SPIRAL2 Cryomodule Production Results and Analysis

P.-E. Bernaudin (GANIL)

On behalf of the GANIL, IPNO, Irfu and LPSC teams
Talk outline

1. The SPIRAL2 superconducting Linac
2. Cryomodules production
3. Achieved performances
4. Conclusions & perspectives
1. The SPIRAL2 superconducting linac
The SPIRAL2 superconducting accelerator

12 low beta cryomodules (0.07) and 7 high beta cryomodules (0.12)
L~35 m

<table>
<thead>
<tr>
<th>Particles</th>
<th>p⁺</th>
<th>D⁺</th>
<th>1/3</th>
<th>1/6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q/A</td>
<td>1</td>
<td>1/2</td>
<td>1/3</td>
<td>1/6</td>
</tr>
<tr>
<td>I (mA) max.</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>W₀ min. (Mev/A)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>W₀ max. (Mev/A)</td>
<td>33</td>
<td>20</td>
<td>14.5</td>
<td>8.5</td>
</tr>
<tr>
<td>CW max. beam power (KW)</td>
<td>165</td>
<td>200</td>
<td>44</td>
<td>48</td>
</tr>
</tbody>
</table>
Cryomodules general design

Common features:

- QWR cavities, 88 MHz
- Bulk niobium
- 4.5K operation
- Same power coupler
- Separate vacuum
- BCP treatment
2. Cryomodules production
Production strategy

Prototyping stage
- Cavities prototypes
- Coupler prototypes

Pre-series stage
- Cryomodules prototypes, featuring pre-series cavities and couplers (≠ prototypes)

Production stage
- Series components (including upgraded prototype cryomodules)

All three stages:
- Design
- Manufacturing
- Assembling
- Testing

Low beta
- Irfu
- LPSC
- IPN

Power coupler
- Industry
- LPSC
- IPN

High beta
- Industry
- LPSC
- IPN

Three independent teams.
Implementation

8 low beta and 5 high beta cryomodules qualified in a row
Other cryomodules in assembly phase
3. Achieved performances
Cavities performances in vertical cryostat

Very homogeneous results
Cavities performances in vertical cryostat

Dispersion of $Q_0$ at nominal gradient

- 71% of cavities

<table>
<thead>
<tr>
<th>Number of cavities</th>
<th>low beta</th>
<th>high beta</th>
</tr>
</thead>
<tbody>
<tr>
<td>-35%</td>
<td>4,0E+08</td>
<td>1,4E+09</td>
</tr>
<tr>
<td>-25%</td>
<td>7,6E+08</td>
<td>2,7E+09</td>
</tr>
<tr>
<td>-15%</td>
<td>4,8E+08</td>
<td>2,6E+09</td>
</tr>
<tr>
<td>-5%</td>
<td>7,0E+08</td>
<td>4,6E+09</td>
</tr>
<tr>
<td>+5%</td>
<td>5,9E+08</td>
<td>3,7E+09</td>
</tr>
<tr>
<td>+15%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+25%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+35%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Maximum gradient reached

- 71% of cavities

<table>
<thead>
<tr>
<th>$E_{acc}$ (MV/m)</th>
<th>low beta</th>
<th>high beta</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>6,5</td>
<td>6,5</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cavities</th>
<th>low beta</th>
<th>high beta</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6,5</td>
<td>6,5</td>
</tr>
<tr>
<td>5</td>
<td>7,4</td>
<td>7,1</td>
</tr>
<tr>
<td>10</td>
<td>12,2</td>
<td>10,5</td>
</tr>
<tr>
<td>15</td>
<td>10,7</td>
<td>8,9</td>
</tr>
</tbody>
</table>

Target (10 W limit)

- $4,0E+08$ for low beta
- $1,4E+09$ for high beta

Computed (simulation codes)

- $7,6E+08$ for low beta
- $2,7E+09$ for high beta

Achieved in vertical cryostat, at nominal gradient

- $4,8E+08$ for min low beta
- $2,6E+09$ for min high beta
- $7,0E+08$ for max low beta
- $4,6E+09$ for max high beta
- $5,9E+08$ for mean low beta
- $3,7E+09$ for mean high beta

Nominal gradient

- $6,5$ for low beta
- $6,5$ for high beta

Max gradient reached in vertical cryostat

- $7,4$ for min low beta
- $7,1$ for min high beta
- $12,2$ for max low beta
- $10,5$ for max high beta
- $10,7$ for mean low beta
- $8,9$ for mean high beta
Cavities performances in cryomodules

<table>
<thead>
<tr>
<th></th>
<th>low beta</th>
<th>high beta</th>
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</thead>
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<tr>
<td>target (10 W limit)</td>
<td>4.0E+08</td>
<td>1.4E+09</td>
</tr>
<tr>
<td>Computed (simulation codes)</td>
<td>7.6E+08</td>
<td>2.7E+09</td>
</tr>
<tr>
<td>achieved in vertical cryostat, at nominal gradient</td>
<td>min 2.8E+08</td>
<td>2.0E+09</td>
</tr>
<tr>
<td></td>
<td>max 5.5E+08</td>
<td>3.9E+09</td>
</tr>
<tr>
<td></td>
<td>mean 4.4E+08</td>
<td>3.0E+09</td>
</tr>
</tbody>
</table>

He level

Gas flow

Q₀ in cryomodules: calorimetric measurements (lower accuracy)

Max gradient reached

Max gradient in cryomodules: administrative limit (avoid quench)

Not yet tested in cryomodule

Spare cavities
Cryomodules cryogenic performances

Cryogenic losses at 4 K (static)

Measurement methods:
- helium gas flow meter, and/or
- helium level decrease in buffer (better accuracy)

Cryogenic losses at 4 K (total)

All cryomodules (but 1) to specs:
- **Low beta**: static performances compensate for dynamic losses
- **High beta**: cavity low dynamic losses compensate for underestimated static losses
Other cryomodules performances

- **Tuning systems**
  - Effective tuning range
    - Low beta: 13 kHz (restricted to protect the cavity)
    - High beta: 10 kHz
  - Reliability: low beta system heavily cycled
  - Hysteresis
    - Low beta: up to 4 Hz (cavity bandwidth is 130 Hz)
    - High beta: ~20 Hz (cavity bandwidth is 80 Hz)

- **Cavities sensitivity to pressure (He bath)**
  - Dependant on chemical etching intensity
  - Always better than specifications (< 8 Hz/mbar)
  - Simulations proved reliable

- **X-Rays emission by cryomodules**
  - Diagnostics sensitive to X-rays (BEM, BLM)
  - Low beta cavities emission homogeneous (usually a few μSv/h)
  - High beta cavities emission: nil or strong (~20 mSv/h)
4. Conclusions & perspectives
SPIRAL2 cryomodules performances

SPIRAL2 cryomodules tests results:

- Achieved gradients and $Q_0$
- Dispersion of performances
- Decrease of performance VC -> cryomodule
- Achievable performances for short and compact cryomodules
- Etc.

But:

- New low $\beta$ cavity designs, new cavities treatment (EP): enhanced performances
- SPIRAL2 cryomodules not yet operated on-line and with beam: *we can expect some decrease of performances - how much?*
Installation tests

Cryomodules to warm sections beam line connections:

No $Q_0$ loss, no maximum gradient loss, same field emission

Transportation test:

<table>
<thead>
<tr>
<th></th>
<th>Before</th>
<th>after</th>
</tr>
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<tbody>
<tr>
<td>X-rays dose rate at nominal gradient ($\mu$Sv)</td>
<td>730</td>
<td>9</td>
</tr>
<tr>
<td>Total losses at 4K and nominal gradient (W)</td>
<td>15.4</td>
<td>13.2</td>
</tr>
</tbody>
</table>
Thank you for your attention !...