Machine protection studies

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Outline

- Assumptions and past works
- Phase jump and phase slip
- Phase jump MD in the SPS
- Mitigations and conclusions

Assumptions and past work

- Three failure cases identified
  - Phase slip
  - Phase jump
  - Voltage drop
- Maximum theoretical phase shift per turn of 44 degrees
  - Simulation results [1] identified the **phase slip** case as most critical, 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 [1]
  - Phase slip is most critical, up to 1.12 MJ lost after 10 turns (0.8 MJ after 3 turns)
  - Mitigation: phase advance between crab cavities and primary collimators must be lower than 60 degrees

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

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

Courtesy B. Lindstrom

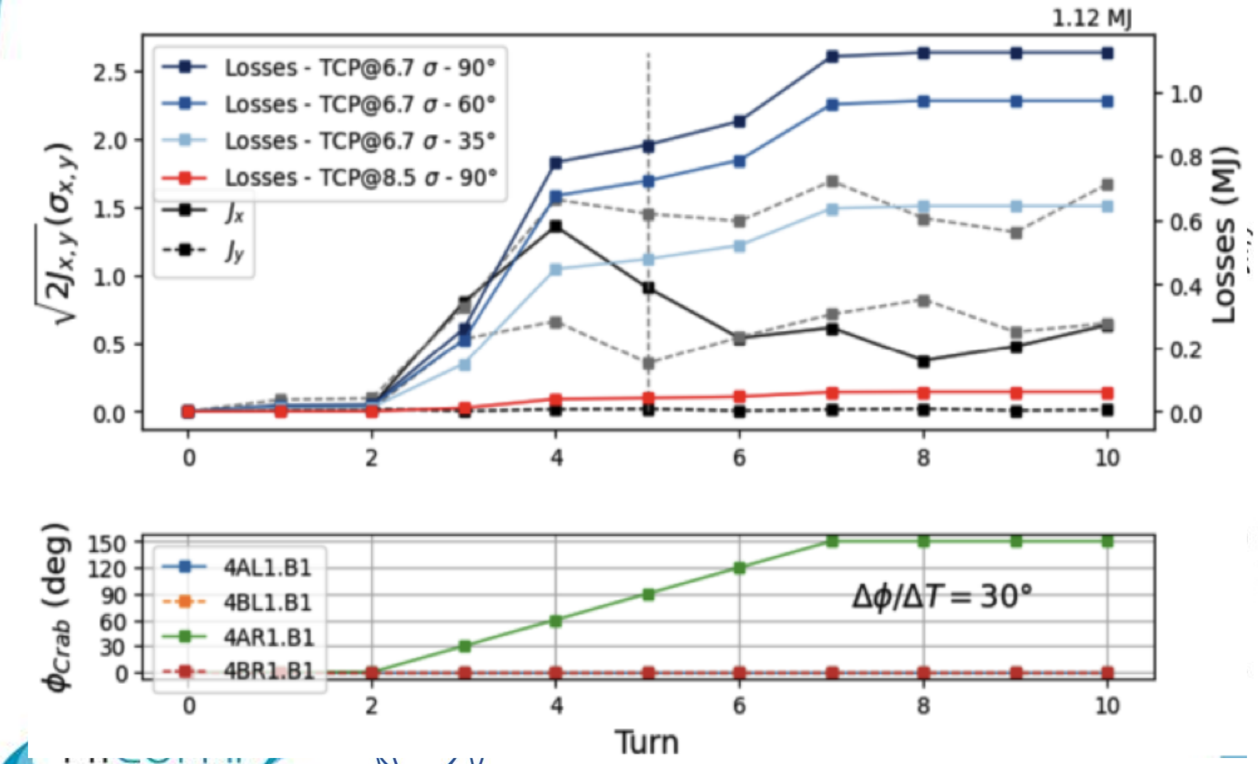
	Beam parameters
Beam energy	7 TeV
Beam stored energy	674 MJ
Bunch intensity	2.2 x 10^{11} p^+/bunch (2736 bunches)
Beam emittance	2.5 μm
Crossing angle at IP1-5	500 μrad
Crab cavity voltage	3.45 MV
1-sigma bunch length	0.25 ns

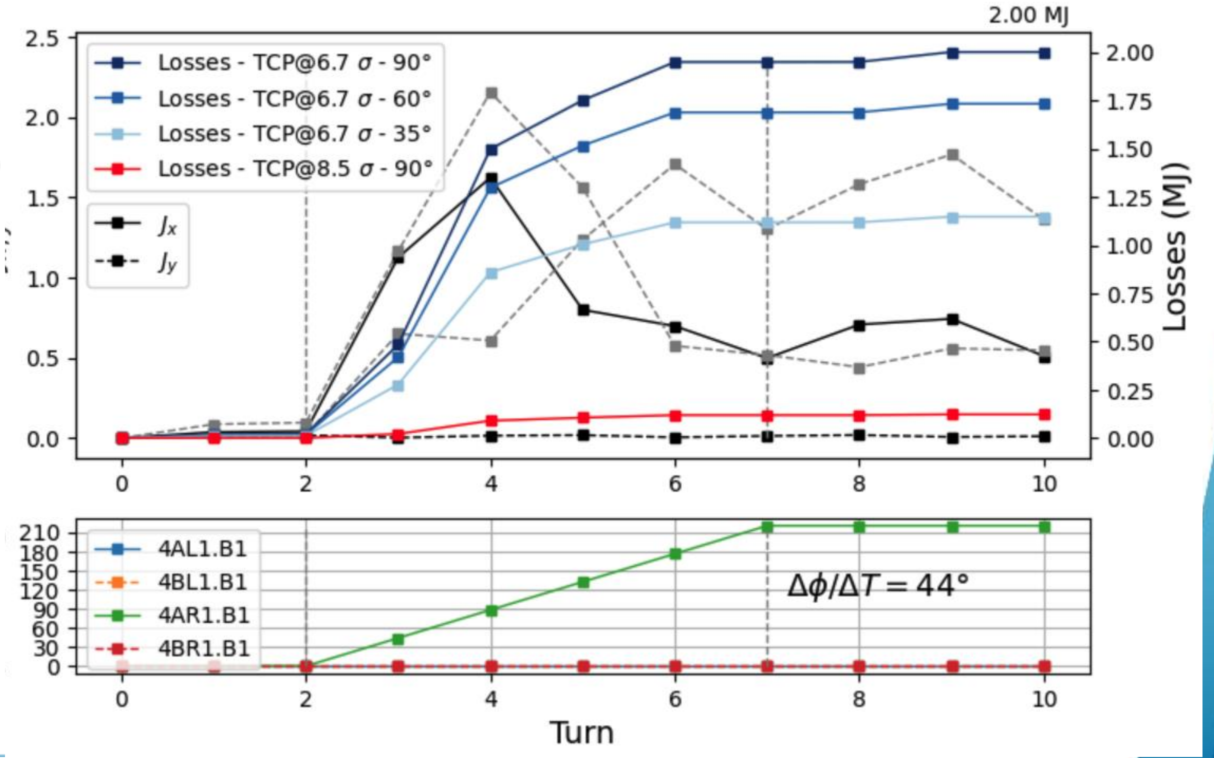
- HL-LHC layout v1.5 with round optics (β* 15 cm)
- Collimator settings: TCP @ 6.7 sigma and 8.5 sigma

(1) Machine protection challenges for Run 4", Chamonix, 2023

Phase slip – Simulation results

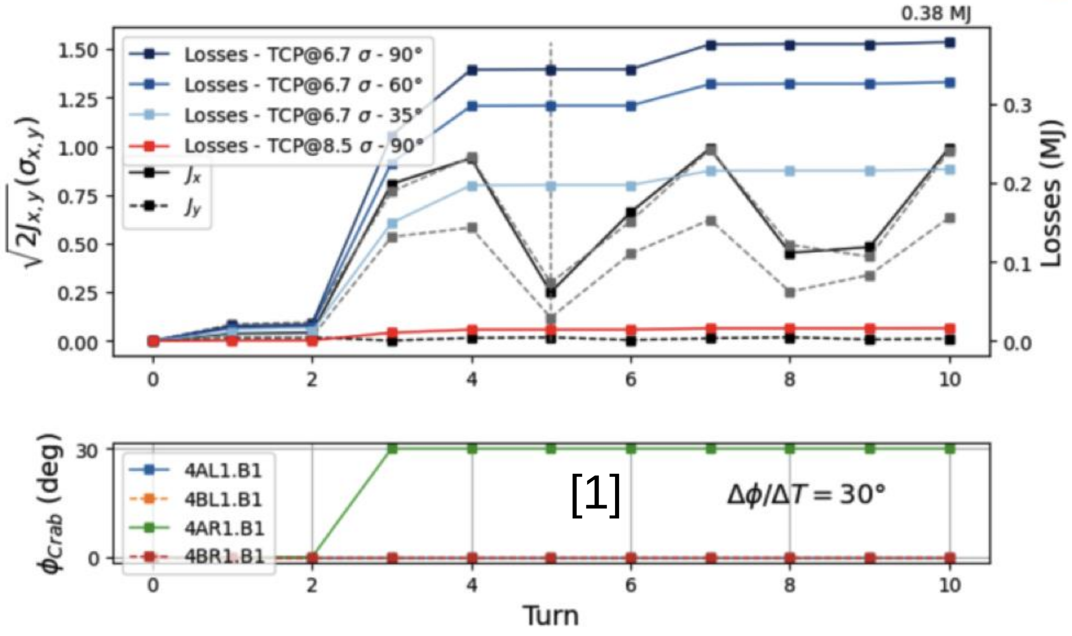
- IP1 is slightly more critical with maximum losses for a phase slip failure of 4AR1.B1
- Phase advance from CC to TCP should be limited to avoid exceeding the 1 MJ limit (within 3 turns) defined for machine protection
  - Assuming theoretical limit for the maximum phase shift per turn (44 degrees): lower than 35 degrees
  - Using recent estimate from SPS test stand experience (30 degrees): lower than 60 degrees

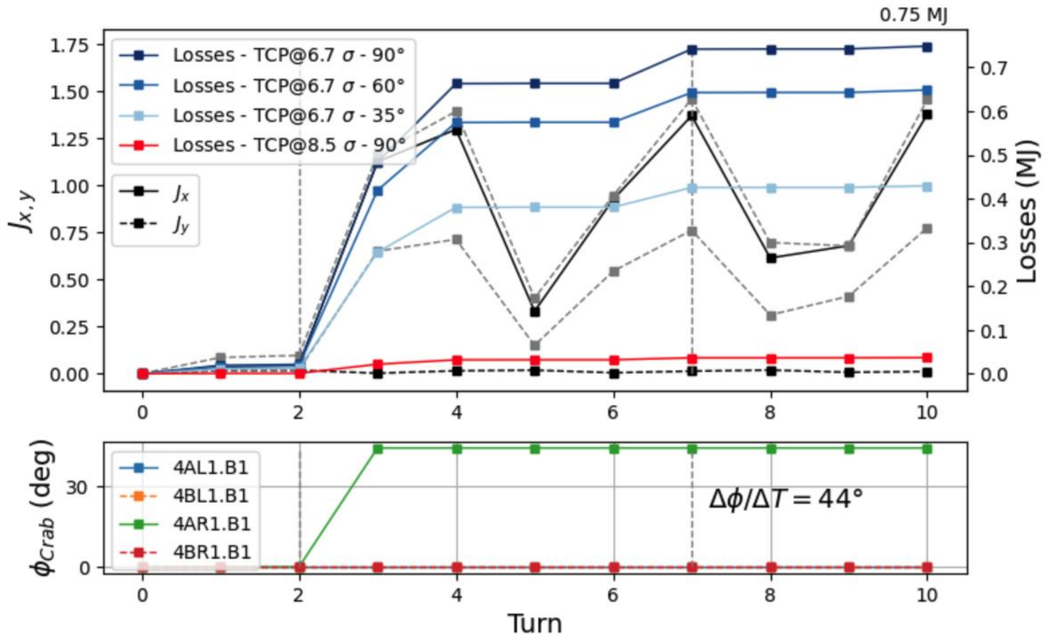




Phase jump – Simulation results

- Case similar to the 2023 SPS MD (see next slides)
- Maximum losses after 10 turns of 0.75 MJ

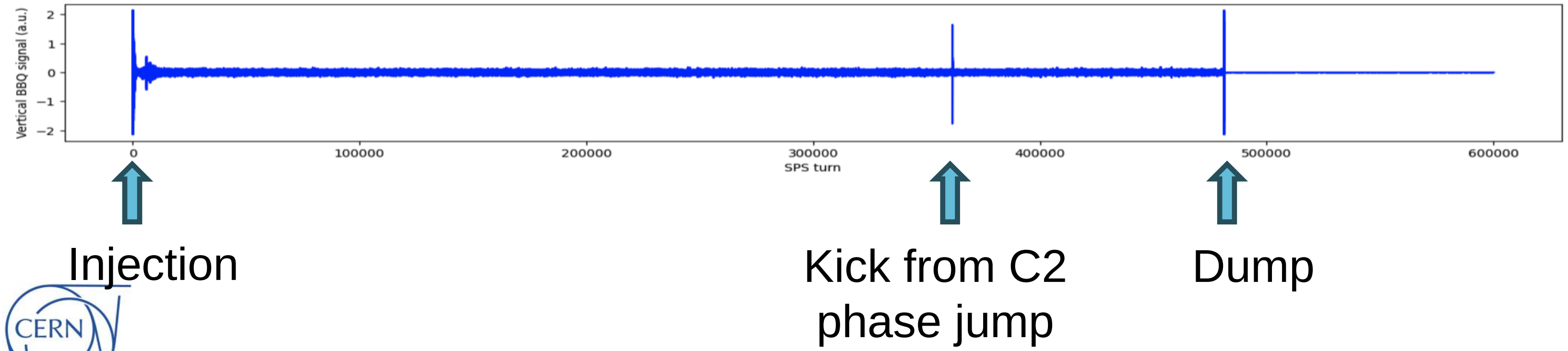




(1) Machine protection challenges for Run 4”, Chamonix, 2023

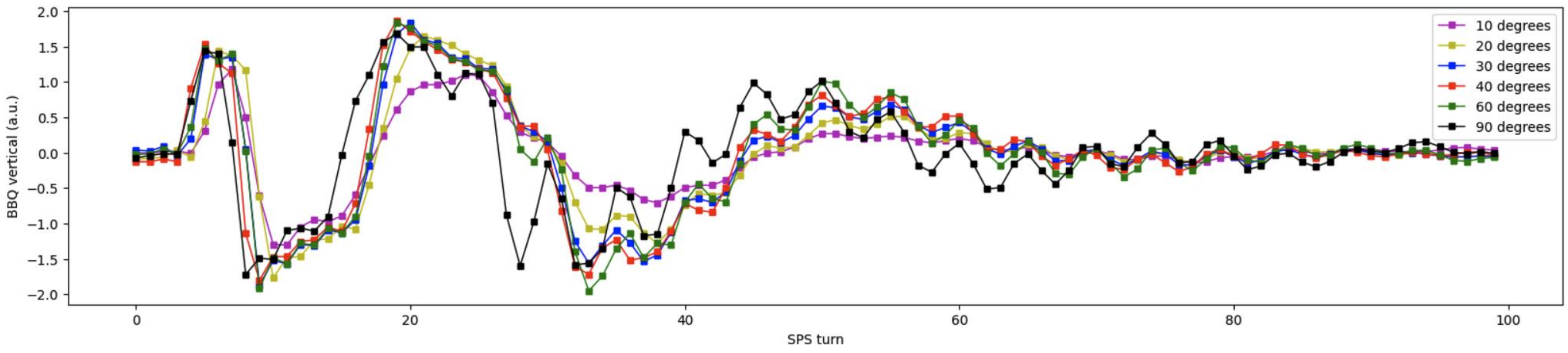
SPS MD

- SPS MD on 7 June 2023 included **phase jump tests with beam** to measure the effect on the beam and attempt to infer the maximum allowed phase shift per turn.
- Phase jump provoked on cavity 2 (cavity 1 at constant phase) with the **feedback of**, at **constant voltage** of 1 MV, at flat bottom with the **cavities counter-phased** (so-called “transparent mode”).
- Data collection
  - Turn by turn BBQ data
  - Closed-orbit (1 ms sampling rate)
  - Beam intensity (5 ms sampling rate)
  - Did not recover synchronised head-tail monitor data



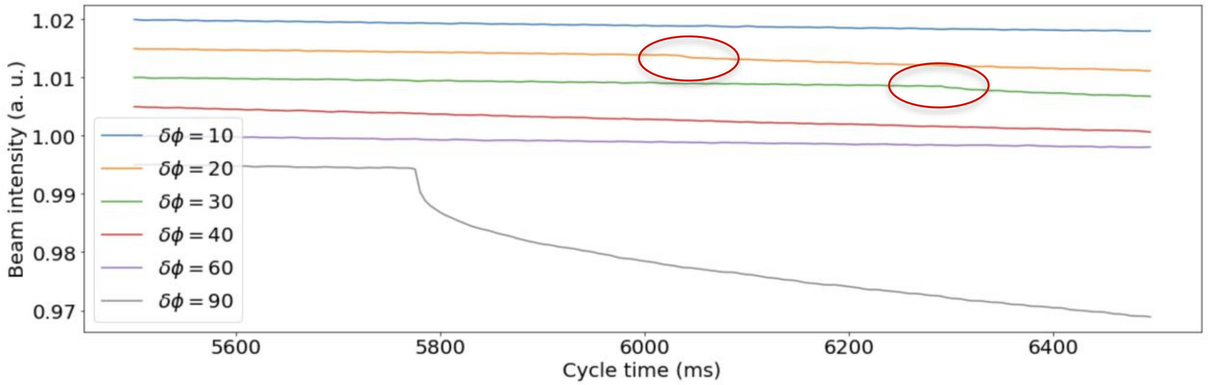
SPS MD – Turn by turn dynamics

- Phase jump of 10, 20, 30, 40, 60 and 90 degrees with RF feedback off
- BBQ signal show similar response amplitude and dynamics for phase jumps from 20 to 90 degrees. The amplitude for the 10 degrees jump is ~30% lower.
  - Cannot distinguish the different dynamic behaviour between the different phase shifts → non conclusive

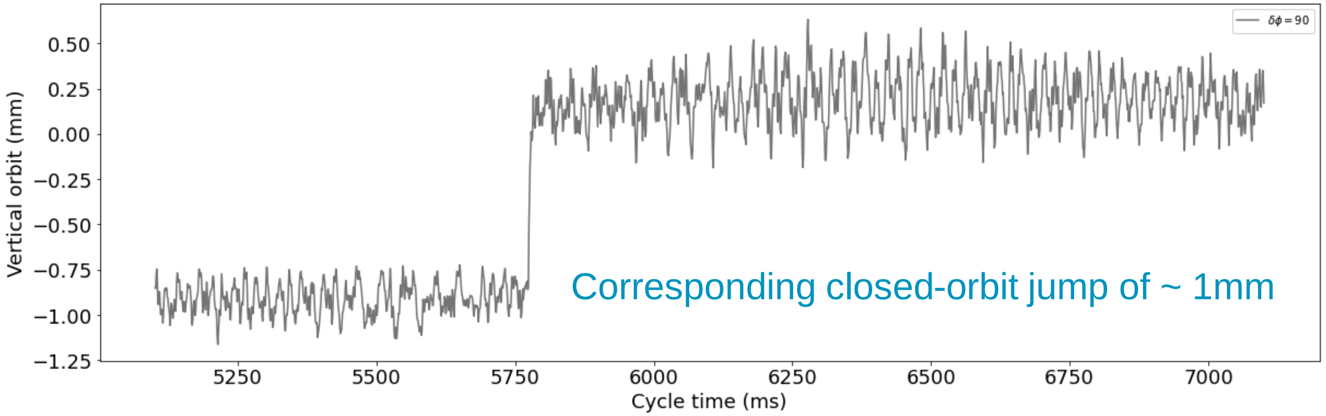


SPS MD – Orbit jump and beam losses

- Beam losses were observed for the 20, 30 and 90 degrees jump
- Beam loss data could not be retrieved for the 40- and 60-degrees phase jump



Clear indication of hitting the aperture limit for the 90 degrees case



Corresponding closed-orbit jump of ~ 1mm

Conclusions

- Non-conclusive results from 2023 SPS MD
- Measurements **do not provide additional input** on the dynamics of the failure case due to the limited time resolution of the BPMs (1 ms) and BLMs (5 ms) in the SPS → **Simulations remain** the best way to **predict the criticality** of the failure cases.
- The maximum **achievable phase change per turn** must be reviewed: theoretical limit 44-degree versus 30-degree limit observed experimentally in 2022. In case of 44 degrees the losses would increase to 2 MJ within 10 turns.
- Future experimental studies on crab cavity failure cases (**phase slip, quench**) in the SPS require improved **turn-by-turn diagnostics** of the orbit and beam losses.
  - Use timing event to trigger phase jump
  - Trigger turn-by-turn recording of BPMs
  - Trigger turn-by-turn recording of LHC type BLMs in the SPS

References and prior works

- T. Baer, *Very Fast Losses of the Circulating LHC Beam, their Mitigation and Machine Protection*, CERN-THESIS-2013-233
- B. Yee-Rendon et al., *Fast crab cavity failures in HL-LHC*, CERN-ACC-2014-0107
- A. Santamaria Garcia, *Experiment and Machine Protection from Fast Losses caused by Crab Cavities in the High Luminosity LHC*, CERN-THESIS-2018-142
- B. Lindstrom, Criticality of fast failures in the High Luminosity Large Hadron Collider, CERN-THESIS-2020-318
- B. Lindstrom, ColUSM #157, 2022
- D. Wollmann, S. Redaelli, Chamonix 2023

Backup

Optics at the location of the crab cavities

- For reference

Crab cavity	Beta X	Beta Y
4AL1.B1	3617.6	3666.4
4BL1.B1	3574.7	3545.1
4AR1.B1	3665.5	3618.4
4BR1.B1	3544.2	3575.5
4AL5.B1	3632.1	3706.7
4BL5.B1	3597.6	3608.5
4AR5.B1	3706.4	3632.2
4BR5.B1	3608.2	3597.6

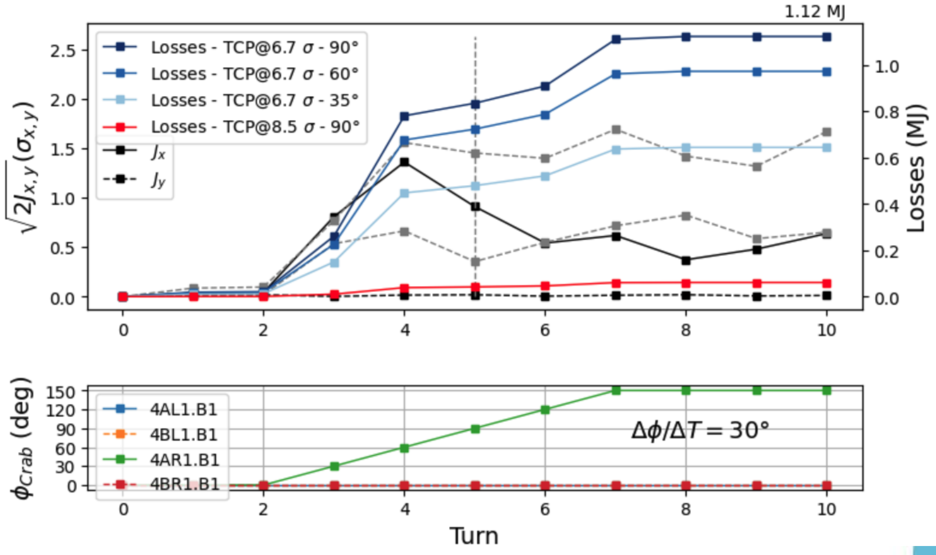
Collimator gaps

	Collimator	Sigma	Gap (mm)
Run III	TCP.D6L7.B1	5.7	1.09
	TCP.C6L7.B1	5.7	1.51
HL-LHC v1.4	TCP.D6L7.B1	6.7	1.09
	TCP.C6L7.B1	6.7	1.51
HL-LHC v1.5	TCP.D6L7.B1	8.5	1.38
	TCP.C6L7.B1	8.5	1.91

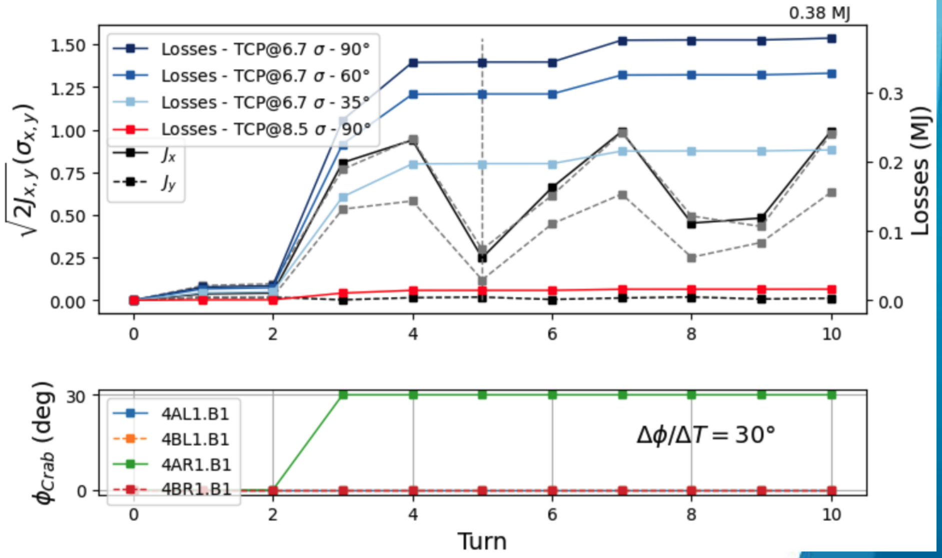
Crab Cavity failure: worst cases 4AR1.B1

- **Phase slip**
  - Phase change in one crab cavity over 5 turns by **30 degree per** turn
  - Shift of centre of bunch by **1.4 sigma** within two turns after the start of the failure
  - **Up to 1.12 MJ lost** after 10 turns (0.8 MJ after 3 turns)
- **Phase jump**
  - Phase change of **30 degree in one turn**
  - Shift of centre of bunch by **1.0 sigma** within two turns after the start of the failure
  - Up to 0.38 MJ lost within 10 turns (0.35 MJ after 3 turns)
- **Voltage drop**
  - Drop of voltage to **zero within one turn**
  - Up to 0.59 MJ lost within 10 turns (0.5 MJ after 3 turns)

Phase slip



Phase jump



Voltage drop