

DESIGN OF THE 352 MHz, BETA 0.50, DOUBLE-SPOKE CAVITY FOR ESS

P. Duchesne, S. Bousson, S. Brault, P. Duthil, G. Olry, D. Reynet, IPN Orsay, CNRS/IN2P3, France
S. Molloy, ESS, Lund, Sweden

Abstract

The ESS proton accelerator contains a superconducting sector consisting in three families of superconducting radiofrequency (SRF) bulk niobium cavities, operating at a nominal temperature of 2 K: a family of Spoke cavities for the medium energy section followed by two families of elliptical cavities for higher energies. The superconducting Spoke section, having a length of 58.5 m, consists in 14 cryomodules, each of them housing two 352.2 MHz beta=0.50 Double-Spoke Resonators (DSR). The operating accelerating field is 8 MV/m. The choice of the Spoke technology is guided by the high performances of such structures. Benefitting from 10 years of extensive R&D experience carried out at IPNO, the electromagnetic design studies came out with a solution that fulfils requirements of beam dynamics analysis and manufacturing considerations. Pursuing the same objective, the mechanical design of the cavity and its helium vessel were optimized by performing intensive coupled RF-mechanical simulations. In this paper, we present a review of the RF and mechanical design studies of the Spoke cavity. We will conclude with the integration of the Spoke cavity with its ancillaries inside the cryomodule.

SUPERCONDUCTING SPOKE CAVITIES

The superconducting spoke section of the linac accelerates beam from the normal conducting section to the first family of the elliptical superconducting cavities (Fig. 1). 28 spoke cavities, grouped by 2 in 14 cryomodules, are needed to accelerate beam from 78 MeV up to 200 MeV (total length of 58.5 m) Details of the ESS accelerator layout are specified in [1] and are now being optimized to meet the cost objectives. Acceleration will be performed by a single family of $\beta 0.50$ bulk niobium double spoke cavities (3 accelerating gaps), operating at 2 K and a frequency of 352.2 MHz. The chosen operating accelerating field is 8 MV/m (the accelerating length is defined as $(n+1)\beta\lambda/2$ with n = number of spoke bars). The required RF peak power is about 300 kW for 50 mA beam intensity, corresponding to 10 kW of average power.

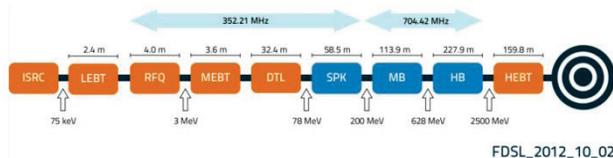


Figure 1: Schematic of the ESS accelerator layout.

The choice of spoke cavities for ESS linac is guided by the potential of high performances and intrinsic

advantages. In addition to all well-known advantages of superconducting cavities - high efficiency, large beam aperture and high reliability - spoke cavities also:

- have multi-gap capabilities
- are compact and stiff
- exhibit high cell-to-cell coupling
- are less sensitive to HOM or trapped modes
- have no dipole steering effect
- have a wide β range
- exhibit a high longitudinal acceptance

ELECTROMAGNETIC (EM) DESIGN

Spoke cavity EM design is guided by the frequency, the optimum beta and then the optimization of the peak surface fields. Whereas the most important parameter for the beam is the accelerating field or the voltage seen by the particles, one of the most important criteria of the optimization is the peak surface fields to accelerating gradient ratio; that is to minimize the electric and magnetic peak surface fields for a given accelerating field. Another important factor to optimize is the cavity overall length: a spoke cavity has re-entrant end-cups which can be increased to give more volume to stored energy, thus leading to peak surface fields' decrease. Of course, the drawback is a lower real-estate gradient due to the higher longitudinal space taken by the cavity for the same voltage.

Following the beam dynamics simulations, a set of parameters was established in order to fulfil the requirements. These are summarized in Table 1.

Table 1: Double Spoke Parameters and Requirements

Beam mode	Pulsed (4% duty cycle)	
Frequency	352.2	[MHz]
Optimal beta	0.50	
Temperature	2	[K]
Gradient Eacc	8	[MV/m]
Lacc (= $\beta \times n_b$ of gaps $\times \lambda / 2$)	0.639	[m]
Bpk/Eacc	<8.75	[mT/(MV/m)]
Epk/Eacc	<4.38	
Beam tube diameter	50 (min)	[mm]
Peak power	300 (max)	[kW]

Preparation of the Simulations

CST Microwave Studio (MWS) software has been used to design and optimize the cavity.

The cavity has been modeled directly by using the 3D CAD tools of MWS. The first mode which is calculated for a Spoke cavity is the fundamental mode TM_{010} used for acceleration. In order to save cpu-time, we have performed calculation of this first mode only and we have used $\frac{1}{4}$ of the model (see Fig. 2) with magnetic boundary condition ($H_{\text{tangential}}=0$) for both symmetry planes.

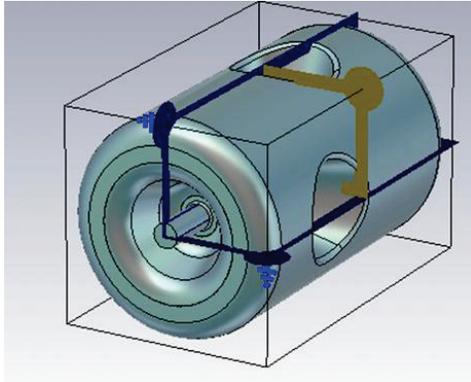


Figure 2: Boundary conditions and symmetry planes.

A benchmark has been performed to determine the number of meshcells which will be used for the iterative calculations with the hexahedral mesh type. We observed a convergence of both E_{pk}/E_{acc} and B_{pk}/E_{acc} ratios for approximately 100000 meshcells.

The main goal of the RF design is to get both E_{pk}/E_{acc} and B_{pk}/E_{acc} ratios, less than respectively, 4.38 and 8.75 mT/(MV/m). The optimization procedure has been divided in three parts:

- 1/ Optimization of the geometry without any additional ports (like RF coupler port) on the cavity body
- 2/ RF coupler integration on the cavity body and Q_{ext} calculation
- 3/ Final calculation with all ports: RF coupler, pick-up probe ports and ports dedicated to the cavity preparation (chemistry and rinsing)

Feedback from Former Spoke Cavity Fabrication at IPNO

Since 10 years by now, three Spoke-type cavities (two Single-Spokes and one Triple-Spoke) have been designed by IPNO, prepared and tested in vertical and horizontal cryostats at 4 K and 2 K. Our experience in designing spoke resonators and the feedback from the manufacturers have led us neither to use the cylindrical nor the racetrack shape for the spoke base geometry (=connection between the Spoke bar and the cavity body). The cylindrical shape led to too high magnetic field and the racetrack one brings too many difficulties for the forming but, above all, for the welding of the spoke bases to the cavity body. As a consequence, for the ESS DSR optimization, we decided to start the optimization of the spoke base by using a conical shape.

Parameterization of the Model

Mainly 13 parameters have been studied to determine their impact on the E_{pk}/E_{acc} and B_{pk}/E_{acc} values and thus, to optimize the cavity overall shape (see Fig. 3).

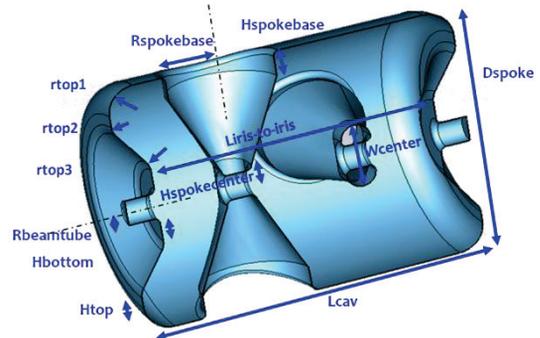


Figure 3: Parameters list for spoke optimization.

Final Geometry

After varying all parameters, we ended up with a set of parameters which gave us good results (see Fig. 4).

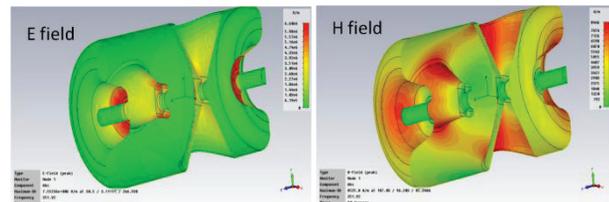


Figure 4: Electric (left) and Magnetic (right) fields distributions.

The second mesh type (tetrahedral) has been used to cross-check the results. The discrepancies vary from ~4% for B_{pk}/E_{acc} to ~10% for E_{pk}/E_{acc} whereas the G factor and r/Q values are in perfect agreement (see table 2).

One can note that the E_{pk}/E_{acc} ratio is slightly higher than the target value of 4.38. It is the result of a compromise between the cavity length, the end-cap shape feasibility and the tuning sensitivity.

Table 2: Double Spoke Parameters (Cavity without Ports)

Mesh type	Hexahedral (1.2 millions)	Tetrahedral (650000)
Beta optimal	0.50	0.50
E_{pk}/E_{acc}	4.96	4.47
B_{pk}/E_{acc} [mT/(MV/m)]	7.03	6.74
G [Ohm]	133	133
r/Q [Ohm]	428	427

RF coupler sizing

It has been decided to fix the inner diameter of the coupler to 100mm (see [2]). For a 50 Ohms impedance line, it gives an antenna diameter of 43.43 mm.

Taking these values into account, we have calculated the Qext value which can be achievable by varying the antenna tip penetration by a 20 mm overall range(see Fig. 5) and we have checked the peak surface E and B fields' values on the antenna for different location of the coupler port with respect to the cavity centre.

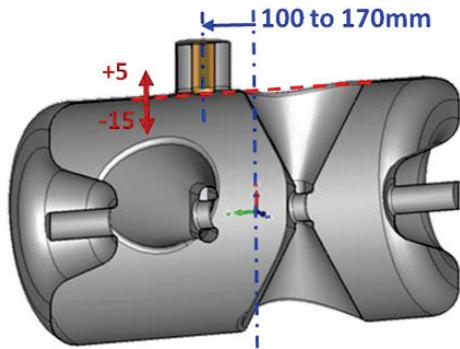


Figure 5: MWS model of the cavity with antenna.

Taking $1.5 \cdot 10^5$ as a reference for the Qext, it can be achieved by setting the coupler port centre to 120mm from the cavity centre with a 5mm antenna tip penetration into the cavity. Epk antenna/Epk cavity is around 7% and Hpk antenna/Hpk cavity is less than 5%.

Last Results

The fabrication of 3 cavities has started this summer. Taking into account some technical issues which appeared during internal reviews and discussions with the manufacturers and some new requirements from ESS, we needed to adjust some parameters: cavity diameter, rounded edges, coupler port location, and antenna tip penetration. The last results are shown hereafter in Figure 6 and Table 3:

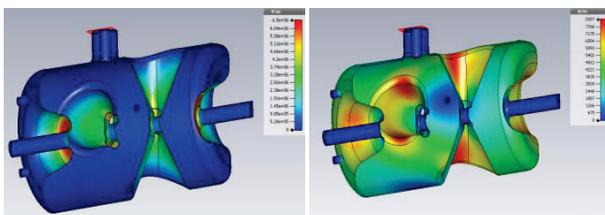


Figure 6: Electric (left) and Magnetic (right) fields distributions.

Table 3: RF Parameters with the Final Geometry

Mesh type (nb of meshcells or tetrahedrons)	Hexahedral (2.2 millions)	Tetrahedral (600000)
Beta optimal	0.50	0.50
Epk/Eacc	4.51	4.33
Bpk/Eacc [mT/(MV/m)]	6.99	6.89
G [Ohm]	131	130
r/Q [Ohm]	425	426

MECHANICAL DESIGN

The mechanical design of the double spoke resonator and its helium vessel was performed taking into account several criteria: a good accessibility for the preparation of the cavity, taking into account all loads from the manufacturing phase to the operation phase, most of the geometric shapes compatible with the manufacturing constraints. We performed a complete mechanical optimization of the cavity and its helium vessel from static calculations to RF-mechanical coupled simulations.

General Description of the Geometry

The cavity (total length of 994mm) is made of high-RRR (>250) bulk niobium and is composed of a cylindrical outer conductor (inner diameter 480 mm), two spoke bars and two re-entrant end-cups (see Fig. 7). The walls thickness is fixed to a minimum of 4 mm based on the mechanical calculations and manufacturing considerations. In order to improve the High Pressure Rinsing (HPR) process, four ports (inner diameter=28 mm) are added on one of the end-cups. Some ribs are welded on each end-cup in order to have Von Mises stresses below 50 MPa during the leak test operations at 300 K. The design of these ribs has evaluated from initially a donut to a simple disc with a ring to facilitate the manufacturing and assembly processes. In order to stiffen the top of the spoke bars where the most important stresses concentrations appeared under fluctuation pressure, some ribs were finally added (n°5 in Fig.7).

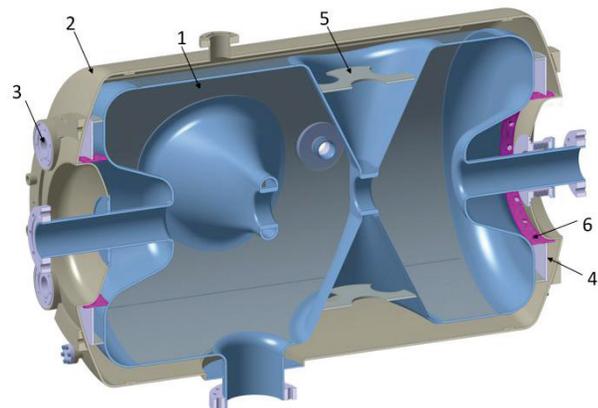


Figure 7: View of the Double Spoke cavity with its helium vessel (1: cavity, 2: helium vessel, 3: HPR ports, 4: disc rib, 5: spoke bar rib, 6: ring rib).

The helium vessel is made of 4mm-thick titanium sheets. The similar thermal expansion coefficients of titanium and niobium, allow us to connect the vessel to the cavity by electron beam welding and by consequence to increase the stiffness of the cavity. Thus, all ports of the cavity are welded to the vessel. To limit some stresses concentrations on these welding areas and at the same time to reduce considerably the sensitivity to helium pressure, some ring ribs have been connected to the end-cups of the vessel and to those of the cavity (see Fig. 7).

07 Cavity design

O. Cavity Design - Accelerating cavities

The assembly is achieved by the use of some end-cups realized in two parts for the helium vessel.

Mechanical Studies

Numerical simulations were performed with the multi-physics finite element code ANSYS. Different load cases were studied taking into account the life cycle of the cavity: the leak tests during the fabrication phase, the cool down and the nominal operation inside the cryomodule.

The risk of plastic deformations of the cavity could appear at room temperature because of the low yield strength limit of the Niobium at 293 K, around 50 MPa. This is especially the case during the leak test of the bare cavity and during the cool down. The design of the cavity in term of thickness and stiffeners was defined in order not to exceed 50 MPa (see Fig. 8 & 9). According to the pressure test result, the critical pressure, limited by the stresses areas around the spoke bars, can be estimated to 2 bars (see Fig. 9).

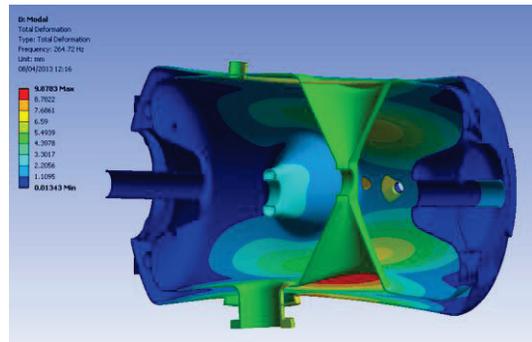


Figure 10: First critical mode of the cavity at 265 Hz.

Evaluating the frequency sensitivity of the cavity during its operation was performed with some mechanical-electromagnetic coupling simulations with Ansys software. To check the finite element model, the RF results from Ansys were first compared with those from MWS. To be as realistic as possible, the numerical model consists in an half of the cavity with its helium vessel.

Moreover, the boundary conditions have to reflect the cryomodule configuration, in particular to take into account the Cold Tuning System (CTS) stiffness. Indeed, the CTS, fixed on one of the end-cups of the helium vessel, pulls on the beam tube by the mean of a stepping motor and two piezoelectric actuators for respectively, the slow/coarse and fast/fine tuning (Fig. 11) [3]. As a consequence, the RF sensitivity of the cavity to the pressure fluctuation and to the Lorentz Forces Detuning depends on the CTS stiffness. The calculations were realized according to two extreme boundary conditions cases: 1/ without CTS: the beam tubes are free, 2/ with infinitely stiff CTS, one beam tube is fixed to the CTS supports (on the helium vessel) along the beam axis.

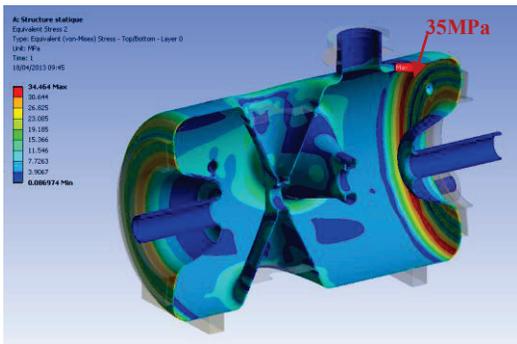


Figure 8: Von Mises stresses for leak test of the bare cavity-Max. stress of 35MPa on the end cups.

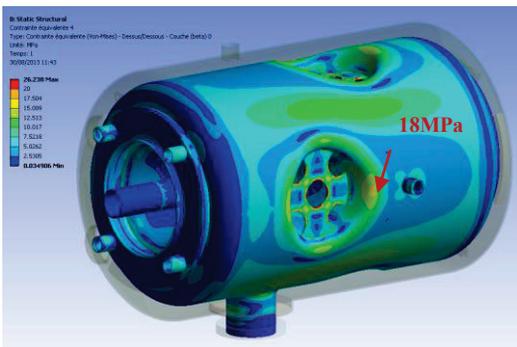


Figure 9: Von Mises stresses for pressure test ($\Delta P=0.1MPa$) with the jacketed cavity- Max. stress of 18MPa on the top of the Spoke bar.

The mechanical eigenmodes of the cavity could be excited by some external sources (pumping and cryogenic systems). This phenomenon can affect the resonant frequency 352 MHz of the cavity and produce some problems of microphonics. The first critical mode that deforms the inner volume of the cavity (265 Hz) is much higher than 50 Hz (see Fig. 10).

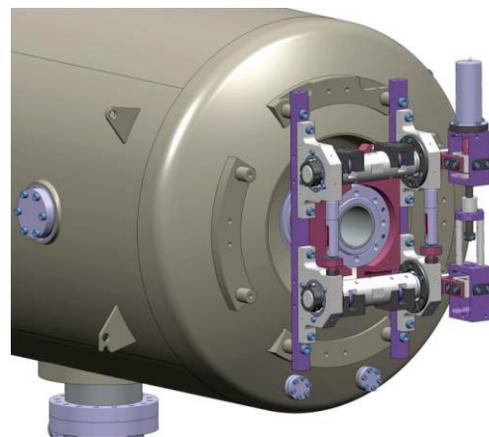


Figure 11: View of the Cold Tuning system on the cavity/helium vessel assembly.

All results of frequency sensitivities of the cavity are presented in the table 4.

Table 4: Frequency Sensitivities of the Cavity

Stiffness of the cavity	20	[kN/mm]
Tuning sensitivity $\Delta f/\Delta z$	135	[kHz/mm]
Sensitivity to helium pressure K_p		[Hz/mbar]
Without CTS	16.5	
With CTS	26	
Lorentz detuning factor K_L		[Hz/(MV/m) ²]
Without CTS	-5.13	
With CTS	-4.4	

Among the different versions of the cavity designed during the optimization phase, the version with some ring ribs between the cavity and the helium vessel provides the best sensitivity results: the sensitivity to the helium pressure K_p is estimated in a range between 16.5 and 25 Hz/mbar, the Lorentz factor is defined in the range of [-5.13, -4.4] Hz/(MV/m)². For the last case, the Lorentz radiation pressures are calculated for an accelerating gradient of 8MV/m (Fig. 12). The maximum frequency shift due to Lorentz forces, 328 Hz, is four times less than the frequency bandwidth 1530 Hz.

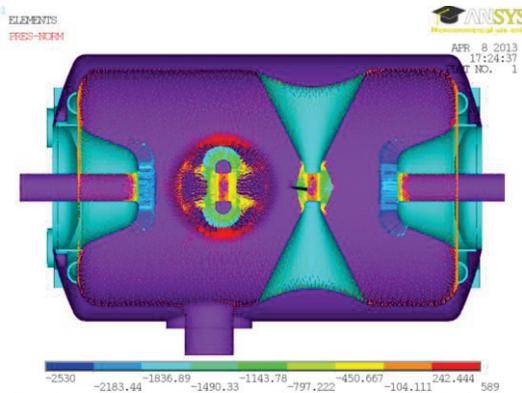


Figure 12: Lorentz radiation pressures (Pa) for an accelerator field of 8MV/m.

From the tuning sensitivity estimated to 135 KHz/mm, the tuning range at low temperature has not to exceed 173 kHz. It corresponds to a Von Mises stress value of 400 MPa at 2 K.

The RF sensitivity of the cavity can be expressed as a function of the CTS stiffness. Indeed, the frequency shift induced by any mechanical loading can be written as a linear combination of the frequency shift obtained with an infinitely stiff CT and that induced by the longitudinal sensitivity. For example, the Lorentz factor K_L can be defined as a function of the CTS stiffness (Fig. 13):

$$K_L = K_L^\infty + \frac{\partial f}{\partial z} \frac{\vec{F}^\infty \cdot \vec{u}_z}{(K_{cav} + K_{CTS}) E_{acc}^2}$$

This formula was checked by simulation for some specific CTS stiffness values (CTS simulated as a spring).

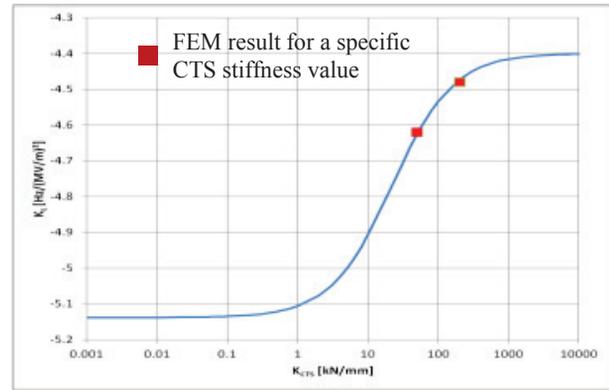


Figure 13: Lorentz factor K_L as a function of the CTS stiffness.

Then, taking a CTS stiffness equals to 100 kN/mm (=calculated value), the sensitivity to helium pressure fluctuation can be estimated to 24 Hz/mbar and the Lorentz Forces Detuning factor to -4.5 Hz/(MV/m)².

INTEGRATION IN THE CRYOMODULE

Each cryomodule houses a couple of Double Spoke Resonators. Each cavity, rinsed by High Pressure Rinsing in a ISO 4 clean room, is assembled with its RF power coupler. Two assemblies (cavity + power coupler) are then coupled together via a stainless steel beam line bellow. Two UHV gate valves are positioned at each end of this string to form a fully clean enclosure for future RF operations. Each cavity is oriented so that the maintenance operations of the cold tuning systems are facilitated after insertion in the vacuum vessel (Fig. 14).



Figure 14: String of two double spoke cavities.

Outside the clean room, the cavities string is dressed with the magnetic shield, mounted around each resonator, the cryogenic piping, the cold tuning system and the thermal shield. The detail of the cryomodule assembly is specified in [4].

Taking into account the weight and the total length of the cavities' string, the assembly and alignment methods, the static heat load, a supporting system based on rods was chosen. This already proven solution is consistent with a simple and precise alignment performed from outside the vacuum vessel and allows a possible adjustment after the cooling down. The vertical and lateral position of each cavity is adjusted by 8 identical antagonist tie rods, placed by 4 in a vertical plane. The position of the cavity string along the beam axis is provided by 4 tie rods and invar rods placed in a

horizontal plane. The detail of the supporting system is specified in [4].

CONCLUSION

Since March of 2013, three prototypes have been launched in production: one is manufactured by SDMS (France) and two others by ZANON (Italy). Up to now, some issues have been identified, especially the forming of the spoke bars and the end cups. The delivery of these prototypes is planned for May 2014.

REFERENCES

- [1] ESS Technical Design Report, (2013); <http://europeanspallationsource.se/accelerator-documents>
- [2] E. Rampnoux, S. Bousson, S. Brault, D. Reynet, Design of 352.21 MHz RF input power coupler and window for the ESS, SRF 2013, these proceedings.
- [3] N. Gandolfo, S. Bousson, S. Brault, P. Duchesne, P. Duthil, G. Olry, D. Reynet Deformation tuner design for a double Spoke cavity, SRF 2013, these proceedings.
- [4] D. Reynet, P. Duthil, S. Bousson, S. Brault, P. Duthil, D. Reynet, and S. Molloy, "Design of the ESS Spoke cryomodule", SRF 2013, these proceedings.