EXPERIMENTS WITH THE CERN SUPERCONDUCTING 500 MHz CAVITY

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We report on a series of experiments with a superconducting 500 MHz single cell cavity of “spherical” shape fabricated from niobium sheet material. Design, fabrication and different room temperature surface treatments of cavity including ion bombardment cleaning are discussed. An experimental test set up was used which includes diagnostic systems such as: temperature mapping of the outside cavity wall in subcooled helium, scanning solid state X-ray detector close to the cavity wall, light detection from the cavities inside, probes to measure internal free electron currents and a spectrum analyser to detect the electron induced excitations of higher order cavity modes.

The following general characteristics of the cavity were observed: At 4.2 K an accelerating field of 3 MV/m can be achieved safely with low losses \( Q = 2 \times 10^9; P_{\text{diss}} = 8.4 \text{ W/m} \). The residual rf losses are concentrated in the high electric field region of the cavity surface and cannot be attributed to normal conducting metallic impurities but show dielectric loss properties. Resonant electron loading (multipacting) was never observed. At field levels exceeding 3 MV/m non-resonant electron currents start to load the cavity \( Q \) and give rise to the excitation of higher order cavity modes. The electron sources are point like and located in the high electric field region of the cavity. The field emission nature and the location of the electron sources are determined by temperature mapping and X-ray diagnostic measurements and analyzed by computer simulation of electron trajectories. In the region between 4 and 5 MV/m the cavity field is limited by thermal instabilities (quenching) originating from point like loss regions predominantly found at the bottom part of the cavity. Some of these defects were observed to be created during high field operations of the cavity in several instances.

1. Introduction

At CERN the design of a Large Electron Positron storage ring called LEP is currently under way. In the present design [1] the use of normal conducting acceleration cavities is foreseen allowing an electron energy of \( \sim 90 \text{ GeV/c} \). The use of superconducting rf cavities could provide the possibility to increase this energy. It also would allow at lower energies a substantial power saving as compared to the copper cavities. In order to study the possible use of superconducting cavities a feasibility study, that aims at the installation and testing of a multicell cavity in a storage ring, was started in 1979 at CERN. Similar studies are going on at present at KfK, Karlsruhe [2] Cornell University [3] and KEK, Japan [4].

In April 1979 a first series of measurements on 3 GHz single cell Nb cavities [5] was started for testing different geometries, fabrication methods and surface treatments. From these results, two major conclusions for a possible LEP cavity were drawn. Cavities obtained by different fabrication methods (spinning or deep-drawing from niobium sheet material) and submitted to different surface treatments (electropolishing with a subsequent high temperature annealing versus chemical polishing) gave comparable performances with respect to the maximum achieved acceleration fields \( E_{\text{acc}} \approx 10 \text{ MV/m} \) and the quality factors (a few \( \times 10^9 \)). The absence of electron multipacting in the “spherical” * cavities as indicated by measurements of the Genova group [6] at 4.5 GHz and predicted by computer simulations at Wuppertal [7] was confirmed also for the 3 GHz cavities. In the light of these very encouraging results it was decided

* We use this name for the cavity shape shown in fig. 1.
to proceed with a first single cell accelerator cavity. For reasons of a possible test at DESY a frequency of 500 MHz was chosen. Because of the absence of electron multipacting by which superconducting cavities were so much plagued in the past and also as an alternative to the development program with sharp cornered cylindrical cavities going on at KfK Karlsruhe [2] the spherical shape was adopted. It was decided to use niobium and to plan for operation at 4.2 K.

Right from the beginning of the programme a special effort was devoted to the development and construction of cavity diagnostics including systems which allow a precise temperature and X-ray mapping as well as a visual inspection of the cavity during operation. Furthermore a special emphasis was put on simple fabrication methods and surface treatments.

2. The cavity

2.1. Cavity fabrication

The cavity parameters have been computed by SUPERFISH [8] and the main results are listed in table 1. Its main dimensions are given in fig. 1. A beam tube diameter of 12 cm has been chosen as a compromise between large internal coupling and small peak fields. Circular roundings were adapted and as a consequence the cavity body ends with flat regions of ~5 cm width. The cavity has been fabricated out of cross-rolled, 2 mm thick Nb sheet material *. The two halves of the cavity body were formed by spinning on a lathe and by using three intermediate annealings of 1 h in a vacuum-furnace at 1050°C. After the final shaping tolerances of the order of a few 1/10 mm were obtained in axial and radial direction **.

Parts were joined by electron beam welding: a first fixing by point weldings from outside, a nearly through welding from outside and a final welding with a slightly defocalised electron beam from inside (vacuum \(-6 \times 10^{-5}\) mbar) giving a final welding with an internal width <3 mm. The welding shrinkage per weld amounts to 0.2 mm after the final welding. The cavity has a weight of 18 kg, a total surface of ~1 m² and a volume of ~70 l.

* Kawecki reactor grade niobium, crystal size: 40 μm, Vickers hardness 70, Ta contamination <1000 ppm.
** Later cavities had been spun at higher speed and only one intermediate annealing was needed. By using a second Al-alloy dye of slightly decreased diameter tolerances of about 2/10 mm were obtained.

Table 1

<table>
<thead>
<tr>
<th>Some computed parameters of the 500 MHz cavity a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>Quality factor (Q) (Nb at 4.2K) b)</td>
</tr>
<tr>
<td>Shunt impedance/quality factor (R/Q)</td>
</tr>
<tr>
<td>(E_p/E_{acc})</td>
</tr>
<tr>
<td>(H_p/E_{acc})</td>
</tr>
<tr>
<td>Geometry factor (G)</td>
</tr>
</tbody>
</table>

a) Obtained with SUPERFISH. \(E_{acc}\) is the effective acceleration field including transit time factor.
\[E_{acc} = (2/\pi) \int_0^{l/2} E \, e^{ikz} \, dz; l: \text{total length of cavity including beam tubes.}\]

b) Value computed from the experimental data of this report assuming negligible residual losses.

Fig. 1. Layout of 500 MHz test cavity (dimensions are in mm). A: rf input; B: rf probe; C: electron probe; D1–D10: X-ray detectors; E: viewing port; F: retractable electrode for IBC; G: pumping line for cavity (turbo molecular pump and ion sputter pump); H: cryostat cover; R1–R39: resistors for temperature mapping; W: weldings (the direction of the electron beam is indicated).
Fig. 2. Scanning electron microscope photography of the Nb surface (magnification: X 320) (a) Before surface treatment; (b) after CP of 20 μm; (c) after CP of 100 μm; (d) after CP of 6 min in contact with air.

2.2. Surface treatments

Having in mind a possible large scale application of superconducting rf cavities we have applied surface treatments to the cavity which can be performed without large cost or sophisticated equipment.

Prior to welding a few material checks and treatments are performed. A simple check for iron inclusions at the surface is obtained by immersing the half cells for a few hours in water*. Iron inclusions can then be detected by their rusting. Many spots (about 5–10 per dm$^2$) have been detected by this method. They seem to be partly due to the rolling procedure and the subsequent smoothing of the plates by steel brushes, partly due to iron pick-ups during manipulations at the workshops. After the first chemical polishing* of 20 μm no more iron inclusions could be detected by immersion method. In fig. 2a a scanning electron microscope photograph of the etched surface is shown. It can be seen that the brushing marks are still visible. Therefore and in order to remove the damaged layer due to the rolling another 70 μm of Nb are removed by chemical etching (fig. 2b). After each etching procedure an anodisation at ~100 V is applied and the half cells are inspected for local colour changes.

After welding the standard procedure performed is a chemical polishing (CP) of 20 μm. The temperature rise during the chemical polishing (three minutes) is

* Following a recipe of the Cornell group.

* Etching solution 33% HF, 33% HNO$_3$, 33% H$_3$PO$_4$ giving at 20°C an etching rate of ~6 μm/min.
about $20^\circ$C. It takes one minute to fill the cavity and about 30 s. for emptying the cavity and immersing it in demineralised water. The emptying period was made as short as possible because the etching of the solution is increased by the contact with air and by the fast temperature increase of the Nb wall once it is no longer in contact with the acid bath. This additional etching is particularly dangerous at the lower flat part of the cavity body. We have analyzed, by a scanning electron microscope, this enhanced etching of an acid film on Nb samples kept horizontally in air. After one minute exposure no change of the surface as compared to a sample etched by immersion in the acid bath is found. However, after a six minute exposure metallic stains well-bound to the crystal lattice (grey oxide?) can be detected (fig. 2d). An X-ray analysis reveals only Nb (with a possible inclusion of O and C).

After chemical treatment the cavity is rinsed in a H$_2$O + H$_2$O$_2$ bath with ultrasonic agitation. The final rinsing (fig. 3) is made in filtered dust free methanol combined with ultrasonic agitation. The “wet” cavity then is protected by covers against dust, mounted inside its support system and connected in a laminar air flow system to its vacuum system. Pumping starts typically after an assembly time of five hours while the cavity is in a vertical position. The final rinsing also has been performed replacing the methanol by dust free distilled water. The cavity is then dried in a horizontal position in a dust free room and afterwards connected to the vacuum system. Excellent results have been obtained by using this method. As there are many indications that dust particles can produce rf losses and act as electron sources, we try to detect dust particles inside the cavity prior to final mounting in a dust free room by using the fluorescence of dust particles under UV light irradiation. It is known that by this method one cannot detect inorganic dust particles or very small particles. However, it can give at least a general indication for the cleanliness of the metal surface.

*Oxipolishing* following the method developed at Siemens [9] has been applied once.

Another surface treatment applied is *Ion Bombardment Cleaning* (IBC), a glow discharge cleaning of the type used extensively for degassing vacuum chambers of accelerators [10]. With the help of a retractable Nb anode (fig. 1) an argon discharge at 200 V can be applied in situ without a subsequent exposure to air. We are currently preparing new experiments in S band cavities in order to clarify the role of different parameters as, e.g., intensity and gas compositions for this interesting surface treatment which may be applied to cavities installed in an accelerator.

Before cool down, the cavity and its vacuum system can be baked out to a temperature of about $250^\circ$C.

3. Experimental set-up

3.1. Cavity set-up

In fig. 1 a schematic view of the experimental layout and in fig. 4 a photograph of the cavity mounted below the cryostat cover is shown. As the 2 mm walls of the cavity cannot withstand atmospheric pressure a support system is necessary. Vacuum is ob-
Fig. 4. (a) Photography of the cavity mounted below the cryostat cover with support and temperature mapping resistors. (b) Close up view of resistors.

3.2. The rf system

Different regulation systems allow to operate the cavity at the fundamental mode and at higher modes with a frequency up to 1.5 GHz. $Q$-values and field levels can be measured with the help of an automated data acquisition system [11]. A spectrum analyser gives information on higher order mode excitation and its amplitude behaviour (down to 60 db with respect to the fundamental mode). Its logarithmic display is conveniently used for decay measurements over many decades of power level. Rf power is coupled to the cavity with a fixed coaxial coupling system at the lower beam tube. Two rf probes are mounted at the upper beam tube (fig. 1), one being used for field calibration and detection of higher modes, the other for the rf regulation system and electron current detection.

* Developed by C. Benvenuti at CERN.
3.3. Temperature mapping

In a recent experiment at CERN [12,13] it was shown that a detailed temperature map of superconducting cavity can be obtained. Such a map shows all significant energy loss areas of a cavity and thus gives a better insight into loss mechanism during operation and field limiting processes. For such a measurement the cavity is immersed in a subcooled helium bath (bath temperature 2.3–2.5 K, bath pressure 1000 mb) and a chain of 39 carbon resistors (fig. 4a) is moved around outside of the cavity. Resistors 1 and 39 are located at the beam tube. In order to ensure a good thermal contact between resistors and cavity walls the resistors slide under spring tension (fig. 4b). The use of subcooled He is essential because bubbles are absent and therefore microconvection is inhibited. This reduces the cooling capacity of liquid He substantially and larger temperature differences at the carbon thermometer can be obtained. As the cooling mechanism is convection inside the liquid helium the geometry of the cooled surface and its orientation with respect to the gravitational field influences the temperature increases measured by the resistors. In a test experiment the temperature increase produced by an electrical heater across a 2 mm thick Nb wall has been measured over three decades for different orientations of the heated surface [14]. The result is given in fig. 5. At temperature differences of about 2000 mK film boiling sets in and results in a very steep increase of temperature. A point like heat source at the inside of the cavity wall (2 mm thickness) produces at the outside a region of increased temperature with a half width of ~20 mm.

The temperature scanning system is shown in fig. 4a. It can be rotated in minimum steps of 0.33°. The point like heat sources can be localised with an accuracy of ±3 mm. The reproducibility of temperature measurements has been checked and is better than ±10%.

In fig. 6 typical temperature maps obtained with an automated data acquisition system [11] are

![Fig. 5. Temperature increase produced by a heat source across a horizontal 1.5 mm Nb wall inside a subcooled He bath at 2.5 K. For other positions ΔT changes by less than 10%. At a bath temperature of 2.3 K, ΔT increases by 14% (courtesy W. Weingarten).](image)

![Fig. 6. Temperature maps of the superconducting cavity for three different accelerating fields. The surface of the cavity body is projected on a plane. On the x axis the distance along a circle of constant latitude is plotted. The y axis shows the number of resistor (see fig. 1). The temperature increase is plotted along the vertical axis. A region of increased rf losses shows up at the top flat region of the cavity. For $E_{\text{acc}} = 3.12$ MV/m three lines of electron impact and an isolated lossy region can be seen in addition.](image)
shown. In fig. 7 typical temperature profiles of the cavity are shown, measured by one resistor along its path around the resonator for different field levels. Plots of this kind give the possibility of locating and evaluating precisely the field dependence of specific lossy regions inside the cavity.

3.4. X-ray and light detection systems

In the course of the experiments it was found useful to develop a system of X-ray detectors giving — similarly to the $\Delta T$ maps — information on the spatial distributions of X-ray intensity around the cavity. Therefore 10 solid state radiation detectors [15] were mounted in a rotating frame similar to the one used for the resistors in order to allow X-ray mapping of the cavity. The detectors have a sensitive surface of 6 mm diameter and a thickness of 100 $\mu$m. They are used in a charge sensitive mode and can therefore be considered as solid state ionisation chambers, allowing relative intensity measurements but giving no information on the X-ray energy. Solid state detectors turn out to be particularly well suited for this application because they can work at very high radiation intensity (estimated to range up to 300 R/h near the cavity wall), because their leakage current drops at He temperature to an unmeasurable value and because no bias is needed at this temperature. They are used in direct contact with the liquid He bath and up to now no detrimental effects due to temperature cycling have been detected. The data acquisition and computer system used for the temperature mapping has been extended to the X-ray system allowing X-ray plots similar to the $\Delta T$ plots shown in figs. 6 and 7. In fig. 8 a typical X-ray map is shown. We note that the X-ray intensity is attenuated by a factor $>100$ just outside the cavity walls for X-ray energies $E_x < 60$ keV.

Additional but less specific information on X-ray intensities and X-ray energies can be obtained outside the cryostat with a NaI detector and an ionization chamber which is used for long range comparison of X-ray intensities. Electron currents inside the cavity are detected by one of the rf probes (fig. 1) at the

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**Fig. 7.** a) and b) Temperature profiles measured by resistor 4 along its path around the cavity for two different acceleration fields (see also fig. 6). Note the change of scale. c) Same for resistor 10 at high field: an isolated lossy region at $\phi = 130^\circ$ and three regions of electron impact show up.

**Fig. 8.** (a) X-ray map of the cavity. The same representation as for the temperature maps has been chosen (cf. fig. 6). X-ray intensities are given in mV. (b) Typical X-ray profile obtained with one solid state detector.
upper beam tube with a sensitivity >1 nA. Light can be detected during cavity operation at the viewing part above the cryostat cover (fig. 1) either visually or by means of a photo-multiplier.

4. Experimental results

4.1. Summary of results

In table 2 we give a summary of results obtained up to now with the single cell cavity.

The standard treatment i.e. a chemical polishing has been applied for the three first measurements and comparable results in Q values and electron loading were obtained. From the temperature and X-ray maps one finds that this kind of treatment produces a new surface without memory effect for previous regions with increased rf losses or electron activity. After the first measurement a bake out to 350°C has given an improvement in low and high field Q value. Later on a bake out temperature of 200°C was not exceeded because of heavy oxidation of the niobium wall at air.

Ion bombardment cleaning (IBC) has been applied in the measurements 4 and 6. IBC at low dose reduced the $Q_0$ value by more than a factor of two and definitely increased the electron emission. A bake out at 200°C did not improve the cavity performances. A second IBC at threefold ion dose brought the $Q_0$ value back to the initial value. The electron loading could be reduced considerably by high field processing but remained somewhat higher than the initial CP treatment.

At measurement 8 the cavity was filled with liquid He in order to block electron loading inside the cavity. Despite the fact that the cavity was filled at a bath temperature below the λ point and across a dust filter with pore size of 0.45 μm, the $Q_0$ value decreased from $3.9 \times 10^9$ to $6 \times 10^6$ making high power work impossible. After emptying the cavity by evaporating the liquid He through the filter and after repumping the cavity (at 4.2 K) to $2 \times 10^{-7}$ mbar the $Q_0$ rose to $10^8$. The temperature maps showed a strong increase of rf losses at the lower flat region presumably due to impurities (oil) contained in the liquid He. For the first time visible light could be seen and a considerable electron activity was observed already at field levels $E_{acc} = 1.25$ MV/m. The electric loading could not be reduced by a high field processing. A bake out of the cavity at 200°C did not improve the cavity performance.

<table>
<thead>
<tr>
<th>Run no.</th>
<th>Treatments and operation conditions</th>
<th>$Q_0$ (low field 4.2 K $\times 10^9$)</th>
<th>$E_{acc}$ without $e^-$ loading (MV/m)</th>
<th>$E_{acc}$ maximum (MV/m)</th>
<th>Field limitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CP 70 + 20 μm, 2 bake out upright position</td>
<td>2.1</td>
<td>3.5</td>
<td>4.6</td>
<td>quench at weld</td>
</tr>
<tr>
<td>2</td>
<td>CP 50 μm, methanol rinsing upright position</td>
<td>1.8</td>
<td>3</td>
<td>4.4</td>
<td>quench at bottom flat</td>
</tr>
<tr>
<td>3</td>
<td>CP 18 μm (upside down position) methanol rinsing, bake out</td>
<td>1.7</td>
<td>3.5</td>
<td>4.67</td>
<td>quench at bottom flat</td>
</tr>
<tr>
<td>4</td>
<td>IBC $8 \times 10^{17}$ Ar$^+$/cm$^2$</td>
<td>0.7</td>
<td>3</td>
<td>3.7</td>
<td>quench at bottom flat</td>
</tr>
<tr>
<td>5</td>
<td>bake out (200°C)</td>
<td>0.7</td>
<td>3</td>
<td>3.7</td>
<td>same as (4)</td>
</tr>
<tr>
<td>6</td>
<td>IBC $2.2 \times 10^{18}$ Ar$^+$/cm$^2$</td>
<td>1.7</td>
<td>3</td>
<td>4.1</td>
<td>electron loading</td>
</tr>
<tr>
<td>7</td>
<td>only warm up to room temperature</td>
<td>1.7</td>
<td>3</td>
<td>4.1</td>
<td>electron loading</td>
</tr>
<tr>
<td>8</td>
<td>filling with liquid He evacuating and pump down</td>
<td>1</td>
<td>1.25</td>
<td>1.5</td>
<td>electron loading</td>
</tr>
<tr>
<td>9</td>
<td>bake out (200°C)</td>
<td>1</td>
<td>1.25</td>
<td>1.5</td>
<td>electron loading</td>
</tr>
<tr>
<td>10</td>
<td>OP 3x, leaks, upright position, $H_{ext} &gt; 500$ m Oe</td>
<td>0.5</td>
<td>2.2</td>
<td>3</td>
<td>electron loading</td>
</tr>
<tr>
<td>11</td>
<td>exposure to dust free air, leaks</td>
<td>0.5</td>
<td>~2.5</td>
<td>~3</td>
<td>electron loading</td>
</tr>
<tr>
<td>12</td>
<td>CP 20 μm + 20 μm, upright position, water rinsing, drying in horizontal position</td>
<td>2.5</td>
<td>3</td>
<td>&gt;3.7</td>
<td>electron loading</td>
</tr>
</tbody>
</table>
In experiment 10 we tried to remove the impurities left by the liquid He filling by a threefold oxipolishing. From temperature maps one concludes that at least parts of the impurities have been removed. However, the results are not conclusive because a leak developed during the cool down and the cavity had to be brought up to air. The low $Q_0$ value may be due to the operation of a 5 T magnet in the vicinity of the cavity, rising the external field to values well above the earth magnetic field. This experiment was extended over a period of 500 h during which CW operation at 2.2 MV/m was applied i.e. just below the level where electrons are produced and no measurable degradation in $Q_0$ and $E_{acc}$ was found. However, in the course of this experiment and additional point with increased rf losses suddenly developed at the lower flat region which later on disappeared again. We suspect that this was due to a dust particle which fell down from the upper parts of the cavity and subsequently was burned away. Measurements number 11 was done in order to check that an exposure to air does not change the distribution and nature of regions with increased rf losses. Such an exposure will be necessary once a new scanning electron microscope designed to be operated inside the cavity is used for the detection and identification of such regions. All high loss points remained unchanged. Within measuring accuracy the $Q_0$ values and the electron activity also did not change. After dismounting of the cavity a considerable number of luminescent particles (5–10 light points/cm²) were observed at the bottom flat region whereas only a few particles were seen at the top flat. A rinsing in dust free methanol reduced the number of light points to the one observed previously at the top flat region. It was possible to identify some of these light points with the sources observed in the temperature maps. As the light points, the rf losses and the electron sources were mainly concentrated at the lower flat region a different rinsing procedure was applied in measurement 12. Instead of methanol, distilled water was used and the cavity was dried in a horizontal position. It was hoped that residues would not concentrate at the lower flat parts and this was confirmed by the measurements. During all measurements the following behaviour of the cavity resonance frequency was found: the frequency change between room temperature and 4.2 K is 240 kHz. One cycle between these temperatures produced frequency changes smaller than a few kHz.

4.2. Multipacting

The absence of electron multipacting in the spherical cavity as indicated by measurements of the Genova group [6] at 4.5 GHz, at Wuppertal and CERN [5] for 3 GHz and predicted by computer simulations at Wuppertal [7] was confirmed. It

![Fig. 9. Unloaded $Q$ values as a function of $E_{acc}$ for three different measurements. For measurement 2 a $Q$ dip around 0.4 MV/m can be seen. The decrease for $E_{acc} > 3$ MV/m is due to electron loading.](image-url)
should be remembered that the measurements were done after different surface treatments (CP, IBC, OP). Exposures to air, liquid helium and different rinsing liquids (methanol and water) also did not give rise to multipacting. It is expected that this absence of multipactor will also hold for a multicell spherical cavity. For the \( \pi \) mode this has already been shown at 4.5 GHz up to a field level of 8.2 MV/m [16] and at 3 GHz up to 5.6 MV/m [17]. In the first experiment on a 4 cell 500 MHz cavity performed at CERN by our group no multipacting has been observed up to the maximum achieved field level of 2.8 MV/m.

4.3. RF losses

4.3.1. \( Q \) variations with field level

In fig. 9 we show a few measured \( Q_0 \) values as a function of acceleration field. The highest \( Q_0 \) values at low power were obtained after a standard surface treatment and amount to \( 2.6 \times 10^9 \) and \( 5.1 \times 10^9 \) at 4.2 and 2.3 K, respectively. They correspond to a residual resistance of \( 5 \times 10^{-8} \) \( \Omega \). From the temperature dependence of the BCS resistance a theoretical \( Q_0 \) value at 4.2 K of \( 3.6 \times 10^9 \) is expected. At field values above \( \sim 3 \) MV/m one observes a decrease of the \( Q_0 \) value which is due to electron loading (see also sect. 4.5).

As the field decay in this range is not a simple exponential function and as it is difficult to measure it precisely on a scope we have calculated \( Q_0 \) by using the two well known relations

\[
E_{\text{acc}} = \left( \frac{R}{Q} \right) \frac{1}{l(1 + \beta)^2} P_l Q_0 \right)^{1/2} \tag{1}
\]

and

\[
E_{\text{acc}} = \alpha U_1 ; \tag{2}
\]

\( R/Q \) and \( l \) are defined in table 1; \( \beta \): coupling factor; \( P_l \): incident rf power; \( U_1 \): rf probe signal (quadratic diode characteristics!); \( \alpha \): calibration factor obtained at low rf power level.

Combining (1) and (2) one gets

\[
Q_0 = \frac{\alpha^2 U_1 (1 + \beta)^2}{R \cdot \frac{1}{Q} \cdot l \cdot 4\beta \cdot P_l}
\]

\( Q_0 \) was also measured with the help of a logarithmic amplifier.

Fig. 10. a) Temperature map obtained after a three-fold oxidopolishing; b) temperature profile at bottom (high loss) region; c) temperature profile at top (low loss) region.

Fig. 11. Mean value of rf power dissipated at the cavity wall for the 39 resistors (cf. fig. 1) and comparison with the \( F^2 \) and \( H^2 \) distribution of the fundamental mode. The mean values are obtained by integrating losses over the angular interval \( \phi = 0-360^\circ \) and applying the calibrations of fig. 5.
4.3.2. Spatial distribution of rf losses

The temperature maps obtained with the resistor system provide a unique facility for localizing and measuring rf losses inside the cavity. One of the main conclusions of these plots is that losses are not at all uniformly distributed and are in particular not found in the regions where the magnetic surface field is high. On the contrary, at the equatorial welds where the magnetic field is almost at its maximum and where the surface structure is disturbed, the rf losses show their minimum. For field levels where electron loading can be neglected, one can distinguish three kinds of losses (fig. 6):

- uniform losses corresponding to the BCS resistance;
- homogeneous losses exceeding the normal BCS losses which are preferentially concentrated in the region where $H$ and $E$ are big and which in some cases seem to be produced by many point like losses,
- well isolated point like losses.

In fig. 10a a typical distribution at low field level where electrons are not yet visible is given. As may be seen losses are largely concentrated at the lower flat regions. In figs. 10b and 10c the temperature distribution for a given resistor at the high loss region and the low loss region is given. Comparing these two $\Delta T$ distributions one sees that losses can be orders of magnitude higher in the high loss region and many peaks can be distinguished. It is to be noted that the half width of this peaks corresponds nearly always to $\sim 20$ mm; this is the measured half width for point like heat sources and indicates that loss regions have indeed dimensions which are small compared to the half width. In fig. 11 we have plotted for each resistor $R1-R39$ the mean value of power dissipation over the angular interval $\varphi = 0-360^\circ$ (i.e. the latitude dependence of mean values; for plots of this kind we subtract the losses produced by electron trajectories or by strong point like heat sources). Again the asymmetry of losses is clearly seen and impurities with significant dielectric losses must be assumed. One may compare these losses with the magnetic and electric field distributions of the fundamental mode (fig. 12). It is not possible to fit the measured power loss with a linear superposition of $E^2$ and $H^2$ even if one assumes a uniform lossy layer all over the cavity walls. By integrating all losses the total losses can be
determined and a correspondence with the measured \(Q_0\) within 20% has been found. The rather uniform losses outside the high loss regions always correspond to \(Q_0\) values somewhat above \(2 \times 10^9\) i.e. about 50% of the value expected for \(Q_{BCS}\) at 4.2 K.

Besides the high loss regions isolated points of increased losses have also been found. One of these can be seen in the temperature map of fig. 6. In fig. 13a its temperature profile is given and in fig. 13b the projection of the temperature distribution on a plane is shown. This distribution with a half width of \(\sim 15\) mm indicates a point like heat source. This point was seen for the first time in run number 3 (after a CP of 18 \(\mu\)m) and resisted to all treatments up to run 10 where an oxipolishing was applied. We therefore presume that it is a surface inclusion of some normal conducting material with a thickness of the order of 1 \(\mu\)m. Points of this nature have been found causing no fast break down up to magnetic field levels of 160 G and their rf losses are negligible with respect to the total losses produced at the cavity wall. From the temperature distribution alone it is not possible to determine the size and resistivity of such a point like loss because the product \(R_s \cdot S\) (\(R_s\) surface resistance, \(S\) surface of the loss region) determines the loss \(P_H\). A more detailed analysis of the heat loss and conduction across the cavity wall and into the He bath could elucidate this question. We can give an estimate of the product \(R_s \cdot S\) for a typical point like heat source situated in the region of maximum magnetic and vanishing electric field for which one finds \(R_s \cdot S = 6 \times 10^{-6} \, \Omega \, \text{cm}^2\).

Assuming e.g. an iron inclusion \((R_{Fe}^s = 2 \times 10^{-2} \, \Omega\) at 500 MHz\) one gets \(S = 0.3 \, \text{mm}^2\) as an area for the bad region.

4.3.3. Field dependence of rf losses

The \(Q_0\) values measured in the different runs are normally constant up to field levels were electron loading sets in. One therefore would expect that the dominant rf losses show a quadratic dependence in field. This is confirmed by the temperature maps taken at different field levels. We note that this dependence may show up only after rf processing when the electron activity at low field levels has become small. This general behaviour does not exclude a different behaviour for isolated lossy spots. In fig. 14 a few field dependencies for such regions are shown. The \(E_{acc}^3\) and \(E_{acc}^4\) dependence may be explained by a temperature dependence of the resistance or by the increase in size of a normal conducting region around the bad spot. More detailed observations and calculations [18] have to be performed in order to explain these phenomena. One of the lossy spots shows a switching from lower to higher losses at a field level of \(E_{acc} = 2.3\) MV/m (fig.
14) *. This switching may be due to a transition from a superconducting to a normal state. Other loss regions showing a switching behaviour at much lower field levels \(E_{\text{acc}} < 0.4 \text{ MV/m}\) were observed in regions of high electric field. Therefore it may also be possible that the change in resistivity is due to a transition insulator–semiconductor under the action of a high electric field. All these switchings result in a reduction in \(Q_0\) values (fig. 9).

4.3.4. Dependence of rf losses on surface treatments

One of the striking features of temperature distributions after a chemical polishing (CP) is the concentration of losses at the bottom flat region of the cavity. We remember that a CP is done in the vertical position as well as the following rinsing procedures in \(\text{H}_2\text{O} + \text{H}_2\text{O}_2\) and in dust free methanol. A priori one cannot exclude that any of these treatments is responsible for the asymmetric distribution of losses. In order to check the influence of CP the cavity was turned up side down during one treatment (measurement 3), rinsed by dust free methanol in the same position and mounted and pumped in the normal position afterwards. The difference in rf losses for both positions is shown in fig. 15. One concludes from this that either the CP or the rinsing procedure seems to concentrate lossy material at the bottom flat. The concentration of residues from the methanol evaporation during pump down which should preferentially occur at the lower flat or a condensation of molecules seems not to be harmful.

It was possible to remove this asymmetry by an improved chemical treatment (measurement 12). During this treatment the acid emptying of the cavity was achieved within 15 s. The final rinsing was done with \(\text{H}_2\text{O}\) instead of methanol and the water was dried while the cavity was placed in the horizontal position. This treatment not only removed the asymmetry of losses but also reduced them to the smallest values ever obtained (fig. 15). Furthermore no increased losses at the equator region where the remaining rinsing water should have concentrated was found. This is another hint for the fact that losses are produced preferentially in the regions where high electric and magnetic field coexist. It is to be noted that in a further experiment after a warm up of the cavity a slight increase of losses at the bottom flat was again observed. This seems to indicate that losses may be due to dust particles and other impurities originating from the upper parts of the vacuum system or from gas condensation at the bottom flat.

IBC can greatly affect the resistivity of lossy regions as can be seen from fig. 16. The rf losses obtained after an upside down CP treatment and their asymmetry is considerably increased by the first IBC treatment at low intensity. The asymmetry increase cannot be explained by the cathode used for the IBC. A second IBC with a three times higher dose rate reduced the losses everywhere nearly to the initial

* Below the switch field the temperature peak disappears completely and only a uniform background remains.
values. This behaviour could be explained by the argon gas which is introduced during the IBC at the lower beam tube and is pumped through the upper beam tube. At the beginning of the IBC impurities are removed from the walls and are deposited preferentially by the argon flow at the upper cavity walls. With increasing sputtering and pumping time impurities are removed from the cavity leaving a surface with less rf losses and decreased asymmetry of losses [19].

A drastic increase of rf losses and change of their distribution was seen after the cavity had been filled with liquid He and was repumped again (at 4.2 K). As expected the additional losses are now concentrated at the lower flat region. The spatial distribution of losses shows a peak nearly at the region of maximum electric field (fig. 17) typical for dielectric losses. This behaviour can be explained by the oil contained in liquid He which remained at the bottom flat part after removing the liquid He from the cavity.

As a general conclusion for the rf losses one may state that high losses tend to show a more asymmetric distribution and are more dielectric in nature than low losses.

4.4. Light detection

Light and soft X-rays can be detected during operation of the cavity at the upper viewing part (fig. 1). It is however at present not possible to see directly the cavity body and in particular the iris rounding where light emission is most suspected to occur and therefore the light can reach the viewing part only after internal reflections. The result of an observation of visible light as a function of $E_{\text{acc}}$ with the help of a multiplier is given in fig. 18. The measured points are plotted against $E_{\text{acc}}^{1/2}$ and lie on a straight line. The following model [20] can explain this behaviour. One assumes a small particle well insulated thermally from the Nb wall which is heated up to a temperature $T$ either by the electric or the magnetic rf field and loses its energy by black body radiation. For this particle with a surface $S$ and a surface resistance $R_s$, we can write to a first approximation and by assuming quadratic dependence of losses on $H$ (or $E$):

$$\frac{1}{2} \chi R_s H^2 = \sigma T^4 S \cdot e \cdot$$

with $\chi$ a factor depending on the exact geometrical shape of the particle; $\chi$ is normally of the order of unity

$$\sigma = 5.57 \times 10^{-12} \text{ W/cm}^2 \text{ (°C)}^4$$

$e$ the emissivity.

From eq. (3) one gets

$$T = (\frac{1}{2} \chi R_s H^2 / \sigma e)^{1/4}.$$  

(4)

The electron multiplier detects light with high efficiency only in a small wave length interval. According to the laws of black body radiation and for $T > 1000°\text{C}$ one gets the following expression for the light intensity $I_\lambda$ radiated in the wave length interval $\lambda, \lambda + d\lambda$

$$I_\lambda d\lambda = \frac{2\pi c^2}{\lambda^5} \exp(-hc/\lambda kT) \ d\lambda.$$  

(5)

substituting (4) into (5) one obtains

$$I_\lambda \sim \exp - hc/k\lambda(\frac{1}{2} \chi R_s H^2 / \sigma e)^{1/4}$$

(6)

or $I_\lambda \sim \exp - (K/H^{1/2})$

where $K$ is constant for a given point source and measuring layout.

From the slope of the exponential one may determine $R_s$ once $\chi, \lambda, e$ and $H$ are known. For the light source of fig. 18 we assume $\chi = 1, e = 1$ and $H = H_p/2$ giving $R_s = 5.4 \times 10^{-2} \text{ Ω}$. This is the right order of magnitude of $R_s$ for a metallic particle.
4.5. Electron loading phenomena

4.5.1. General observations

For all surface treatments applied one observes above a definite field level the onset of electron loading which increases rapidly with field level. Electrons show up by the following phenomena:

- $Q_0$ degradation;
- temperature increase along a definite meridian due to impinging electrons (electron trajectories);
- X-ray and electron intensity increasing exponentially with field;
- light production;
- higher mode excitation.

It turns out that electron trajectories are generally the most sensitive way for detecting electrons, and can be seen at field levels where neither X-ray intensity, nor electron emission or higher mode excitation can be detected. In some cases electron trajectories have already been detected at field levels $E_{acc} < 1$ MV/m where a $Q_0$ degradation is barely detectable. The highest field levels without electron loading ($E_{acc} > 3$ MV/m) have been obtained after the standard surface treatments (table 2). These levels cannot be increased very much by high field processing. Typical $Q$ degradations due to electron loading are shown in fig. 9. Ion bombarded surfaces show initially a much stronger electron loading which starts already at field levels $E_{acc} \sim 1$ MV/m. Rf-processing of a few hours can improve this situation considerably and field levels of 3 MV/m without electron loading have been reached. Altogether the electron activity remains somewhat higher after IBC.

4.5.2. Electron emission from point sources

The most striking phenomena linked to the electrons inside the cavity are shown by the temperature and X-ray maps. We give two examples in figs. 19 and 20.

Well defined temperature enhancements can be seen extending along one meridian of the cavity body. From plots of this kind the azimuth and the width of the temperature distribution can be obtained. It turns out that these distributions are centred within measurement errors to the same meridian all over its length (fig. 21a). The half width is varying along this meridian but does not show a systematic increase or decrease and does nowhere exceed the half width of a point like source (fig. 21b). We can therefore assume that the temperature distributions are produced by a line like heat source whose lateral extension is small against the measured half width. We attribute these temperature distributions to an electron source located at the meridian of the temperature distribution. It emits electrons which are accelerated by the electric rf field and which for the TM$_{010}$ mode remain within the meridian plane of the source. The electron impact on the cavity wall produce the temperature distributions shown. From the small width one concludes that electrons are emitted with small transverse momenta and that back scattered electrons do not play a dominant role for the temperature increase along the trajectories.

The fit for the measured temperature distribution is obtained by assuming a point source for electrons which may be either of the thermionic type emission:

$$j = AT^2 \exp \left(-\frac{\phi}{kT}\right)$$  (Richardson)

or of field emission type which for niobium can be written:

$$j = 1.54 \times 10^{-10} \left(\frac{\beta E}{\phi}\right)^2 \times \exp \left[\frac{6.83 \times 10^9 \phi^{3/2}}{\beta E} - \frac{\nu(t)}{\beta E}\right]$$

(Fowler-Nordheim)  (8)

with:

- $j$: current density in A/cm$^2$;
- $A$: $1.2 \times 10^2$ A/cm$^2$ K$^2$ (thermionic constant);
- $\phi$: work function of metal: for niobium we assume $\phi = 4$ eV;
- $k$: $8.617 \times 10^{-5}$ eV/K: (Boltzmann constant);
- $\beta$: field enhancement factor;
- $E$: electric field at electron source in V/m;
- $t = 3.79 \times 10^{-5} \sqrt{\beta E}/\phi$;
- $\nu(t)$: a function tabulated in reference [21]. $\nu(t)$ is for most practical cases of the order of 1.

For a thermionic source it is assumed that electrons are emitted independently of the rf phase (although an additional field emission enhancement cannot be excluded). Field emission sources are characterized by the local field enhancement $\beta$ and the work function $\phi$ of the emitter; they emit electrons preferentially at high field level. The electron impact energies are below 1 MeV. Therefore their range inside Nb remains below 0.5 mm and more than 95% of their energy is lost inside the Nb wall by absorption; the remaining part is emitted as X-ray radiation. Since the losses in the area outside the electron impact lines increase with $E_{acc}^2$, the backscattered elec-
trons cannot contribute significantly to these losses. We therefore conclude that the main portion of the impact energy is dissipated locally around the point of impact.

In order to understand the nature of the electron emitting region (field emission or thermionic emission) extensive computer calculations have been made for the simulation of the measured \( \Delta T \) and X-ray distributions. We give here only a few typical results. Electron trajectories are calculated by using a SUPERFISH [8] field map under the assumption of negligible electron energy at emission. A trajectory family is calculated for different emission phases with respect to the electric rf field \( E = E_0 \sin \omega t \). Each family is characterized by the quantities \( s_0 \) (source location) \( E_{\text{acc}} \), and \( \beta \). The work function of the emitting source is unknown and it is assumed to be equal to the one of niobium (\( \phi = 4 \) eV).

In figs. 22–25 some typical trajectory families and their dependence on \( s_0 \), \( E_{\text{acc}} \) and on the nature of the emission process is shown. From a careful comparison of computed electron trajectories and their energy depositions along one meridian with the rf loss distributions derived from the measured temperature distributions one can determine \( s_0 \), \( E_{\text{acc}} \) and the nature of the emission process. In no case the assumption of thermionic emission has given a reasonable fit; we therefore conclude that field emission dominates the behaviour of electron sources (cf. figs. 26a and 26b).

We have analysed up to now 14 electron trajectories. For a few of them the fit was performed for different field levels. The shape of the distribution is
very sensitive to $s_0$ especially if the source is close to the iris rounding. Therefore the source location can be determined with a precision of $\pm 2$ mm in $s_0$ and $\pm 2^\circ$ in angle. The values of $\beta$ influences the shape of

Fig. 21. a) Meridian $\varphi$ for the electron trajectories of fig. 20 measured by the different resistors. The large fluctuations at both ends of the trajectory are due to measuring errors. b) same as a) for the half width $\sigma$ of the electron trajectory.

Fig. 22. Trajectory family for the same emission point $s_0$ but different $E_{acc}$. Trajectories are shown in $5^\circ$ steps of emission phase with respect to $E(t) = E_0 \sin \omega t$. The corresponding electron impact energies and power loss is also shown.

Fig. 23. Trajectory family for the same $E_{acc}$ but different emission point $s_0$. 
the measured temperature distributions less critically and variations of up to ±30% have been found for the same trajectory at different field levels. In order to fit the measured temperature distributions we have not included the true secondaries and the increase of the residual resistance by wall heating. As expected the fits become very poor if higher order mode are excited in the cavity. Of the 14 sources analysed 13 are located at the region of maximum electric field (on the iris rounding); only one source has been found to lie at the outer border of the flat region where \( E \approx E_p/2 \). No clear correlation of source position with the regions of increased losses (section 4.3.2) has been found, but a definite concentration of sources at the bottom part is observed because 12 out of 14 sources are located there.

For the later analysis of X-rays distributions and radiation damage the electron impact energies and intensity distributions are important. They are therefore included in figs. 26–28. Typical electron impact energies range up to 700 keV.

The losses produced by an electron trajectory family also allow computation of the mean current emitted by an electron source. For a typical source one finds that the total losses are about 1.8 W at \( E_{\text{acc}} = 3.3 \text{ MV/m} \) as computed from the \( Q_0 \) degradation. For a mean impact energy \( E_{\text{el}} = 150 \text{ keV} \) one then gets for the mean electron current \( I_{\text{el}} = 12 \mu\text{A} \). If one assumes that this intensity is spread out uniformly over the whole length of the cavity body \( (l = 50 \text{ cm}) \) and over a 1 mm wide region one finds that the number of impinging electrons along a trajectory is \( I_e = 3.8 \times 10^{13} \text{ e}^-/\text{cm}^2 \text{ s} \).

After a standard surface treatment a large number of electron sources becomes visible at field levels \( E_{\text{acc}} > 3 \text{ MV/m} \). High field processing reduces this number within a few hours. New sources have also been observed appearing and sometimes disappearing again during processing. Ion bombarded surface show initially a great number of electron sources which become visible already at field levels as low as \( E_{\text{acc}} = 1 \text{ MV/m} \). High field processing reduces this number within a few hours dramatically to values comparable to the ones for chemically polished surfaces. Chemical polishing and oxipolishing removes all electron sources but produces new ones whose location shows no correlation with previous ones. Ion bombardment

Fig. 25. Electron current and power loss as a function of \( s \) corresponding to fig. 22b) for the same \( E_{\text{acc}} \) and \( s_0 \) but different emission conditions.
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$E_{\text{acc}} = 4.0 \text{ MV/m}$

$S_0 = -24.8 \text{ cm}$

Fig. 26. Fit of measured power loss of an electron trajectory family for run 301. The measured values are indicated by crosses. The computer fit is given by a solid line. (a) fit for a thermionic emission source; (b) fit for a field emission source with the parameters indicated; (c) electron current and impact energy corresponding to the fit (b); (d) computed X-ray intensity corresponding to the fit (b). The peaks of the measured X-ray intensities are indicated by arrows.

Cleaning sometimes removes electron sources, sometimes does not and may even increase the emissivity of a source. A bake out at 200°C or an exposure to dust free air seems to have no detrimental influence on the electron loading. The field emission nature of electron sources and their concentration in the region of high electric fields seems established but there remains great uncertainty with respect to the origin of these sources. An interesting observation is that the number of electron sources increase rapidly above a definite field level and remains almost constant (typically 5–15) up to the highest field levels obtainable.

4.5.3. X-ray maps

Additional information on the electron loading can be derived from the X-ray maps. In fig. 29 the X-ray distributions corresponding to the temperature map given in fig. 6 are shown. These distributions show a broad background of X-rays on which for a few detectors sharp intensity peaks are superimposed. These X-ray peaks are always located at the meridian of an electron trajectory family (fig. 19). A fit for the intensity peaks is obtained in the following way: One assumes the source location $S_0$ and $(\beta, \phi_0)$ parameters obtained from the associated temperature distribution and calculates the corresponding impact energy and intensity distributions for the electrons. The X-ray intensity produced by the primary electrons and measured by the X-ray detectors is computed by taking into account the cross section for thick target bremsstrahlung and its distribution in angle and energy, the transmission of X-rays across the Nb wall, the solid angle subtended by the detectors and its efficiency for X-ray detection [22]. In this way a satisfactory fit with the measured X-ray peaks has been obtained for most of the electron sources. We give an example in figs. 26 and 27 which confirms the
parameters chosen for the corresponding temperature fits.

Computations of this kind including only primary electron effects cannot explain the large X-ray background observed whose integrated intensity is by far exceeding the intensity of the X-ray peaks. They also do not allow an explanation of the X-ray spectra measured outside the cryostat which can range up to energies exceeding the energies of primary electrons.

X-ray energies up to 1.5 MeV have been measured at field levels $E_{acc} = 4$ MV/m; such high X-ray energies can possibly be explained by back scattered electrons which are reaccelerated in the high electric field regions [23–25].

4.5.4. Field enhancement factors

It is useful to compare the $\beta$ values determined from the trajectory fits with $\beta$ values obtained by the usual Fowler–Nordheim fits to the X-ray intensity and electron current. X-rays are measured with an ionization chamber outside the cryostat located at the equator plane of the cavity and by the solid state X-ray detectors. A few results obtained by different methods are given in table 3 and are compared with $\beta$ values obtained from trajectory analysis. A typical Fowler–Nordheim plot for the electron current is given in fig. 30. From table 3 one concludes that the $\beta$ values lie in the range obtained in similar 500 MHz cavities at other laboratories [26,4]. The $\beta$ values obtained after an ion bombardment cleaning treatment are somewhat higher than the ones obtained after a chemical polishing. It has also been shown that the $\beta$ values for a given source can be decreased by rf processing. This is in line with observations on trajectories, where a decrease of intensity and even a complete vanishing of electron sources has been observed during processing. The $\beta$-values obtained in experi-
Fig. 29. X-ray intensity profiles as a function of the azimuth $\varphi$ for different detectors. For the position of detectors see fig. 1. X-ray intensity is plotted in relative units. The measurement corresponds to the temperature map of fig. 6.

measurement number 4 from electron current, X-ray intensity outside the cryostat and from the background of the solid state detectors agree reasonably well. It is suspected that the X-ray intensities of the peaks obtained by the solid state detectors (fig. 29) are more specific for the associated electron source than overall X-ray measurements like e.g. measurements outside the cryostat. Indeed the values obtained from the solid state detector “peaks” differ from one source to the other. The agreement with the trajectory fits is rather poor but one should keep in mind that the trajectory fit is rather insensitive to $\beta$.

Table 3
Field enhancement values $\beta$

<table>
<thead>
<tr>
<th>Measurement number</th>
<th>Treatment</th>
<th>from electron current</th>
<th>from X-rays outside cryostat</th>
<th>from solid state detectors</th>
<th>from trajectory analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Background (mean value)</td>
<td>Peaks</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>CP</td>
<td>-</td>
<td>-</td>
<td>$545 \pm 27$</td>
<td>$400 (\varphi = 160^\circ)$</td>
</tr>
<tr>
<td>3</td>
<td>CP</td>
<td>602</td>
<td>576</td>
<td>-</td>
<td>$471 (\varphi = 108^\circ)$</td>
</tr>
<tr>
<td>4</td>
<td>IBC</td>
<td>881</td>
<td>921</td>
<td>$829 \pm 67$</td>
<td>$1234 (\varphi = 267^\circ)$</td>
</tr>
<tr>
<td>6</td>
<td>IBC</td>
<td>705</td>
<td>808</td>
<td>-</td>
<td>$929 (\varphi = 221^\circ)$</td>
</tr>
<tr>
<td>12</td>
<td>CP</td>
<td>640</td>
<td>730</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
4.5.5. Excitation of higher modes

Above a definite threshold field higher mode excitation is a way for detecting electrons inside a cavity. In the course of the experiments up to 6 higher modes have been excited. The modes which have been observed and their identification are given in table 4. At the threshold field level for higher mode excitation it may take minutes before a higher mode is slowly built up; an increase of the field level decreases rapidly the excitation time which at high field levels becomes equal or inferior to the rise time of the fundamental mode. Higher modes change the electron landscape of the cavity. Excitation of other electron sources, shifts and suppression of trajectories and a change of X-ray intensity have been observed. Higher modes can be excited to a field level comparable to the fundamental mode. They may grow at the expense of other higher modes and always at the expense of the fundamental mode; in some cases the additional input power is no longer increasing the stored energy of the fundamental mode but only the ones of higher modes. High field processing may decrease higher mode excitation as it does other electron activities. Normally the first excited mode is the TM_{110} deflecting mode which is also the most tenacious one. This is understandable because its field configuration favours excitation by electron trajectories with an emission point in the region of E_p. The TM_{110} mode is sometimes found at two frequencies (Δf ≈ 1 MHz) caused by a slight ellipticity of the cavity. Although the most convenient way of observing higher modes is a spectrum analyser, useful information can also be obtained with the help of the transmitted signal whose height generally is changed by the excitation of a higher mode.

4.6. Production of regions with increased rf losses

During measurements 2, 3 and 4 (table 2) irreversible surface damage was observed after a few hours of rf operation at field levels above E_{acc} = 3.5 MV/m. These “home made” areas of increased resistivity lead to a fast rf breakdown (quench) at field levels between 4.2 and 4.8 MV/m and confirm observations of other groups [27,28] of irreversible surface damages caused by electron impact. The three quench regions observed were situated at the outer rim of the bottom flat part of the cavity where H ≈ H_p, and E ≈ E_p/2. They were associated in two cases (and most likely also in the third case), with an electron trajectory family situated at the same meridian. Initially they do not show up on the temperature maps, but can be detected after their formation already at field levels well below the quench field by the temperature increase they produce (fig. 31). In figs. 32 and 33 such a region together with the corresponding isotherms is shown. As may be seen by comparison with fig. 13 the temperature increase has a half width only slightly exceeding the one for a point like heat source. The slightly increased extension along the meridian is probably due to a convection effect inside.
Fig. 31. Temperature map showing a quench (a) and its precursor (b).

Fig. 33. Temperature distribution (isotherms) around the quench region of fig. 31 (cf. also fig. 13).

the liquid helium. We assume therefore that the damage region has an extension of a few mm at the most.

These quench regions can be removed by a chemical polishing of 20 μm. Also IBC at a dose rate >8 × 10^{17} Ar+/cm² removes the quench region. As the IBC process affects only a few monolayers of the Nb oxide [29] one concludes that this type of damage reaches only into a depth of a few 10 Å. A bake out did not affect the quench region. In one case the field dependence of the damage area was measured and the result is shown in fig. 14 and indicates a phase change already mentioned in section 4.3.3. Surface defects of this type have not been observed to be produced at field levels below $E_{acc} = 3.5$ MV/m.

Fig. 32. Temperature profile of the quench region of fig. 31. a) after production of a (non self pulsing) quench; b) before quench at a field of 2.9 MV/m; c) before quench at a field level of 1.73 MV/m.
A possible explanation takes into account that the quench region lies at the meridian of an electron source. Trajectory calculations for these sources have shown that in two cases the quench position corresponds to a maximum of the electron impact energy (which in this region is of the order of 250 keV and 320 keV, respectively) but not to the region of maximum electron intensity (figs. 26 and 28). The third quench region is not located at these regions; but in this case we cannot entirely exclude the hypothesis that the quench region coincides with the source region. It is known from ESCA measurements [30] that electron bombardment can produce suboxides in the Nb matrix with reduced $T_c$. Impinging electrons also can reduce Nb$_2$O$_3$ to lower conducting oxides which could explain the switching behaviour of the surface damages.

4.7. Field limitations

In measurement number 2, 3 and 4 a fast field breakdown was the ultimate field limit. It is remarkable that in all three runs it was the electron damage which produced the field breakdown although in all cases this region is in competition with many other regions of increased losses of which some show a comparable power dissipation. The quench was produced always at the lower bottom part of the cavity where also most of the electron sources were detected and is caused by a temperature increase of the electron damage area above $T_c$ [31]. In all cases the film boiling limit is exceeded at the quench location. This is indicated by a temperature increase of about 1500 mK at the outside wall of the cavity. In figs. 32a and 33a the large temperature increase at the quench region is shown together with its isotherms. Comparing this with other point like heat sources (fig. 13) or with the quench precursor (fig. 33b) one sees that a much larger region is effected by the temperature increase indicating the formation of a large gas bubble around the quench region cooling. The convection effect of this gas bubble increases temperatures at its meridian up to the equator of the cavity. The power release of a fast quench is so big that it can even be observed in He II.

Obviously the quench field level must depend on the bath conditions and this is what is observed. For run 5 the field limit was

$$E_{acc} = 3.7 \text{ MV/m at 4.2 K (He I)}$$

$$4.12 \text{ MV/m at 2.1 K (He II)}$$

$$3.3 - 3.5 \text{ MV/m at 2.3 K (subcooled He I)}$$

In fig. 34 the transmitted signal corresponding to a fast field breakdown is shown. It corresponds to a poor cooling condition (subcooled He I) which inhibits the field build up after the quench. The cavity remains at a lower field level determined by the coupling conditions and the reduced $Q_0$ caused by the normal conducting quench region. A $Q_0$ degradation (and decrease of the coupling coefficient) is observed. If cooling conditions are improved by decreasing the temperature below 2.17 K the well known self pulsing behaviour of the thermal instability is obtained.

5. Conclusions

The results obtained up to now in 12 measurements of the single cell 500 MHz cavity allow the following conclusions.

5.1. Cavity design

Spinning from Nb sheet material and electron beam welding followed by appropriate surface treatments is an adequate fabrication technique for superconducting accelerator cavities. The spherical shape not only avoids multipacting but is very favourable for surface treatments. Flat regions should be avoided and elliptical roundings should be introduced in order to reduce $E_p/E_{acc}$. 

![Figure 34. Transmitted rf signal under quench conditions. The signal is obtained with a spectrum analyser (logarithmic amplifier). The quench reduces the signal level from -14.2 to -28 dbm and is not self-pulsing.](image-url)
5.2. Surface treatments

We have used simple treatments and especially avoided high temperature annealing. Our standard treatment is chemical polishing and has given results for $Q_0$ and $E_{\text{acc}}$ which are comparable to those obtained by electropolishing and high temperature annealing [2,4]. It is not yet clear if the top-bottom asymmetry found after the standard treatment is due to the chemical polishing, to the rinsing or to the drying procedure. We succeeded in suppressing this asymmetry and getting very small rf losses by a faster drainage of the etching solution and rinsing with dust free H$_2$O which is evaporated under dust free conditions in a horizontal position of the cavity. Ion bombardment cleaning seems to be an interesting in situ surface treatment. It has been applied twice and its potential has to be explored in more detail.

5.3. Diagnostic systems

The development of temperature and X-ray mapping devices as well as a possibility of visual inspection during operation turned out to be of invaluable help for obtaining much more specific informations on rf losses and electron phenomena.

5.4. Multipacting

No electron multipacting has been observed under any circumstances.

5.5. Rf losses

$Q_0$ values at 4.2 K up to $2.5 \times 10^9$ and corresponding to residual resistances of 52 n$\Omega$ have been obtained after standard treatments. In a long experiment of 500 h no deterioration of $Q_0$ value and of accelerating field has been observed. This $Q_0$ value was also not degraded by an exposure of the cavity to dust free air for a few hours.

After our standard treatment different kinds of rf losses are observed besides the normal BCS losses.

(a) Large regions with increased resistivity are observed. They can be produced in an asymmetric way by the standard CP treatment. They are not explainable as losses induced by the magnetic field alone but are on the contrary produced by the electric surface field and show a maximum in regions where both $H$ and $E$ are large. These losses can be strongly influenced by IBC. It is to be noted that the rf losses reach their minimum at the region of the equatorial welds where the magnetic field is at its maximum and the electric field vanishes.

(b) Besides these more uniform losses point like defects exist. They do not generally contribute significantly to $R_{\text{res}}$ but give rise locally to high heat fluxes producing thermal instabilities. These local defects can be there from the very beginning of an experiment or can be produced during high field operation. The field dependence of these losses can be stronger than the normal $E^2$ dependence. In particular they can show a reproducible switching behaviour hinting to a phase transition (e.g. superconducting $\rightarrow$ normal) at a given field level. The point defects are predominantly located at the bottom part of the cavity and can be thermally stable up to magnetic surface fields of at least 150 G.

5.6. Non-resonant electron loading

After a standard treatment and for $E_{\text{acc}} > 3$ MV/m electron loading sets in as can be seen from $Q_0$ degradation, exponentially increasing X-ray, light and electron intensity and, most striking, from heating due to electron impact. These electrons are produced by field induced emission from point sources which are located at the region of maximum electric field. The number of the sources can be significantly decreased by high field processing tending normally after a few hours to a stable electron activity. By IBC the electron emissivity of the cavity surface is enhanced. In the 500 MHz range non resonant electron loading above 3 MV/m is a severe limitation for the achievable acceleration fields. Therefore a better understanding of field induced emission has to be aimed at.

5.7. Thermal instabilities – quench fields

Although electron loading appears after each standard treatment at field levels above 3 MV/m it does not limit the maximum attainable field ($E_{\text{acc}} = 4-5$ MV/m) which is caused by a local temperature increase of the rf-surface above $T_c$ and accompanied by film boiling at the cavity outside. The quench location always coincides with one of the point like defects mentioned above and is always located at the bottom of the cavity. In two (out of three) cases and most likely also in the third one the quench is located at the meridian of an electron source and of electron trajectories. We conclude that the defect may be due to a radiation damage produced by electron impact.
One of the defects has been produced definitely after a few hours operation at high field level.

As a final conclusion for application purpose we can state that acceleration fields $E_{acc} = 3 \text{ MV/m}$ and $Q_0$ values up to $2 \times 10^9$ at 4.2 K have been repeatedly obtained. This corresponds to an rf power input $P_{diss} = 8 \text{ W/m}$ and can be considered a sound basis for the construction of a four cell accelerating cavity which is presently under test at CERN.

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References

[29] A. Mathewson, private communication.