Crab cavity failure modes and mitigation

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Thanks to Daniel Wollmann, Roderik Bruce, Riccardo De Maria, Helmut Burkhardt, Rama Callaga, Philippe Baudrenghien, Mathieu Valette, Robert Apsimon, Graeme Burt

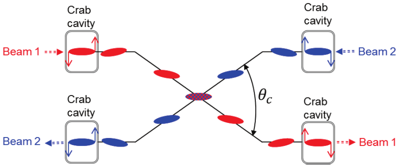
Outline

Crab cavities for HL-LHC

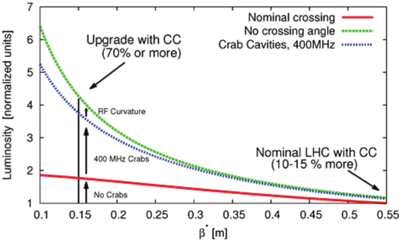
- RF cavities which kick the beam transversly
- RF $\Rightarrow$ kick depends on z
  - At 3.4 MV and 7 TeV, max kick of 0.49 urad
  - Corresponds to 1.6 σ
- Installed around IP1/IP5 to create a z-dependent bump
  - 2–4 cavities per IP/side/beam
  - Bunch head and tail travels through IP at displaced orbit
- Compensates for luminosity loss due to crossing angle

  $\rightarrow$ Can keep the luminosity leveled for longer

  (See talk by H.Burkhardt later today)



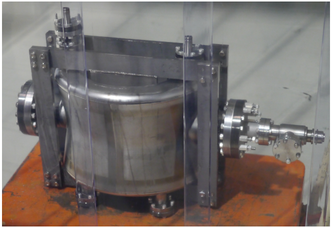
Beam collissions with crab cavity [1]



Luminosity dependence on β^* for the LHC [1]

Crab cavities

- Superconducting cavities
- Made of solid Niobium metal
- Several designs in progress
- Cavity must be compact relative to RF frequency



Double Quarter Wave

RF dipole

Quench

1. Loss of superconductivity
   – phase transition
2. Normal conducting area heats up
   $\Rightarrow$ Starts a runaway process
3. Quenched spot spreads;
   $v \approx 100\ \mathrm{m/s}$
4. Q-factor drops
5. Increased power demand
   to keep field nominal
6. Interlock is triggered, cutting
   power to the cavity
7. The field decays
8. Lorentz force changes,
   cavity detunes

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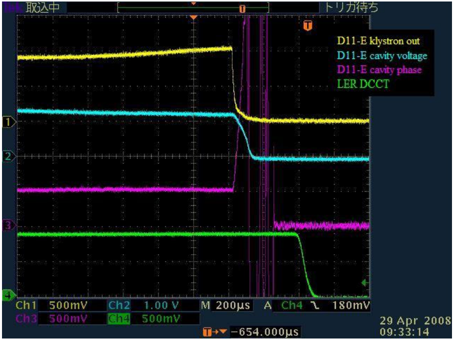
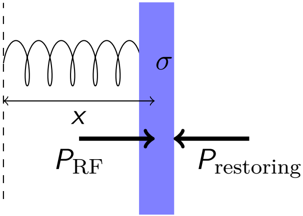


Input power, cavity voltage and phase, and beam current during crab cavity quench at KEK [2]

Controller/LLRF/amplifier problem

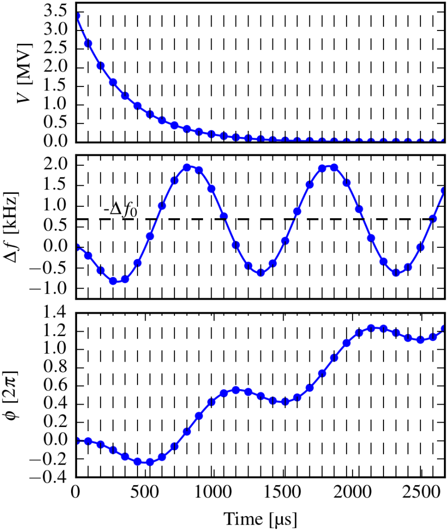
- Cavity is OK
- Input signal is incorrect
  - Technical problem with LLRF, controller, amplifier
  - Operator error
  - Bad input signals
  - ???
- Result limited by input power and cavity parameters [3]
  - Voltage decay: $V(t) = V_0 e^{-t/\tau}$; $\tau \approx 4$ LHC turns
  - Phase shift $\mathrm{d}\phi/\mathrm{d}t \leq \frac{\omega}{2Q_L}\sqrt{\frac{8(R/Q)_\perp Q_L P_\mathrm{max}}{V_0^2} - 1} \approx 60^\circ/\mathrm{turn}$
- Rapidly changing field level may cause detuning

Dynamic cavity behaviour



- For calculating dynamic detuning, need: Cavity mass, stiffness, radiation pressure
- Equation of motion (normalized by area): $P_{\mathrm{RF}} - P_{\mathrm{restoring}} = \sigma \ddot{x}$
- Forces: $P_{\mathrm{RF}} = k_F V^2$, $P_{\mathrm{restoring}} = k_R x$
- Detuning: $\Delta f \propto x$
- With damping: $\frac{\mathrm{d}^2 \Delta f}{\mathrm{d}t} + 2\xi\omega_m \frac{\mathrm{d}\Delta f}{\Delta t} + \omega_m^2 \Delta f = \omega_m^2 K_t V^2$ [4]
  - For illustration: $\omega_m/(2\pi) = 1\ kHz$, $K_t = -200\ Hz/MV^2$, $\xi = 0$
  - Likely overestimated frequency & Lorentz detuning coefficent; cavities are becoming heavier and stiffer.
- In real cavity, multiple mechanical modes present
- Not taking into account external forces (helium boiling, etc.) that may also shock the cavity

Dynamic cavity behaviour – plots for illustration ($f_m = 1$ KHz, $K_t = -200\ Hz/MV$, $V_0 = 3.4\ MV$)



Simulation setup

- HL-LHC v1.2
- 2 crabs / IP / side / beam
- Opening voltage 3.4 MV/cavity (Nominal for 4 crabs $\approx$ 2.8 MV/cavity)
- Closing voltage matched to minimize orbit beating
- Cavity failure simulations:
  - Fail upstream cavities
  - Failures of Beam 1 (and Beam 2)
  - Failures in IP1 and IP5
- Tracked for 200 turns, including 150 before failure
- SixTrack v4.5.38

Collimator settings:

IR	*Element*	*Setting*
IR7	Primary	**5.7**
	Secondary	7.7
	Absorber	10.0
IR3	Primary	15.0
	Secondary	18.0
	Absorber	20.0
IR6	Secondary	8.5
	Dump prot.	9.0
IPs	TCT (IP&5)	10.9
	TCT (IP2)	30.0
	TCT (IP8)	15.0

Settings are in σ relative to $\epsilon_\mathbf{n} = \mathbf{3.5}\ \mu\text{m}$

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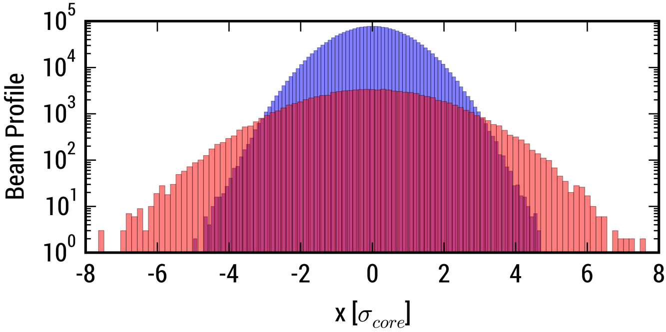
Simulation setup – beam distribution

Transverse

- Double gaussian distribution [5]
- 95% in the core, $\epsilon_N = 2.5\mu m$
- 5% in the tail, $\sigma_{\text{tail}} = 1.8\,\sigma_{\text{core}}$



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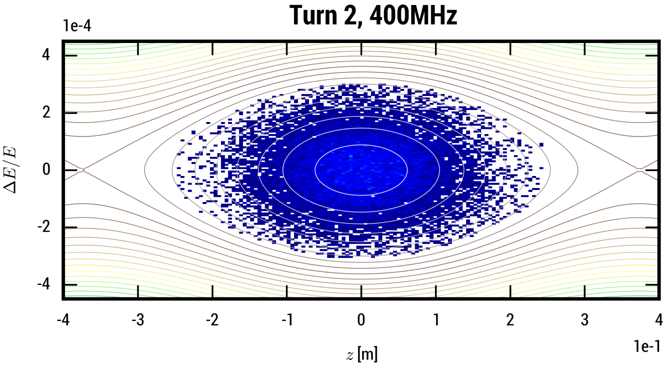
Longitudinal

- Multivariate Gaussian
- Fitted to bucket with some margin



Simulated failure scenarios

Cavities as seen by the beam:

- *z*-dependent transverse kick

  (and a small *z* and *x*- or *y*-dependent longitudinal kick)

- Depends on phase ϕ & voltage V
- $\phi(t) = \int_0^t 2\pi \Delta f(t')\,\mathrm{d}t'$

Scenarios for simulation:

- 60° phase jump (2,3,4 cavities)
- Exponential voltage decay
- Phase sweep (detuning)
- Voltage decay + Lorentz force detuning

Scenarios selected to show impact of different parameters

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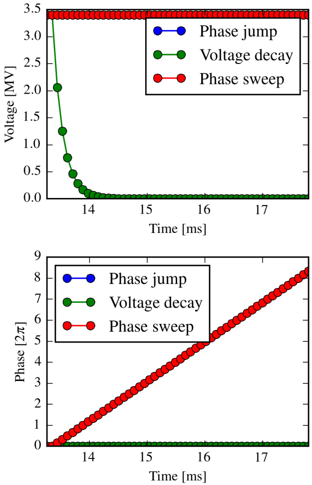

Losses – overview B1 / ATLAS (percent of beam)

Scenario	5 turns	50 turns
Voltage decay	0.001	0.028
Voltage decay + Lorentz detune	0.003	0.032
60° phase jump	0.075	0.217
60° phase jump (3 cav.)	0.935	1.919
60° phase jump (4 cav.)	9.480	15.305
60°/turn detune	0.357	0.857
120°/turn detune (≈ tune)	5.921	100

- Small losses from voltage decay
  - As long as orbit stays centered! (change in beam-beam kick?)
- Anything phase-related quickly increases the losses
- Increasing total voltage ⇒ deeper "cut"
- Detuning can excite orbit oscillations
- Variation between the IPs – to be studied...
- Exact numbers affected by beam distribution

Losses – overview B1 / CMS (percent of beam)

Scenario	5 turns	50 turns
Voltage decay	0.004	0.057
Voltage decay + Lorentz detune	-	-
60° phase jump	0.138	0.359
60° phase jump (3 cav.)	3.181	6.162
60° phase jump (4 cav.)	25.612	35.587
60°/turn detune	2.043	5.877
120°/turn detune ($\approx$ tune)	-	-

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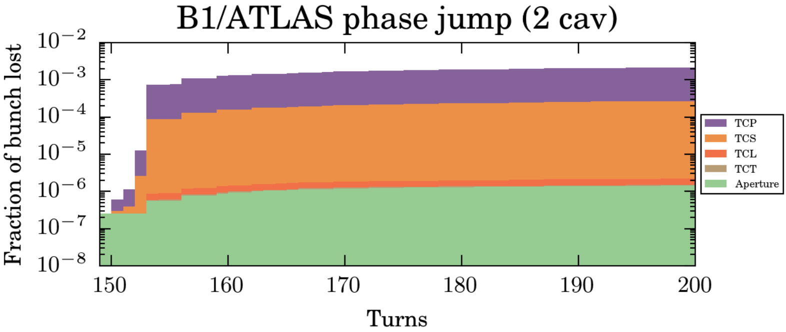
Losses – time



- Rapid initial rise
- 3-turn oscillation of losses (1/Q)
- Beam should be dumped 3-5 turns after failure
- After the initial fast rise, losses rise "slowly"

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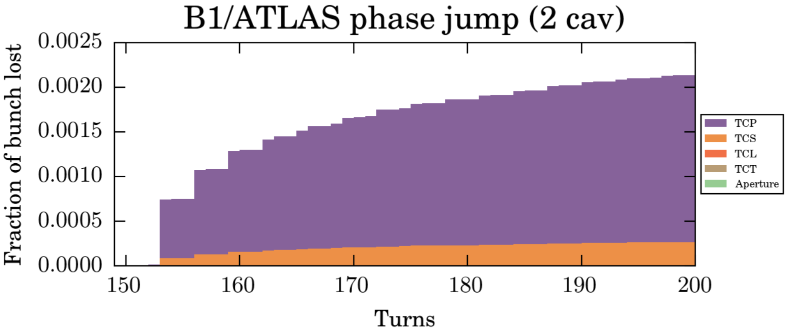

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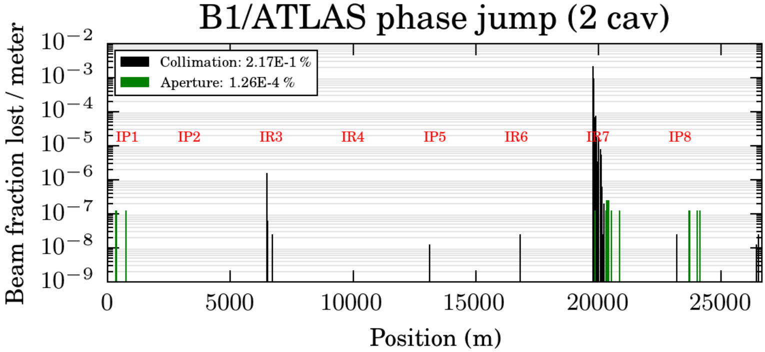
Losses – distribution



- Most losses in IR7
- Some leakage to first bend

Mitigation possibilities – quench

- Even the "mild" scenarios see losses in the 1‰ range
  - This corresponds to 0.7 MJ
    – almost at collimation limit (1 MJ)
  - Dump beam ASAP (3-5 turns)
- Key: Early detection of problem
  - While the cavity is still controllable
  - Use rising input power demand
- Keep field as stable as possible
  - Keep cavity on frequency and phase!
  - Let voltage voltage drop if power demand too high
- If possible, synchronize non-failed side
- Complication:
  Beam loading may make detection more difficult
  - Look at correlations between cavities or use BPM

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Summary

- Losses seem manageable
- Most of the losses are in IR7
- For "small failures", beam distribution is important
  – electron lens may help
- Losses rise rapidly
- In case of failure, dump the beam ASAP
- Simulations highlights the importance
  of controlling the cavity phase
- Need reliable ways to detect failures,
  ideally while field is still nominal

Outlook

Ongoing simulation work:

- Understand B2 and IP5 results
- Study effect of beam-beam kick
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In general:

- SPS test should be enlightening
  - Cavity with low Q_L and high field
  - LLRF system
  - Beam loading
- Need to find good failure detection mechanisms

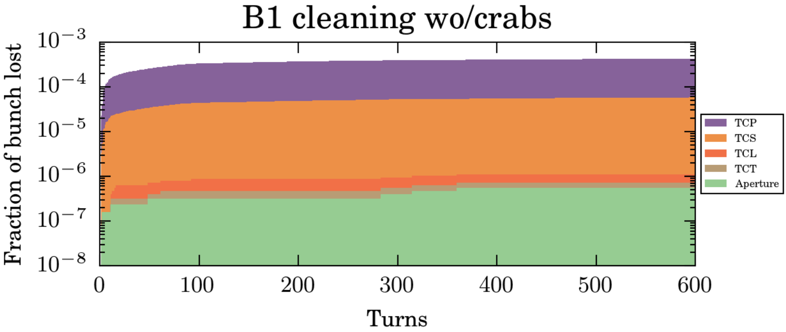
Bibliography I

- [1] Q.Wu: *Crab cavities: Past, present and future of a challenging device*; IPAC'15
- [2] K.Nakanishi, Y.Funakoshi, M.Tobiyama: *BEAM BEHAVIOR DUE TO CRAB CAVITY BREAKDOWN*; IPAC'10
- [3] A. Santamaría García, K.Sjobak, R.Bruce, H.Burkhardt, F.Cerutti, R.Kwee-Hinzmann, A.Lechner, A.Tsinganis *MACHINE PROTECTION FROM FAST CRAB CAVITY FAILURES INTHE HIGH LUMINOSITY LHC*; IPAC'16
- [4] K.Sjobak, R.Bruce, H.Burkhardt, A.MacPherson, A.Santamaría García, R.Kwee-Hinzmann *Time scale of crab cavity failures relevant for high luminosity LHC*; IPAC'16

Bibliography II

[5] Bruce Yee-Rendon, Ricardo Lopez-Fernandez, Javier Barranco, Rama Calaga, Aurelien Marsili, Rogelio Tomás, Frank Zimmermann, and Frédéric Bouly *Simulations of fast crab cavity failures in the high luminosity Large Hadron Collider* Phys. Rev. ST Accel. Beams 17, 051001, 6 May 2014

Matching the distribution



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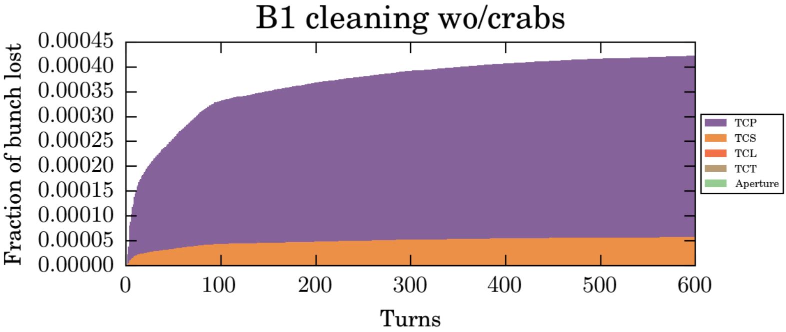

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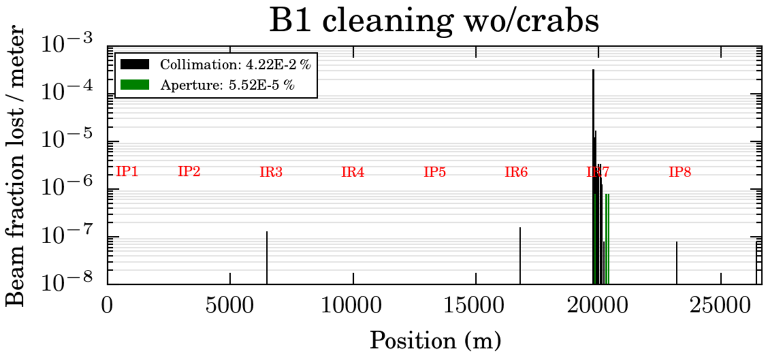
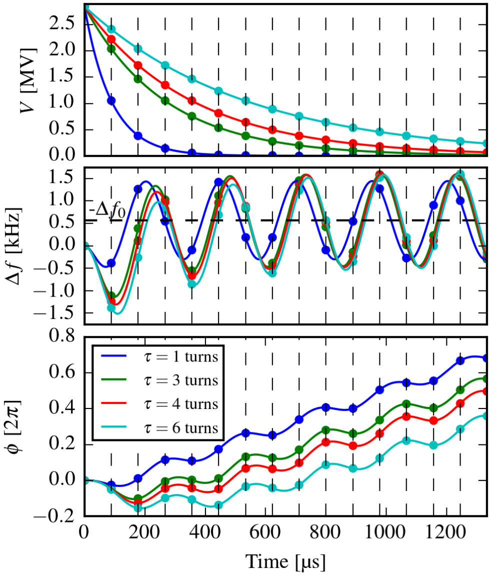


Lorentz detuning – scan τ [4]



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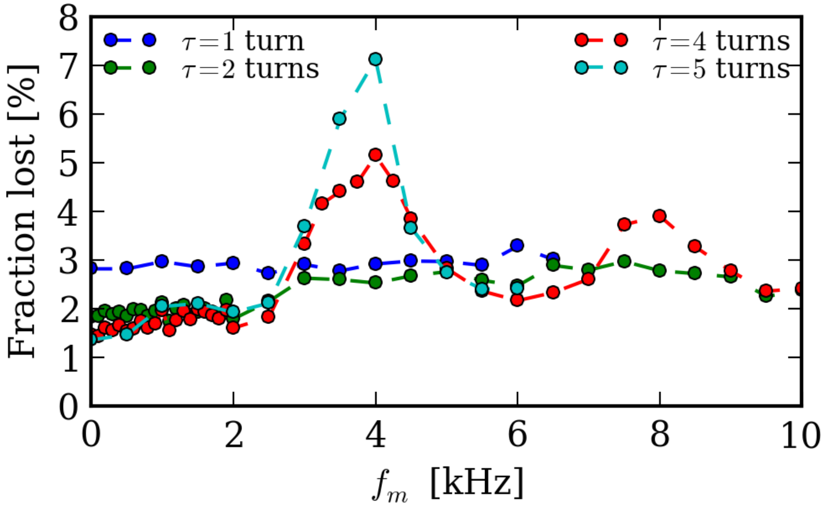
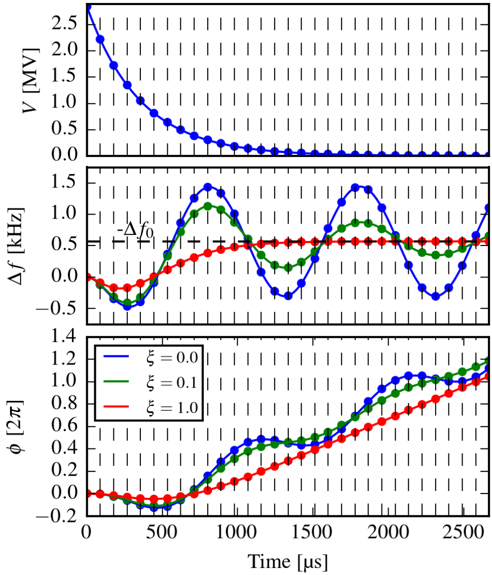


Lorentz detuning – scan ξ [4]



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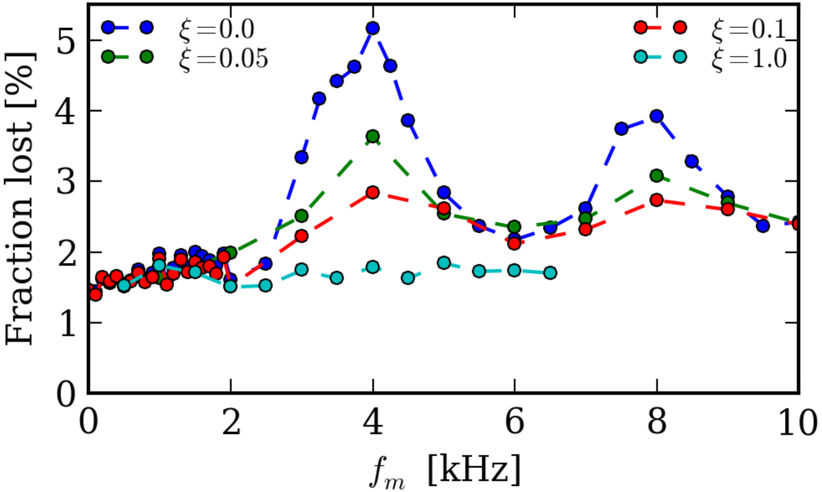

Lorentz detuning – loss time [4]