Collimation after LS1: cleaning and β* reach

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Acknowledgements:

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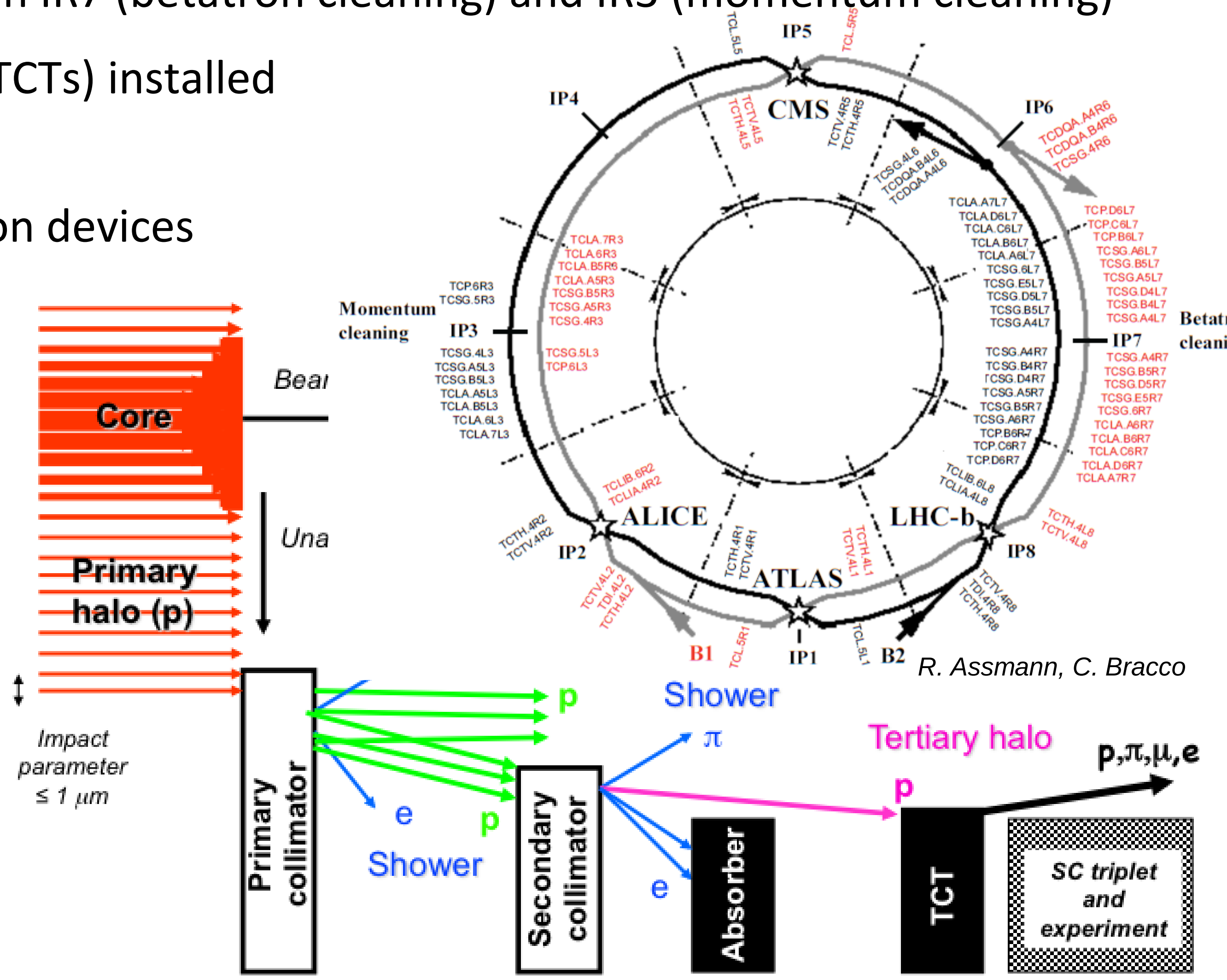
Outline

- Introduction: LHC collimation system
- Calculations of collimator settings so far
- Changes in LS1 – BPM button collimators
- Collimator settings and beta* after LS1.
- Brief outlook for HL-LHC – what is different compared to after LS1?
- Conclusions

LHC Collimation system as installed

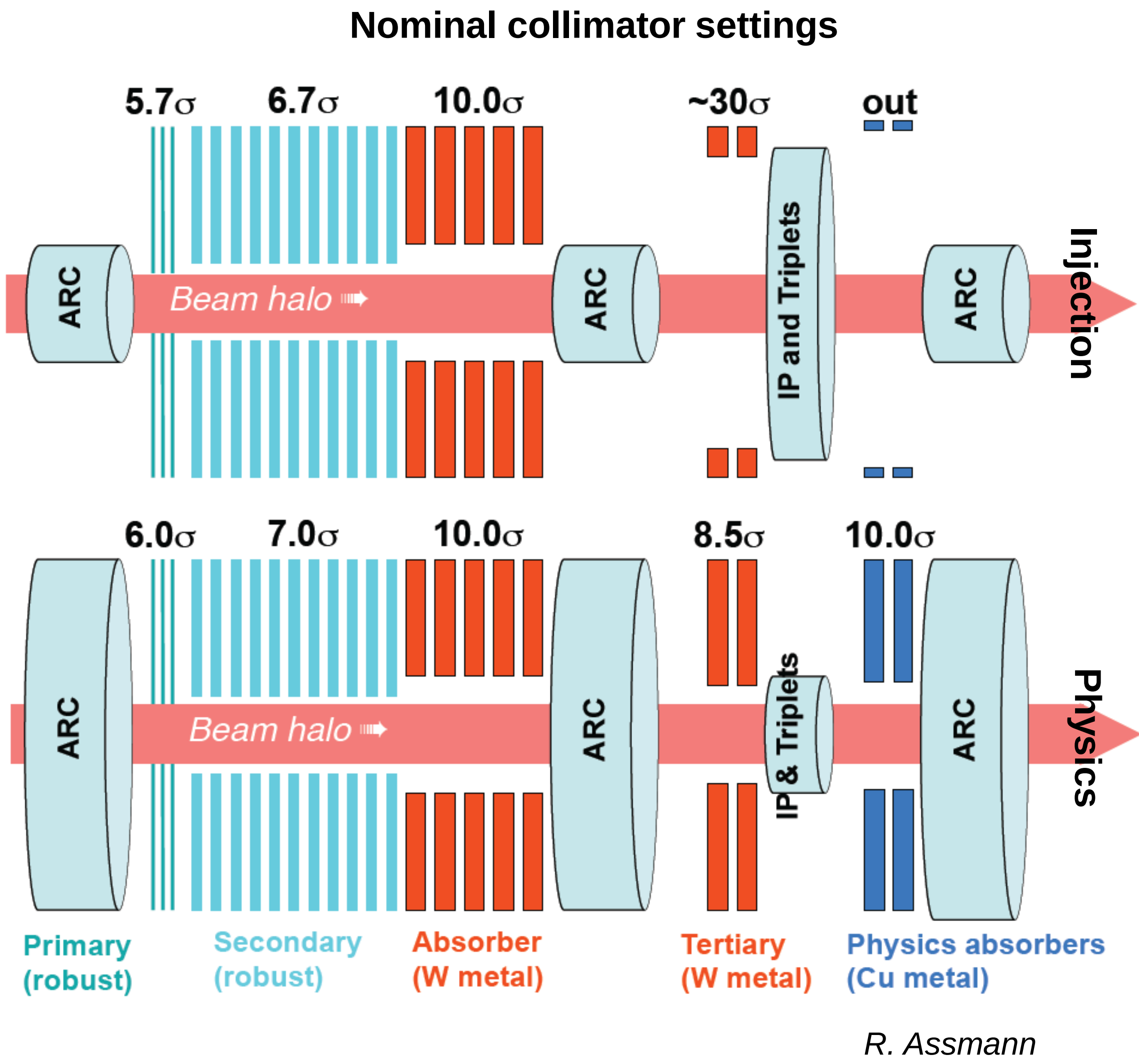
- Collimators installed in IR7 (betatron cleaning) and IR3 (momentum cleaning)
- Tertiary collimators (TCTs) installed around experiments
- Beam dump protection devices in IR6 – should intercept beam in case of fast dump failures
- Multi-stage system in IR7 and IR3



R. Assmann, C. Bracco

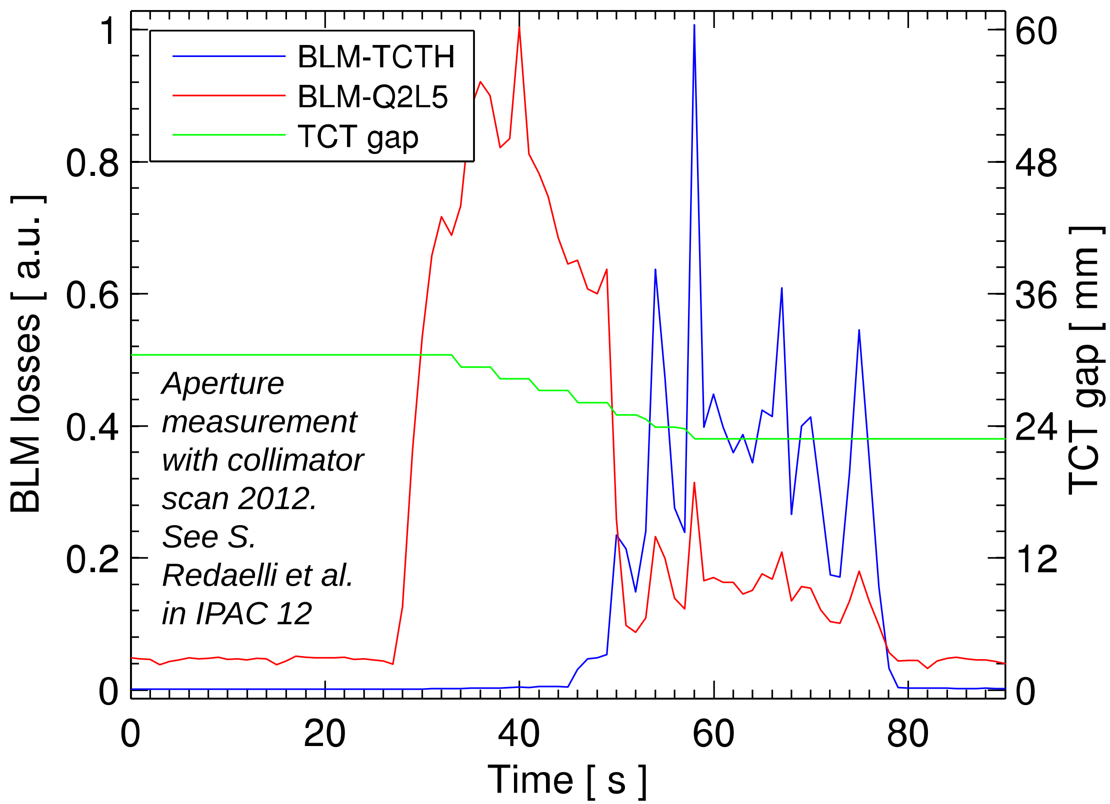
Principles for collimator settings

- Collimation system designed for
  - **Cleaning:** protect cold aperture from unavoidable beam losses as particles drift out from the core of the beam. Hierarchy in IR7 and IR3 determines performance
  - **Protection:** If losses are too high, BLMs trigger a beam dump before a quench occurs. If single-turn failure (asynchronous dump), BLMs too slow. Rely on robustness of collimators and correct hierarchy to avoid damage. Hierarchy with respect to IR6 crucial
- Bottlenecks in machine different at injection and top energy



Aperture to protect

- During design stage, collimator settings calculated to guarantee protection for apertures >8.4 σ (including tolerances on mechanics, orbit, beta-beat, energy offsets etc – using n1 method in MADX)
- Safe approach
  to avoid bad surprises
- With LHC built, machine aperture measured – larger aperture found than the worst-case scenario worked out beforehand
- Example: measured triplet aperture on-momentum in IR1 = 11 σ at β^*=60cm and 4 TeV, while n1 method gives 6.3σ (with 3mm orbit, 20% beta beat, off-momentum).



- In the future: maintain n1 approach as baseline, but consider both options

β* dependence on collimator settings

- More aperture available => allows to squeeze to smaller β*
- Simple scaling model successfully used to extrapolate measured aperture to other β* and crossing angle – used to calculated run parameters in 2011 and 2012 (see talk Evian 2010 and 2011, S. Redaelli LMC 2011)
- On the other hand, so far larger retractions used in the hierarchy than in design
- Possible β* depends both on the collimator settings and the required margin as well as the available aperture

Calculation of margins in hierarchy

- In IR7, non-critical cleaning margins in 2010 and 2011 calculated by keeping the same retraction in mm as at injection (intermediate collimation scheme) in order to provide sufficient room for imperfections (optics / orbit stability)

- In 2012, we reduced margins in IR7 to "tight" settings based on empirical studies (see MD notes).
  - Not yet at nominal settings, but getting closer! TCP now at 4.3 σ, same setting as nominal in mm. But larger retraction to TCS in order to keep hierarchy.
  - Goal is still to achieve nominal settings (better understanding of the hierarchy limits and efficiency dependence, more frequent alignments or even new hardware (see later)
  - Tighter settings gain room for protecting a smaller aperture

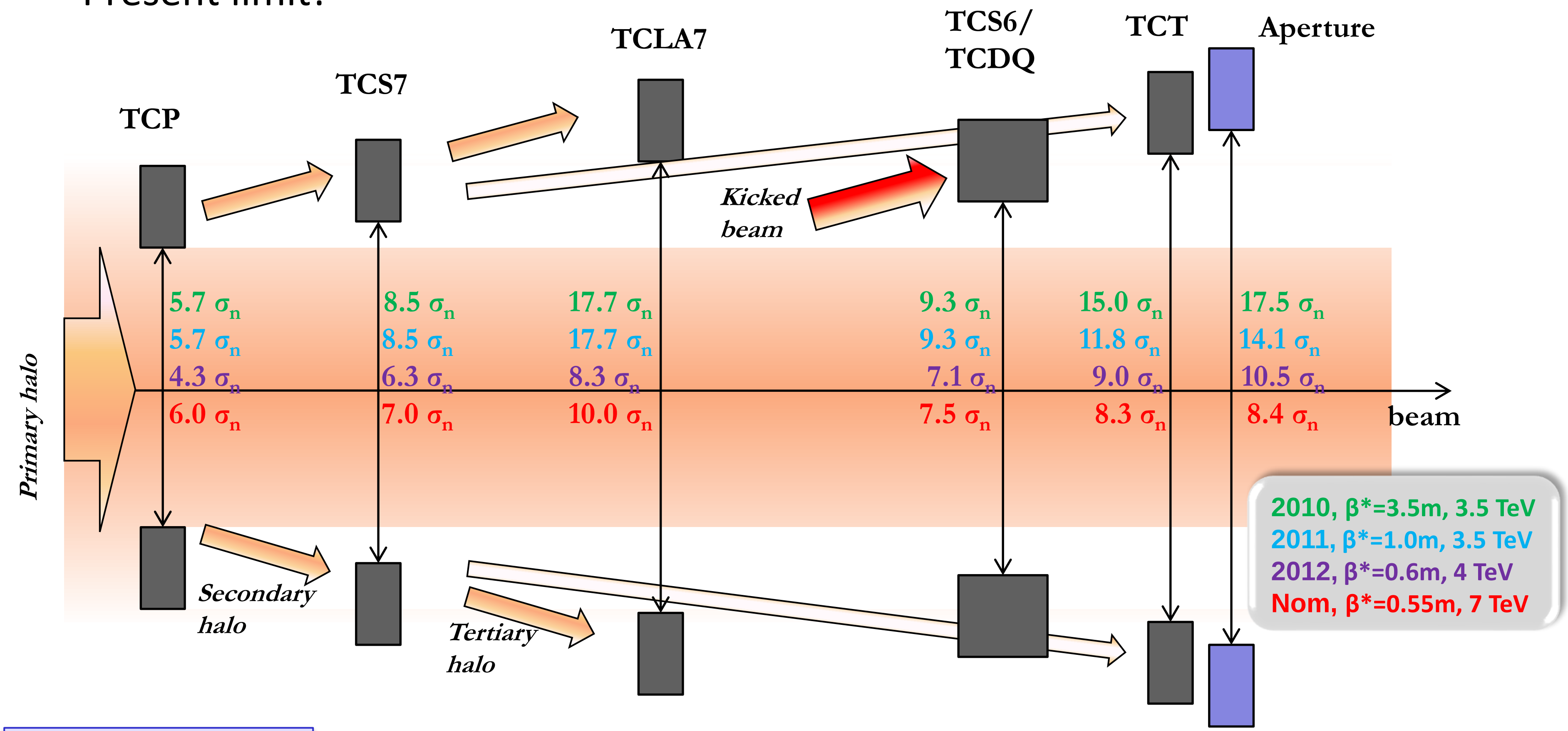
Calculation of critical margins

- Critical margins: If margins IR6-TCTs-aperture are violated, sensitive equipment (TCTs or aperture) might be exposed and even damaged in the unlikely case of an accident
- Critical margins calculated based on in-depth analysis of previous runs
- Components of critical margins: orbit, β –beat, lumi scans, positioning errors and setup errors
- Philosophy: Margins should be respected more than 99% of time => risk of damage < 1 in ~300 years for TCTs, less than 30000 years for triplet (see Evian 2010)
- Summing in square the estimated margin needed for 99% safety from orbit and β variations at the collimators, reproducibility of collimator positioning, setup error. Adding van der Meer scans separately

$$\boxed{\Delta_{total} = |\Delta_{vdM}| + \sqrt{\sum_i \Delta_i^2}}$$

Collimator settings 2010-2012

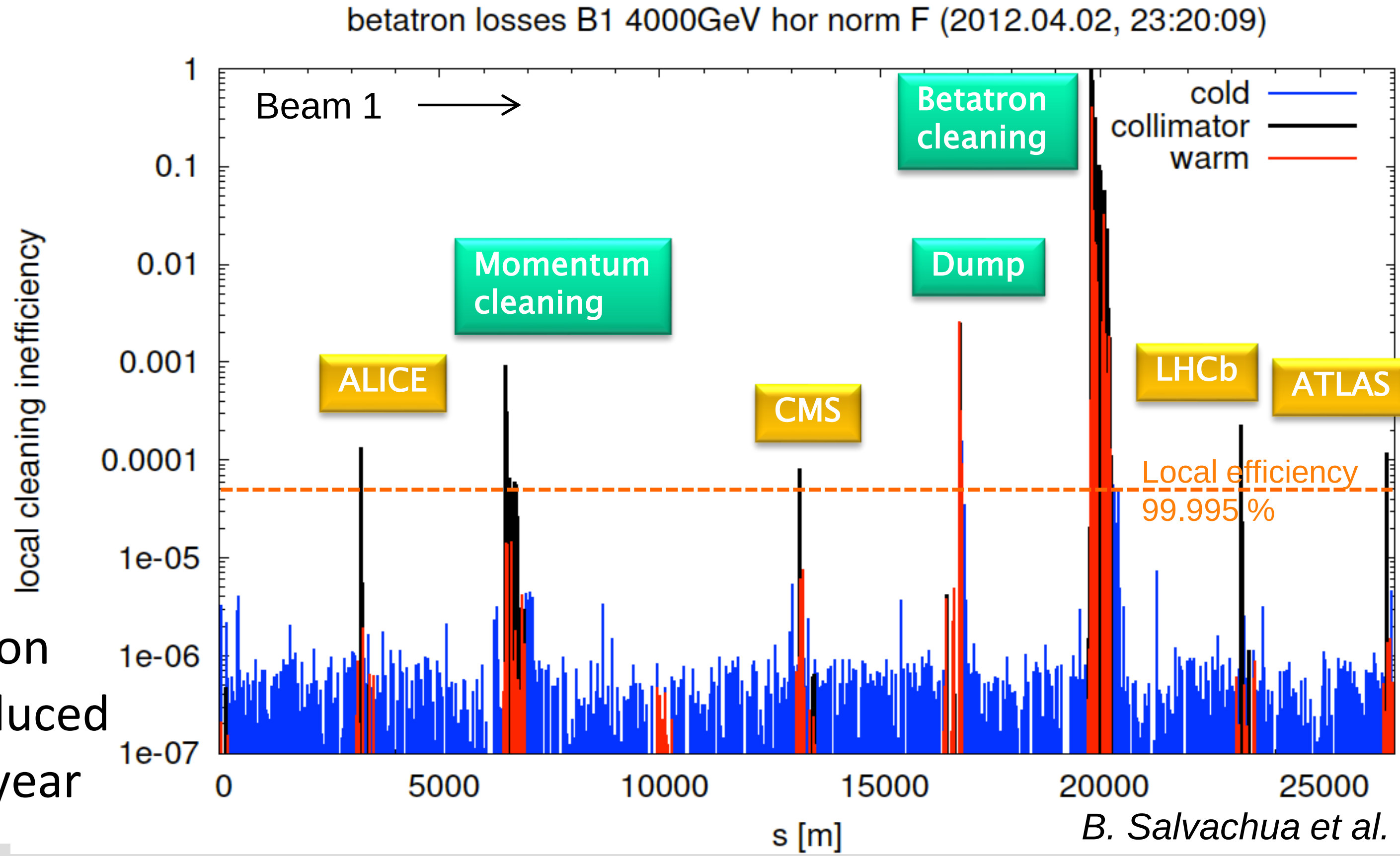
- Tighter collimator settings allowed to squeeze β* down to 60cm in 2012. Present limit!



σ calculated with emittance = 3.5µm

Present collimation performance

- Successfully put tight settings into operation in 2012 - only 1 beam-based alignment per year sufficient!
- Excellent cleaning inefficiency, factor ~5 better than with relaxed settings in 2011 (*see G. Valentino, Evian 2011, and B. Salvachua, MD note*)
- No quenches with circulating beam
- Lifetime dips in ramp and squeeze due to instabilities (under study in impedance team)
- Careful optimization of the LHC has reduced losses during the year



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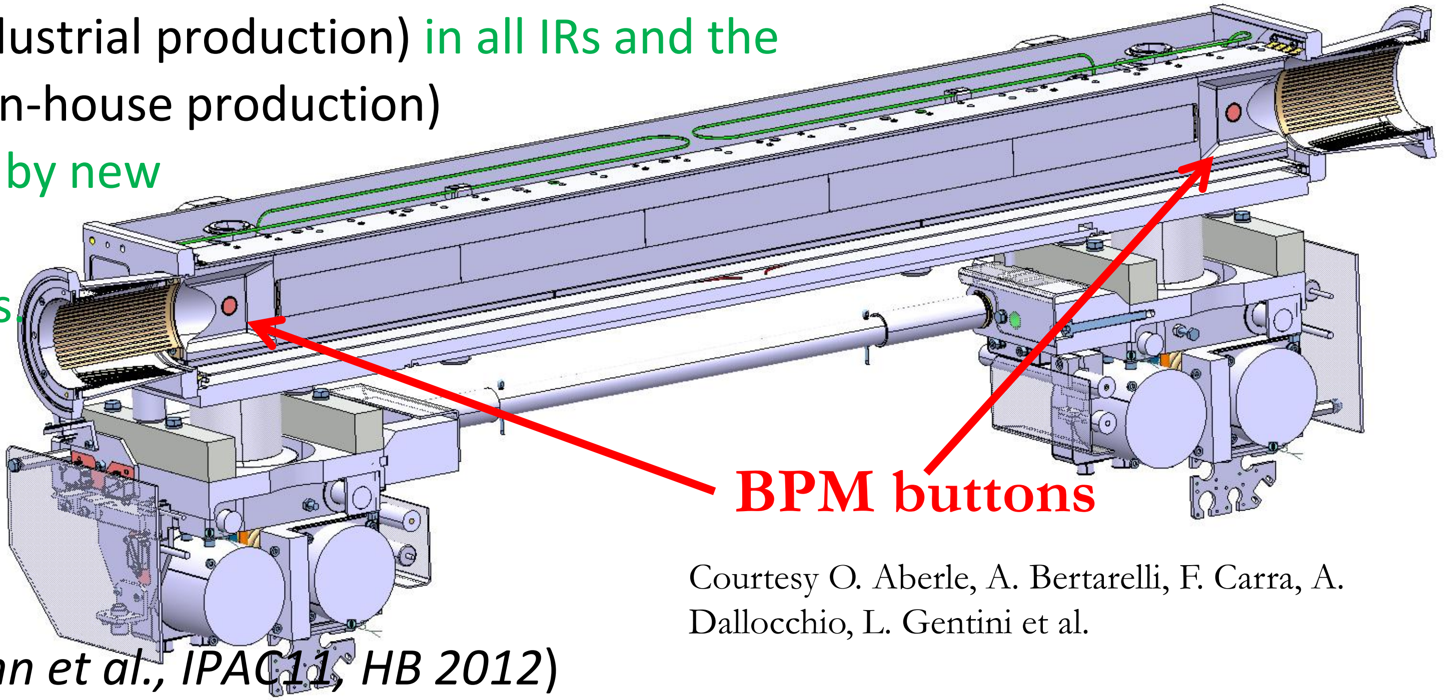
LS1 improvements – integrated BPMs

- The 16 TCTs (industrial production) in all IRs and the 2 TCSGs in IR6 (in-house production) will be replaced by new collimators with integrated BPMs.
- Tests in the SPS with mock-up collimator very successful (see *D. Wollmann et al., IPAC11, HB 2012*)



Courtesy O. Aberle, A. Bertarelli, F. Carra, A. Dallocchio, L. Gentini et al.

- Gain: can re-align dynamically during standard fills. No need for special low-intensity fills
  - Drastically reduced TCT setup time (gain of a factor ~100) => more flexibility in IR configuration
  - Reduce orbit margins in cleaning hierarchy => more room to squeeze β*

Preliminary scenarios after LS1

- Beam assumptions:
  - 6.5 TeV
  - 25 ns (beam-beam separation needs to be increased to 12 σ, the emittance from injectors can increase up to 3.5 μm but could also be as small as 1.6 μm) or 50 ns (we can keep the same beam-beam separation as 2012 and same emittance)
- BPM button collimators: assume pessimistically 50 μm precision of orbit at TCTs and TCSG6 as upper limit from SPS tests – in reality better precision expected.
  - Can reduce to 0.1 σ margin for orbit between dump protection and TCTs
  - Can reduce to 0.8 σ margin for orbit between TCTs and triplet – orbit can still move in triplet
- We can not move in the TCPs further than today in mm (impedance, orbit)
- Assuming same excellent aperture, β-beat and orbit precision as 2011/2012 (2012 orbit analysis still to be done)

Preliminary collimator settings after LS1

- Including increased margin from BPM button collimators
- Using same philosophy for calculating margins IR6-TCTs-triplets as in 2012
- **No constraints from impedance** accounted for
- **New iteration** of needed margins will be done when HiRadMat test results on **TCT damage limit** are fully analyzed

	Case 1: same as today in mm	Case 2: Keeping retractions in σ	Case 3: Nominal retractions
TCP 7	5.5	5.5	5.5
TCSG 7	8.0	7.5	6.5
TCLA 7	10.6	9.5	8.5
TCSG 6	9.1	8.3	7.0
TCDQ 6	9.6	8.8	7.5
TCT	10.0	9.1	7.7
aperture	**11.4**	**10.5**	**9.1**

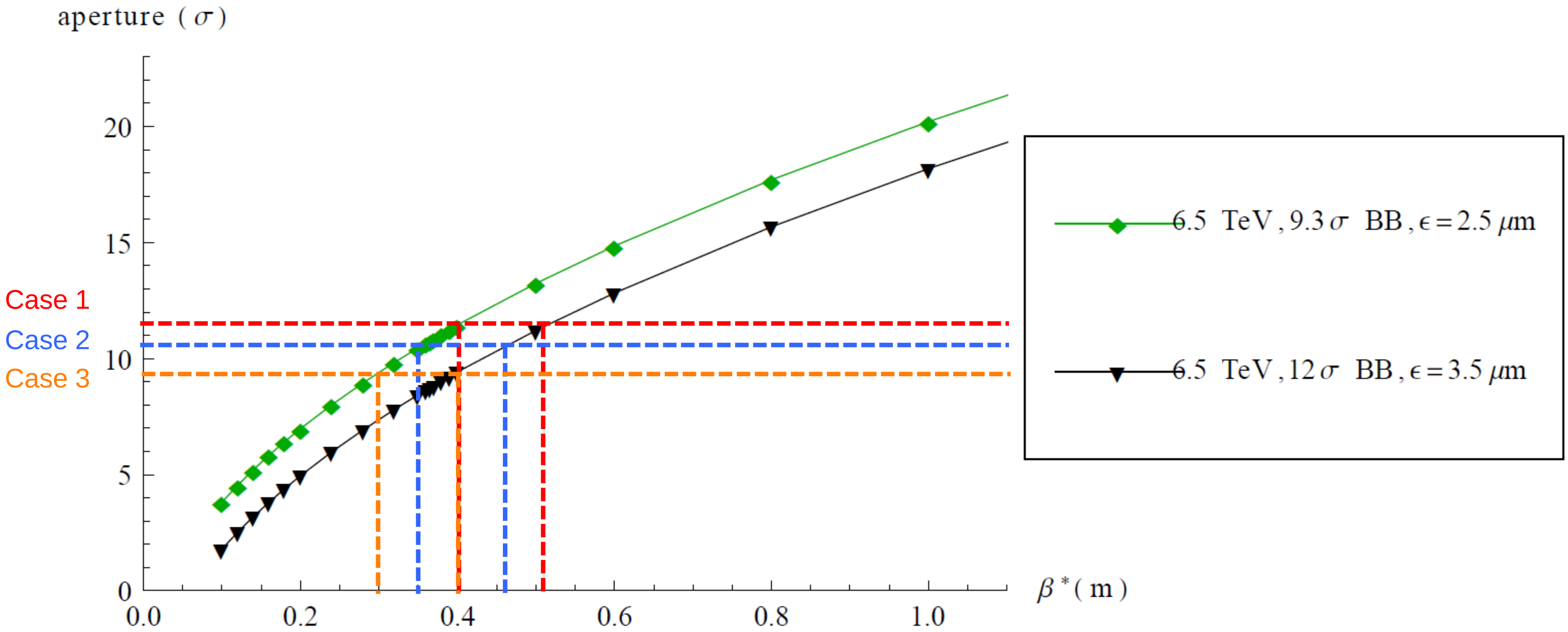
Should work for cleaning hierarchy

Might require more frequent setups to keep hierarchy

Probably not for startup after LS1

Preliminary β* and aperture after LS1

- Aperture scaled from most pessimistic 2011/2012 measurements.
- If we could have 1.6μm emittance at 25ns, the aperture/crossing angles are almost the same as for 50 ns and 2.5μm
- By going to 25ns, we could lose 10cm in β* if the emittance is large (3.5 μm), nothing if the emittance can be pushed down to 1.6 μm



Preliminary β* reach

- Not accounting for impedance constraints, we could reach β* between 30cm and 50 cm
- β* rounded to nearest 5 cm, crossing angle to nearest 10 μrad

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TCT	10.0	9.1	7.7
aperture	11.4	10.5	9.1
Half crossing angle (50/25 ns) [μrad]	*140/190*	*150/200*	*160/210*
β (50 / 25 ns) [cm]*	*40/50*	*35/45*	*30/40*

Aim for this as starting scenario

Can we achieve these settings?

- Pileup – might consider leveling
- Octupoles: today running at about 500A, max current is 550A. Possibly we will be limited in octupole strength at 6.5 TeV
  - Ongoing work in impedance team and beam-beam team to explore limit and optimize octupole settings. Beam-beam could possibly be used to stabilize colliding bunches (W. Herr, E. Metral et al.)
  - If we do not manage stabilize the beam, we might have to open collimators and step back in β*.
- Losses in ramp and squeeze: Need to carefully optimize the machine (BLM thresholds, octupoles etc) – significant improvement observed during 2012
- No optics constraints treated: We know that off-momentum β-beat and spurious dispersion are more important for smaller β* (S. Fartoukh et al.). Have seen in MD that octupoles have negative influence on aperture (still to be understood in detail). Will the aperture be worse? If so, we might have to step back in β*.

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Considerations for HL-LHC

- Aperture:
  - New inner triplets with larger aperture allow smaller β^*.
  - We don't know the aperture as precisely as in present machine, where we have measured. New shape of beam screen
- Collimator settings:
  - Collimators will have aged – to be replaced in LS3 with an updated design (integrated BPMs, lower impedance, higher shock resistance)
  - More BPM button collimators means gain in margin and β^* reach
  - Lower impedance from collimators, but higher intensities. Lifetime dips? Could possibly be mitigated by electron lens. Careful machine optimization necessary
  - ATS optics should be carefully studied in terms of cleaning and failure scenarios. New aperture bottlenecks in Q4-Q6? Are any new protection devices needed?
- Promising for β^* but still a lot of work to be done!

Conclusions

- The collimation system must protect the machine and constrains β*
- Calculation of collimator settings for maximizing luminosity performance without compromising protection and cleaning
- Tools for determining settings and β* based on running machine have been established during 3 years of operation.
- So far machine protection has been the limiting factor for β* - has to be considered also in the future.
- Tight settings introduced in 2012 based on 2011 performance and MDs. β*=60cm made possible and successfully put into operation
- TCTs and TCSG in IR6 to be replaced in LS1 by collimators with integrated BPMs
- Preliminary performance estimates: 35cm<β*<50cm could be in reach at 6.5 TeV provided octupole strength and impedance do not cause trouble. Collimator settings could be limited by impedance

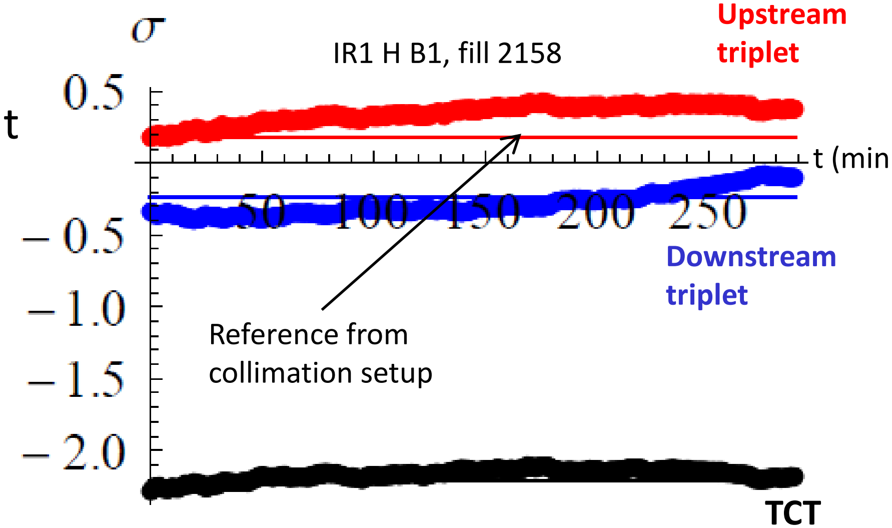
Backup

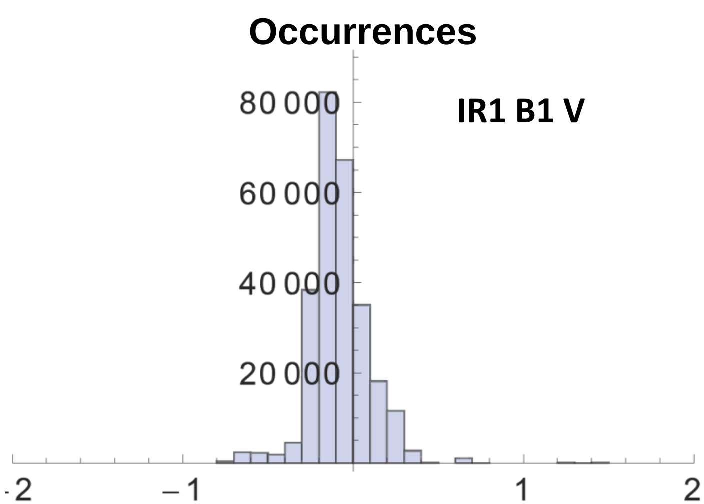
Components of critical margins (IR6-TCTs-aperture)

- Positioning (reproducibility of collimator setting between fills. Affected by e.g. power cuts). Assuming 40 μm
- Setup errors (precision of collimation setup): 10 μm steps used in setup
- Lumi scans: Assuming pessimistically 0.2 σ
- β -beat:
  - not measured continuously during the year.
  - Assuming 10% (actually even better this year in most parts of the machine)
- Orbit:
  - margin calculated based on measured orbits in previous run.
  - Reduction in margin calculated based measured orbit at both locations for all fills
  - Taking a 99% confidence interval on the reduction in margin
  - Result from 2011 run: 1.1 σ needed both between IR6-TCT and TCT-aperture

2011 orbit stability triplets/TCTs

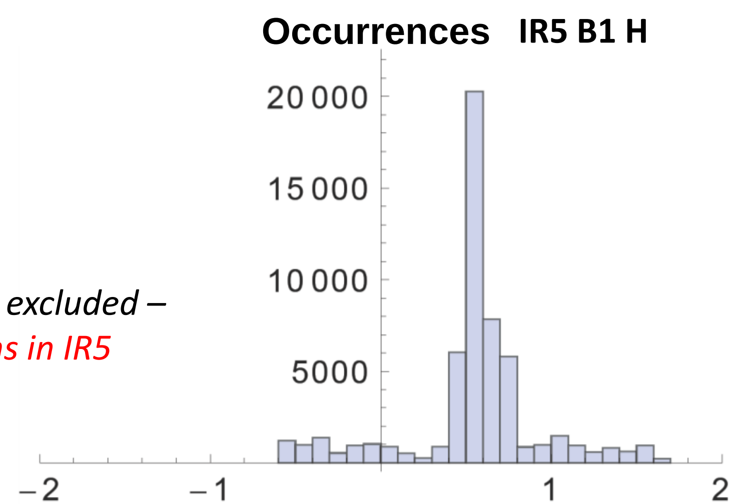
- Very good stability within fills
- In many cases better than 2010 in σ. Consistent with larger beam size from smaller β*
- IR1 now stable within 0.6 σ for 99% coverage. For IR5, 1.1 σ still needed in spite of β*=1m
- Possibly part of margin due to temperature effects. Still room for improvement?





change in min margin (σ)

BPMS.2L5.B1 excluded –
BPM problems in IR5



What Can Happen?

Error case:

1. We need an asynchronous dump or one module pre-trigger while we are at low β^* (probability 10^{-7} per second).
2. We need to be out of orbit tolerance from IR6 to a TCT in one IR (probability 10^{-2}).
3. We need to be at maximum beta beat error from IR6 to a TCT in one IR (probability 10^{-2}).
4. Both errors must point in the same bad direction (probability 0.25).

   ➔ Then one TCT is at risk for damage from single bunch (benign damage). Still very unlikely, due to phase advance conditions that must be met.

5. The TCT is out of tolerance with respect to triplet aperture (probability 10^{-2}).
6. We are fully squeezed (aperture assumption).
7. Beams have additional beam-beam offset reserved for van-der Meer scan.

   ➔ Then the triplet aperture can be hit by fraction of a bunch, if conditions for TCT hit (see above) are met.

2012 collimator settings in physics

- Settings of collimators at 4 TeV, using square sum of margins except lumi scans (see Evian, Chamonix)

	2012 tight settings, Nom. σ (ϵ=3.5μm)	2012 settings, Real σ (ϵ=2.0μm)	2011 settings, Nom. σ (ϵ=3.5μm)
TCP 7	4.3	5.7	5.7
TCSG 7	6.3	8.3	8.5
TCLA 7	8.3	11.0	17.7
TCSG 6	7.1	9.4	9.3
TCDQ 6	7.6	10.1	9.8
TCT	9	11.9	11.8
aperture	10.5	13.9	14.1

- Settings for 2012 very similar to 2011 settings but with real emittance
- No change in IR3 or at injection
- With the tight settings, we can protect the aperture much closer to the beam => we can allow smaller β*.
- Proposed β* =60 cm as 2012 baseline, successfully put into operation