Design and prototyping of the Spoke Cyromodule for ESS linac

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on behalf of the IPNO team and ESS colleagues
The European Spallation Source (ESS) LINear ACcelerator

ESS Linac is special and innovative:

- Mainly based on SRF (Superconducting Radio Frequency) technology
- Very powerful (~4 times higher than SNS)
- First accelerator to use (double) Spoke cavities
- Challenging accelerating gradients

<table>
<thead>
<tr>
<th>Top-level requirements</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse length (ms)</td>
<td>2.86</td>
</tr>
<tr>
<td>Energy (GeV)</td>
<td>2</td>
</tr>
<tr>
<td>Peak current (mA)</td>
<td>62.5</td>
</tr>
<tr>
<td>Pulse repetition frequency (Hz)</td>
<td>14</td>
</tr>
<tr>
<td>Average power (MW)</td>
<td>5</td>
</tr>
<tr>
<td>Peak power (MW)</td>
<td>125</td>
</tr>
</tbody>
</table>
The European Spallation Source (ESS) LINAC

**Source** → **LEBT** → **RFQ** → **MEBT** → **DTL** → **Spokes** → **Medium β** → **High β** → **HEBT & Contingency** → **Target**

**SRF LINAC:** ~312 m

**SRF cavity cooling:** 2 K in saturated He II bath (⇒ simple techno.+ few energy stored + pressure control)

**CNRS CONTRIBUTION (CNRS/IN2P3/IPNO)**

- **Elliptical section** (~256 m):
  - design of the 40 cryomodules (collaboration with CEA)

Design, construction and installation of the main parts of the **Spoke section** (~56 m)

Moderated neutrons to experiments lines
- 13 cryomodules
- Cryogenic Distribution System for the Spoke section (CDS-SL):
  - 13 valve boxes (managing cryofluids distribution and cryogenic process)
  - Cryogenic Distribution Line (CDL)
A cryomodule: what is it and what for?

- SRF technology

**CRYOMODULE**

- Superconducting radiofrequency (SRF) cavity

RF electro magnetic wave (352 MHz)

**Cryomodule functionalities**

1/ To provide a cryogenic environment to the cold mass (cavity) = horiz. cryostat:
   - distributing the cryofluids to cool-down and maintain at cold $T^\circ$ (LHe, LN$_2$)
   - limiting the heat loads

$T^\circ \leq 2K$
A cryomodule: what is it and what for?

2/ To support the cavities and perform accurate alignment
   - with respect to the beam axis
   - with respect to other linac components (cryomodules, diagnostics, tunnel)

NB: alignment must be preserved during thermal and pressure cycles
A cryomodule: what is it and what for?

3/ To offer magnetic shielding
   - from the local magnetic sources
   - from the earth magnetic shield

NB: the magnetic shield might be cooled (for better performances)
A cryomodule: what is it and what for?

4/ To provide all interfaces between the cavity and the tunnel:
- beam pipe
- RF
- cryogenic
- vacuum
- diagnostic (instrumentation)
- mechanical (support and alignment)
Cavity and liquid helium tank: design

- He Tank: Ti 4 mm
- Dish end: Ti 3 mm
- Cavity: Nb 4 mm
- Coupler port: Ti 3 mm
- 4x HPR ports

**RF shape optimizations**

- Lorentz detuning coeff. : \( K_l = \Delta f/Eacc^2 \sim -5.5 \text{ Hz/(MV/m)}^2 \)
- Pressure sensitivity : \( K_p = \Delta f/\Delta p \sim 15 \text{ Hz/mbar} \)
- Tuning sensitivity : \( \Delta f/\Delta z = 130 \text{ kHz/mm} \)

**Mech. reinforcements**

Coupling RF with mechanical models:

**DOUBLE-SPOKE CAVITY**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [MHz]</td>
<td>352.21</td>
</tr>
<tr>
<td>Beta_optimum</td>
<td>0.50</td>
</tr>
<tr>
<td>Operating gradient [MV/m]</td>
<td>9.0</td>
</tr>
<tr>
<td>Bpk [mT]</td>
<td>62</td>
</tr>
<tr>
<td>Epk [MV/m]</td>
<td>39</td>
</tr>
<tr>
<td>G [Ohm]</td>
<td>130</td>
</tr>
<tr>
<td>r/Q [Ohm]</td>
<td>426</td>
</tr>
<tr>
<td>Lacc</td>
<td>0.639</td>
</tr>
<tr>
<td>( Lacc = (\text{beta optimal} \times \text{nb of gaps} \times \lambda/2) [\text{m}] )</td>
<td>0.639</td>
</tr>
<tr>
<td>Bpk/Eacc [mT/MV/m]</td>
<td>6.88</td>
</tr>
<tr>
<td>Epk/Eacc</td>
<td>4.34</td>
</tr>
</tbody>
</table>
• **Prototypes, preparations and tests** •
  - **Etching**
    - 3 positions; T < 15°C; 
    - ~ 8 hours 
    - $\Rightarrow$ 200 $\mu$m
  - **High Pressure Rinsing**
    - 100 bars; 6 ports; 
    - ~ 12 hours

• **Tests in vertical cryostat**
**Coupler**

- Single ceramic window
- TiN coating (nm): $\sim 5 - 10$
- Frequency [MHz]: 352.21
- P max [kW]: 400

⇒ 4 prototypes manufactured (PMB; CST)

**Inner conductor (antenna)**

- Electromagnetic RF wave
- MUSICC 3D soft. ⇒ multipacting simulations

**Outer conductor (antenna)**

- SHe cooling 5 → 300 K
- 2.5 mm
- 1.55 mm
- RF = ON

⇒ SHe: 46 mg/s

**RF power coupler**

- (1 ceramic window)
- Inner water cooling circuit
- 1.55 mm
- 2.5 mm
- SHe: 46 mg/s
**Conditioning bench for the RF couplers**

- **RF power couplers 2/4**

- **Conditioning bench for the RF couplers**

- **Model: RF to thermal, mechanical coupling (ANSYS HFSS ↔ mech.)**

- **Preliminary tests of the cooling system**
  - IR heating inside the cavity
  - Radiated heat: up to 1 kW

- **Validation (rough agreement)**

- **P$_{RF}$ = 400 000 W; DC = 5%**
- **Water mass flow rate: 3.6 g/s**

- **Coupler 1**
- **Coupler 2**
- **H field**
- **Plunger**

- **Point 29.8°C**

- **FLIR**
**Conditioning bench for the RF couplers**

- Installed at CEA Saclay (klystron 352 MHz)
- Integration (RF, mech., electronics…) done by IPNO

⇒ one coupler failure (break of ceramic window) during RF tests (half of the nominal power)

⇒ one coupler conditioned
Example of qualifying tooling and assembly procedures

- Tooling to assemble the coupler onto the cavity (inside ISO 4 cleanroom)

3D printed mock-ups of:
- the RF coupler
- the double wall tube

✓ Test of the assembly procedure
Cold tuner system

**Goals:**

- To tune the resonance frequency of the cavity
  - after cool-down
  - Large and slow action
- To balance:
  - microphonics (pressure waves)
  - Lorentz forces detuning
  - Small and fast action
- By changing RF volume of the cavity

**Technology:**

- Double lever type CTS

### COLD TUNER SYSTEM

<table>
<thead>
<tr>
<th>Slow tuning (stepper motor)</th>
<th>Fast tuning (piezo actuators)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. stroke (mm)</td>
<td>Tuning range (at 2 K) (Hz)</td>
</tr>
<tr>
<td>1.3</td>
<td>~ 800</td>
</tr>
<tr>
<td>Tuning range (kHz)</td>
<td>~ 170</td>
</tr>
<tr>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>Tuning resolution (kHz)</td>
<td></td>
</tr>
</tbody>
</table>

Stepper motor

Piezo-actuators
Cavities magnetic shield

- Material: Cryophy®
- Actively cooled (better performances)

- Magnetic shields fabricated
- Assembly test performed
- To be tested within the cryomodule
The ESS Spoke cryomodule

Cryodistribution Interface to VB

Ø ~ 1.3 m

2.86 m
The ESS Spoke cryomodule

2 double Spoke cavities @ 2 K (sat. HeII):
- Dynamic heat loads: 2 x 2.5 W
- Beam loss: 1.5 W

2 RF power couplers
- 2 x 1.75 W @ 2 K
- Heat intercept: SHe 3 bara; 5-300 K
  Liquefaction power: 2 x 0.50 g/s

Rest of static heat loads @ 2 K: ~ 6.5 W
(total ~ 10 W)

Dynamic heat loads ~ 2/3 x Static heat loads

The Prototype Spoke cryomodule

Instrumentation (measurement of T, P, cryo levels)

Cavities Supporting system
- 2 Magnetic shields
- 2 spoke cavities
- 2 RF power couplers
The Prototype Spoke cryomodule

Supporting system for the string of cavities

- Antagonist rods
- Optimization
- Optical fiducials + windows for the alignment diagnostic
- For vacuum and cryogenics operating conditions: alignment might be possible
- Assembly tested (no cold mass)
The Prototype Spoke cryomodule

Cryomodule thermal shield

- Material: Al6062
- Thickness: 2 mm
- Thermal shield fabricated
- Assembled and supported (rods)
- He 20 bars (machine)
- Sat N₂ (Proto)
- Instrum. and cool-down test

⇒ 30 W @ 80 K
Prototyping the Spoke section

- A prototype and test valve box:
  - Prototype valve box ⇒ to validate the valve box concepts
    ⇒ to validate the prototype Spoke cryomodule
  - Test valve box ⇒ to validate 13 series Spoke cryomodules
    ⇒ Compromise between an optimized test stand and a demonstrator (cryoprocess, assembly)

- A versatile (flexible) valve box
  - Tests at IPNOrsay (FRANCE)
  - Tests at Uppsala University (SWEDEN)
    ⇒ To manage different cryogenic infrastructures
Prototype Spoke valve box

Prototype valve box

- Cryodistribution line
- Cryoliquids supply
- He phase separator
- Cold vapours exhaust
Prototype Spoke valve box status

- Vacuum vessel
- Cryodistribution piping
- Cryodistribution components
- Ready for factory acceptance tests

He/He Heat exchanger
(Superfluid helium production)
## Crymodule components

**All components received and tested**

- Cavities
  - 3 prototypes manufactured
  - All tested beyond ESS requirements
  - However $Q_0$ decrease observed after several thermal cycles

$\Rightarrow$ Hydrides formation on the inner surface of the cavity induce defects that are not recovered at room $T^\circ$

$\Rightarrow$ UHV furnace installed at Supratech facilities (IPNO)
$\Rightarrow$ Thermally and vacuum qualified up to 1400 °C

$\Rightarrow$ Heat treatment procedure tested on samples and 1.3 GHz cavity
$\Rightarrow$ 1 Spoke cavity to be annealed (650 °C) by the end of this summer
Cryomodule components
- All components received and tested
  - Couplers
    - 4 prototypes manufactured
    - 1 coupler failure during RF conditioning (analysis)
    - 1 coupler conditioned
    - Conditioning of others couplers to be done
- Assemblies of subparts tested

Assembly of the cryomodule started with a string of 2 mock-up cavities
- To test the assembly procedure
- To validate the magnetic shield
  (spatial measurements of the attenuation of the environment magnetic field at room and N₂ T° by this summer)
- To validate the cryogenic process
  (helium tanks of the cavities have the same volume and geometry as the Spoke cavities)
**Spoke prototype valve box**

- Factory acceptance tests next week
- Installation at Orsay to perform the first cryogenic test of the prototype Spoke cryomodule at IPNO
Thank you for your attention