Crab Cavity R&D

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Center for Accelerator Science
Old Dominion University
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Crabbing System

\[ V_T = \frac{cE_b \tan \frac{\theta_c}{2}}{2\pi f \sqrt{\beta_x \beta'_x}} \]
ODU Cast of Characters on Crabbing Systems

- **Subashini De Silva**
  - PhD ODU 2014: “Investigation and optimization of a new compact superconducting cavity for deflecting and crabbing applications”
  - 2015 IEEE PAST Award, 2015 ODU College of Science Lee Entsminger Outstanding PhD Dissertation Award
  - Research Scientist at ODU
  - RF separator for 12 GeV upgrade, Crabbing system for LHC High Luminosity Upgrade

- **Alejandro Castilla**
  - PhD ODU December 2016: “Crabbing System for an Electron-ion Collider”
  - Now at CERN, Crabbing System for LHC High Luminosity Upgrade

- **Salvador Sosa**
  - PhD student, Continuing work of Alejandro Castilla

- **HyeKyoung Park**
  - ODU PhD Physics Student and JLab Engineer
  - Superconducting RF separator for 12 GeV upgrade
  - Crabbing system for LHC High Luminosity Upgrade

- **Rocio Olave**
  - ODU Post-doc, now part-time
Deflecting and Crabbing Applications

499 MHz Deflecting Cavity for Jefferson Lab 12 GeV Upgrade

- 300 mm
- 680 mm
- Total transverse voltage = 5.6 MV

400 MHz Crabbing Cavity for LHC High Luminosity Upgrade

- R = 42 mm
- < 150 mm
- 194 mm
- Total transverse voltage = 10 MV per beam per side

CMS

ALICE

ATLAS

LHC-B

R = 20 mm

5th Pass Beam Line

R = 42 mm

Pass 5
Parallel-Bar Cavity to RF-Dipole Cavity

S. U. De Silva, PhD thesis, ODU 2014
RF Dipole Cavity Properties

- Compact design
  - Supports low frequencies
- Fundamental deflecting/crabbing mode has the lowest frequency
  - No LOMs, no need for notch filter in HOM coupler
  - Nearest HOM widely separated (≈ 1.5 fundamental)
- Low surface fields and high shunt impedance
- Good balance between peak surface electric and magnetic field
- Good uniformity of deflecting field due to high degree symmetry
- Many degrees of freedom to tailor design to application
## Proof-of-principle cavities

<table>
<thead>
<tr>
<th>Frequency</th>
<th>499.0</th>
<th>400.0</th>
<th>750.0</th>
<th>MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture Diameter (d)</td>
<td>40.0</td>
<td>84.0</td>
<td>60.0</td>
<td>mm</td>
</tr>
<tr>
<td>d/(λ/2)</td>
<td>0.133</td>
<td>0.224</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>LOM</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>MHz</td>
</tr>
<tr>
<td>Nearest HOM</td>
<td>777.0</td>
<td>589.5</td>
<td>1062.5</td>
<td>MHz</td>
</tr>
<tr>
<td>$E_p^*$</td>
<td>2.86</td>
<td>3.9</td>
<td>4.29</td>
<td>MV/m</td>
</tr>
<tr>
<td>$B_p^*$</td>
<td>4.38</td>
<td>7.13</td>
<td>9.3</td>
<td>mT</td>
</tr>
<tr>
<td>$B_p^<em>/E_p^</em>$</td>
<td>1.53</td>
<td>1.83</td>
<td>2.16</td>
<td>mT/(MV/m)</td>
</tr>
<tr>
<td>$[R/Q]_T$</td>
<td>982.5</td>
<td>287.2</td>
<td>125.0</td>
<td>Ω</td>
</tr>
<tr>
<td>Geometrical Factor ($G$)</td>
<td>105.9</td>
<td>138.7</td>
<td>136.0</td>
<td>Ω</td>
</tr>
<tr>
<td>$R_T R_S$</td>
<td>$1.0 \times 10^5$</td>
<td>$4.0 \times 10^4$</td>
<td>$1.7 \times 10^4$</td>
<td>Ω²</td>
</tr>
</tbody>
</table>

At $E_T^* = 1$ MV/m

### 499 MHz Deflecting Cavity for Jefferson Lab 12 GeV Upgrade
- Length: 44 cm

### 400 MHz Crabbing Cavity for LHC High Luminosity Upgrade
- Length: 53 cm

### 750 MHz Crabbing Cavity for MEIC at Jefferson Lab
- Length: 35 cm
400 MHz Proof-of-Principle Cavity for LHC

- Cavity reached a $V_T$ of 7.0 MV
  - Cavity was retested with Nb coated flanges provided by CERN
  - $Q_0$ increased by a factor of 3 from $4 \times 10^9$ to $1.2 \times 10^{10}$

- Multipacting was processed easily and did not reoccur

- Results were confirmed by CERN
<table>
<thead>
<tr>
<th><strong>Frequency</strong></th>
<th><strong>499.0</strong></th>
<th><strong>MHz</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture Diameter (d)</td>
<td>40.0</td>
<td>mm</td>
</tr>
<tr>
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<tr>
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<td>4.38</td>
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</tr>
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<td>$B_p^<em>/E_p^</em>$</td>
<td>1.53</td>
<td>mT/(MV/m)</td>
</tr>
<tr>
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<td>982.5</td>
<td>Ω</td>
</tr>
<tr>
<td>Geometrical Factor ($G$)</td>
<td>105.9</td>
<td>Ω</td>
</tr>
<tr>
<td>$R_TR_S$</td>
<td>$1.0 \times 10^5$</td>
<td>Ω²</td>
</tr>
</tbody>
</table>

At $E_T^* = 1$ MV/m

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**Graph:**
- **Qo** vs. $E_T$ (MV/m) for 2.0 K and 4.2 K
- **Quench**

**Table:**
- **$V_f$ (MV)**: 0.0, 1.5, 3.0, 3.3, 4.2, 4.5
- **$E_p$ (MV/m)**: 0.0, 14.3, 28.6, 42.9
- **$B_p$ (mT)**: 0.0, 21.9, 43.8, 65.7
750 MHz Crabbing Cavity for Jlab MEIC

Multipacting

Cryogenic Tests

\[ E_T = 13.5 \text{ MV/m} \]
\[ V_T = 2.7 \text{ MV} \]
\[ E_P = 60 \text{ MV/m} \]
\[ B_P = 126 \text{ mT} \]
Prototype Design vs. Proof-of-Principle

Surface Electric Field

Surface Magnetic Field

Transverse Electric Field

* At energy content of 1 J
Prototype design has improved rf-properties

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Prototype</th>
<th>P-o-P</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of fundamental</td>
<td>400</td>
<td>400</td>
<td>MHz</td>
</tr>
<tr>
<td>Frequency of 1st HOM</td>
<td>632</td>
<td>590</td>
<td>MHz</td>
</tr>
<tr>
<td>Deflecting Voltage ($V_T^*$)</td>
<td>0.375</td>
<td>0.375</td>
<td>MV</td>
</tr>
<tr>
<td>Peak Electric Field ($E_p^*$)</td>
<td>3.65</td>
<td>4.02</td>
<td>MV/m</td>
</tr>
<tr>
<td>Peak Magnetic Field ($B_p^*$)</td>
<td>6.22</td>
<td>7.06</td>
<td>mT</td>
</tr>
<tr>
<td>Peak Electric Field ($E_p^{**}$)</td>
<td>32.6</td>
<td>35.9</td>
<td>MV/m</td>
</tr>
<tr>
<td>Peak Magnetic Field ($B_p^{**}$)</td>
<td>55.6</td>
<td>63.1</td>
<td>mT</td>
</tr>
<tr>
<td>$B_p/E_p$</td>
<td>1.71</td>
<td>1.76</td>
<td>mT/(MV/m)</td>
</tr>
<tr>
<td>Stored Energy ($U'$)</td>
<td>0.13</td>
<td>0.195</td>
<td>J</td>
</tr>
<tr>
<td>$[R/Q]_T$</td>
<td>427.4</td>
<td>287.0</td>
<td>Ω</td>
</tr>
<tr>
<td>Geometrical Factor (G)</td>
<td>106.7</td>
<td>140.9</td>
<td>Ω</td>
</tr>
<tr>
<td>$R_T R_S$</td>
<td>$4.6 \times 10^4$</td>
<td>$4.0 \times 10^4$</td>
<td>$\Omega^2$</td>
</tr>
</tbody>
</table>

*At $E_T = 1$ MV/m  ** At $V_T = 3.35$ MV
Cavity and HOM Couplers Fabrication
SPS-RFD Cavity Test Results

- At low fields for both rf tests $Q_0$ is $> 1.0 \times 10^{10}$
- Multipacting was processed easily and didn’t reoccur
- No field emission observed during Test 2

<table>
<thead>
<tr>
<th>At 2.0 K</th>
<th>Test 1</th>
<th>Test 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max $V_t$ [MV]</td>
<td>4.0 MV</td>
<td>4.4 MV</td>
</tr>
<tr>
<td>$E_p$ [MV/m]</td>
<td>38</td>
<td>42</td>
</tr>
<tr>
<td>$B_p$ [mT]</td>
<td>66</td>
<td>73</td>
</tr>
<tr>
<td>$Q_0$ at 3.4 MV</td>
<td>$5.5 \times 10^9$</td>
<td>$8.5 \times 10^9$</td>
</tr>
<tr>
<td>$R_s$ [nΩ]</td>
<td>10.5</td>
<td>12.6</td>
</tr>
</tbody>
</table>
Lessons Learned

- Perform bulk BCP after final weld
- Bulk BCP of the two SPS-RFD cavities were done before final weld to control frequency shift due to processing
- Due to quality of final welds additional bulk BCP was done on both RFD cavities
- Frequency shift due to bulk BCP $\rightarrow$ 40 kHz (140 microns uniform removal)
- Frequency shift is comparatively small $\rightarrow$ Not a critical parameter in frequency control
Magnetic Shielding and Helium Tank
Tuner Engineering
Cryostat Engineering
Crabbing Cavity for JLEIC

- Horizontal local crabbing system
  - Two interaction points
  - Four crabbing cavity locations – per interaction point (per beam - per side)
- Crabbing cavity frequency – 952.6 MHz
- Luminosity > $10^{33}$ cm$^{-2}$s$^{-1}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Electron</th>
<th>Proton</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>10</td>
<td>100</td>
<td>GeV</td>
</tr>
<tr>
<td>Beam current</td>
<td>0.72</td>
<td>5.0</td>
<td>A</td>
</tr>
<tr>
<td>Bunch frequency</td>
<td>952.6</td>
<td></td>
<td>MHz</td>
</tr>
<tr>
<td>Crab crossing angle</td>
<td>50</td>
<td></td>
<td>mrad</td>
</tr>
<tr>
<td>Betatron function at IP</td>
<td>10</td>
<td></td>
<td>cm</td>
</tr>
<tr>
<td>Betatron function at crab cavity</td>
<td>200</td>
<td>363</td>
<td>m</td>
</tr>
<tr>
<td>Integrated transverse voltage per beam per side</td>
<td>2.8</td>
<td>20.8</td>
<td>MV</td>
</tr>
</tbody>
</table>

![Graph showing crabbing voltage vs. \(\beta\)-function at crabbing cavity]
Challenges for JLEIC Crabbing System

- Higher frequency than demonstrated so far
  - Properties degrade rapidly as ratio of aperture to wavelength increases

- Constraints on transverse and longitudinal space available
  - Multi-cell cavities

- Crabbing in continuously variable direction
  - Independent and simultaneous horizontal and vertical crabbing
  - Not anymore in baseline
Aperture-dependent Properties

- Electromagnetic properties of “TE” cavities are quite sensitive to beamline aperture (separation between the poles)
Cavity Options for Crabbing System

• Squashed elliptical cavity

• Single-cell RF-Dipole cavity

• Multi-cell RF-Dipole cavity
952.6 MHz Cavity – Single Cell Cavity

- Compact design
- No lower order modes
- Properties degrade drastically with increasing beam aperture

<table>
<thead>
<tr>
<th></th>
<th>(A)</th>
<th>(B)</th>
<th>(C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>952.6</td>
<td></td>
<td>MHz</td>
</tr>
<tr>
<td>Aperture</td>
<td>50</td>
<td>60</td>
<td>70</td>
</tr>
<tr>
<td>1(^{st}) HOM</td>
<td>1431.0</td>
<td>1420.4</td>
<td>1411.5</td>
</tr>
<tr>
<td>(V_t^*)</td>
<td>0.157</td>
<td></td>
<td>MV</td>
</tr>
<tr>
<td>(E_p^*)</td>
<td>4.2</td>
<td>4.8</td>
<td>5.4</td>
</tr>
<tr>
<td>(B_p^*)</td>
<td>9.3</td>
<td>11.3</td>
<td>13.6</td>
</tr>
<tr>
<td>([R/Q]_t)</td>
<td>136</td>
<td>81</td>
<td>50</td>
</tr>
<tr>
<td>(G)</td>
<td>145</td>
<td>155</td>
<td>166</td>
</tr>
<tr>
<td>(R_sR_x)</td>
<td>2.0\times10^4</td>
<td>1.3\times10^4</td>
<td>8.3\times10^3</td>
</tr>
</tbody>
</table>

* \(E_t = 1\) MV/m
952.6 MHz Cavity – Multi-Cell Cavity

- A 3-cell design study with varying beam aperture
- Two lower order modes – 1\textsuperscript{st} and 2\textsuperscript{nd} harmonic of the crabbing mode
- High shunt impedance
- Similar peak surface fields as single cell cavity

<table>
<thead>
<tr>
<th></th>
<th>(A)</th>
<th>(B)</th>
<th>(C)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency</strong></td>
<td><strong>952.6</strong></td>
<td><strong>MHz</strong></td>
<td></td>
</tr>
<tr>
<td>Aperture</td>
<td>50</td>
<td>60</td>
<td>70</td>
</tr>
<tr>
<td>LOM</td>
<td>790, 879</td>
<td>773, 870</td>
<td>757, 862</td>
</tr>
<tr>
<td>1\textsuperscript{st} HOM</td>
<td>1409</td>
<td>1383</td>
<td>1335</td>
</tr>
<tr>
<td>$V_t^*$</td>
<td>0.157</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_p^*$</td>
<td>4.7</td>
<td>5.1</td>
<td>5.6</td>
</tr>
<tr>
<td>$B_p^*$</td>
<td>8.7</td>
<td>10.0</td>
<td>11.4</td>
</tr>
<tr>
<td>$[R/Q]_t$</td>
<td>494</td>
<td>323</td>
<td>219</td>
</tr>
<tr>
<td>$G$</td>
<td>161</td>
<td>170</td>
<td>179</td>
</tr>
<tr>
<td>$R_t R_s$</td>
<td>$8.0 \times 10^4$</td>
<td>$5.5 \times 10^4$</td>
<td>$3.9 \times 10^4$</td>
</tr>
</tbody>
</table>

* $E_t = 1$ MV/m
952.6 MHz Squashed Elliptical Cavity

- Squashed elliptical design has reduced peak surface fields
- Has a monopole – lower order mode
- Requires wide beam pipe separation

<table>
<thead>
<tr>
<th></th>
<th>(A)</th>
<th>(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>952.6 MHz</td>
<td></td>
</tr>
<tr>
<td>Aperture</td>
<td>60</td>
<td>70</td>
</tr>
<tr>
<td>LOM</td>
<td>699.4 MHz</td>
<td>697.6 MHz</td>
</tr>
<tr>
<td>1st HOM</td>
<td>1041.1</td>
<td>1033.1</td>
</tr>
<tr>
<td>$V_t^*$</td>
<td>0.157 MV</td>
<td></td>
</tr>
<tr>
<td>$E_p^*$</td>
<td>2.16</td>
<td>2.29</td>
</tr>
<tr>
<td>$B_p^*$</td>
<td>7.2</td>
<td>7.46</td>
</tr>
<tr>
<td>$[R/Q]_t$</td>
<td>50.8</td>
<td>49.4</td>
</tr>
<tr>
<td>$G$</td>
<td>342.9</td>
<td>340.8</td>
</tr>
</tbody>
</table>
| $R_R_s$          | $2.75 \times 10^4$ | $1.7 \times 10^4$ | Ω²

* $E_t = 1$ MV/m
### Design Comparison

<table>
<thead>
<tr>
<th></th>
<th>Squashed Elliptical</th>
<th>Single-Cell RFD</th>
<th>Multi-Cell RFD</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency</strong></td>
<td>952.6</td>
<td></td>
<td></td>
<td>MHz</td>
</tr>
<tr>
<td><strong>Aperture</strong></td>
<td></td>
<td>70</td>
<td></td>
<td>mm</td>
</tr>
<tr>
<td><strong>LOM</strong></td>
<td>697.6</td>
<td>None</td>
<td>757, 862</td>
<td>MHz</td>
</tr>
<tr>
<td><strong>LOM Mode Type</strong></td>
<td>Monopole</td>
<td>Dipole</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>1st HOM</strong></td>
<td>1033.1</td>
<td>1411.5</td>
<td>1335</td>
<td>MHz</td>
</tr>
<tr>
<td><strong>Total ( V_t ) (e/p)</strong></td>
<td></td>
<td>2.8 / 20.8</td>
<td></td>
<td>MV</td>
</tr>
<tr>
<td>(per beam per side)**</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>( V_t ) (per cavity)</strong></td>
<td>2.2</td>
<td>1.2</td>
<td>4.2</td>
<td>MV</td>
</tr>
<tr>
<td><strong>No. of cavities</strong></td>
<td>2 / 10</td>
<td>3 / 18</td>
<td>1 / 5</td>
<td></td>
</tr>
<tr>
<td>(per beam per side)**</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>( E_p )</strong></td>
<td>32</td>
<td>41.2</td>
<td>49.8</td>
<td>MV/m</td>
</tr>
<tr>
<td><strong>( B_p )</strong></td>
<td>104.3</td>
<td>103.7</td>
<td>101.4</td>
<td>mT</td>
</tr>
<tr>
<td><strong>( R_s ) [( R_{res} =10 , \text{n\Omega} , \text{&amp;} , 2.0 , \text{K} )]</strong></td>
<td></td>
<td>16.3</td>
<td>n\Omega</td>
<td></td>
</tr>
<tr>
<td><strong>( P_{diss} ) (per cavity)</strong></td>
<td>4.6</td>
<td>2.8</td>
<td>7.4</td>
<td>W</td>
</tr>
</tbody>
</table>
R&D Plan for Crabbing System for JLEIC

• Year 1: Integration of beam physics requirements and crabbing system design
  – Define the beam physics requirements and constraints on crabbing system
    • Voltage
    • Impedance
    • Multipoles
    • HOM damping requirements
    • Smallest beam aperture compatible with beam physics requirements
    • Multi-cell geometries, other geometries

  — Crabbing at “arbitrary angle”
    • Include horizontal and vertical crabbing cavities

  – Will required close interaction and iteration between beam physics and cavity design
R&D Plan for Crabbing System for JLEIC

• Years 2 and 3: Design and prototyping
  – Cavity prototype design (driven by beam physics)
    • Aperture
    • Impedances (HOM damping requirement)
    • Nonlinearities and instabilities (Multipole components, quenches, Multipacting simulations)
  – HOM couplers design and prototyping
  – Cavity prototype fabrication and testing
  – HOM couplers fabrication and testing
Test of Crab Cavities with Hadron Beam

General plans

- 2 cryomodules for SPS tests
  - 1 cryomodule with 2 identical cavities (type «vertical» - DQW)
    - Design as much as possible coherent with LHC
    - To be tested in SPS in 2018
  - 1 cryomodule with 2 identical cavities (type «horizontal» - RFD)
    - Design to be done as LHC prototype
    - To be tested in SPS after LS2, in 2021

- 2 cavities pre-series for LHC (one of each type)

- 8 cryomodules (4 of each type) for installation in LHC during LS3
  + 2 spares (1 of each type)

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SPS test prototype (2 CMs)

preparation

SPS Test (CM1)

LHC pre-series

(2 Industrial Dressed Cavities)

LHC series production & Installation (8 CMs)

OC, International Review of the Crab Cavities Performance, 3 April 2017
Work Plan for Proof-of-Principle

• Quarter 1: Beam physics study
  – Initiate electromagnetic design study
  – Initiate beam physics requirements and specifications
    • Transverse voltage for both electron and proton beams
    • Requirements on HOM impedance
    • Requirements on multipole components

• Quarter 2: Electromagnetic design with beam physics
  – Determine smallest beam aperture compatible with beam physics
  – Investigate preliminary rf designs of cavities: rf-dipole (single and multi-cell, squashed TM$_{110}$)
Work Plan for Proof-of-Principle

- Quarter 3: Electromagnetic design with beam physics
  - Requirements completed
    - Transverse voltage for both electron and proton beams
    - Requirements on HOM impedance
    - Requirements on multipole components
  - Electromagnetic design
    - Down select between rf-dipole and TM$_{110}$ geometries
    - Optimize rf geometry for best rf properties
    - HOM study
    - Multipacting analysis
  - Initiate engineering design
  - Initiate HOM and FPC coupler design
  - Procurement of material
    - Agreement with ODURF that PoP cavity can be capitalized (no overhead on material)
Work Plan for Proof-of-Principle

• Quarter 4:
  – Electromagnetic design and beam physics
    • Higher order modes
    • Impedances
  – Engineering design
    • Complete engineering design
    • Initiate fabrication
    • Design tooling fixtures
    • Design tooling
  – Procurement of material
Work Plan for Proof-of-Principle

• Quarter 5:
  – Electromagnetic design and beam physics
    • Higher order modes
    • Impedances
    • Multipoles
    • Complete design of HOM couplers
  – Fabrication
    • Dies and tooling fixtures
    • Initiate fabrication of Cu or Al cavity
    • Initiate fabrication of Nb cavity

• Quarter 6:
  – Electromagnetic design and beam physics
    • Higher order modes
    • Impedances
    • Multipoles
  – Complete fabrication of cavity parts
Work Plan for Proof-of-Principle

- **Quarter 7:**
  - Electromagnetic design and beam physics
    - Higher order modes
    - Impedances
    - Multipoles
    - Instabilities
  - Complete cavity fabrication
  - Room temperature measurements and testing
    - Higher order modes frequencies and impedances
    - Multipoles

- **Quarter 8:**
  - Room temperature measurement and testing
    - Higher order modes frequencies and impedances
    - Multipoles
  - Nb Cavity processing
  - Cryogenic testing of Nb cavity
Fabrication

499 MHz Deflecting Cavity
Fabricated at Jefferson Lab

400 MHz Crabbing Cavity
Fabricated at Niowave Inc.
RF-Dipole Crabbing Cavity

Proof of Principle Cavity

Prototype Cavity

Prototype cavity
- Well separated HOMs
- Reduced surface electric and magnetic fields
- High shunt impedance
- Improved multipacting levels compared to P-o-P cavity
- Reduced multipole components

<table>
<thead>
<tr>
<th></th>
<th>P-o-P Cavity</th>
<th>Prototype Cavity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>1st HOM</td>
<td>590</td>
<td>633.5</td>
</tr>
<tr>
<td>$V_t$</td>
<td>3.4</td>
<td>MV</td>
</tr>
<tr>
<td>$E_p$</td>
<td>37</td>
<td>33</td>
</tr>
<tr>
<td>$B_p$</td>
<td>64</td>
<td>57</td>
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<tr>
<td>$[R/Q]_t$</td>
<td>287</td>
<td>430</td>
</tr>
<tr>
<td>$G$</td>
<td>141</td>
<td>107</td>
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<tr>
<td>$R_sR_s$</td>
<td>$4.0 \times 10^4$</td>
<td>$4.6 \times 10^4$</td>
</tr>
</tbody>
</table>

#S.U. De Siva and J.R. Delayen, PRAB 16, 082001 (2013)
Multipacting

- Extensive simulations of multipacting have been performed using the SLAC ACE3P suite of codes
- Multipacting occurred in the proof-of-principle cavities where predicted, was easily processed, and did not reoccur
HOM Damping

- No lower-order mode
- Frequency of first HOM is about 1.5 that of fundamental deflecting mode

Nearest cavity mode ~230 MHz away
FPC and HOM Coupler Designs

- Coupler at locations of low field region on cavity body
  - Minimizes RF heating on the coupler components
- Location preserves field symmetry
  - Electrical center moved by 50 microns
- Selective coupling (V-coupler) to reduce the number of filters
- FPC/HOM ports oriented to keep clearance for the second beam pipe
FPC and HOM Couplers

**FPC**
- Outer diameter – 62 mm
- Inner diameter – 27 mm
- Interface to LHC main coupler design
- $Q_L = 5.0 \times 10^5$
- Hook shaped coupler reduced RF heating $\rightarrow$ 69 W

**V HOM**
- Doesn’t couple to fundamental mode
  - No filter necessary
- Damps vertical dipole modes and some accelerating modes

**H HOM**
- Horizontal HOM high pass filter to cut off fundamental mode
- Couples to horizontal dipole modes and accelerating modes
- Both options damp adequately to meet impedance requirements
HHOM – High Pass Filter

- High pass filter
  - Simple filter design
  - Damps horizontal deflecting and accelerating modes
  - Demountable coupler
  - Low fields in the filter

- Dimensions
  - Center rod diameter: 14 mm
  - Larger cylinder diameter: 74 mm
  - 50 ohm port: 14mm/32.2mm
Engineering Activities

• SPS Cavities under production by DOE LARP

• HOM prototyping to be launched (JLAB or CERN); production for SPS will be done by CERN

• Helium vessel designed by CERN and will be produced by LARP

• Tuning system will be produced by CERN

• Magnetic shielding to be finalized by STFC
Impact of Beam Aperture (84 → 100 mm)

- Preliminary design looks promising
  - Still room for further optimization

- Remains to be done
  - HOM damping
  - Multipole components
  - Multipacting analysis

<table>
<thead>
<tr>
<th>Aperture</th>
<th>84</th>
<th>100</th>
<th>mm</th>
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<tbody>
<tr>
<td>Frequency</td>
<td>400</td>
<td></td>
<td>MHz</td>
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<tr>
<td>Nearest HOM</td>
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<td>MHz</td>
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<tr>
<td>$E_p^*$</td>
<td>3.6</td>
<td>4.2</td>
<td>MV/m</td>
</tr>
<tr>
<td>$B_p^*$</td>
<td>6.2</td>
<td>6.9</td>
<td>mT</td>
</tr>
<tr>
<td>$B_p^<em>/E_p^</em>$</td>
<td>1.71</td>
<td>1.66</td>
<td>mT/(MV/m)</td>
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<tr>
<td>$[R/Q]_T$</td>
<td>429.7</td>
<td>277.7</td>
<td>Ω</td>
</tr>
<tr>
<td>Geometrical Factor ($G$)</td>
<td>106.7</td>
<td>112.2</td>
<td>Ω</td>
</tr>
<tr>
<td>$R_T R_S$</td>
<td>$4.6 \times 10^5$</td>
<td>$3.1 \times 10^4$</td>
<td>Ω²</td>
</tr>
<tr>
<td>At $E_T^*$ = 1 MV/m</td>
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</table>
### 952.6 MHz Multi-Cell Cavity for JLEIC

- A 3-cell design for Jefferson Lab Electron-Ion Collider

#### Frequency Table

<table>
<thead>
<tr>
<th>Parameter</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>790, 879</th>
<th>773, 870</th>
<th>757, 862</th>
<th>1409</th>
<th>1383</th>
<th>1335</th>
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<tr>
<td>Aperture</td>
<td>50</td>
<td>60</td>
<td>70</td>
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<td>60</td>
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<tr>
<td>LOM</td>
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<td>MHz</td>
<td>MHz</td>
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<td></td>
<td></td>
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<tr>
<td>1st HOM</td>
<td>1409</td>
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<td>MHz</td>
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<td>MHz</td>
<td></td>
<td></td>
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<tr>
<td>$V_t^*$</td>
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<td>MV</td>
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<td>$E_p^*$</td>
<td>4.7</td>
<td>5.1</td>
<td>5.6</td>
<td>MV/m</td>
<td>MV/m</td>
<td>MV/m</td>
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<tr>
<td>$B_p^*$</td>
<td>8.7</td>
<td>10.0</td>
<td>11.4</td>
<td>mT</td>
<td>mT</td>
<td>mT</td>
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<tr>
<td>$[R/Q]_t$</td>
<td>494</td>
<td>323</td>
<td>219</td>
<td>Ω</td>
<td>Ω</td>
<td>Ω</td>
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<tr>
<td>$G$</td>
<td>161</td>
<td>170</td>
<td>179</td>
<td>Ω</td>
<td>Ω</td>
<td>Ω</td>
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<tr>
<td>$R_t R_s$</td>
<td>$8.0 \times 10^4$</td>
<td>$5.5 \times 10^4$</td>
<td>$3.9 \times 10^4$</td>
<td>Ω²</td>
<td>Ω²</td>
<td>Ω²</td>
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<td></td>
</tr>
</tbody>
</table>

* $E_t = 1\ MV/m$
Detector Solenoid in the Interaction Region

- If not assessed, this tilt could considerably reduce further the luminosity
- Specially important when ramping the solenoid strength
Twining and Variable Crabbing Kick

- A variable crabbing direction is possible with a family of crab cavities with different orientations.

- The coupling range will determine the angle range to cover by the twins.

- If the range is small, the twin component of the kick is only a small correction and could be done with 1 or few cavities.
Bunch at IP with and w/o crabbing

**Bunched Beam parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>$N$ particles</td>
<td>10,000</td>
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<tr>
<td>$\varepsilon_{nx}$</td>
<td>0.35 $\mu$m</td>
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<tr>
<td>$\Delta p/p$</td>
<td>$3 \times 10^{-4}$</td>
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<tr>
<td>$\sigma_s$</td>
<td>1 cm</td>
</tr>
</tbody>
</table>

Gaussian distribution
3 - sigma

Crab angle $\approx 25$ mrad
Recommendations for LHC-RFD – Cavity Processing

- Currently bulk BCP, light BCP and HPR are done in vertical orientation
- Recommendation → Perform chemical processing horizontal orientation with rotation
  - Allows uniform removal
  - Better acid circulation and drainage
- Use of a high pressure rinse set up facilitating multiple port rinsing (Rinsing through FPC and HHOM ports)
  - Allows reducing field emission
This R&D plan should take the crabbing system from TRL 2-3 to TRL 4-5 (low to medium)

Risk: Beam physics requirements could lead to inefficient cavity geometry, or challenging engineering

Alternative technical approach:
- Investigate other cavity geometries
- Investigate process improvements
  - Nitrogen doping
  - Nb$_3$Sn coating