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

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- CONTEXT
- 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: $E_{acc} = 8 \text{ MV/m}$
- Peak field specifications: $E_{pk} < 35 \text{ MV/m}$, $B_{pk} < 70 \text{ mT}$
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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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>
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

- **Coupling calculations:** \( Q_{ext} = 1.5 \cdot 10^5 \) (with the parameters 50mA and 8MV/m)
  - **Coupler port location (Ø=100mm):**
    Variation of the coupler port center from 100 to 170mm (↔ distance to the origin)
  - **Penetration of the antenna:** Variation from +5 to -15 mm

  \( Q_{ext} = 1.5 \cdot 10^5 \) for:
  - 5mm of tip penetration
  - coupler port location: 120mm

- **Mesh type**
  - **Hexahedral** (2.2 millions meshcells)
  - **Tetrahedral** (600000 tetra.)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hexahedral</th>
<th>Tetrahedral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beta optimal</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>( \frac{E_{pk}}{E_{acc}} )</td>
<td>4.51</td>
<td>4.33</td>
</tr>
<tr>
<td>( \frac{B_{pk}}{E_{acc}} ) [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>

- \( \frac{E_{pk}}{E_{acc}} > 4.38 \): compromise between the cavity length, end cap shape feasibility and tuning sensitivity.
- \( L_{acc} = \frac{3}{2} \times \text{beta optimal} \times \lambda \)

- **MWS model of the cavity with antenna** – **G. Olry**
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**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)
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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
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- 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

⇒ Check no plastic strains
⇒ Define maximum pressure during cool down
⇒ Check sensitivity to microphonics

Mechanical model: cavity with its helium vessel
Mechanical simulations

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**Static and modal analysis**
(ANSYS Mechanical V14)

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- Define maximum pressure during cool down
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**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

- Define sensitivity for the cold tuning system
- Define a range for the pressure and Lorentz detuning factors

Mechanical model: cavity with its helium vessel

RF-Mechanical model: cavity with its helium vessel
Static results

- Leak test on the bare cavity:
  - 37 MPa (End cup)
  - 43 MPa (HPR port)

  \[ \sigma_{\text{max}} < 50 \text{ MPa} \] (Yield stress of Niobium at room T°)
  \[ \Rightarrow \text{The donut ribs are necessary} \]

Mechanical modes

<table>
<thead>
<tr>
<th>N°</th>
<th>Frequency</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 &amp; 2</td>
<td>212Hz</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>

\[ \Rightarrow \text{First critical mode (mode 3) >> 50 Hz} \]
RESULTS ON THE RF SENSITIVITY

**Sensitivity to Helium bath pressure fluctuation**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Δf (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>Condition</th>
<th>Δf (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L$ without CTS (free ends)</td>
<td>-5.13</td>
</tr>
<tr>
<td>$K_L$ with stiff CTS</td>
<td>-4.4</td>
</tr>
</tbody>
</table>

$\Delta f = -328$ Hz **

**FEM result with a specific CTS stiffness**

**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 $\Delta f/\Delta z$</td>
<td>135 kHz/mm</td>
</tr>
</tbody>
</table>

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

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

- Replacement of the donut rib by a titanium disk:
  Leak test on the bare cavity:
  - 35 MPa
  $\Rightarrow$ Manufacturing and assembly easier

ESS Double Spoke Cavity – S. Brault
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Assembly of the cavities with:
- power coupler
- cold-warm transitions, dished ends and bellows
- warm Ultra High Vacuum gate valves

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

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

- Assembly outside the clean room
  - Magnetic shield
  - Cryogenic distribution
  - Thermal shield and supporting rods
  - Cold tuning system...
Assembly outside the clean room

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- Tooling for cryostating
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.
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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

Prototype mounted on the triple Spoke cavity (Eucard) at IPNO
THANK YOU FOR YOUR ATTENTION