LHC Crab-cavity Aspects & Strategy
Rama Calaga (for the LHC-CC collaboration)
IPAC10, Kyoto, May 25, 2010

• LHC Upgrade & Crab Crossing
• New Road Map
• SPS, a first validation step

“Upgrade Scenarios”

<table>
<thead>
<tr>
<th></th>
<th>Nominal</th>
<th>Ultimate +Crabs</th>
<th>Phase II +Crabs</th>
<th>Phase II +LPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_b \times 10^{11}$</td>
<td>1.1</td>
<td>1.7-2.3</td>
<td>2.3</td>
<td>4.2</td>
</tr>
<tr>
<td>$\beta^* \text{ [cm]}$</td>
<td>55</td>
<td>25-30</td>
<td>14-25</td>
<td>25</td>
</tr>
<tr>
<td>$\theta_c \text{ [} \mu \text{rad]}$</td>
<td>285</td>
<td>315-348</td>
<td>509</td>
<td>381</td>
</tr>
<tr>
<td>Pile Up</td>
<td>19</td>
<td>44-111</td>
<td>150</td>
<td>280</td>
</tr>
</tbody>
</table>

- All scenarios aim at x3-10 Luminosity increase
- Luminosity leveling vital $\rightarrow$ constant luminosity
- Bunch intensity beneficial, **NOT** easily digestible in the injectors (safety!)
X-Angle Problem!

Long-Range Beam-Beam
(~10σ Nominal Sep)

Head-On Beam-Beam
(Limited by Max Tune Shift)

Why Crab Cavities:

- Increase peak luminosity with increasing x-angle due LR Beam-Beam
- Increase intensities beyond head-on beam-beam limit
- Level luminosity desired by experiments (reduce Pile-up, radiation damage)
### Naive Comparison

<table>
<thead>
<tr>
<th></th>
<th>Energy [GeV]</th>
<th>Circumference [km]</th>
<th>Current [A]</th>
<th>$\xi_{BB}$</th>
<th>$\Phi_{\text{Piwinski}}$</th>
<th>Crab Freq [MHz]</th>
<th>Crab Voltage [MV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>KEK-B</td>
<td>3.5-8.0</td>
<td>3</td>
<td>2.0</td>
<td>0.09</td>
<td>0.75</td>
<td>509</td>
<td>1.5</td>
</tr>
<tr>
<td>LHC</td>
<td>7000</td>
<td>27</td>
<td>0.5-0.85</td>
<td>&lt; 0.01</td>
<td>0.6-1.4</td>
<td>400</td>
<td>5-10</td>
</tr>
</tbody>
</table>
Reduction Factor

Nominal LHC & KEK-B

LHC Upgrade

\[ R_\Phi = \frac{1}{1 + \Phi^{1/2}} \]

Eff. beam size
\[ \sigma \rightarrow \sigma / R_\Phi \]
Luminosity Leveling

Advantages:

Constant Luminosity (~3 x 10^{34})
Less pile up at start (Nominal ~ 19, Upgrade 100-300 events/crossing)
Less peak radiation on IR magnets/detector

Crabs → Natural knob w/o lattice change

Graphic courtesy G. Sterbini
**Luminosity Gain, Crabs**

Freq: 400 MHz, Volt < 10 MV, $\beta_{cc}$: ~5 km

<table>
<thead>
<tr>
<th>${E, \max \beta_{\text{crab}}}$</th>
<th>3.5 - 5 TeV</th>
<th>7 TeV</th>
<th>Increase Peak Luminosity</th>
<th>Increase Int. Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta^* = 55$ cm</td>
<td></td>
<td></td>
<td>10%</td>
<td>-</td>
</tr>
<tr>
<td>$\beta^* = 30$ cm</td>
<td></td>
<td></td>
<td>40%</td>
<td>19%</td>
</tr>
<tr>
<td>$\beta^* = 25$ cm</td>
<td>$\epsilon\downarrow$, $N_b\uparrow$</td>
<td></td>
<td>63%</td>
<td>22%</td>
</tr>
<tr>
<td>$\beta^* = 14$ cm</td>
<td></td>
<td></td>
<td>190%</td>
<td>31%</td>
</tr>
</tbody>
</table>

Integrated luminosities:

$N_b = 1.7 \times 10^{11}$, $\beta^* = 0.14$ cm, Run time = 10 hrs, TAT = 5 hrs

(Burn off, IBS, rest gas scattering)

Approx: 265 fb$^{-1}$/yr (217 fb$^{-1}$/yr w/o CCs) $\rightarrow$ 2 yr reduction in run time (for 3000 fb$^{-1}$)

Int Luminosities: G. Sterbini
2 Main Challenges, Crabs

SC Technology upgrade (factor 5 gradient or larger)
   New design strategy than conventional

LHC machine protection (350 MJ stored energy)
   5% of nominal bunch beyond damage threshold
   Fast failure detection to safely abort beam
LHC Constraints

Bunch length: 7.55 cm (lowest frequency 800 MHz)

B1-to-B2 separation: 194 mm (PB 800 MHz ~ 250mm radius)

With few exceptions....
(IR4, collimation, exps)
**Possible Schemes**

- **Backup Option, Conventional**
  - 1-2 Cavities/beam

- **Baseline Option**
  - 4 Cavities/IP

Compact cavities -OR- doglegs needed for conventional cavities *(impractical)*
Conventional to Compact

Compact cavities aiming at small footprint (150 mm) & 400 MHz, 5-10 MV/cavity

WEPEC084
HWDR, JLAB, OD

MOPEC022
HWSR, SLAC-LARP

WEPEC049
DR, UK, TechX

Rotated Pillbox, KEK
# Performance Chart

Kick Voltage: 5 MV, 400 MHz

<table>
<thead>
<tr>
<th></th>
<th>HWDR (J. Delayen)</th>
<th>HWSR (Z. Li)</th>
<th>4-Rod (G. Burt)</th>
<th>Rotated Pillbox (N. Kota)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometrical</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cavity Radius [mm]</td>
<td>200</td>
<td>140</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Cavity Height [mm]</td>
<td>382</td>
<td>194</td>
<td>169</td>
<td>668</td>
</tr>
<tr>
<td>Beam Pipe [mm]</td>
<td>50</td>
<td>45</td>
<td>45</td>
<td>75</td>
</tr>
<tr>
<td>RF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak E-Field</td>
<td>29</td>
<td>65</td>
<td>103</td>
<td>85</td>
</tr>
<tr>
<td>Peak B-Field</td>
<td>94</td>
<td>135</td>
<td>113</td>
<td>328</td>
</tr>
<tr>
<td>$R_T/Q$</td>
<td>319</td>
<td>275</td>
<td>667(?)</td>
<td>-</td>
</tr>
</tbody>
</table>

†Exact voltage depends on cavity placement & optics
†Cavity parameters are evolving
New Roadmap

- CERN must pursue crab crossing following KEK-B success
- Both local (baseline) & global should pursued
- High reliability (cavity, machine protection, impedance & mitigation)
- No validation in LHC required (ex: SPS as test bed with KEK-B cavities)
- Coordination & timing: both short term & long term upgrades of LHC

Diagram:

- **T0, 2010**
  - LHC-CC09
  - Chamonix 2010

- **+T2**
  - Compact Cavities
  - Validation

- **+T5**
  - Cryomodule Dev
  - SPS Tests

- **+T8**
  - Installation & Commissioning

Alternate
- Elliptical Cavity
- 800 MHz

- **+T4**
  - Elliptical Cavity
  - Cryomodule

\(^{1}\)Time scales approximate
Machine Protection, 350 MJ !!

100's of interlock systems → complex
Best/worst case scenario:
Detection - 40μs (½ turn), response - 3 turns

USER_PERMIT signal changes from TRUE to FALSE

a failure has been detected...

Crabs must be LHC safe !!

Courtesy J. Wenniger
Some Failure Scenarios

Time scales:

- Power supply trips (50-300 Hz > 7 ms) → greater than 300 turns
- RF arcing (few μs) → Response of cavity voltage/phase slower
- Mechanical changes (100's of ms) → high Q SC cavity
- Quench, abrupt amplitude or phase changes

No passive way to guarantee machine protection

- Qext may not help for beam driven failure time constant
- Voltage slope determined by unchangeable constants (R/Q, Δx, I...)
- Active orbit and RF feedback a requirement (cavity to cavity across IR ~1μs)

Some info courtesy J. Tuckmantel
**Left-Right Voltage Failure**

Local Crabs, IP5

\[ x_{D_{cc}}(z,s) = \sqrt{\frac{\beta(s) c \tan(\frac{\theta}{2})}{\beta^*}} \frac{1}{\omega} \sin\left(\frac{\omega z}{c}\right) \cos(\Delta \phi_1 - \pi Q) \frac{\cos(\Delta \phi_0 - \pi Q)}{\cos(\Delta \phi)} , \]

Change in 180° phase → factor 2
SPS Tests

Crabs potentially in SPS is at **COLDEX.41737** (4020 m, LSS4)  
Crab Bypass similar to COLDEX to move it out of the way during high intensity operation

SPS beam tests, 2010 to check lifetime @55GeV coast with 2µm norm emittance

**Machine protection**  
Setup with 2 collimators: No effect at 1\textsuperscript{st} & full crab effect at 2\textsuperscript{nd} second collimator  
Primary goal is beam measurement (No implementation of interlocks, BPMs-fast & RF-slow)  
Failure scenarios (for example: abrupt voltage/phase changes, RF trips etc..)
KEK Cavities in SPS

No show stoppers to test the KEK-B cavity in SPS

Modifications required to adapt to SPS (for example: static freq change \sim 2\ MHz)

Earliest possible: End of 2012

Crab voltage: \{\text{HER, LER}\} - 1.6\ MV, 1.5\ MV (design: 1.44\ MV)
Operational voltage: \{\text{HER, LER}\} - 1.4\ MV, 0.9\ MV
Trip rate: Average 1/day (HER), 0 for LER (from up to 25)
CONCLUSIONS

- Key motivation
  - Luminosity gain & leveling with reducing $\beta^*$
  - Technical challenge to develop and validate compact cavities
  - Ensure machine protection under different cavity failure modes

- KEK-B experience
  - Vital operational experience with high currents
  - Dedicated experiments to identify potential issues for LHC (ex: phase noise)

- SPS tests
  - Validate differences between protons & electrons

Many thanks to all the LHC-CC collaborators
A1: Possible Future

Proposed in 2006 but was abandoned due to large $x$-angle ($5 \text{ mrad} ?$) + Flat Beams ?

No parasitic collisions

Independent & easy IR optics

100-mm asymmetric coil design

$G_{\text{max}} = 247.6 \text{ T/m, } I_{\text{max}} = 15.34 \text{ kA for } J_{c}(12\text{T},4.2\text{K}) = 3000 \text{ A/mm}^2$

Two types of quadrant coils address the field coupling issue.

R. Gupta, BNL & Crab Team
# A2: LHC Aperture Specs

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Aper-H [mm]</th>
<th>Beam-to-Beam Separation [mm]</th>
<th>Max Outer Radius [mm]</th>
<th>L [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_3$</td>
<td>69</td>
<td>420</td>
<td>395</td>
<td>9.45</td>
</tr>
<tr>
<td>Crabs</td>
<td>84</td>
<td>220 (300)</td>
<td>195</td>
<td>10</td>
</tr>
<tr>
<td>$D_4 + Q5$</td>
<td>73</td>
<td>194</td>
<td>169</td>
<td>15.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Aper-H [mm]</th>
<th>Beam-to-Beam Separation [mm]</th>
<th>Max Outer Radius [mm]</th>
<th>L [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_1$</td>
<td>134</td>
<td>-</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>Crabs</td>
<td>84</td>
<td>194</td>
<td>150</td>
<td>10</td>
</tr>
<tr>
<td>$D_2$</td>
<td>69</td>
<td>-</td>
<td>-</td>
<td>10</td>
</tr>
</tbody>
</table>

†2nd beam pipe inside He vessel
A3: Impedance Requirements

Longitudinal criteria:
Nominal intensity, 450 GeV: \(~60 \text{ k}\Omega\) (determined by 200 MHz cavities)
Upgrade intensity: \(~10 \text{ k}\Omega\) – two cavities

Transverse criteria:
Nominal intensity, 450 GeV: \(~2.5 \text{ M}\Omega/\text{m}\) – single cavity
Upgrade intensity: \(~0.4 \text{ M}\Omega/\text{m}\) – two cavities (additional factor of \(\beta/\langle\beta\rangle\))

<table>
<thead>
<tr>
<th></th>
<th>Freq [GHz]</th>
<th>R/Q [Ω]</th>
<th>(Q_{\text{ext}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monopole</td>
<td>0.54</td>
<td>35.17</td>
<td>~10 - 100</td>
</tr>
<tr>
<td></td>
<td>0.69</td>
<td>194.52</td>
<td></td>
</tr>
<tr>
<td>Dipole</td>
<td>0.80</td>
<td>117.26</td>
<td>(10^6)</td>
</tr>
<tr>
<td></td>
<td>0.81</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.89</td>
<td>93.4</td>
<td>~10^2 - 10^3</td>
</tr>
<tr>
<td></td>
<td>0.90</td>
<td>6.79</td>
<td></td>
</tr>
</tbody>
</table>

** Main RF cavities, \(Q_{\text{ext}}\) \~ 10^2 - 10^3
**A4: Crab Phase Noise**

Modulated noise (measured, 30 Hz - 32 kHz)
- Preliminary BB simulations $\leq 0.1\sigma$ (10%/hr)
- Tolerance relaxed in the case of lumi-leveling

White noise (extremely pessimistic)
- Ohmi: Strong-strong BB $\leq 0.02\sigma(\tau)$

### KEK-B measured spectrum (K. Akai et al.)

\[ \Delta x_{IP} = \frac{c}{\omega_{RF}} \theta \delta \phi \]

\[ \Delta \xi \propto \frac{\xi^2}{\beta^* \Delta x^2} \]
A5: Noise Exps, KEK-B

Strong effect close to $\sigma$-mode

Weaker effect close to $\pi$-mode

R. Tomas et al., 2008
A6: Collimation (Global Scheme)

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

Y. Sun et al. PRST-AB 12, 101002 (2009)
A7: SPS Test Objectives, Protons

Safe beam operation (low intensity) & reliability
  Tests, measurements (orbits, tunes emittances, optics, noise)
  Voltage ramping & adiabaticity
  Collimation, scrapers to reduction of physical aperture with & w/o crabs
  DA measurements (possible?)

Intensity dependent measurements (emittance blow-up, impedance)
  Coherent tune shift and impedance
  Instabilities
  Beam-beam effects (BBLR – tune scan, current scan)
  Other non-linearities (octupoles)

Operational scenarios
  Accumulation of beam with crab-on & crab off
  Beam loading with & w/o RF feedback & orbit control
  RF trips and effects on the beam
  Energy dependent effects
  Long term effects with crab-on, coasting 120 GeV
### A8: Compact Cavity (LARP-AES)

**Assembly Process**

**Foreseen Challenges**
- Multipacting
- Fabrication & field validation
- Tuning & HOM damping
- Integration (SPS & LHC)

†Courtesy AES