In situ dynamic heat load measurements of the SPIRAL2 LINAC superconducting cavities

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Outline

- **Introduction**
  The LINAC and its cavities

- **Heat load measurements**
  Why, how and other stuff …

- **Heat load based observers**
  Impact on operation
Introduction

SPIRAL2 LINAC

- ECR ions sources
- Slow and fast chopper
- 12 low beta superc. QWR
- Solid state RF amplifiers
- Room temperature Q poles
- 14 high beta superc. QWR

Highlights

- 2014 - Assembly
- 2017 - First cool down
- 2018 - Subsystems commissioning
- 2019 - LINAC Commissioning
- 2020 - 16 kw CW H⁺ acceleration
Introduction

Cryomodules 3D Layout

Figure 2. Cryomodules 3D layout
# Introduction

## Cavities properties

### Similarities

<table>
<thead>
<tr>
<th>Property</th>
<th>Type</th>
<th>( \lambda/4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Bulk Niobium</td>
<td></td>
</tr>
<tr>
<td>Operating temperature</td>
<td>4.3 K</td>
<td></td>
</tr>
<tr>
<td>Design cavity field</td>
<td>6.5 MV/m</td>
<td></td>
</tr>
<tr>
<td>Alignment constraints</td>
<td>( \approx 1 \text{ mm} )</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>88.0525 MHz</td>
<td></td>
</tr>
<tr>
<td>Coupling type</td>
<td>Capacitive</td>
<td></td>
</tr>
</tbody>
</table>

### Differences

<table>
<thead>
<tr>
<th>Property</th>
<th>Type A</th>
<th>Type B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Lower part in Cu</td>
<td>Entirely Nb</td>
</tr>
<tr>
<td>Number</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>( \beta_{\text{opt}} )</td>
<td>0.07</td>
<td>0.12</td>
</tr>
<tr>
<td>( Q_0 )</td>
<td>( 3.5 \times 10^8 )</td>
<td>( 1.4 \times 10^9 )</td>
</tr>
<tr>
<td>( E_{pk} / E_a )</td>
<td>5.36</td>
<td>4.76</td>
</tr>
<tr>
<td>( B_{pk} / E_a )</td>
<td>8.7</td>
<td>9.35</td>
</tr>
<tr>
<td>Coupling factor ( Q_i )</td>
<td>( 5.5 \times 10^5 )</td>
<td>( 1.1 \times 10^6 )</td>
</tr>
</tbody>
</table>
Heat load measurements
The importance of heat load measurements

- Every CM / cavity has its signature / personality
- Thermal signature gives many clews to understand it
  - Vacuum
  - Quality factor
  - Cryogenic control
- Dynamic thermal behaviour can give useful information
- Correlations with X emissions, temperatures, accelerating fields can give clews on specific issues and how to solve them
Heat load measurements

How to ...

- Close inlet valve
- Open outlet valve
- Measure liquid helium level variations and pressures
- Fit the measurements to the calculated volumes (3D model of the phase separators) with respect to helium properties variations

The dissipated power is determined by:

$$ P_T = \frac{dV}{dt} \rho C_l $$
Heat load measurements

Static measurements

- Done every beginning of run
- Ensures that there is no degradation in the structure of the cryostat
- No degradation observed for CMAs since the first full cool down
- Static heat load degradation for CMBs still to be understood

Figure 4. Static annual heat load measurements
Heat load measurements

Dynamic measurements

- Thermal dissipation as a function of the accelerating field
- Includes effects such as:
  - Multipactor
  - Field emission
  - Surface particle pollution
  - Coupling
  - …

\[
P_T = \sum_i P_{i_d}(E_{cav}) + P_0
\]
Heat load measurements

Dynamic measurements

- Measurements of $P_T$ for different values of $E_{cav}$
  - Fit 1: $P_T = A E_{cav}^2 + P_0$
    - Conductance dominated behaviour
  - Fit 2: $P_T = A E_{cav}^3 + P_0$
    - Nb Q drop taken into account

![Type A cryomodules measurements](image)

Figure 5. Type A cryomodules dynamic heat load measurements
Heat load measurements

Dynamic measurements

- Measurements of $P_T$ for different values of $E_{cav}$

- **Fit 1**: $P_T = AE_{cav}^2 + P_0$
  - Conductance dominated behaviour

- **Fit 2**: $P_T = AE_{cav}^3 + P_0$
  - Nb Q drop taken into account

Figure 5. Type A cryomodules dynamic heat load measurements
Heat load measurements

Dynamic measurements

- Measurements of $P_T$ for different values of $E_{cav}$
- **Fit 1**: $P_T = A E_{cav}^2 + P_0$
  - Conductance dominated behaviour
- **Fit 2**: $P_T = A E_{cav}^3 + P_0$
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Figure 5. Type A cryomodules dynamic heat load measurements
Heat load measurements

Dynamic measurements

- Measurements of $P_T$ for different values of $E_{cav}$
  - Fit 1: $P_T = A E_{cav}^2 + P_0$
    - Conductance dominated behaviour
  - Fit 2: $P_T = A E_{cav}^3 + P_0$
    - Nb Q drop taken into account

Figure 6. Type B cryomodules dynamic heat load measurements
Heat load measurements

Dynamic measurements

- Measurements of $P_T$ for different values of $E_{cav}$
- Fit 1: $P_T = A E_{cav}^2 + P_0$
  - Conductance dominated behaviour
- Fit 2: $P_T = A E_{cav}^3 + P_0$
  - Nb Q drop taken into account

$P_T = A E_{cav}^3 + P_0$

Figure 6. Type B cryomodules dynamic heat load measurements
Heat load measurements

Correlations and dependencies

- Cavities temperatures
- Beam loss monitors
- Anomalies diagnostic

\[ T_{\text{cav}} = A E_{\text{cav}}^2 + T_0 \]

Figure 7. Type A cryomodules dynamic heat load correlated cavity temperatures measurements
Heat load measurements
Correlations and dependencies

- Cavities temperatures
- Beam loss monitors
- Anomalies diagnostic

Figure 8. Heat load correlations with cavity temperature and beam loss monitor measurements for CMA11
Heat load measurements

Correlations and dependencies

- Cavities temperatures
- Beam loss monitors
- Anomalies diagnostic

Figure 9. Heat load fits for CMA11
Heat load based observers

Automatic heat load compensation

- **Why?**
  - Heat load budget kept constant at all times
  - Liquid helium flow equally distributed
  - Cavities voltage ramp up heat load management
  - Better pressure and liquid helium level control

![Diagram](image)

Figure 10. Heat load distribution in the LINAC

- **Variable compensation**
- **E_{cav} dependance**

- Static heat load
- Dynamic heat load
- Distributed compensation
- Anomalies
Heat load based observers

Automatic heat load compensation

- Measure $P_T(E_{cav})$
  - Liquid helium level decay
- Calculate $P_T(E_{cav})$
  - $P_T = \frac{(E_{cav}\lambda\beta)^2}{R} + P_0$
- Calculate the heater compensation
  - $P_{heater} = C_0(E_{cav,set}^2 - E_{cav,var}^2) + C1$

Figure 11. Calculated and measured heat loads heat map
Heat load based observers

Automatic heat load compensation

- Measure \( P_T(E_{cav}) \)
  - Liquid helium level decay
- Calculate \( P_T(E_{cav}) \)
  \[
  P_T = \frac{(E_{cav}\lambda\beta)^2}{R} + P_0
  \]
- Calculate the heater compensation
  \[
  P_{heater} = C_0(E_{cav, set}^2 - E_{cav, var}^2) + C1
  \]

Figure 11. Calculated and measured heat loads heat map
Heat load based observers

Automatic heat load compensation

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Figure 12. Heat load dynamic compensation heat map
Heat load based observers

Knowledge of the cryogenic system can allow to know or to predict its behaviour

Use of informations such as valves positions, pressures and liquid helium levels

Can give an almost real time heat load observer

Figure 13. Heat load model based estimation for SPIRAL2 [A. Vassal et al (2019)]
Conclusion

Heat load measurements are a valuable tool for

- Verification of cavities performance
- Diagnostic of field dependent anomalies

In the big data and AI era, they can also contribute to:

- Give a better visibility of system evolution
- In correlation with other measurements (BLM, RF, …), they can contribute to better tagging which is critical for AI
- Contribute to a more intelligent kind of operation