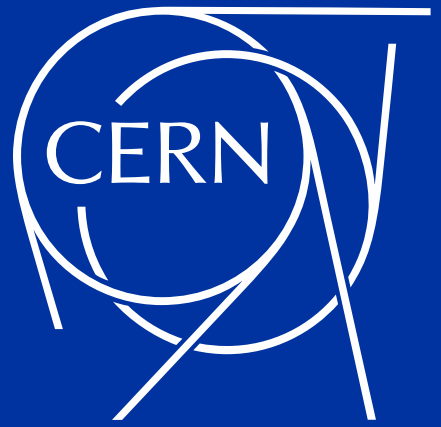


Allowed number of bunches for ADT coherent excitation during Run III and for HL-LHC

Cédric Hernalsteens, Daniel Wollmann

13th August 2021, 211th MPP meeting

https://fast-failures.docs.cern.ch

ADT coherent excitation

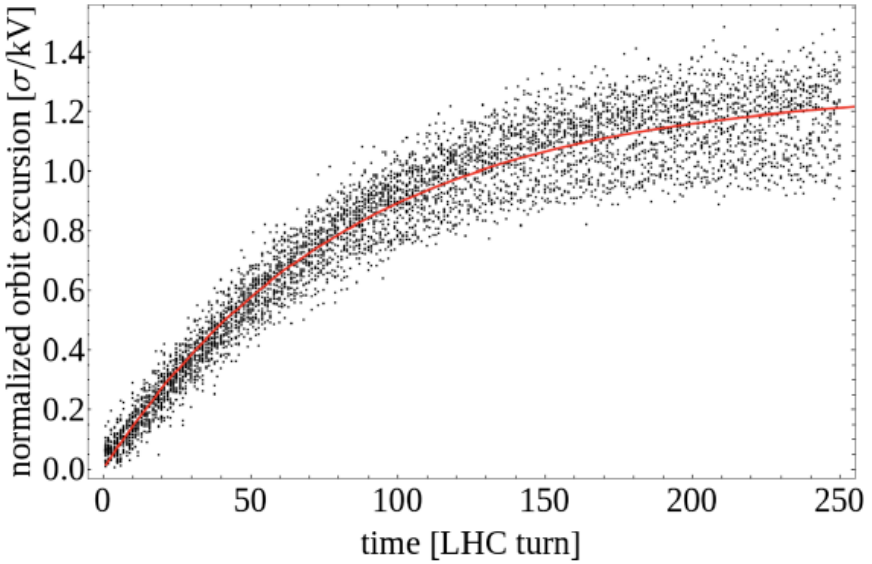
ADT operation in coherent excitation mode

- Potential fast-failure leading to beam losses reaching the critical loss limit within few milliseconds
- Orbit excursion is a superposition of coherent excitation and always-on damping (see figure)

Objectives

- Provides estimates on the **time-dynamics of beam losses** for various ADT operation modes
- Determine the **operational envelope** for allowed operation with the ADT in coherent excitation during **Run III** and for **HL-LHC**, in terms of
  - Length of the excitation window (number of bunches)
  - Maximum allowed voltage

ADT model from measurements



Measured coherent excitation of the beam by the ADT normalized to the applied voltage at 6.5 TeV with fitted scaling law

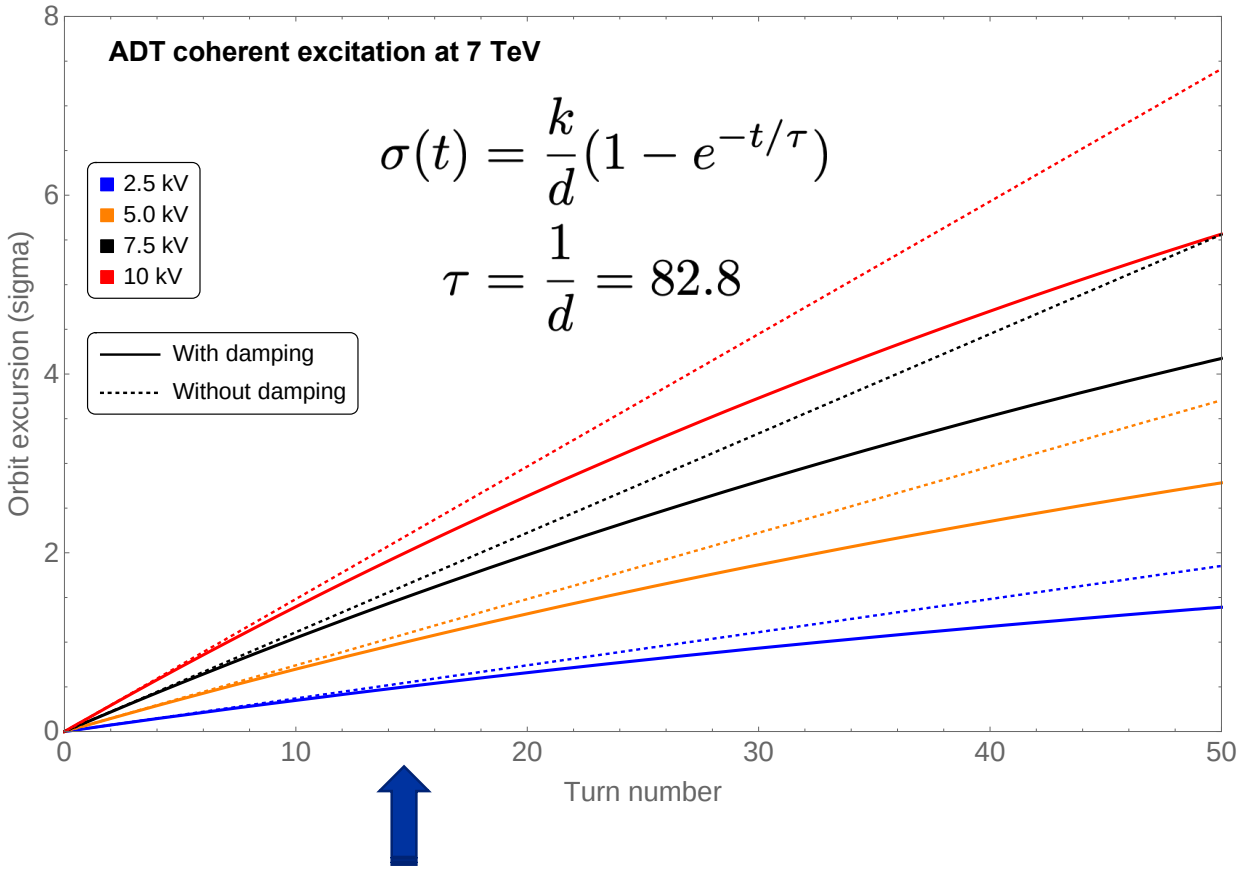
$$\frac{d}{dt}\sigma(t) = k - d \cdot \sigma(t)$$

$$\sigma(t) = \frac{k}{d}\left(1 - e^{-d \cdot t}\right)$$

B. Lindstrom, *et al.*, Phys. Rev. Accel. Beams **23**, 081001.

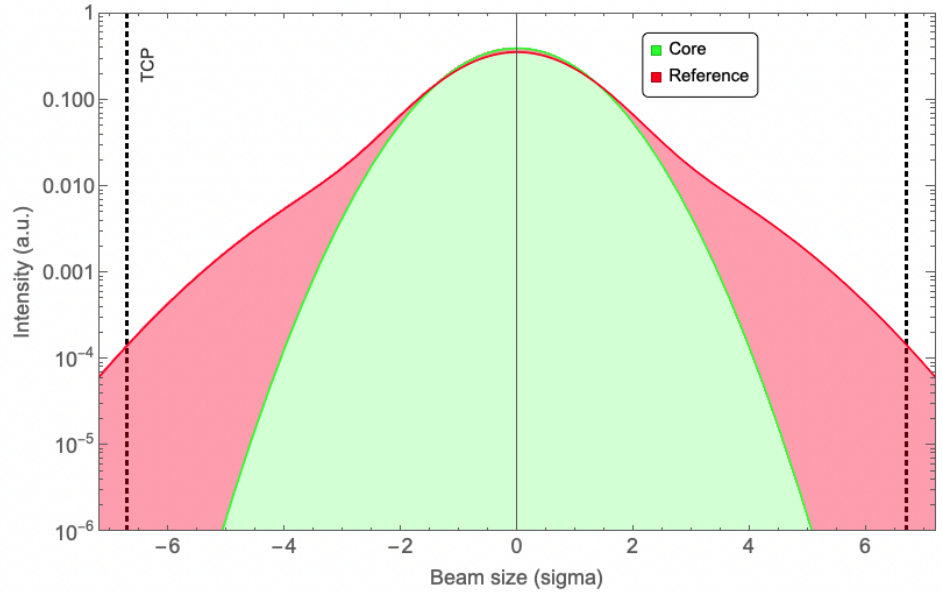
Parametric models

ADT excitation



Critical orbit excursion reached around turn 14 for a full machine

Beam distribution

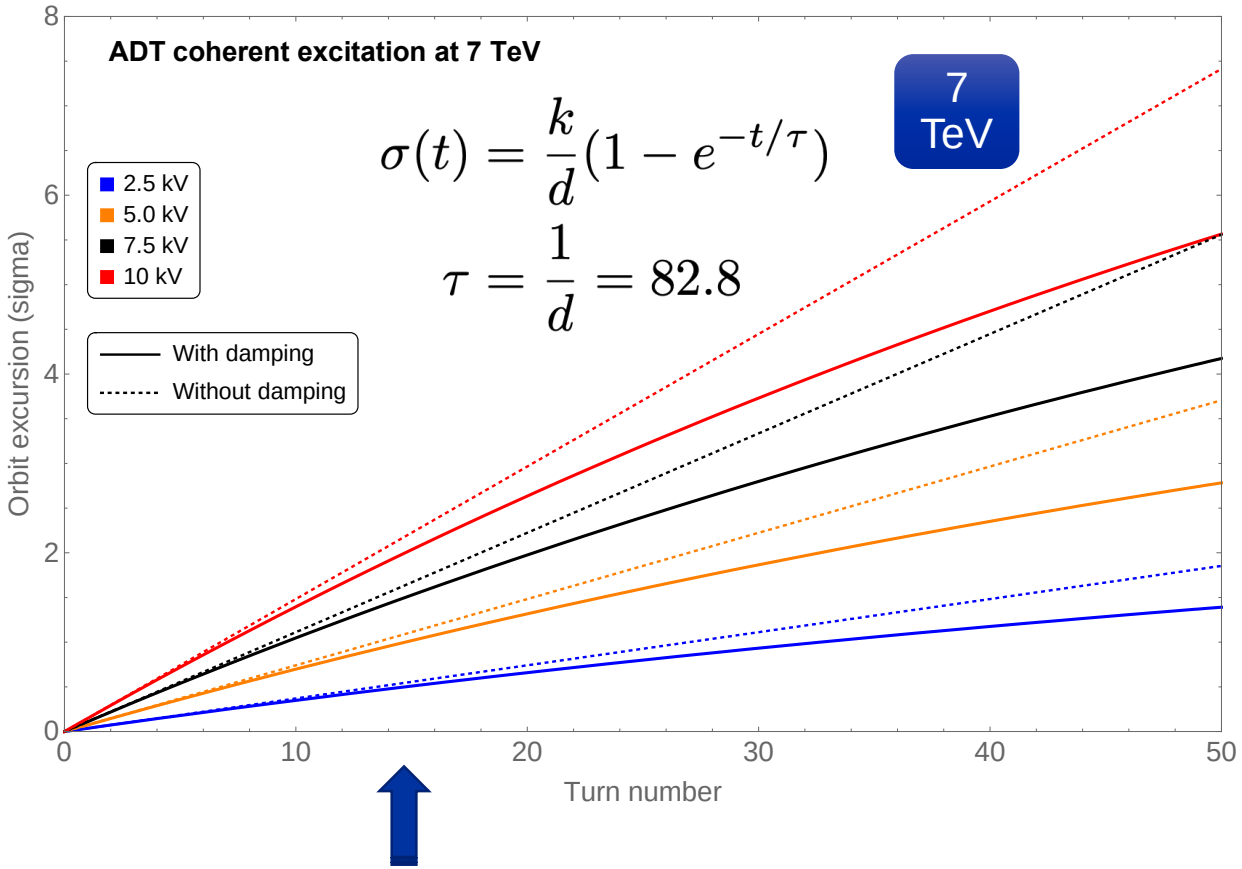


	LHC Run III	HL-LHC
Beam energy	450 GeV and 7 TeV	
Bunch intensity	1.8 e11 protons/bunch	2.2 e11 protons/bunch
TCP settings	6.5 sigma*	6.7 sigma
BCCM threshold	6e11 @ 450 GeV *and* 3e11 @ 7 TeV **	

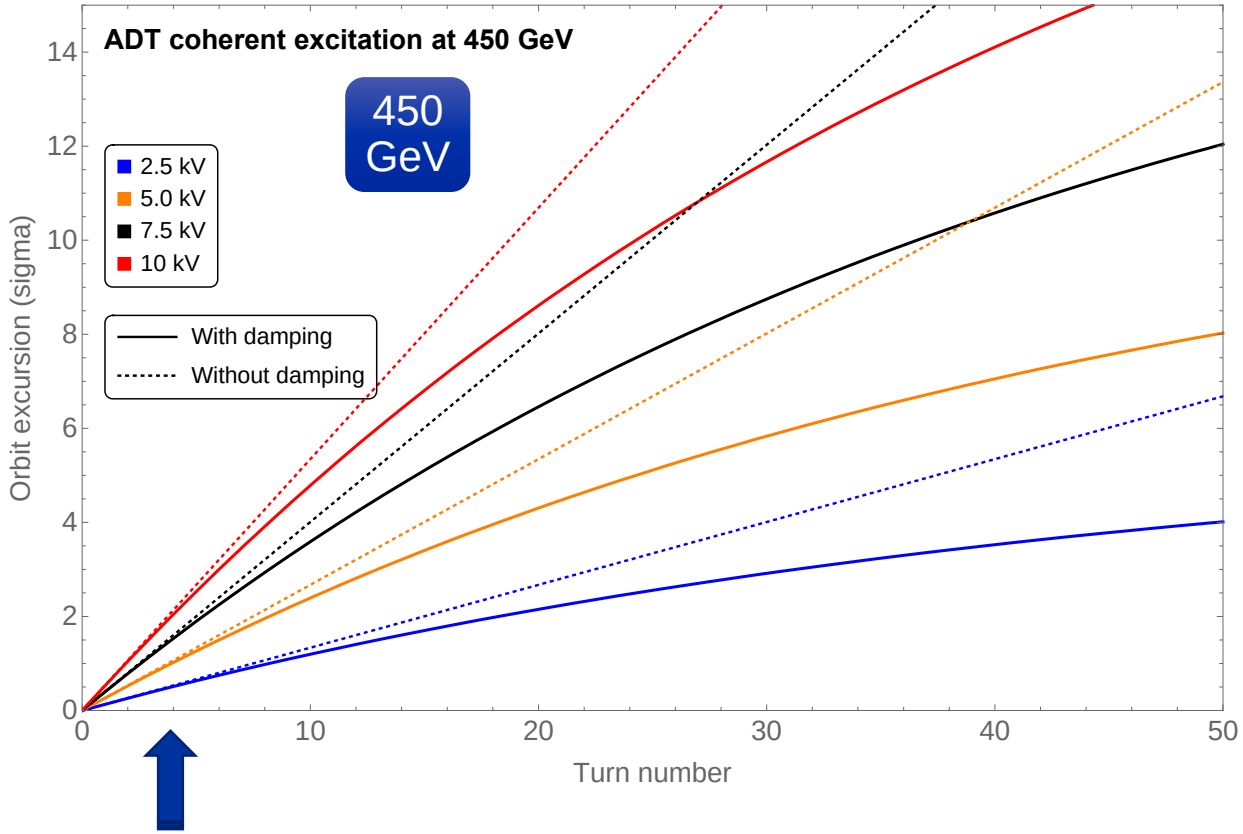
* 5.5 sigma scaled from 3.5 μm down to 2.5 μm
** for short windows (≤ 64 turns)

Parametric models

ADT excitation



Critical orbit excursion reached around turn 14 for a full machine

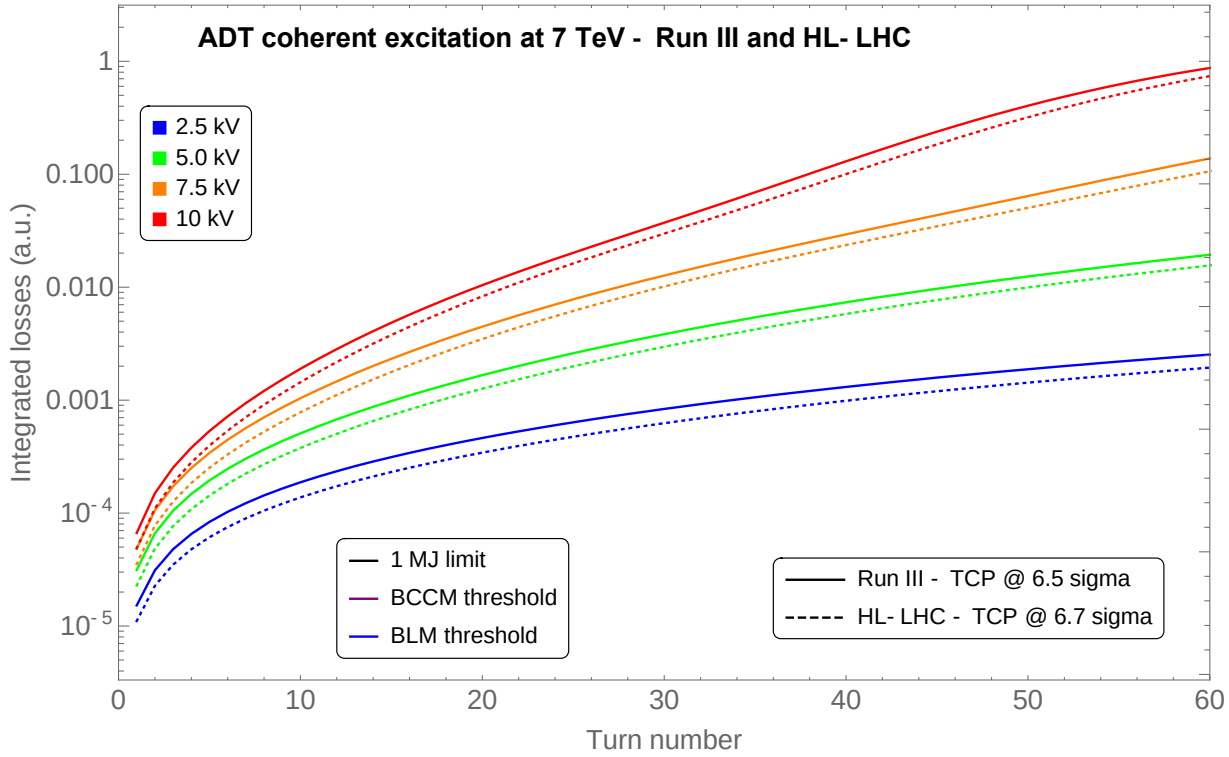


Critical orbit excursion reached around turn 4 for a full machine

Much faster excitation at 450 GeV!

Integrated beam losses

- **Semi-analytical model to compute the losses: integration over the beam distribution**
- **1 MJ of beam losses used as baseline critical loss limit assumed for machine protection**
- **BLM detection with operational threshold for RS01-06 at 125kJ (assumed in IR7 over a few milliseconds)**
- **BCCM threshold at 3e11 protons for 1-turn window**
- **Key considerations**
  - Failure detection is **indirect**: BLMs and BCCM.
  - The failure onset is not observable. Failure onset to damage limit margin is less relevant for indirectly detected failures.
  - Need to consider the **margin between failure detection and critical loss limit**.
  - Need to consider **injection and top energy** as much more strength available at 450 GeV

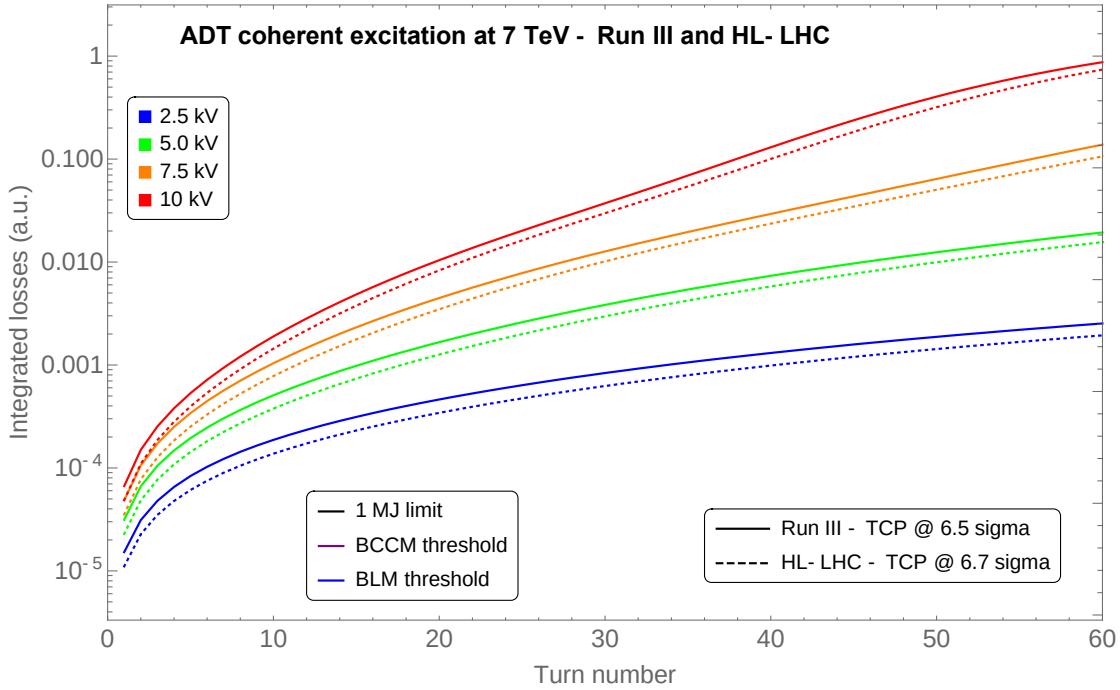


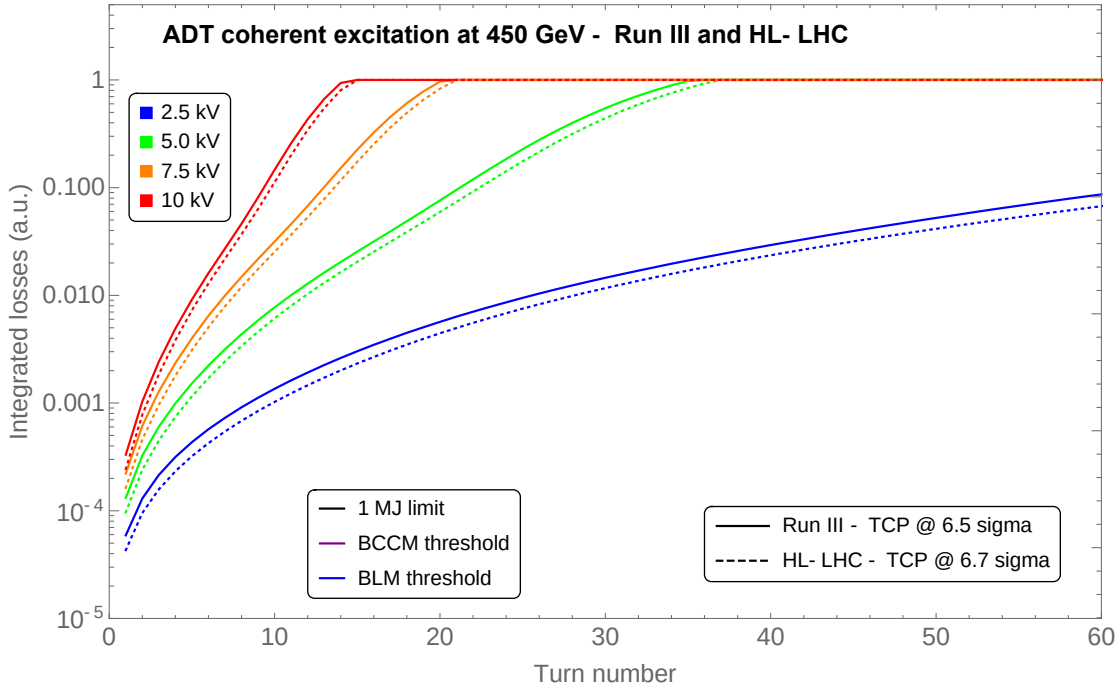
➢ **Integrated fractional beam losses as a function of the turn number for different ADT voltages.**

➢ **BCCM and BLM thresholds shown for a full machine (2748 bunches).**

Integrated beam losses

- **Integrated fractional beam losses as a function of the turn number for different ADT voltages.**
- **BCCM and BLM thresholds shown for a full machine (2748 bunches).**

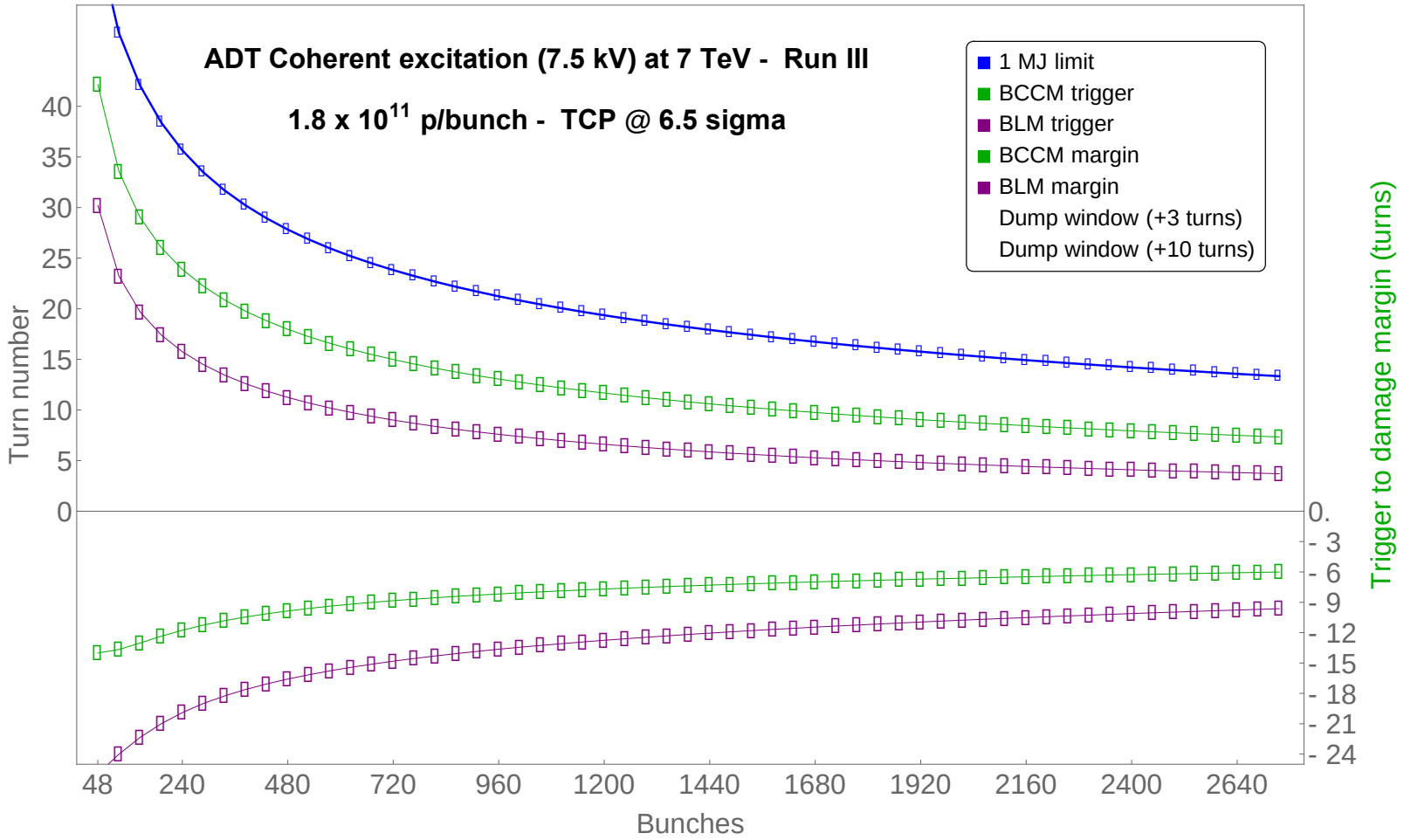




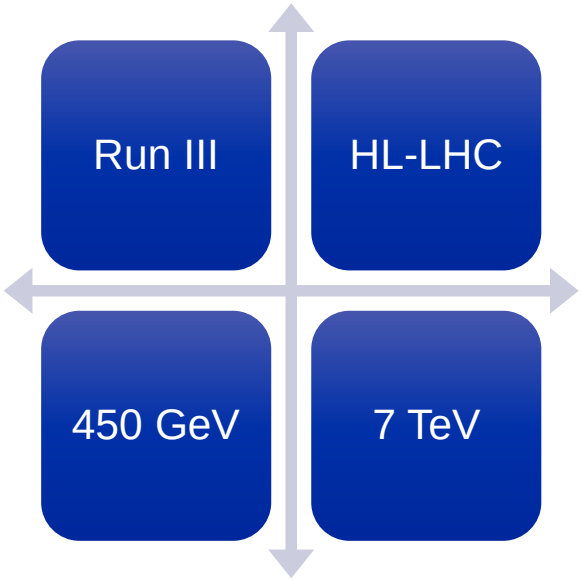
- **Key considerations**
  - Failure detection is **indirect**: BLMs and BCCM.
  - The failure onset is not observable. Failure onset to damage limit margin is less relevant for indirectly detected failures.
  - Need to consider the **margin between failure detection and critical loss limit**.
  - Need to consider **injection and top energy** as much more strength available at 450 GeV

Losses and margins – Run III – 7.5 kV

1. For a given number of bunches, compute
   - The 1MJ critical loss limit
   - The BCCM loss limit
   - The BLM loss limit
2. With the loss limits, inverse the loss v. time relationship (see previous slide/figure)
3. Obtain the turn number at which the event occurs
4. Compute the **trigger to damage margin**



Results and proposals

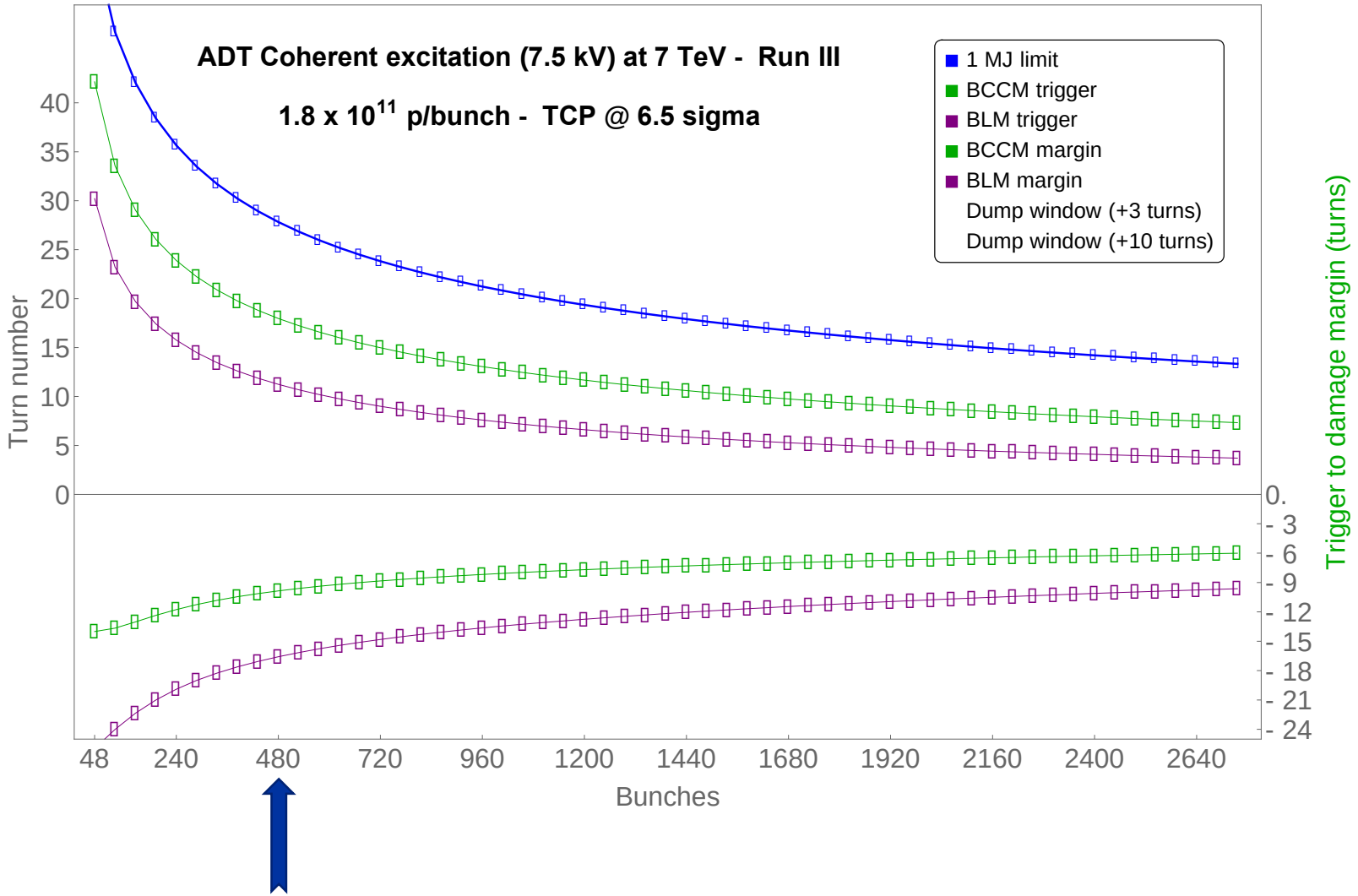


Losses and margins – 7.5 kV

Run III

7 TeV

Conservative 10 turn margin even for the BCCM trigger with up to **2 full batches**



2 batches (480 bunches) proposed as maximum allowed number of bunches

Losses and margins – 10.0 kV

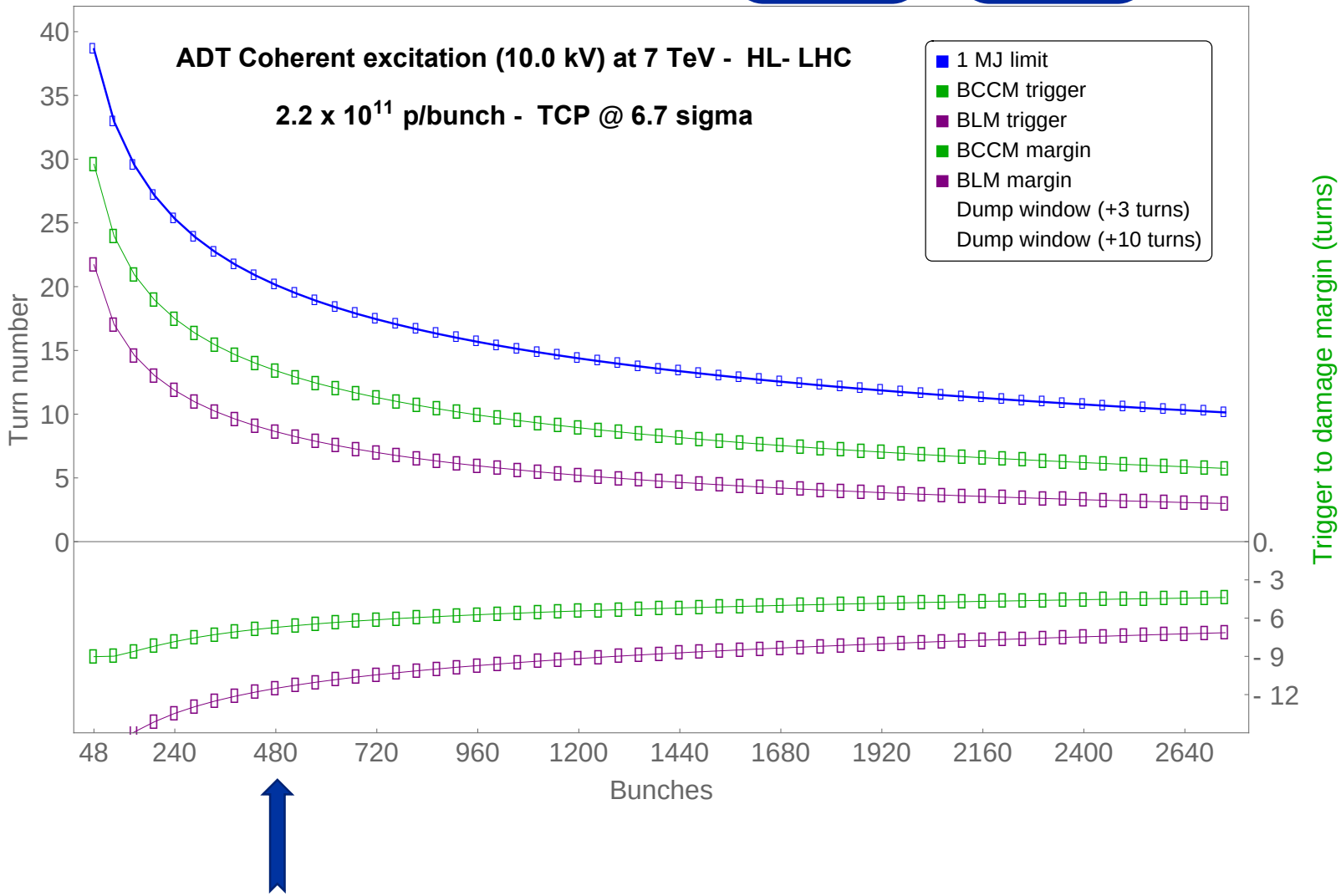
HL-LHC

7 TeV

Margin w.r.t BCCM threshold always below 10 turns

2 batches still provide sufficient margin w.r.t BLM threshold and acceptable limit w.r.t BCCM threshold (7 turns)

2 batches (480 bunches) proposed as maximum allowed number of bunches



Losses and margins – 7.5 kV

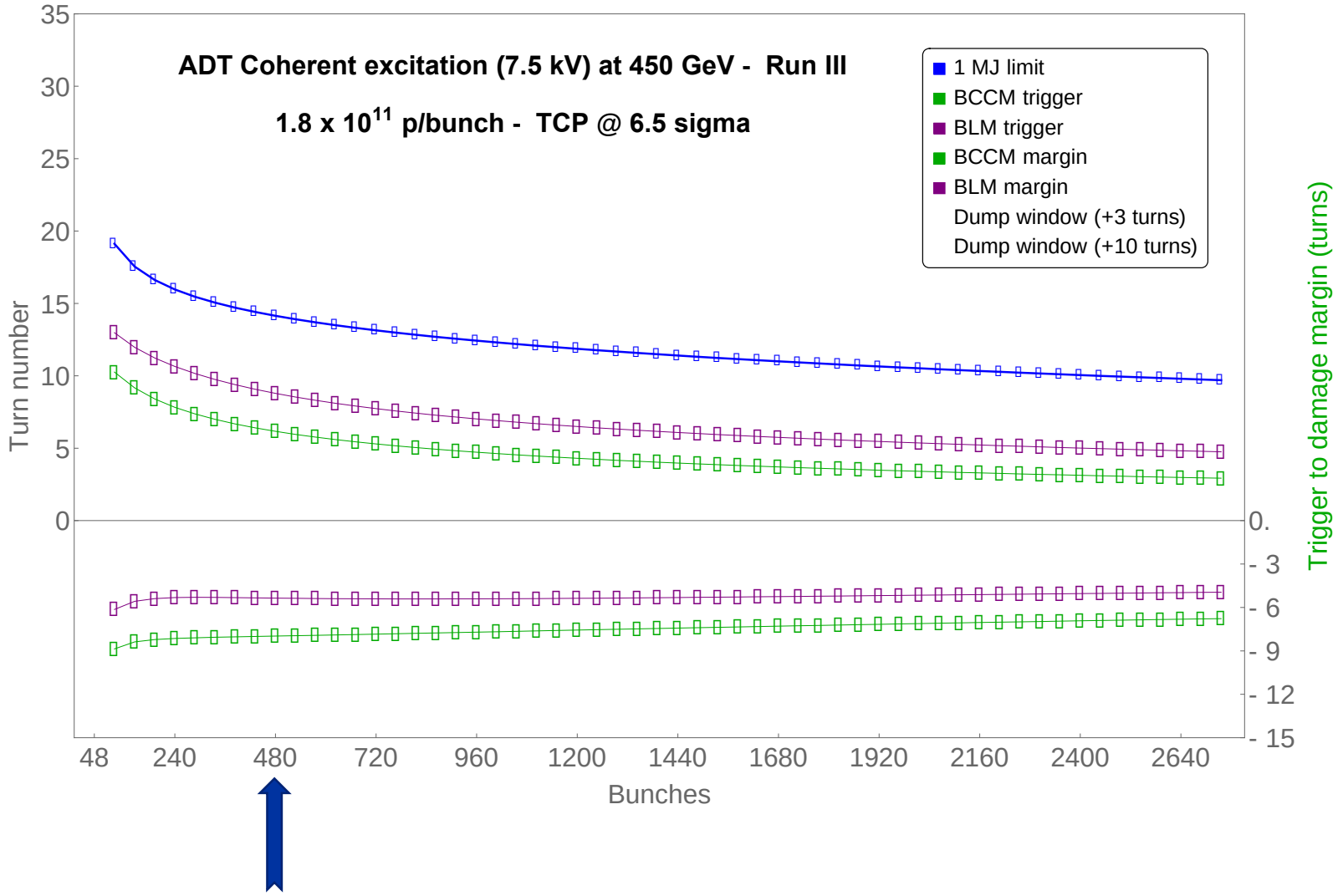
Run III

450 GeV

BLMs do not trigger first (BCCM is the first trigger)

Limited margin with the BLMs…

… but relatively flat curve as a function of the number of bunches!



2 batches (480 bunches) provide a 5 turn margin (BLMs) and 8 turn margin (BCCM)

Losses and margins – 10.0 kV

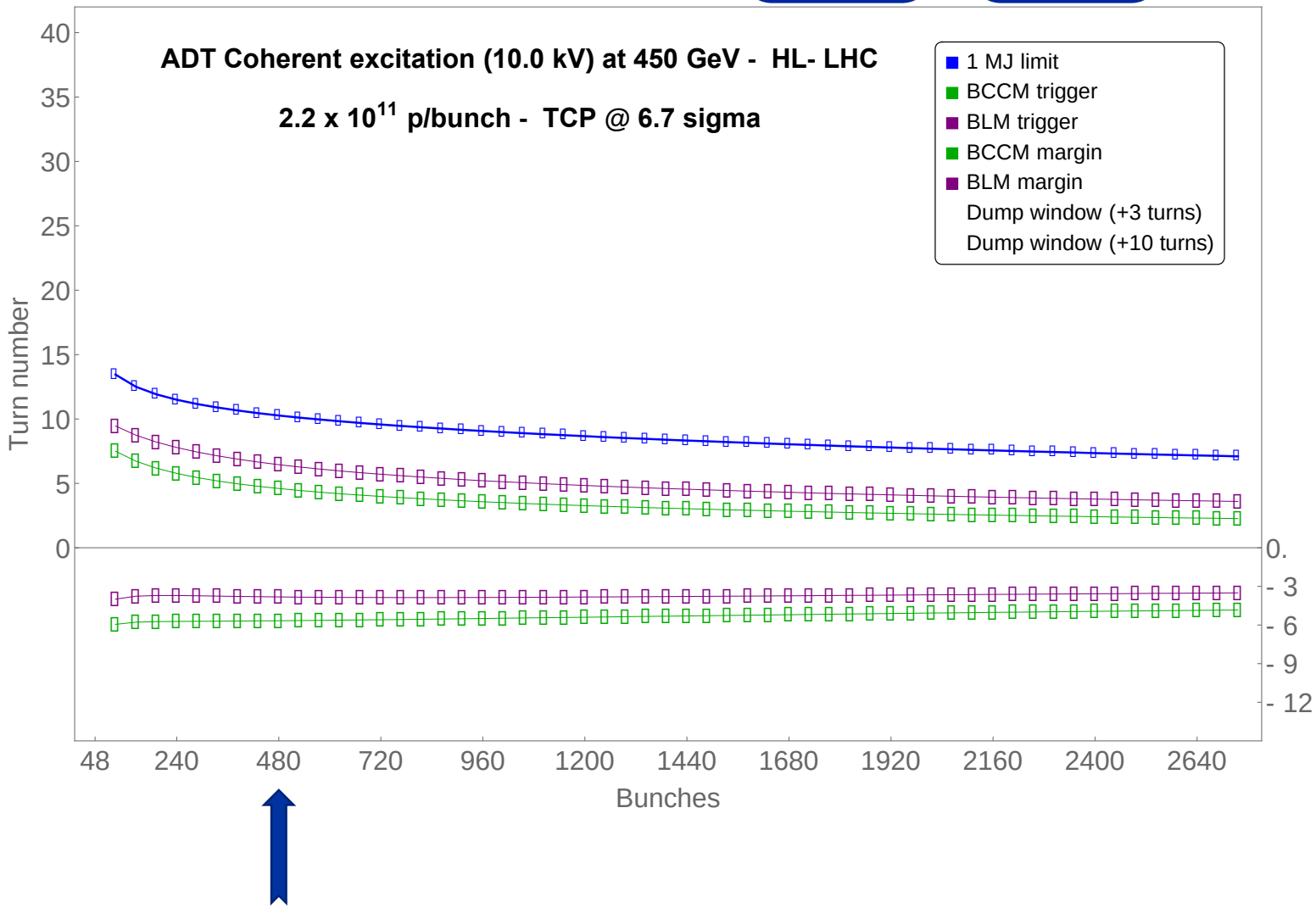
HL-LHC

450 GeV

BLMs do not trigger first (BCCM is the first trigger)

Very limited margin with the BLMs…

Need to reduce the voltage?



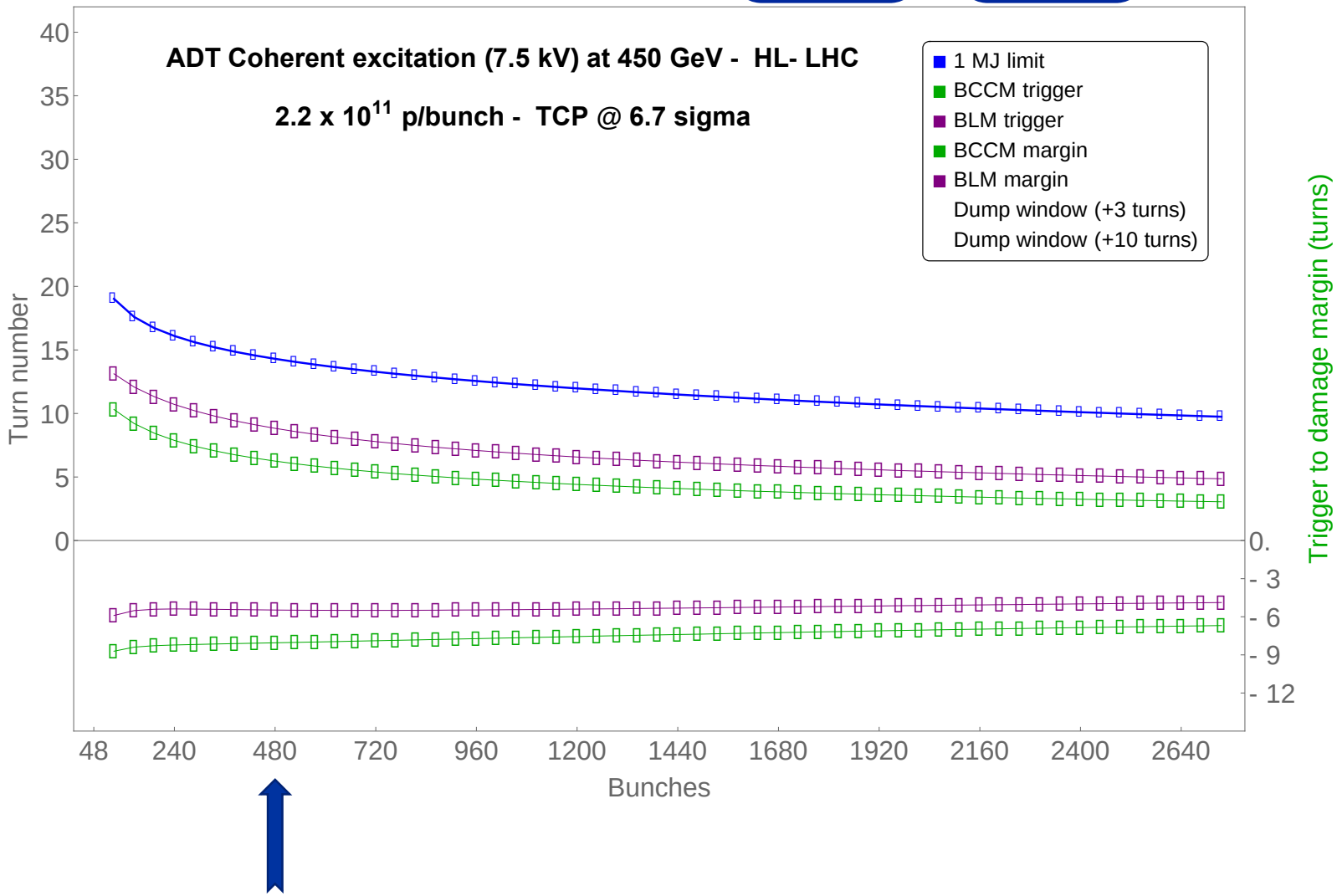
2 batches (480 bunches) provide a 4 turn margin (BLMs) and 6 turn margin (BCCM)

Losses and margins – 7.5 kV

HL-LHC

450 GeV

Reducing the voltage to 7.5 kV restores acceptable margins.



2 batches (480 bunches) provide a 5 turn margin (BLMs) and 8 turn margin (BCCM)

Losses and margins – 5.0 kV

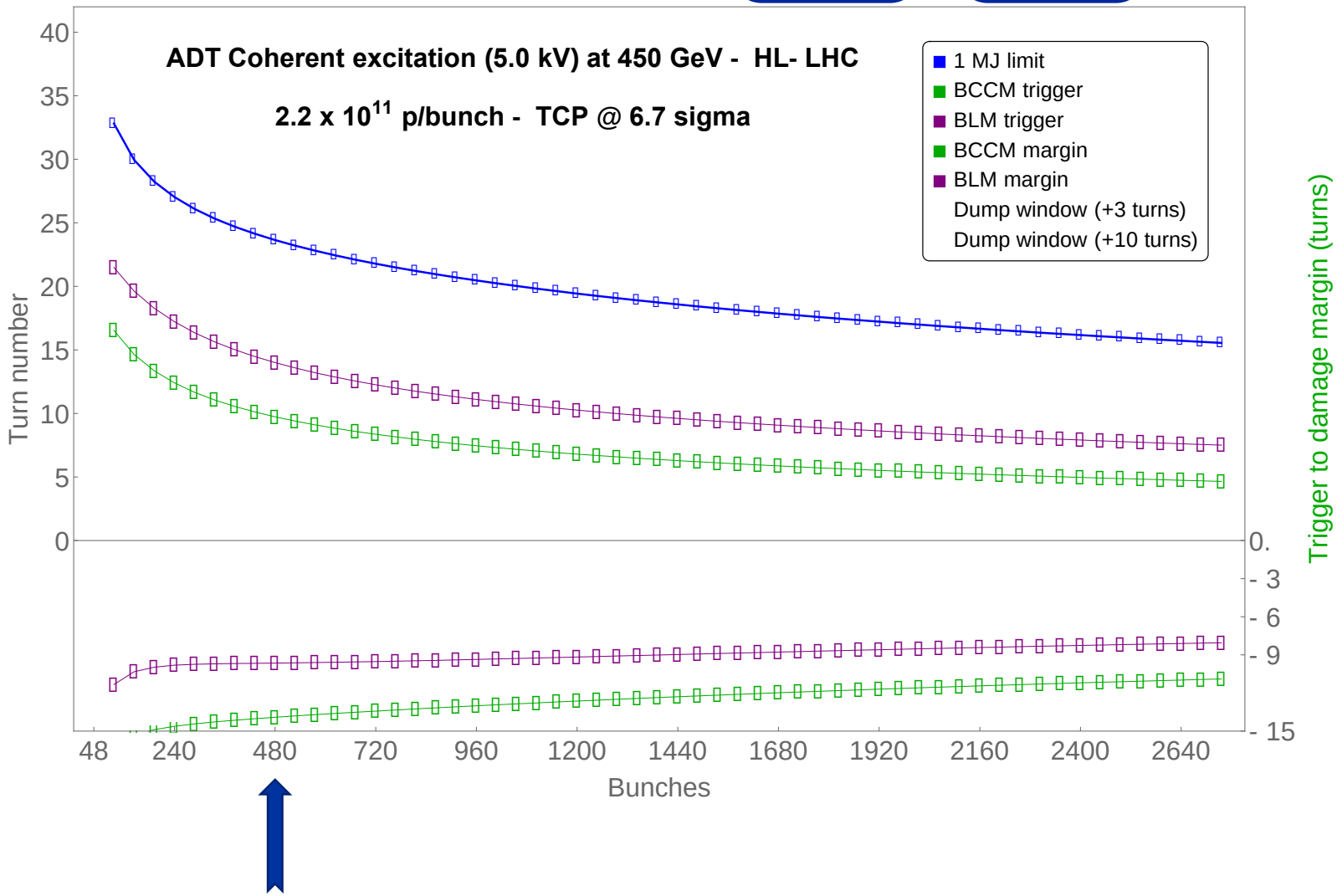
HL-LHC

450 GeV

Further reducing the voltage to 5.0kV restores a 10-turn margin for 2 batches (similar margin as for top energy)

Note that the BCCM still triggers first

2 batches (480 bunches) provide a 10-turn margin (BLMs) and 15-turn margin (BCCM)



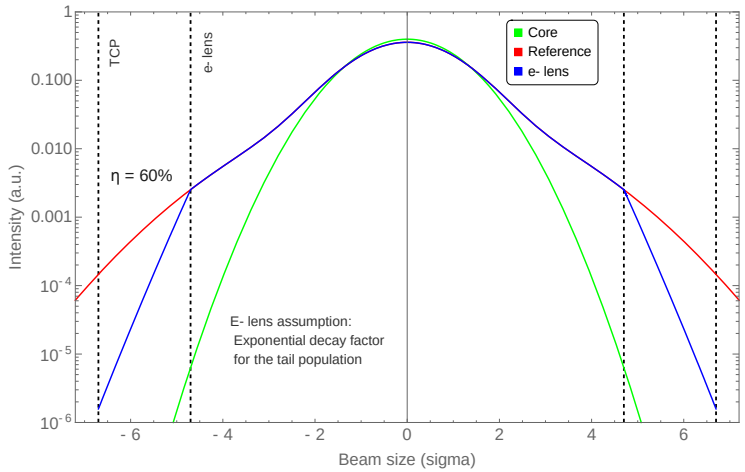
Conclusions and proposals

- **Conclusions**
  - Estimates provided for LHC Run 3 and HL-LHC for the margin between the failure trigger (BLM or BCCM thresholds) and the damage limit machine protection threshold
  - Maximum voltage (10.0 kV) is not an issue at 7 TeV but needs to be limited at 450 GeV
- **Proposal**
  - **Limit the ADT window length to 2 batches (480 bunches) for Run 3 and for HL-LHC**
  - **ADT window length: 14.4 µs or bunch by bunch**
  - **Limit maximum voltage (for beam excitation) at injection energy**
  - Provides flexible use of the ADT during operation and MD's while preserving sufficient margin

Baseline filling scheme

- **BCMS**
  - 5x48b/inj, SPS batch spacing 200ns and LHC batch spacing 800ns
  - **240b/inj**, train length of **6.8 µs**

A few more things…

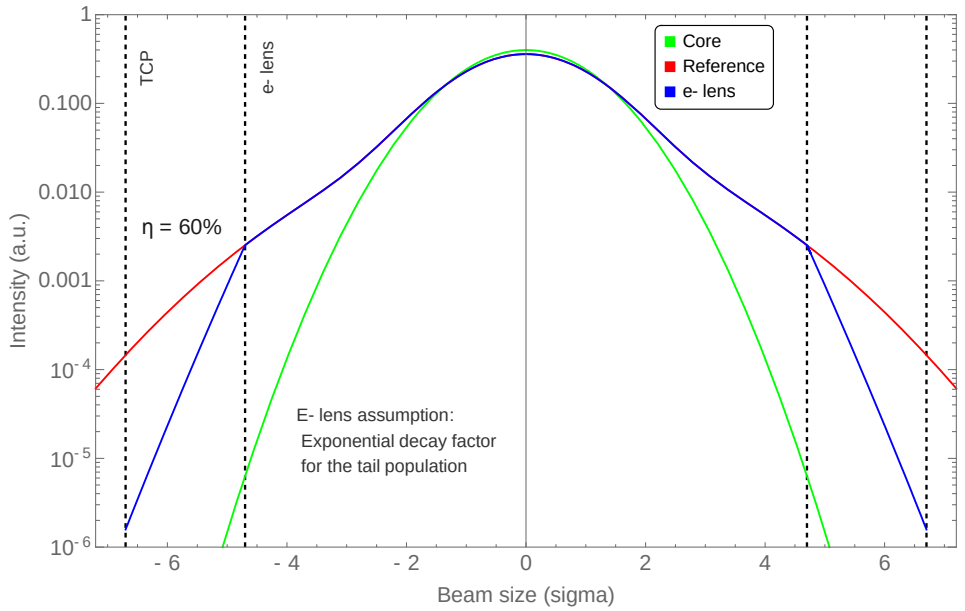


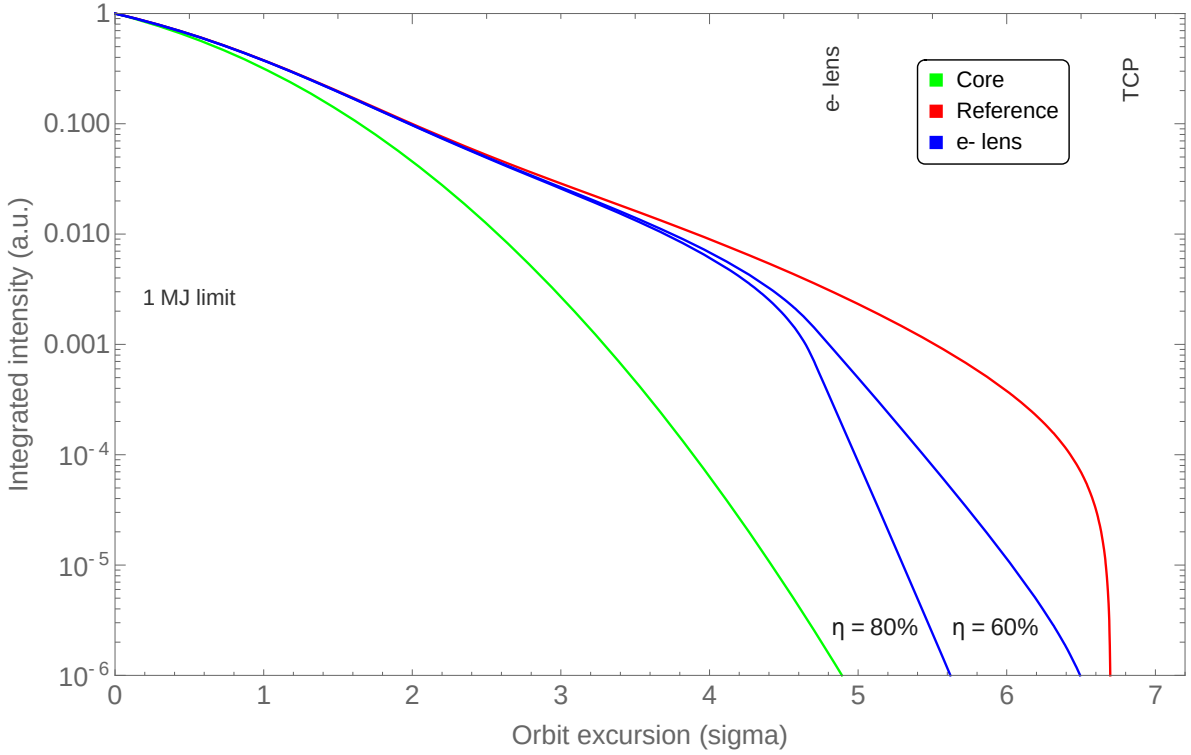
Depleted transverse halo

Considerations for the hollow electron-lens

Integrated beam losses with e-lens

- **Transverse distribution with depleted beam halo**
- **A given integrated loss level happen at a later turn with increasing depletion level**

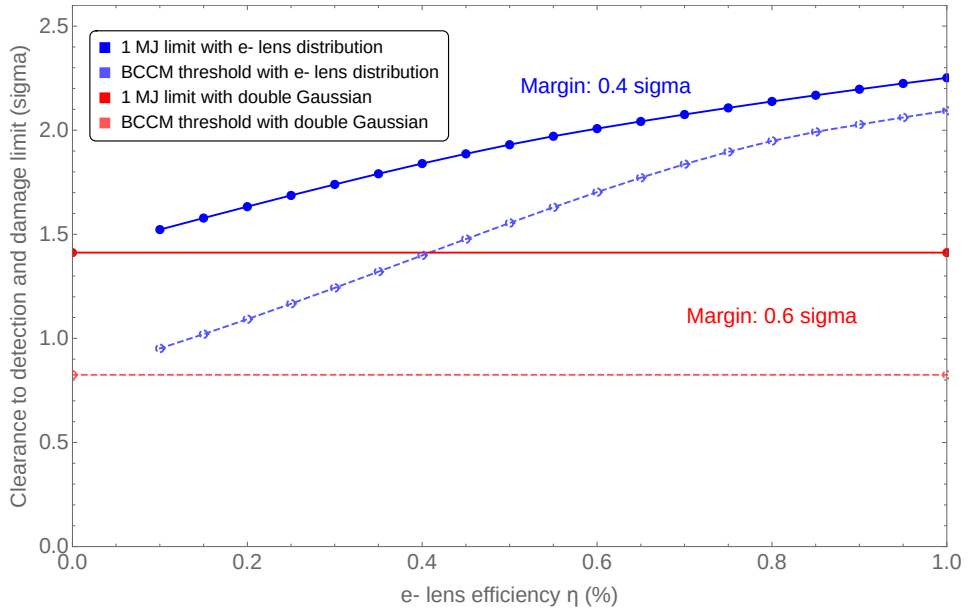


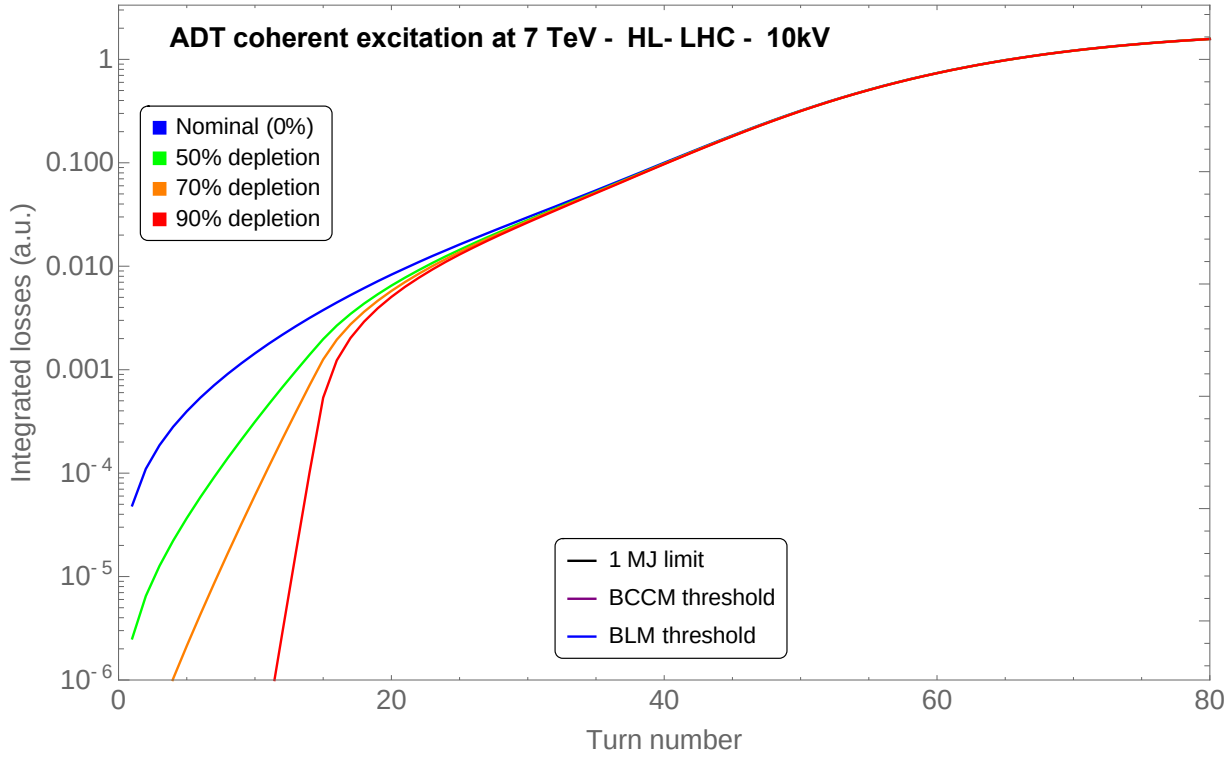


- **Integrated fractional beam losses as a function of orbit excursion.**
- Larger orbit excursions can be tolerated at the price of increased steepness of the integrated losses curve

Integrated beam losses with e-lens

Margins between given thresholds (BCCM or BLM) and damage limit are reduced with increased halo depletion

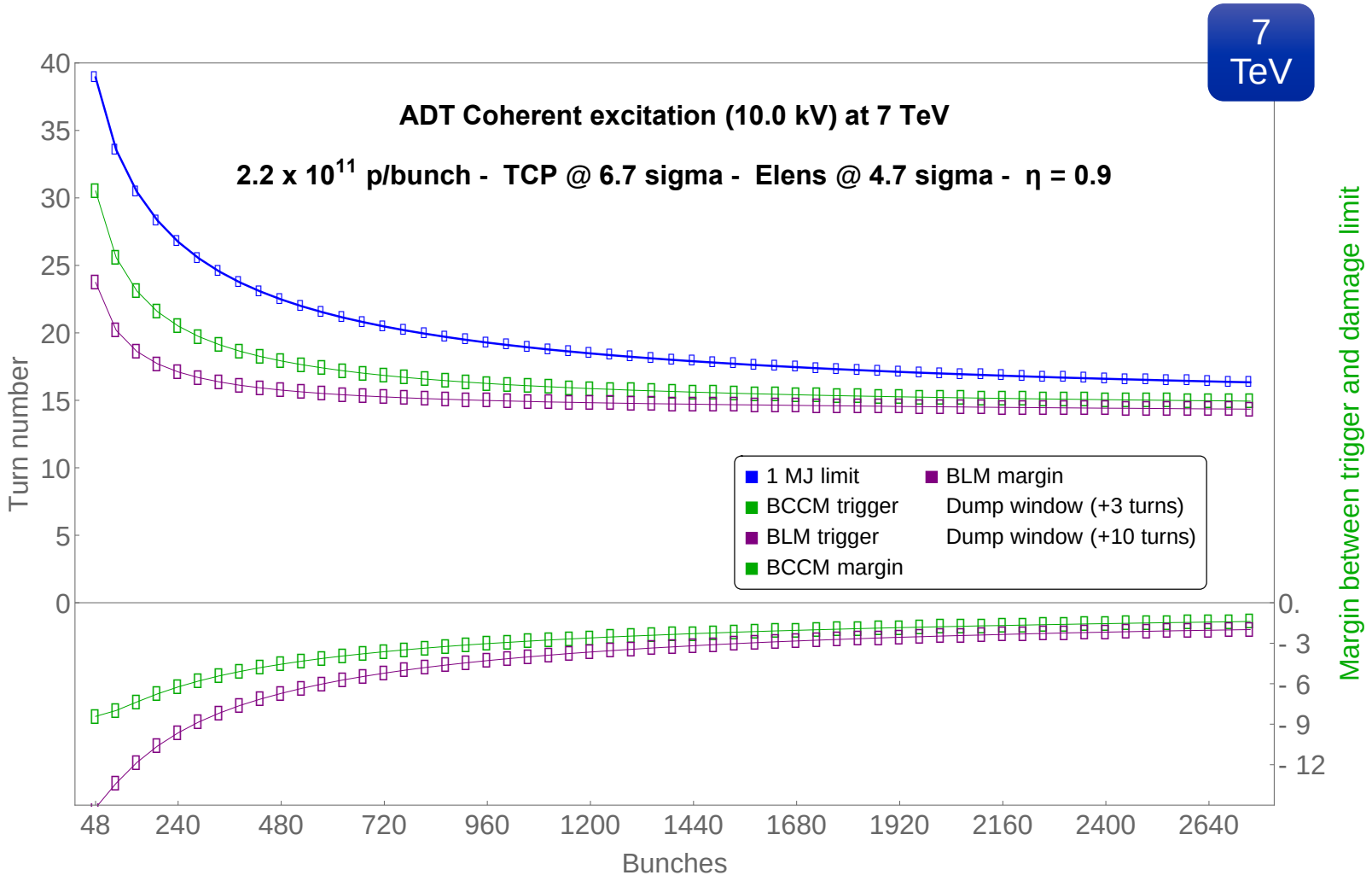




- **Integrated fractional beam losses as a function of the turn number for different halo depletion.**
- **BCCM and BLM thresholds shown for a full machine (2748 bunches).**

Losses and margins – HL-LHC – E-lens - 10.0 kV

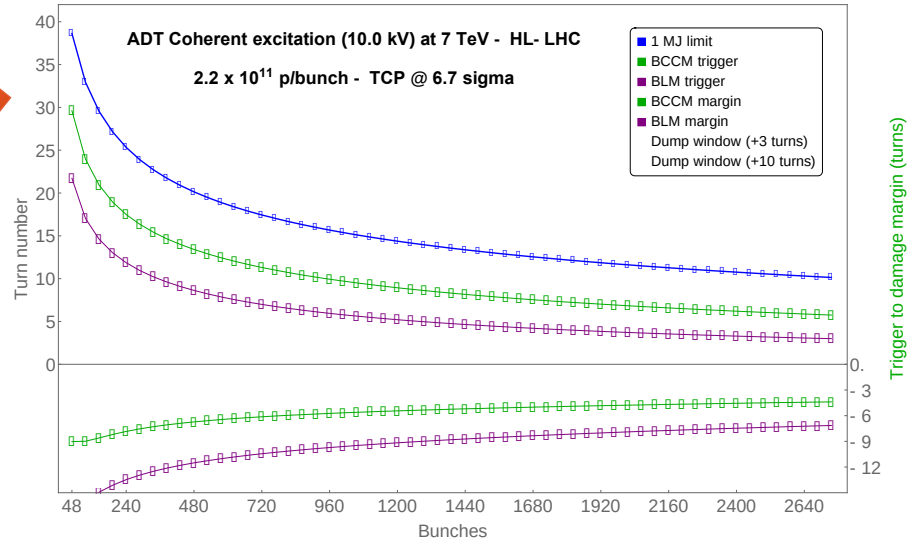
- **For 90% depletion 1 batch can still be considered safe with enough margin**



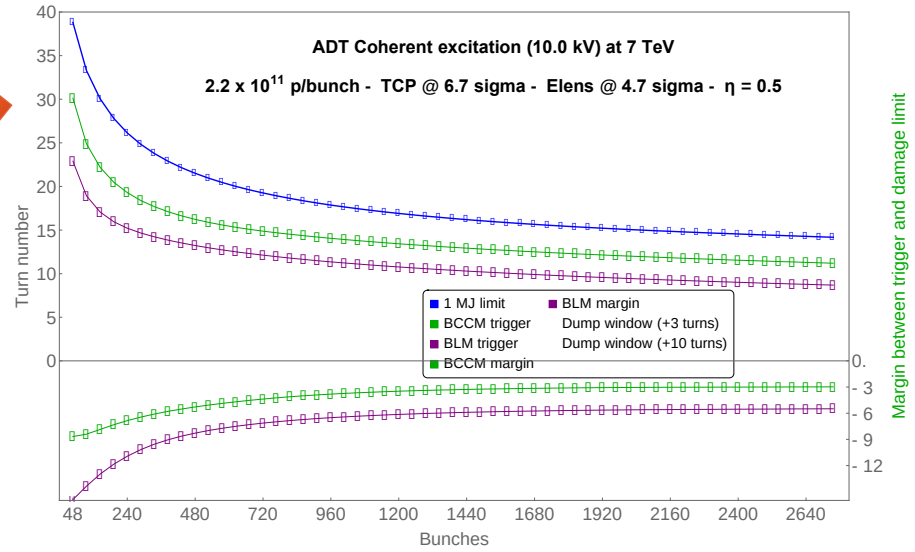
Losses and margins – HL-LHC – E-lens - 10.0 kV

7 TeV

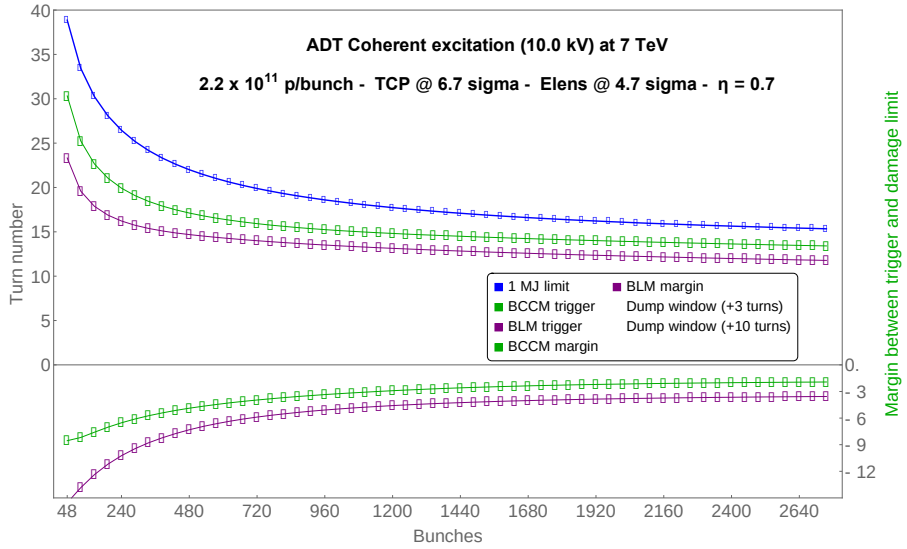
No e-lens



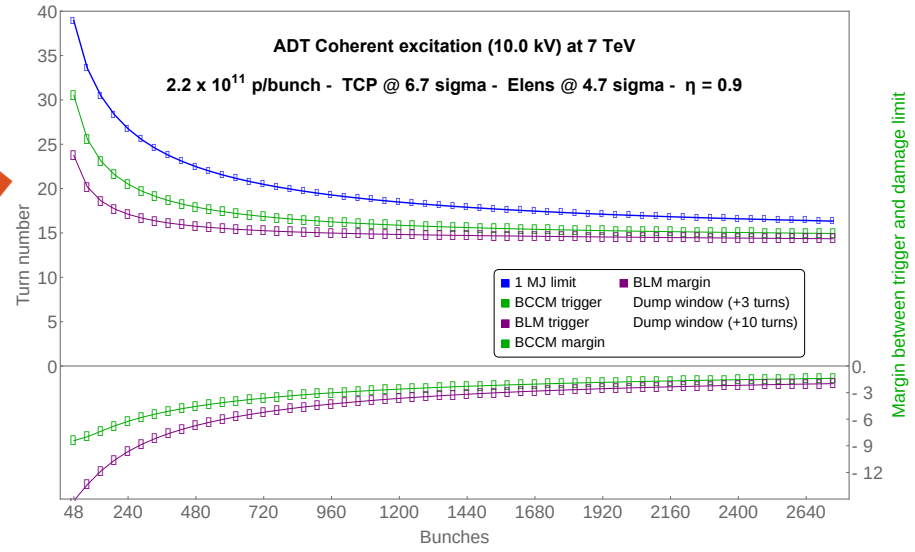
50%



70%

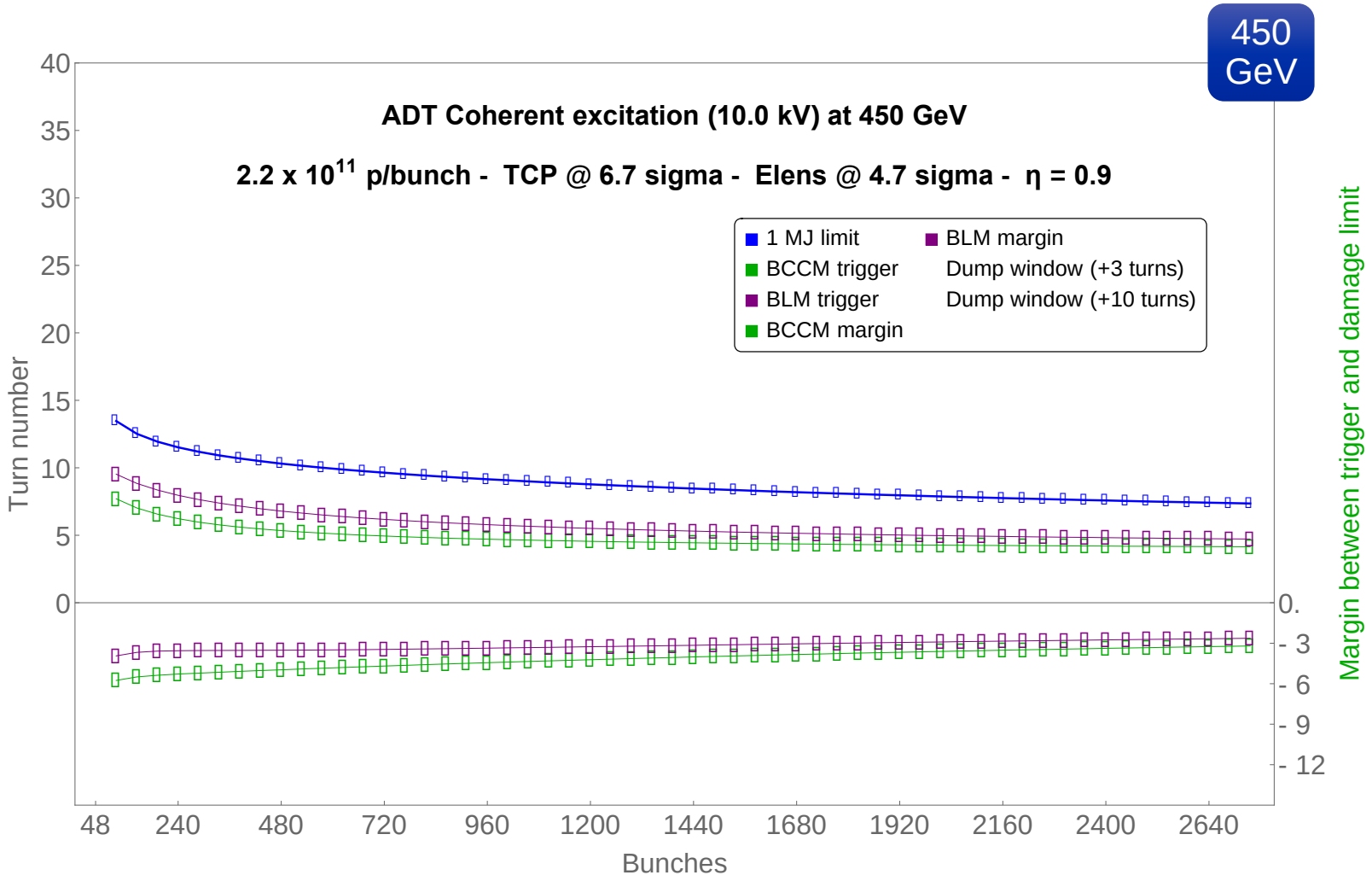


90%



Losses and margins – HL-LHC – E-lens - 10.0 kV

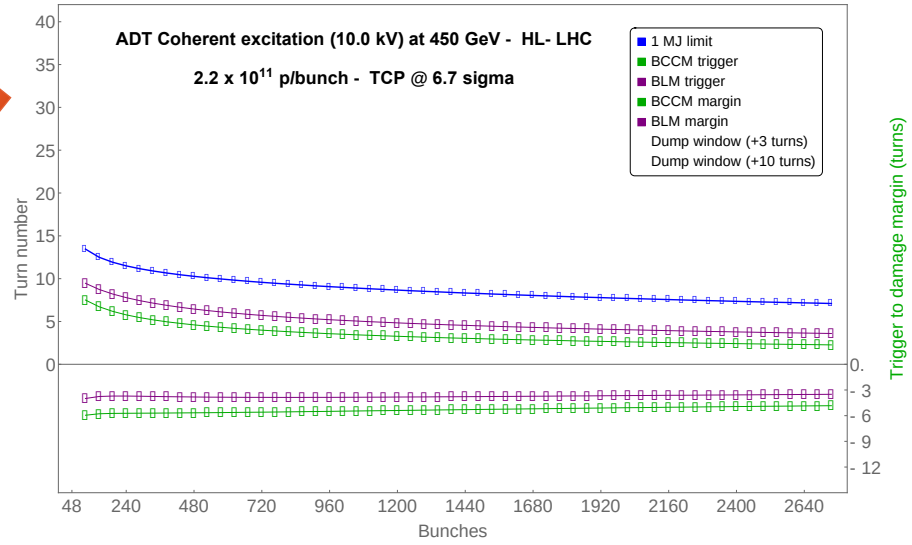
- **Extremely limited margin even for a single batch**
- **Losses are high even for a non-depleted distribution**



Losses and margins – HL-LHC – E-lens - 10.0 kV

450 GeV

No e-lens



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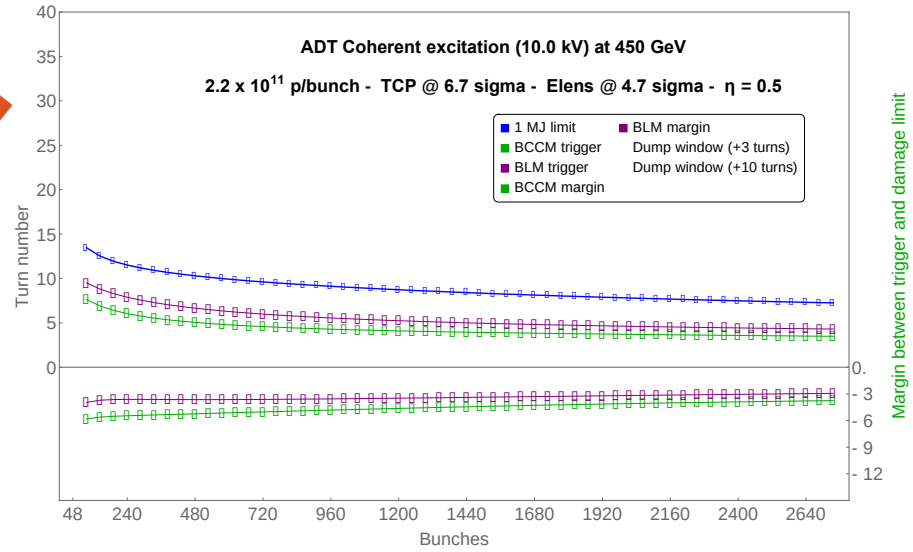

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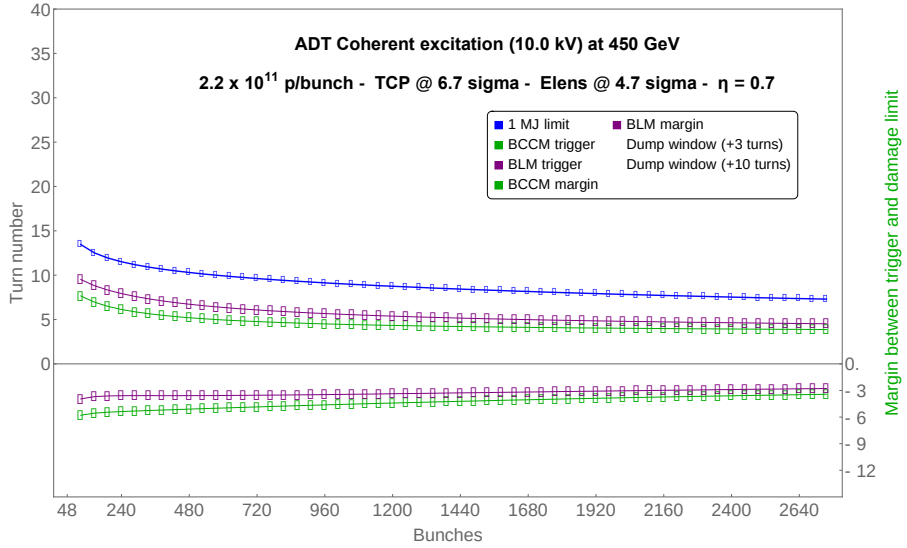

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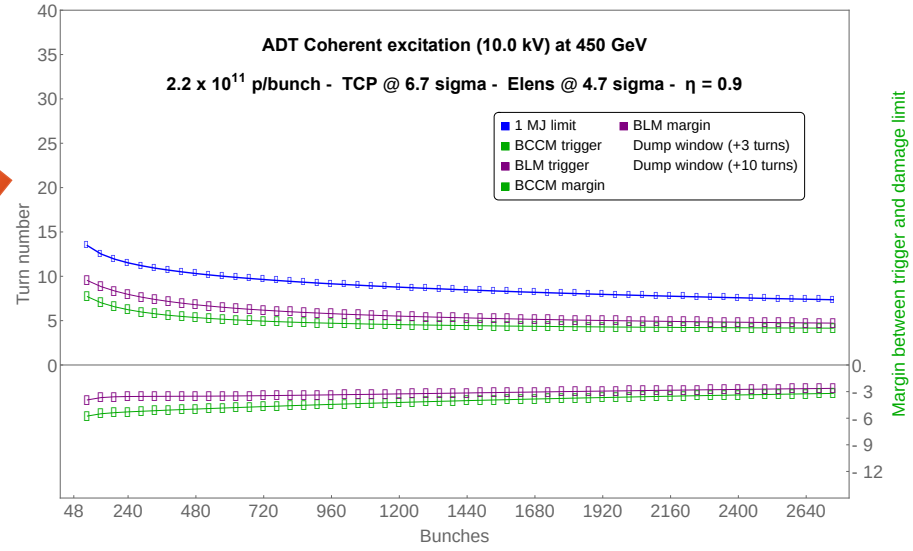
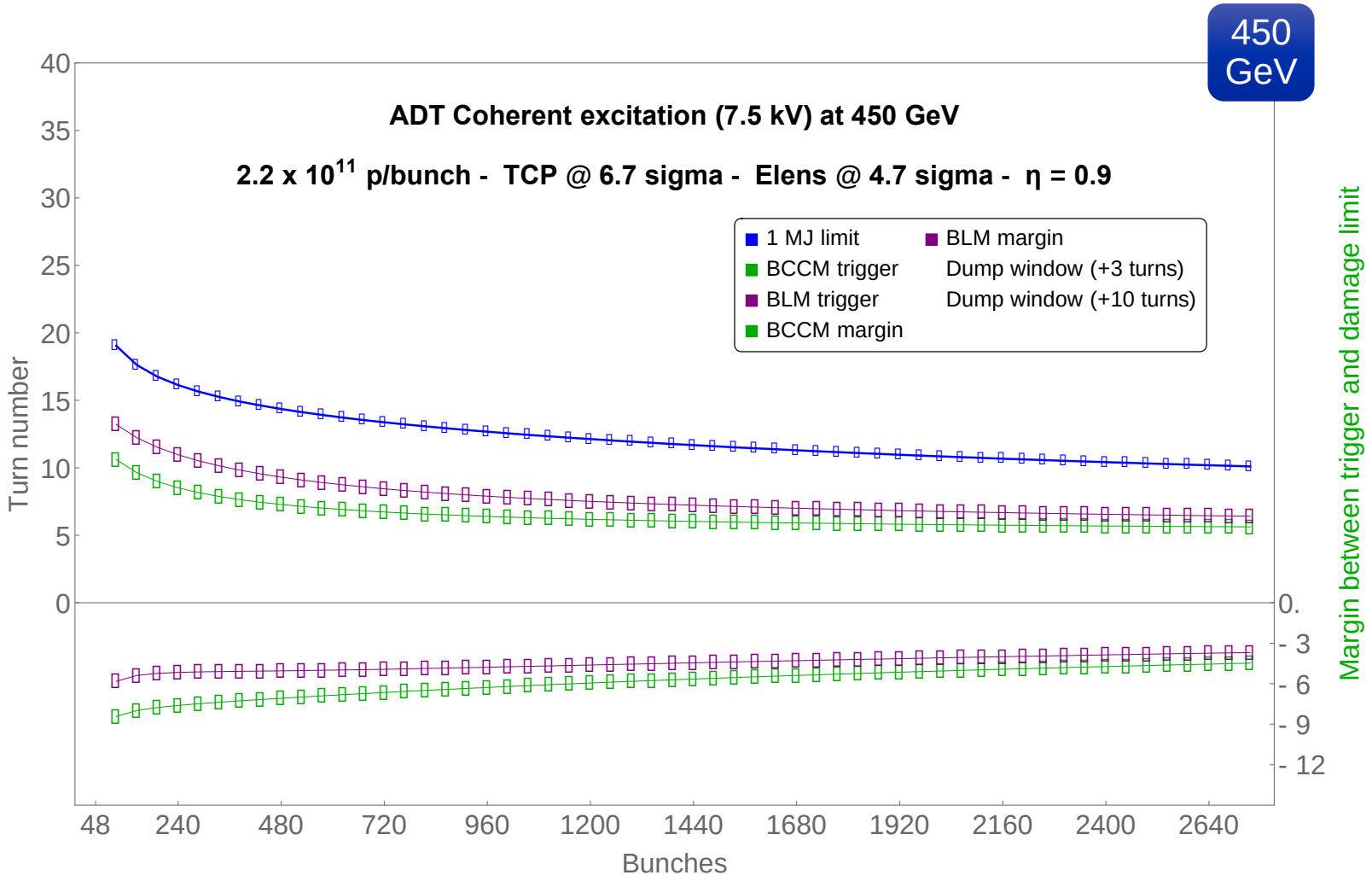


Losses and margins – HL-LHC – E-lens – 7.5 kV

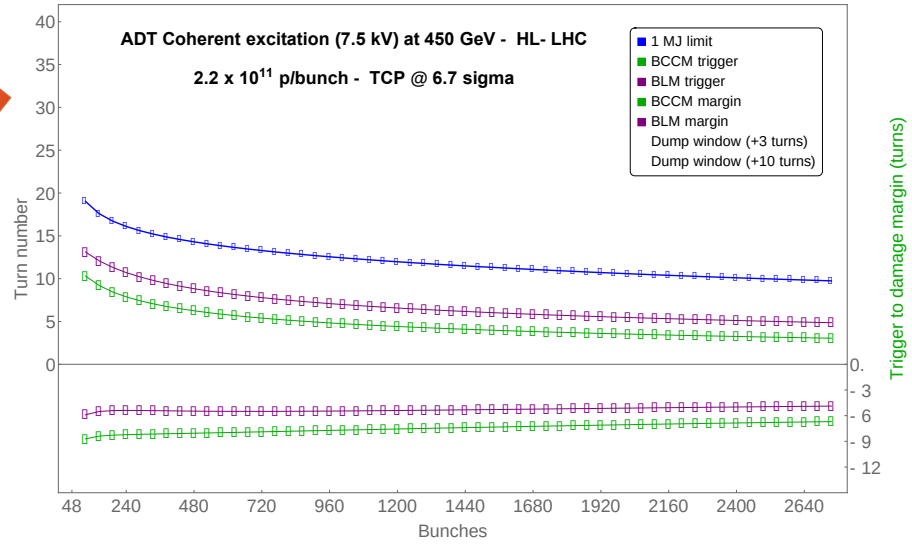
- **Reducing the voltage to 7.5 kV restores enough margin for 1 batch**
- **Due to the very fast losses, the e-lens efficiency (halo depletion factor) does not affect the results strongly**



Losses and margins – HL-LHC – E-lens – 7.5 kV

450 GeV

No e-lens



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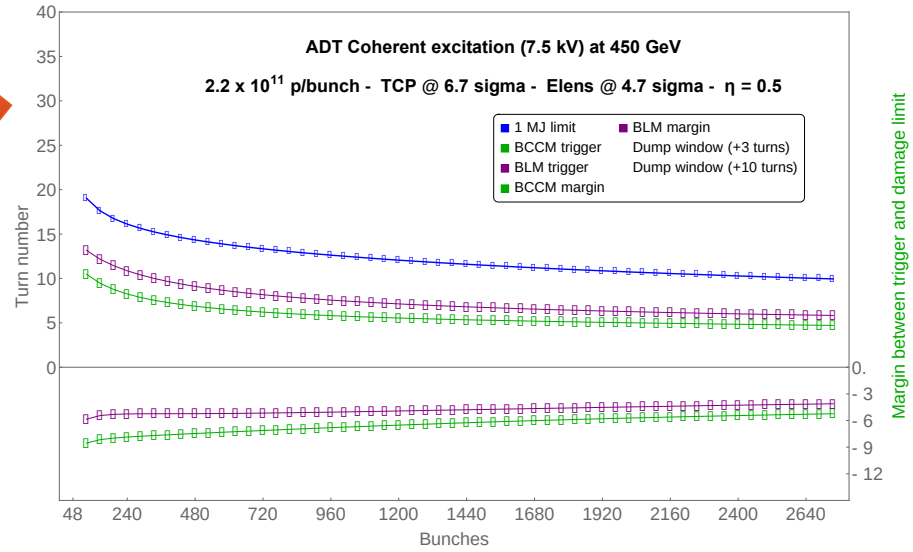

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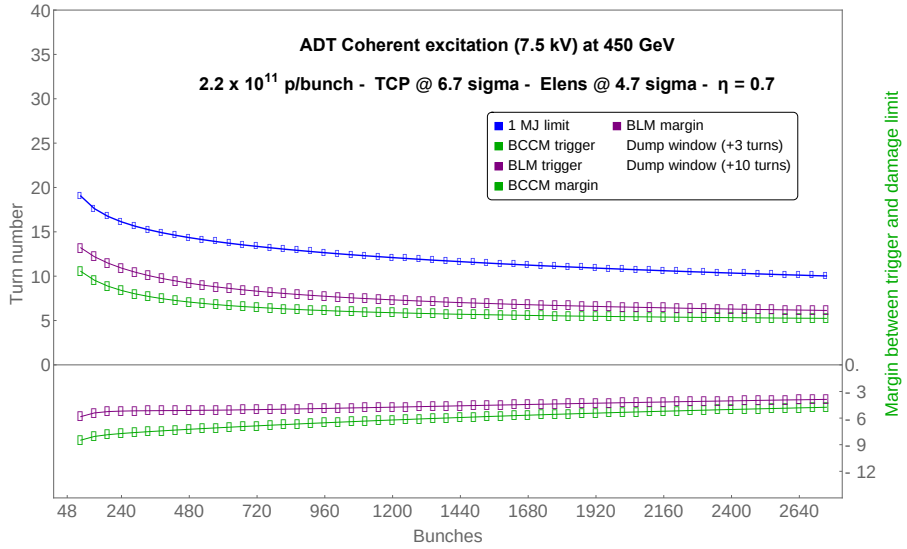

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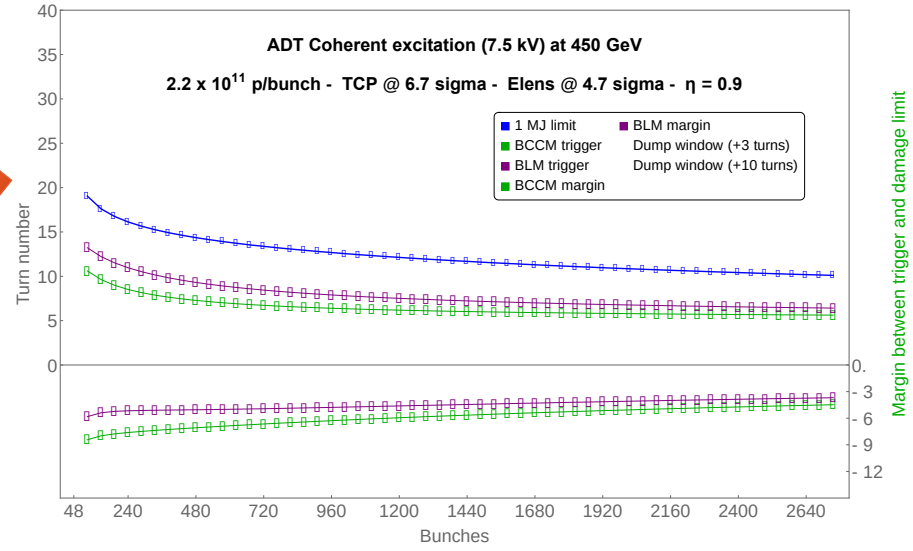


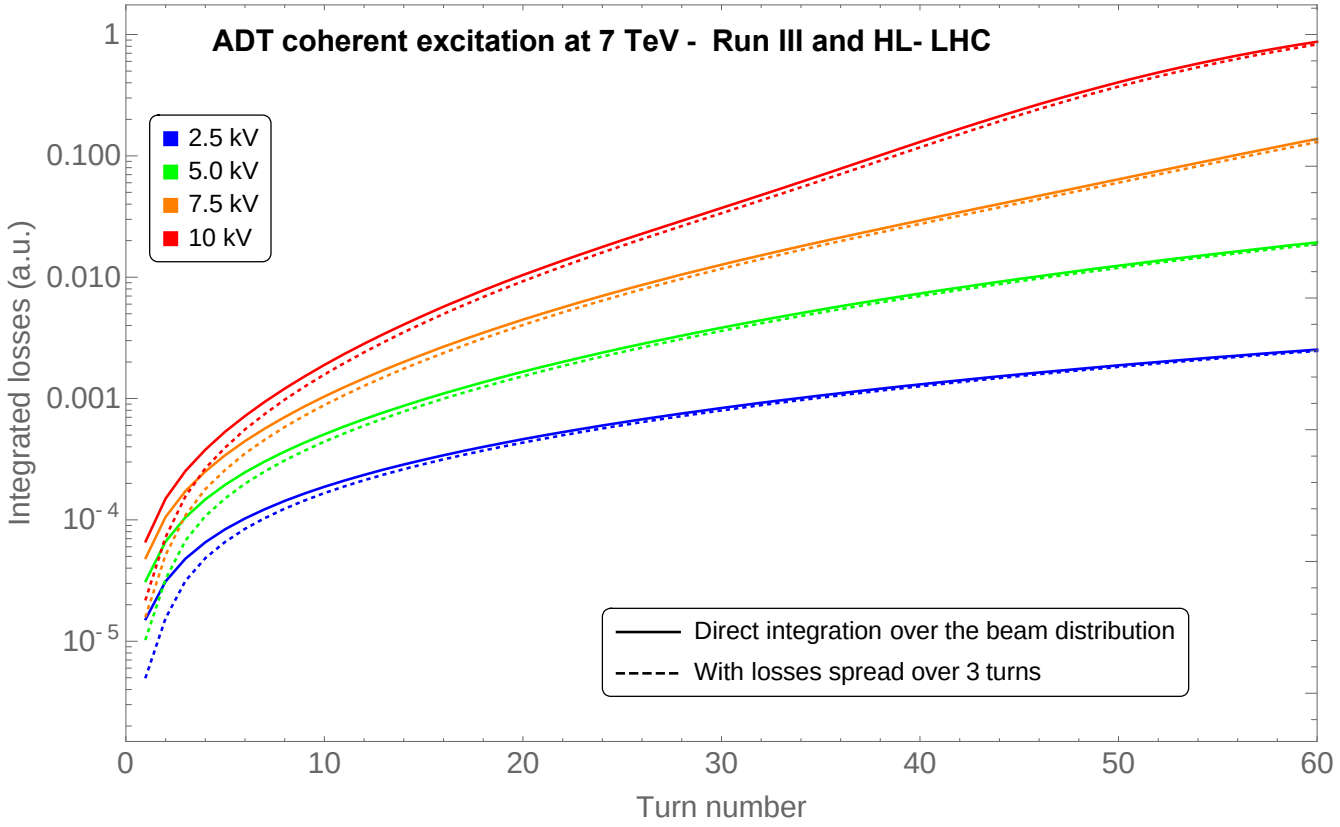
Proposal for depleted transverse halo

- **Proposal**
  - **Limit the ADT window length to 1 batches (240 bunches) for HL-LHC with HEL operation**
  - **ADT window length: 6.8 µs**
  - **Limit maximum voltage at injection energy**
  - Similar margin as for Run 3 and HL-LHC without HEL operation

A more refined model for the beam losses

Integrated beam losses

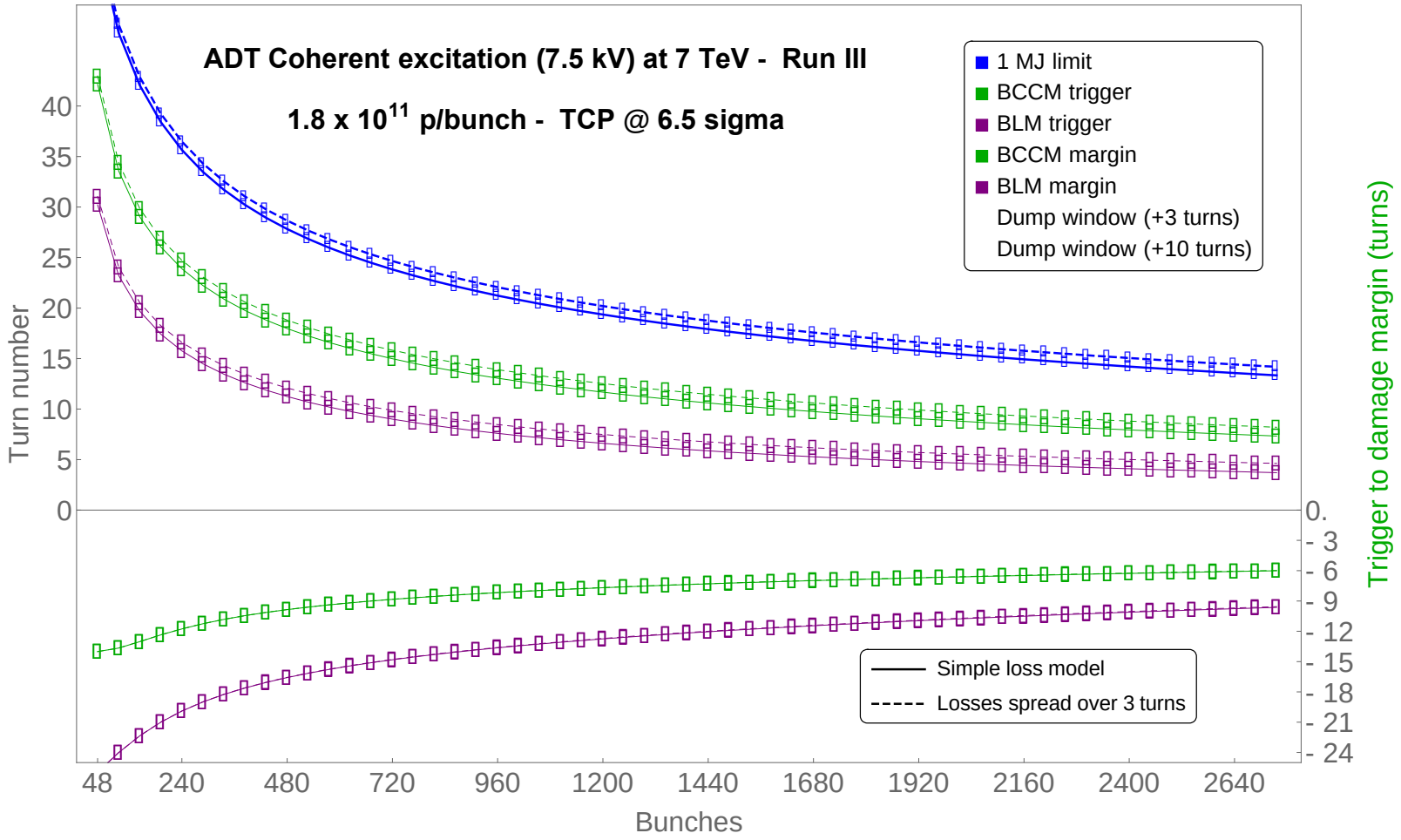
- More realistic semi-analytical model to compute the losses: integration of the beam distribution with delayed losses spread over 3 turns (fractional part of the tune close to 1/3)
- Few differences except at the loss onset
- No conclusive difference observed for the main results as the loss thresholds are rigidly offset in time

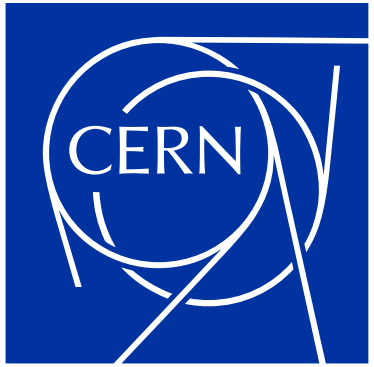


- Integrated fractional beam losses as a function of the turn number for different ADT voltages.
- The two models are shown: direct integration over the beam distribution and integration with losses spread over 3 turns

Losses and margins – Run III – 7.5 kV

- **Margins are the same for the two models**





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