



## **Crab Cavity failures: parameters and combined failures**

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# Outline

- Introduction: Crab Cavity failure studies
  - Main failure parameters
  - Dependency of losses on phase advance
  - Passive protection from phase advance
  - Interlocking
- Combined failures associated with CC failures
  - Missing beam-beam kick scenarios during dumps
  - Associated orbit shift and losses
- Conclusion and outlook

# Crab Cavities Failures Studies

- Crab Cavities (CC) will be installed in the LHC to compensate for the geometrical factor luminosity loss.
- Transverse deflecting voltage of **3.4 MV** ↔ **kick up to 1.6  $\sigma$**  with **short timescales**:

$$\tau_{decay} = 4.5 \text{ turns}, \quad \frac{d\varphi}{dt} < 29^\circ/\text{turn}$$

(from physical limitation on worst case failure scenarios)

- Failures have been studied [1] and the **main parameters have been identified**:
  - Cavity RF field (phase, voltage, frequency): with ongoing efforts [2] to model the field behavior during a quench and the coupling to the beam.
  - Beam distribution: with high importance of the energy ratio in the last 2  $\sigma$  of the distribution (up to 1% in beam scraping measurements).
  - Phase advance: from the CC to the collimators.

[1, Crab Cavity Failure Studies Meetings 1-8]

[2, Modeling the Low Level RF Response on the Beam during Crab Cavity Quench, IPAC'17, K. Sjobak *et al.*]

# Phase advance to the collimation system

- The **losses during failures** studied until now (voltage drop, phase jump, detuning) **depends strongly on the phase advance** from the CC to the TCP [3].
  - E.g. 5-turn losses for a  $60^\circ$ /turn detuning of 2 CC out of 4:  
ATLAS B2: 0.03% ( $16^\circ$ )    CMS B1: 2.04% ( $-134^\circ$ )
- Using a simple model (linear optics + analytical calculation of the losses), **the phase advance** from CC to collimators **was scanned**, assuming a  $29^\circ$ /turn detuning failure for 1 CC out of 2:  
**A phase advance below  $25^\circ$ , allows keeping the losses before dump below damage limits**  
(0.15% of HL-LHC beam)

# Interlocking

- Relying on phase advance for protection implies:
  - Reliable phase adv. from the CC to the TCPs during a failure, i.e. a **new interlock on phase adv.** (as for the TCT [4]) needs to be studied and proposed.
  - A **reliable and fast (<1 turn) interlock from the CC field**: very fast failures of the crab cavities need to be already taken into account during the **early stage of the low level electronics development** and **benefit from the SPS tests of 2018.**
  - Verifying that no other aperture restriction is exposed due to avoiding the TCP: **SixTrack simulations (with 4 CC) show the TCS damage limit is not reached within 50 turns for ATLAS B2 (15°).**

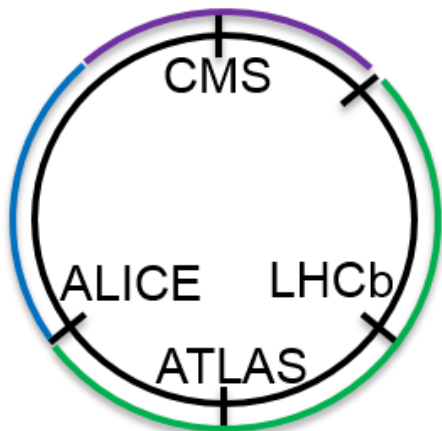
# Combined failures

- The previous considerations allow **little margin** and don't take **combined failures** into account.
- Synchronous **failure of other equipment** is **interlocked** against and usually involves **longer timescales**.
- Correlated failures have to be studied:
  - CC are independent systems but are coupled via the beam loading and it should be **verified via FLUKA** simulations if a large **UFO can quench two CCs**.
  - The **loss of long range beam-beam (LRBB) kick** has already been identified [5] as a source of orbit shift for Hi-Lumi and would happen systematically in case of CC failure, due to the dump.

# Missing beam-beam kick scenarios

- A delay of up to two turns can occur between the dumps of B1 & B2.
- Due to the non-synchronicity of the abort gaps in IR6 and the position of the crossing IPs, there are **several different scenarios**.
- The orbit offsets associated with these various scenarios were simulated with MAD-X.

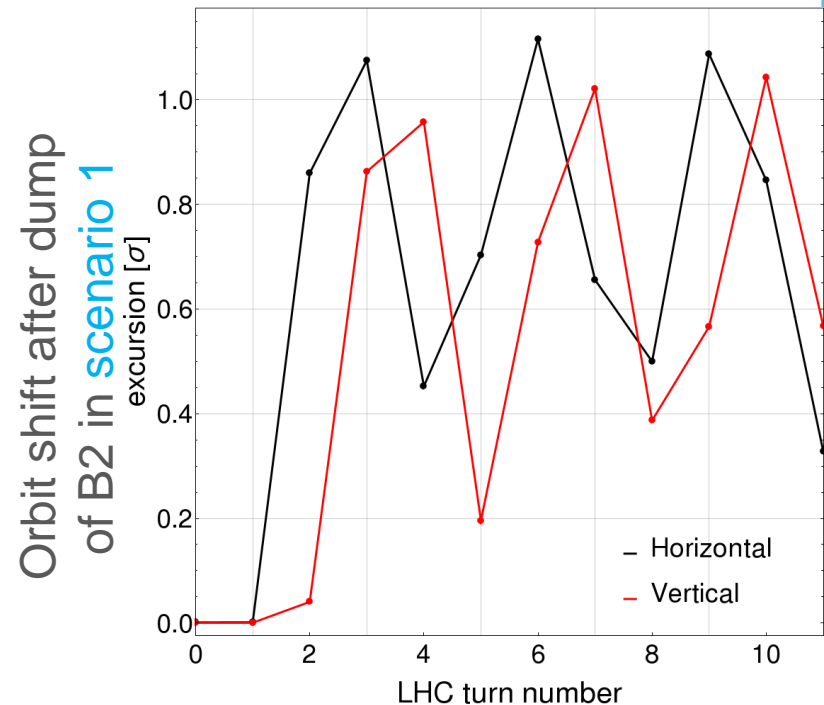
Example for B1:



25% of the beam will see BB only in LHCb

50% of the beam will see missing BB from CMS

25% of the beam will see missing BB from ALICE



# Associated losses

- Within 2 turns of a CC failure, a **residual crabbing of up to  $1\sigma$**  could be observed in the collimation area.
- The losses were **estimated analytically** from the tilted distribution and the offset, and weighted according to each LRBB kick loss scenario.

CC failing	1 turn dump delay	2 turn dump delay
ATLAS / B1	0.017%	0.070%
ATLAS / B2	0.018%	0.069%
CMS / B1	0.091%	<b>0.236%</b>
CMS / B2	0.019%	0.105%
None	0.010%	0.060%

Above collimation damage limit (0.15% of full beam)



# Conclusion and outlook

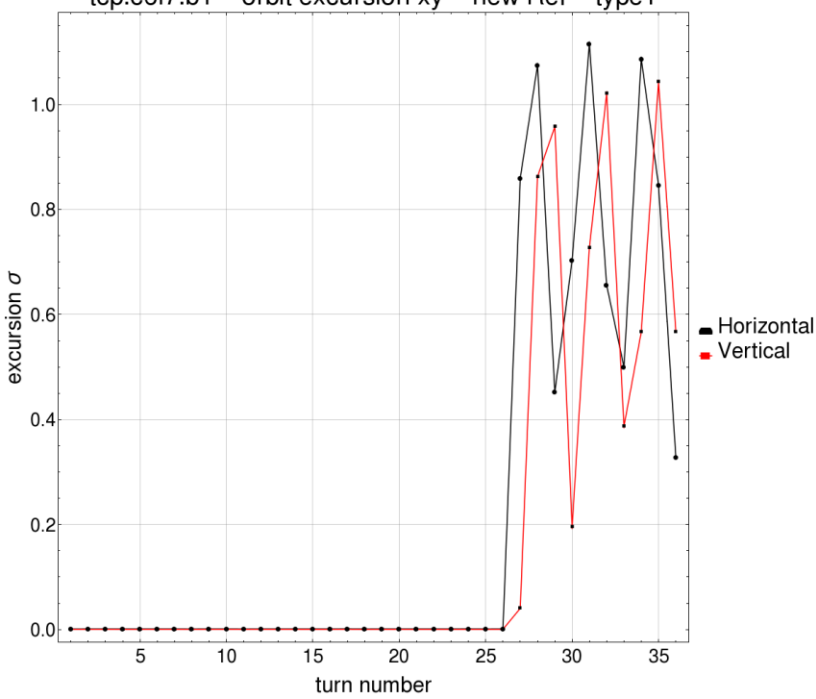
- The losses caused by a CC failure are **strongly phase advance dependent**. It is therefore possible to mitigate these failures by adjusting this parameter (especially for CMS B1).
- Correlated failures exist, such as the missing beam-beam kick due to the dump of the other beam.
- A dedicated **interlock from the CC**, based on field and phase, is necessary and should **request the dump of both beams**, to limit delays to one turn.
- **Other combined failures** such as the quench of two CC due to an UFO are still to be studied.



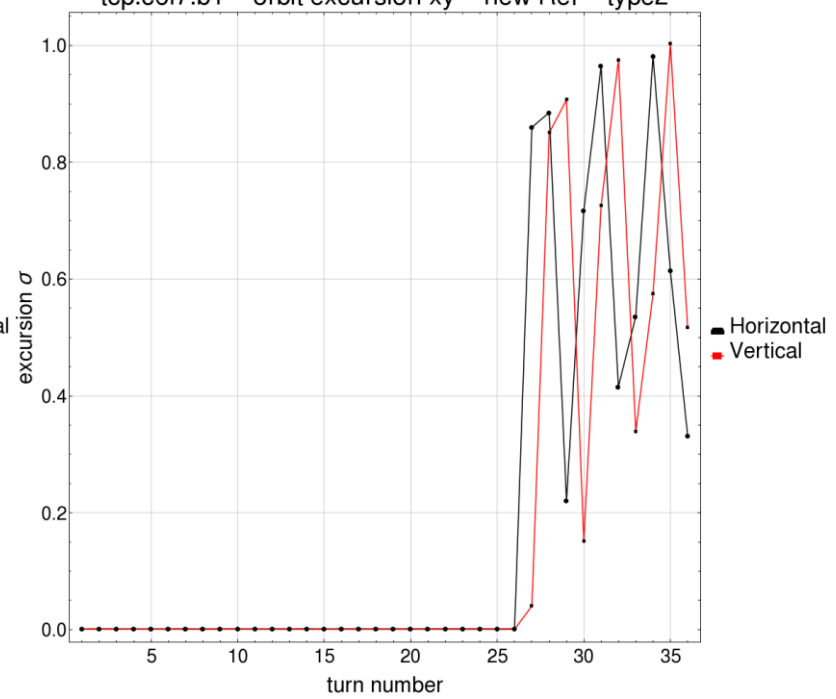
***Thank you for your attention,  
any questions ?***



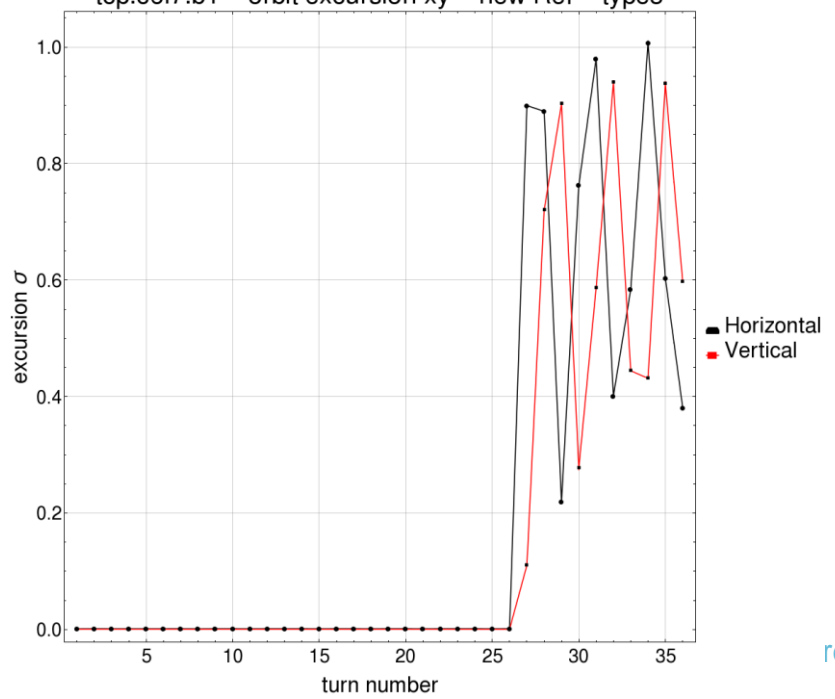
tcp.c6l7.b1 - orbit excursion xy - new Ref - type1



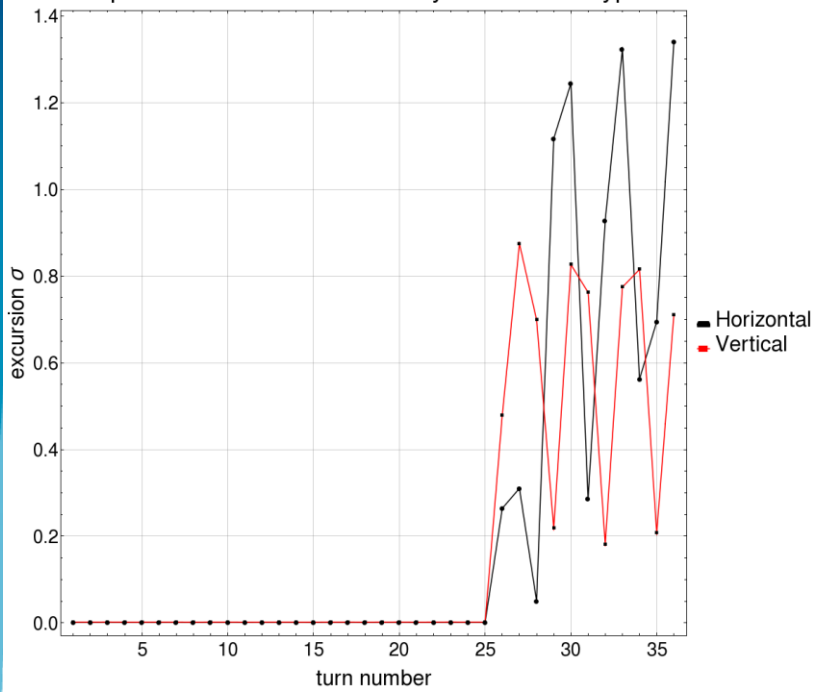
tcp.c6l7.b1 - orbit excursion xy - new Ref - type2



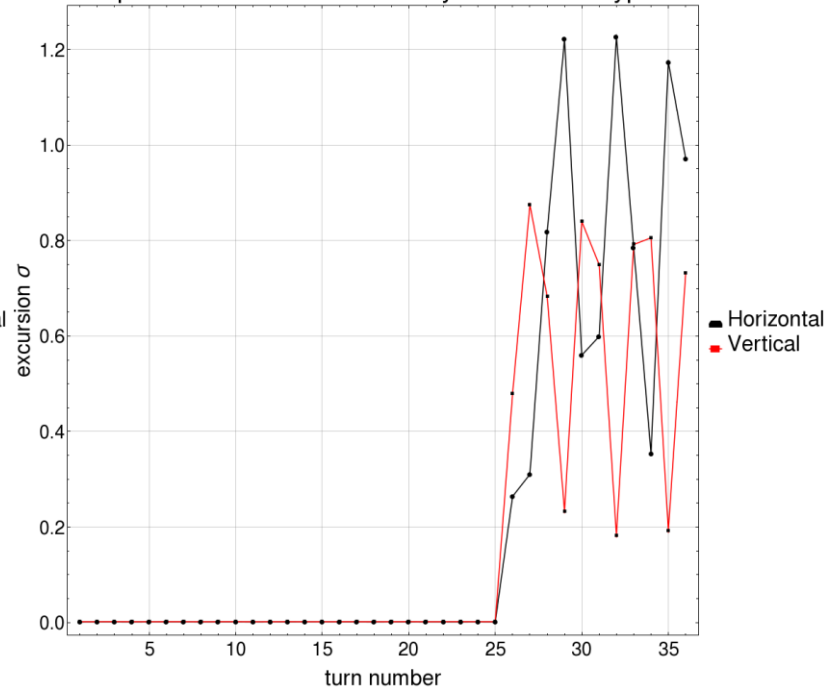
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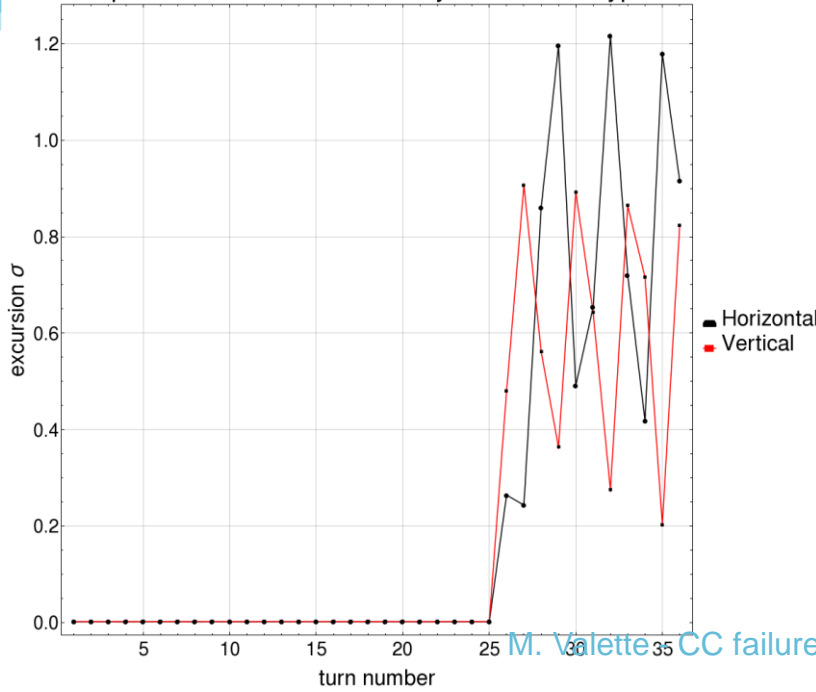
tcp.c6r7.b2 – orbit excursion xy – new Ref – type1



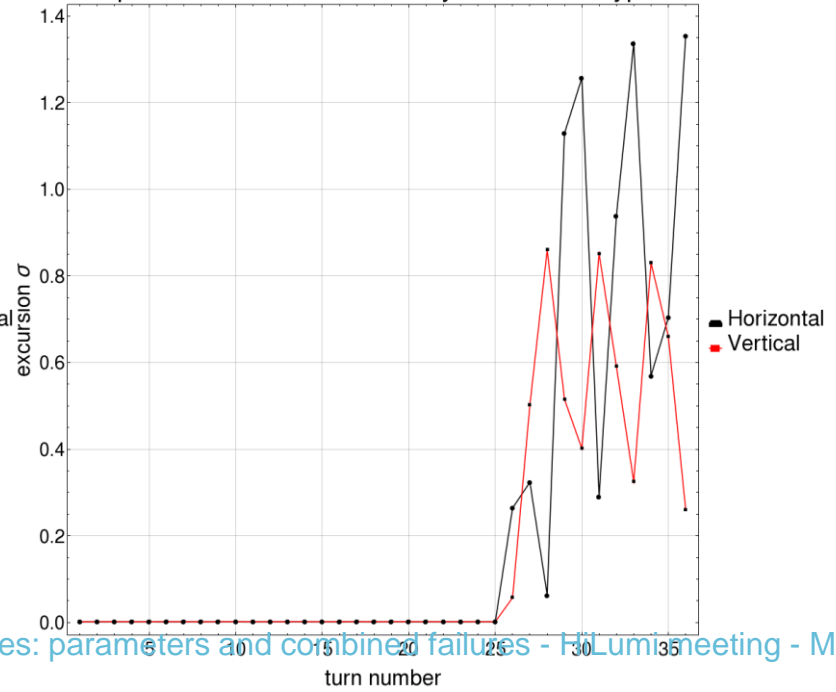
tcp.c6r7.b2 – orbit excursion xy – new Ref – type2



tcp.c6r7.b2 – orbit excursion xy – new Ref – type3

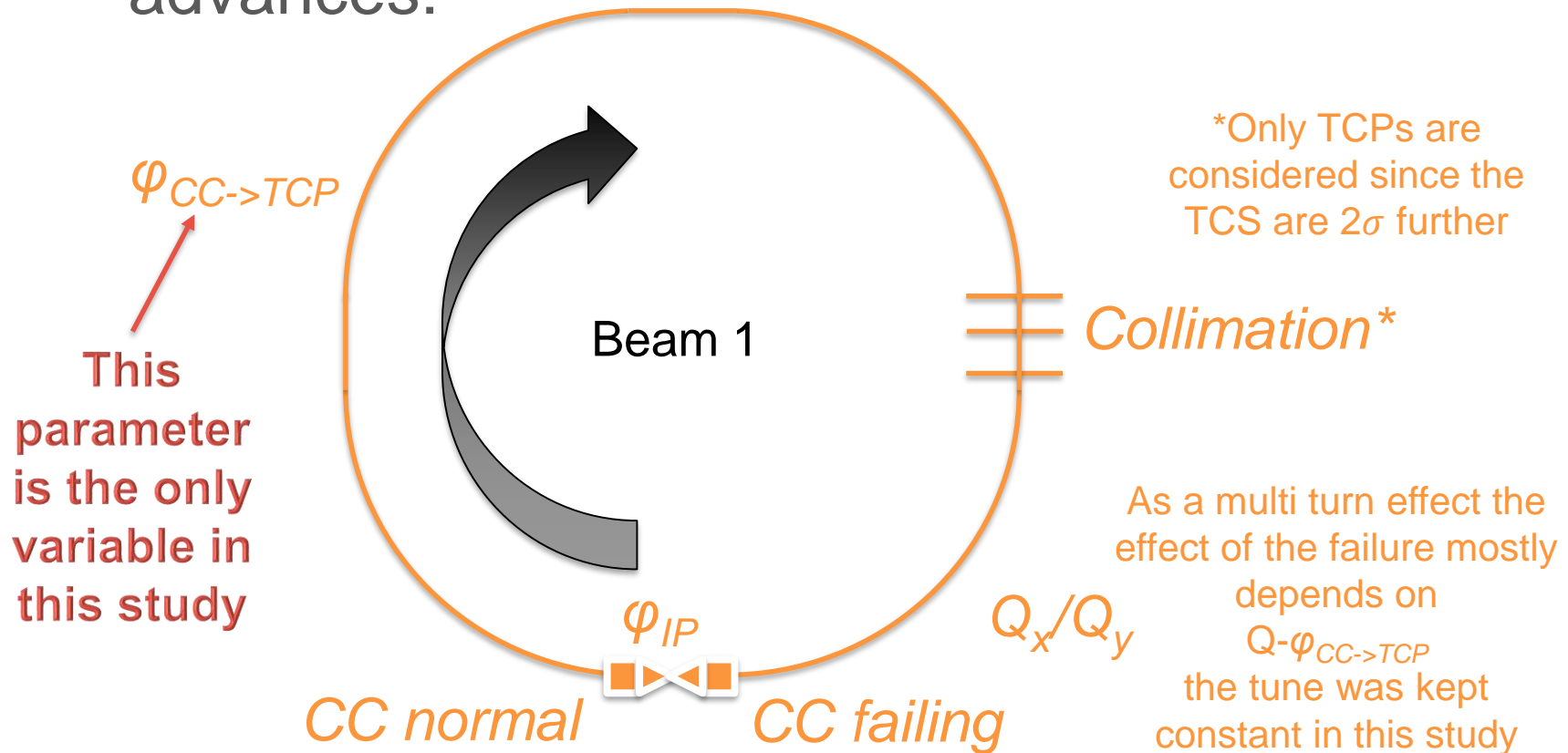


tcp.c6r7.b2 – orbit excursion xy – new Ref – type4



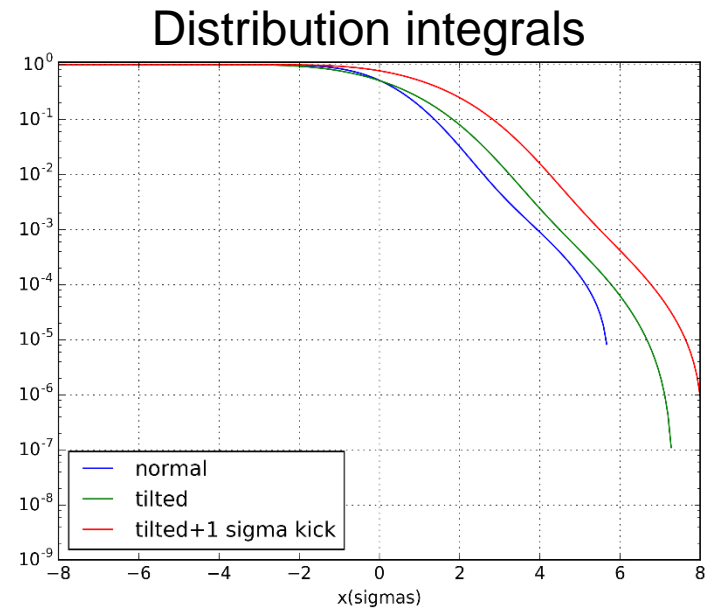
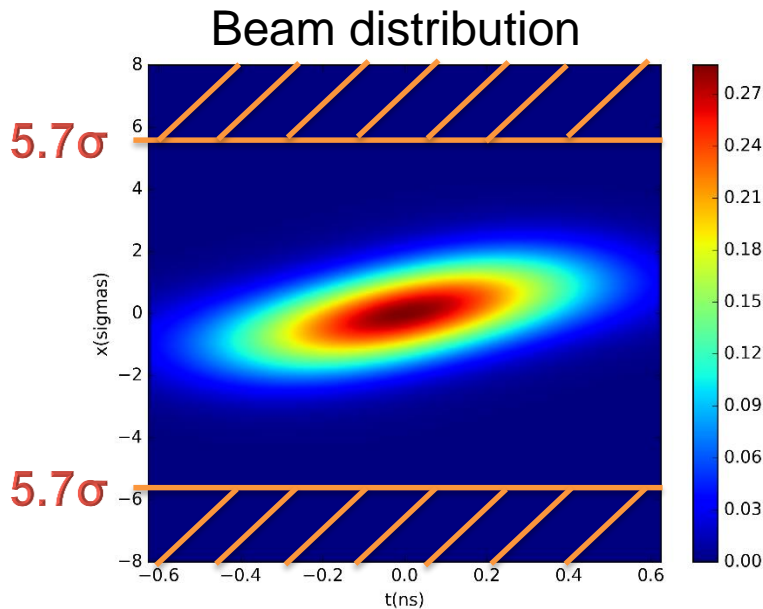
# Model

- The LHC optics are simulated with transfer matrixes, the only input needed are the phases advances:



# Model

- The tilted beam distribution is then reconstructed from the position of these three particles.

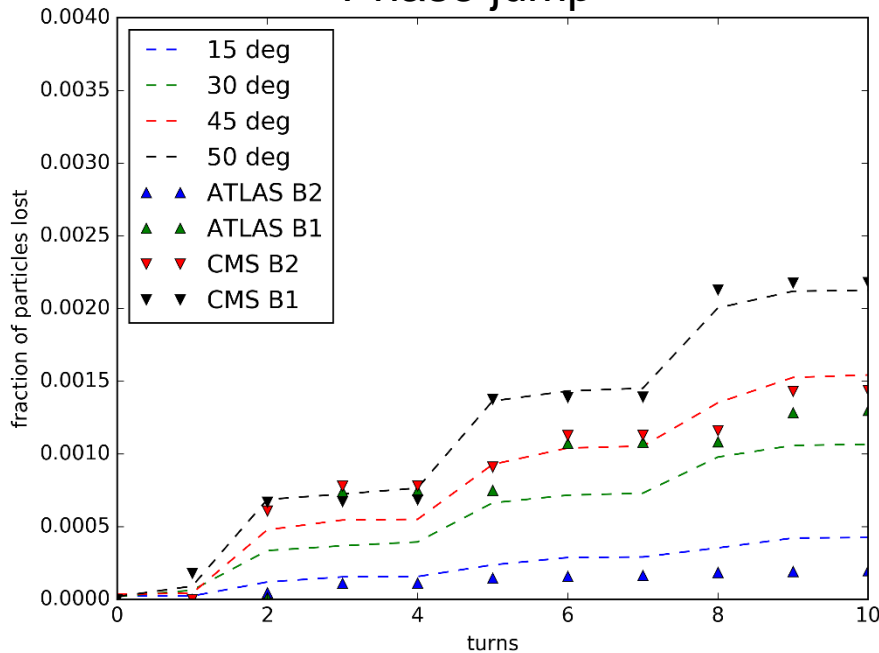


- The distribution is then integrated from the aperture limit, this proportion of the beam is then lost.

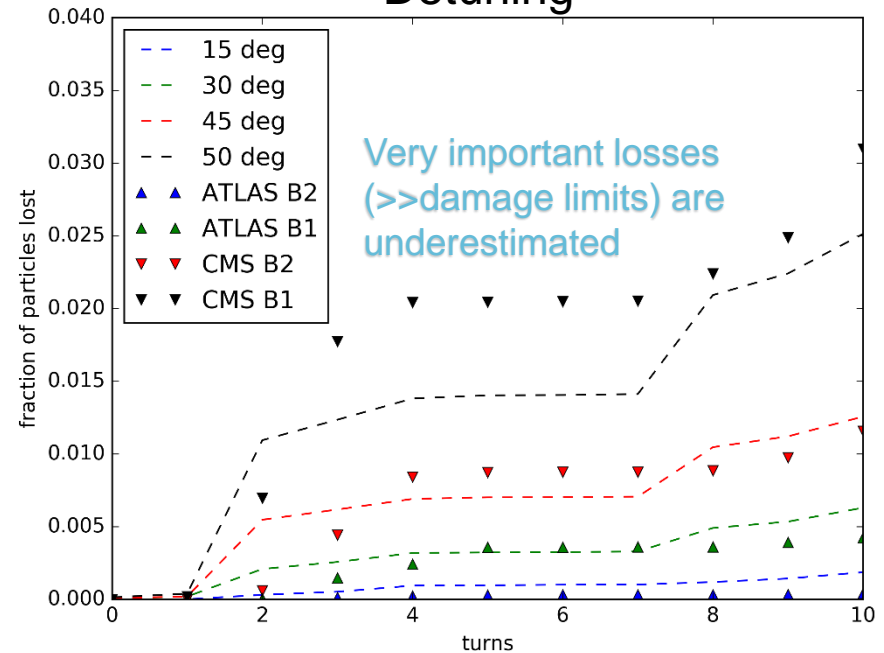
# Results

- The results from these calculations are here compared with SixTrack simulations done for the 4 sets of Crab Cavities (2 IP\*2 Beams) for two reference failure cases:
  - 60 degrees phase jump
  - 60 degrees per turn detuning

### Phase jump



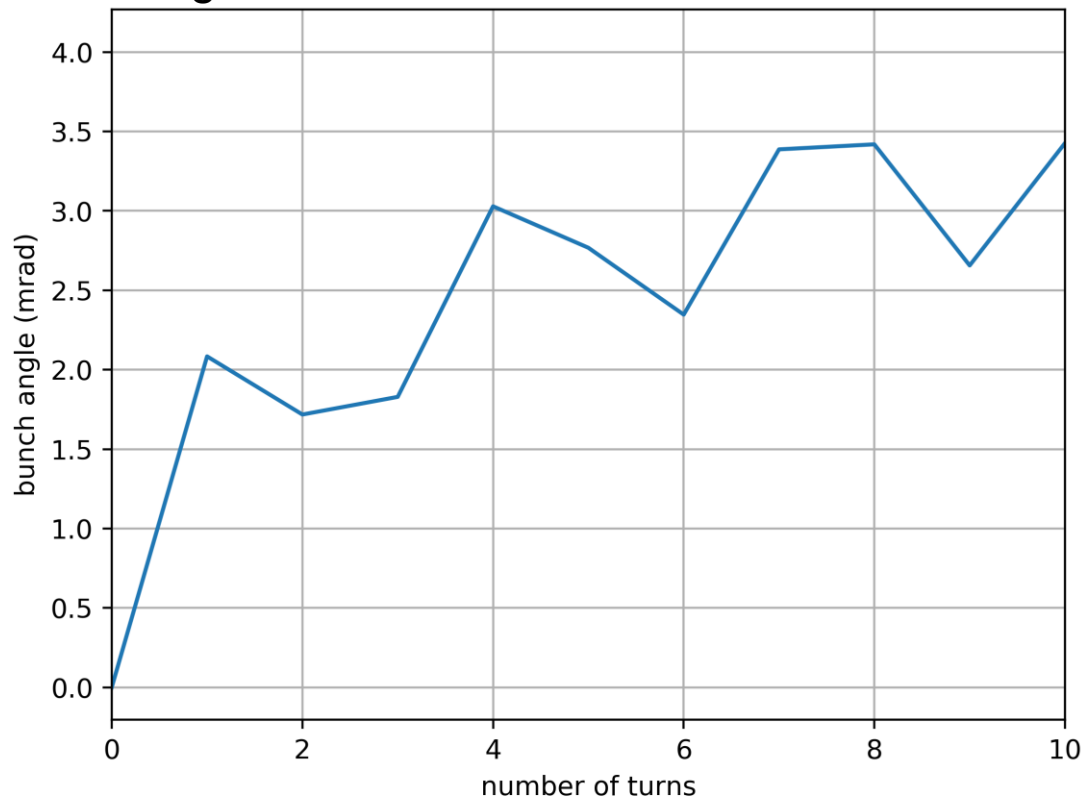
### Detuning



Losses for low phase advances are overestimated (conservative)

Very important losses (>>damage limits) are underestimated

## Crabbing @TCP in the first few turns of a CC failure



## Losses wrt phase advance

