QUARTER-WAVE CAVITIES FOR THE SPIRAL 2 PROJECT

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Abstract

Spiral 2 is the next accelerator project at GANIL. It consists of a CW superconducting linac accelerating a 5 mA deuterons beam up to 40 MeV, and a target/source system for production of rare isotopes. In addition, the linac is able to accelerate a 1 mA ion beam with q/A = 1/3 up to 14.4 MeV/u. The superconducting accelerating part of the linac is a combination of two β families of quarter-wave and/or half-wave resonators. The RF base frequency is 88 MHz for the lower energy part and 176 MHz for the high energy section. A design with a high energy part at 88 MHz is also evaluated. We review the RF optimisation and properties of the quarter-wave resonators for the different beta and frequency families. The mechanical aspects related to the frequency stability of the cavities, namely helium pressure effects and tunability have been studied using coupled RF and structural 3D codes.

INTRODUCTION

The superconducting linac of Spiral 2 [1] accelerates a 5 mA deuteron beam from 2.5 MeV at the RFQ exit up to 40 Mev, thus covering a large span of reduced velocity, from 0.04 to 0.2. For the sake of efficiency, independently phased cavities with a small number of accelerating gaps have to be used. Quarter-wave (QWR) or half-wave (HWR) resonators are the cavities of choice for this purpose, and have been adopted in a large number of existing (QWR only) or proposed machines [3, 4]. The operation temperature is 4 K, RF frequencies 88 or 176 MHz and the cavities are in bulk niobium. The linac design leads to the definition of two β families for cavities [2]. The design options are summarized in table 1, where β_{opt} is the reduced velocity of the ions at which the transit time factor of the cavity is maximum.

linac A	88 MHz β_{opt}=0.07	176 MHz β_{opt}=0.14
linac B	88 MHz β_{opt}=0.07	88 MHz β_{opt}=0.12

Table 1: Cavity families

In various laboratories, a large number of elliptic SC cavities have reached routinely peak electric surface field (E_{pk}) ratings of 40 MV/m without field emission provided they were high pressure rinsed and prepared in clean room conditions. This rating of 40 MV/m has been chosen as the design limit of the peak field for the QRWs. The peak magnetic field (B_{pk}) upper limit is fixed at 80 mT. The maximum design gradient was chosen initially at 8 MV/m which sets the upper limit for the E_{pk}/E_{acc} ratio at 5 and the maximum value for the B_{pk}/E_{acc} ratio at 10 mT/(MV/m). In this paper, we use the definition $E_{acc} = V_{acc}/(\beta_{opt}\lambda)$, where $V_{acc} = \int E_z(z)e^{i\omega z/c}dz$.

RF OPTIMISATION

The RF calculations have been performed using Ansoft HFSS v8.5 and Vector Fields SOPRANO v8.7. Starting from a simple QWR shape with a straight stem, flat top (shorted side), cylindrical drift tubes, the RF profile was optimised in order to decrease peak fields. Enlarging the inner conductor of a coaxial line reduces B_{pk}. The consequent volume reduction of the magnetic region of the resonator has to be compensated by increasing the cavity height. This was applied to the QWRs together with a conical shaping of the stem, bringing B_{pk}/E_{acc} from a typical 14 down to about 9-10 mT/(MV/m). The flat top is replaced by a half torus, which helps fluids evacuation during cavity preparation. Enlarging the upper side of the conical stem reduces the torus minor radius which stiffens the cavity, and increases the frequency of its first mechanical mode. The highest E field region is the central drift tube. Maximizing radii of curvature while keeping the E field density as uniform as possible on its surface leads to adopt a donut shape. This reduces the E_{pk}/E_{acc} ratio down to about 5. The same method was applied to all four cavities that were studied. The resulting parameters are displayed in table 2.

frequency [MHz]	88	88	176	176
β_{opt}	0.07	0.12	0.14	0.12
E_{pk}/E_{acc}	5.5	4.9	5.4	5.0
B_{pk}/E_{acc} [$\frac{mT}{MV/m}$]	8.9	9.0	10.1	9.4
r/Q [Ω]	639	507	503	500
beam tube ϕ [mm]	30	50	30	30
cavity ext. ϕ [mm]	220	370	220	200

Table 2: Characteristics of λ/4 cavities

Since a 176 MHz β=0.12 prototype cavity should be built and tested before the end of 2004, most efforts have been directed towards this particular QWR. All studies concerning coupling, mechanics and steering effects presented in this paper focus on this prototype.

COUPLING

Unlike most of heavy ion linacs, the SPIRAL 2 project requires that a large RF power be transferred to the beam, typically 10 to 15 kW. At such levels, the regular cable/antenna power feeds have to be replaced by a power coupler. Electric coupling is convenient since a coaxial coupler can be installed on the cavity bottom plate, in a low magnetic field region and co-linear to the cavity, which simplifies the cryostat design. The coupling port has been defined for the 176 MHz prototype cavity. Multipacting (MP) simulations of 50 Ω coaxial lines of 30 and 40 mm diameter with MUPAC [5] have been carried out for a 176 MHz traveling wave (TW) . The simulations covering the 0-20 kW range show that a 2 point MP barrier is present for both diameters before 1 kW, but it is much thinner in the case of the 30 mm diameter coaxial line, and should be easier to process. Calculations at 88 MHz in TW showed that no MP exist in the 0-20 kW range for either diameters. HFSS simulations on the 176 MHz β=0.12 cavity with an off-center 30 mm coupling port demonstrate that the nominal coupling is reached for a 8 mm penetration of the antenna (round tip). If necessary a Q_{ext} lower than 10^5 can be reached by increasing the antenna penetration.

MECHANICAL BEHAVIOR

Helium Pressure Effects

The nominal value of Q_{ext} of 10^6 sets the cavity 3 dB bandwidth to 176 Hz for 176 MHz resonators. The amplitude of the He pressure fluctuations in the 4 K cryostat is expected to be 10 to 20 mbars. This implies He pressure sensitivity df/dP in the order of 10 to 5 Hz/mbar has to be reached in order to limit the extra RF power consumption. We have to determine if a cavity built out of 3 mm thick niobium sheets is mechanically sound. The main effect of pressure exerted on the outer surface of the QWR is a global displacement of the stem due to the deformation of the toroidal top of the resonator.

This effect has been evaluated using a combination of 3D structural and RF codes, using a common mesh for the RF surface. First the FEM code CASTEM (CEA) is used to define a shell model of the cavity and perform the structural calculations. The displacements are applied to the mesh nodes of the RF surface. It is in turn imported into EDS I-DEAS which generates the 3D mesh of the RF volume. The latter is grown on the surface mesh in such a way that surface nodes are common to both meshes. The 3D mesh is then read by SOPRANO which computes the EM eigenmodes of the structure. A set of calculations for different pressure ratings is fitted to derive df/dP. For the prototype cavity, the computed values range from -11 Hz/mbar to -15 Hz/mbar while changing the mechanical boundary conditions on the beam tube flanges from fixed to free. The amplitude of the frequency fluctuations δf_0 would then be in the order of 100 to 300 Hz, which is not acceptable.

In order to reduce df/dP we have studied a stiffener which limits the deformation of the toroidal top of the cavity and the vertical displacement of the stem Δz. Calculations show that 1 bar He pressure induces a $\Delta z = -0.08$ mm on the bare cavity, which is reduced by a factor of 4 by stiffening. The stiffener reduces δf_0 to 80 Hz, which makes the cavity operable, and raises the first mechanical mode frequency from 96 to 172 Hz.

Tuning Efficiency

The accuracy of the fundamental mode frequency f_0 may be impaired by manufacturing errors and deformations which occur during cooldown and are difficult to predict accurately. The tuning system should be able to recover the correct f_0 at 4 K. A location for the cold tuning system (CTS) has to be determined which should maximize the tuning range and help reducing the distance between cavities to a minimum. A solution consists in hanging the CTS arms on the cavity outer shell, perpendicular to the beam direction (fig. 1).

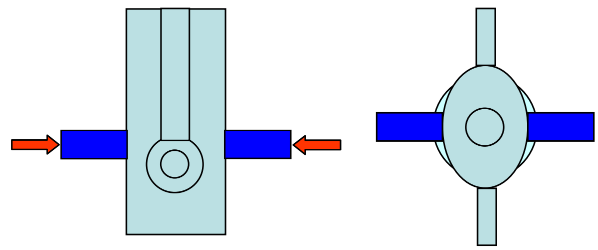

Figure 1: Principle of CTS action

Squeezing the cavity results in a frequency shift. The first step was to choose the arms fixing points on the wall that would maximize the gap length variation while remaining in the elastic domain. For niobium, the yield stress changes dramatically between 300 K ($\sigma_y \simeq 50$ MPa) and 4 K ($\sigma_y \simeq 350$ MPa), the tuning range will thus be much wider in cryogenic operation than at room temperature. The tuning sensitivity has been evaluated using the same combination of FEM codes than for the pressure calculations (table 3).

case	$\frac{\Delta f}{\Delta L}$ kHz/mm	Δf_{max} 300 K kHz	Δf_{max} 4 K kHz
A	-300	15.5	110
B	-180	14.5	100

Table 3: Tuning efficiency

In case A, the CTS is attached to the cavity at the same height than the beam tube. In case B, it is located ~100 mm above. Although the tuning sensitivity is almost double in case A than in case B, the maximum tuning range are similar, since most deformations are located in the region of the drift-tubes to external cylinder junction, which is stiff. In case B, most deformations are limited to the less stiff outer cylinder, the mechanical stress is therefore reduced comparatively. Since less deformation occurs in the region of the gaps, the tuning efficiency is also impaired with respect to case A. Beam dynamics favors a reduced inter-cavity spacing, still cavity assembly should be possible. The B setup is preferred because the access to the beam tube area is easier while connecting cavities together.

176 MHZ β= 0.12 PROTOTYPE

The prototype features a Nb removable bottom plate mounted on Conflat flanges. A special copper gasket ensures both vacuum sealing and RF contact between the cavity body and the cover. Using such a cover provides a large opening for BCP residues evacuation and an easy access for high pressure rinsing.

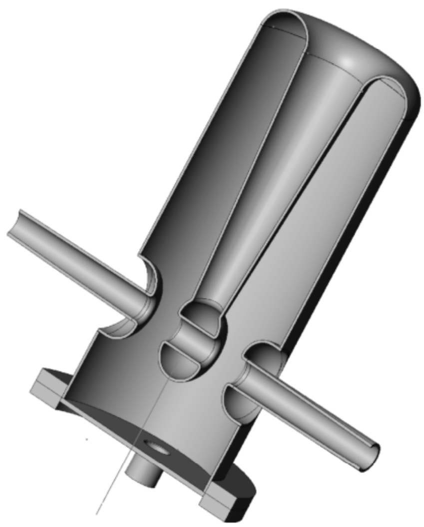

Figure 2: 176 MHz β = 0.12 prototype

The drawback of such a normal conducting RF gasket lies in the increased losses. They have been computed for the prototype cavity (table 4) and show that, the dissipated power in the Cu gasket is only a small fraction of the total losses as long as it is kept at 4.5 K.

part	Rs @ 4.5 K	Power (mW)
removable end plate	40 nΩ	0.56
copper gasket	0.15 mΩ	180
s.s. beam tube	3.5 mΩ	30
cavity body	40 nΩ	6200

Table 4: RF losses at 8 MV/m

The end cover is located in a low magnetic field area, implying low RF losses (less than 1 mW at maximum accelerating gradient). Therefore it needs not be immersed in liquid He, making the He tank design simpler. Instead, it is cooled by a thermal connection to the He box by copper braids.

STEERING EFFECT

In QWRs, E_y and B_x do not cancel on beam axis due to the structure vertical asymmetry. As a consequence, each ion with charge q experiences a vertical deflecting force $F_y = q(E_y + \beta c B_x)$ while traveling through the cavity, causing a global steering effect to the beam. In addition, this phase and velocity dependant force is not constant along the beam, and therefore is a source of emittance growth. We have evaluated the normalized deflection D_y on the beam, and tried to cancel it by tilting the drift tube faces as in [6] (fig. 3).

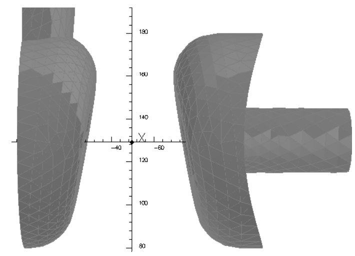

Figure 3: Drift tube tilt

Calculations for a tilt angle of 0, 5 and 10 degrees on the prototype QWR illustrate three cases, respectively no compensation, compensation and over compensation (fig. 4).

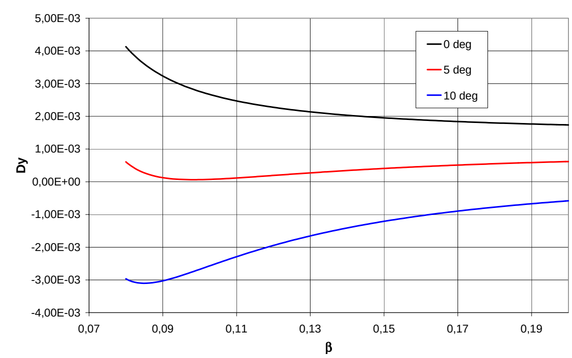

Figure 4: Steering effect compensation

One important result is that the peak electric field is not increased by changing the face angle from 0 to 5 degrees. Although this compensation method is efficient, the correction will no be implemented on the prototype cavity since multiparticle simulations of the linac with 3D RF field maps indicate that the contribution of the cavities to the emittance growth is negligible.

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