Update on failure case studies

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WP7

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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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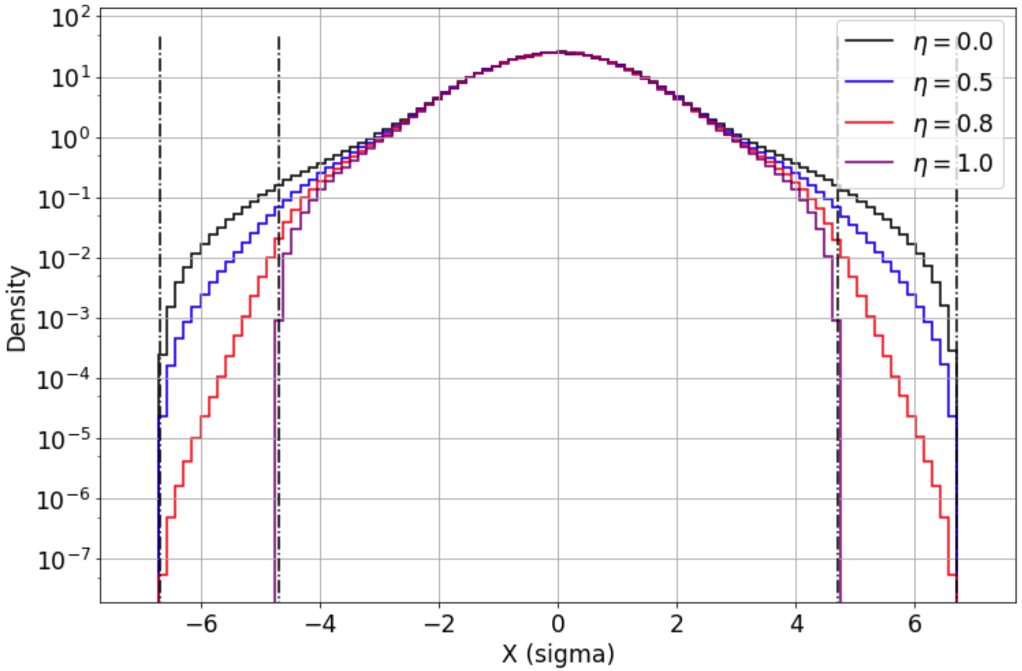
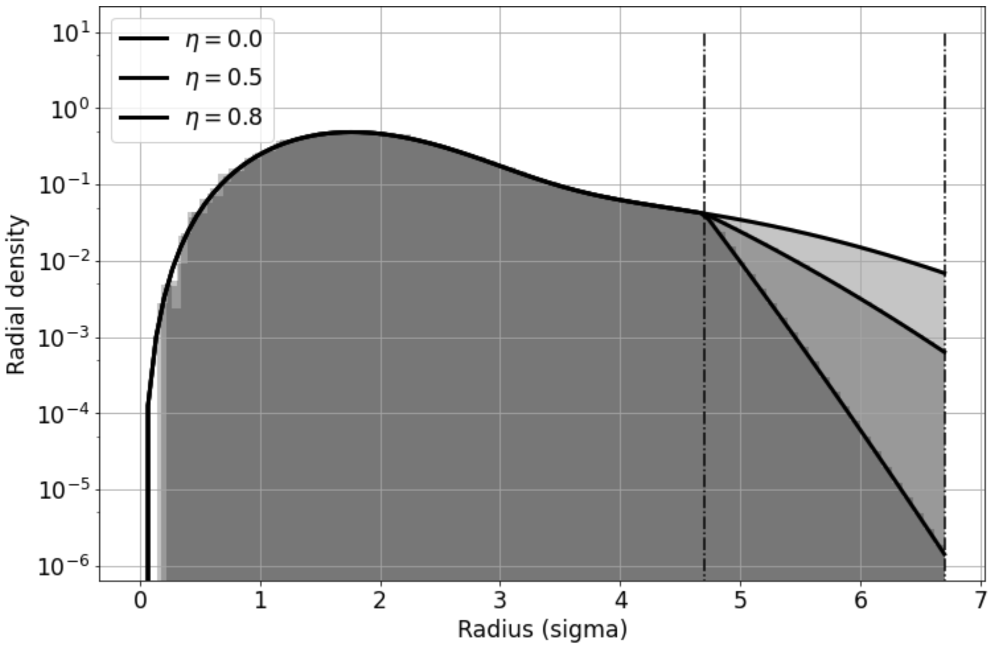
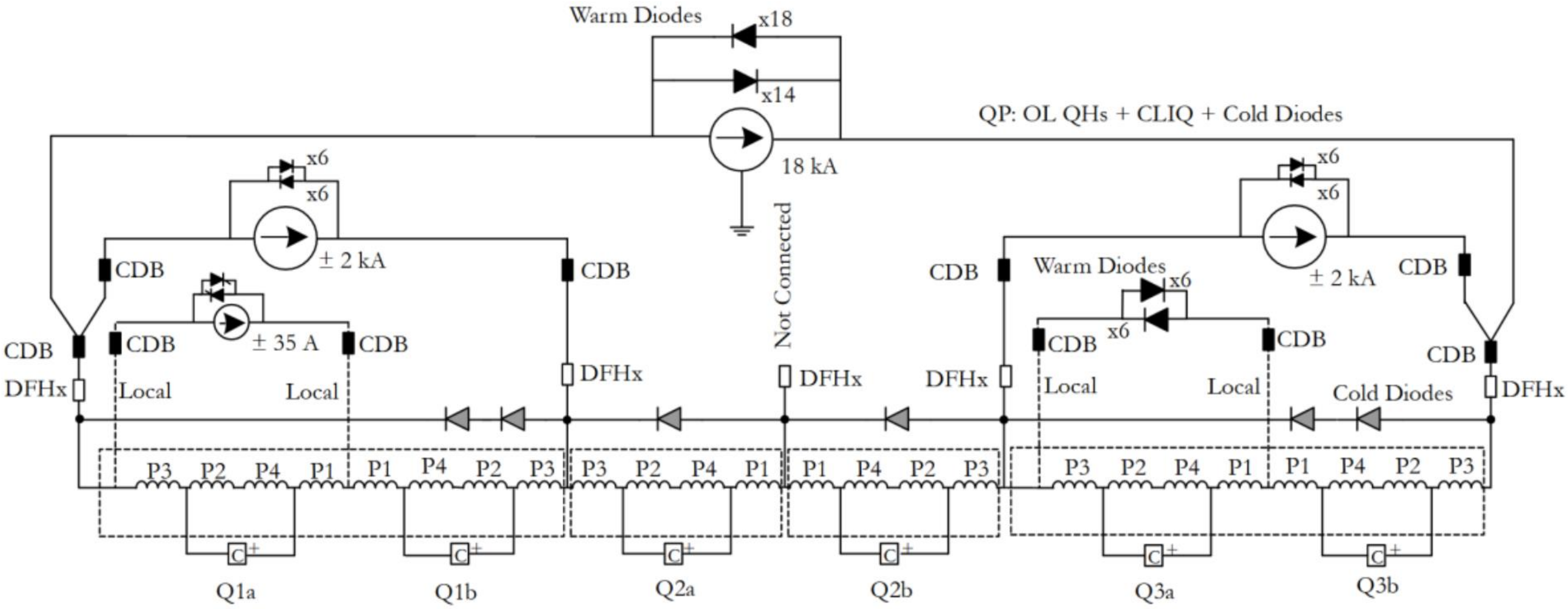




CLIQ connection scheme



CLIQ - 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**)

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

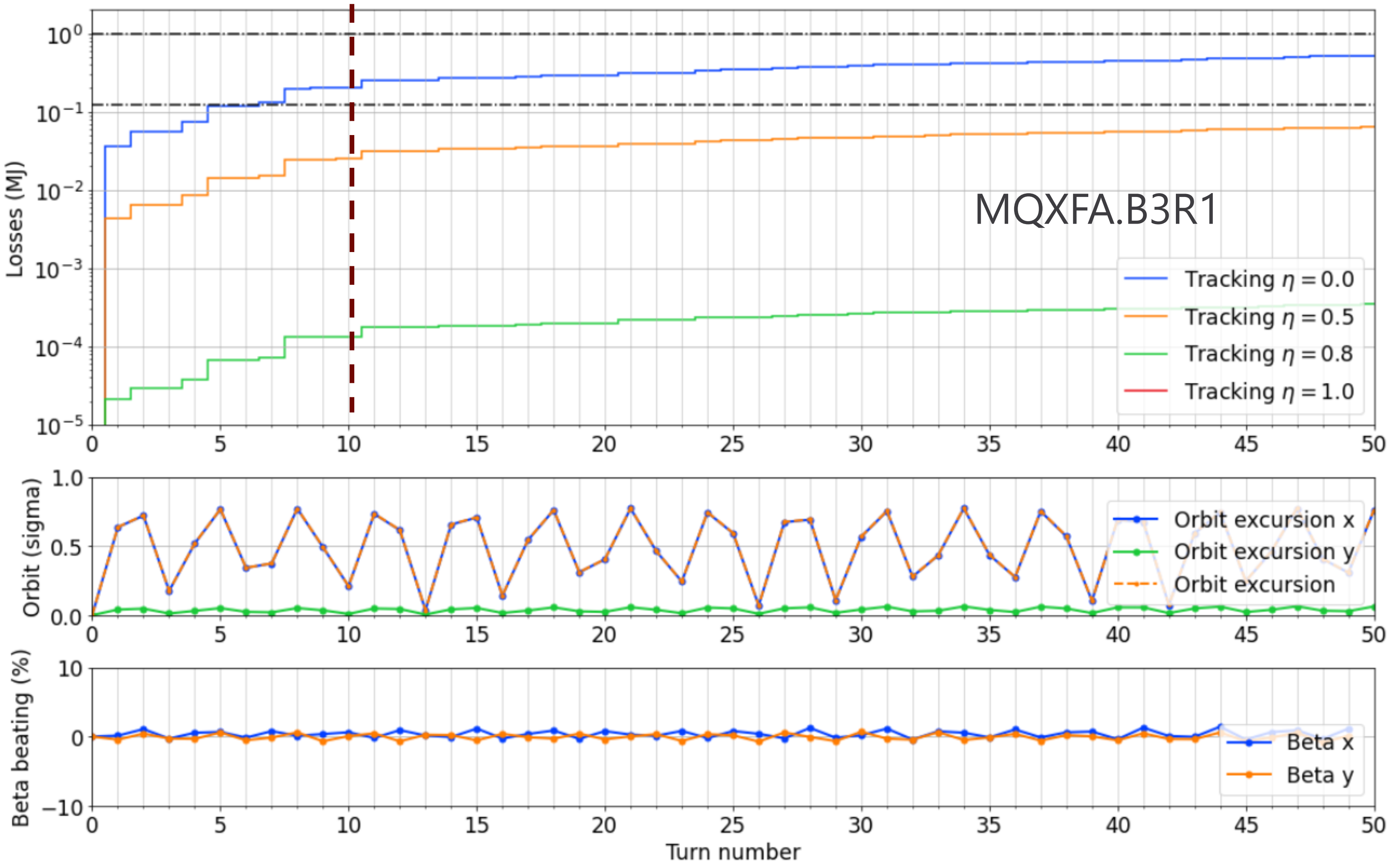
Quench heaters impact on the beam

- 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.

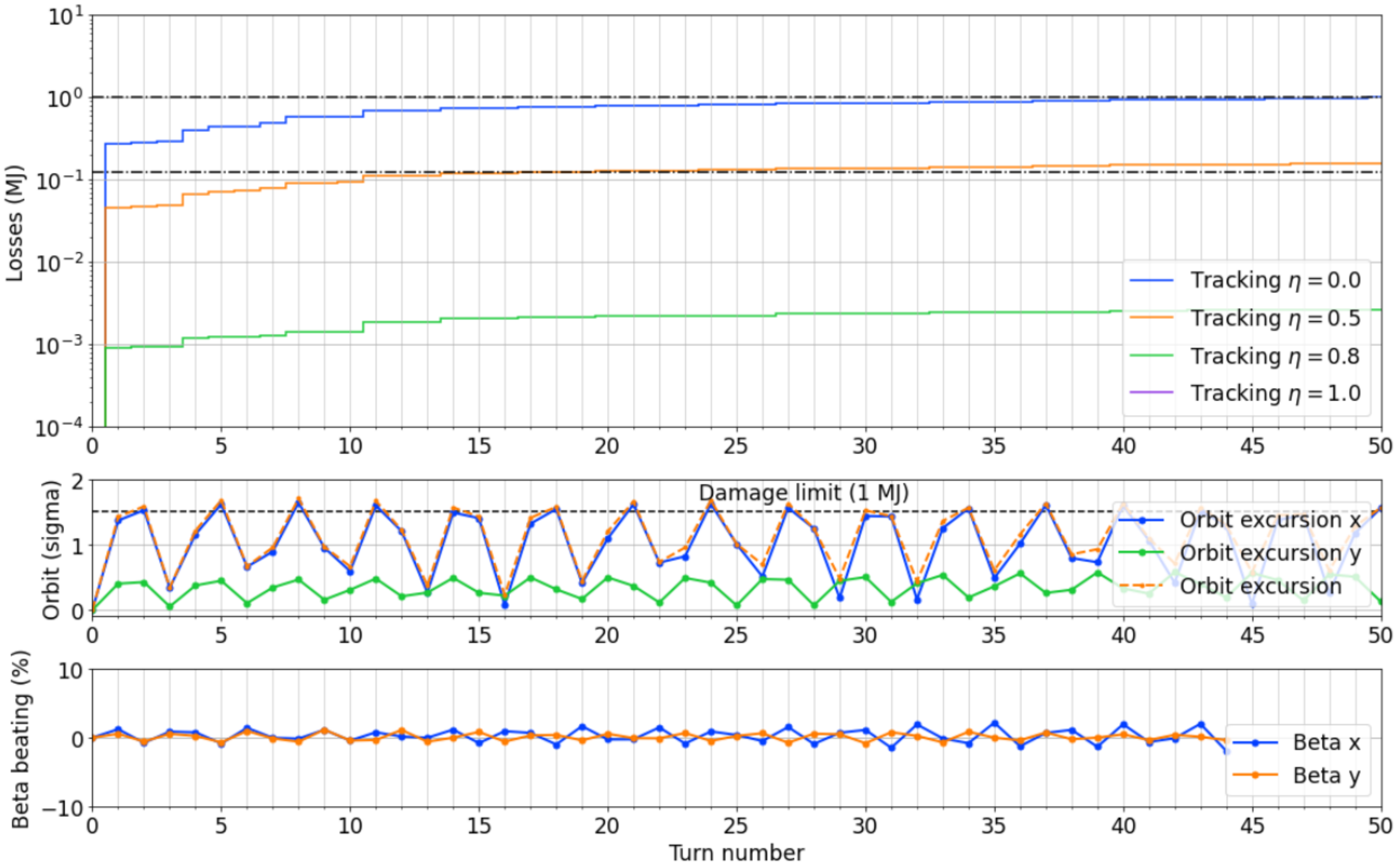
- The spurious triggering, for all magnets (triplets, D1 and D2), is interlocked by the QPS with direct connection to the BIS

Quench heater spurious discharge with depleted halo



Q3 – Single QH circuit (worst case)

Quench heater spurious discharge



D1 – Single QH circuit (worst case)

Crab cavity failure cases

- Maximum phase shift per turn: 44 degrees
- Assume worst case scenario in case of phase advance (90 degrees) between CC and TCP
  - Results rescaled to other phase advances in post-processing
- Conservative assumption on complete collimation phase space coverage

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

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

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

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

$$R/Q_\perp = 500\,\Omega$$
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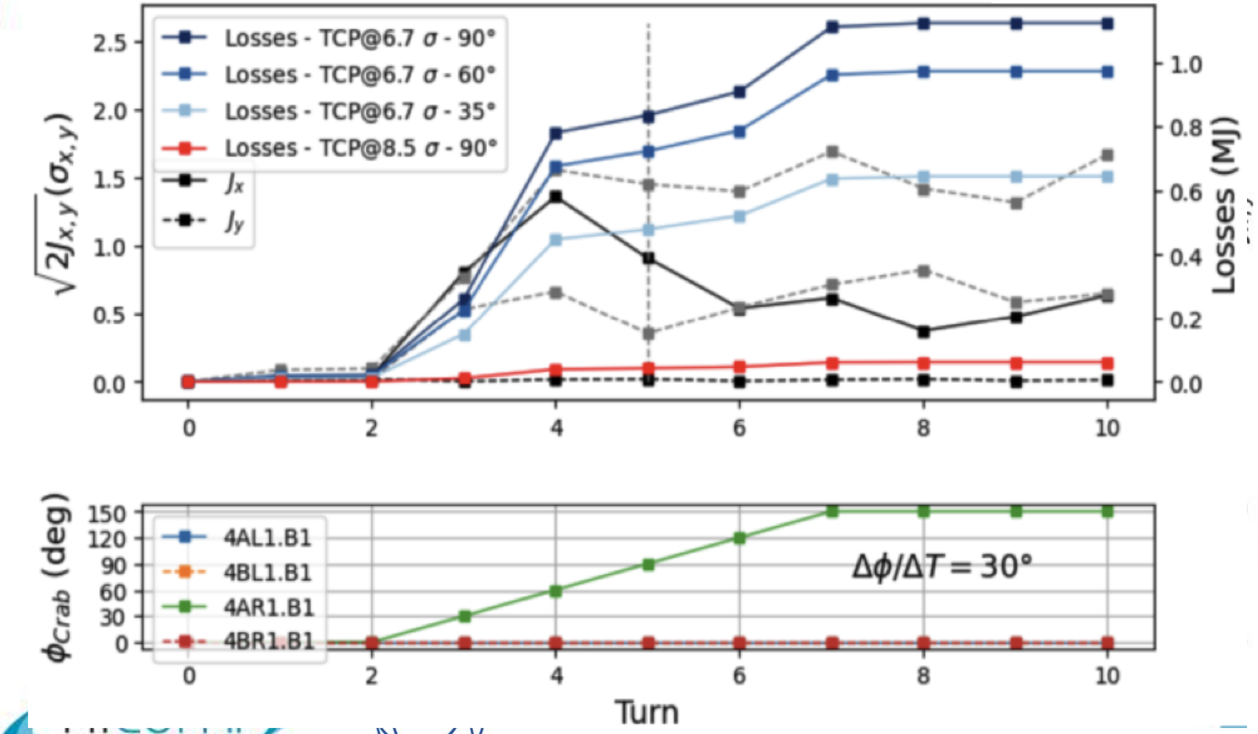
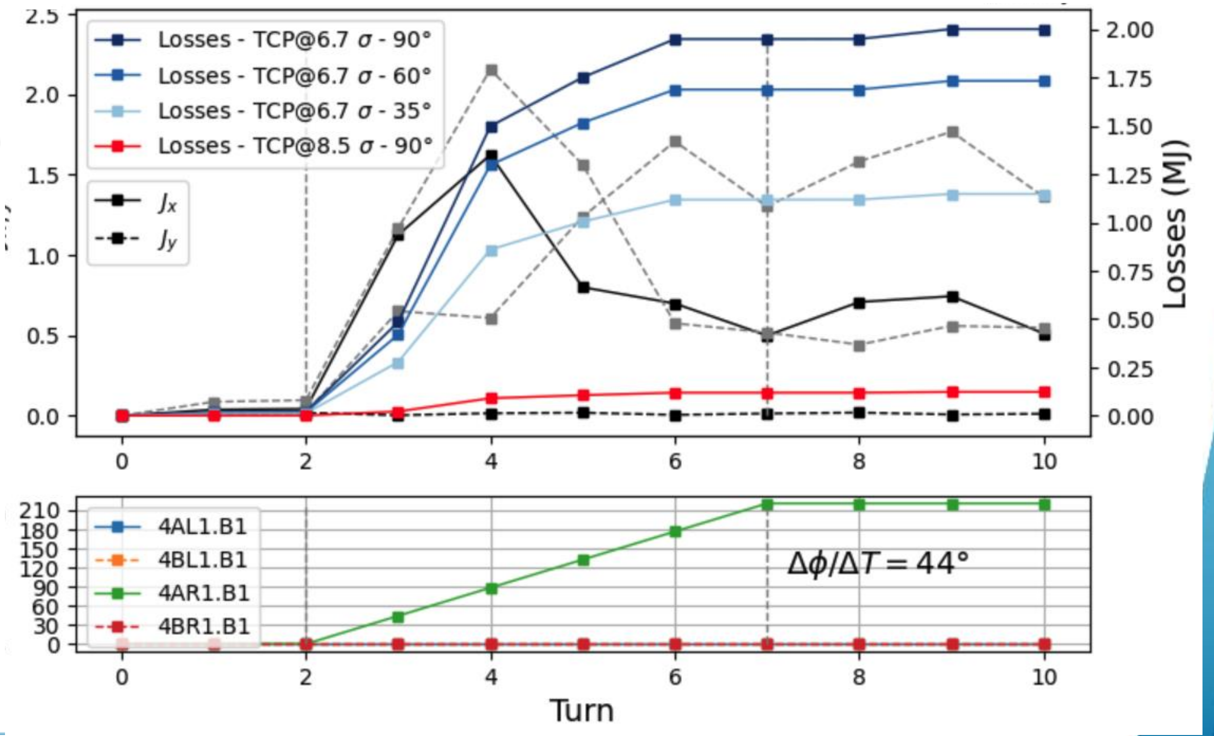
Round optics

1.12 MJ

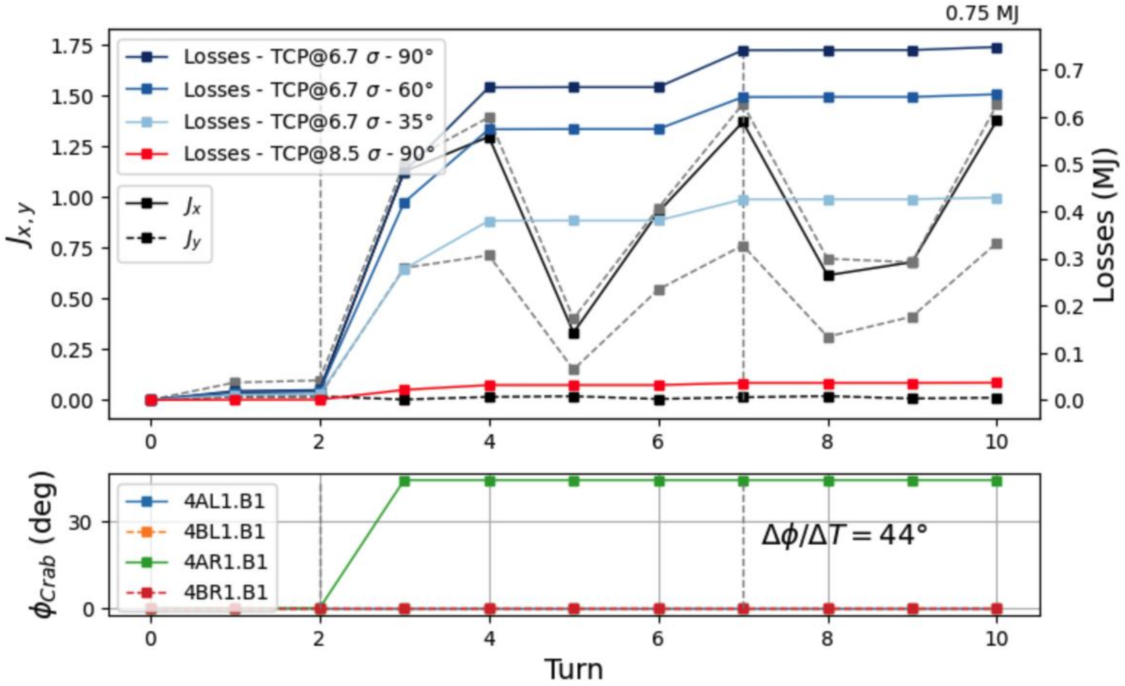


2.0 MJ

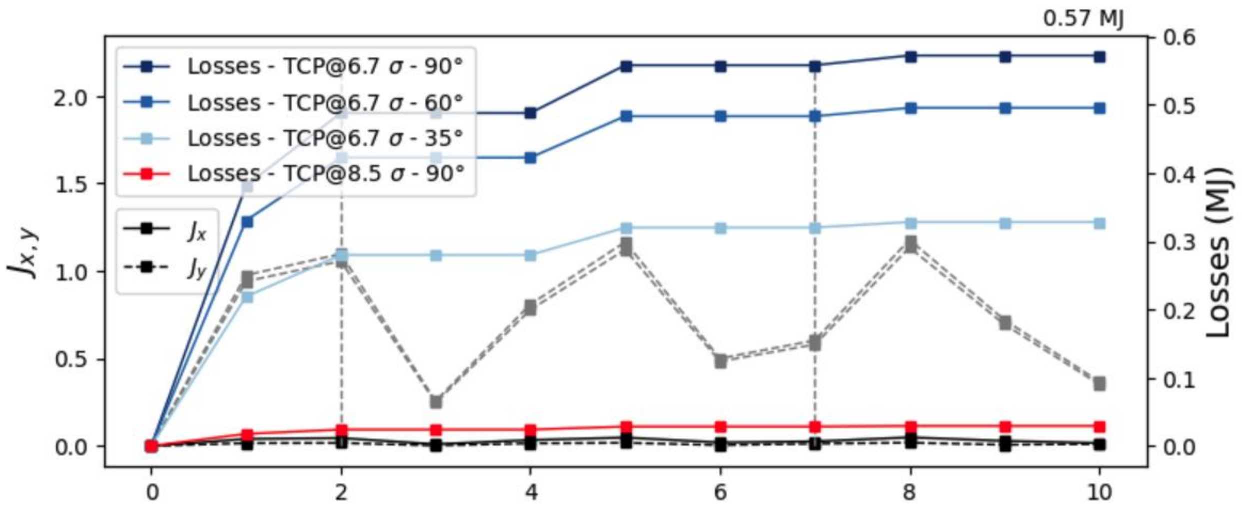


Crab cavity failure cases

Phase jump



Voltage drop



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

- 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