Feasibility Study Baseline Layout and Prospects for FCC-hh

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Overview

- **Current design of FCC-hh**
  - Changes from last FCC Week
- **Alternative configurations**
- **Current and future work**

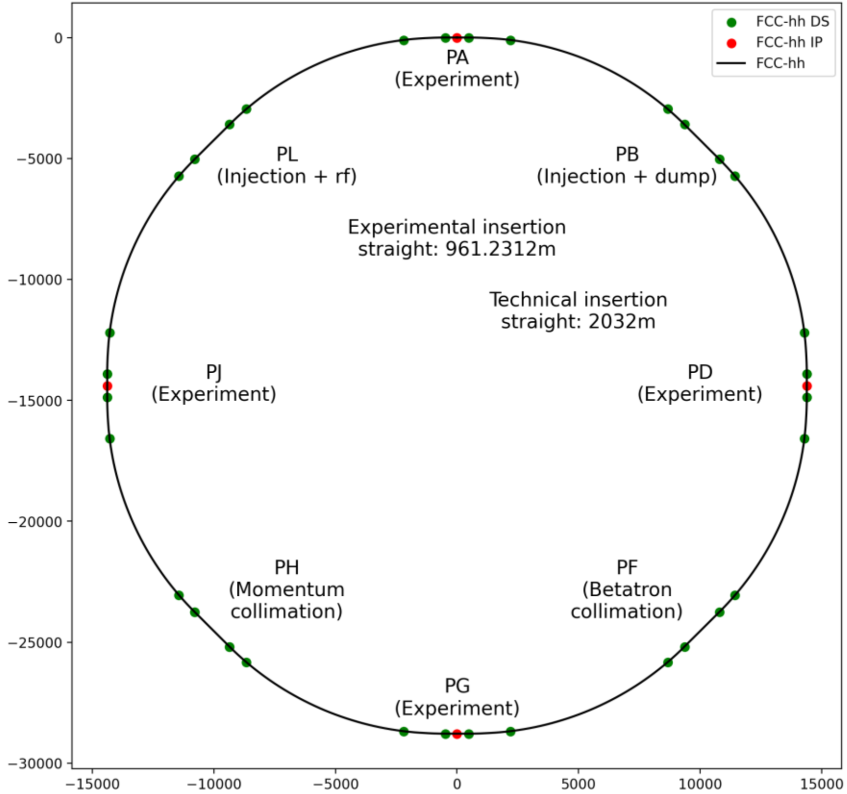
FCC-hh: Layout & main parameters

Status at last year's FCCWeek

Parameter	Value
Collision energy CoM [TeV]	84.6 – 120.8
Dipole field [T]	14(Nb_3Sn) - 20(HTS/Hybrid)
Circumference [km]	90.657

- Adapted layout and lattice following placement studies.
- Maximize dipole filling factor to maximize collision energy.

- Follow up conclusions from FCCWeek2024 and feasibility study midterm review.



FCC-hh: Layout

Circumference: 90.657 km

4464 MB, 14.187m,14T

→ 42.3 TeV / **84.6 TeV** CoM

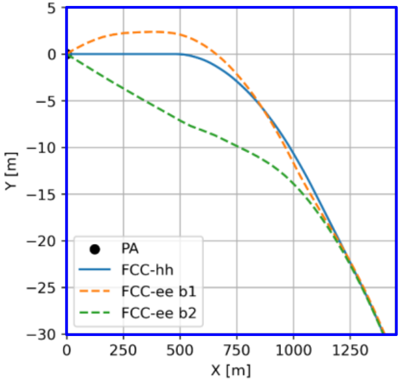
Limiting factor: aperture at injection.

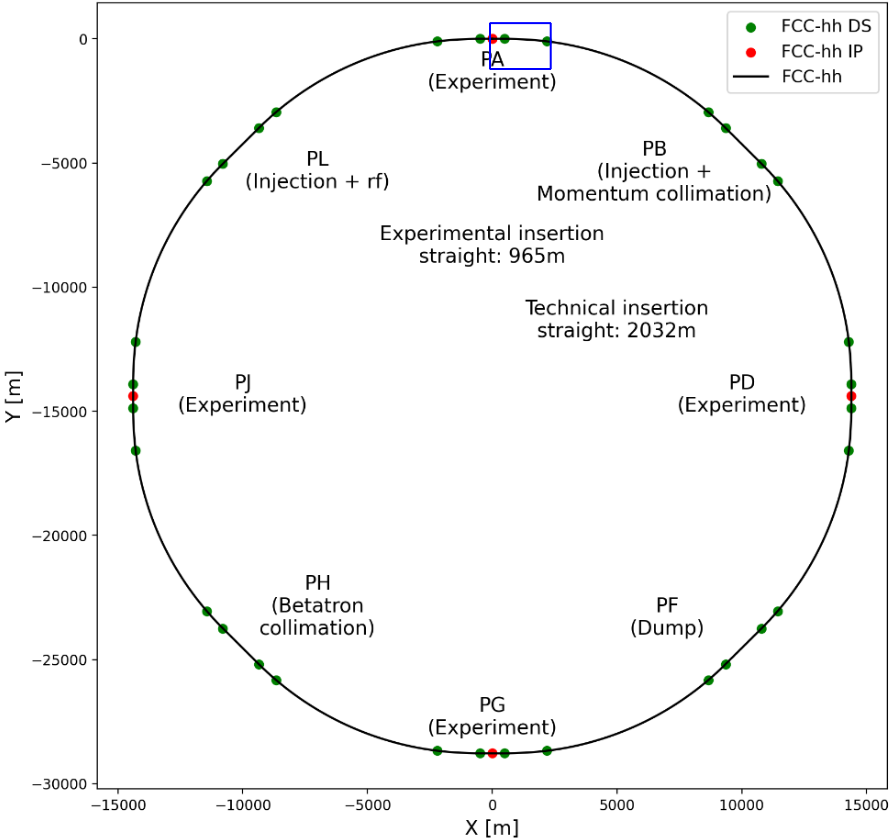
Here we consider injection at **3.3TeV**

Survey comparison: FCC-hh and FCC-ee.

Agreement between IP positions (sub-mm)

Compared to V24.4GHC

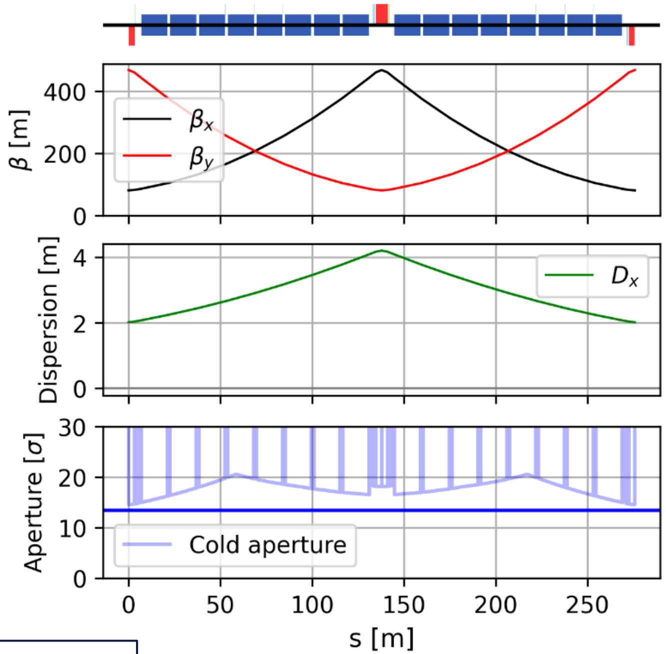


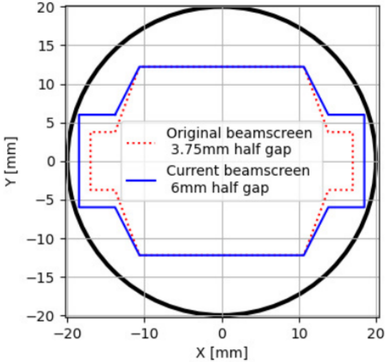


Long arc cells

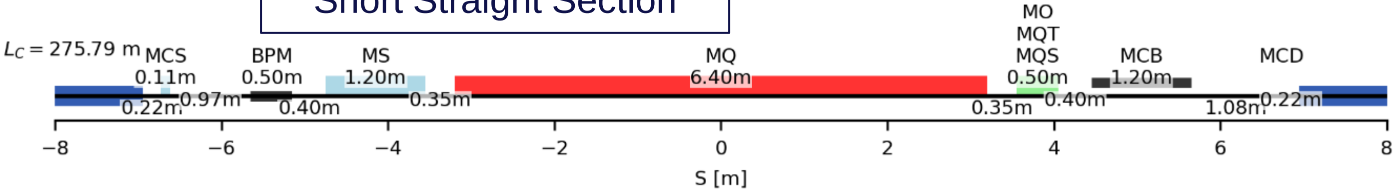
~275m

	CDR cell 12-dipole	12-dipole	16-dipole
# dipoles	4668	4288	4464
Cell length [m]	213.030	213.030	**275.792**
Circumference [km]	97.75	**90.657**	**90.657**
CoM energy @14T [TeV]	88.477	81.275	**84.611**

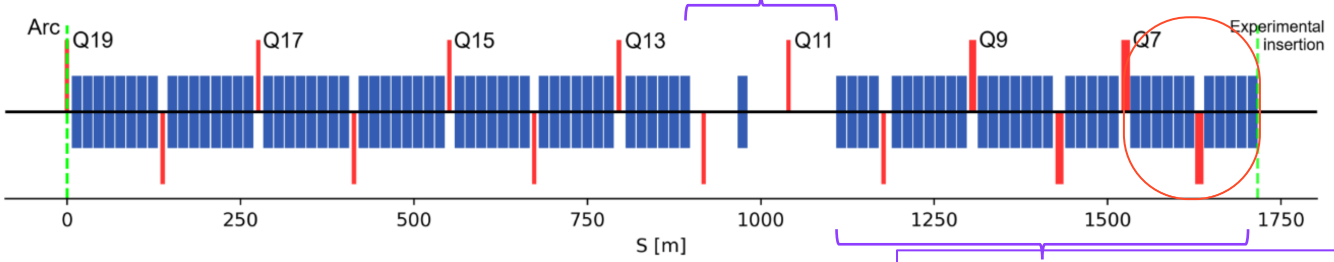




Short Straight Section



Dispersion suppressors

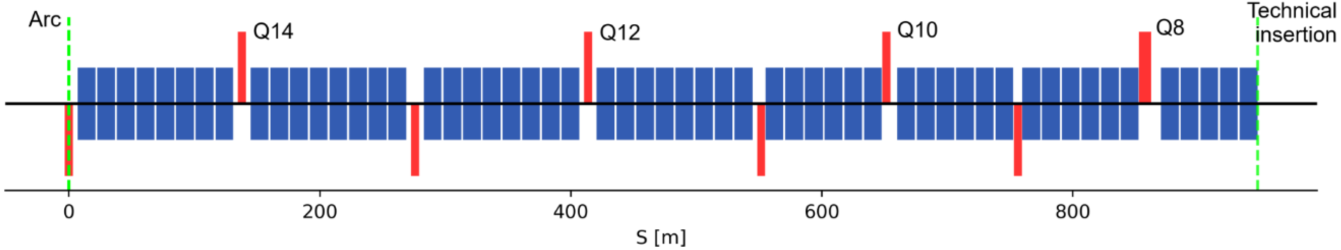


Break of the continuous dipole sequence shifts radially the IPs

Q7, Q6 (and drift to Q5) part of dispersion suppressor ≠ LHC!

Challenge for aperture

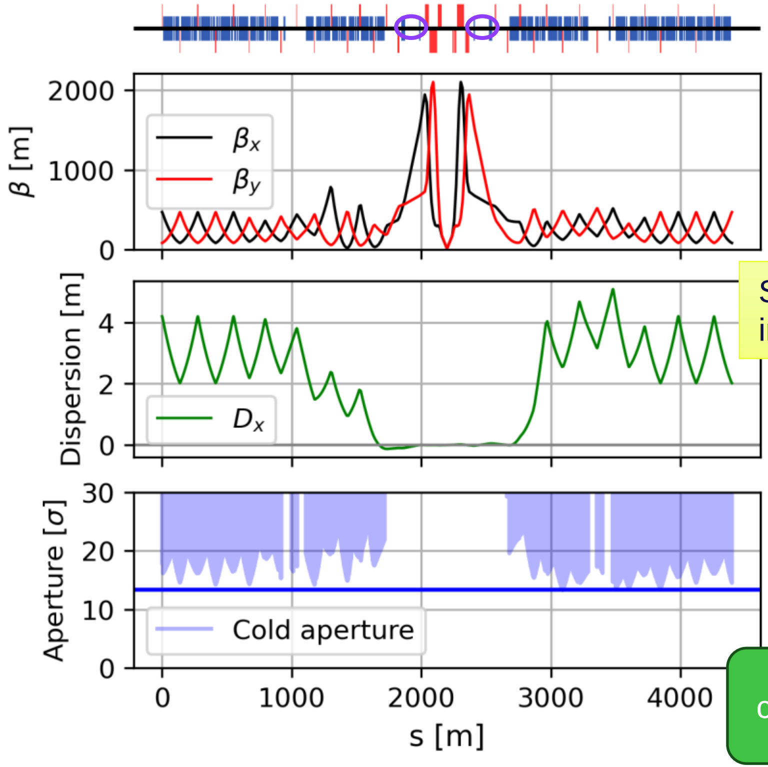
Shorter half-cells and longer quadrupoles enable optics matching satisfying aperture constraints



Space reserved for collimators around selected quadrupoles. Possible to redistribute these drifts following results from collimation studies.

Experimental straight sections

Injection $\beta^* = 10\text{m}$



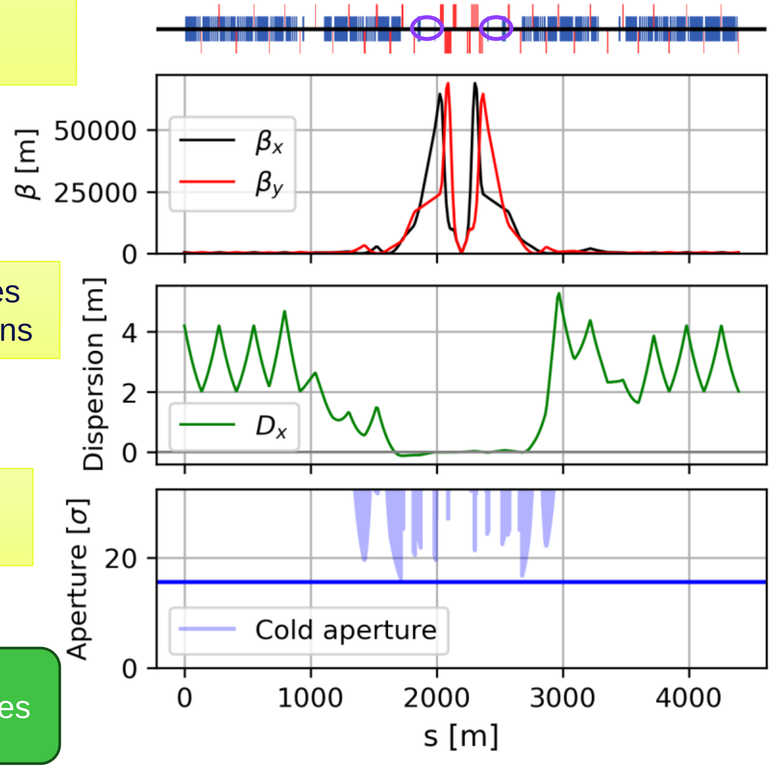
Four identical experimental insertions except for crossing scheme

Superconducting dipoles in experimental insertions

Reserved space for non-linear correctors

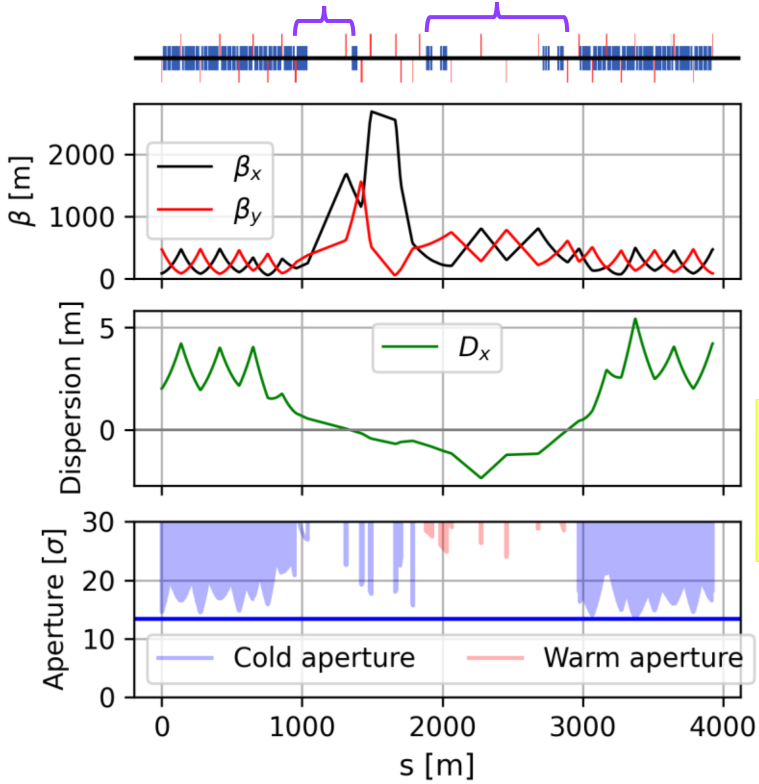
New matching with constant phase advances during squeeze

Collision $\beta^* = 30\text{cm}$



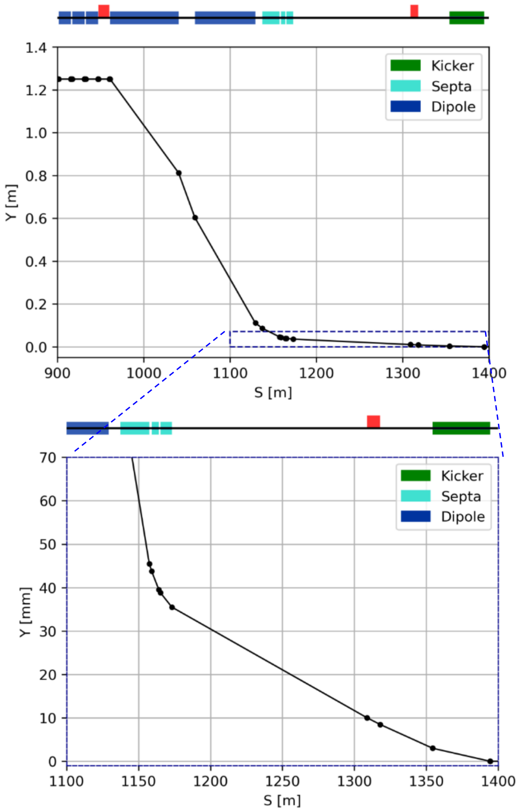
Injection beam 1 & momentum collimation – PB

Additional constraints for injected beam

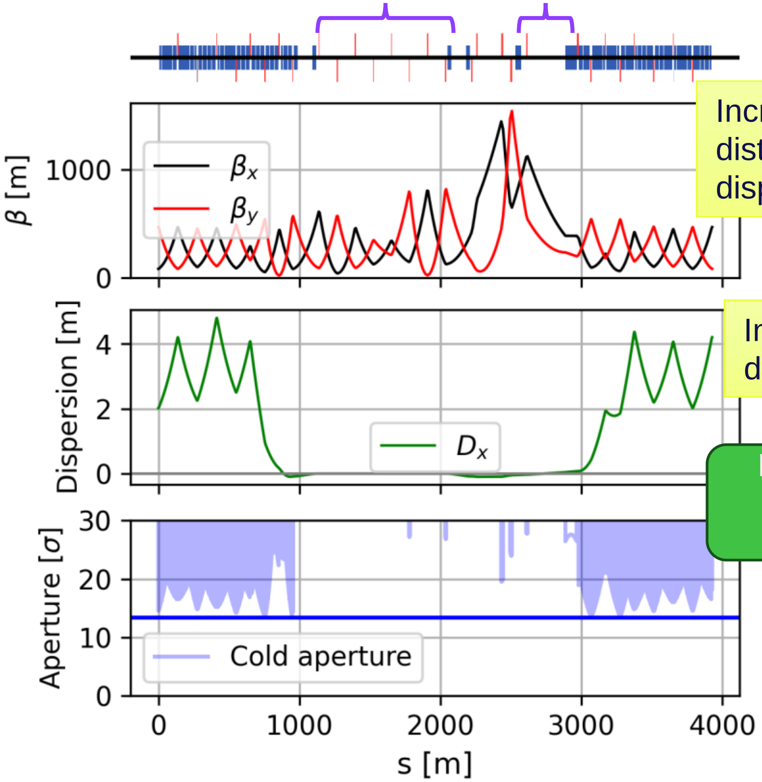


Injection and collimation systems separated by matching section.

Iterated on the design of PB.
Fewer quadrupoles are required.
Homogenized magnet families.



Injection beam 2 and RF – PL



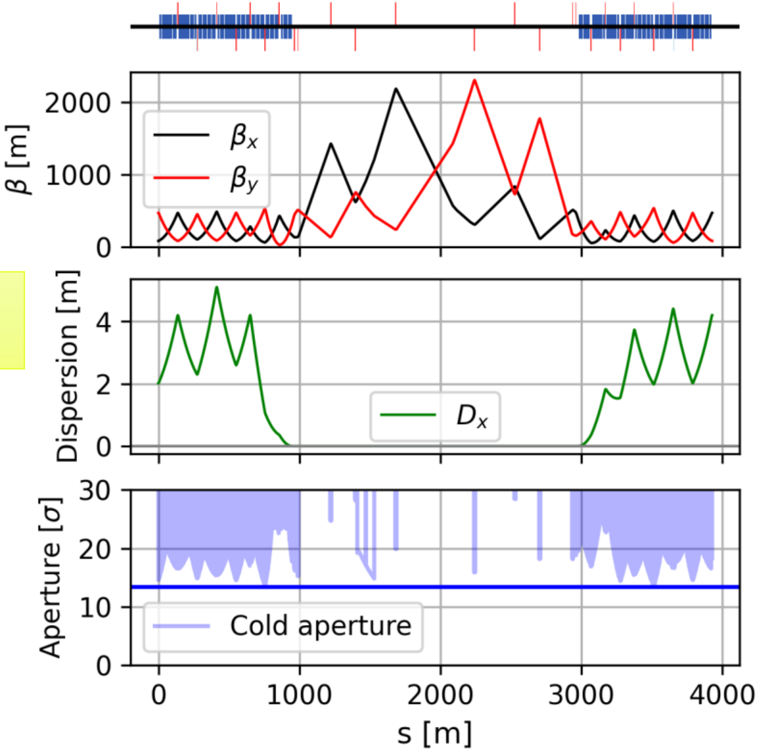
Increased inter-beam distance for RF cavities in dispersion free region

Increased inter-beam distance for RF elements

Large reduction in the number of quadrupoles

Beam dump – PF

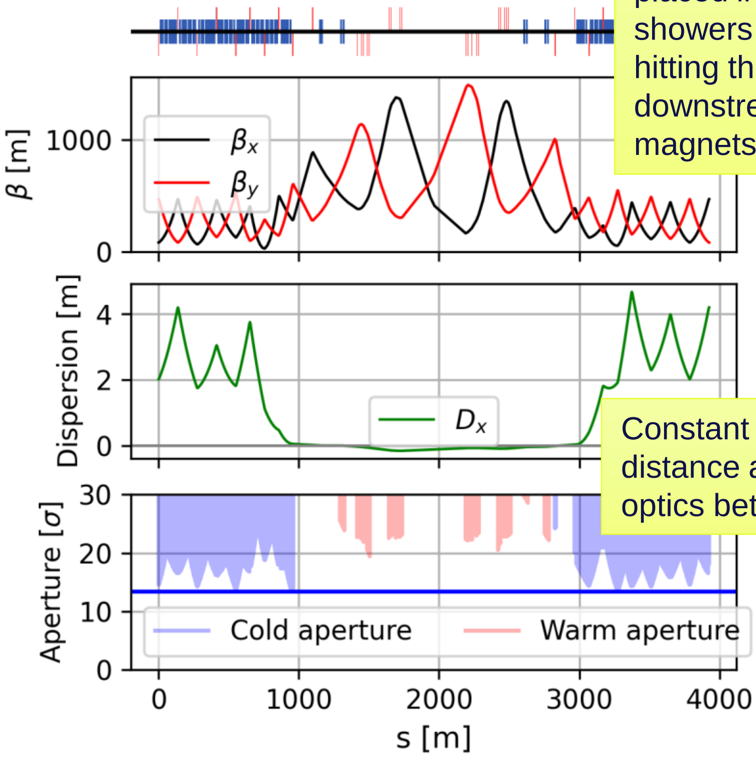
Transition from injection to collision tunes rematching dispersion suppressors



High beta collimation optics following HL-LHC studies

Betatron collimation – PH

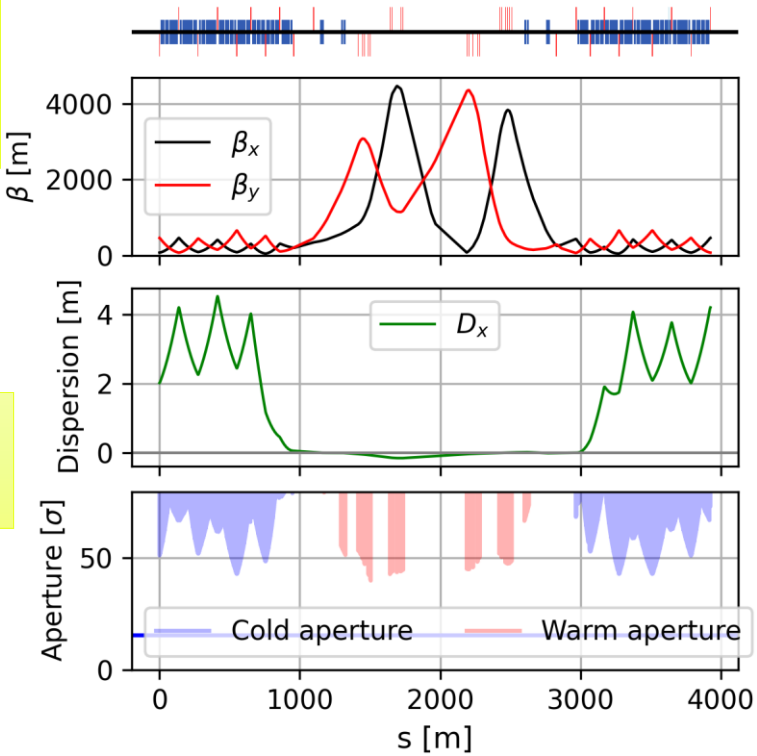
Low beta



Primary collimators placed in doglegs to avoid showers of neutrals hitting the coils or downstream cold magnets

Constant inter-beam distance allows shared optics between both beams

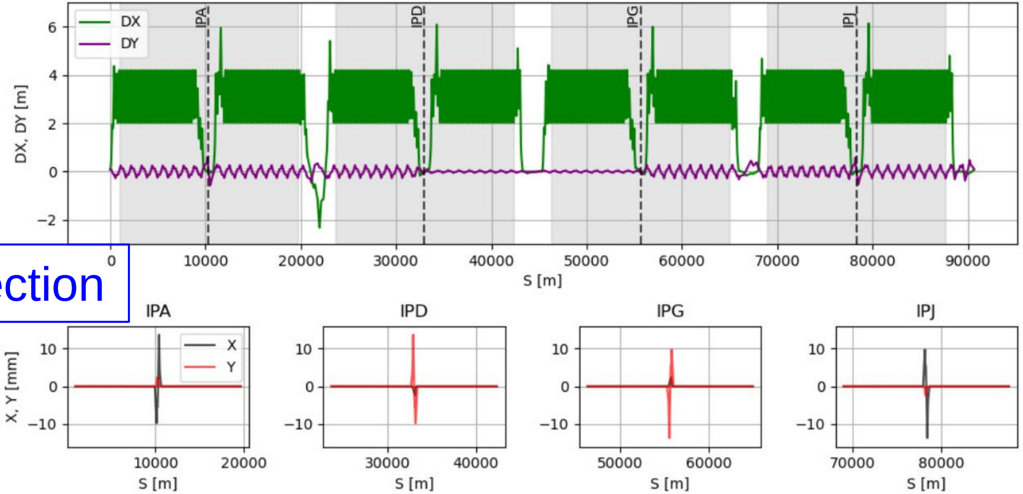
High beta



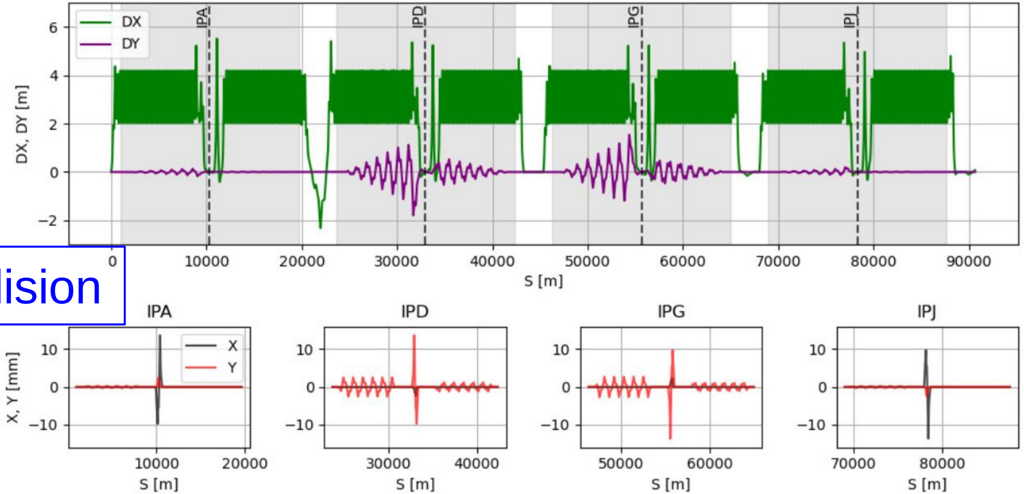
All together

- Crossing scheme
- Correction of spurious vertical dispersion
- Transition from injection tunes to collision tunes
- Beam clearance within specifications
- Fewer magnet families
- **85 TeV** CoM

Injection



Collision

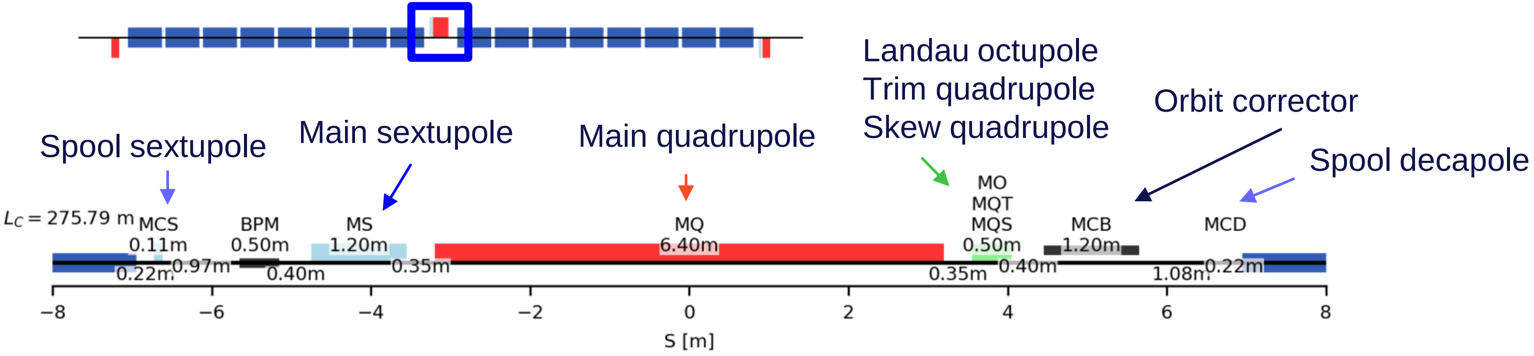


Going beyond the Feasibility Study

- Footprint reduction of short straight sections
- Treat dipole length as a free parameter
- Combined-function main dipoles

Increase energy at flat top

Review of short straight sections



Landau octupole
Trim quadrupole
Skew quadrupole

Orbit corrector

Spool decapole

Spool sextupole

Main sextupole

Main quadrupole

Arcs with fewer **longer cells** have less short straight sections and **fewer corrector slots**. However, **higher β-functions** and **dispersion** make correctors more **efficient**!

Review of short straight sections

Main quadrupole

- Longer cells require lower gradient.

6.4 m to 4.1 m *

Orbit correctors & main sextupoles

- Modest increase of dipole corrector strength allows shortening while keeping the same integrated strength.
- Sextupoles still able to correct chromaticity

1.2 m to 1.1 m

Nest orbit corrector with main sextupole

Trim quadrupoles, skew quadrupoles and octupoles

- Able to correct tune and linear coupling.
- Maintain the same amplitude detuning considered in previous studies.

0.5 m to 0.45 m

These changes have been studied in conjunction with the magnet design.

* depending on the required integrated gradient

G. Perez-Segurana, E. Todesco and M. Giovannozzi, "Study of the corrector systems for the new lattice of the CERN hadron-hadron Future Circular Collider", in Proc. IPAC'24, Nashville, TN, May 2024, pp. 79-82. doi:10.18429/JACoW-IPAC2024-MOPC15

Dipole length as a free parameter

Outcome from last year's FCC Week:

~14.3m **was** a soft-limit (transport). Followed up by the HFM forum.

Should consider longer dipoles, up to 20m.

Check impact on integration.

For now, considered up to 16m to fit within the diameter of the shaft to lower the magnets.

FS baseline (and CDR): 14.187m

This enables packing completely the arcs without loosing space!

Arc of n cells consists of $2n$ blocks of dipoles and $2n-1$ short straight sections.

Approximate the length of each SSS with the quadrupole length require for different cell lengths.

Divide each of the dipole blocks into an integer number of dipoles (and their interconnects).

An approximation. Does not take into account deviations from the regular arc cell in the DS.

Extremely helpful finding a starting point!

Dipole length as a free parameter

FS baseline: 14.187m

Candidate solutions per injection energy
☆3.3 TeV
☆1.7 TeV
☆1.3 TeV

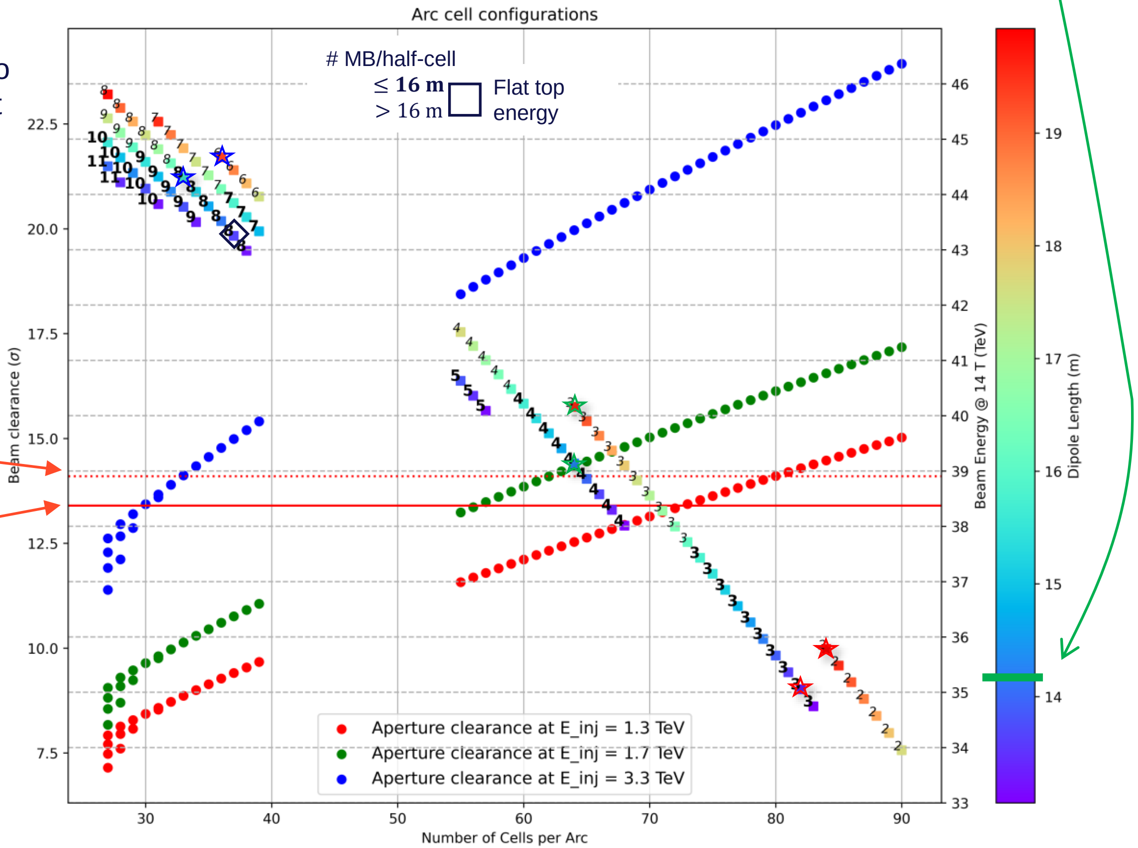
◇ Closest to FS report

Limiting factor: aperture clearance at injection (13.4σ).

So far, we studied only **3.3 TeV**, but also **1.7 TeV** and **1.3 TeV** options are being considered.

14.1σ
lowest I've been able to match DS

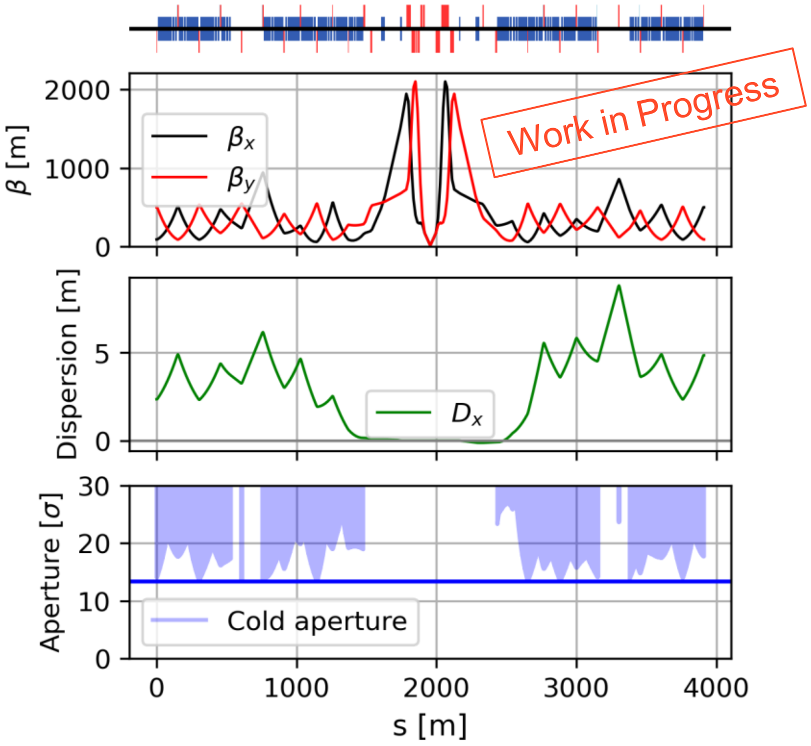
13.4σ
limit



An approximation. Does not take into account deviations from the regular arc cell in the DS.

Dipole length as a free parameter + new SSS

Initial optics matching - PA



Start the study of this lattice by matching the experimental insertions. Technical insertions to be done next.

- Reduce last 3 half-cells to 6-dipoles and redistribute the dipole length trough the arc.
- Allow longer MQs in DS for matching flexibility.
- Replicate radial IP shift.
- Replace lone MQ12s by a pair of MQYs (aperture)

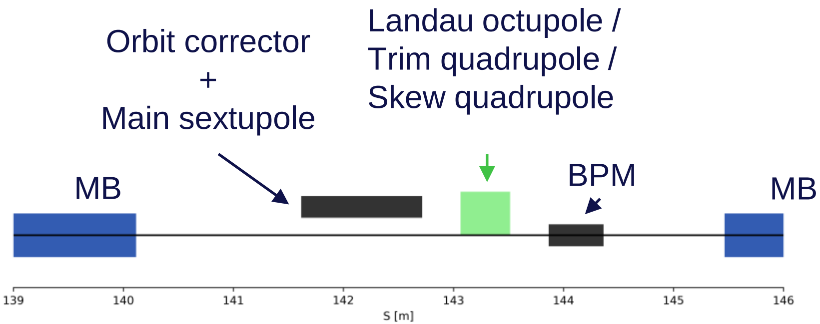
In previous designs, matching the experimental insertions has been the most challenging due to the absorption of Q6 and Q7 into the DS.
Justifies the margin in aperture when considering the regular arc…

4128 Dipoles, 15.99 m **and** shortened SSS
➔ 44.1 TeV, 88.2 TeV CoM @14 T
FS report: 84.6 TeV CoM @14 T

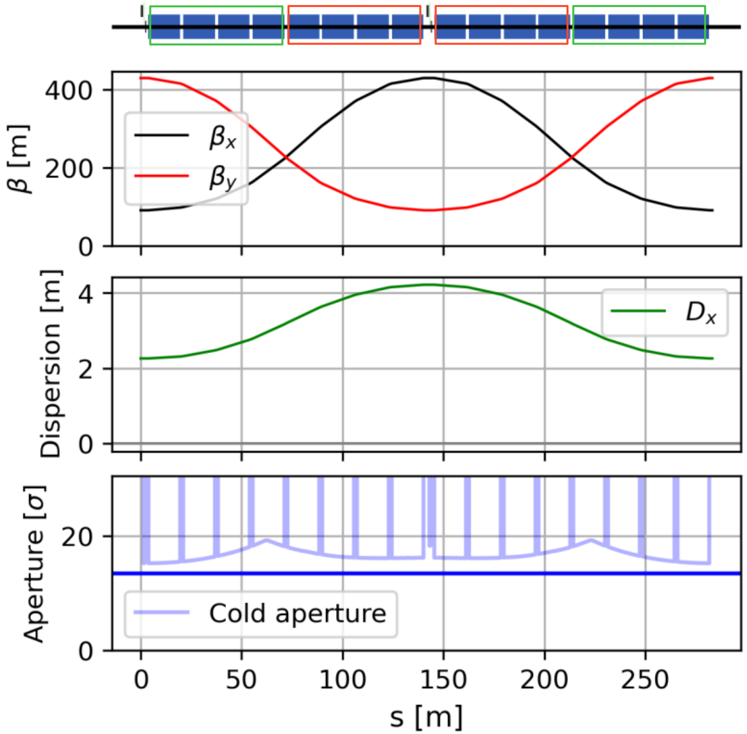
Combined-function arc cells

Same number of focusing and defocusing dipoles: only even number of dipoles per half cell.

Short straight section still has slots for correctors



Short Straight Section



Giovannozzi, M., Todesco, E. Combined-function optics for circular high-energy hadron colliders. Eur. Phys. J. Plus 137, 361 (2022). https://doi.org/10.1140/epjp/s13360-022-02583-0

Giovannozzi, M. Considerations on combined-function optics for high-energy storage rings and colliders. EPJ Techn Instrum 9, 5 (2022). https://doi.org/10.1140/epjti/s40485-022-00081-2

Dipole length as a free parameter + combined-function

Candidate solutions per injection energy
☆3.3 TeV
☆1.7 TeV
☆1.3 TeV

No more MQs in the regular arc cell. Higher impact in shorter cells. Smaller $\beta_{x,y}$ and D_x allow longer cells (fewer SSS).

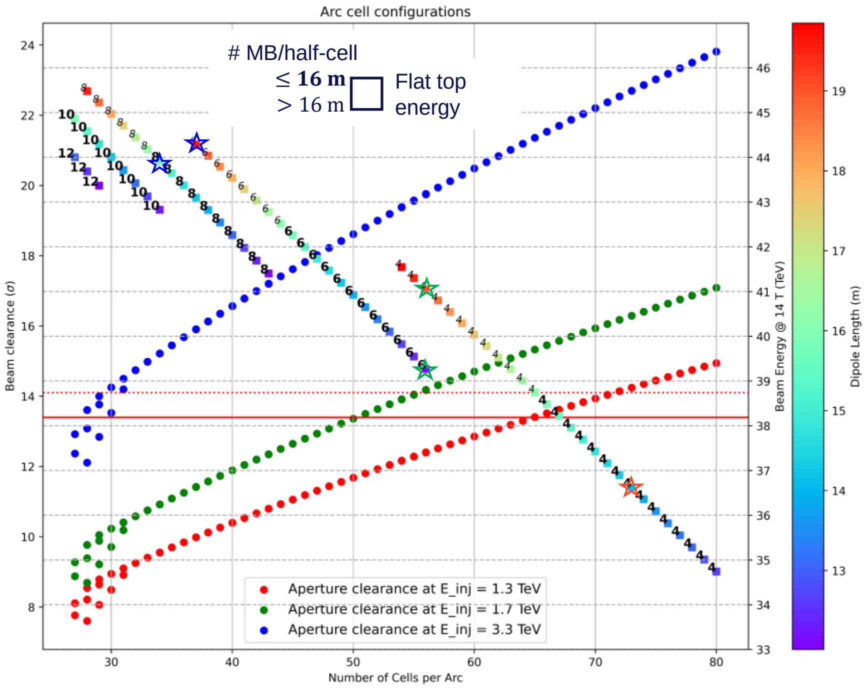
Reduction of dipolar field due to the required quadrupolar component,

$$B_{0,CF} = B_{0,FODO} - \lambda\, r_c\, G\,,$$

with G as the quadrupole gradient, r_c the coil aperture and λ is a geometrical coefficient ~1.15.

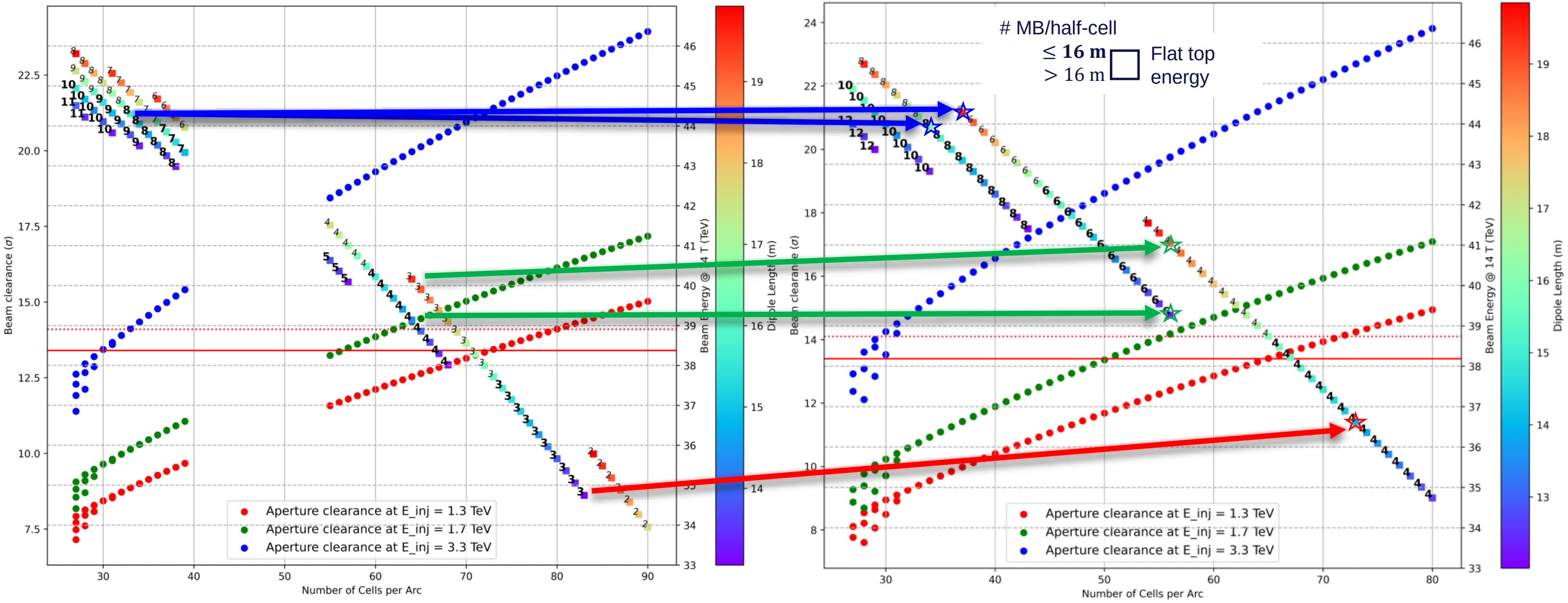
In this *simplified model*, combined-function MB look promising. Specially for injection scenarios at **1.7 TeV** and **1.3 TeV**.

However, these energy values are an *overestimate*. Space will be required in the DS to match into the insertions.



E. Todesco and M. Giovannozzi, "Combined-function optics for the lattice of the CERN hadron-hadron Future Circular Collider ring", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 594-597. doi:10.18429/JACoW-IPAC2023-MOPL032

Dipole length as a free parameter + combined-function



Separate function

Combined-function

Conclusions and next steps

- Baseline design as presented in the feasibility study represents a complete lattice, with a significant recovery in CoM energy thanks to the meticulous optimisation carried out in the last few years.

- Most of the conclusions about performance, rely heavily on results from the CDR era (beam-beam, dynamic aperture, …). Some, extrapolations from HL-LHC studies (aperture requirements).

- Launched several exploratory studies seeking the greatest impact.
  - Maximize utilization of the length of the arcs freeing the length of the main dipole.
  - Lattices based on combined-function dipoles. Beam dynamics implications to be studied.

- Next milestones
  - Full ring optics with new dipole length and short SSS.
  - Determine potential of combined-function lattice.

- Beam dynamics studies (beyond lattice design) should be undertaken in the future.

Thank you
for your attention.