Design of the 352MHz, beta 0.50, Double-Spoked Cavity for ESS

Patricia DUCHESNE, Guillaume OLRY
Sylvain BRAULT, Sébastien BOUSSON, Patxi DUTHIL, Denis REYNET
Institut de Physique Nucléaire d’Orsay

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- RF DESIGN OF THE RESONATOR
- MECHANICAL DESIGN OF THE RESONATOR
- INTEGRATION IN THE CRYOMODULE
- STATUS OF THE PROTOTYPES
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ESS Superconducting Spoke section:

- 28 Double Spoke cavities (3 accelerating gaps)
- \( \beta = 0.50 \)
- Frequency: 352.2 MHz
- Grouped by pair in 14 cryomodules
- Operating temperature: 2K
- Accelerating gradient: \( E_{acc} = 8 \) MV/m
- Peak field specifications: \( E_{pk} < 35 \) MV/m, \( B_{pk} < 70 \) mT
Activities of IPN Orsay Laboratory on ESS Spoke section:

- Design
- Fabrication of prototypes
- Tests of prototypes:
  - Vertical tests of cavities
  - Power couplers conditioning (Test bench @CEA/Saclay)
  - Tests of CTS
  - Low power tests of cryomodule (High power tests at UPPSALA)
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SPECIFICATIONS FOR THE DOUBLE SPOKE CAVITY

Parameters established by the beam dynamics simulations:

<table>
<thead>
<tr>
<th>DOUBLE-SPOKE CAVITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam mode</td>
</tr>
<tr>
<td>Frequency [MHz]</td>
</tr>
<tr>
<td>Beta_optimal</td>
</tr>
<tr>
<td>Temperature (K)</td>
</tr>
<tr>
<td>Bpk [mT]</td>
</tr>
<tr>
<td>Epk [MV/m]</td>
</tr>
<tr>
<td>Gradient Eacc [MV/m]</td>
</tr>
<tr>
<td>Lacc (=beta optimal x nb of gaps x λ /2) [m]</td>
</tr>
<tr>
<td>Bpk/Eacc [mT/(MV/m)]</td>
</tr>
<tr>
<td>Epk/Eacc</td>
</tr>
<tr>
<td>Beam tube diameter [mm]</td>
</tr>
<tr>
<td>RF peak power [kW]</td>
</tr>
</tbody>
</table>
OPTIMIZATION OF THE GEOMETRY

- **Main goal**: fulfil the criteria of the peak surface field to accelerating gradient ratios
  \[
  \frac{E_{pk}}{E_{acc}} < 4.38 \quad \frac{B_{pk}}{E_{acc}} < 8.75 \text{ [mT/MV/m]}
  \]

- **The optimization method of the RF design**: 
  - Parameterization of the geometry
  - Sensitivity analysis on the ratios \( E_{pk}/E_{acc} \) & \( B_{pk}/E_{acc} \)
  - CST MicroWave Studio (MWS)
  - Results cross-checked with to mesh types: hexahedral and tetrahedral

- **Geometry of the spoke bars**: 
  Based on our feedback from two Single-Spoke resonators and a Triple-Spoke resonator fabrication (EURISOL)

⇒ Achievement of an acceptable solution
RF RESULTS

- Last modifications (included in the prototypes)
  - Technical issues for manufacturing
  - New ESS requirements

<table>
<thead>
<tr>
<th>Mesh type</th>
<th>Hexahedral (2.2 millions meshcells)</th>
<th>Tetrahedral (600000 tetra.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beta optimal</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Epk/Eacc</td>
<td>4.51</td>
<td>4.33</td>
</tr>
<tr>
<td>Bpk/Eacc [mT/MV/m]</td>
<td>6.99</td>
<td>6.89</td>
</tr>
<tr>
<td>G [Ohm]</td>
<td>131</td>
<td>130</td>
</tr>
<tr>
<td>r/Q [Ohm]</td>
<td>425</td>
<td>426</td>
</tr>
</tbody>
</table>

- Epk/Eacc > 4.38: compromise between the cavity length, end cap shape feasibility and tuning sensitivity.
- Lacc = 3 / 2 x beta optimal x lambda

Coupling calculations: \( Q_{ext} = 1.5 \cdot 10^5 \) (with the parameters 50mA and 8MV/m)

- Coupler port location (\( \varnothing = 100 \text{mm} \)):
  Variation of the coupler port center from 100 to 170mm (\( \leftrightarrow \) distance to the origin)

- Penetration of the antenna: Variation from +5 to -15mm

\[ Q_{ext} = 1.5 \cdot 10^5 \] for:

\( \Rightarrow \) 5mm of tip penetration

\( \Rightarrow \) coupler port location: 120mm

MWS model of the cavity with antenna – G. Olry
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MECHANICAL STUDIES

Criteria taken into account

- **Cavity preparation:** High Pressure Rinsing (HPR)  
  ➔ easy and efficient

- **Life cycle of the cavity:** Leak tests & cryomodule tests  
  ➔ No risk of damage (plastic deformation at room T°)

- **Manufacturing constraints:** Metal forming & Assembly process  
  ➔ Feasible (at a reasonable cost)

Integration of the Helium vessel

- Connections with the beam tubes: Flange / bellows (For the tuning)

- **Helium vessel:** Titanium grade 2  
  ➢ Ease of assembly with niobium  
  ➢ No problem of thermal stresses  
  ➢ May act as a reinforcement of the cavity

- Standard dished end cups

⇒ Result of the iterative numerical simulations
Mechanical simulations

Different load cases studied according to the life cycle of the cavity

Static and modal analysis
(ANSYS Mechanical V14)

- Leak tests during fabrication
- Pressure test (Cool down at 4K)
- Mechanical vibration modes

\[ \text{Check no plastic strains} \]
\[ \text{Define maximum pressure during cool down} \]
\[ \text{Check sensitivity to microphonics} \]

RF-Mechanical coupled analysis
(ANSYS APDL & EMAG V14)

- RF sensitivity by pulling on beam tubes
- RF sensitivity due to the He bath pressure fluctuation
- RF sensitivity due to the Lorentz forces

\[ \text{Define sensitivity for the cold tuning system} \]
\[ \text{Define a range for the pressure and Lorentz detuning factors} \]
STATIC AND MODAL RESULTS

☑️ Static results

▪️ Leak test on the bare cavity:

- Pressure test with $\Delta P = +0.1$ MPa:
  - $\sigma_{\text{max}} < 50$ MPa (Yield stress of Niobium at room $T^\circ$)
  - The donut ribs are necessary

- Max pressure (Cool down) estimated to be 1.47 bar at $\sigma_{\text{max}} = 50$ Mpa

☑️ Mechanical modes

<table>
<thead>
<tr>
<th>No.</th>
<th>Frequency</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 &amp; 2</td>
<td>212 Hz</td>
<td>Beam tube on CTS side</td>
</tr>
<tr>
<td>3 &amp; 4</td>
<td>265Hz &amp; 275Hz</td>
<td>Spoke bar/Helium vessel</td>
</tr>
<tr>
<td>5 &amp; 6</td>
<td>285Hz</td>
<td>Coupled mode Cavity/Helium vessel</td>
</tr>
<tr>
<td>7</td>
<td>313Hz</td>
<td>Helium vessel</td>
</tr>
<tr>
<td>8 to 11</td>
<td>315Hz to 365Hz</td>
<td>Coupled mode Cavity/Helium vessel</td>
</tr>
<tr>
<td>12</td>
<td>396Hz</td>
<td>beam tubes</td>
</tr>
</tbody>
</table>

⇒ First critical mode (mode 3) $>> 50$ Hz
RESULTS ON THE RF SENSITIVITY

- **Sensitivity to Helium bath pressure fluctuation**
  
<table>
<thead>
<tr>
<th>Type</th>
<th>Sensitivity (Hz/mbar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K_p without CTS (free ends)</td>
<td>+16.5</td>
</tr>
<tr>
<td>K_p with greatly stiff CTS*</td>
<td>+26.0</td>
</tr>
</tbody>
</table>

*The beam tube is connected rigidly to the helium vessel at the level of the 4 CTS supports (along the beam axis)*

- **Sensitivity to Lorentz forces detuning**
  
<table>
<thead>
<tr>
<th>Type</th>
<th>Sensitivity (Hz/(MV/m)^2)</th>
<th>Δf   (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K_L without CTS (free ends)</td>
<td>-5.13</td>
<td>-328</td>
</tr>
<tr>
<td>K_L with stiff CTS</td>
<td>-4.4</td>
<td>-282</td>
</tr>
</tbody>
</table>

**bandwidth = 1530 Hz**

- **RF sensitivity for cavity tuning**
  
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness of the cavity</td>
<td>20 kN/mm</td>
</tr>
<tr>
<td>Tuning sensitivity Δf/Δz</td>
<td>135 kHz/mm</td>
</tr>
</tbody>
</table>

⇒ At 2K: the tuning range is +173 kHz (1.28mm of max displacement not to exceed 400 MPa)
aoke Last modifications (included in the prototypes)

- Adding of some new stiffeners on the Spoke bars:
  Pressure test with $\Delta P = 0.1$ Mpa:
  - Maximum pressure (Cool down) estimated to 2.77 bars

- Replacement of the donut rib by a titanium disk:
  Leak test on the bare cavity:
  - Manufacturing and assembly easier
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CAVITY ASSEMBLY INTO THE CLEAN ROOM

- High Pressure Rinsing HPR (100bars) in clean room ISO 4

- Assembly of the cavities with:
  - power coupler
  - cold-warm transitions, dished ends and bellows
  - warm Ultra High Vacuum gate valves

The orientation of each cavity is chosen in order to facilitate the maintenance operations of the cold tuning system after insertion in the vacuum vessel.
Assembly outside the clean room

- Magnetic shield
- Cryogenic distribution
- Thermal shield and supporting rods
- Cold tuning system ...

Tooling for cryostating

ESS Spoke Cryomodule – D. Reynet, S. Brault, P. Duthil
Details in: “Design of the ESS Spoke cryomodule”, SRF 2013, these proceedings.
Principle of supporting system

Several considerations:
- 2 cavities: length = 2.86m, weight <500 Kg (with thermal shield)
- Static heat load
- Assembly and alignment methods

- Antagonist tie rods in some vertical planes
  - Vertical and lateral positions
  - 4 identical tie rods by vertical plane

- Tie rods and invar rods in a horizontal plane
  - Position along beam axis

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FABRICATION OF PROTOTYPES

- **Cavity: 3 prototypes**
  - 1 by SDMS (France)
  - 2 by ZANON (Italy)
  - **Start of contract:** March 2013
  - Ongoing discussions about the manufacturing of:
    - the Spoke bars in several pieces
    - the end cups of the cavity
  - **Delivery:** April 2014

- **Power coupler: 4 prototypes**
  - 2 by SCT (France)
  - 2 by PMB (France)
  - **Start of manufacturing:** September 2013
  - **Delivery:** November 2013

- **Cold Tuning System: 2 prototypes**
  - ESIM (France): mechanical components
  - NOLIAC (Denmark) & PHYSIK INSTRUMENTE (Germany): Piezo actuators
  - **Delivery:** done
THANK YOU FOR YOUR ATTENTION