RFD cryomodule design for SPS tests
International Review of the Crab Cavity for HL-LHC -20/06/2019

Teddy Capelli on behalf of the WP4 collaboration in particular:
STFC Daresbury, CERN EN/MME, ATS/DO, BE/RF, EN/ACE, EN/SMM, HSE, TE/CRG, TE/VSC.
Review of previous design (DQW for SPS test)
SPS test stand
See presentation of G.Vandoni

SPS beam vacuum layout for test stand – courtesy Chiara Pasquino TE/VSC

3891mm  Total length between Y chambers

See presentation of G.Vandoni
# Modifications / differences of RFD cryomodule

- Cryomodule for RFD cavities
- LHC like Prototype
- **Improvement with respect to lesson learnt from first DQW cryomodule**
- Assembly at STFC – Daresbury (UK) and transport to CERN

## DESIGN ACTIVITIES

<table>
<thead>
<tr>
<th>Activity</th>
<th>Details</th>
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</table>
| **RFD Cavity** (Raphael Leuxe / Laurene Giordanino – CERN EN/MME) | - New shape  
- Cavity length: 919mm (SPS/DQW Cavity = 660mm) -> +520mm!  
- Tooling for forming  
- Welding sequence |
| **Magnetic shield** (N.Templeton STFC) | - Design and integration of cold magnetic shield  
- Design and integration of warm magnetic shield |
| **Radiofrequency equipment** (Sebastien Calvo / Frida Eriksson – CERN BE/RF) | - HOMs and Antenna design for manufacturing  
- RF coaxial line for HOMs and pick up |
| **Beam vacuum** (EN/MME – TE/VSC) | - Second beam pipe + RF valves  
- Beam screen in second beam pipe  
- Shield for bellows  
- Vacuum instrumentation definition and integration  
- Vacuum chambers + bellows |
| **Support and alignment** (EN/MME – EN/SMM - STFC) | - Cavity support and alignment system  
- Cryomodule support and alignment  
- FSI definition |
| **Tuner** (Kurt Artoos – CERN EN/MME) | - Frame  
- Double pipe + thermalisation  
- Actuation |
| **Cryogenic** (EN/MME – TE/CRG) | - Biphase line + New cooling lines (Beam screen cooling 4.5K, HOMs..)  
- Safety devices (safety valve, pressure measurement..)  
- Exchangeability of level gauges  
- Thermal screen cooling circuit (CERN, STFC)  
- Thermal intercepts  
- Cold warm transition (definition of thermal budget and pre design)  
- MLI design |
| **Thermal screen and MLI** (CERN, STFC) | - Aluminum design with clamped Ss pipes  
- Adaptation of MLI principle |
| **Cryostat vessel design** | - Replace oring gasket by welded connection  
- Vacuum barrier in the jumper on service module side |
| **Transport of cryomodule** (K.Artoos CERN, E.Jordan STFC) | - Risk analysis  
- Frame for transport  
- Internal locking for transport |
| **Tooling** (P.Minginette CERN EN/MME, E.Jordan STFC) | - Tooling for welding of cavity  
- Definition and design of tools for RFD cryomodule assembly  
- Adaptation of design to existing assembly tools |
| **Instrumentation** | - Definition and integration of instrumentation (T*, Mag sensor, ..)  
- Rooting of cables. |
LHC integration – preliminary study

See presentation of P.Fessia

LHC integration – courtesy M. Gonzalez de la Aleja – CERN ATS/DO

Section view of LHC
More details on drawing LHCLJ___0020
RFD/SPS Cryomodule overview
CAVITY design
- Mechanical design done from 2K RF design
- Splitting of the cavity optimized for manufacturing
  (Anticipation of deformation, thickness variation and welding shrinkage)
- Helium tank design on-going

Courtesy R.Leux & L.Giordanino CERN-EN/MME – cavity design & forming tooling
Courtesy P.Minginette CERN-EN/MME – tooling for machining and welding
RFD Cavity tooling for manufacturing

Tooling for forming, machining and welding:

- Forming methodology adapted according to lessons learnt with DQW cavity manufacturing
- Design of forming, machining and welding tooling
- Strategy specific for each cavity type (new design needed for RFD)

See presentation of M.Garlasche

H-HOM box forming

Tooling for machining and welding

Courtesy R.Leuxe & L.Giordanino CERN-EN/MME – cavity design & forming tooling
Courtesy P.Minginette CERN-EN/MME – tooling for machining and welding
Cold Magnetic Shield (STFC)

Cold magnetic shield (2K):
- RFD Cold Magnetic Shields designed & delivered to CERN in Apr ‘15
- Changes in cavity design mean shield designs require revision
- Approach taken to modify & reuse existing shields (as much as possible)
- Detailed design: Complete
- Integration checks: On-going
- Specification & Tender: On-hold
- Analysis for cool down stress and deformation

New Parts
Modified Parts
Unchanged

Courtesy N. Templeton - STFC
FPC, HOMS and Pick up

CERN responsible for HOMS, FPC & Pick-Up - E.Montesinos BE/RF

HOMs and Antenna for RFD prototypes, under manufacturing at CERN:
- Mechanical design in progress
- Collaboration BE/RF – CERN workshop (EN-MME)

FPC outer pipe:
- Mechanical design to be adapted
- Definition of the coating process according to the lesson learnt from DQW
- Collaboration EN/MME – BE/RF – TE/VSC

See presentation of E.Montesinos
Beam section of RFD Cryomodule

Beam vacuum chamber type 1
Beam screen Cold/Warm transition Long
Beam screen
Inter beam screen plug-in module
Beam screen Cold/Warm transition Short
Beam vacuum chamber type 2

Beam vacuum chamber type 2
Cavity Cold/Warm transition Long
Inter cavities plug-in module
Cavity Cold/Warm transition Short
Beam vacuum chamber type 1
Beam screen

- Cold bore <3K (for cryo pumping)  
  *(HL-LHC design report V.01 §12.6)*
- Beam screen actively cooled (4-20K)
- Need a new cryogenic circuit
- Maximize the beam aperture see EDMS 1864637
- Limited room inside the cryomodule (cold bore max aperture = 84mm)

**Diagram:**

- **Cold bore**: 84mm max aperture
- **Beam screen**: Actively cooled (4-20K)
- **CF flange**
- **Fixed centering ring**
- **Sliding centering ring**
- **Adjustable Sliding support**
- **Bimetallic transition**

Collaboration CERN EN-MME / TE-VSC

See also the presentation of G.Riddone

*International Review of the Crab Cavity for HL-LHC - T.Capelli - 20/06/2019*
Beam screen

- Stainless steel screen with «random» holes for pumping
- Copper layer on the inner surface (th. 0.075mm)
- Ø4.76mm cooling pipe welded on screen (He gaz @ ~20K)
- 1 bellows for differential contraction
- Aperture calculation -> 1.5mm clearance on the radius (calculation made with worse case LHC dipole method)

Remaining studies:
- Centering optimization
- Welding sequence to be reviewed
- Thermal calculation

Compensation of differential contraction (up to 1.7mm)
RF bridges for bellows

- Need to “screen” every bellows on the beam lines
- Large lateral displacement (6 mm max.)
- Deformable RF fingers design from triplet area (C.Garion – J.Perez Espinos CERN TE/VSC)
- 4 configurations to be designed

Copper Beryllium deformable RF fingers:
- Circular aperture
- C17410
- 0.1 mm thick, 3 mm width, gap: 1.4 mm
- 3 convolutions

Extracted from presentation of C.Garion 33rd HL-LHC TCC– 13 July 2017
Beam vacuum instrumentation & interconnexion

Study of CRAB Cryomodule interconnexion for LHC
Courtesy: R.Tavares Rego CERN TE/VSC - N.PERAY CERN EN/MME
Cavity support
- Design adapted from DQW
- Modification with respect to lesson learnt from DQW

Alignement tolerances
- X-Y: **0.5mm (3σ)** for mechanical alignment
  + 0.5mm for operation errors
- Rz < 0.3°
- Rx, Ry (mean axis of CC inside Φ0.5mm)

- « FLAT » (Adjustment on Z, free on X & Y)
- « CONE » (Adjustment on X and Z, fixed on Y)
- « VEE » (Adjustment on X and Z, free on Y)

Flexible blades (x2)
Locking rods (x4)
Cavities position monitoring system

- Frequency Scanning Interferometry system (*tested and validated during SPS test*)
- 8 targets per cavity
- Measure distances between FSI heads and centres of CCR targets used
- Positions of the FSI heads to be measured
- Anticipation of deformation (Thermal contraction, vacuum forces..etc)

See presentation of M.Sosin

Courtesy M.Sosin – CERN EN/SMM
Cavity tuning system

- Adaptation of DQW design
- Modification following lessons learned with DQW
- No pre tuning

See presentation of K. Artoos on freq. tuning

DQW design overview
RF COAXIAL LINES

CERN responsible for HOMS, FPC & Pick-Up - E.Montesinos BE/RF

Design constraints:
- insulation vacuum (not cooled by convection)
- RF power
- Thermal load to 2K bath
- Alignment and thermal contraction compensation
- Limited room for installation inside the cryomodule

Datas
- 2 V-HOMS coaxial lines
- 2 H-HOMS coaxial lines
- 2 Antennas coaxial lines
- Size and design standardized for all lines
  - Non magnetic S.Steel with copper coating
  - Extremities compatible with standard connector
  - Shapal ring for thermalisation of inner line
  - Alumina for vacuum feedthrough

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International Review of the Crab Cavity for HL-LHC - T.Capelli - 20/06/2019
Cryogenic equipment

- New cooling line for beam screen
- Safety valve on cryomodule side
- Exchangeability of level gauges
- Pressure measurement set up
- Bolted temperature sensors
- Distribution of pipes for cooling equilibrium
- Adaptability to LHC slope

Datas:
- surface 2k / beam vacuum: ~1m²
- surface 2k / insulation vacuum: 3.6m²
- Volume of helium: 166L
- Biphase inner diameter: 100mm

See presentation of K. Brodzinski
Cryogenic Jumper

- Integration of new beam screen line
- Standardization of LHC interface
- Symmetrical jumper interface (allows the rotation of cryomodule)
Thermal screen (STFC)

- **DQW-SPS design:**
  - Copper plates th. 3mm
  - Copper pipes brazed to plates
  - Operating pressure 18 bars
  - Transition copper/s.steel for final welds

- **RFD design:**
  - Aluminium plates th. 3mm
  - SS316 Cooling circuit for cryoline integration and pressure safety
  - ‘Semi-Active’ cooling circuit allows thermalisation direct to pipe (brazed copper braids)
  - Al1100 panels give significant cost and weight savings for series production
  - Optimisation & detailed design ongoing

![Diagram of Thermal Screen](image)
Pipe Panel Connections (STFC)

- SS 316 Pipes pre-assembled to Al block
- Pipes are pre-loaded with clamp
- Al block welded
- Pipe-block is integrated into cooling circuit
- Al blocks are fastened to panel
- Validation see ‘EDMS No. 1977794’
  - Thermal Characterisation of Stainless Steel Tube in Alluminium Block for Applications in Thermal Shield, A Nuñez Chico – EDMS 1977794
- TCC > 500 W/m2K
Analysis

- Steady State Thermal Analysis
- Non-Linear Material properties
- Pipe Convection: 400 W/m² @ 50 K
- Thermal Contact Conductance: 500 W/m²K
- Heat Loads (see table)

Shield Temperature

- Preliminary analysis shows that design changes minimise temperature gradient across the shield
- Max dT panels: ~2 K
- Max dT Pipe, panels and braids: ~20 K

Panels Temperature

<table>
<thead>
<tr>
<th>Heat Source</th>
<th>Heat Load (W)</th>
<th>QTY</th>
<th>Total (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPC</td>
<td>36.0</td>
<td>2</td>
<td>72</td>
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<tr>
<td>HOM Coax</td>
<td>9.0</td>
<td>4</td>
<td>36</td>
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<tr>
<td>Blades</td>
<td>7.7</td>
<td>4</td>
<td>30.8</td>
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<tr>
<td>CWI</td>
<td>5.0</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>Tuner</td>
<td>7.6</td>
<td>2</td>
<td>15.2</td>
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<tr>
<td>Instrumentation</td>
<td>8.0</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Screen Supports</td>
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</tr>
<tr>
<td>BPhase Support</td>
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<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Pick-ups</td>
<td>2.0</td>
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<td>4</td>
</tr>
</tbody>
</table>

Thermal Screen Heat Load Estimates v0.1.xlsx

Two dimensional models of the Crab cavity for HL-LHC by T. Capelli 20/06/2019
RFD Thermal Screen - Next Steps

Design
- Clamp - Cooling circuit integration
- FPC cover
- Stress relief features
- Braid design & integration
- Detailed Design

Analysis
- Self weight & stiffness
- Cool down stress
Warm Magnetic Shield (STFC)

- DQW Design to be repeated for RFD Pre-Series
- No configuration change required
- Only minor changes from DQW lessons learnt
- Warm Magnetic Shield has many interfaces!
- Design is dependant on Top Plate & Lower OVC design freeze
- Curie temperature (460 C) to be considered in design & implementation of OVC welding

~150 kg

2mm MuMetal

Top Joint EM Gasket

Window Joint Spring Fingers

Top Assembly

FPC Cover

Tapped OVC Spacers

Windows

Sliding Joints for OVC Tolerance

Lower Assembly

Courtesy N.Templeton - STFC
Cryostat vessel design

DQW outer vessel:
- Large gaskets
- Overall dimensions: 2800x960x1300

RFD outer vessel:
- Large gaskets removed
- Overall dimensions: 2800x950x1300

Gaskets version study

Welded version
Vacuum vessel—welded concept

- Gaskets removed
- Integration of the additional vacuum instrumentation
- All the leak tight welds are accessible from outside

DQW-SPS cavity string assembly

RFD cavity string assembly

RFD welded vacuum vessel
Vacuum vessel– welded concept

- Reinforcement study (on-going)

- Transport restraint (integration study to be done)
  See presentation K.Artoos
End
HL-LHC-WP04—CRAB CAVITIES DQW CRYOMODULE FOR SPS

Teddy Capelli – EN/MME (CERN) on behalf of design team
Coaxial lines

Design from DQW, length/position adapted to RFD
Results: tests 1 and 2

- **Test 1:** 3 cycles between +/- 2 mm at 1 mm/min
  - $|F|_{\text{max}} = 27.7 \text{ N}$ downward direction

- **Test 2:** 2 cycles between +/- 5 mm at 1 mm/min
  - $|F|_{\text{max}} = 47.7 \text{ N}$ downward direction

Test performed at Mechanical Measurement lab of CERN (L.Bianchi – M.Guinchard)

International review of the Crab Cavity performance for HiLumi – CERN – 3 april 2017
Instrumentation

- Glue replaced by bolted connection

Cryogenic instrumentation (not complete, for illustration)

Liste of instrumentation (cryo + mechanical):
- 13 CERNOX temperature sensors
- ~20 PT100
- 2x 8x heating cartridge 5W
- 2x He tank heater 100W
- ~20 strain gauges

... Many of these equipments are already at CERN
# Pipe Convection & Parameters

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Diameter D (m)</td>
<td>0.015 (15 mm)</td>
</tr>
<tr>
<td>Mass Flow Rate m (kg/s)</td>
<td>3.80E-03 (3.8 g/s)</td>
</tr>
<tr>
<td>Pressure P (Bar)</td>
<td>20</td>
</tr>
<tr>
<td>Temperature T (K)</td>
<td>50</td>
</tr>
<tr>
<td>Temperature T (K)</td>
<td>70</td>
</tr>
</tbody>
</table>

| Specific Gas Constant R<sub>p</sub> (J/kg K) | 2078 |
| Density ρ (kg/m³)              | 16.04 |
| Mean Fluid Velocity U (m/s)   | 1.34  |
| Dynamic Viscosity µ (Pa.s)    | 2.10E-05 |
| Reynolds Number Re            | 15,360 |

- **Specific Heat c<sub>p</sub> (J/kg K):** 5188
- **Fluid Thermal Conductivity k (W/m K):** 0.066859 (See kHe data)
- **Prandtl Number Pr:** 1.63
- **Nusselt Number Nu:** 89.5 (Ref)
- **Heat Transfer Coefficient h (W/m².K):** 399.0 (Ref)

Thermal screen: we discussed to use ID 10 mm but I reanalyzed this circuit and changed my position to use ID 15 mm as in DQW. Diameter of 10 mm would be largely sufficient for required flow but considering the fact that we have experience about gas speed/vibrations in pipe of 15 mm which does not has influence on RF, we should not introduce such change and use ID = 15 mm. Below I give main characteristics of this circuit as information to Niklas.

**Assumptions:** Tin/out=50/70 K, heat load=400 W, ID=15 mm, PHe=20 bara

Output: required mass flow=3.8 g/s, gas speed=1.63 m/s, deltaP=6.5 mbar (considering 20 m line with 20 elbows).

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1237-meng-cal-0011-v1.0-Thermal Screen Cooling Circuit