

DESIGN STUDY OF A 176 MHz SRF HALF WAVE RESONATOR FOR THE SPIRAL-2 PROJECT

J-L. Biarrotte*, S. Blivet, S. Bousson, T. Junquera, G. Olry, H. Saugnac

CNRS / IN2P3 / IPN Orsay, France

Abstract

In November 2002, the decision was taken to prepare an R&D program to study and develop the superconducting resonators (QWR and HWR) proposed for the Spiral 2 project. In this context, IPN Orsay started the design study of a 176 MHz $\beta=0.14$ half-wave SRF cavity and its integration in a cryomodule, in close connection with the requirements coming from the beam dynamics along the Spiral-2 superconducting linac. The final aim is to build and test a first HWR prototype before summer 2004. The main results of this on-going study are presented here.

adopted: 88 MHz for the low beta section ($\beta=0.07$), and 176 MHz for the high beta section ($\beta=0.14$).

In parallel, a R&D program was started to study and develop the superconducting resonators (quarter-wave and half-wave resonators) proposed for the SPIRAL-2 project, and to build two first prototypes at 176 MHz, $\beta=0.14$: one QWR [2], and one HWR, in order to compare directly the performances of both kind of resonators. In this context, IPN Orsay started the design study of a 176 MHz, $\beta=0.14$ half wave resonator and of its associated ancillaries and cryomodule.

INTRODUCTION

A two years detailed study on a new ISOL-type facility for the production of high intensity exotic beams at GANIL (SPIRAL-2 project) has been recently launched in France. The driver accelerator has to accelerate 5 mA deuterons up to 20 MeV/u, 1 mA ions of mass-to-charge ratio $A/q=3$ up to 14.5 MeV/u, and even higher A/q ions (up to 6) in a later stage.

Due to its modularity and the high beam power, the linac solution was chosen [1]. Figure 1 shows the schematic layout of the driver in the present phase of the project. A first injector includes two ECR sources (for deuterons and $A/q=3$ ions), the associated LEBT, and a common RFQ cavity. A second injector for injecting higher A/q ions is also planned to be connected into the MEBT. The beam is then accelerated up to a total energy of more than 40 MeV by independently phased superconducting resonators, providing a safe CW operation and a high flexibility in the acceleration of different ion species and charge-to-mass ratios.

HALF WAVE RESONATOR DESIGN

There is only a very small number of existing prototypes of half-wave resonators. A first result was obtained by the ANL group in 1991 [3], and more recently, a very good result was obtained at MSU [4] with a 322 MHz HWR prototype for the RIA project. Several new developments are also presently underway since a few years for a use in light ions high-intensity linac projects (COSY in Juelich, RIA in Argonne, SPES in Legnaro...). Actually, a major advantage of the HWR for this kind of application is that, unlike the QWR, the cavity does not present any beam steering effect: thanks to the intrinsic field symmetry, there is no deflecting magnetic or electric field in the beam axis region.

Preliminary approach

The design of such a resonator consists in reaching a reasonable compromise between optimal electromagnetic performances, acceptable mechanical characteristics, and ease of fabrication and preparation.

Our first goal in this cavity design was to optimise the RF properties of the resonator, i.e. maximize the energy gain per cavity, while maintaining the electric and magnetic peak surface fields E_{pk} and B_{pk} below reasonable values (respectively 40 MV/m and 80 mT).

First calculations were made using a standard shape HWR, with cylindrical inner and outer conductors. It appeared that choosing a ratio of 1/3 between the inner conductor and the outer conductor diameters allows reaching a good compromise between low peak field values and high accelerating fields. Figure 2 shows the evolution of the E_{pk}/E_{acc} and B_{pk}/E_{acc} parameters for 176 MHz, $\beta=0.14$ cavities with different diameter ratios. Note that we use a definition of the accelerating field value E_{acc} calculated at the optimal beta (here, $\beta=0.14$) and normalised to the accelerating length $L_{acc}=\beta\lambda$.

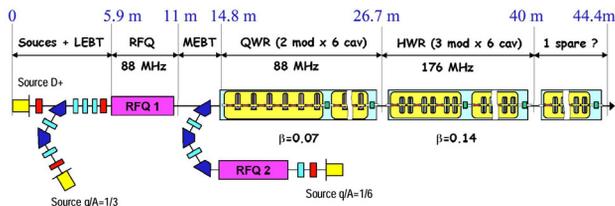


Figure 1: Architecture of the Spiral-2 driver linac.

In March 2003, after a preliminary phase of linac design including detailed beam dynamics calculation, the choice of the superconducting linac frequencies was

* biarrott@ipno.in2p3.fr

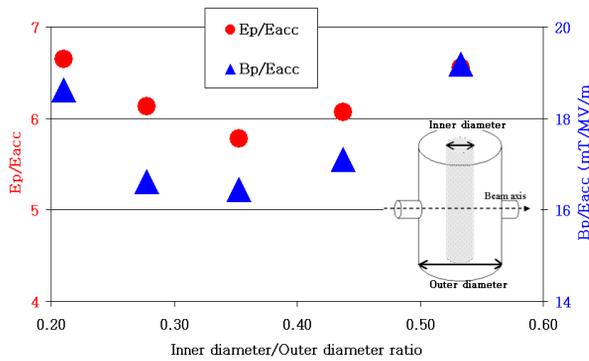


Figure 2: Optimisation of the cavity inner over outer diameter ratio.

Optimisation in the electric field region

The next step in the design optimisation was the study of the electric field region situated around the beam axis. A racetrack shape in this zone for the inner and outer conductors is favourable compared with a basic cylindrical shape.

First of all, concerning the inner conductor, a racetrack shape in the beam axis region allows to reach a better distribution of the surface electric fields, and thus to minimize the electric field peak value E_{pk} as well as the ratio E_{pk}/E_{acc} .

Concerning the outer conductor, the same racetrack shape is also interesting for two main reasons. The first one is that such a shape in the beam axis region increases the mechanical tuning range of the cavity. The second one is that it minimizes the quadrupole fields' asymmetry around the beam axis, that could otherwise imply serious emittance growth since the linac lattice includes transverse focusing by solenoids [5]. Figure 3 shows the electric focusing electric fields profile along the beam axis (5mm off axis) in a HWR with a cylindrical shape (left) and in a HWR with a racetrack shape (right).

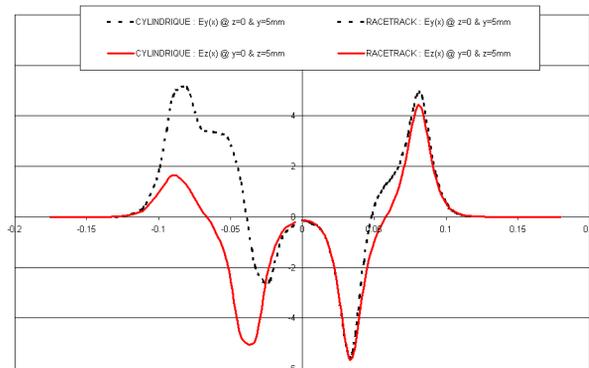


Figure 3: Transverse electric fields E_y (black dot curve) and E_z (red curve) along the x beam axis (5 mm off axis). Left: cylindrical shape. Right: racetrack shape.

For the inner conductor, this racetrack shape is achieved by simply squeezing with a forging press the centre part of the cylinder. For the outer conductor, two different solutions were analysed (see Figure 4). The first

one uses the same squeezing method (“Juelich-type” [6]), whereas the second one consists in adding a spherical-like re-entrant shape at the beam port position (“Argonne-type” [7]). Whereas no significant difference was found between these two models concerning the RF properties, the mechanical parameters are very different. The “Juelich-type” cavity has the advantage to have a higher tuning sensitivity (about twice the “Argonne-type” cavity’s one), but the drawback of a quite low mechanical stiffness (about 3 times less than the “Argonne-type” cavity’s one).

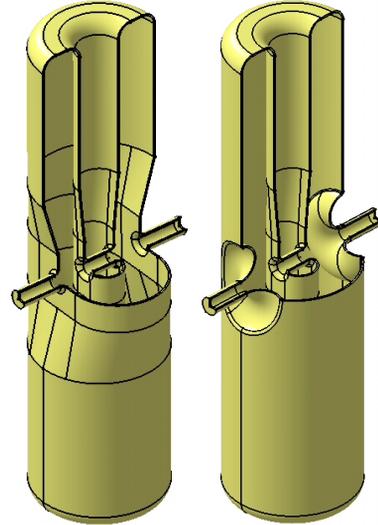


Figure 4: “Juelich-type” (left) and “Argonne-type” (right) HWR models.

For our SPIRAL-2 prototype, we finally chose an electric field region’s shape as showed on Figure 5. The outer conductor is an optimised compromise between the two above shapes, that maximizes the mechanical stability of the cavity (and especially decrease the helium bath pressure variations effects), while keeping a good mechanical tuning range to cope with manufacturing and cool down processes uncertainties.

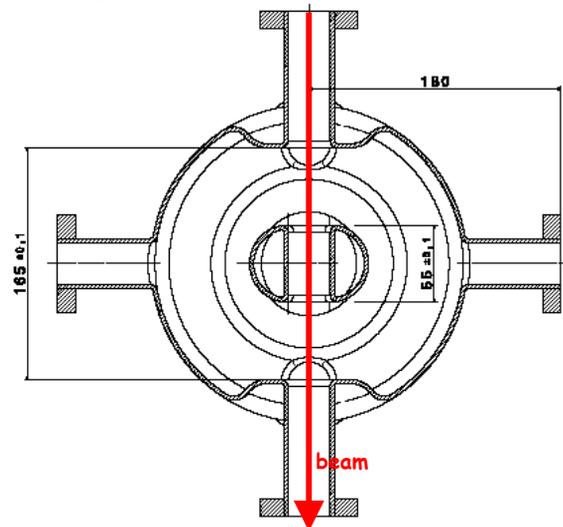


Figure 5: Horizontal cut view of the final HWR prototype in the beam axis region.

The two beam ports are 30 mm diameter, such as the pick-up and power coupler ports, which are positioned in this beam axis region to ensure the required coupling value (by electrical coupling) while avoiding possible embarrassing dissipations due to the presence of magnetic field.

Optimisation in the magnetic field region

The cavity design was finally achieved by optimising the magnetic field region. This is made by using an inner conductor with a conical shape that allows to more evenly distribute the magnetic field value along the bar, and to reduce the B_{pk}/E_{acc} ratio. Note anyway that such a shape leads to increase the total cryogenic losses on the cavity walls, and, on the mechanical point of view, to decrease the tuning sensitivity of the cavity since the magnetic fields comes nearer to the beam axis, i.e. to the tuning area. Here again, a compromise has to be found between an acceptable tuning sensitivity, acceptable RF losses and a minimized peak magnetic field value.

The final shape of the cavity is showed on Figure 6. Four ports have been added for the needs of the cavity preparation (chemistry + high pressure rinsing).

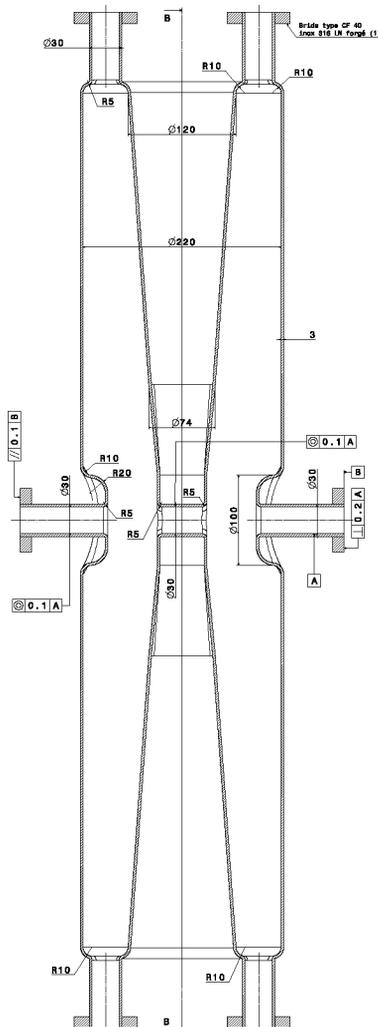


Figure 6: Vertical cut view of the final HWR prototype.

Main characteristics

The main characteristics of the optimised cavity are summarized in Table 1.

During all the design study, RF calculations were performed using models imported from the CATIA software into the MAFIA 3D code, and always using the same mesh size (2 mm) in order to allow a precise comparison between each model. Mechanical simulations were performed with the COSMOS/Geostar FEM code, with models also imported from CATIA. The tuning sensitivity was computed using the MICAV module integrated in Geostar.

Table 1: SPIRAL-2 HWR performances

Frequency	175.92 MHz
Optimal β	0.14
Cavity diameter	0.22 m
Beam aperture	30 mm
$L_{acc} = \beta\lambda$	0.24 m
E_{pk}/E_{acc}	4.71
B_{pk}/E_{acc}	9.89 mT/(MV/m)
E_{acc} @ 80mT	8.1 MV/m
V_{acc} @ 80mT	1.94 MV
$R/Q (=V_{acc}^2/\omega U)$	221 Ω
$G = R_s.Q_0$	40 Ω
Q_0 @ 4K ($R_{res}=20$ n Ω)	1.3×10^9
Dissipated power @ 4K	12.8 W @ 8MV/m 8.5 W @ 6.5MV/m
Niobium thickness	3 mm
Cavity stiffness along beam axis	2000 N/mm
VM stress under vacuum load (with 1 free end beam tube)	<16 MPa
Tuning sensitivity (to be checked)	26 kHz/mm

Thanks to this optimisation process, the accelerating field performed by the cavity at $B_{pk}=80$ mT has increased from 5 MV/m (basic HWR shape) to more than 8 MV/m, which was the initial goal of the study.

Nevertheless, one has to note that an operating accelerating field of only 6.5 MV/m is presently used for the SPIRAL-2 linac design purpose. This choice allows to keep a certain margin on the achievable peak fields (the operation goal becomes 65 mT and 30 MV/m instead of 80 mT and 38 MV/m), and to allow an eventual increase of the $\varnothing 30$ beam tube openings if needed.

CRYOMODULE DESIGN

Cavity ancillaries

The HWR cavity will be equipped with a stainless steel helium tank, a power coupler, and a cold tuning system.

Figure 7 shows a preliminary view of the 10 kW power coupler, which is under study at the LPSC Grenoble laboratory.

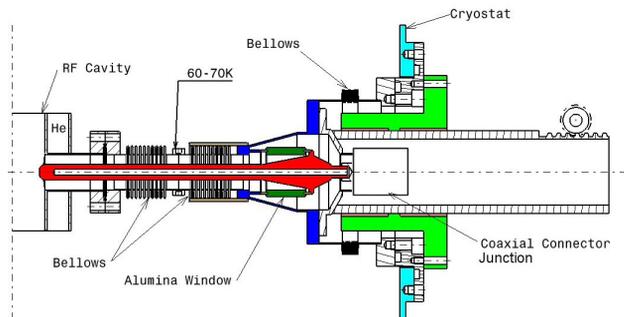


Figure 7: Coupler structure (courtesy of LPSC Grenoble).

Figure 8 shows the conceptual design of the cold tuning system (CTS), based on the pantograph principle. The stepping motor, the screw/bolt mechanism and piezo actuators are placed outside the cryostat in order to increase the reliability by avoiding operating this fragile system at low temperature.

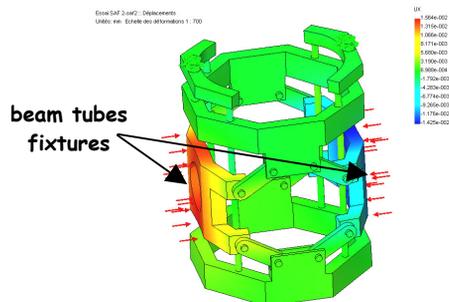


Figure 8: HWR cold tuning system.

The goal for the tuner design is especially to be able to stay inside the frequency bandwidth of the cavity despite any perturbation, so as to avoid using a dynamic cold tuning system. First calculations show for example that frequency fluctuations corresponding to 20 mbar pressure variations on the 1 bar helium bath will stay within the cavity bandwidth only if the CTS stiffness is at least 15 kN/mm. Moreover, in order to correct the uncertainties of the different fabrication and installation procedures (forming, welding, etching, cooling down...), the CTS must be able to perform a total displacement range which is for the moment estimated to ± 2 mm, leading to a tuning range of around ± 50 kHz.

Cryomodule concept

Each HWR cryomodule contains 6 cavities and 3 SC solenoids spaced with lengths as short as possible, according to the beam dynamics requirements.

The HWR cryomodule is based on the separated vacuum concept. This choice offers a warranty on the

cavity (and coupler) preparation quality (surface cleanliness), which is absolutely mandatory to reach the high peak surface fields foreseen in the HWR cavities.

Resonators and solenoids are first aligned and fixed on a stiff frame ("cavity string") inside the clean room. The beam vacuum (cavities, solenoid, and power coupler up to the warm window) is pumped and closed with two extremities valves. All the RF surfaces are thus totally protected from contamination when the cavity frame is outside the clean room. Figure 9 shows the case where 2 cavities are mounted per cavity string, but another option could be to have the all-6 cavities on a single cavity string. The final choice will depend on the alignment procedure study, which is presently underway.

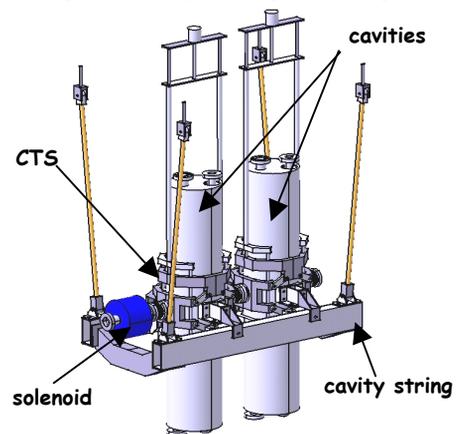


Figure 9: HWR cavity string.

The cavity string is then introduced into the vacuum vessel by its axis, and fixed to epoxy-glass antagonist rods allowing to maintain constant the cavity string axis position after cool down. Warm parts of the power coupler, tuner, beam pipes and cryogenic tubing are then connected to the cryostat vacuum vessel.

Figure 10 shows a scheme of the whole cryomodule. The total length is about 3.4 m from valve to valve, and the tank diameter is 1.5 m. Each cryomodule will be fed with 4K and 60K helium from only one cold box, allowing more compliance for maintenance operations. The fluid lines will be connected to the cryomodule with bayonet joints.

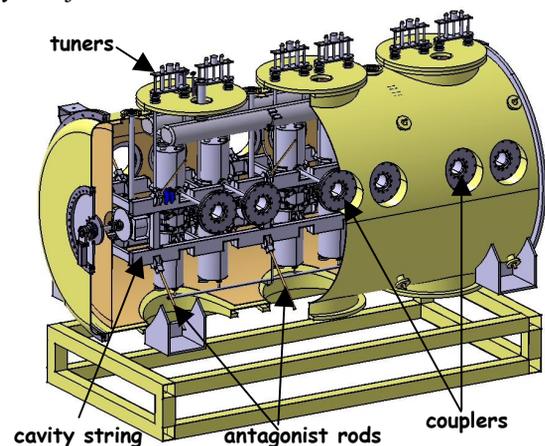


Figure 10: HWR cryomodule.

Beam dynamics considerations

Four 176 MHz, $\beta=0.14$ HWR cryomodules (i.e. 24 cavities) are needed for the high-energy section of the SPIRAL-2 linac. This result directly comes from the linac optimisation study, which consisted in finding the best linac architecture, giving both fine beam dynamics characteristics and short linac length.

In each cryomodule, a (011) period is used, where 0 is a SC solenoid and 1 a SC cavity, because this lattice ensures a good efficiency of the cavities for this range of β . As a comparison, a (01) period is used in the low energy 88 MHz, $\beta=0.07$ QWR family, where the beam is more difficult to focus.

In order to make the beam dynamics easier and more efficient, the distances between elements have to be as small as possible. The most critical length appears to be the warm transition between two cryomodules: if this distance is too long, the beam is not focused enough in the longitudinal plane due to the de-bunching effect in the drift space, which is especially critical at low energy.

Beam dynamics simulations have been made to try to quantify this effect. They show that a beam halo (and then beam losses) quickly appears when increasing the inter-module length, as shown on Figure 11. The situation could be even worse in the reality since these calculations were made with “ideal” 6D waterbag beam distributions at the linac input, and without using the cavities 3D field maps.

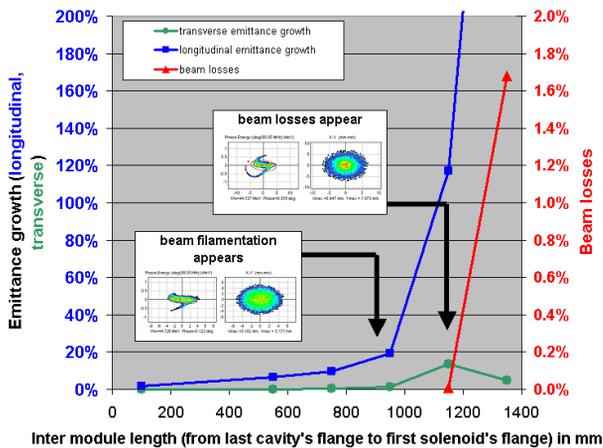


Figure 11: Impact of the inter-module length on the emittance growth and on the beam losses.

To safely manage this warm transition, the actual specifications imposed by the beam dynamics studies thus lead to very short inter-modules of 550 mm from the last cavity of a module to the first solenoid of the subsequent module. The useful length of the warm section, where a diagnostic box and all the vacuum connections have to be inserted, is even shorter (<350 mm), as shown in Figure 12. Thorough studies are underway to evaluate the technological feasibility of such a solution.

A possible back-up solution would consist in changing the linac main architecture, using small cryomodules containing only one (or two) cavity, alternated with warm

quadrupoles doublets for the transverse focusing instead of SC solenoids (see Figure 13). This modular scheme leads in a – not that much – longer linac, and is very attractive for several reasons: smoother beam behaviour (mainly because of the FDO lattice regularity), high modularity, simpler technological challenge, etc., for a similar cost. This back-up solution, that also preferentially uses 88 MHz QWR cavities only, is presently considered as a serious candidate by the SPIRAL-2 team project to replace the actual reference solution shown in Figure 1.

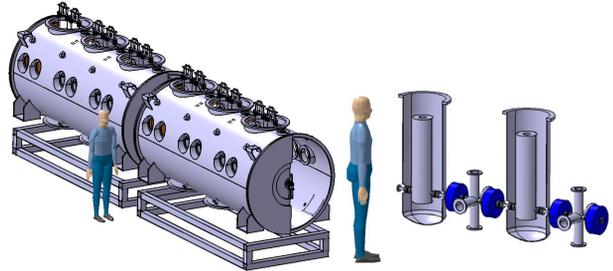


Figure 12 (left): View of two subsequent cryomodules in the reference design using SC solenoids.

Figure 13 (right): View of two subsequent cryomodules in the new alternative design using warm focusing.

CONCLUSION

The complete design study of a 176 MHz $\beta=0.14$ HWR cavity for the SPIRAL-2 project is now nearly achieved. The construction of a first prototype is about to be launched, for a cold test at IPN Orsay before summer 2004. The final decision to build such a prototype should be taken before end September 2003, depending on the final choice for the SPIRAL-2 linac architecture, as mentioned here above.

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