

# High Luminosity LHC

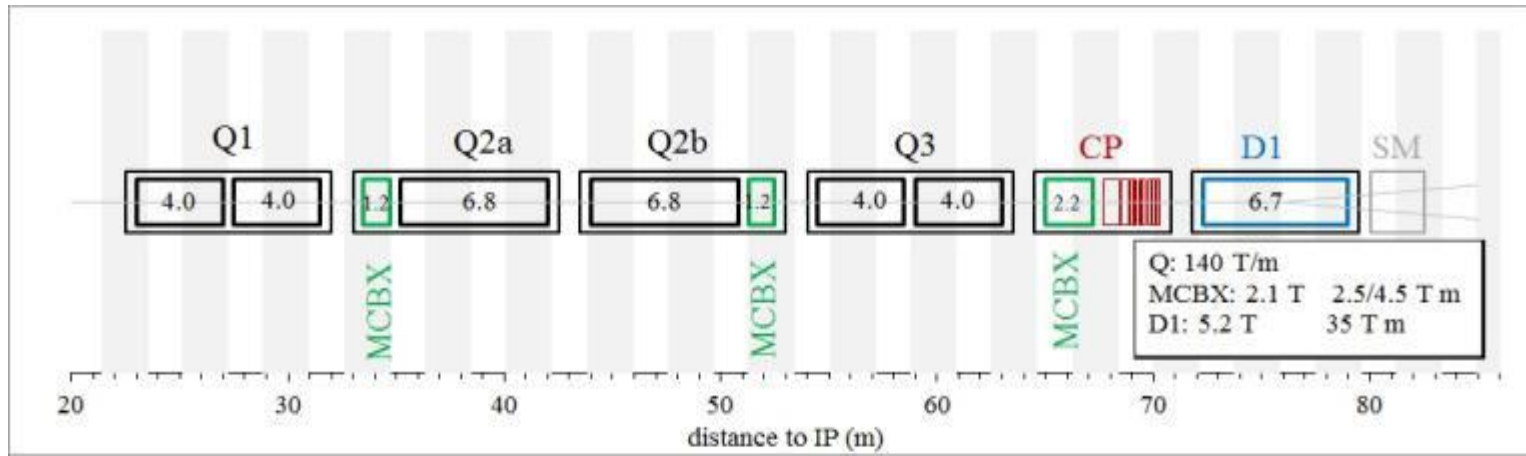
## Summary on WP2: what is frozen and what can change?

G. Arduini for WP2 Task Leaders and Collaborators

# Introduction

- Certainly not a detailed summary covering all the **important** contributions

# Triplets area: TAS, Q1-Q3, D1



HL-LHC triplet layout

E. Todesco

# Baseline layout (Triplet/D1)

Equipment name	Aperture type /ID (H/V) [mm]	BS aperture type / min ID <sup>(1)</sup> (H/V)	Magnetic length/length [m]	# apertures/ separation [mm]	Strength [T/m, T.m, MV,...]
TAS	Round/60	-		1/-	-
Q1a/b (MQXFA)	Round/150	Octagonal/>98/>98	4.002	1/-	140 T/m
MCBX2a (MCBXFBH/V)	Round/150	Octagonal/>118/>118	1.2	1/-	2.5 T×m
Q2a/b (MQXFB)	Round/150	Octagonal/>118/>118	6.792	1/-	140 T/m
MCBX2a (MCBXFBH/V)	Round/150	Octagonal/>118/>118	1.2	1/-	2.5 T×m
Q3a/b (MQXFA)	Round/150	Octagonal/>118/>118	4.002	1/-	140 T/m
MCBX3 (MCBXFBH/V)	Round/150	Octagonal/>118/>118	2.2	1/-	4.5 T×m

**(1) Including tolerances. Need to specify/demonstrate them!!**

# Baseline layout (Triplet/D1)

Equipment name	Aperture type / ID (H/V) [mm]	BS aperture type / min ID <sup>(1)</sup> (H/V)	Magnetic length/length [m]	# aperture/separation [mm]	Strength [T/m, T.m, MV,...]
a2 corr. (MCQ SX)	Round/150	Octagonal/>118/>118	0.716	1/-	1 T.m
b6 corr. (MCTX)	Round/150	Octagonal/>118/>118	0.339	1/-	8 T.m
a6 corr. (MCTS X)	Round/150	Octagonal/>118/>118	0.087	1/-	1 T.m
b5 corr. (MCDX)	Round/150	Octagonal/>118/>118	0.079	1/-	2 T.m
a5 corr. (MCDS X)	Round/150	Octagonal/>118/>118	0.079	1/-	2 T.m
b4 corr. (MCOX)	Round/150	Octagonal/>118/>118	0.137	1/-	4 T.m
a4 corr. (MCO SX)	Round/150	Octagonal/>118/>118	0.137	1/-	4 T.m
b3 corr. (MCSX)	Round/150	Octagonal/>118/>118	0.121	1/-	6 T.m
a3 corr. (MCSS X)	Round/150	Octagonal/>118/>118	0.121	1/-	6 T.m
D1 (MBXA)	<b>Round/150</b>	Octagonal/>118/>118	6.69	1/-	35 T.m

See M. Giovannozzi  
 No expected changes  
 provided triplet field quality  
 confirmed

**Changes since last HL-LHC/US-LARP meeting**

6.25 (E.Todesco-12/11/13) not yet in HLLHCv1.0

**Task 2.2 – M. Giovannozzi et al.**



# Triplet/D1

- Significant work has been done for the field and corrector specifications by CERN and collaborators (**US-LARP/SLAC**)
- Next steps:
  - Consolidate error tables (e.g. new D1 error table based on dynamic aperture estimates)
  - Clarify fringe field effects
  - Impact of latest version of the lattice (HLLHCv1.0)
  - Iterate as soon as magnetic measurements available

# Recommended target for D1 field quality

Reduce b7m and b9m a factor of 2 relative to D1\_errortable\_v1.

skew	mean	uncertainty	random	normal	mean	uncertainty	random
a2	0	0.679	0.6790	b2	0	0.200	0.200
a3	0	0.282	0.2820	b3	-0.9	0.727	0.727
a4	0	0.444	0.4440	b4	0	0.126	0.126
a5	0	0.152	0.152	b5	0	0.365	0.365
a6	0	0.176	0.176	b6	0	0.060	0.060
a7	0	0.057	0.057	b7	0.4 → 0.2	0.165	0.165
a8	0	0.061	0.061	b8	0	0.027	0.027
a9	0	0.020	0.020	b9	-0.59 → -0.295	0.065	0.065
a10	0	0.025	0.025	b10	0	0.008	0.008
a11	0	0.007	0.007	b11	0.47	0.019	0.019
a12	0	0.008	0.008	b12	0	0.003	0.003
a13	0	0.002	0.002	b13	0	0.006	0.006
a14	0	0.003	0.003	b14	0	0.001	0.001
a15	0	0.001	0.001	b15	-0.04	0.002	0.002

# Triplets-D1 beam screen heat load

- The various contributions to power deposition have been estimated:
  - from luminosity debris (WP10: F. Cerutti, L. Esposito)
  - from electron cloud (G. Rumolo, G. Iadarola).  
Countermeasures will be applied, namely nanographite coating and possibly clearing electrodes but some margin kept (assumed SEY of 1.1) for possible scrubbing and potential limits on the minimum SEY
- from impedance (B. Salvant)
- Necessary input for cryogenics design

# Triplet beam screens (impedance)

B. Salvant

- Expected from theory, accounting for the weld on the side and magneto-resistance, accounting for factor 2 in addition (**could be worst case for 2 beams in same aperture, pessimistic**). Not yet accounting for the change of impedance linked to the transverse position inside the triplets

Power loss for 2 beams in mW/m Nominal bunch length	Nominal (25 ns)	ultimate (25 ns)	HL-LHC (25 ns)	HL-LHC (50 ns)
# bunches $N_b [10^{11} \text{ p}]$	2808 1.15	2808 1.8	2808 2.2	1404 3.5
Q1 BS (nominal)	563	989	2060	2610
Q2/Q3 BS (nominal)	445	781	1630	2060
Arc BS	290	509	1060	1350
Q2/Q3 BS (HL-LHC)	189	332	693	877
Q1 BS (HL-LHC)	157	276	575	728

- Large aperture pays off

# Total heat load on the triplet beam screen

Bunch intensity is larger but also chamber is wider. For the **same SEY**:

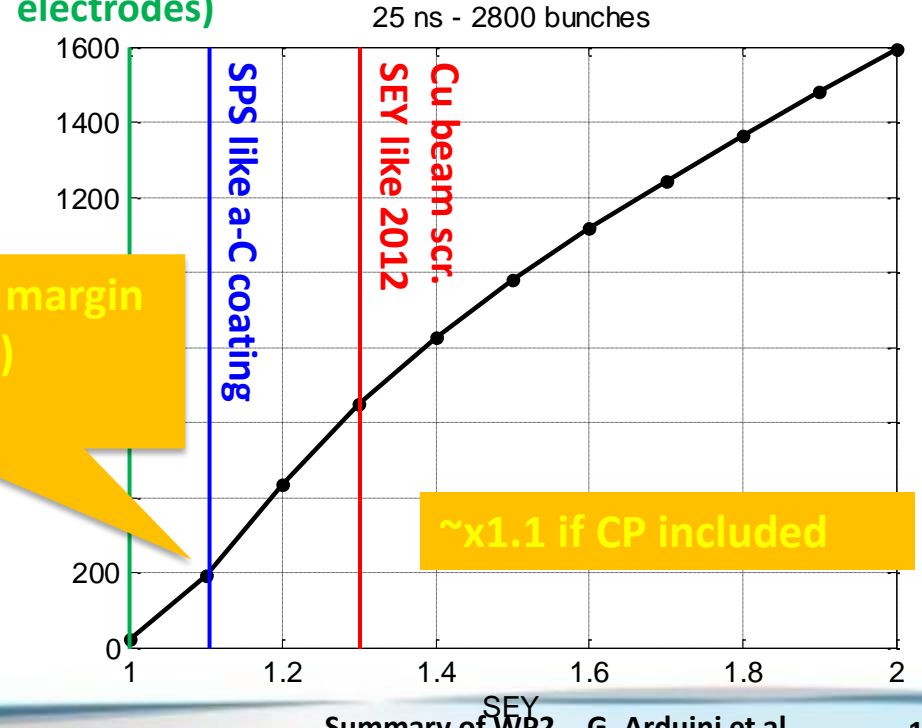
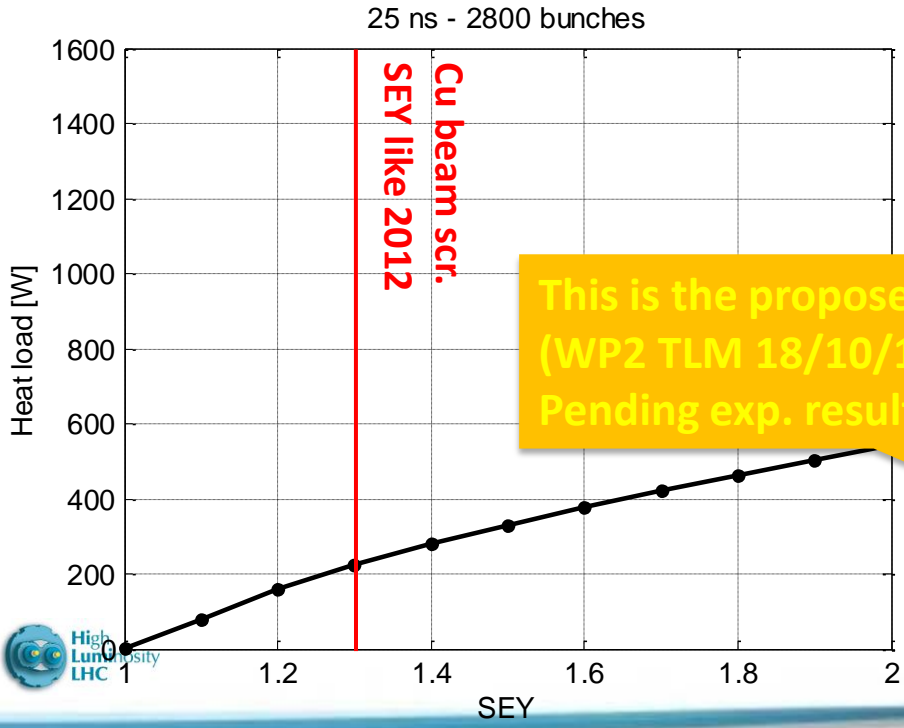
- energy of multipacting electrons is quite similar
- number of impacting electrons about x2 larger
- Total **heat load about x2 larger**

**Already planned (nanographite) and possibly clearing electrodes**

**Present triplets ( $1.15 \times 10^{11}$  p/b)**

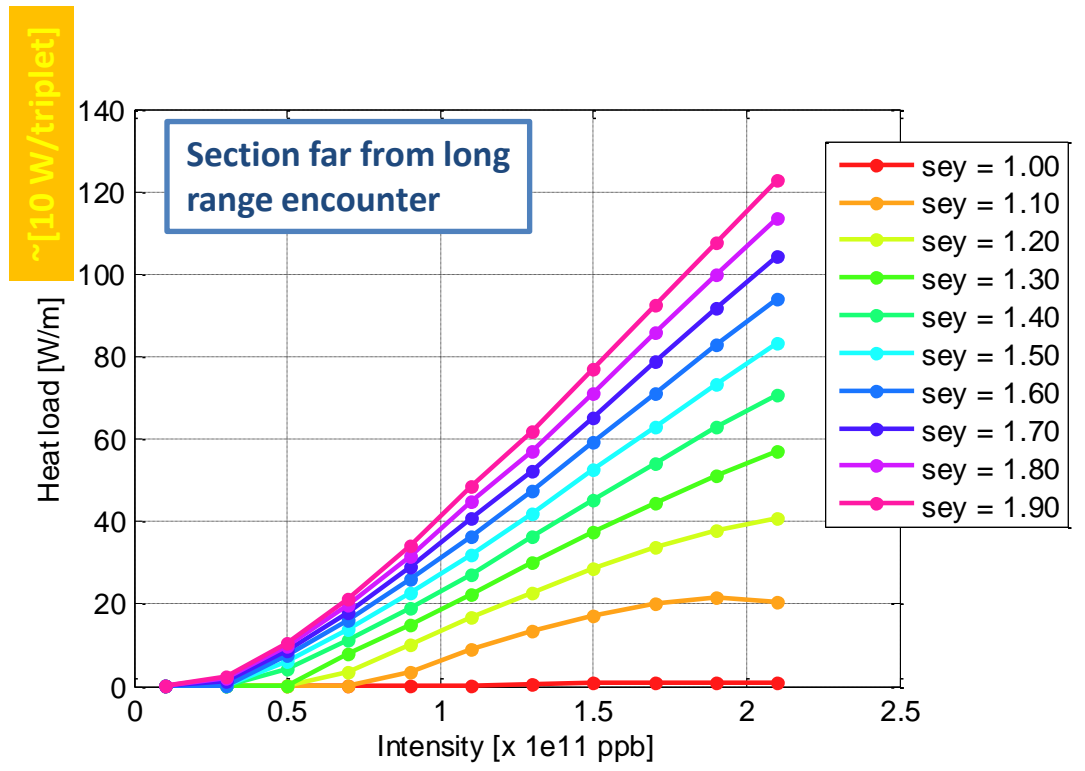
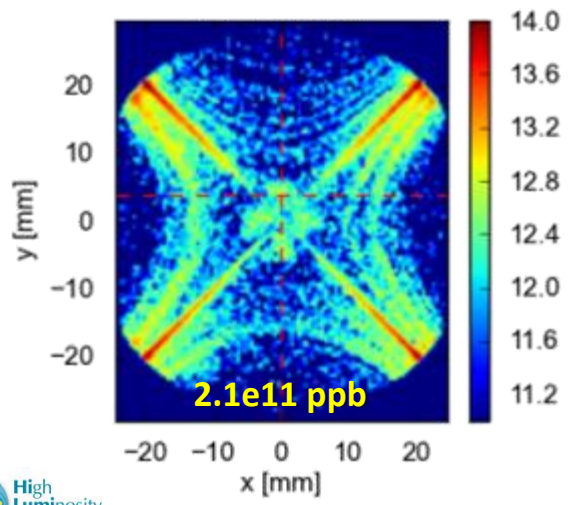
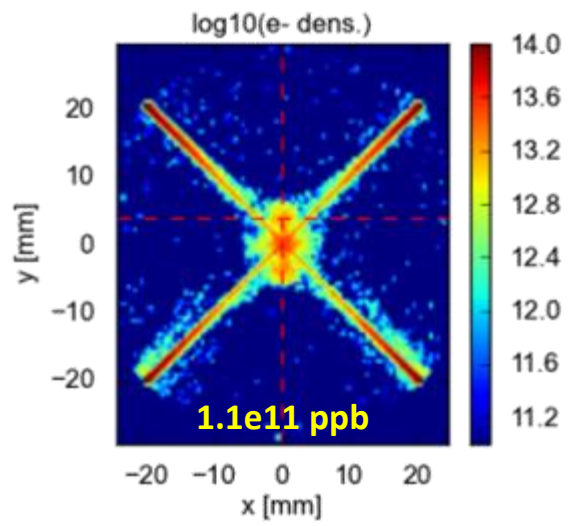
**Full suppression (SEY $\approx$ 1 or clearing electrodes)**

**HiLumi triplets –  $2.2 \times 10^{11}$  p/b**




Inner triplets in IP2 and IP8 will still have the **present design**:

- Increase bunch intensity leads to more than **x2 larger heat load**
- e-cloud **suppression strategies needed** also also on these magnets **Planned?**



# Triplet/D1

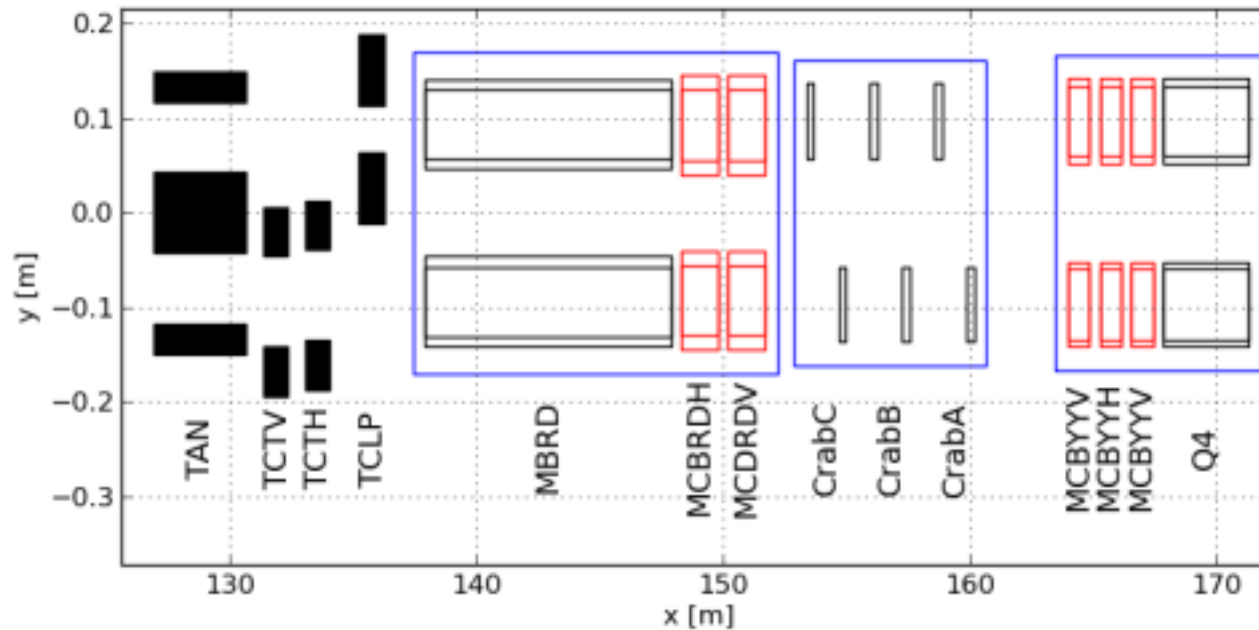
- Ground motion in IT/D1 area (<10s):
  - effect on orbit negligible in the range <10 s
  - Need to evaluate movements of the cold masses w.r.t. ground
  - effect on emittance blow-up
- BPM resolution:
  - Realistic values of few  $\mu\text{m}$  are to be expected
  - Need  rion?
  - Is lu
- Misalignment Correction:
  - Alignment errors in the range of 0.5 mm tolerable
- Tolerances on powering of the IT:
  - Implications of the new triplet powering scheme being addressed
  - Is the ripple correlated in phase via the mains
  - Need interaction with WP6 (power converters) - started



# What can change?

- TAS aperture:
  - Possible request to reduce aperture. To be investigated but motivation to be clarified → WP8
- The dipole correctors will be further studied to assess whether their strength is optimal for ensuring the performance reach of HL-LHC. In particular:
  - Tests of orbit correction performance under different conditions, including margins for IP displacement.
  - Assessment of required optics flexibility as it impacts on the performance of the orbit correctors.

# Matching section




R. De Maria

# Baseline layout

*Italics: to be finalized*

Equipment name	Aperture type /ID (H/V) [mm]	BS aperture type / min ID (H/V)	Magnetic length/length [m]	# aperture/separation [mm]	Strength [T/m, T.m, MV,...]
TAN (TAND)	<i>Elliptical/82/74</i>	-	3.7	2/145	-
D2 (MBRD)	Round/105	<i>Rectell./82/64 (H)</i>	10	2/186	35 T.m
MCBRDH	Round/105	<i>Rectell./82/64(H)</i>	1.5	2/194	7 T.m
<b>~4.7 T. Feasible?</b>					
MCBRDV	Round/105	<i>Rectell./82/64(H)</i>	1.5	2/194	7 T.m
Crab-cavities	<i>Round/84</i>	-	~0.4	2/194	12.5 (3 cavities) <sup>(1)</sup>
<b>Needed?</b>					
MCBYYH	Round/90	<i>Rectell./74/64(HV)</i>	0.9	2/194	3.2 T.m
MCBYYV	Round/90	<i>Rectell./74/64(HV)</i>	0.9	2/194	3.2 T.m
Q4 (MQYY)	Round/90	<i>Rectell./74/64(HV)</i>	3.5	2/194	125 T/m
<b>Longer MQY in HLLHCv1.0</b>					
<b>LHC nominal</b>					

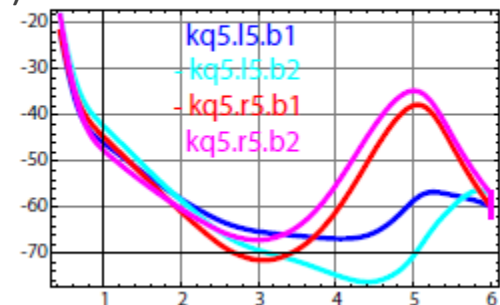
 New baseline with 4 crab cavities (01/11/2013) with 3.5 MV/cavity not yet included in HL-LHCv1.0

# Matching section

- D2:
  - Significant improvement in expected field quality (thanks to WP3!) but improvement is still necessary in particular for b2 and b3 → WP3
  - Need to agree on another version of the table. Interest to shorten D2 (higher field) compatibly with field quality (**assessment of impact on DA at SLAC has been vital**).
- Q5:
  - Three options considered:
    - 2 MQY
    - MQY at 200 T/m if operated at 1.9K (but this might be at the limit)
    - 2 MQYY
  - Energy deposition for Q5 with 70 mm aperture to be done
  - Optics constraints to be fully evaluated
- Q6:
  - Can we get the required gradient for at 4.5 K? Too tight? At 1.9 K?

M. Korostelev

Q5, [% of 160 T/m]



# Matching section: Heat load

L. Esposito, F. Cerutti

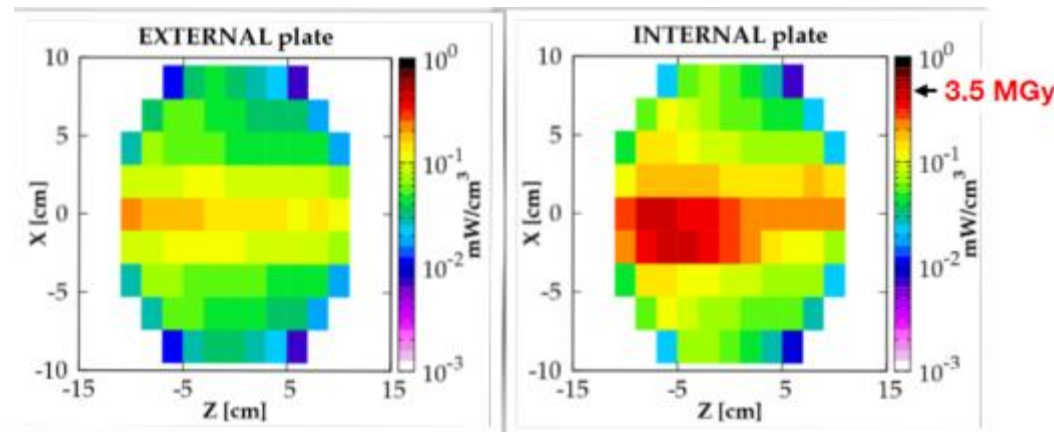
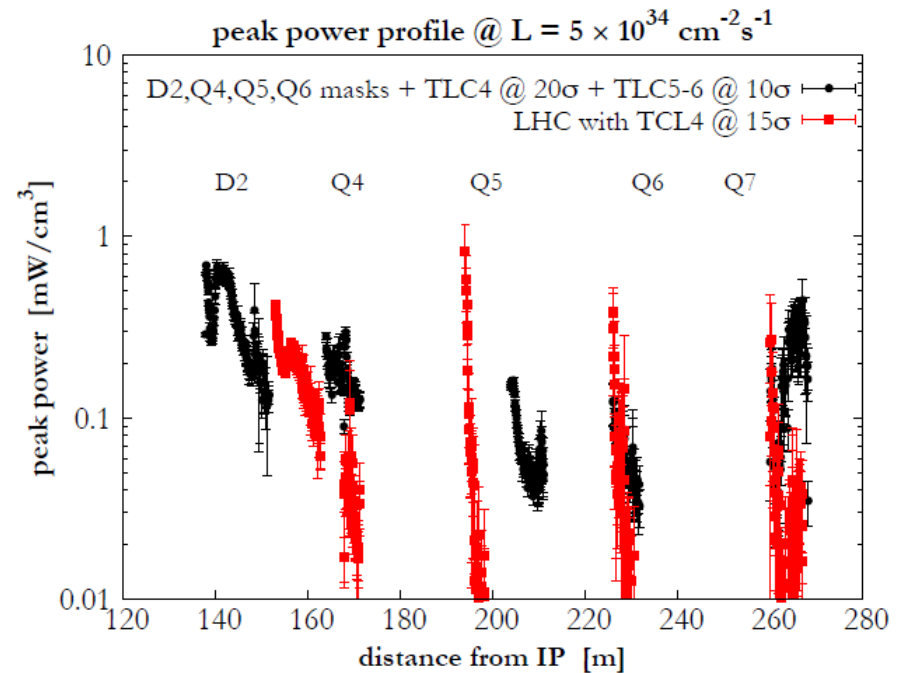
- Energy deposition due to debris well advanced. We have a viable scenario (thanks to WP10!) to be confirmed with 70 mm aperture MQY or double MQY → WP10

- Contributions from

- Impedance
- E-cloud

Need to be assessed once beam screen type/dimension are finalized

- Same e-cloud countermeasures as for triplet should be foreseen/studied



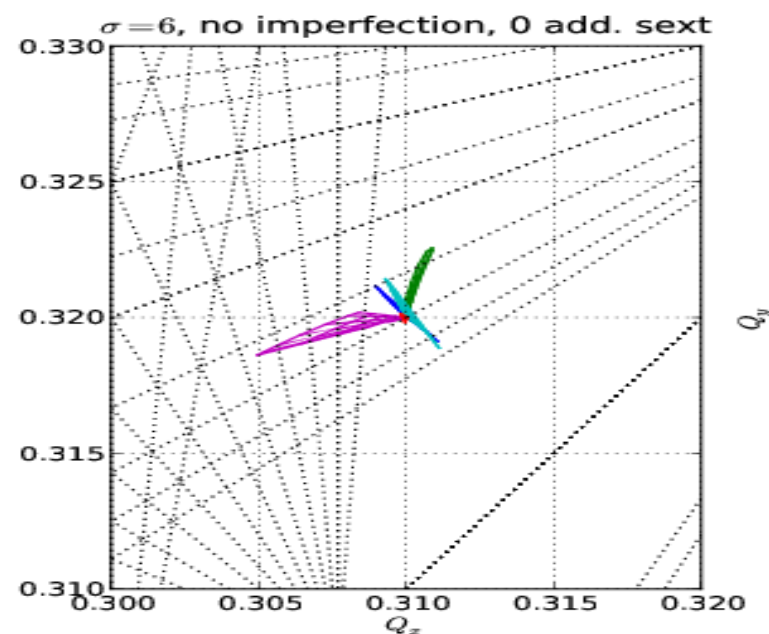
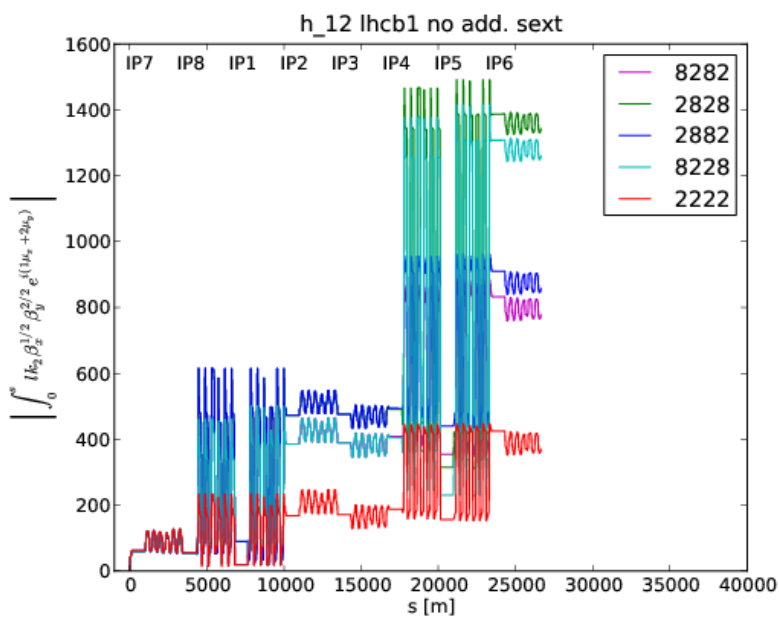
# Others

- Need to confirm field quality requirements constraints with latest optics version HLLHCv1.0 (do not expect significant changes) once latest update of D1 and D2 tables agreed
- Need to confirm field quality requirements at injection

# Arc45-56, 81-12 additional sextupole

**MS in Q10**<sup>(1)</sup> by replacing an MCBC with and MSCB (at least 4 defocusing MS in Q10 in Arc 12, 56 Beam 1 and Arc 81, 45 Beam 2, but beneficial for  $\beta^*$  reach in the other Plane/ Beams):

- needed for 3<sup>rd</sup> resonance compensations in ATS regime, 11  $\sigma$   $\rightarrow$  8  $\sigma$  DA losses<sup>(2)</sup> without HL-LHC new element imperfection to be re-evaluated with realistic magnetic imperfections and beam-beam.



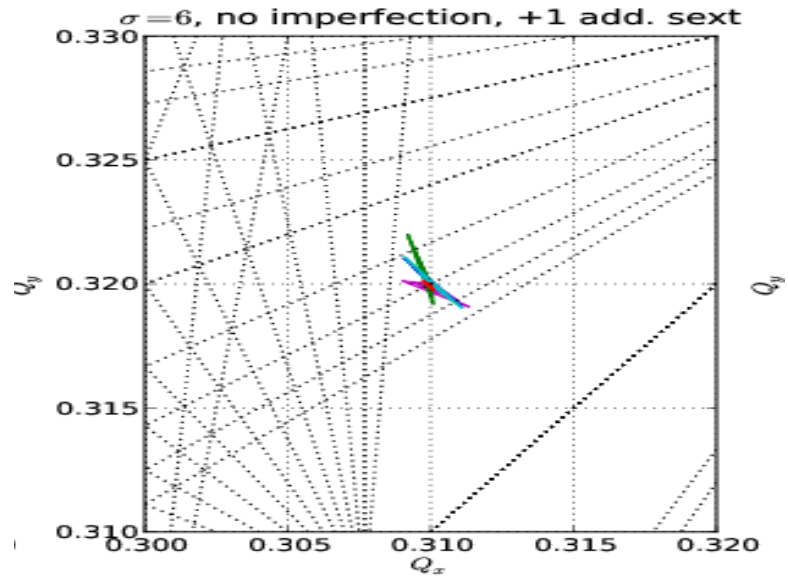
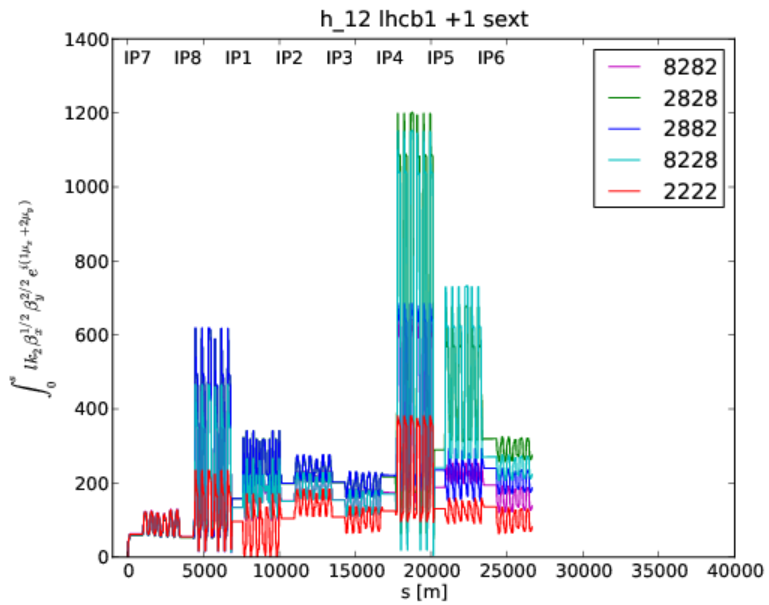
1) S. Fartoukh, SLHC Pr. 49  
 2) R. De Maria, S. Fartoukh, SLHC Pr. 50



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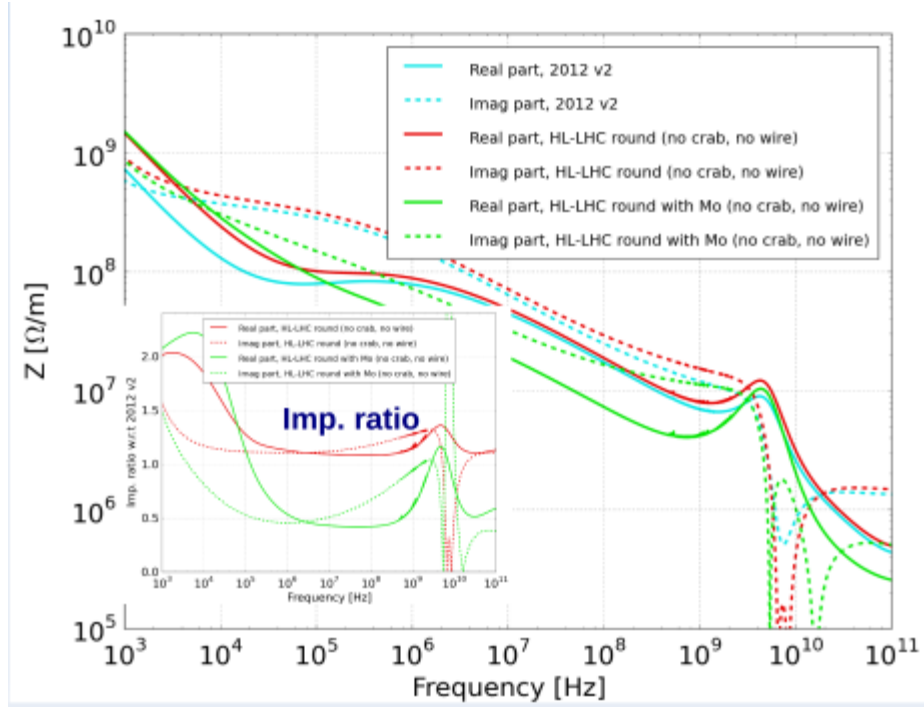
- needed for 3<sup>rd</sup> resonance compensations in ATS regime, 11  $\sigma$   $\rightarrow$  8  $\sigma$  DA losses<sup>(2)</sup> without HL-LHC new element imperfection to be re-evaluated with realistic magnetic imperfections and beam-beam.



...and we should not forget that we need 2 new Q5 in IR6

# Impedance

- Model with increasing level of detail!!
- Mo/Gr collimators will help in reducing significantly the impedance → study/implementation to be pursued
- Geometric impedance is not negligible (thanks INFN-LNF!!) need to be kept under control



Impedance Increase due to BPM Cavity

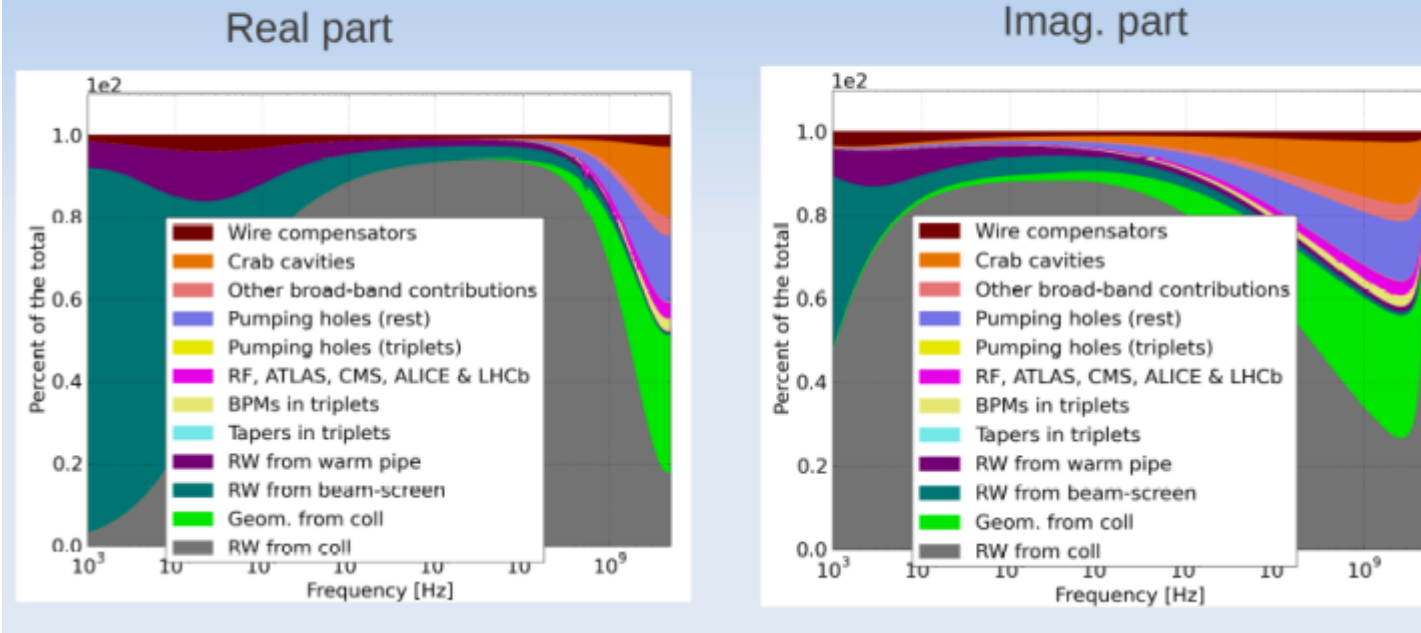
The transverse effective impedance is estimated to be about 20% higher

	With BPM cavity	Without BPM cavity
Half gaps (mm)	$k_1$ [V/Cm]	$k_1$ [V/Cm]
1	$3.921 \cdot 10^{14}$	$3.340 \cdot 10^{14}$
3	$6.271 \cdot 10^{13}$	$5.322 \cdot 10^{13}$
5	$2.457 \cdot 10^{13}$	$2.124 \cdot 10^{13}$

M. Zobov, O. Frasciello, S. Tomassini (INFN)

# Impedance and its effects

- Vertical dipolar impedance:

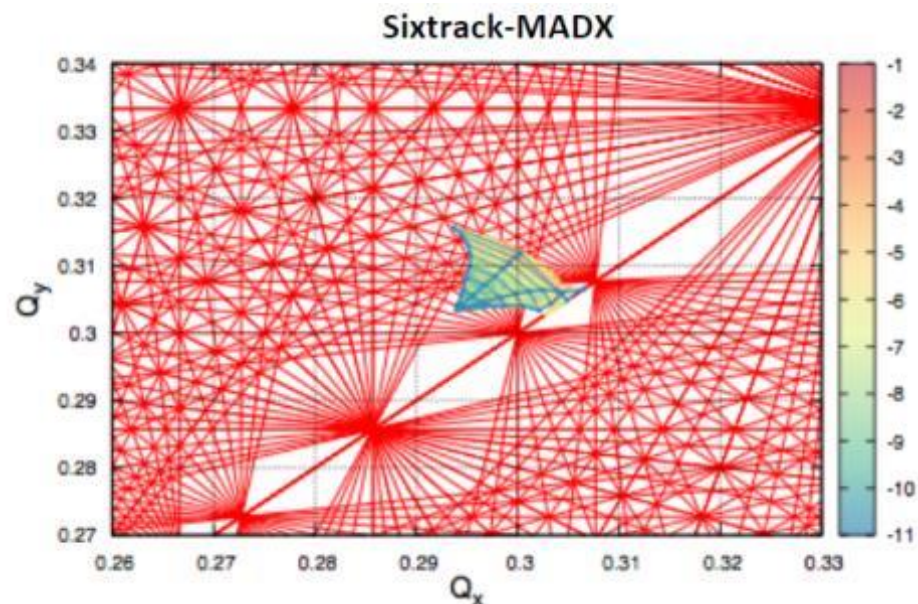
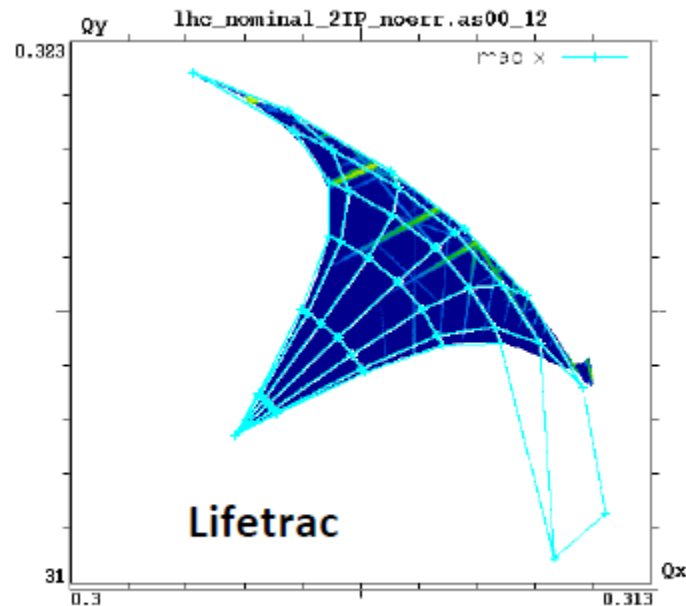


- Need to address/assess more precisely:
  - Crab cavities (in particular if we have 4 of them)
  - Triplet BPMs
  - BBLR
- Need to translate these estimates in Beam Stability limitations → next to come

# Beam-beam

- We have an impressive list of tools to estimate the various beam-beam effects!!
- Priority must be given now to:
  - Benchmark the models against:
    - simple formulas
    - **observables** (emittance blow-up, luminosity lifetime, PACMAN effects) → we have plenty of data from LHC!
  - Detailed work absolutely necessary!!
  - Need to do that before considering more complicate schemes (BBLR, crab kissing)!!
- Emittance blow-up, tails, losses are likely more adequate observables to guide us in the qualification of the beam-beam effects

We need to simulate and to **measure** them reliably



# Alternative scenarios

	HiLumi baseline	Proposed layouts v1	Proposed layouts v2
Q4	MQYY, G=125 T/m @1.9K Ø = 90 mm, L = 4.5 m	MQYY, G=125 T/m @1.9K Ø = 90 mm, L = 3.5 m	MQYY, G=125 T/m @1.9K Ø = 90 mm, L = 3.5 m
Q5	MQYL, G=160 T/m @4.5K Ø = 70 mm, L = 4.8 m	MQYL, G=160 T/m @4.5K Ø = 70 mm, L = 4.8 m	MQYL, G=160 T/m @4.5K Ø = 70 mm, L = 4.8 m
Q6	MQML, G=160 T/m @4.5K Ø = 56 mm, L = 4.8 m	MQYL, G=160 T/m @4.5K Ø = 70 mm, L = 4.8 m	MQML, G=160 T/m @4.5K Ø = 70 mm, L = 4.8 m
Q7	2×MQM, G=200 T/m @1.9K Ø= 56 mm, L = 3.4 m	2×MQM, G=200 T/m @1.9K Ø= 56 mm, L = 3.4 m	2×MQM, G=200 T/m @1.9K Ø= 56 mm, L = 3.4 m
Q7+		2×MQM, G=200 T/m @1.9K Ø= 56 mm, L = 3.4 m	2×MQM, G=200 T/m @1.9K Ø= 56 mm, L = 3.4 m

- possibility to reduce crab cavity voltage by 20% (rounds optics)
- possibility to gain lattice flexibility in collision
- Q5 apertures below the n1 limit for flat beams

Look more at:

⇒ Transition optics

⇒ High  $\beta^*$  > 5 m optics (inj, vdm)

with 1×MQ(M) + 2×MQTL instead of 2×MQM for Q7+

# Conclusions

- We are now in the phase where we are consolidating and detailing the nominal layout (optics, stability) but also the nominal parameters (collective effects). May be less exciting work than inventing new scenarios but Important work and will require frequent iterations

- Alternative/enhancement scenarios:

- 200 MHz
- Crab kissing
- Long range wire compensator
- ....

will be investigated in parallel (but with priority on nominal scenario) in order to come out with (possibly one) alternative/enhanced solution

# Conclusions

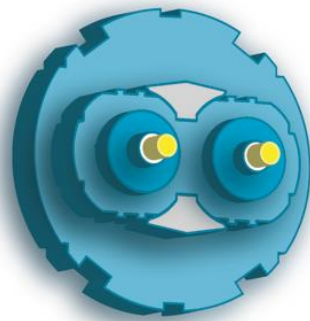
- Parameters for the triplet/D1 and correctors are stabilizing for the presently known magnet field quality (and length...) but it will be important to iterate to include properly fringe field effects and measurement results
- Matching section still has some open points:
  - D2,Q5 in particular
  - Finalization requires:
    - D2 field error analysis and impact
    - completing the analysis of the optics transitions

# Conclusions

- Review of LHC & Injector Upgrade Plans (RLIUP) was useful/took quite some effort to:
  - develop intermediate scenarios
  - re-assess previous scenarios (flat-beams)
  - sketch new options (200 MHz)
- Pile-up limitation is certainly making the HL-LHC goals quite challenging. We should make sure that margins are sufficient to allow operation at higher luminosity (in the experiments and the machine)

- I would like to acknowledge here the invaluable contributions of:
  - CERN colleagues
  - European Institutions (CEA, CI, CSIC, DESY, EPFL, INFN-LNF, STFC, UNILIV, UNIMAN)
  - KEK
  - US-LARRP (FNAL, LBNL, SLAC)

Accelerator Physics studies are part of the Risk Reduction!!!



# High Luminosity LHC



The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.



# Recommended target for D2 field quality

- 1) Use D2\_errortable\_v4 and further reduce b3m a factor of 2.
- 2) Minimize the b2 term or compensate its impact on beta function. Correction options are not yet decided, but may include adjustment of Q4 gradient or D2 spool-piece correctors.

skew	mean	uncertainty	random		normal	mean	uncertainty	random
a2	0	0.679	0.6790		b2	±25	2.5	2.5
a3	0	0.282	0.2820		b3	<b>3.0→1.5</b>	1.5	1.5
a4	0	0.444	0.4440		b4	±2.0	0.2	0.2
a5	0	0.152	0.152		b5	-1.0	0.5	0.5
a6	0	0.176	0.176		b6	0	0.060	0.060
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a14	0	0.003	0.003		b14	0	0.001	0.001
a15	0	0.001	0.001		b15	0	0.002	0.002

