DESIGN AND MULTIPHYSICS ANALYSIS OF β=0.18 HALF-WAVE RESONATOR FOR IFMIF-DONES ACCELERATOR

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Abstract

The IFMIF-DONES facility will irradiate and characterize materials to be used in fusion reactors using a neutron flux produced by the interaction of a deuteron beam with a liquid lithium target. A superconducting RF linac will accelerate the beam to the final energy of 40 MeV through two series of superconducting half-wave resonators operating at 175 MHz. The study of a new design for the second family of 27 cavities (optimized for β = 0.18) has been recently presented by INFN, to optimize it from the point of view of production, while maintaining its performance close to what was observed at the first CEA prototype. This paper describes the electromagnetic and mechanical design of the β = 0.18 HWR, conducted in a Multiphysics approach of the cavity optimization. The contributions of pressure, tuners, Lorentz's force, thermal expansion, construction techniques are analysed up to meet physical and mechanical requirements.

INTRODUCTION

The International Fusion Materials Irradiation Facility – DEMO Oriented Neutron Source (IFMIF-DONES) [1-3], currently under construction in Granada (Spain), is a state-of-the-art facility whose main goal will be the testing of materials to be used in the DEMO fusion reactor [4]. Material specimens will be exposed to a neutron flux of 10^{14} $cm^{-2}s^{-1}$ produced by the interaction of a deuteron beam of unprecedented intensity with a liquid lithium target. A complex accelerator system was designed to achieve the required deuteron beam parameters of 40 MeV energy and 125 mA CW current (for a total power of 5 MW) [3, 5]. A superconducting radiofrequency (SRF) linac composed of 46 half-wave resonators (HWRs) acts as the final acceleration stage. The resonators, made of Niobium and operating at 175 MHz, are organized in two families optimized for different deuteron velocities: the first two cryomodules house 19 "low-β" cavities (optimized for $\beta = 0.115$), while the remaining three cryomodules house 27 "high-β" cavities (optimized for $\beta = 0.18$).

Italy has recently joined the IFMIF-DONES project in official capacity and, as part of the in-kind agreement, the Italian National Institute for Nuclear Physics (INFN) will procure the high-β family of resonators. Starting from the prototype designed by the French Alternative Energies and Atomic Energy Commission (CEA) [6] and incorporating the experience collected at the Facility for Rare Isotope Beams (FRIB) with similar devices [7-9], a new design was developed by the Legnaro National Laboratories (LNL) and the Torino section of INFN.

ELECTROMAGNETIC DESIGN

The IFMIF-DONES high-β HWRs are required operate at 4 K and reach a nominal accelerating field of 4.2 MV/m and a quality factor higher than 10^9. Furthermore, considering the high current of the accelerated beam, each cavity operates with an RF input power of up to 200 kW. The required beam aperture diameter is 50 mm. An extensive study, described in [10], was carried out at INFN-LNL to define an electromagnetic design which satisfies all requirements, while keeping the surface electric and magnetic fields under control to avoid field emission and quenching. A 3D model of the final design is shown in Fig. 1 and its electromagnetic properties, simulated with CST Studio Suite [11] are listed in Table 1. The quality factor is estimated assuming a surface resistance of 30 nΩ for Nb in superconducting regime. Multipacting simulation studies were also conducted, revealing two barriers (one for very low accelerating field and one for medium-high accelerating field). This is consistent with experimental tests of the CEA protype, which showed that both barriers can be overcome either by adequate conditioning or by shaping appropriately the input power pulse. An advantage of this design is that its geometry allows it to be almost entirely built from formed metal sheets (as described in the next section), reducing the cost and simplifying the manufacturing process.

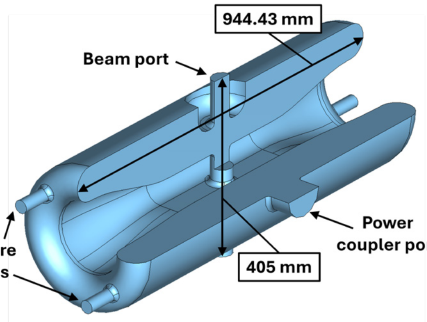

Figure 1: Cross-section view of the inner volume of the cavity. The relevant dimensions are also shown.

Table 1: Simulated electromagnetic properties of the LNL HWR design.

Frequency [MHz]	175
β_{opt}	0.18
E_{peak}/E_{acc}	4.91
B_{peak}/E_{acc} [mT/(MV/m)]	8.59
R/Q [Ω]	224.4
G [Ω]	51
Q (assuming $R_s = 30$ nΩ)	$1.7 \cdot 10^9$

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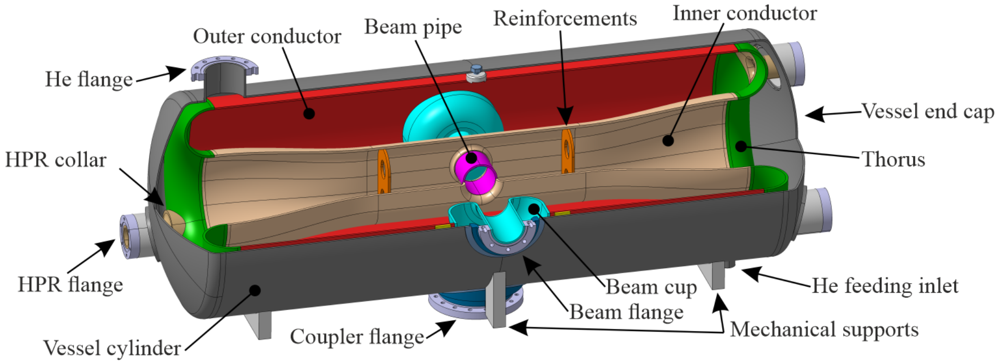

Figure 2: Design of the high-β cavity.

MECHANICAL DESIGN

After a satisfactory RF design was achieved, the mechanical design of the cavity and its surrounding jacket was carried out by INFN-Torino.

The Niobium cavity is made of many components obtained by deep drawing or spinning of metal sheets and then welded with electron beam welding (EBW) technology. The jacket, made of Titanium grade 2, is also obtained from metal sheets which are Tungsten inert gas (TIG) welded. The flanges, made by Ti45Nb alloy, are the interfaces at which cavity and jacket are EBW welded.

The design phase combines 3D modelling and finite element method (FEM) analysis with the software Ansys [12] in an iterative workflow: simulations results point out weak spot in the design, to be corrected and verified again with a new simulation. This approach defined the actual design (Fig. 2) in terms of components thickness, the need for internal reinforcements on the inner conductor, the use of round end caps for the jacket and the configuration of installation supports. Pressure during normal operations is set at 1.3 bar; 2 bar is the maximum allowed pressure during operation, while 2.9 bar is the theoretical value for Pressure Equipment Directive (PED) certification.

The whole geometry was simulated with a design pressure of 2 bar, using as acceptance criteria the value of Von Mises stresses on Niobium, to be compared with yield limit at 20° C: $\sigma < 50$ MPa. Figure 3 shows a stress distribution on the cavity: maximum values about 40 MPa on the cavity and 60 MPa on the jacket, except for one single spot at 84 MPa (Titanium yield limit at 20° C is about 270 MPa).

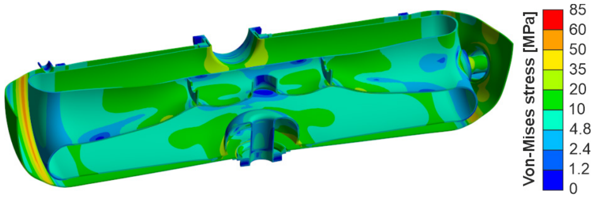

Figure 3: Stress distribution on the cavity, due to a pressure load of 2 bar.

The cavity is installed on three supports, welded on the jacket. The central one is fixed, while the others allow only translation on cylinder axis: this configuration allows cavity contraction on longitudinal axis during cooling transients, while the beam axis keeps its nominal position. The high-pressure rinsing (HPR) pipes are connected to the jacket without the use of bellows, improving reliability but causing high stress in the interface between pipes and torus. For this reason, currently the HPR pipes are the only components made from bulk Nb. Alternative solutions to overcome this limitation are under investigation in an ongoing study by INFN.

After the mechanical design was detailed, a new set of simulations was carried out, to verify cavity behaviour in all the operational phases. Stress and displacement during normal operation at 1.3 bar were verified; stress distribution during an overpressure event of 2.9 produced values over Nb yield limit but still behind rupture (properties at 20° C). Thermo-structural simulations evaluated the displacement during a warming transient from 4 K to 20°C: the deformed cavity at 20° C is the geometry to be manufactured. Cooling transient was also simulated to confront stress distribution on Nb and Ti with yield limits as function of temperature. The buckling analysis evaluated instability modes and the corresponding pressure values; a safety factor of 9 was obtained. Finally, a multiphysics workflow in Ansys, combining electromagnetic and structural analysis in collaboration with INFN-LNL, defined the change of frequency due to pressure, Lorentz force, tuning force applied on beam port flanges. This study is still ongoing, so the frequency results described in the next section were obtained with CST Studio Suite instead.

FREQUENCY SENSITIVITY

The CST multiphysics workflow combines the thermomechanical solver (to calculate the expected deformation, found to be consistent with Ansys) and the eigenmode solver (to calculate the displaced resonance frequency). Table 2 reports the results obtained for different scenarios, covering the typical phenomena expected in operation.

Table 2: Simulated frequency sensitivity in response to different causes of deformation of the cavity-jacket assembly.

Cause of deformation	Frequency variation
He pressure	-2.19 kHz/bar
Cooling to 4 K	381 kHz
Tuning mechanism	92 kHz/mm
LFD	-3.8 Hz/(MV/m)^2

First, the liquid He used to cool the cavity to the operating temperature of 4 K applies a pressure to the outer surfaces of the cavity and to the inner surfaces of the vessel. The resulting deformation was simulated for multiple values of pressure (note that the cooling is expected to take place at 2 bar to speed up the process). The resonant frequency of the structure was found to scale linearly with the pressure, as shown in Fig. 4, with a slope of -2.19 kHz/bar. This agrees with expectations, looking for example at the cavities developed for FRIB [8] which feature a similar structure but a smaller length and hence are slightly more rigid, with a sensitivity of about 2 kHz/bar. This is considered acceptable for the operation of DONES.

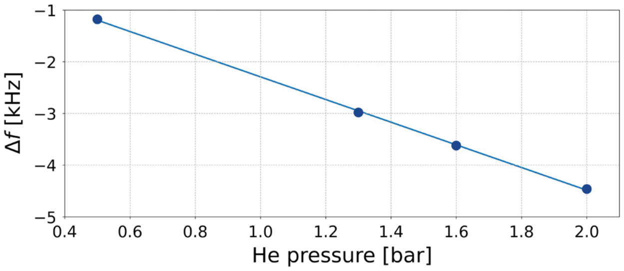

Figure 4: Simulated frequency variation for different values of He pressure.

A much bigger effect comes from the thermal contraction resulting from the cooling of the assembly from room temperature to the operating temperature of 4 K. A first estimate of the deformation assumes in first approximation a thermal expansion coefficient independent of temperature for all materials. The effect of the He pressure, assumed to be 2 bar to speed up the cooling process as described before, was accounted for in the simulation, but its effect is much smaller with respect to the thermal contraction. The deformed structure resonates at a frequency that is 381 kHz higher than the unperturbed one. It is thus imperative to keep this effect into account in the manufacturing of the resonators: the dimensions must be scaled up accordingly so that the cooled structure achieves the target resonating frequency of 175 MHz, as mentioned previously.

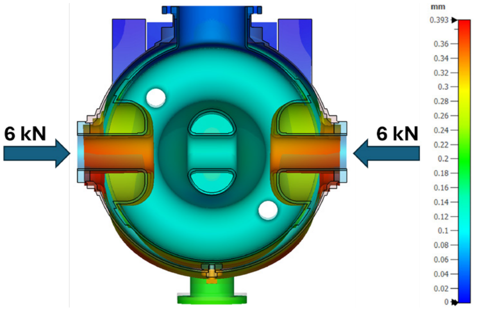

Figure 5: Section view of the deformed cavity after the application of a 6 kN force to each beam port. The displacement is scaled up by a factor 30 for better visualization. The undeformed geometry is overlayed.

To account for and react to slight shifts of the resonating frequency, which can result from small manufacturing errors or from transient phenomena during operation, a tuning system will be put in place to recover the operating frequency of 175 MHz. The system applies a pressure to the beam ports of the cavity, pushing them towards the inside of the cavity as shown in Fig. 5. The resonating frequency is thus shifted by applying a controlled, local deformation. This process was simulated by applying the same force to each beam port. The operating He pressure of 1.3 bar was also considered, though its effect is once again of second order. The frequency variation and the shortening of the flange-to-flange distance due to the applied force follow a linear correlation, as shown in Fig. 6, with a slope of 92 kHz/mm. A force of 8.57 kN is needed to reduce the flange-to-flange distance by 1 mm. This is considered satisfactory for the expected operational needs.

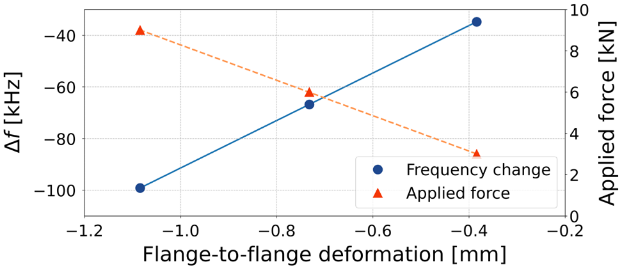

Figure 6: Simulated frequency sensitivity and stiffness resulting with respect to the tuning process.

Finally, the Lorentz force detuning (LFD), i.e. the effect of the pressure applied by the electromagnetic field generated inside the cavity onto the cavity itself, was estimated to be -3.8 Hz/(MV/m)^2, acceptable for this kind of cavity.

CONCLUSIONS AND OUTLOOK

A new design for the high-β half-wave resonators of IFMIF-DONES has been proposed by INFN-LNL and INFN-Torino. The model was built in a multiphysics optimization approach and respects the electromagnetic and mechanical requirements for operational use. The frequency sensitivity to the deformation caused by different processes was estimated. The results agree with expectations coming from the behaviour of similar structures and are deemed acceptable. It is planned to proceed with the construction and testing of two prototypes, before moving on with the full-scale production.

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