Low- and intermediate-β, 352 MHz superconducting half-wave resonators for high power hadron acceleration

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Two prototypes of superconducting, 352 MHz coaxial half-wave resonators with $\beta = 0.17$ and $\beta = 0.31$ have been designed, constructed, and tested at INFN-LNL, in the framework of the SPES and EURISOL DS projects. Main features of these double-wall, 2-gap structures are compactness, mechanical stability, and easy installation in different kinds of cryostats. Their acceleration capabilities are similar to the ones of Spoke resonators with similar β. These cavities are being developed for acceleration of high power hadron beams in the 5–100 MeV/u energy range.

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I. INTRODUCTION

Superconducting coaxial half-wave resonators (HWRs), first proposed and prototyped in the early 1990s [1], have been recently rediscovered as a steering-free alternative to quarter-wave resonators (QWR) [2]. HWRs show their optimum application range for frequencies of ~150–350 MHz and for beam velocities of $\sim 0.06 < \beta < 0.4$, where they can prevail in some aspects over other, more popular, resonator geometries. On the low frequency side, compared to the more compact QWRs, the main advantage of HWRs is the absence of vertical beam steering [3] which can introduce beam losses in high power beams. On the other side of the range, around 352 MHz [the most common frequency in high power proton radio frequency quadrupole resonators (RFQs)], HWRs can be made with very compact size and relatively low cost, making them a possible alternative to Spoke cavities [4] for filling the gap between RFQs and multicell (spoke or elliptical) superconducting cavities in high power linacs.

The program in superconducting HWR development at Laboratori Nazionali di Legnaro [5] includes 352 MHz cavities with $\beta = 0.17$ and 0.31 (and eventually 176 MHz HWRs with $\beta = 0.09$ and 0.15), with similar design and components to reduce the fabrication cost and risk; this plan resembles the QWR development program previously pursued at INFN-LNL [6]. The development started in the framework of the SPES project for 5 mA cw proton and deuteron beams up to 100 MeV, and it is presently continuing in the EURISOL-DS one [7]. These resonators could be used also in radioactive beam postaccelerators. The first prototype with $\beta = 0.31$ was constructed and tested in 2004 [8]. The second one, $\beta = 0.17$, was tested this year.

II. RESONATORS CHARACTERISTICS

A. Mechanical design

The INFN-LNL HWRs (Fig. 1) are characterized by a double-wall coaxial structure terminated by thick plates, with integrated helium vessel [9]. This makes them very compact and stiff, even if the resonators are made in a large part of 2 mm thick Nb sheets. The cavities are of 2 types, "flattened" and "cylindrical," named after their inner conductors' shapes (see Fig. 2), with maximum physical lengths along the beam axis of 232 and 286 mm, respectively. The beam port aperture diameter is 30 mm, as specified by the beam dynamics calculations of the related linac projects (a significant increase of this value, if needed, would require increasing of the resonator's size).

A $1\frac{5}{8}$-inch port for a coaxial rf coupler is located at the resonator's equator, at one side of the outer conductor. According to the rf power requirements, a larger coupling port up to $3\frac{1}{8}$-inch could be implemented in the same design without major difficulties. Two more, 16 mm ports are available for rf probes. The rf port's position was chosen also in order to facilitate chemical polishing. These resonators are designed for cryostats which have in common the rf-beam volume and the one required for thermal isolation, included in only one vacuum system; all ports, however, are equipped with flanges that allow for use in cryostats with vacuum separation.

A tuning cup (Fig. 3) is welded to the outer conductor, at the opposite side from the coupler. To improve the frequency stability against pressure fluctuations, the membrane which provides tuning is cooled by thermal con-

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FIG. 1. The INFN-LNL low-β (left) and medium-β 352 MHz superconducting half-wave resonators.

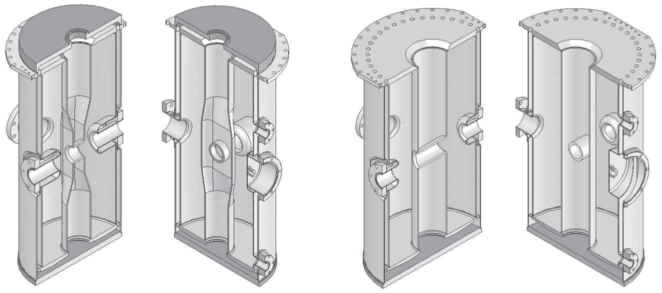

FIG. 2. Sketches of the 352 MHz, $\beta_0 = 0.17$ (left) and $\beta_0 = 0.31$ half-wave resonators, cut in two perpendicular planes.

FIG. 3. Detail of the tuning cup before welding.

duction and is not exposed to liquid helium. Differently from Spoke and other HWR cavities, this tuner is decoupled from the beam ports and its force requirements could be significantly reduced. The beam ports and the rf ports flanges are made of NbTi, as well as the outer flange of the tuning cup where a tuning mechanism can be easily mounted. A drawback of this system, still under development, is the limited tuning range (below 100 kHz at present) that requires a very precise cavity construction.

The top flange connects the cavity to the helium reservoir through a conflat flange. In the older $\beta = 0.31$ cavity, like in many double-wall QWRs, this flange is made of AISI304 stainless steel and is connected to the cavity by means of an indium seal and screws. In the newer, $\beta = 0.17$ unit, the flange is made of Ti (with a brazed stainless steel conflat flange) and it is welded to the cavity. This makes the resonator a single piece of equipment, connected to the cryogenic system only through the conflat flange. This modification simplifies considerably the resonator assembly in the cryostat, and will be extended also to the $\beta = 0.31$ HWR design.

B. Electromagnetic design

The resonators rf parameters, calculated with the HFSS code, are shown in Table I. The E_p/E_a and B_p/E_a values are not far from the ones of the LNL QWRs working at lower frequency. Different conventions are used to define the active resonator length L_{ac} required for gradient calculation (see Fig. 4). We have used $L_{\max}$, the maximum space occupied by the electromagnetic field along the beam axis (except for the field decaying to zero along the beam port tubes); L_{ac} so defined is usually close to the resonator physical length along the beam axis L_{re} (~ 78% in the LNL HWRs). In HWRs, L_{ac} coincides with the outer conductor inner diameter. In Spoke cavities, the usual definition of active length (“Spoke definition” from now on) is the minimum distance between the beam ports (L_{int} in the figure). Although the two definitions of L_{ac} are perfectly equivalent from the operational point of view, it should be noted that the second one can be significantly lower than L_{re} (e.g. 39% in the low-β HWR described

TABLE I. Resonators parameters.

β_0	0.17	0.31	
$U/{E_a}^2$	0.067	0.086	$\mathrm{J/(MV/m)^2}$
B_p/E_a	12	10.4	mT/(MV/m)
E_p/E_a	5.8	3.9	
R_{sh}/Q_0	1230	1180	Ω/m
$R_s \times Q_0$	55	66	Ω
Tuning df/dh	~70	~107	kHz/mm
Active length L_{ac}	180	224	mm
Maximum Length L_{re}	232	286	mm
Aperture a	30	30	mm
Design E_a	5	6	MV/m

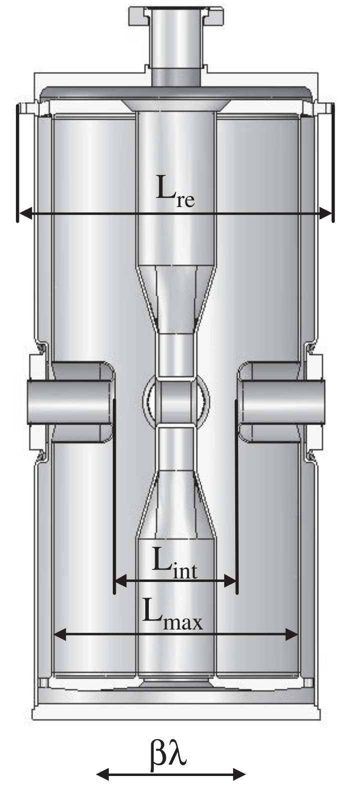

FIG. 4. Different definitions (L_{int}, L_{max}, and $\beta\lambda$) in use for L_{ac}, the resonator active length, sketched in a low-β HWR schematic. L_{re} represents the maximum physical length of the resonators along the beam axis.

here). Some authors use also $L_{\mathrm{ac}} = \beta\lambda$, where β is the resonator optimum velocity; $\beta\lambda$ is usually between L_{int} and L_{max}.

The design gradient in operation at 4.2 K was set at 5 and 6 MV/m (10 and 7.7 MV/m with the Spoke definition) for the low- and medium-β units, respectively, with 10 W rf power. This gives 0.9 and 1.34 MeV/q energy gain, respectively. The specified maximum surface fields in operation are $B_p \sim 62$ mT and $E_p \leq 30$ MV/m, reliably achievable according to the available statistics in cavities of similar frequency and β.

The accelerating field profile was an important part of our calculations. While the HWR symmetry prevents vertical beam steering, we had to take into account the effect of the side tuner, that could cause horizontal steering, and the one of the quadrupolar symmetry that could cause unwanted quadrupolar focusing-defocusing. Similarly to rf defocusing, these effects are a function of the particle velocity and phase. We have compared these data at -30 deg synchronous phase, at the specified operation gradient and in the useful β range.

We found that the side tuner steering, at operation ϕ, β, and E_a, is weak compared to rf defocusing and negligible in the low-β resonator (Fig. 5). The quadrupole steering is below 0.03 mrad, considerably weaker than natural rf defocusing especially at low velocity, where the beam dynamics is more demanding. In the medium-β HWR, the rf defocusing itself can be used to compensate tuner steering within 0.01 mrad by simply displacing the cavity 0.4 mm aside (Fig. 6).

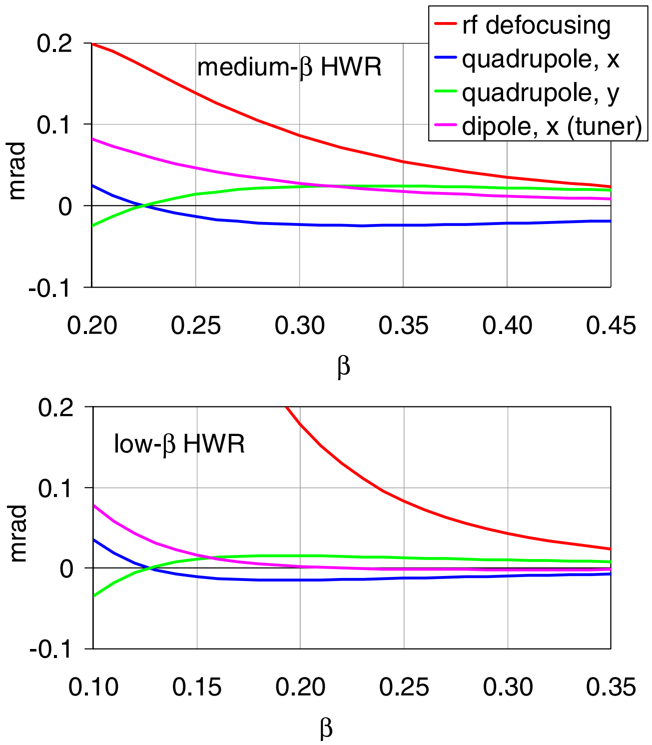

FIG. 5. (Color) Beam steering (without compensation) and rf defocusing vs β in the low- and medium-β cavities, at operation gradient and $-30°$ synchronous phase.

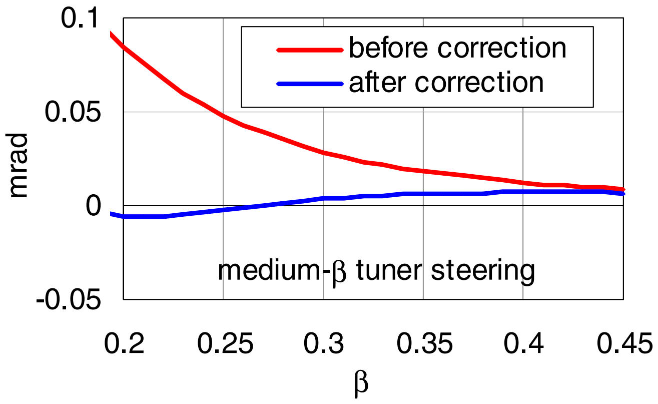

FIG. 6. (Color) Tuner horizontal beam steering compensation in the medium-β cavity. Steering (mrad) vs β. Blue line: on axis; red line: 0.4 mm off axis.

III. RESONATOR CONSTRUCTION AND TESTING

The construction includes a first preliminary tuning by means of cavity length adjustment; this requires an inter-

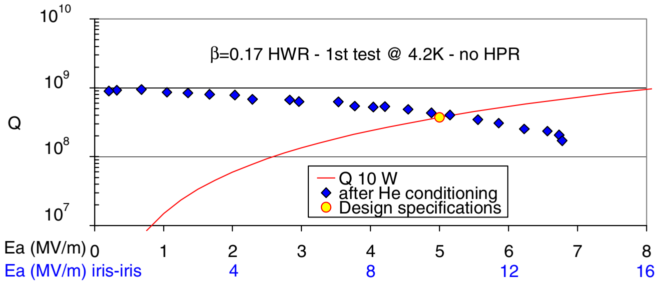

FIG. 7. (Color) Low-β HWR performance at 4.2 K. Active length 180 mm (90 mm with the Spoke definition, corresponding to the gradient $E_{\mathrm{a\ iris\text{-}iris}}$).

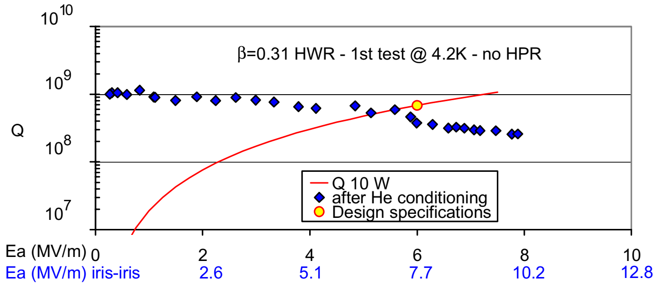

FIG. 8. (Color) Medium-β HWR performance at 4.2 K. Active length 224 mm (175 mm with the Spoke definition, corresponding to the gradient $E_{\mathrm{a\ iris\text{-}iris}}$).

mediate frequency test of the cavity, assembled but not welded yet. After welding all resonator parts exposed to rf, except for the tuning cup, visual inspections of the rf surface are possible through the cup aperture. This allows also limited access and, if necessary, further surface finishing. The final frequency adjustment is done by welding the tuning cup in the proper position.

Both cavities have been constructed in Italy, in 2003 (medium-β) and in 2005 (low-β). The final chemical polishing was done at CERN. The resonators were tested at 4.2 K at INFN-Legnaro before any further surface treatment; the test results are shown in Figs. 7 and 8. Further testing is planned after high pressure water rinsing (HPR) of both resonators; this treatment is expected to reduce field emission and improve Q at high gradient.

A. Medium-β cavity test at 4.2 K

The medium-β resonator was tested at 4.2 K in 2004 [8]. It showed multipacting (MP) around $E_a \sim 0.17$ MV/m, that could be easily conditioned with a few watts rf power. The low-power Q was 9.1×10^8, corresponding to a residual resistance $R_{\mathrm{res}} \sim 21$ nΩ. The maximum gradient reached during the test was 7.9 MV/m (10.1 MV/m with the Spoke definition), and the maximum surface fields were $E_p \sim 31$ MV/m and $B_p \sim 82$ mT, limited by quench. The accelerating field at the nominal 10 W rf power was 5.6 MV/m, corresponding to $\sim$1.25 MeV/q acceleration, about 7% below the design specifications. Because of improper dimensioning of the old coupler, however, we could apply only little rf and helium conditioning during the test, since most of the power was reflected back to the rf source. The resonator could withstand 45 W before quenching.

B. Low-β cavity test at 4.2 K

The low-β resonator was tested in 2006. A new low-power, $1\frac{5}{8}$-inch movable coaxial coupler was mounted at the coupler port to eliminate the difficulties encountered with the previous HWR. In spite of the tight geometry, no significant multipacting (MP) was detected, neither at room temperature nor at 4.2 K. We have done relatively fast cooldown, crossing the 150–60 K region with most of the resonator within about 1 h.

The measured low-power Q was 7.9×10^8 ($R_{\mathrm{res}} \sim 30$ nΩ). The nominal 5 MV/m field was reached with the nominal 10 W power after 2 hours helium conditioning with $\sim$150 W. The maximum gradient was $E_a = 6.8$ MV/m (13.6 MV/m with the Spoke definition), limited by quench above 40 W rf power. The maximum peak fields were $E_p \sim 39$ MV/m and $B_p \sim 81$ mT. The resonator was very stable against He pressure (-4.3 Hz/mbar) and Lorentz force [-8 Hz/(MV/m)^2] with the tuner membrane left free. The low-β resonator performance reached the design specifications.

IV. POSSIBLE APPLICATION AND COMPARISON WITH OTHER GEOMETRIES

Coaxial HWRs at the frequency of 352 MHz partly share with Spoke cavities the same range of applications. Compared to Spoke cavities, coaxial HWRs have in general a smaller size: while the length along the inner conductor is $\sim\lambda/2$ for both geometries, the width at the equator of HWRs can be significantly less than that. This results in a reduced volume, a more compact mechanical structure, and the possibility to mount a small size tuner at the resonator side, removing the need of a beam port tuner which increases the resonators length L_{re}.

Spoke cavities, on the other hand, can be built with more than 2 gaps, larger aperture, and larger geometrical factor $\Gamma = Q \times R_s$; these characteristics become increasingly important at higher β. In the range $0.1 < \beta < 0.4$, however, the smaller size of HWRs and their easy assembly procedure can result in cost reduction of the linac. In Table II we compare energy gain per unit charge in operation (V_{acc}) calculated for typical 352 MHz, 2-gap Spoke and HWR resonators with similar optimum β. To make the comparison independent from the niobium surface characteristics, which largely depend on the surface treatment, we have normalized the values to the same maximum magnetic surface field B_p (which appears to put the main physical limits to cavity operation) and to the same surface

TABLE II. Main rf parameters and dimensions in typical 352 MHz coaxial HWR and 2-gap Spoke resonators with similar optimum β, calculated from data available in literature. To compare different geometries and L_{ac} definitions, V_{acc}, P_{rf}, and E_p have been normalized to the following specified working conditions: (1) $B_p = 62$ mT and $R_s = 96.4$ nΩ.

	Low-β			Medium-β		
Resonator type	HWR	Spoke [10]	Spoke [11]	HWR	Spoke [12]	Spoke [11]
β optimum	0.17	0.21	0.18	0.31	0.29	0.35
Aperture (mm)	30	50	50	30	25	60
L_{re} (mm)	232	286	385	286	303	450
L_{ac} (mm)	180	99	85	224	187	200
L_{ac} definition	L_{max}	L_{in}	$\beta\lambda$	L_{max}	L_{in}	$\beta\lambda$
U/E_a^2[mJ/(MV/m)^2]	67	39	21	86	51	71
$\Gamma = R_s \times Q$ (Ω)	55	64	72	66	71	101
V_{acc} (MV) (1)	0.93	0.83	0.69	1.34	1.21	1.50
P_{rf} (W) (1)	6.9	9.2	4.1	9.9	7.2	8.4
E_p (MV/m) (1)	30	21	29	23	29	23

resistance R_s. Radio frequency power dissipated P_{rf} and maximum electric surface field E_p are also shown for the same B_p. We have chosen the medium-β HWR specified working conditions, but the relative results are of course independent from this arbitrary choice.

We can observe that the energy gain that can be expected in HWRs is comparable to the one expected for typical SPOKE cavities. Taking into account the role which is played by the beam port aperture, whenever 2-gap, 352 MHz cavities are required and compactness is an important parameter, the coaxial HWR geometry could be used without loss of performance.

V. CONCLUSIONS

The 352 MHz, $\beta = 0.17$ and $\beta = 0.31$ HWRs developed at INFN-LNL have small size and short physical length along the beam direction, easy handling and preparation, good mechanical characteristics. They can be installed in different kinds of cryostats, with either common or separate vacuum. They show little or no multipacting and, in spite of their compactness, they can have nearly equivalent acceleration capabilities of 2-gap Spoke resonators of similar β. The side tuner solution decouples the tuning membrane from helium pressure fluctuations; further increase of the cavity tuning range, desirable to relax construction tolerance, will be subject of future research and development work. The rf parameters and the first test results at 4.2 K, although performed without high pressure rinsing of the resonators rf surfaces, show that HWRs could be profitably used for the first part of high power, cw proton and hadron linacs.

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