LHC Crab Cavity Progress & Outlook
R. Calaga, E. Jensen, CERN
SRF2013, September 27, 2013

On behalf of the LHC-CC collaboration
Special Ack: CERN, RF, EN & TE Groups
Present Performance, LHC

- 2011: ~5.6 fb\(^{-1}\)
- 2012: 23 fb\(^{-1}\)

After present shutdown (2014-20) → 60 fb\(^{-1}\)/yr

(Higgs mass, spin, indications of strength & couplings to fermions & bosons)
HL-LHC Upgrade (2020-30) 250–300 fb⁻¹/yr

A total of 1.2 km of the LHC to be upgraded

ATLAS/CMS

60m common channel

Crab cavities, why?

32 parasitic collisions/IP → Total 128
(need separate beams with crossing angle)
Elucidating the Higgs mechanism...
(i.e. from which grape the bottle is made of?)

To elucidate the Higgs mechanism all three main contenders use extremely demanding SCRF technology:

High Luminosity LHC: Accelerating RF and Crab Cavities (novel designs & precision timing)

A circular Higgs Factory collider: 10 to 20 GV of CW SCRF

A linear Higgs Factory collider, the ILC: 250 GV of pulsed SCRF
To Maximize Collision Efficiency

"π - Bump"

First proposed by R. Palmer 1988

Applied to circular $e^+e^-$ collider 2007
LHC Crab Scheme

- 3 cavities /IP side per beam
- Between D2 & Q4

7km ring
(26-450 GeV)

2-Cavity Test Module
SPS

ALICE
SECTOR 12
SPS

ATLAS

CMS

H-Crabbing
V-Crabbing
SPS
SPS Test Module

Proof of principle demonstration with protons

Important beam tests
Technology validation, performance, stability
Effects on the beam, cavity failures, radiation

SPS BA4 bypass

3.5m
### RF Dipole (ODU-SLAC) vs. 4-Rod (UK) vs. ¼ Wave (BNL) vs. KEKB

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RF Dipole (ODU-SLAC)</th>
<th>4-Rod (UK)</th>
<th>¼ Wave (BNL)</th>
<th>KEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity Radius [mm]</td>
<td>140.5</td>
<td>140</td>
<td>139</td>
<td>550</td>
</tr>
<tr>
<td>Cavity length [mm]</td>
<td>535</td>
<td>383</td>
<td>344</td>
<td>375</td>
</tr>
<tr>
<td>Beam Pipe [mm]</td>
<td>84</td>
<td>84</td>
<td>84</td>
<td>305</td>
</tr>
<tr>
<td>Peak E-Field [MV/m]</td>
<td>33</td>
<td>34</td>
<td>38</td>
<td>34</td>
</tr>
<tr>
<td>Peak B-Field [mT]</td>
<td>56</td>
<td>79</td>
<td>70</td>
<td>98</td>
</tr>
<tr>
<td>$R_T/Q$ [$\Omega$]</td>
<td>427</td>
<td>565</td>
<td>426</td>
<td>47</td>
</tr>
<tr>
<td>Nearest Mode [MHz]</td>
<td>577</td>
<td>371-378</td>
<td>582</td>
<td>~350</td>
</tr>
</tbody>
</table>

**Kick Voltage**: 3.4 MV, 400 MHz
Favorable distribution of peak surface fields
(And compact due to quasi TEM or TE11-like)

- x3-4 bigger transversely
- 40% higher Bp
- x6 smaller R/Q
- HOMs well separated

Same with other designs
All Prototypes in Bulk Niobium (2011-12)
Summary of Cavity Tests:

All cavities built by Niowave Inc. in bulk Niobium
Surface treatment and first RF tests in the last 6 months
1 very good result, 2 moderate-to-good results

Only 4Rod cavity results are presented, see next talks for the other cavities
End plates from solid ingot
  *Wire EDM pre-forms from ingot*
  Machine all surfaces

Outer shell in two-part sheet metal

Courtesy: Lancaster U, Niowave Inc.
Surface Treatment
Niowave

4Rod Cavity Treatment-Testing
(Ack: BE-RF, TE-VSC, EN-MME)

H₂ Degassing, CERN

High Press Rinsing
CERN

RF Measurements
CERN-SM18

600°C, 48 hrs

1st test performed Nov 2012
2nd test in Aug-Sep 2013
4Rod Cavity $Q_v$ vs. $V_\perp$

Second test after light BCP (2013)
(Vacuum leak persists but better)

Target $R_s \approx 10$ n$\Omega$

$R_s \approx 90$ n$\Omega$

$1.8 \text{ K}$
$2.0 \text{ K}$
$3.5 \text{ K}$
$4.5 \text{ K}$

Multipacting
Thermal Runaway
Quench

Ack: BE-RF-SRF/PM
4Rod: R vs. T Curve

Rs from the classical BCS fit $\sim 45 \, n\Omega$

\[ R_{\text{res}} = 45 \, [n\Omega] \]

Measurement (\( V_T = 0.12 \, MV \))

\[ \text{Fit}_{\text{BCS}} + R_{\text{res}} \]

Ack: BE-RF-SRF/PM
Enzo! I only answered "maybe" to your questions

- Vacuum leak significant at superfluid transition
- Separate 2K & 1.8K measurements

\[ R_{res} = 45 \,[\text{n}\Omega] \]
Latest Cavity Designs

Waveguide or waveguide-coax couplers

Coaxial couplers with hook-type antenna

Coaxial couplers with different antenna types

COMPLEX FABRICATION
Dressed Cavity Concepts

He 2-Phase line

LOM port

Input port

He-Jacket +
B-Shield

Modified
Saclay Tuner

4 Rod Cavity

LHC 2nd beam tube

Double Quarter Wave Tuner transverse plane

RF Dipole
Longitudinal tuning
Cryostat Proposal for SPS

Top Loading

Side Loading

1000mm

2160mm

Simplified cryostat for easy assembly/access/maintenance
(LHC system would be a natural extension)

S. Pattalwar, T. Jones
(4Rod Cavity)
Cryostat Integration into SPS

CERN-EN-MME & Daresbury
(4Rod Cavity)

Integration into SPS Bypass
Input Coupler Interface

Cryomodule

Common Vertical Power Coupler interface imposed for all cavities

SPS type disk ceramic adapted for 62mm, 50Ω coaxial coupler (with coax-waveguide transition WR2300)

Double-walled tube interface between cavity-vacuum vessel
RF Layout

Driver: 2.5kW (6x500W)

LEP Type 400 MHz, 40kW Tetrode

Cryomodule

E. Montesinos, P. Baudrenghien
Two primary circuits 2 K and 80 K (main interface from the top)
Cavity operated at 2K saturated Helium
Power couplers and Cold/Warm transitions intercepted with LN2 at 80 K.
Planning Overview

Cavity Testing  Prototype Cryomodule  Production

2013  LS1  2015  2017  LS2  2019  2022  LS3

Jlab: 7 MV, 35 nΩ
CERN: 3MV, 45 nΩ
BNL, 1.3 MV, Poor Surface

CERN: Material under procurement

Thermal runaway
Outlook

Today

A new path for the deflecting (SRF) world, very promising results
Several emerging applications (colliders, light sources, linacs)

Near Future

Cryomodule(s) development & integration
Reliability, transparency & precision RF control with SPS beam
Potential for thin films for quench mitigation

Key challenge

To assemble this international puzzle together
A Last Thought

3D-Printing of Nb-Cavities (?)

The klein bottle opener
ODU RF-Dipole
Courtesy: ODU-Jlab

Low field multipacting easily processed did not reoccur

Achieved fields:

\[ V_T = 7.0 \text{ MV} \]
\[ E_p = 75\text{MV/m}, \quad B_p = 131\text{mT} \]

Expected \( Q_0 = 6.7 \times 10^9 \) (10\( \Omega \))
Achieved \( Q_0 = 4.0 \times 10^9 \) (35\( \Omega \))

Calculated \( Q_0 \) from SS flanges: \( 3.7 \times 10^9 \)

The slight higher residual resistance likely due to acid contamination
Q is low, $\sim 3 \times 10^8$ (independent on the temp, expected $8.5 \times 10^9$)

No Q-disease or not due to SS flanges

CW mode 0.96 MV (thermal load), pulsed mode reached 1.34 MV (200 W amplifier)

Low field multipacting ($\sim 0.1$ MV) easily conditioned
First tests performed w/o final light BCP (2012) at 2K
(Vacuum leak due to bad NbTi flanges)
Multipacting of complex 3D geometries require sophisticated analysis (ex: ACE3P code)

4-Rod
Low Field

Double Ridge
Medium Field

Quarter Wave
High Field

No serious barriers
RF conditioning sufficient
(Courtesy Burt, Li, Wu)
Like IR magnets, higher order components of the deflecting field important

<table>
<thead>
<tr>
<th>$\text{mTm/m}^{n-1}$</th>
<th>MBRC</th>
<th>4-Rod</th>
<th>Pbar/DRidge</th>
<th>$\frac{1}{4}$-wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_2$</td>
<td>55</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$b_3$</td>
<td>7510</td>
<td>1162</td>
<td>455</td>
<td>1076</td>
</tr>
<tr>
<td>$b_4$</td>
<td>82700</td>
<td>84</td>
<td>24.6</td>
<td>92</td>
</tr>
<tr>
<td>$b_5$</td>
<td>$2.9\times10^6$</td>
<td>$-2.29\times10^6$</td>
<td>$-2.1\times10^6$</td>
<td>$-0.1\times10^6$</td>
</tr>
<tr>
<td>$b_6$</td>
<td>$52\times10^6$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$b_7$</td>
<td>$560\times10^6$</td>
<td>$-638\times10^6$</td>
<td>$700\times10^6$</td>
<td>$7\times10^6$</td>
</tr>
</tbody>
</table>
Δ\( x_{IP} = \frac{\theta_c}{k_{RF}} \delta \varphi \)

Main RF phase jitter
\( \Delta \varphi = 0.005^0 \) @400 MHz

For Crabs (\( \theta_c = 570 \mu \text{rad} \)):
\( \Delta x_{IP} = 0.3 \mu \text{m} \) (5% of \( \sigma_x^* \))

Independent control of ampl/phase
Strong feedback across IP