DEVELOPMENT OF SRF SPOKE CAVITIES FOR LOW AND INTERMEDIATE ENERGY ION LINACS

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Abstract

The fabrication of the first European spoke cavity prototype has been achieved in July 2002. A series of mechanical and RF tests at warm and cold temperature was performed this year. These tests have demonstrated, on the one hand, the good feasibility, stiffness and tunability of the spoke cavity and, on the other hand, its excellent RF performances with a maximum accelerating field of 12.5 MV/m reached at 4.2K.

INTRODUCTION

Spoke cavities have been studied for 3 years at IPN Orsay. Beam dynamics studies [1] dedicated to the EURISOL [2] and XADS [3] European projects have pointed out that this kind of cavity is particularly suited to be used from typically 20 MeV up to 100 or 150 MeV (for proton linacs). In this framework, IPN has studied a 2-gap, beta 0.35, 352 MHz spoke cavity. The optimization of the RF parameters (done with MAFIA [4]) and the structural analysis (done with ACORD-CP [5]) are presented in [6-8]. The prototype has been fabricated, from February to July 2002, by the French company Cerca [9] and a series of tests started since the delivery date.

First of all, we will describe the measurements performed at room temperature to know in particular the mechanical properties of the cavity like its sensitivity versus displacement and load, its mechanical stiffness, the frequency shift due to fabrication and vacuum load, the accelerating field profile… Then, we will show the results obtained during the three tests, in January, March and July 2003, performed at 4.2K into our new vertical cryostat. Finally, the recent developments made on the new beta=0.15 spoke cavity will be presented.

TESTS AT ROOM TEMPERATURE

Dimensional Controls

Before the tests, we studied the frequency variation (i.e. Δf~+300 kHz) observed between the "theoretical" value calculated with MAFIA ($f_{calculated}$=358.55 MHz) and the frequency measured at the delivery ($f_{measured}$=358.85 MHz). Note: calculations and measurements have been done for the cavity at atmospheric pressure.

Thanks to the dimensional measurements of the main cavity pieces (e.g. the spoke bar, the cavity length…) done by Cerca during the fabrication process and the respective sensitivities calculated with MAFIA, we had estimated the frequency variation due to fabrication errors. As we can see in Table 1, the estimation (i.e. +455 kHz) is in good agreement with the measurement. On one hand, the little difference between the "theoretical" frequency and the "real" one and on the other hand, the very good accelerating field flatness due to strong magnetic coupling between both cells (see section above) means that spoke cavity doesn't need to be tuned at room temperature. It's a strong advantage as compared to elliptical cavities for instance.

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Table 1: Estimation of the frequency variation due to fabrication errors.

Areas	Sensitivity with MAFIA (kHz/mm)	Errors (mm)	Frequency variation (kHz)
Cavity diameter	950	-0.1	+95
Spoke base diameter	650	-0.2	-130
Racetrack width	800	-0.2	+160
Racetrack thickness	600	+0.2	-120
Wall-to-wall cavity length	450	+1.0	+450
		Total variation	**+455**

The Test Set Up

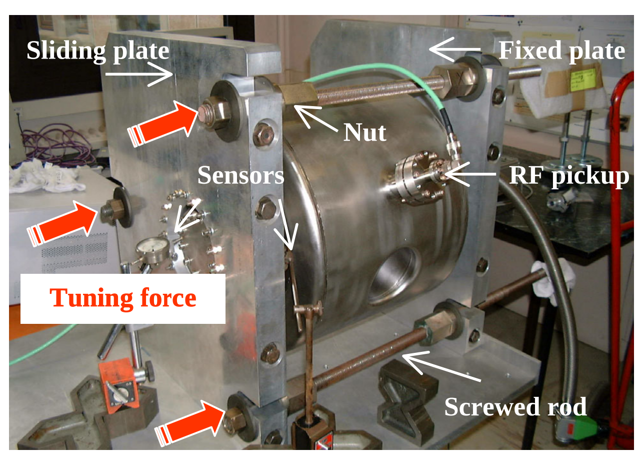

Figure 1: The spoke cavity on the test bench during the tuning sensitivity measurements. Red arrows symbolize the efforts applied on the cavity.

The test set up used to check mechanical properties is shown on Figure 1. The cavity is settled between two plates which are maintained by three screwed rods. The pulling (or pushing) efforts are applied by means of three nuts. Displacements were measured with the sensors placed on each flanges (one of them, behind the fixed sheet, is not visible). The frequency shift is read directly on a Network analyser.

Before each vacuum pumping or fixed displacement, the cavity is prestressed by pulling the cavity of about 0.4 mm (the maximum elongation is 1 mm in order to stay below the Niobium yield strength limit of 50 MPa). Note: while we were testing the frequency variation due to vacuum pumping, we checked the sealing of the weldings. No leakage was observed (the minimum threshold of gauge detection was 1.0 10^{-9} mbar.l/s).

Sensitivity Versus Vacuum Load

Two series of several pumping cycles each were done to measure the frequency shift of the cavity (1 cycle means making the vacuum inside the cavity and to go up back to the atmospheric pressure). The total average frequency shift observed was about ±110 kHz. The results of the measurements are noticed in Table 2. From these values, and taking into account the frequency correction due to the permitivity change (here, it's about –110 kHz from vacuum to P_{atm}), we have deduced the frequency shift due to the cavity deformations during the pumping, i.e. ±220 kHz (+ for vacuum→P_{atm} and – for P_{atm}→vacuum).

Table 2: Frequency shift measurements during the pumping cycles

	Series n°1 Δf (kHz)	**Series n°2 Δf (kHz)**
Vacuum→P_{atm}	+117	+103
P_{atm}→Vacuum	-117	-124
Vacuum→P_{atm}	+104	+103
P_{atm}→Vacuum	-104	-105
Vacuum→P_{atm}	+112	+103
Average	**±111**	**±108**

Sensitivity Versus Displacement

Measurements of the frequency variation as a function of the elongation along the beam axis have been done using the test set up shown on Figure 2. Taking into account the prestress of the cavity, we took care of not exceeding 1 mm of total elongation. That's why the displacement shown on x-coordinate is limited to 0.4 mm at maximum.

8 measurements were done (6 during the first series and 2 during the last one for which we have "shaked" the test bench in order to see a possible effect on the measurements). The mean value of all measurements is 575 ± 25 kHz/mm (minimum 535 kHz/mm and maximum 610 kHz/mm). Note: differences between values at the origin (i.e. zero-displacement) are due to different prestresses values.

This measured tuning sensitivity is consistent with the estimations calculated with MAFIA software (450<Δf/Δz<800 kHz/mm) and more recently with COSMOS/MICAV software (Δf/Δz=630 kHz/mm).

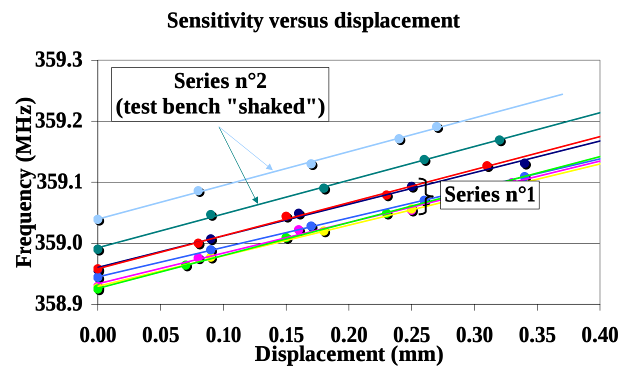

Figure 2: Frequency variation versus displacement. Measurements (points) and fit functions (lines).

Sensitivity Versus Load

Unfortunately, we were not be able to measure the load applied on the cavity during the tuning sensitivity measurements done at IPN. So, we used the tensile testing machine installed at the LAL/Orsay (Figure 3).

The loading process and the data acquisition were fully controlled by a computer. The maximum displacement was computed up to 0.8 mm. We noted the values of the frequency every 0.1 mm.

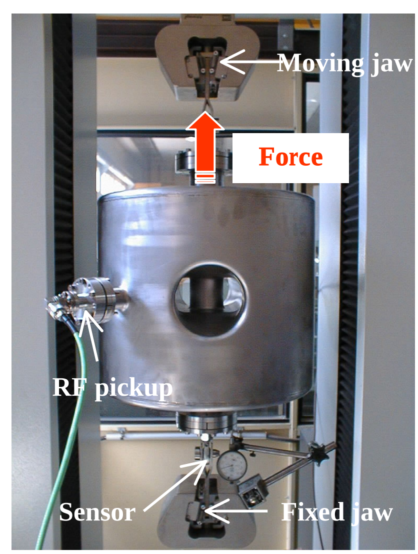

Figure 3: The spoke cavity placed between both jaws.

The result of this test is shown in Figure 4. As for the tuning sensitivity, the slope of the fit function (blue line) gives us the sensitivity of the cavity versus the load, i.e. Δf/ΔF=243 Hz/N.

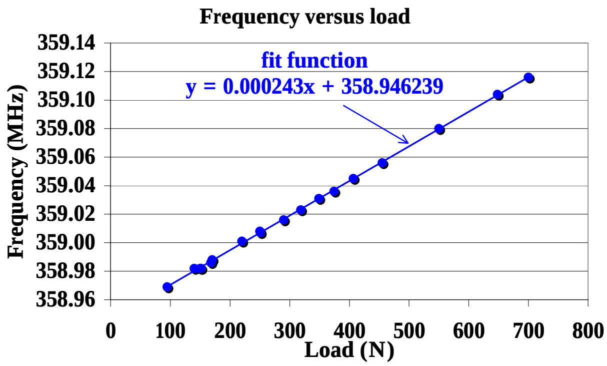

Figure 4: Frequency variation versus the load.

Stiffness

Based on the previous sensitivities measurements, we deduced the stiffness of the cavity, that is to say $K_{measured}$=2366 ± 103 N/mm. Calculations performed with two mechanical codes (i.e. ACORD-CP and SAMCEF software [10]) showed considerable differences. We found the following values: K_{ACORD}=3625 N/mm and K_{SAMCEF}=3300 N/mm, that is to say a variation of +46% compared to the average value of 3465 N/mm.

This big variation was also observed for the Los Alamos [11] and Argonne [12] type spoke cavities (i.e. respectively +56% and +29%). Note: the measured value is always lower than that predicted. Therefore, we have to improve the model we used with these simulation codes, which does not take into account important details such as the weld beads or the niobium thickness change caused by the chemistry process, for instance.

Accelerating Field Profile Measurement

Conventional bead-pull measurement method was used to obtain the accelerating field profile on the cavity axis (see Figure 5).

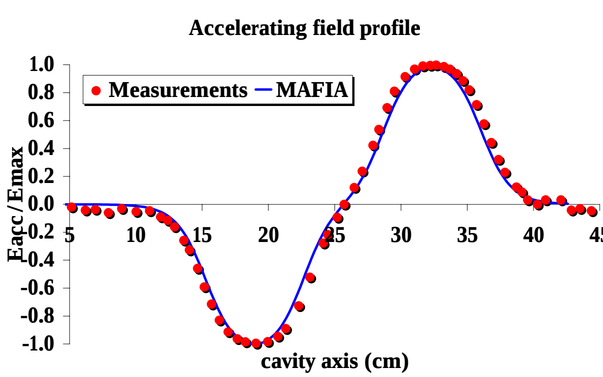

Figure 5: Accelerating field profile.

We measured about sixty points and compared them with the profile given by MAFIA. As we said before, the field is similar on both gaps due to the very strong magnetic coupling between each cell of the cavity. By modelling the 2-gap cavity with its RLC equivalent circuit, one can calculate this coupling coefficient (Eq. 1):

$$\frac{f_\pi}{f_{\pi/2}} = \frac{1}{\sqrt{1+2K}} \qquad (1)$$

where K is the coupling coefficient, f_π the frequency of the fundamental mode (π-mode) and $f_{\pi/2}$ the frequency of the harmonic ($\pi/2$-mode). With the frequencies f_π and $f_{\pi/2}$ of our spoke cavity, we found K=21% (compared, for instance, to a few percent for the elliptical cavities).

TESTS AT T=4.2K

The β0.35 spoke cavity was tested 3 times this year (respectively, in January, March and July 2003). All tests were done at 4.2K but we planned to perform a new test at 2K, in December, thanks to an upgrade of the cryogenic lines and the cryostat. As one can see on Figure 6 below, due to the large dimensions of the cavity, we had to build a new vertical cryostat.

A 200W RF power amplifier was used to feed power into the cavity. We used a capacitive coupling in two different conditions: i.e. in March, a fixed antenna attached to one of the beam tube and, in January and July, a movable coupler attached to the “nominal” coupler port. In both cases, transmitted power was picked up with a antenna attached to one of the radial port (see Figure 9).

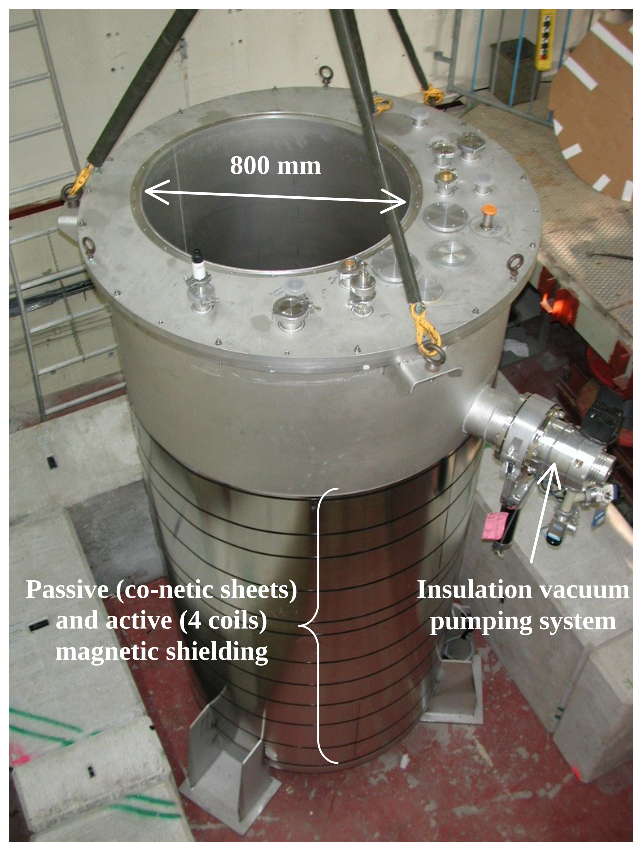

Figure 6: New vertical cryostat during installation at IPN/Orsay.

Cavity Preparation

The chemistry and the cleaning of the cavity were made using the CEA/Saclay existing facilities. Buffered Chemical Polishing (BCP) (Figure 7) and High Pressured Rinsing system (HPR) with ultra pure water at 80 bars were used. For HPR, the cavity is spinning while the nozzle goes up and down inside the cavity (Figure 8). We turned over the cavity after a complete cycle of cleaning. The final assembly (i.e. the antenna, the coupler the pick up and the beam tube flanges) was done inside a class 100 clean room (also at CEA/Saclay, see Figure 9).

Figure 7: Spoke cavity into the acid bath.

Figure 8: HPR process.

Figure 9: Final assembly of the cavity into the clean room (class 100). Note: in this case, the antenna was attached to the beam port.

Test N°1 in January

For this first test, the cavity was only chemically polished because the HPR apparatus was not yet ready. 240 µm were removed (i.e. ~120 µm/side). We knew that the lack of HPR was going to induce a strong electron activity and to limit the accelerating field value [13-14]. But, we made this test to check, in particular, the correct operation of the installation (Power amplifier, cryogenic lines, cryostat…).

We used a movable power coupler connected to the nominal coupler port (range of the antenna ~ 12 mm).

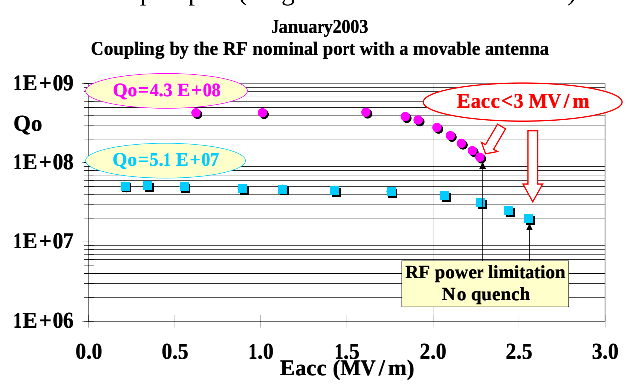

Figure 10: First results with the movable coupler. Antenna tip position: retracted into the coupler port at minimum position (pink points) and penetrated at maximum toward the cavity (blue squares).

As expected, we observed a very strong electron activity starting at 1.5 MV/m and we never exceeded 3 MV/m (Figure 10). To illustrate this intensive activity into the cavity, one can see how the antenna and the interior of tube looks like on Figure 11.

Moreover, Q_0 values (4.3 10^8 and 5.1 10^7 for the extreme positions of the antenna, at low field) were lower than expected (i.e. at least 1.6 10^9 with a residual resistance of 20 nΩ). Because of the location of the coupler port (at 45° compared to the spoke bar), we thought that extra-losses might be due to the cavity magnetic field surrounding the antenna. Actually, at fixed input power level, we saw that the external quality factor changed when varying the position of the antenna whereas it should have been constant (Figure 12).

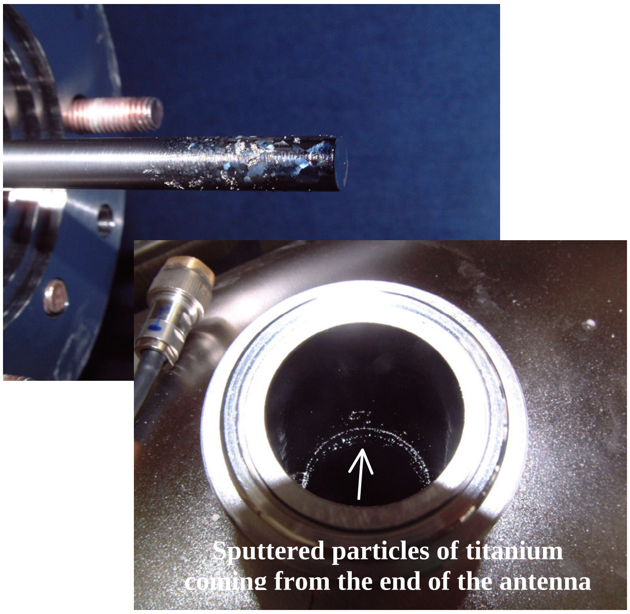

Figure 11: Pictures of the antenna (top) and the coupler port tube (bottom).

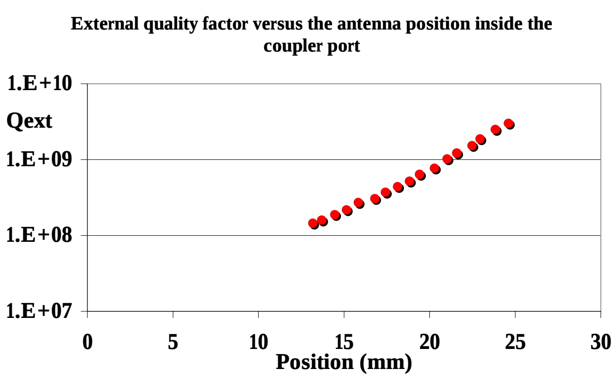

Figure 12: Variation of the external quality factor versus the antenna position. Note: the origin on x-coordinate represents the beginning of the tube.

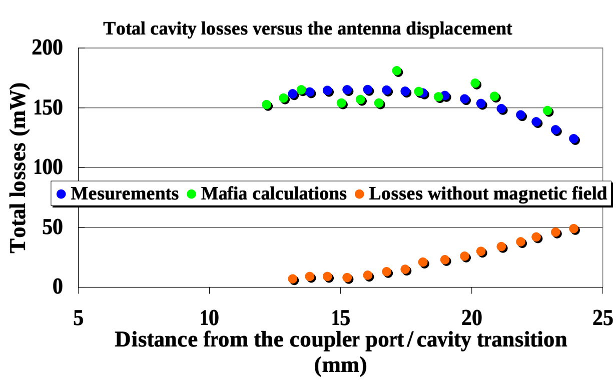

Figure 13: Total losses into the cavity versus the position of the antenna. The input power was fixed to 170 mW.

More recently, we performed a MAFIA simulation in order to study the losses we measured during this test. As one can see on Figure 13, calculations explain these losses due to the magnetic field around the antenna tip.

This problem was affecting the design of our new prototype. That's why, the power coupler port was shifted of 45° where there is no magnetic field at all (see Figure 16). We checked also that we could fed without difficulties the cavity through the port, at this specific location.

Test N°2 in March

There were two principal differences with the first test:

- a complete cleaning with HPR process.
- a fixed coupler attached to one of the beam tube in order to avoid the extra-losses due to the magnetic field.

We reached 10.3 MV/m with a low-field Q_0 value of 2.0 10^9. Strong electron activity started around 5 MV/m and we proceeded, in a few minutes, a "light" multipacting barrier around 1.5 MV/m. Helium processing allowed us to reach 12.2 MV/m without quenching (limitation came from the power amplifier). Cavity performances exceeded the XADS requirements of Eacc=6.2 MV/m at Q_0=5 10^8.

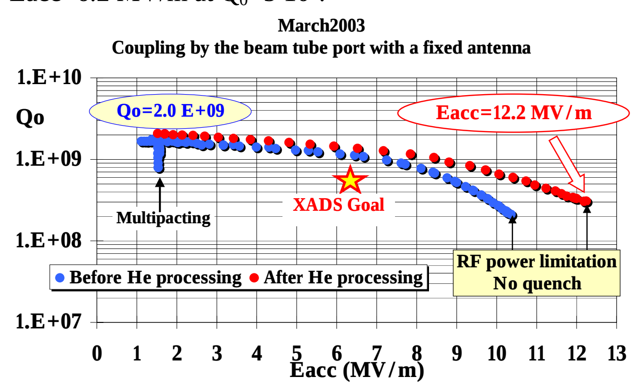

Figure 13: Results of the second test.

We measured also the Lorentz force detuning factor K. We found K=-5.6 Hz/(MV/m)^2, which underlines the stiffness of the cavity.

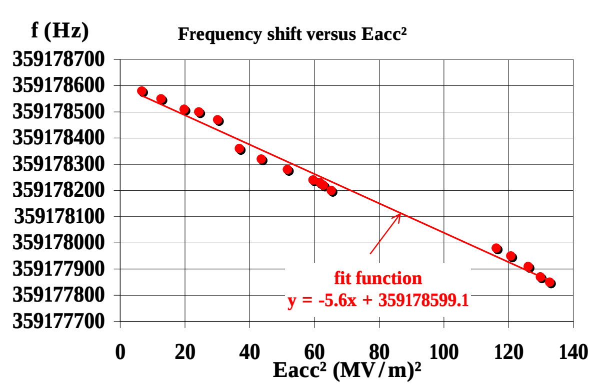

Figure 14: Frequency variation versus Eacc^2. The slope of the fit function gives the Lorentz force detuning factor K.

At last, we studied the “100K” effect. After warming up the cavity between 80K and 100K during 67 hours, the residual resistance grew up from 10 nΩ to 70 nΩ.

Test N°3 in July

This test was carried out to complete the study on the extra-losses which we measured during the first test and to validate the RF performances reached during the second one.

So, we saw the same variation of the external quality factor as depicted in Figure 12. Secondly, we reached 12.5 MV/m with a low-field Q_0=4.8 10^8 (Figure 15). At this accelerating field value, the corresponding peak magnetic field is 103 mT. Again, the limitation was the RF power available but no thermal quench.

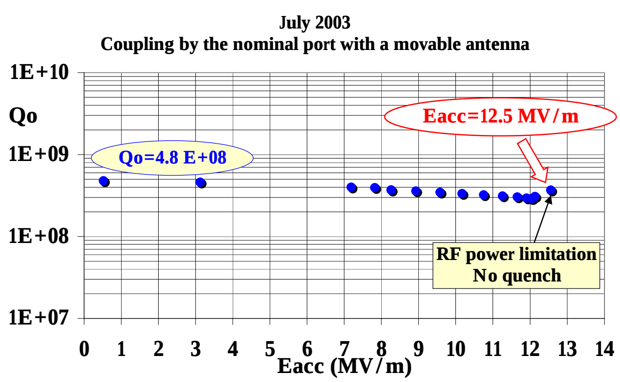

Figure 15: Test results with the movable coupler.

CONCLUSION

Tests performed on the β0.35 spoke cavity prototype have demonstrated the great potential of this type of cavity in term of RF performances (Eacc=12.5 MV/m) and mechanical behavior (very low sensitivity to errors fabrication, good stiffness, accelerating field flatness…).

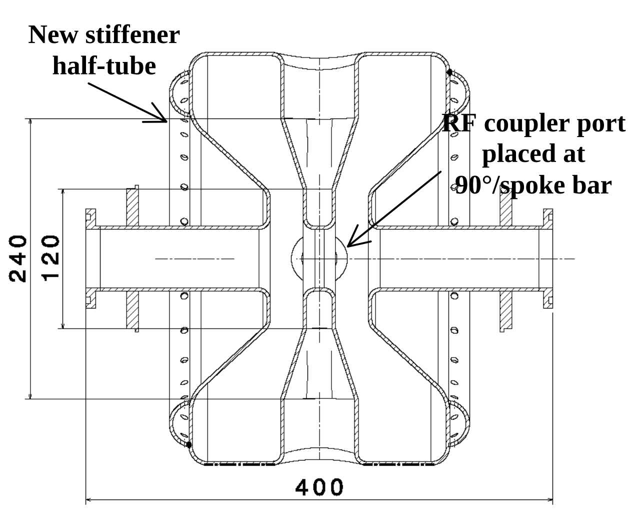

Figure 16: 2D drawing of the new prototype β0.15 spoke cavity.

A new prototype (β0.15, 350 MHz, 2-gap), equipped with a stainless steel helium tank, will be ordered in November. The main goals will be to validate the location of the power coupler (locaced at 90° compared to the spoke bar) and the new stiffening system (see Figure 16).

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