FZJ SMALLEST SC TRIPLE-SPOKE CAVITY

E. Zaplatin, W. Braeutigam, M. Pap, M. Skrobucha, Forschungszentrum Juelich, Germany

P. Kneisel Thomas Jefferson National Accelerator Facility, USA

Abstract

The paper describes the design, fabrication and test results of the smallest superconducting triple-spoke cavity (resonant frequency 760 MHz, β=0.2) developed at Forschungszentrum Juelich.

CAVITY DESIGN

The cavity electrodynamics design aims to optimise the cavity geometry to reach the highest accelerating efficiency, in other words to minimize values of peak electrical and magnetic fields on the cavity surface relative to the accelerating electrical field on the cavity axis (B_{pk}/E_{acc} and E_{pk}/E_{acc}). The detailed cavity RF analyses have been published elsewhere [1]. The geometry and parameters of the cavity are shown in Fig.1 and Table.1.

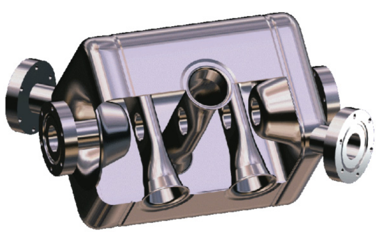


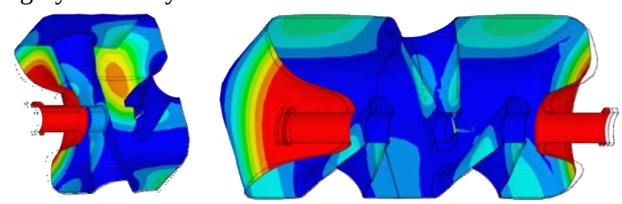
Figure 1: 3D view of triple-spoke cavity.

The strategy of cavity structural design should include the integrated simulations of RF and mechanical properties called coupled analyses. This cavity is not stiffened since the cavity is aimed as a prototype for the fabrication process development. The conducted coupled analyses resulted in the understanding of the cavity behaviour under different external conditions and proper experimental result interpretations. The main two structural effects, which are under investigation that affect the cavity working ability, are the cavity frequency dependence on the external pressure and Lorentz forces.

Table 1: Some parameters of triple-spoke cavity

Frequency	MHz	760
β=v/c		0.2
$R_{aperture}$	mm	12
$\beta\lambda$ /2	mm	78.6
R_{cavity}	mm	71.5
R/Q	Ohm	78
QR_s	Ohm	74
E_{pk} / E_{acc} *)		4.96
B_{pk} / E_{acc} *)	mT/MV/m	10.1
*) L_{cav} = N_{gaps} * $\beta\lambda$/2, where N_{gaps}=4 – number of gaps		

By the cavity under vacuum the pressure differential changes the cavity shape and shifts the RF frequency of the accelerating mode. Inward deformation of end cups (the region of high electric field, Fig.2a) increases the capacitance and hence reduces the frequency. Inward deformation near central spoke (high magnetic field region) reduces the inductance and hence increases the frequency. Thus the effects tend to cancel one another.
For the Lorentz forces (Fig.2b) inward deformation of end cups increases the capacitance and hence reduces the frequency but outward deformation of cavity walls (high magnetic field region) increases the inductance and hence decreases the frequency. Thus the effects tend to add one another. The uncertainty with the cavity wall thickness changes the results of the structure optimisations. This makes the possibility of the final structure adjustment highly necessary.



a) b)

Figure 2: Cavity deformations by external pressure (a) and Lorentz forces (b) (red – max, blue – min).

The cavity structural behaviour can be accurately generalized to the case of an arbitrary boundary condition, characterized by its longitudinal stiffness K_{ext}, [2] (Fig.3). The different thickness of the end cup wall has been considered with cavity walls 1.8 mm and spoke walls 1.0 mm thick.

CAVITY FABRICATION

The Central Department of Technology (ZAT) of Forschungszentrum Jülich was essentially involved in design, construction and fabrication of the cavity. The detailed mechanical design was dominated by the intention to simplify e-beam welding of the cavity. Significant efforts were made to minimize the number of welding seams and to keep them completely two-dimensional. The niobium walls are formed of 2 mm thick Nb sheets, spokes and end cups of 1.5 mm. The novelty of SC RF technology for ZAT together with the complexity of the mechanical construction and the electron-beam welding joints, suggested to devote a substantial effort in building a full scale model from oxygen free copper first. This allowed testing a number of technological issues before proceeding on the full Nb version. All pre-fabricated parts have to be precisely machined before final assembly. As the realization of sc accelerating structures was a first time task for ZAT in

2001 some extra efforts were made to develop know-how and to establish adequate production procedures. For example milling is used to achieve the final shape of the

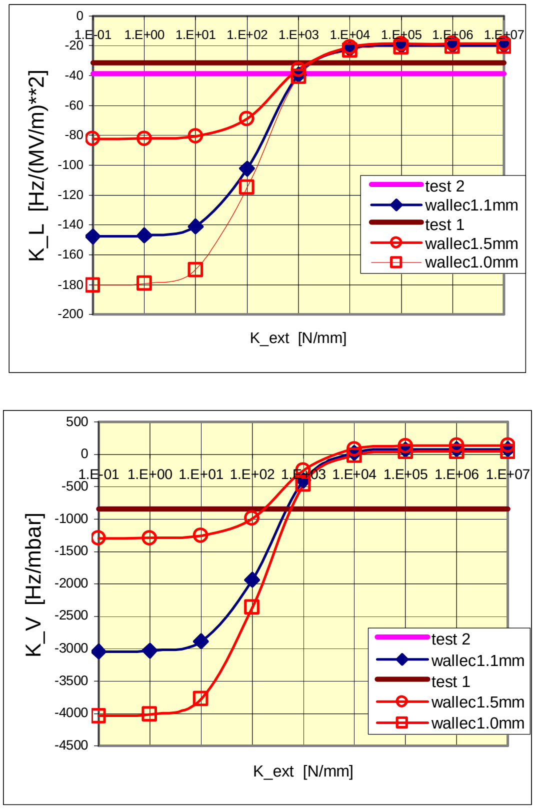


Figure 3: Cavity structural analyses results.

end caps and to prepare all seams for welding. So this process was carefully optimized with respect for tooling, cooling fluids, machining speed and other parameters. Further high quality e-beam welding requires preparation by etching. To optimize this process a number of samples with original and machined surfaces were exposed to the acids for different times to study the removal of material. Finally, the quality of e-beam welding is considered to be the key issue for SC cavity with high accelerating gradients. To study only the most important parameters of

End cup Spoke Completed Nb cavity

Figure 4: Cavity fabrication.

welding a time consuming process has to be accepted especially when quality assessment was not possible on the site at that time. We are deeply grateful to the colleagues at DESY who supported our work by careful examination of probes and a lot of invaluable advices. Different components and the completed cavity are shown on Fig.4.

After welding in our in house electron beam welding machine the triple-spoke cavity received its chemical treatment (BCP) at Saclay. Approximately 100 µm of Niobium were removed. Then the cavity was cleaned by High Pressure Rinsing to remove field emission emitters and the first set of coupler and antenna were mounted on the cavity. The sealed cavity was transported under vacuum to Juelich.

TEST RESULTS

The main tests of the cavity have been conducted at Jefferson Lab. The cavity was shipped from Juelich to Jlab assembled and under vacuum.

By the test 1 the cavity was attached to one of test stands and after the pumping line had been evacuated to a pressure of 2e-7 mbar, the valve on the cavity was opened. The vacuum degraded to app. 5 e-4 mbar, but recovered quickly.

During the cryogenic test the Q-value of the cavity was measured as a function of temperature between 4.2K and 2K as well as the pressure sensitivity of the cavity between 830 mbar and 20 mbar. At 4.2K and also at 2K the Q-value was measured as a function of field and the Lorentz force detuning coefficient was derived from the resonant frequency change with increasing field in the cavity (Fig.7).

Prior to test 2, the cavity was hydrogen degassed at 600°C for 10 hrs. A buffered chemical polishing (bcp) with 1:1:4 solution of HF : HNO_3 : H_3PO_4 followed in steps of 1-2 min, during which the acid was kept inside the cavity. On a sample it was determined that this solution removes app. 0.9 micron of material per min at room temperature. The resonant frequency of the cavity was measured every 5 min of bcp. This procedure was repeated for a total of 25 min of acid exposure. We estimate, that approximately 20 microns were removed from the surface after the furnace treatment.

The cavity was subsequently high pressure rinsed in vertical position. Because of the small beam pipe and iris diameter a special rinse nozzle had to be fabricated and the rinsing was done in 3 steps: the HPR wand was set to a fixed axial position and the cavity was rotating; after app. 20 min the HPR wand was lowered to a second position and another 20 min of HPR was carried out. The cavity was then turned upside-down and the part of the cavity, which could not be reached in the first set of rinses because of constraints in rinse system, was then rinsed for an additional 20 min.

After the HPR the cavity was dried in a class 10 clean room for several hours and then all auxiliary parts such as blank flanges, input and output probe and pump out port with valve were assembled. The input coupling probe and the output coupling probes had been shortened by app. 10 db, because in the first test both external Q-values were too strong for tests at 2K with higher Q-values. The cavity was attached to the cryogenic test stand and evacuated to a pressure of p~ 2e-8 mbar prior to cool down. Figure 5 shows the temperature dependence of the surface resistance between 4.2K and 2K. The data were analyzed with Halbritter's BCS surface resistance program and material parameters such as gap value, mean free path and residual resistance were derived from the analysis keeping the coherence length, the London penetration depth and the critical temperature constant. The residual resistance of R_{res} = 6.8 nOhm is quite low.

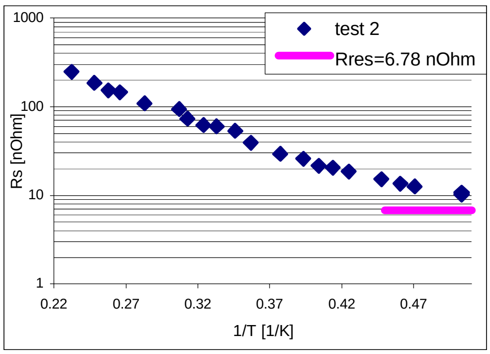


Figure 5: T-dependence of the surface resistance.

The sensitivity of the cavity frequency to the pressure in the helium bath is shown in figure 6 between 830 mbar and 23 mbar. The frequency changes df/dp=840 Hz/mbar. The Lorentz force detuning during the high power test at 2K was measured. The result is shown in figure 6: the Lorentz-force detuning coefficient of –38.7 Hz/(MV/m)^2 is rather high because of the cavity thin walls.

Figure 7 shows the Q vs E_{acc} performance of the cavity in both tests (1 and 2) at 4.2K and at 2K. In test 2 the cavity was limited at Eacc ~ 9 MV/m by a quench at 4.2K; at 2 K no quench was encountered up to Eacc ~ 12.5 MV/m; the available rf power limited the achievable accelerating gradient. During both tests we encountered some multipacting as indicated, which could be processed away within a few hours.

The performance of this cavity compares quite well with other cavities – elliptical or spoke. From the table 1 one can calculate peak surface fields of E_{peak} = 62 MV/m and H_{peak} ~ 126 mT. The residual resistance of R_{res} ~ 6.8 nOhm would give a Q-value of Q (2K) ~ 1.5 x 10^{10} in a 1300 MHz ILC-type cavity.

In a review paper [2] on spoke cavities the best performances was reported by ANL for triple spoke cavities of β = 0.5 and 0.62 (f = 345 MHz) after electropolishing and hydrogen degassing at 600°C. Q-values > 10^{10} at 2K (corresponding to residual surface resistances < 10 nOhm) up to accelerating gradients of E_{acc} ~ 12 MV/m were measured. These cavities were nearly without field emission, whereas in our case field emission was encountered above E_{acc} ~ 7.5 – 8 MV/m. Obviously, the cleaning of the β = 0.2 spoke cavity seems to be more difficult because of the small distances between the spokes than for higher β and lower frequency spoke cavities with larger gaps between the spokes. Also, in our case the high pressure rinsing system was not optimized for the small beam pipe/iris diameter.

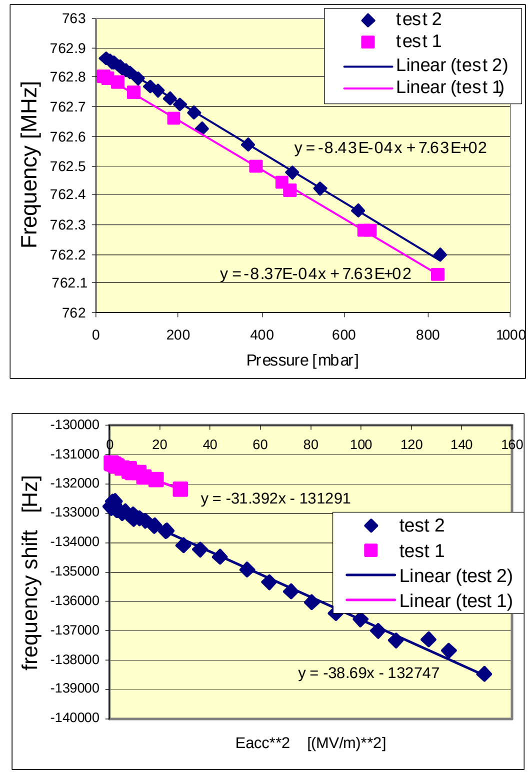


Figure 6: Pressure sensitivity and Lorentz force detuning measured during high power tests.

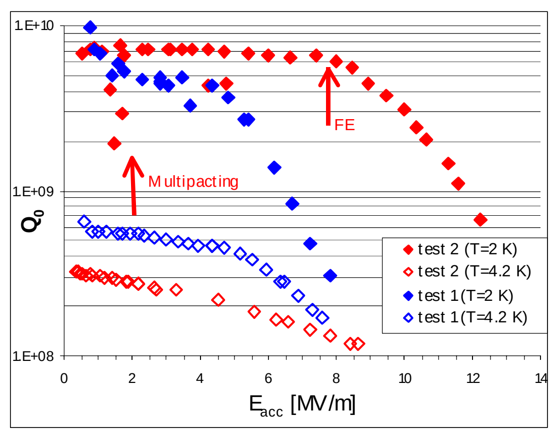


Figure 7: Q vs E_{acc}. The gradient in test 2 at 2K was limited by rf power, no quench.

ACKNOWLEDGEMENT

We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" program (CARE, contract number RII3-CT-2003-506395)

REFERENCES

[1] E. Zaplatin et al., "Triple-Spoke Cavities at FZJ", EPAC'04, Lucerne, July 2004.
[2] P. Pierini et al., CARE/JRA3: Annual report 2005.
[3] M. Kelly, SRF 2007, Beijing, China.