IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

SUPERCONDUCTING STRUCTURES FOR A 130 MeV RECYCLOTRON*

U.Klein, D. Proch
University of Wuppertal, FB 8, Gaußstr.20, 5600 Wuppertal, W. Germany
and
T. Grundey
Institut für Kernphysik, TH Darmstadt, 6100 Darmstadt, W. Germany

Abstract

We report about feasibility studies of a proposed 3 GHz recyclotron using 20 cell rf structures of spherical shape. As first step a 5 cell Nb cavity was fabricated by deep drawing and electron beam welding. Only chemical etching was used as global surface treatment. After detection of the breakdown location by a resistor network we applied a local mechanical grinding technique. An accelerating field of $E_{acc} = 5.6$ MV/m at $Q_0 = 3.2 \cdot 10^9$ was reached after two mechanical treatments. These results slightly exceed the design values of the recyclotron. No multipacting was observed, indicating that the spherical shape effectively suppresses this type of field limitation in multicell structures.

Introduction

The proposed 130 MeV recyclotron[1] is a cw electron accelerator for use in nuclear physics research. It consists of 10 superconducting linac structures and a three pass isochronous recirculation system. An accelerating field of 5 MV/m is designed for the one meter long units working at 3 GHz in the π-mode. At the operating temperature of 1.8 K we aim at an unloaded quality factor of $Q_0 = 3 \cdot 10^9$. The cells of the rf structure are of spherical shape. According to computer simulations of electron trajectories this cell geometry should be free of multipacting[2]. This is in agreement with measurements at single cell spherical cavities[3,4]. Experiments, however, show that in multicell structures multipacting can be a much worse problem compared to identically shaped single cell cavities[5]. A five cell structure seems suitable to study this multicell phenomenon.

This structure can also be used to gain experience with cheap fabrication techniques and to find a preparation procedure as simple as possible. Nb cavities are usually fabricated by machining or by forming sheet material. In further treatments they are processed by a combination of chemical polishing, electropolishing high temperature firing, oxipolishing and rinsing. We used deep drawing for fabrication and tried to restrict the preparation to chemical polishing and rinsing.

Fabrication

The fabrication of the cells is done in several steps (Fig. 1a). First, a disc (Ø 150 mm) of 2 mm Nb sheet material (Kawecki) is formed by deep drawing to an ashtray like cup. The cups are annealed at 1100°C and the surplus material is cut away. Deviations of the opening from an ideal circle are less than ± 30 µm. At next the iris aperture is deep drawn. After a short chemical polishing the cups are welded together by an electron beam. In a set of 19 cells 17 showed a resonance frequency in an interval of 3.5 MHz giving an upper limit for typical variations of the cell diameter of ± 45 µm. Individual chemical polishing (50-200 µm) of the single cells adjusts the right single cell resonance frequency within 300 KHz. Before the final welding the field flatness is measured and optimized by permutation of the cells. A field unflatness of less than ± 2% was achieved. Deep drawing, machining and electron beam welding was performed at Interatom GmbH., Bensberg.

Experimental Set-Up

The five cell Nb cavity together with the mechanical support-system, the microwave probes and the vacuum pump line is shown in Fig. 1b. The superconducting resonator was tested in the temperature range of 4.2 K to 1.7 K using a conventional vertical He-bath cryostat. The cavity was evacuated by an ion getter pump in a permanent vacuum system except for the first six tests where we used the pinch-off technique. The rf properties were measured by observation of the reflected and transmitted microwave signals. 35 carbon resistors (100 Ω Allen Bradley) were arranged around the iris and equatorial welding seams to localize the breakdown region. To increase the sensitivity for the detection of heat pulses these measurements were carried out in subcooled Helium[6].

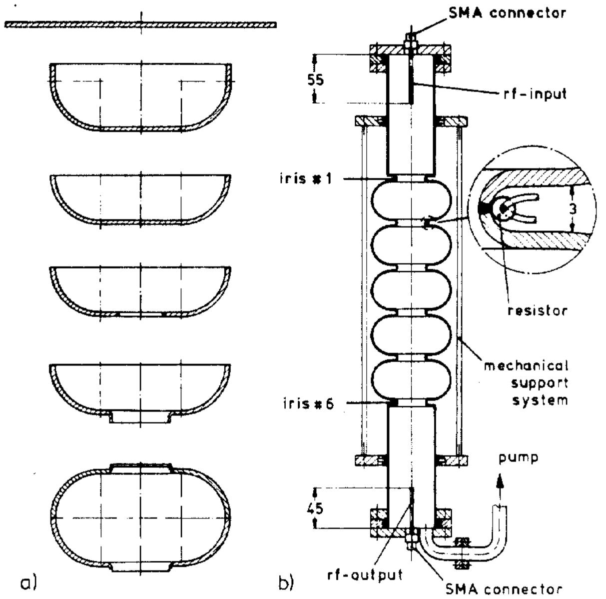

Fig. 1: a) steps of fabrication of one cell
b) test set-up for the 5 cell structure

The rf properties of the five cell structure were calculated with LALA[7] giving a geometry factor of 293Ω, enhancement factors $E_{peak}/E_{acc} = 3.0$, $H_{peak}/E_{acc} = 41$. G/(MV/m) and a normalized shunt impedance r/Q = 20Ω/cm. The frequency of the accelerating π-mode is 3.00 GHz, the cell-to-cell coupling 3.8%.

Experimental results

After fabrication the 5 cell structure was chemically polished (CP) in 33% vol. HF (48%), 33% vol. HNO_3 (65%) and 33% vol. H_3PO_4 (85%) for 60 sec at room temperature removing about 15 µm of Nb. After cleaning (see Table 1) the cavity was mounted in wet condition. Pumping for two days resulted in a vacuum of better than 10^{-8}Torr when the cavity was pinched off. After some hours in test 1 the cavity showed a gas discharge breakdown, obviously due to a Helium leak. Therefore, the cavity was flooded with clean N_2 and the leak was fixed for test 2. Before test 3 the resonator was mounted upside down. All three tests showed almost the same results: an accelerating field of $E_{acc} \simeq 2$ MV/m at $Q_0 \simeq 3 \cdot 10^8$. The field was limited by quenching. A reproducible Q-switch of 20% occurred at $E_{acc} = 0.22$ MV/m, pro-

---

*Supported in part by Deutsche Forschungsgemeinschaft

0018-9499/81/0600-3222$00.75©1981 IEEE

Test	Treatment	Q_0 at $E_{acc,max}$	$E_{acc,max}$ [MV/m]	Location of breakdown	Remarks
1	CP 15, H_2O, $H_2O+H_2O_2$+US, Meth., pinched off	$3\cdot10^8$	2.0		He gas discharge breakdown, leak problems, PBM, Q_{sw}
2	opened, flooded with N_2, leak fixed, heated 100°C	$3\cdot10^8$	2.0		Q_{sw}
3	warmed up, mounted upside down	$3.4\cdot10^8$	2.1		Q_{sw}
4	CP 50, H_2O+US, Meth.+US, heated 100°C, pinched off	$\sim5\cdot10^7$	0.5	Iris 5	first test with resistor network Q_{sw}
5	local grinding Iris 5, CP 10, H_2O, Meth+US, heated, pinched off	$2.1\cdot10^8$	3.1	Iris 5	
6	warmed up, μ-metal shielding mounted	$9\cdot10^8$	3.1	Iris 5	first test with mag. shielding only breakdown field+Q_0 measured
7	H_2O, Acet., Meth., continuously pumped	$1.1\cdot10^9$	4.2	Iris 2 loc.a,	first test with continuous pumping system, Q_{sw}
8	local grinding Irises 2a,5,6 CP 20, H_2O, Acet+US, Meth., pumped	$3.2\cdot10^9$	5.6	Iris 2 loc.b	
9	warmed up, pumped for 14 days	$3.2\cdot10^9$	5.6	Iris 2 loc.b	
10	local grinding Iris 2b, CP 20 H_2O+US, Acet+US, Meth., pumped	$3.2\cdot10^9$	5.5	Iris 4	leak problems, PBM
11	warmed up	$3.2\cdot10^9$	5.3		flange tightened, leak tested resistor network not mounted
12	fired at 1300°C for 5 h, dry mounted	$4\cdot10^8$	5.7	Iris 3	bad rf connector caused leak problems, PBM, $I_\gamma \approx 1$ mR/h
13	CP 20, H_2O+US, Acet+US, Meth.	$4.5\cdot10^9$	5.7		resistor network not mounted

Table 1: Measurements of the 5-cell spherical structure, $f_{\pi\text{-mode}} = 3.00$ GHz, $T = 1.7$ K.

CP 15 = 15 μm chemical polishing; H_2O, Meth, ... = rinsing in H_2O, Methanol,...;
US = ultrasonic cleaning; PBM = excitation of pass band modes; Q_{sw} = Q-switch observed, I_γ=γ-intensity outside cryostat.

ducing a step in the Q_0 vs. E_{acc} plot (Fig. 2). These disappointing results were believed to be due to a surface damage layer, as observed in machined cavities. Therefore, the resonator was CP by 50 μm resulting in even worse values of $E_{acc} = 0.5$ MV/m at $Q_0 = 5\cdot10^7$. As detected by the resistor network the breakdown occurred at iris 5, where two dark spots were present already before the 50 μm CP. Most likely these defects were holes looking dark due to shadow effects. According to good results with ground welds[8] we used an abrasive wheel (CRATEX, USA, rubberized abrasives, Nr. 74, extra fine) in connection with a dentist's-like motor drive and ground an area of about 1.5 cm^2 until the dark spots disappeared. This treatment was followed by CP of 10 μm only. Now the structure showed an improved breakdown field of $E_{acc} = 3.1$ MV/m at $Q_0 = 2.1\cdot10^8$. Up to this test no magnetic shielding was used. To exclude the degradation of the cavity Q due to frozen-in earth magnetic flux, the structure was warmed up and a μ-metal shielding (CRYOPERM, Vacuumschmelze Hanau) was mounted. In fact the Q_0 improved to $9\cdot10^8$ at the same breakdown field. For the next test we only cleaned the resonator by a rinsing procedure which this time also included Acetone. The structure was connected to a continuous pumping system and showed a further improved breakdown field of 4.2 MV/m. Motivated by the first successful grinding we now applied this technique at the new breakdown areas followed by 20 μm CP. In test 8 the field increased to $E_{acc} = 5.6$ MV/m at $Q_0 = 3.2\cdot10^9$. A third grinding did not increase the performance but the breakdown now occurred at iris 4, which could not be reached with our present tool. At this point in the series of measurements the proposed design values have been reached by simple fabrication and preparation techniques. We now heated the structure at 1300°C for 5 h (Karlsruhe furnace) to investigate whether this moderate firing could further improve the obtained results. Tests 12 and 13 showed that this was not the case.

During all the measurements the γ-intensity outside the cryostat was monitored with a sensitivity of 0.01 mr/h. Only in tests suffering from vacuum problems γ-radiation was detected. The highest intensity of $I_\gamma \approx 1$ mr/h was observed during test 12.

Influenced by the success of local grinding and by the observation of imperfections at or near the breakdown location, we investigated a piece (150 mm x 150 mm) of our Nb sheet material by a Secondary Electron Microscope (SEM). On that piece 18 of these imperfections could be found by eye, which all showed up to be small holes with typically 0.2 mm in diameter and depth. For the SEM inspection the piece was cut into small samples (10 mm x 20 mm) and treated by 100 μm CP and rinsing. Around all holes numerous etching pits are accumulated. In two of those etching pits contaminations of Fe and Zn were detected.

Discussion

It was one aim of our measurements to investigate the multipacting behaviour of multicell spherical cavities. Usually multipacting manifests itself by an additional power absorption at distinct field levels which may finally limit the maximum achievable field strength. No such phenomena were experimentally observed. The maximum cavity fields were determined by quenching. This is caused by a local thermal instability as indicated by the observation of pre-breakdown heating. Some measurements showed vacuum problems due to a cold leak. During these tests other passband modes were excited and irregularities could be seen on the rf trace in a broad field range. These phenomena changed with time in an unsystematic way and never showed resonant behaviour.

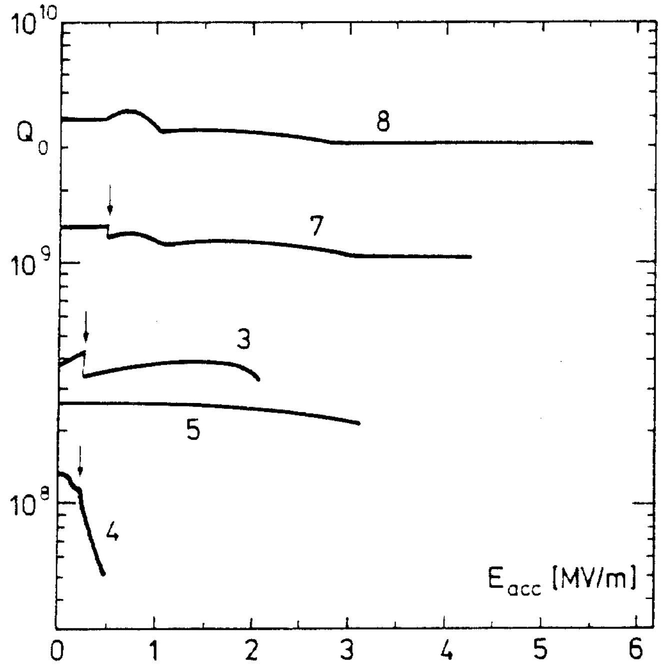

Fig. 2: Plot of Q_0 versus accelerating field for different measurements. The numbers correspond to the test numbers as in the table of experimental results. Arrows indicate Q-switches.

Furthermore, they disappeared at high field levels, especially near the quenching field. In test 12 the cavity vacuum was controlled by an additional pump. The described phenomena could be switched on and off with decreased or increased cavity vacuum. We therefore conclude that the curious effects were always due to He-gas in the presence of electric fields.

The influence of frozen-in earth magnetic field on the rf losses of the cavity can be seen as difference in Q_0 for test 5 and test 6. This loss mechanism is well known but reported values[9,10] for the additional surface resistance are not conformable within a factor of ten. We measured an increase of the surface resistance by $10^{-6}\Omega$ in agreement with ref.10. Shielding the ambient field to less than 30 Milligauss resulted in residual Q_0's of up to $6\cdot10^9$ so that we did not investigate this question further.

Two different Q-switches (Fig. 2) at distinct field levels (at 0.22 MV/m in tests 1,2,3,4; at 0.5 MV/m in test 7) were observed. The one at 0.22 MV/m disappeared after the first grinding, the other one after the second grinding. In test 7 the Q-switch at 0.5 MV/m could be localized by the resistor network in the area of breakdown (iris 2, location a). We therefore conclude that the Q-switch and the breakdown are initiated by the same local defect.

The most interesting result is the improvement of the breakdown field after local grinding the breakdown area. This indicates that the local property of the bulk material determines the breakdown field rather than the general condition of the surface. The inspection of the cavity surface by an endoscope showed about 10 of the described imperfections in the region of the irises. It is remarkable that such holes could be found at or nearby each of the detected breakdown areas. The resolution of the resistor network, however, is not sufficient to definitively exclude an accidental coincidence. The two inclusions found in the SEM investigations had a diameter of about 4 µm. Comparing with thermal instability calculations[11] it is not obvious whether imperfections of this size can produce a breakdown in the observed field range.

Due to the geometry of the grinding tool only a small ring of about 10 mm width around the iris could be ground. This area shows high electric and reasonable magnetic fields. The increase of the breakdown field by grinding only this area demonstrates that the location of breakdown need not necessary be in the peak magnetic field region. This suggests that a combination of electric (dielectric) and magnetic heating initiates the thermal instability. Recent measurements of a 500 MHz spherical cavity at CERN[12] using an elaborate rotating resistor network support this hypothesis.

Conclusion

No multipacting was observed in the 5 cell spherical cavity in all five passband modes. We therefore conclude that also for a reasonable tuned 20 cell structure multipacting should not be a problem. A maximum accelerating field of 5.6 MV/m at $Q_0 = 3.2\cdot10^9$ has been obtained with chemical polishing, rinsing and local grinding of the observed breakdown areas. Our measurements indicate that imperfections which are already visible on the sheet metal are possible breakdown locations. In the construction of the 20 cell cavity we therefore locally ground the material during the first steps of fabrication.

Acknowledgments

It is a great pleasure to thank Professor H.Piel for his valuable discussions, G.Nissen for his work on the heat pulse detection system, the CERN EF division for the SEM investigations and for their apparative support and Dr.Greiner for the endoscope scanning at the St. Joseph Hospital, Wuppertal. The firing has been done at the KFK Karlsruhe with the gratefully acknowledged help of H.Baumgärtner.

References

1. H.Heinrichs et al., Proc.Conf.Nuclear Physics with Electromagnetic Interactions, Mainz, W.Germany (1979)
2. U.Klein and D.Proch, Proc.Conf.Future Possibilities for Electron Accelerators, Charlottesville, Va., USA (1979)
3. V.Lagomarsino, G.Manuzio, R.Parodi and R.Vaccarone, IEEE Trans. MAG-15, 25 (1979)
4. U.Klein, D.Proch and H.Lengeler, Report WU B 80-16, Univ. of Wuppertal (1980)
5. G.Arnolds, H.Heinrichs, R.Mayer, N.Minatti, H.Piel and W.Weingarten, IEEE NS-26, 3775 (1979)
6. H.Piel, Proc. Workshop on RF Superconductivity, KfK-Report 3019, Kernforschungszentrum Karlsruhe (1980)
7. W.F.Rich, M.D.J.MacRoberts, Report LA-4219, Los Alamos Scientific Laboratory (1969)
8. H.Padamsee, M.Banner, J.Kirchgessner, M.Tigner and R.Sundelin, IEEE MAG-15, 602 (1979)
9. C.M.Lyneis, Report HEPL 737, Stanford University
10. B.Piosczyk, P.Kneisel, O.Stolz and J.Halbritter, IEEE NS-20, 108 (1973)
11. A.Deniz and H.Padamsee, Report CLNS-434, Cornell University
12. P.Bernard et al., CERN/EF 81-2(1981).