Detection and Analysis of Uncontrolled Beam Loss in the High Luminosity LHC

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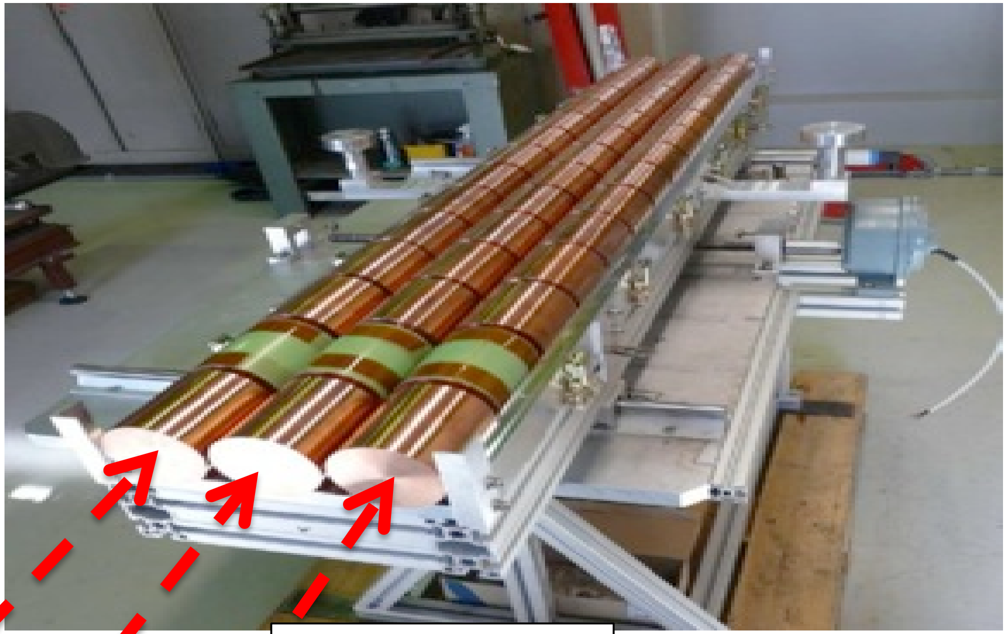
Scope of project

- Study of uncontrolled beam loss scenarios
  - How failure occurs
  - Effect on the beam
  - Subsequent beam losses (intensity, location)
  - Time scales
- Detection of failures
  - How to limit time between detection of failure and beam dump
- Mitigation of or protection against failures
- Simulations *(mainly beam tracking and optics calculations)*
- Experiments *(using very fast diamond beam loss monitors)*
- Also important to protect beam from unnecessary dumps!

Beam induced damage

- SPS beam shot at copper cylinders
- 1.5e11 protons per bunch @ 440 GeV



Target 3
144b
σ = 0.2mm

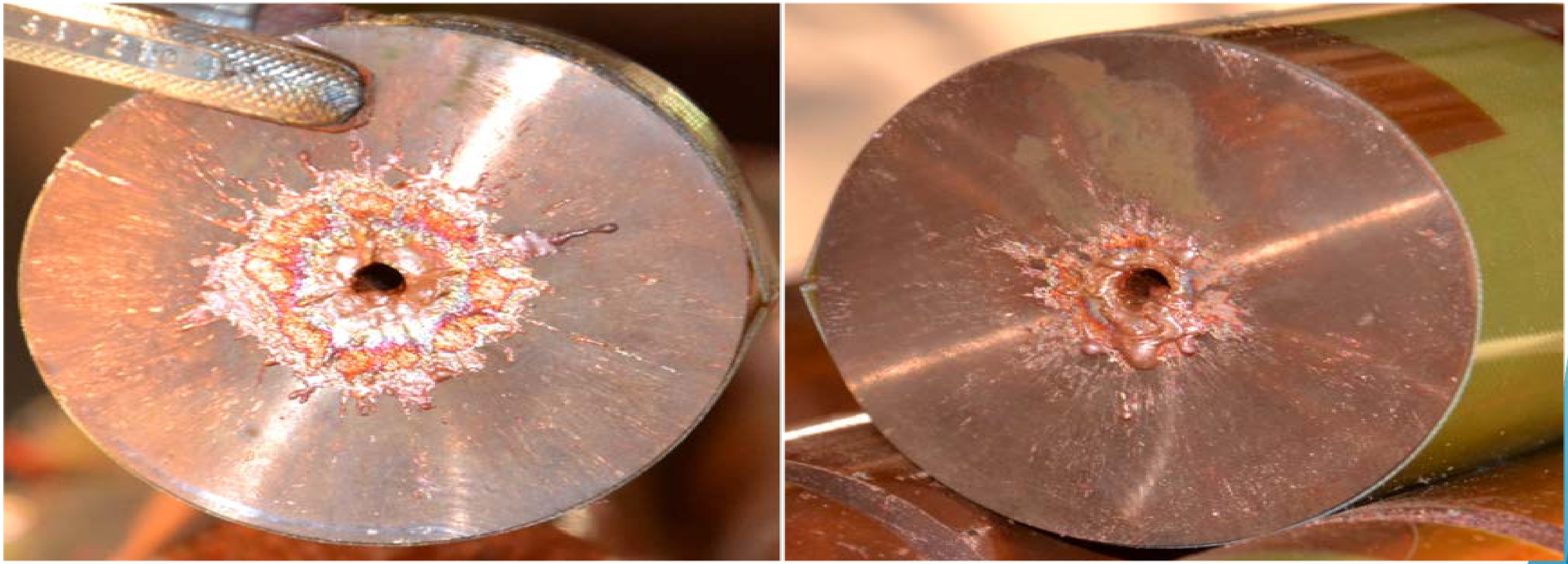
Target 2
108b
σ = 0.2mm

Target 1
144b
σ = 2mm

Courtesy of F.Burkart

Beam induced damage

- 144 bunches of 1.5e11 protons per bunch, 440 GeV



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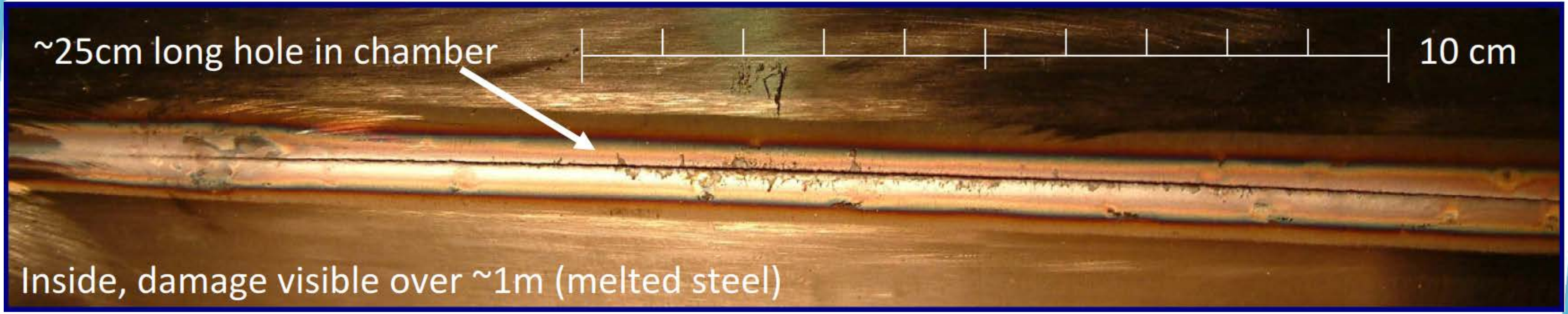
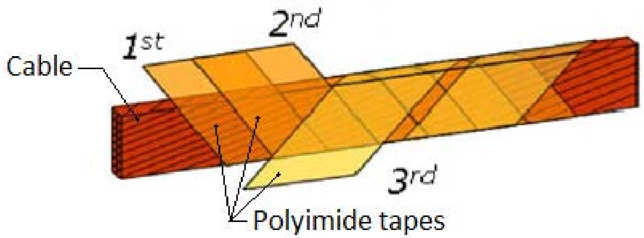
LHC Injection Failure

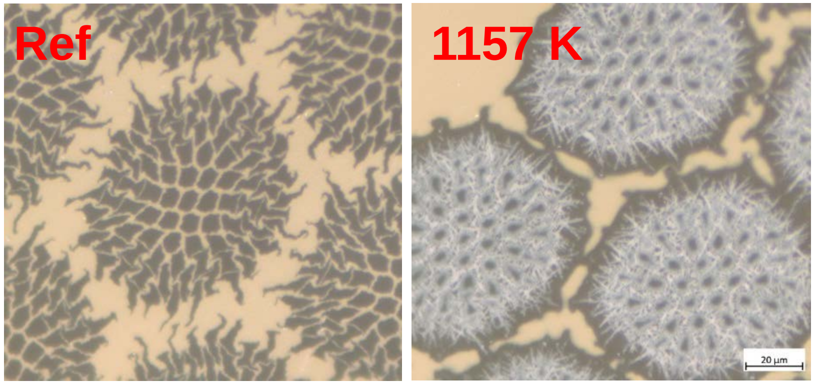
- Before LHC commissioning, SPS beam hit aperture in LHC injection transfer line
- 3.4e13 protons @ 450 GeV
- Required changing chamber and a quadrupole



Magnet damage

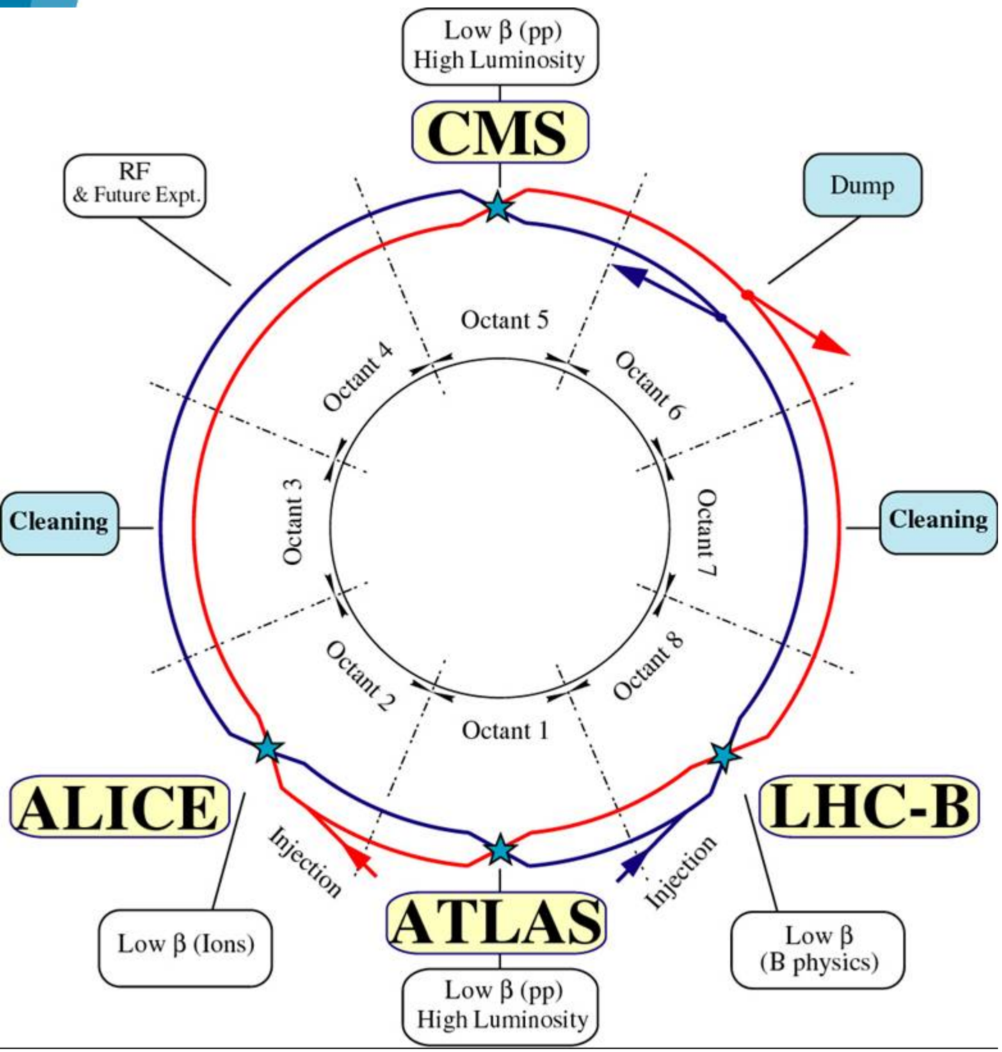
- Decomposition of insulation
  - => short circuit
- Decomposition of superconducting strands
  - => degradation of superconducting properties
- Need replace magnet
  - => min. downtime ~3 months





Courtesy of V.Raginel

LHC overview



- Most of ring – periodic lattice of FODO cells
- Around interaction points, matching section
  - Triplet quadrupoles (Q1,Q2,Q3) – very large beta functions
  - Separation and recombination dipoles (D1 and D2)

High Luminosity LHC (HL-LHC) changes

- To attain higher luminosity, higher bunch intensity and smaller β* (bunch size in collision point)
- Many changes in layout (e.g. Triplet quadrupoles, crab cavities ...)

	LHC	HL-LHC
# bunches	2808	2808
Bunch intensity [protons per bunch]	1.15e11	2.2e11
β* [cm]	55	15
Stored Beam energy (@ 7 TeV) [MJ]	362	693

Failure Classifications

- Slow failures (> 1 s)
  - Cryogenics, failure of orbit/tune feedback...
  - Manual intervention possible
- Fast failures (> 15 ms)
  - Trip of RF system, superconducting circuit/magnet power problem
  - Protection by multiple systems
- Very fast failures(> 3 LHC turns, 270 μs)
  - UFOs (macroparticles entering beam), resistive magnet power problem, transverse damper failure, crab cavity failure
  - Protection by fastest systems
- Ultrafast failures(< 3 turns)
  - Injection/extraction failure, loss of beam-beam kick, quench heaters
  - Protection dump not possible (rely on passive protection)

Accelerator Physics – some basic concepts

- Beta function describes the oscillation of off-center particles, a function of the quadrupoles
  - Beta function is also related to the beam size
- Transverse bunch particle distribution can be modelled as sum of two 2d-Gaussians (beam core + beam halo)
- 1 σ [m] ~ 1 standard deviation/width of distribution
  - $\sigma(s) = \sqrt{\beta(s)\epsilon}$
  - $s : longitudinal\ distance$
  - $\epsilon : emittance, average\ transverse\ spread\ in\ phase\ space$
  - Off-center particles remain at constant radius in phase space
    - Normalized to beam σ – convenient unit
    - Phase must be taken into account for very fast failures

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Collimation system overview

- Smallest aperture bottleneck
- Designed to clean off-center particles
- First elements to intercept the beam for most failures
- Consists of three sets
  - Primary collimators (TCP, ~5.5 σ aperture, ~2 mm)
    - Carbon
    - Diffuses protons
  - Secondary
    - Carbon
    - Shower creation
  - Tertiary
    - Tungsten
    - Absorbs showers
- Orbit excursion of ~3 σ at 7 TeV enough to damage

Damage limits

- Collimator system
  - 288 nominal bunches (one SPS beam) at 450 GeV
  - 8 nominal bunches at 7 TeV
    - ~Half this for HL-LHC
- Magnets
  - Quench limit: ~1e9 protons @ 450 GeV, ~1e7 protons @ 7 TeV
  - Damage limit: 1e12 protons @ 450 GeV, 1.e11 protons @ 7 TeV

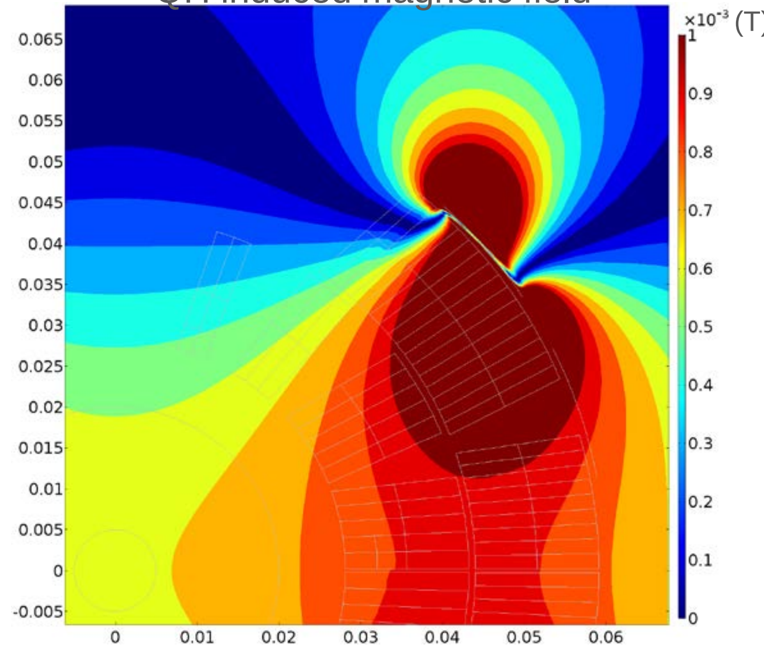
Magnet protection

- When a quench occurs
  - Usually localized
  - Must be spread quickly (~100 ms) to diffuse the resistive current loss throughout the magnet
- Quench heaters: resistive plates attached to magnet (current system)
- A new system for heating whole magnet at once in development – explained further down
- Both types induce magnetic field in beam area
  - Affects the beam!

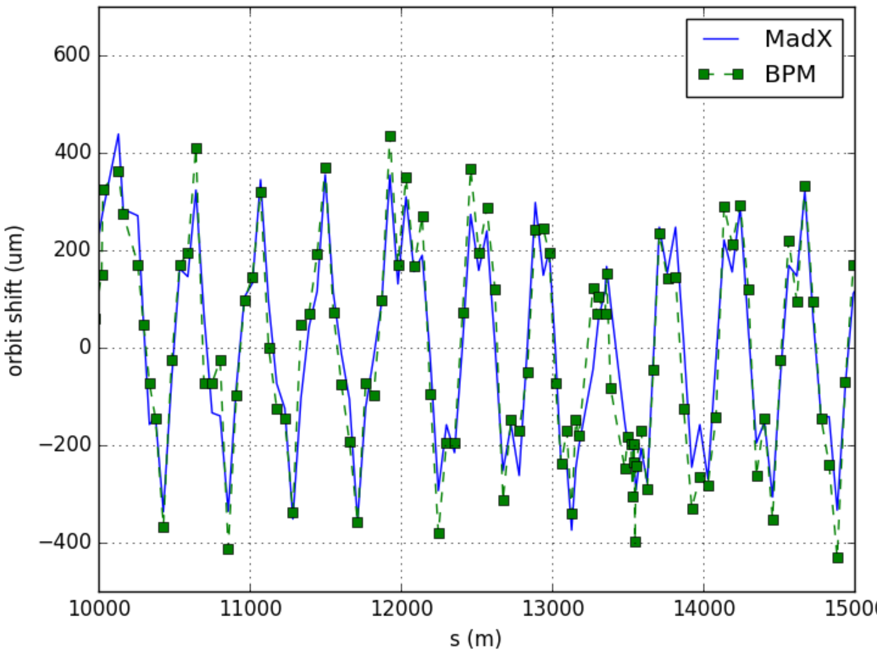
Quench heaters in Dipoles

- From simulations: the QH cause a 0.7 mT field in the beam area
- Associated orbit change: +/- 400 µm, confirmed experimentally
- A delay of up to 3 ms (35 turns) between QH firing and dump
- In HL-LHC triplet quadrupole, up to 52 σ kick
  - **Imperative to dump first**

QH induced magnetic field

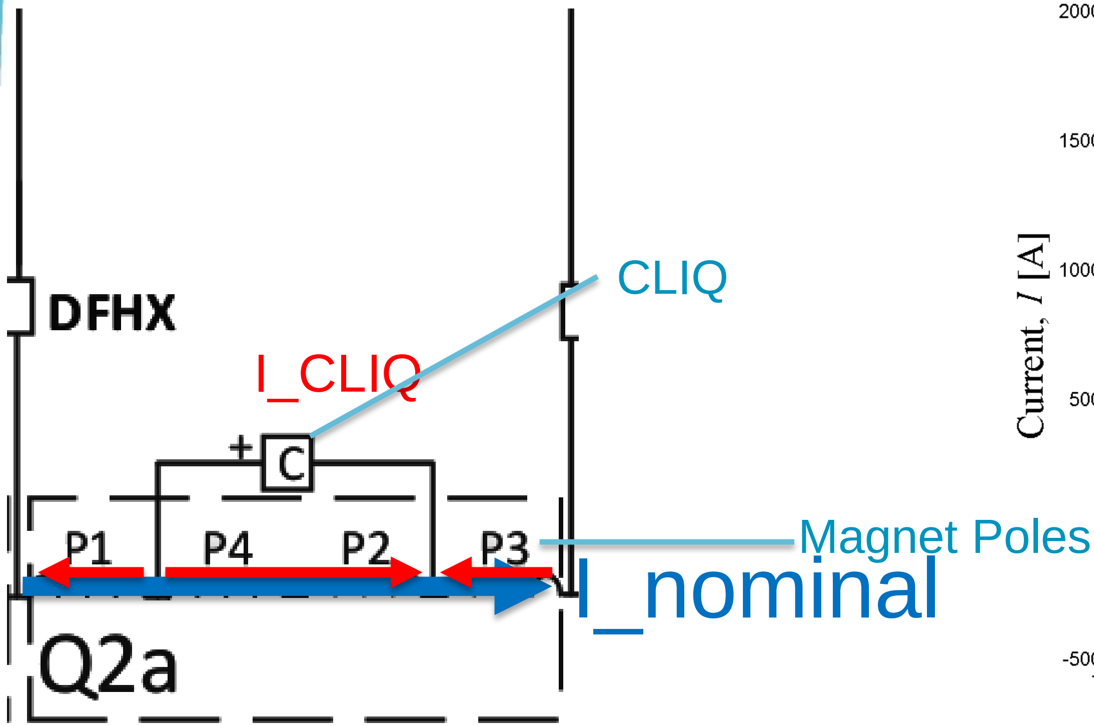


Measured and simulated orbit change

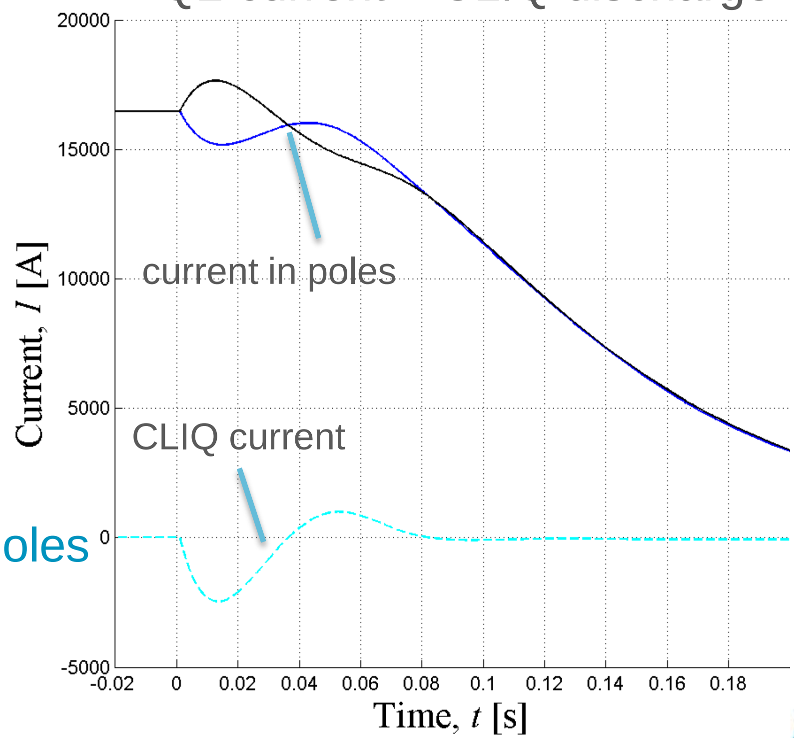


CLIQ – Coupling Loss Induced Quench

- CLIQ – a new type of quench protection system
- Capacitor discharges current in magnet circuit
- 2 kA of current going into the magnet coils – imperative to study its criticality
- Poles P3 and P1 see lower current
- Poles P4 and P2 see higher current
- Heat is deposited in the copper matrix via inter-filament and inter-strand coupling losses, causing a quench



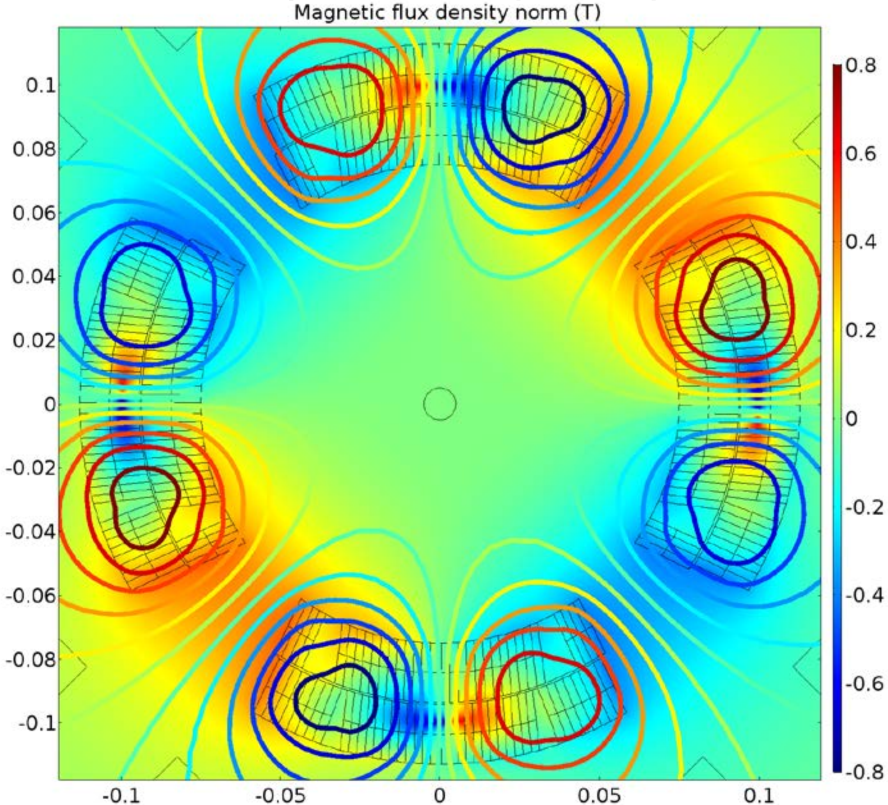
Q2 current – CLIQ discharge



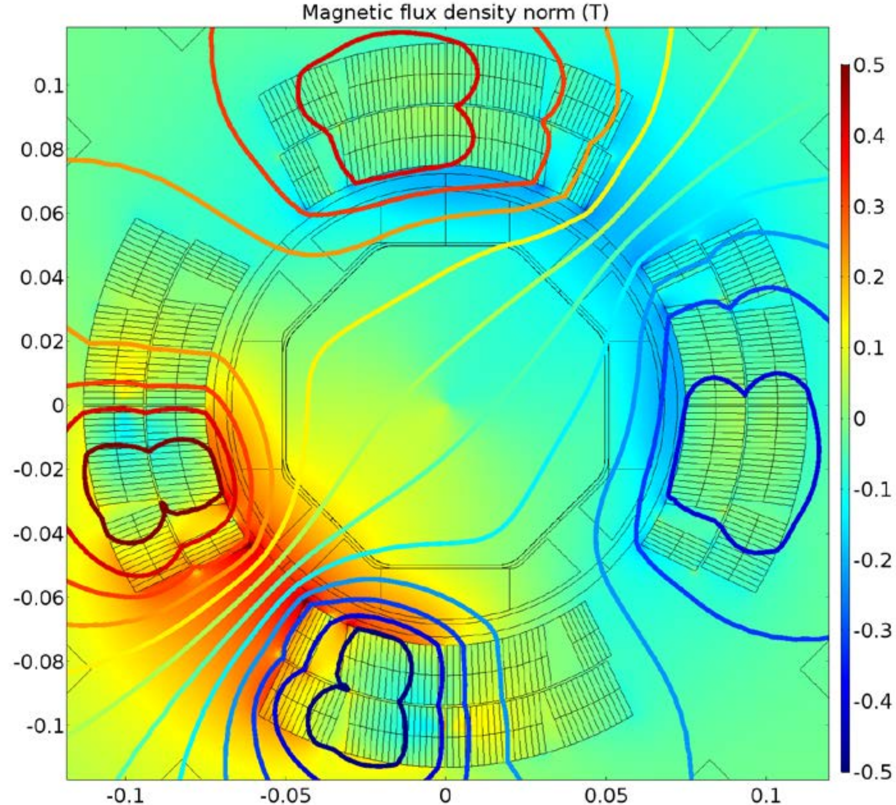
CLIQ in Triplet (Q2 and Q3)

- Differences in connection, different magnetic fields.
- Q1 electrically same as Q3
- From optics, Q3 has larger beta function, and is thus more critical
- **Q2**: **Symmetric** discharge -> **Quadrupolar** field -> **beta beating**
- **Q1/Q3**: **Asymmetric** discharge -> **Skew dipolar** field -> **orbit excursion**

Q2, peak field (12 ms)

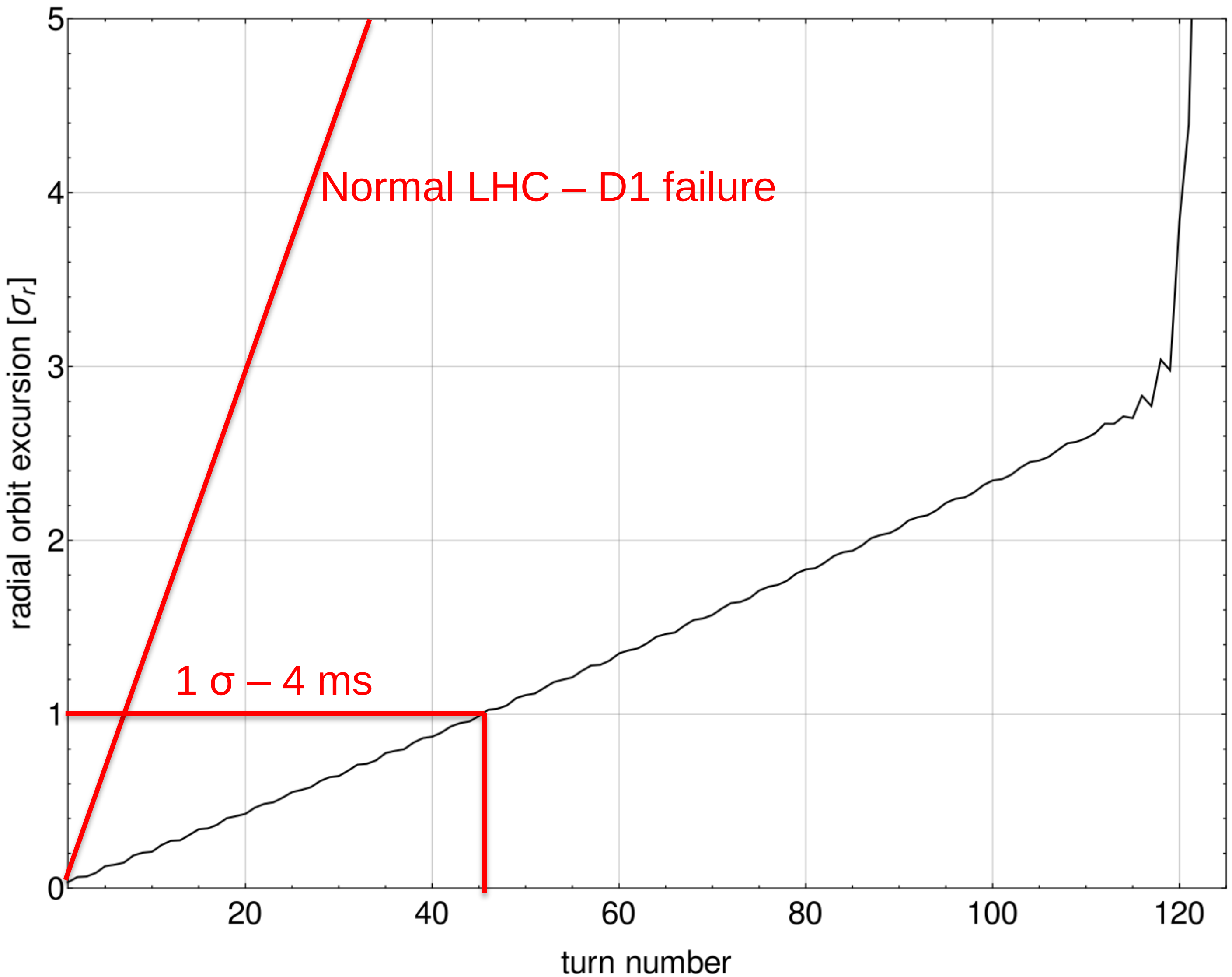


Q3, peak field (20 ms)



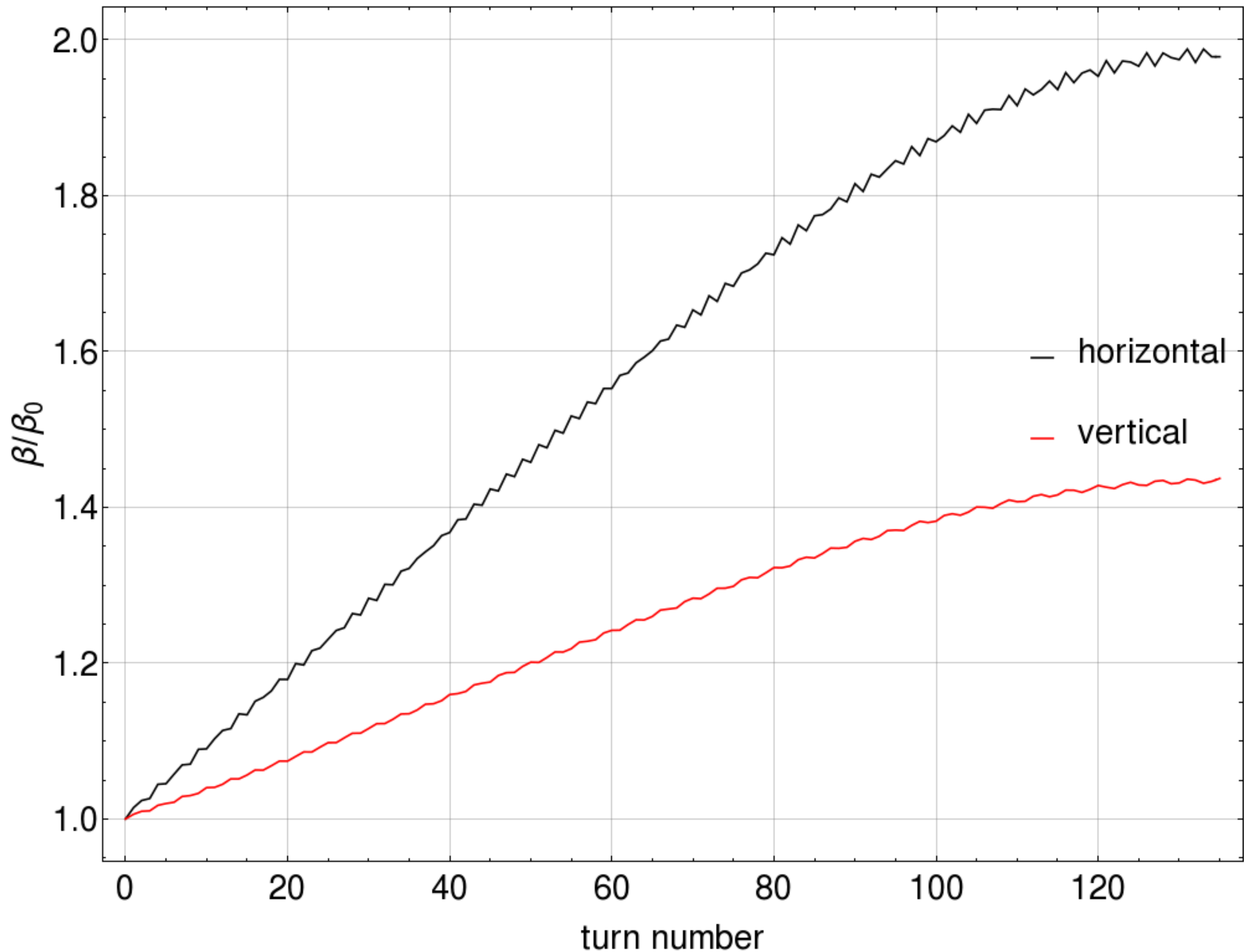
Q3 – orbit excursion

- Beam lost shortly after LHC turn 100



Q2 – Beta Beating

- Beta beating of up to 100 % at the TCPs
- Beam size changes -> losses at TCPs



Crab Cavities

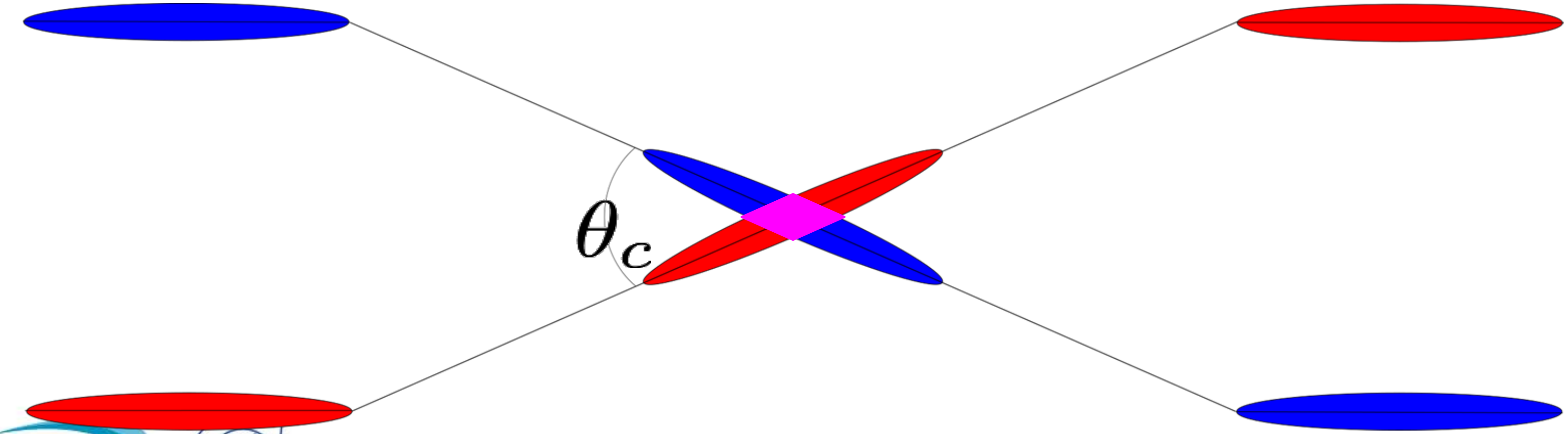
- In HiLumi LHC, due to smaller β* and to limit beam-beam effects the crossing angle will be increased
- → Lower luminosity:

$$L = \frac{n_b f_{rev} N_p^2}{4\pi \sigma_x^* \sigma_y^*} * F(\theta_c)$$

Geometric Factor

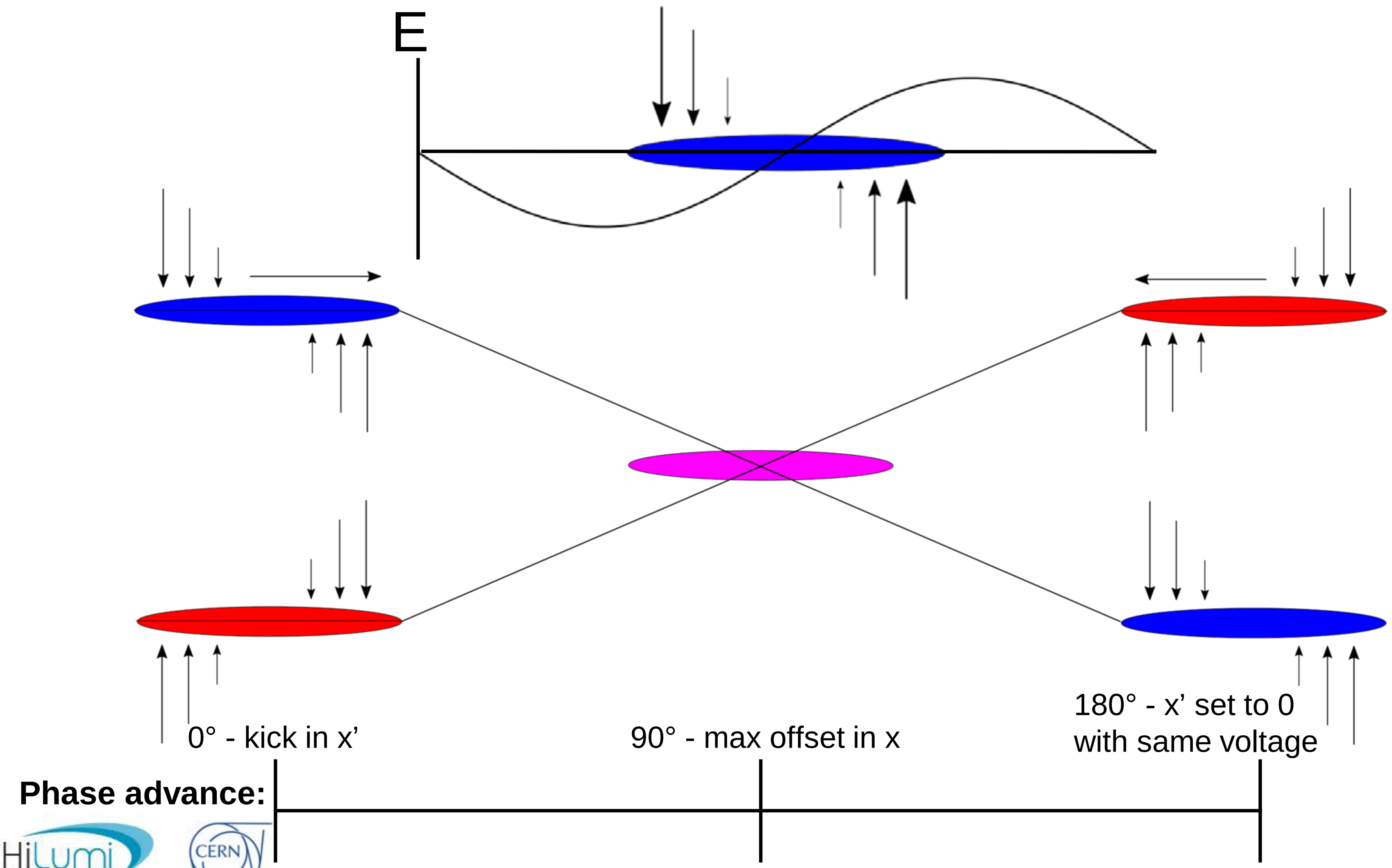
Piwinski Reduction (Geometric) Factor

	2012 LHC	2015 LHC	HL-LHC
$\theta_c[\mu rad]$	313	290	590
$F(\theta_c)$	0.88	0.85	0.31



Crab Cavities

- Cavity with sinusoidal transverse kick - bunch is tilted - better overlap at crossing point

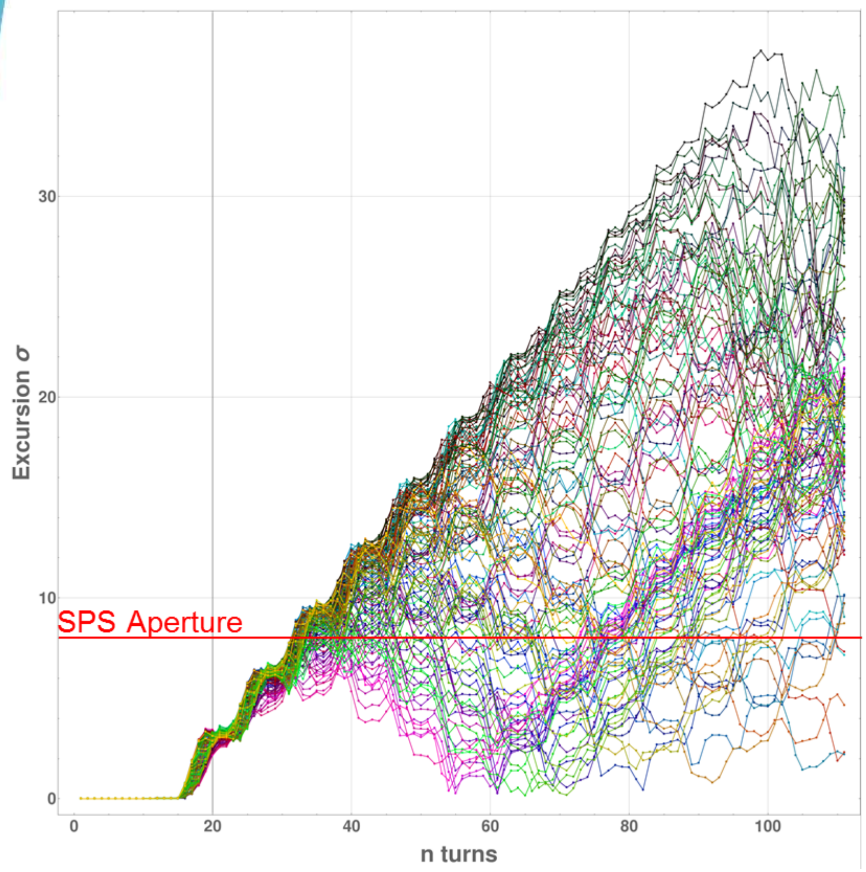


Crab Cavities – failure modes

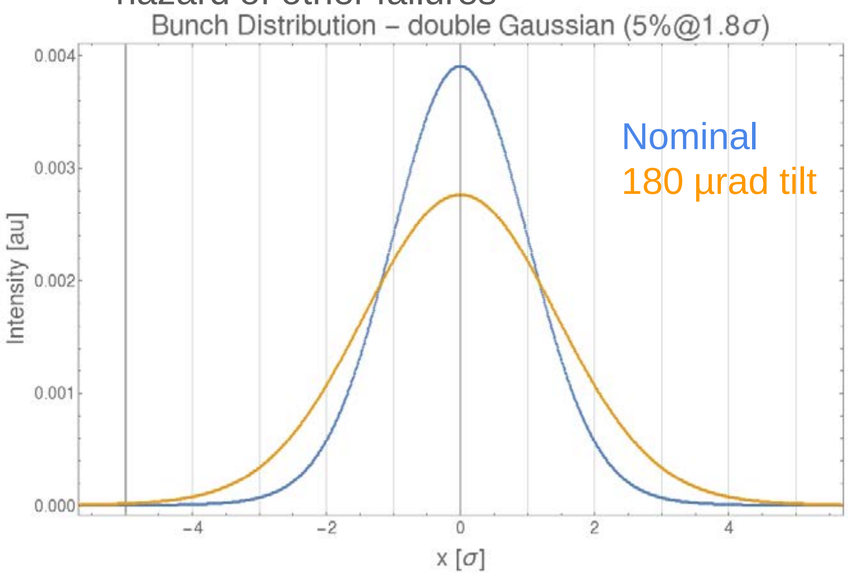
- Voltage drop (~4 LHC turns)
  - Residual crabbing outside Interaction Point large
- Phase change (must be driven by the RF control)
  - Kicks beam core out of orbit
- Quench (combination of the above)

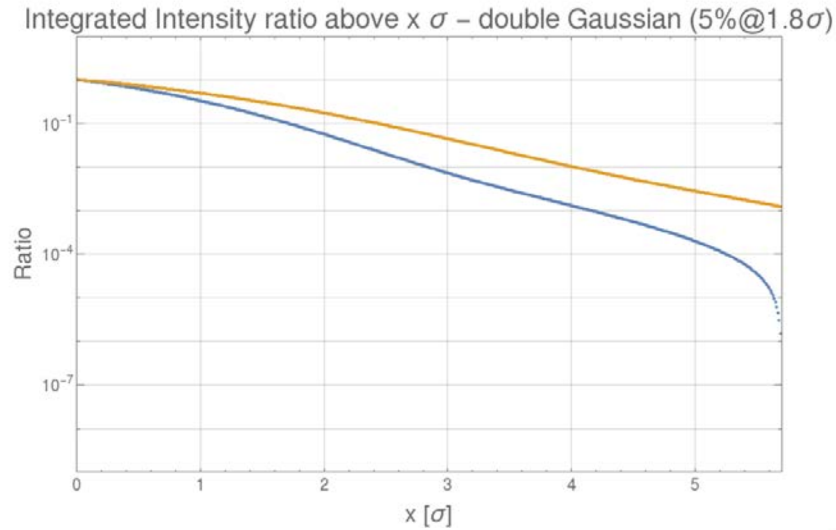
Consequences of CC failure

- Phase shift causes beam core to be transversally kicked - can give fast beam loss



- If crabbing not compensated (e.g. voltage drop), transverse beam distribution wider - increases hazard of other failures





Combined failures – beam beam effect

- The two beams interact with each other electromagnetically in crossing points
  - Transverse kick (orbit change, main issue)
  - Emittance growth
  - Tune spread
  - ...
- Dumping one beam gives sudden loss of beam-beam kick
- After a given failure, beams will always be dumped
  - -> this type of combined failure must thus always be considered

Current work...

- Experiment on Thursday
  - Studying UFO dynamics using diamond beam loss monitors
- Two IPAC papers *(preliminary titles)*
  - Results of UFO dynamics studies with beam in the LHC
  - Crab cavity failures combined with loss of beam-beam effect in the HL-LHC
- Article on ”Fast failures in the LHC and HL-LHC”
  - First draft by end of this year...

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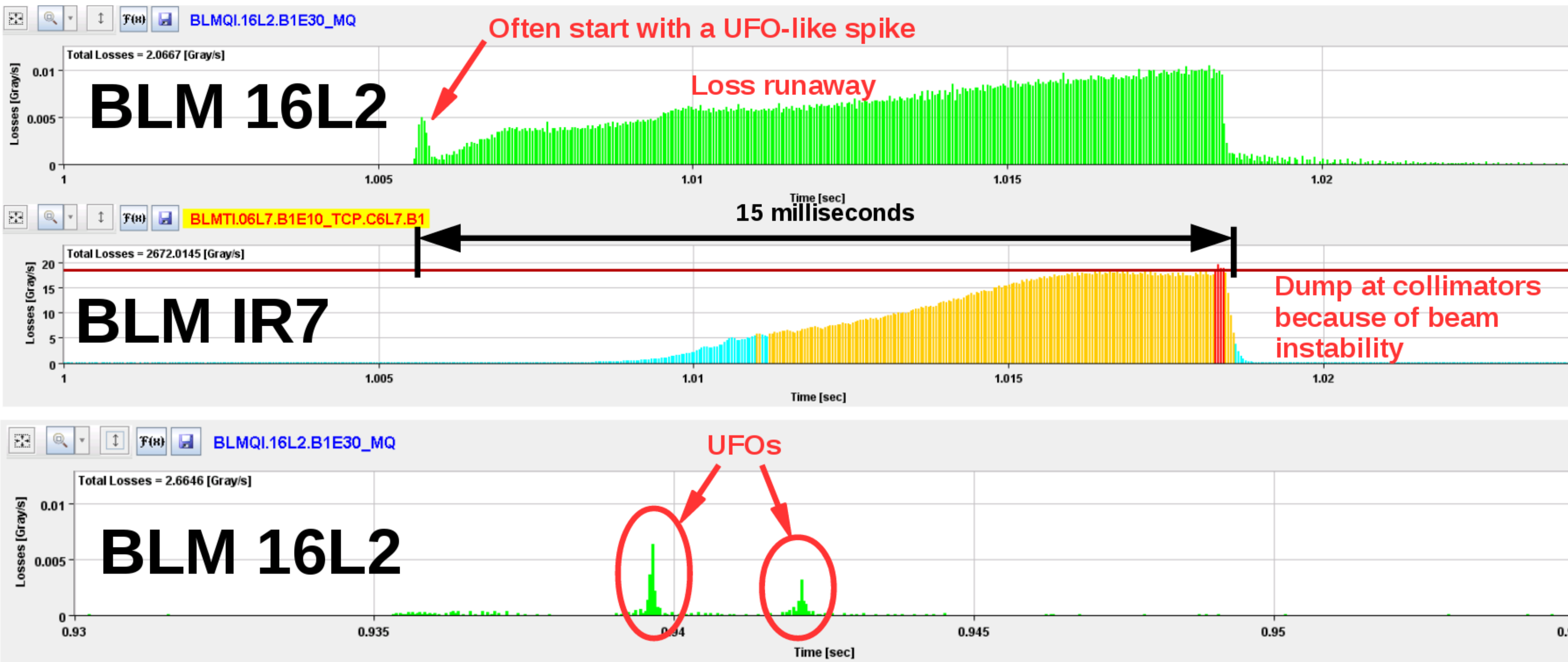
Thank you!

Introduction

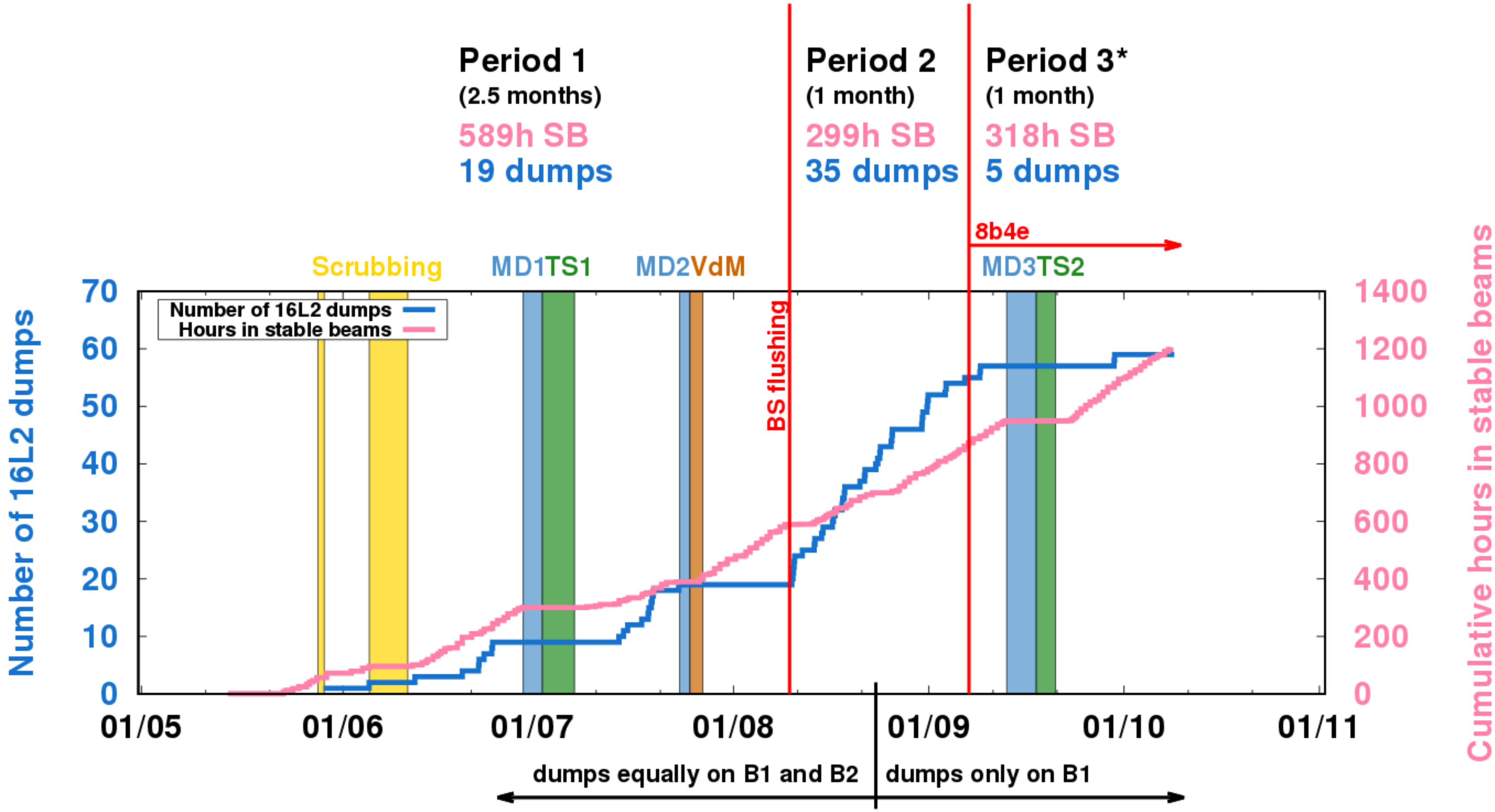
- 16L2 refers to loss events in an interconnection in LHC sector 16L2
- Three types:
  - Steady state losses (**resolved**)
  - UFO-like losses causing beam instability (fast loss rise, beam dump, quench)
  - UFO-like losses not causing instabilities (do not dump)



Courtesy of A.Lechner

Introduction

- 61 dumps since May until 25th Oct *(7 more until 28th Nov)*
  - 294 dumps due to faults, 64 due to beam losses (incl 16L2)



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Observables and Goals

- **Hypothesis:**
  - Solid macro-particle enters beam -> gives UFO-like losses
  - Macro-particle evaporates -> charged particle cloud -> beam instability -> losses in TCPs

- Local dBLM: direct losses from 16L2 interaction (relatively low signal)
- IR7 dBLM: losses due to build-up of instabilities

- From local data, study the UFO dynamics
  - Bunch blow-up in H or V
  - Displacement of bunches in H,V or diagonally
    - -> Tells us which direction the UFO is coming from (see MD on UFO dynamics with wirescanner)

- From IR7 data, study how the instability develops

- Fastest losses observed in the LHC

16L2 Machine Development test (MD)

- Unique opportunity with UFOs on demand
  - High bunch intensity, many bunches and high energy seems to trigger them
- Foreseen to conduct MD before end of this run
  - Various combinations of blown up and displaced bunches
  - -> study UFO dynamics as shown by previous MD2036 using wirescanner
  - -> understand 16L2 in case it reoccurs

- Challenges for dBLM part:
  - Optimize signal
  - Use many bunches with set properties for better statistics
    - How many bunches required will be an outcome of current analysis
      - From understanding the histogram
    - How to combine signals from the different bunches to draw conclusions
      - Increasing statistics without destroying relevant data

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