Limits on collimator settings and reach in β*

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on behalf of the collimation team

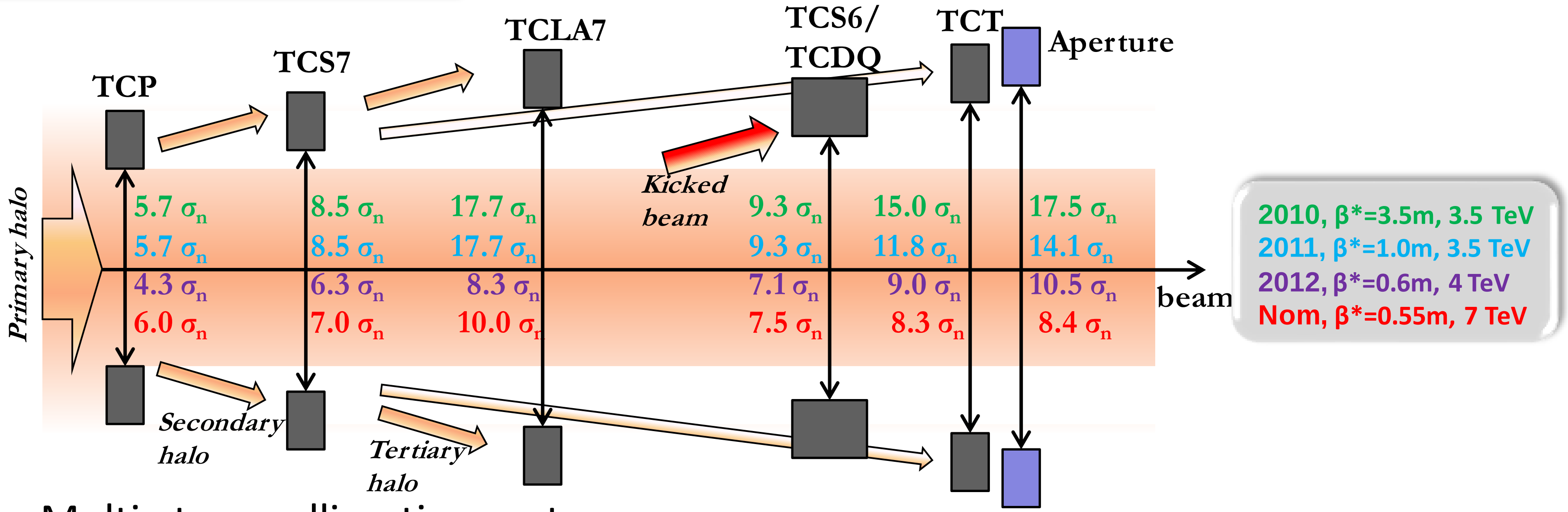
Acknowledgement: G. Arduini

Outline

- Introduction: Influence of LHC collimation system on machine performance
- Review of past evolution of collimator settings and their influence on machine performance
- Changes in LS1 and preliminary post-LS1 scenarios
- Considerations to push performance limits in the future

Collimation system

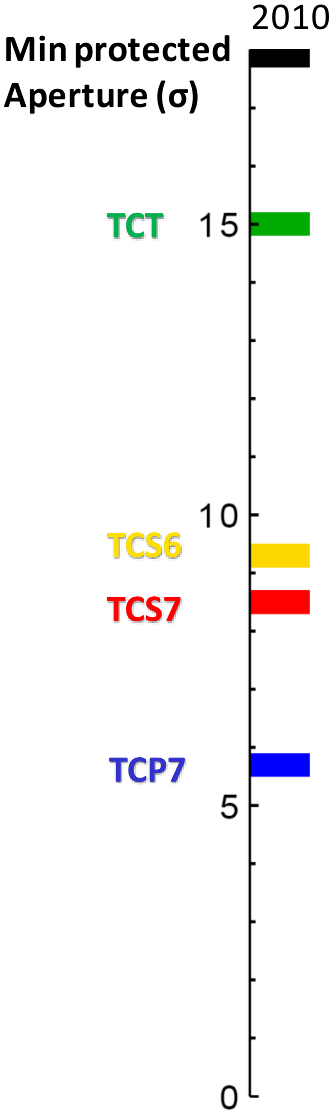
σ calculated with emittance = 3.5µm



- Multi-stage collimation system
- Collimation hierarchy has to be respected in order to achieve satisfactory protection and cleaning
  - Protection: avoid damage during abnormal operation or failures
  - Cleaning: removal of unavoidable halo during standard operation
- Smaller β* causes smaller aperture margin – collimation hierarchy limits β*

Evolution of collimator settings and β*

- 2010: conservative approach with large margins between IR6 and TCTs. β*=3.5m
- 2011: *(Evian 2011)*
  - Detailed analysis of margins – gain by moving in TCT
  - Detailed analysis of aperture based on 2010 measurements at injection – squeezed to β*=1.5m
  - New aperture measurements at 3.5 TeV, squeeze – could reduce β* further to 1.0m *(CERN-ATS-Note-2011-110 MD)*
- 2012: *(Evian 2011 and Chamonix 2012)*
  - Gain from tight collimator settings instead of relaxed
  - Slight gain in orbit
  - Gain from statistical approach – adding margins in square
  - β* successfully squeezed to 60cm
- Similar evolution after LS1?

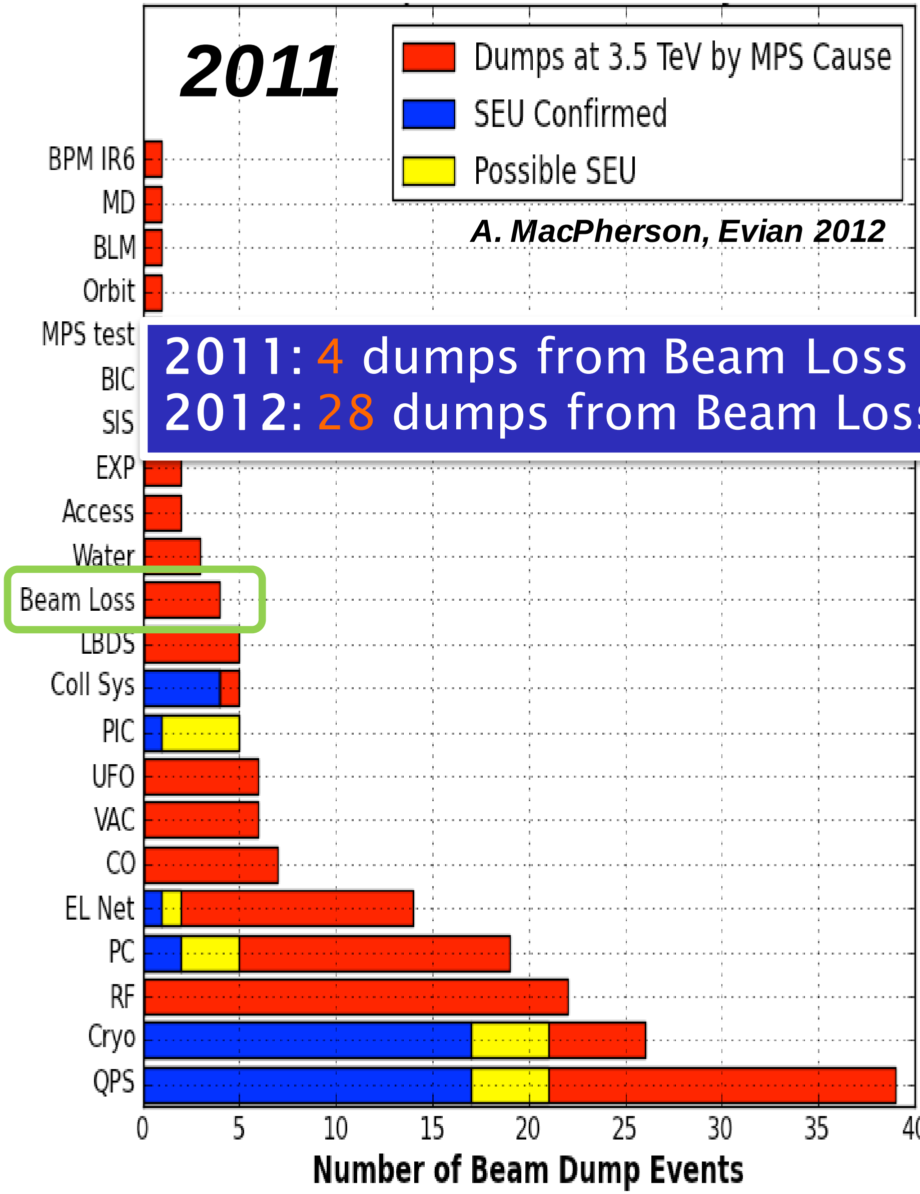


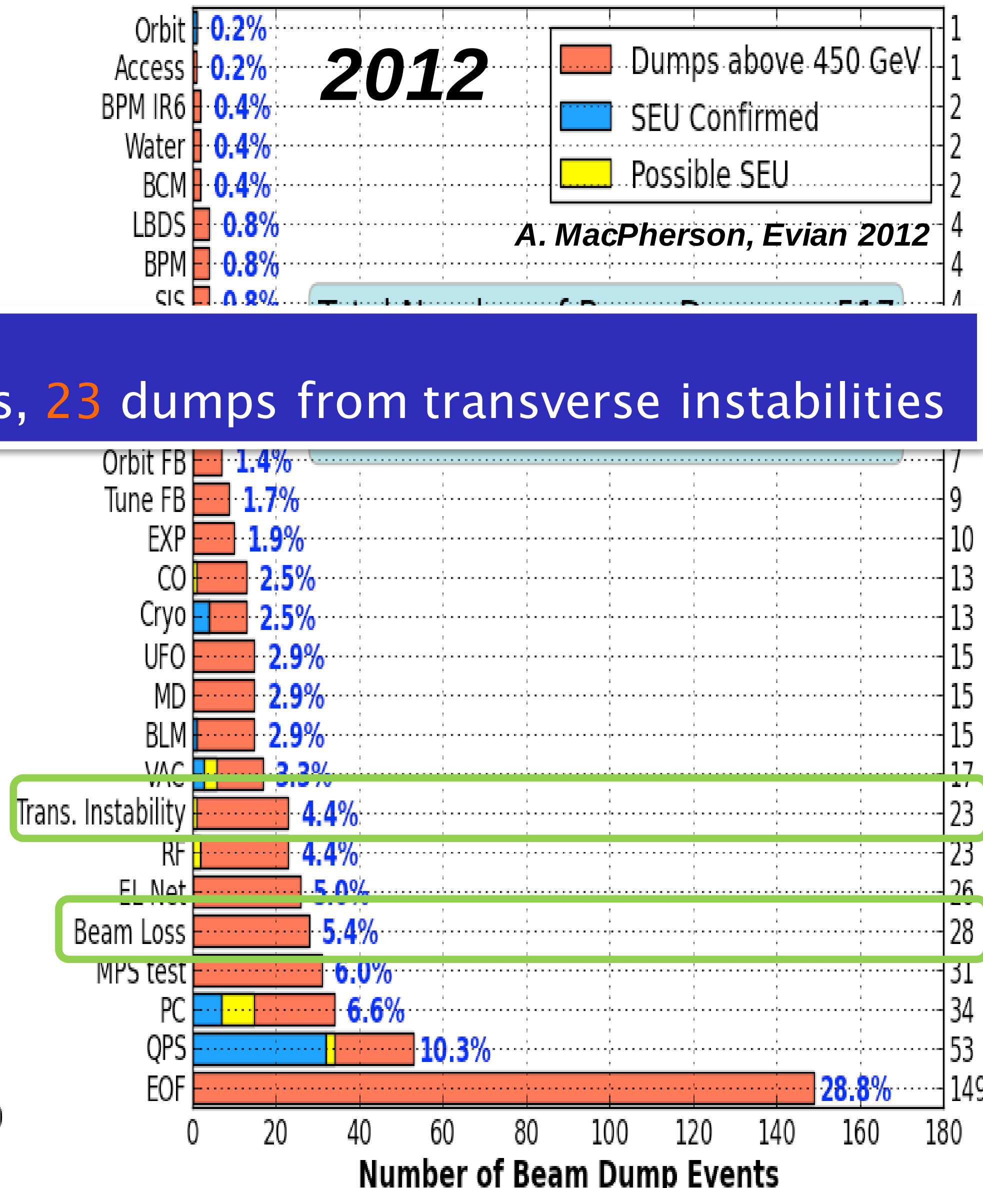
Limits on LHC performance from collimation

- Aperture that we can protect sets limit for β* - moving in collimators frees space to squeeze further
  - So far this has been our main limitation – collimator settings have been optimized to minimize β*
- Other limitations starting to appear in 2012 run
  - More cases of high beam losses and dumps related to tighter settings (orbit movements scraping off beam or impedance effects?)
  - Beam lifetime and cleaning performance limits the maximum intensity – too high losses in cold magnets cause dumps and operational downtime
  - Collimator settings should optimize cleaning while not inducing high losses through too tight gaps or instabilities
- Operational flexibility: time needed for setup and qualification
- Radiation to electronics

Not discussed in this talk

Beam dumps in 2011 vs 2012

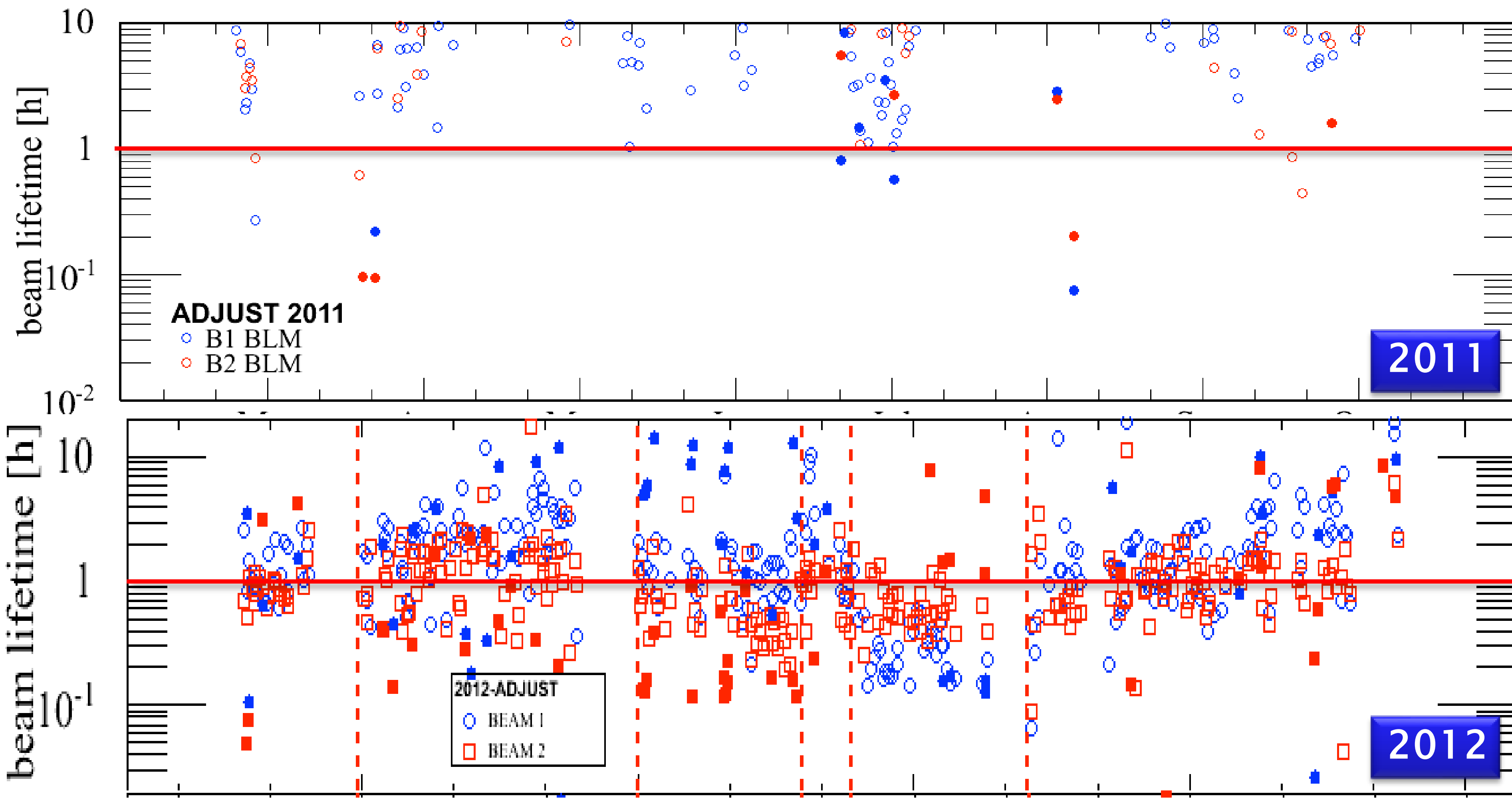




2011: 4 dumps from Beam Loss

2012: 28 dumps from Beam Loss, 23 dumps from transverse instabilities

Lifetime in 2011 and 2012 in adjust



B. Salvachua

2011 vs 2012

- Tighter collimator settings likely cause of worse lifetimes and more dumps
- Extrapolation to 7 TeV: smaller quench margin (but present thresholds too low?), higher total intensity, maybe limits on octupole current etc. Lifetime extrapolation unclear. Should we be worried?
  - Easy way out is always to open collimators and step back in β*
- Clear that we can improve the lifetime through operational optimization (octupole strength and polarity, chromaticity, new collision beam process etc)
- Hard intensity limit from collimators probably not yet reached
  - Injectors could maybe have delivered 10-15% higher bunch intensity, but other limitation causing us to hold back was blow-up in the LHC
- With the quench test in hindsight, could we have raised the BLM thresholds and had fewer dumps? See later talks.

Worth going to tight settings?

- Assuming that all additional 2012 dumps from transverse instabilities and beam losses were caused by the tighter settings
  - 47 additional beam-loss related dumps in 2012
  - With a 4 hour turnaround: 184 hours = 7.7 days lost
  - With an average luminosity in stable beams of 3.6e33 $cm^{-2} s^{-1}$, we lost 2.4 fb^{-1}
- Alternative: we could have stayed at relaxed collimator settings at β^*=90cm
  - Scaling the total luminosity achievable in 2012 without dumps (25.7 fb^{-1}) by ratio of the peak lumi, we would have had 18.5 fb^{-1} instead of the 23.3 fb^{-1} achieved
  - In spite of dumps, tight settings still paid off in integrated luminosity!
- **Conclusion: we probably did the right thing in 2012 to push β^* to the limit!**

Integrated luminosity as function of the number of dumps

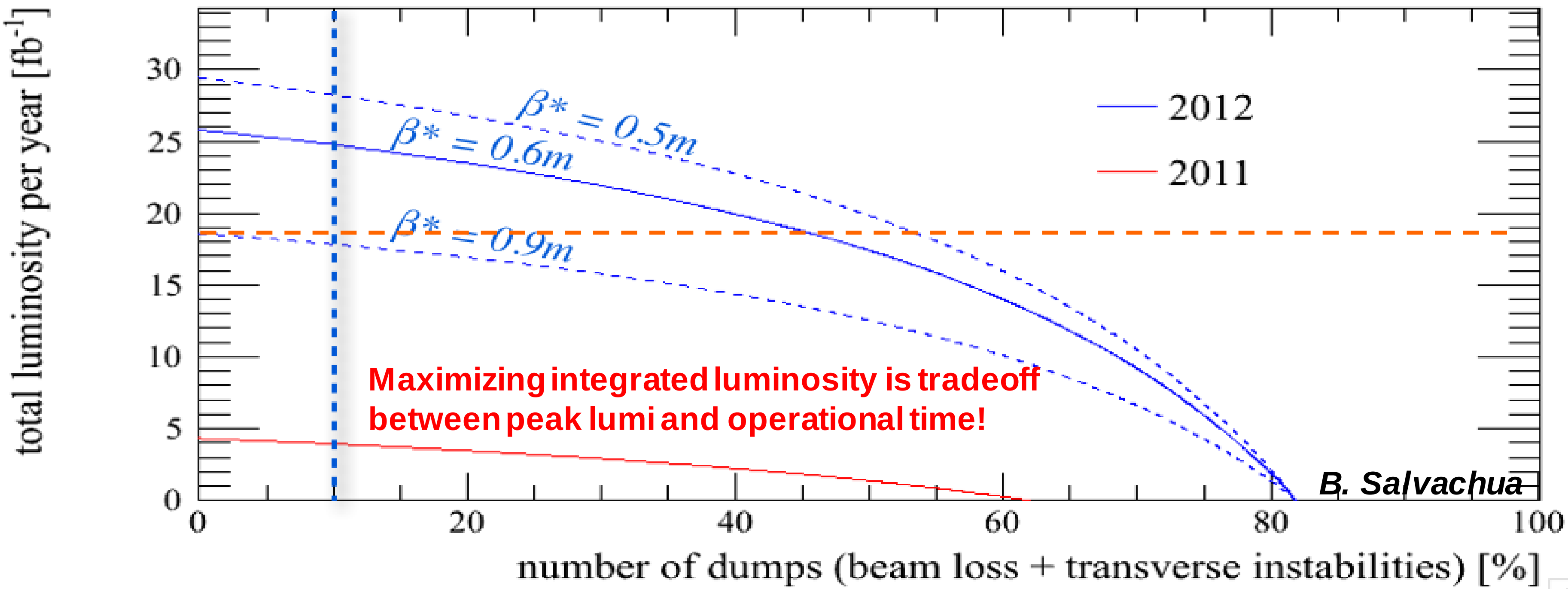
$$L_{tot} = L_{avg} n_{stab} T_{stab}$$

$$T_{tot} = n_{stab}(T_{stab} + T_{down}) + n_{dump} T_{dump}$$

- Solve for total luminosity as function of the number of dumps for qualitative picture
- β*=90cm only pays off if, at β*=90cm, n_{dump} >45%

2011
LHC available days: 160*0.56
average luminosity time per fill: 5.76 h
mean turn around time: 3.87 h
average luminosity: 1.16e33cm-2s-1

2012
LHC available days: 205*0.58
average luminosity time per fill: 5.96 h
median turn around time: 2.8 h
average luminosity: 3.6e33cm-2s-1



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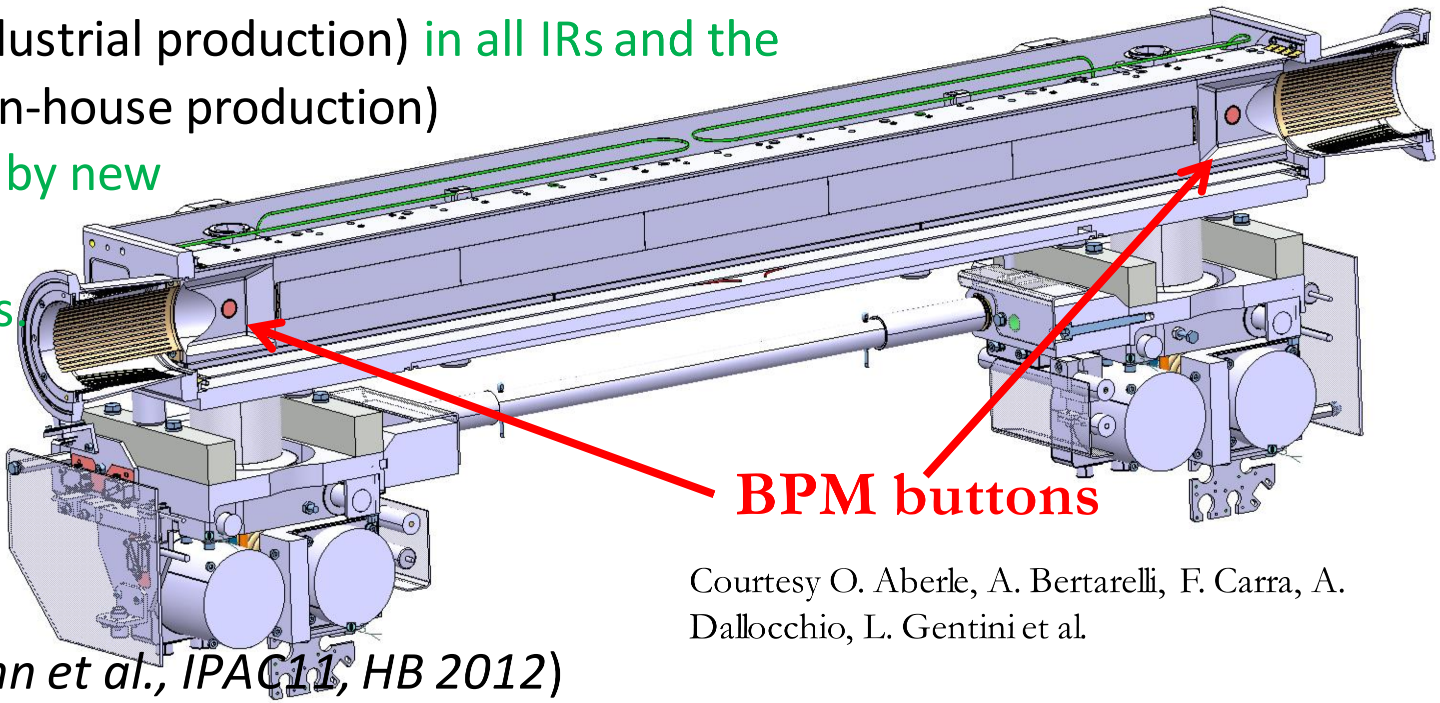
LS1 improvements – integrated BPMs

- 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 collimator settings after LS1

- Using same philosophy for calculating margins IR6-TCTs-triplets as in 2012

	Case 1: relaxed settings, no BPM buttons	Case 2: same as today in mm, no BPM buttons	Case 3: Keeping retractions in σ, no BPM buttons	Case 4: same as today in mm, BPM buttons	Case 5: Keeping retractions in σ, BPM buttons,
TCP 7	6.7	5.5	5.5	5.5	5.5
TCSG 7	9.9	8.0	7.5	8.0	7.5
TCLA 7	12.5	10.6	9.5	10.6	9.5
TCSG 6	10.7	9.1	8.3	9.1	8.3
TCDQ 6	11.2	9.6	8.8	9.6	8.8
TCT	12.7	11.1	10.3	10.0	9.1
aperture	14.3	12.6	11.7	11.2	10.3

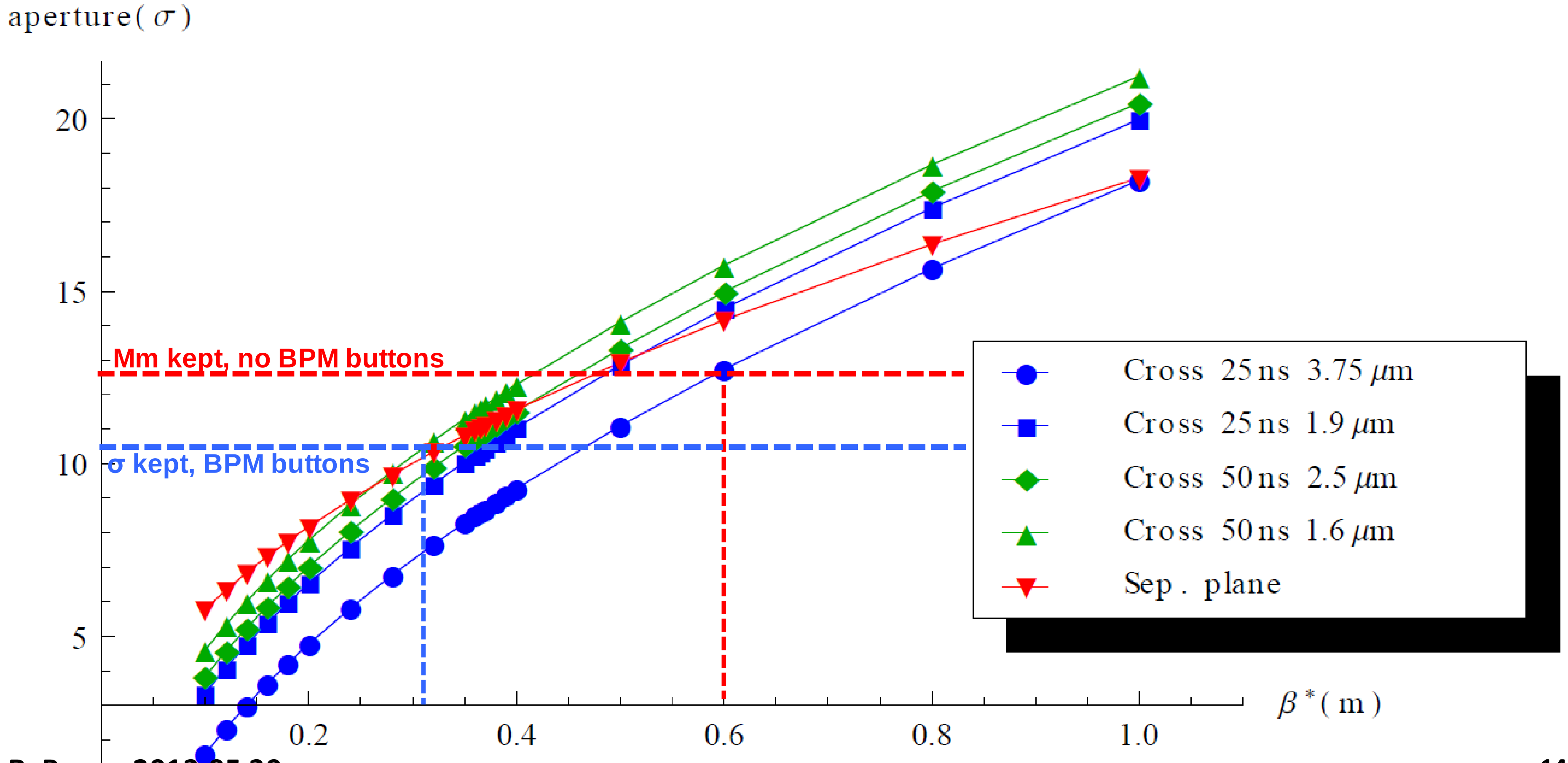
Should work for cleaning hierarchy

Might require more frequent setups

- **No constraints from impedance** accounted for
- Full use of BPM buttons require following the beam – movement scheme and interlocking still to be defined. Not for the startup directly after LS1.
- **New iteration** of needed margins will be done when HiRadMat test results on are fully analyzed and **TCT damage limit** calculated in realistic scenario. No dramatic changes expected.

Preliminary β*-reach

- Crossing plane aperture scaled from most pessimistic 2011/2012 measurements (11 σ at 4 TeV, 60cm, 145 μrad) to 6.5 TeV configurations
- Reach in β* between ~31cm and ~60cm in crossing plane unless reverting to relaxed settings



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TCSG 6	10.7	9.1	8.3	9.1	8.3
TCDQ 6	11.2	9.6	8.8	9.6	8.8
TCT	12.7	11.1	10.3	10.0	9.1
aperture	**14.3**	**12.6**	**11.7**	**11.2**	**10.3**
Half crossing angle (25 ns) [μrad] ϵ=1.9 or 3.75 μm	129/165	140/180	149/189	154/194	163/205
β* (25 ns) [cm] ϵ=1.9 or 3.75 μm	**62/72**	**50/60**	**45/55**	**42/52**	**37/46**

Startup in 2015? (Case 1, Case 2)

>2016? (Cases 3–5)

- Which configuration maximized integrated luminosity?

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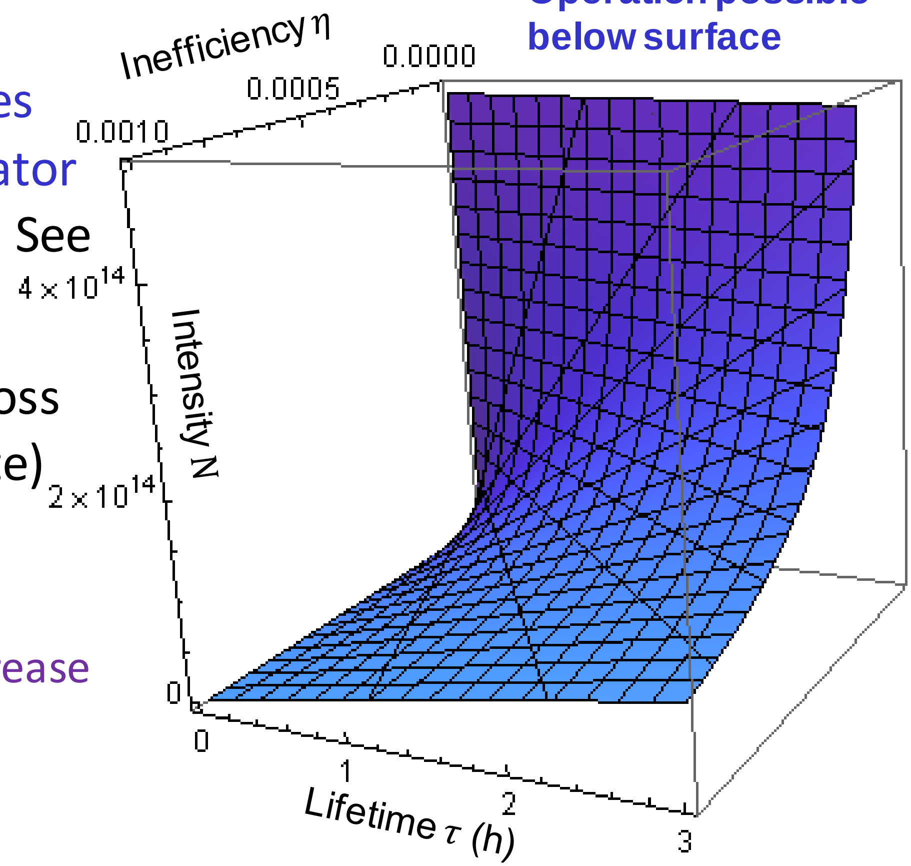
Considerations for the future

- After LS1, need to ensure that we don't lose in integrated lumi due to more dumps. Optimum between pushing β* and operational downtime?
- Ideally: predict the probability of high losses causing a dump as a function of the collimator gaps and intensity - extremely challenging! See next talk N. Mounet for impedance
- For collimation, operation possible if the loss rate on magnet (inefficiency x total loss rate) stays below quench limit: $\frac{N\,\eta}{\tau} \leq R_q$
  - Best: increase lifetime τ. Second best: Decrease cleaning inefficiency η. Having margins in η provides operational flexibility!
    Bad: Decrease intensity N

Operation possible below surface



Improvements for the future (1)

- Without knowing the exact dependence of the dump probability on the collimator settings, we can still improve
- If we are not limited by impedance from IR7/3: smaller margins
  - Aim for nominal settings in IR7. BPM buttons in IR7 might help
- Improvements in β*, without changing significantly the impedance (not touching IR3/7):
  - BPM button collimators: reduce TCT margins, keep the main impedance contributors in IR7 and IR3 unchanged. Smaller β* permitted without increasing impedance!
  - Improved models for margins, accounting for the actual TCT and triplet damage limit (see talk in MPP review). Smaller β* permitted without increasing impedance!
  - More robust TCTs?
  - HL-LHC: upgraded triplets with larger aperture etc.

Improvements for the future (2)

- Improving the beam lifetime
  - Operational optimization very important: Octupole currents and polarity, chromaticity, how and when we go into collisions etc
  - Collimators with new materials in IR7 and IR3, reducing total impedance. Better lifetime?
  - Retracting some collimators to gain impedance, e.g. combined cleaning in IR3 - retract IR7 completely? However, phase space coverage for machine protection might be an issue.
  - Retracting the hierarchy at the expense of β^*
- Improve cleaning:
  - DS collimators
  - But cleaning (losses in the DS) might not be the only bottleneck causing dumps…

Limits at primary collimators

- Observed minimum beam lifetime in 2012 about 0.2 h
  - With nominal intensity: corresponding primary loss rate of 500 kW
  - With 2.2e11 p/bunch and 2808 bunches (HL-LHC): loss rate of about 1 MW
    - For robustness of collimators, presently known max allowed rate is 1 MW. Zero margin!
- We only achieved 64% of quench level in quench test (see talk A. Verweij) => at 4TeV, relaxed settings, quench expected at 1.6MW of primary losses!
- Scale to 7 TeV: quench limit down by factor 4.5, inefficiency down factor >3
  - Expected quench also at about 1 MW, but uncertainty on inefficiency scaling
  - We might hit dump/damage limit of primary collimators before the DS quench limit
    - Dump at quench level or factor 3 below? Need to consider BLM thresholds at TCP and DS
    - But note large uncertainty on scaling of quench limit and inefficiency to 7 TeV!
  - Shows that the improvement of the lifetime is extremely important
  - Need to do further studies to examine the detailed collimator damage limit at 7 TeV
  - Need to study possibilities of increasing damage limit in the future

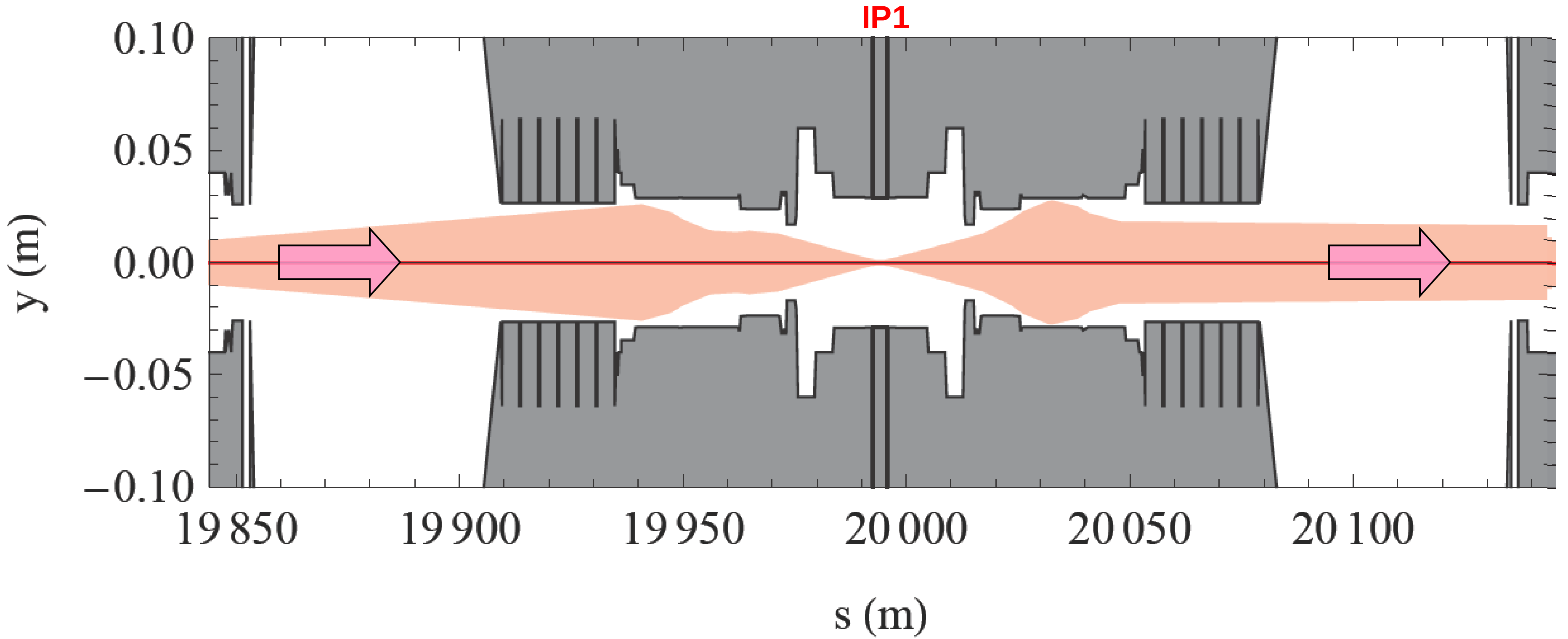
Conclusions

- The collimation system must provide sufficient cleaning and protection. Aperture protection constrains β*
- During 2010-2012, evolution towards tighter settings for minimized β*. Similar evolution after LS1?
- In 2012 run, more beam-loss related dumps due to tighter collimator settings
- In integrated luminosity, it probably still paid off to go to tight settings
- Preliminary performance estimates: 30cm<β*<60cm, depending on plane at 6.5 TeV provided octupole strength and impedance do not cause trouble.
- For the future: make sure that more dumps don't cause loss in integrated lumi.
  - Good beam lifetime and cleaning needed in order not to cause intensity limits.
  - Improved cleaning from DS collimators (~factor 10) could provide important operational flexibility, e.g. improve performance also with relaxed settings
  - Upper limit on TCP losses should be carefully studied

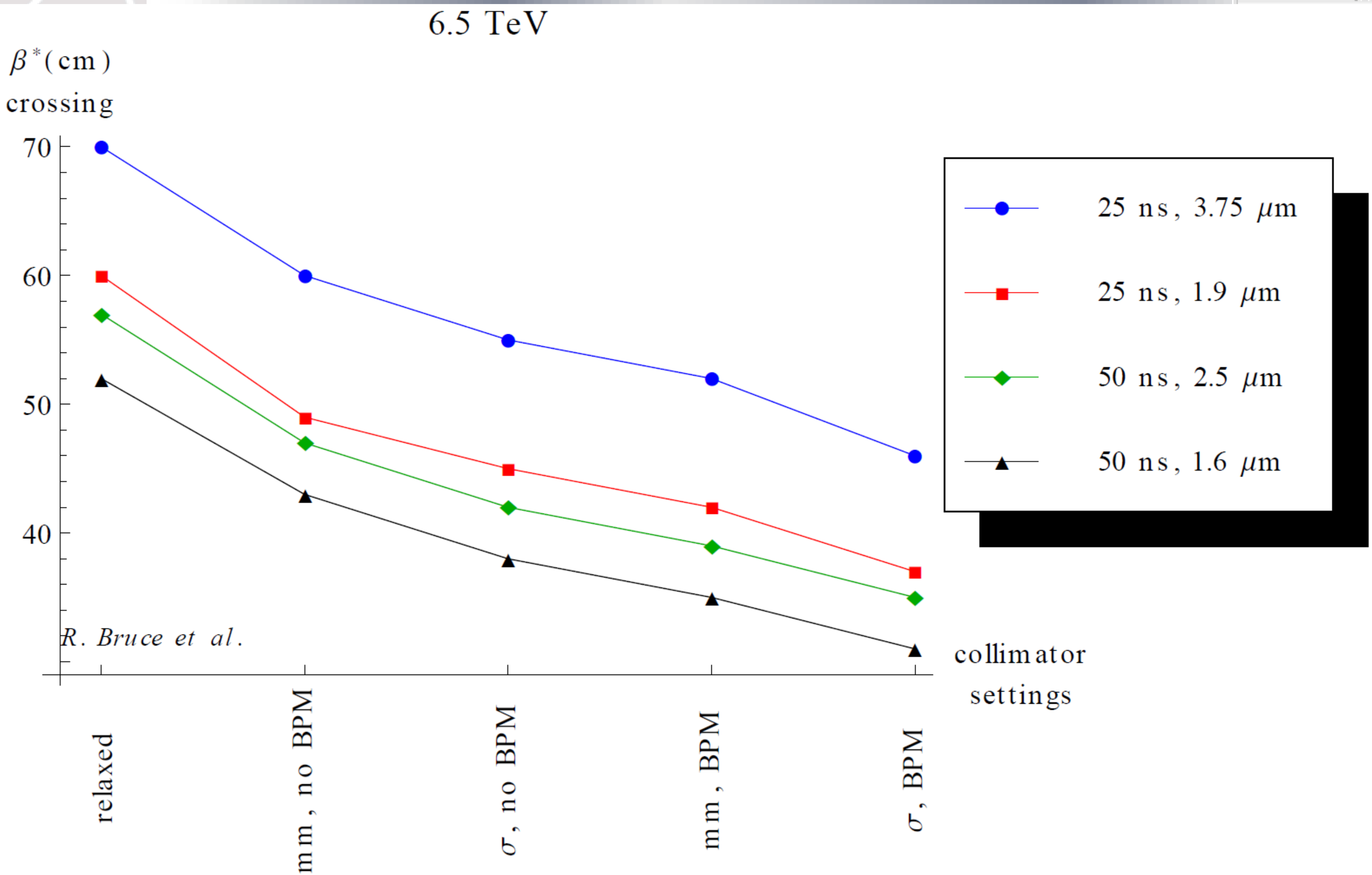
Backup

Aperture and β*

- Main limitations when going to smaller β*
  - Magnetic limits: max gradient in quadrupoles and chromaticity
  - Beam-beam limit …
  - Aperture limit: decreasing margins in triplet when decreasing β. Present limit!



Summary: β*-reach in crossing plane



Can we achieve these settings?

- 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.)
  - With present octupole polarity, possibly not enough strength at 6.5 TeV for too small emittance. With opposite polarity, need larger crossing angle or squeeze in flat mode (S. Fartoukh)
  - If we do not manage stabilize the beam, we might have to open collimators and increase β*.
- No optics constraints treated: We know that off-momentum β-beat and spurious dispersion are more important for smaller β* (S. Fartoukh et al.). Will the aperture be worse? If so, we might have to step back in β*. ATS?
- Careful aperture measurements required as part of commissioning before final decision on β* is taken.
- Operational procedures to be established for BPM collimators – possibly startup period required to gain operational experience before full gain in margin is exploited

Summary: preliminary β*-reach

50 ns, 2.5 um	beta* crossing (cm)	beta* separation (cm)	Half crossing angle (urad)	BB sep (sigma)
mm scaled, no BPM	47	49	129	9.3
mm scaled, BPM	39	39	141	9.3
2 sig retraction, no BPM	42	43	136	9.3
2 sig retraction, BPM	35	33	150	9.3

50 ns, 1.6 um	beta* crossing (cm)	beta* separation (cm)	Half crossing angle (urad)	BB sep (sigma)
mm scaled, no BPM	43	49	108	9.3
mm scaled, BPM	35	39	119	9.3
2 sig retraction, no BPM	38	43	115	9.3
2 sig retraction, BPM	31	33	127	9.3

25 ns, 3.75 um	beta* crossing (cm)	beta* separation (cm)	Half crossing angle (urad)	BB sep (sigma)
mm scaled, no BPM	60	49	180	12
mm scaled, BPM	52	39	194	12
2 sig retraction, no BPM	55	43	189	12
2 sig retraction, BPM	46	33	205	12

25 ns, 1.9 um	beta* crossing (cm)	beta* separation (cm)	Half crossing angle (urad)	BB sep (sigma)
mm scaled, no BPM	49	49	141	12
mm scaled, BPM	42	39	154	12
2 sig retraction, no BPM	45	43	149	12
2 sig retraction, BPM	37	33	163	12