DESIGN AND TEST OF A SUPERCONDUCTING QUARTER-WAVE-RESONATOR

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Summary

A superconducting quarter-wave-resonator at 325 MHz has been designed that could be used as a dispenser for the Heidelberg postaccelerator. The design study utilized the computer codes SUPERFISH and URMEL as well as a theory considering the quarter-wave-resonator as a piece of transmission line shorted at one end. These calculations were used to optimize $H_p/\lambda_{acc}$, $E_p/\lambda_{acc}$ and $U/\lambda_{acc}^2$. According to measurements with a model resonator the copper body of a first prototype resonator has been machined. In first experiments with an electrochemically plated lead surface an unloaded quality $Q_0 = 6 \times 10^7$ has been measured. The highest accelerating field obtained in that test amounted to $E_{acc} = 1.8 \text{ MV/m}$ at $Q_0 = 1.0 \times 10^9$.

Introduction

During the last years several heavy-ion postaccelerators have been built or are under construction which are based on superconducting resonators [1,2]. The low-beta structure which is most favourable because of the ease of machining and the straightforward cooling technique is the lead-plated quarter-wave-resonator (QWR) [3]. The essential advantage which superconducting resonators offer to accelerator physics, reduced power consumption and therefore higher accelerating fields, is utilized in this study on the QWR. The small size and the ease of machining make superconducting resonators very attractive for accelerator physics. The discussion of the cylindrical geometry of the QWR is limited essentially by three processes: the peak electric field $E_p$ gives an upper limit for the effective accelerating field $E_{acc}$, by the onset of field emission, the peak magnetic field $H_p$ can cause a magnetic breakdown and the stored energy $U$ determines the power necessary to run the resonator phase-stabilized. Therefore these quantities were theoretically investigated by the use of computer calculations.

Resonator Design

The operation of a superconducting resonator is limited essentially by three processes: the peak electric field $E_p$, gives an upper limit for the accelerating field $E_{acc}$, by the onset of field emission, the peak magnetic field $H_p$ can cause a magnetic breakdown and the stored energy $U$ determines the power necessary to run the resonator phase-stabilized. Therefore these quantities were theoretically investigated by the use of computer calculations.

Advantage can be taken of the almost entirely cylinder-symmetrical geometry of the QWR. The drift-tubes give a small perturbation to the symmetry and produce a loading capacity that results in a reduction of the resonant frequency compared to the unloaded resonator. The influence of the drift-tubes was taken into account by calculating their capacity and converting it to a cylinder-symmetrical capacity of the same size. The shape of the loading capacity was chosen in such a way that the cylinder-symmetrical resonator used in the calculation equals a cut through the actual resonator on the beam axis. The result of a calculation obtained with the program SUPERFISH [5] is shown in fig. 1. By means of SUPERFISH calculations the values $U/\lambda_{acc}^2$ and $H_p/\lambda_{acc}$ were minimized by changing the diameter and taper of the inner conductor. Care was taken to get a minimum variation of the magnetic field along the inner conductor. Additional calculations using the computer code URMEL [6] served as a cross-check for the SUPERFISH results.

Fig. 1. Result of a SUPERFISH calculation. The horizontal axis is the symmetry axis of the resonator. Shown are the electric field lines.

The peak electric field occurs at the end of the inner conductor. It therefore depends on the curvature radius of the drift-tubes, the gap length and the length of the inner drift-tube, which is equal to the smaller diameter of the inner conductor. The curvature radius and the gap length were optimized with SUPERFISH by calculating the ratio $E_p/\lambda_{acc}$ for different drift-tube sizes in a cavity resonator in the TM 010-mode at 325 MHz. The curvature radius and the gap length should be large due to the field magnification effect, the inner drift-tube should be long because of the $1/\beta$-dependence of the electric field in a coaxial resonator. The gap-to-gap distance $l$ is fixed by $l = \beta \lambda/2$, $\beta = $ design velocity, $\lambda = $ free space wavelength. On the other hand the gap-to-gap distance is equal to the sum of the inner drift-tube length and the gap length. Therefore a compromise between the two contrary effects had to be chosen.

A copper-plated brass model of the resonator has been machined to compare the calculated values with experimental measurements. The agreement with SUPERFISH and URMEL calculations is reasonable and better than with the values obtained in a simple QWR-theory [3] considering the QWR as a piece of transmission line shorted at one end (table 1).

<table>
<thead>
<tr>
<th>Table 1</th>
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<tr>
<td>Comparison of the various theoretical calculations with the measurement on the model resonator.</td>
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<table>
<thead>
<tr>
<th>Frequency [MHz]</th>
<th>SUPERFISH</th>
<th>URMEL</th>
<th>QWR</th>
<th>Experiment</th>
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<tr>
<td>327</td>
<td>325</td>
<td>300</td>
<td>319</td>
<td></td>
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<tr>
<td>Quality</td>
<td>8920</td>
<td>9100</td>
<td>10500</td>
<td>7980</td>
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<tr>
<td>$R_{sh}$ [Mfl/m]</td>
<td>48.4</td>
<td>47.7</td>
<td>59.7</td>
<td>45.8</td>
</tr>
<tr>
<td>$P_{sh}$</td>
<td>0.145</td>
<td>---</td>
<td>0.128</td>
<td>0.137</td>
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<tr>
<td>$U/\lambda_{acc}^2$ [MV/m$^2$]</td>
<td>15.1</td>
<td>15.5</td>
<td>12.4</td>
<td>19.8</td>
</tr>
<tr>
<td>$E_p/\lambda_{acc}$</td>
<td>6.7</td>
<td>7.6</td>
<td>4.6</td>
<td>6.6</td>
</tr>
<tr>
<td>$H_p/\lambda_{acc}$ [G/(MV/m)]</td>
<td>76.1</td>
<td>78.4</td>
<td>70.6</td>
<td>---</td>
</tr>
<tr>
<td>TTF (s)</td>
<td>0.81</td>
<td>---</td>
<td>0.88</td>
<td>0.82</td>
</tr>
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</table>
As a consequence of the \(1/r\)-dependence of the electric field in the cylinder the electric field on the beam axis is not symmetrical to the center of the gap. The bead-pull measurement shows a shift of the peak electric field towards the center-drift-tube (fig. 2). The field distribution in the gap originates from a folding of the homogeneous field in the gap, the \(1/r\)-dependence in the cylinder and the edge effect of the drift-tube rounding. Experimentally it has been found that this shift of the peak electric field towards the center decreases with increasing gap length and for constant gap length with increasing drift-tube capacity. This is due to the fact that for a coaxial resonator with outer radius \(r_2\) and inner radius \(r_1\) the electric field is proportional to \(1/\ln(r_2/r_1)\) and that the increased drift-tube capacity homogenizes the field in the gap.

![Fig. 2: Bead-pull measurement. The square of the electric field versus the position on the beam axis is shown.](image)

**Manufacturing of the Prototype Resonator**

Based on the calculations and model measurements the copper body of a prototype resonator was machined (fig. 3). The only difference to the geometry of the model resonator is an enlargement of the curvature radius of the drift-tubes from 5 to 8 mm inferring a shortening of the inner conductor of 16 mm. Its dimension sizes are given in fig. 4.

![Fig. 3: Prototype resonator.](image)

The resonator without drift-tubes was machined in three pieces which were electron-beam-welded together. The inner conductor with the center drift-tube at the end was produced from one solid rod of copper. The shorting-plate between inner and outer conductor together with a stub for the inner conductor and one for the outer cylinder was electron-beam-welded to the inner conductor and mirror-finished afterwards. The mirror-finished outer cylinder was then electron-beam-welded to the shorting-plate using a penetrating weld from the outside. At the end of the stub for the outer cylinder a 7 mm thick, 6 mm high copper ring was left over. This ring filled the space behind the welding-seam at the inside of the resonator (fig. 4). It avoided breaking-through of the electron-beam and hurting the polished surface of the inner conductor. After welding this ring was removed from the open end of the resonator by turning on the lathe. This technique was applied to avoid cracks in the weld that have been observed without penetrating weld. Finally the outer drift-tubes machined with 40 pm oversize in diameter relative to the hole were cooled to liquid nitrogen temperature and shrunk into the outer wall.

The important parameters of the resonator are almost identical to the values obtained with the model. The omission of joints raises the \(Q\)-value to the value computed with SUPERFISH, the enlarged drift-tubes improve \(E_{p\text{acc}}\) from 6.6 to 6.2 and cause a slight reduction of shunt impedance which is of minor importance for a superconducting resonator.

**First Measurements**

The superconducting lead surface was prepared in two different ways. In a first experiment the resonator was lead-plated to a thickness of 3 \(\mu\)m and chemically polished afterwards following essentially the technique developed at Caltech [7]. Aged polish solution was applied etching the lead surface until it appeared bright followed by a rinsing procedure including successively the use of chelate, ammonia and acetone. After the final acetone rinsing the resonator was immediately stored in vacuum. The preparation technique for the
second experiment did not employ the chemical polishing. The electrochemically plated, 1.3 µm thick lead layer was only rinsed with deionized water and acetone before storage in vacuum.

In both experiments the resonator was assembled into the cryostat and pumped down to 2 x 10⁻⁶ mbar. Then the resonator was baked for some hours at 60°C. The heat-shield of the cryostat was filled with liquid nitrogen. Liquid nitrogen flowing in a cooling channel which is soldered onto the outer resonator wall was used to precool the resonator. Finally the inner stem was slowly filled with liquid helium. During the bakeout and cooling procedure the resonator was RF-conditioned for some hours with the available power of 75 W corresponding to ε₀ = 0.1 MV/m.

In the experiment with the polished lead surface the maximum electric field could be reached within minutes after cooling to 4.2 K, no serious electron levels were detected. The highest available accelerating field ε₀ = 1.8 MV/m which was connected with a moderate radiation of 40 mrem/h outside the cryostat was limited by a resonator breakdown. The power consumption at this field amplitude was 14 W at Q = 1.0 x 10⁷. The unloaded quality at low field was measured to be Q₀ = 6 x 10⁶.

In the second experiment some hours of RF-conditioning at 4.2 K were necessary to run the resonator with the unpolished lead surface at a maximum field ε₀ = 1.2 MV/m. The power consumption amounted to 16 W at Q = 4 x 10⁶. The low field quality was again Q₀ = 6 x 10⁶.

These results indicate that the superconducting quality is limited by some additional loss mechanism. A possible reason could be the imperfectly plated beamholes of the outer drift-tubes and the hole for the coupler. The improvement of the superconducting quality of the resonator will be the object of further research.

Acknowledgement

The authors would like to thank Dr. J.M. Brennan for his help in becoming familiar with the special problems of superconducting resonators and in setting-up the necessary experimental apparatus.