Hi Lumi LHC
Crab Cavity Cryomodules

Niklas Templeton
STFC Daresbury Laboratory
UK Crab Cavity Cryomodules WP Lead
Crab Cavity Cryomodules for Hi Lumi LHC

- Hi Lumi LHC Crab Cavities
- Crabs Collaboration
- Design Features & Innovations
- RFD SPS Prototype Cryomodule Build
- UK Lessons Learnt (so far)
Hi Lumi LHC Crab Cavities

To **maximise discovery potential of LHC** by increasing rate of collisions
- 400 MHz crab cavities to **mimic head on collision**
- 4 cavities installed either side of Interaction Points

**Double Quarter Wave (DQW)** – vert. crabbing at CMS
- RF design by BNL & CERN
- Supplied by CERN & R.I.

**Radio Frequency Dipole (RFD)** – horiz. crabbing at ATLAS
- RF design by ODU
- Supplied by US-AUP & Zanon

Bunches colliding without crab crossing (left) & with the crab crossing (right)
### 5 DQW cryomodules
- Cavities + processing + helium vessels by Research Instruments (DE) & CERN
- Cold magnetic shields by UK
- HOM couplers + antennas by CERN
- 4 CM by UK (STFC) & 1 CM at CERN with some components from CERN
- All cavities & CM cold validation tests at CERN (and a back up at Uppsala-Sweden)

### 5 RFD cryomodules
- Bare cavities by Zanon (IT) under US-AUP
- Processing + cold magnetic shield + helium vessel + HOM couplers + antennas + cold tests by US-AUP
- 5 CM by TRIUMF-Canada with some components by CERN
- CM cold validation tests at CERN

### 20 RF Systems
- High power amplifiers (IOT) CERN-KEKB
- High power RF lines, circulators, loads by CERN-KEKB
- $\mu$TCA platform for LLRF by CERN
Dressed Cavity Equipped

- Tuner
- Fundamental Power Coupler
- Bolted Ti He Tank
- Inner Mag Shield
- Secondary Line
- Survey Targets
- RF Pick-Up
- Tuner Frame
- HOM Coupler

Survey Targets

Tuner

Fundamental Power Coupler

Inner Mag Shield

Secondary Line

RF Pick-Up

Tuner Frame

HOM Coupler
Cavity Support System

- FSI Head
- TOP PLATE
- Target
- FSI Position Monitoring
- Flexure Blades
- 5-Point Kinematic Adjustment
- Common Support Plate
- FPC Fixed Point
- Flexure Blade Support
- ~200kg Offset Mass

N Templeton - TTC Dec '23
Thermal Screen

- **Al6061 Panels (t=2mm)**
- **Al Stiffeners & Nut Plates**
- **Ti Compensation Washers**
- **Cu Braids - Direct to Pipes**
- **St. Steel Cryo Circuit**
- **Al Pipe-Panel Clamps**
- **Series Pipe-Panel Clamps**

- ✓ Low Cost
- ✓ Minimal Brazing/Welding
- ✓ Ease of Assembly
- ✓ Thermal Performance Validated
Build Overview

Thanks to Teddy Capelli

Guide Rods

Cryostating Infrastructure

Crane Lift

Fine Adjustment

2 Bays

N Templeton - TTC Dec '23
Detailed Build Procedures

- Poster logic + tooling & infrastructure
- Part of Traveller (QA)
- Troubleshoots & de-risk build
- Captures critical requirements, torques & sign-off
- ‘BOM kits’ pre-prepared by sub-step

Step 11

1. Installation of insulation vacuum instrumentation
2. Installation of secondary beam line vacuum assemblies
3. Installation of blow-off valve for insulation vacuum
4. Inspection and leak check of UHV secondary line

11-3 Install Blow-Off Valve

Over 900 produced!

N Templeton - TTC Dec '23
RFD Highlights (1/2)

Cavity string pre-cleanroom

Cleanroom assembly

First Welds

Upper cryo install

Top plate integration

Load Transfer Complete
RFD Highlights (2/2)

- Thermal Screen
- 50K MLI
- Instrumentation
- Lower Cryomodule Integration
- Shipping
RFD Lowlights…

4 Lessons Learnt

…with memorable titles

“Learn from the mistakes of others. You can't live long enough to make them all yourself.” – Eleanor Roosevelt
Protect Ya Bellows

Issue: hydroform bellows dent pre-cleanroom

Impact: minor (thankfully)

Root cause: assembly procedure execution error

Mitigations:
- **Better comms** between engineers & technicians
  - Procedure roll-out & sign-off
  - More technical oversight
  - Many phone calls
- **Additional bellows protection** installed
Issue: **Re-design** of test rig & **re-qualification** of Bi Phase line

Impact: **Many months delay** to manage QA & resolve NCs

Root Cause: Poor supplier QA

Mitigations: developed & brought in-house:
- Welding & weld engineering
- Steel procurement
- Design of weld-test-transport jigs
Respect Yo QMS  (Quality Management System)

Issue: removal & replacement of NC bellows sub-assembly after delivery

Impact: Many weeks to fabricate, re-work & re-qualify

Root Cause: QA processes not followed

Mitigations:
- Improved quality training & refreshers
- More QA oversight
- Local instructions to remove QMS barriers
Mo Checks – Less Problems

Issue: **damage** to power couplers **discovered at CERN**

Root cause **analysis & resolution: on-going**

Hypothesis: complex load transfer issue

Mitigations:
- Tooling design improvements
- **More** intermediate **test & checks**
  - ISO4 glovebox for beamline tests
  - Fundamental power coupler checks

### BUILD CHECK & TEST (HOLD) POINTS

<table>
<thead>
<tr>
<th>Step #</th>
<th>Activity</th>
<th>Alignment</th>
<th>RF</th>
<th>Leak Test</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Cavity string pre-assembly</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>ISO4 string assembly</td>
<td>Y</td>
<td>RF</td>
<td>Beamline</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>FPC assembly</td>
<td>Y</td>
<td>RF</td>
<td>Beamline</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Bi Phase welding</td>
<td></td>
<td></td>
<td></td>
<td>Welds</td>
</tr>
<tr>
<td>4</td>
<td>Tuner &amp; thermal links</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Top plate integration</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td>Welds</td>
</tr>
<tr>
<td>6</td>
<td>Top plate load transfer</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Lower cryolines &amp; instr’n</td>
<td></td>
<td></td>
<td>Welds</td>
<td>Instr’n</td>
</tr>
<tr>
<td>8</td>
<td>2K MLI</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Thermal Screen &amp; 50K MLI</td>
<td></td>
<td></td>
<td>Welds</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Cryomodule load transfer</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Vacuum equipment</td>
<td></td>
<td></td>
<td>2ndline</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Cryomodule doors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Outgoing acceptance</td>
<td>Y</td>
<td>Y</td>
<td>Insu-vac, Beamlines</td>
<td>Pressure, LN2, Instr’n</td>
</tr>
<tr>
<td>14</td>
<td>Transport tooling &amp; frame</td>
<td></td>
<td></td>
<td></td>
<td>Shockloggers</td>
</tr>
</tbody>
</table>
Hi Lumi Crab Cavity Cryomodules

RFD SPS Cryomodule delivered Oct '23 with many challenges & obstacles overcome!

Next: series LHC Cryomodules:

- DQW: 1x CERN + 4x STFC
- RFD: 5x TRIUMF

- >10k components (5k unique)
- >900 procedure pages
- 56 CM welds (24 types)
Thanks!  

Questions?

Thanks to all Hi Lumi Crabs collaborators for their contributions
HL-LHC-WP04—CRAB CAVITIES RFD CRYOMODULE FOR SPS TESTS

Poster by Teddy Capelli
RFD Thermal Budget

<table>
<thead>
<tr>
<th>Source</th>
<th>2 K</th>
<th>10 K</th>
<th>80 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation</td>
<td>3.4</td>
<td>-</td>
<td>30.0</td>
</tr>
<tr>
<td>CWT</td>
<td>6.0</td>
<td>1.0</td>
<td>50.6</td>
</tr>
<tr>
<td>Supports Cav1</td>
<td>0.4</td>
<td>2.1</td>
<td>8.0</td>
</tr>
<tr>
<td>Supports Cav2</td>
<td>0.5</td>
<td>0.9</td>
<td>5.0</td>
</tr>
<tr>
<td>FPC</td>
<td>4.8</td>
<td>4.6</td>
<td>46.4</td>
</tr>
<tr>
<td>VHOM lines</td>
<td>1.4</td>
<td>2.6</td>
<td>13.0</td>
</tr>
<tr>
<td>VHOM antennas</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HHOM lines</td>
<td>1.4</td>
<td>2.6</td>
<td>13.0</td>
</tr>
<tr>
<td>HHOM antennas</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pickup lines</td>
<td>2.0</td>
<td>-</td>
<td>10.6</td>
</tr>
<tr>
<td>Pickup antennas</td>
<td>0.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tuner</td>
<td>0.8</td>
<td>-</td>
<td>10.2</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>2.3</td>
<td>-</td>
<td>10.0</td>
</tr>
<tr>
<td>He level sensor</td>
<td>0.4</td>
<td>-</td>
<td>0.8</td>
</tr>
<tr>
<td>Cryo safety device</td>
<td>0.7</td>
<td>-</td>
<td>4.8</td>
</tr>
<tr>
<td>Beam screen</td>
<td>1.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Beam impedance</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cavity</td>
<td>20.0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Total: 46.2  13.8  202.4

Thermal analysis cold-warm transition
See EDMS 2433067 - J.Swieszek EN-MME
Transport Frame Design & Test

- 38mm drop test performed with a dummy CM
- ~80% shock isolation
Welding Developments at Daresbury

- Weld Procedure Specifications
- Sample qualification: dye & macroscopic
Upper (Bi Phase) Cryoline

Support for bellows dP