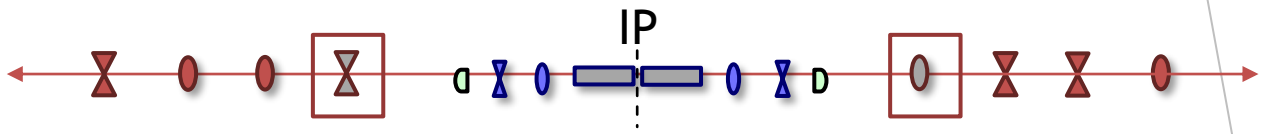
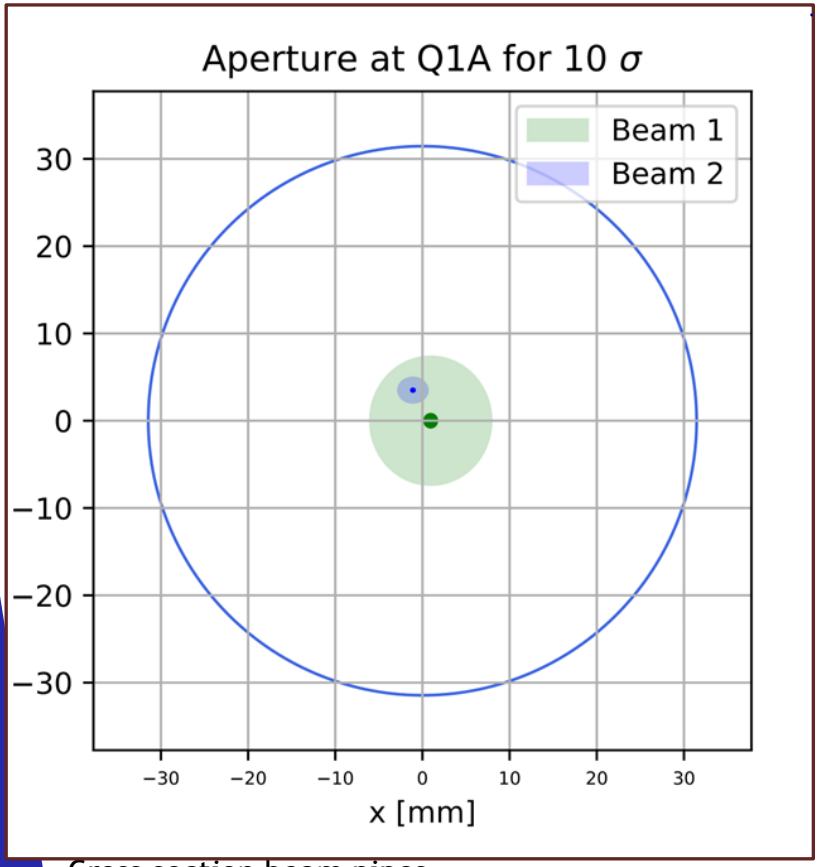
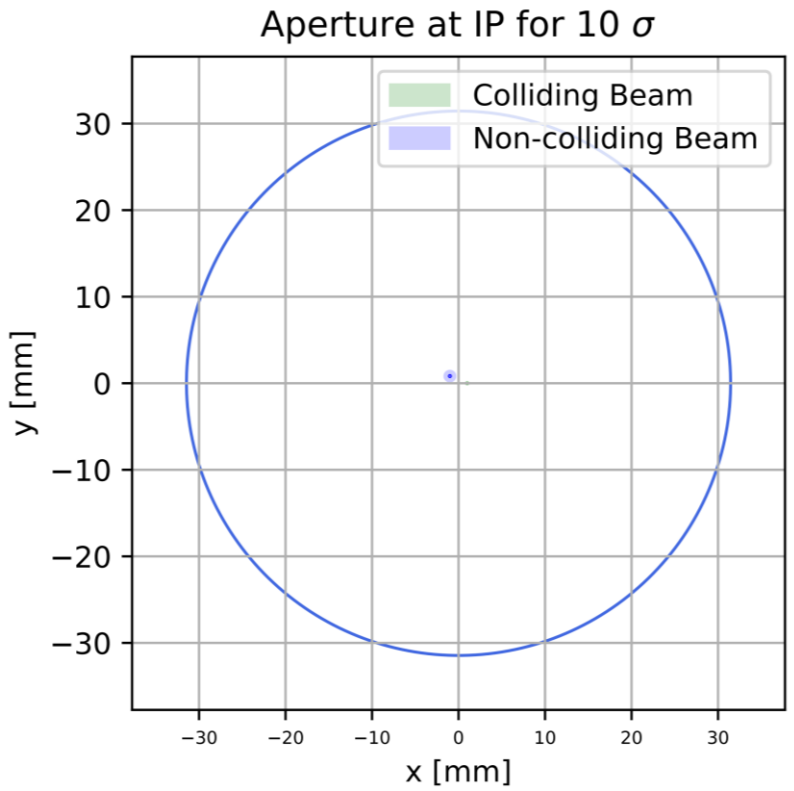
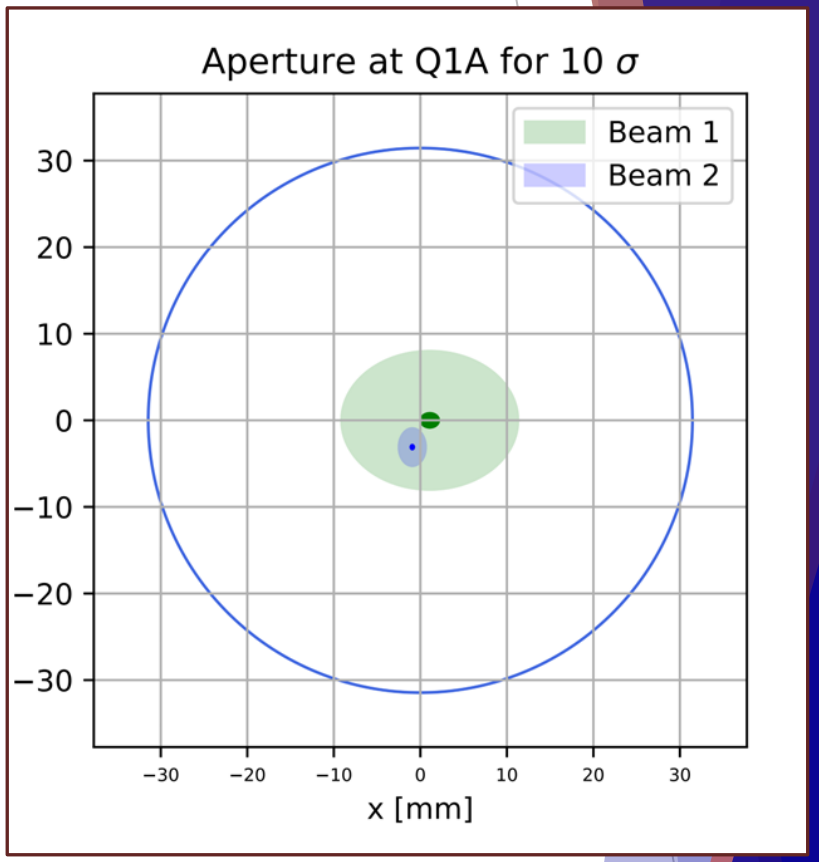
Apertures in the Beam Pipe





Cross section beam pipes





At the IP:
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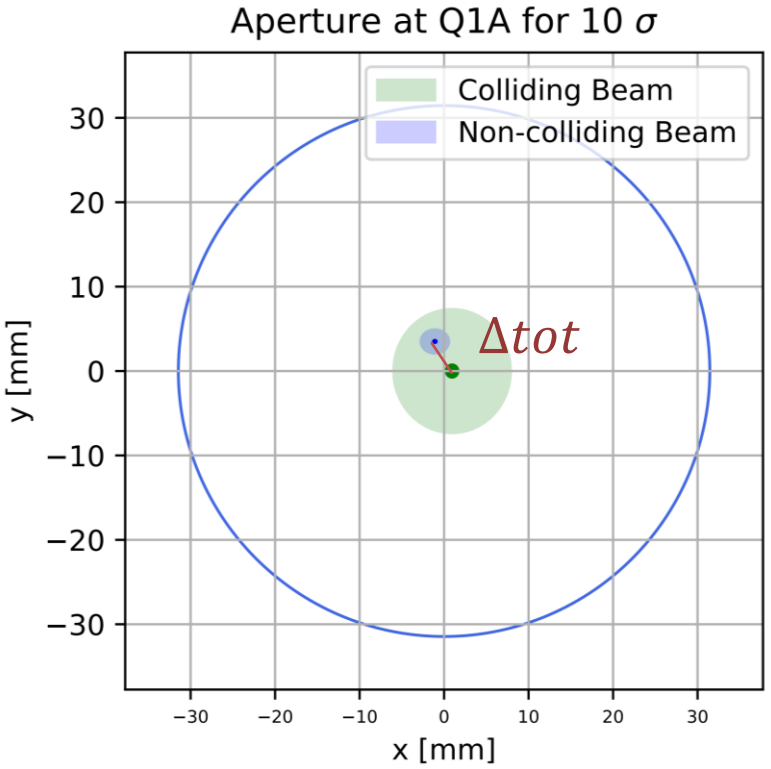
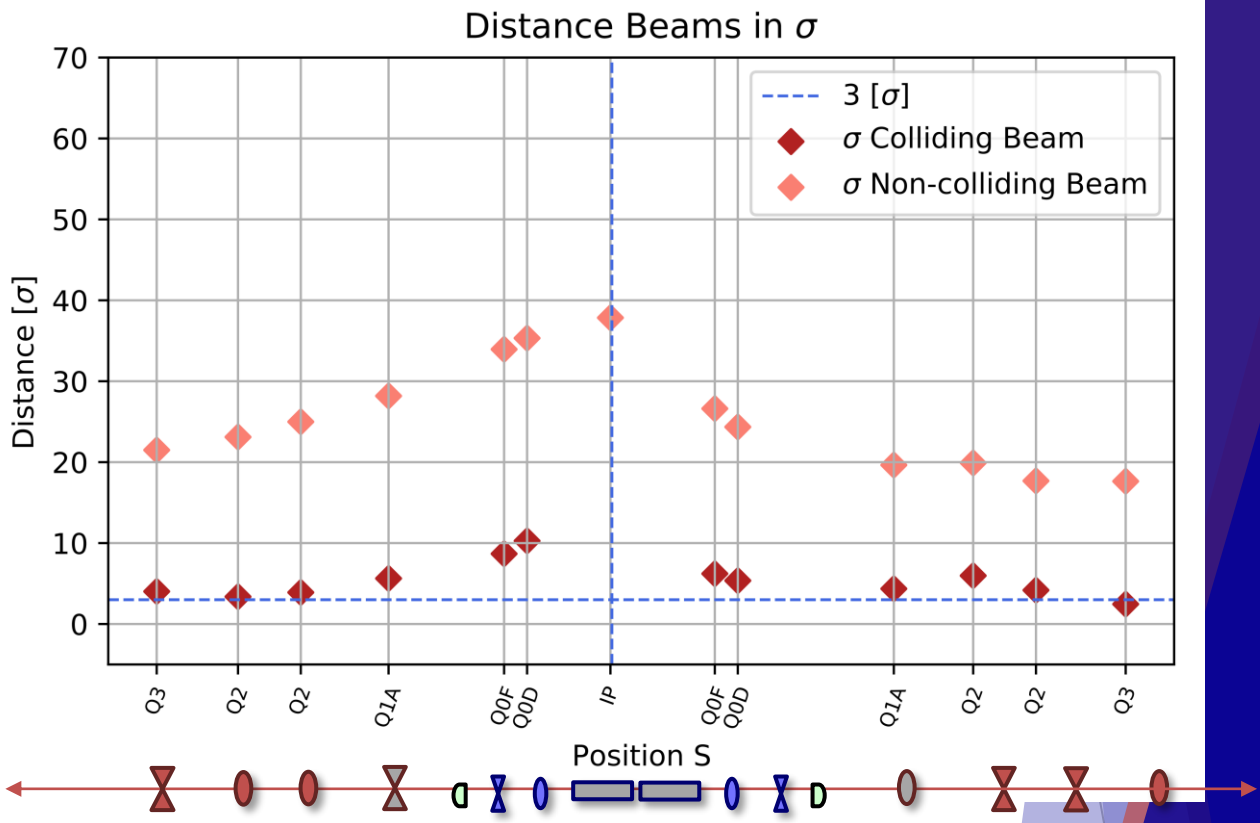
Inter-beam Distance LHC

Total Distance between the beams in the shared interaction region in units of σ



$$\Delta tot\ [\sigma] = \frac{\Delta tot\ [m]}{\sigma_{B1,2}[m]}$$



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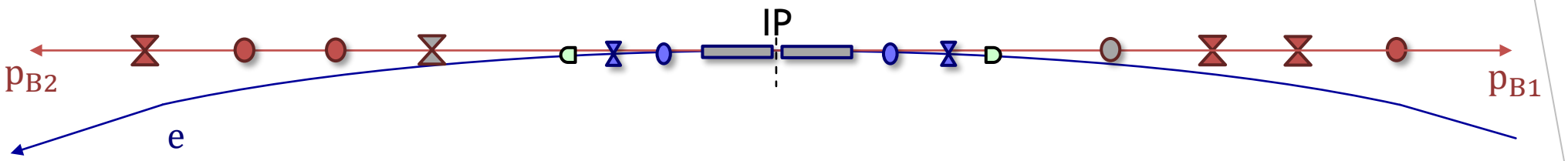
Outlook



Parameter	Unit	LHeC		
		CDR	Run 5	Run 6
E_e	GeV	60	30	50
N_p	10^{11}	1.7	2.2	2.2
ϵ_p	μm	3.7	2.5	2.5
I_e	mA	6.4	15	20
N_e	10^9	1	2.3	3.1
β^*	cm	10	10	7
Luminosity	$10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1	5	9

LHeC Parameters CDR 2020

- Proof of principle calculations performed for the LHC
- Need to be adapted to HL-LHC (new triplets!)
- Improvement of the inter beam distance
- Further focusing of the colliding beam to reach luminosity goals!

$$L = \frac{N_1 \cdot N_2 \cdot n \cdot f}{4\pi\sigma_x\sigma_y}$$

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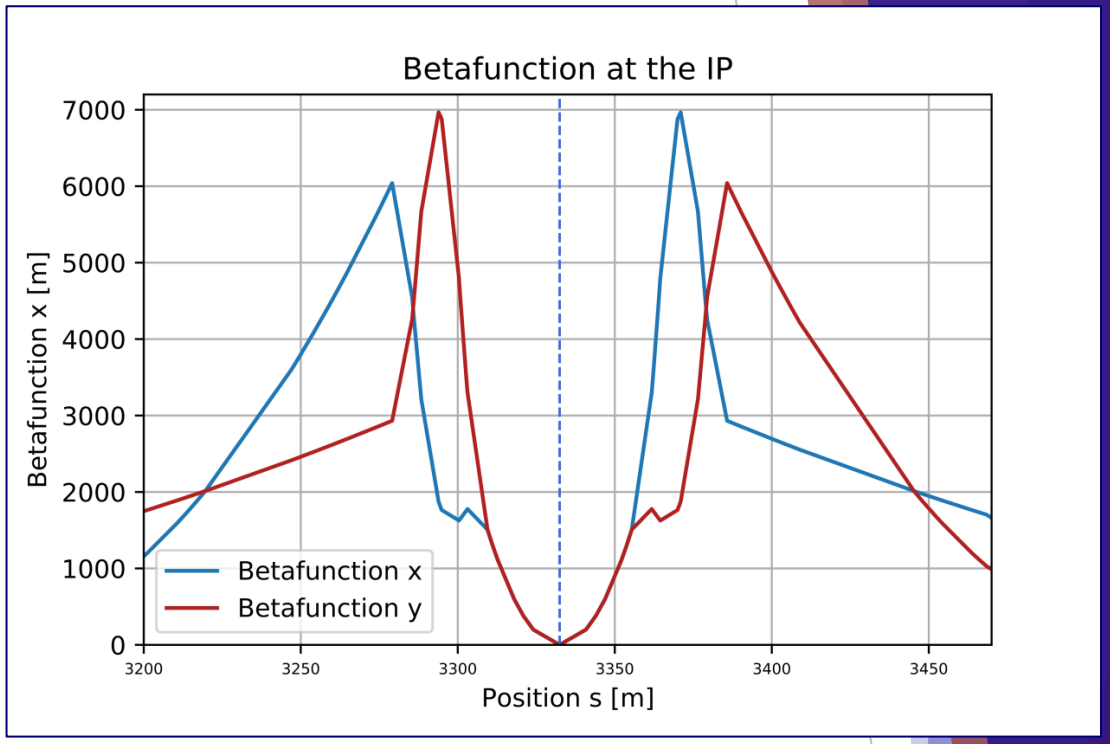
Appendix

Minibeta Optimization

- Betafunction in a drift space: $\beta(l) = \beta^* + \frac{l^2}{\beta^*}$
- Find optimal β^*: $\frac{d\beta(s)}{d\beta^*} = 1 - \frac{l^2}{\beta^{*2}} = 0$
- Smallest beta at the end of the drift for: $\beta^* = l$
- At ALICE the drift space has a length of 23m



An variation of the second beam between the design 10m and 23m could lead to optimized distances between the beams

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How does this affect our collider?

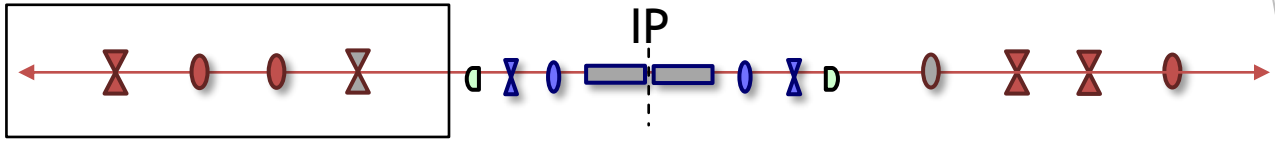
$$L = \frac{N_1 \cdot N_2 \cdot n \cdot f}{4\pi\sigma_x\sigma_y}\,[cm^{-2}s^{-1}]$$

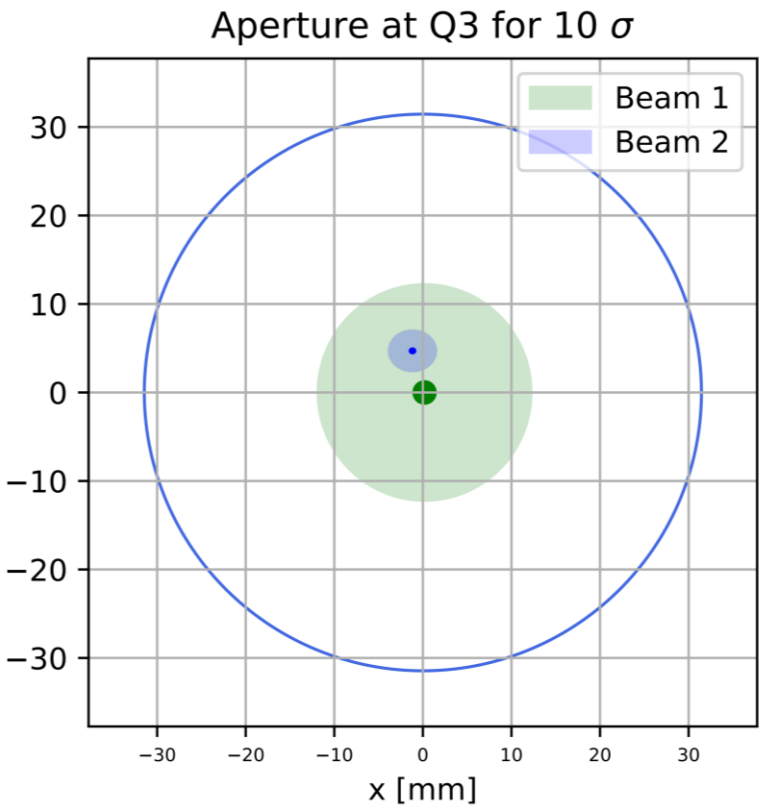
- Using the formula for beta in a drift: $\beta(l) = \beta^* + \frac{l^2}{\beta^*}$
- For the standard LHC this yields at ATLAS and CMS: $\beta(23) = 0.55m + \frac{23m^2}{0.55m} = 963\text{m}$
- How far can we go in betastar with a drift of 15m?

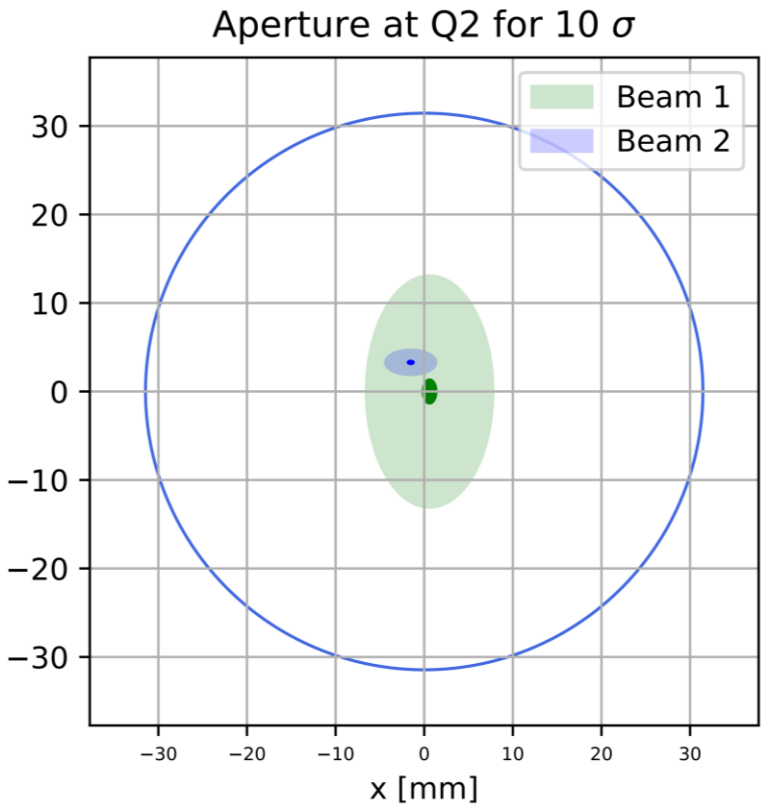
$$\beta(15) = x\,m + \frac{15m^2}{x\,m} = 963\text{m} \quad \Rightarrow \quad x = 0.234m$$

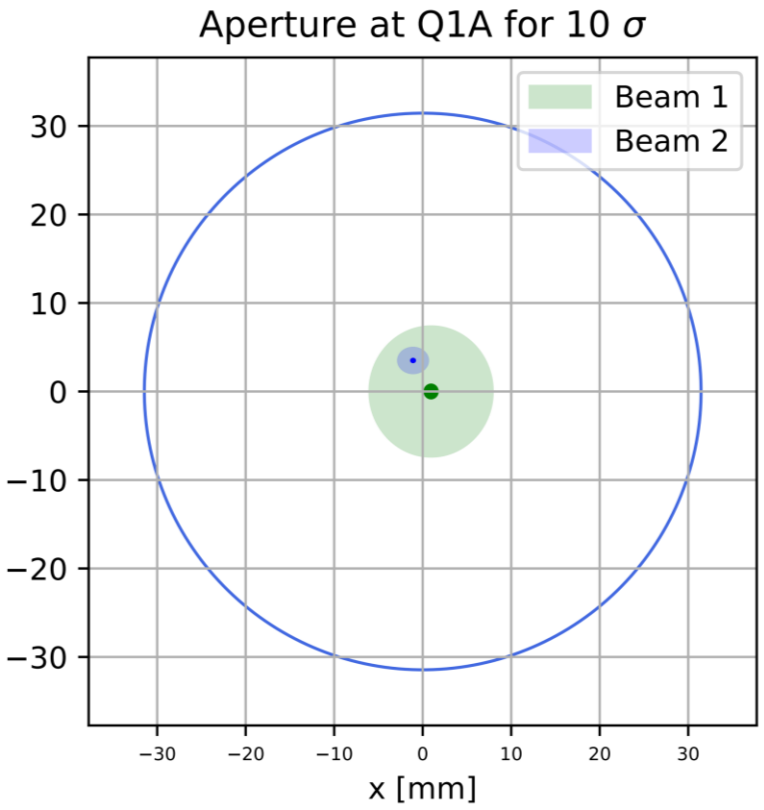
LHC Data

Apertures of the Proton Beams









Cross section beam pipes

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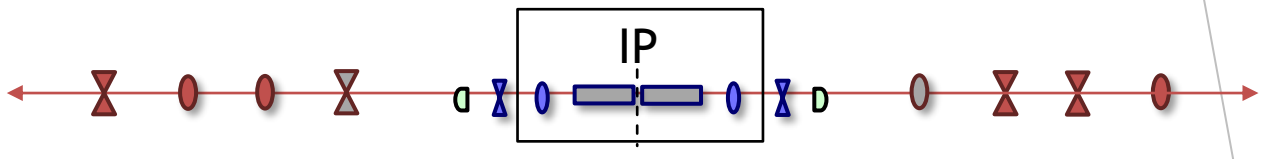
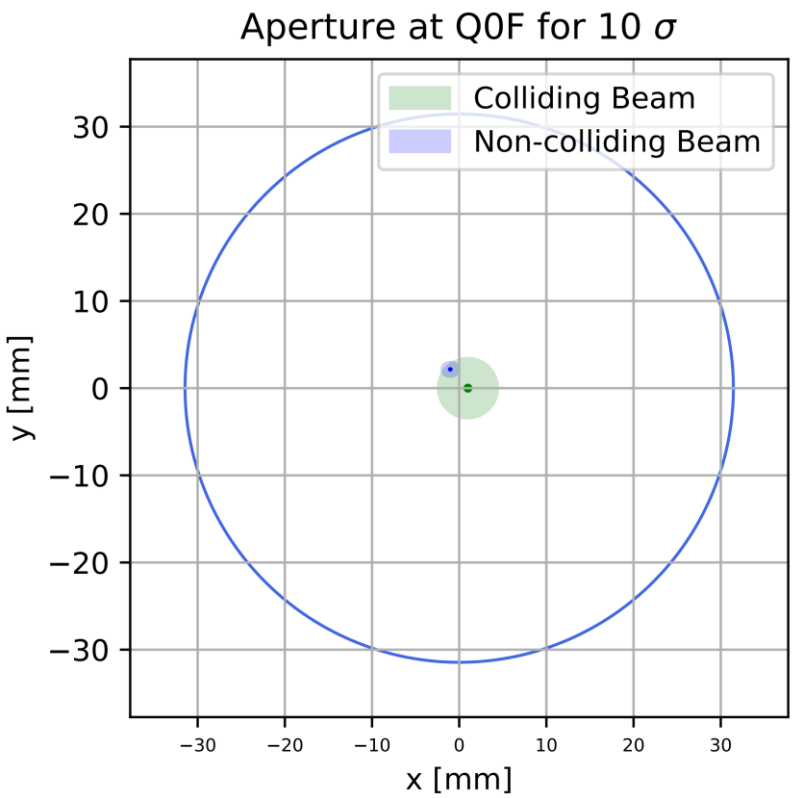
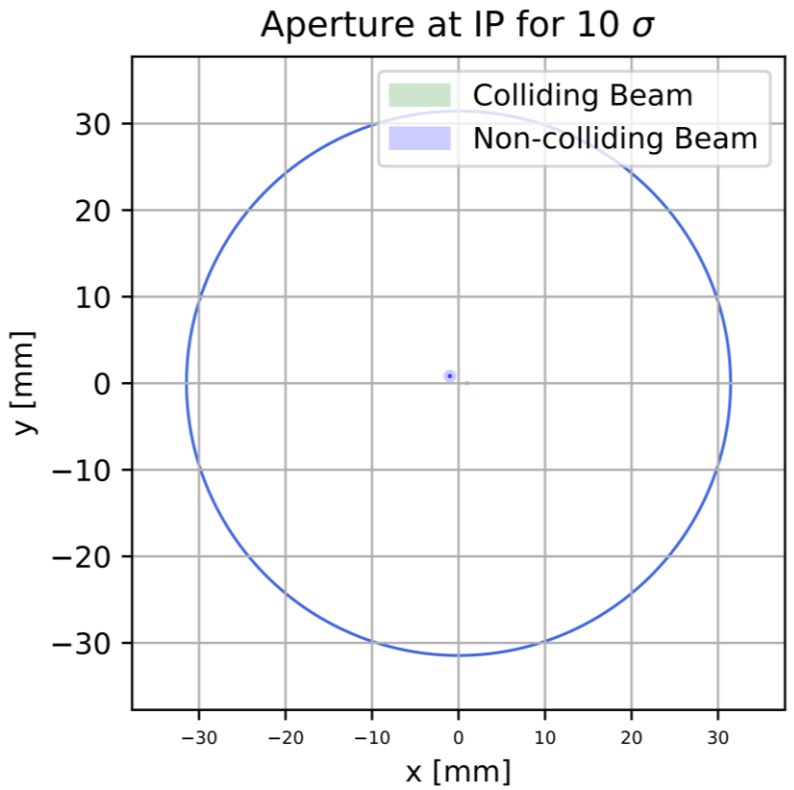
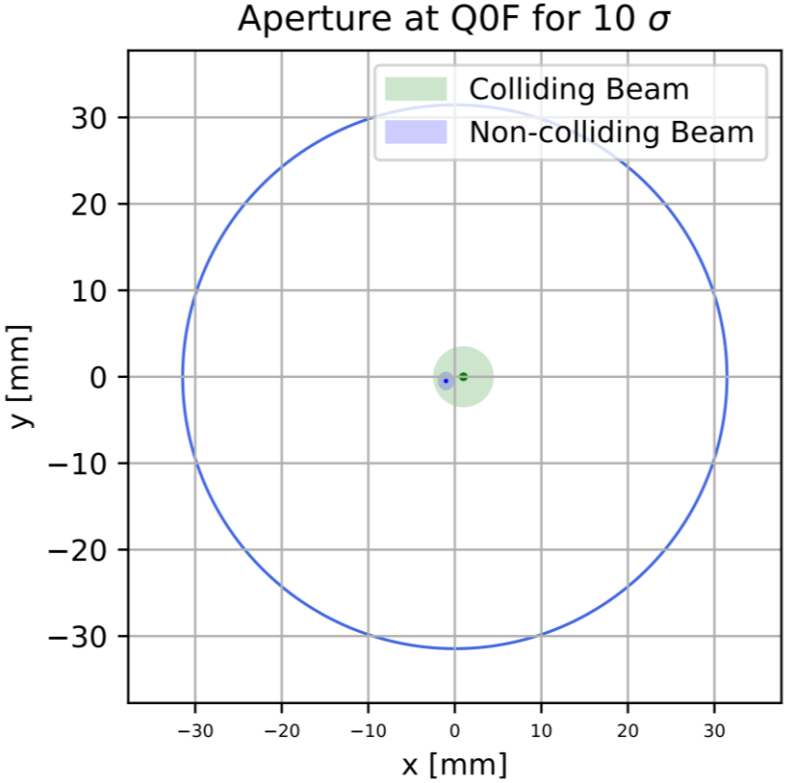
Apertures of the Proton Beams









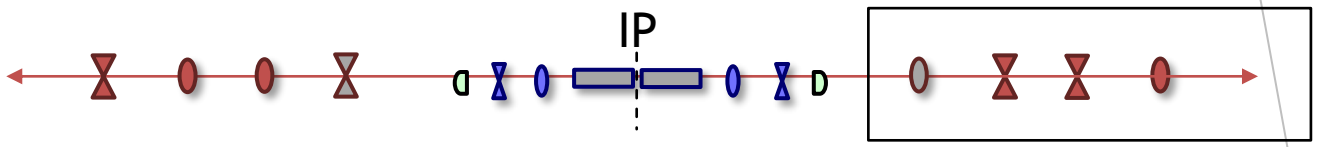
Cross section beam pipes

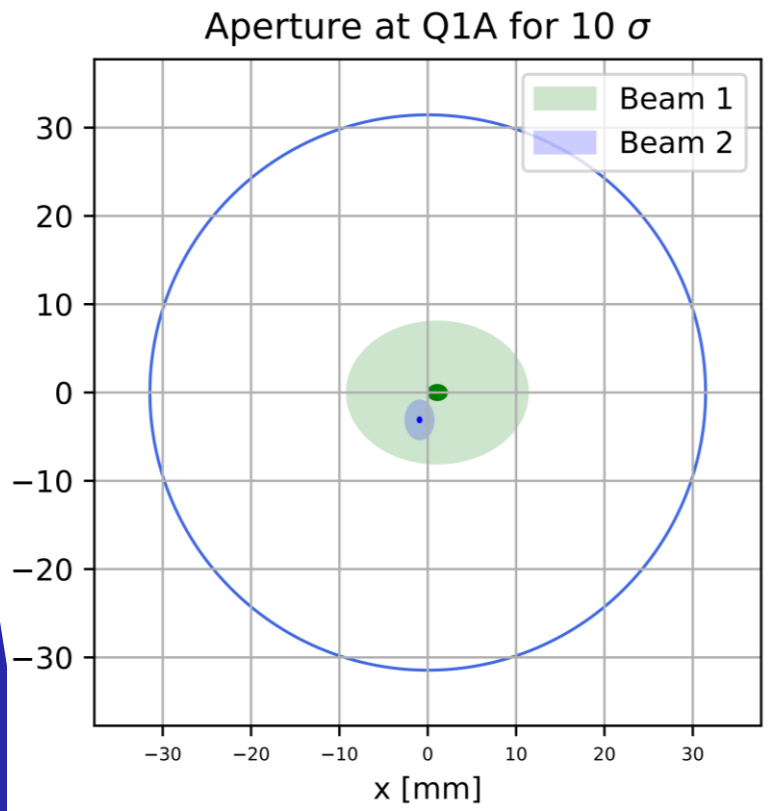
At the IP:

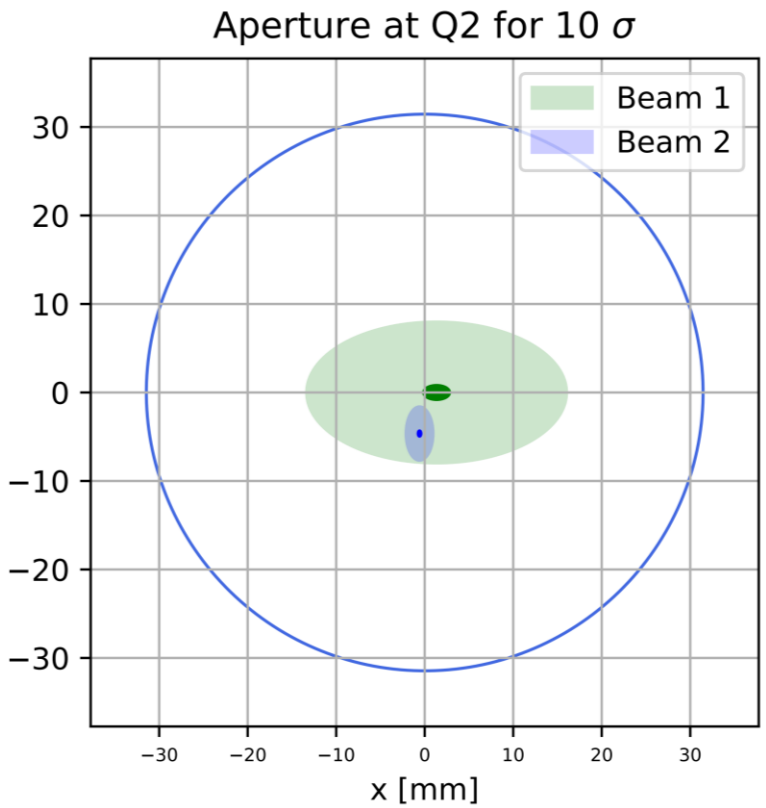
ß*= 0.35m Colliding Beam

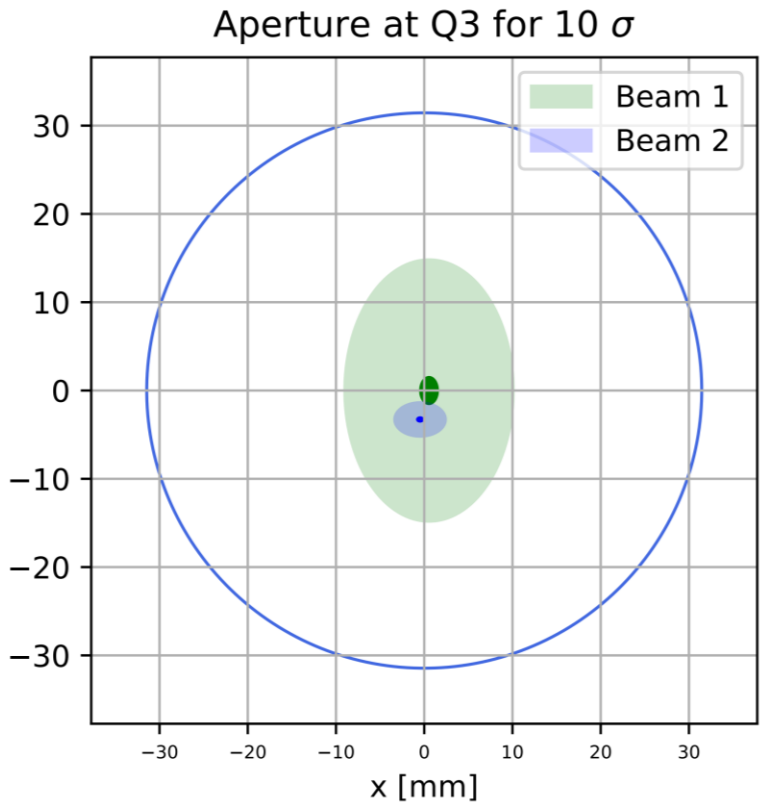
ß*= 10m Non-colliding Beam

Apertures of the Proton Beams









Cross section beam pipes

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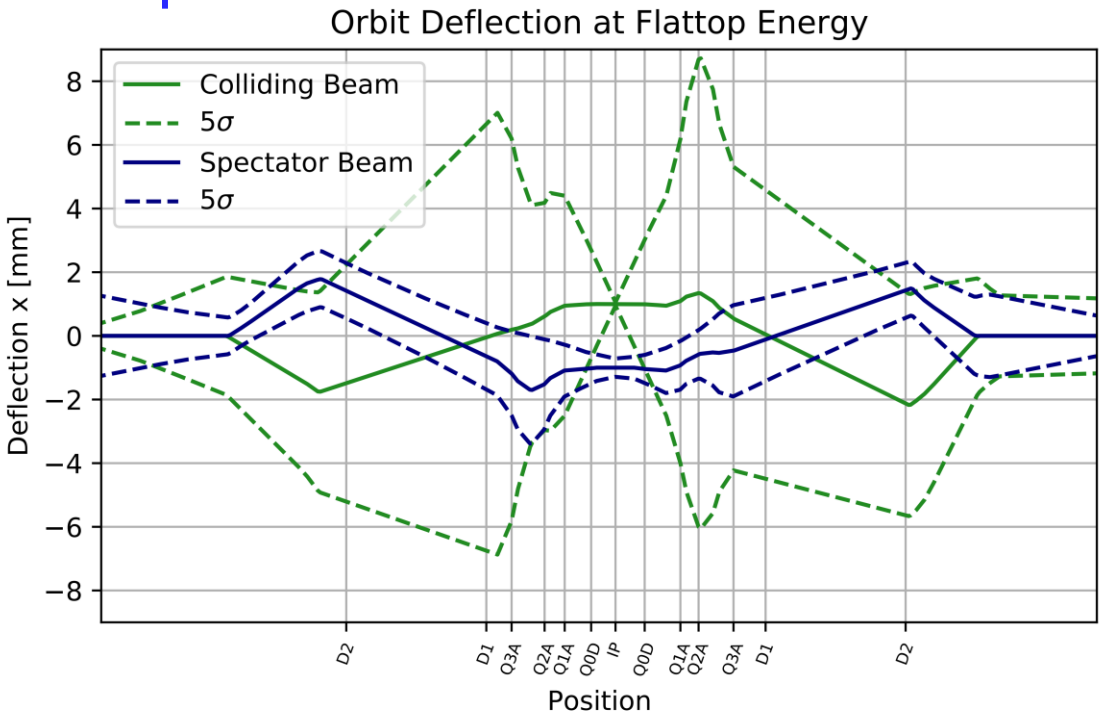
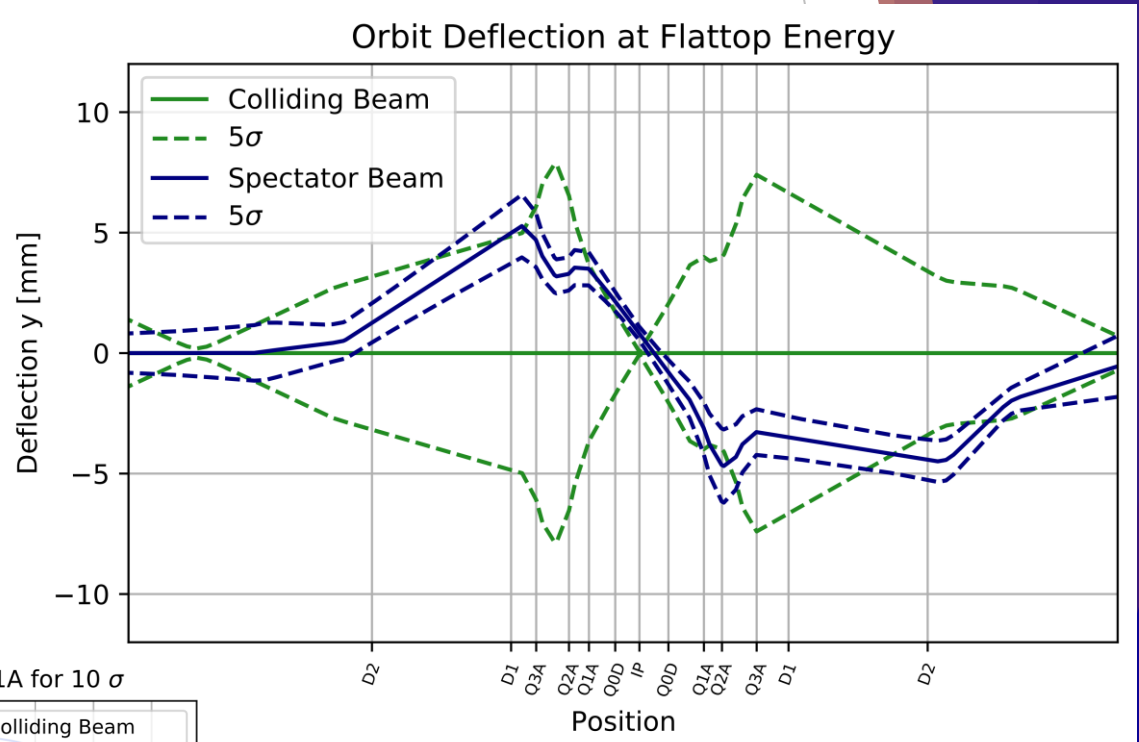
Proton Optics and Orbit

x-plane



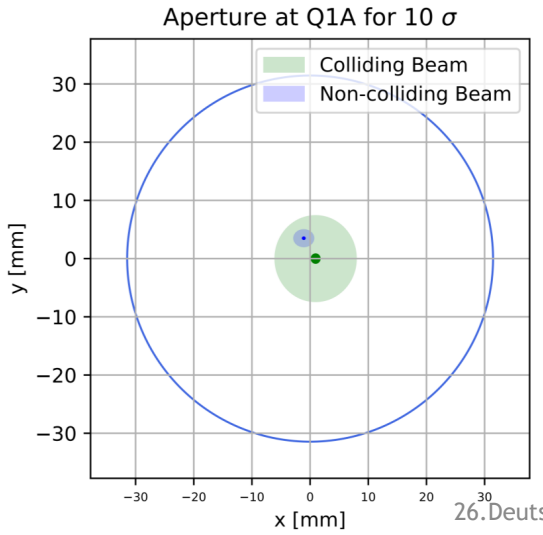
y-plane



At the IP:

β_1^*= 0.35m

β_2^*= 10m … 23m



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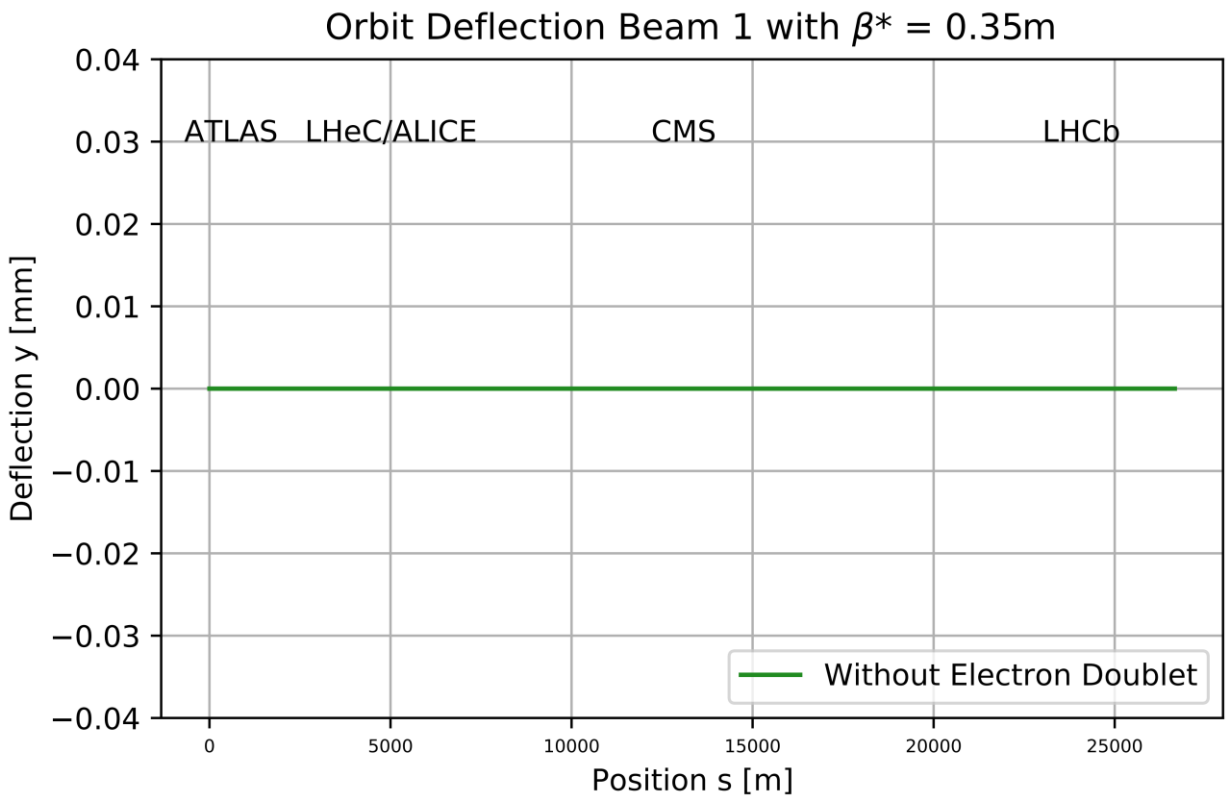
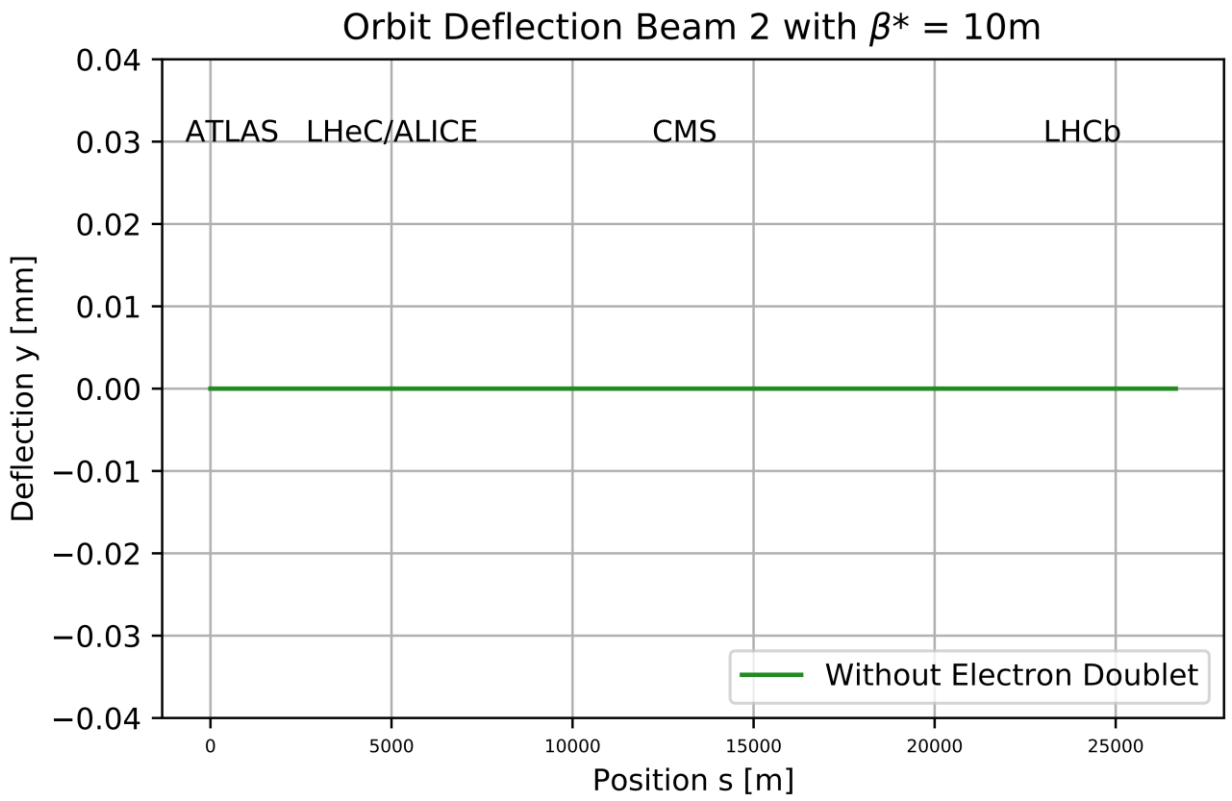
Impact on the Proton Orbits y-plane

- Colliding Beam



- Spectator Beam



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Impact on the Proton Orbits y-plane

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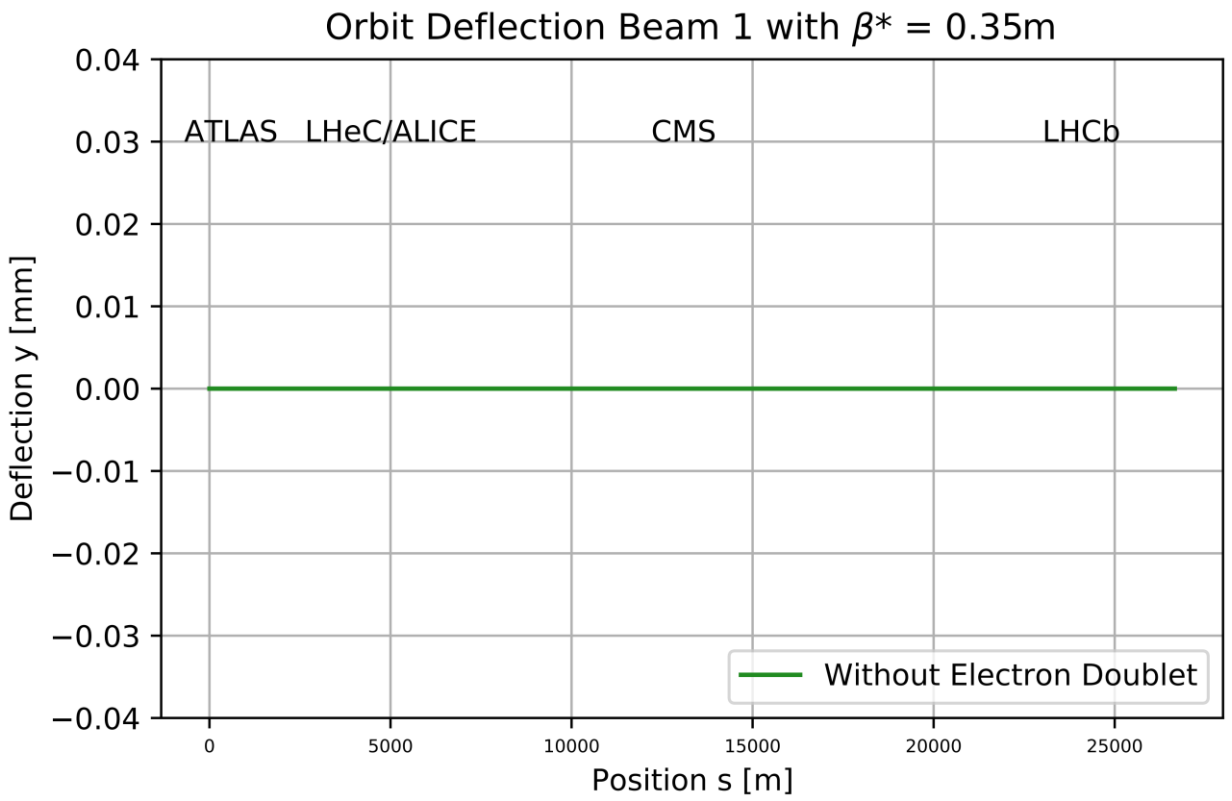

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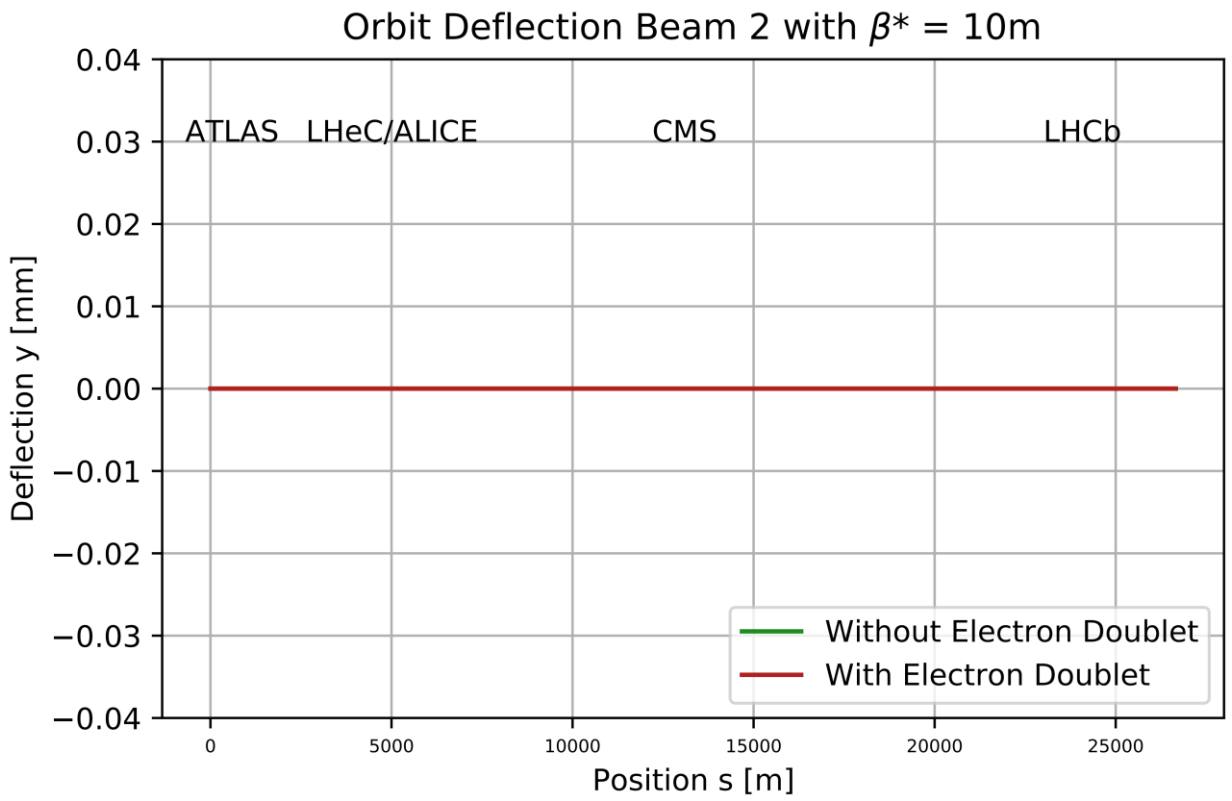

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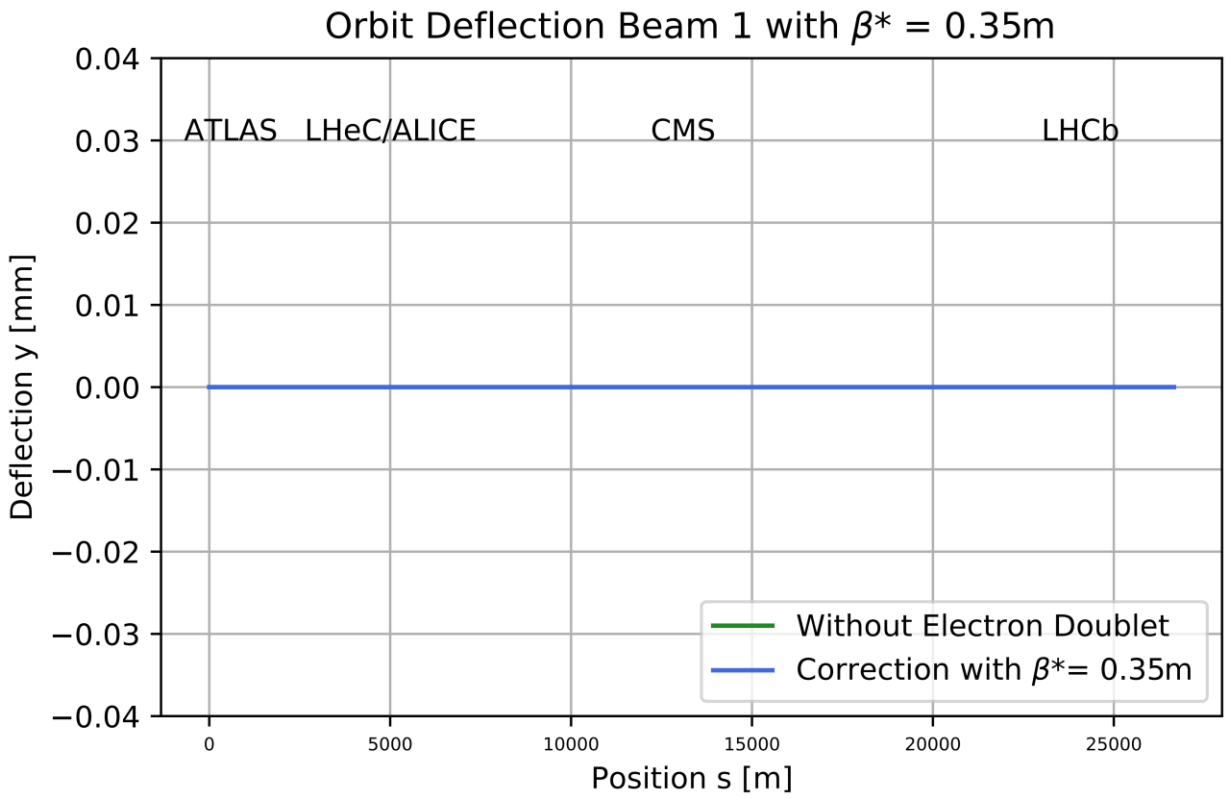

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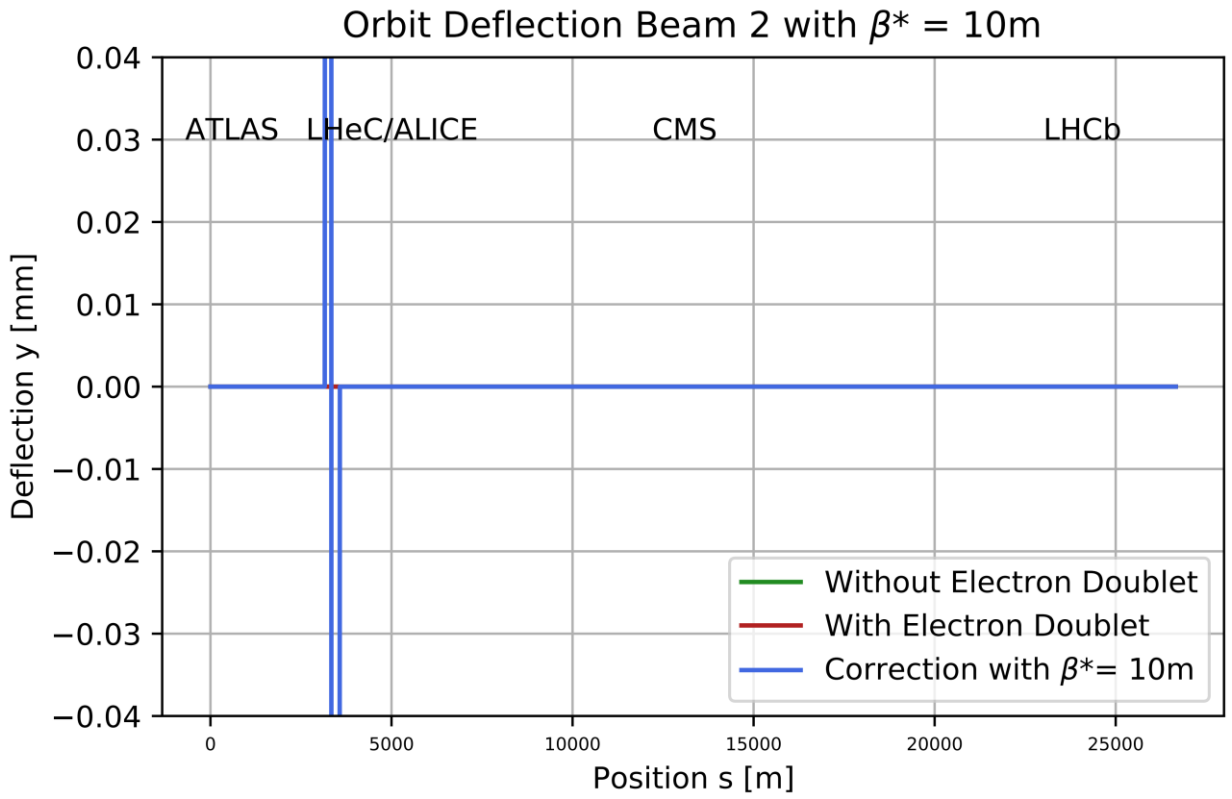

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Impact on the Proton Orbits y-plane

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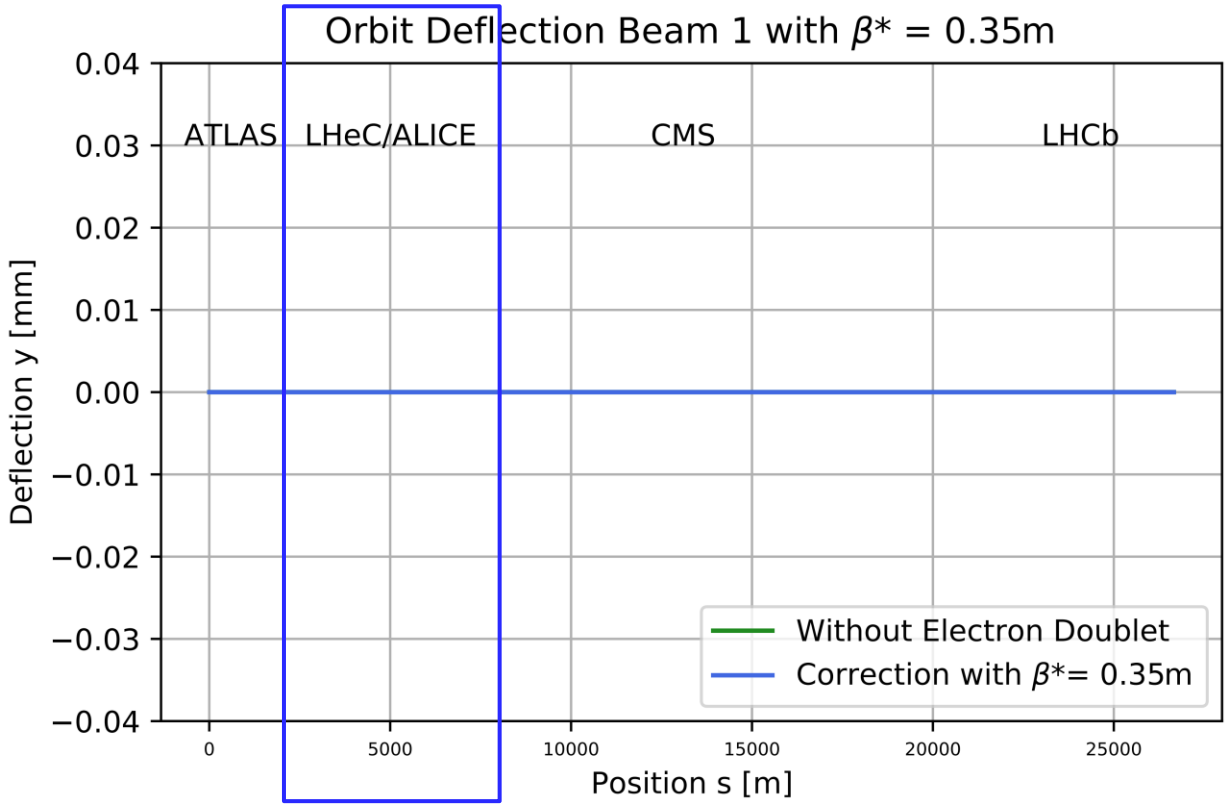

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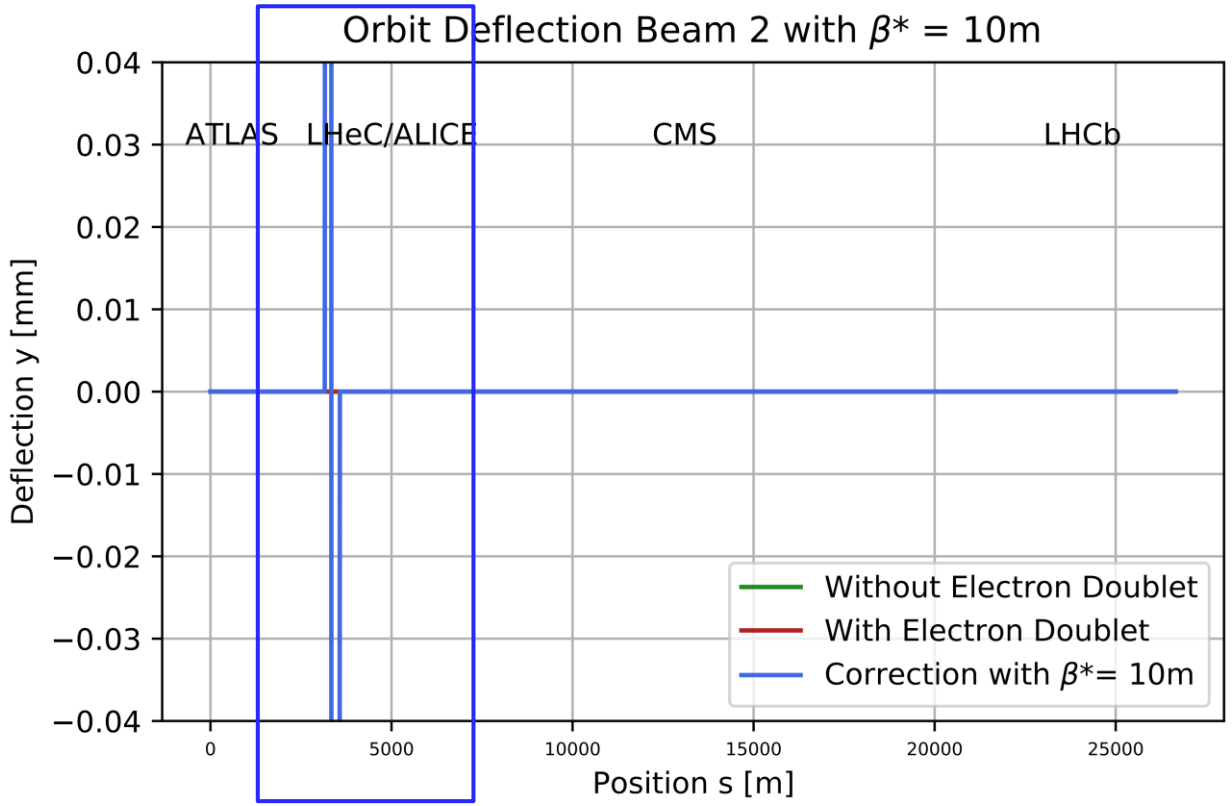

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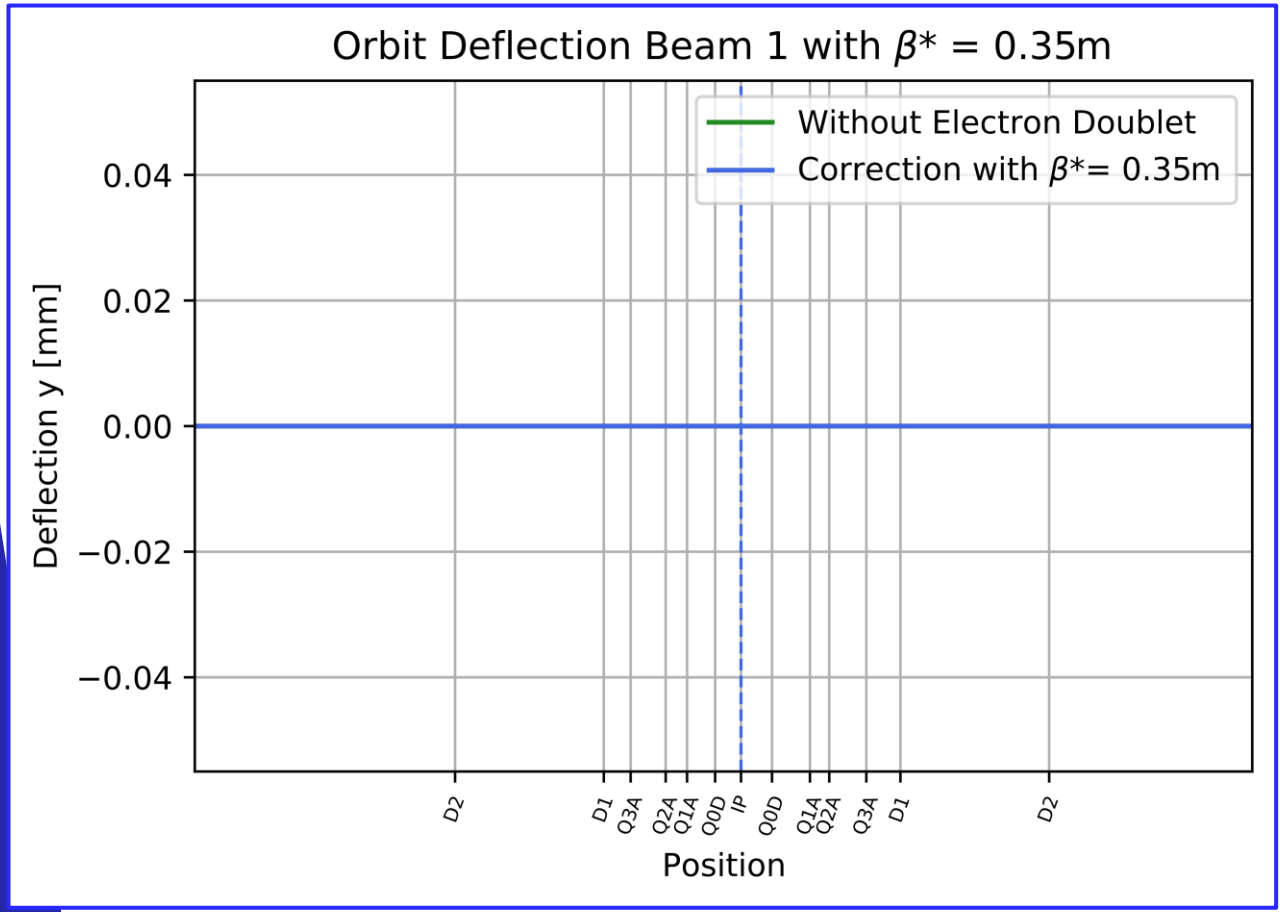

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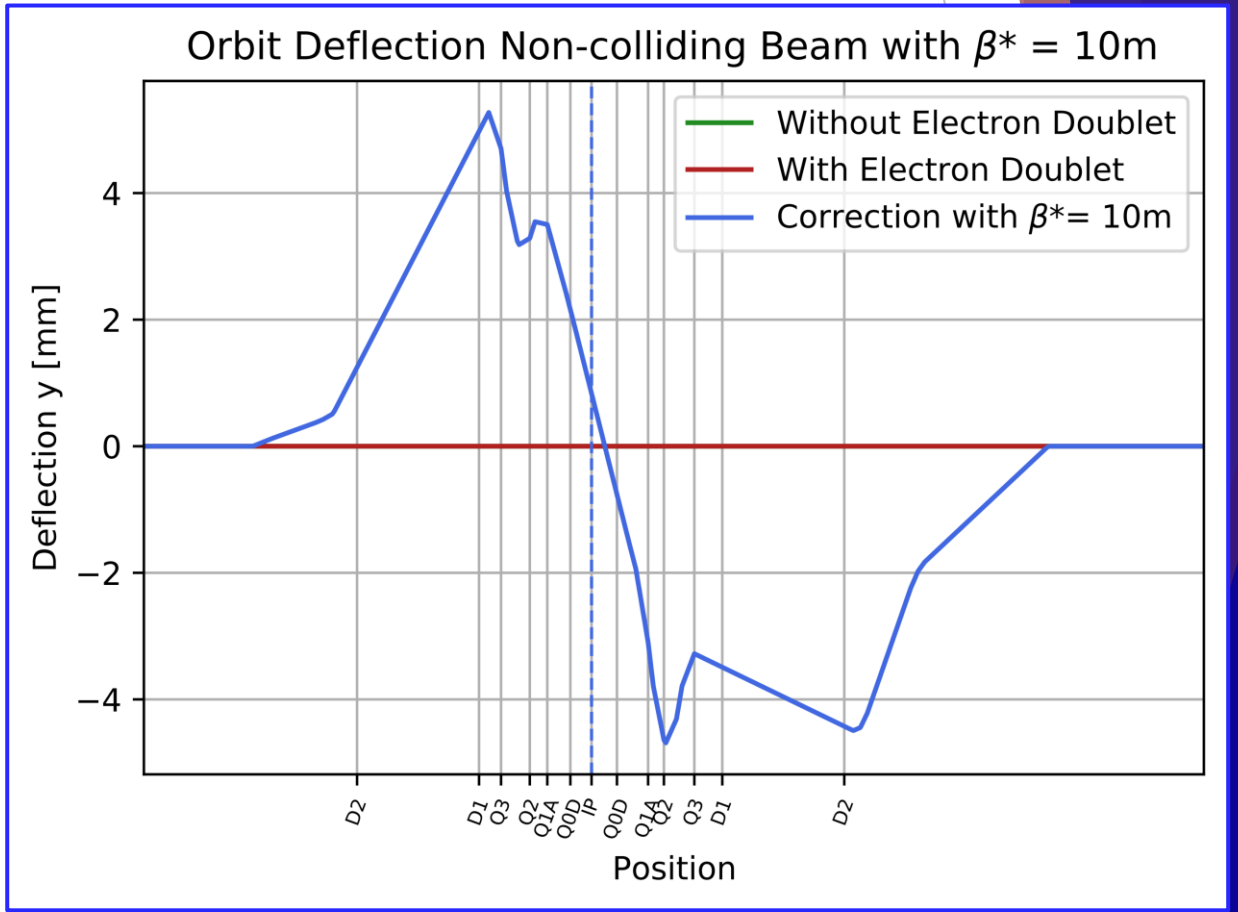

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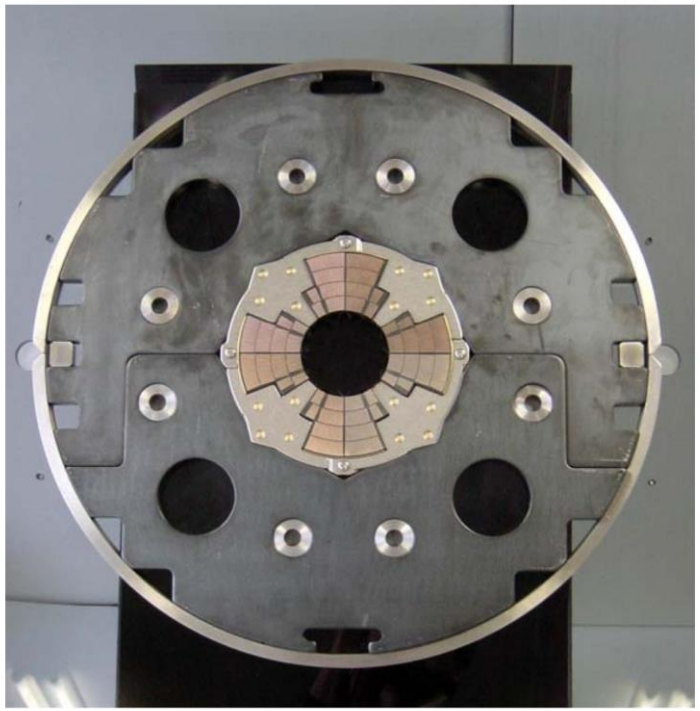
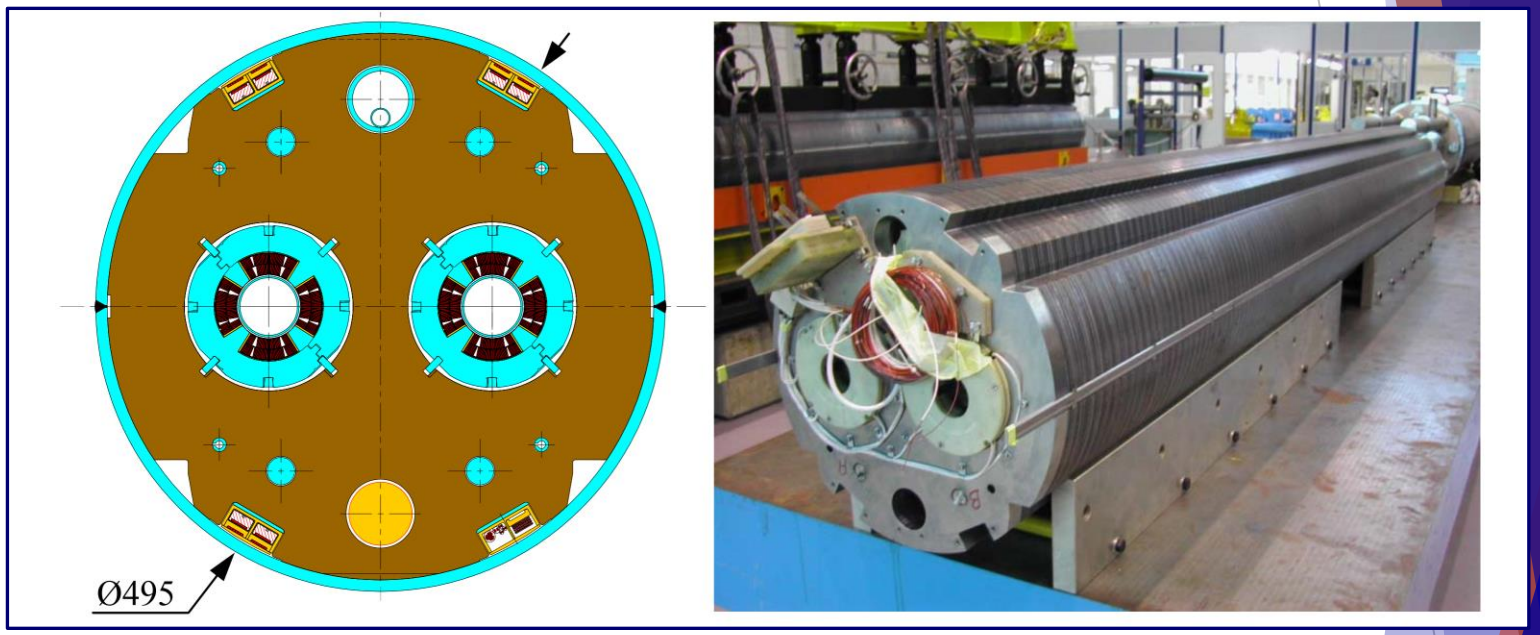
Magnets constraints in the LHC IR



Inner Triplet Quadrupole

- On each side of the IP, there are 3 antisymmetric minibeta quadrupoles
- They are succeeded by 6 matching quadrupoles on each side



Matching Quadrupole

Both Beams see the same field in the Triplet

The Beams have their own Coils, they are however restricted in their difference through the yoke

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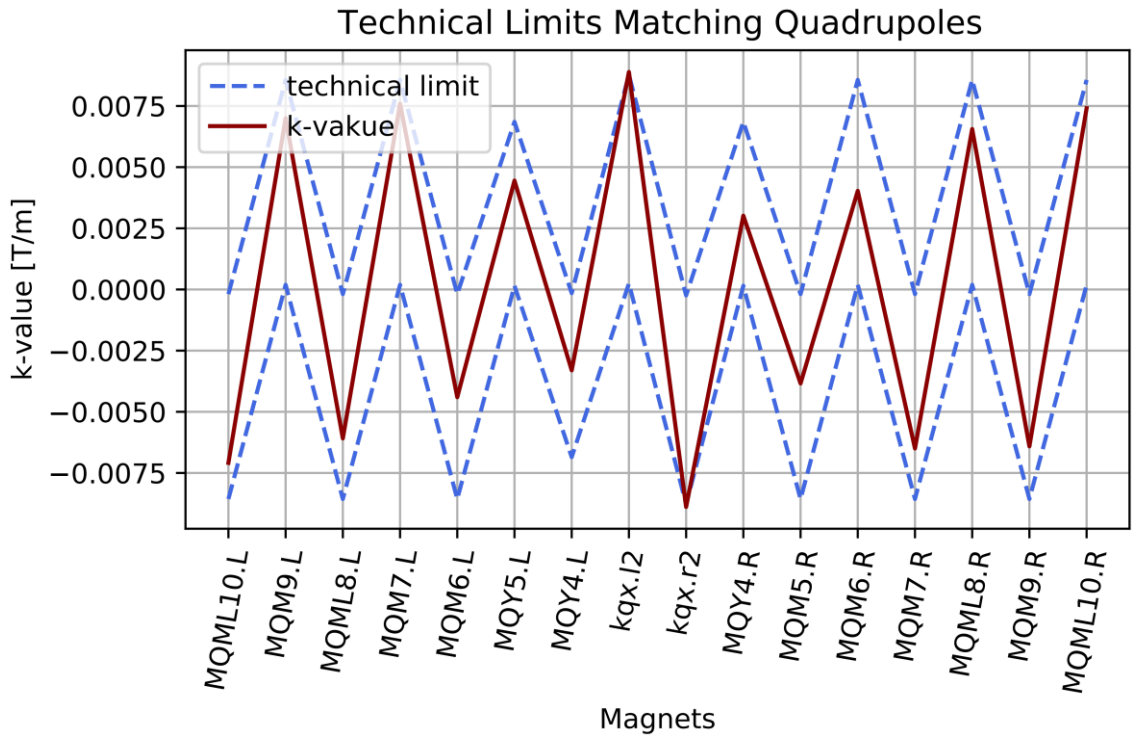
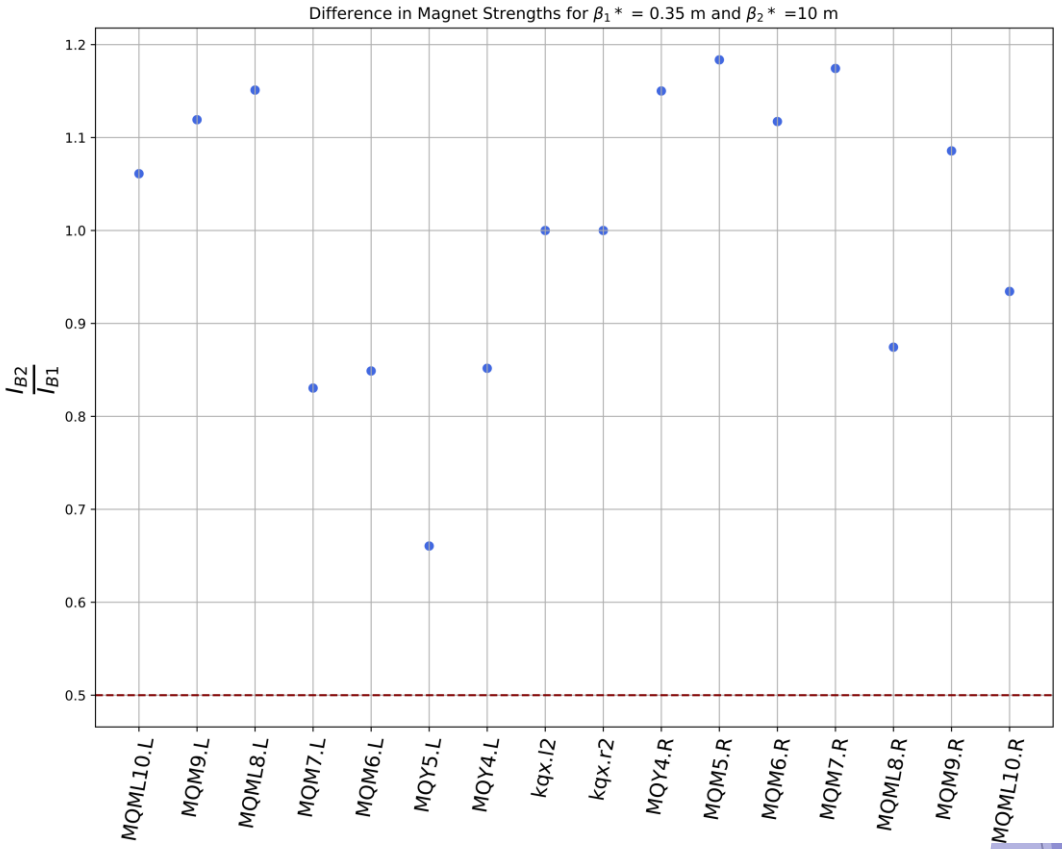
Magnet Limitations

Gradient Limitations Beam 1
Matching Quadrupoles



Gradient Dependencies Beam 1
and Beam 2 Matching Quadrupoles



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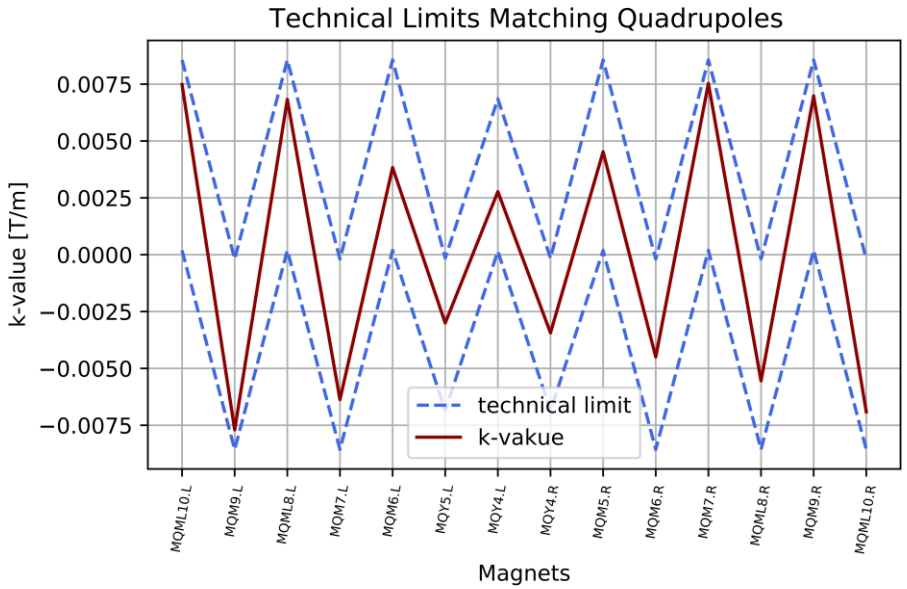
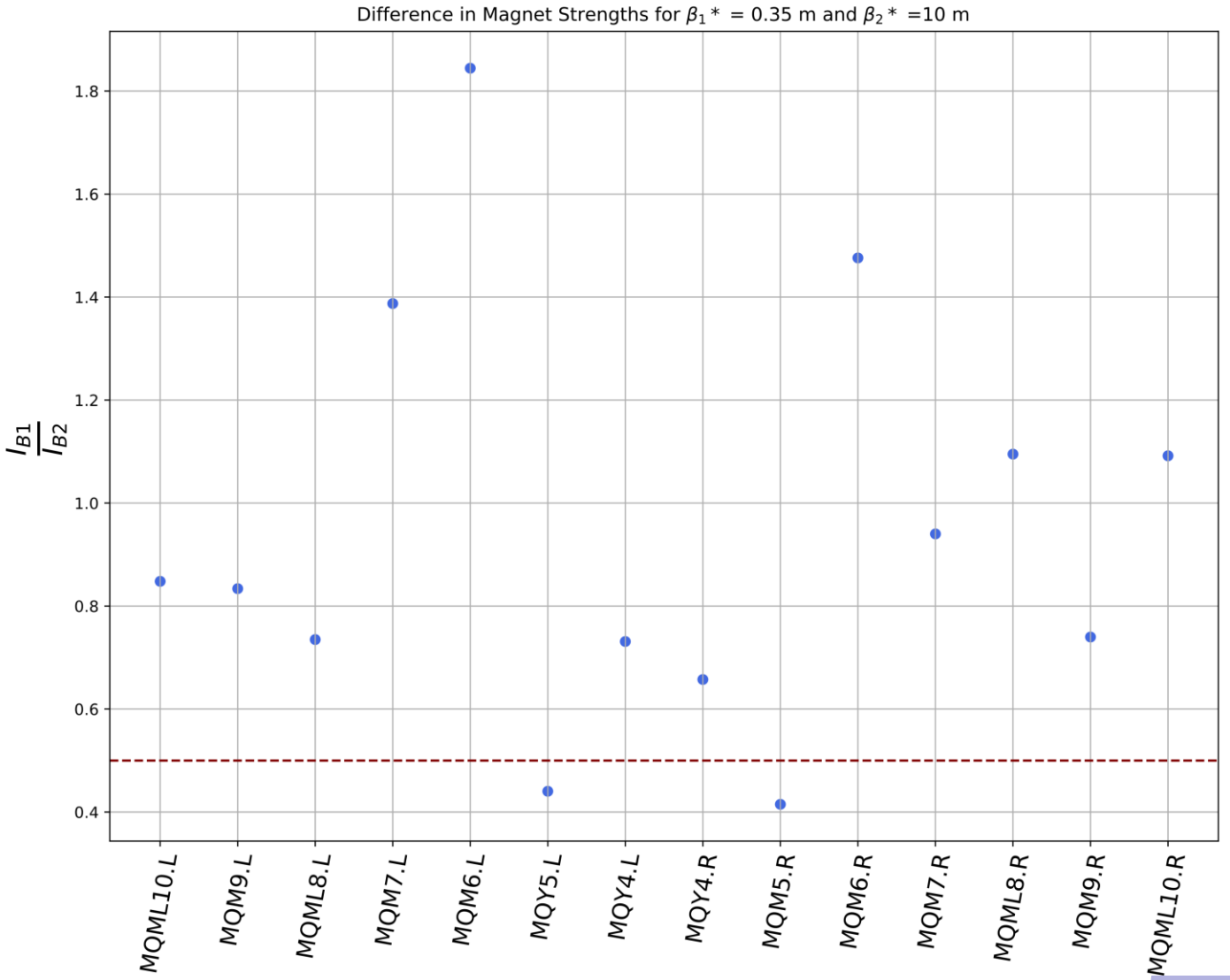
Magnet Limitations

- Still necessary to change some copper wiring for the dependencies of the magnets for B1 and B2





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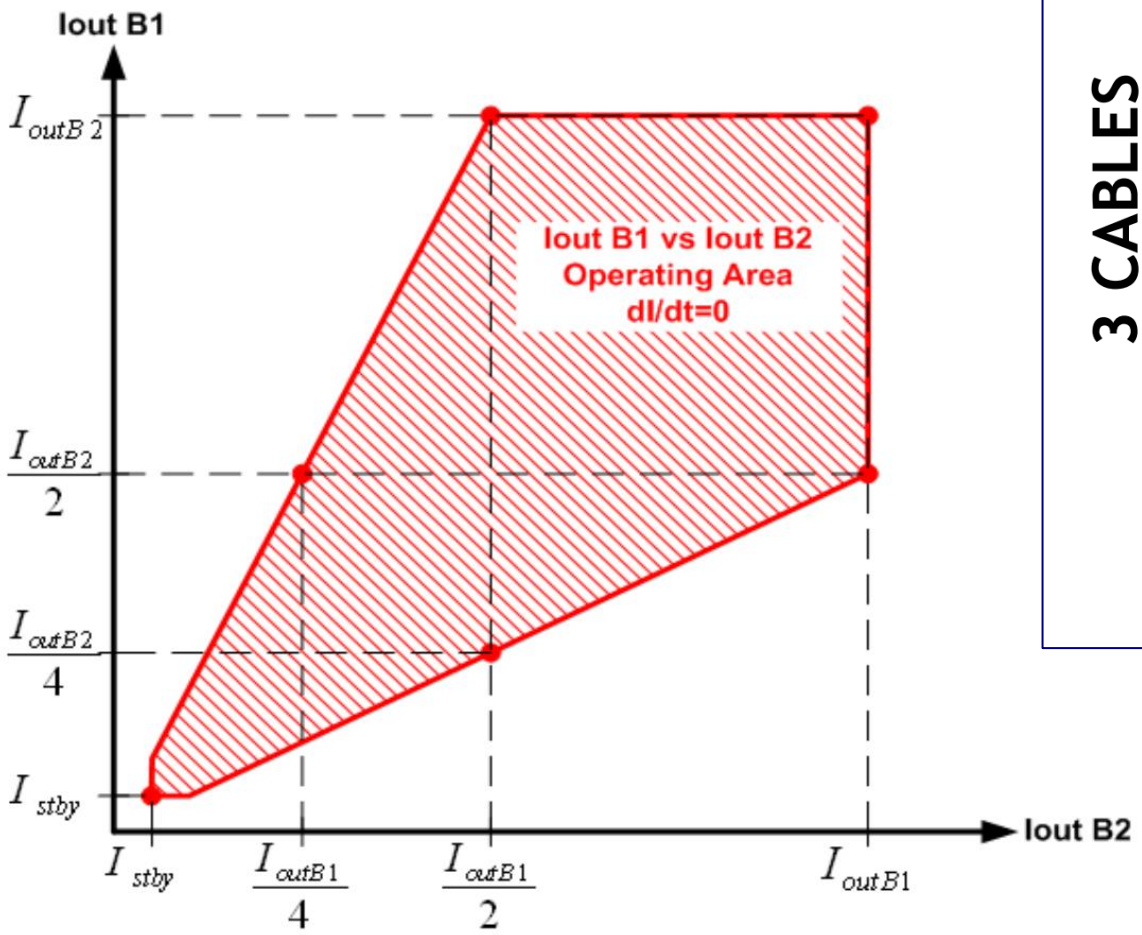
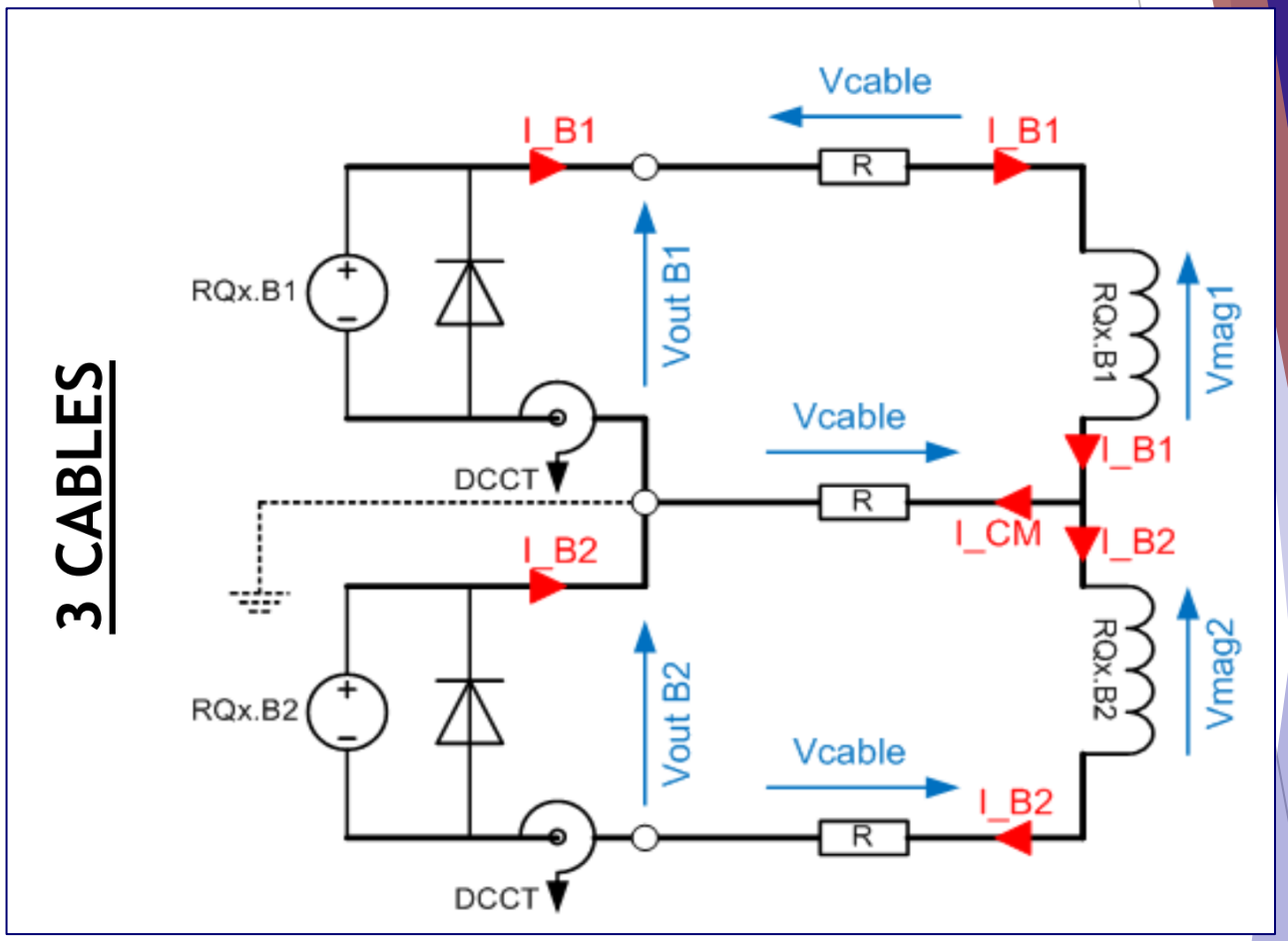
Matching Quadrupoles Constraints

- The coils of the matching quadrupoles allow a difference in their strength of up to 50%





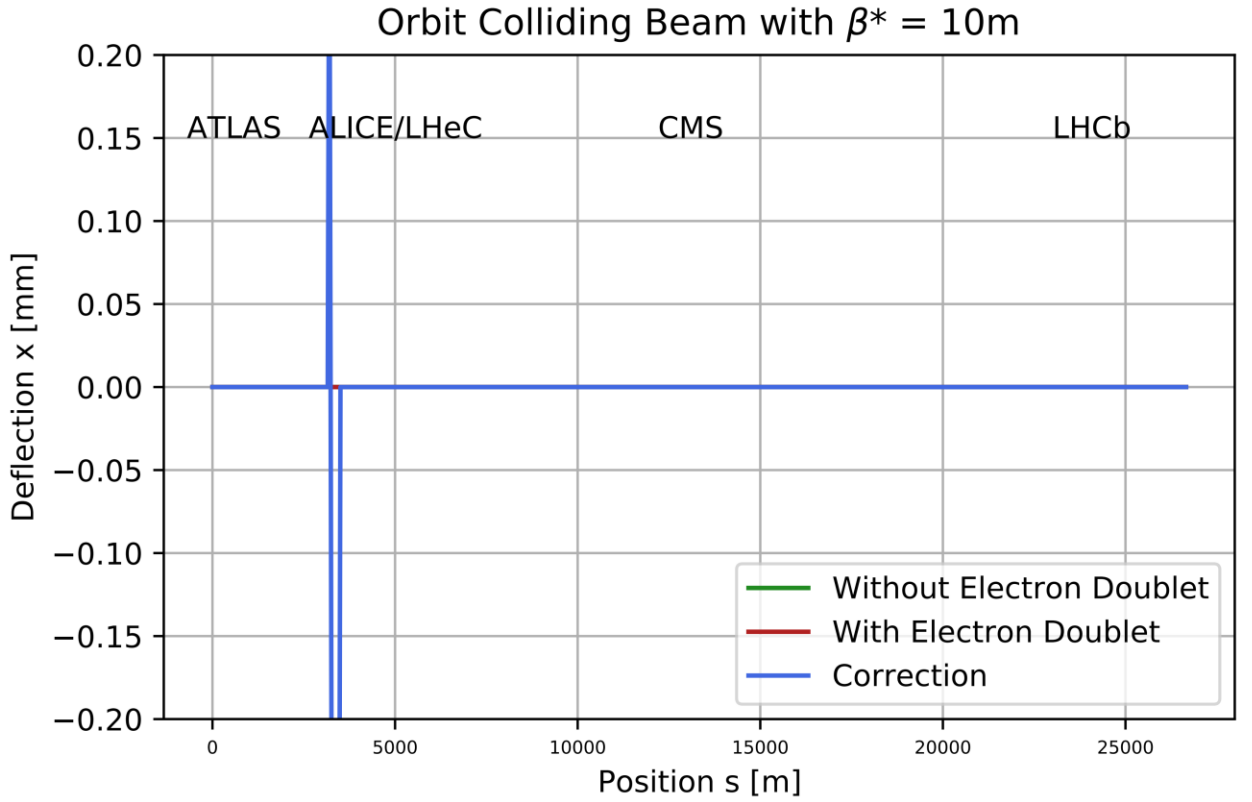
HL-LHC Data

High Luminosity -LHC Orbit Corrections

HL-LHC

- Implementation of stronger magnets with bigger apertures in the IRs
- Material change: Nb3Sn instead of NbTi

- Implementation of the electron IR of the HL-LHC
- Use of symmetric beams with a β^* of 10m at the IP



preliminary results

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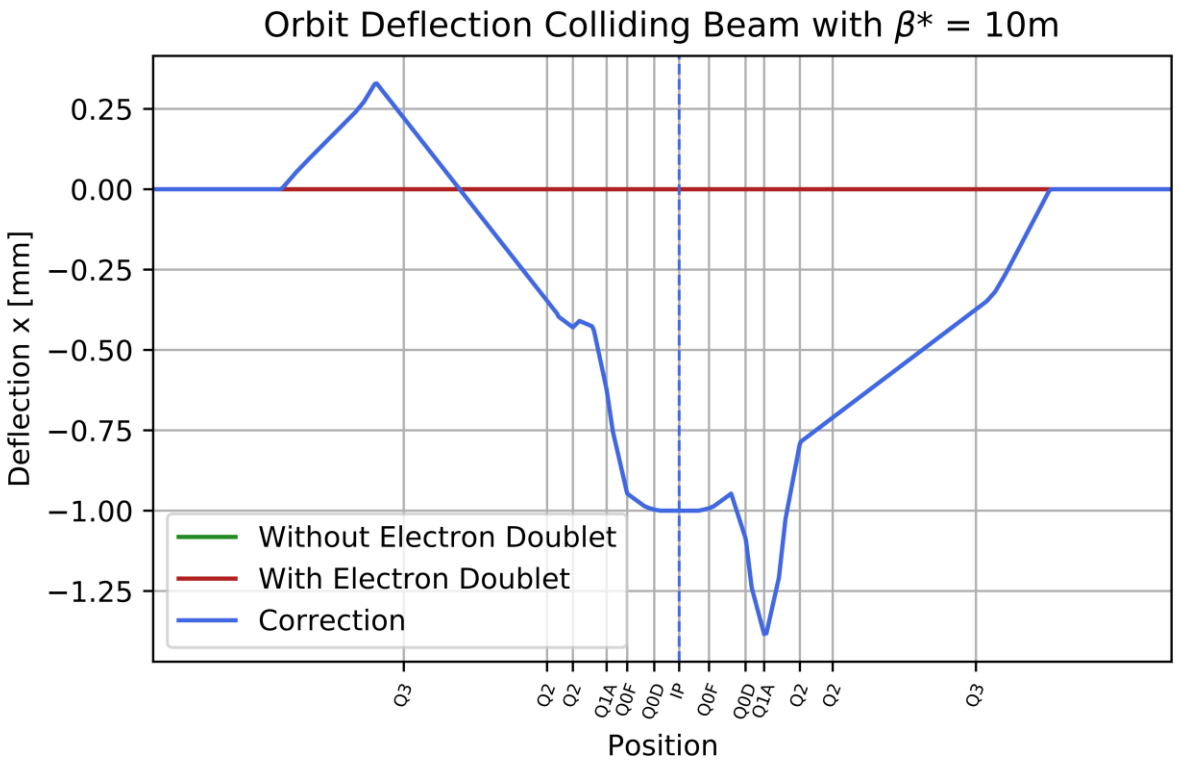
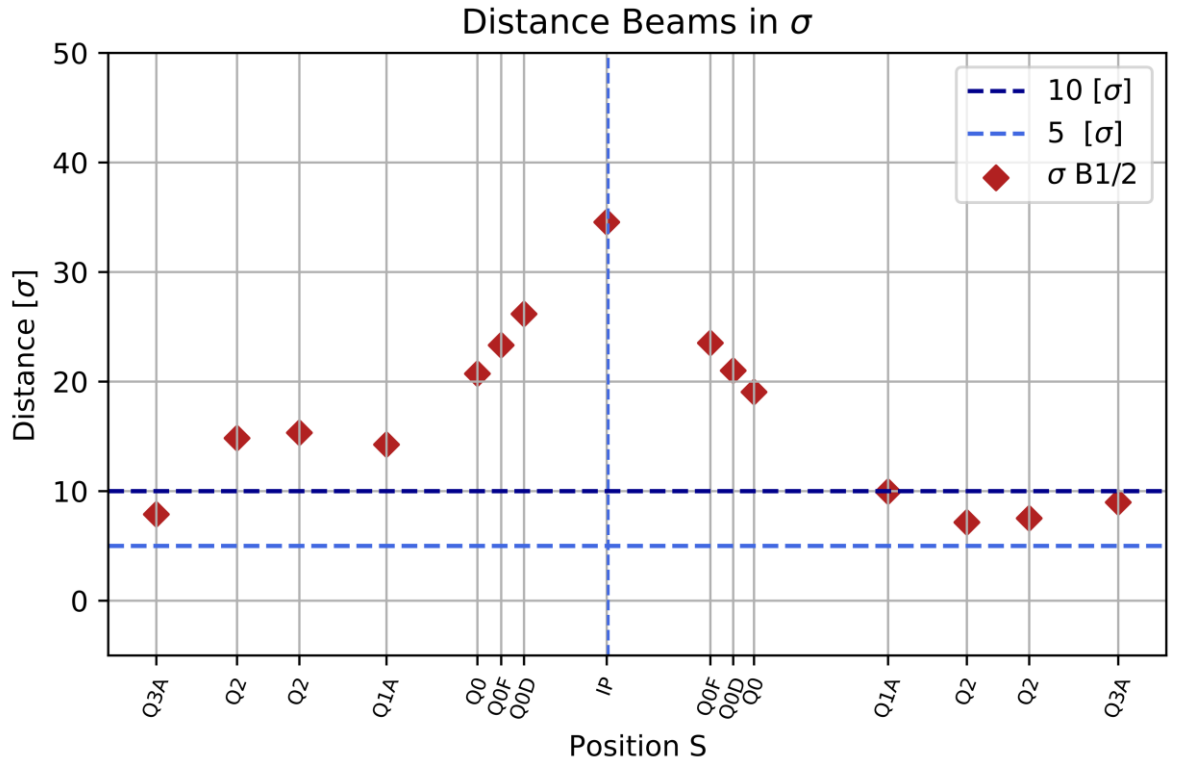
High Luminosity -LHC Orbit Corrections





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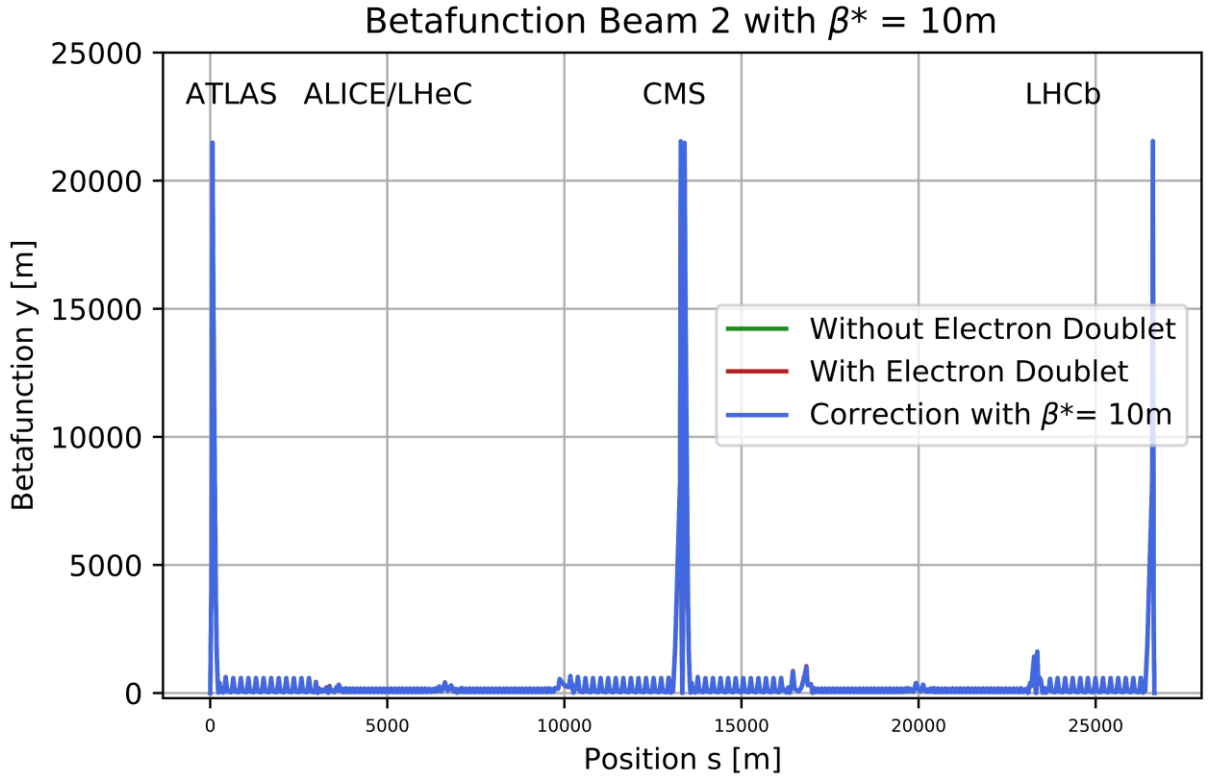
Achromatic Telescopic Squeeze Optics

- The quadrupoles in their IRs reach their limits -> chromaticity rises
- Push the Luminosity further using the telescopic squeeze:

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



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Achromatic Telescopic Squeeze Optics Corrections

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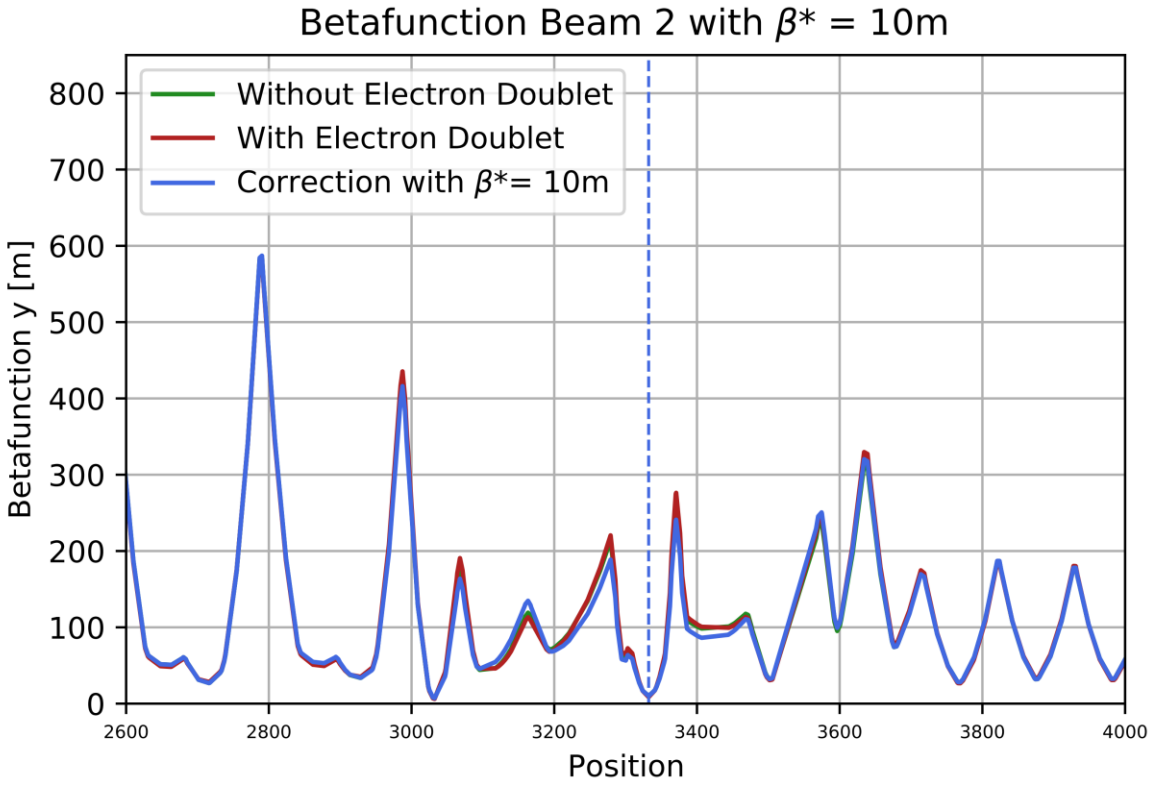

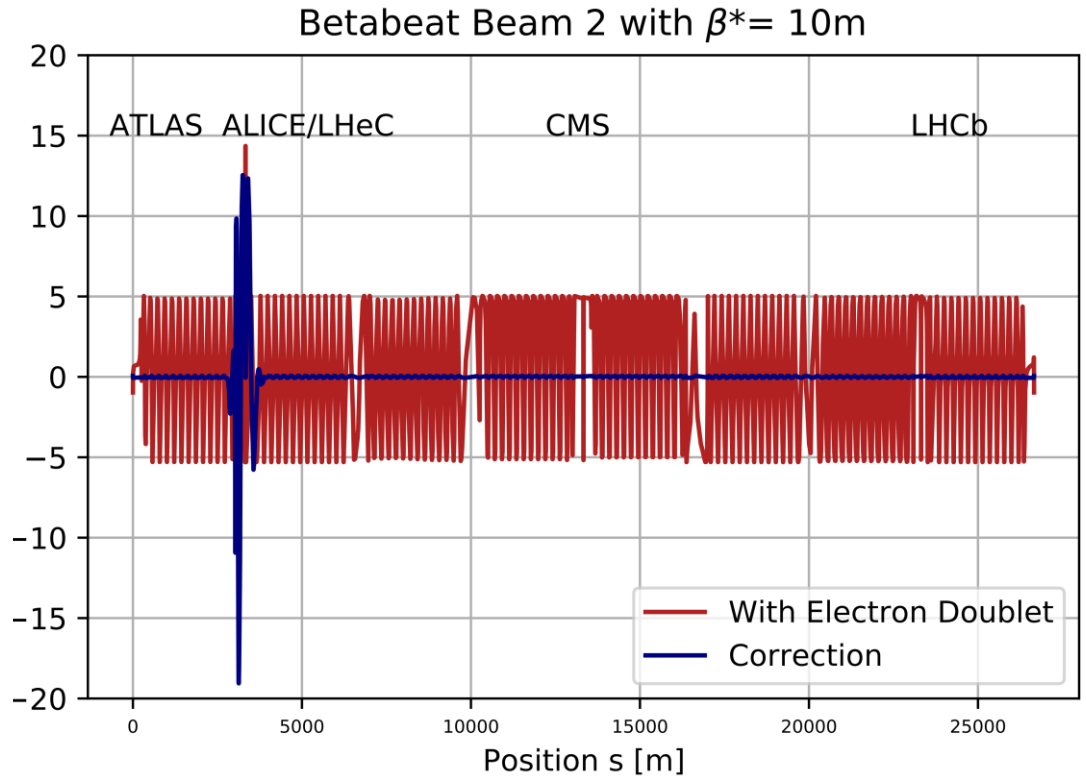

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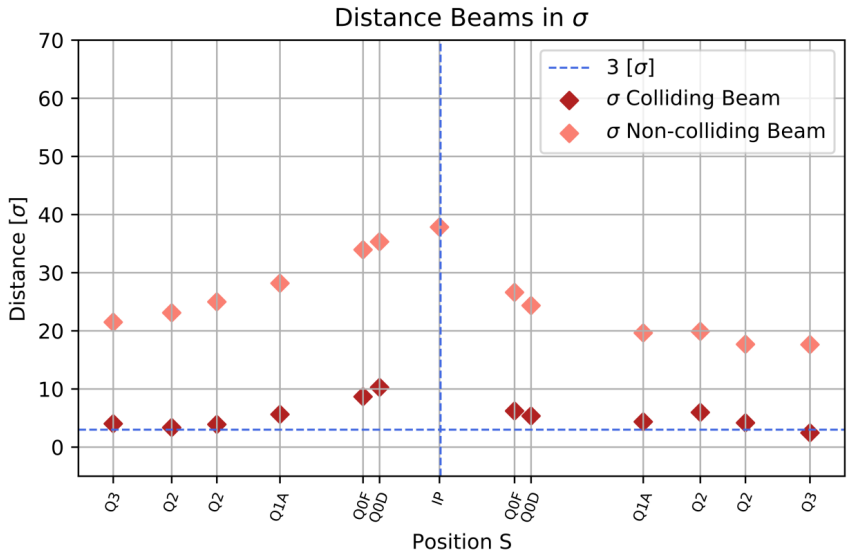
Summary

- Successful implementation of the electron interaction region in the LHC and the HL-LHC lattice
- Optics and Orbit can be corrected for LHC and HL LHC
- Squeeze of the colliding beam down to 35cm for the LHC



Outlook for the HL-LHC

- More aggressive ß* for the colliding beam to increase the luminosity
- Increase the inter-beam distance:

1. By using the orbit correctors to distance the non-colliding beam further from the orbit

2. By sweeping different ß* values for the non-colliding beam

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