Aperture calculations and tolerances

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With essential input from
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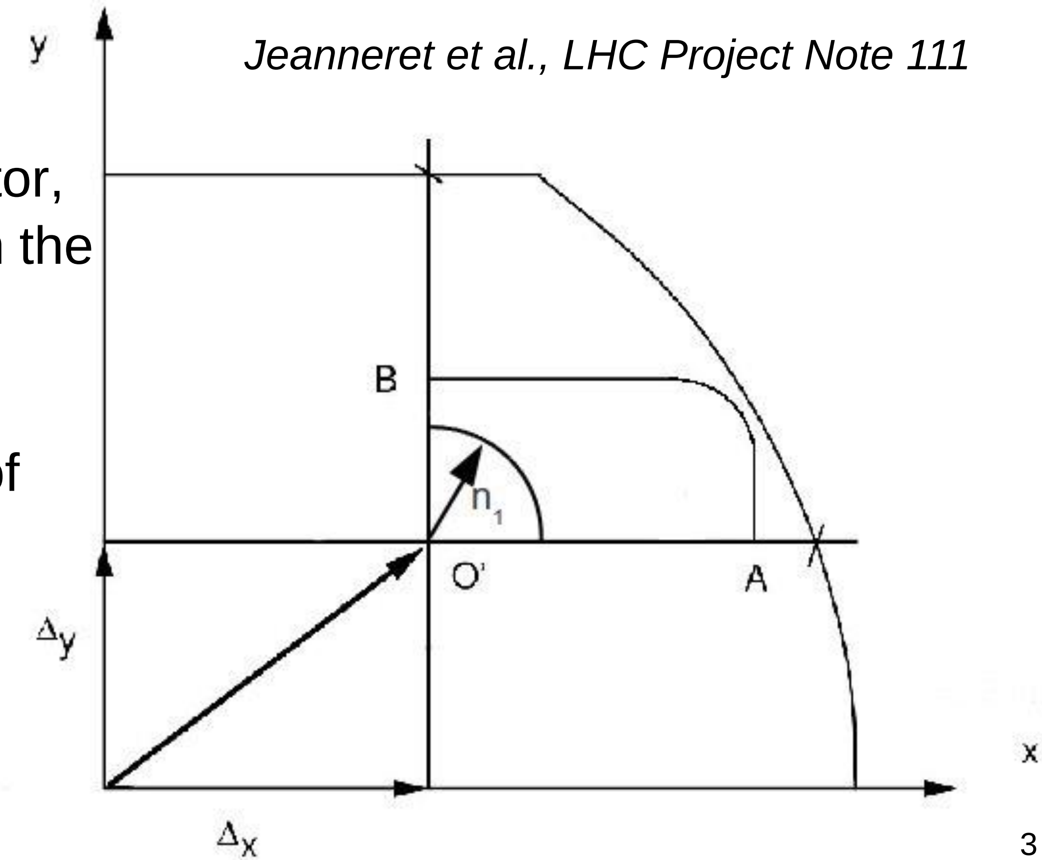
Outline

- Review of traditional method for aperture calculations – n1 model
- Run 1 experience and evolution of β*
  - Proposal for updated parameters in n1 calculation
- Comparison between n1 model and aperture measurements from Run 1
- Application to HL – work in progress
- Summary

n1 model

- Available aperture limits the reach in β* and constrains freedom of optics design. Insufficient aperture margin => risk for beam dumps, quenches or in worst case damage
- During LHC design, n1 model used to calculate apertures and qualify them for cleaning
- n1 (locally) is the largest opening of the primary collimator, in units of betatron σ, for which the local aperture is still protected from the secondary halo
- Numerically: assumed shape of secondary halo moved and rescaled according to various errors and tolerances
- Aperture qualified if n1>7

Jeanneret et al., LHC Project Note 111



Design tolerances

- Some design tolerances for top energy, in experimental IRs

Parameter	Value	Unit
Primary halo extension	6	σ
Secondary halo extension, hor./ver.	7.3	σ
Secondary halo extension, radial	8.4	σ
Normalized emittance ϵ_n	3.75	μm
Radial closed orbit excursion x_{co}	3	mm
Momentum offset δ_p	8.6×10^{-4}	–
Fractional beam size change from β-beat k_β	1.1	–
Relative parasitic dispersion k_D	0.27	–

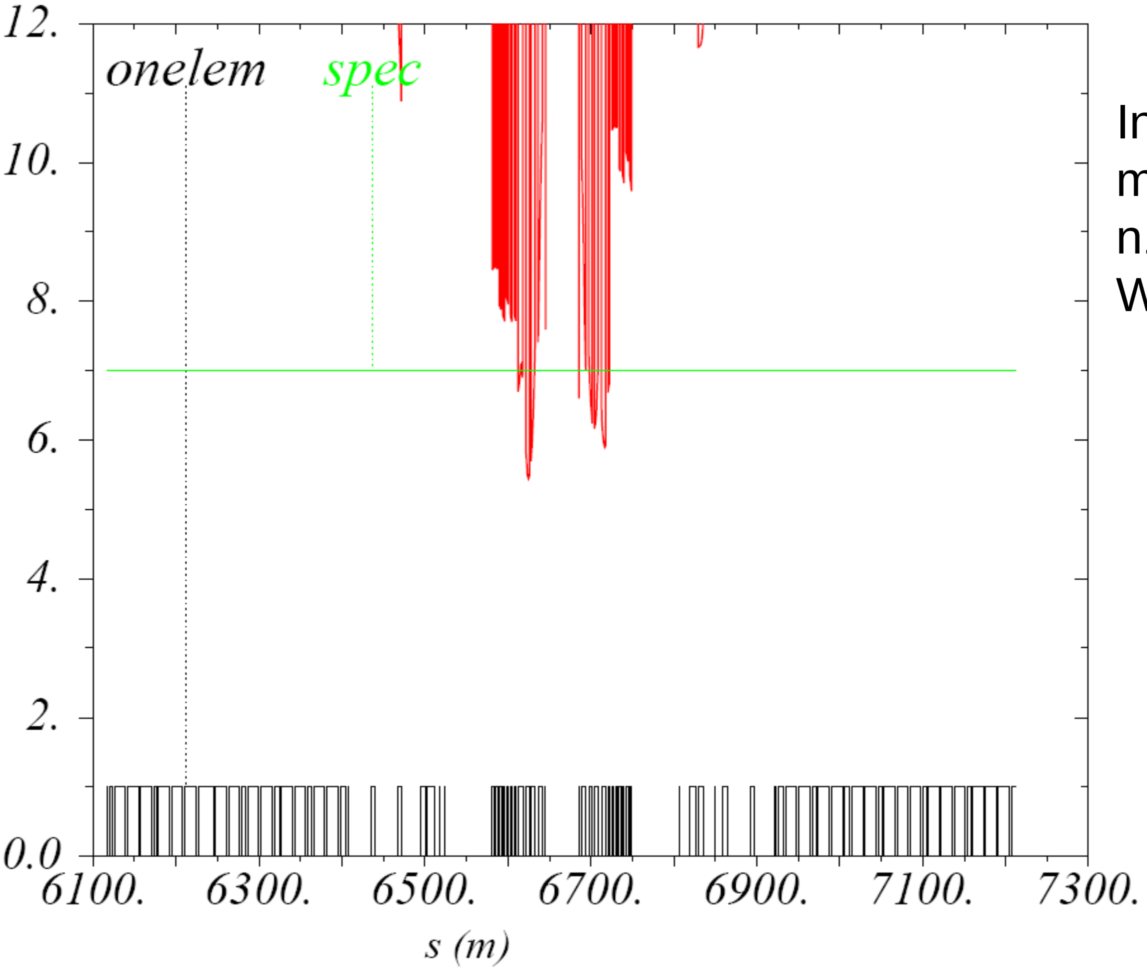
- Full parameter lists can be found in LHC design report
- Worst case scenario – tolerances added linearly

Run 1 experience

- Started with conservative approach 2010 : **β*=3.5m**
  - to give space for increased operational tolerances and
  - guarantee that tertiary collimators are not damaged during async dumps
- 2010: First local aperture measurements with beam in IR1/5 triplets (at injection) showed a very well aligned machine, better than foreseen
  - Together with a new model for calculating the collimator hierarchy, the available aperture allowed **β*=1.5m** in 2011. Aperture scaled.
- 2011: First aperture measurements in IR1/5 with squeezed optics allowed further reduction to **β*=1.0m**
- 2012: **β*=0.6m** with tight collimator settings and further improvements of the collimation hierarchy models
- **Progressive evolution of performance** based on measurements and OP experience coupled with better models of collimation hierarchy. Aperture measurements in physics crucial part!

n1 for 2012 physics conditions

- Using the design tolerances, n1=4.9 or n1=5.4 depending on whether vacuum markers used. **Significantly below n1=7**!



In reality, from aperture measurements we had n1 of about 9.
What is different?

Differences wrt OP case

- n1 method assumes all errors add linearly. Not likely when considering single limiting elements (IR triplets)
- Different collimator settings
  - n1 halo shape assumption not accounting for off-momentum tail and leakage of primary halo past secondary collimators
  - Machine protection constraints = > n1=7 not adequate as qualifying condition
  - Better to consider directly the aperture in units of σ and conceptually easier
  - slightly smaller emittance (3.5µm vs 3.75µm) used to position collimators
- Orbit, off-momentum component and β-beat – following slides
- All in all, significant gain in aperture compared to design assumption. Roughly half from off-momentum component, other half from orbit and β-beat (see following slides)
  - Gain used to squeeze β* and to compensate for increased collimation margins for machine protection

Optics errors

- Factor ~3 better optics correction at end of Run 1 than foreseen (R. Tomas et al.) Achieved peak β-beat of 7%

RECORD LOW β BEATING IN THE LHC — Phys. Rev. ST Accel. Beams **15**, 091001 (2012)

TABLE III. rms and peak β- and $D_x/\sqrt{\beta_x}$-beating values at $\beta^* = 0.6$ m for the virgin machine and after local and global corrections.

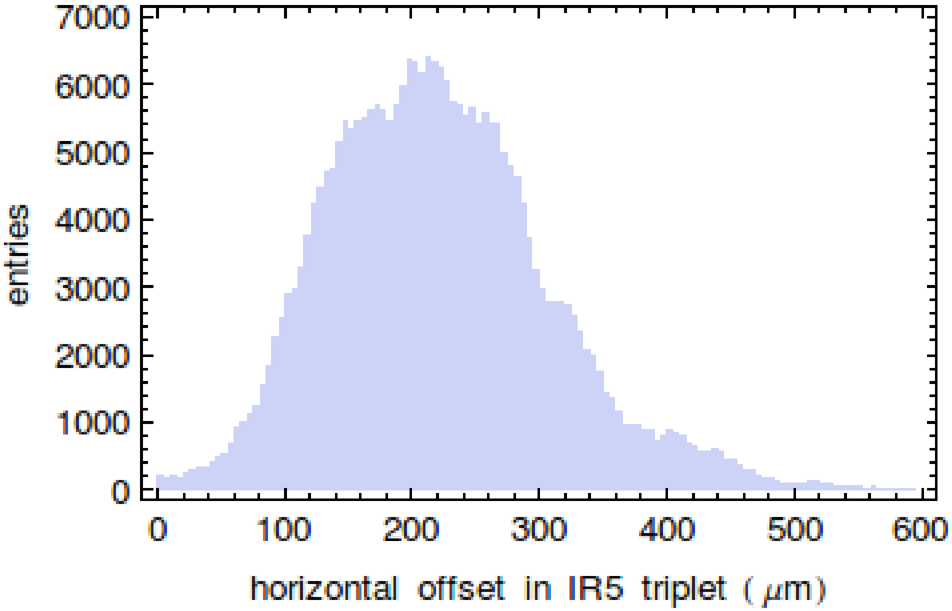
	Beam 1						Beam 2					
	$\Delta\beta/\beta$ [%]				$\Delta D_x/\sqrt{\beta_x}$ $[10^{-2}\sqrt{\text{m}}]$		$\Delta\beta/\beta$ [%]				$\Delta D_x/\sqrt{\beta_x}$ $[10^{-2}\sqrt{\text{m}}]$	
	H		V				H		V			
	rms	peak	rms	peak	rms	peak	rms	peak	rms	peak	rms	peak
Before corrections	20	44 ± 2	34	93 ± 5	1.8	5.8 ± 0.2	33	99 ± 5	23	67 ± 2	2.1	9.2 ± 0.4
Local corrections	6.2	15 ± 2	7.9	19 ± 2	1.2	3.2 ± 0.1	4.1	10 ± 2	3.9	12 ± 2	0.7	2.6 ± 0.2
Global corrections	2.2	7 ± 4	1.8	6 ± 2	0.3	1.5 ± 0.7	1.8	6 ± 2	1.5	7 ± 3	0.4	2.4 ± 0.2

- However, optics correction increasingly difficult in HL-LHC (enhancement of errors from the arcs, large enhancement in the IRs, strict phase advance constraints) => (proposal R. Tomas)
  keep for now 20% β-beat in aperture calculation for HL-LHC

- Reduce fractional parasitic dispersion from arc from 27% to 10%

Orbit tolerances

- Orbit variations smaller than design tolerance of 3mm observed in Run 1
  - Peak variations in 2012 around *measured* reference orbit of about 500 µm in IR triplets
  - Measured reference deviates in IR1/5 triplets from MADX reference by 1mm – up to 1.7mm in isolated cases
  - However potential issue with triplet orbit measurement - drifts probably more reliable than absolute
- Proposal (J. Wenninger): assume for now 2mm orbit uncertainty for HL – BPMs less reliable at larger apertures, orbit measured at larger excursions.
  - Fill-to-fill repdoducibility expected to stay similar to Run 1



Off-momentum contribution

- Off-momentum component not accounted for in Run 1 aperture calculation
  - chromaticity measurements done only with safe intensities – physics beam stays on-momentum. RF failures interlocked.
- In old n1 calculation, off-momentum contribution accounted for as a dispersive shift of central orbit
- New proposal for HL:
  - Reduce off-momentum contribution from 8.6e-4 to 2e-4 to account for bunch length. collimation hierarchy should be respected for this momentum offset
    - Avoids optics design with "hidden" problematic off-momentum behavior
  - include also off-momentum β-beat, which changes the beam size.
    - do 3 twiss evaluations with positive, negative and zero δ (S. Fartoukh, R. De Maria)

Proposal for new n1 parameters

- OP experience can be used to update n1 input parameters

Parameter	Old value	New value	Unit
Closed orbit excursion	3	2	mm
Fractional beam size change from β-beat	1.1	1.1	
Normalized emittance	3.75	3.5	µm
Momentum offset	8.6e-4	2e-4	
Relative parasitic dispersion	0.27	0.1	

Worked out in close collaboration WP2-WP5
With essential input from R. De Maria,
S. Fartoukh, R. Tomas, J. Wenninger

- During the design stage (e.g. for HL-LHC) the method to calculate apertures should include sufficient margins but not push all parameters to the limit
- How do the calculated apertures – with old and new parameters – compare with aperture measurements with beam?

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Overview of aperture measurements

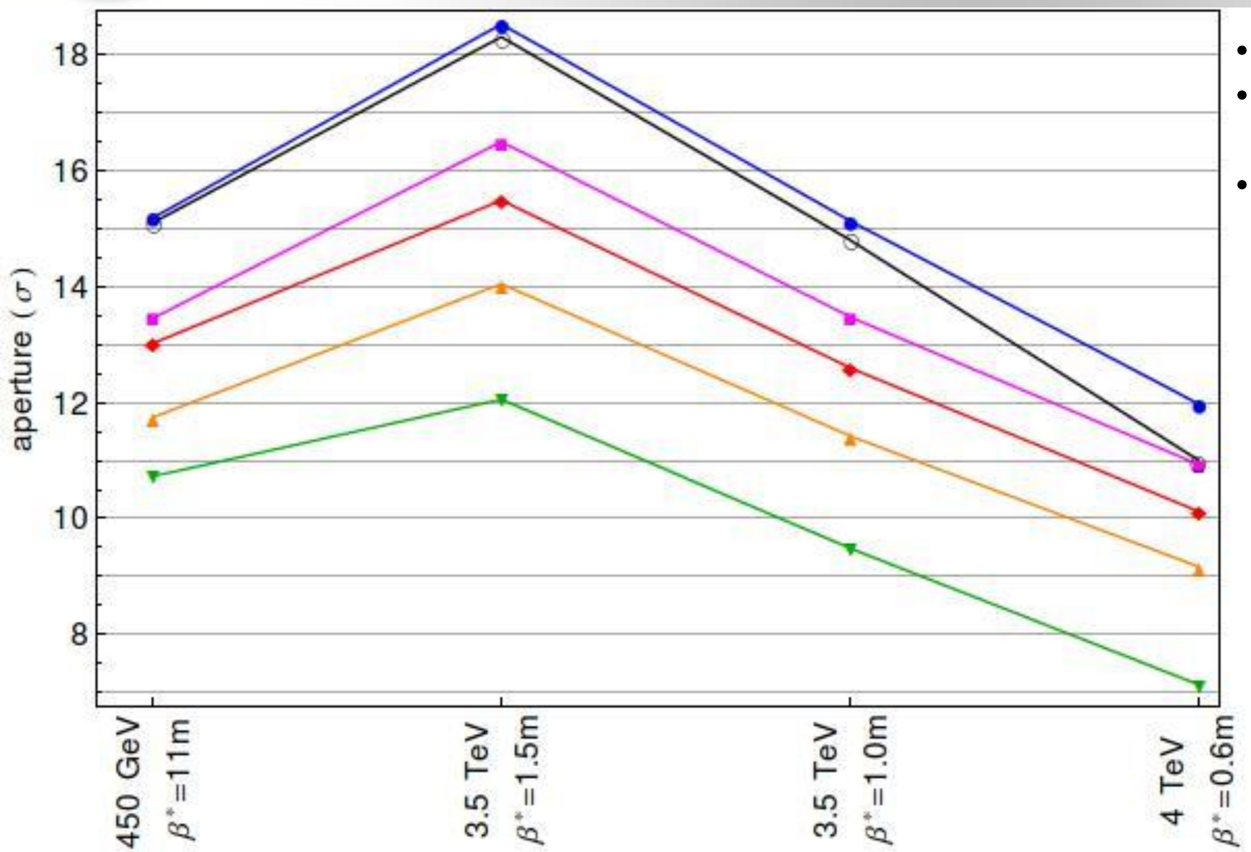
- **2009-2010**
  - Global and local aperture for selected elements at injection, kicker method
- **2010**
  - Global aperture at injection, crossing 1/3 resonance (used for decrease in β*)
- **2011**
  - Global aperture at injection, crossing 1/3 resonance
  - **Triplets IR1/5** using bump method
    - Injection
    - β*=1.5m
    - β*=1m

    } used for decrease in β* (β*=1.5m, β*=1m)
  - IR2 triplet, β*=1m (used for Pb-Pb run)
- **2012**
  - Global aperture at injection, ADT method
  - **Triplets IR1/5** using ADT method - β*=60 cm
  - IR8 triplet at injection, bump method (used to evaluate possible vertical crossing)
- **2013**
  - IR2 triplet with ADT method (used for p-Pb run)

n1 parameters for comparison

- Compare aperture measurements with several calculation methods:
    1) 1D aperture: (Aperture – |orbit|) /σ : most optimistic, "perfect" aperture (zero errors, zero tolerances)
    2) 2D ap. with 5% β-beat, 0.5mm orbit, dp=0 : achieved in Run 1
    3) 2D ap. n1 with 10% β-beat, 1mm orbit, dp=2e-4 : slightly more pessimistic
    4) 2D ap. n1 with 20% β-beat, 2mm orbit, dp=2e-4 : current HL proposal
    5) 2D ap. n1 with 20% β-beat, 3mm orbit, dp=8.6e-4 : "standard" n1, but calculating aperture instead of primary collimator setting
- Using 10% spurious dispersion in 3) – 6), 27% in 5)

IR1/5 triplet aperture measurements

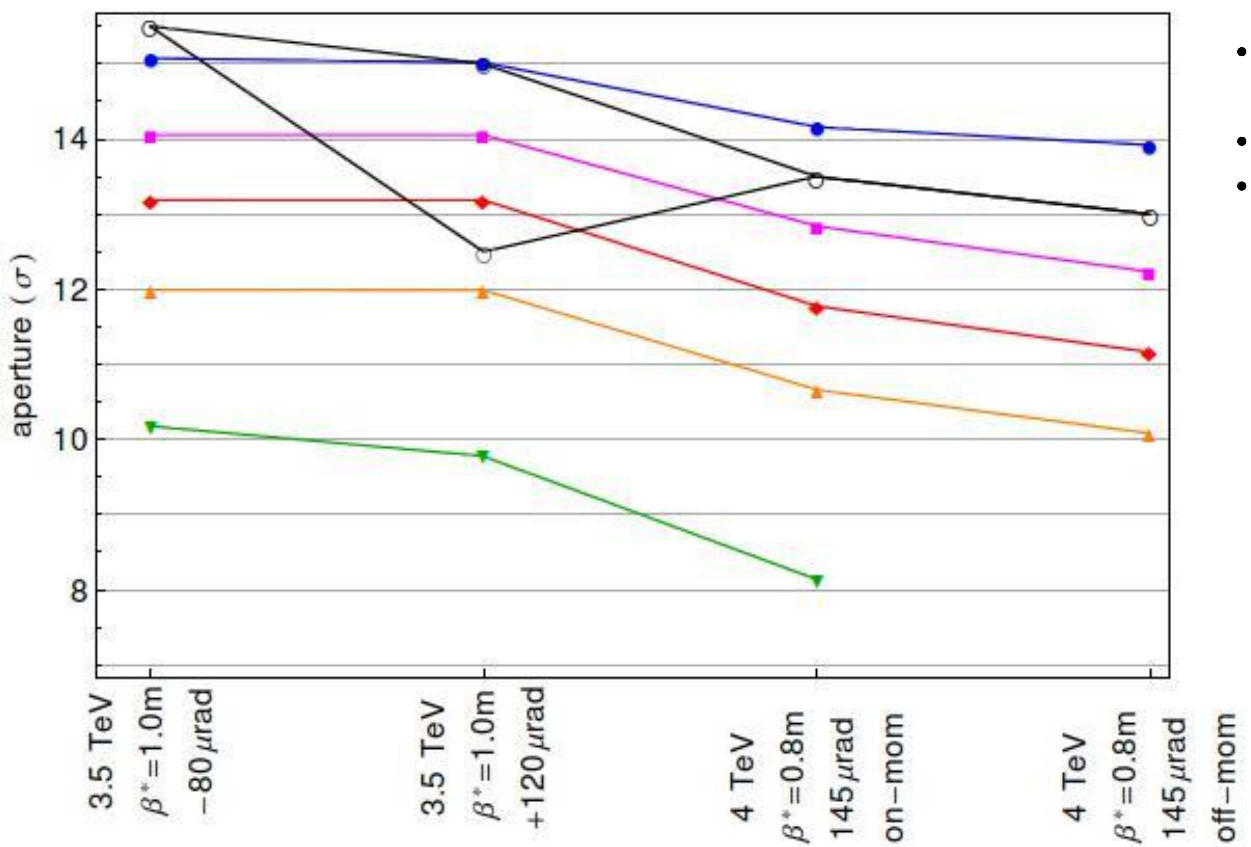


- *Assmann et al., IPAC11 TUPZ006*
- *Redaelli et al., CERN-ATS-Note-2011-110 MD*
- *Redaelli et al., IPAC12 MOPPD062*

- Aperture very close to the ideal value! But: still measured only one side.
- 2012 measurement breaks trend. ADT method vs bump? Or real physical effect? For 2012, the Run 1 method gives a very accurate result

IR2 aperture measurements

- IR2 aperture measured both on-momentum and off-momentum
  - Few off-momentum measurements - not given high priority in operation
- one “bad” measurement point at TCTVB – now removed
  - Proposed HL n1 more conservative than “bad” point



- *Redaelli et al., CERN-ATS-Note-2012-017 MD*
- *Redaelli et al., IPAC12 MOPPD062*
- *Hermes et al., CERN-ACC-NOTE-2013-001*

Outcome of comparison with measurements

- LHC apertures generally very well aligned. Very small influence of errors
  - Measured aperture close to the design values!
  - Fully exploited to push performance to unexpected levels
- The old n1 gives a pessimistic aperture
- The new proposed n1 tolerances give more realistic aperture but still on the conservative side. Unexpected point in IR2 covered.
- The proposed parameters have some margin to measurements but we also need margins during the design stage.
- If HL-LHC will be as good as the present machine in terms of optics, orbit correction etc (or hoping that it will be better!), once the machine is built, there could still be some room for improvement
- Using achieved Run1 parameters in n1 model reproduces 2012 measurement accurately and is more conservative than 2010-2011 data

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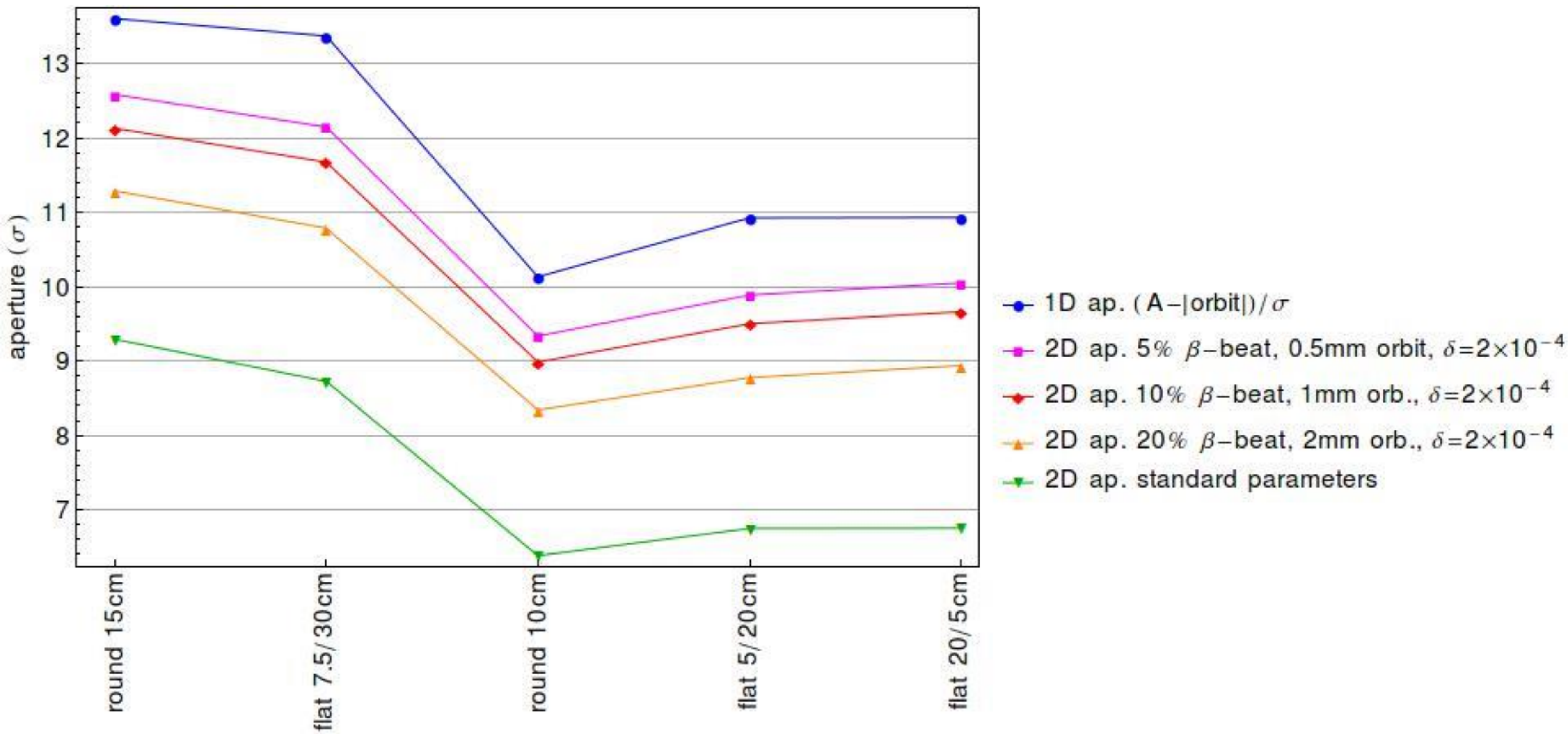
Application to HL

- Using the same parameter sets, applying the calculation to HL
- Compare with aperture protected by collimation. Baseline: around 12 σ.
- collimation hierarchy depends on machine errors,
  - smaller β-beat implies smaller margins and a smaller protected aperture.
  - Each set of aperture tolerances corresponds to a different protected aperture.
  - If we reduce errors, we gain both in aperture and collimation hierarchy!
- Baseline collimator settings do not account for impedance constraints. If beam instabilities become an issue: open collimators => lose in aperture
- Exploiting gain of integrated BPM buttons => reduction of margins
    - Interlocking strategy to be defined – gain to be confirmed in Run 2

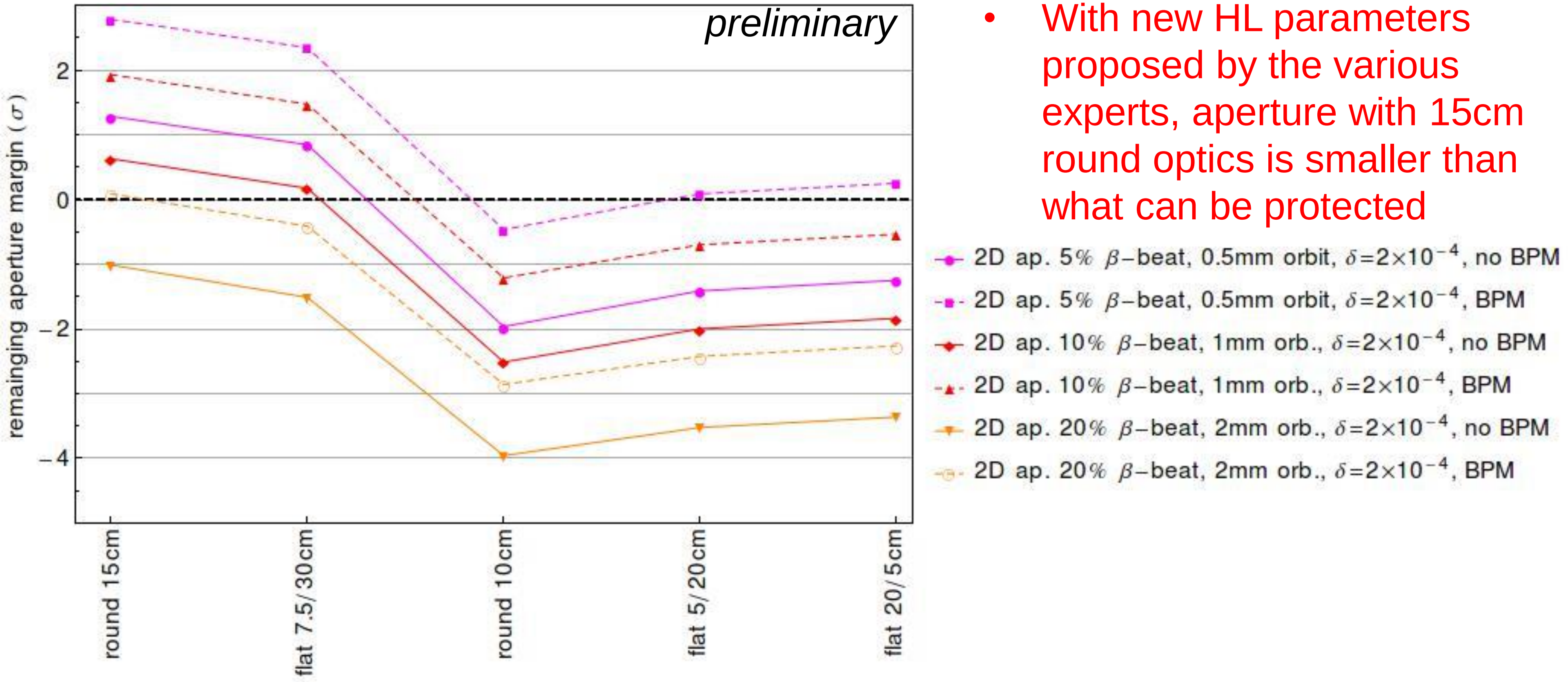
Aperture margin in HL-LHC

Calculated aperture with same methods for different HL configurations



Calculated – protected aperture in HL

- For full consistency: compare aperture in each case with collimation hierarchy with the same errors. Plotting difference between calculated and protected aperture. Protected aperture function of tolerances.
- Positive numbers means that the aperture is qualified

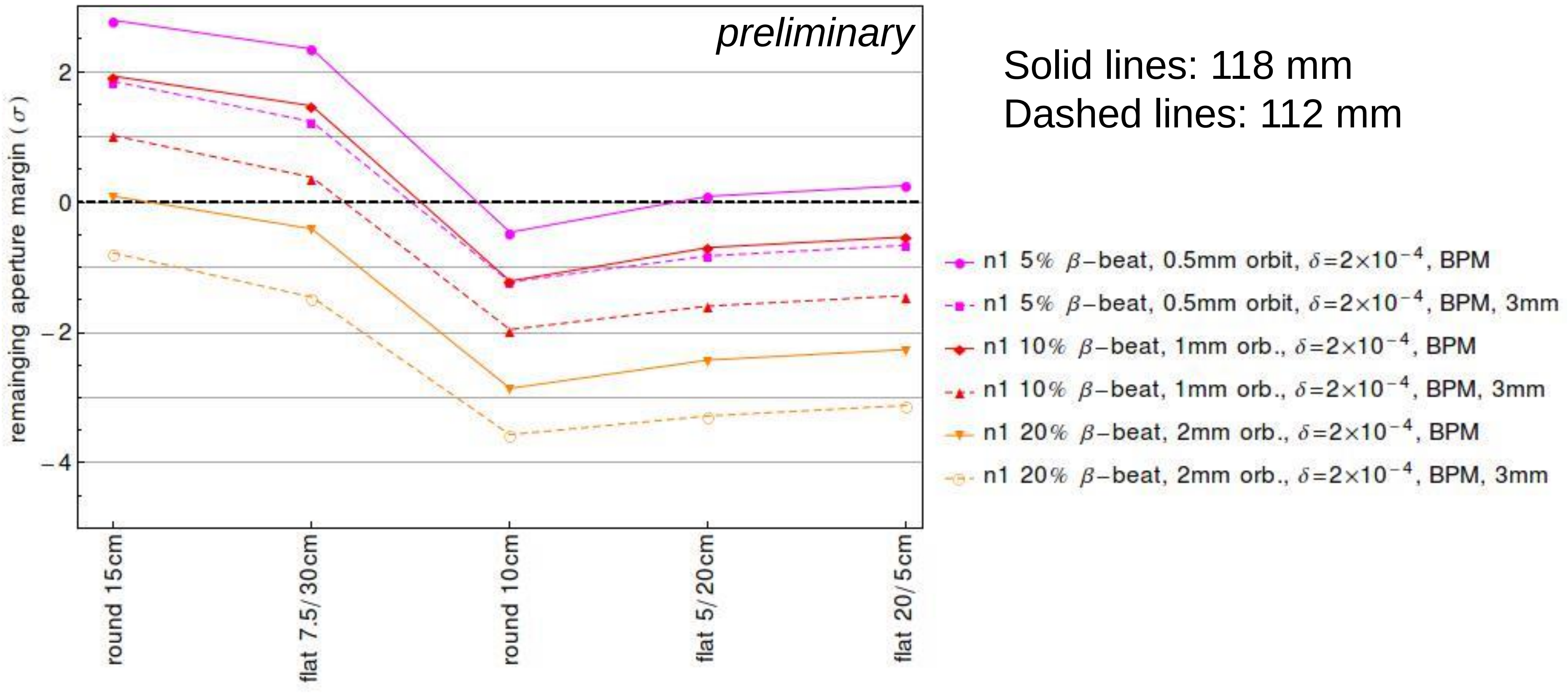


- With new HL parameters proposed by the various experts, aperture with 15cm round optics is smaller than what can be protected

Mechanical tolerances

- Calculations include mechanical tolerances for ground motion and fiducialization.
- Not included: manufacturing tolerance of beam screen – still to be defined.
  - Target value of full opening: 118 mm
  - But: with old phase I ISO tolerances, full opening goes down to 112mm. => loss of 3mm aperture, corresponding to almost 1 σ!
  - It is crucial to ensure excellent tolerances and that the target can be met
  - Compare aperture margins with inclusion of potential 3mm of beam screen tolerance (dashed lines) – situation is significantly worse!

Calculated – protected aperture in HL with 3mm beam screen tolerance



Solid lines: 118 mm
Dashed lines: 112 mm

- Mechanical alignment needs to stay excellent. Studies of the required mechanical tolerances and on the means to improve them are vital

Observations on HL aperture

- To achieve an acceptable aperture, we have to work on all fronts to ensure that errors are smaller.
  - To reach an acceptable aperture at β*=15cm, need to improve:
    - ensure BPM buttons can be fully exploited, work for 10% β-beat and 1mm orbit.
    - 2015 experience will help. Further studies of the ATS correctability are required
    - Flat optics requires tighter collimator settings
  - To reach superflat 5/20cm optics, additional significant efforts are needed:
    - 5% β-beat, 0.5 mm orbit (as reached in Run 1, neglecting off-momentum) and BPM buttons fully exploited
  - Mechanical tolerances need to stay excellent.
  - Try to gain every mm possible in all parameters!
- It is not unrealistic to reach an acceptable aperture, but an effort is needed to ensure smaller errors and margins
- As in Run 1, aperture measurements will be a crucial part of the performance validation. Need to have high priority.

Summary

- Careful n1 method used during LHC design
  - Run 1 experience shows LHC aperture in many cases measured close to ideal design value! One unexplained measurement in IR2 significantly worse.
- **New proposal for HL parameters** based on expert advice – less pessimistic but still on the conservative side. Room for improvement?
- With new parameters, HL 15 cm aperture is below what can be protected.
  - Need work effort to ensure the same (if not better) optics and orbit correction as in Run 1 and/or smaller aperture protected by collimation.
  - Using the actually achieved Run 1 parameters or including gain from BPM buttons, the baseline optics is OK for aperture/collimation. No reason to panic!
  - Important to assess limits on beam stability and find possible solutions
  - Run 2 experience will provide essential input. Beam measurements crucial.
  - Beam screen and mechanical tolerances to be reviewed – very important to keep them small! Parameters to be revised in the future

Backup

Global aperture at injection

- 2010: Assmann et al., IPAC11, TUPZ006. Min: 12.5 sigma
- 2011: Assmann et al., IPAC11, TUPZ006. Min: 12.0 sigma
- 2012: elogbook Min: 11.5 sigma
- Same bottlenecks, but we lost 0.5 sigma every year (error bars on measurements still to be defined)