R&D Crab Cavities, HL-LHC

R. Calaga on behalf of HL-LHC WP4
HB2016, Malmo, 6 Jul 2016

Special Acknowledgement: BE-ABP, BE-RF, EN-MME, TE-VSC, USLARP & UK-STFC
HL-LHC Crab Cavities

- 8 cavities per IP (Total 16) Between D2 & Q4

2-Cavity Test Module
SPS-BA6
**Crab Cavities, HL-LHC**

Use 8-superconducting crab cavities per IP (ATLAS & CMS) to compensate up to 590 μrad x-angle

**Goal:** To recover ~ 70% of peak luminosity

**Piwinski angle:**

\[
\Phi = \frac{\sigma_z}{\sigma_x} \left( \frac{\theta_c}{2} \right)
\]

\[
V_{\text{crab}} = \frac{cE \tan(\phi_c)}{\omega R_{12}} \cdot \frac{2 \sin(\pi Q)}{\cos(\phi_{cc-ip} - \pi Q)}
\]

Total voltage ~10-12 MV
Frequency Choice

LHC bunches are long ($4\sigma = 1$ ns)
Main RF system is 400 MHz

$$L \propto \frac{N_b^2}{\sigma^2} R \Phi F_{RF}$$

400 MHz from crabs is a good compromise between RF curvature & luminosity gain
## Layout/Parameters

<table>
<thead>
<tr>
<th></th>
<th>unit</th>
<th>SPS</th>
<th>LHC</th>
<th>HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong></td>
<td>TeV</td>
<td>0.026-0.45</td>
<td>7.0</td>
<td>7.0</td>
</tr>
<tr>
<td><strong>Bunch length</strong></td>
<td>[ns]</td>
<td>~2.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td><em><em>β</em> (IP)</em>*</td>
<td>[m]</td>
<td>-</td>
<td>55 (40)</td>
<td>15</td>
</tr>
<tr>
<td><strong>RF Freq</strong></td>
<td>[MHz]</td>
<td>200.3</td>
<td>400.79</td>
<td>400.79</td>
</tr>
<tr>
<td><strong>Voltage</strong></td>
<td>[μrad]</td>
<td>-</td>
<td>300</td>
<td>590</td>
</tr>
<tr>
<td><strong>Piwinski Angle</strong></td>
<td>-</td>
<td>0.65</td>
<td>3.14</td>
<td></td>
</tr>
</tbody>
</table>

Diagram:

- **IP**
- **Q1-3**
- **D1**
- **D2**
- **Crab C**
- **Q4**

2\textsuperscript{nd} beam pipe inside He-vessel.
Quasi-TEM Class Cavities

Two cavity types designed (hor/ver) for the LHC

Fundamental mode is the deflecting mode
HOMs are spaced farther away making HOM damping easier
## Performance Chart

<table>
<thead>
<tr>
<th>Metric</th>
<th>Double Ridge (ODU-SLAC)</th>
<th>Double Wave (BNL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity Radius [mm]</td>
<td>140.5</td>
<td>139</td>
</tr>
<tr>
<td>Cavity length [mm]</td>
<td>557</td>
<td>344</td>
</tr>
<tr>
<td>Beam Pipe [mm]</td>
<td>84</td>
<td>84</td>
</tr>
<tr>
<td>Peak E-Field [MV/m]</td>
<td>33</td>
<td>38</td>
</tr>
<tr>
<td>Peak B-Field [mT]</td>
<td>56</td>
<td>70</td>
</tr>
<tr>
<td>$R_t/Q$ [Ω]</td>
<td>429</td>
<td>426</td>
</tr>
<tr>
<td>Nearest Mode [MHz]</td>
<td>~700</td>
<td>581</td>
</tr>
</tbody>
</table>

**RF**

- 194 mm
- B1
- B2
- < 60 MV/m
- < 100 mT

**Geometrical**

- Kick Voltage: 3.4 MV, 400 MHz
First Prototypes

Proof of principle concepts built and kick field demonstrated
Two designs retained for the LHC (horizontal and vertical)
Overall Planning

The project is implemented in 2 main phases:

SPS validation of the technology with proton beams before LS2

Construction of 8 Modules (16 cavities) by 2025
Crab Cavity Cryomodule

2K Service Module (SPS only)

2-Phase Line

RF Input (40-80 kW)

HOM Couplers

Alignment Monitoring

Sym Tuner

Sector Valves
SPS Cavities, CERN

Modifications to the prototypes with strong HOM damping for SPS/LHC

CERN cavity production recently started with DQW cavity shaping & welding trials. 2 DQW cavities to be manufactured by Spring 2017
Cavity Production, US

2+2 cavities under production USLARP/DOE program (Niowave Inc.)

Frequency Trimming & final welding
Surface Treatment

Surface treatment is non-trivial with these geometries

Chemistry on fully assembled cavity

Chemistry on intermediate parts
Helium Vessel

Novel bolted He-vessel design with superficial welds for leak guarantees minimal stress during entire life cycle.

The vessel provides the needed structural integrity & controlled tuning interface to the outside environment.

Internal cold-magnetic shield for better stray field control (x60 reduction).
He-Vessel Prototype

Full scale model built with the complete assembly & welding sequence qualified
Pressure test (2.6 bar) & leak tests

Position sensors and metrology during the assembly sequence reveals a peak
deforation of upto approx 250 μm during the assembly.
Frequency Tuner

Actuation system to be tested with an existing cavity

Concentric Ti-cylinders to push/pull the capacitive plates symmetrically

For RFD, the body is tuned in similar fashion

Precision $\sim 0.5 \, \mu m$ (100 Hz)
Cavity BW $= 800$ Hz
HOM Couplers

Two types of “broadband” lumped element couplers for DQW/RFD (additional probes for specific HOMs)

Specially design HOM test boxes for coupler verification & conditioning
Higher Order Modes

The circulating high beam current (1.1 A) and dense spectrum of the LHC filling scheme implies strong HOM damping.

Non-Resonant Case:

\[ P_{HOM} = (\sum k_n - k_0) \cdot q \cdot I_b \]

Resonant Case:

\[ P_{HOM} = I_b^2 \cdot \frac{R}{Q} \cdot Q_L \cdot F_n^2 \]

HOM Power can be from 100 W to a few kW (numerical computation)
Exact HOM frequency & overlap with beam spectrum hard to predict
Impedance Budget

Due to the 8-cavities/beam with 1.1 A and the placement at high-b location has strict impedance budget

Longitudinal budget of 200 kΩ total (7.0 TeV)
Transverse budget $\sim 0.5$ MΩ/m
Power Coupler & Amplifier

Re-use existing SPS-800 MHz IOT trolley with modified cavity output

Recently tested up to 60 kW-CW
**Cavity Alignment**

Baseline solution for the LHC to maintain the intra-cavity transverse displacements to within 0.5 mm

*(Recall: 1 mm offset in the cavity amounts to ~40 kW of RF power)*

3-point supporting system

Blade-type flexures for additional stiffness

FSI targets on cavity flanges

Additional BCAM – Wire Targets for SPS tests
Cryomodule Assembly

Tight alignment tolerances during full assembly (< 0.5mm)
Cryostating using a top plate assembly
Multiple vacuum sectorization valves for efficient pumping and module replacement. RF circulators/loads & cryogenic service module on movable table (51 cm movement)

Once installed in 2017, it will be a unique facility capable of testing SRF cavities with high energy proton beams (up to 450 GeV)
RF Noise

\[
\Delta V_T \ll \frac{1}{\tan(\theta/2)} \frac{\sigma_x^*}{\sigma_z}
\]

\[
\Delta x_{IP} = \frac{\theta_c}{k_{RF}} \delta \phi
\]

Ongoing simulations & SPS tests to define the final specification for LHC-LLRF
Proposal for amplitude noise reduction with damper & noise shaping for bunch tail population control
LLRF & IP Cross Control

**Fast regulation**: Maintain cavity phase w.r.t to bunch, reduction of the FM impedance & noise reduction

**Slow regulation**: IP regulation for closure of crab bump both during stable operation and during cavity failures
Final Remarks

The R&D towards the SPS beam tests is a vital step before their implementation in the LHC.

Several new & novel concepts for the cavity/cryomodule components due to complex requirements for the LHC

The new class of deflecting cavities have become an important part of the SCRF community and will play a strong role in beam manipulations in many future machines.
A1: Need for a Crossing Angle

4 interaction regions with ~120m common beam-pipe for 2-beams at each IR. It implies 120(+) parasitic encounters.

Large crossing angle needed (8-12°) to separate the beams.
A2: Cavity Surface Treatment

Complex shapes of the crab cavities requires fluid dynamics simulations
Optimum inlet/outlet ports
Minimize the std. deviation of the acid flow rate for uniform etching

All other ports outlets
Gravity acts down as shown in images