MULTIMODE INVESTIGATIONS ON RF LOSSES AND FIELD LIMITATIONS OF SINGLE-CELL NIOBIUM CAVITIES AT L- AND S-BAND FREQUENCIES

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Abstract

Systematic measurements on single-cell cavities are best suited for a better understanding of anomalous and fundamental rf loss mechanisms of superconductors. We have started test series on several elliptically shaped accelerator cavities fabricated from high purity Nb. By means of an adjustable input and output coupling system six modes with residual Q values well above 10^9 between 1.5 GHz (TM_{010}) and 3.5 GHz including the TE_{011} mode can be excited properly. For all of these modes rf loss distributions and field limitations have been investigated by temperature mapping and will be discussed on the basis of URMEL and URMEL T calculations. First measurements have given for the TE_{011} mode magnetic surface fields up to 100 mT at Q values well above 10^{10}.

Introduction

Superconducting cavities built from high purity niobium are capable to provide cw accelerating gradients beyond 5-8 MV/m which are typical design values for present projects like CEBAF, SDALINAC, HERA, LEP and TRISTAN [1]. Higher field (≥ 10 MV/m) and Q_0 ($\geq 10^{10}$) levels are interesting for future linear accelerators at frequencies above 1 GHz. The fundamental field limitation given by the superheating magnetic field at the surface of the superconductor is about 200 mT for Nb [2]. Depending on the mode of operation this corresponds to an accelerating field of typically 45 MV/m for velocity of light structures. The presently observed field and Q_0 limitations are caused by anomalous losses due to defects or contaminants on the surface. Quenching can be suppressed by improving the thermal conductivity of the cavity wall [3]. At present field emission loading is the most stringent obstacle especially for large cavities [4].

In order to investigate the physical origin of anomalous losses and to improve the performance of superconducting cavities systematically, we have started multimode measurements on single-cell cavities built from high purity Nb. A special apparatus with adjustable coupling probes has been constructed to enable optimum rf power transfer into all high Q_0 modes. Scanning systems of resistor thermometers and photodiodes will provide useful information about local rf losses and X-radiation [5]. Most interesting is the comparison of the fundamental TM_{010} (1.5 GHz) with the TE_{011} (2.9 GHz) mode which has no electric surface fields. Therefore electric and magnetic field and Q_0 limitations can be studied separately in the same superconducting accelerator cavity.

Experimental Techniques

The cryogenic test system is shown schematically in Fig. 1. Side-coupling from the beam tubes close to the cell was chosen because of several reasons. At first this guarantees similar coupling strength $\beta = Q_0/Q_{ext}$ for all interesting modes including the TE_{011} (see Fig. 2 and Tab. 1) which can be easily adjusted from outside of the cryostat. Furthermore

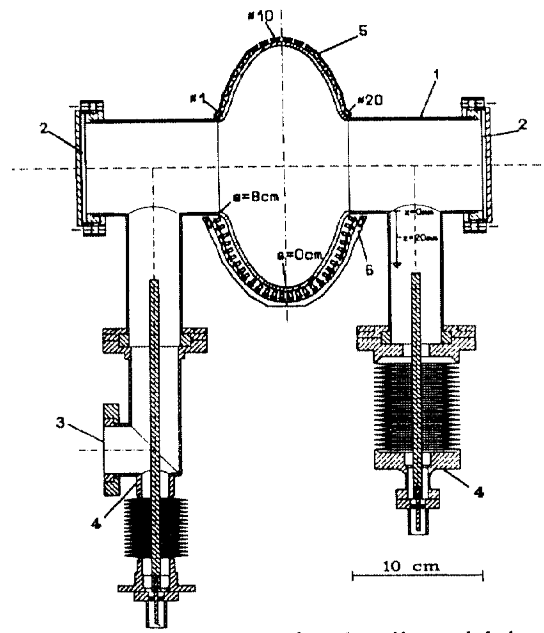

Fig. 1: Experimental set-up for the elliptical L-band cavity: 1) Nb resonator; 2) Nb plates with In sealing; 3) UHV pumping port; 4) adjustable rf coupling probes; 5) resistor thermometers; 6) photodiodes with LED.

coaxial coupling of fundamental and higher order modes is an important alternative to waveguide coupling for future accelerating structures. Last but not least dust contamination especially from coupling parts is prevented best for the horizontally mounted superconducting cavity. The length of the cut-off tubes (10 cm) allows Q_0 levels up to 10^{11} for the TM_{010} and TE_{011} mode without limitation by rf losses in the flange region. Rotating frames with 20 thermometers and 26 photodiodes have been developed for use in subcooled and superfluid helium.

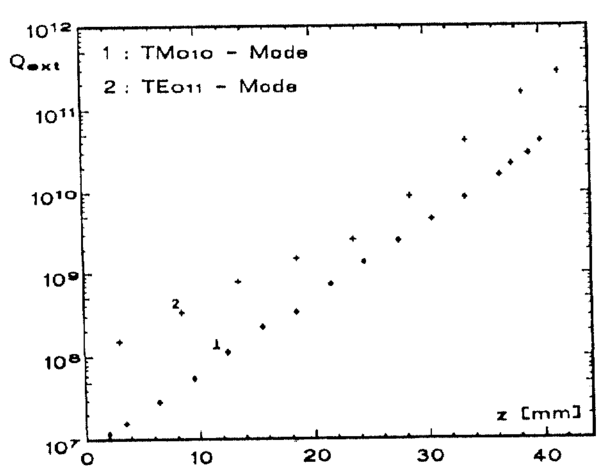

Fig. 2: Dependence of the external Q_{ext} on the position z of the input coupling probe as defined in Fig. 1.

Tab. 1: Characteristic data for the interesting modes of the elliptically shaped cavity (Abbrevations are explained in the text).

Mode	f [MHz] calc.	f [MHz] exp.	Q_{ext} (z=18 mm)	G [Ω] calc.	G [Ω] exp.	$E_p/\sqrt{PQ}$ $[V/m/\sqrt{W}]$	at s [cm]	$H_p/\sqrt{PQ}$ $[\mu T/\sqrt{W}]$	at s [cm]	Q_0 resid.
TM_{010}	1490.3	1490.62	$2.8\cdot10^8$	256	256	168	8.0	.463	3.0	$1.3\cdot10^{10}$
TE_{211}	2692.1	2690.94 2691.32	$2.1\cdot10^{10}$ $2.8\cdot10^{10}$	415	426	110	7.0	.80	7.0	$4.9\cdot10^9$ $4.9\cdot10^9$
TM_{210}	2767.2	2767.6	$1.3\cdot10^8$	397	---	150	4.0	.55/.60	.5/7.0	---
TE_{011}	2915.5	2920.16	$1.3\cdot10^9$	> 700	888	0	---	.513	7.0	$3.9\cdot10^{10}$
TE_{311}	3285.5	3285.18	$3.4\cdot10^9$	480	413	100	3.0	.45	4.0	$3.8\cdot10^9$
TM_{310}	3409.7	3410.23 3410.52	$1.2\cdot10^{12}$ $4.4\cdot10^{10}$	480	535	140	4.0	.55/.40	.5/6.0	$7.3\cdot10^9$ $8.0\cdot10^9$

In Tab. 1 the data of all high Q_0 modes at L- and S-band frequencies are listed. Beside the rotational symmetric TM_{010} and TE_{011} these are the quadrupole and sextupole modes of the TE_{m11} and TM_{m10} families. The Q_0 of the dipole modes (m = 1) and higher order modes of the TM_{0np} family is loaded too strongly by additional losses in the beam tube region. The identification of all modes is facilitated by the excellent agreement between the measured and calculated resonant frequencies and by the twinning for $m \geq 1$. All computations have been performed with high resolution using URMEL and URMEL T [6]. Assuming a frequency dependent surface resistance of $R_s(f) = 0.32\,\mu\Omega \cdot f^2$ [GHz] for superconducting high purity Nb at 4.2 K, the measured geometric factors $G = Q_0 \cdot R_s$ confirm about the calculated ones with the exception of the TE_{011} mode. The latter discrepancy has been corrected by a manual integration of the squared surface fields.

For the investigation of field and Q_0 limitations the surface field distribution in all of these modes has to be considered. The calculated calibration factors for the peak magnetic and electric surface fields H_p and E_p normalized to $\sqrt{P_0\,Q_0}$ (Tab. 1) and the field patterns H(s) and E(s) show (s see Fig. 1) that multimode testing provides a quality control of different parts of the cavity surface. In Fig. 3 this is demonstrated for the most interesting modes. Valuable additional information about the equator welding should result from the modes TE_{021} (4.29 GHz) and TE_{012} (4.30 GHz) at C-band frequencies.

Several elliptically shaped cavities were fabricated by deep-drawing and electron beam welding of high purity Nb sheets (RRR ≈ 150). For the cut-off tubes and flanges only reactor-grade Nb was used. The final surface preparation consisted of a chemical polishing (50 μm) in a 1:1:1 solution of $HF{:}HNO_3{:}H_3PO_4$ followed by extensive rinsing in demineralized, filtered water. The cavities were assembled under laminar air flow conditions.

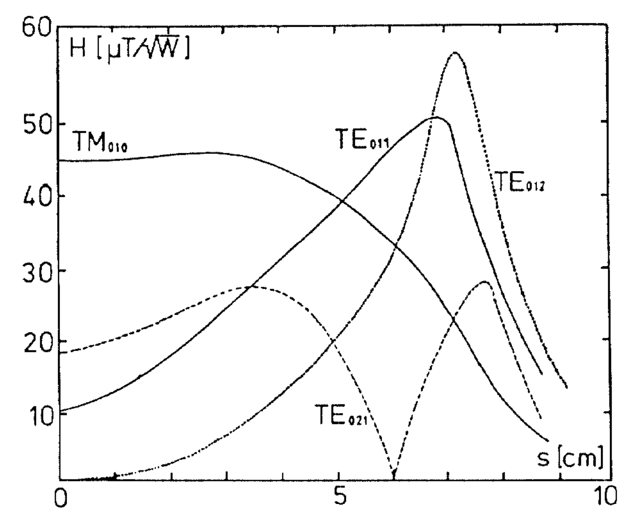

Fig. 3: Magnetic field pattern H(s) along the inner cavity surface for the rotational symmetric modes.

First Results and Discussion

As expected for all modes with a sharp cut-off of the fields in the beam tubes high residual Q_0 levels above $3\cdot10^9$ were measured at 1.4 K (see Tab. 1). In those modes where twins could be coupled sufficiently, very similar Q_0(1.4 K) values were achieved for both orientations. Therefore the dominant part of their residual losses has to be caused in the same way. This suggests either similar local fields at large defects or more probably a relative homogeneously distributed residual surface resistance. The latter assumption is confirmed by the average $R_s(1.4\,K) = G_{exp}/Q_0(1.4\,K)$ which is 88 nΩ and 70 nΩ for the TE_{211} and TM_{310} modes, respectively. Much lower R_s(1.4 K) of about 20 nΩ were measured in the same test for both the TM_{010} and TE_{011} mode. This discrepancy shows that temperature maps of the cavity surface normalized to the calculated magnetic and electric field distributions will be necessary for a deeper understanding of the origin and frequency dependence of the residual surface resistance.

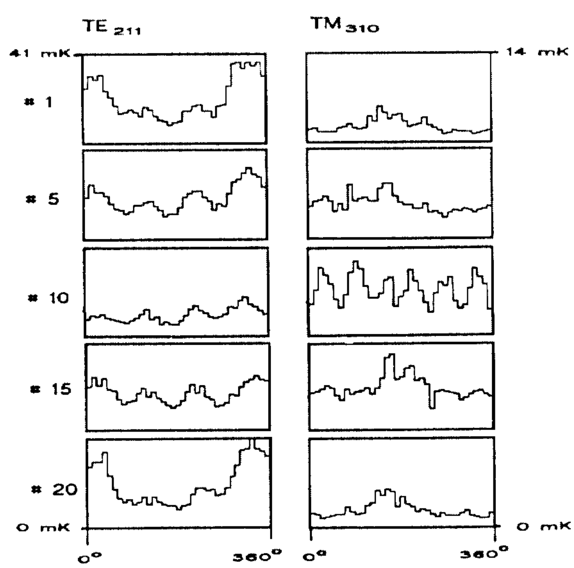

Fig. 4: Temperature maps ΔT(φ) of the TE_{211} and TM_{310} mode measured with five resistors (position # see Fig. 1) in subcooled helium at 3.3 K for H_p = 12 and 8.8 mT.

At this level of residual losses the temperature dependent BCS part of the surface resistance becomes dominant for Nb at frequencies above 1 GHz and temperatures above 2.2 K. Therefore the standard thermometry in subcooled helium provides only information about the field distribution of the modes (Fig. 4). Furthermore the rf heating resulting from $R_{BCS}(T)$ limits the achievable field levels to about 60 mT/f [GHz] in subcooled helium [7]. Therefore we are installing now specially constructed thermometers for use in superfluid helium [8] which have been tested successfully in a calibration set-up (Fig. 5).

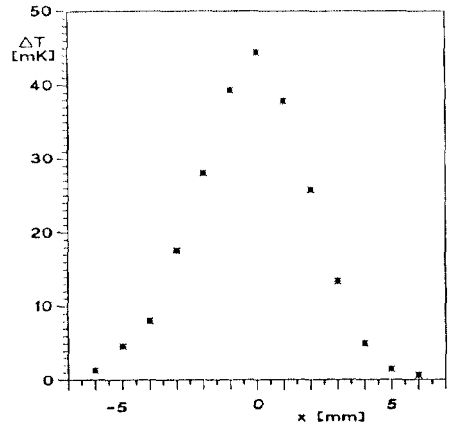

Fig. 5: Spatial distribution of the temperature signal $\Delta T(x)$ measured by a sliding thermometer on a Nb plate in superfluid helium at 1.4 K. The signal is produced by a heat input of 60 mW into an area of 5 mm diameter. The corresponding thermometer efficiency is about 5 %.

In the initial tests we have focused so far on the rotational symmetric modes for which in general the highest Q_0 and field levels were achieved (Tab. 2). While in tests LI1-2 and LI2-1 the maximum Q_0 at low fields were nearly three times higher in the TE_{011} than in the TM_{010} mode, about the same Q_0 values were measured in test LI1-1. In parallel for the TE_{011} mode H_p was close to 100 mT twice but only 61 mT once. These observations suggest for LI1-1 the existence of a relative large defect contributing significantly to the residual losses in the TE_{011} mode. Nevertheless Q_0 values above 10^{10} have been achieved regularly which decrease only moderately at high field levels (Fig. 6). In both modes the achievable fields were always limited by local thermal breakdown in the high magnetic field regions, i.e. close to the equator in the TM_{010} and close to the iris in the TE_{011} mode. In the accelerating mode slight field emission loading was observed at moderate field levels up to $E_{acc} = 9$ MV/m. As expected field emission never appeared in the TE_{011} mode.

Tab. 2: First results on residual Q_0 and maximum surface fields for two cavities in the TM_{010} and TE_{011} mode. The corresponding accelerating field of the TM_{010} is calculable by $H_p/E_{acc} = 4.7$ mT/(MV/m).

Test No	f [MHz]	Q_0 low field	Q_0 high field	H_p [mT]	Quench # / angle
LI1-1	1490.62	$1.5 \cdot 10^{10}$	$6.1 \cdot 10^{9}$	42.7	10 / 80°
	2919.61	$1.7 \cdot 10^{10}$	$8.5 \cdot 10^{9}$	61.1	- / -
LI1-2	1490.53	$8.0 \cdot 10^{9}$	$4.4 \cdot 10^{9}$	30.6	13 / 0°
	2919.69	$2.3 \cdot 10^{10}$	$6.8 \cdot 10^{9}$	98.8	1 / 200°
LI2-1	1489.97	$1.3 \cdot 10^{10}$	$6.8 \cdot 10^{9}$	36.7	10 / 18°
	2917.87	$3.9 \cdot 10^{10}$	$2.7 \cdot 10^{10}$	93.8	1 / 170°

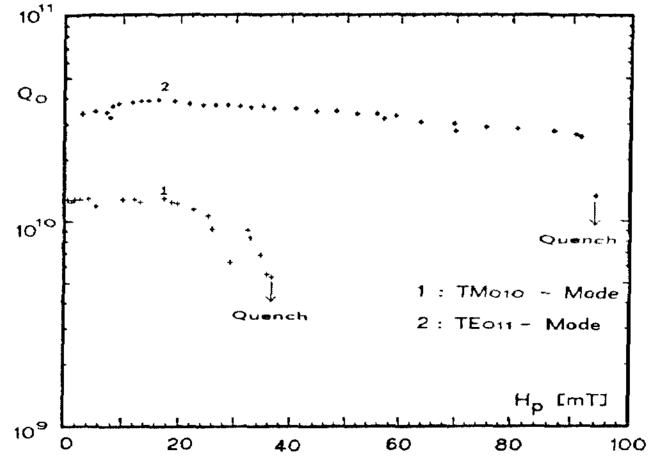

Fig. 6: Comparison of $Q_0(H_p)$ dependencies measured at 1.6 K in the TM_{010} and TE_{011} mode of cavity LI2

Conclusions

We have developed a multimode test system for the systematic investigation of field and Q_0 limitations of superconducting accelerator cavities. Adjustable rf coupling as well as improved diagnostic techniques like thermometry in superfluid helium are ready to uncover the rf losses at L- and S- band frequencies for high field levels. In the TE_{011} mode which intrinsically shows no field emission, magnetic surface fields up to 100 mT at Q_0 levels well above 10^{10} have been achieved already in the first tests. Local guided repair and postpurification methods will be applied next to come closer to the fundamental limits of superconducting niobium cavities.

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