Recap. of failure cases for round and flat optics

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Outline

- Fast failure cases, machine parameters and assumptions
- CLIQ spurious discharge
- Quench heater spurious discharge
- Crab cavity failure cases
- Conclusions

Fast failures

- Failures: events leading to uncontrolled beam losses
  - Protection from **ultra-fast failures** (damage limit reached within 3 turns) relies on passive absorbers
  - Protection from **fast failures** (damage limit reached within 10ms – 100 turns) relies on dedicated interlocks
- Machine protection **critical loss level** for fast failures: **1 MJ** deposited in IR7 within 10ms. This is a conservative assumption for machine protection. The exact damage limit for the collimation system depends on many factors.
- Key quantitative parameters:
  - time from failure onset to critical loss level (expressed in machine turns)
  - time from failure detection to critical loss level must provide sufficient margin (machine turns) to safely dump the beam
  - time from failure detection to beam dump is known

Machine parameters

- HL-LHC v1.6 sequences with round (15.0 cm) and flat optics (7.5 cm / 18.0 cm)
- Regular (6.7) and relaxed (8.5) collimation settings are compared
- Simulations performed with xsuite (and compared to MAD-X)

	Beam parameters
Beam energy	7 TeV
Beam stored energy	674 MJ per beam
Bunch intensity	2.2e11 p^+/bunch (2736 bunches)
Beam emittance	2.5 μm
TCP settings	6.7 sigma and 8.5 sigma
Half crossing angle at IP1-5	250 μrad
Landau octupoles	Both polarities compared
Transverse distribution with halo	$0.8 \times \mathcal{G}(\sigma{=}1) + 0.2 \times \mathcal{G}(\sigma{=}2)$

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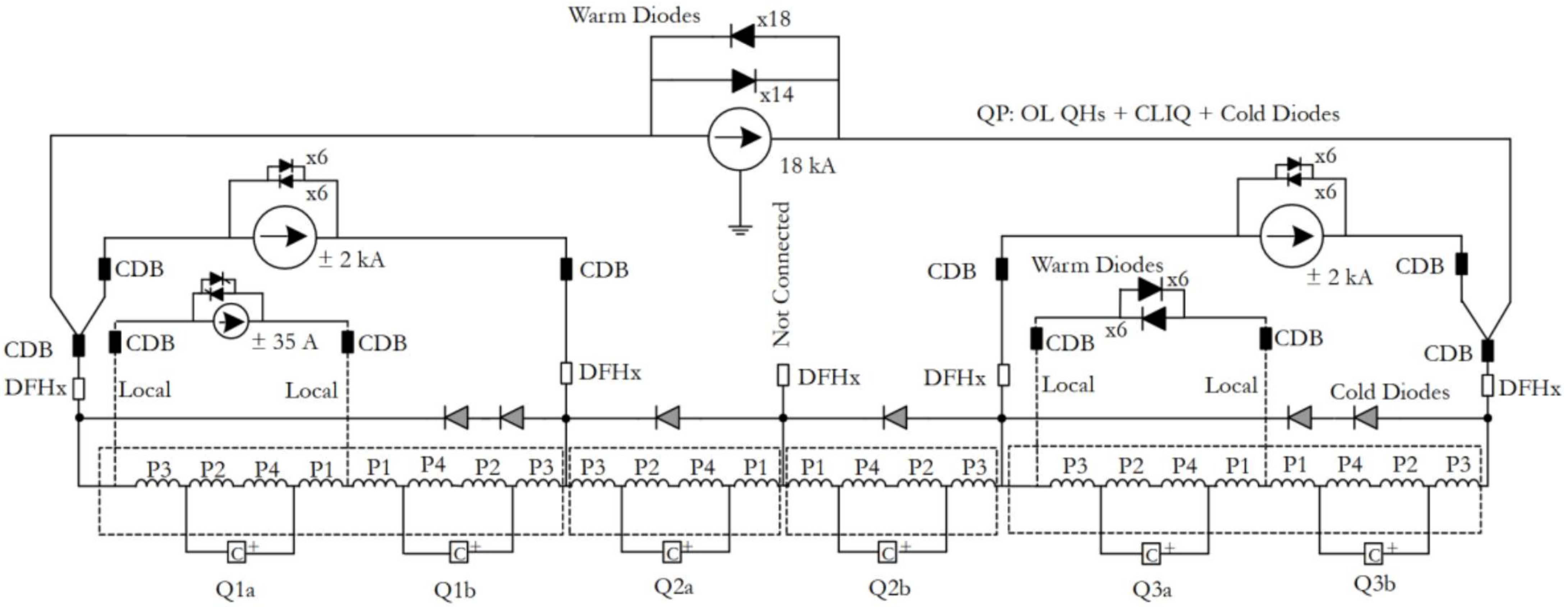
CLIQ connection scheme

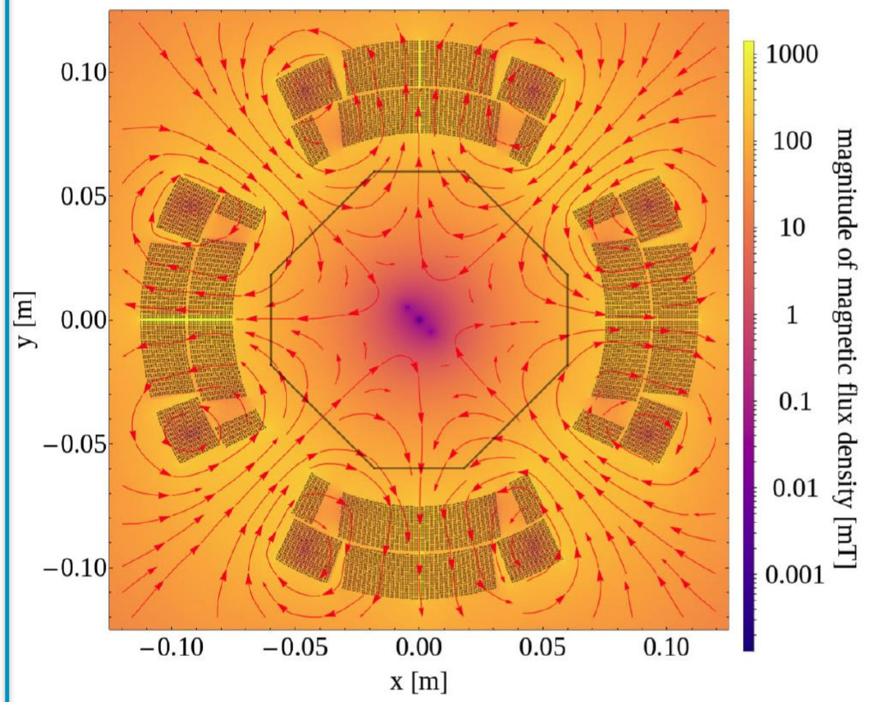


CLIQ and impact of magnet protection on the beam

- Quench protection system will trigger a beam dump before firing CLIQ and/or QHs
  - Interested in the spurious discharge failure mode
- Baseline connection scheme features the same connection for all magnets

Impacts of flat optics:
- Larger β-function in one plane
- Crossing bump affects feed-down

Baseline connection



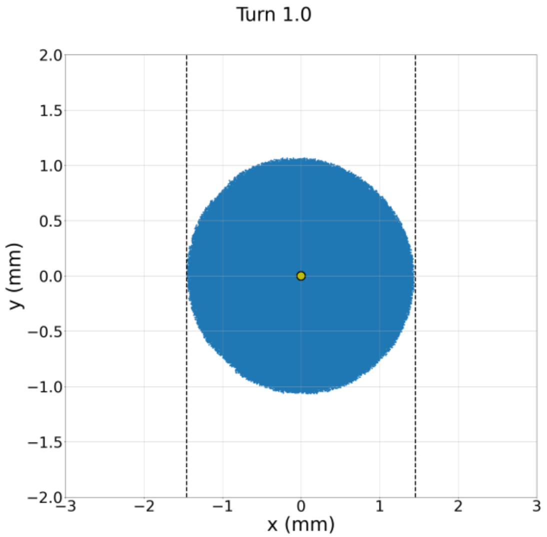
Field dominated by a **skew-octupolar** component

LEDET/SIGMA simulations (E. Ravaioli) – Difference w.r.t main field after 5ms

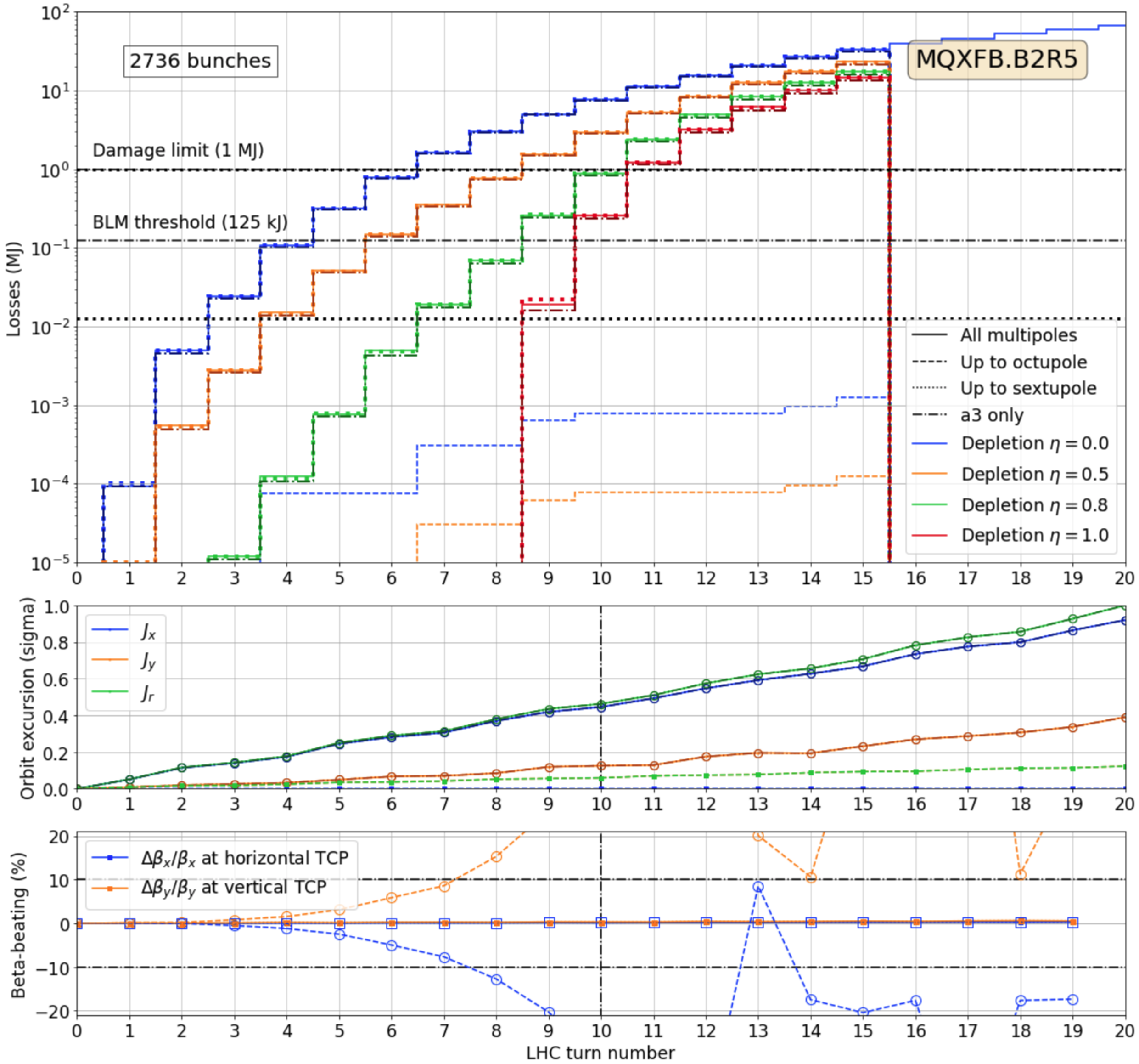
CLIQ discharge beam losses – Round optics

- Beam losses cannot be explained by orbit shift alone

- Beam losses tracked to effect of skew octupolar field generated by the CLIQ discharge leading to a loss of DA



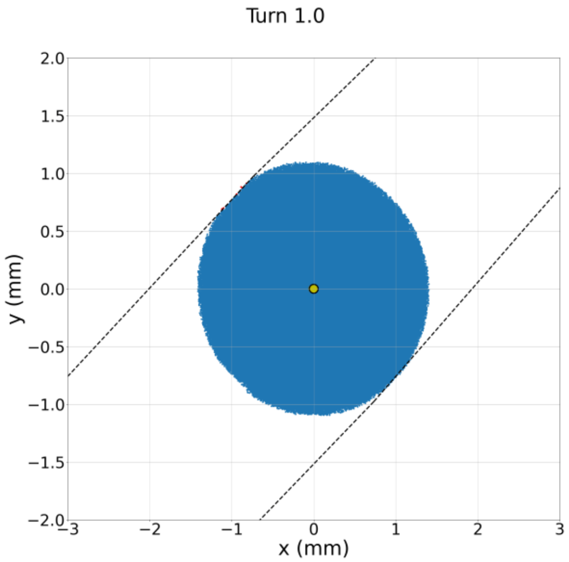
TCP.D6L7 (vertical)

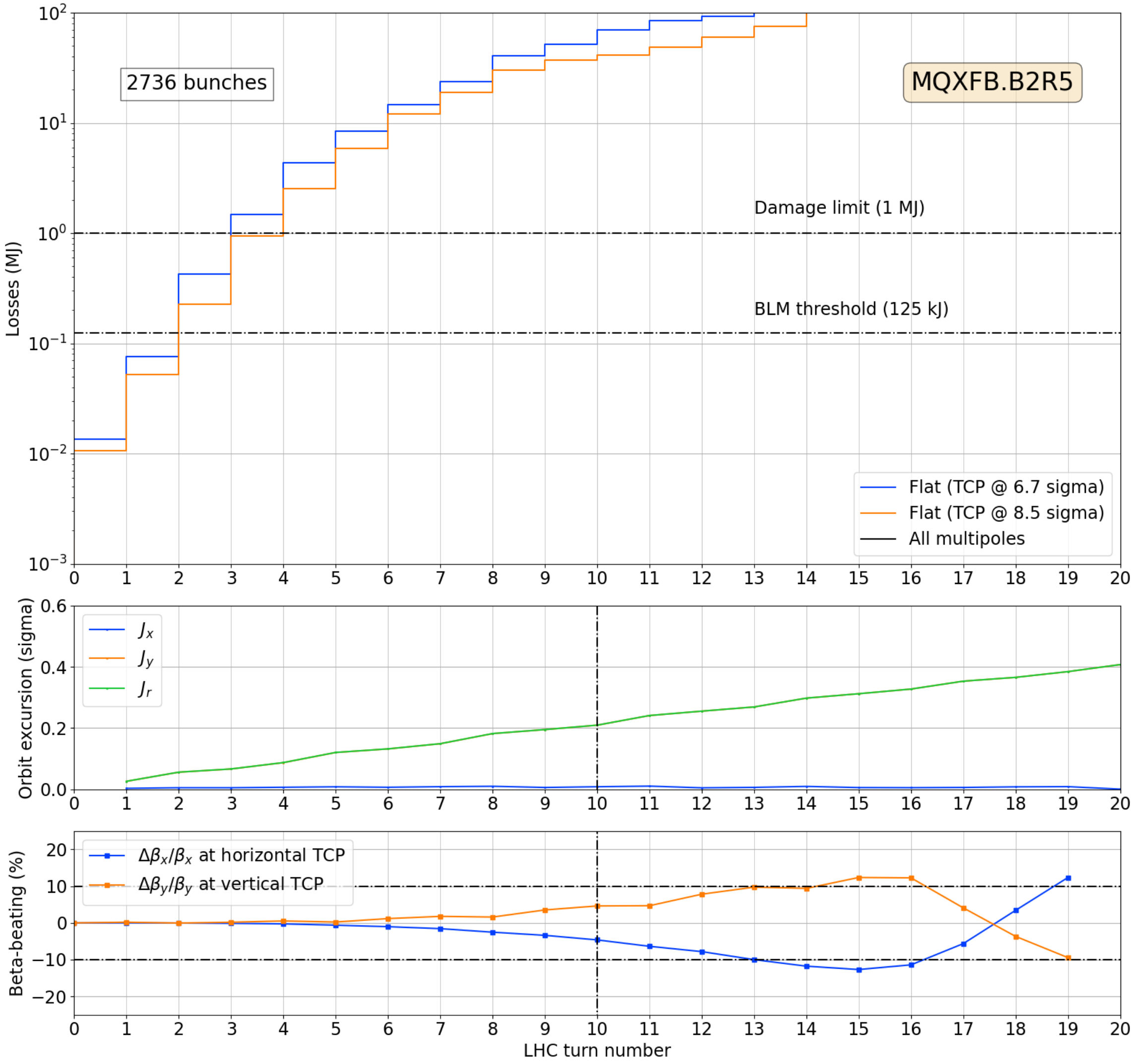


CLIQ discharge beam losses – Flat optics

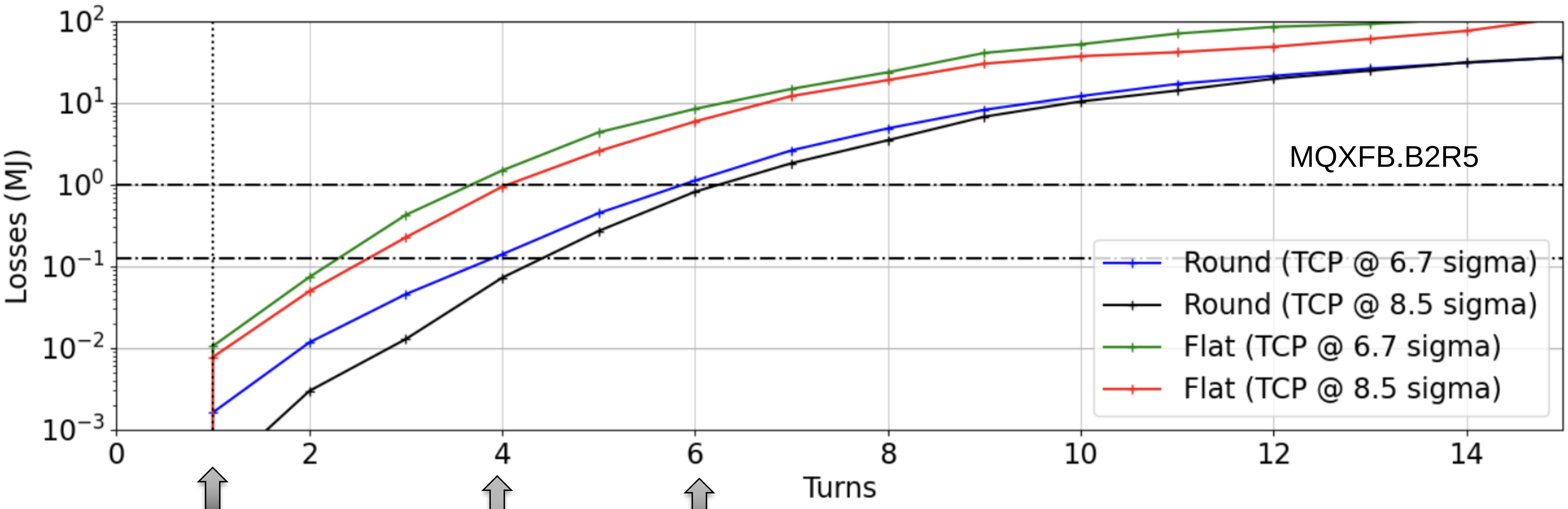
- Orbit drift and beta-beating reduced compared to round optics despite the beam loss dynamics being faster!

- Beam losses reach critical loss level (1 MJ) within **3 turns**!
- Dedicated interlock would react only within **5 turns**





CLIQ discharge beam losses

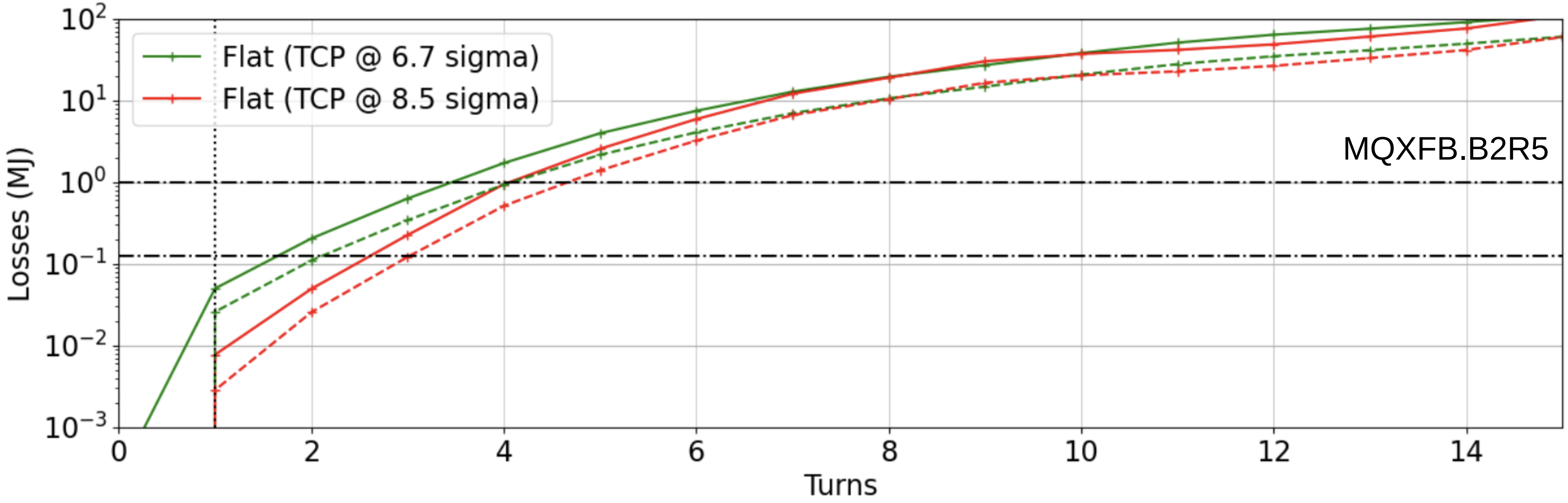


Onset of failure

Critical losses
for flat optics

Critical losses
for round optics

CLIQ discharge beam losses



Intensity at EOL: 1.2e11 ppb

CLIQ - Criticality and interlocking

- Protection is assured by a **fast dedicated interlock**
  - See T. Podzorny, PDSU-CLIQ/DQHDS interlocking via BIS concentrator (Thursday morning)
- For **round optics**, the design (and measured) reaction time prevent reaching the critical loss limit (1 MJ), 50 us margin

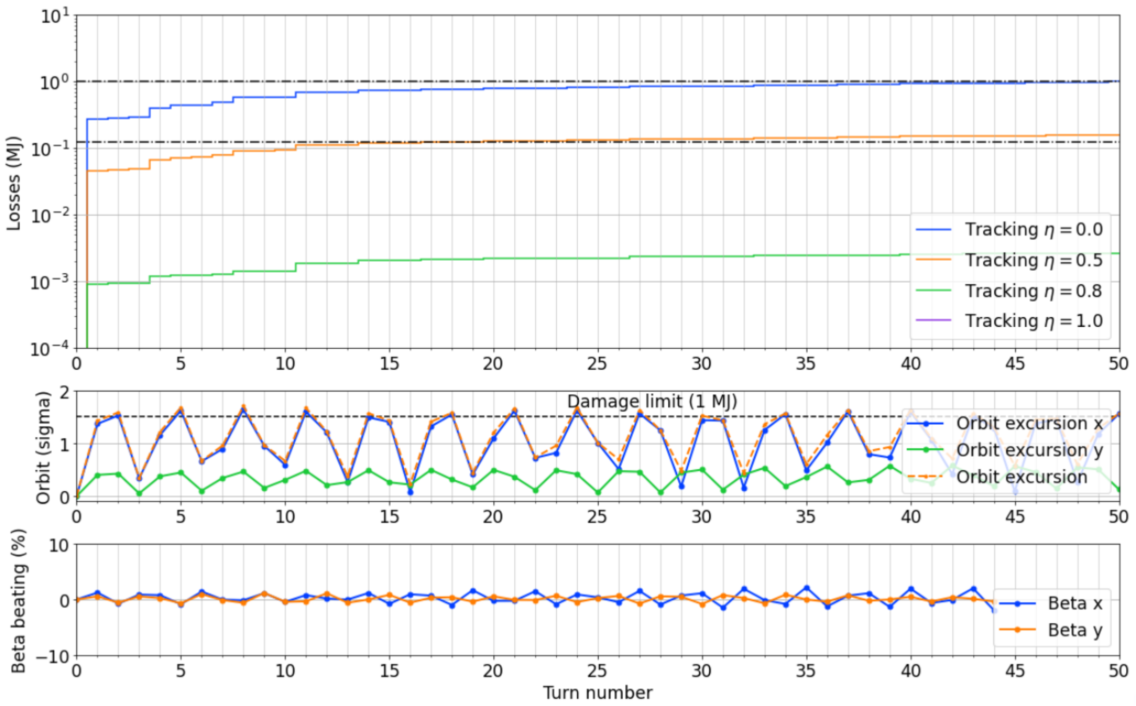
Onset to damage margin	450 µs
Measured detection time	120 µs
Propagation via BIS from P1 to P6	100 µs
LBDS synchro.	89 µs
Extraction	89 µs
Margin	**50 µs**

Onset to damage margin	270 µs
Measured detection time	120 µs
Propagation via BIS from P1 to P6	100 µs
LBDS synchro.	89 µs
Extraction	89 µs
Margin	**-130 µs**

- For **flat optics**, under conservative assumptions, the critical loss level is exceeded
- Losses up to 7 MJ in the collimation system by the time the beam is dumped

Quench heaters impact on the beam

- Effects of QH fired on circulating beams routinely observed for LHC main dipoles. Very fast current rise (30 us) leads to orbit oscillation before beams are dumped.
- Larger impact expected for HL-LHC due to amplification from beta-functions. Connection schemes were optimized to reduce the dipolar components. However, firing all QH from the triplets would lead to a > 30 sigma kick.
- For round and flat optics, the most critical circuit remains the D1. Critical loss levels reached after ~40 turns.
  - Sufficient time for BLMs and BCCM to provide diverse redundancy interlocking.
- The spurious triggering, for all magnets (triplets, D1 and D2), is interlocked by the QPS with direct connection to the BIS



D1 – Single QH circuit (worst case)

Crab cavity failure cases - Phase slip

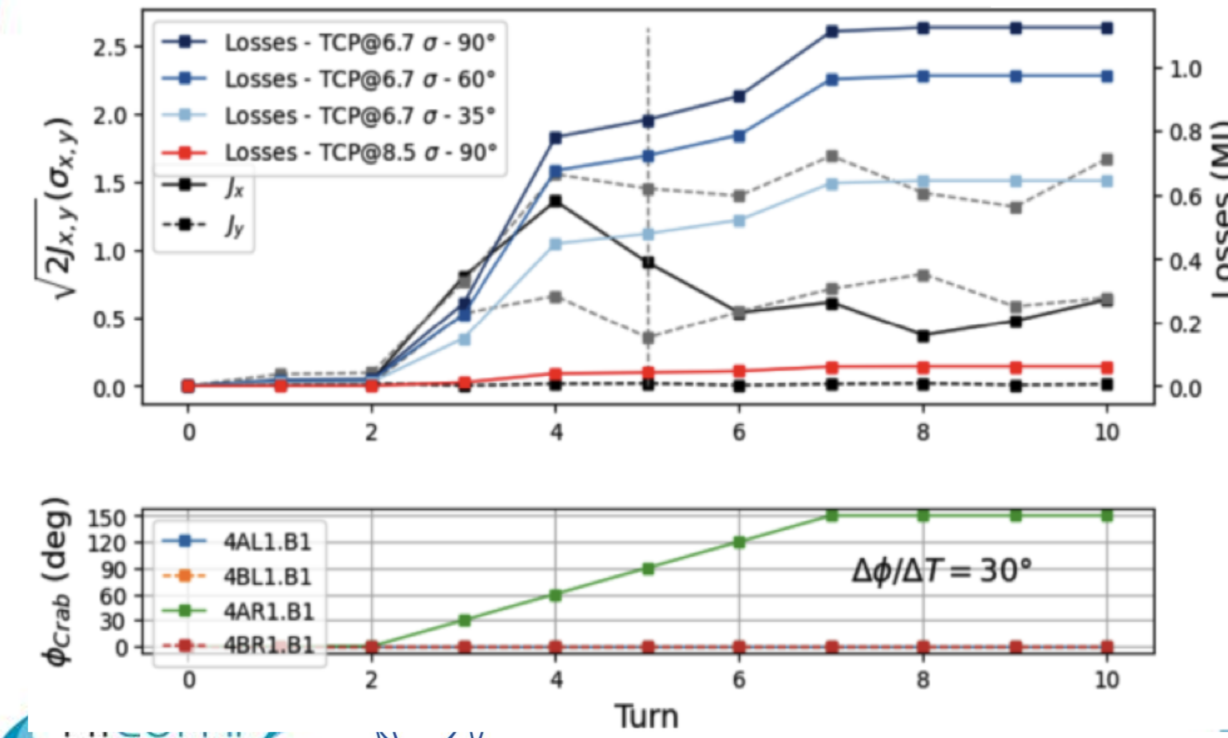
- Phase advance from CC to TCP should be limited to avoid exceeding the 1 MJ limit (within 3 turns) defined for machine protection
  - Assuming theoretical limit for the maximum phase shift per turn (44 degrees): lower than 35 degrees
  - Using estimate from SPS test stand experience (30 degrees): lower than 60 degrees

$$\max\left(\frac{d\phi(t)}{dt}\right) = \frac{\omega}{2Q_L}\sqrt{\frac{4(R/Q_\perp)Q_L P_{max}}{V_0^2} - 1}$$

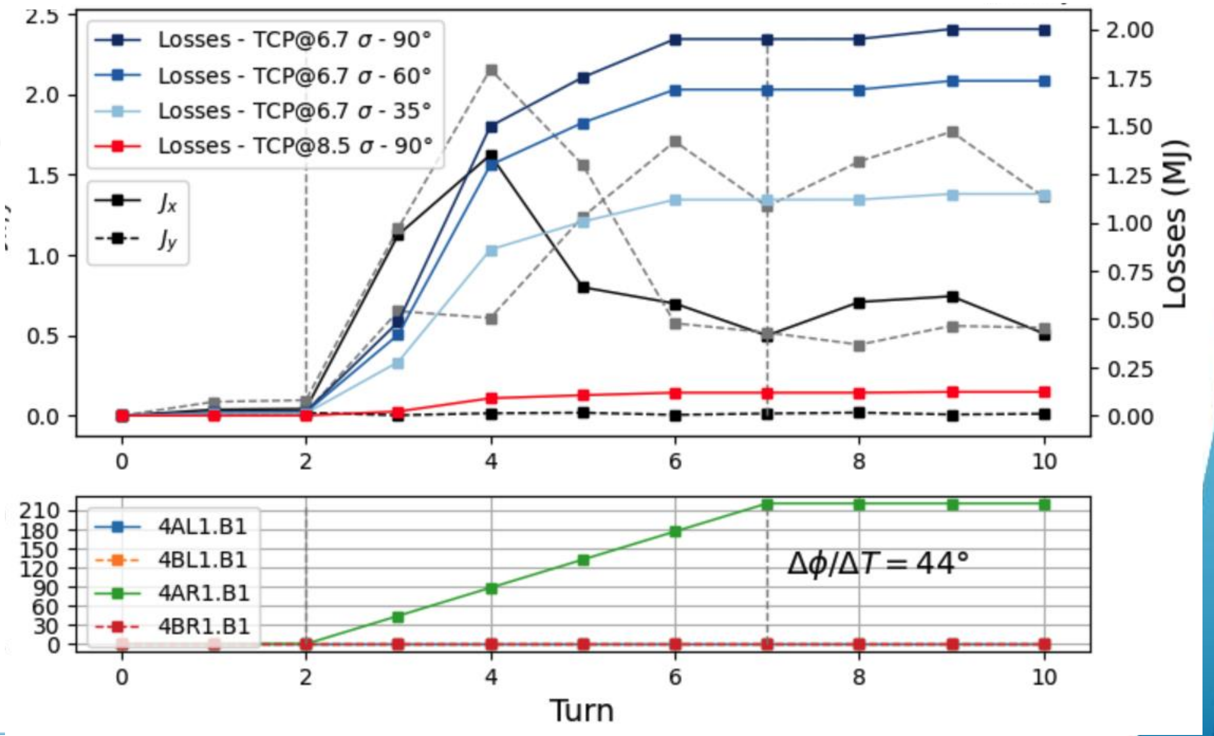
$$R/Q_\perp = 500\,\Omega$$
$$P_{max} = 100\,kW$$
$$V_0 = 3.4\,MV$$
$$Q_L = 3\cdot 10^5$$

Round optics

1.12 MJ



2.0 MJ

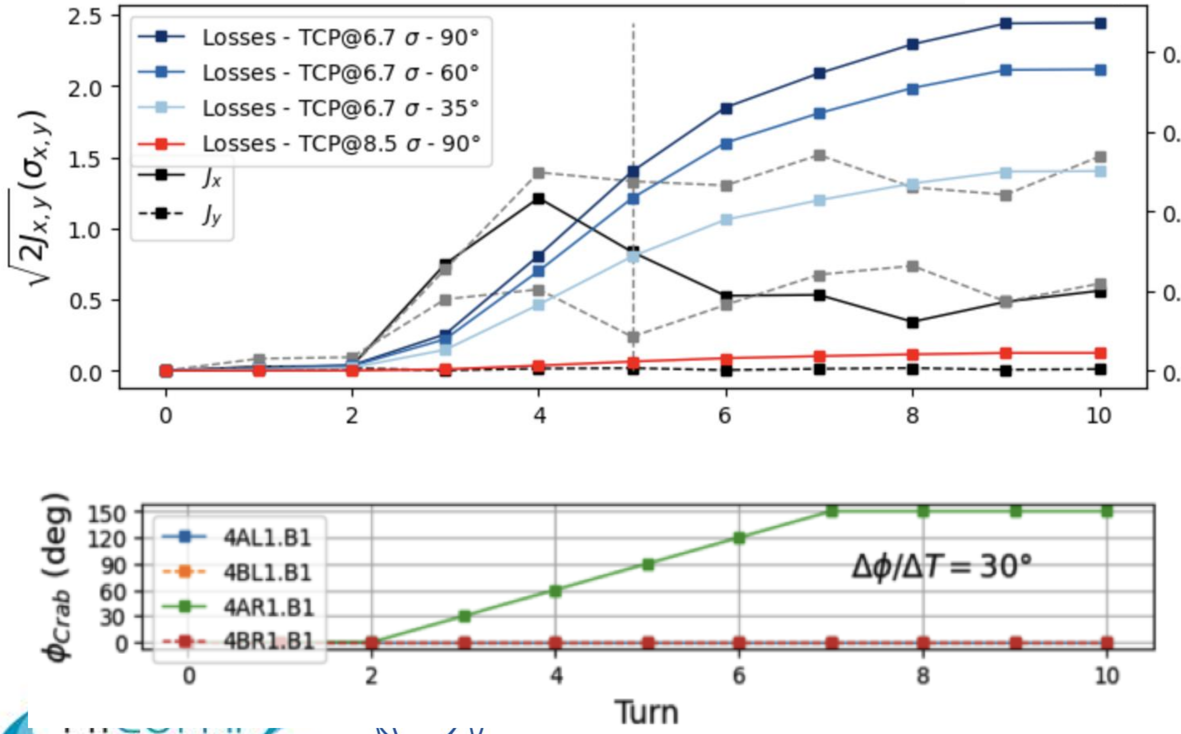


Crab cavity failure cases - Phase slip

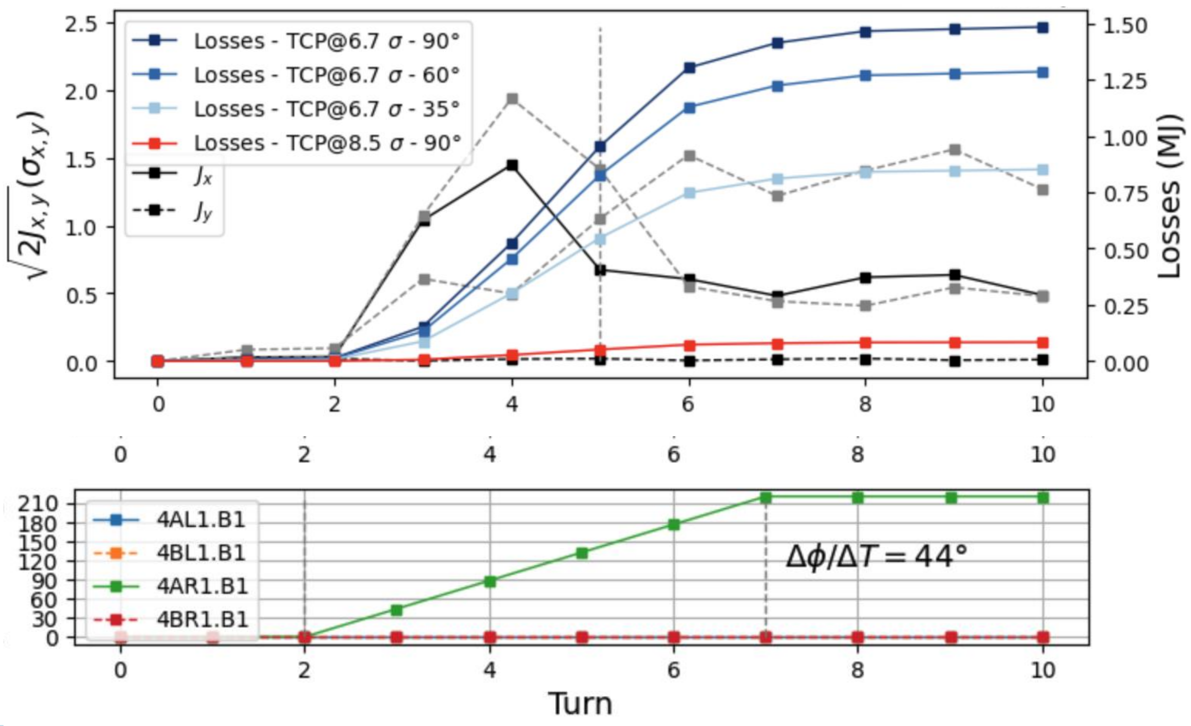
- For flat optics the situation is improved
  - Assuming theoretical limit for the maximum phase shift per turn (44 degrees): up to 35 degrees
  - Using recent estimate from SPS test stand experience (30 degrees): no limitation

Flat optics

0.87 MJ



1.48 MJ



CC failures

- Maximum theoretical phase shift per turn of 44 degrees
  - Simulation results identified the **phase slip** case as most critical, orbit shift by 1.6 sigma within two turns after the start of the failure → up to **2 MJ lost after 10 turns.**
  - **Mitigation**: phase advance from CC to TCP must be lower than 35 degrees to remain below the 1 MJ within 3 turns
  - Experience from the SPS test stand indicated that the phase shift per was further limited to 30 degrees (system tripped)
- Criticality is reduced by the flat optics (VH)

Conclusions

- Fast failures have been reviewed for round and flat optics with xsuite
- Protection against CLIQ spurious discharge
  - Enssured by a dedicated fast interlock acting ensuring beam extraction within 400 us after the onset of the failure
  - Round optics: losses remain below 1 MJ
  - Flat optics: losses up to 7 MJ
- Protection against quench heaters spurious discharge is ensured by a dedicated interlock
  - Most critical case is D1
  - Still sufficient margin for flat optics
- Most critical crab cavity failure mode is phase slip
  - Protection is ensured by limiting the maximum allowed phase advance between the CC and the TCP to 35 degrees
  - Situation slightly more favorable for the flat optics