LHC Crab Cavities and Related Machine Protection

DESY & UHH AccPhySem
Tobias Baer
July, 3rd 2012

1. LHC Upgrade Scenarios and Crab Cavities
2. Failure Scenarios and Analytical Approach
3. Static Failure Simulations (MAD-X)
4. Dynamic Failure Simulations (MAD-X)
5. Mitigation and Conclusion
1. LHC Upgrade Scenarios and Crab Cavities

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5. Mitigation and Conclusion
LHC Upgrade Programs

Today

- p-p and p-pb^{82+} collider.
- 7 TeV/beam.
- Luminosity: $10^{34} \text{cm}^{-2} \text{s}^{-1}$.

**LEP**
- Construct. 
- Physics 
- Upgr

**LHC**
- Design, R&D 
- Proto 
- Construct. 
- Physics

**HL-LHC**
- Design, R&D 
- Construct. 
- Physics

- 27 km long.
- e^+ – e^- collider.
- 105 GeV/beam.

**LHeC**: hadron-e^- collider.

**LEP3**: e^+ – e^- collider, >120 GeV/beam.

**HE-LHC**: 20T dipole magnets, **16.5 TeV/beam**.

- Peak luminosity (virtual) > $2 \cdot 10^{35} \text{cm}^{-2} \text{s}^{-1}$.
- Larger bunch intensity.
- **Smaller beam size** at interaction point ($\beta^*$).
- Requires **luminosity leveling** to limit average **pile-up to \(\approx 140\)**.

O. Brüning and F. Zimmermann, IPAC12, MOPPC005

July, 3rd 2012

Tobias Baer
Geometric Luminosity Loss

- The crossing angle (to mitigate long-range beam-beam) leads to a geometric luminosity reduction.

- **Crab cavities** have a time dependent transverse deflection and can restore the geometric luminosity loss (and level the luminosity).

\[ \theta \propto \frac{1}{\sqrt{\beta^*}} \]

W. Herr

I. Ben-Zvi et al., HHH-2008
Crab Cavity Status

• Crab cavities are used in KEKB since 2007.
• Enormous advance in compact crab cavity design.
  
  Three designs, 400 MHz, 3 MV kick, r < 150 mm.
  
  First prototypes are constructed.

• Still several main challenges ahead:
  RF noise, impedance, machine protection, …

KEKB crab cavity.

ODU/JLAB/SLAC  ULANC  BNL
LHC Machine Protection

- Main challenge: Beam energy of **362MJ** (HL-LHC: up to **700MJ**)
  
  \[
  \text{Damage level (sensitive equipment): } \approx 10\text{kJ} \quad \text{R. Schmidt, Pac07}
  \]
  
  \[
  \text{Quench limit of superconducting elements: few mJ/cm}^3
  \]

- Over 200 protection systems can request a beam dump
  
  \[
  4000 \text{ BLMs (40\(\mu\)s resolution), power converter, software interlock system, etc.}
  \]

Up to \(\approx 3\) turns between failure detection and beam dump.
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KEK Crab Cavity Quench

- Full decay of crab cavity in $\approx100\mu$s ($\approx1$ turn).
- Oscillations of Crab Cavity phase (up to 50° in 50$\mu$s).

K. Nakanishi et al., IPAC’10, WEPEC022.
Analytical Approach

- Transverse deflection by crab cavity:
  \[ x'_{cc}(z) = -\frac{q \cdot V}{E} \cdot \sin \left( \Phi + \frac{\omega \cdot z}{c} \right) \]

- Optimal voltage to compensate crossing angle:
  \[ V_0 = \frac{c \cdot E \cdot \tan \left( \frac{\Theta}{2} \right)}{q \cdot \omega \cdot \sqrt{\beta^*} \beta_u \cdot \sin(\Delta \varphi) \cdot n_{cc}} \]

- Maximal transverse displacement by CC:
  \[ \frac{\bar{x}_{cc}(z)}{\sigma_x} = -\frac{c \cdot \tan \left( \frac{\Theta}{2} \right)}{\omega \cdot \sigma_x,IP \cdot \sin(\Delta \varphi) \cdot n_{cc}} \cdot \sin \left( \Phi + \frac{\omega \cdot z}{c} \right) \]
  \[ = 4.05 \] (upgrade optics, \( \beta^* = 15 cm \), \( n_{cc} = 1 \))

\( \sigma_x \) = horizontal beam size
\( q \) = particle charge
\( E \) = particle Energy (7 TeV)
\( V \) = voltage of crab cavity
\( \Phi \) = phase of crab cavity
\( \Theta \) = full crossing angle (590/285µrad)
\( \varphi \) = phase advance CC -> IP (= \( \pi/2 \))
\( \omega \) = angular frequency of CC (2 \( \pi \cdot 400 \) MHz)
\( z \) = longitudinal position of particle
\( c \) = speed of light
\( n_{cc} \) = number of independent CCs per beam on either side of IP.

<table>
<thead>
<tr>
<th></th>
<th>upgrade optics</th>
<th>nominal optics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximal displacement with ( \sin \left( \Phi + \frac{\omega \cdot z}{c} \right) = 1 )</td>
<td>( 4\sigma_x )</td>
<td>( 1\sigma_x )</td>
</tr>
<tr>
<td>For ( z = 7.55 cm = 1 \cdot \sigma_z ):</td>
<td>( \bar{x}_{cc}(z = 7.55 cm) \approx 2.36\sigma_x )</td>
<td>( 0.60\sigma_x )</td>
</tr>
</tbody>
</table>
Failure Scenarios

Slow (external) failures
- Power cut
- Thermal problems
- Mechanical changes (tuner problem)

Fast external failures
- Control-logics failure
- Operational failure
- Equipment failure
- …

Timescale determined by $Q_{ext}$

Internal failures
- Arc in coupler
- Multipacting
- Cavity quench

Timescales $< 1$ turn possible.

J. Tuckmantel, „Failure Scenarios and Mitigation“, LHC-CC10
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Failure Simulations

- MAD-X tracking studies (thintrack module)
- Crab cavity local scheme IP5, beam 1.
- **No splitting of crab cavity kicks.**
- Optics:
  - SLHCv3.1b, $\beta^* = 0.15m$ (IP1/5), $\beta^* = 10.0m$ (IP2/8), $\Theta = 590 \mu$rad.
  - Nominal optics, $\beta^* = 0.55m$ (IP1/5), $\beta^* = 10.0m$ (IP2/8), $\Theta = 285 \mu$rad.
- Instantaneous failure of single crab cavity, constant (e.g. at $V=0$) afterwards.
- Tracking for $\approx 20$ turns.
Voltage Failure

- Instantaneous change of voltage of CC.R5.B1 to zero.
- **Beam losses mainly at primary collimator** (TCP.C6L7.B1).

Upgrade optics SLHC3.0 4444_thin,
IP1/5: $\beta^* = 0.15m$, $\Theta = 580\mu$rad, CC Local scheme IP5, 400/10,000 particles,
Gaussian particle distribution $\epsilon_n = 3.75\mu m \cdot rad., \sigma_z = 7.55cm.$
Bunchshape at primary collimator TCP.C6L7.B1 directly after failure.
Bunchshape at primary collimator **TCP.C6L7.B1**, 1 turn after failure.

Static Failure of CC.R5.B1

Bunchshape at primary collimator TCP.C6L7.B1, 2 turns after failure.

![Graph showing bunchshape with 5.7σ deviation]
Maximal Displacement

To isolate effect of CC failure and to be independent of particle distribution:

• Maximal displacement:

\[ \bar{x} = \sqrt{x_\beta^2 + (\alpha \cdot x_\beta + \beta \cdot x'_\beta)^2} \]

with \( x_\beta = x - D_x \cdot \frac{\Delta p}{p}, \) \( x'_\beta = x' - D_{px} \cdot \frac{\Delta p}{p} \).

constant around LHC (apart from IRs).

• Initial consitions:

\( x, x', y, y', \frac{dp}{p} = 0. \)

• Displacement of up to \( 5\sigma \) (\( n_{cc} = 1 \)).

up to \( 1.7\sigma \) with \( n_{cc} = 3 \).
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Fast external failures (e.g. control/operational failure):

- Time constant of crab cavity failures:
  \[ \tau_0 = \frac{Q_{\text{ext}}}{\pi f} \approx 1\text{ms} \approx 11 \text{turns}. \]

- Maximal voltage change per turn:
  \[ \frac{\Delta V}{V} = 2 - 2\exp\left(-\frac{89\mu s}{1\text{ms}}\right) = 17\%. \]

- Phase change in first turn:
  \[ \arctan\left(\frac{\Delta V}{V(1-\Delta V/V)}\right) = 5.3^\circ. \]

\(Q_{\text{ext}}\) determines time constant of fast external failures.

T. Baer et. al, „LHC Machine Protection Against Very Fast Crab Cavity Failures“, IPAC’11, J. Tuckmantel, CERN-ATS-Note-2011-002 TECH
Voltage Failure

- **Dynamic voltage change** of CC.R5: $V_0 \rightarrow -V_0$.
  
  $Q_{\text{ext}} = 1'250'000$.
  
  *Failure starts after turn 10.*

- Resulting maximal displacement in 5 turns with $n_{cc}=1$:

  $$
  \bar{x} = 2.1\sigma_x \text{ at } z = \pm 2.4\sigma_z,
  $$

- **The (longitudinal) bunch center is not displaced.**
In case of a **dephasing** of the crab cavities, the (longitudinal) **bunch center** is maximally displaced by up to **2. $1\sigma_x$ in 5 turns** ($n_{cc}=1$).
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Scaling Laws

\[
\frac{\bar{x}_{cc}(z)}{\sigma_x} = -\frac{c \cdot \tan\left( \frac{\Theta}{2} \right)}{\omega \cdot \sigma_{x,IP} \cdot \sin(\Delta \varphi) \cdot n_{cc}} \cdot \sin\left( \Phi + \frac{\omega \cdot z}{c} \right)
\]

\[\propto \frac{1}{\omega \cdot \beta^* \cdot n_{cc}}\]

if only one CC is affected, i.e. no common failure scenarios

The maximal displacement for \( \sin\left( \Phi + \frac{\omega \cdot z}{c} \right) = 1 \).
Highly overpopulated tails observed: 

*In horizontal plane about 4% of beam beyond $4 \sigma_{\text{meas}}$.  
Corresponds to $\approx 20\text{–}30 \text{ MJ}$ with HL-LHC parameters.*

Collimation system designed for fast accidental losses of up to **1MJ**.  

*R. Assmann, „Collimation for the LHC High Intensity Beams“, HB2010*

Need to **deplete tails** (e.g. by **hollow electron lens**) such that crab cavity failures are compliant with collimation system specifications.

*F. Burkart et al., CERN-ATS-Note-2011-057 MD (LHC)*
Hollow Electron Lens

- **Hollow $e^-$ beam** around proton beam core to **increase transverse diffusion rate** for particles with large betatron amplitues.

  *Depletion of transverse tails (not efficient for luminosity production) without effect on beam core.*

- **Positive experience in Tevatron**, particularly no emittance growth or instabilities observed.

- Fast gating on dedicated bunch trains possible.

Strongly coupled RF feedback to regulate voltage difference of CCs on either side of IP.

Similar coupled feedback loop is planned to be installed for 200MHz traveling wave cavities in CERN SPS.

Can provide additional mitigation for certain failures but cannot replace passive protection against severe failure scenarios.

courtesy of P. Baudrenghien et al., LHC-CC11.
Mitigation Options

• Mitigation options:
  • Larger $\beta^*$ (flat IR optics).
  • Smaller crossing angle (beam-beam wire compensator).
  • Higher crab cavity frequency.
  • Crab kick by several INDEPENDENT crab cavities.
  • Larger $Q_{\text{ext}} (= \text{slower time constant of ext. failures})$.
  • Coupled RF feedback.
  • Hollow electron lens to deplete transverse tails (essential).

• Requires: single turn redundant failure detection and interlock.
  • on cavity level.
  • on beam level, e.g. head-tail-monitor.
Possible Scenarios

Tolerable scenarios for internal and external failures with losses below 1MJ in max 5 turns:

<table>
<thead>
<tr>
<th>Scenario 1: 3 CCs</th>
<th>Scenario 2: $\beta^* = 25\text{cm}$</th>
<th>Scenario 3: 800 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC frequency (f)</td>
<td>400 MHz</td>
<td>400 MHz</td>
</tr>
<tr>
<td>Number of independant CCs ($n_{cc}$)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>$Q_{\text{ext}}$</td>
<td>1’250’000</td>
<td>1’250’000</td>
</tr>
<tr>
<td>$\beta^*$</td>
<td>15 cm</td>
<td>25 cm</td>
</tr>
<tr>
<td>Distance from collimators to be depleted below 1MJ.</td>
<td>1.7$\sigma$</td>
<td>1.0 $\sigma$</td>
</tr>
</tbody>
</table>

Magnet quenching in failure case not excluded.

T. Baer et al., IPAC’12, MOPPC003
Outlook

- Long shutdown 1: Splice consolidation
- Long shutdown 2: LHC injector upgrade
- Long shutdown 3: HL-LHC and CC installation

SPS CC Test
LHC CC Test Pt. 4


Technical Design

Construction
Conclusion

• Crab Cavities are essential to **compensate the geometric luminosity loss** (and to level the luminosity) for HL-LHC.

• **Crab cavity failures** can lead to **global betatron oscillations with large amplitudes** (up to $5\sigma$ for $n_{cc}=1$) on very fast timescales.

  *Unacceptable with multi-MJ tails.*
  
  *Better understanding of failure scenarios (e.g. quench dynamics) needed.*

• Many **mitigation options.** In general: The more effective the crab cavities, the worse are their failure scenarios.

  *Transverse tail depletion with **hollow e-lens** is essential.*
  
  *Counteract failures with **strongly coupled RF feedback.***

• Crab cavity tests in SPS and LHC are foreseen prior to final installation in 2022.
Thank you for your Attention

Further information:


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Analytical Approach

- Horizontal kick by crab cavity:
  \[ x'_{cc}(z) = -\frac{q \cdot V}{E} \cdot \sin \left( \Phi + \frac{\omega \cdot z}{c} \right) \]

- Optimal voltage to compensate crossing angle (local scheme):
  \[ V_0 = \frac{c \cdot E \cdot \tan \left( \frac{\Theta}{2} \right)}{q \cdot \omega \cdot \sqrt{\beta^* \beta_u} \cdot \sin(\Delta \varphi) \cdot n_{cc}} \]

- Optimal voltage for compensating cavities:
  \[ \tilde{V_0} = -\sqrt{\frac{\beta_u}{\beta_d}} \cdot \cos(\Delta \varphi_{cc}) \cdot V_0 \]

---

\( q \) = particle charge
\( E \) = particle Energy (7 TeV)
\( V \) = voltage of crab cavity
\( \Phi \) = phase of crab cavity (0°)
\( \Theta \) = full crossing angle (590 µrad)
\( \Delta \varphi \) = phase advance CC -> IP (~ 90°)
\( \Delta \varphi_{cc} \) = phase advance CC\(_u\) -> CC\(_d\) (181.4°)
\( \omega \) = angular frequency of CC (2\(\pi\cdot400 \) MHz)
\( z \) = longitudinal position of particle
\( c \) = speed of light
\( \beta^* \) = beta function at the IP
\( \beta_{u,d} \) = beta function at upstream/downstream CC.
\( n_{cc} \) = number of CCs per beam on either side of IP.
In case of a dephasing of the crab cavities left and right of the IP, the (longitudinal) bunch center is maximally displaced, by up to $2 \times 2\sigma_x$ in 5 turns.

Maximal displacement with Gaussian transverse and longitudinal beam distribution.

Maximal displacement with Gaussian longitudinal beam distribution.

Opposite phase change of both crab cavities. Nominal Gaussian transverse ($\epsilon_n = 3.75\mu m \cdot rad$) and longitudinal ($l = 7.55cm$) beam distribution.

Opposite phase change of both crab cavities. Nominal Gaussian longitudinal ($l = 7.55cm$) beam distribution.
Single particle emittance:

\[ \epsilon = \left( \frac{\alpha x_\beta + \beta x'_\beta}{\beta} \right)^2 + \frac{x^2_\beta}{\beta} \]

with \( x_\beta = x - D_x \frac{\Delta p}{p}, \ x'_\beta = x' - D_{px} \frac{\Delta p}{p} \).

Maximal displacement:

\[ \bar{x} = \sqrt{\epsilon \cdot \beta} = \sqrt{x^2_\beta + (\alpha \cdot x_\beta + \beta \cdot x'_\beta)^2} \]
90° Phase Change

- Maximal phase change in first turn:
  \[ \varphi = \arctan\left( \frac{\Delta V}{V} \right) = 5.3°. \]

- Phase change is fastest if cavity voltage changes as well.

Illustration of 90° voltage change.

Amplitude of cavity voltage.
Static Failure Scenarios
Very Simple Approximation

\[ \Delta x_{CC,IP}(z) = -\frac{\theta}{2} \cdot z \]

Displacement at IP needed to compensate the crossing angle (\(\Theta, z\) small)

For \(\Theta = 580\mu\text{rad}\), \(\beta_{IP} = 0.15\text{m}\), \(\varepsilon_{\text{norm}} = 3.75\mu\text{m}\cdot\text{rad}\), \(E = 7\text{TeV}\), \(\sigma_z = 7.55\text{cm}\):

\[ \Delta x = -2.52 \frac{\sigma_x \cdot z}{\sigma_z} \]

Expected beamlosses from simple Monte Carlo:

Particle is lost if \(|\text{RAND}_{\text{Gauss}} + 2.52 \cdot \text{RAND}_{\text{Gauss}}| > 5.7\)

\(-\) Expected loss: \((3.5 \pm 0.2)\%\)
Simple Approximation (MC)

Beamloss approximation with simple Monte Carlo (upgrade optics):

• Failure of single cavity ($V \to 0$):

  Particle is lost if $|x + x_{cc}(z) \cdot k(\Delta\phi_{CC\to TCP})| > 5.7 \cdot \sigma_x$

  -> expected loss: $(0.88 \pm 0.06)\%$

• Phase error of single cavity ($\Phi \to \pi/2$):

  Particle is lost if $|x + x_{cc}(z, \Phi = \pi/2) \cdot k - x_{cc}(z, \Phi = 0) \cdot k| > 5.7\sigma_x$

  -> expected loss: $(24.8 \pm 0.3)\%$
Content

Static Tracking Studies with upgrade optics (MAD-X)

- Fast Voltage Decay
- Phase Error
Phase Error of CRAB.L5.B1


Massive beam loss within few turns, mainly at TCP.C6L7.B1

Upgrade optics SLHV3.0
4444_thin, IP1/5: β*= 0.15m,
θ=580μrad, CC Local scheme
IP5, 400/10,000 particles
Phase Error of CRAB.L5.B1

Bunchshape at TCP.C6L7.B1 directly after failure.
Losses vs $\beta^*$

For Illustration