LHC machine configuration in the 2016 proton run

R. Bruce, G. Arduini, B. Goddard, G. Iadarola, S. Redaelli

With essential input from:

F. Antoniou, H. Bartosik, P. Baudrenghien, A. Bertarelli, N. Biancacci, J. Boyd, C. Bracco, F. Carra, L. Carver, P. Collier, R. De Maria, S. Fartoukh, M. Fraser, M. Giovannozzi, P. Gradassi, P. Hermes, D. Jaquet, M. Lamont, K. Lee, A. Mereghetti, E. Metral, D. Mirarchi, Y. Papaphilippou, T. Pieloni, E. Quaranta, G. Rumolo, B. Salvachua, B. Salvant, R. Schmidt, J. Uythoven, G. Valentino, J. Wenninger, D. Wollmann, M. Zerlauth

Outline

- General strategy for 2016
- Parameters for pushed performance (luminosity) in 2016
- Ways to push β* in 2016
  - Focus on collimation hierarchy
- Proposed configurations in 2016
- Conclusions

SPOILER ALERT!

Some similarities to Evian talk

Strategy in 2015 vs 2016

- **2015**
  - Commissioning year, coming out of LS1.
  - New parameters: Increased energy to 6.5 TeV, 25 ns bunch spacing
  - Put focus on feasibility, stability and ease of commissioning.
  - Main priority: Get LHC running at 25 ns and 6.5 TeV
  - Performance should not be main focus, but we should also not be overly pessimistic
  - Started relaxed: β^*=80 cm, 2012 collimator settings in mm, 11 σ beam-beam separation, standard 25 ns filling scheme

Strategy in 2015 vs 2016

- **2016**
  - Production year
  - With 2015 OP experience and MDs: can push performance
  - Performance = *integrated luminosity*
    - Depends both on peak performance, availability, turnaround, parameter evolution in stable beams… (see other talks)
    - This talk: LHC parameters for increased peak performance, keeping in mind that we should not jeopardize availability

Pushing luminosity

Higher intensity

Increase bunch intensity

Increase number of bunches

$$\mathcal{L} = \frac{N_1 N_2 f_{\mathrm{rev}} k_B}{4\pi\beta^* \epsilon_{xy}} F$$

Increase F: shorter bunches, smaller crossing angle

$$\frac{1}{\sqrt{1 + (\frac{\sigma_s}{\sigma_x}\frac{\phi}{2})^2}}$$

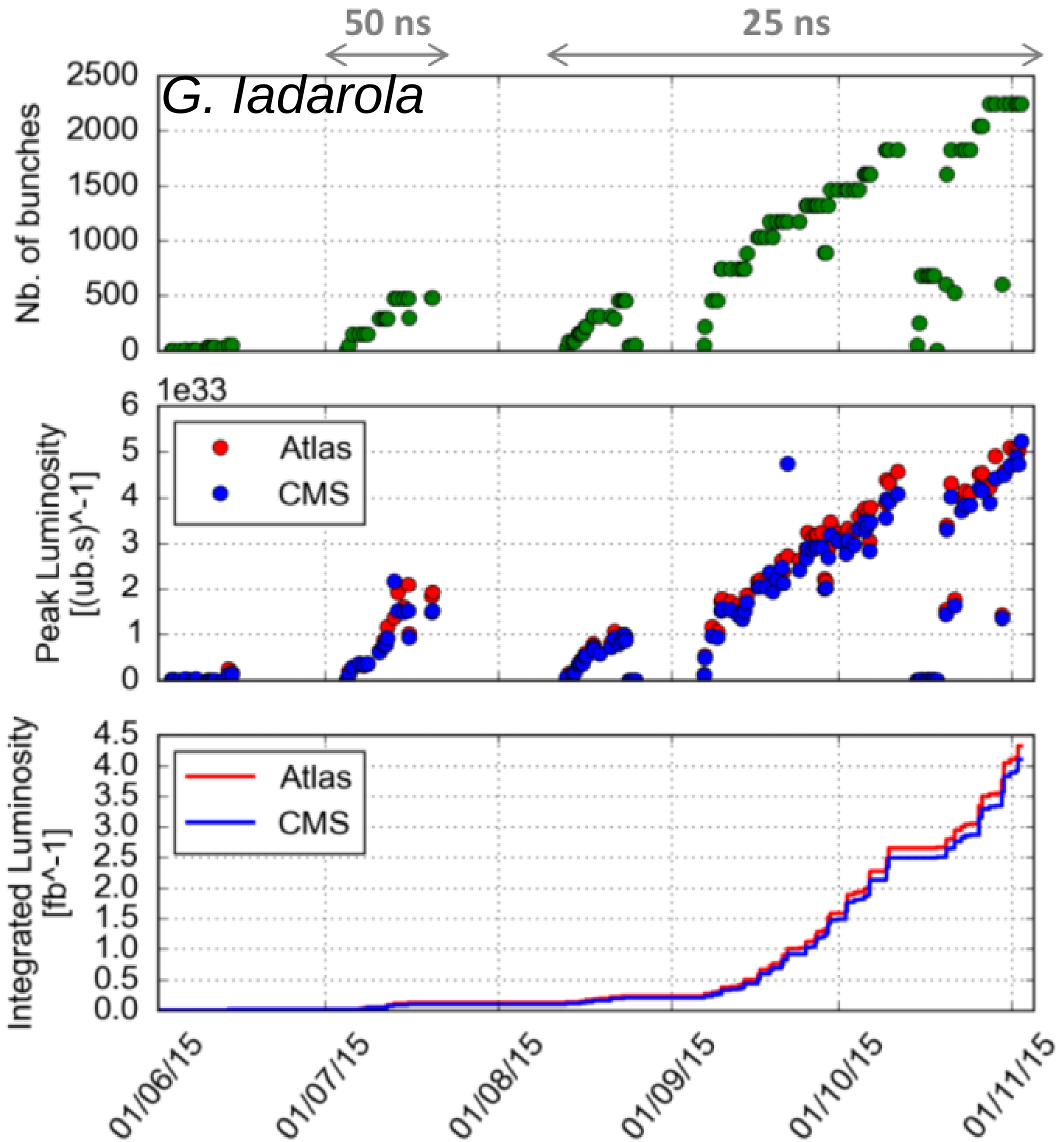
Smaller β*

Smaller emittance

Smaller beam size

Number of bunches

- Through scrubbing, good hope to finalize intensity rampup to 2748 bunches (see talk G. Iadarola)
- Important for luminosity production



Bunch population and emittance

- Given by parameters at injection from SPS (see talk R. Steerenberg)
- Main schemes: standard 25 ns (used in 2015) and BCMS
  - In 2015: achieved at injection ~2.6 μm emittance and ~1.2e11 p/bunch.
  - BCMS gives higher brightness (smaller emittance and same bunch intensity), but also fewer bunches. Limited to 144 bunches/injection in Run 2
- Proposed as baseline to finish intensity rampup with standard 25 ns
  - could then decide whether to move to BCMS with blown-up emittances and decrease emittance gradually until we see limitations
  - BCMS interesting option, but could cause stability issues (see talk K. Li).
  - BCMS interesting if we are limited in number of bunches

Beam parameters

	Standard 25 ns		BCMS	
	injection	*collision*	*injection*	*collision*
Bunch population	~1.3e11	~1.3e11	~1.3e11	~1.3e11
Transv. emittance	2.7 μm	3.4 μm	1.9 μm	>2.4 μm
N.o. bunches	2748	2748	2268*	2268
Collisions IR1/5		2736		2256

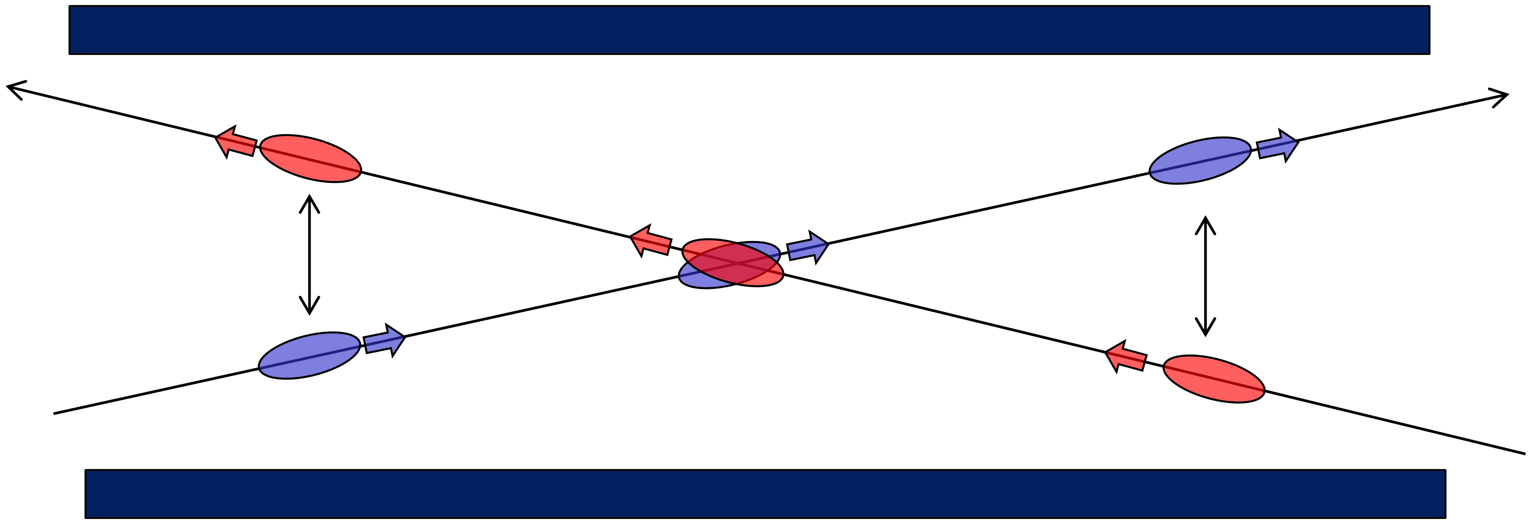
H. Bartosik, G. Iadarola, D. Jaquet, G. Rumolo

*Could be increased to 2412 if the abort gap keeper is modified for 144b injections

- Transmission through LHC cycle: assuming 25% emittance blowup (standard beam, talk M. Kuhn, Evian15) and 98% intensity transmission (see talk G. Papotti)
- Note: BCMS emittances can be improved, but work required. Need to know this early

Increasing geometric factor

- Fewer collisions when bunches are not fully overlapping



- Decrease bunch length and crossing angle to minimize effect
- Crossing angle limited by beam-beam separation and aperture

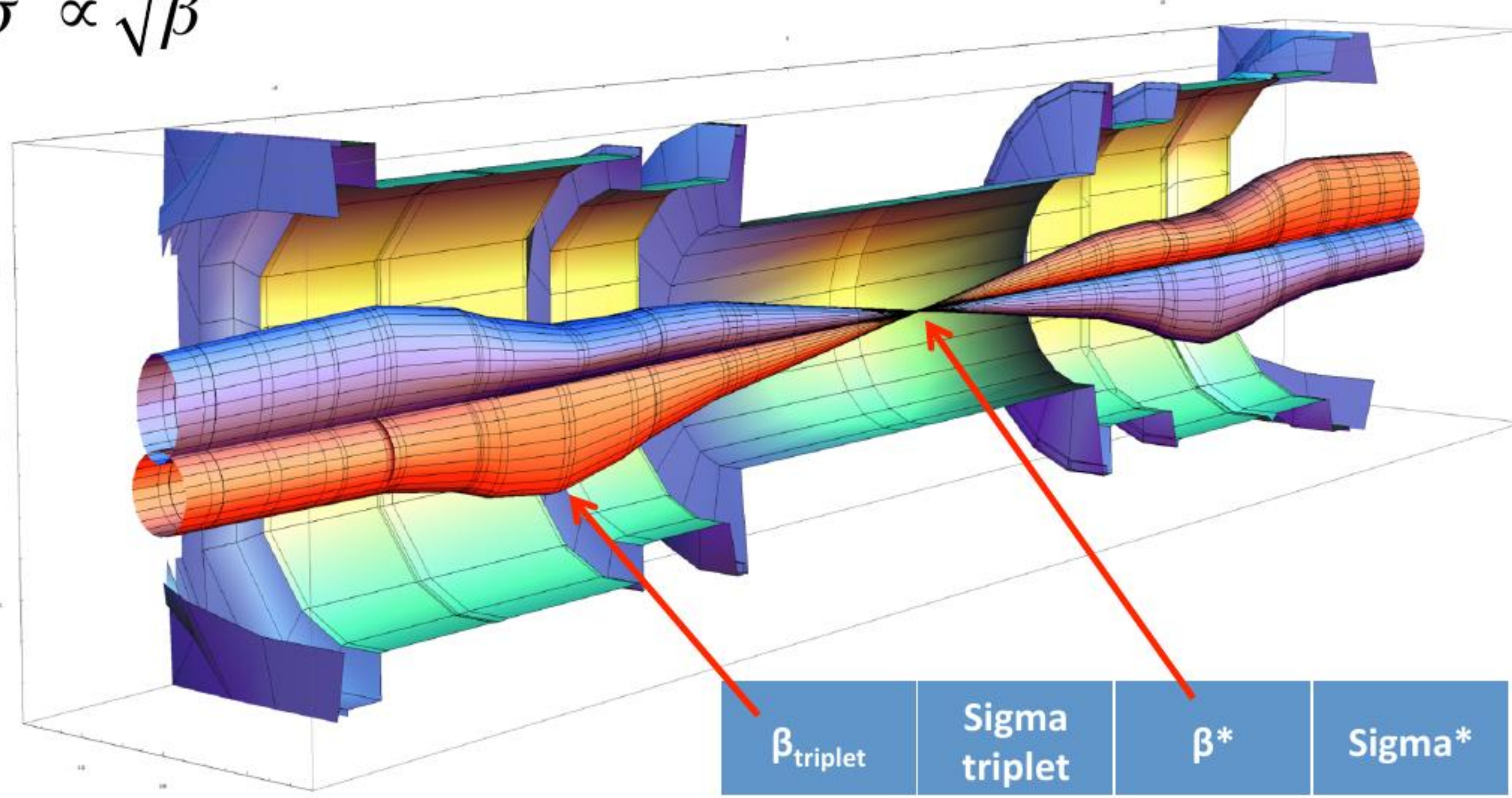
Increasing geometric factor

- Decreasing bunch length:
  - Limited by electron cloud effects (talk G. Iadarola) and longitudinal instabilities (talk P. Baudrenghien, H. Timko)
  - At least for the start, keep ~1.3 ns (10 cm) bunch length. Once intensity rampup is finished, consider gradual decrease towards ~1 ns (7.5 cm).
    - bunch shrinking during fills: probably require longitudinal blowup to to stay above instability threshold (talk P. Baudrenghien)
- Crossing angle:
  - MDs have demonstrated possibility to reduce IR1/5 beam-beam separation from 11 σ to 10 σ for 3.75 μm emittance (see talk K. Li Chamonix, T. Pieloni Evian)
  - New IR2 crossing scheme, similar to IR8: no switching of external crossing is needed at polarity change

Reducing β*

- β* in LHC so far limited mainly by aperture considerations

$$\sigma^* \propto \sqrt{\beta^*}$$



$\beta_{triplet}$	Sigma triplet	β*	Sigma*
~4.5 km	1.5 mm	55 cm	17 um

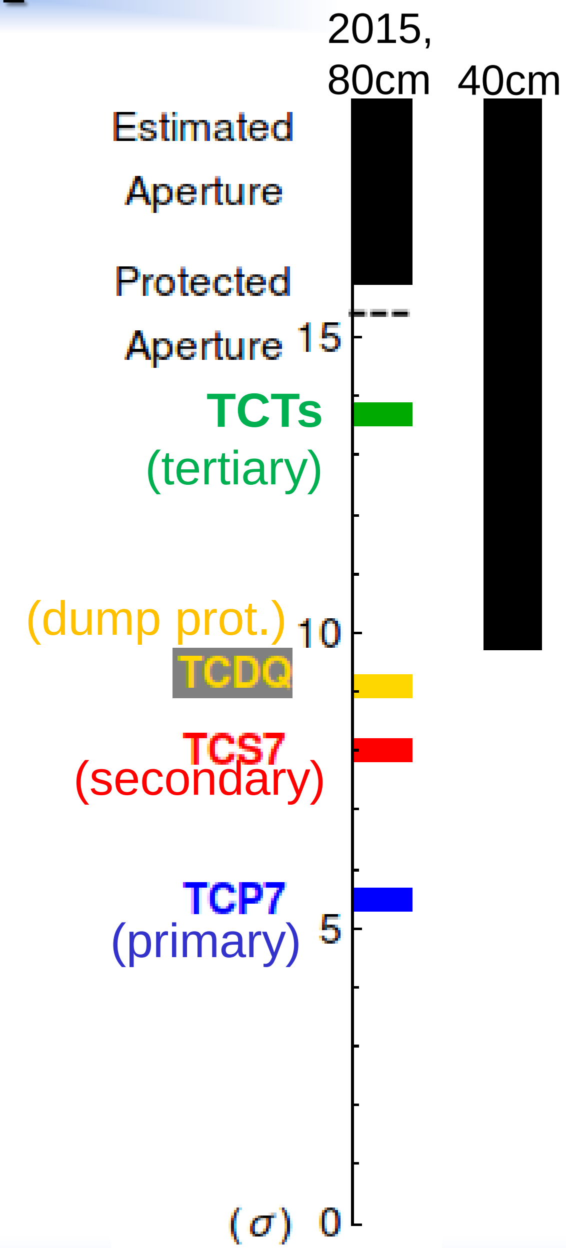
Image courtesy John Jowett

Ways of reducing β*

- β*: several ways to reduce.
  - Profit of better than expected aperture (done in run 1, but now "aperture gold mine" is probably depleted)
  - Reduce beam-beam separation (gains aperture – talks T. Pieloni and K. Li)
    - Reduction to 10 σ for 3.75 μm emittance possible
  - Optimize collimation hierarchy to protect smaller aperture

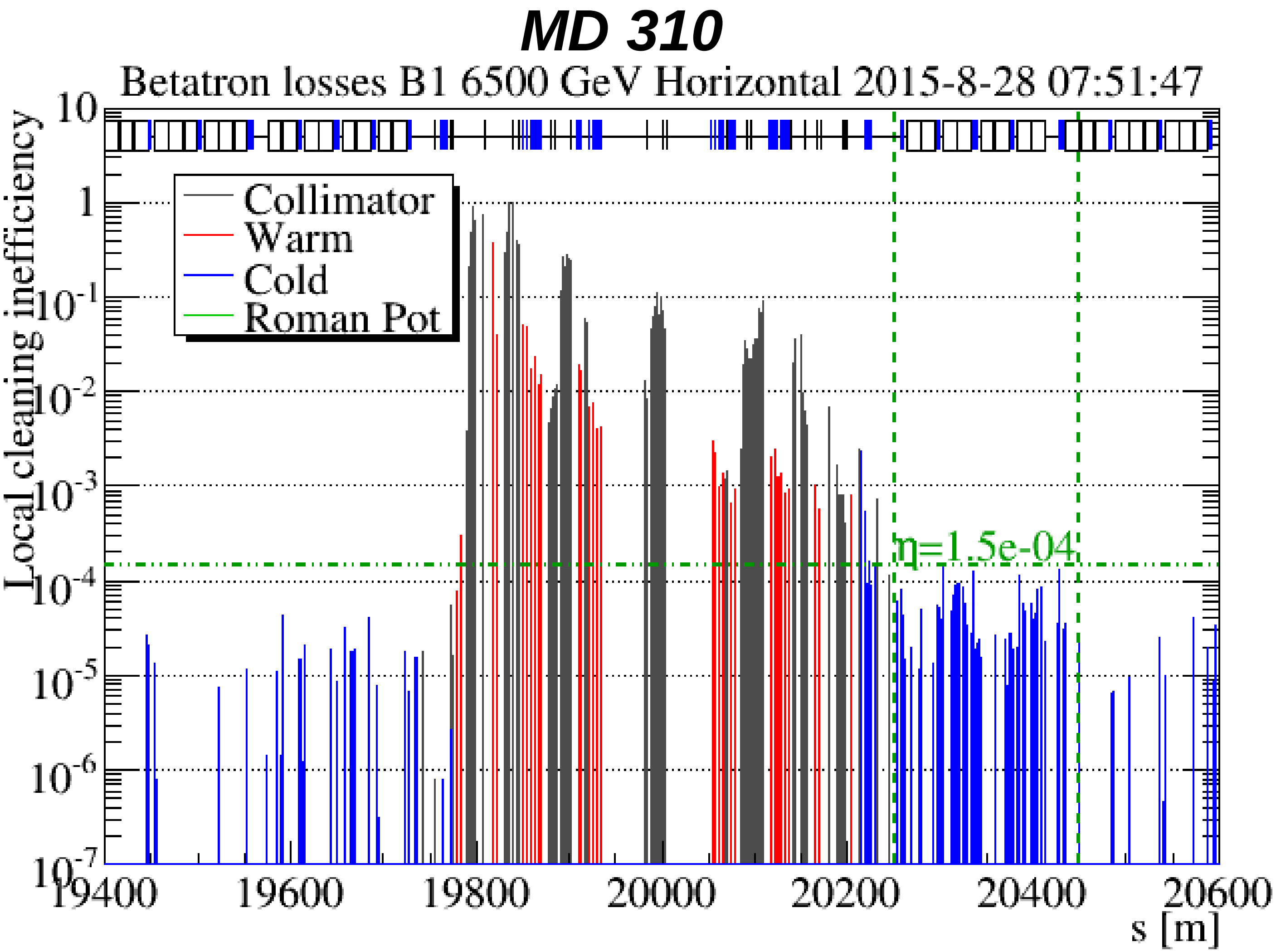
Collimation hierarchy and aperture

- Collimators ordered in hierarchy, must protect aperture
- Need to significantly reduce collimation margins to accommodate small β*
- Series of MDs carried out:
  – MD 307: 40 cm aperture measured in excellent agreement with predictions.
    - But aperture measurements with ions worse. Partly understood
  – MD 310: Are tighter collimator settings possible without jeopardizing cleaning and protection?



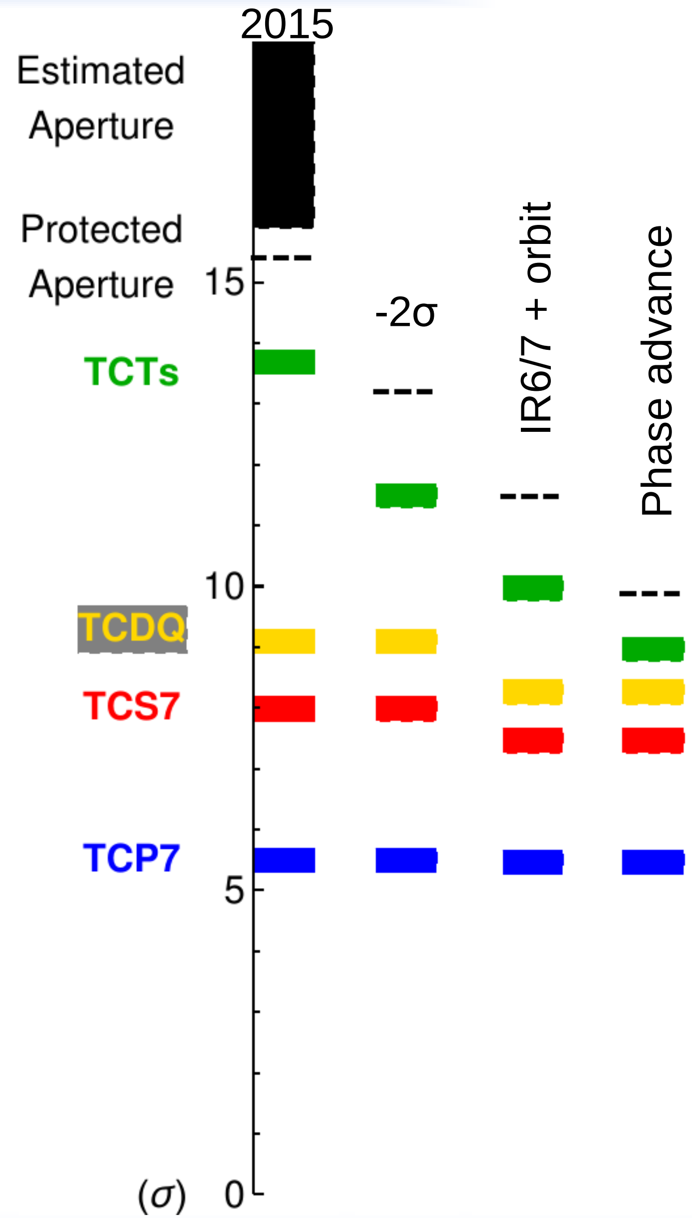
Measured loss map at β*=40 cm

- Cleaning even better (factor ~2) with tighter hierarchy.



Reducing collimation margins

- Could remove 2 σ added when stepping back to 80 cm
- Reduce cleaning margins
  - MDs: OK for impedance to reduce to 2 sig retraction between TCP and TCS
  - MDs: 2012 margins in σ OK for long term cleaning stability (Talk B. Salvachua)
- Reduce machine protection margins
  - Margins to protect TCTs and triplets against asynchronous beam dumps
  - Profit of slightly better orbit stability
  - New method: use phase advance from dump kicker



Asynchronous beam dump

- Standard dump: extraction kickers fire when no beam passes

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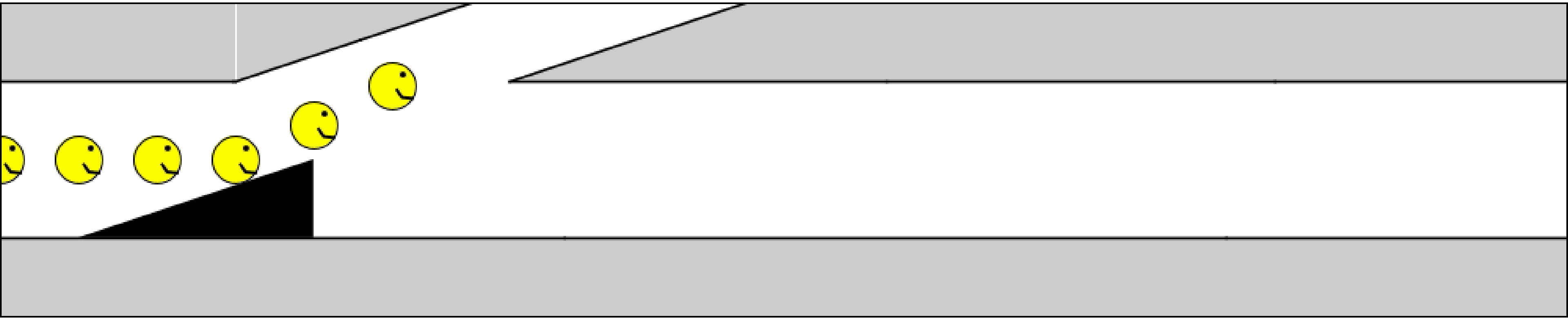
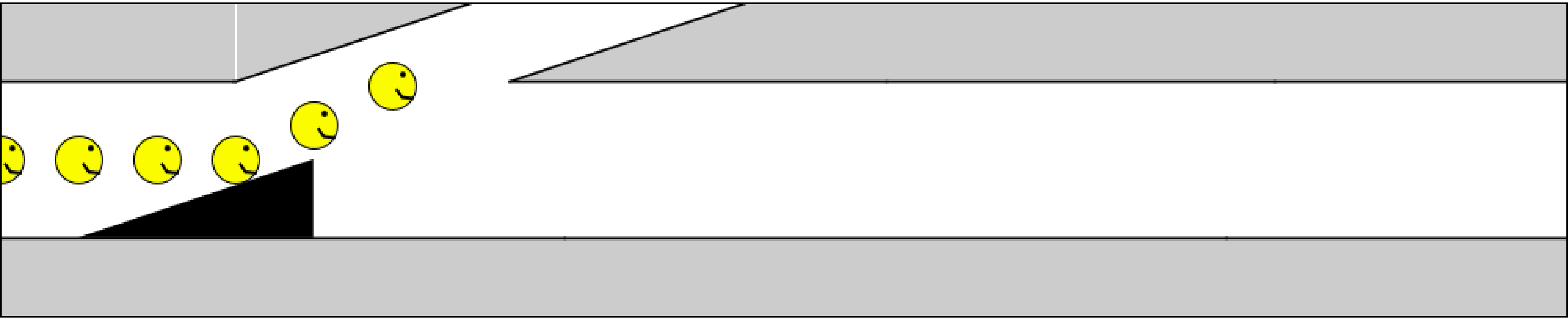


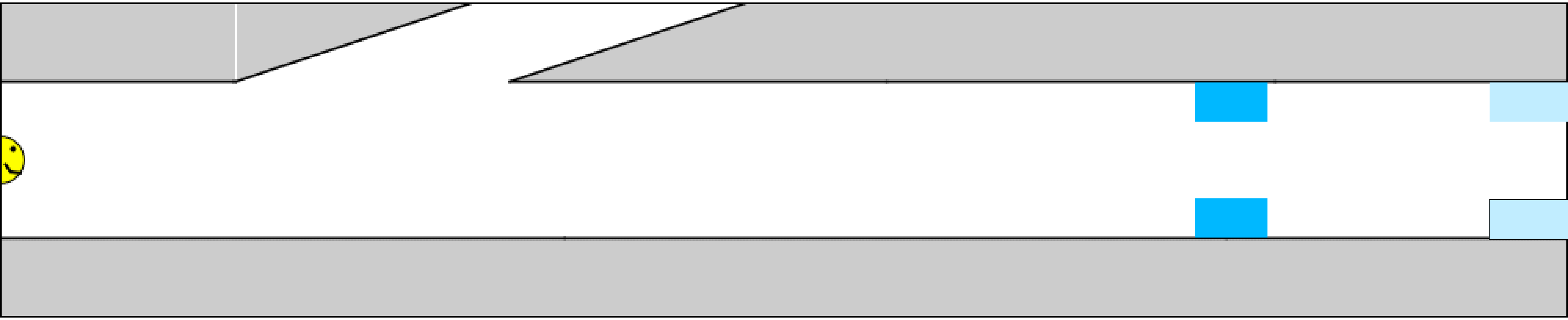
- Asynchronous dump: kicker(s) fire when beam passes – kicked beam damage could TCTs/triplets. TCDQ should protect

Asynchronous beam dump

- Standard dump: extraction kickers fire when no beam passes

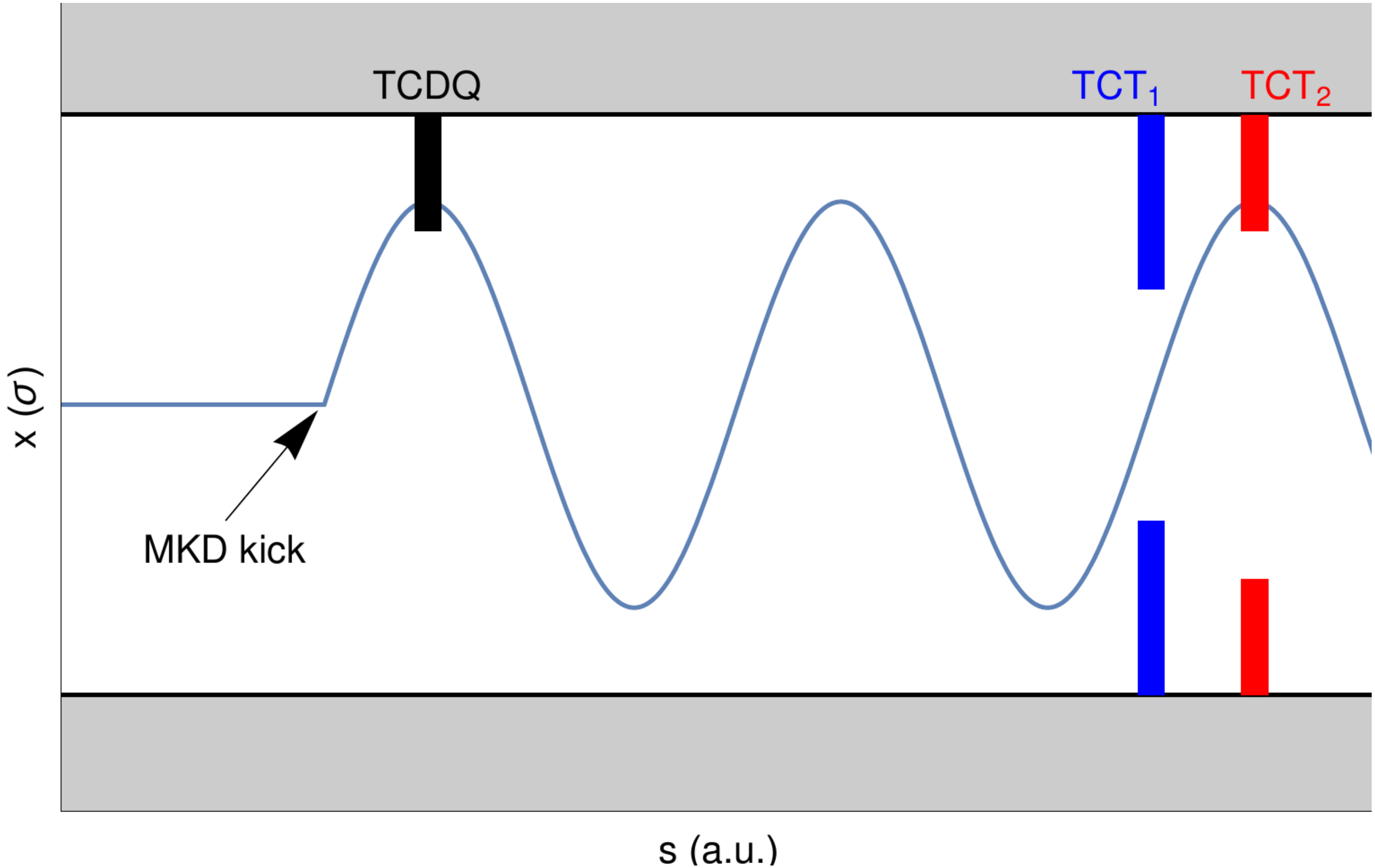


- Asynchronous dump: kicker(s) fire when beam passes – kicked beam damage could TCTs/triplets, if at “bad” phase



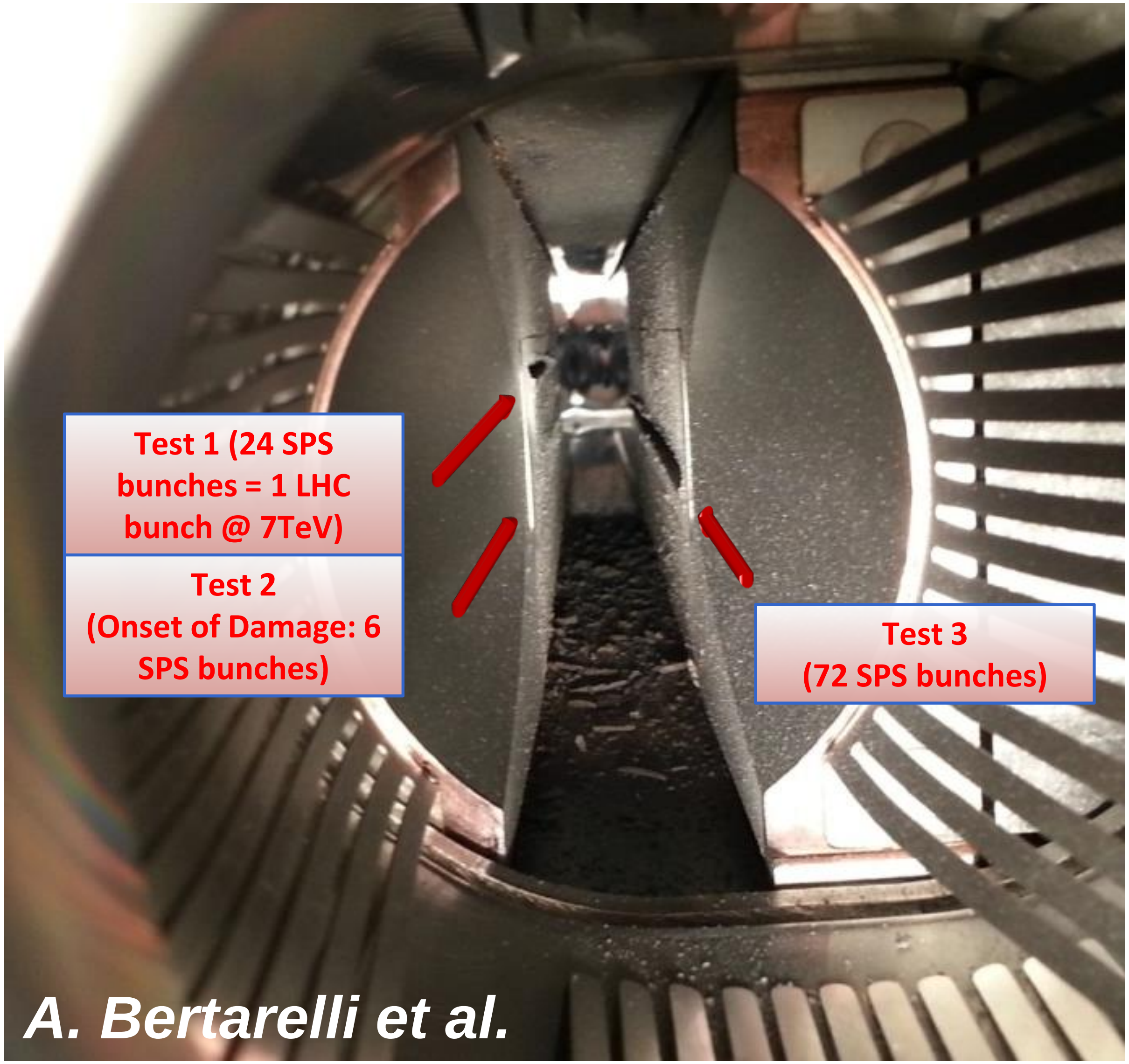
Gain in margin from phase advance

- TCTs at "good" phase advance can go much closer to the beam



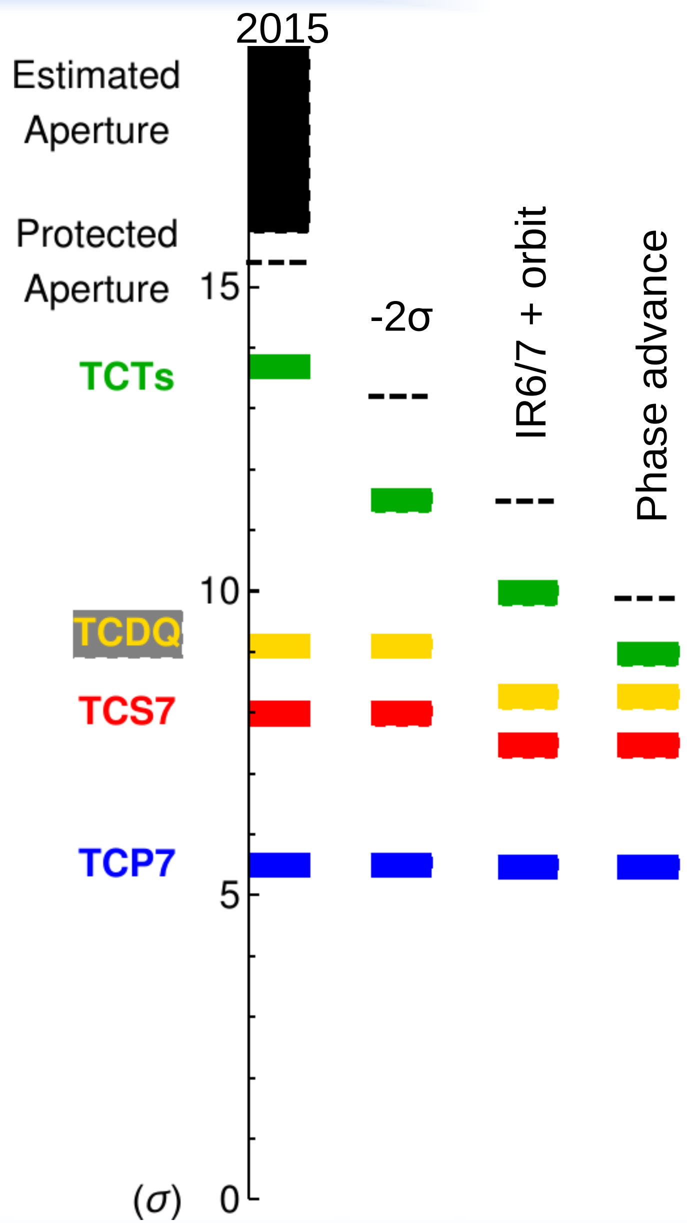
What can happen if a TCT is hit?

- Impacts studied in HiRadMat
- Significant damage observed

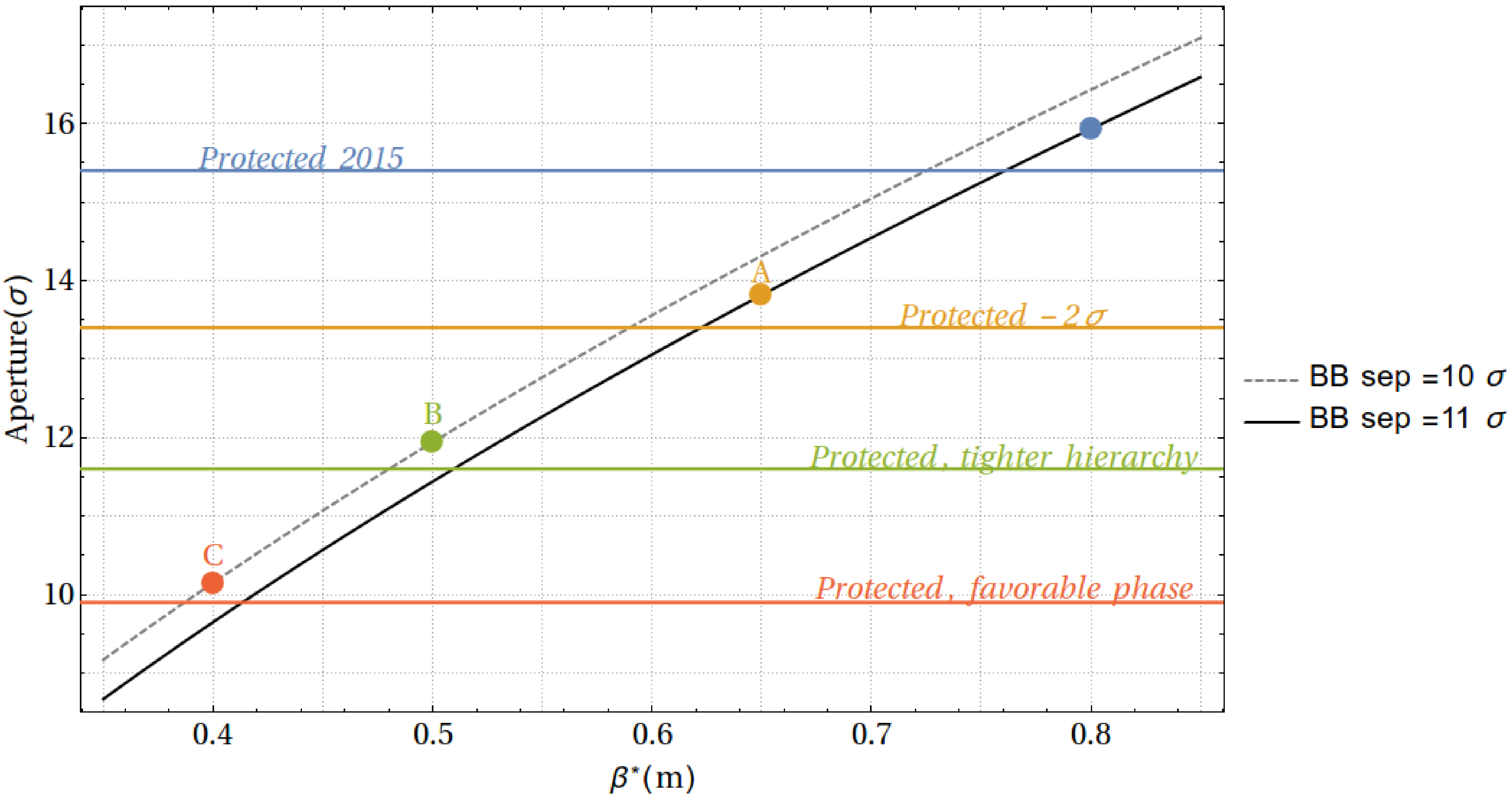


Other limitations for moving in TCTs

- At phase advance close to zero, no primary losses from asynch dump expected on TCTs / triplets
- Other constraints limit the innermost TCT setting
  - Cleaning hierarchy: we don't want secondary halo on TCTs
  - Experimental background: leakage of showers from TCTs to the experiments
  - MD studies carried out to verify our proposed settings
- With collimator settings fixed, can calculate reach in β*



β*-reach 2016



- With tighter hierarhcy in IR7/6, 10σ BB separation, optics with re-matched phase, and assuming aperture does not deteriorate => β*=40 cm possible

Scenarios for 2016 from Evian

A: β=65 cm*

- 160 μrad half Xing (11 σ BB)
- Remove 2 σ additional margin from 80cm

Collimator	Setting
TCP IR7	5.5
TCSG IR7	8.0
TCSG IR6	9.1
TCDQ IR6	9.6
TCT IR1/5	11.5
P. Aperture	13.4
C. Aperture	13.8

B: β=50 cm*

- Use tighter IR7/6 hierarchy, 10 σ BB (165 μrad), better orbit in 2015

Collimator	Setting
TCP IR7	5.5
TCSG IR7	7.5
TCSG IR6	8.3
TCDQ IR6	8.3
TCT IR1/5	10.0
P. Aperture	11.5
C. Aperture	11.9

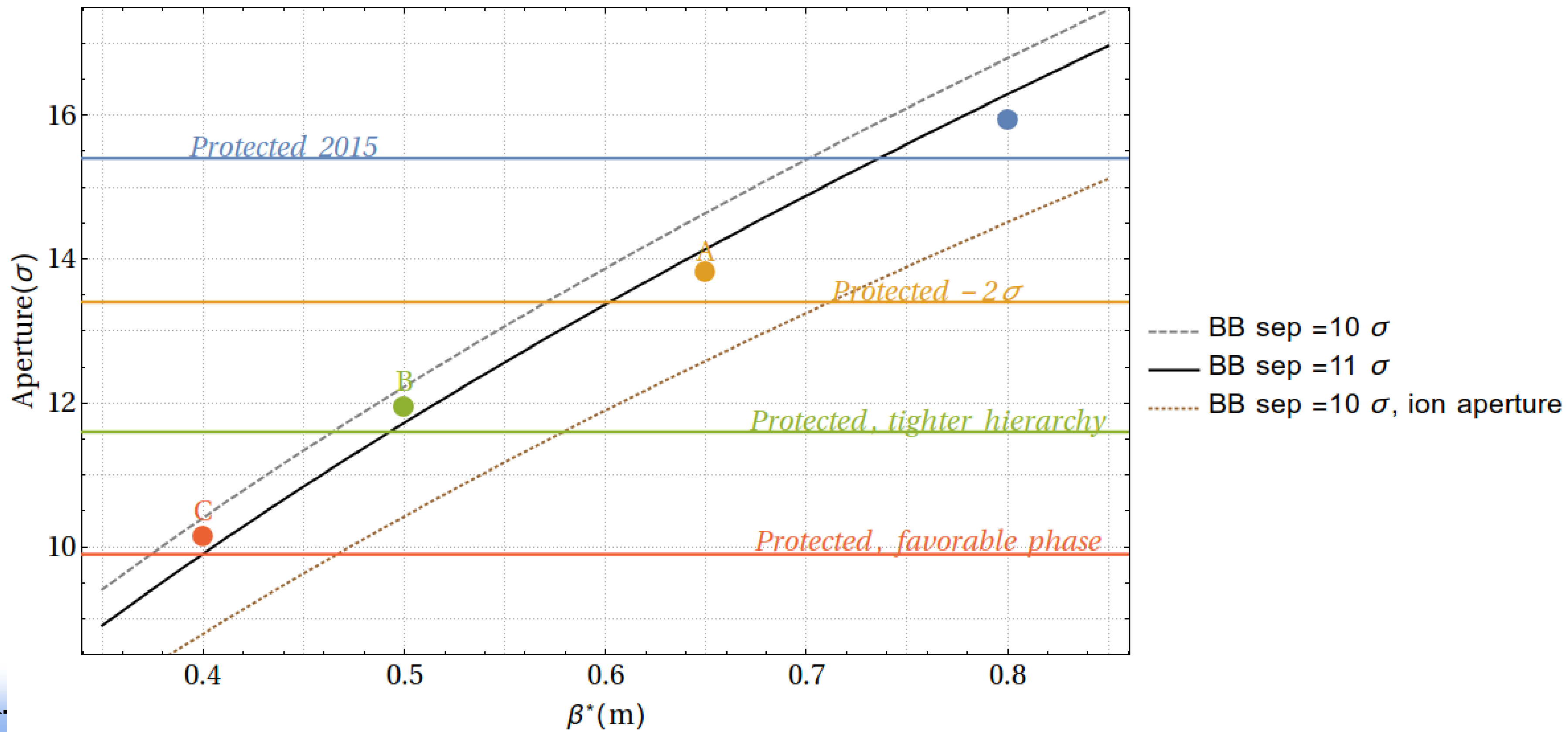
C: β= 40 cm*

- In addition to 50 cm, rely on phase
- 185 μrad half Xing (10 σ BB)

Collimator	Setting
TCP IR7	5.5
TCSG IR7	7.5
TCSG IR6	8.3
TCDQ IR6	8.3
TCT IR1/5	9.0
P. Aperture	9.9
C. Aperture	10.2

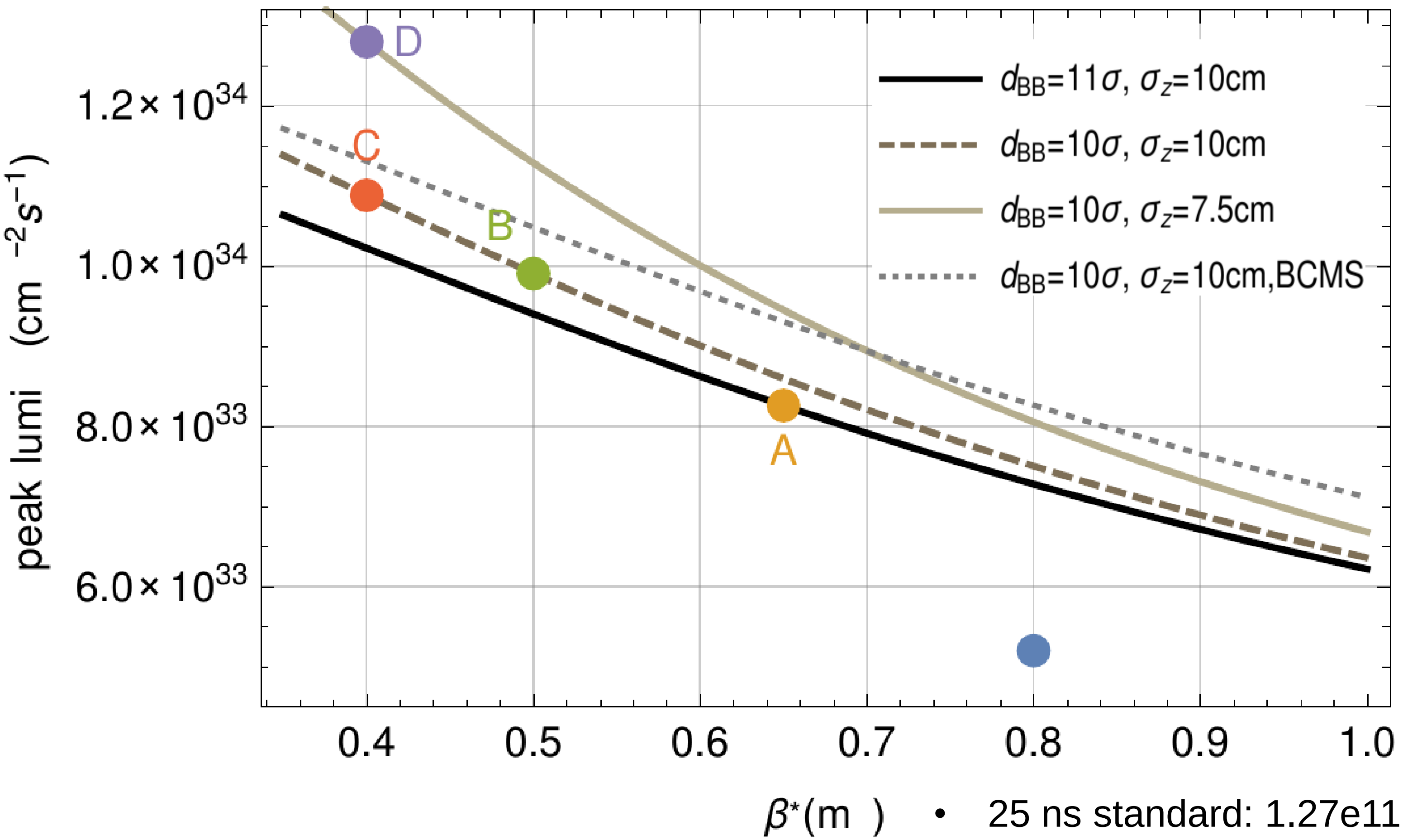
In case of worse aperture

- Calculating the aperture by scaling the *first* heavy-ion measurement, we lose 5-10 cm in β*
  - Aperture loss explained largely by optics and orbit
  - Uncertainty: aperture not measured with both signs of crossing angle
  - If necessary, can add more granularity on β* based on aperture measurement



Peak luminosity examples

- Showing peak performance – difference in integrated performance is smaller, especially for very long fills



- 25 ns standard: 1.27e11 p/bunch, 2736 bunches, ε=3.4μm
- BCMS: 1.27e11 p/bunch, 2256 bunches, ε=2.4μm (optimitistic?)

Integrated luminosity examples

- Calculated time evolution from LHC luminosity model (F. Antoniou, Y. Papaphilippou)

Relative increase in integrated lumi

8h fill length

β* \ $4\sigma_t$	1.3 ns	1.0 ns
50 cm	1	1.1
40 cm	1.08	1.19

20h fill length

β* \ $4\sigma_t$	1.3 ns	1.0 ns
50 cm	1	1.04
40 cm	1.07	1.12

- Caveat: bunch length contribution expected to decrease if longitudinal blowup is used during stable beams to avoid instability

Considerations for 2016 scenario

- Should choose best performance without jeopardizing safety and availability
- Availability: are there reasons to believe that availability would be worse in the more pushed 40 cm scenario?
  - Main availability bottlenecks in 2015 independent on β*
  - New orbit interlocks – should set with so large margin that they never trigger. Need to assess controls availability
  - Smaller beam-beam separation and tighter collimators proposed for both 50 cm and 40 cm. Based on MD results – should not cause problems.
    - Could envisage also 50 cm, relying on phase, keeping relaxed collimators and 11 σ beam-beam

Proposed actions to ensure safety

- Regardless of final choice of β*, decision in optics team to have optics with improved phase advance
- 20 deg and TCTs at 9σ: about as much margin as in 2015 between TCT setting and damage level! At 0 deg, more margin
- At startup, qualify two TCT settings with asynch dump test with different loss in margin TCDQ-TCT. Losses should be similar at small phase
- Avoid off-energy phase beating: Present orbit interlock dumps at dp/p=2.5e-4 (would give ~5 deg of phase beating)
- Add in XPOC more detailed analysis of standard dumps?
- With these measures, should be at least as safe as in 2015
- Possible additional measures for increased safety
  - Use collimator BPM interlock to dump outside the qualified interval.
  - Interlock on phase (quadrupole currents) under study for any choice of β* (M. Zerlauth, K. Fuchsberger et al.)

Decision flow on β*

- Phase advance
  - Agree on the approach of using the phase advance to squeeze the machine protection margins
- Measure aperture
  - Verify that we still get the predicted “good” aperture?
- Availability
  - Come to a conclusion on whether we think we won’t introduce availability issues by going to 40 cm
- Decide β*
  - 40 cm if we have positive answers on the above points

Summary

- 2015 : commissioning year, 2016: production year
- 2016 goal: increase performance as much as possible within safe limits, without penalty on availability
- Proposed strategy
  - Fix crossing angle, β* early on – takes time to recommission
    - Based on MDs and OP experience, presented viable scenarios for 65 cm, 50 cm and 40 cm and reduced 10 σ beam-beam separation
    - β*=40 cm expected to be within reach, but final decision on β* to be taken early in commissioning after aperture measurements
  - Finalize intensity rampup with 2015-like beam. Maximize n.o. bunches, gradually increase bunch intensity
  - Then, consider reducing bunch length and/or emittance (BCMS?)

2016 baseline parameters (startup)

Parameter	Value @ injection	Value @ collision
Energy [TeV]	0.45	6.5
β* (1/2/5/8) [m]	11 / 10 / 11 / 10	**0.4-0.5** / 10 / **0.4-0.5** / 3
Half X-angle (1/2/5/8) [μrad]	-170 / 170 / 170 /170	-185* / 200 / 185* / -250
Tunes (H/V)	64.28 / 59.31	64.31 / 59.32
Separation (1/2/5/8) [mm]	-2 / 3.5 / 2 / -3.5	-0.55 / 1/ 0.55 / -1
Emittance (BCMS/standard) [μm]	1.9 / 2.7	2.4 / 3.4**
Bunch intensity [p]	≤ 1.3e11	≤ 1.3e11***
4 σ bunch length [ns]	1.2	1.25
Collimator settings	"nominal"	"2σ retraction"

* Corresponding to 10 σ beam-beam separation at 40 cm. At 50cm, it should be 165.
** Assuming 25% blowup (M. Kuhn, Evian15).
*** Assuming 98% transmission