Crab-Cavity Failures, LHC

J. Barranco, R. Tomas, B. Yee, F. Zimmermann
T. Baer, J. Wenninger
P. Baudrenghien, R. Calaga, E. Ciapala, E. Jensen, J. Tuckmantel
MPP Meeting, April 13, 2011, CERN

Layout & failure mechanisms review

Tracking tools & studies

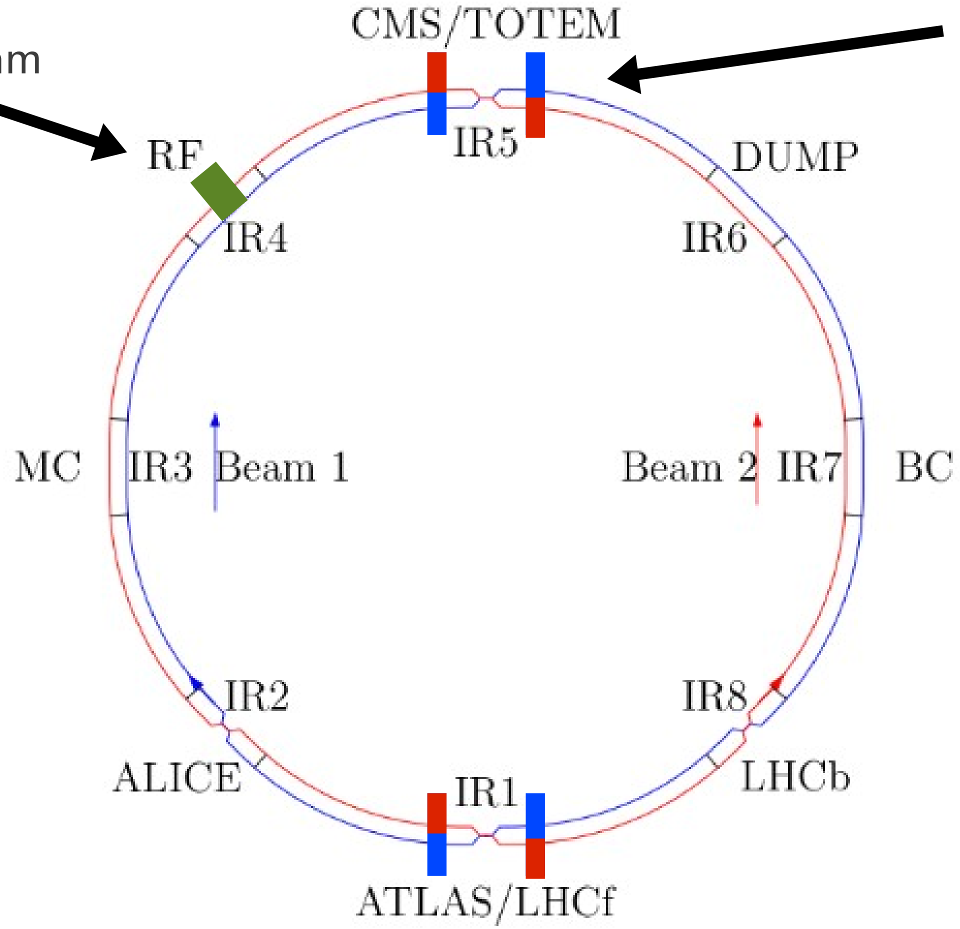
Comments on future studies

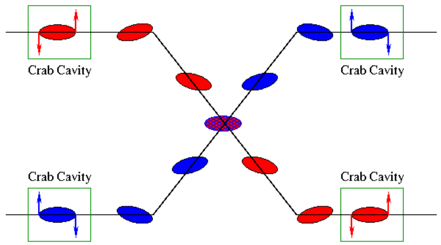
Ack: Collimation team for their input

Layout

Single test module /beam
@IR4, Global Scheme

BASELINE
4 modules per beam
@IR5 & IR1, Local Scheme





** For this study ONLY nominal LHC optics is considered
See T. Baer's talk for upgrade optics

Basic Parameters

Voltage = 3 MV/cavity (2-3 cavites /module)

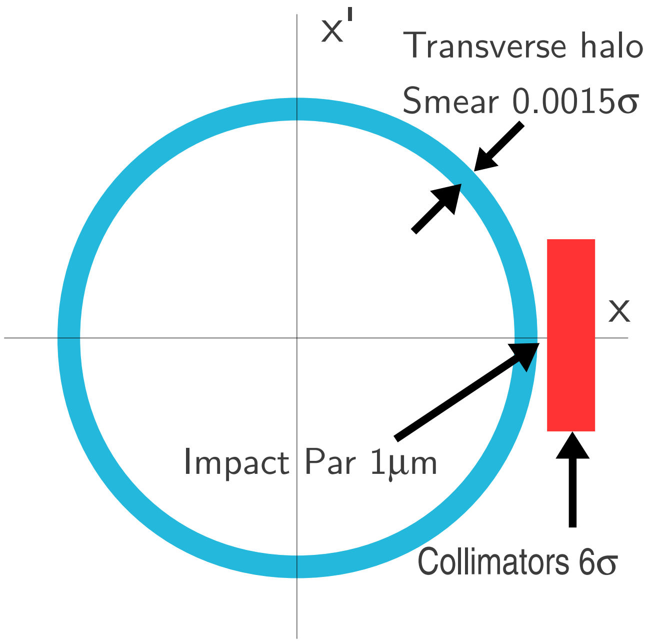
Frequency = 400 MHz (800 MHz not excluded)

Qext = 10^6, R/Q ~300 Ω

Cavity tuning/detuning ~ 3 kHz

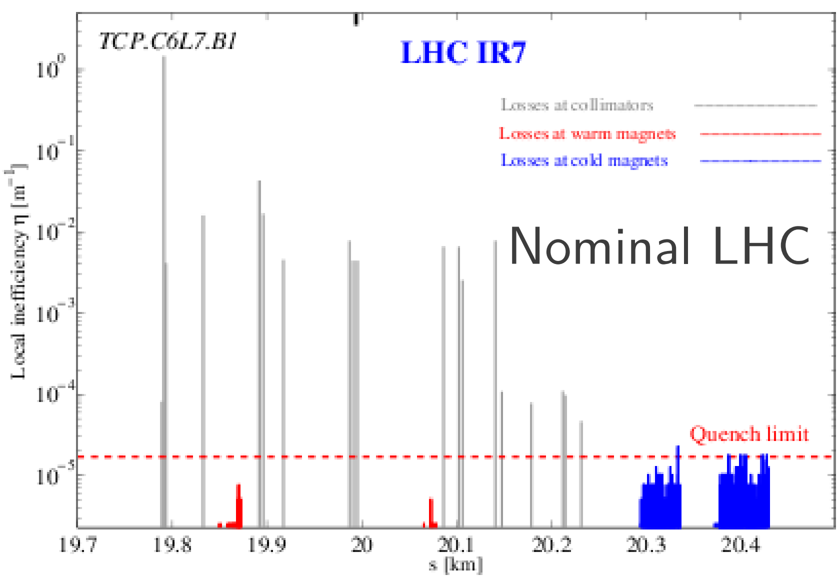
RF power source = 60 kW (< 18 kW nominal for zero orbit)

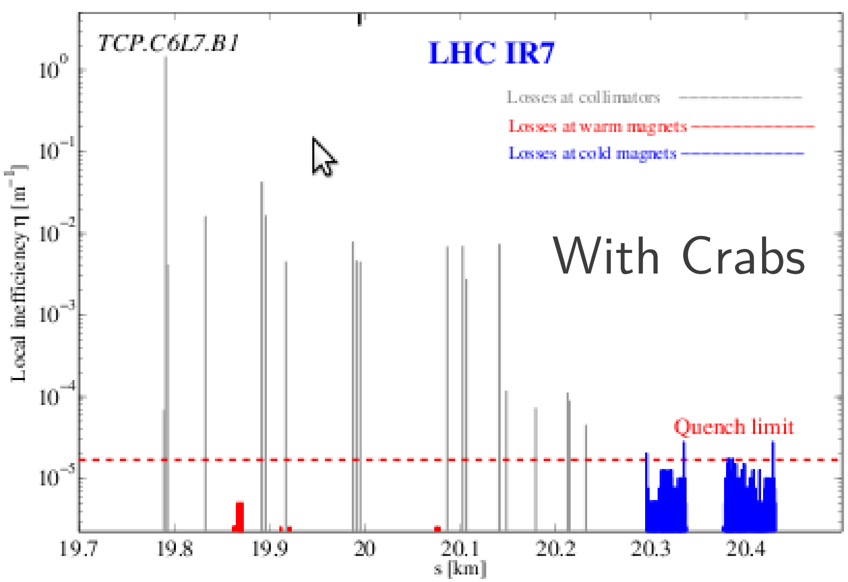
Global Steady State (2010 studies)



- Loss maps with crabs similar to w/o crabs
  - Additional 0.5σ aperture
  - Hierarchy preserved (primary, secondary, tertiary)
- Maximum DA decrease $\sim 1\sigma$ (13σ nominal)
  - Suppression of synchro-betatron resonances

Y. Sun et al. PRST-AB 12, 101002 (2009)





Machine Protection, 350 MJ !!

J. Wenniger (LHC-CC10)

100's of interlock systems → complex

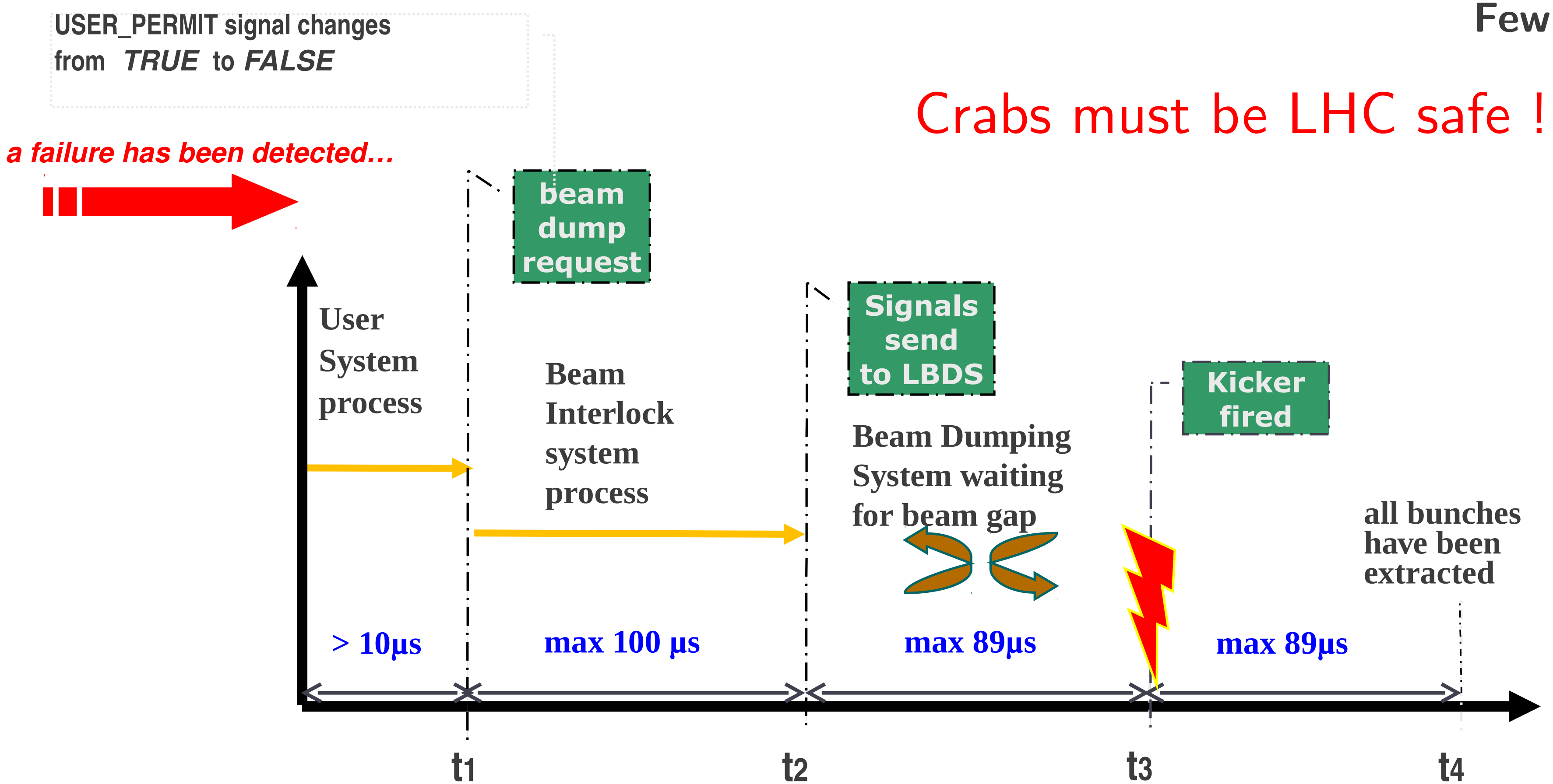
Best/worst case scenario:

Detection - 40µs (½ turn), response - 3 turns

Quench limit

Few mJ

Crabs must be LHC safe !!



Potential Failure Scenarios

Some info: J. Tuckmantel

Some "slow" failures

- Power supply trips (50-300 Hz > millisec) $\rightarrow$ > 300 turns
- RF arcing (few µs) $\rightarrow$ Response of cavity τ_F (millisec)
- Operator mistake $\rightarrow$ Response of cavity τ_F (millsec)
- Mechanical changes $\rightarrow$ high Q SC cavity (100's of ms)

$$\tau_F = 2Q_{ext}/\omega$$

Fast failures

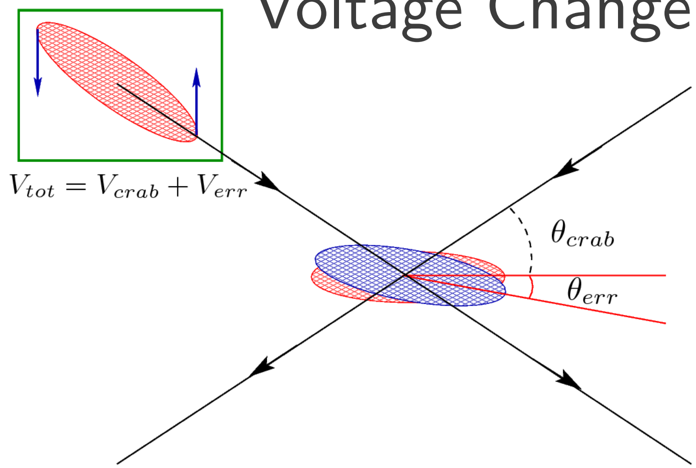
- Cavity quench or RF breakdown
- Sudden discharge in the cavity or couplers
- Fast orbit changes (due to what?)

LHC Collimation, maximum allowed losses (R. Assmann, HB2010):

- Slow: 0.1% of beam per second for 10s
- Transient: 5×10^{-5} in ~ 1ms
- Fast: Upto 1 MJ in 200ns into 0.2mm^2

Crab Cavity Failures

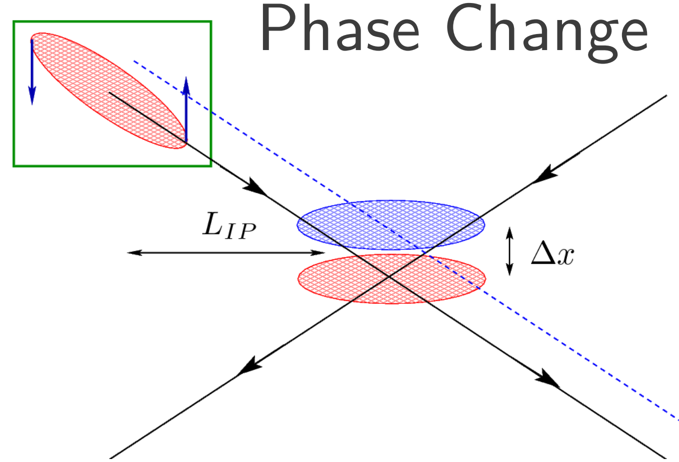
Voltage Change



Change in crossing angle

Over -or- under compensation

Phase Change



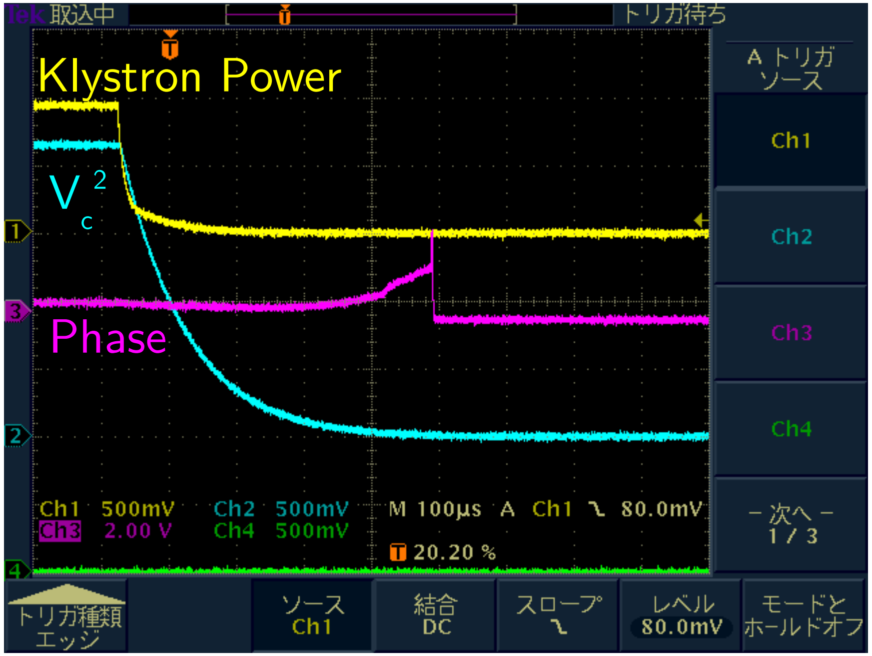
Offset at the collision point

Change in closed orbit

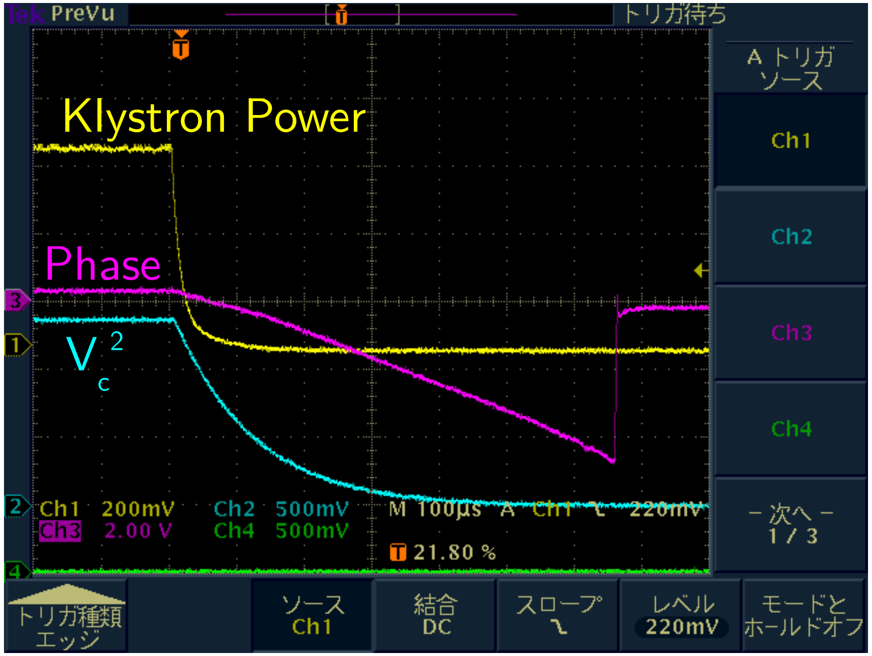
KEKB: RF Off (No Beam)

K. Nakanishi et al., LHC-CC10

HER Ring



LER Ring

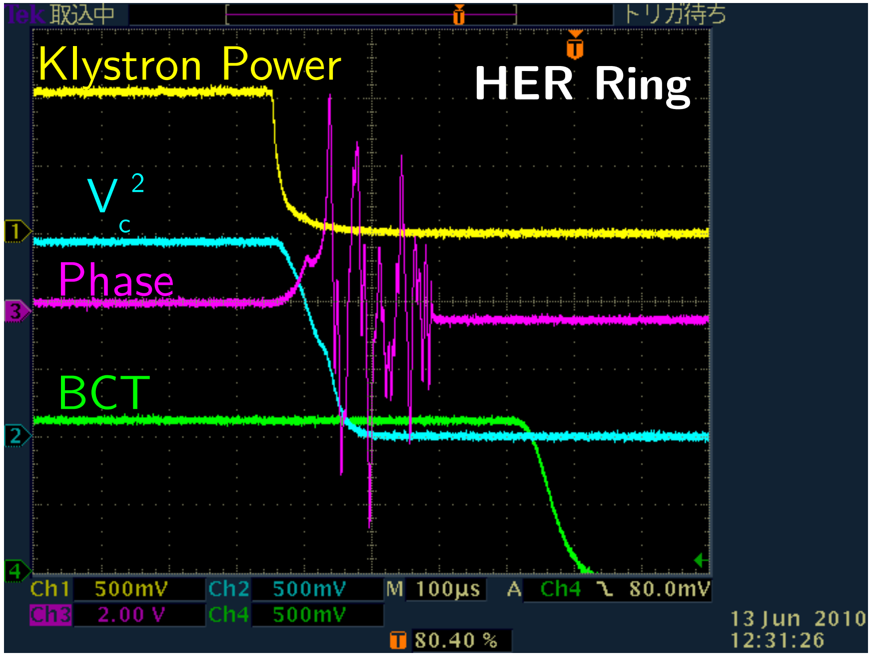


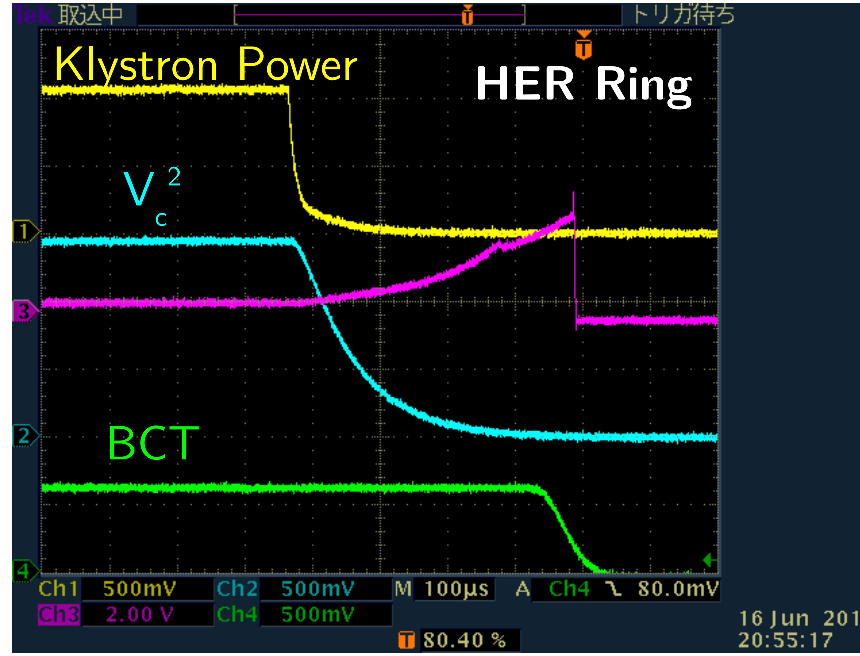
Mainly gradual changes in phase is observed

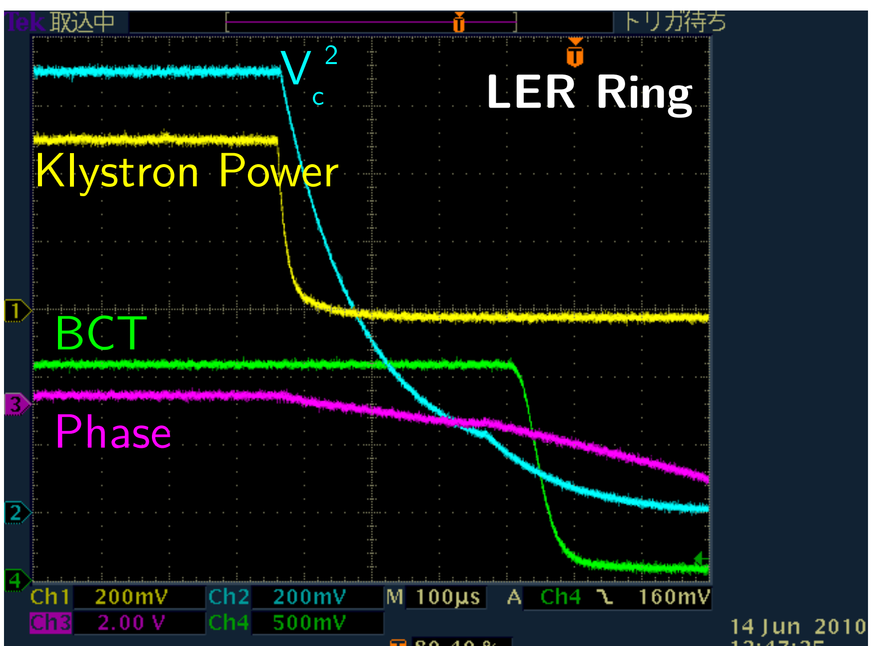
Some erratic phase behavior in HER cavity → possible input coupler discharge

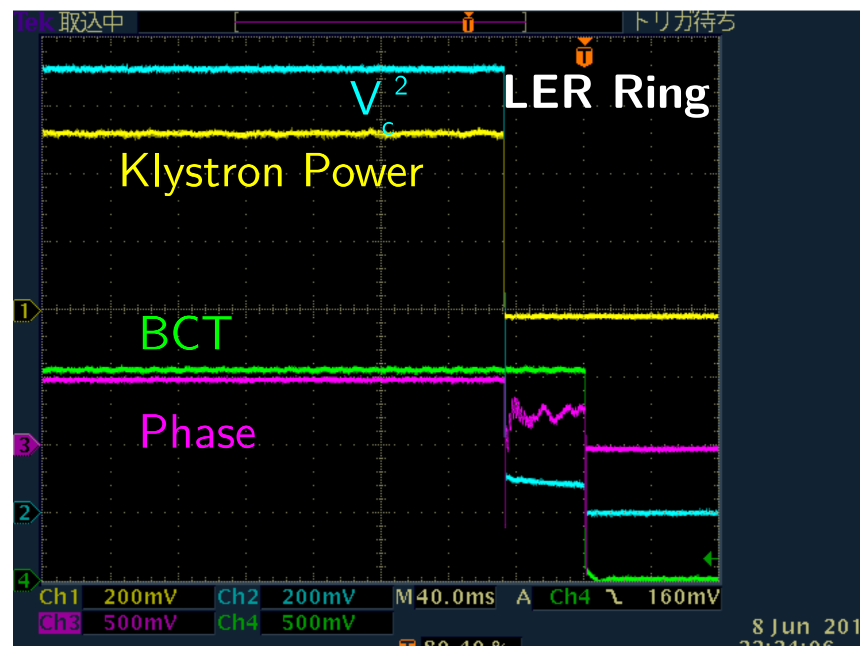
KEKB: RF Off <u>with</u> Beam

K. Nakanishi et al., LHC-CC10



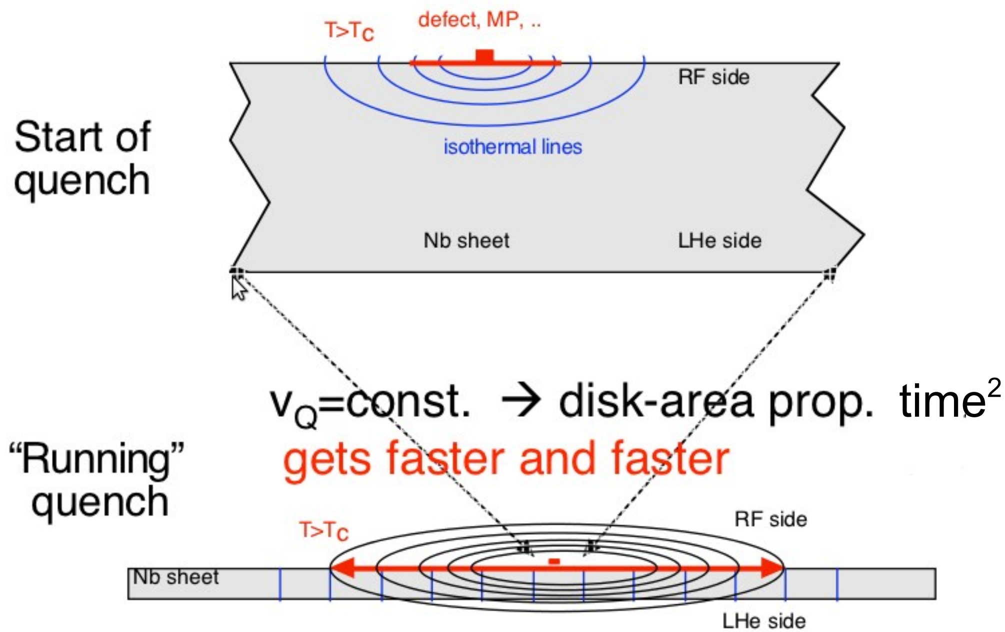






Cavity Quench

Some info: J. Tuckmantel, LHC-CC10



"Slow" thermal process (milli-seconds) → slow decay of the stored energy

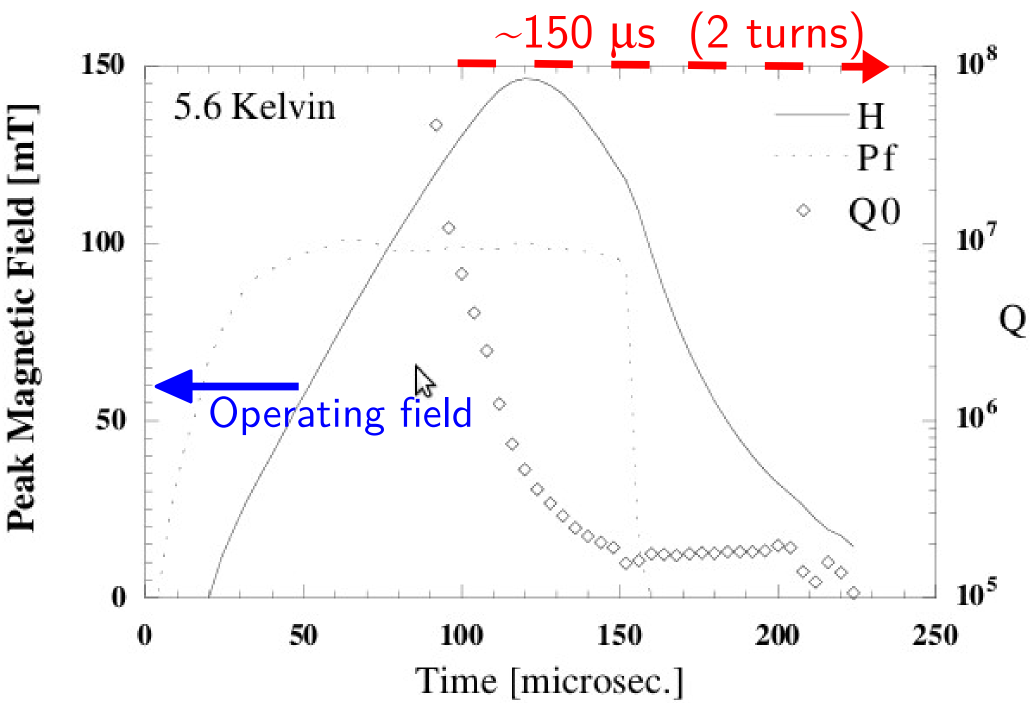
- Feedback tries to keep the demanded voltage (until power is available)

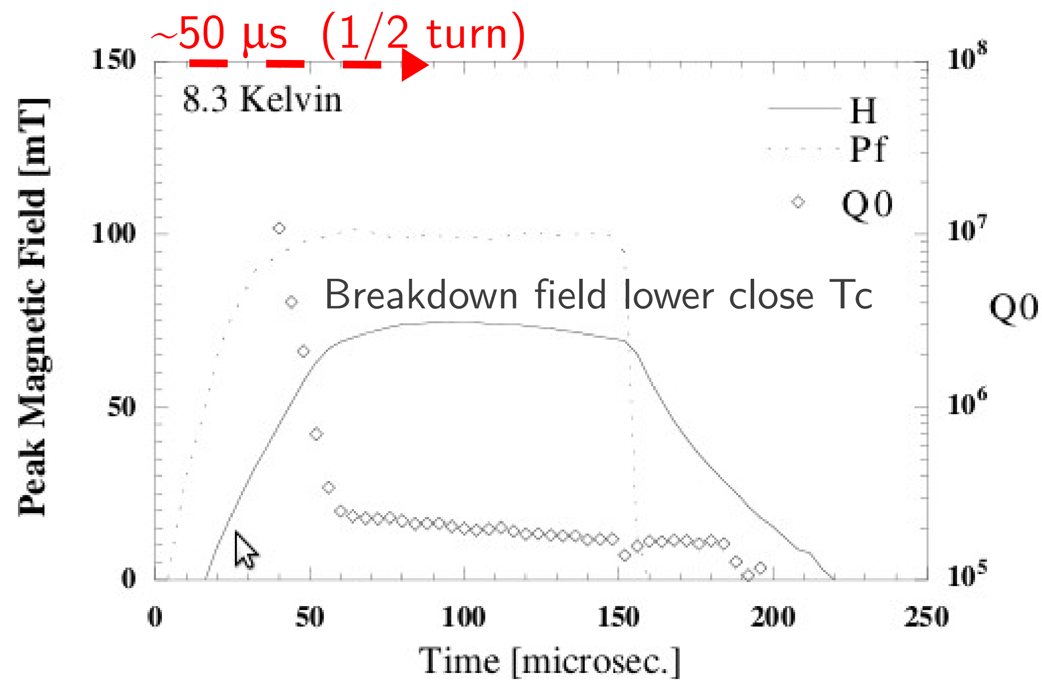
Remedy is to cut the RF power (also in all other cavities for safety)

- Thermometric response time for transients changes are not optimal
- But the transmitted RF power increases sharply with quench area

Cavity Quench

H. Padamsee et al., PAC95





Transient cavity Q meas. from high power RF pulses → thermal breakdown

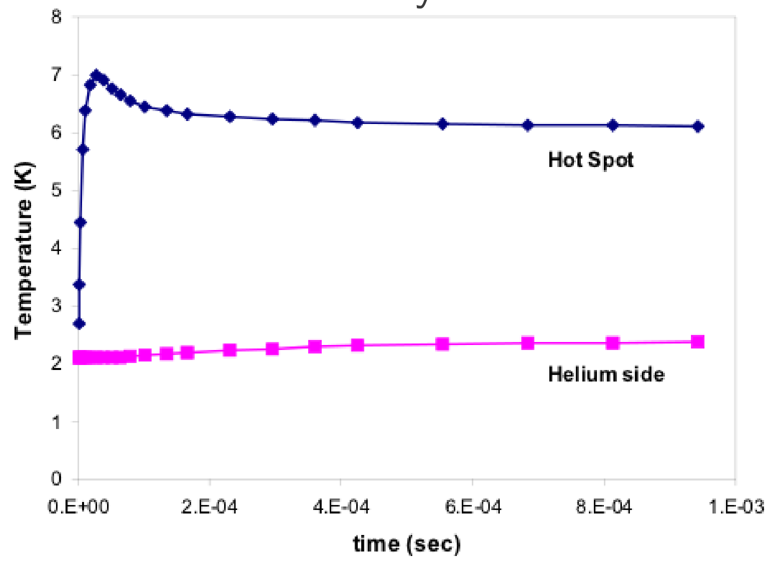
- Nominally performed during cavity processing (T_{start} 2K)
- Determine the "H_c^{RF}" limit for 2K

Nb coated cavities on OFE-Cu could be more quench resistant

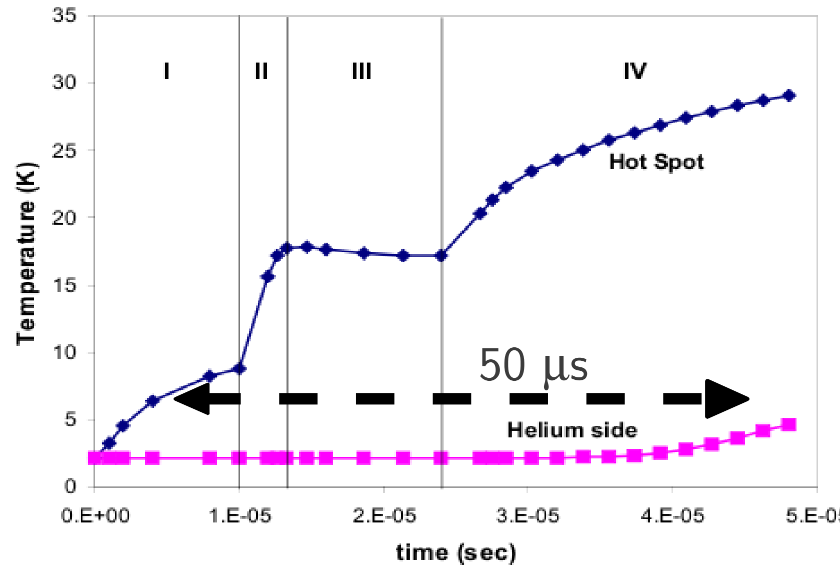
Quench Simulations

S. H. Kim, PAC2003 (SNS)

Thermally Stable

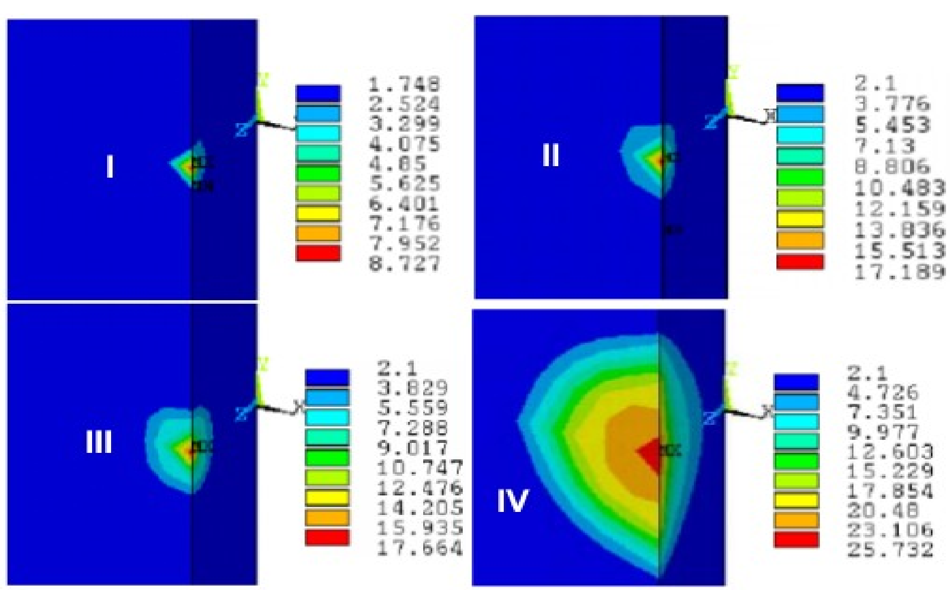


Thermally Unstable



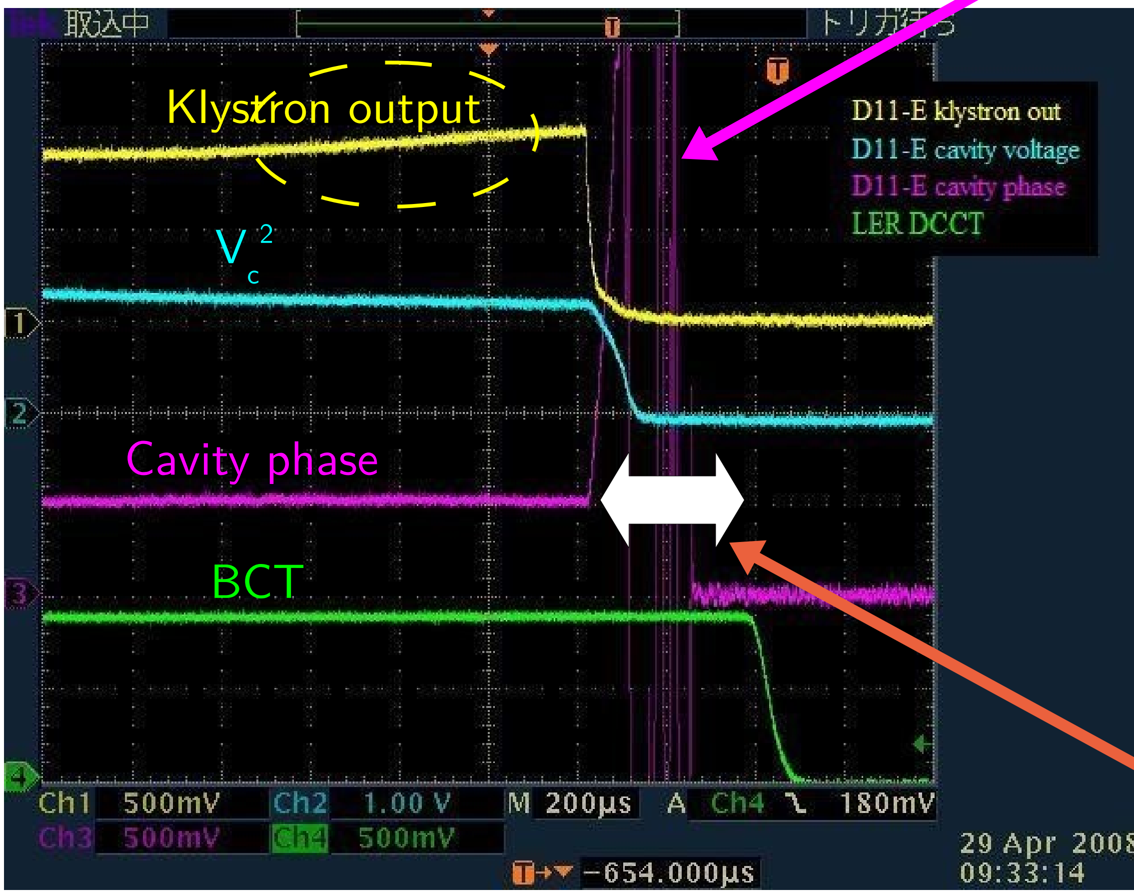
Using ANSYS 3D with local defects to measure dynamic evolution of surface temperature with increasing surface field

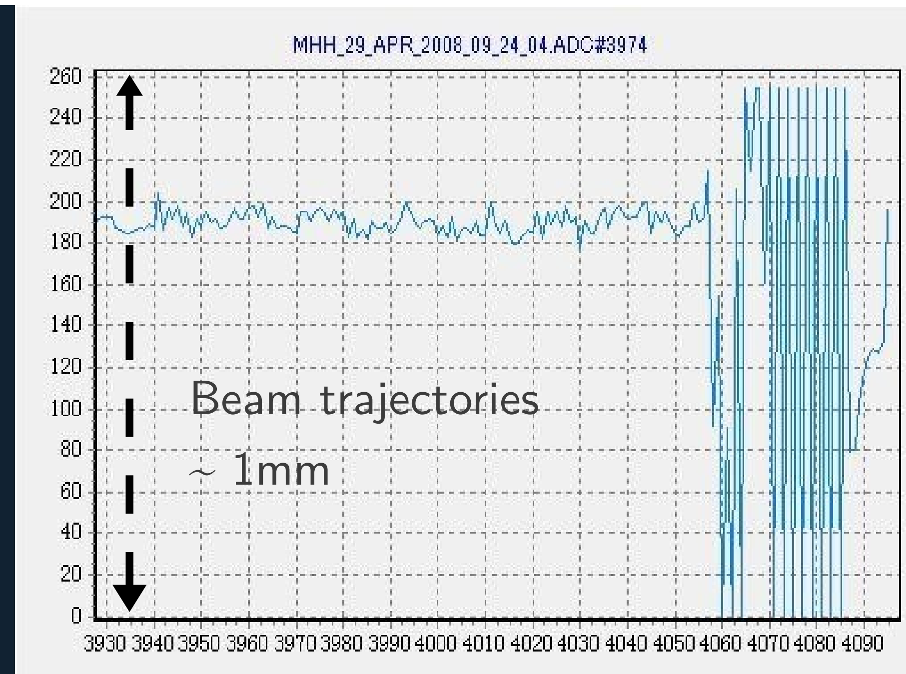
2mm Sample



KEKB: Cavity Quench?

Could be a cavity quench
(N. Kota, IPAC10)





~50 deg in ~100 µs (1 LHC turn)

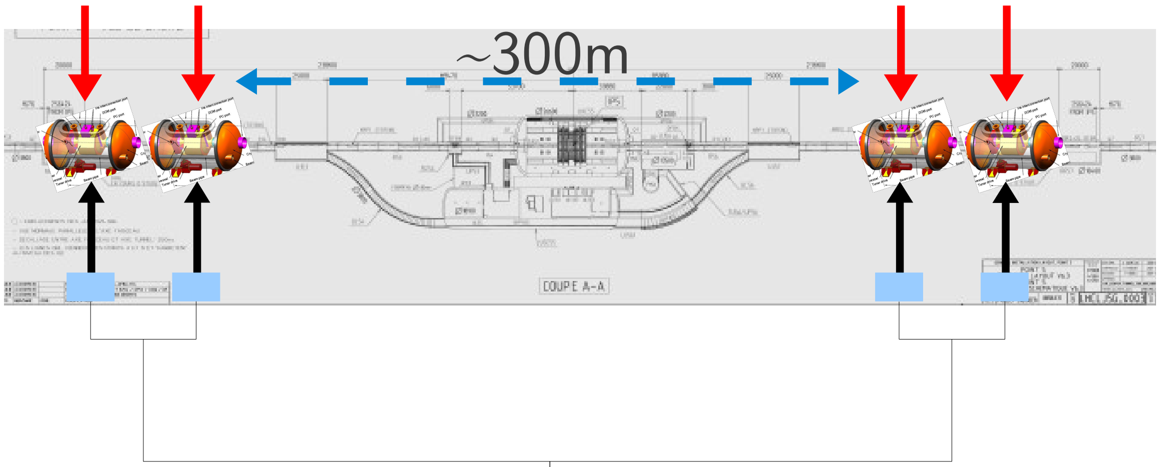
Initial phase change looks real, but phase behavior at "zero voltage",

<u>what is actually measured</u> ? $\Delta x \sim 5$mm (90 deg phase change)

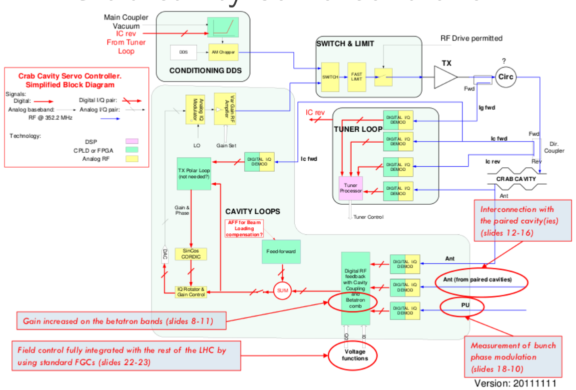
LHC RF Distribution

P. Baudrenghien (LHC-CC11)

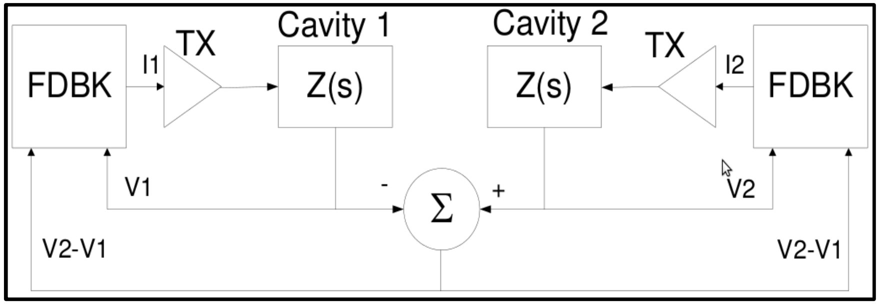
Independent high power RF (60 kW → IOTs)

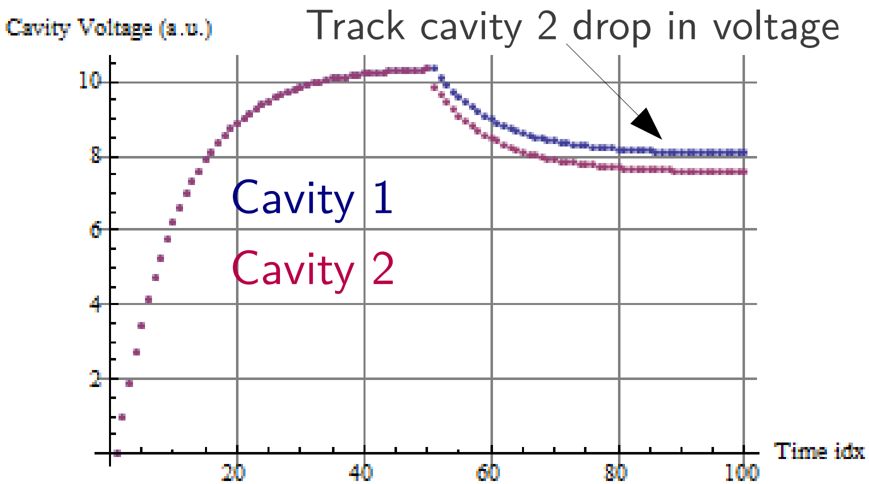


Crab cavity servo controller



LLRF (Strongly coupled feedback)





Intermediate Comments

Single cavity failure

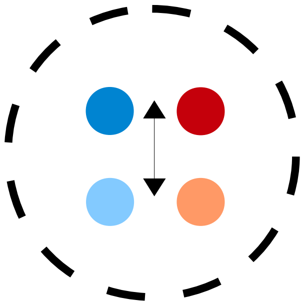
- Main detection mechanism is form RF loops
- Action: Switch off RF & dump beam (turn-around-time)
- (If all voltages ramped down, maybe can still keep beam)

Multi-cavity failures (this is not studied yet)

- Mainly from power cut or cryo-failures (“slow”)

Running w/o crabs (passive)

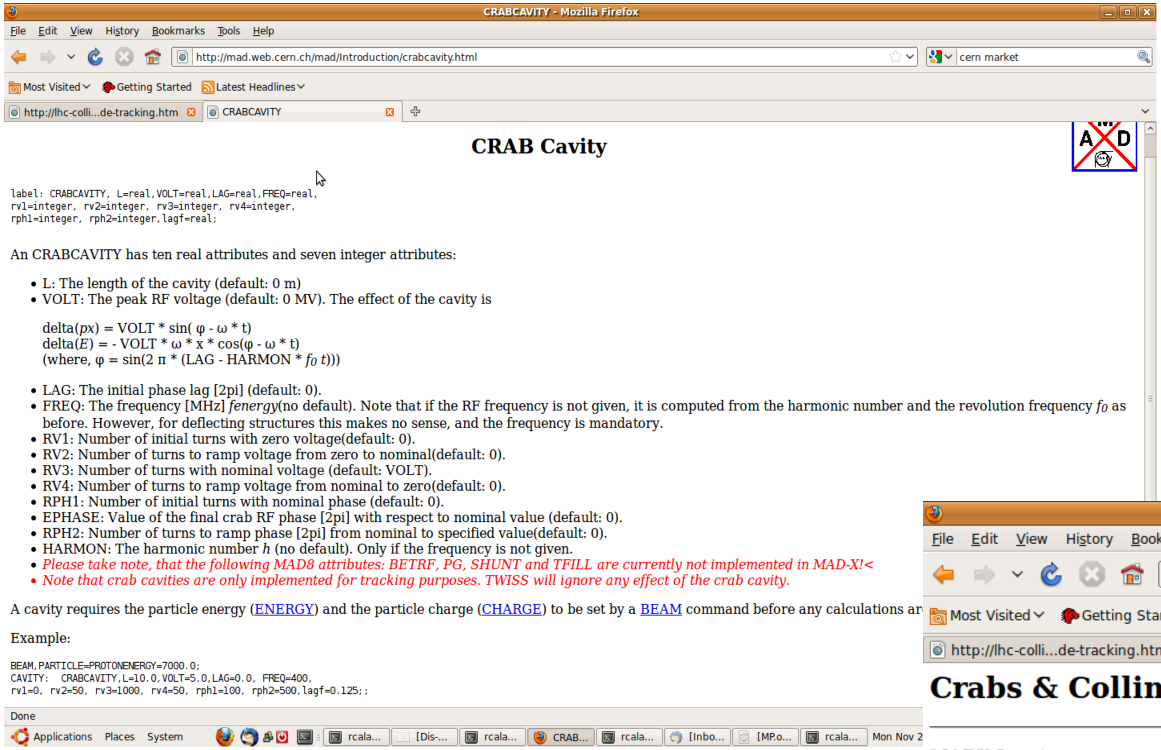
- Detuned and damped (like HOMs in main RF cavities)
- Built in physical Y-chambers bellows like in SPS (?)



RF interlock $\rightarrow$ RF feedback (slow & fast) should be limited

- No fast (μs) transient changes in voltage/phase
- Coupled feedback could be useful to bring to safe voltage

Crabs In MADX & SIXTRACK



CRAB Cavity

```
label: CRABCAVITY, L=real,VOLT=real,LAG=real,FREQ=real,
rv1=integer, rv2=integer, rv3=integer, rv4=integer,
rph1=integer, rph2=integer,lagf=real;
```

An CRABCAVITY has ten real attributes and seven integer attributes:

- L: The length of the cavity (default: 0 m)
- VOLT: The peak RF voltage (default: 0 MV). The effect of the cavity is

  delta(px) = VOLT * sin(φ - ω * t)
  delta(E) = - VOLT * ω * x * cos(φ - ω * t)
  (where, φ = sin(2 π * (LAG - HARMON * f_0 t)))

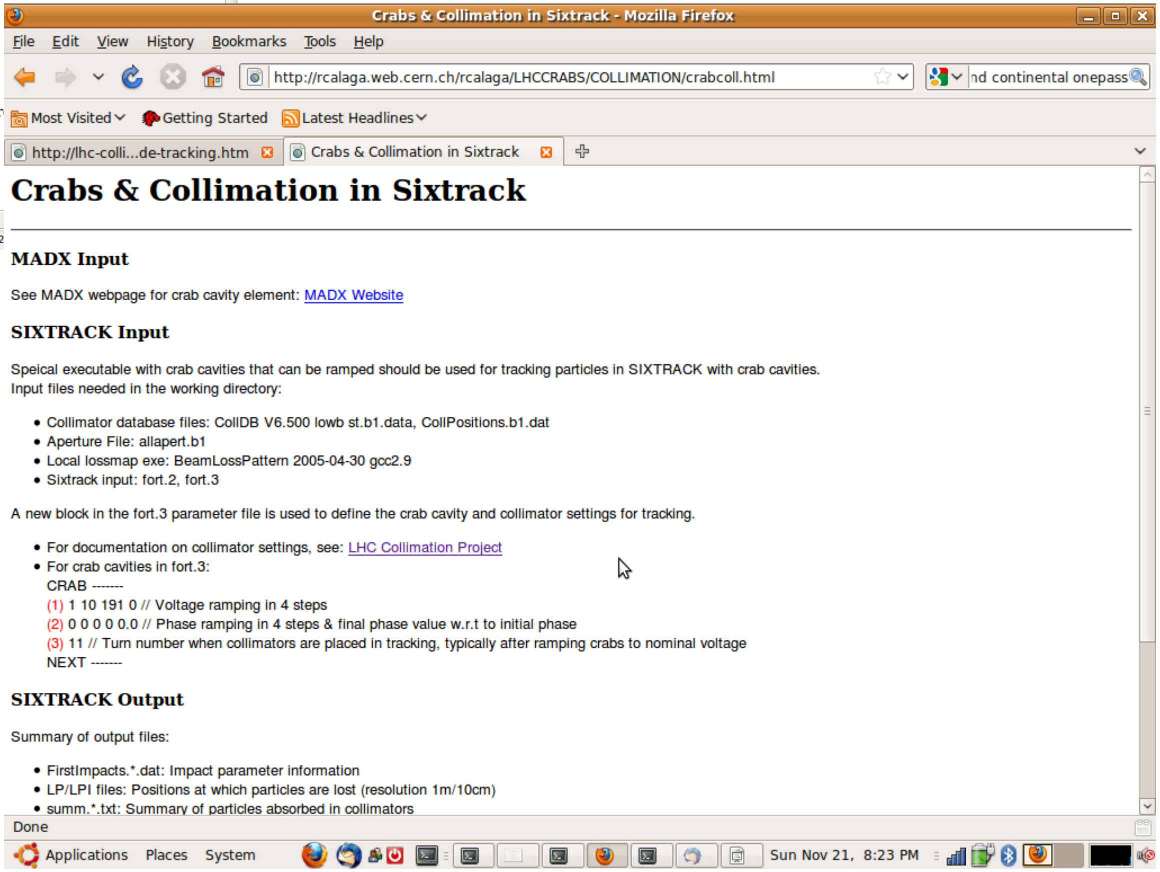
- LAG: The initial phase lag [2pi] (default: 0).
- FREQ: The frequency [MHz] *fenergy*(no default). Note that if the RF frequency is not given, it is computed from the harmonic number and the revolution frequency f_0 as before. However, for deflecting structures this makes no sense, and the frequency is mandatory.
- RV1: Number of initial turns with zero voltage(default: 0).
- RV2: Number of turns to ramp voltage from zero to nominal(default: 0).
- RV3: Number of turns with nominal voltage (default: VOLT).
- RV4: Number of turns to ramp voltage from nominal to zero(default: 0).
- RPH1: Number of initial turns with nominal phase (default: 0).
- EPHASE: Value of the final crab RF phase [2pi] with respect to nominal value (default: 0).
- RPH2: Number of turns to ramp phase [2pi] from nominal to specified value(default: 0).
- HARMON: The harmonic number *h* (no default). Only if the frequency is not given.
- *Please take note, that the following MAD8 attributes: BETRF, PG, SHUNT and TFILL are currently not implemented in MAD-X!<*
- *Note that crab cavities are only implemented for tracking purposes. TWISS will ignore any effect of the crab cavity.*

A cavity requires the particle energy (ENERGY) and the particle charge (CHARGE) to be set by a BEAM command before any calculations ar

Example:

```
BEAM,PARTICLE=PROTONENERGY=7000.0;
CAVITY:  CRABCAVITY,L=10.0,VOLT=5.0,LAG=0.0, FREQ=400,
rv1=0, rv2=50, rv3=1000, rv4=50, rph1=100, rph2=500,lagf=0.125;;
```

Only linear ramp available for now



Crabs & Collimation in Sixtrack

MADX Input

See MADX webpage for crab cavity element: MADX Website

SIXTRACK Input

Speical executable with crab cavities that can be ramped should be used for tracking particles in SIXTRACK with crab cavities.
Input files needed in the working directory:

- Collimator database files: CollDB V6.500 lowb st.b1.data, CollPositions.b1.dat
- Aperture File: allapert.b1
- Local lossmap exe: BeamLossPattern 2005-04-30 gcc2.9
- Sixtrack input: fort.2, fort.3

A new block in the fort.3 parameter file is used to define the crab cavity and collimator settings for tracking.

- For documentation on collimator settings, see: LHC Collimation Project
- For crab cavities in fort.3:
  CRAB -------
  (1) 1 10 191 0 // Voltage ramping in 4 steps
  (2) 0 0 0 0 0.0 // Phase ramping in 4 steps & final phase value w.r.t to initial phase
  (3) 11 // Turn number when collimators are placed in tracking, typically after ramping crabs to nominal voltage
  NEXT -------

SIXTRACK Output

Summary of output files:

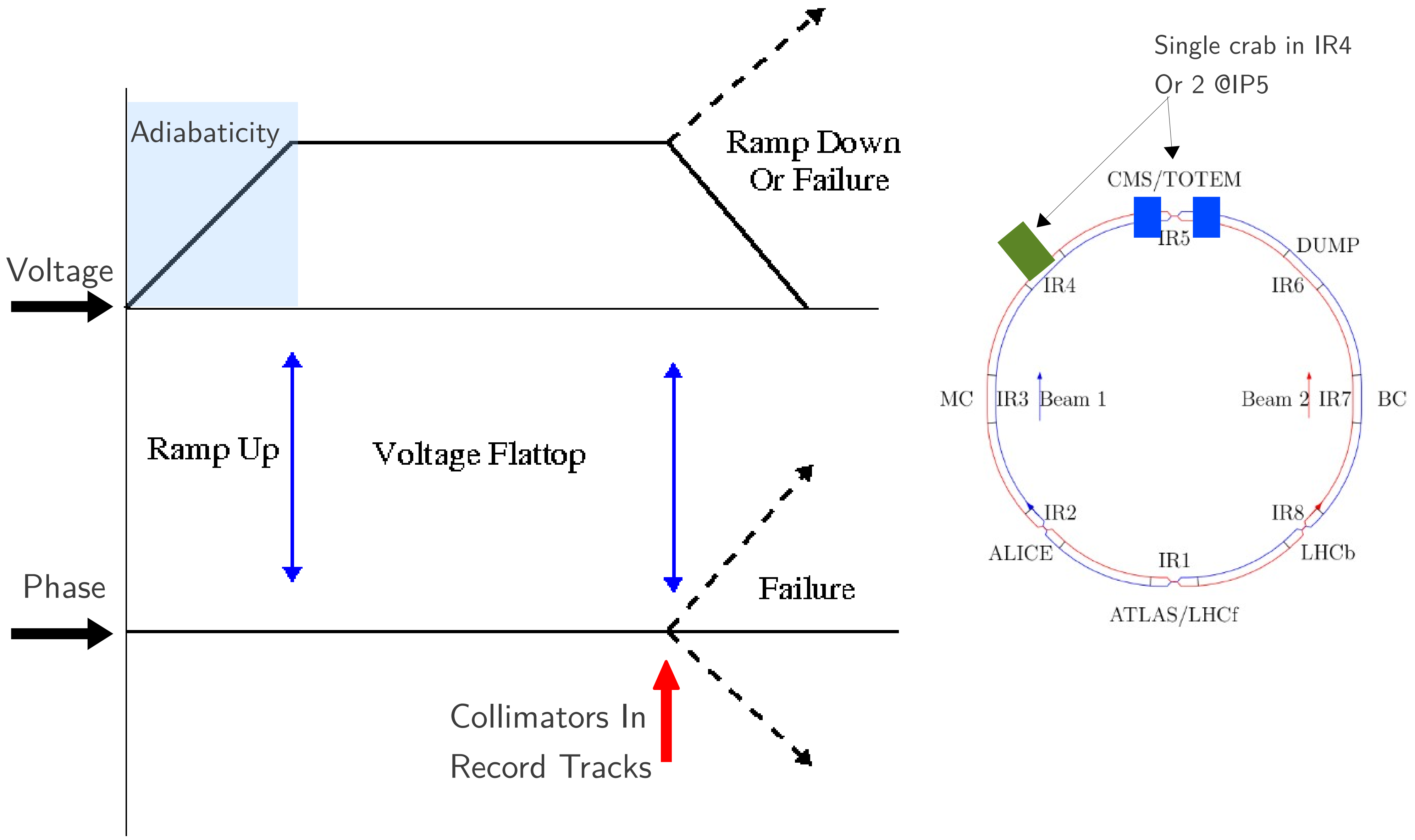
- FirstImpacts.*.dat: Impact parameter information
- LP/LPI files: Positions at which particles are lost (resolution 1m/10cm)
- summ.*.txt: Summary of particles absorbed in collimators

SIXTRACK only 2 CRABS possible

Database with multiple crabs underway

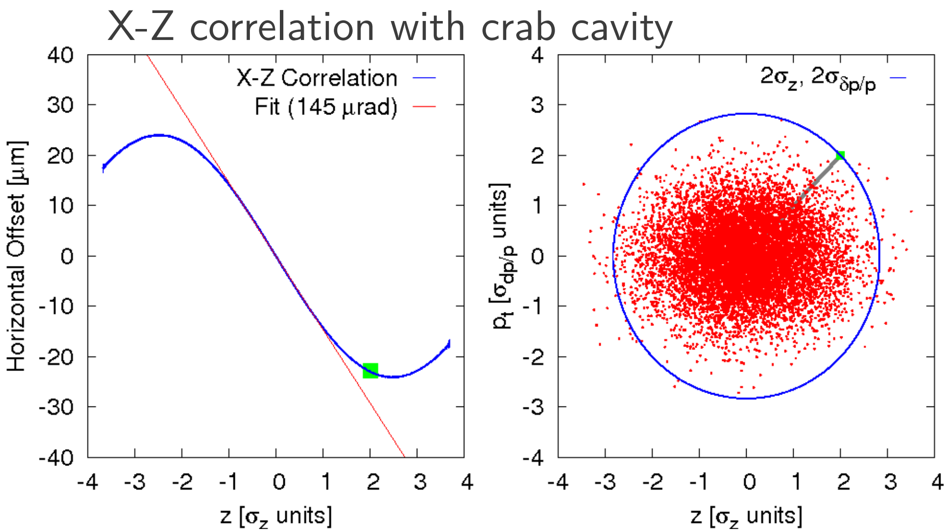
Crab-Cavity Failure Setup

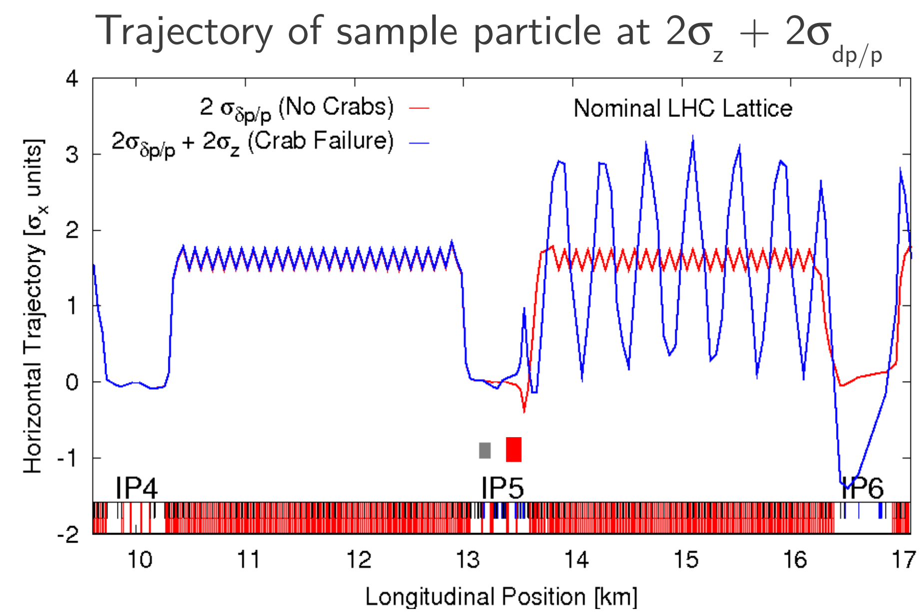
Voltage is kept constant during phase failure and vice-versa



Sixtrack & MADX are now setup for failure scenarios (J. Barranco, R. Calaga, R. Tomas)

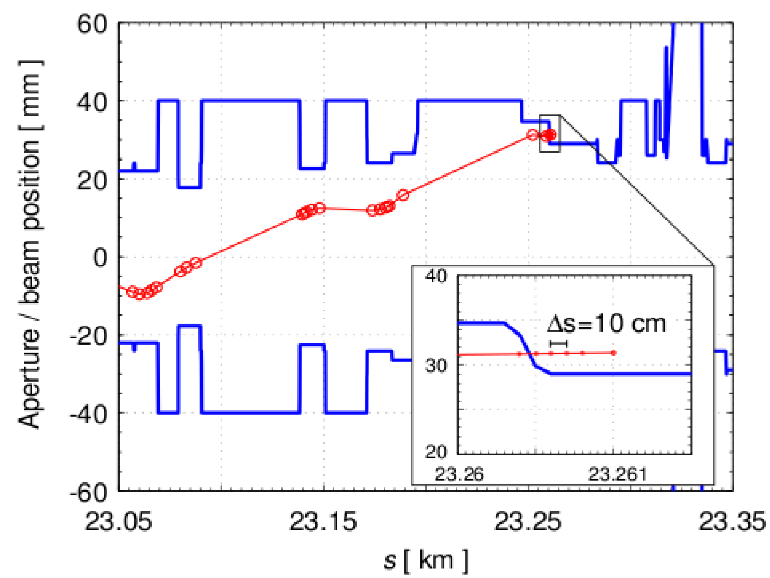
Failure, Simulation Setup



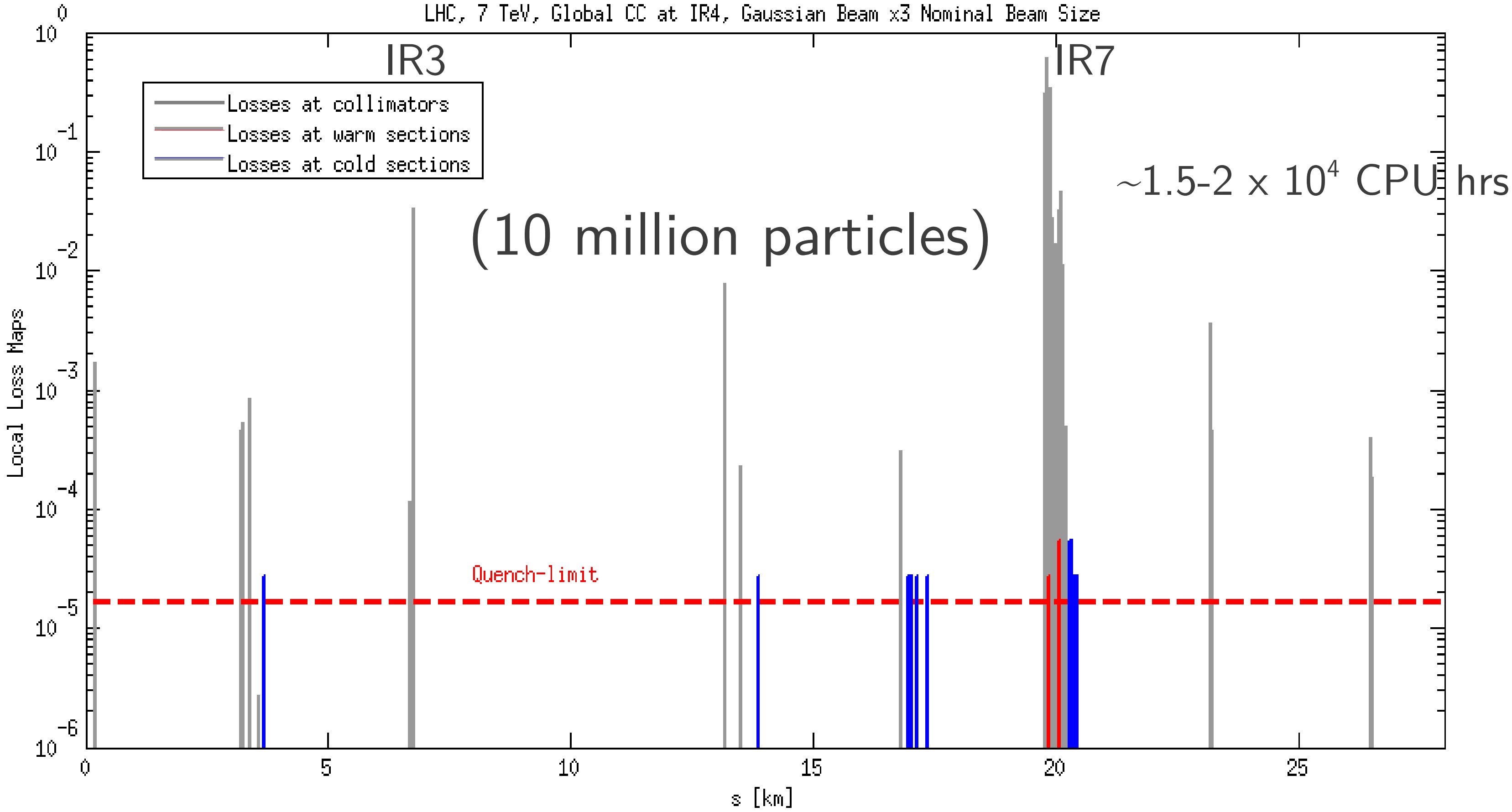


Immediately after failure:

- All trajectories are recorded after failure
- Aperture model applied to within 10cm resolution
- (courtesy collimation team)



Example Loss Map (Pessimistic Case)



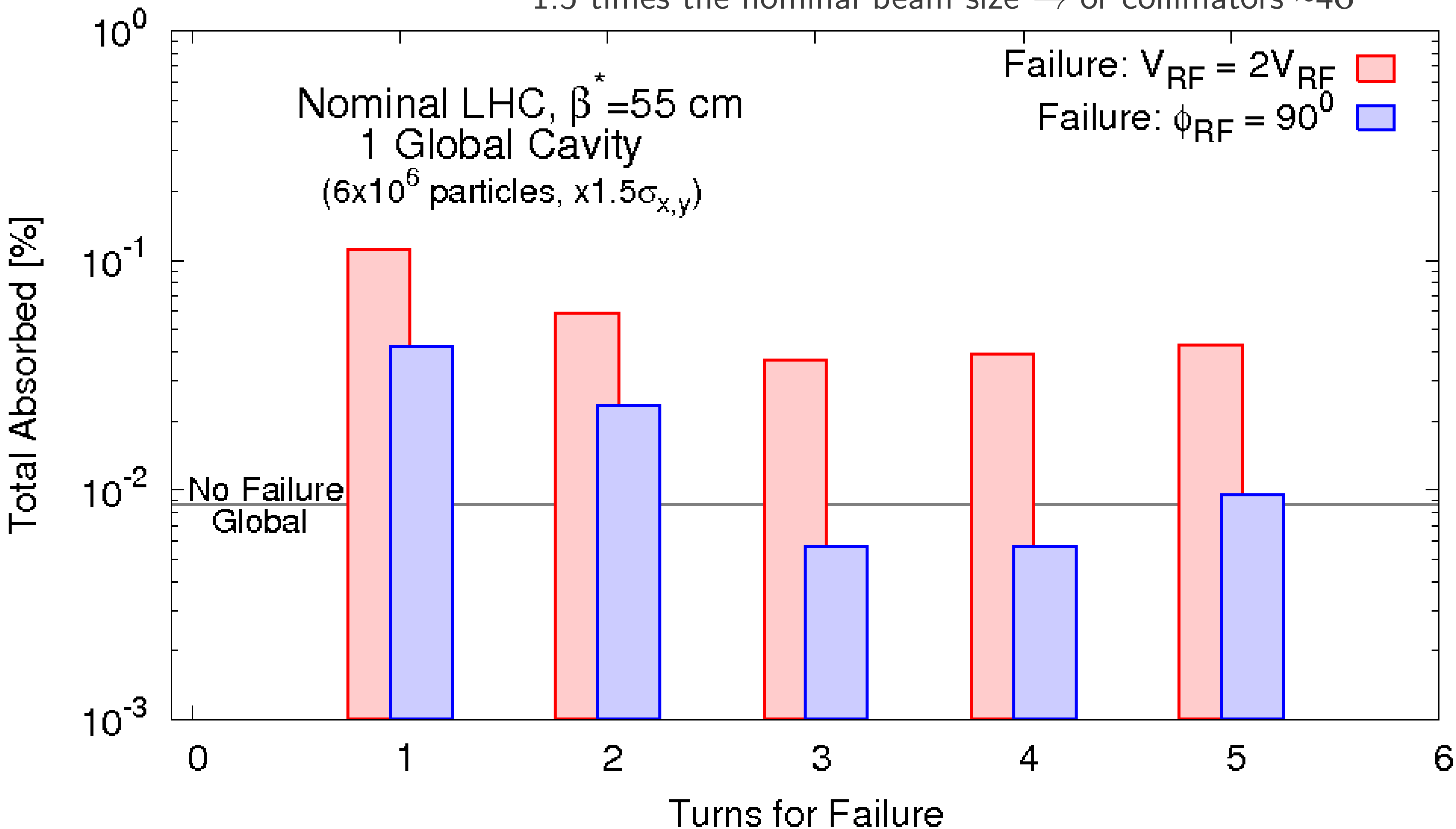
- Beam size is 3-times nominal beam (to overpopulate tails)
- A failure of 3-turns induced where phase shift 90 degree occurs
- 4% of total particles absorbed in the collimators

% Absorbed Due To Failure

Global Scheme

Main losses are in the collimators in IR7, IR3 and the TCTs

1.5 times the nominal beam size → or collimators ∼4σ

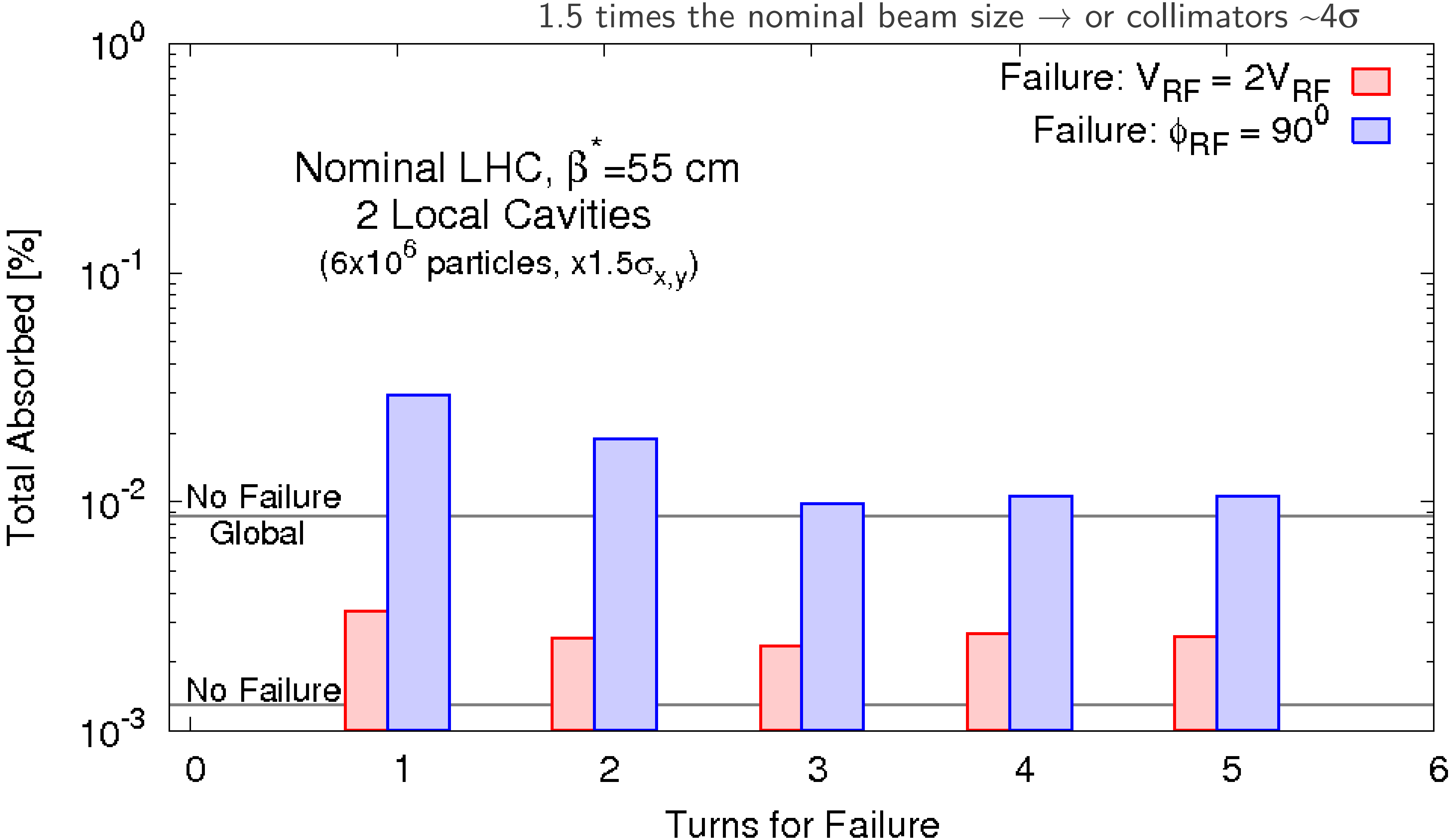


% Absorbed Due To Failure

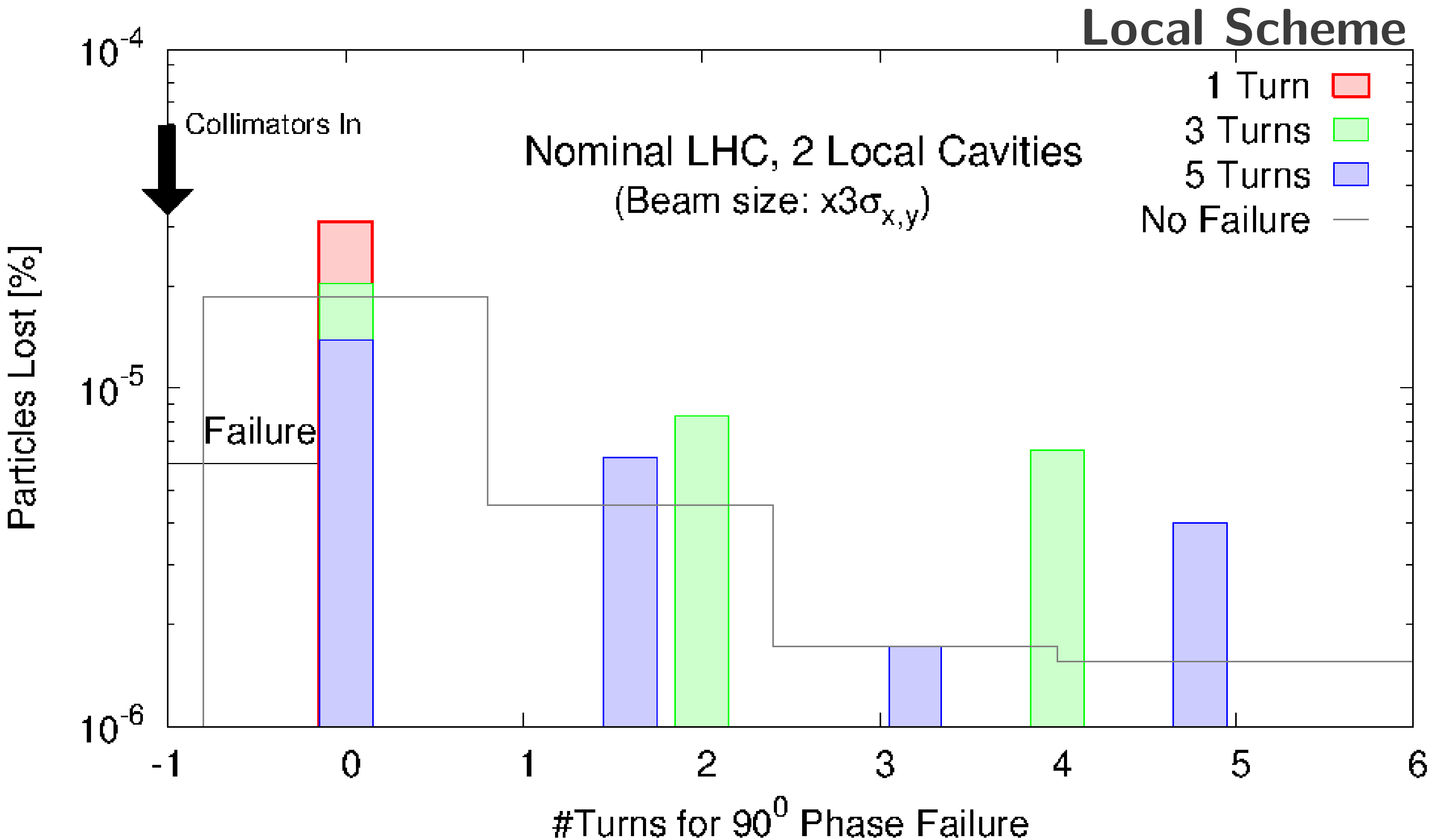
Local Scheme

Main losses are in the collimators

1.5 times the nominal beam size → or collimators ~4σ



% Lost Due To 90^0 ϕ–Failure



Artificially large beam → collimators effectively at 2σ (scraping)

No particles lost for x1.5 the beam size (statistics)

Comments since PAC11

Real beam distribution is more like a double Gaussian

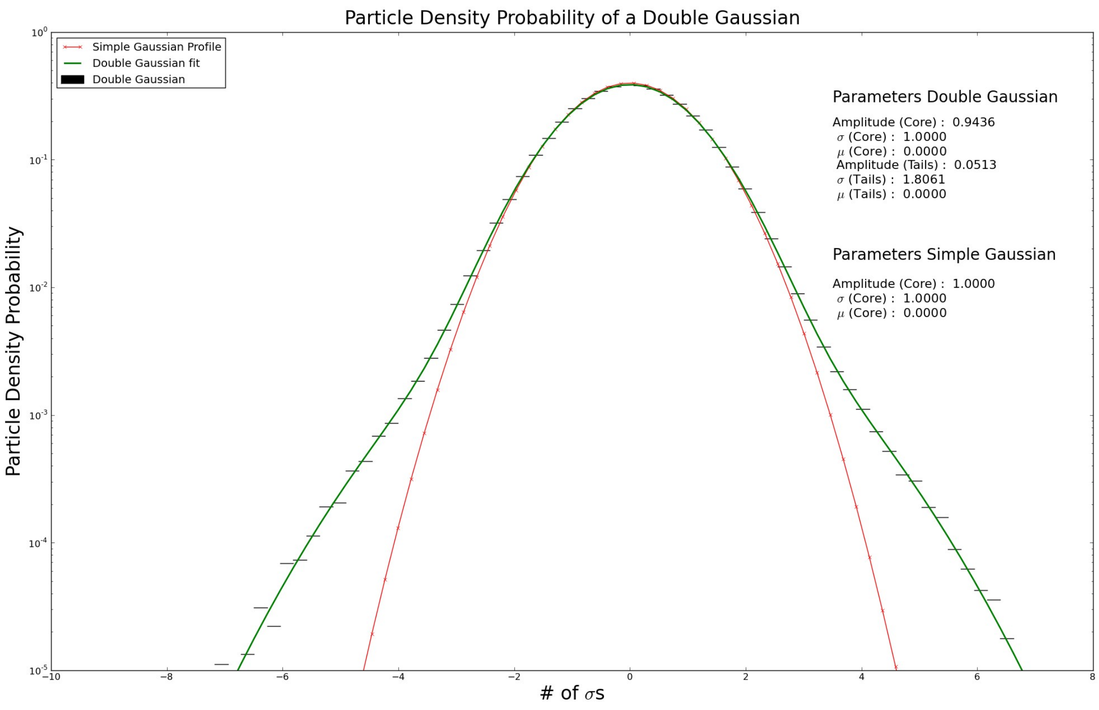
CMS vernier scans and collimation Mds (benchmark)

Collimators should be placed at the beginning

Sixtrack now modified and simulations underway

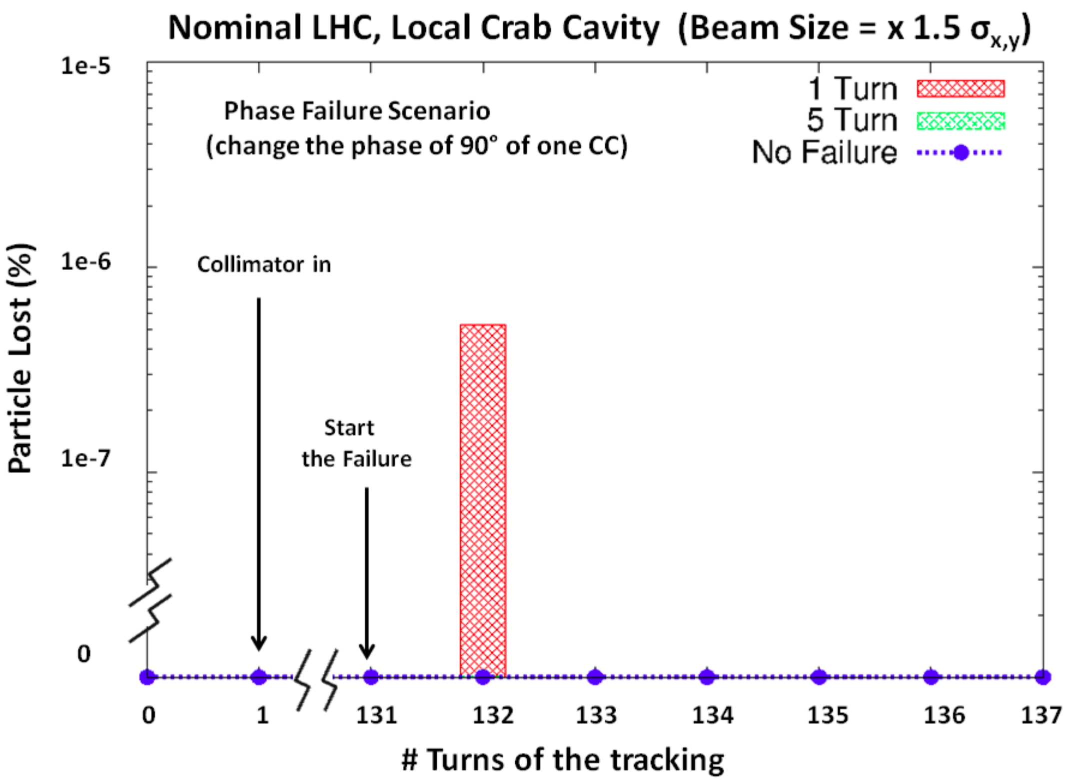
Need a realistic sixtrack lattice for upgrade with some beta* margin

Distrib generated from
CMS measurements
B. Yee et al.



“Latest Results”

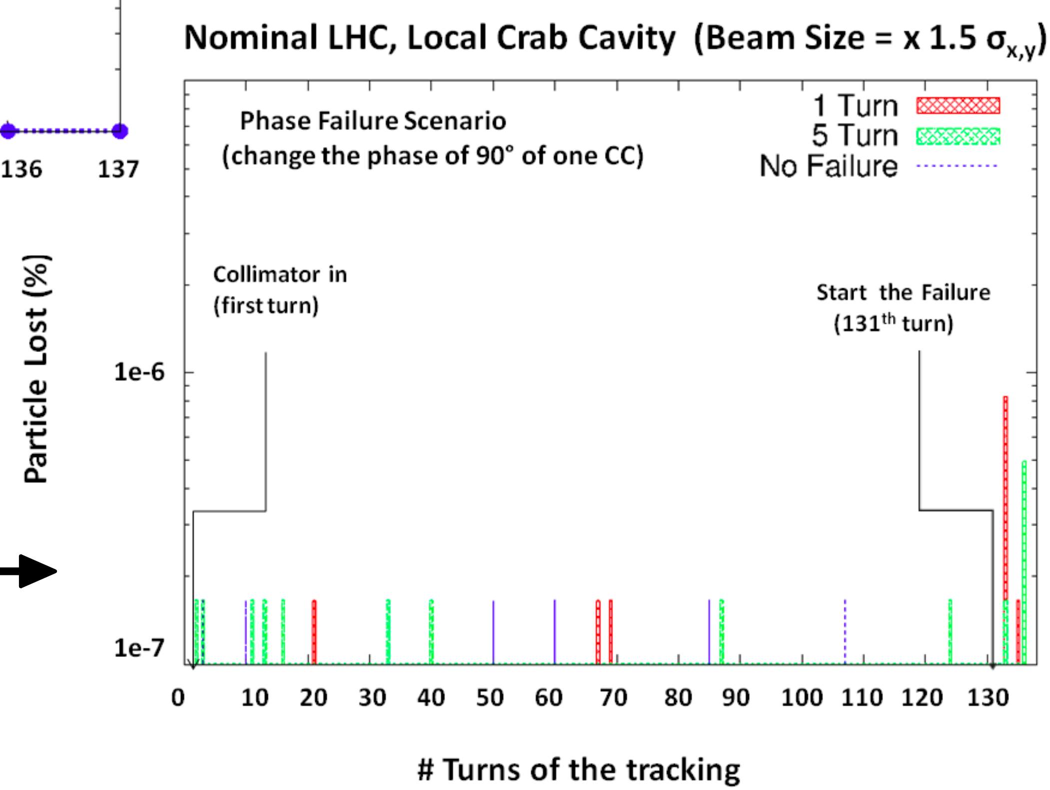
B. Yee et al.



Phase Failure by 90 degrees

Gaussian Distrib
(Collimators @4σ)

Double Gaussian Distrib
(Collimators @4σ)



Last Comments

Crab cavity failures should be in the shadow MP

- Nominal LHC shows no noticeable (?) effects even with 1-turn failures
- Prevent fast failures at design stage and design fast RF interlocks (ongoing)
- <u>SPS tests invaluable!!</u>

HL-LHC Upgrade ($\beta^*\sim$15cm, $\phi\sim$0.6mrad)

- See T. Baer's talk for the "worst case scenario"
  - Obviously I wouldn't choose this option
- Steps towards a crab specific option
  - Optics $\rightarrow$ fine tune for a crab specific safe optics
  - Technology limits $\rightarrow$ stick to 3MV/cavity (~60 mT Hs)
  - Impedance $\rightarrow$ 2 cavities /beam/IP side with 3rd as optional
  - LR beam-beam $\rightarrow$ small emittance, higher intensity & x-angle + leveling
  - Work more closely with the collimation team for the upgrade