The ATLAS Energy Upgrade Cryomodule

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MOOCAU04
Introduction

- A new cryomodule containing 7 \( \beta=0.15 \) quarter-wave cavities is now operating with beam in the ATLAS heavy ion linac, increasing energy by 30-40%.

- This represents the first successful demonstration of separate cavity and insulating vacuum systems for a low-\( \beta \) cryomodule.

- Maximum voltages of 3.75 MV per cavity have been achieved. ~1 MV/cavity is today’s state-of-the-art for operations.
Features

- Optimized electromagnetic and structural design of the cavities
- Cancellation of beam steering effect due to the RF field in the QWR
- State-of-the-art surface processing, clean-room assembly, low-particulate pumping and venting systems (THPPO029)
- Top-loaded cryomodule design which minimizes components involved in clean assembly
Location in the ATLAS Tunnel

- 30 m
- 40 MV
- 4.5 m
- 14.5 MV
Section View

- 7 cavities installed
- Beam valves pass through angled endwalls of box

4.5 m
### Cavity Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>109.125 MHz</td>
</tr>
<tr>
<td>beta</td>
<td>0.15</td>
</tr>
<tr>
<td>$U_0$</td>
<td>37* J</td>
</tr>
<tr>
<td>Active length</td>
<td>25 cm</td>
</tr>
<tr>
<td>$E_{PEAK}$</td>
<td>48* MV/m</td>
</tr>
<tr>
<td>$B_{PEAK}$</td>
<td>88* mT</td>
</tr>
<tr>
<td>$R_{sh}/Q$</td>
<td>548 Ohm</td>
</tr>
</tbody>
</table>

*at 3.75 MV/cavity = 15 MV/m
Accelerating Fields

- 15 MV/m achieved on-line in 2 cavities:
  - $V_{\text{MAX}} = 3.75$ MV, $E_{\text{PEAK}} = 48$ MV/m, $B_{\text{PEAK}} = 88$ mT
**Tuners & Microphonics**

Measured cavity microphonics – simultaneous operation at 2 MV/cavity (avg.)

- To date no cavities have lost lock due to microphonics

\[ \sigma_{\text{RMS}} = 1-2 \text{ Hz} \]

1.2 kHz/s slew rate on-line

(TUPPO031)
Beam-Based Performance Data

- Accelerate Carbon +6 beam through the cryomodule
- Measure beam energy via time-of-flight
- Use TRACK code to fit accelerating voltage to TOF data
- Power dissipation to LHe measured at the refrigerator (dynamic load):
  - 55W at 14.5 MV ($Q = 1.0 \times 10^9$)

<table>
<thead>
<tr>
<th>Cavity Number</th>
<th>Beam Energy [MeV]</th>
<th>Cavity Voltage [MV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>174.0</td>
<td>1.96</td>
</tr>
<tr>
<td>2</td>
<td>184.5</td>
<td>1.89</td>
</tr>
<tr>
<td>3</td>
<td>196.1</td>
<td>2.13</td>
</tr>
<tr>
<td>4</td>
<td>208.5</td>
<td>2.29</td>
</tr>
<tr>
<td>5</td>
<td>219.7</td>
<td>2.12</td>
</tr>
<tr>
<td>6</td>
<td>229.9</td>
<td>1.92</td>
</tr>
<tr>
<td>7</td>
<td>241.5</td>
<td>2.24</td>
</tr>
<tr>
<td><strong>Total voltage</strong></td>
<td><strong>14.5</strong></td>
<td></td>
</tr>
</tbody>
</table>
Maximizing Performance

- VCX fast tuner is 30-year old technology
- VCX limit = 2.3 MV/cavity (avg.)
- Cavity performance has outstripped VCX capability
- VCX will not be part of future designs
- Performance increase possible:
  - Low measured microphonics
  - Reduce VCX tuning window

<table>
<thead>
<tr>
<th>Cavity Number</th>
<th>Cavity Voltage [MV]</th>
<th>Max. Achievable Voltage [MV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.96</td>
<td>2.88</td>
</tr>
<tr>
<td>2</td>
<td>1.89</td>
<td>2.75</td>
</tr>
<tr>
<td>3</td>
<td>2.13</td>
<td>3.75</td>
</tr>
<tr>
<td>4</td>
<td>2.29</td>
<td>3.13</td>
</tr>
<tr>
<td>5</td>
<td>2.12</td>
<td>2.75</td>
</tr>
<tr>
<td>6</td>
<td>1.92</td>
<td>2.08</td>
</tr>
<tr>
<td>7</td>
<td>2.24</td>
<td>3.75</td>
</tr>
<tr>
<td>Total voltage</td>
<td><strong>14.5</strong></td>
<td><strong>21.1</strong></td>
</tr>
</tbody>
</table>
**RF System**

- 109 MHz, 250 W solid-state water-cooled amplifiers + LLRF for 8 cavities in 1 rack

- I&Q type LLRF controller has the following feedback loops:
  - frequency - use slow tuner
  - amplitude - adjust input drive power
  - phase - use VCX

- Slow and Fast tuner controllers

- Voltage pulsers are used to switch VCX diodes
Cavity Fabrication

- Die hydroformed RRR300 niobium
- Conventional machining/wire EDM
- EBW, electropolish, flash BCP
- HPWR, clean handling

hydroforming
electron beam welding
electropolish
Wire EDM
flash BCP
String Assembly (inside clean room)

- Cavities pre-assembled w/coupler & VCX
- Cavity assemblies installed on support frame
- Inter-cavity bellows & vacuum manifold installed
- Beam valve spools installed
- 2 people, 1 month to complete
Final Assembly (external to clean room)

clean cavity string  
dressed string suspended from lid  
module closure
Alignment

- Tolerances not critical for ATLAS
- Installation alignment in the tunnel: ± 0.5 mm
- Alignment crosshairs referenced to beam centerline
- Viewports on vacuum vessel endwalls
- Check with beam: no observed losses
Cooldown

- LHe:
  - Cavities
  - Solenoid
  - 15W static

- LN2:
  - Thermal shield
  - Coupler intercepts
  - Beam valve intercepts
  - VCX fast tuners
  - 200W static
Summary

- Represents the first full implementation of clean techniques for low-β cavities
- Provides a factor 3 performance gain over existing ATLAS technology
- Cryomodule design is a strong basis for next generation ion linacs
- Further developments will maximize the potential of state-of-the-art QWRs
  - TUPPO016