Crab Crossing for LHC Upgrade

Rama Calaga (on behalf of LHC-CC Collaboration)

SRF2011, July 29, 2011

- LHC and its upgrade
- Evolution of technology concepts & studies
- Planning & future activities
The LHC

27 km @1.9K to accelerate protons to 7TeV

400 MHz SRF, 16MV

2 high-luminosity experiments

2 experiments to study anti-matter & heavy ions
LATELY INSIDE THE LHC:
2 PROTONS 0.00000000000000001 SEC BEFORE THE COLLISION

...yet no Higgs or is there

# LHC: Today & Future

<table>
<thead>
<tr>
<th></th>
<th>Today</th>
<th>Design</th>
<th>Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy [TeV]</strong></td>
<td>3.5</td>
<td>7.0</td>
<td>7.0</td>
</tr>
<tr>
<td><strong>Intensity [x 10^{11}]</strong></td>
<td>1.1-1.2</td>
<td>1.15</td>
<td>≥ 1.7</td>
</tr>
<tr>
<td><strong>N. Emittance (µm)</strong></td>
<td>2.2-2.5</td>
<td>3.75</td>
<td>≥ 3.75</td>
</tr>
<tr>
<td><em><em>β</em> (cm)</em>*</td>
<td>150</td>
<td>55</td>
<td>15</td>
</tr>
<tr>
<td><strong># of bunches</strong></td>
<td>1380</td>
<td>2808</td>
<td>2808</td>
</tr>
<tr>
<td><strong>L_{peak} \ [x 10^{34}]</strong></td>
<td>0.19</td>
<td>1</td>
<td>~8*</td>
</tr>
<tr>
<td><strong>L_{int} [fb^{-1}/yr]</strong></td>
<td>~2</td>
<td>67</td>
<td>250</td>
</tr>
</tbody>
</table>

*Luminosity leveling → 5 \times 10^{34} \ [cm^{-1} s^{-1}]*

Ultimate goal by 2030: 3000 fb^{-1} (Radiation damage limit ~700 fb^{-1})
X-Angle & Reduction

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

\[ \Phi = \frac{\sigma_z \theta_c}{\sigma_x} \]

\[ V_{RF} \propto \frac{1}{\sigma_x^4} \]

\[ V_{CRAB} \propto \theta_c \]

Nominal LHC

LHC Upgrade

32 Long-range /IP

Unfavorable voltage scaling

Effective recovery + lumi leveling

Inefficient overlap
Crab Crossing, Evolution

R. Palmer, 1988, LC

KEK-B
2007-2010

Elliptical Technology

Light Sources
EIC, LC, HA

LHC

+5-10 yrs

+20 yr

New Technology

+10 yr

Proposed in 2005
# Cavity Specification

<table>
<thead>
<tr>
<th>Baseline</th>
<th>Unit</th>
<th>LHC</th>
<th>KEK-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>MHz</td>
<td>400 (800)</td>
<td>509</td>
</tr>
<tr>
<td>Deflecting Voltage</td>
<td>MV/Cav</td>
<td>5</td>
<td>2.0 (0.9-1.5)</td>
</tr>
<tr>
<td>Peak E-field</td>
<td>MV/m</td>
<td>&lt; 45</td>
<td>28</td>
</tr>
<tr>
<td>Peak B-field</td>
<td>mT</td>
<td>&lt; 80 mT</td>
<td>82 mT</td>
</tr>
<tr>
<td>Aperture (diameter)</td>
<td>mm</td>
<td>84</td>
<td>130</td>
</tr>
<tr>
<td>Cav Outer Envelope</td>
<td>mm</td>
<td>&lt; 150</td>
<td>866/483</td>
</tr>
<tr>
<td>Module length</td>
<td>m</td>
<td>~ 1m</td>
<td>1.5 m</td>
</tr>
<tr>
<td>HV crossing</td>
<td>-</td>
<td>Desirable</td>
<td>N/A</td>
</tr>
<tr>
<td>$\beta^*$ (IR1/IR5)</td>
<td>cm</td>
<td>15-25</td>
<td>63/0.7</td>
</tr>
<tr>
<td>$\beta$ crab</td>
<td>km</td>
<td>~ 5</td>
<td>0.2/0.04</td>
</tr>
<tr>
<td>Non-linear harmonics</td>
<td>Units $[10^{-4}]$</td>
<td>2-3</td>
<td>N/A</td>
</tr>
<tr>
<td>Impedance Budget</td>
<td>Longitudinal, Transverse</td>
<td>60k$\Omega$, 2.5M$\Omega$/m</td>
<td>-</td>
</tr>
</tbody>
</table>

### RF

- Frequency
- Deflecting Voltage
- Peak E-field
- Peak B-field
- Aperture (diameter)
- Cav Outer Envelope
- Module length
- HV crossing
- $\beta^*$ (IR1/IR5)
- $\beta$ crab
- Non-linear harmonics
- Impedance Budget

### Geometrical

- Beam-beam separation

### Optics

- $\sigma_z = 7.55$ cm
Two-Cell Elliptical

- Frequency: 800 MHz
- Strong HOM damping & compact

L. Xiao et al.

Only fits in one location in the LHC (IR4)

*Highly constrained*

Y. Yakovlev et al.
2009

Decision to focus on concepts with compact size

Frequency: 400 MHz
BP radius: 42 mm
Outer envelope: < 150 mm
Worldwide Design Effort

~4yr of design evolution

Exciting & rapid development of deflecting cavities

(BNL, CERN, CI-DL-LU, FNAL, KEK, ODU/JLAB, SLAC)
LU-DI (JLAB) Design

4-Rod TEM Cavity

Towards Conical rods

Prototype Tuner for CEBAF Upgrade

HOM Damping Concepts

Courtesy G. Burt et al.
ODU-JLAB Design

Improved properties
Cylindrical shape
Fewer HOM modes

Niowave-STTR, Phase I

B-Field
Top plane

E-Field deflection
Mid plane

Phase II approved
For building cavity prototype
(ODU-Niowave)

Courtesy J. Delayen et al.
KEK-Kota Design

Rotated Pillbox with shielding cones
HOM studies and damping scheme underway

Power Coupler

HOM Damping

Courtesy K. Nakanishi et al.
SLAC-LARP Design

RF design: supported by LARP
Mechanical design: supported by Phase I SBIR

TE11 like mode
B-field deflection
Parallel bar & $\frac{1}{2}$-Wave cavities fit only for horizontal crossing!

Only works for one experiment

In 2010, design efforts to focus on dual crossing (HV)
¼ Wave Concept

Ultra compact & fits HV crossing

Accelerating voltage (need for suppression)
Present Status

4-rod design has advanced

Engineering meeting for fabrication (mid-August)

Merging of efforts between ODU & SLAC

Parallel bar & ridged waveguide concepts → common design

¼ wave concept to continue towards final design

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<thead>
<tr>
<th></th>
<th>4-Rod</th>
<th>Double Ridge</th>
<th>1/4-Wave</th>
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<tbody>
<tr>
<td>$V_T = 2.5$ MV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_{pk}$</td>
<td>33 MV/m</td>
<td>25 MV/m</td>
<td>48 MV/m</td>
</tr>
<tr>
<td>$B_{pk}$</td>
<td>49 mT</td>
<td>55 mT</td>
<td>110 mT</td>
</tr>
<tr>
<td>$R/Q_\perp$</td>
<td>953 Ω</td>
<td>285 Ω</td>
<td>264 Ω</td>
</tr>
<tr>
<td>1st HOM</td>
<td>375 MHz</td>
<td>619 MHz</td>
<td>675 MHz</td>
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</table>
Some Key Issues

Beyond the cavity technology:

a. RF Phase noise $\rightarrow$ emittance blowup

b. Abrupt cavity failures $\rightarrow$ Machine damage

c. Impedance $\rightarrow$ beam instabilities
**Crab Phase Noise**

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

\[ \delta \phi_{\text{crab}} \leq \frac{4 \pi \Delta x_{\text{max}}}{\lambda_{RF} \theta_c} \quad (\Delta x_{\text{max}} \sim 10 \text{ nm}) \]

KEKB observations \( \rightarrow \) Modulated noise 30 Hz - 32 kHz

Weak-strong beam-beam simulations \( \leq 0.1\sigma \) (10%/hr)
Strong-strong BB simulations \( \leq 0.02\sigma.(\tau) \)

Dedicated measurements with induced noise in KEK \( \leq 0.03^0 \)
**LHC measurements** with beam-beam & damper noise planned for 2011-12
**Machine Protection**

**Requirement**
Stay above the 3-turn beam-abort threshold

**Tracking studies**
Nominal LHC → Losses due 1-turn voltage/phase failure is non-issue
→ Additional checks needed for different distributions

Upgrade optics (SLHC v3) under study

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**Graphical Representation**

- **LHC, 7 TeV, Global CC at IR4, Gaussian Beam v3 Nominal Beam Size**
- **3-turn phase failure by 90°**
- **Quench limit**
- **Few mJ**
- **350 MJ**

**Legend**
- Losses at collimators
- Losses at warm sections
- Losses at cold sections

**Graph Details**
- x-axis: s (km)
- y-axis: Local Loss Rate
- Quench limit indicated by dashed line
- Collimators marked on the graph
SPS As a Testbed

Long. Position: 4009 m +/- 5m
Total length: 10.72 m
βx, βy: 30.3m, 76.8m

Emittance growth, cavity operation & failures with hadron beam
# Budget Overview

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<tbody>
<tr>
<td>R&amp;D (3-4 cavities)</td>
<td>3.55</td>
<td>5.6</td>
<td>3.4</td>
<td>2.35</td>
<td>3.3</td>
<td>1.15</td>
<td>0.1</td>
<td></td>
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<tr>
<td>Cavity Construction</td>
<td></td>
<td>3.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>17.5</td>
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<td>Cryostats</td>
<td></td>
<td>4.0</td>
<td></td>
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<td>30</td>
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<td>RF Systems</td>
<td></td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.5</td>
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<tr>
<td>LLRF &amp; Controls</td>
<td></td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>10 cryomodules + Ancillaries</td>
<td></td>
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</table>

Present support (R&D):

US-LARP ($0.4M/yr), EU-FP7 (~1.5M€/yr), SBIR/STTR ($1.25M)
Future & Challenges

Fabrication
Complex shapes, but this community already has experience
Build warm prototypes to gain experience & HOM measurements

Cavity treatment
Independent platform for each prototype but common procedure
Field gradient demonstration (+ multipacting, mechanical effects etc..)

Cryostat & Couplers
Adopt a common platform (after prototyping), for example could use
bandpass filter for the HOM extraction

RF & Beam tests
Cavity deflecting gradient, multipacting and quench properties with
and w/o beam, field assymetry, cavity alignment, impedance measurements,
damping properties, mechanical stability, tuning, emittance growth,
field ramping, RF controls, phase and voltage stability etc..
**A1: Draft Optics (SLHC v3)**

S. Fartoukh, R. deMaria

New elements (SLHC v3)

- Q1-Q3, D1, TAN, D2, Q4-Q5
- + crab cavities (~10 m, 10 MV)

Crossing angle change

- Closed orbit excursion (~3 mm)
- Remote cavity alignment