



Measured Linear Imperfections in the HL-LHC D2 Magnets

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CERN

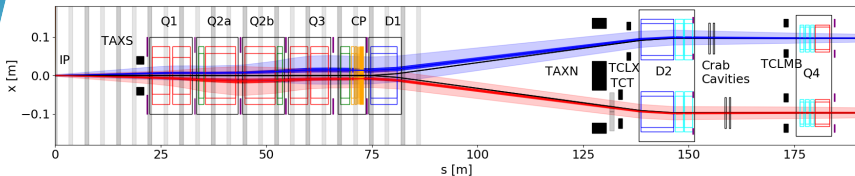
17.01.2025

- Introduction
- Default Scenario
- Spare Scenario
- Conclusions

Outline

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Expected Errors



- Out-of-spec [1] errors found in some produced D2 magnets coils [2]:
 - a_2 up to ± 6 units (spec: ± 2.7 units).
 - b_2 up to ± 10 units (spec: ± 4 units).
- Values revised multiple times through 2024.

Measured Errors

Magnet	Aperture	a_2		b_2	
		June [units]	Nov. [units]	June [units]	Nov. [units]
MBRD1	AP01	1.23	1.28	-4.84	-5.04
	AP02	-1.27	-1.28	4.88	5.26
MBRD2	AP04	-1.49	-1.09	-1.30	-4.52
	AP03	1.49	1.09	1.30	4.52
MBRD3	AP05	1.56	-1.09	9.19	-4.63
	AP06	-1.56	1.09	-9.26	4.56
MBRD4	AP07	1.56	-1.09	9.08	-4.74
	AP08	-1.56	1.09	-9.08	4.74
MBRD5	AP09	1.56	-1.09	9.63	-4.19
	AP10	-1.56	1.09	-9.27	4.56
MBRD6	AP12	7.19	7.68	-9.63	-4.02
	AP11	1.25	0.79	9.34	4.32

Placement

- Former studies [3, 4] showed:
 - Placement matters!
 - b_2 errors up to ± 10 units are easily correctable.
- ⇒ Right of IP1 preferred location for large a_2 errors.

Location	Scenario	
	Default	Spare
l1	MBRD2	MBRD1
r1	MBRD3	MBRD6
l5	MBRD4	MBRD4
r5	MBRD5	MBRD5

Correction Algorithms

- Linear equation system **minimizing f_{1001} and f_{1010} at crab-cavities and closest IP.**
- Correction via arc **skew quadrupoles (MQS).**

a_2

Approaches:

- 1 arc: **Arc next to D2.**
- 2 arcs: ~~arcs left and right of IP next to D2.~~
- 3 arcs: ~~arc next to D2 ± 1 arc.~~
- ~~All arcs.~~

-
- Two correction approaches:
 - Linear equation system **minimizing β -beating.**
 - ~~Re-match tune.~~

b_2

- Correction via **adjacent quadrupoles**
 - ~~Q4, (possibly using only highest β -plane)~~
 - ~~Q4 and Q5.~~
 - **Q4, Q5 and Q6.**

Simulation Setup

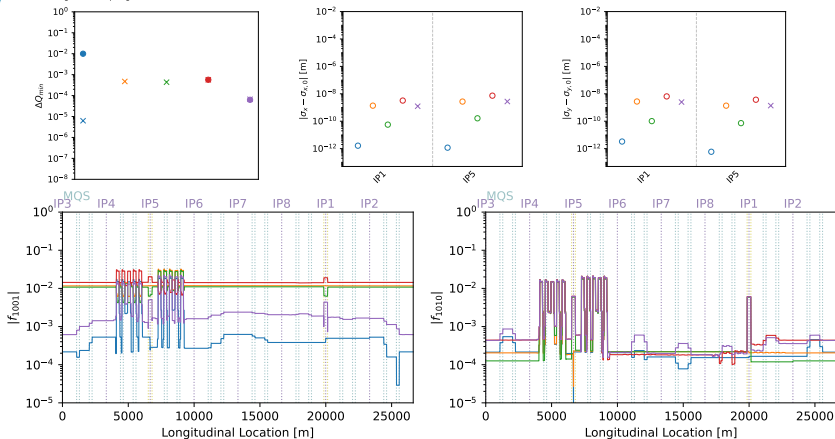
Step	Output
<ul style="list-style-type: none">Initialize HL-LHC lattice $\beta_{x,y}^* = 15$ cm round optics or $\beta_{x/y}^* = 7.5$ cm, $\beta_{y/x}^* = 30$ cm (IP 1/5) flat-optics	Nominal
<ul style="list-style-type: none">Apply a_2/b_2 errors.	Before correction
<ul style="list-style-type: none">Do orbit and tune matching of the partially uncorrected machine.	D2 correction
<ul style="list-style-type: none">Perform the a_2/b_2 correction as described.	Global coupling
<ul style="list-style-type: none">Perform a final global coupling correction and tune matching.	correction / Baseline

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Default Scenario: Coupling

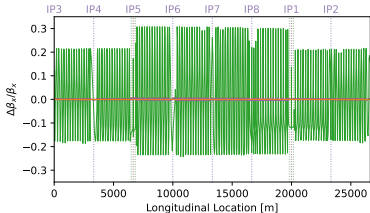
x, o baseline
x, o before correction
x, o global coupling correction
x, o nominal
x, o D2 correction



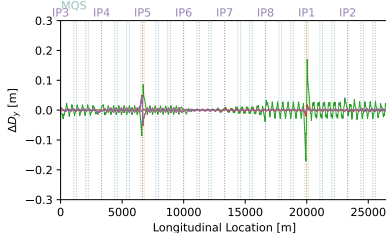
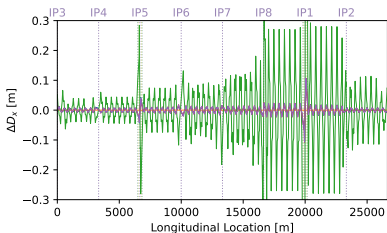
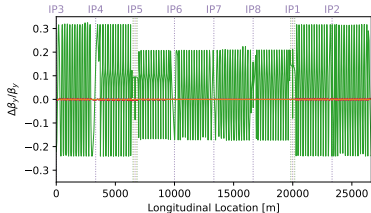
- Global Coupling: $\Delta Q_{\min} \approx 10^{-4}$
- Change in beam-size at IPs $\approx 10^{-8}$ m
- Coupling RDTs relatively close to Baseline

Default Scenario: β and Disp.

— baseline (0.2%) — nominal (0.0%)
— before correction (30.8%) — D2 correction (0.7%)
— global coupling correction (0.7%)



— baseline (0.2%) — nominal (0.0%)
— before correction (32.5%) — D2 correction (0.6%)
— global coupling correction (0.7%)



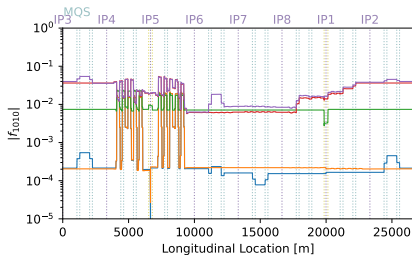
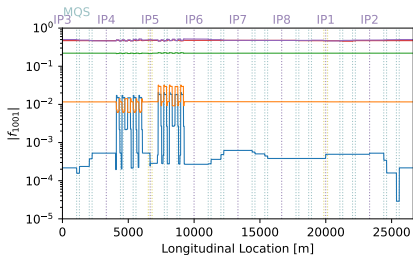
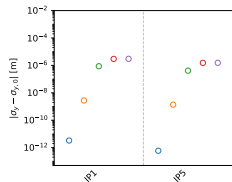
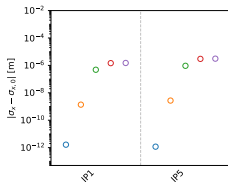
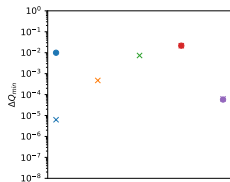
- β -beating $\leq 1\%$
- Change in Dispersion ≤ 0.1 m

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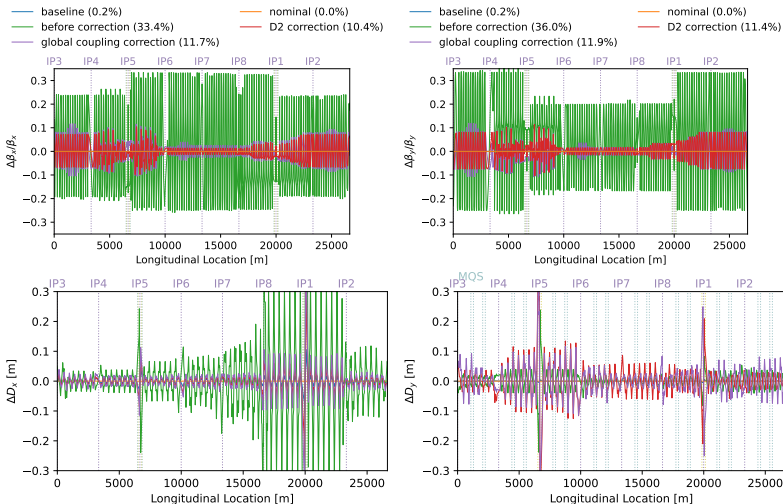
Spare Scenario: Coupling

x, o baseline
x, o before correction
x, o global coupling correction
x, o nominal
x, o D2 correction



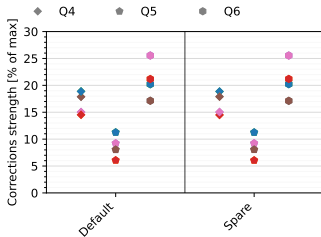
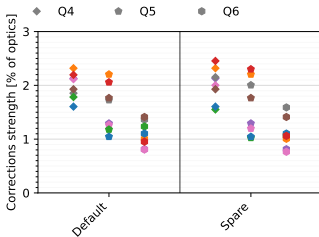
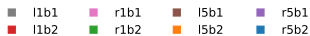
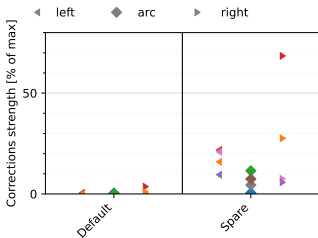
- Global Coupling: $\Delta Q_{\min} \approx 10^{-4}$
- Change in beam-size at IPs $\approx 10^{-5}$ m
- Coupling RDTs not correctable.

Spare Scenario: β and Disp.



- β -beating up to 12%
- Change in Dispersion ≥ 0.1 m

Corrector Strengths



- Default: skew < 4 %, normal < 2.5 %
- Spare: skew up to 40 % – 70 %, normal < 2.5 %

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Conclusions

- Measured b_2 errors correctable even out-of-spec.
- Measured a_2 errors correctable where within spec.
- MBRD6 with large a_2 errors disruptive of optics.
⇒ Cannot not be used as Spare.

Thank you very much for your attention!

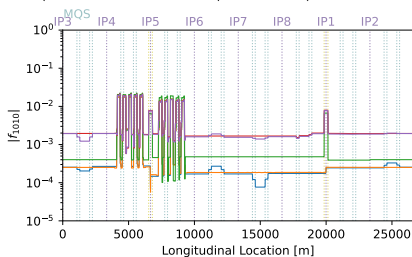
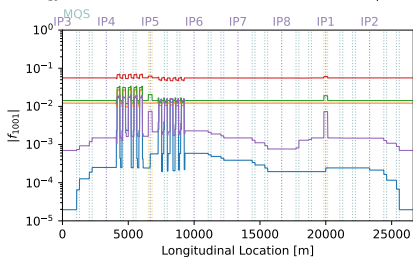
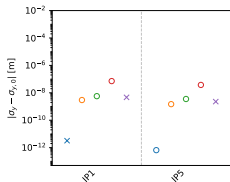
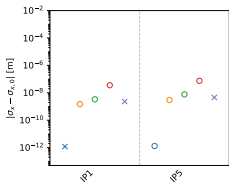
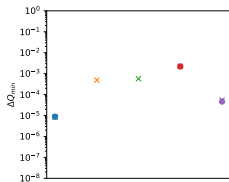
References

- [1] E. TODESCO, *Acceptance Criteria of INFN-Genova in-kind Contribution (Recombination Dipole D2) Rev. 1.3*, TRACEABILITY LHC-MBRD-ES-0002, CERN, Geneva, Switzerland, Oct. 2021.
URL: https://edms.cern.ch/ui/file/2051868/1.3/D2_accept.v1.3.pdf.
- [2] B. CAIFFI, *MBRD field quality*, HiLumi WP2, CERN, Apr. 2024.
URL: <https://indico.cern.ch/event/1409292>.
- [3] J. DILLY AND R. TOMÁS, *Impact of Expected Quadrupole Errors in the New Separation Dipoles on the HL-LHC Optics*, Accelerators & Technology Sector Note To be published, CERN, Geneva, Switzerland, 2025.
- [4] J. DILLY AND R. TOMÁS, *Linear Imperfections of D2 and Voltage Spikes in MQXFA*, HL-LHC Collaboration Meeting, Genoa, Italy, Oct. 2024.
URL: <https://indico.cern.ch/event/1421594/contributions/5979581/>.

Backup Slides

Default Scenario: Coupling

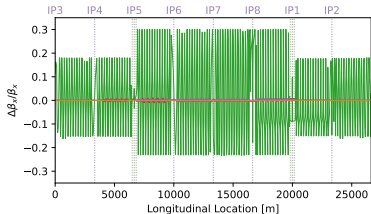
x, o baseline
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x, o global coupling correction
x, o nominal
x, o D2 correction



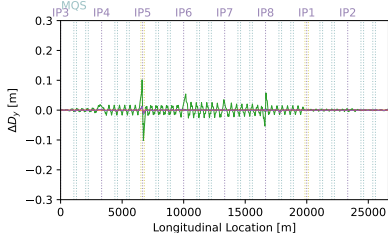
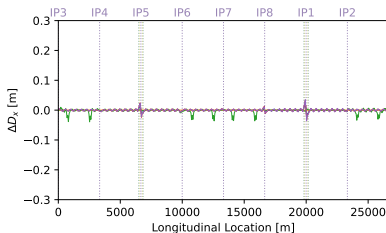
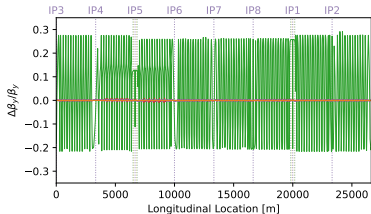
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- Change in beam-size at IPs $\approx 10^{-8}$ m
- Coupling RDTs relatively close to Baseline

Default Scenario: β and Disp.

— baseline (0.2%) — nominal (0.0%)
— before correction (30.1%) — D2 correction (1.0%)
— global coupling correction (0.7%)



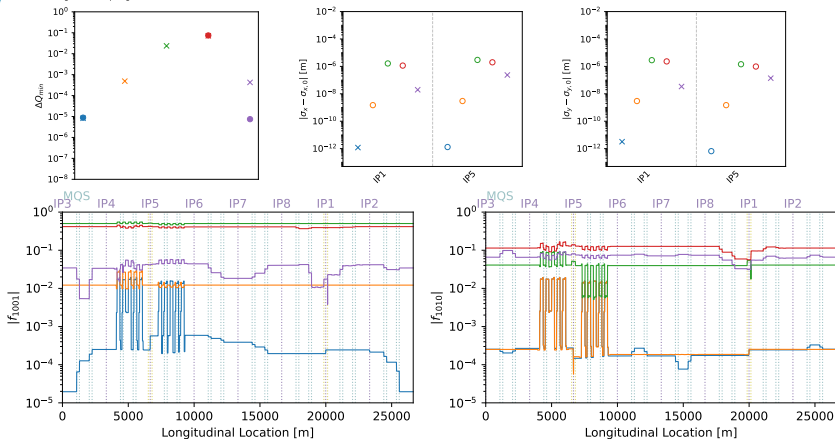
— baseline (0.2%) — nominal (0.0%)
— before correction (29.1%) — D2 correction (0.9%)
— global coupling correction (0.4%)



- β -beating $\leq 1\%$
- Change in Dispersion ≤ 0.1 m

Spare Scenario: Coupling

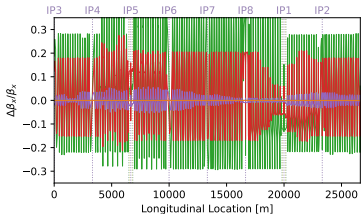
x, o baseline
x, o before correction
x, o global coupling correction
x, o nominal
x, o D2 correction



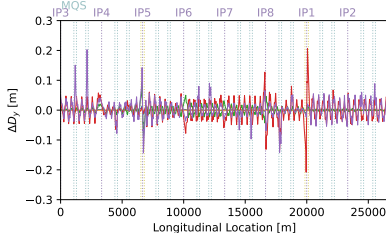
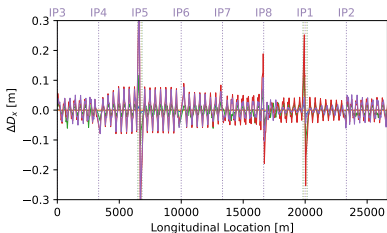
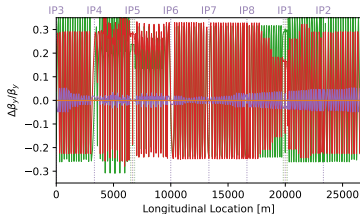
- Global Coupling: $\Delta Q_{\min} \approx 10^{-4}$
- Change in beam-size at IPs $\approx 10^{-5}$ m
- Coupling RDTs not correctable.

Spare Scenario: β and Disp.

— baseline (0.2%) — nominal (0.0%)
 — before correction (41.2%) — D2 correction (27.5%)
 — global coupling correction (5.7%)



— baseline (0.2%) — nominal (0.0%)
 — before correction (44.8%) — D2 correction (39.7%)
 — global coupling correction (5.4%)



- β -beating up to 12%
- Change in Dispersion around IP1 ≥ 0.1 m