**DOCUMENT TYPE:** Technical Note

**TITLE:** Cryogenic distribution aspects of the Spoke cryomodule

Discussion about the location of the cryovalves and heat exchanger

**SUMMARY AND OBJECT OF THE DOCUMENT:**

- Placing cryovales and heat exchanger in cryomodule or in the valve box?
- Mechanical, cryogenic and furniture aspects of such choice

**DISTRIBUTION LIST:**

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<table>
<thead>
<tr>
<th>Author</th>
<th>Verified by</th>
<th>Approved by</th>
</tr>
</thead>
<tbody>
<tr>
<td>P. DUTHIL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Institute: IPNO-IN2P3-CNRS</td>
<td></td>
<td></td>
</tr>
<tr>
<td><a href="mailto:duthil@ipno.in2p3.fr">duthil@ipno.in2p3.fr</a></td>
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**VERSIONS SUMMARY**

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1 **OBJECT OF THIS DOCUMENT**

In the context of the ESS Spoke design, ESS has chosen to place the cool-down and Joule-Thomson cryovalves within the cryomodule. The helium/helium heat exchanger is also placed within cryomodule. Even though the choice of placing the LHe II production the closest from the cold mass seems judicious, this document presents the harmful consequences of it. Considering the mechanical integration of the cryomodule, its assembly sequence, some thermal and cryogenic calculations and some project aspects, it discusses this alternative.

2 **THE SPOKE CRYOMODULE**

2.1 **ESS context**

The European Spallation Source (ESS) aims at being the world’s most powerful neutron source feeding multidisciplinary researches. At least 17 European countries are now designing this facility including a linear accelerator raising the energy of a proton beam up to 2500 MeV, a heavy-metal target station, a large array of state-of-the-art neutron instruments and a suite of laboratories.

2.2 **The Spoke linac**

The superconducting part of the linear accelerator consists in 41 cryomodules holding Spoke, medium beta and high beta elliptical superconducting radiofrequency (SRF) resonators. The roughly 59 m long Spoke section will contain 13 cryomodules maintaining 26 paired $\beta=0.5$ 352.2 MHz SRF double Spoke cavities, made in bulk niobium, at a temperature of 2K in a saturated helium bath to generate an accelerating field of 9 MV/m per resonator.

2.3 **The Spoke cryomodule**

A prototype cryomodule having two Spoke cavities equipped with their 300 kW RF average power couplers is now being designed and will be constructed and tested at full power by the end of 2015 for the validation of all chosen technical solutions. It thus integrates all the interfaces necessary to be operational within a linac machine (vacuum, cryogenic, RF and fluids distributions and controls, safety, alignment diagnostic and control, etc). This prototype will have to guarantee the performances guided by beam dynamics while optimizing the energy consumption and will aim at assessing the maintenance operations issues.

*Figure 1 – Overview of the ESS Spoke cryomodule and main dimensions.*
An overview of the Spoke cryomodule is shown on Figure 1 indicating its main dimensions. It consists in a vacuum vessel housing and protecting from the ambient temperature the so-called string of (two) cavities (cf. Figure 2 (a)) which accelerates the proton beam and insures a high vacuum quality. Each cavity is equipped with a helium tank which is fully filled by saturated 2 K superfluid helium. Each cavity is also protected from the surrounding magnetic field by use of a magnetic shield (cf. Figure 2 (b)) which might also be cooled down to obtain a satisfactory magnetic permeability before the normal to Meisner state transition of the cavity. The RF power is supplied into each cavity by use of a special RF feedthrough, the RF power coupler, which is thus connected at one side to the (cold) cavity and at the other to the (warm) vacuum vessel. A cold tuner is also connected to each cavity insuring proper tuning during operations.

![Figure 2 - String of two double Spoke cavities equipped with (a) their RF coupler, cold/warm transitions and UHV (warm) gate valves and (b) magnetic shields.](image)

The string of cavities and the relevant cryogenic distribution is considered to be the cold mass and shown on Figure 3. The string of cavities ends at both sides by UHV gate valves which will be connected to the vacuum vessel and hence maintained at ambient temperature. Connection between the cold part of the beam pipe and the vacuum vessel (UHV warm valves) is established by use of two cold to warm transitions (CWT). They extend the beam pipe till the vacuum vessel, facing beam vacuum and offering, via the thermal shield, a heat interception of the conductive heat coming from the vacuum vessel to the cold cavities (cf. Figure 4 (b)).

![Figure 3 - Cold mass of the ESS Spoke cryomodule.](image)

This cold mass is then protected against thermal radiations by use of a thermal shield cooled at a temperature ranging between 40 and 50 K by circulation of supercritical helium at a pressure of 19.5 bars (cf. Figure 4 (a)).
The cryomodules are fed with cryogenic fluids by the Cryogenic Transfer Line (CTL) which lies all along the LINAC and by valve boxes. Connection between a cryomodule and a valve box is achieved by a cryogenic jumper. A principle scheme of the cryogenic distribution is shown on Figure 5. ESS has chosen to produce LHe II locally within each cryomodule. The helium supplied by the CTL (at a temperature of 5K and a pressure of 3 bars; shown in red on Figure 5) is hence subcooled to a temperature of about 2.2 K within a heat exchanger by use of the enthalpy of the cold vapors leaving the cryomodule (light blue). It is then isenthalpically expanded within a cryogenic valve to produce LHe II.

![Figure 4](image-url) - (a) Cold mass and thermal shield – (b) Thermal shield and cold to warm transitions.

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![Figure 5](image-url) - Principle scheme of the cryogenic distribution of the Spoke cryomodule.

### 2.4 The cryovalves

A model of one of the cryovalve is presented on Figure 6. The supplier might be WEKA and, considering the catalog characteristics and the required mass flow rates to properly operate the Spoke cryomodule, both valves are DN2. Their “cryogenic length” $h$ is 875 mm in order to minimize heat loads at low temperature.
2.5 The He/He heat exchanger

The chosen He/He heat exchanger is a fin/fin heat exchanger produced by the company DATE and similar to the ones used in the LHC. Such a heat exchanger, designed for a helium mass flow rate of 1.5 g/s is shown on Figure 7. It is similar to the one which might be used for the ESS Spoke cryomodule.

![Figure 7 - DATE He/He heat exchanger.](image)

Required helium mass flow rates for the operation of the Spoke cryomodule are indeed [1]:

- Minimum (static regime): 0.35 g/s
- Nominal (dynamic regime): 0.7 g/s
- Maximum (safety margin for sizing the cryogenic distribution): 1.5 g/s.
3 DISCUSSIONS ABOUT THE LOCATION OF THE VALVES AND OF THE HEAT EXCHANGERS

3.1 Assembly chronology of the Spoke cryomodule

Because of their large length, the two valves are assembled to the cryomodule at the end of the sequence of the cryomodule assembly (cf. Figure 8). Otherwise, the cryostating tooling could not be set up and inserting the string of cavities within the vacuum vessel would not be possible. It follows that the cryogenic distribution within the Spoke cryomodule cannot be finalized before the very end of the assembly sequence by the welding of the cryolines onto the valves.

The partially mounted cryodistribution requires additional toolings (or functions) to support the hanging cryogenic pipes during the cryostating. Although they will be maintained by the cryovalves after the welding, they have indeed to be hold before. If additional tooling is required for this function, it has then to be removed once the cryostating is achieved in order to not increase the heat load at low temperature.

To finalize the cryodistribution, the welding operations and the helium leak tests will have to be performed inside the cryomodule with the following constraints (cf. Figure 9):
- a very limited space for: the operating tools; the operator himself;
- a narrowed visibility;
- the presence of very delicate components: MLI, instrumentation....

Figure 8 – Assembly of the Spoke cryomodule (selected steps).
Thus, dedicated tooling and protections will have to be designed and provided for those operations. An experienced welder will be required during the assembly phase.

![Diagram of cryovalves and distribution lines](image)

*Figure 9 – Connecting the cryovalves to the distribution lines: welding location.*

If there is no cryogenic valve in the cryomodule, the cryogenic distribution of the cryomodule is thought to be a subsystem that can be manufactured, assembled and tested independently. It will then be mounted onto the string of cavities outside the cryomodule during the "dressing phase"; then inserted within the cryomodule, simultaneously with the string of cavities during the cryostating phase. The cryodistribution will be finalized by connecting the jumper.
3.2 Mechanical integration – Vacuum vessel

The two cryovalves are placed at both extremities of the cryomodule, close to the dish ends (cf. Figure 11). This location is necessary to provide some space and visibility for the welding of the valves to the cryogenic distribution lines. The cryogenic jumper is located at the centre of the cryomodule: it is the optimal position for the (low pressure) pumping line and for the burst disk. This jumper connection is also the entry point of all the cryogenic lines within the cryomodule. The He/He heat exchanger is connected to the low pressure pumping line and sub-cools the higher pressured helium inlet. Integrating this heat exchanger within the cryomodule involves to place it above the bi-phase pipe, thus at the cryogenic jumper connection. It is thus possible to connect this heat exchanger onto the high and low pressure lines while assembling the jumper connection basement. However, and in order to provide sufficient access for the mounting operations, the jumper connection has then to be large, with a diameter wider than 500 mm. The diameter of the vacuum vessel being 1300 mm, this large connection strongly affects the mechanical behaviour of the vacuum vessel requiring to add 2 stiffeners. IPNO has thus studied the possibility of placing the heat exchanger further away in the jumper (cf. Figure 11). The jumper connection can thus be reduced, but the heat exchanger has to be placed in the horizontal portion of the jumper as it is not possible to place it vertically due to the tunnel roof height. Although the nominal operation of the heat exchanger in this horizontal position is not seen as potentially problematic by the manufacturer (since considered mass flow rates are sufficient), the transient fill-in of the heat exchanger during cool-down is more risky and no such heat exchanger has been tested in this position. It follows that placing the heat exchanger vertically in the valve box would be a good choice. It does indeed have no impact on the size of the valve box (cf. Figure 10 – Heat exchanger in the valve box.).
For maintenance operation, the command inset of the cryovalves can be disassembled. A minimum distance of 875 mm is thus required above the inset valve interface for this operation. As the diameter of the vacuum vessel of the Spoke cryomodule is of about 1300 mm, the inset interfaces of the cryovalves will be at an altitude of 2.380 m above the ground of the tunnel. A distance of 820 mm only will be left above the valve. This is not sufficient for the valve disassembling. **Thus, for this operation, the Spoke cryomodule will have to be moved from its nominal locations within the tunnel.**

The height of the valve box being smaller than the diameter of the spoke cryomodule, it seems however possible to disassemble the cryovalves which are mounted it.

### 3.3 Mechanical integration – thermal shield

Cryogenic valves can be provided with a thermal plug to achieve a heat intercept at intermediate temperature. In our case, this interception would be done by thermally connecting this plug to the 40-50 K thermal shield. It allows to save more than 0.1 W of heat load at 2 K per valve [2].

**For the Spoke cryomodule, this thermal link is possible but not easy.** The valves are mounted onto the cryomodule at the end of the assembly phase, the thermal shield being already placed into the vacuum vessel. Holes are made in the thermal shield to let the valves pass through. Special hoods are designed to connect the thermal interface of the valve to the thermal shield. They are mounted on the valve before inserting the valve into the cryomodule. Then, those hoods are connected to the thermal shield (from the inside). It has to be underlined that the thermal shield will be covered by Multi Layer Insulation: 30 layers for a total thickness of about 15 mm. As a sufficient distance of about 180 mm is expected between the thermal shield and the vacuum vessel, it will be possible to connect the MLI of the thermal shield to the ones of the thermal hoods (valves heat interceptions) and suppress optical path.

If cryogenic valves were placed in the valve box only, the thermal shield of the cryomodule would be simpler. **Thermal hoods for the heat interception would not be needed.** Indeed, cryovalves in the valve box are more easily equipped with heat interception. They can even act as a support for part (or total) of the thermal shield of the valve box.

### 3.4 Cryogenic aspects

As already mentioned, the jumper connection is the entry point of all the cryogenic lines within the cryomodule. Especially, the high pressure line that feeds both the cool-down line and the JT valve. Thus, placing those two cryovalves within the cryomodule increases the length of the cool-down line and of the fill-in line (JT line). This is because those lines, entering the cryomodule from the jumper connection, have to go towards the cryomodule extremities to pick-up the cryovalves and then to go back whether to the other extremity to feed the other cavity (case of the cool-down line shown in purple on Figure 11) or to the centre to feed the bi-phase pipe (JT line shown in green on Figure 11). In Table 1, the lengths of the cryogenic lines are reported for the two configurations: JT valve, cool-down valve and heat exchanger within the cryomodule or placed in the valve box. It can be seen that placing the cryovalves and the heat exchangers within the valve box makes the cryolines shorten. Only the pumping line is lengthen.
Table 1 – Lengths of the cryogenic lines.

<table>
<thead>
<tr>
<th>Position of the cryogenic valves and the heat exchanger:</th>
<th>in the cryomodule</th>
<th>in the valve box</th>
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<tbody>
<tr>
<td>Fill-in line</td>
<td></td>
<td></td>
</tr>
<tr>
<td>From CTL to HEx</td>
<td>2 620</td>
<td>400 (TBC)</td>
</tr>
<tr>
<td>From HEx to JT valve</td>
<td>2 565</td>
<td>800 (TBC)</td>
</tr>
<tr>
<td>From JT valve to bi-phase pipe</td>
<td>1 678</td>
<td>2 620</td>
</tr>
<tr>
<td>Total</td>
<td>6 863</td>
<td>3 820</td>
</tr>
<tr>
<td>Pumping line</td>
<td></td>
<td></td>
</tr>
<tr>
<td>From bi-phase pipe to HEx</td>
<td>910</td>
<td>2 680</td>
</tr>
<tr>
<td>From HEx to CTL GRP</td>
<td>1 889</td>
<td>4 00 (TBC)</td>
</tr>
<tr>
<td>Total</td>
<td>2 799</td>
<td>3 080</td>
</tr>
<tr>
<td>Cool-down line</td>
<td></td>
<td></td>
</tr>
<tr>
<td>From CTL to cryo valve</td>
<td>5 205</td>
<td>4 00 (TBC)</td>
</tr>
<tr>
<td>From Cryo valve to cavities</td>
<td>1 291</td>
<td>4 340</td>
</tr>
<tr>
<td>Total</td>
<td>6 496</td>
<td>4 640</td>
</tr>
</tbody>
</table>

Placing the heat exchanger in the valve box indeed increases the distance between the helium saturated bath and might rise the temperature at the inlet of the low pressure circuit by augmenting the length of the line exposed to heat radiation from the 50 K thermal shield. This could hence increase the outlet temperature of the high pressure circuit, reducing the efficiency of the isenthalpic expansion for the superfluid production. Considering that this pumping line will be covered by 10 layers of MLI, inducing a maximum radiated heat flux of 0.1 W/m² and considering a perfect heat exchange between the pipe and the fluid, it follows that the maximum temperature rise is less than 0.01 K/m for a minimum mass flow rate of 0.35 g/s. Thus, placing the heat exchanger within the valve box (1.8 m further away from the saturated bath) will not affect the efficiency of the superfluid production for the Spoke cryomodule [1]. Furthermore, the vapours being colder within the jumper (as not yet heated by the heat exchanger), the pressure drop at maximum mass flow rate is slightly lower.

Finally, placing the cool-down valve within the valve box allow to have a 25% increase of available mass flow rate of helium at the very beginning of the cool-down as the helium flowing within the cool-down valve will not be heated within the jumper [1].

Figure 11 – Spoke cryomodule with the cryogenic jumper connection and the two cryogenic valves; cryogenic distribution.
3.5 **Cryovalves as a furniture package**

Placing the cool-down cryovalve, JT cryovalve and the heat exchanger within the cryomodule involves that those three components will be provided by:

- the supplier of the Spoke cryomodule;
- the supplier of the medium beta elliptical cryomodule;
- the supplier of the high beta elliptical cryomodule;
- the supplier of the cryodistribution (which also requires cryovalves).

No scale effect is foreseen for those 4 different purchases.

Standardization about cryovalve or heat exchanger models and manufacturers will have to be carried out by ESS with discussions with the different responsibles for the different workpackages.

Implementing both the heat exchanger and those two cryovalves into the valve box makes possible to provide all this cryogenic equipment in one unique step as being part of the general cryogenic distribution. This could also be done in a unique in-kind contribution.

4 **REFERENCE**
