Sorting options for HL-LHC magnets

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Acknowledgements: INFN Team, J. Dilly, A. Foussard, R. De Maria, L. Fiscarelli, S. Izquierdo Bermudez, E. Todesco, R. Tomás, A. Wegscheider

Hi-Lumi annual meeting - 9 October 2024

HIGH LUMINOSITY LHC

14th

HL-LHC COLLABORATION MEETING

GENOA, ITALY, 7-10 October 2024

Jointly organised by **INFN** and **CERN**, the **14th HL-LHC Collaboration Meeting** will take place in person in **Genoa**, Italy from **7th to 10th October 2024**. This edition will provide the occasion to showcase the successful production and validation of the first series D2 magnets, produced by ASG in Genoa as an in-kind contribution by INFN (Italy), as well as the completion of production of the MgB_2 wires for the superconducting link by ASG.

Based on the traditional programme with plenary and work package parallel sessions, this meeting will serve as a technical update forum for the 8th Cost and Schedule Review, scheduled for 11th to 14th November 2024. The main objectives will be to update all HiLumi collaborators on the advancement of the series production of components for the project, to showcase the status of the IT String test stand installation at CERN, and to update all collaborators on the latest schedule changes.

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For more details and registration : HL-LHC.Secretariat@cern.ch / hilumilhc.web.cern.ch

Outline

- General considerations on sorting benefits
- The case of triplet magnets
- The case of D2 recombination dipoles
- Conclusions

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LHC experience on sorting

- When compared to a random installation, sorting has guarded against
  - a loss of mechanical aperture estimated at 1.5 mm,
    - Obtained by applying installation shifts and selection of slots depending on geometry data
  - an increase of beta-beating by 5 to 10%
    - Obtained by pairing main quadrupoles
  - a loss of dynamic aperture estimated at 1 σ
    - Obtained by pairing main dipoles to cope with b3 errors
    - NB: also a2 errors have been optimised…

L. Bottura et al., “Magnet Acceptance and Allocation at the LHC Magnet Evaluation Board”, 22nd Particle Accelerator Conf. (PAC’07)

LHC experience on sorting

- Summary of the general sorting benefit
  - Low Beta Quadrupoles
    - Sorting was based on the geometry, in view of maximizing the aperture.
    - The alignment shifts specified for these magnets have been optimized to achieve an aperture of 8.4 σ, with a minimum quadrupole feed-down, so that local orbit corrections should require at most 30 % of the dipole corrector strength.
  - Cold Separation and Recombination Dipoles
    - Field quality was within the specifications, and the best magnets were allocated to the most critical slots.
    - The analysis of aperture was done on a one-by-one basis. The main issue was the observed deviations (up to 2 mm) between the expected straightness and the measured shape of the cold bore. Installation shifts were sufficient to recover the specified aperture.

L. Bottura et al., "Magnet Acceptance and Allocation at the LHC Magnet Evaluation Board", 22nd Particle Accelerator Conf. (PAC'07)

LHC experience on sorting

- Some pre-requisite for an efficient sorting
  - Large variation of the physical observable that one wants to optimise
  - Sufficient number of magnets available to sort
    - In this respect, the delay in the installation of the LHC dipoles has had a very positive impact on the sorting performance
  - Magnet data available early on
    - This allows maximising the number of compatible slots, before the hardware type is too specific

L. Bottura et al., “Magnet Acceptance and Allocation at the LHC Magnet Evaluation Board”, 22nd Particle Accelerator Conf. (PAC’07)

Magnet sorting: quantities to control

- Based also on the LHC experience, three observables should be used for sorting:
  - Mechanical aperture (beam aperture)
  - Transfer function (beta-beating)
  - Field quality (strength of correct magnets, DA, lifetime)
- A hierarchy between the observables has to be defined.

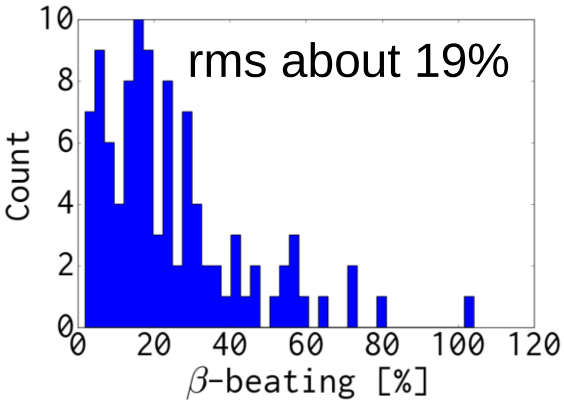
Magnet sorting: strategies

- Aperture
  - Define installation shifts.
- Transfer function
  - Matching magnets in the same circuit (applicable to Q2).
- Field quality
  - The phase advance cannot be used to cancel multipole components.
  - The guiding criterion is the minimisation of the strength used by the CP magnets and distribute magnets so that the CP magnets are used almost in the same way on the four sides of IP1/5.
  - Dipoles and quadrupoles have different systematic multipoles, which suggests optimising the field quality in blocks
    - D1 and D2 (the fields are opposite…the average between the two apertures should be considered for D2)
    - Triplet quadrupoles

Estimate of possible benefits of sorting

- Beta-beating
  - Q2 sorting is the baseline since the decision of removing the trim between Q2A and Q2B.
  - In the case of perfect sorting the difference in transfer function can be made < 13 units with 90% probability.
  - From LHC experience: we should prevent unknown situations.

Extreme case with +30 units in Q2a and -30 in Q2b (no sorting, max β-beating for 100 seeds).10 units TF error in the rest and 5mm misalignments in all. J. Coello in HL-LHC Magnet Circuits Internal Review 2017



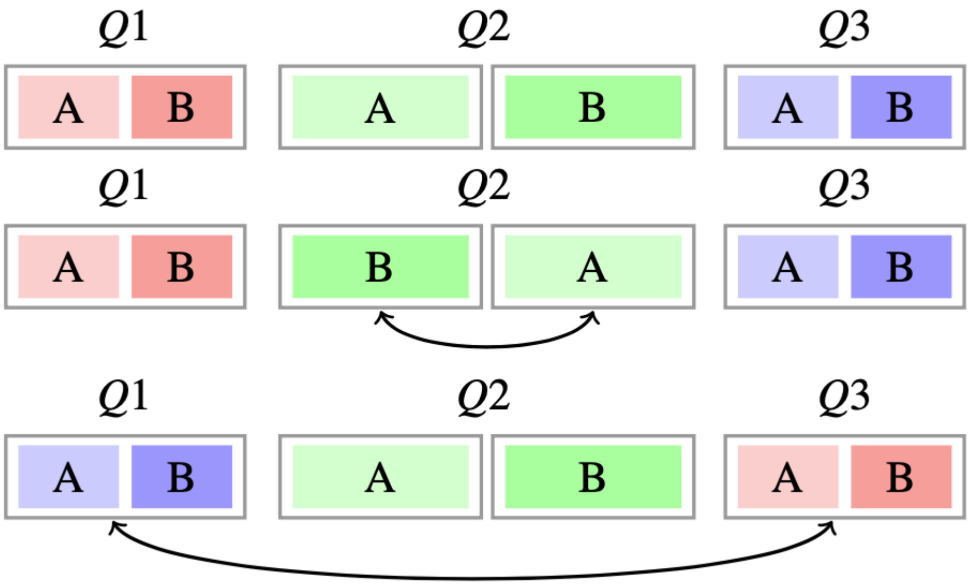
R. Tomás, “Desiderata for sorting: transfer function”, Kick-off meeting on sorting in the HL LHC

Outline

- General considerations on sorting benefits
- The case of triplet magnets
- The case of D2 recombination dipoles
- Conclusions

The case of the triplet quadrupoles

- The sketch of the HL-LHC triplet quadrupoles



Allowed transformations

- **Pairing**: Triplet magnets of the same family can be swapped, e.g. between A and B for Q2, and between Q1 and Q3, in the same IP side.
- **Swapping**: Magnets of the same family can be exchanged between IPs and IP sides.

Powering

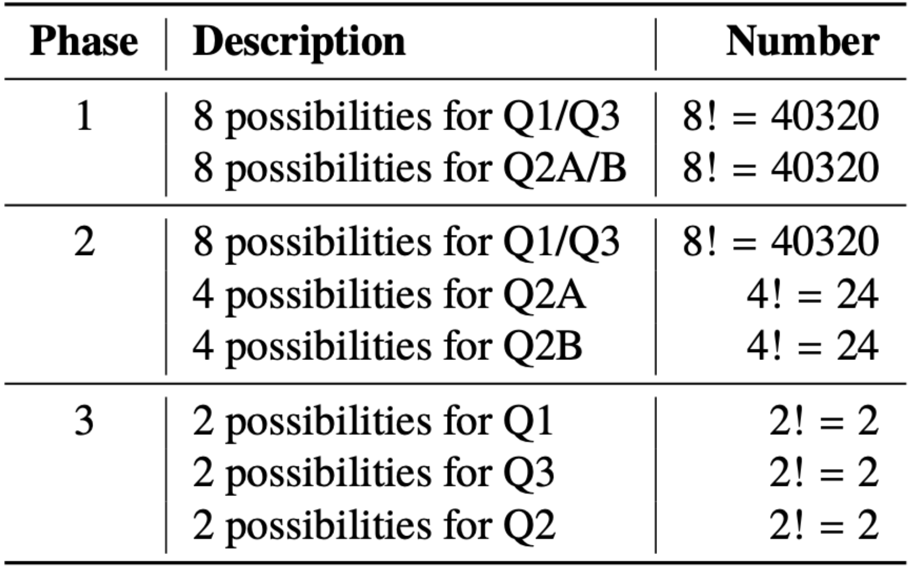
- Q1, Q2A, Q2B, Q3 are in series (18 kA power converter).
- Q1 and Q3 have an additional 2 kA circuit for trimming.

T. Pugnat et al., “Sorting strategies for the new superconducting magnets for the CERN HL-LHC”, [15th International Particle Accelerator Conf. (IPAC’24)]

The case of the triplet quadrupoles

The hardware stage defines how many slots are compatible with each object

- **Phase 1**: assembly of the main part of the cryostat, main vacuum vessel, thermal shield, cold mass supports and instrumentation feedthroughs.
- **Phase 2**: after the powering tests, equipment specific to the installation slot is added.
- **Phase 3**: installation of beam vacuum equipment.



Phase	Description	Number
1	8 possibilities for Q1/Q3	8! = 40320
	8 possibilities for Q2A/B	8! = 40320
2	8 possibilities for Q1/Q3	8! = 40320
	4 possibilities for Q2A	4! = 24
	4 possibilities for Q2B	4! = 24
3	2 possibilities for Q1	2! = 2
	2 possibilities for Q3	2! = 2
	2 possibilities for Q2	2! = 2

T. Pugnat et al., “Sorting strategies for the new superconducting magnets for the CERN HL-LHC”, [15th International Particle Accelerator Conf. (IPAC’24)]

The case of the triplet quadrupoles

The choice in terms of observable is the beta-beating generated by the error in the transfer function

$$\frac{\Delta\beta_z}{\beta_z}(s) = \mp\sum_i \Delta K_{1,i}\beta_{z,i}\frac{\cos\left(4|\psi_{z,i}(s)| - 2\pi Q_z\right)}{2\sin(2\pi Q_z)}$$

To consider the effect of the errors on both planes each permutations are marked/scored, and the best one is recorded

$$\text{score} = \sqrt{\left\langle\left(\frac{\Delta\beta_x}{\beta_x}\right)^2\right\rangle_s + \left\langle\left(\frac{\Delta\beta_y}{\beta_y}\right)^2\right\rangle_s}$$

NB: at this stage, the TF error is only due to the intrinsic variability of the magnet construction process.

The simulations are carried out:

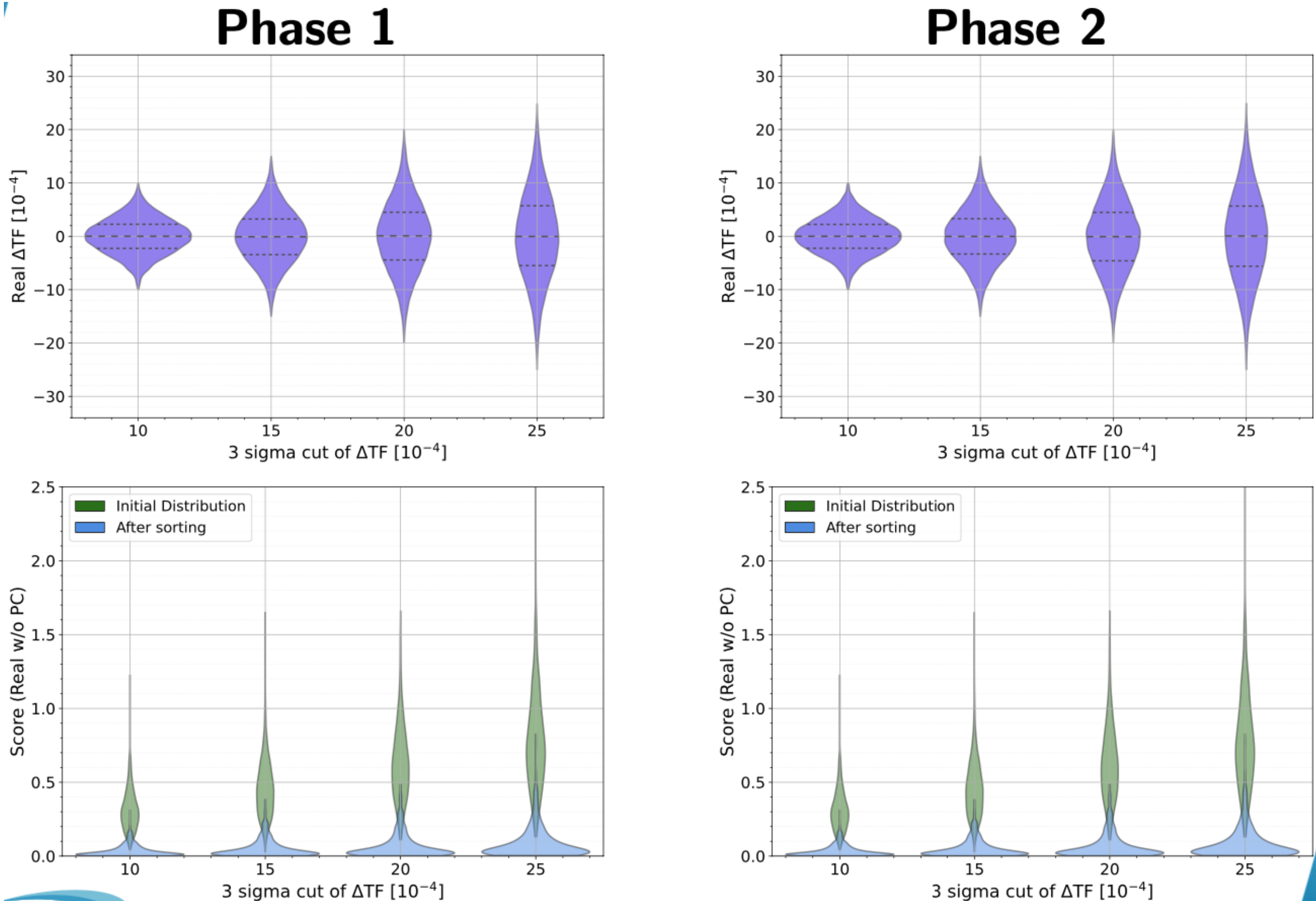
- Varying the sigma of the **TF error**
- Neglecting the circuit powering (independent powering assumed)

T. Pugnat et al., “Sorting strategies for the new superconducting magnets for the CERN HL-LHC”, 15th International Particle Accelerator Conf. (IPAC’24)

The case of the triplet quadrupoles

Errors are Gaussian cut at 3 σ

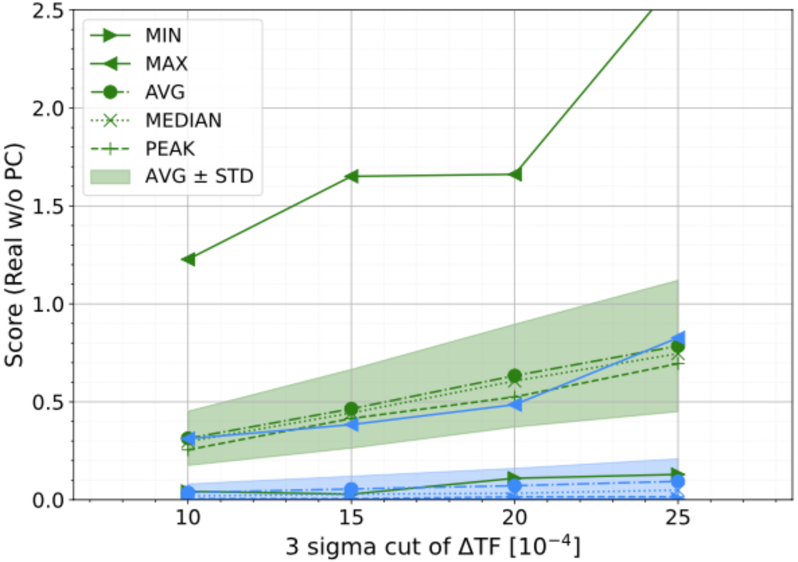
Correspondingly, the impact of the sorting is evaluated



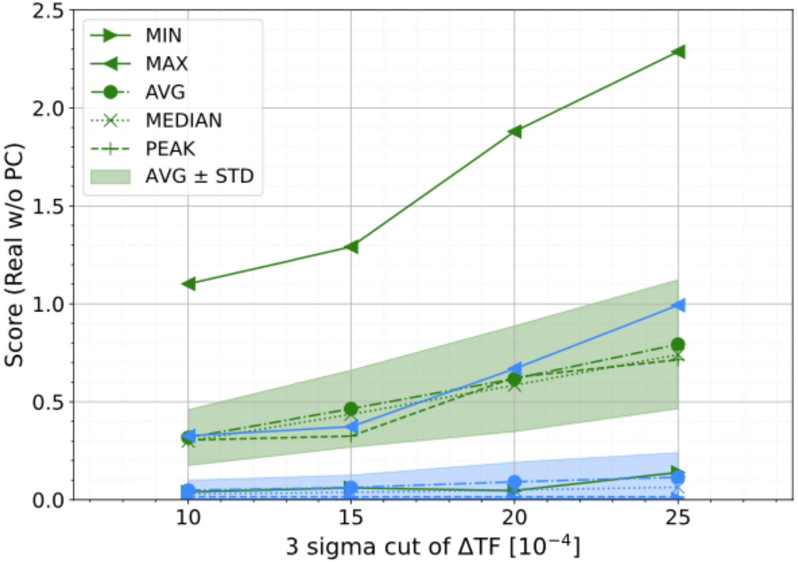
The case of the triplet quadrupoles

Dependence of the statistical indicators of score function distribution as a function of the error distribution.

Phase 1



Phase 2



The case of the triplet quadrupoles

Descriptive statistics of score distributions.

Effectiveness is clear, as well as the relevance of performing the sorting early on (**Phase 1**).

Peak indicates the value of maximum of the distribution, hence the the most-probable value

Phase 1

3 Sigma	Step	MIN	AVG	MEDIAN	PEAK	MAX	STD
10	ID	0.043	0.313	0.297	0.255	1.227	0.138
	AS	0.001	0.037	0.020	0.005	0.312	0.044
15	ID	0.029	0.464	0.443	0.415	1.651	0.201
	AS	0.002	0.055	0.028	0.005	0.384	0.065
20	ID	0.110	0.634	0.606	0.525	1.661	0.262
	AS	0.002	0.072	0.033	0.015	0.486	0.088
25	ID	0.129	0.785	0.746	0.695	2.661	0.335
	AS	0.003	0.094	0.049	0.015	0.827	0.115

Phase 2

3 Sigma	Step	MIN	AVG	MEDIAN	PEAK	MAX	STD
10	ID	0.040	0.318	0.300	0.305	1.102	0.142
	AS	0.002	0.049	0.029	0.015	0.326	0.051
15	ID	0.061	0.465	0.436	0.325	1.291	0.196
	AS	0.002	0.062	0.038	0.015	0.373	0.063
20	ID	0.047	0.618	0.585	0.625	1.880	0.270
	AS	0.004	0.092	0.050	0.015	0.669	0.100
25	ID	0.140	0.793	0.741	0.715	2.287	0.329
	AS	0.004	0.115	0.064	0.015	0.993	0.125

PEAK: using step-size of 0.01; ID: Initial Distribution;
AS: After sorting;

The case of the triplet quadrupoles

- In the previous scenarios, the treatment of TF errors is like each quadrupole is powered independently.

- As a first step, the special powering scheme has been represented assuming that pairs of quadrupoles are powered in series and for each pair of errors $\frac{\Delta K_1}{K_1}, \frac{\Delta K_2}{K_2}$

$$\frac{\Delta K_i}{K_i} \to \frac{\Delta K_i}{K_i} - \frac{1}{2}\left(\frac{\Delta K_1}{K_1} + \frac{\Delta K_2}{K_2}\right)$$

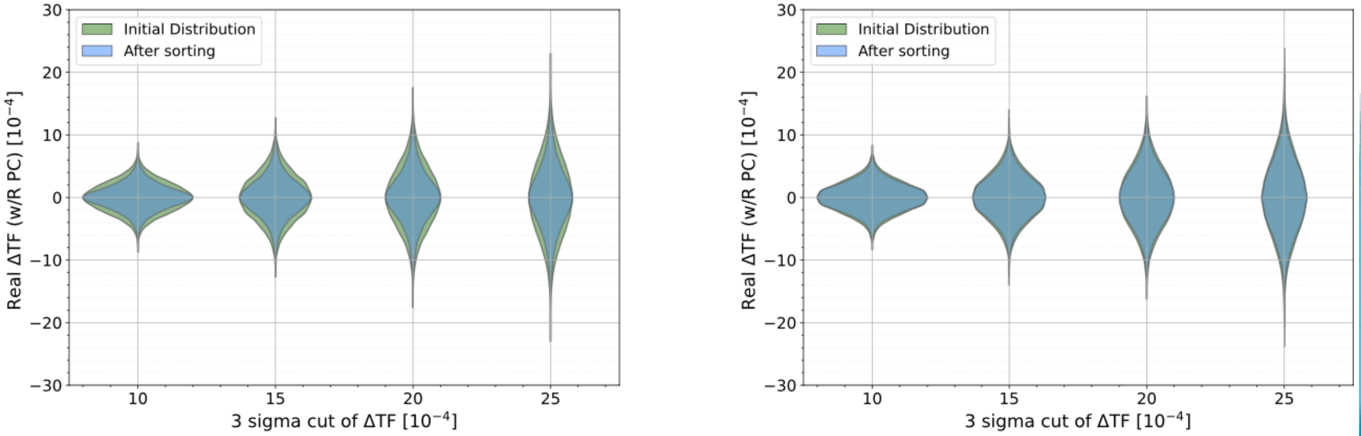
- This already improves the distribution of errors

The case of the triplet quadrupoles

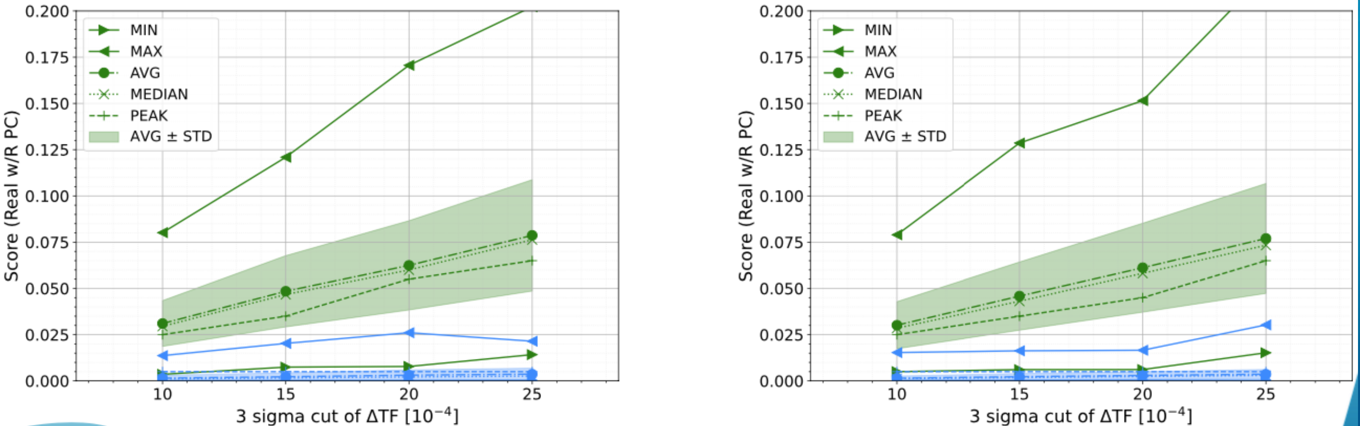
Errors are Gaussian cut at 3 σ. Note the reduction with respect to slide 16 (and with respect to the horizontal scale).

Phase 1

Phase 2



Dependence of the statistical indicators of score function distribution as a function of the TF error.

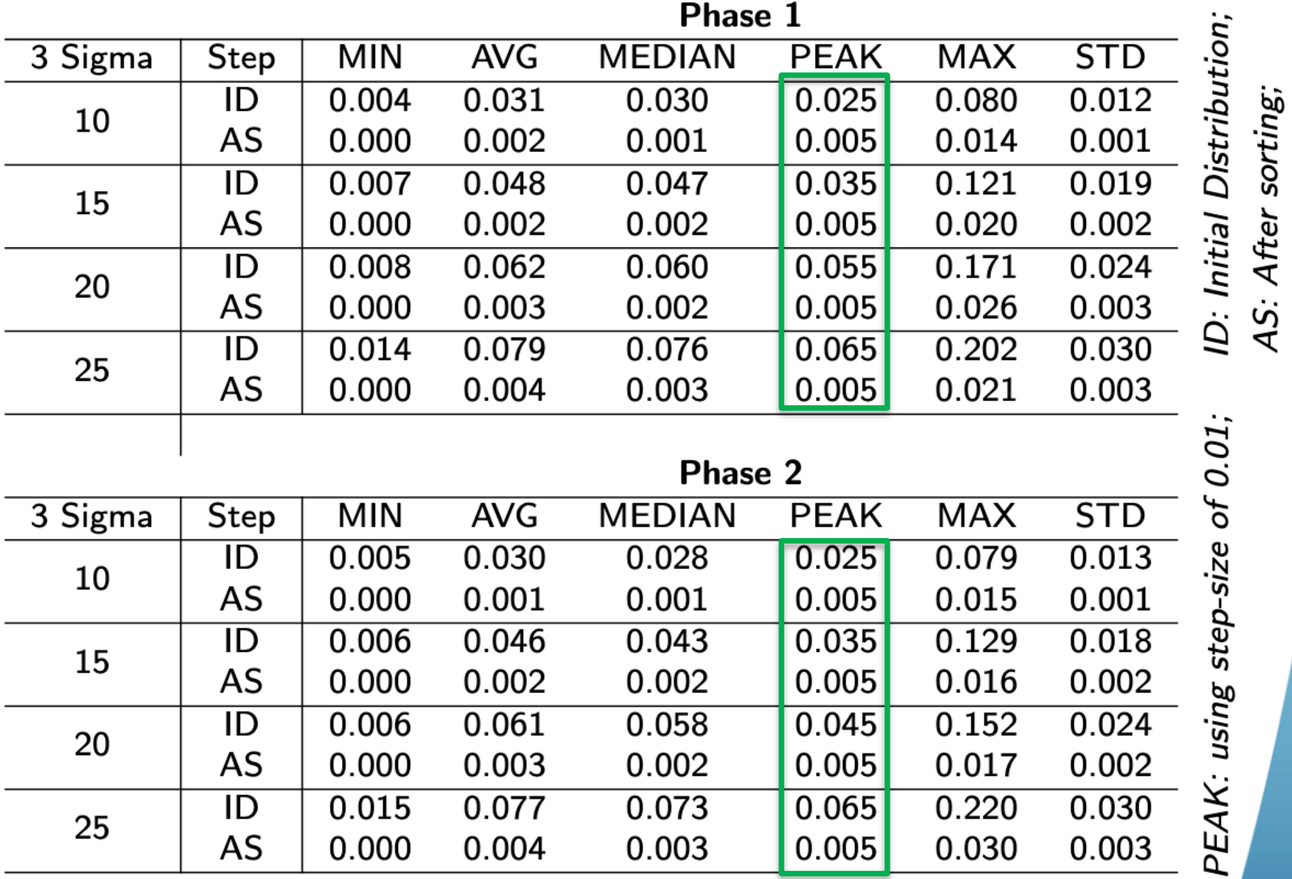


The case of the triplet quadrupoles

Descriptive statistics of score distributions.

The initial distribution is about a factor of 10 better than what shown on slide 17.

Peak indicates the value of maximum of the distribution, hence the the most-probable value



Phase 1

3 Sigma	Step	MIN	AVG	MEDIAN	PEAK	MAX	STD
10	ID	0.004	0.031	0.030	0.025	0.080	0.012
	AS	0.000	0.002	0.001	0.005	0.014	0.001
15	ID	0.007	0.048	0.047	0.035	0.121	0.019
	AS	0.000	0.002	0.002	0.005	0.020	0.002
20	ID	0.008	0.062	0.060	0.055	0.171	0.024
	AS	0.000	0.003	0.002	0.005	0.026	0.003
25	ID	0.014	0.079	0.076	0.065	0.202	0.030
	AS	0.000	0.004	0.003	0.005	0.021	0.003

Phase 2

3 Sigma	Step	MIN	AVG	MEDIAN	PEAK	MAX	STD
10	ID	0.005	0.030	0.028	0.025	0.079	0.013
	AS	0.000	0.001	0.001	0.005	0.015	0.001
15	ID	0.006	0.046	0.043	0.035	0.129	0.018
	AS	0.000	0.002	0.002	0.005	0.016	0.002
20	ID	0.006	0.061	0.058	0.045	0.152	0.024
	AS	0.000	0.003	0.002	0.005	0.017	0.002
25	ID	0.015	0.077	0.073	0.065	0.220	0.030
	AS	0.000	0.004	0.003	0.005	0.030	0.003

PEAK: using step-size of 0.01; ID: Initial Distribution;
AS: After sorting;

The case of the triplet quadrupoles

- The last aspect to be included is the presence of errors due to the measurements of the TF.
  - The analysis of the error sources of the stretched wire show that the sag correction is the largest contribution and must be carefully corrected. Residual deviations can be ∼4 units (systematic)
  - In addition, the cross calibration of different wire systems show that deviation can be 2 units (systematic)
  - The repeatability is at the level of 1 unit (random 1-σ)
  - The cross check against the rotating coil show a deviation of ∼2 units
  - The cold-warm correlation is not yet well established (better than 10 units on 3 magnets)

L. Fiscarelli et al., "New TF measurement errors", Special Joint HiLumi WP2/WP3 meeting Tuesday 30 Apr 2024

The case of the triplet quadrupoles

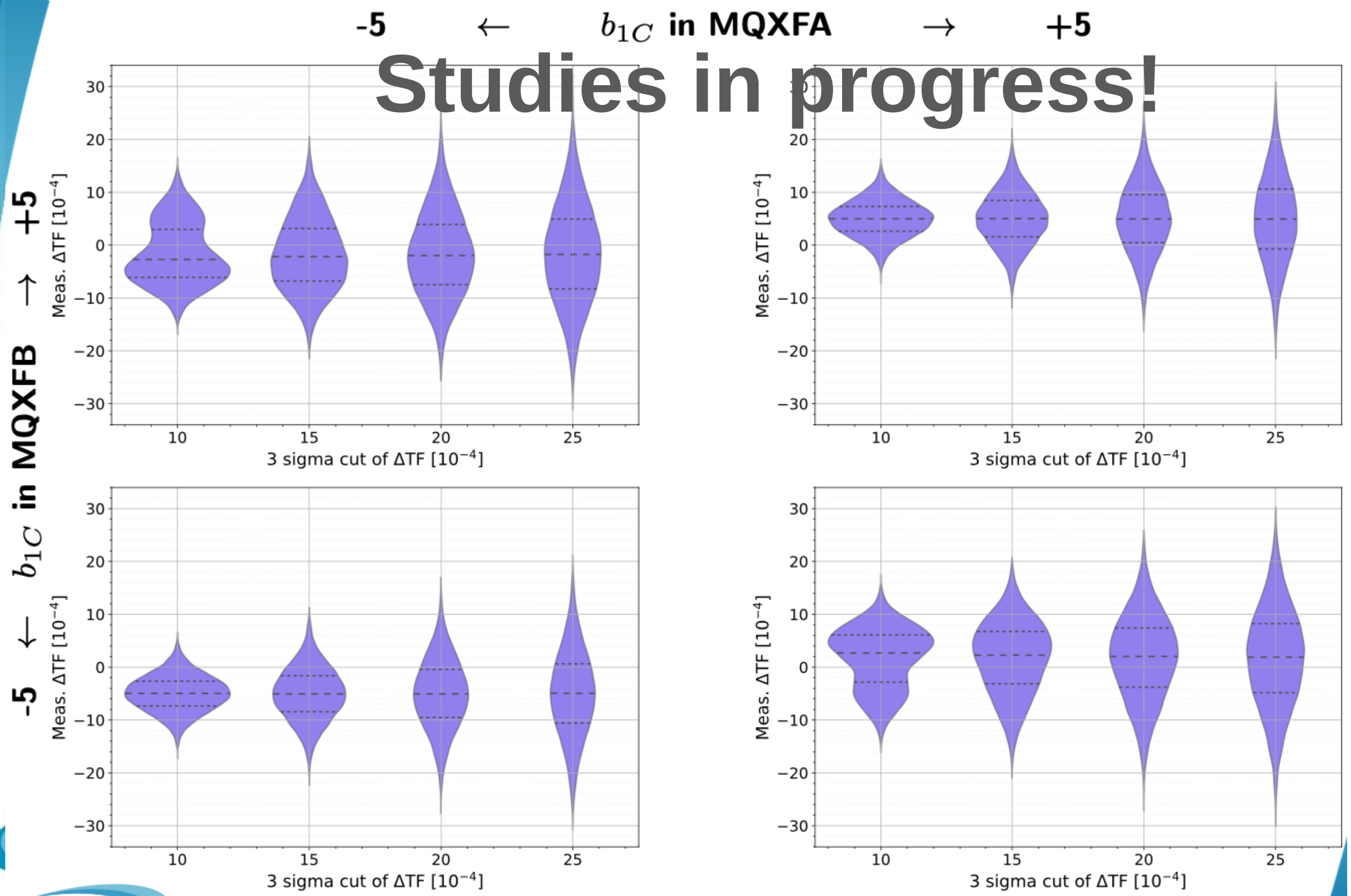
- The last aspect to be included is the presence of errors in the measurements of the TF.

Error	Type	Distribution	Amplitude
Calibration[1]	Systematic	Uniform	[-5,+5] units
Precision[2]	Random	Gaussian	σ = 1 unit

- [1] It is the same for all magnets under the assumption that the measurement system and the measurement procedure are kept the same.
- [2] It changes randomly from magnet to magnet.

L. Fiscarelli et al., “New TF measurement errors”, Special Joint HiLumi WP2/WP3 meeting Tuesday 30 Apr 2024

The case of the triplet quadrupoles



Studies in progress!

Impact of the calibration error (b_{1C}) on the measured TF errors.

The horizontal axis represents the σ of the initial “real” TF error distributions.

Outline

- General considerations on sorting benefits
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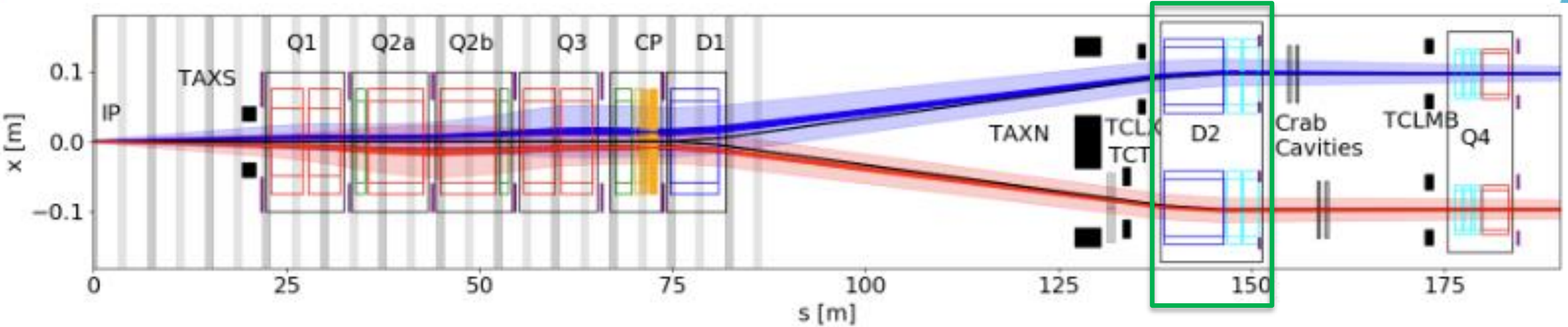
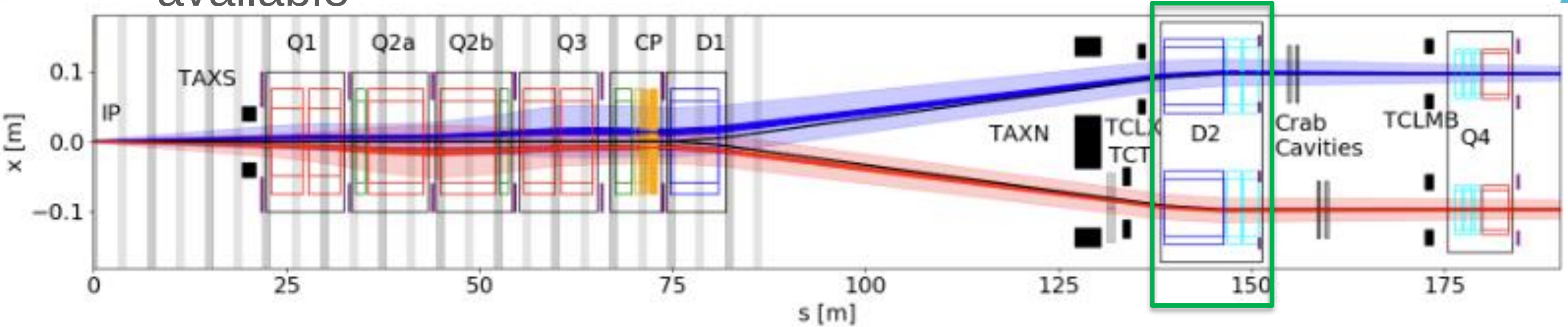
The case of D2 recombination dipoles

- Is it possible to perform sorting of D2 to improve DA?
- This topic was recently considered, triggered by discussions with the INFN Team (see talk by J. Dilly on a related topic).



The case of D2 recombination dipoles

- Six D2 magnets will be available
  - Four for installation in the tunnel
  - Two as spares
- This provides 360 possible configurations to probe (indeed 720, as Beam 1 and Beam 2 should be considered).
- The computations are on-going, but preliminary results are available

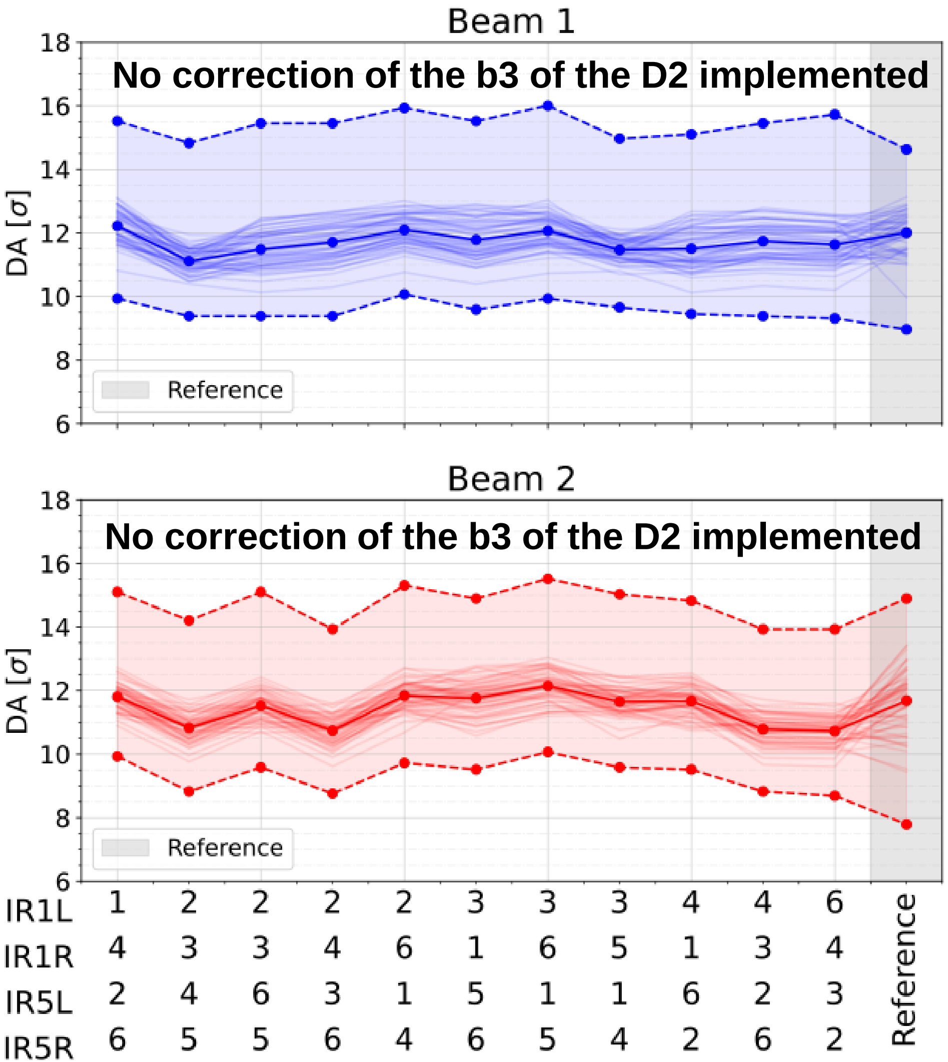


The case of D2 recombination dipoles

Interesting variation of DA as a function of installed D2 magnets.

Work still in progress:

- Increase the number of cases
- Check the impact in case the D2 magnets with large a2 components are left as spares.


No correction of the b3 of the D2 implemented

No correction of the b3 of the D2 implemented

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Conclusions

- Sorting has proven to be an efficient approach to deal with magnet imperfections in the LHC.

- The case of triplet magnets of the HL-LHC has been studied (correction of beta-beating from TF errors)
    - Interesting potential: is it really feasible (availability of data early on)?

- The case of D2 recombination dipoles has been studied (DA improvement)
    - Some DA improvement observed. It should be feasible to apply sorting.
    - The a2 component is a potential source of concern: mitigation measures would have precedence on sorting for DA optimisation.

- The analyses continue…

HiLumi
HL-LHC PROJECT

Thank you for your attention!

Back-up slides

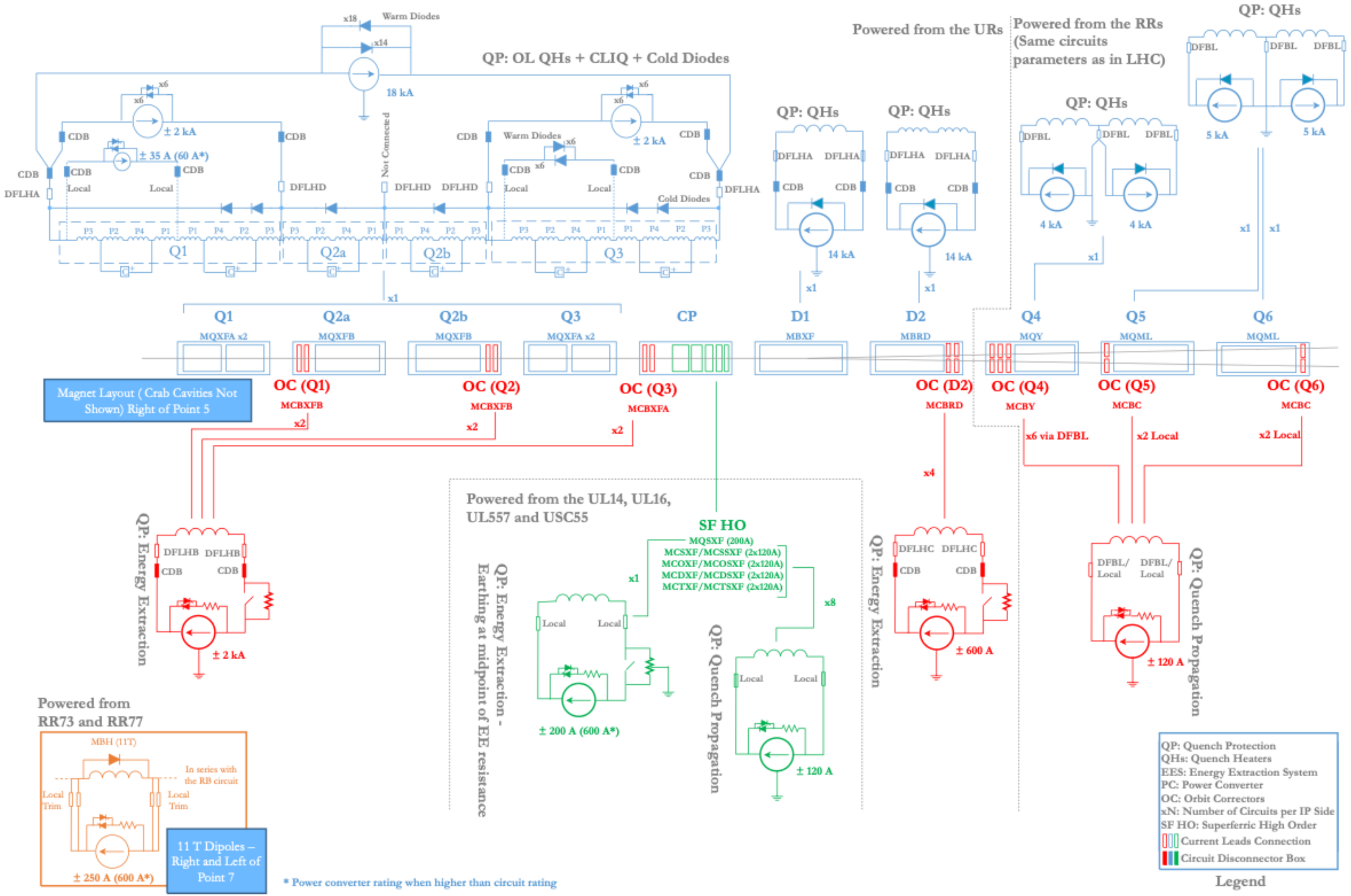
Strategy of sorting simulations

- Assign random sequences of TF errors to Q2 magnets (no errors assigned to Q1 and Q3 magnets)
  - Perform all permutations compatible with the cryostating phase.
  - Retain the 100 sequences with lowest score function.
- Assign random sequences of TF errors to Q1 and Q3 magnets (the Q2 errors with the lowest beta-beating from the previous simulation are assigned)
  - Perform all permutations compatible with the cryostating phase.
  - Retain the 100 sequences with lowest score function.
- Take all combinations of the 100 best sequences of Q2 errors and 100 best sequences of Q1 and Q3 errors
  - Retain the sequence with the lowest score function

Estimate of possible benefits of sorting

- Aperture
  - Any deviation from the nominal shape should be corrected with installation shifts for
    - aperture reasons
    - corrector strength
  - Assumed deviation for triplets: 0.5 mm
  - Nominal sigma: 3 mm
  - Gain: 0.2 sigma -> effect on β* -> 3%
  - From LHC experience: we should prevent unknown deviations.

R. De Maria, "Alignment and mechanical tolerances for HL-LHC in Point 1 and 5", LHC-G-ES-0023, EDMS 2458050



Magnet Layout (Crab Cavities Not Shown) Right of Point 5

11 T Dipoles – Right and Left of Point 7

* Power converter rating when higher than circuit rating

QP: Quench Protection
QHs: Quench Heaters
EES: Energy Extraction System
PC: Power Converter
OC: Orbit Correctors
xN: Number of Circuits per IP Side
SF HO: Superferric High Order
▯▯▯ Current Leads Connection
▮▮▮ Circuit Disconnector Box

Legend

Circuits Layout Version 3.5