Path to SPS Testing
Prototype Design
ODU/SLAC RF Dipole Cavity

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Acknowledgments

• Work performed by

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  – Julius Nfor (ODU)
  – Rocio Olave (ODU)
  – HyeKyoung Park (ODU/JLAB)
Outline

• Proof-of principle design and results
• Prototype design vs proof-of-principle cavity
  – RF parameters
  – Multipacting
  – Field flatness and multipoles
  – Higher Order Mode analysis
• Mechanical analysis
  – Mechanical strength
  – Pressure sensitivity
  – Lorentz force detuning
• Tuner
• Helium tank
• Cryostat concept
• Summary and Future plan
Proof of Principle Design

• Design requirements
  – Frequency = 400 MHz
  – Beam aperture = 84 mm
  – Total transverse voltage = 10 MV
  – Transverse voltage per cavity = 3.4 MV

• Transverse electric and magnetic fields

• Surface electric and magnetic fields
Basic Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_T^*$</td>
<td>0.375</td>
<td>MV</td>
</tr>
<tr>
<td>$E_p^*$</td>
<td>4.02</td>
<td>MV/m</td>
</tr>
<tr>
<td>$B_p^*$</td>
<td>7.06</td>
<td>mT</td>
</tr>
<tr>
<td>$B_p^<em>/E_p^</em>$</td>
<td>1.76</td>
<td>mT/(MV/m)</td>
</tr>
<tr>
<td>$U^*$</td>
<td>0.195</td>
<td>J</td>
</tr>
<tr>
<td>$[R/Q]_T$</td>
<td>286.95</td>
<td>Ω</td>
</tr>
<tr>
<td>Geometrical Factor ($G$)</td>
<td>140.86</td>
<td>Ω</td>
</tr>
<tr>
<td>$R_T R_S$</td>
<td>$4.04 \times 10^4$</td>
<td>Ω²</td>
</tr>
</tbody>
</table>

- No lower order modes
- Separation of HOMs from fundamental mode ~ 190 MHz

HOM Properties

![Graph showing R/Q vs. Frequency (MHz)]
Fabrication

Fine grain Nb – RRR 353-405
Cavity thickness – 3 mm
Surface Treatment, Preparation and Testing

- Bulk BCP – 85 μm
- Heat treatment – At 600°C for 10 hours
- Light BCP – ~10 μm
- High Pressure Rinse – 3 passes
- Assembly in the clean room

- RF Test Plan
  - High power tests at 2 K and 4 K
  - Rs vs. T
  - Pressure test
  - Lorentz detuning
  - No He processing was done

- RF Tests Performed
  - 2 K high power test
  - Cavity warmed up to 4 K
  - 4 K high power test
  - Cavity cooled down to 2 K
  - 2 K high power test
Assembly

- Followed by a HPR of 3 passes
- Ultrasonic degreased hardware
- Leak tested
- Assembly in clean room
Preparation for Test

- Cable calibration
  - $Q_1 = 2.76 \times 10^9$
  - $Q_2 = 8.62 \times 10^{10}$

- LLRF control

- Test with 500 W rf amplifier
2 K and 4.2 K Test Results

- Expected $Q_0 = 6.7 \times 10^9$
  - At $R_S = 22$ nΩ
  - And $R_{res} = 20$ nΩ
- Achieved $Q_0 = 4.0 \times 10^9$
- Achieved fields
  - $E_T = 18.6$ MV/m
  - $V_T = 7.0$ MV
  - $E_P = 75$ MV/m
  - $B_P = 131$ mT

Quench
Low-field Q

- Calculated Q due to stainless steel flanges: $3.7 \times 10^9$
- Measured Q: $4.0 \times 10^9$
499 MHz Deflecting Cavity for JLab Upgrade

- 4.2 K test yesterday
- Confirms multipacting easily processed and does not reoccur
- $R_{\text{res}} < 10 \, \text{n}\Omega$
499 MHz Deflecting Cavity for JLab Upgrade

- 2 K test last night
- No multipacting
- $R_{\text{res}} \sim 5 \, \text{n}\Omega$
Summary

• Proof-of-Principle cavity achieved 7 MV deflecting voltage cw

• Residual surface resistance a little high (34 nΩ)
  – Consistent with losses in stainless steel flanges

• Multipacting quickly processed and did not reoccur

• Proof-of-Principle cavity has achieved its purpose

• Ready to move on to the prototype cavity

• Reasonably confident that 10 MV can be achieved with 2 cavities
Prototype Design vs. Proof-of-Principle

ODU/SLAC Cavity Design Evolution

Prototype Design

<table>
<thead>
<tr>
<th>Cavity Dimensions</th>
<th>Prototype Design</th>
<th>Proof-of-Principle</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>140.5</td>
<td>170</td>
<td>mm</td>
</tr>
<tr>
<td>Iris-to-iris Length</td>
<td>535</td>
<td>528</td>
<td>mm</td>
</tr>
<tr>
<td>Beampipe aperture</td>
<td>42</td>
<td>42</td>
<td>mm</td>
</tr>
</tbody>
</table>
Prototype Design vs. Proof-of-Principle

Surface Electric Field

Surface Magnetic Field

Transverse Electric Field

* At energy content of 1 J
Prototype Design vs. Proof-of-Principle

Prototype design

Multipacting Simulations

Proof-of-Principle

Using Track3P from the ACE3P Code Suite developed at SLAC
Multipacting Simulations
Multipacting Simulations

MP region moves upward at high voltages

MP region at a lower voltage

(incomplete data)
MP continues to higher deflecting voltages

larger curvature

small bump

HOM Multipacting, H3 smaller-\(r\)

HOM Multipacting, HB large-\(r\)+bump
Prototype Design vs. Proof-of-Principle

Field flatness / Multipoles

### Multipole Components

<table>
<thead>
<tr>
<th>Multipole</th>
<th>Prototype Design</th>
<th>Proof-of-Principle</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_3$</td>
<td>455.2</td>
<td>$3.0 \times 10^3$</td>
<td>mT/m</td>
</tr>
<tr>
<td>$b_4$</td>
<td>24.62</td>
<td>0</td>
<td>mT/m²</td>
</tr>
<tr>
<td>$b_5$</td>
<td>$-2.19 \times 10^6$</td>
<td>$-4.6 \times 10^5$</td>
<td>mT/m³</td>
</tr>
</tbody>
</table>

At $V_T = 10$ MV

Shift in electrical center of 55 $\mu$m due to the asymmetry introduced by the couplers.
Prototype Design vs. Proof-of-Principle

Higher order mode analysis

Wide frequency separation between modes

Nearest cavity mode ~230 MHz away

Nearest cavity mode ~190 MHz away
Couplers

- Outer diameter: 62 mm
- Inner diameter: 27 mm

FPC

- Height: 113 mm
Pick-up Port

Pick up port - Q-ext (142,000 hex meshcells)

Q_ext

probe offset from waveguide (mm)
### Prototype Design vs. Proof-of-Principle

<table>
<thead>
<tr>
<th>RF PARAMETERS</th>
<th>Prototype design</th>
<th>Proof-of-Principle</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<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>3.66</td>
<td>4.02</td>
<td>MV/m</td>
</tr>
<tr>
<td>Peak magnetic field ($B_p^*$)</td>
<td>6.14</td>
<td>7.06</td>
<td>mT</td>
</tr>
<tr>
<td>$B_p / E_p$</td>
<td>1.67</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>Geometrical factor ($G = QR_S$)</td>
<td>106</td>
<td>141</td>
<td>Ω</td>
</tr>
<tr>
<td>$[R/Q]_T$</td>
<td>427.2</td>
<td>287</td>
<td>Ω</td>
</tr>
<tr>
<td>$R_T R_S$</td>
<td>$4.54 \times 10^4$</td>
<td>$4.04 \times 10^4$</td>
<td>Ω$^2$</td>
</tr>
</tbody>
</table>

* at $E_T = 1$ MV/m

<table>
<thead>
<tr>
<th>At $V_T = 3.4$ MV</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak electric field ($E_p$)</td>
<td>33.2</td>
<td>36.5</td>
<td>MV/m</td>
</tr>
<tr>
<td>Peak magnetic field ($B_p$)</td>
<td>55.7</td>
<td>64.0</td>
<td>mT</td>
</tr>
</tbody>
</table>

Prototype is superior to Proof-of-Principle across all parameters.
Electromagnetic design is now frozen.
Multipacting studies in waveguide couplers under way.
Mechanical Analysis

Mechanical strength – Stress

Weak area identified
(LHC crab cavity meeting, December 2012)

4mm thick formed plate added

4mm thick stiffeners added

Worst case scenario:
Allowable stress 70 MPa
at room temperature and 2.6 bar external pressure
Results (Stress intensity)

- Main body below 70 MPa
- Stress concentration at coupler ports – solved by machining instead of stamping (flexibility to increase thickness at high stress areas)

Adjacent beam pipe is not needed for SPS test. Then, stiffener will be identical top and bottom and still meets the requirements.
Mechanical Analysis

Pressure Sensitivity  -30 Hz/torr
Tuning Sensitivity  +90 kHz/mm
Lorentz Force Detuning  -20 Hz/(MV/m)^2

Niobium property at 2-4K
Picture not showing adjacent beam pipe but included in the analysis

All characteristics improved from the proof of principle cavity design.
Tuner Options

- JLAB scissor jack tuner fits with minimal scaling
- Tuner can be driven by stepper motor or pneumatic control
- Proven performance of JLAB mechanical tuner
  - Resolution/Deadband/Hysteresis < 2 Hz
  - Frequency drift due to Helium pressure fluctuations
Helium Tank

- Simple stainless steel construction
- All cavity and Helium ports on flat surface
- Bellows connections to compensate thermal contraction
- Dummy pipes or internal structure to reduce Helium volume if required.
Cryostat Concept

Helium tank/Tuner Assembly

Horizontal beam deflection

Vertical beam deflection

Ongoing brain-storming to use identical helium tank for both configuration if it is beneficial
Cryostat Concept

- Cryostat concept including as many parts as possible
  - He tank/tuner assembly
  - Magnetic shielding
  - Helium supply and return lines
- Envelope for SPS (520x1200x3100mm) can be met without the adjacent beam pipe
Summary and Future Plan

• “Final” prototype cavity design
  – Better electromagnetic properties than proof-of-principle
  – Includes power and HOM couplers
  – Complies with safety requirements
  – Complies with dimensional requirements

• Integrated system design study ongoing
  – More complete layout
  – Mechanical tuner
  – Helium tank
  – Cryostat concept

• Ready to build and test “final” prototype cavity