Collimator hierarchy limits: assumptions and impact on machine protection and performance

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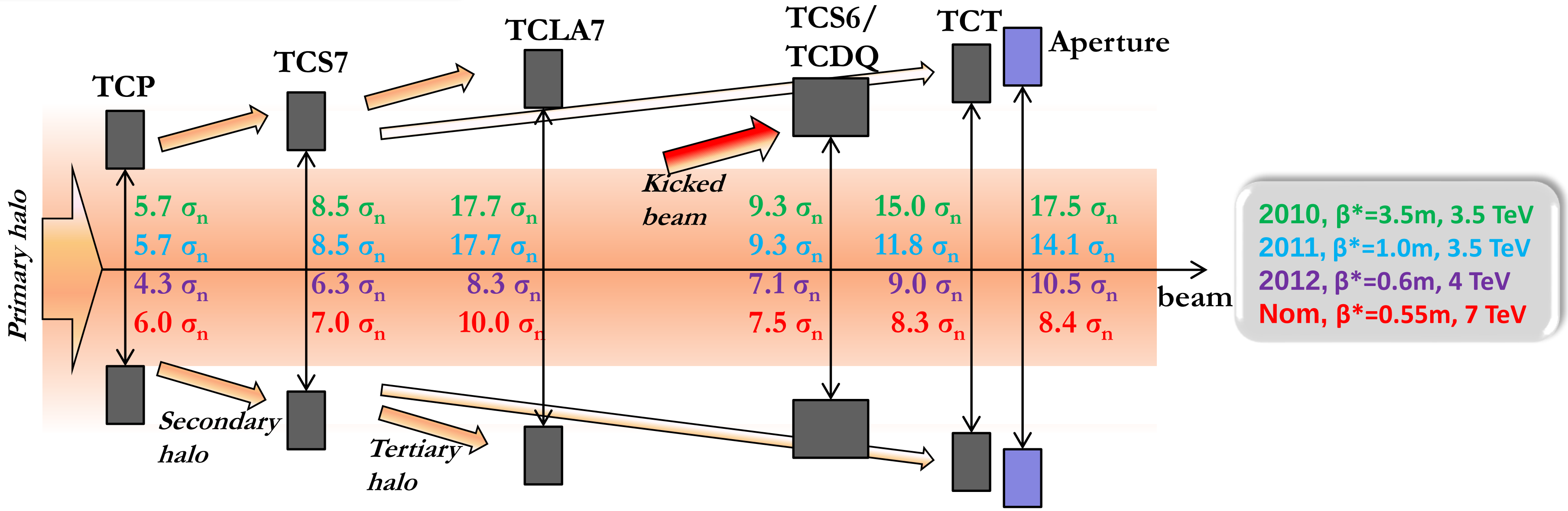
Outline

- Introduction: Influence of LHC collimation system on machine performance
- Review of methods for calculating collimator settings
- Improvements of calculation of margin from optics errors (ongoing work)
- Changes in LS1 and preliminary post-LS1 scenarios
- Future work and conclusions

Collimation system

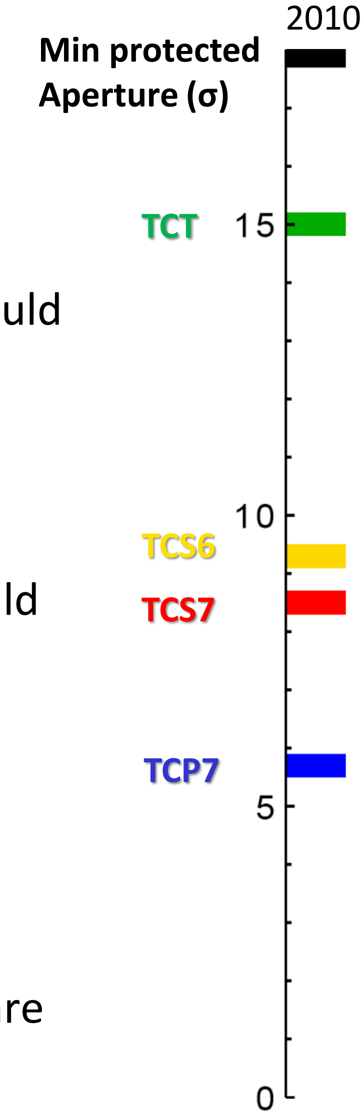
σ calculated with emittance = 3.5μm



- 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
- Aperture that we can protect sets limit for 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 that are really needed – could 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
  - Slight gain in orbit
  - Gain from statistical approach – adding margins in square
  - β* successfully squeezed to 60cm



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Margins for cleaning

- Margins for cleaning (slow losses) are less critical than margins for protection
  - If hierarchy is violated and cleaning performance is insufficient we dump the beam, causing delays in operation, but no machine damage
- Cleaning margins in IR7
  - in 2010 and 2011 calculated by keeping the same retraction in mm as at injection (relaxed settings) in order to provide sufficient room for imperfections (optics / orbit stability)
  - In 2012, we reduced margins in IR7 based on empirical studies: MD on tight settings.
  - Tight settings improve cleaning by up to one order of magnitude at the same time as we get more room to squeeze β^*

Margins for protection

- Collimators should also protect in case of accidents, in particular dump failures.
  - If margins are violated: sensitive equipment risks to be exposed and hit by beam
  - In worst case, this could cause damage
- Critical margins (IR6-TCT-aperture) calculated based on in-depth analysis of previous runs
- Components of critical margins: orbit, optics errors, 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 2010-2011).
- Collimator settings calculated using square sum of errors except van der Meer scans (see Evian 2011 and Chamonix 2012).

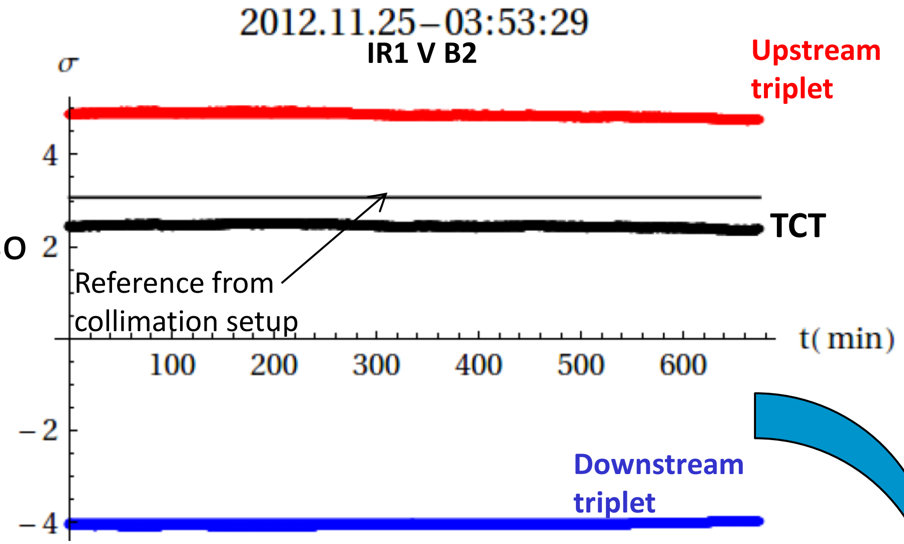
$$\Delta_{total} = |\Delta_{vdM}| + \sqrt{\sum_i \Delta_i^2}$$

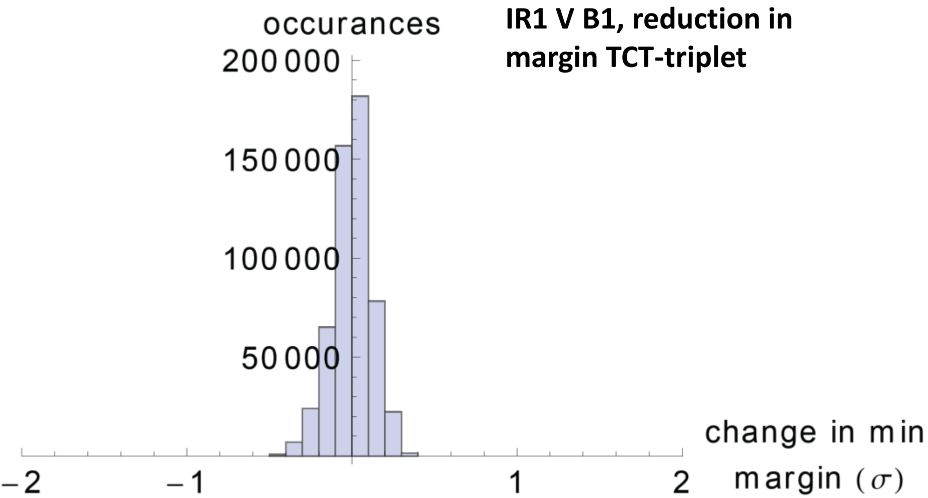
Margins from setup, reproducibility and lumi scans

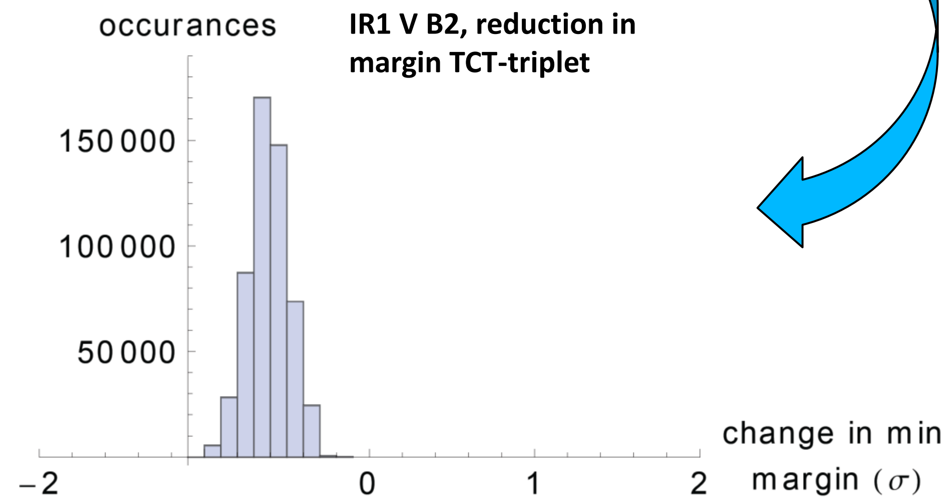
- Setup errors
  - resulting from a non-perfect collimator alignment.
  - Assuming 10 μm as upper limit on the step size
- Reproducibility errors
  - resulting from collimators not going back to the exact same position in subsequent fills.
  - Negligible most of the time, but can be significant after power cuts, although now better recovery procedures are in place
  - Assuming 50 μm
- Lumi scans
  - During scans, orbit is deliberately moved so that margins at TCTs and triplets are reduced
  - Presently assuming 0.2 σ – sufficient for a ±3 σ scan at β^*=60cm, 4 TeV

Margins for orbit – 2012 example

- Calculating reduction in margin (in σ) due to orbit drifts compared to orbit during collimation setup
- Considering all periods with stable beams – so far, sampled every 15 seconds – 1 minute.
- Statistical approach – calculating the needed margin to protect against 99% of observed drifts. Artifacts from temperature effects?







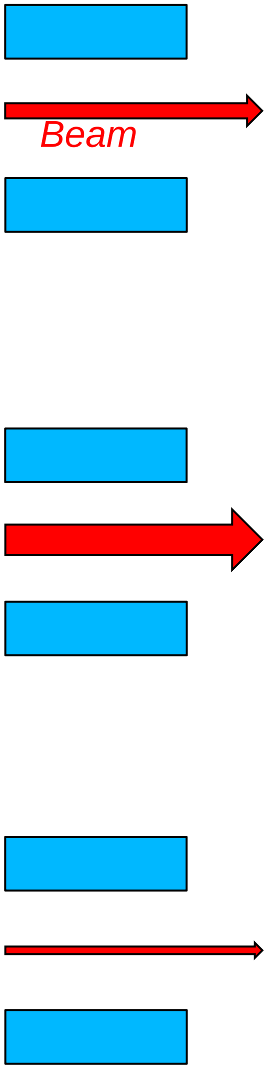
Margins for optics errors

- So far: assume most pessimistic β-beat and calculate needed margin
  - Assuming now +10% at location to protect, -10% at protection device (very pessimistic!)
  - Change in margin (in σ) of an aperture is given by

$$M_\beta = n\left(\sqrt{\frac{\beta_n}{\beta_r}} - 1\right)$$

  - Implicit pessimistic assumption: aperture bottlenecks always at 90 deg from kick
- More detailed model: account for full phase space motion
- First study on leakage to ring collimators during abnormal dumps, including the actual phase advance with imperfections, done in **PhD thesis by T. Kramer (2011)** for beam 1 at 7 TeV, nominal machine

Example:



Nominal: 7.1 σ distance to the beam

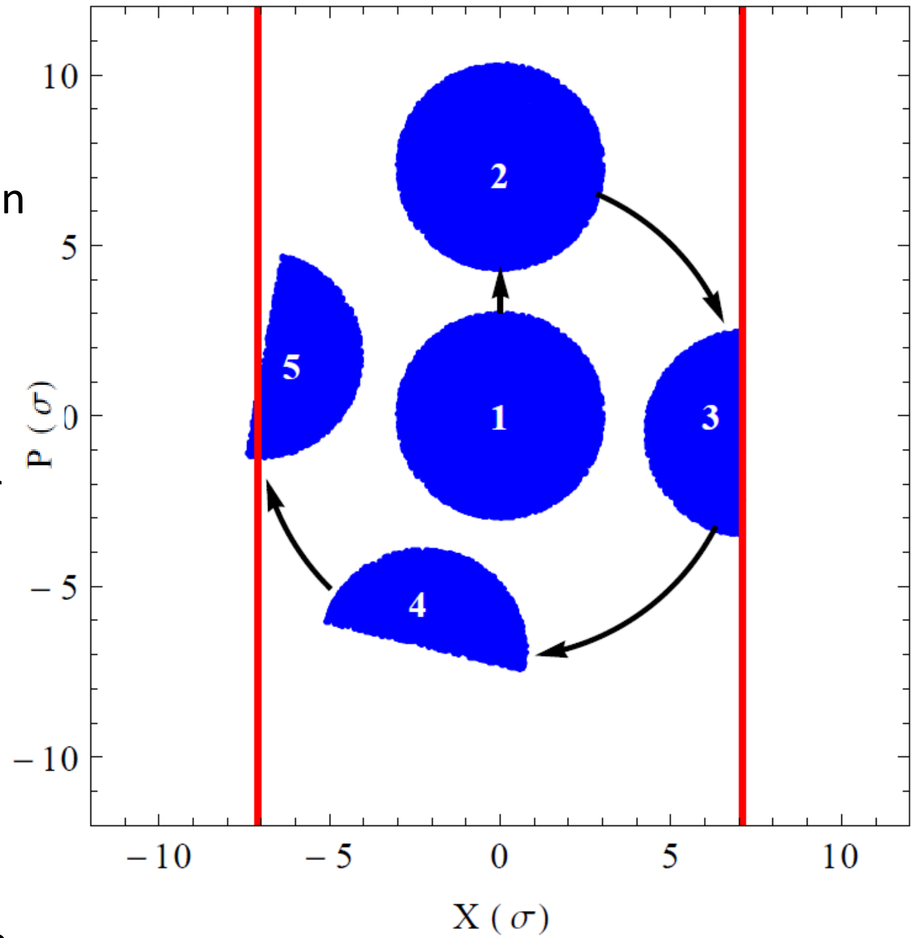
+10% β-beat: 6.8 σ distance to the beam

-10% β-beat: 7.5 σ distance to the beam

Schematic phase space motion

- Example: Initial bunch (1) kicked (2), cut by protection device at 94 deg (3)
- With a favorable phase advance, aperture (4) is not in danger of intercepting remaining beam
- For a less favorable phase advance (5), a fraction of a bunch can still hit an aperture at the same opening as the protection device
- Idea 1 - conservative approach:
  - calculate largest amplitude of surviving beam for given halo extension, e.g. 4.3 σ cut by primary collimators
  - All sensitive equipment should be at larger amplitudes
  - Very pessimistic! Larger margins needed than presently used
- Idea 2: Based on damage limit, we can calculate margin that limits leakage to acceptable level

Normalized phase space of kicked beam



More details to follow in CWG talk

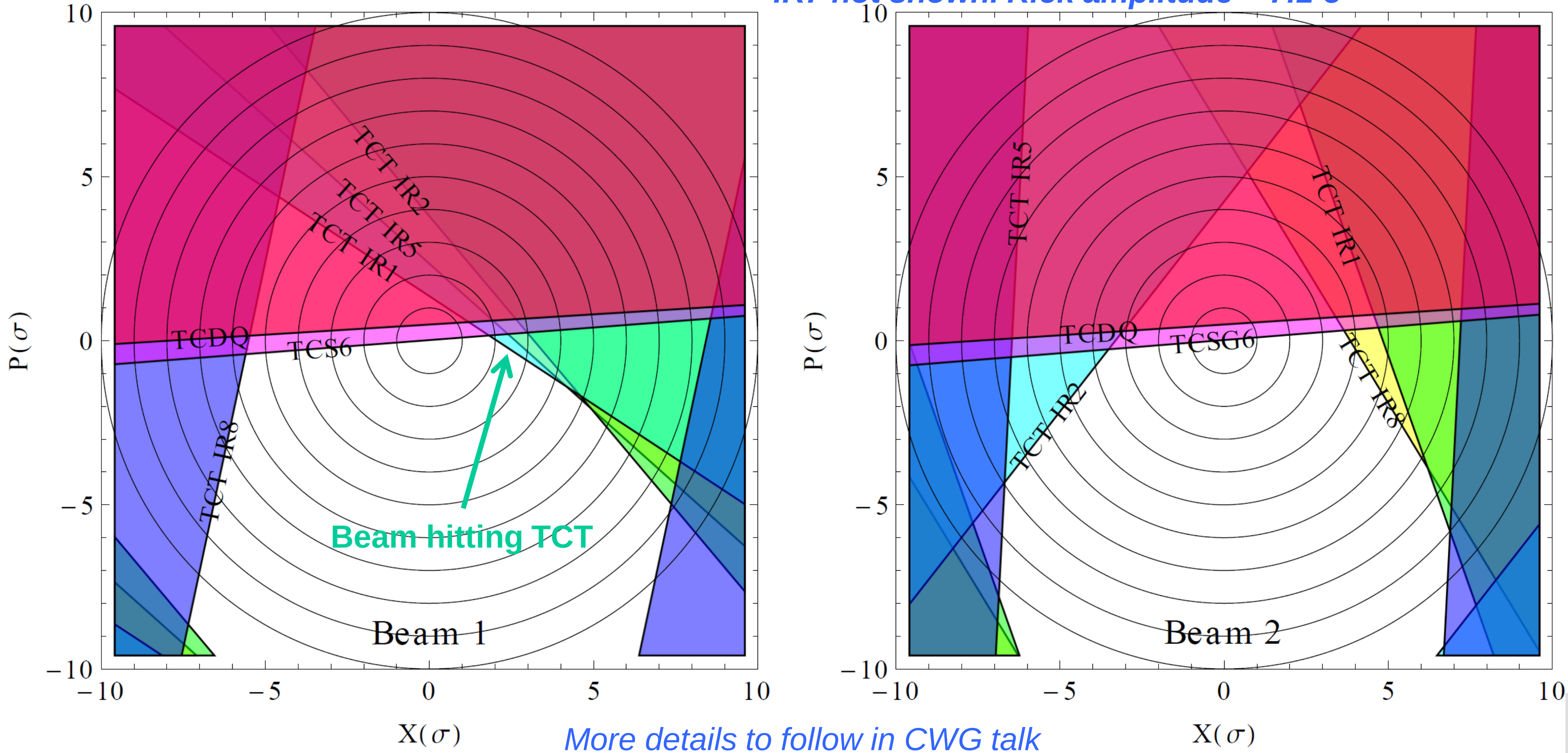
Work in progress: margins with allowed (small) leakage to TCTs

- Each collimator makes cut in the initial phase space (before kick). In linear approximation

$$|C_{0i}X_0 + S_{0i}P_0 + S_{0i}\theta + D_i\delta| \geq A_i$$

- We can integrate bunch distribution over phase space area outside the cut of a collimator but inside all upstream collimators

Example: β*=60cm, all TCTs and IR6 TCSG at 7.1 σ, IR7 not shown. Kick amplitude = 7.1 σ



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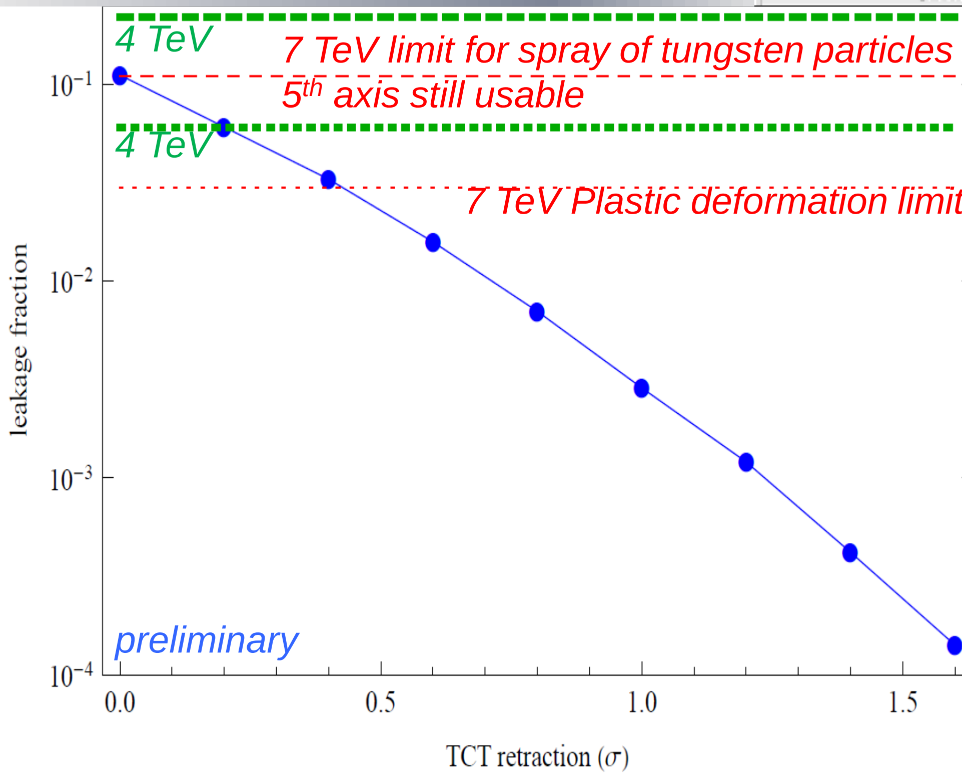
Margins with allowed (small) leakage to TCTs

- Scan over:
  - Different kicks (in this example, 1 bunch every 50 ns along rise of dump kickers)
  - Different configurations of optics errors. 1000 random non-perfect optics configurations with 10-15% β-beat studied – real optics not known within measurement error.
  - Different TCT retractions
- For each TCT retraction, calculating the smallest leakage higher than 99% of all optics configurations
- With TCT damage between 5e9 and 2e10 p (**talk A. Bertarelli**), the leakage with our present 0.55 σ margin is well below damage. 2012 operation was safe, maybe even cautious?



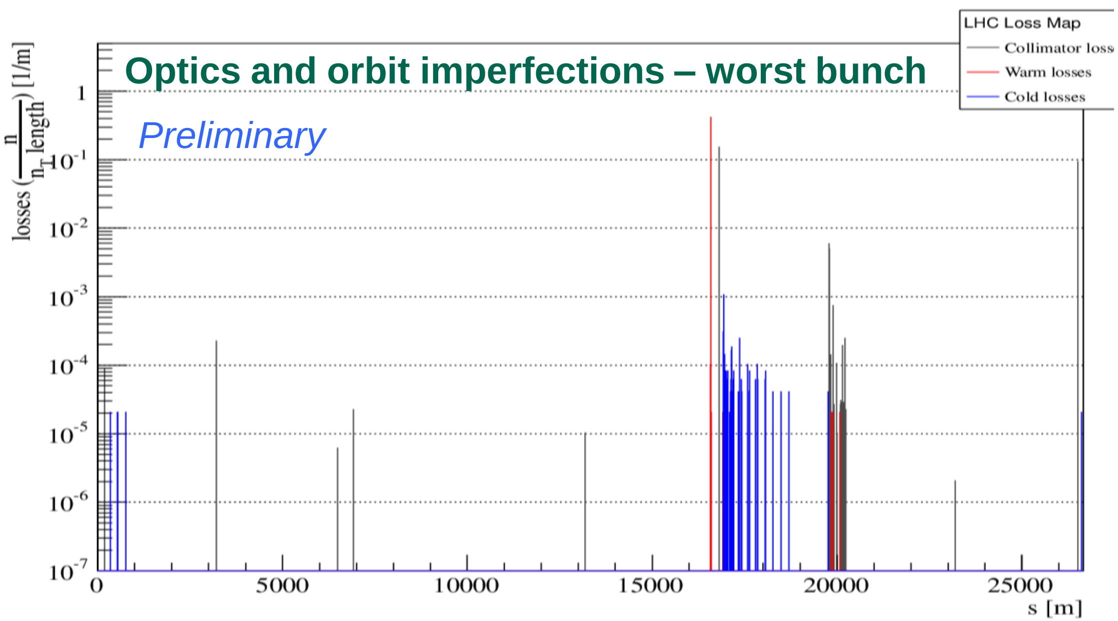
Leakage (in fraction of 1 bunch) hitting the TCT, summed over all bunches during pre-fire of one kicker – 4 TeV, 50 ns, β=60cm*

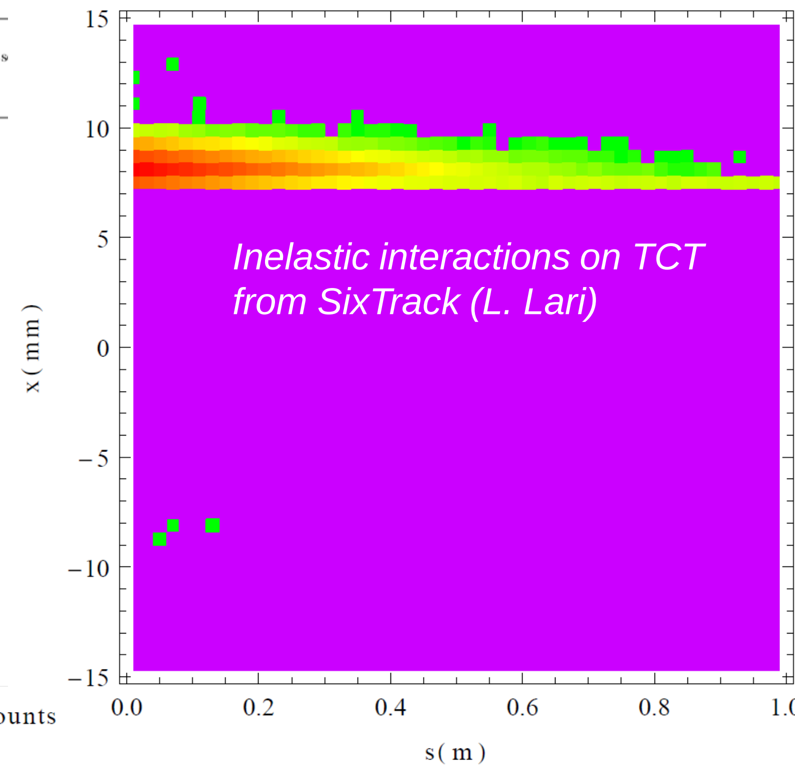
Other failure types still to be studied, as well as 25ns and smaller β*.

Impacts on IR1 TCT

- As by-product, we can estimate impacts on a TCT in a realistic worst-case scenario
- Taking worst case of 1000 random optics error configurations + additional orbit shift in IR7 (VERY pessimistic!)
- Using modified SixTrack (L. Lari), considering 4 TeV and 60 cm
- Integrated over all bunches, about 30% of one bunch hits the TCT in positive x
- Next: FLUKA + Autodyn? (talk A. Bertarelli). Repeat for 6.5 TeV.

More details in CWG March 18





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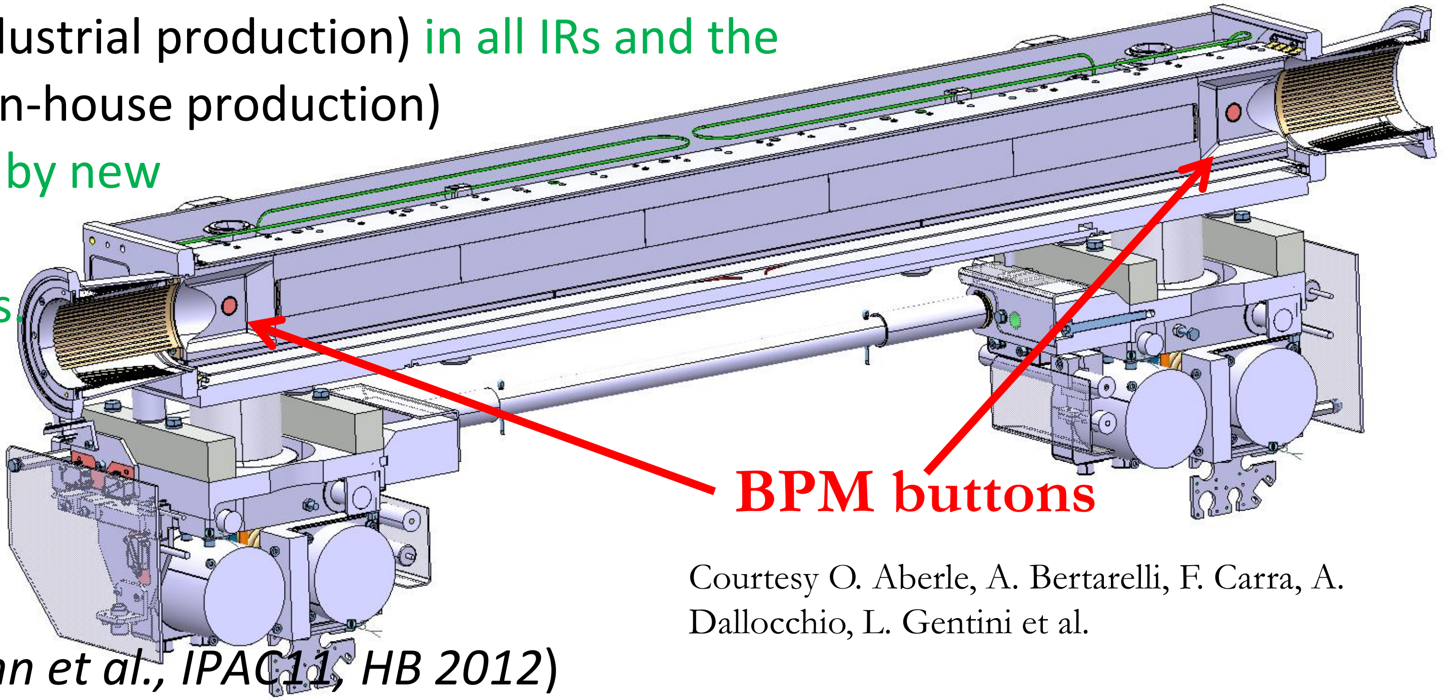
LS1 improvements – integrated BPMs

- 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**

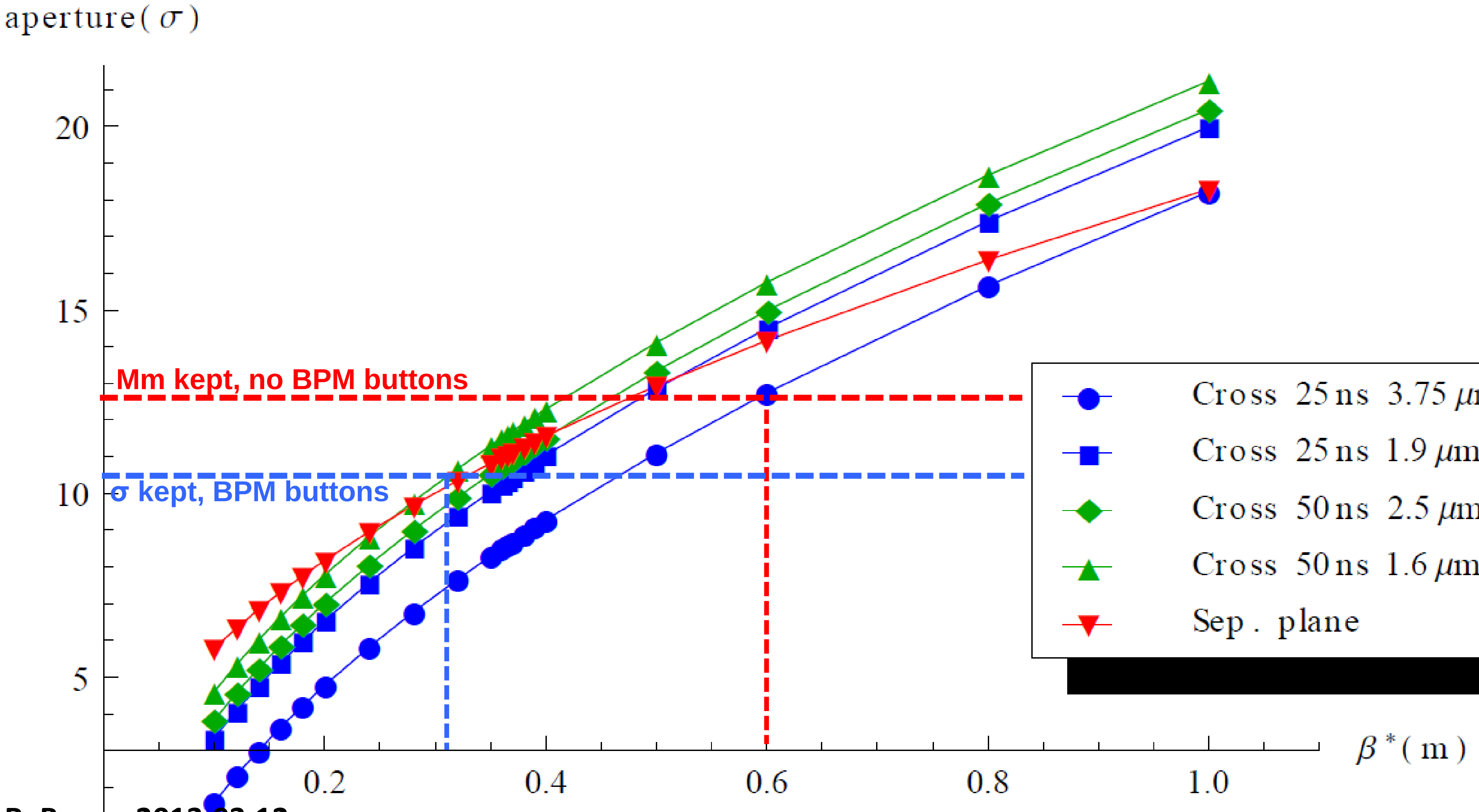
Should work for cleaning hierarchy

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



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

Future work on calculations of collimation margins

- Improved model of margins for optics errors, taking into account material damage limit and allowing small leakage.
  - HiRadMat results to be fully analyzed
  - Realistic failure scenario to be simulated with SixTrack+FLUKA+Autodyn for structural analysis
  - Study needed optics margins at different β* for all dump failure cases
- Checks of margin TCT-triplet – what is the triplet damage limit?
- Can we gain margin in terms of optimized phase advance? Optics by S. Fartoukh with 90 instead of 94 deg phase advance dump kicker – TCDQ to be checked. Can we optimize phase advance to critical TCTs as well?
  - Drawback: how accurately can we actually correct the phase advance in the machine?
- Comment B. Goddard: Can we measure the β-function using the in-jaw BPMs at the collimator to improve the accuracy of the σ-opening?
- comment B. Goddard: Check probabilities for filling the abort gap through RF failure
- So far, we had no asynchronous beam dump in stable beams during 3 years of operation. Are we just lucky or is the beam dump system better and more reliable than expected? Include lower probability of asynchronous dump in calculations?

Conclusions

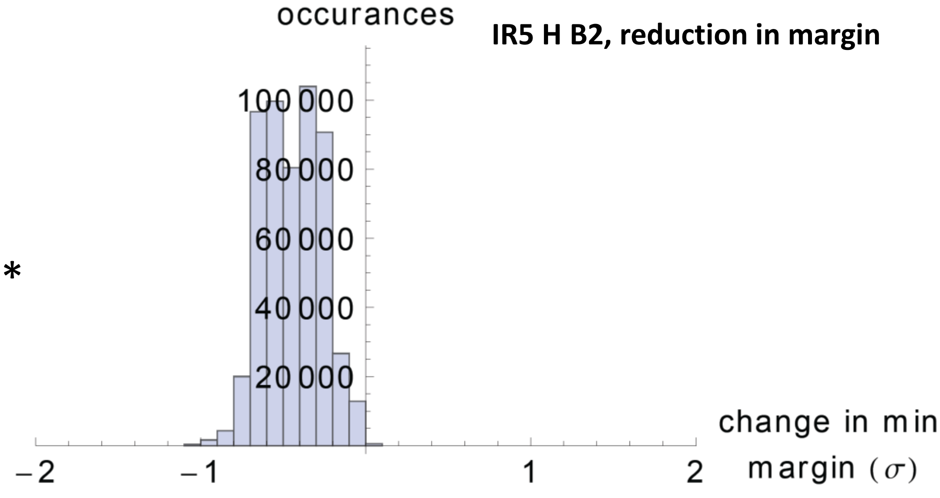
- The collimation system must provide sufficient cleaning and protection
- Collimator settings constrains β^*
- During 2010-2012, evolution towards tighter settings for maximized luminosity.
- Margin components: errors on orbit, optics, lumi scans, reproducibility, setup
- Ongoing work: revision of optics margins in view of improved estimates of TCT damage limit. Margins can allow a small and safe leakage to sensitive equipment
- TCTs and TCSG in IR6 to be replaced in LS1 by collimators with integrated BPMs. Operational experience needed after startup before going to the limit in β^*
- Preliminary collimator settings for after LS1 presented – to be revised after updates in calculation models, but no dramatic changes expected
- Preliminary performance estimates: $30\text{cm}<\beta^*<60\text{cm}$, depending on plane at 6.5 TeV provided octupole strength and impedance do not cause trouble.

Backup

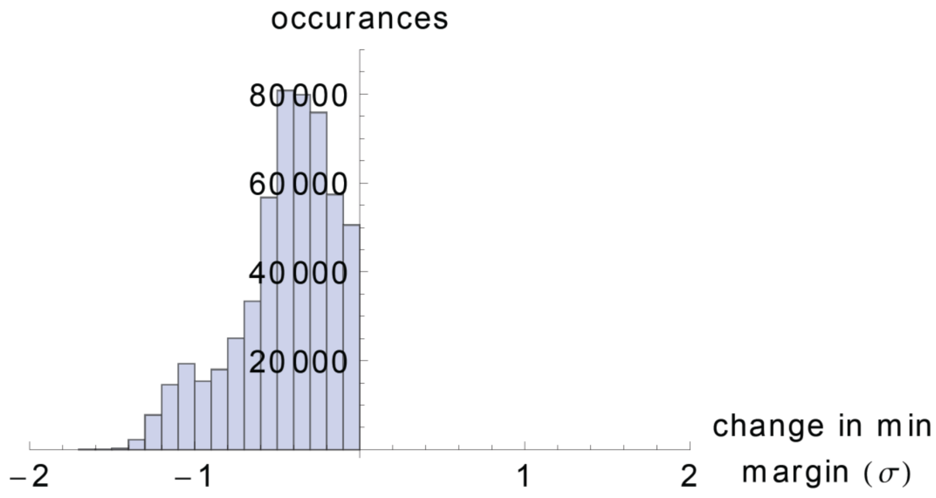
2012 orbit stability in stable beams

- IR5 better than last year
- Worst case is 0.9 σ for a 99% coverage between TCT/triplet (was 1.1 σ in 2011).
- Compatible with change of beam size from β* and energy
- 1.3 σ needed for 99% coverage IR6/TCTs (was 1.1 σ in 2011)
- Slightly worse than expected from change in beam size
- Artifacts from temperature effects? For now we conservatively assume a real effect
- No dramatic changes wrt 2011

IR5 H B2, reduction in margin

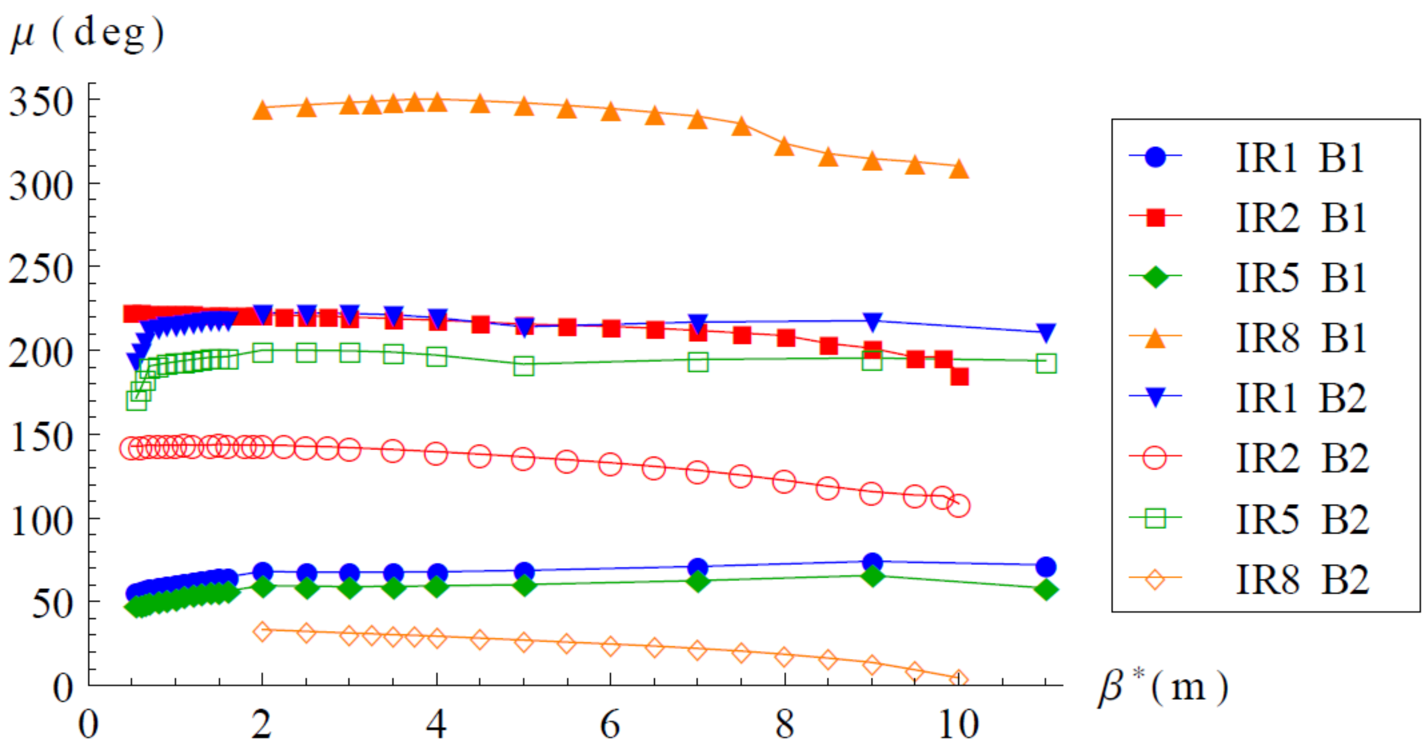


reduction in margin IR6 – IR1 B2 H



TCT phase as function of β*

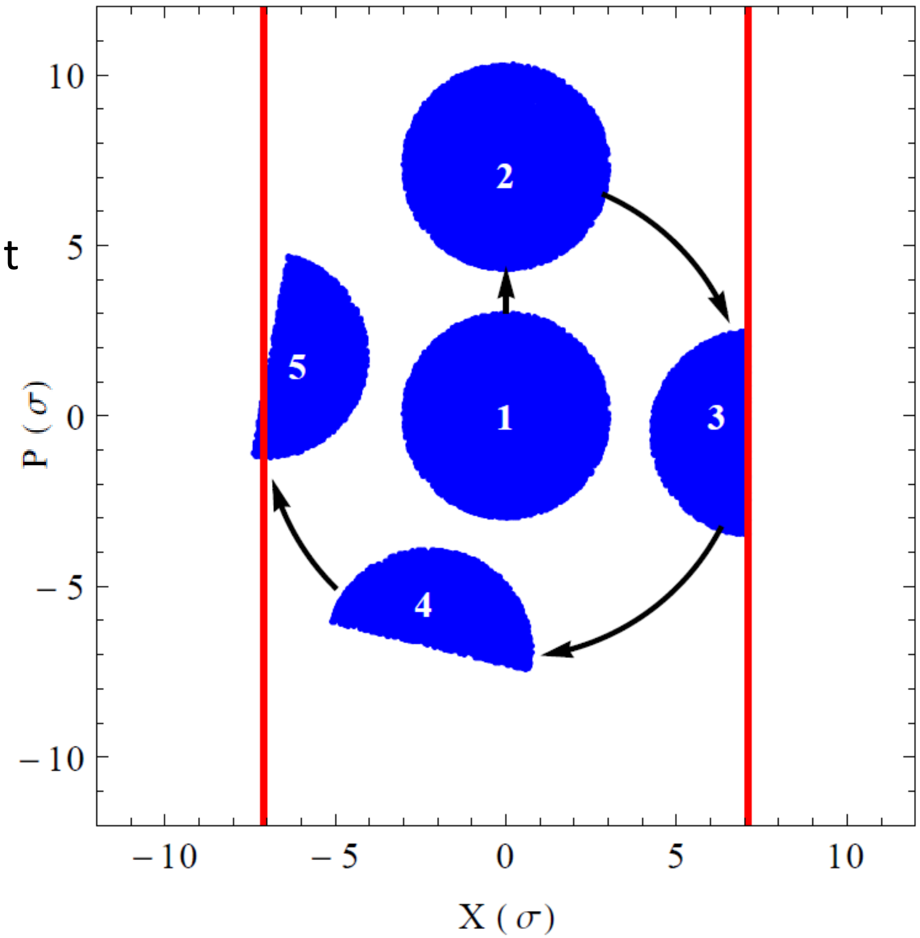
- Phase advance from central dump kicker to the TCTs calculated for each β* in nominal optics
- IR1 B1 most critical – closest to an odd multiple of 90 deg.



Margins for a complete shadowing

- Assume a maximum transverse extension of the beam, given by the cut of primary collimators (radius at **1**).
- Assume the whole beam is kicked by given amplitude (**2**).
- Assume a certain part of the kicked beam is cut by the dump protection (**3**) as function of kick amplitude
- We can analytically calculate the maximum amplitude escaping to a downstream position at given phase advance (**4,5**)
- About 2 σ retraction IR6-TCT needed for complete protection, including errors of +- 10 deg. on phase and 10% beta-beat. 2.8 σ for protection on all phases
- Pessimistic! The TCTs are made to intercept particles and survive a small leakage

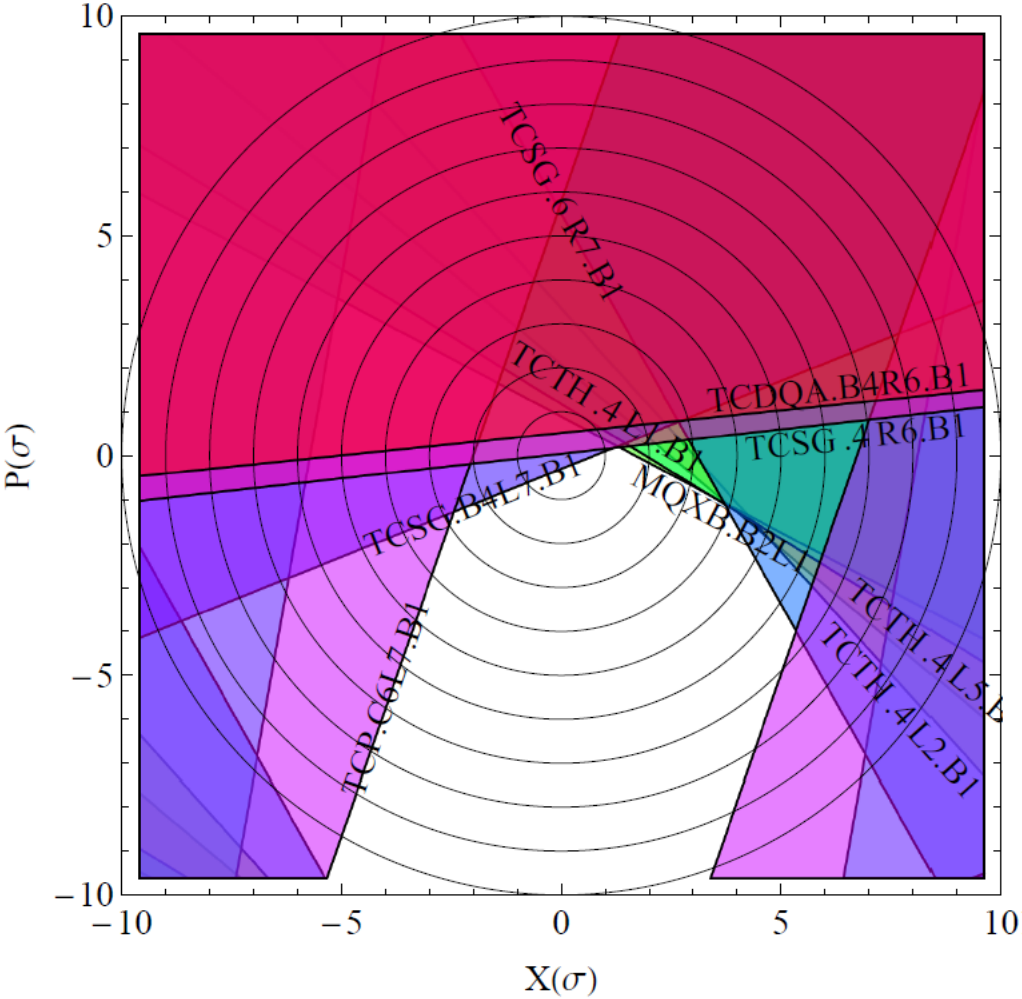
Normalized phase space of kicked beam



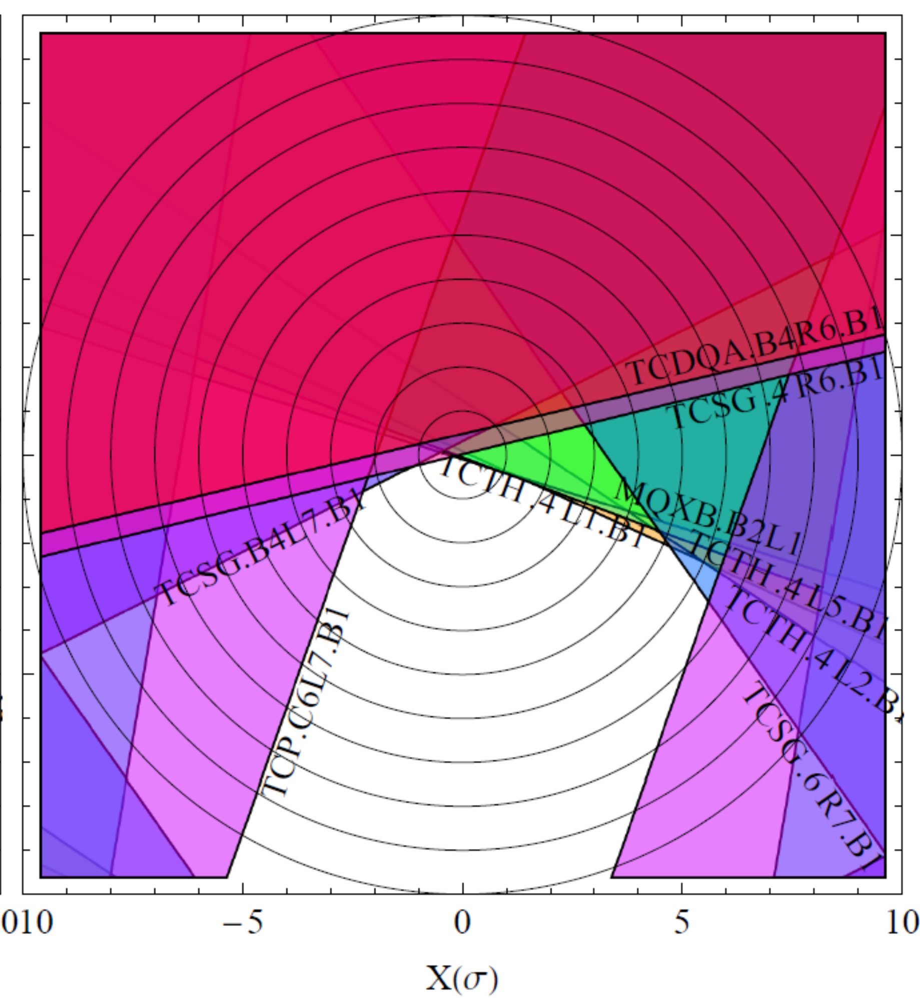
More details to follow in CWG talk

Phase space coverage

Nominal

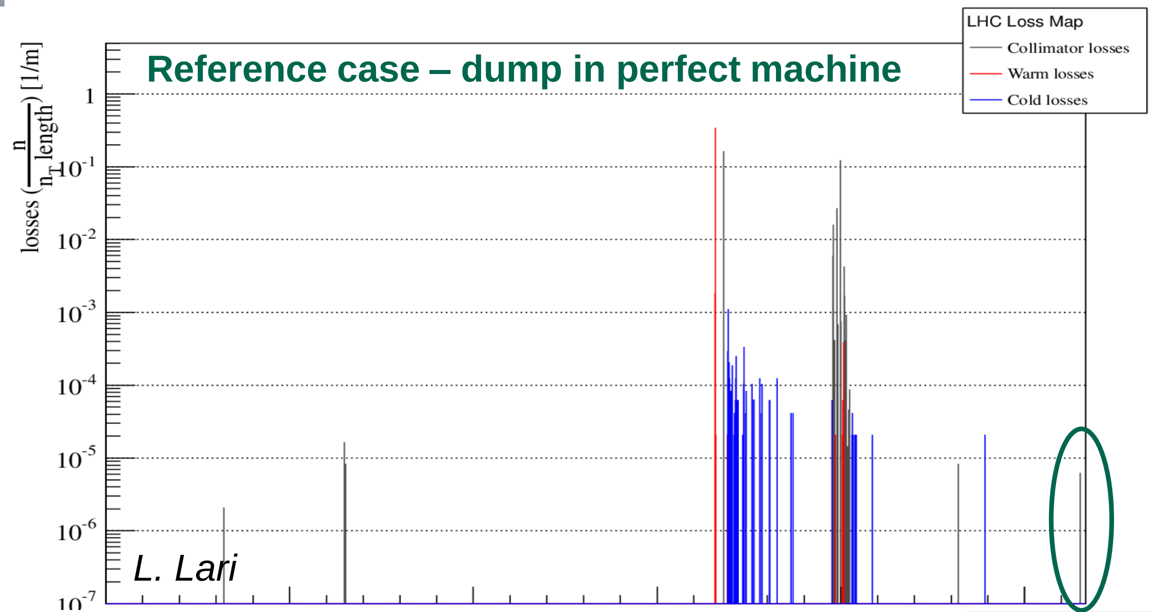


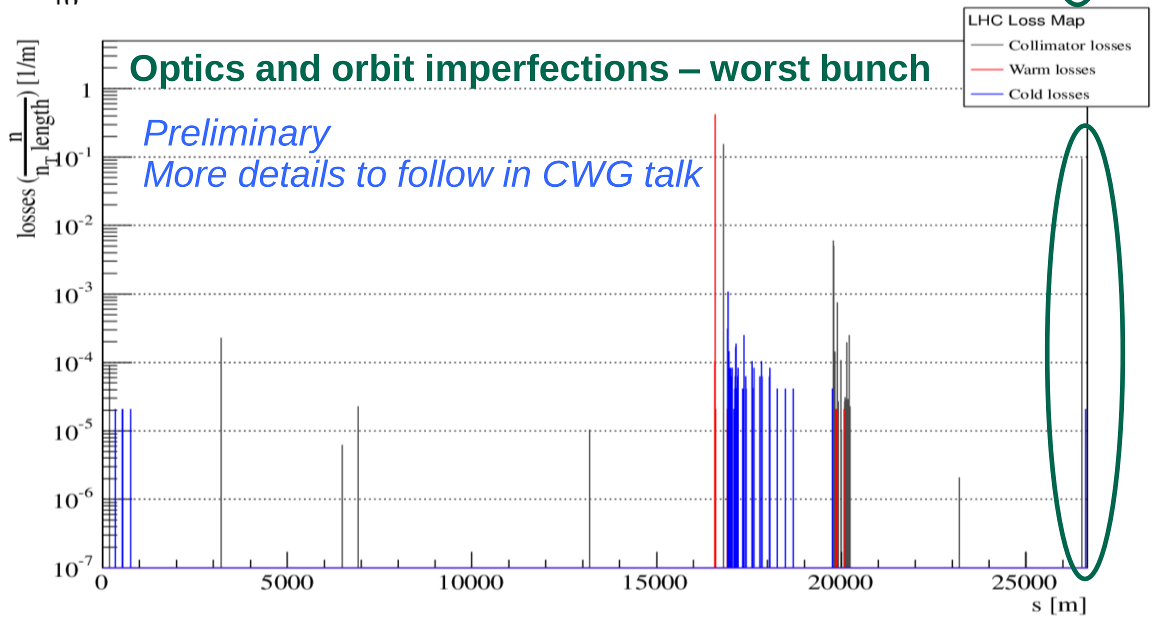
Worst-case of 1000 random configurations



Preliminary worst-case scenario for TCT

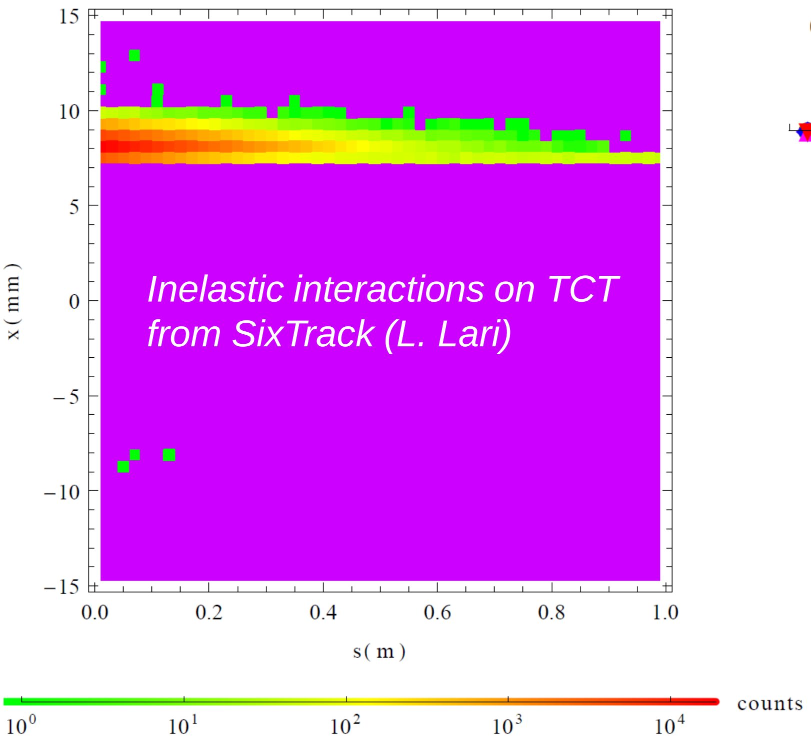
- As by-product, we can estimate impacts on a TCT in a realistic worst-case scenario
- Taking worst case of 1000 random optics error configurations + additional orbit shift in IR7 (VERY pessimistic!)
- Using modified SixTrack – slower than phase-space integration, but includes scattering, sextupoles, multi-turn
- Considering 4 TeV and 60 cm
- TCT can intercept 10% of a single bunch and more when summed over all bunches - but extremely unlikely!

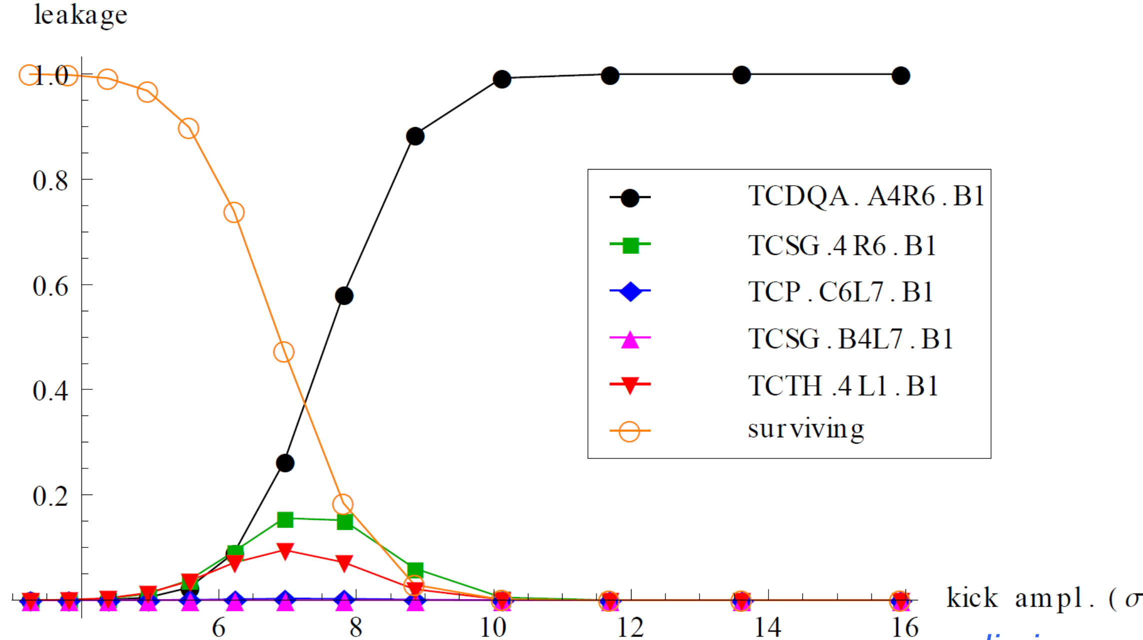




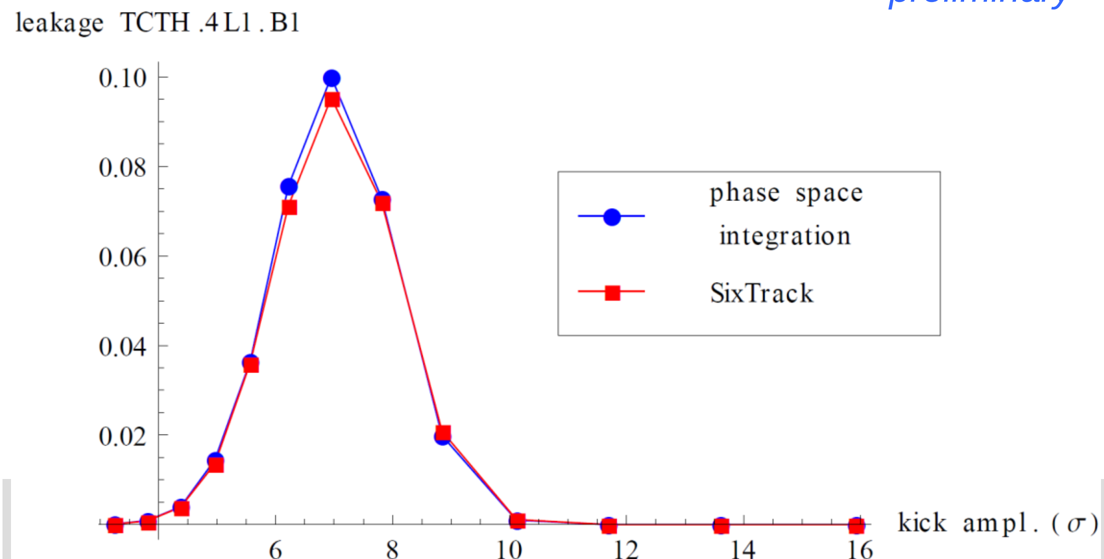
Impacts on IR1 TCT

- As function of kick amplitude, TCT losses reaches maximum at about 7 σ. Integrated over all bunches, 30% of one bunch hits the TCT in positive x
- Next: FLUKA + Autodyn? (talk A. Bertarelli). Repeat for 6.5 TeV.



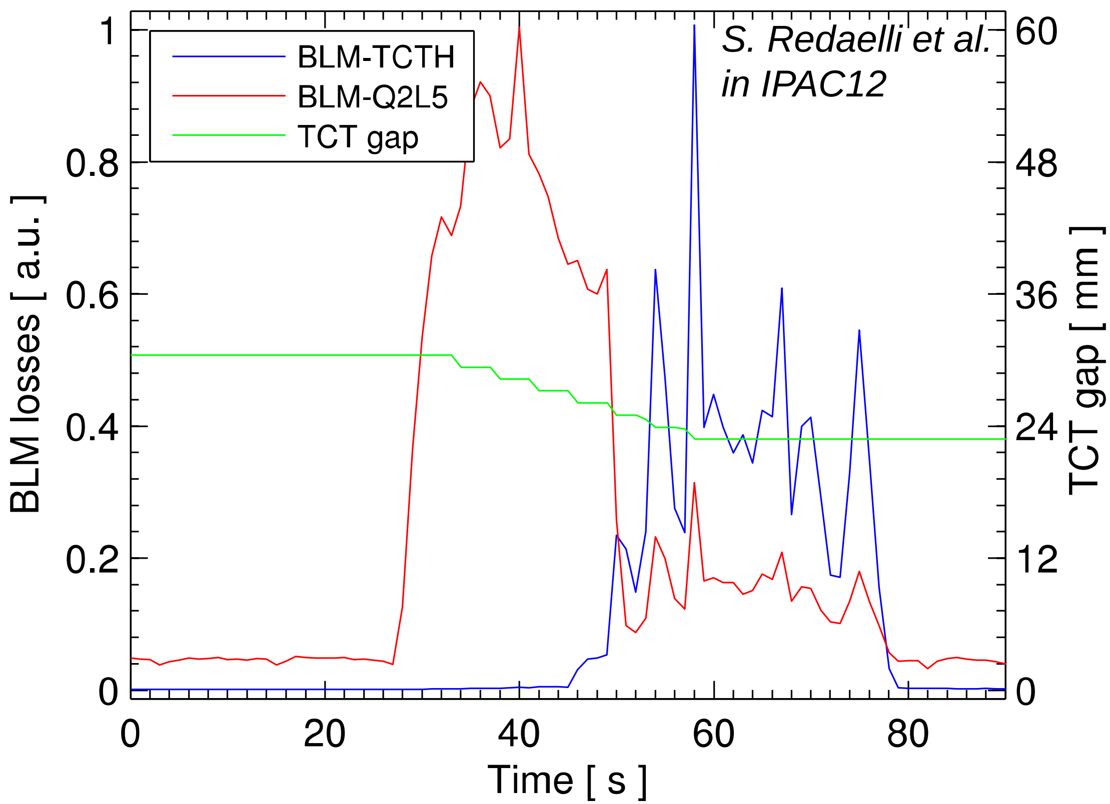


preliminary



Measured aperture 2012

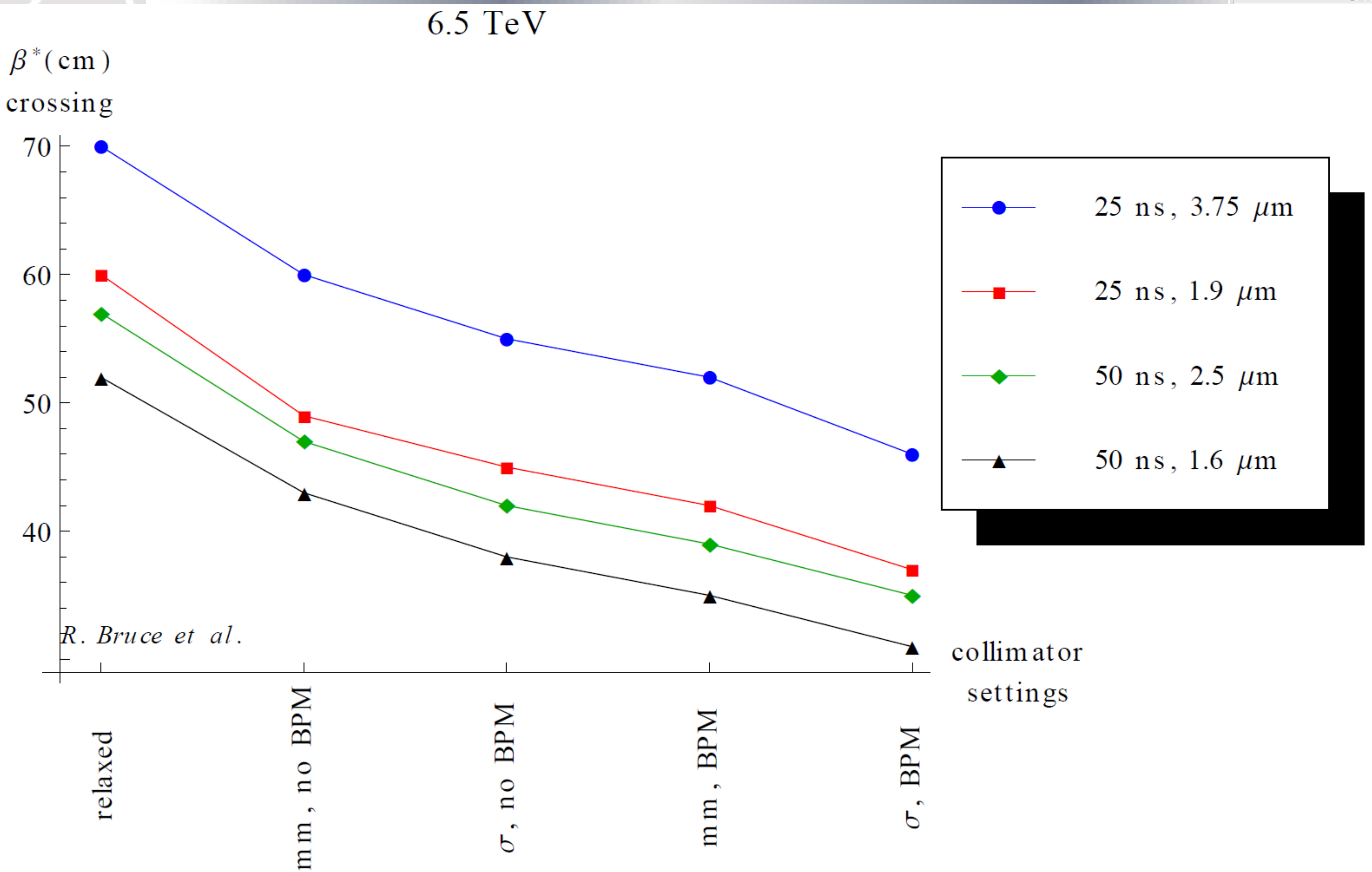
- Aperture measured using a collimator scan and losses provoked by the transverse damper
- Collimator moved in steps while provoking losses. Monitoring BLMs at collimator and aperture bottleneck.
- Significant improvement in measurement speed since last year!
- Result: triplet aperture measured to 11 – 12 σ depending on IP and plane
- Predicted: >10.8 σ



Preliminary scenarios after LS1

- Beam assumptions: 6.5 TeV, 25 ns or 50 ns
- Machine assumptions:
  - Same excellent aperture, orbit, beta-beat as today
  - No drifts of aperture due to e.g. ground motion included. re-measured aperture!
- Collimator assumptions
  - We can not move in the TCPs further than today in mm (impedance, orbit)
  - 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. Reduce to 0.1 σ margin for orbit between dump protection and TCTs and reduce to 0.7 σ margin for orbit TCTs/triplet – orbit can still move in triplet
  - However, this requires following orbit with collimator – need to define interlocking and
  - Full use of BPMs probably not for first startup after LS1 – need operational experience

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