RF Overview of crab Cavities for HL-LHC and potential failure modes

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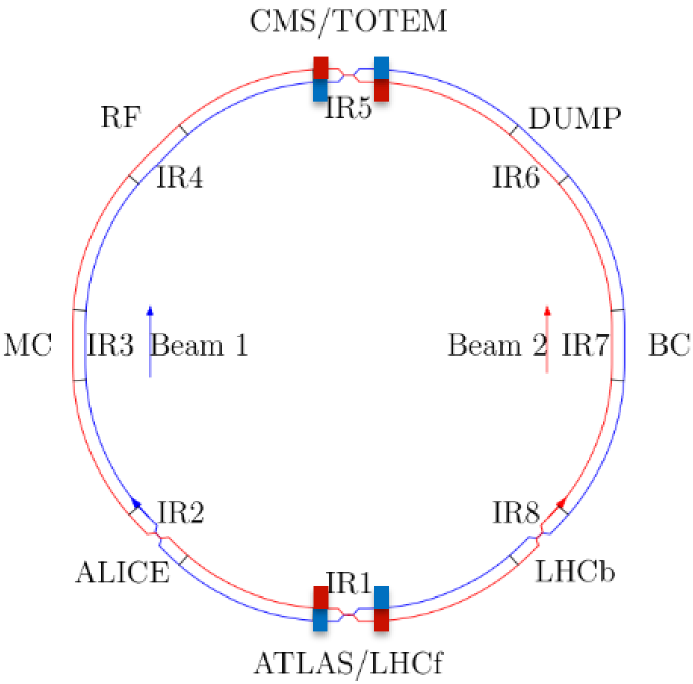
Ack: ABP, BI, OP, RF & MPP

Electron Lens Review, 2016

HL-LHC Crab Layout

16 Superconducting compact RF deflectors (ATLAS + CMS) to partially compensate the geometric angle of 590 μrad[†]

Without Crab Cavities, exploits only 30% of the available peak Luminosity



7.55 cm

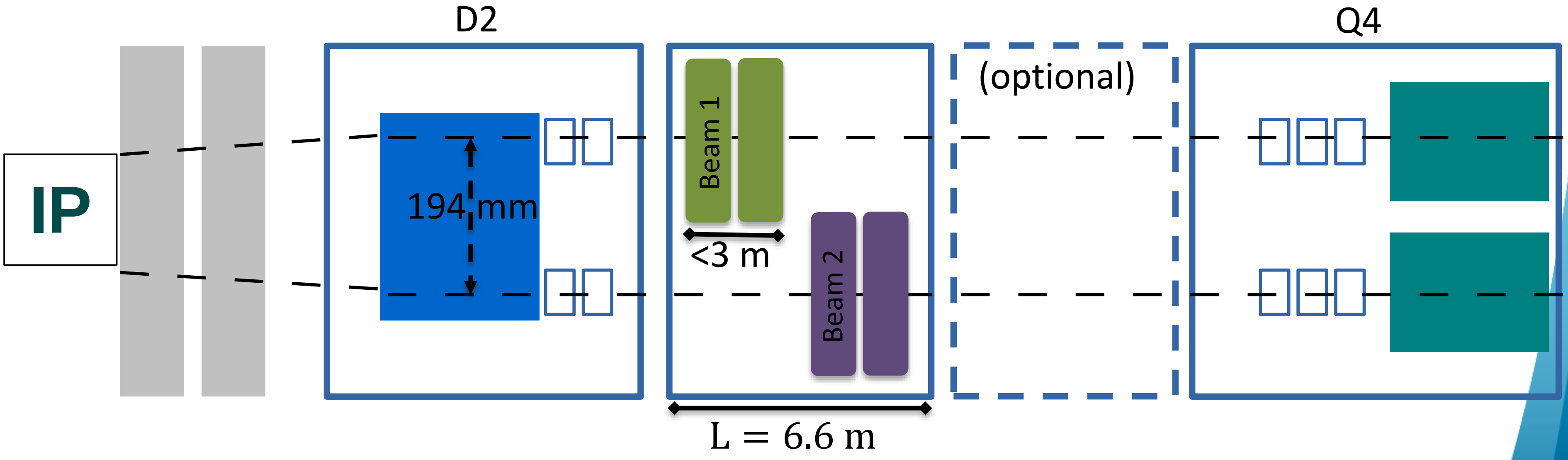
$$\Phi = \frac{\sigma_z}{\sigma_x}\left(\frac{\theta_c}{2}\right) = 3$$

$\sim 7\ \mu m$

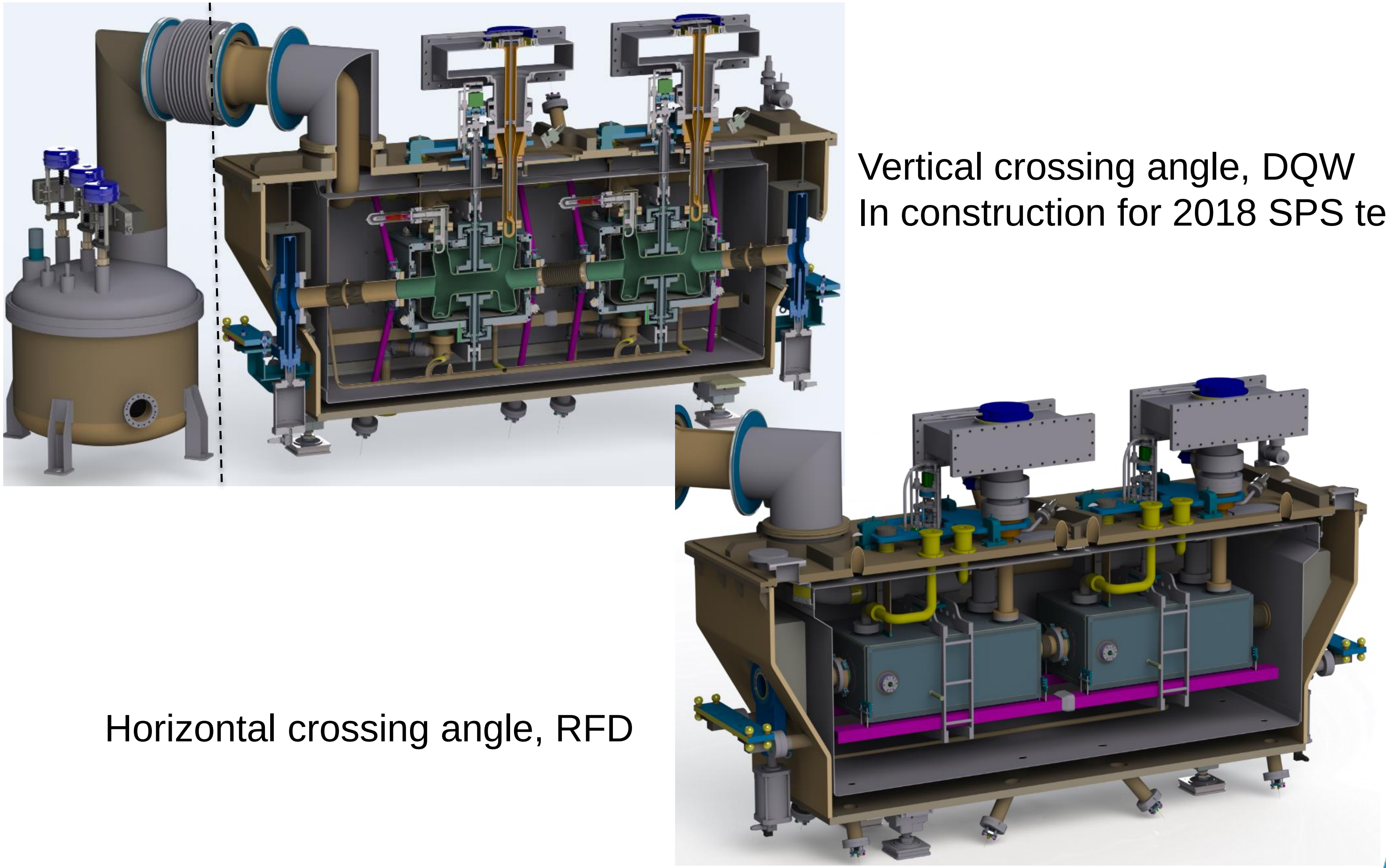
[†] Old baseline

Basic Parameters

- Voltage $= 3.4\ \mathrm{MV}$ /cavity (2 cavities /beam /IP side)
- Frequency $= 400.79\ \mathrm{MHz}$
- $Q_{ext} = 5 \times 10^5, Q_0 \approx 10^{10}$
- RF power source $= 80\ \mathrm{kW}$ (SPS $\leq 40\ \mathrm{kW}$)
- Cavity tuning $= \pm 100\ \mathrm{kHz}$ (LFD $< 0.5\ \mathrm{kHz}$)
- Operating temperature $= 2.0\ \mathrm{K}$



Cryomodules For SPS Tests



Vertical crossing angle, DQW
In construction for 2018 SPS tests

Horizontal crossing angle, RFD

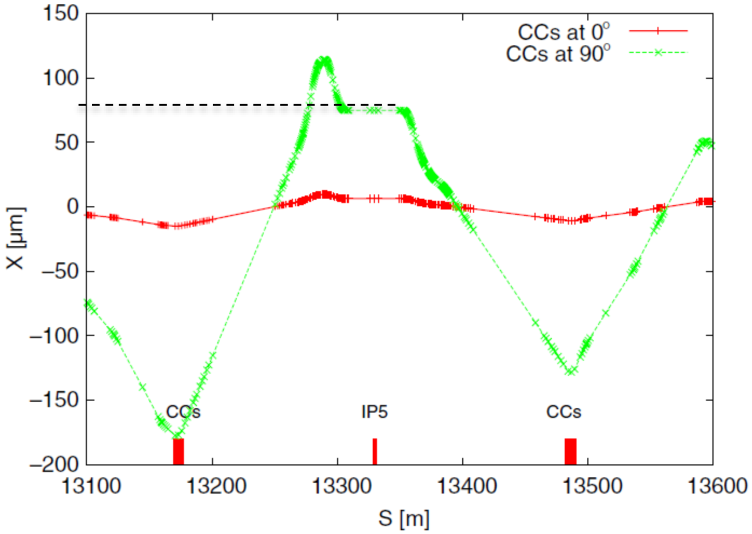
Addition of Crab Cavities

- An RF element giving transverse-longitudinal correlation

- Crab cavity kick (as in MADX & Sixtrack) for simulations
  - $\Delta p_{x,y} = -\frac{q.V.sin(\phi_s + kz)}{E} \qquad \Delta p_z = -\frac{q.V.cos(\phi_s + kz)}{E}.k.x$
- Total voltage ~ 12 MV (only 6.8MV with 2-cavities)
  - $V = \frac{cE.\tan(\theta_c/2)}{q\omega R_{12}\sin(\phi_{cc\to IP})}\,;\ \Delta x \approx R_{12}\frac{V}{E}sin(\phi_s + kz)\sin(\Delta\phi_{cc\to s})$

Example with $V_{total} \sim 10.5$ MV

Orbit offsets with crabbing phase (red) or deflecting phase (green)



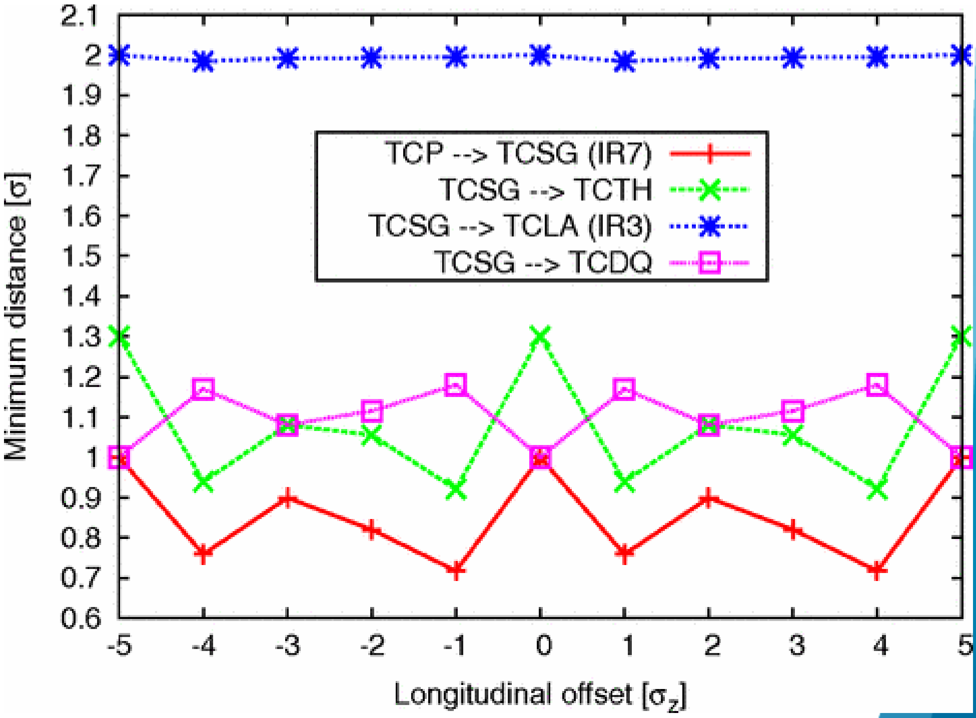
Crab Dispersion & Hierarchy

- Closed orbit both δ-dependent and z-dependent
- $x_{D_{CC}} = \frac{\sqrt{\beta(s)\beta_{CC}}}{2\sin(\pi Q)} \Delta p_x(z).\cos(\Delta\phi - \pi Q)$; $x_\delta = D(s).\delta$

Collimator hierarchy change including crab dispersion

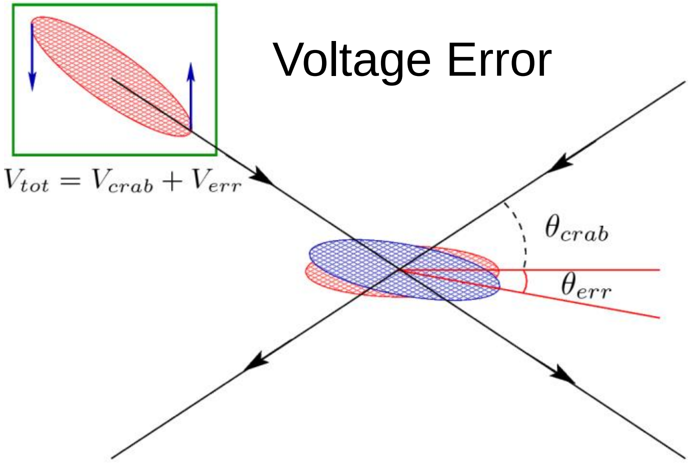
Hierarchy modulated but maintained, $D_{CC}(\pm 1\sigma)$ is most pessimistic

Not an issue with local crab cavities, but during a failure could have an impact



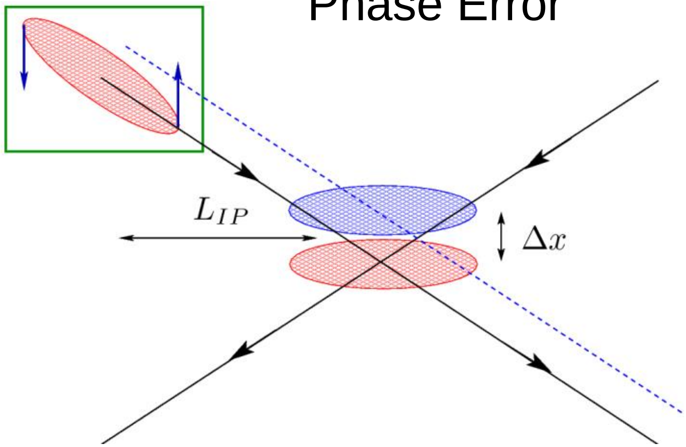
Potential Failure Consequences

Voltage Error



Over or under compensation x-angle, frequency detuning

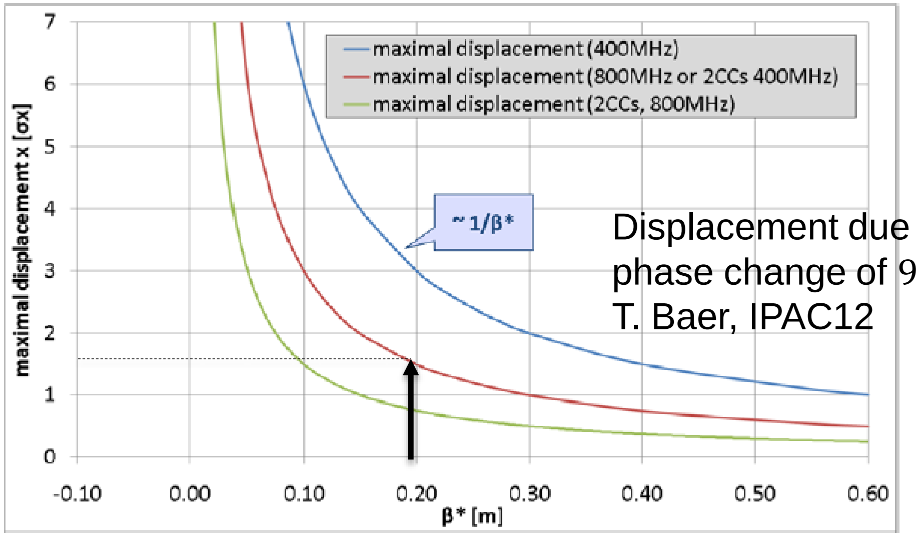
Phase Error



Closed orbit change and offset collisions

Displacement at $1\sigma_z \sim 1.5\sigma_x$

Peak displacement $\sim 2.4\sigma_x$



Displacement due to phase change of 90^0
T. Baer, IPAC12

Potential Failure Modes

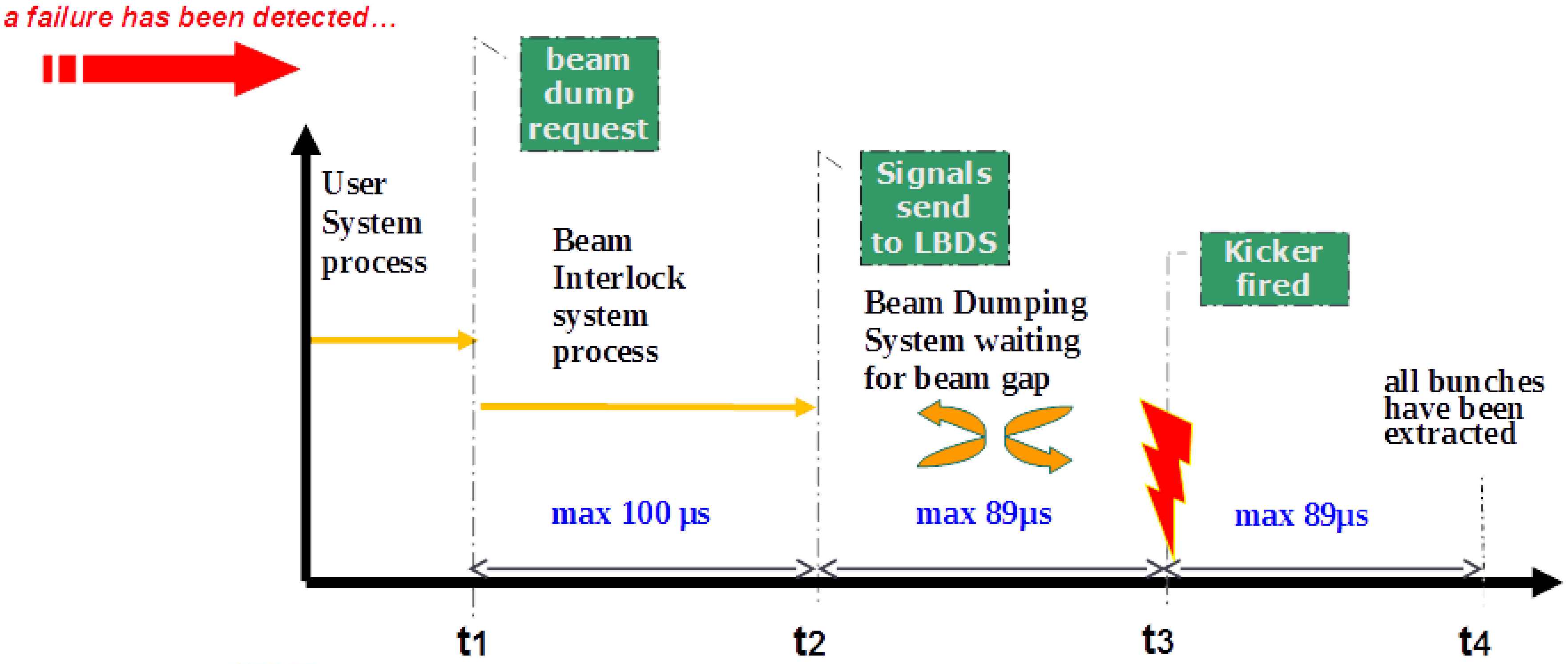
- Cavity stored energy is 10-12 J
- Some "slow" failure
  - RF arcing, $\tau_F \sim 1\ \text{ms}$
  - Power supply trips ($50 - 300\ Hz$): $\tau_F \sim \text{few ms}$
  - Mechanical changes: $\tau_F \sim 100\text{'s ms}$
- Fast Failures (10's $\mu\text{s} - \text{ms}$)
  - Cavity quench, RF breakdown, Sudden discharge
  - Fast orbit changes, external forces
- LHC Collimation, maximum allowed (old numbers)
  - Slow: 0.1% of beam/second for 10s
  - Transient: 5×10^{-5} in 1 ms
  - Fast: Up to 1 MJ in 200 ns into $0.2\ \text{mm}^2$

Machine Protection Constraint

J. Wenninger, LHC-CC10

- Best case protection

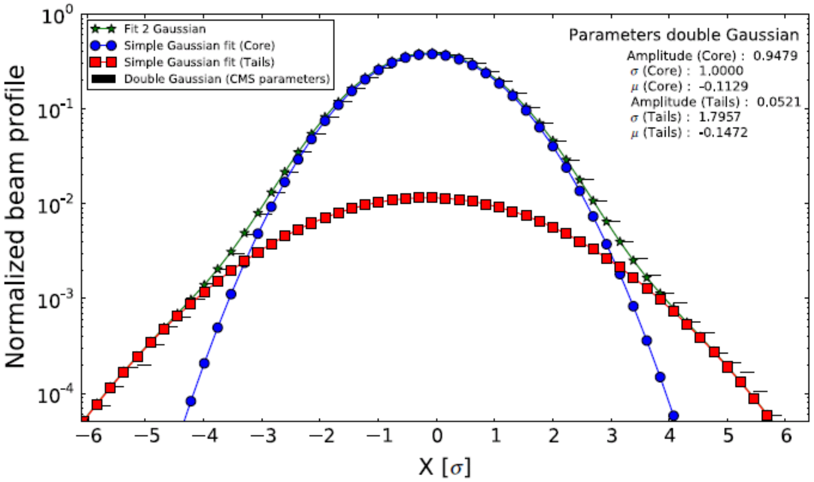
  Detection: 40 μs, Response ~300 μs



Particle Tracking Simulations

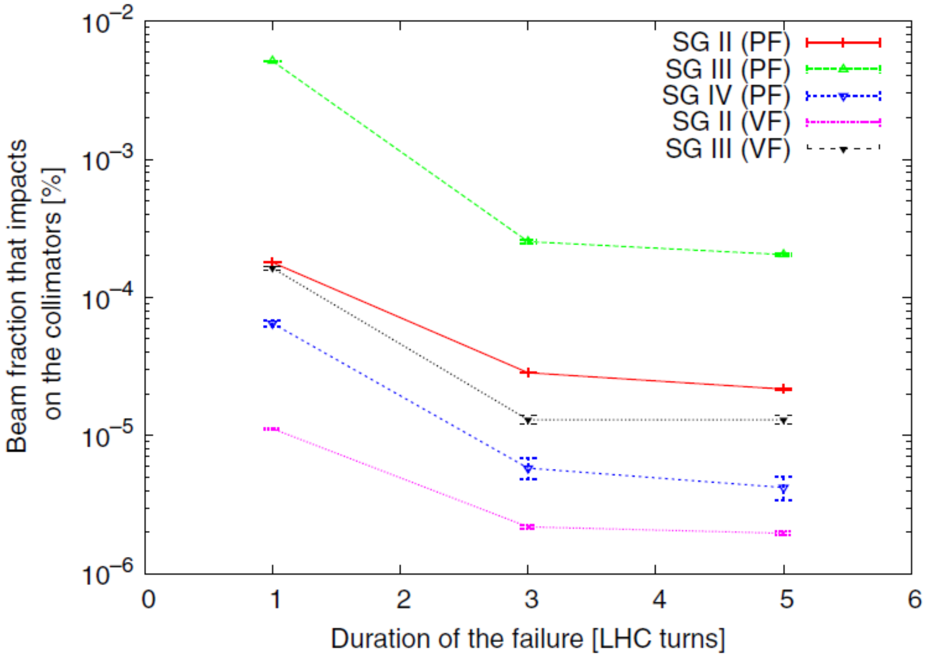
- Since 2010, a long simulation campaign with SIXTRACK is underway
- Crab cavity dynamics, multiple cavity failures, realistic transverse distributions, have resulted in a better understanding on the effect of abrupt failures
- Still important details are missing (beam loading, RF feedback, beam-beam & good quench model), work in progress

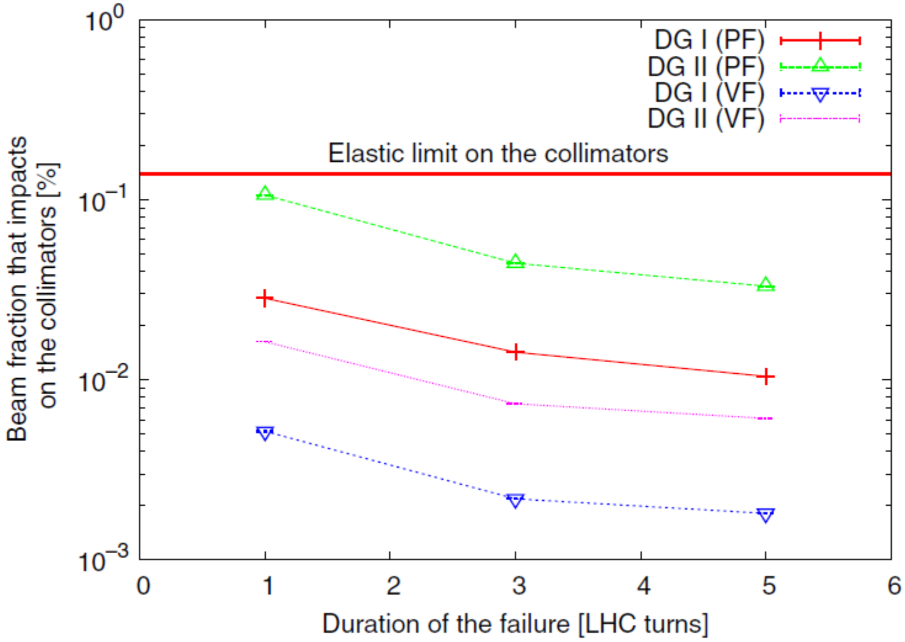
CMS Vernier scans and collimations MDs (2011)



Crab Failures & Particle Losses

- Particle losses on the collimators for simple and double Gaussian bunches for single cavity failure (Voltage: $3.4\mathrm{MV} \rightarrow 0$ or Phase: $0 \rightarrow 90^{0}$)

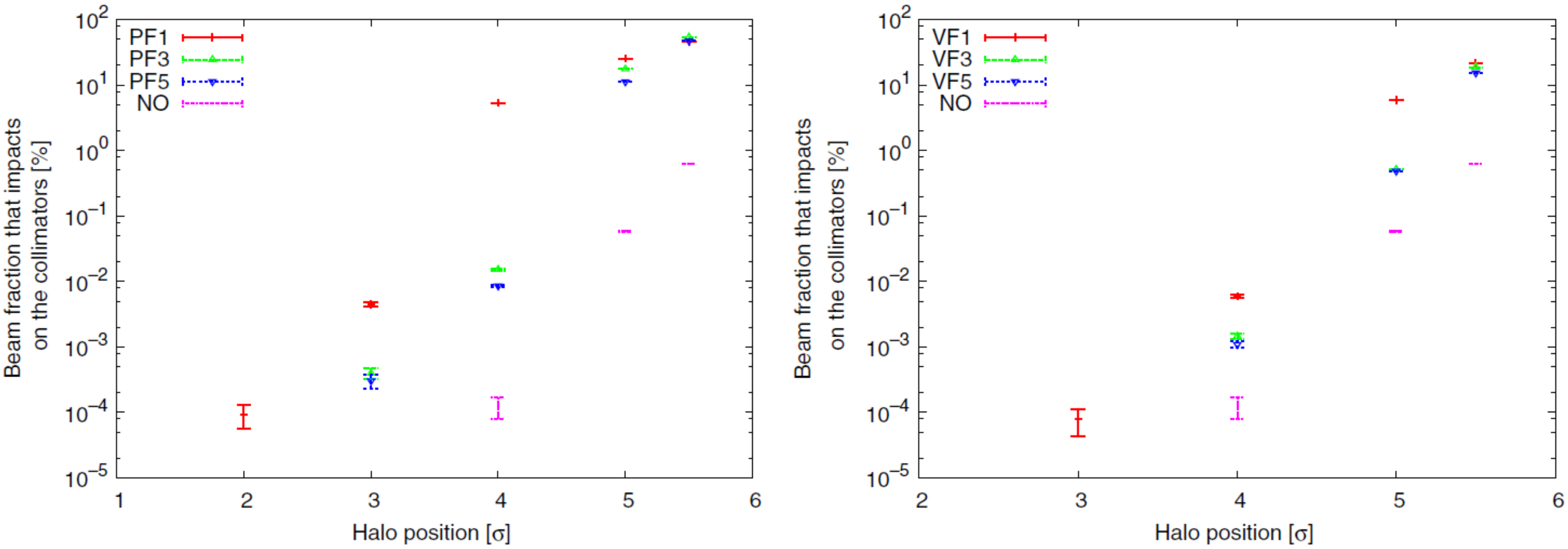




B. R. Yee et al., PRSTAB 17, 051001

Halo-Tracking with Crab Failures

- Thin halo tracked in transverse plane with standard longitudinal distribution is tracked with crab failures

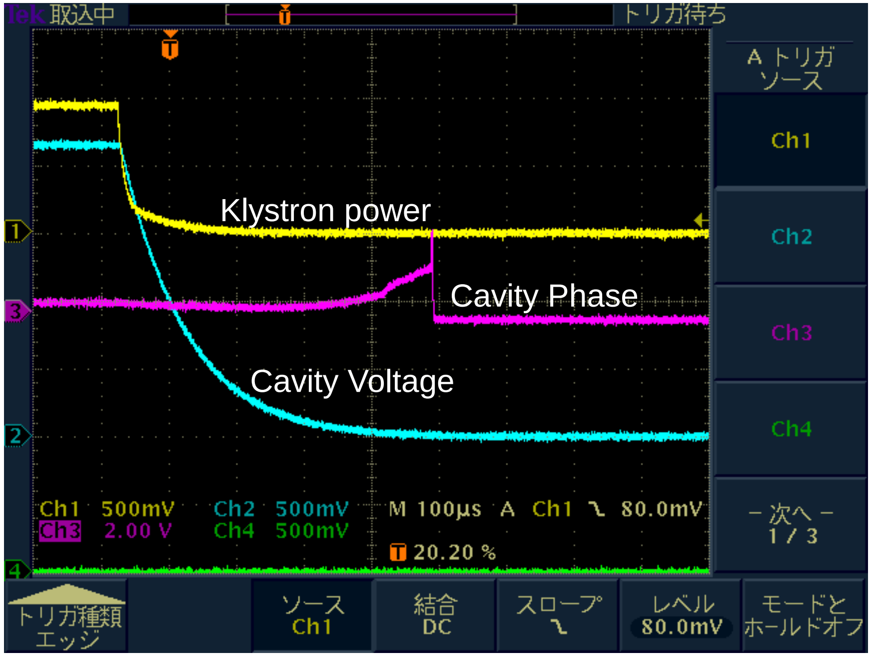


B. R. Yee et al., PRSTAB 17, 051001

KEK-B Failure Observations, No Beam

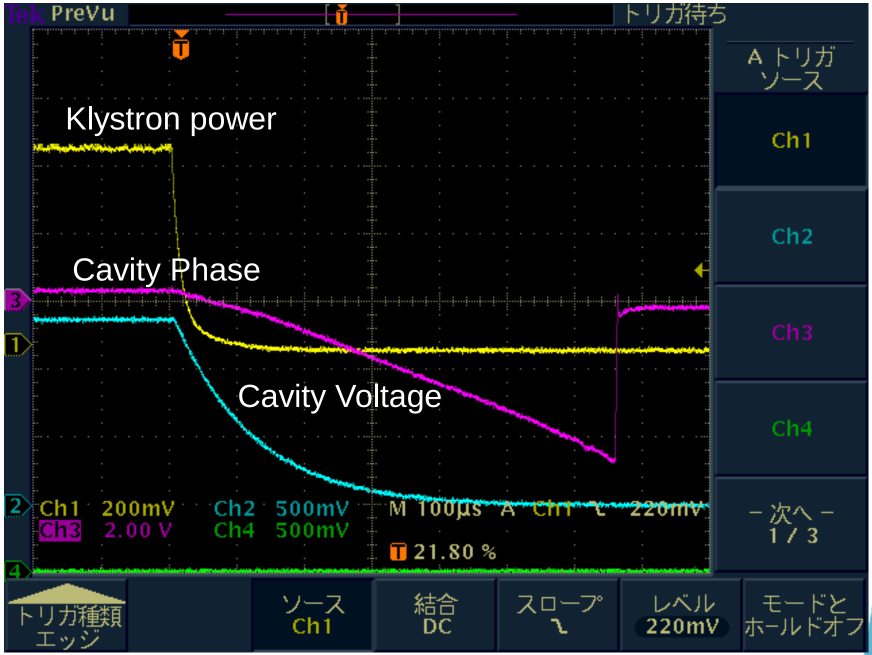
K. Nakanishi, LHC-CC10

HER Ring



$$\tau_{HER} = 84\ \mu s$$

LER Ring

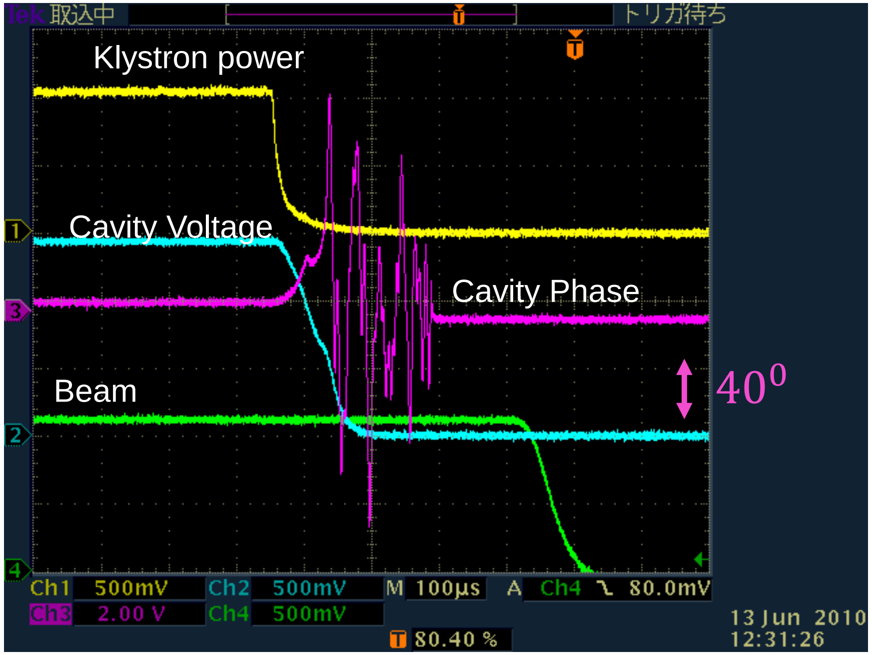


$$\tau_{LER} = 130\ \mu s$$

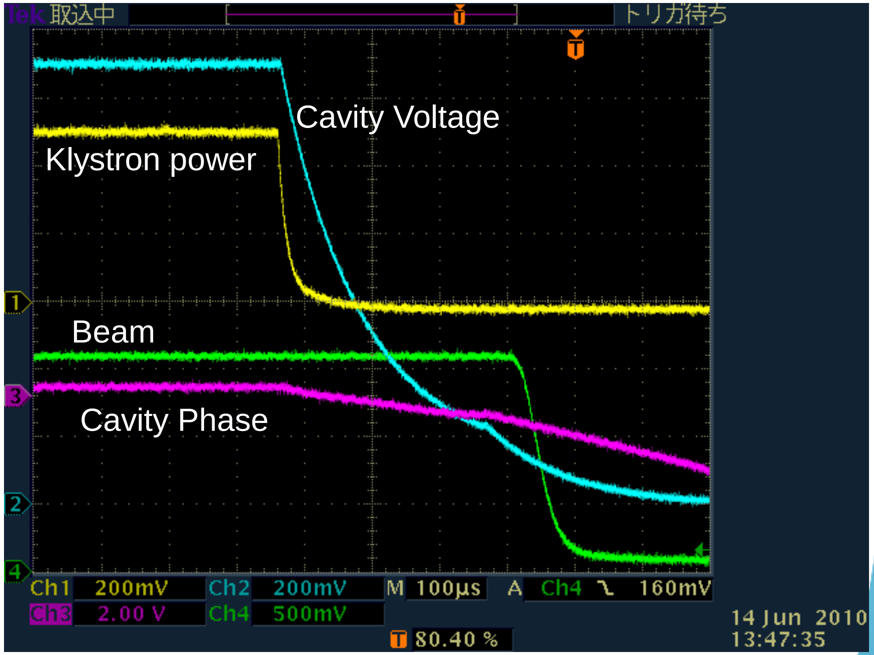
KEK-B Observations, RF Off with Beam

K. Nakanishi, LHC-CC10

HER Ring



LER Ring



KEK-B Observations, RF Off with Beam

K. Nakanishi, LHC-CC10

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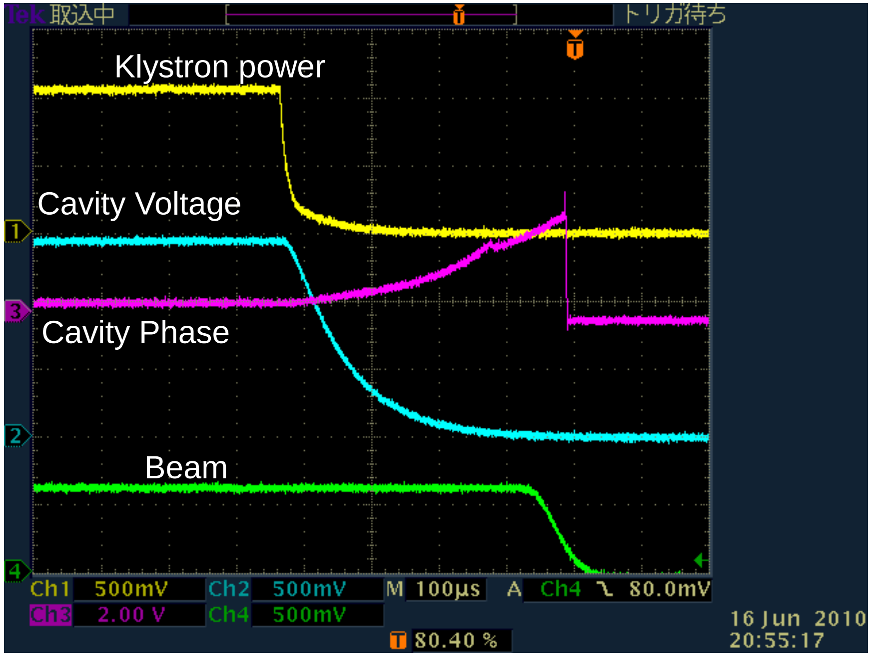
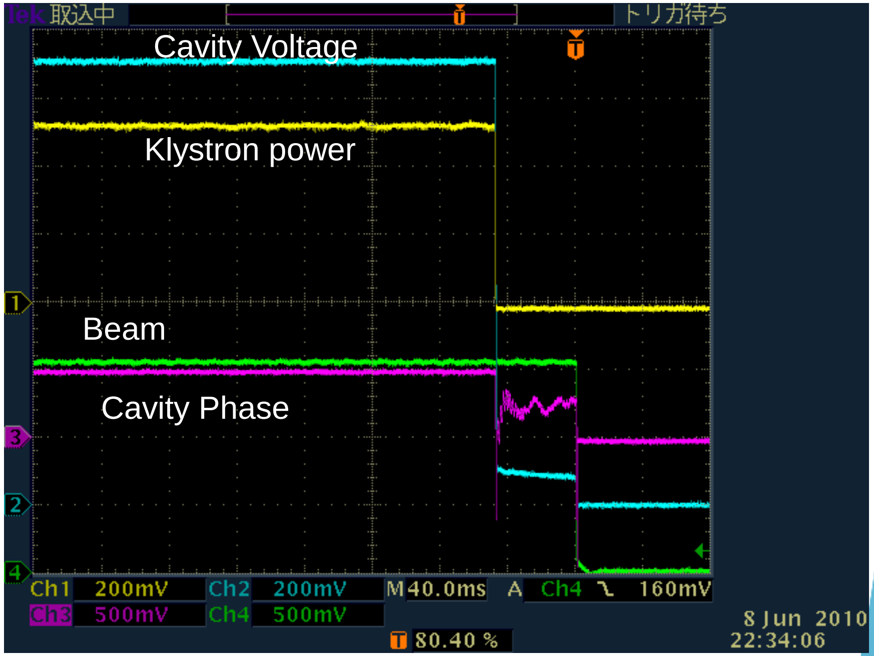
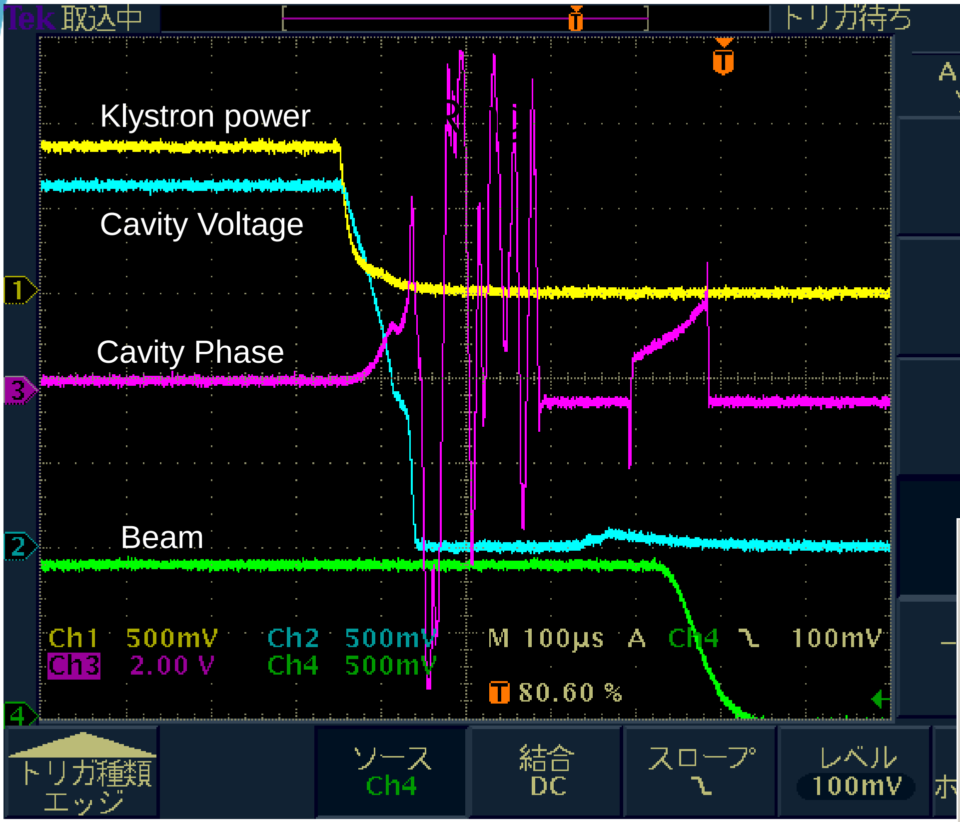


LER Ring



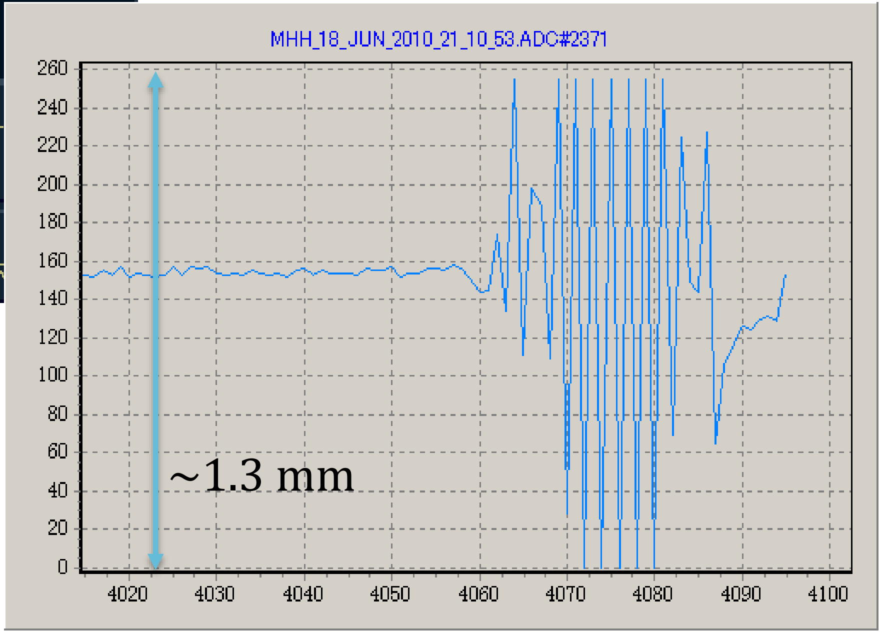
KEK-B Observations, “Beam-Loading”



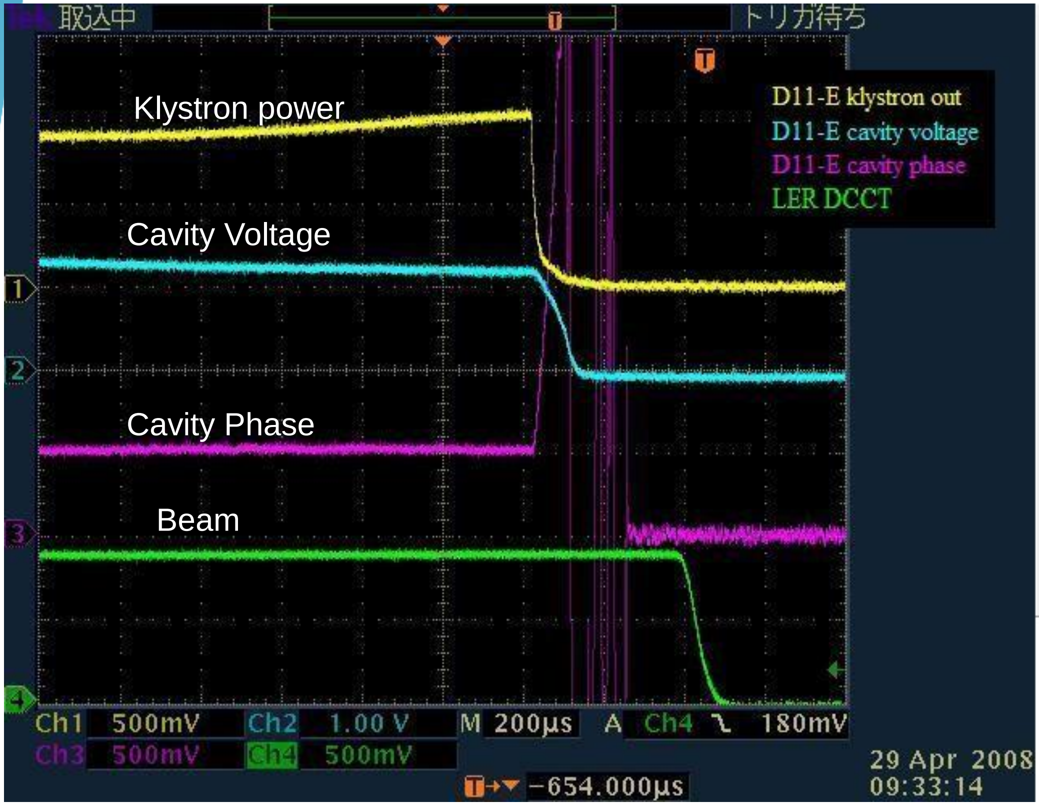
K. Nakanishi, LHC-CC10

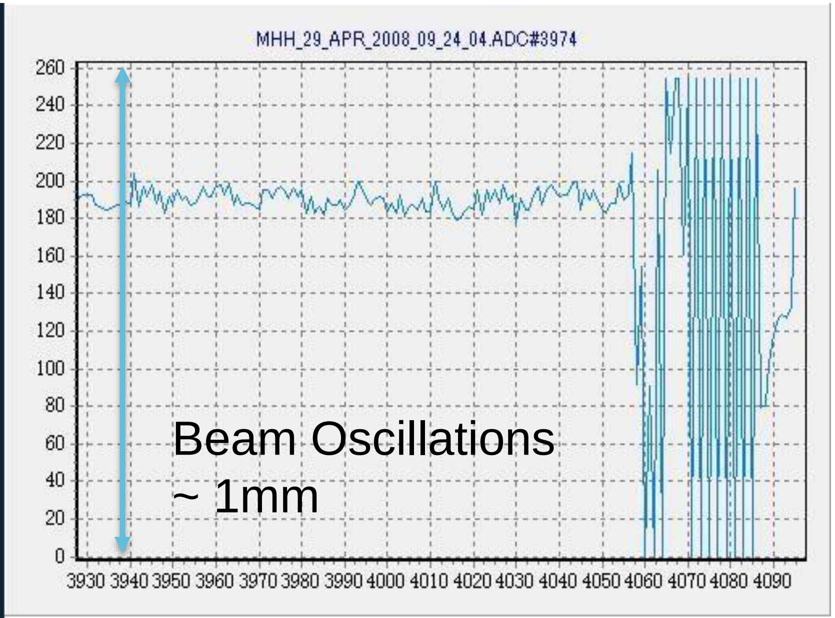
In this case, the positive beam loading don’t help the phase stabilization.

Other experiments show similar results for positive beam loading while negative beam loading has very little effect on the phase



The “Famous Quench” Fast Failure

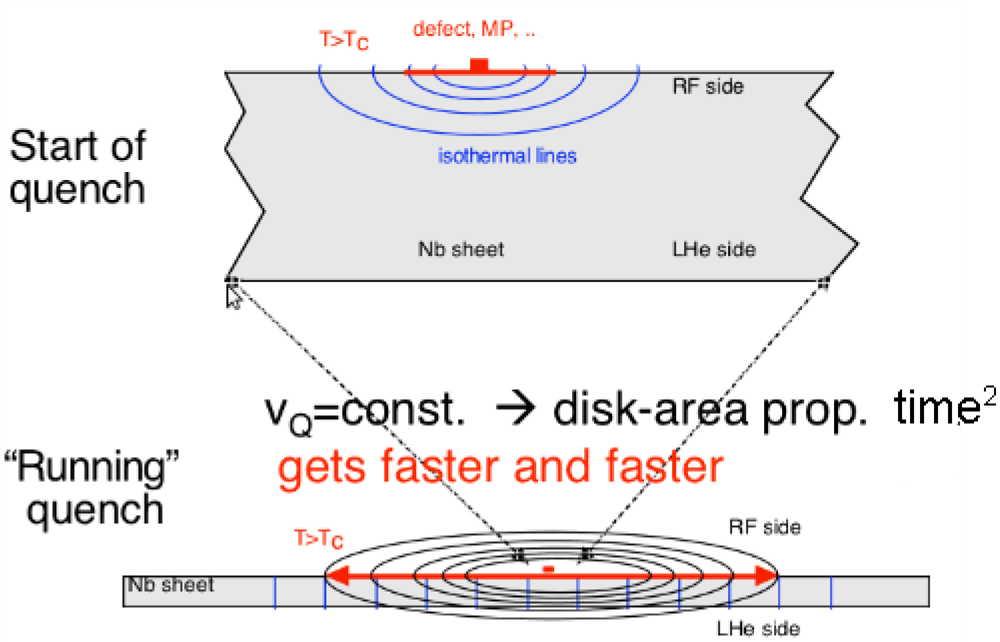




A 90^0 phase change should correspond to $\sim 5\ \mathrm{mm}$ oscillations
Decaying oscillations were seen with RF off and beam induced

Cavity Quench

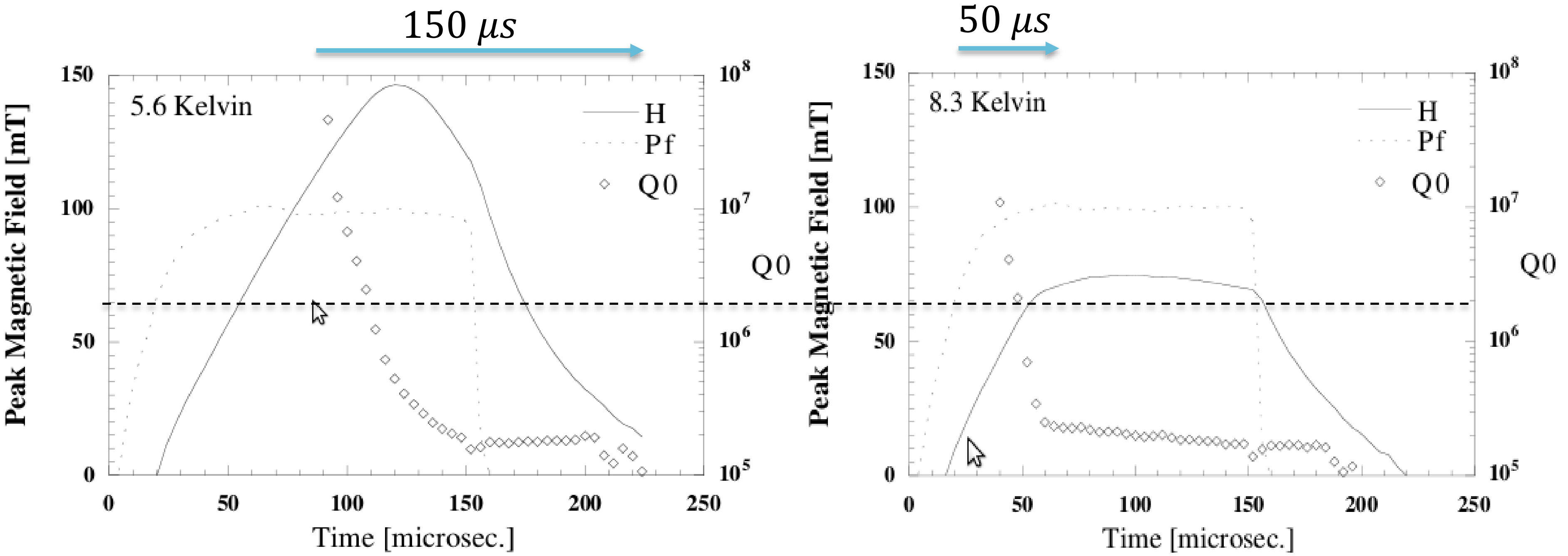
- Slow thermal process (ms): Slow decay of stored energy
- RF feedback will keep voltage set-point until the power limit is reached



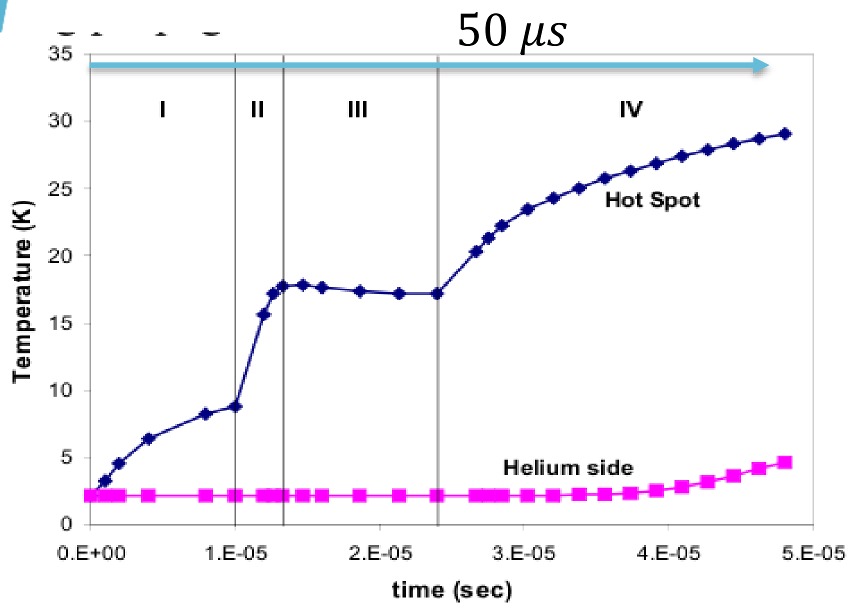
Cavity Quench

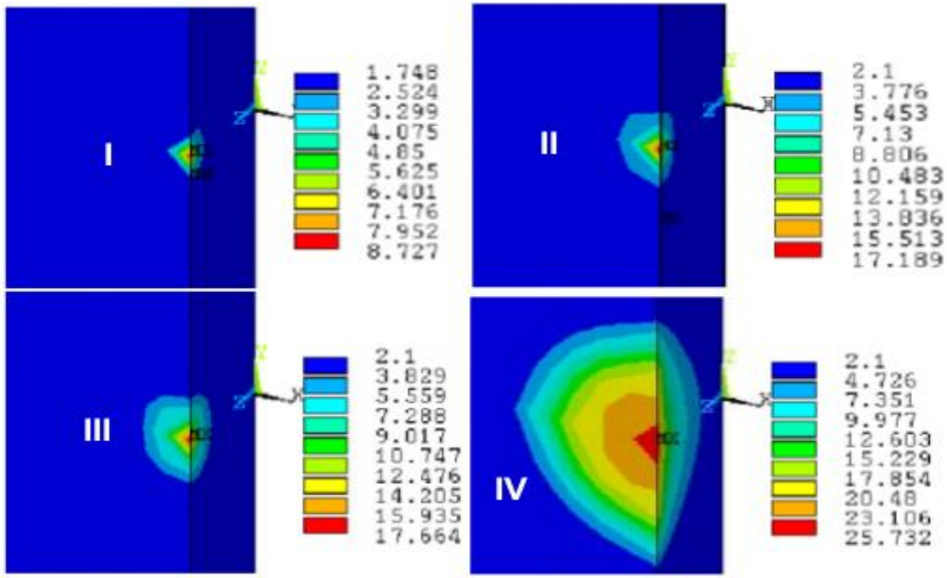
H. Padamsee et al., 1995

- Transient Q_0 measurement using high power RF pulses to induce thermal breakdown
- Determine the super heating field limit H_c



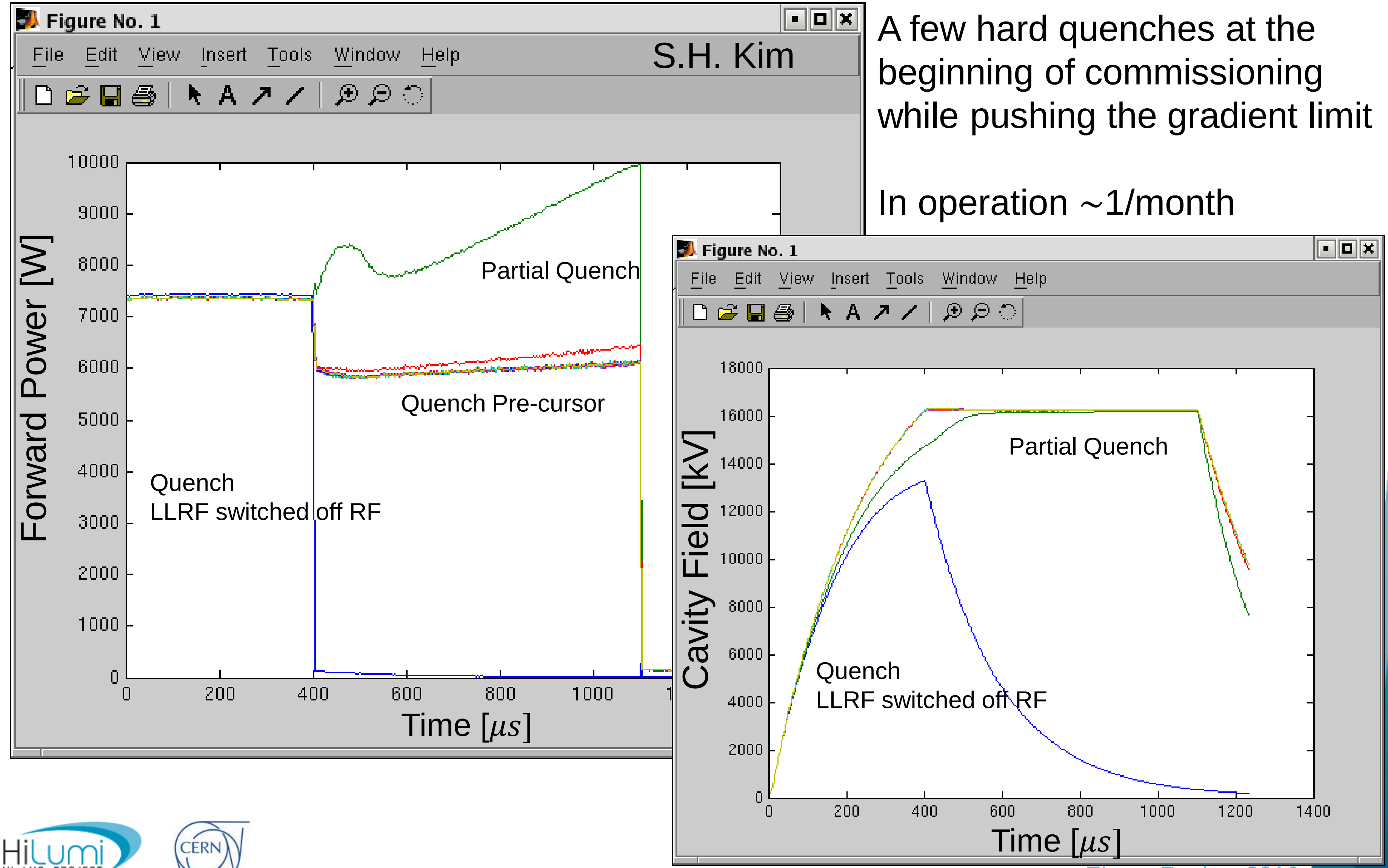
SNS Quench Simulations





Simulations of dynamic evolution of the surface temperature with increasing fields
For example, breakdown from localized defects (ANSYS 3D)

Some SNS Observations



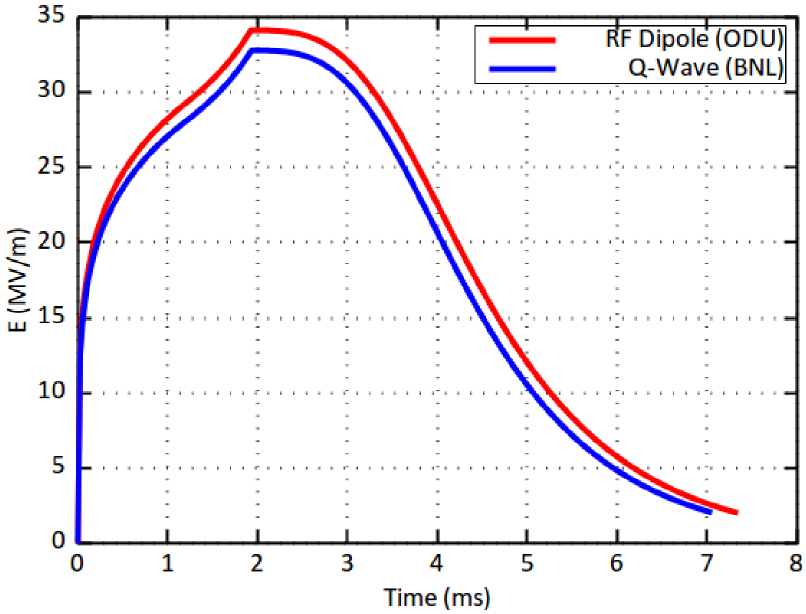
A few hard quenches at the beginning of commissioning while pushing the gradient limit

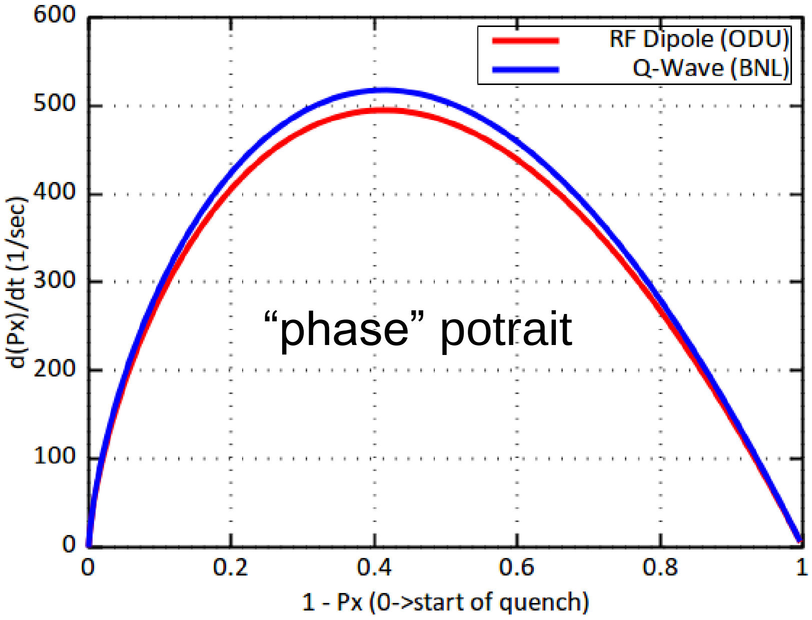
In operation ~1/month

RF Quench Simulations (FNAL)

D. Sergatskov et al., LARP-CM24

- Quench model using thermal defect
- Phase portrait plots (right) have been verified with measurements on spoke cavities
- Energy decay $\tau \sim 2\ \mathrm{ms}$

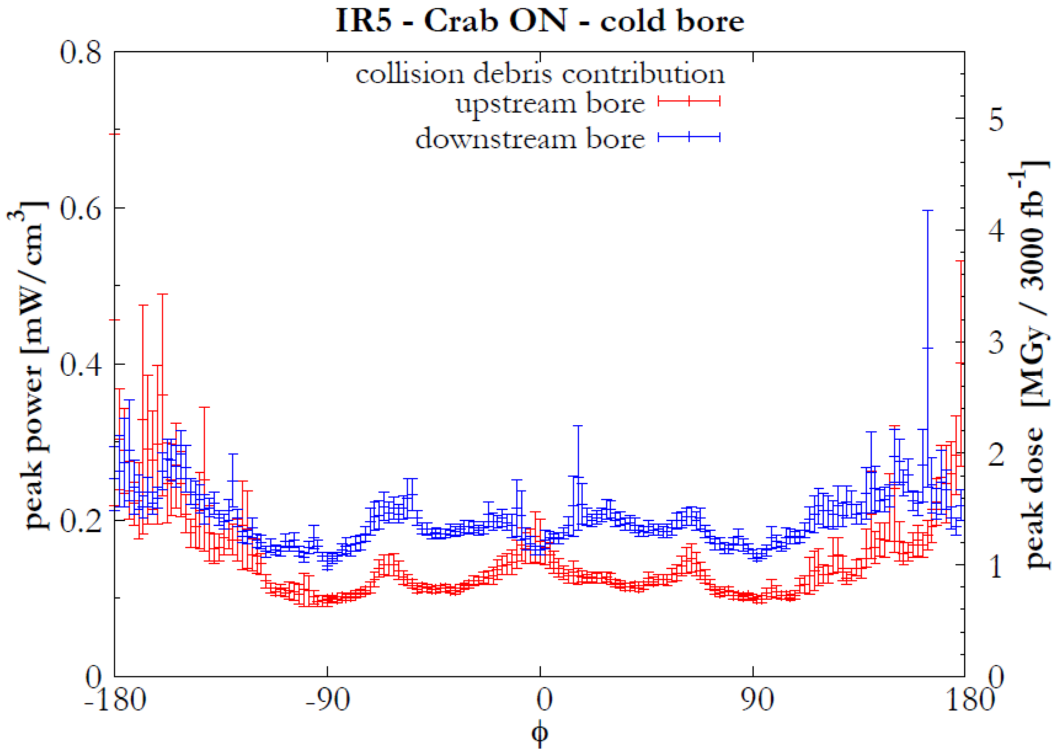




“phase” potrait

Energy Deposition on cold bore

L. Esposito et al., LHC-CC13
Note new dose rates & power losses exist



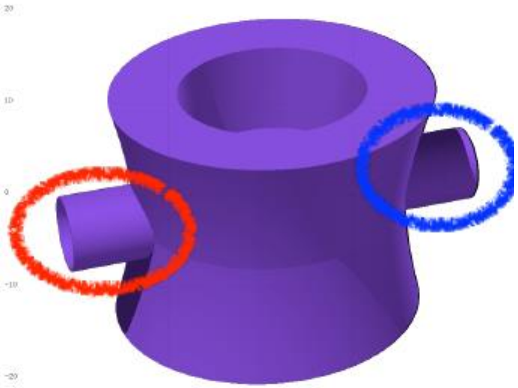
Horizontal plane pointing inside the ring

Pointing downward

Horizontal plane pointing outside the ring

Pointing upward

Horizontal plane pointing inside the ring



Peak power on surface: $0.4\,\frac{\text{mW}}{\text{cm}^3}$

Total power < 0.5 W

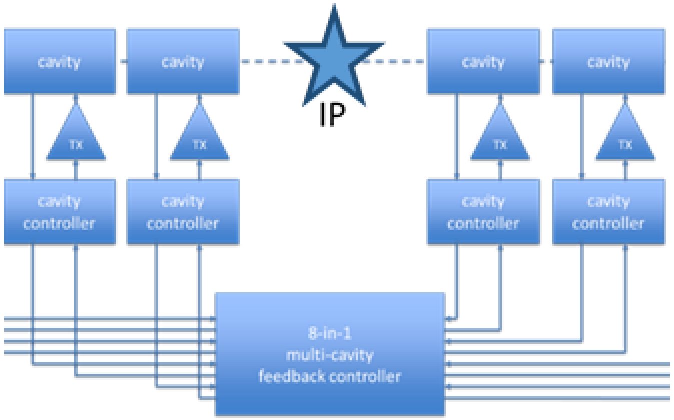
Recall, RF losses $\sim 5 - 10$ W

Peak dose is few Mgy

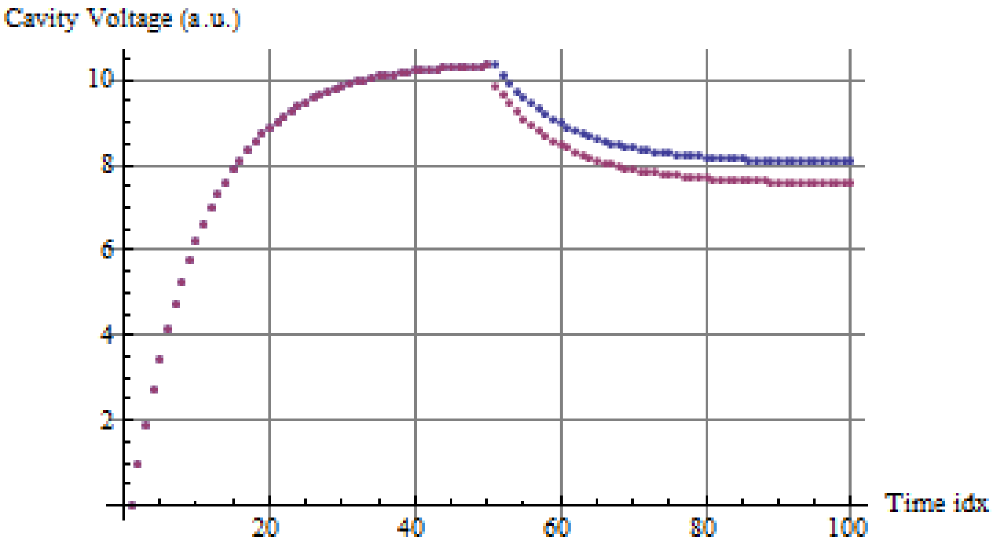
Effect on SRF cavities unknown

Mitigation by Voltage tracking

- $\tau_{cavity} = 400\ \mu s(\ \tau_{LLRF\ local} \sim 1\mu s,\ \tau_{crossIP} \sim 2\ \mu s)$
- The voltage in the LHC cavities across the IP are (can be) regulated w.r.t one another
- Recall, V_t & $\mathrm{I_b}$ are 90^0 out of phase (PW), (i.e.) beam drives crabbing phase



Example voltage tracking across the IP



Final Comments

- Single cavity failure (including 1-turn) seems manageable, multi-cavity failures proportionally worse. Better modeling to improve need of halo-cleaning

- Mitigation over several layers
  - Independent cavity-RF system to minimize multiple failures
  - Operating voltage $\sim 50\%$ below quench field
  - Operating temperature $2\mathrm{K}$ adds to inertia against sudden voltage drop due to quench
  - The large BW $Q_L = 5 \times 10^5$ & $80\ \mathrm{kW}$ RF power helps to compensate strong beam loading
  - β^*- leveling when I_b is highest is likely favorable
  - Tail cleaning with crab cavity shaped noise (if needed) under study

- Main unknown is <u>beam induced failures</u> which will be the focus in SPS tests. Improved modeling with benchmark from SPS tests should clarify the operational sequence

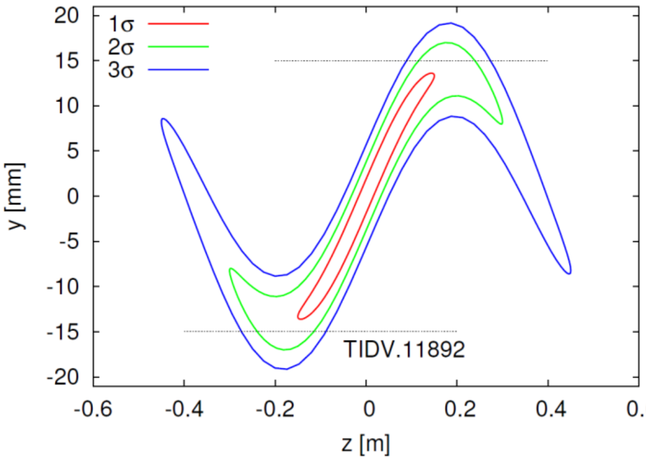
SPS Test Program Summary

- **In-situ cryomodule RF commissioning/testing** in park position
- **RF commissioning** with low-intensity beam, 1-12 bunches
  - *Establish proper RF parameters (operating frequency, amplitude, and phase)*
  - *Verify that CCs are transparent (cavity counter-phasing and detuning)*

- **High intensity** single bunch up to 4x72 trains
  - *Impact on cavity performance (including transient behavior), impedance, stability & machine protection as a function of beam current; interlocks*
  - *Verify cavity stability over many hours (relevant for LHC physics fill)*
- **Long-term behavior** of coasting beams in the SPS with 1-bunch
  - *Study the effects of cavity drifts, emittance growth, non-linear effects such as RF multipoles*

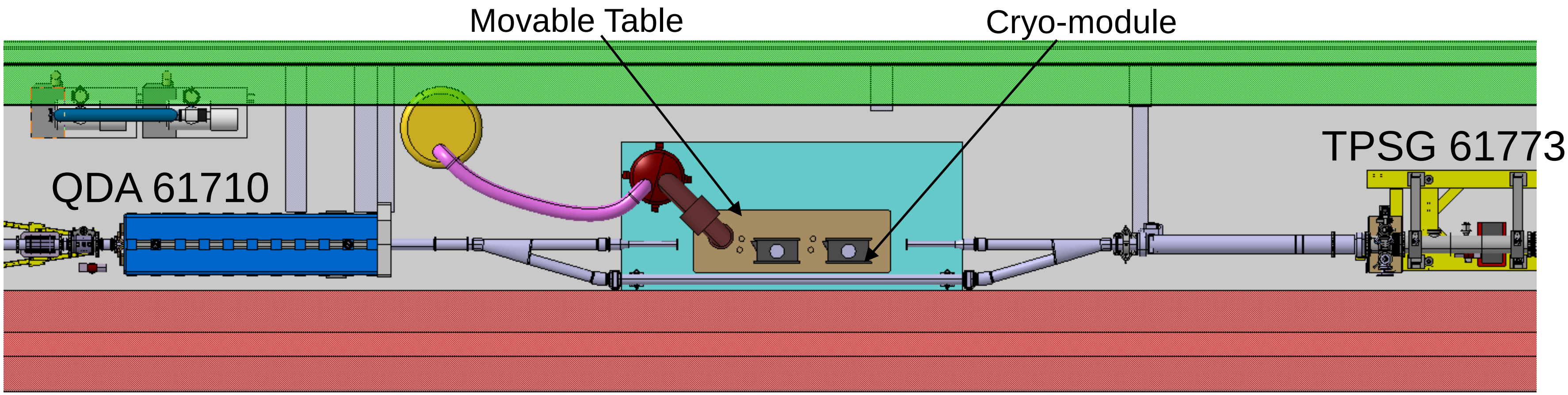
SPS Measurements

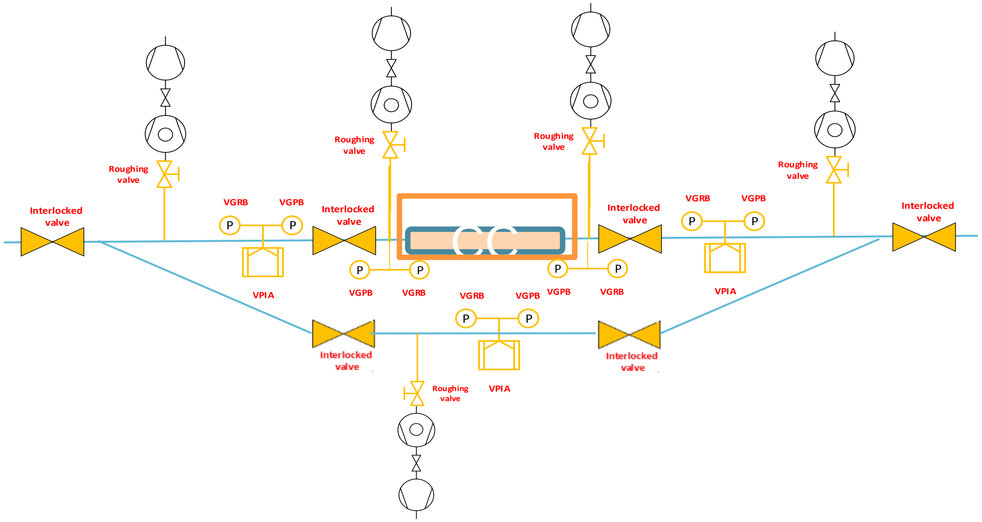
- Beam crabbing (head tail monitor)
- Crab dispersion (standard BPMs)
- Longitudinal collimation (smaller bunch length)
- Emittance growth (wire scanners)
- Crab cavity phase noise (turn-by-turn BPMs)
- Crab cavity b_3 RF multipoles (like ac-dipole)
- Dynamic aperture (on-going simulation)



Motivation is two-fold: Test CCs in view of HL-LHC but also develop techniques for beam based CC qualification for HL-LHC

SPS-LSS6 Implantation





- 11^0 Y-chamber with multiple vacuum sectorization
- Movable table – 510 mm transversely in ~10-20 min with Helium
- Operating pressure $\sim 10^{-10}\mathrm{mbar}$

Courtesy: V. Baglin, F. Galleazzi, G. Vandoni et al.

Tail Cleaning with Crab Cavity Noise

- Shaped noise with approx. Amp vs. freq distribution that is inverse of the tune distribution
- Simulation show good tail cleaning but not with high chromaticity (work in progress)
- Also using single tone analogous to what is presently done in longitudinal plane for emittance blow-up