Crab Cavities

“FROM VIRTUAL REALITY TO REAL REALITY”

R. Calaga, BE-RF, LHC-PW, Chamonix 2012

On behalf of the LHC-CC collaboration
The Real "Problem"

Nominal $\rightarrow$ 4 IRs, 120(+) parasitic encounters

Sufficiently large crossing angle inevitable (8-12$\sigma$ sep)

2011 MD: 36 bunches
50 ns, 2 Collisions

No collisions or LR

8 to 16 LR encounters

Reducing crossing angle

Nominal $\rightarrow$ 4 IRs, 120(+) parasitic encounters

Sufficiently large crossing angle inevitable (8-12$\sigma$ sep)
Consequence

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

\[ \sigma_{\text{eff}} = \sqrt{\sigma_x^2 + \sigma_z^2 \phi_c^2} \]

Upgrade: reduce $\beta^*$ (by factor 2-4)

Consequence $\rightarrow$ approx double the crossing angle (10$\sigma$ sep)

Note: don't forget hour-glass effect (~15% loss for $\beta^*/\sigma_z$)
## Some Numbers

<table>
<thead>
<tr>
<th></th>
<th>2011</th>
<th>2012</th>
<th>after LS1</th>
<th>after LS3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>3.5 TeV</td>
<td>4 TeV</td>
<td>7 TeV</td>
<td>7 TeV</td>
</tr>
<tr>
<td>$\beta^*$ [cm]</td>
<td>100</td>
<td>60</td>
<td>55</td>
<td>15</td>
</tr>
<tr>
<td>$2\phi$ [μrad]</td>
<td>260</td>
<td>313</td>
<td>247</td>
<td>473</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$R_\phi(\sigma_z = 7.55\text{cm})$</th>
<th>0.94</th>
<th>0.85</th>
<th>0.82</th>
<th>0.37</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_\phi(\sigma_z = 10.1\text{cm})$</td>
<td>0.76</td>
<td>0.74</td>
<td></td>
<td>0.28</td>
</tr>
</tbody>
</table>

Assume: $2 \phi \approx d \sqrt{\epsilon / \beta^{ip}}$

$\epsilon_N = 2.5 \ \mu\text{m}, \ d=10$

very inefficient
For the Upgrade

\[ N_b = 2 \times 10^{11} \text{ p/b} \]
\[ \varepsilon_N = 2.5 \text{ \mu m} \]
\[ \beta^* = 15 \text{ cm} \]

\[ L_{pk} < 7 \times 10^{34} \text{ (12\sigma sep), little margin for leveling} \]

Note: don't forget synchro-betatron resonances \( \Phi \sim 2-4 \)
BBLRs might alleviate partially
To Recover

\[ \Delta p_x = \frac{qV}{E} \cdot \sin(\phi_s + \omega t) \]

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

$R_{12} = 30 \text{ m}$  
$R_{12} = 25 \text{ m}$

$\sim 6\text{MV/ IP-side (2 cavities)}$

400 MHz

800 MHz

Voltage / IP-side [MV]

Crossing Angle - $2\phi_c$ [μrad]
Why 400 MHz

LHC bunches are long
RF non-linearity (longitudinal)

\[ L \propto \frac{N_b^2}{\sigma^2} R_\Phi F_{RF} \]

Form factor \( \sim 1 \) (\( \beta^* 10-55 \text{ cm} \))

Higher frequency (for example 800 MHz)
“Smaller” cavities
Less voltage (\( V_T \mu \ 1/\omega \)) \( \rightarrow \) Not really
Easier phase noise control? (see later)
**Pillbox Cavity**

\[ f_{res} \propto \frac{1}{R} \quad \text{(independent of length)} \]

R: 400 MHz ~ 610mm
800 MHz ~ 305mm
\{ Too big for IR regions \}

Transverse Cross Section, squash

beam in/out of the plane

crabbing mode (HOM)
RF separator for 10-40 GeV/c from the SPS
Unknown heavy particles, baryonic states/exchange, $K^\pm$ & $p$-bar

Still in use at U-70 setup at IHEP
“1st” e± Crab Cavity

LONG R&D, but short lifetime (2007-2010)

KEK Freq: 508.9 MHz
Power: 50-120 kW
(Qext: 2x10^5, BW: 2.55 kHz)

Complex HOM Damping Scheme

Input Coupler
Main Liq. He Vessel
Bellows
Coaxial Coupler
Sub Liq. He Vessel
Support Pipe
Tuning Rod
Driving Plate
Sub Tuner Mechanical
Pick up Probe
Main Tuner Mechanical + Piezo

Feb 2007
THEY WORK!

The real question: will the technology be efficient/transparent for the HL-LHC operation

Real answer: you may have to wait a little while
The LHC Pillbox

Conceptually simple, but practically difficult (KEKB experience)

Main Constraints:

- Frequency \( \geq 800 \text{ MHz} \)
- Damping LOM/SOM/HOM remains a challenge
- Complexity of multiple frequencies in LHC
- Only vertical crossing at both IPs
- Surface field to kick gradient ratio is poor

2-cell version, USLARP, L. Xiao et al.

1-cell version, CERN, L. Ficcadenti et al.
Pillboxes → TEM Cavities

~4yr of design evolution

Exciting development of new concepts
(BNL, CERN, CI-DL-LU, FNAL, KEK, ODU/JLAB, SLAC)
Short History

Concentric Conducting System
short for coax
Leading to the telephone etc..

80yrs later
similar concepts to be applied
for LHC crab cavities
"Its strongly reentrant form makes the field pattern at the outer radius predominantly TEM with the consequence of only moderate current flow"
\[ Z_0 = V_0 / I_0 \]

Frequency \( \mu \) resonator length
and “not” the gap or radii of the concentric cylinders

142.5 mm
122 mm
194 mm
194 mm
\( \lambda/4 \) Resonator, HOMs

For a pure \( \lambda/4 \) resonator, next HOM is \( x3 \) the fundamental mode.

Therefore, damping is a LOT more easier (for example use a high-pass filter).

\( Z_0 \tan(\beta l) = \frac{1}{\omega C_{\text{gap}}} \)

Note, due to large aperture & residual \( E_z \) the LHC cavity will only a quasi \( \lambda/4 \) resonator.
\( \lambda/2 \) TEM Resonator

Two \( \lambda/4 \) resonators \(\rightarrow\) \( \lambda/2 \)

→ Use HOM (TE\(_{11}\) like) for deflection

→ More elegant is to use two \( \lambda/2 \) resonators

➢ Height of the cavity is symmetric about beam pipe

➢ Only compact in dimension, LHC needs both x-y compactness
\[ \frac{\lambda}{2} \text{ TEM Resonator} \]

ODU, J. Delayen

SLAC, Z. Li

Fill these regions

2010

Full design change

Symmetric Ridges

2011

Also, Initially proposed by F. Caspers (Crab WS 2008)

Joint SLAC-ODU Effort
4R (LU-DI-JLAB)

Four co-linear $\lambda/4$ resonators

$\lambda/4 = 187.5$ mm

4 eigenmodes, mode 2 is our crab mode

500 MHz CEBAF Separator

Conical resonators for mechanical stability

Downside is that the deflecting mode is NOT the lowest order mode
### Performance Chart

<table>
<thead>
<tr>
<th>Geometrical</th>
<th>Double Ridge (ODU-SLAC)</th>
<th>4-Rod (UK)</th>
<th>¼ Wave (BNL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity Radius [mm]</td>
<td><strong>147.5</strong></td>
<td><strong>143/118</strong></td>
<td><strong>142/122</strong></td>
</tr>
<tr>
<td>Cavity length [mm]</td>
<td>597</td>
<td>500</td>
<td>380</td>
</tr>
<tr>
<td>Beam Pipe [mm]</td>
<td>84</td>
<td>84</td>
<td>84</td>
</tr>
<tr>
<td>Peak E-Field [MV/m]</td>
<td>33</td>
<td>32</td>
<td>47</td>
</tr>
<tr>
<td>Peak B-Field [mT]</td>
<td>56</td>
<td>60.5</td>
<td>71</td>
</tr>
<tr>
<td>$R_T/Q$ [Ω]</td>
<td>287</td>
<td>915</td>
<td>318</td>
</tr>
<tr>
<td>Nearest Mode [MHz]</td>
<td>584</td>
<td>371-378</td>
<td>575</td>
</tr>
</tbody>
</table>

**RF**

- Kick Voltage: 3 MV, 400 MHz
- RF 194 mm
- B1 < 60 MV/m
- B2 < 100 mT

Damping more complicated.
**Impedance Thresholds**

**Longitudinal**

- **Impedance:** $2.4 \ \text{M}\Omega \text{ total (7 TeV)}$
- **Strongest monopole mode:** $R/Q = 200\Omega \rightarrow Qe < 1 \times 10^3$
- **Damping:** $Qe < 100-500$

**Transverse**

<table>
<thead>
<tr>
<th>Energy</th>
<th>$\gamma m_p c^2$</th>
<th>Beta-function $\beta_{x,y}$</th>
<th>Impedance $-\text{Re}Z_{th}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>450 GeV</td>
<td>150 m</td>
<td></td>
<td>2.7 MOhm/m</td>
</tr>
<tr>
<td>7 TeV</td>
<td>4 km</td>
<td></td>
<td>1.5 Mohm/m</td>
</tr>
</tbody>
</table>

**Strongest dipole mode:**
- $Z < 0.6 \ \text{M}\Omega/\text{m (0.58 GHz)}$
- $(Q_{ext} = 500)$
HOM Damping

56 MHz Prototype

3-5 stage Chebyshev High pass filter

(placement not fixed yet)

4 Symmetric couplers on the end caps (notch/high-pass ?)

4 asymmetric couplers on cavity body

HOM Broadband

LOM Input

HOM probe
RF “Multipoles”

Linear tune shifts \( \sim 0.0 - 10^{-3} \)
Non-linear effects \( (b3, b4) \) \( \rightarrow \) Negligible
Cavity Tuning Thoughts

Up/down motion ± 2mm → 1 kHz

Push/pull on cavity body

Scissor jack type mechanism

Double lever (Saclay type)

Modified screw/nut (SOLEIL type)

CEBAF Tuner
Multipacting

Low gradient (weak or moderate)

Medium gradient (strong)
beam-pipe region (similar to KEKB)

High Field (weak)

Not a serious worry, will require RF processing

Courtesy G. Burt, J. Delayan, Z. Li
RF Power

$$V_b \propto Q_L I_b \frac{R_T}{Q_0} (k \Delta x)$$

RF Power \(~8\text{kW} \ (V_T=3 \text{ MV})\)

For Comparison,
Main RF 300kW \((V=2 \text{ MV})\)
RF Power Options

50 kW/cavity, moderate power
  Simplified (modified) LHC coupler
  Common platform for 3 cavities designs

Three available choices
  For SPS tests, reuse Tetrodes used in SPS tests

Tetrode (SPS)
  400 MHz, ~50kW

IOTs (TV Transmitter)
  Light Sources
  2.0m x 2.5m

Solid State Amplifiers
  190 kW, 352 MHz
  Single tower < 3m
RF Distribution

~300m

Preliminary thoughts

LLRF (Coupled feedback)

FDBK

Cavity 1

Cavity 2

TX

Z(s)

Z(s)

L1

L2

V1

V1

V2-V1

V2-V1

Need ~20-25 m space for amplifiers on each IP-side

Crab Cryomodule

Waveguides/Coax

Graphic Courtesy: S. Weisz
(Space in bypass extremely limited)
RF Noise

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

For example:
\[ \theta_c = 570 \mu \text{rad}; \ \Delta V/V = 0.4\% \]
\[ \sigma_x^* = 7 \mu \text{m}, \ \sigma_z^* = 7.55 \text{cm} \]
\[ \theta_{\text{err}} = 1.2 \mu \text{rad} \]

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

For example:
\[ \Delta \phi = 0.005^0, \ \theta_c = 570 \mu \text{rad} \]
\[ \Delta x_{IP} = 0.3 \mu \text{m} \ (5\% \ of \ \sigma_x^*) \]

LHC Main RF, \( \Delta \phi = 0.005^0 \) at 400 MHz (Philippe)
(summing noise at all betatron bands from DC → 300kHz)

Note: IOTs & SSAs are less noisy + betatron comb \( (\Delta \phi \leq 0.001) \)
**Planning Overview**

- **Cavity Testing**
- **Prototype Cryomodule**
- **Production of Cryomodules**

**M2: Beam Tests** (2015-16)

**Final Implementation** (2022-23?)

**M2: Compact Validation & Selection** (2012-13)

Detailed planning, see E. Jensen (LHC-CC11)
Fabrication Options

Sheet metal (deep drawing, spinning, hydro-forming)
  Multiple dies, electron-beam welding

Solid Niobium & machining
  Material costs & leak tightness

{Total 16 cavities (2 IPs, B1 & B2)
  With sheet metal (4mm thick)
  We need approx 500-600 kg Niobium (RRR>300)}
Niobium cavity to be delivered in March 2012
Double Ridge Fabrication

Niowave
STTR, Phase I/II

Courtesty: J. Delayan, Niowave

Nov 2011  →  Jan 2012

Testing April 2012
Real Reality?

“If it is real, we believe in it”

The Church of Reality
A1: Leveling, X-Angle

Demonstrated in 2011 w/o affecting other IPs and emittance w/o crabs range is extremely limited

To fully exploit leveling with x-angle, an RF cavity is ideal
A2: Why SC-Cavity

With ~6MV/module, NC-RF is not a viable choice

\[ Q_0 = \frac{G}{R_s} \]

Geometrical factor
\( G \approx 200 \ \Omega \)

Microwave resistance
- Copper \( \sim \) m\( \Omega \)
- Niobium-SC \( \sim \) n\( \Omega \)

\[ R_s = \frac{1}{\sigma \delta} \]

Maximize aperture & minimize # of cavities (reduced impedance)

A choice of 2K cryogenic system optimum for crabs (LHC-CC11)
A3: SPS As a Testbed

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

Cavity validation with beam (field, ramping, RF controls, impedance)
Collimation, machine protection, cavity transparency
RF noise, emittance growth, non-linearities,
Instrumentation & interlocks
A4: SPS, BA4 Setup

RF Power Setup (~50kW, Tetrode)

Courtesy E. Montesinos

Y-Chamber like, similar to present COLDEX
A5: RF Noise, LHC

with 1-T feedback
P. Baudrenghien

Selective reduction at all $f_{rev}$ lines ($V=1.5\text{MV}$, $Q_L=60k$)

Using a betatron comb, we can expect $\sim16\text{dB}$ reduction at selective frequencies
A6: RF Non-Linearity

Tuning (shaping) to suppress multipoles

Voltage deviation over 5mm:
Horizontal: 20% → 5%
Vertical: x2 → 10%

Courtesy G. Burt, J. Delayan
A7: Other Applications

Emittance exchange $x$-$z$ (P. Emma & others)

\[ \varepsilon_x \leftrightarrow \varepsilon_z \]

Momentum cleaning: $Q_{acc} = (f_{cc}/f_0)\eta\delta$ (S. Fartoukh)
For effective $Q_{acc} \sim 0.3 \rightarrow 8\text{GHz}$, too high freq (Y. Sun)

Compensate offset collisions due to beam loading for LHeC (Zimmermann)
May not be needed if phase modulation removes the phase-slip

HE-LHC (16.5 TeV)

\[ \Phi = \frac{\sigma_z}{\sigma_x} \phi_c = 0.6, \text{ similar to nominal} \]

\[ (\sigma_z = 6.5\text{cm}, \sigma_x = 9\mu\text{m}, \phi_c = 160\text{mrad}) \]

\[ R_\Phi = -12\% \text{ wr.t. to head-on} \]
A8: ProjectX Synergy

SRF Deflector
10 MV, 366-447 MHz

Mode I

<table>
<thead>
<tr>
<th>Mode I</th>
<th>TE113</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq</td>
<td>447 MHz</td>
</tr>
<tr>
<td>R/Q</td>
<td>500 Ω</td>
</tr>
<tr>
<td>Epk</td>
<td>34 MV/m</td>
</tr>
<tr>
<td>Bpk</td>
<td>74 mT</td>
</tr>
<tr>
<td>Aperture</td>
<td>75 mm</td>
</tr>
</tbody>
</table>

LHC Type Concept(s)

Courtesy M. Champion, Y. Yakovlev
Cavity reached (ANL 72 MHz)
$E_p=70 \text{ MV/m}, B_p=100 \text{ mT}$
$Q_0 = 1 \times 10^9$ at 4.6 K (IPAC10)