CRITERIA & INSTALLATION STRATEGY FOR THE LHC MAIN DIPOLES

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Acknowledgments:

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Motivations/Limitations (1/2)

- **Preserve and/or optimize the machine performance**
  - **Finding suitable locations in the LHC ring (slots) for out-of-tolerance magnets**
  - **“Sequencing” the main dipoles (MB’s) to control and/or optimize several beam dynamics quality criteria.**

- **… while minimizing any interferences with the installation process**
  - **Do not impose constraints on the stock of available magnets**
  - **Be independent on the installation pattern of a given LHC sector**
    1. Starting from mid-arc
    2. Or starting from the dispersion suppressor (DS)
- **..and fulfilling the hardware constraints imposed by the 4 different types of LHC cryo-dipoles**

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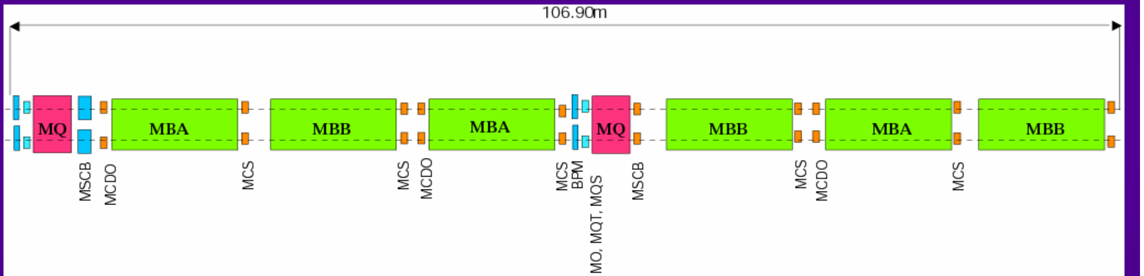
Motivations/limitations (2/2)

- MB**A** (every other dipoles)
  - → With sextupole (b3), octupole (b4) and decapole (b5) spool-pieces.
- MB**B**
  - → With only sextupole (b3) spools.

- **R**: "Anode on the Right"
  - → for Beam 1 (clock-wise) external.
- **L**: "Anode on the Left"
  - → for Beam 1 internal.



MQT: trim quadrupole

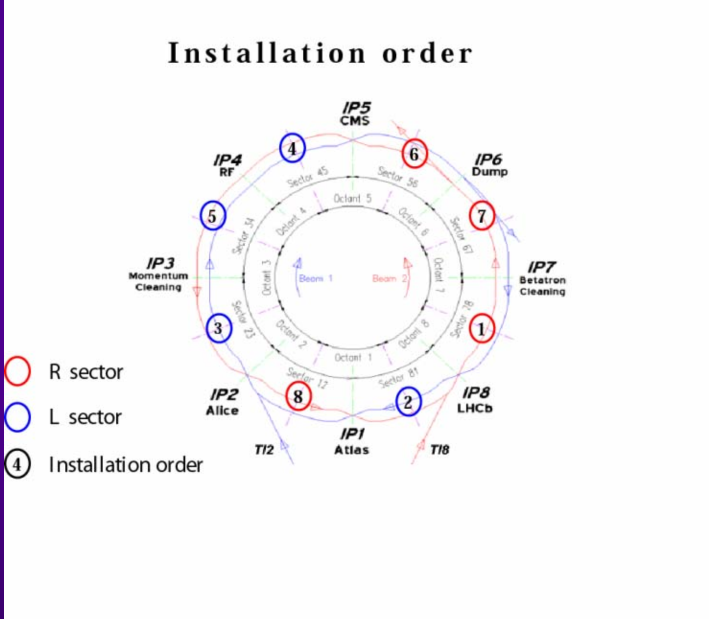
MQS: skew trim quadrupole

MO: lattice octupole

MSCB: sextupole (skew sextupole) + orbit corrector

MCS: spool piece sextupole

MCDO: spool piece octupole + decapole



→4 DIFFERENT TYPES: AL, AR, BL, BR
makes the 1232 LHC main dipoles not freely exchangeable from sector to sector or within a given sector.

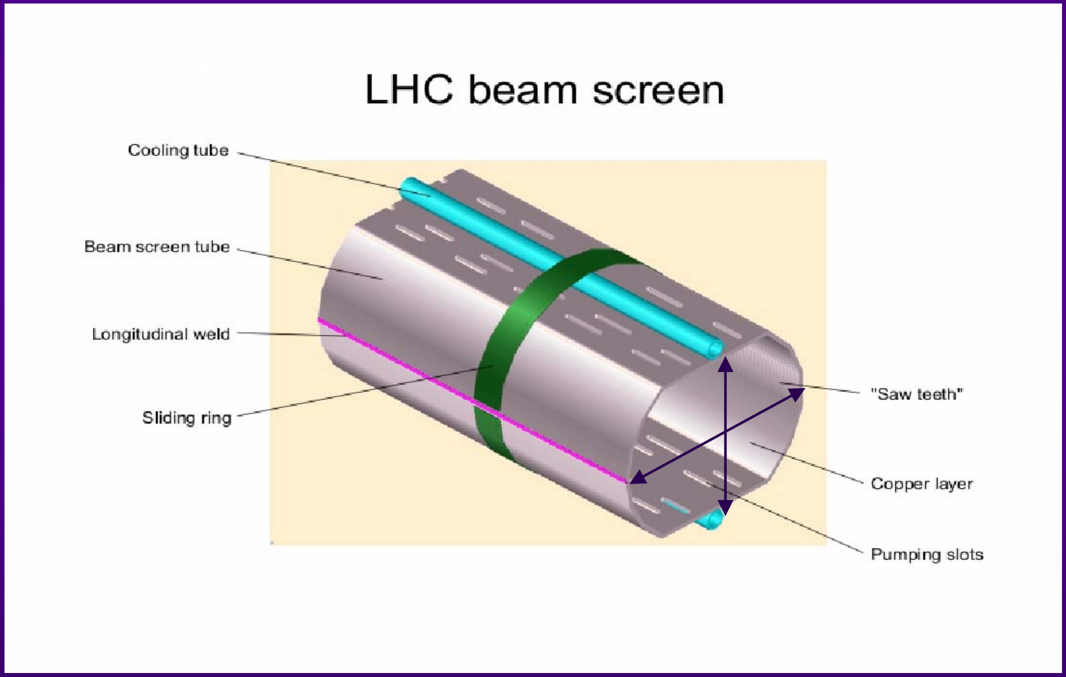
Basic sorting principle

- **Background activity: form *pairs of consecutive magnets* such that deviations from average b3 are locally compensated**
- **With the following exception rules**, listed by order of priority:
  - **Requirement to install a.s.a.p. magnets with out-of-tolerance geometry.**
  - **Requirement to keep in stock some MB's with best geometry for later installation in the dispersion suppressors (6 to 8 MB's per octant).**
  - **Requirement not to install end-to-end** more than **3 magnets with an out-of-tolerance b1 and/or a1 (i.e. transfer function and field direction).**

Magnet classification based on geometry (1/4)

- The LHC must be operated without any losses during all operation stages

→Beam screen dimension:
17 mm half height
22 mm half width



→ Small (no) aperture margin compared to other machine
…but all the machine slots are not equivalent with geometry

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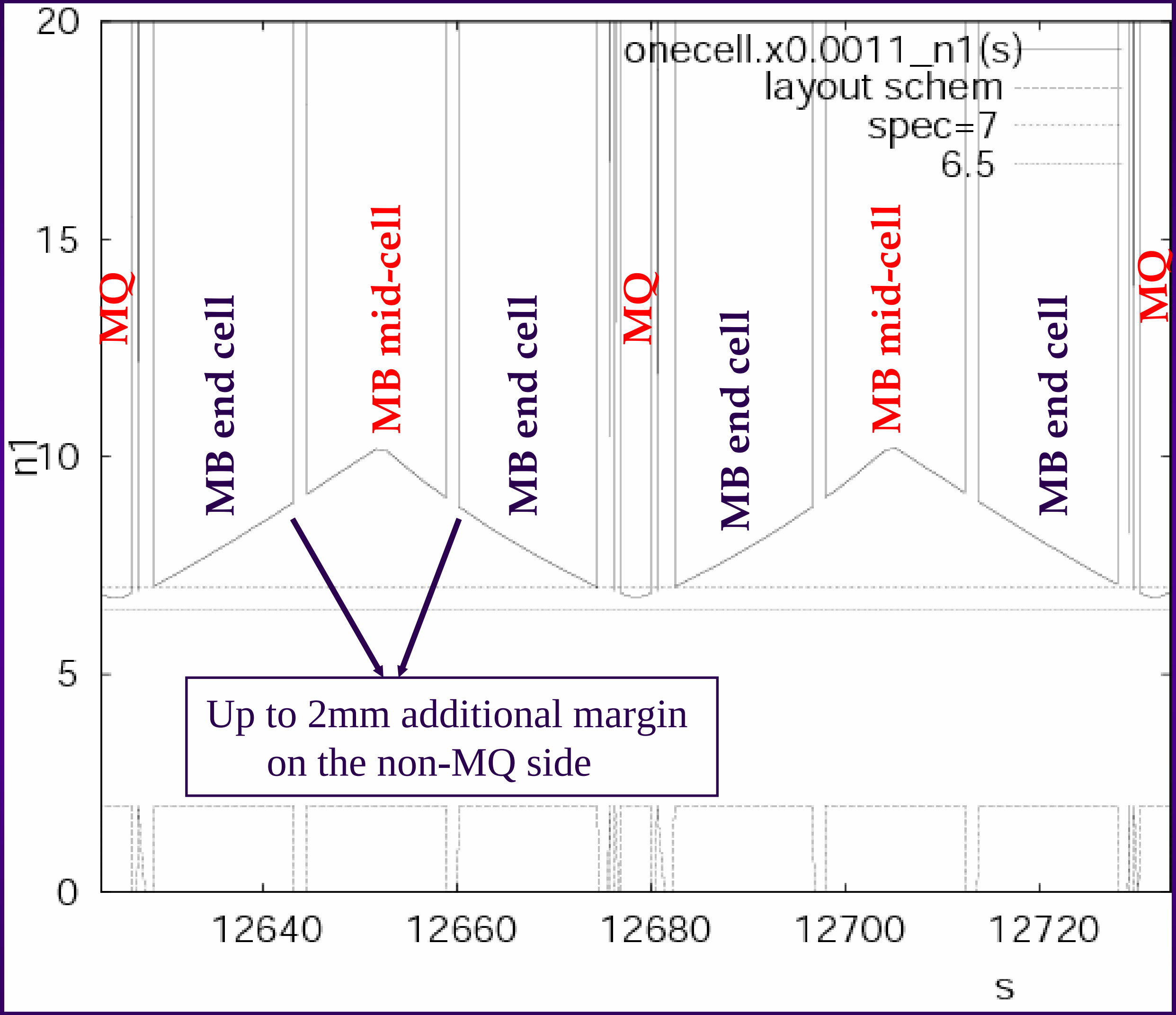
Geometry (2/4)



Mechanical aperture of an LHC arc cell at injection energy expressed in terms of "equivalent n1", that is the depth [σ] of the primary collimator jaws

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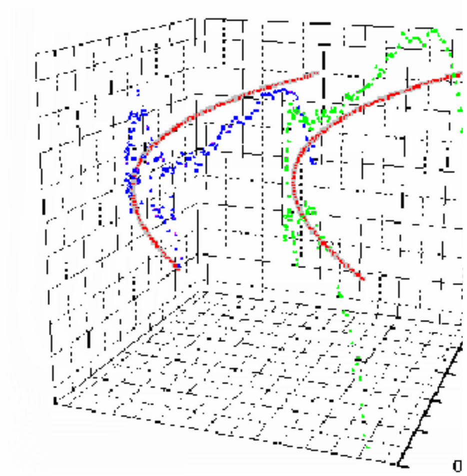
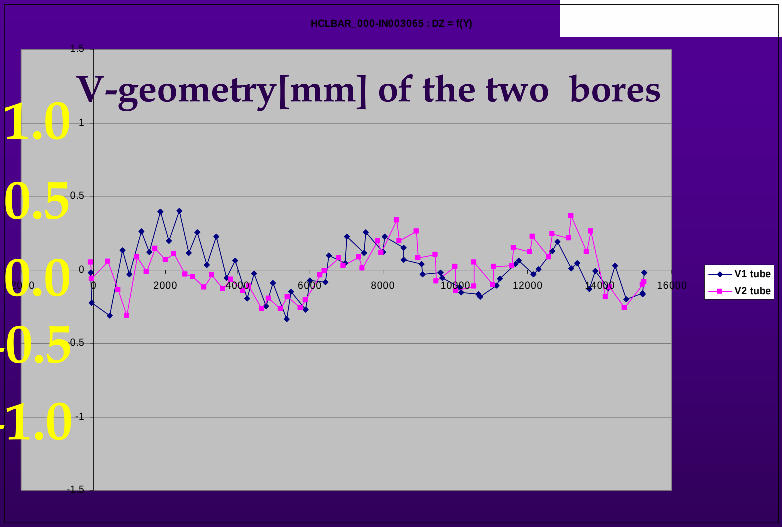
Geometry (3/4)

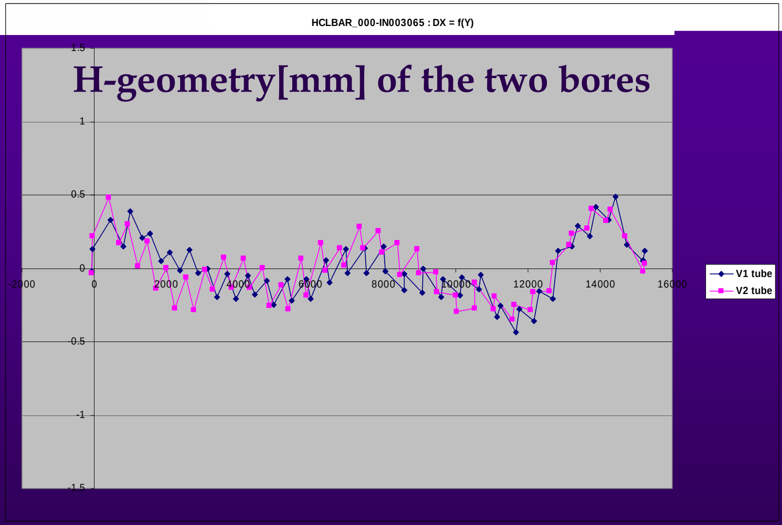
In practice …

The 2-in-1 LHC dipoles, 15 m long, are pre-bent to the nominal sagitta of 9mm, then …



1. 3D-measurement of the centers of the cold bore tubes in the two magnet apertures.
→ so-called "**mechanical axis**"
2. Best fit with two arcs of a circle with nominal radius of curvature and nominal separation
→ so-called "**geometrical axis" (GA)**
3. Projection of the mechanical axis geometry onto the GA





→ Case of a very good dipole ("golden MB ") with the H and V geometry within +/-0.5 mm along 15 m: candidate for critical slot in the LHC dispersion suppressors

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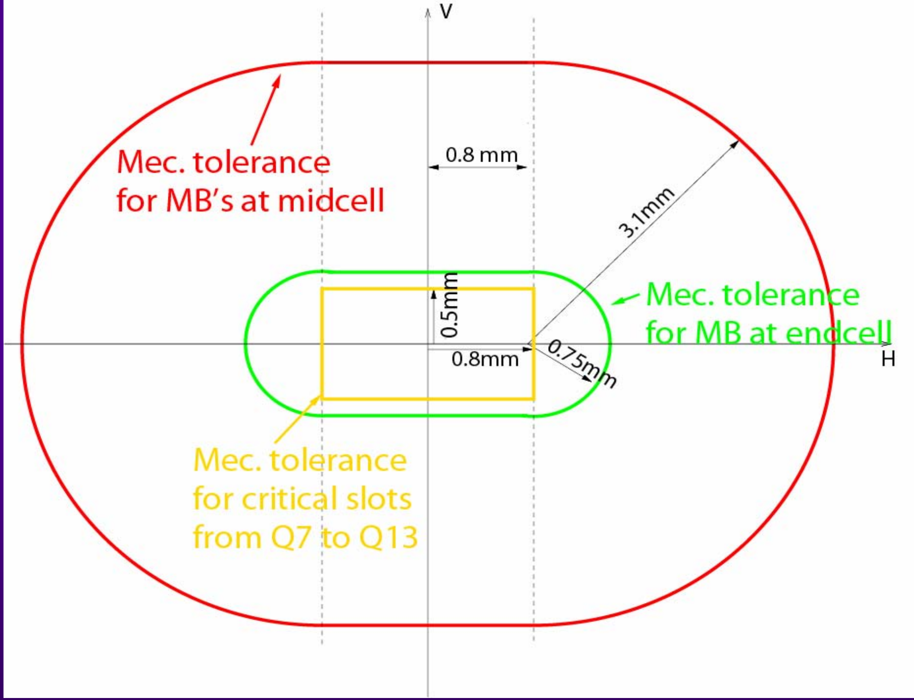
Geometry (4/4)

- Taking into account *operational margins* for linear optics distortion (C.O., β-beating,…), and requesting a *10σ beam clearance at injection* (corresponding to n1=7), the MB's can be split into *three different classes.*

  - → Mid-cell class for magnets with bad geometry to be installed at mid-cell (~30% of the available slots).
  - → Silver class for magnets with "standard" geometry suitable to any slot in the regular arc (~65% of the slots).
  - → Golden class for magnets with best geometry suitable to critical slots in the dispersion suppressors

    (required for ~5% of the slots).



→3 different set tolerances for 3 slot-dependent *machine requirements*

Field quality (1/4)

- Large systematic field error can only be cured by
  - → A Change of the magnet cross-section (2 changes of X-section done so far in 2001 and 2003).
  - → A careful readjustment of the LHC betatron tunes

    ($Q_{x,y}$~.28/.31 in the LHC at injection)
- On the contrary, the impact of out-of spec. random multipoles on the machine performance can be minimized by magnet sorting.
- Random multipoles are well within spec. except:
  - → The random b1(transfer function): on the border of its tolerance band.
  - → The random a1 (Field Direction) : only a few MB's showing a large FD, spread at random over the production.
  - → The random b3: due to the two changes of X-sections and the use of non-nominal shims in the early part of the production).

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Field quality (2/4)

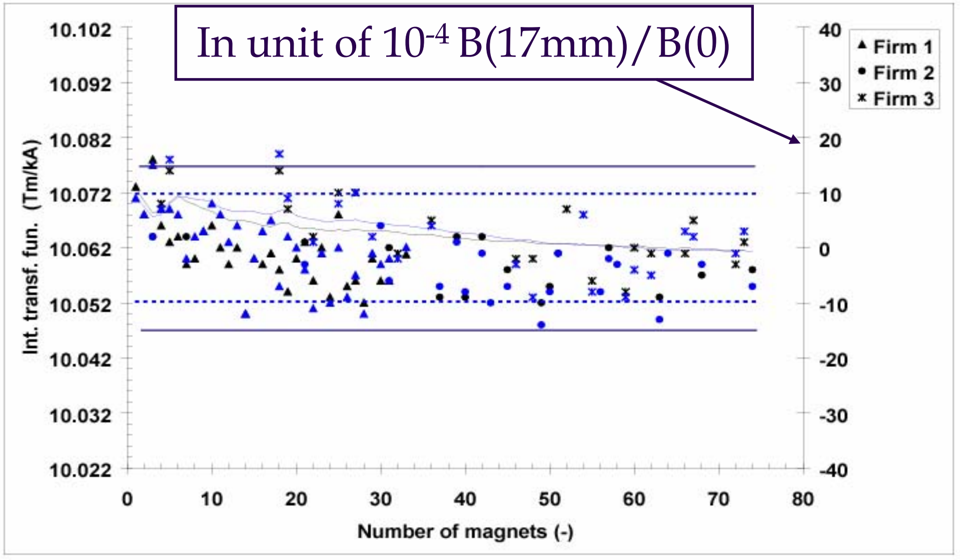
◆ Transfer Function at nominal (same constraints and sorting rules for the Field Direction)

→ Random b1 just within **the spec. of 8 units r.m.s.**

→ **Good correlation between aperture**

→ May degrade the reliability of a global orbit feed-back system foreseen for LHC: **too many MCB's possibly running out of strength at 7 TeV.**

→ The criteria is to control **the b1 running average at the level of each arc cell below 13 units** (corresponding to 40% of the MCB strength).



Integrated TF [Tm/kA] and b1 [units] measured at nominal on the first 70 LHC cryodipoles

→ **2 alarm levels** and corresponding **"TF flags"**

- **TF_0 flag when |b1| < 10 units → "blind installation"**
- **$TF_{\pm}$ when 10<b1<15 or –15<b1< –10 → with the rule that not more than 3 consecutive MB's can be installed with a TF_- or a TF_+**
- **TF! Flag when |b1| > 15 units → sorting on a case by case basis.**

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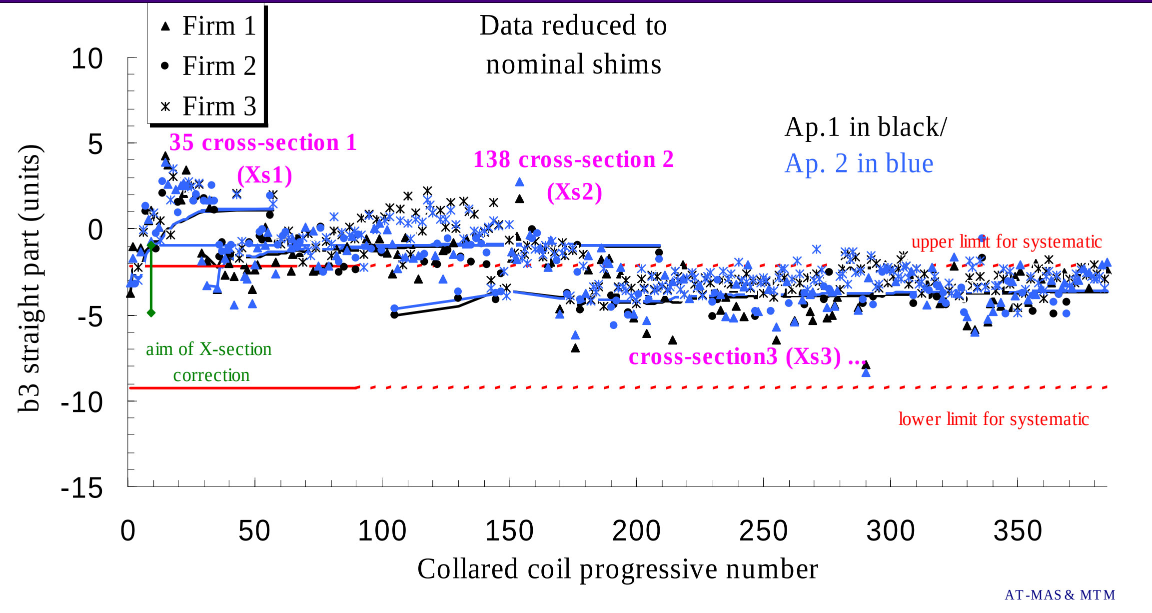
Field quality (3/4)

◆ Sextupole component b3 at injection

- The random b3 is the lowest order multipole impacting on **the LHC dynamic aperture at injection (→ keep <1.4 units r.m.s.)**
- **Mainly of geometric origin.**
- **Again, good correlation between aperture.**
- **Out of spec. in the first 2 sectors** (X-section change)
- Should just meet the AP target in the other sectors, but, is liable to change, **e.g. trends or punctual use of non-nominal shims.**



b3 harmonics [units] at warm (collared coils data)

→ **Sorting** following a **"flip-flop" scheme for the full machine**, i.e. equip two consecutive machine slots with MB's *i* and *i+1* such that

$$\mathbf{| b3^{(i+1)} + b3^{(i)} - 2 \langle b3 \rangle | \text{ is minimized}}$$

(with <b3> the average b3 compensated arc by arc by the dedicated sextupole spools for Q' correction)

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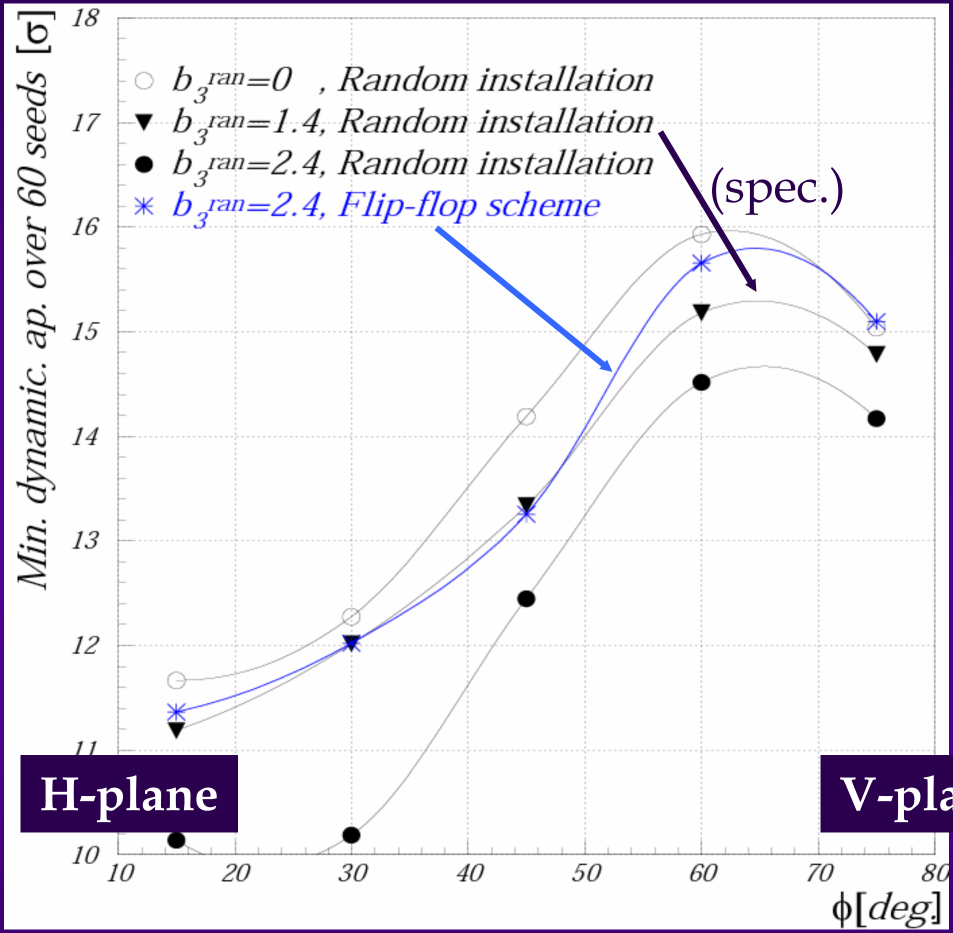
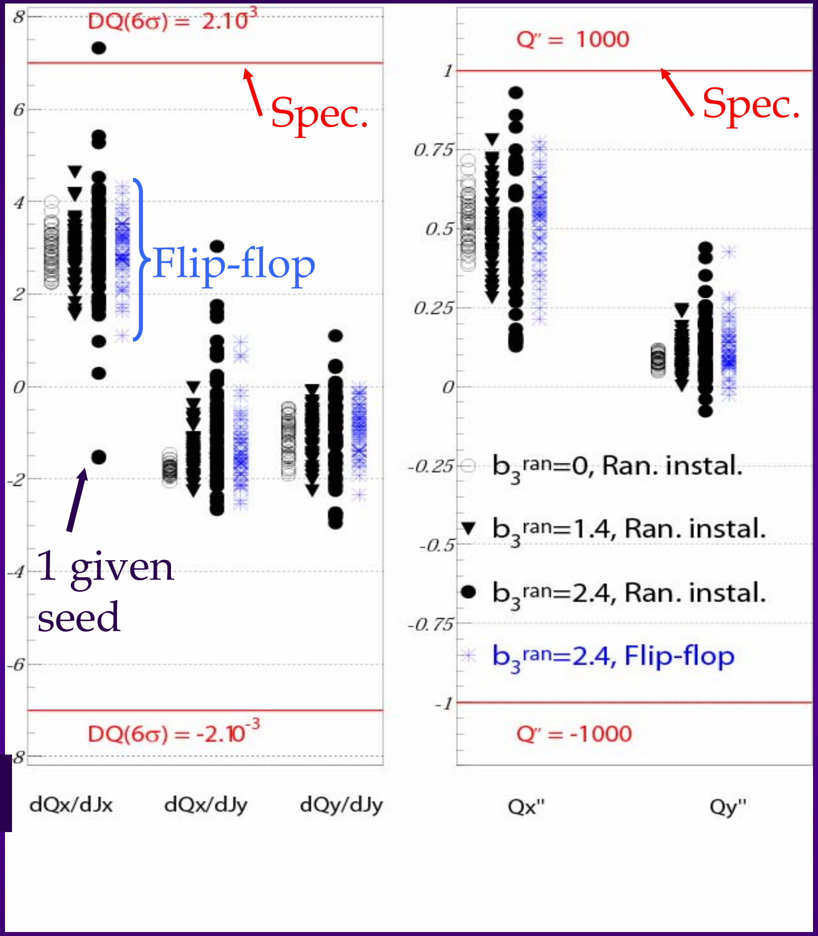
Field quality (4/4)



100'000 turns LHC dynamic aperture (DA) at injection versus phase space angle ϕ.



Detuning dQ/dJ and Q'' due to a3,b3 and b4 at injection. Statistics over 60 different seeds

➔ **The flip-flop scheme allows to stick to the target DA of 11.5 +/- 0.5 σ, even with a random b3 increased by 1 unit r.m.s. w.r.t. its initial specification.**

Summary & Conclusions (1/2)

- The first Priority is given to the dipole geometry
  - → 3 main classes to cope with 3 different categories of slots (DS, end-cell in the regular arc, mid-cell).
- The field quality is generally "second priority"
  - → Control of the b1 running average (Transfer function) at the level of each arc cell ("visual" sorting based on TF flag).
  - → Pairing the magnets with respect to b3 ("flip-flop" scheme)
- … and case by case sorting is performed for magnets exhibiting a non-optimal performance, hardware features or strong FQ anomalies, e.g.
  - Bad training memory → in general not install in the dispersion suppressors.
  - Temperature-sensor out of work → only one such MB allowed per arc cell and, depending on the tunnel slope, on the left or right side of the MQ's equipped with jumper.
  - …

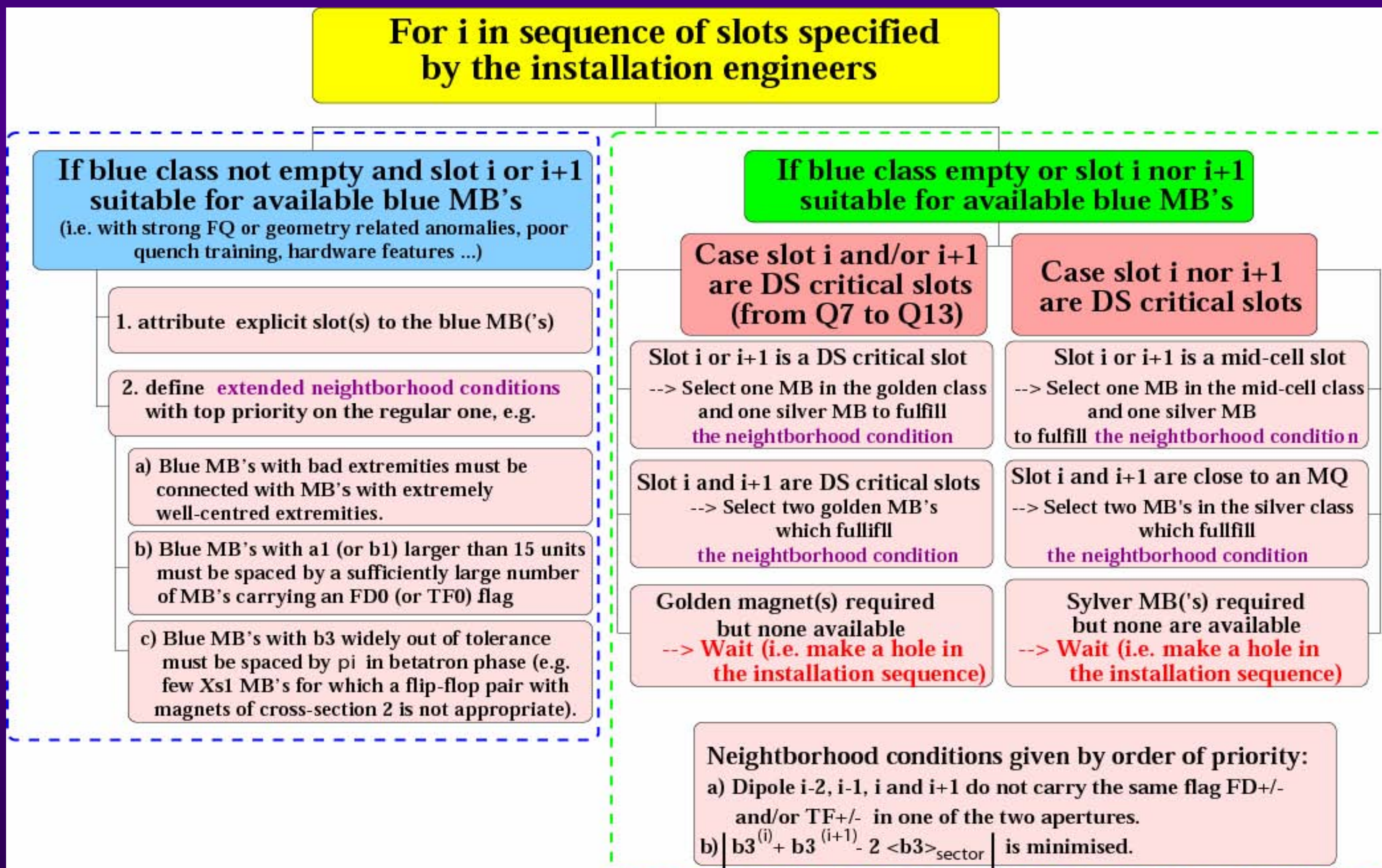
Summary & Conclusions (2/2)

- **With a batch of 10-20 MB's discussed at each session of the CERN Magnet Evaluation Board (MEB), this strategy allows to "digest" dipoles with non optimal FQ and geometry and to follow smoothly the LHC installation sequence.**

- **In the present context of a reduced cold measurement program (all MB cold tested but only 1/3 sampling cold magnetic measurement), the quality of the warm-cold correlation on b1/a1 and b3 is good enough to classify, flag and allocate the non-cold measured magnets [poster WEPKF008].**

Installation flow chart:

…Selecting the next two dipoles to be installed



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