Machine protection considerations for 2017 optics

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Acknowledgement: collimation and optics teams, BE/ABP, C. Bracco, B. Goddard, MPP

Introduction

- As follow-up of Chamonix discussions, need to review status of machine protection studies for 2017 optics
  - Phase advance from dump kickers to TCTs / triplets should ensure that these elements are safe during asynch dumps
- Strategy: phase advance should not deviate more than 30 deg from 0 or 180. Are we sufficiently safe with these margins?
- Contents:
  - Recap of phase advance in different optics
  - Expected TCT losses during asynch dump as function of phase advance MKD-TCT
  - Inner setting where TCT risks to be damaged as function of phase
  - Protected aperture and β* as function of phase
  - Variation of phase from imperfect correction and momentum offset
  - Quantify risk of damage for proposed settings and optics

Phase advance in different optics

- All options on the table for 2017 are better than nominal design report optics

	IR1 B1	IR5 B1	IR1 B2	IR5 B2
Nominal 55cm	56	47	198	176
Nominal 2016 40cm	4	356	177	183
Nominal 2017 33 cm	6	358	178	183
ATS 40 cm 2017	176	167	176	154
ATS 33 cm 2017	179	165	177	155

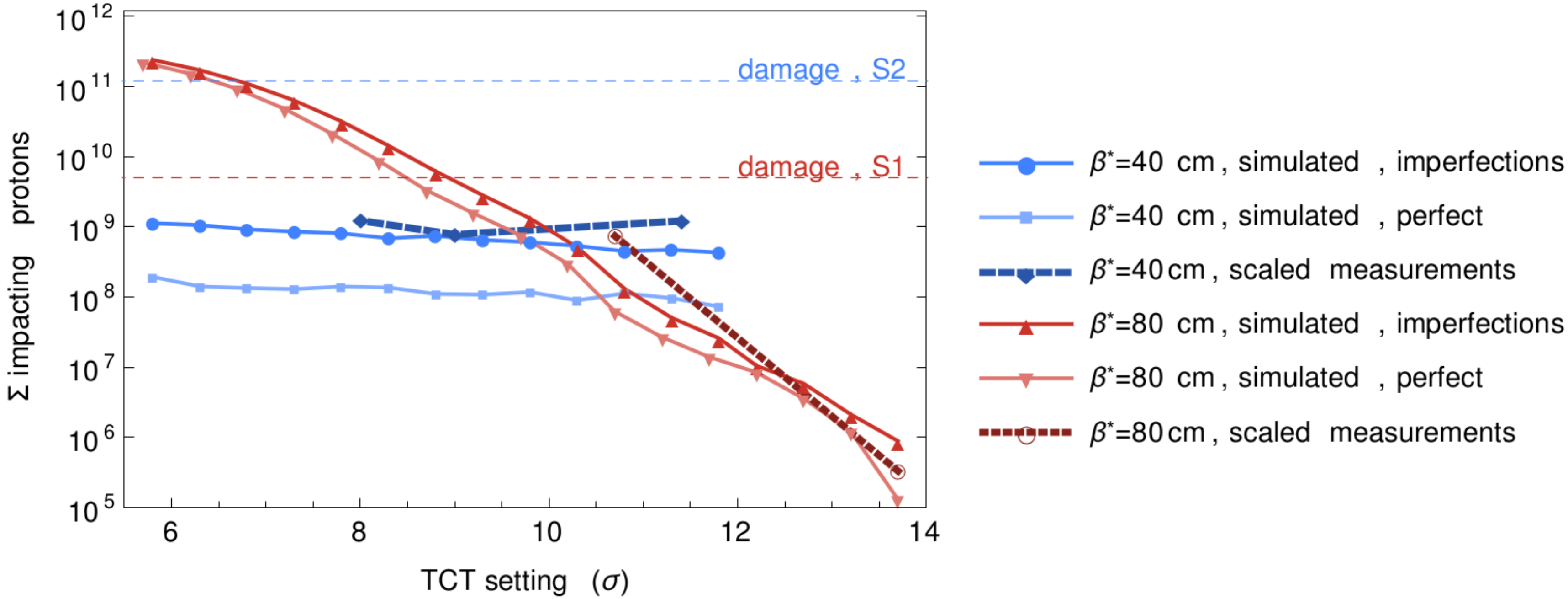
- Perform calculations / simulation studies of asynch dump to assess influence of phase advance

Simulation method of asynch dump

- Simulations using SixTrack with collimation of single-module pre-fire type 2
  - Worst type of beam dump failure – 1 kicker fires first when beam is passing, the others retrigger after some delay
  - Measured kicker data from M. Fraser
- Each bunch in a 25ns train tracked separately in SixTrack with full collimation system in place, after receiving different MKD kicks according to the rise of the kickers
- In the end, summing losses on TCTs over all bunches
- Include 1.2 mm orbit bump in IR6 away from the TCDQ
- Scan over TCT settings with the other collimators constant
- Normalizing to 1.5e11 p/bunch to stay on the pessimistic side for Run II

Measurements vs simulations

- Comparing SixTrack simulations to LHC data for
  - β*=80 cm, 2015, ~60 deg phase advance
  - β*=40 cm, 2016, ~4 deg phase advance



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TCT damage limits

- Ongoing studies ABP/MME/STI on TCT damage limit
- A. Bertarelli et al. MPP workshop 2013, bunch impacting directly on TCT:

	Threshold 1	Threshold 2	Threshold 3
Pulse intensity	$5x10^9$ p	$2x10^{10}$ p	$1x10^{11}$ p

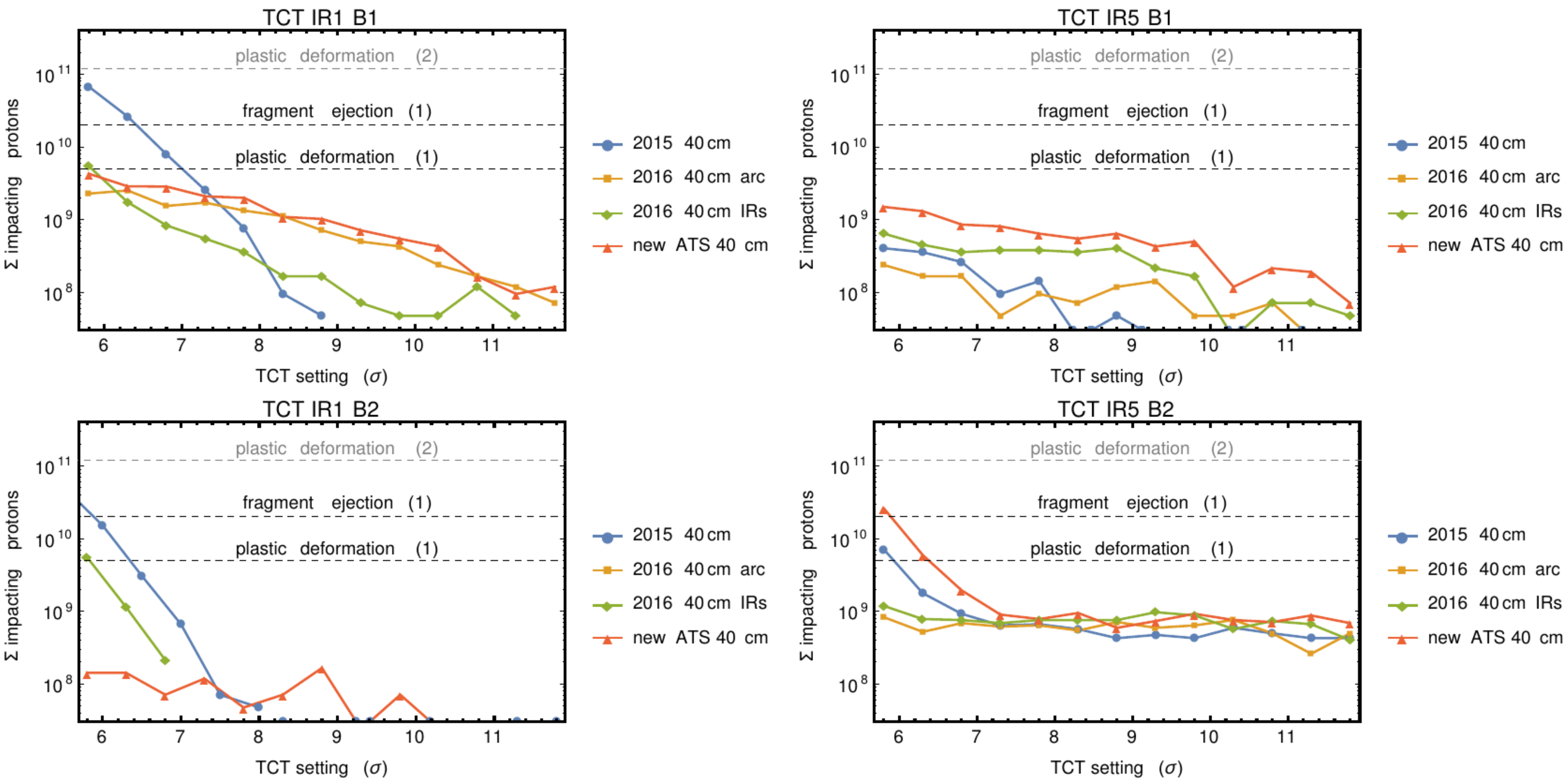
- Updated result, E. Quaranta et al 2016 (paper in preparation), 3-stage simulation (tracking, energy deposition, thermo-mechanical analysis)

Material damage	Thresholds (n. protons)		
	Case 1	Case 2	Case 3
Plastic deformation	1.2×10^{11}	4.6×10^{9}	6.9×10^{9}
Fragment ejection	7×10^{11}	1.8×10^{10}	2.6×10^{10}
Catastrophic damage	1.1×10^{12}	1.4×10^{11}	1.7×10^{11}
	Nom. B2 IR5	*Nom. B1 IR1*	*HL-LHC B2 IR5*

- In the following, relate conservatively simulation results to lowest threshold (plastic deformation) of ~5E9 impacting protons

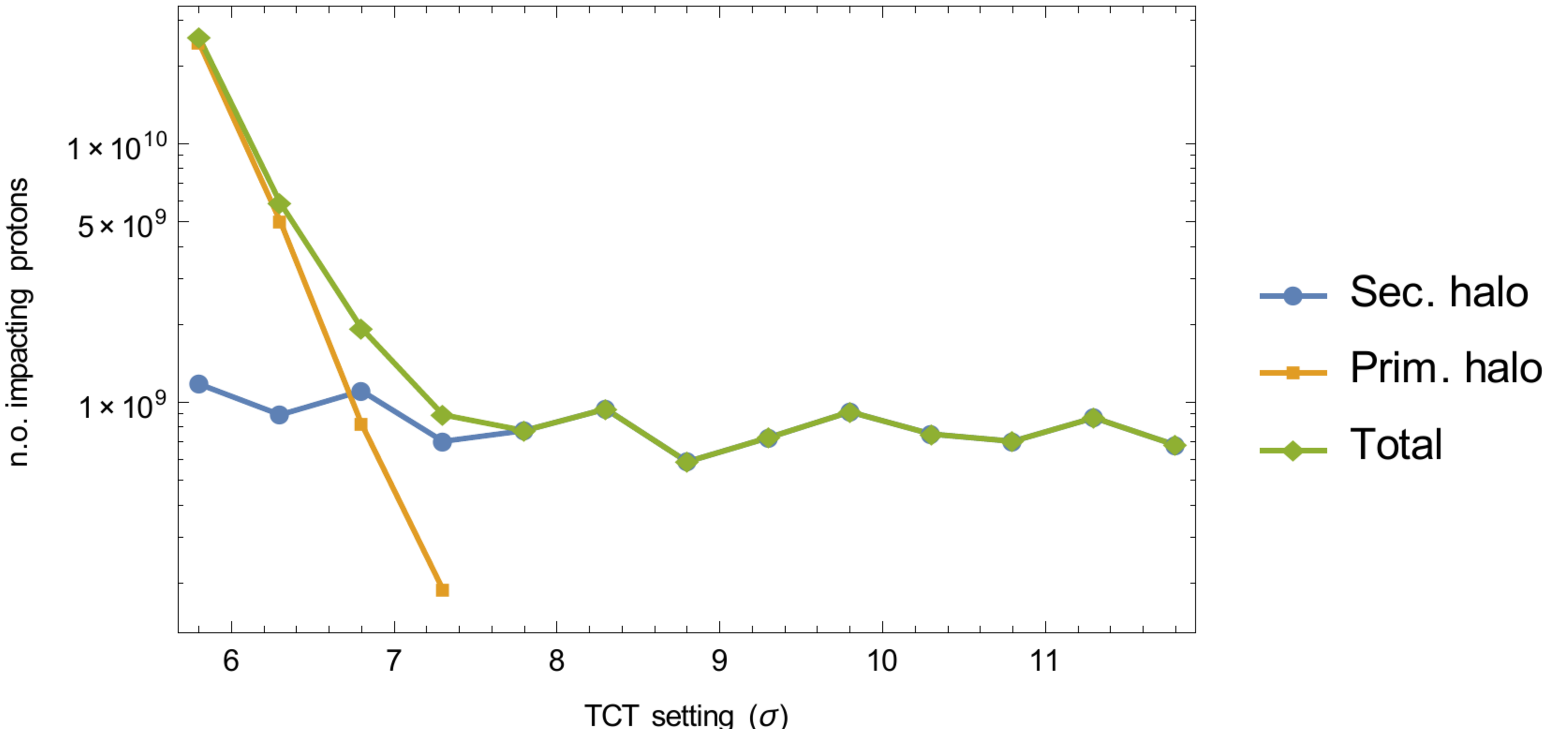
SixTrack results: 2016 settings

ATS 2016, 40 cm, 2016 collimator settings



Analysis of losses – 2016

- Closer look at "worst" TCT with ATS: TCTPH.4R5.B2 with 154 deg phase (150 deg from MKD.A)
- Primary losses dominant/dangerous < 7 sigma with IR6 bump (TcDQ at 10.7 σ)
- With 0.2 σ retraction TCDQ-TCT, op. setting at 8.5 σ in simulated case. Still 1.5 σ margin + the margin in the IR6 bump



ATS 2016, 40 cm, 2016 collimator settings

Proposed 2017 collimator settings

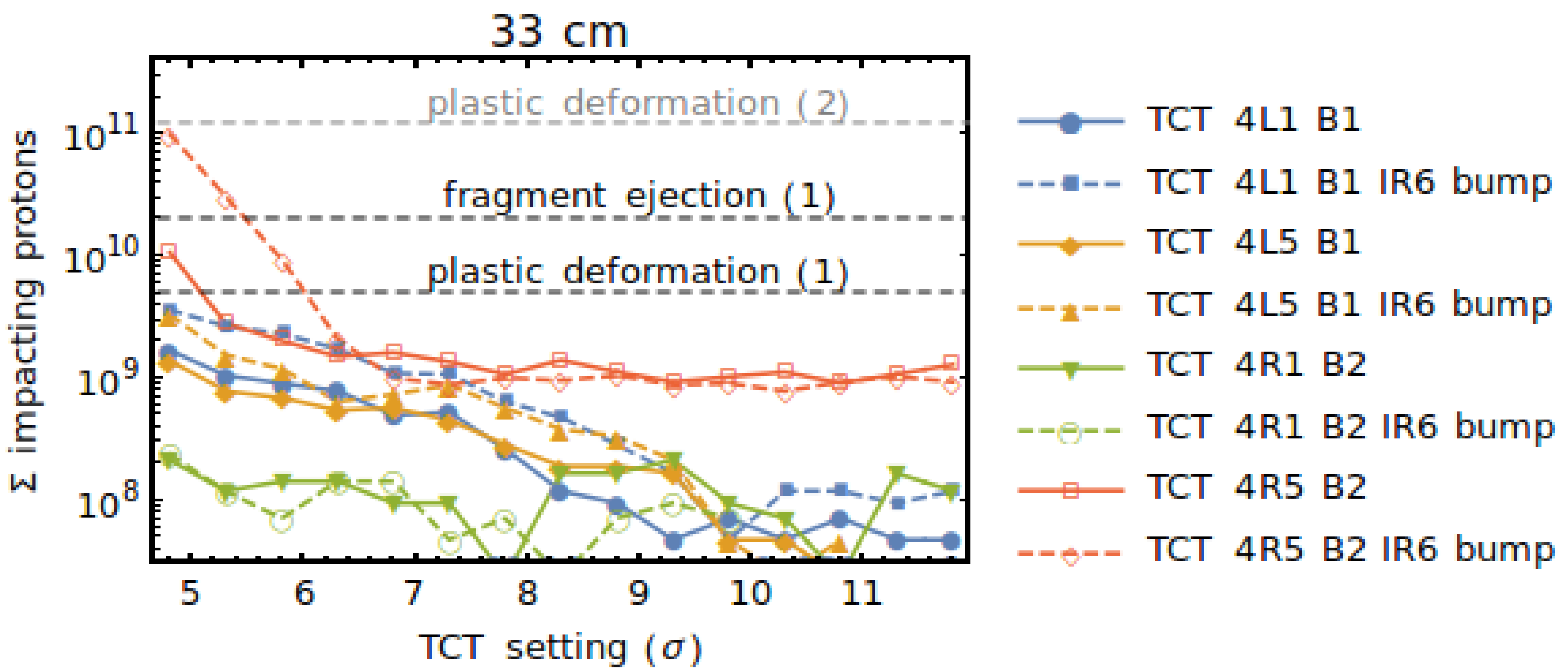
- Collimation working group on 7/11/2016: assess tighter collimator feasibility
- New proposal
  - Reduced TCP-TCSG by 0.5 σ
  - Reduced TCSG-TCT by 0.5 σ
  - Could also push TCP setting in by 0.5 σ
    - Tested in one MD fill
- In total: We gain around 1.0 - 1.5 σ in aperture
- Impedance OK for these settings (see talk L. Carver)

Collimator	2016	2017a	2017b
TCP IR7	5.5	5.5	5.0
TCSG IR7	7.5	7.0	6.5
TCLA IR7	11.0	10.5	10.0
TCP IR3	15.0	15.0	15.0
TCSG IR3	18.0	18.0	18.0
TCLA IR3	20.0	20.0	20.0
TCSG IR6	8.3	7.8	7.3
TCDQ IR6	8.3	7.8	7.3
TCT IR1/5	9.0	8.0	7.5
Aperture 1/5	*9.9*	*9.0*	*8.5*
TCT IR2	37.0	37.0	37.0
TCT IR8	15.0	15.0	15.0

Settings in σ with ε=3.5 μm

SixTrack results for 2017 settings

- Similar trend for 33 cm optics and 2017 settings
  - Only TCTPH.4R5.B2 could give any concern

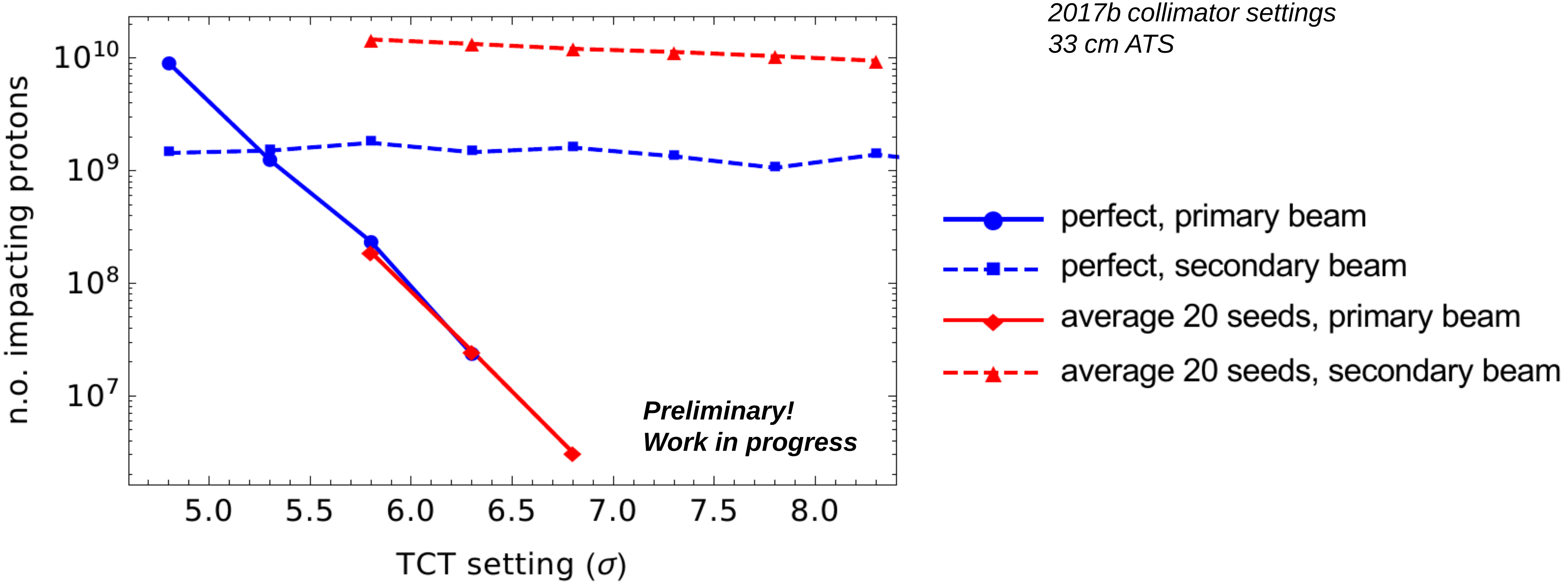


ATS 2017, 33 cm, 2017b collimator settings

Imperfections?

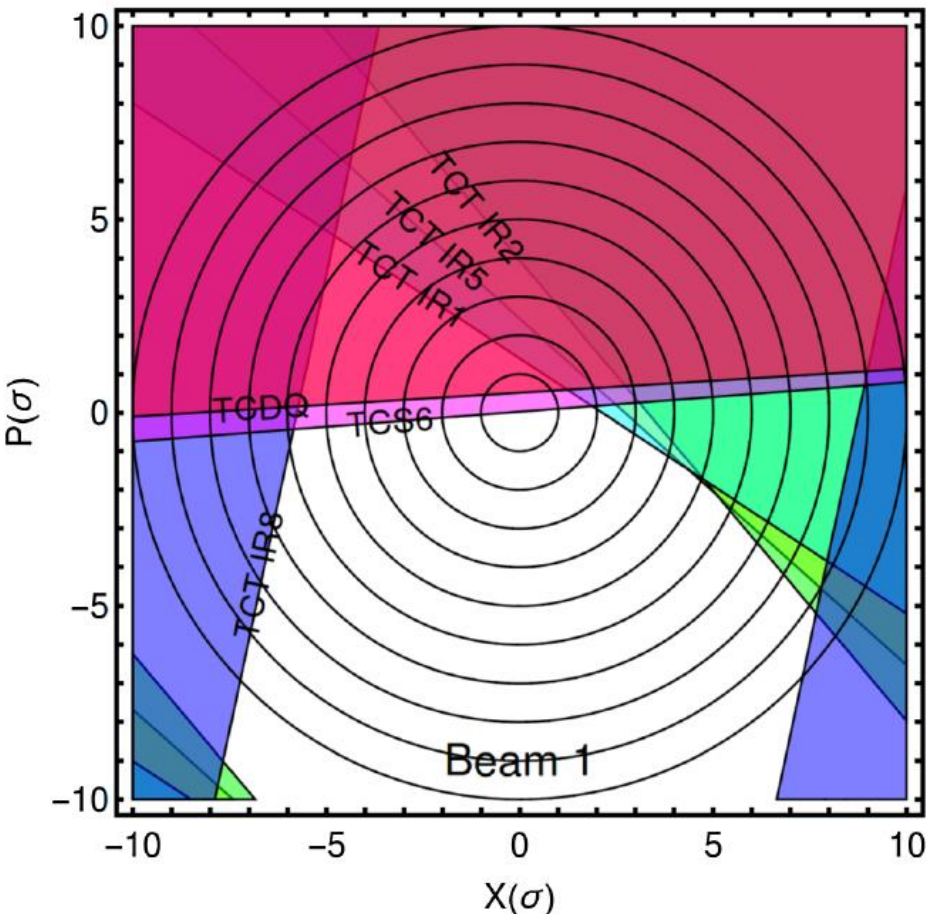
- First results: for TCTPH.4R5.B2, imperfections has negligible impact on primary impact (on average) while increases (on average) secondary impacts (spread out) by factor 5-10
  - Not likely that random errors on all 3 devices causes TCT to be closer than both TCSP and TCDQ
  - Apply correlated error to TCDQ and TCSP?

2017b collimator settings
33 cm ATS



Phase space integration

- For parametric studies, need faster optics-independent method
- Using simplified method to study the dependence of primary impacts on the phase advance
- Integrating beam distribution over the linear cuts in phase space
- Again, studying 25 ns bunches separately and summing over all
- Depends only on settings and phase advance - optics not needed
- All collimators black absorbers => only primary impacts studied

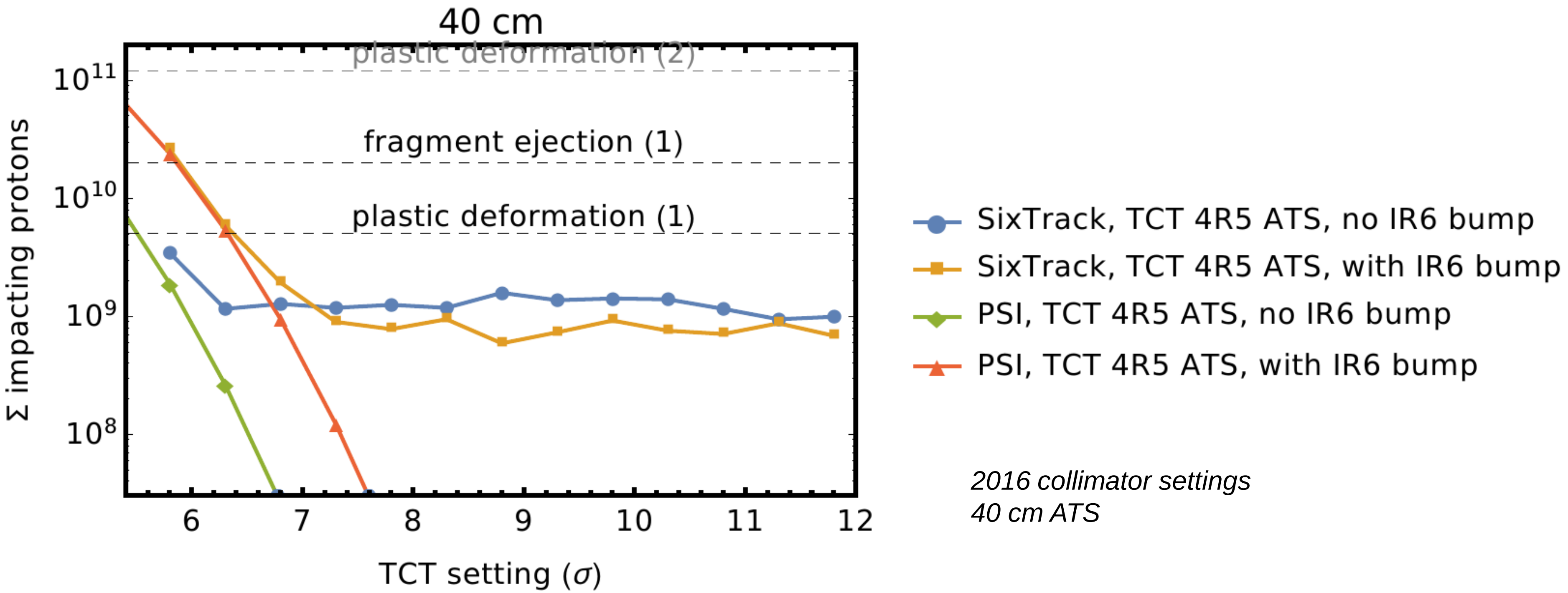


$$|X_i| \geq A_i \Leftrightarrow |C_{0i}X_0 + S_{0i}P_0 + S_{0i}\theta + D_i\delta| \geq A_i$$

Setup described in detail in PRSTAB 18, 061001 (2015)

Comparison with SixTrack for ATS optics

- Phase-space integration (PSI) agrees well with SixTrack for the primary losses



2016 collimator settings
40 cm ATS

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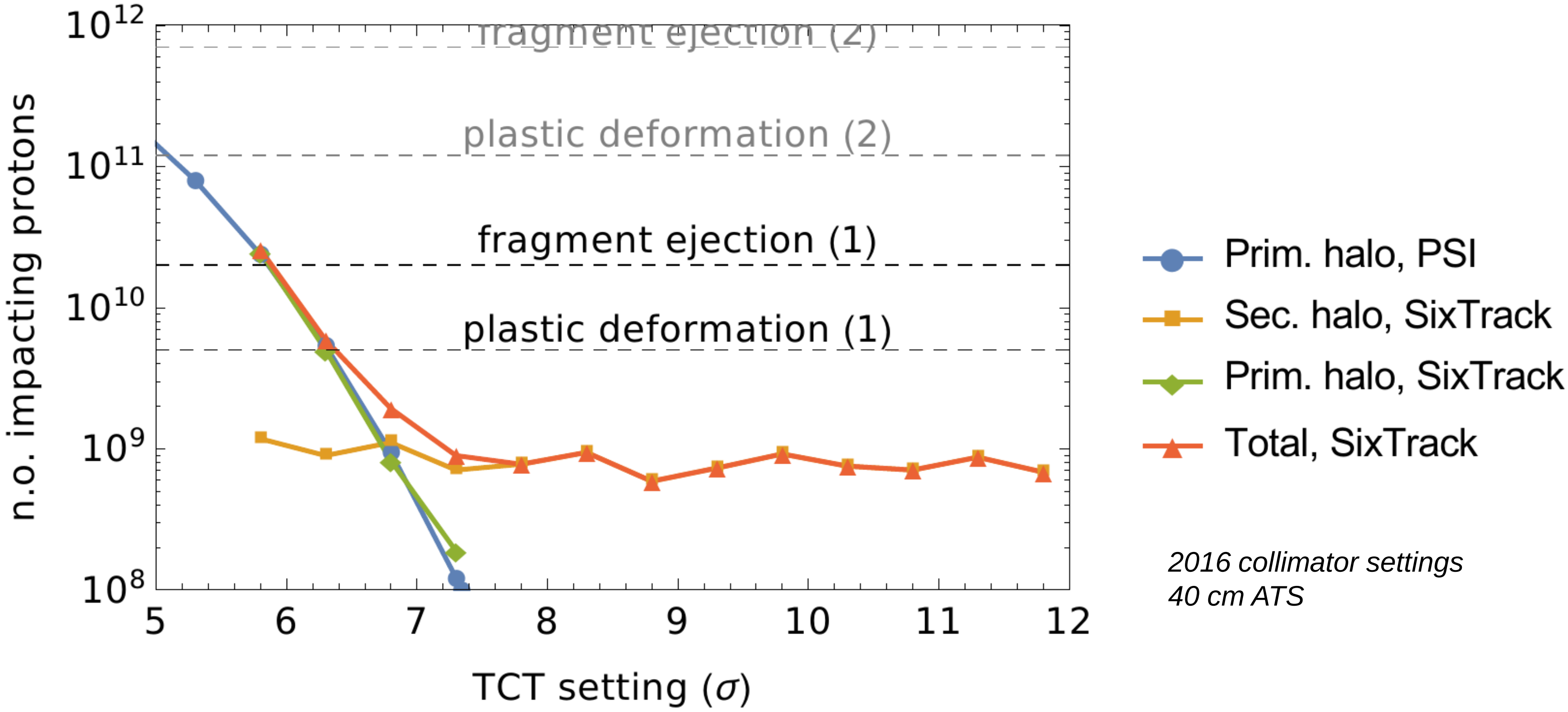
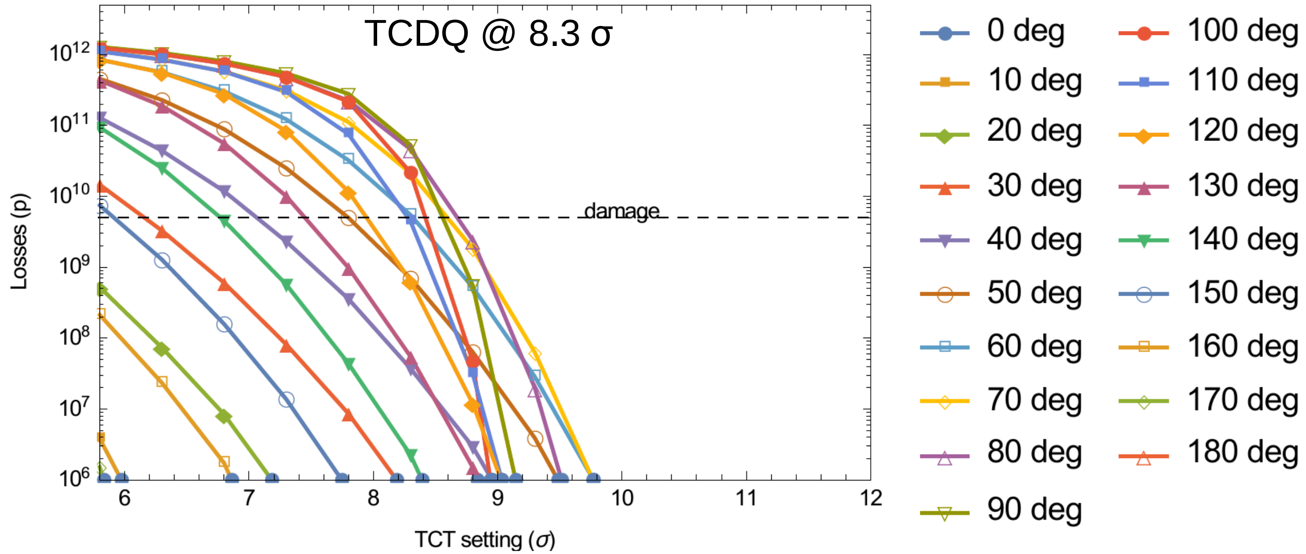
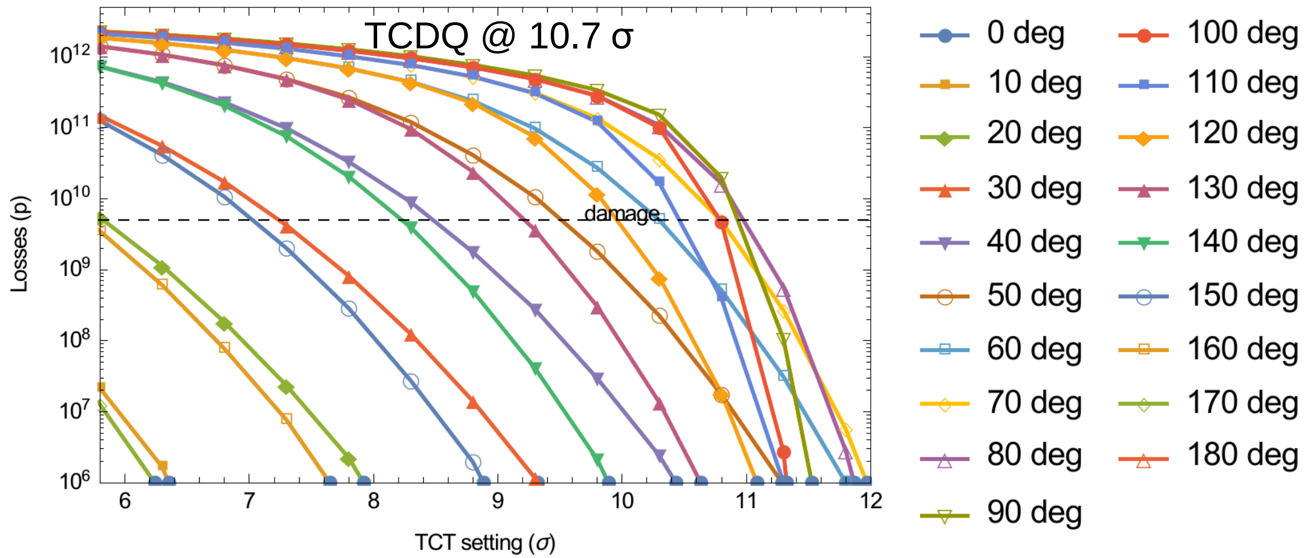


2016 collimator settings
40 cm ATS

TCT losses vs phase and setting

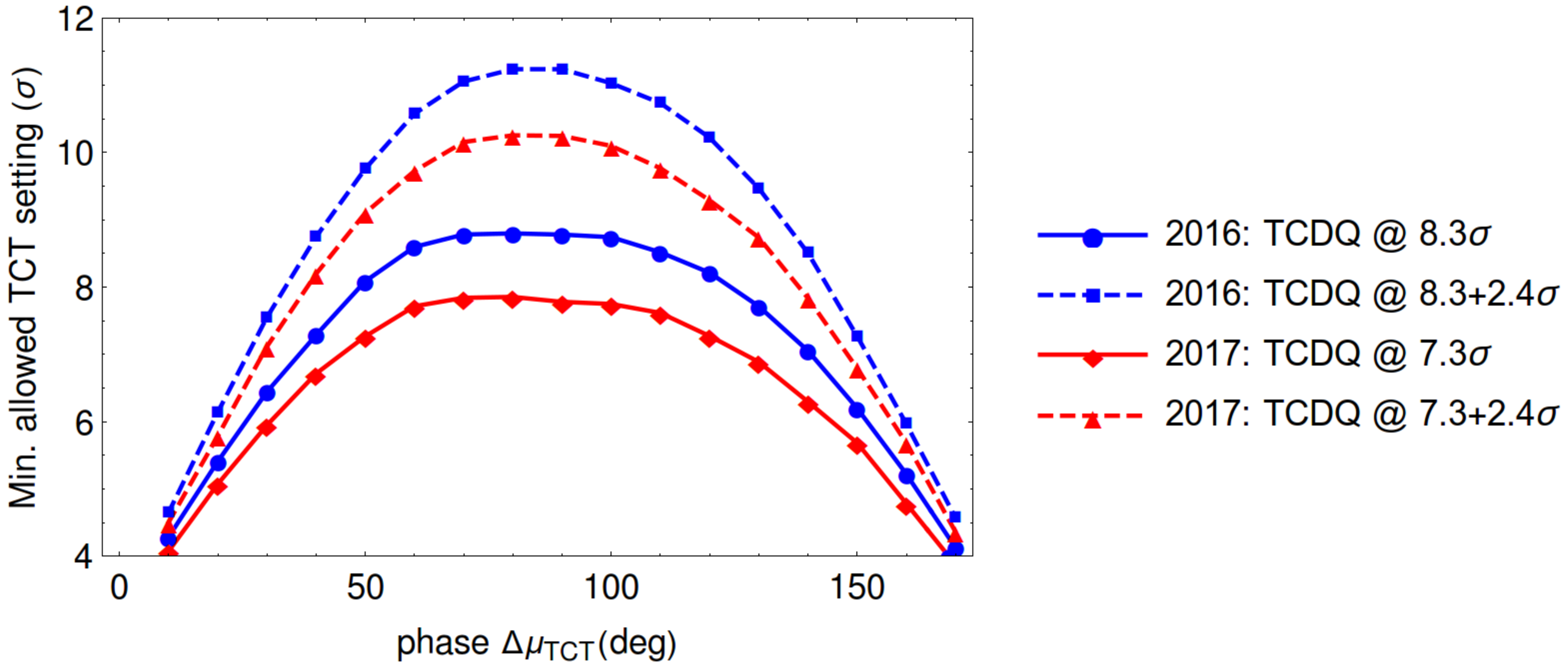
- Phase space integration, neglecting IR7 : include only TCDQ + one TCT
- Check for
  - 2016 nominal TCDQ setting (8.3 σ)
  - with TCDQ misaligned by 1.2 mm as level of interlock (10.7 σ)
- TCDQ phase = 95 deg => asymmetry 90+x and 90-x due to





TCT setting at damage vs phase

- For each phase, solving for setting at which TCTs are damaged, with factor 2 margin – i.e. assuming 2.5E9 protons as limit – and 1.5E11 p/bunch



Observations on TCT damage vs phase

- Every 10 deg gives about 1σ margin if we are far from 90 deg
- At 0 deg phase advance: impossible to damage TCTs with primary beam
- At 20 deg phase advance: TCTs damaged if at about the level of the primary collimator
  - Very unlikely that it goes in so far
  - Still, preferable to have as much safety margin as possible
- For 2017 settings:
  - With nominal TCDQ setting of 7.3 σ, risk damage at 5.7 σ at 150 deg, 5.3 σ at 155 deg
  - with TCDQ misaligned by 1.2 mm, hit damage limit around 6.8 σ at 150 deg, 6.3 σ at 155 deg
- Compare: proposed tightest TCT setting is 7.5 σ

Total margin in different configurations

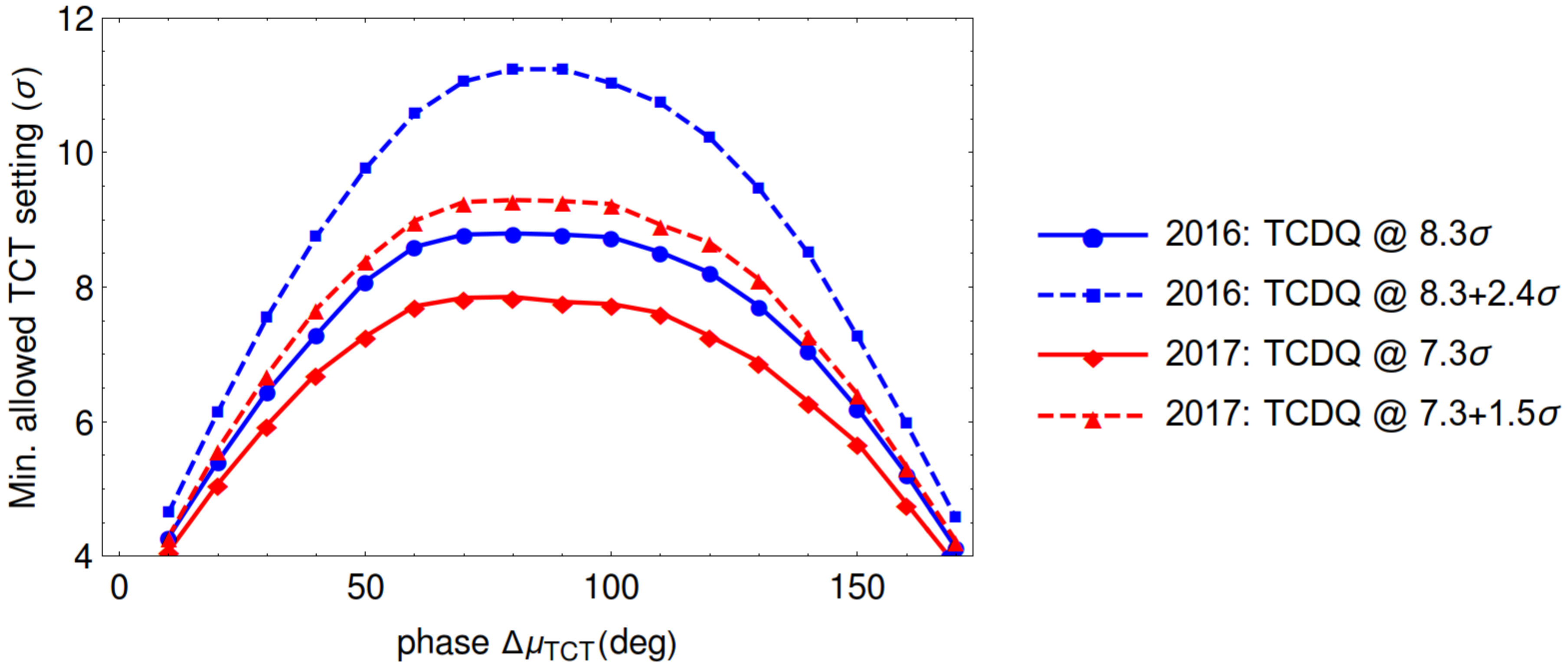
- If we start at 40 cm, TCT could be kept at 9-9.5σ, still with tighter IR7/6
  - Additional safety margin of 1.5 σ – 2 σ compared to tightest TCT setting
  - Total margin from OP setting to risk of damage (pessimistic) : > 3.7 σ
    - 9 – 5.3 = 3.7 σ with TCDQ in place, (9-6.8)+ 2.4 = 4.6 σ with TCDQ misaligned 1.2 mm
  - In this condition, we should have plenty of margin
- Squeeze later to 33 cm?
  - Estimated aperture at 33 cm, 10 σ BB for 2.5 um, is 9.4 σ
    - Caveat: CMS realignment
  - With 0.5 σ safety margin => aperture could go down to 8.9 σ
  - Keep TCT at 7.9 σ
  - => With TCDQ at 7.3 σ, have nominally 0.6 σ margin, almost as 2016
  - Total margin from OP setting to risk of damage: > 2.6 σ
    - 7.9 – 5.3 = 2.6 σ with TCDQ in place, (7.9-6.8) + 2.4 = 3.5 σ with TCDQ misaligned 1.2 mm

Gain with BPM interlocks

- Can we profit of new interlocks with BPM buttons to increase safety? G. Valentino, CWG 05.12.2016:
  - Can introduce interlock with 1.5 σ at TCSP, 1 σ at TCTs
  - In total, up to 2.5 σ total reduction of margin TCDQ – TCT allowed
- Compare: estimated reduction of margin from measured orbit and 10% β-beat is ~2 σ
  - We should never hit interlock limit
- Repeat loss scan with TCDQ misaligned by only 1.5 σ

TCT setting at damage vs phase

- For each phase, solving for setting at which TCTs are damaged, with factor 2 margin – i.e. assuming 2.5E9 protons as limit – and 1.5E11 p/bunch



When would we dump at 40 cm and 33 cm?

- If we start at 40 cm, TCT could be kept at 9-9.5σ, still with tighter IR7/6
  - Assuming TCDQ is at limit of interlock (+ 1.5 σ)
  - TCT at > 9 σ, estimated damage at 6 σ
  - Dump at 1 σ orbit offset at TCT: still need > 2 σ further offset to reach TCT damage limit
- Squeeze later to 33 cm?
  - Assuming TCDQ is at limit of interlock (+ 1.5 σ)
  - TCT at 7.9 σ, estimated damage at 6.0 σ
  - Dump at 1 σ orbit offset at TCT: still need 0.9 σ further offset to reach TCT damage limit

Safety margins with orbit interlock

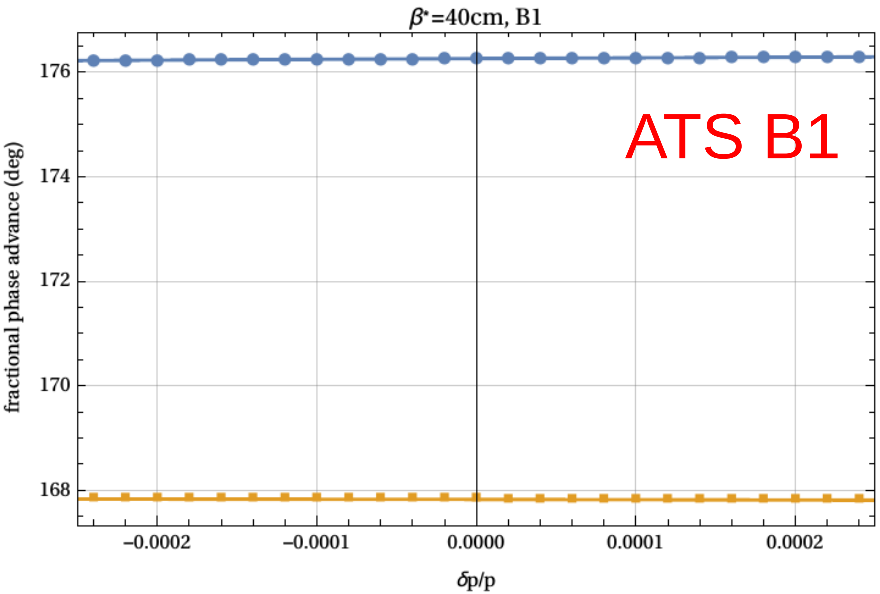
- Assume 33 cm and standard TCT setting of 7.9 σ
- Assuming TCDQ on outer limit of interlock (7.3 σ + 1.5 σ = 8.8 σ)
- Assuming TCT on inner limit of interlock (7.9 σ – 1 σ = 6.9 σ)
- In total, loss of 2.5 σ margin (pessimistic!)
- At 150 deg, estimated ~0.2% of one bunch impacting
  - **3E8 p** impacting for 1.5E11 p/bunch, factor **>15** safety margin to 5E9
- At 155 deg, estimated ~0.03% of one bunch impacting on TCT
  - **4.5E7 p** impacting for 1.5E11 p/bunch, factor **>100** safety margin to 5E9
- Ideally, during commissioning, qualify with asycnch dump test a configuration outside the limit of the interlocks

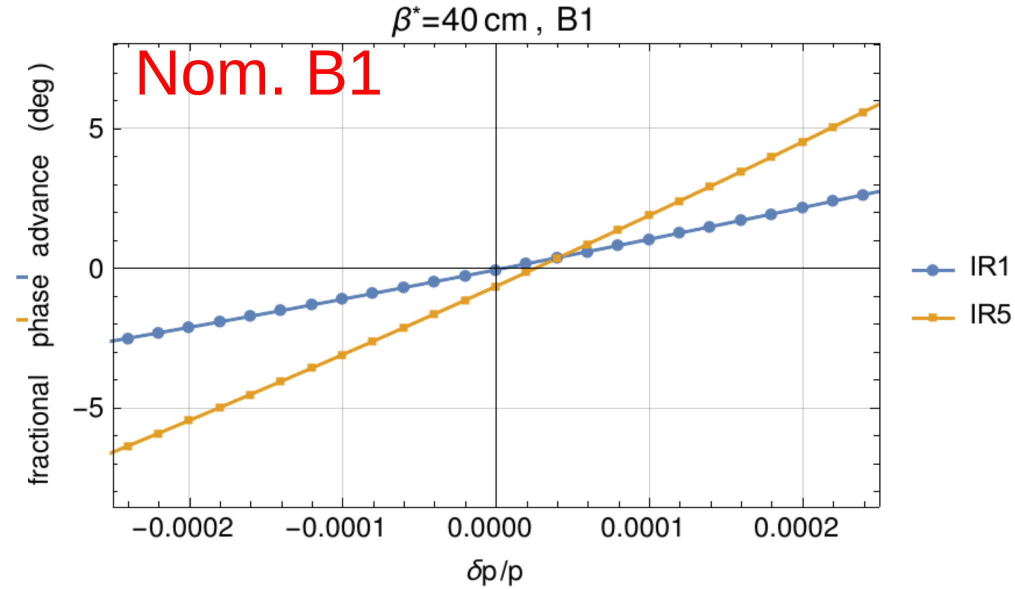
Expected drifts of phase

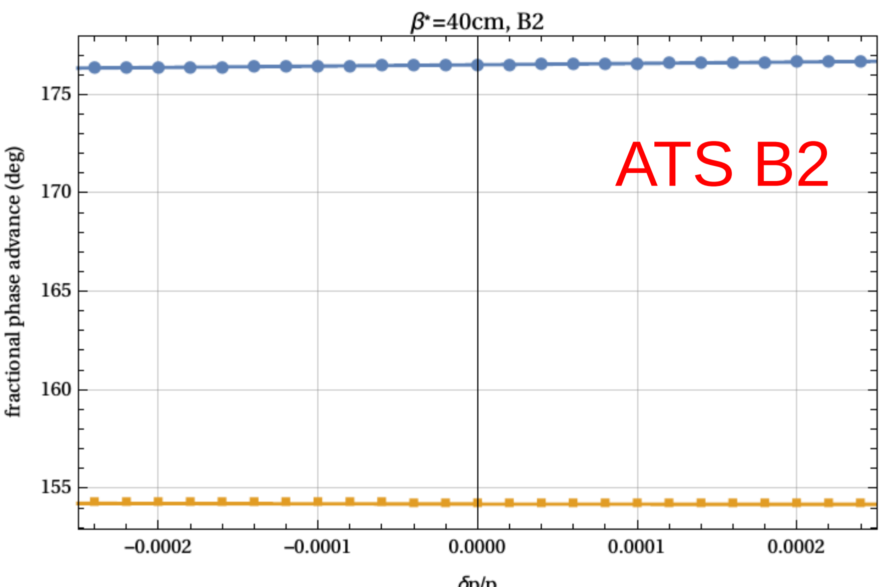
- Sources of drift of the phase
  - Momentum offsets. For dp/p = 2E-4 (orbit interlock in arc) :
    - Phase drift with ATS optics is < 0.2 deg
    - Phase drift with nominal optics is < 8 deg
  - Imperfect optics correction (under study, OMC team)
    - Confident it will not be more than a few deg drift for both optics
  - Drift of optics over time (under study, OMC team)
    - Known to be small. Quantification underway

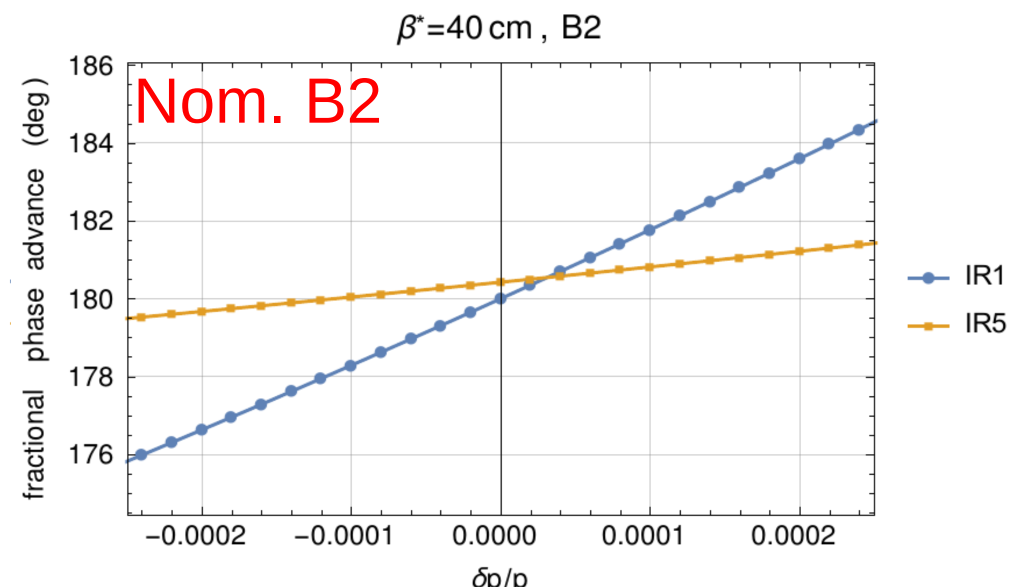
Off-momentum phase beating from MAD-X

2016 optics









Conclusions

- In ATS optics, worst phase advance from MKD.O is ~154 deg on TCTPH.4R5.B2.
  - Effectively reduces margin to damage during asynch dump compared to “perfect” phase
  - Still, very significant improvement compared to past ATS optics
- Using old method with bad phase, need > 2 σ margin TCDQ-TCT for 99% coverage
- Option 1: 40 cm ATS, TCT @ 9-9.5 σ, TCDQ @ 7.3 σ
  - Should have plenty of margin
- Option 2: 33 cm ATS, TCT @ 7.9 σ, TCDQ @ 7.3 σ
  - If using BPM interlocks, should still be safe at the limit of the interlocks, and additional ~1 σ loss needed before risk of damage
  - Would be useful to qualify with asynch dumps with more pessimistic settings than
- Under study: influence of imperfections in simulation
- Need to make sure that correction is good and that phase doesn’t drift over time – discuss with OMC team
- PC interlock? Interlocking at 15 deg gives a (too large?) error tolerance
- If we want to squeeze to the final fraction of σ possible, we eat up the remaining margins at around 31 cm

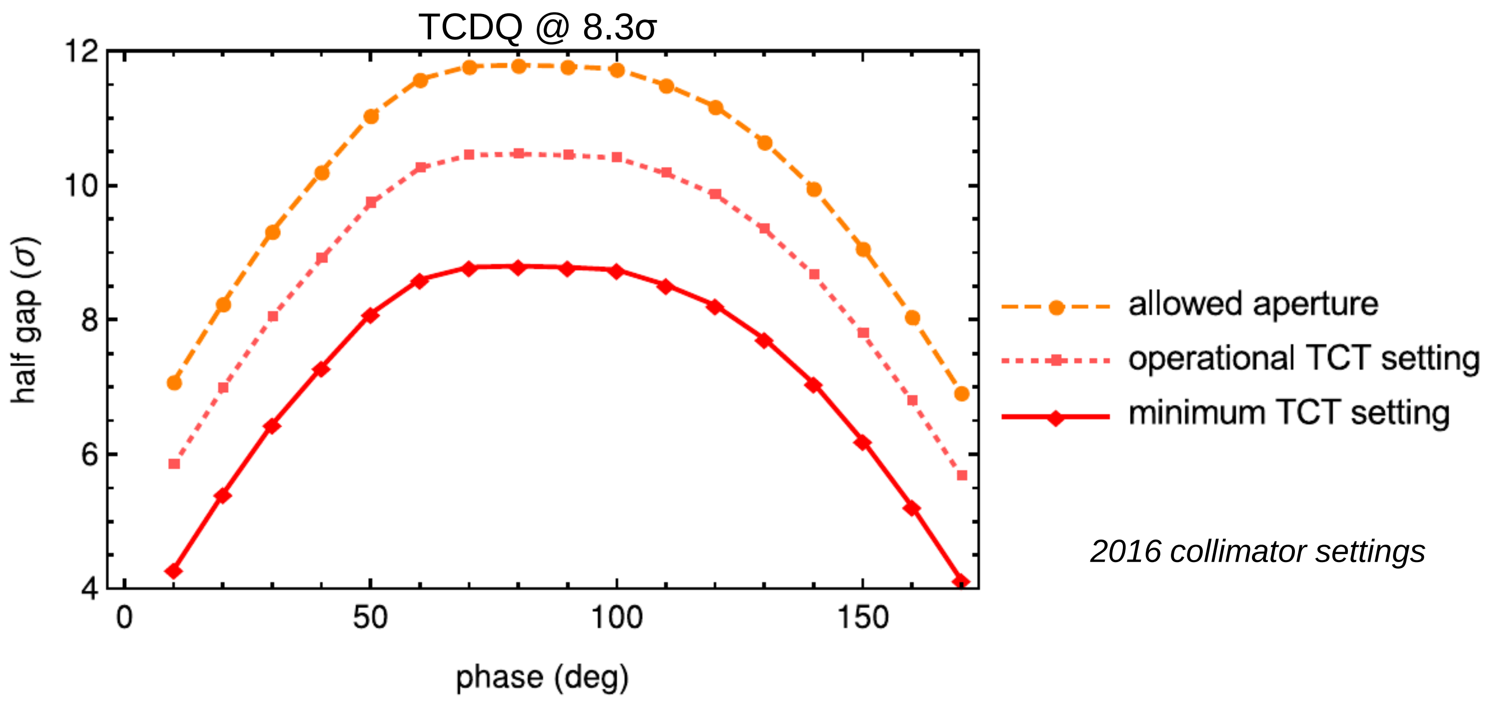
Backup

Safety margins with orbit interlock

- Assume tight TCT setting of 7.5 σ
- Assuming TCDQ on outer limit of interlock (7.3 σ + 1.5 σ = 8.8 σ)
- Assuming TCT on inner limit of interlock (7.5 σ – 1 σ = 6.5 σ)
- In total, loss of 2.5 σ margin (pessimistic!)
- At 150 deg, estimated 1% of one bunch impacting
  - **1.5E9 p** impacting for 1.5E11 p/bunch, factor **>3** safety margin to 5E9
- At 155 deg, estimated ~0.2% of one bunch impacting on TCT
  - **3E8 p** impacting for 1.5E11 p/bunch, factor **>15** safety margin to 5E9
- Ideally, during commissioning, qualify with asycnch dump test a configuration outside the limit of the interlocks

Protected aperture as function of phase

- Starting from the setting where the TCT is damaged, calculating needed margin for orbit and β-beat to determine TCT setting and protected aperture
- Same method as in Run I, but start from setting with TCT@damage instead of TCDQ setting



2016 collimator settings

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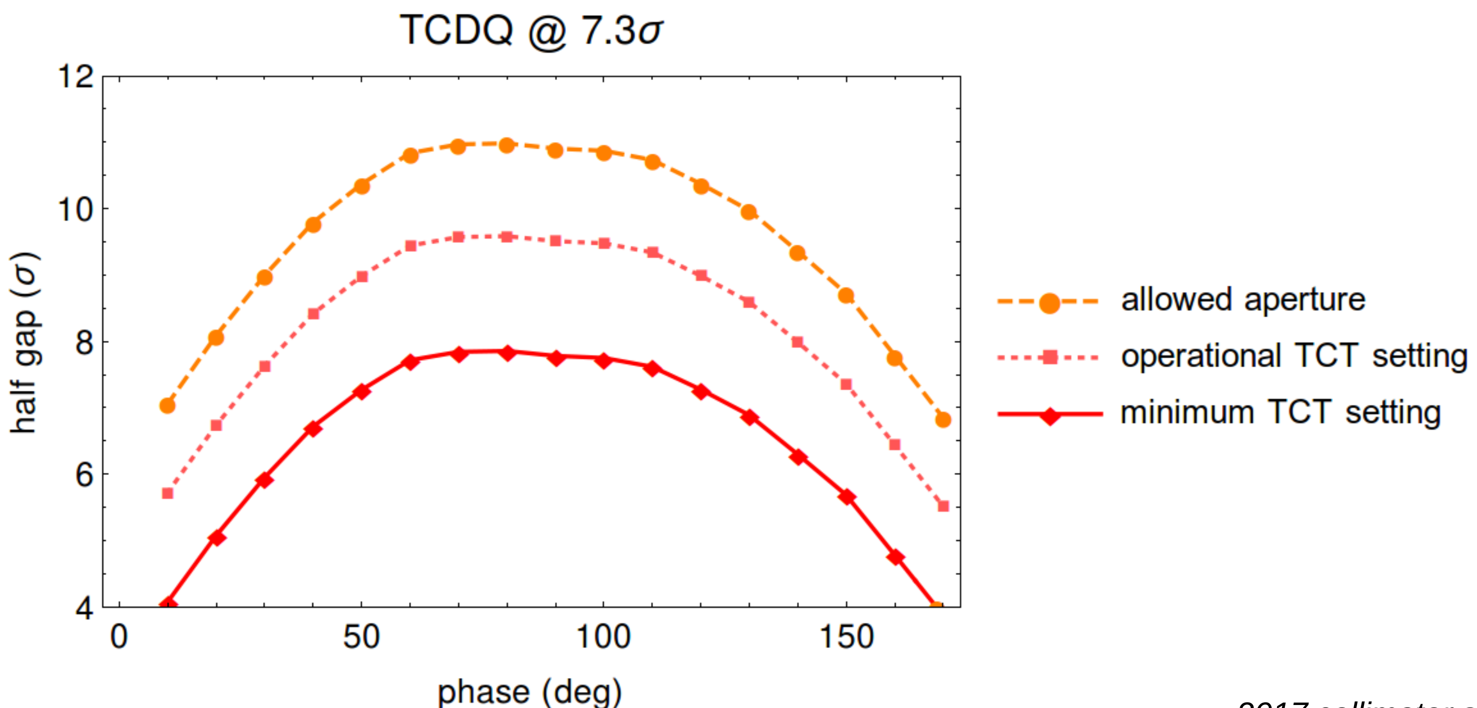
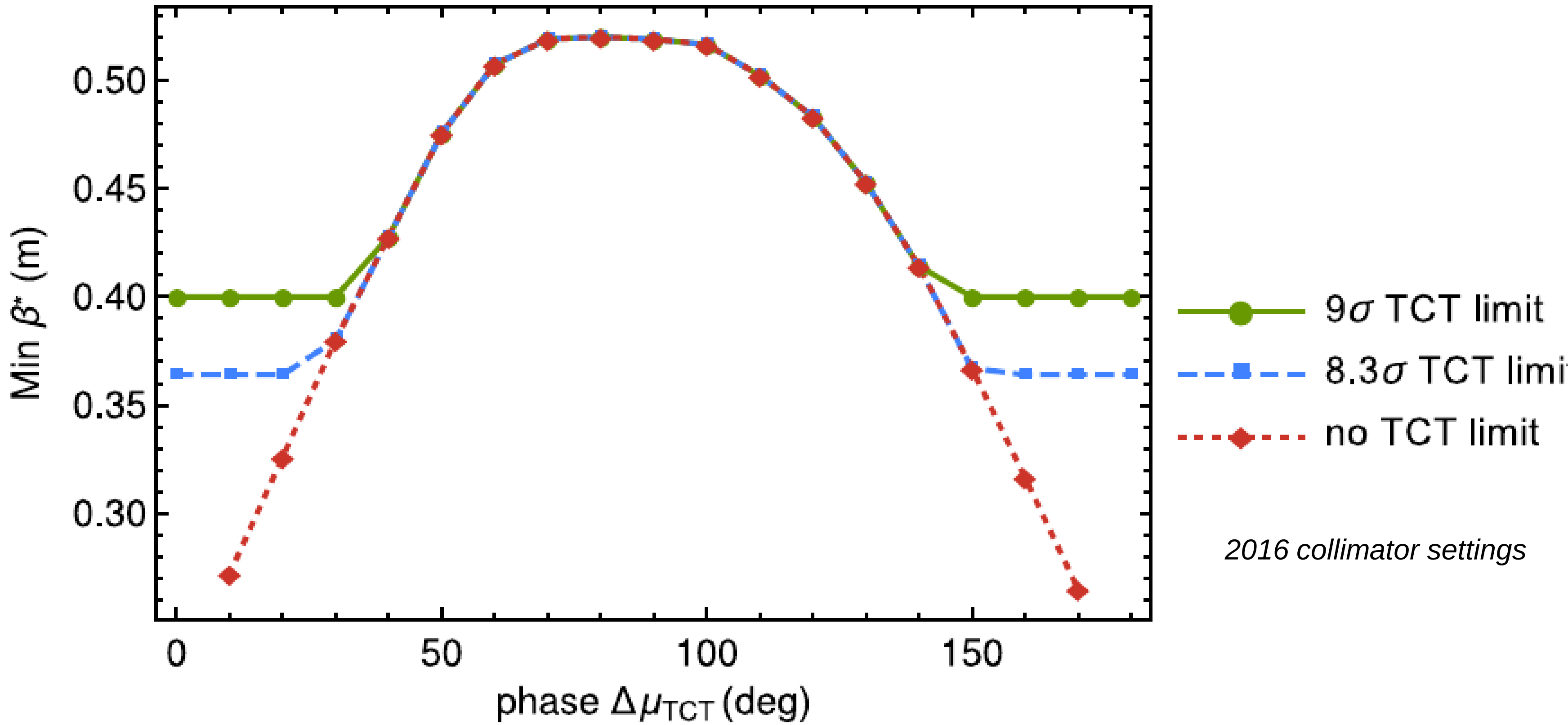


2017 collimator settings

β*-reach as function of phase

- From protected aperture, calculating β*
- For 2016 assumptions, below 30 deg limitation is cleaning and not asynch dump



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β*-reach as function of phase

- For 2017: assume tighter 7.3 σ TCDQ setting and that we don't go below 33 cm anyway