High Gradients in 3 GHz Nine-cell Cavities for Superconducting Linear Colliders

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ABSTRACT

For the design of superconducting linear colliders with CM energies above 300 GeV, accelerating structures with gradients of at least 15 MV/m are required. We have built four prototype 3 GHz nine-cell cavities of optimized shape with reduced peak electric surface field. They have been fabricated from sheet Nb with a RRR value of 270. Advanced surface preparation techniques like heat treatment in UHV at 1350°C with a titanium shield have been applied. Results of systematic test series on the achievable field and Q_0 values of these structures prepared by various techniques will be reported. First temperature maps measured on such a structure at field levels above 10 MV/m in superfluid helium will be presented.

INTRODUCTION

For e^+e^--annihilation experiments beyond LEP II energies, synchrotron radiation enforces to prefer linear accelerators. To achieve the required high beam quality, the use of high gradient superconducting (SC) cavities operating between 1 and 3 GHz is the most straightforward way. The TESLA collaboration was founded in 1989 [1] to prove the feasibility and to develop the parameters of such an accelerator. The design of the TESLA machine is based on accelerating fields (E_{acc}) of 15-30 MV/m at Q values above $5 \cdot 10^9$ in multicell structures. The improvements in preparation and dust free assembly techniques [2] shifted the limits of E_{acc}, caused by anomalous loss mechanisms like field emission and quenching at local defects, to values of ≈30 MV/m in single-cell cavities (Fig. 1) [3,4]. This made possible to approach experimentally the calculated global thermal heating limit [5,6,7]. To prevent both, local and global heating, a high thermal conductivity λ of the Nb is necessary as well as a high quality factor. A reliable procedure for good cavity performance needs firing above 1200°C [5,8] without pickup of residual gases from the furnace vacuum [9]. The single-sided titanisation (SST) technique [3,10] combines the increase of the RRR value ($RRR \approx 4 \cdot \lambda(4.2K)$ [W/mK]) with the reduction of field emission [11]. This reduction is on the one hand due to an effective elimination of surface contamination like microparticles, acid residues, indium etc.. On the other hand, the solid state reaction at 1350°C leads to a homogenisation of interstitially dissolved impurities and a recrystallisation of the niobium resulting in an improved surface quality of the cavity.

The application of these methods to multicell structures led to E_{acc} = 22 MV/m in a five-cell cavity for the SC recyclotron S-DALINAC at the TH Darmstadt [3]. For this cavity shape (Fig.2), the comparably high electric surface field (E_{peak}/E_{acc} = 3.1) favours the limitation of the gradient by field emission loading. This fact and the requirements concerning manufacturing tolerances, field flatness, surface cleaning and HOM-excitation in a linear collider have led to the development of an improved cell shape and the choice of a nine-cell structure [4]. Four S-Band prototypes (f = 3 GHz) were built from sheet Nb with RRR value of 270. Independently of the final frequency of TESLA, this allows their application under high quality beam conditions in the S-DALINAC [12]. In this paper the actual results at the University of Wuppertal and the Cornell University on these structures are summarized.

FABRICATION, PREPARATION AND EXPERIMENTAL SETUP

The cell shape of the nine-cell structures was optimized to a low E_{peak}/E_{acc} ratio of 2.1 (Fig.2), using the URMEL code. Four prototype structures were manufactured by deep drawing and electron beam welding at Cornell University. For the cryotests, they were prepared by standard etching (BCP), rinsing with ultrapure water or dustfree methanol and UHV heat-treatment. The final assembly was performed in a cleanroom (class 10-100). Except for some first tests, adjustable input power couplers were used for an effective He- and RF-processing. While in Cornell processing can be done with short pulses up to 200 kW (HPP) [13], in Wuppertal 400 W cw is available. To enable a guided repair of the structures, a rotatable, high resolution thermometry system for superfluid helium was installed in Wuppertal. Ten thermometers, which consist of stycast isolated carbon resistors, detect the temperature distribution on the outer wall of each cell.

EXPERIMENTAL RESULTS AND DISCUSSION

The results of the cryotests of the cavities T1 - T3 are summarized in Table 1. Present Q(E)-curves are shown in Fig. 3 and 4a. Before the first test of prototype T1 at Cornell, a 80µm layer was removed from the surface by BCP treatment. The resulting residual quality factor of only $Q_0=10^8$ was due to hydride precipitation in the high purity niobium (RRR = 270) [3,14]. Outgassing of the cavity for 2h at 900 °C increased Q_0 to $1.5 \cdot 10^{10}$ at low fields (T1-b), but strong field emission limited E_{acc} to 9.3 MV/m at $Q_0 = 1.3 \cdot 10^9$. The application of short RF pulses with high power up to 40 kW (HPP) reduced the field emission loading significantly. $E_{acc} = 15$ MV/m was achieved at $Q_0 = 6 \cdot 10^9$ limited by local thermal breakdown. A detailed discussion of HPP is given in another paper at this conference [13]. In Wuppertal, a 15 µm BCP and firing at 850°C for 4h resulted in a comparable cavity performance (T1-c) as in test T1-b before HPP, both limited by field emission.

In order to reduce number and activity of intrinsic field emitters, to increase the thermal conductivity and to allow a completely dry surface cleaning, a SST-treatment at 1330°C was performed for 20h. As expected, the onset for field emission increased significantly in the following tests T1-d and T1-e . The quench limitation at $H_p = 67$ mT disappeared due to improved thermal conductivity corresponding to RRR ≈ 750, as measured on several samples after the same treatment. In test T1-d the mechanical creep of the structure at 1330°C caused a very unflat field profile with $E_{max}/E_{min} = 4.2$. The field was concentrated mainly at one end of the structure, where a maximum surface field of $H_p = 88$ mT ($E_p = 42$ MV/m) was obtained, which is plotted in Fig.3a with open squares. The energy gain of an electron accelerated in the whole structure would correspond to $E_{acc} = 12.4$ MV/m. Before test T1-e (filled circles) the cavity was tuned fieldflat, etched 5 µm and fired at 870°C/4h. The maximum surface field was limited by field emission at a lower value than T1-d, with the gradient increasing to $E_{acc} = 16$ MV/m. The structure was then 5 µm chemically etched and tested again at Cornell. On initial rise the cavity showed a further degraded high field behaviour, but the best quality factor at low field level ($Q_0 = 2 \cdot 10^{10}$) of all tests. After HPP the field emission threshold was raised significantly and an accelerating gradient of 20 MV/m was reached (T1-f, crosses).

The second structure T2 was only 25 µm etched, instead of the usual 60 µm, after fabrication and fired at 850°C/4h before the first cryotest to prevent hydride precipitation. This treatment resulted in a nice quality factor of $Q_0 = 7 \cdot 10^9$, but a local thermal breakdown occured at $E_{acc} = 8.3$ MV/m (T2-a, filled triangles). After titanisation the quench limitation disappeared, as expected for the increased RRR, but the Q-value at low field was significantly degraded. After additional 57 µm etching and an 850°C/6h firing, test T2-c (open squares) yielded a good low field performance ($Q_0 = 1.1 \cdot 10^{10}$) and a maximum surface field $H_p = 72$ mT.

To overcome the problems of the unflat field profile after firing at 1350°C the preparation procedure was improved before test T2-d. Additional fixings in the furnace were assembled to avoid the creep of the structure during the titanisation. After the furnace treatment (SST) the field profile was checked and the cavity retuned in the class 1.000-10.000 area of our cleanroom. The field flat cavity was rinsed with dustfree methanol and ultrasonic agitation in a class 10-100 area. The success of this procedure cannot be judged yet. While a $Q_0 = 6.5 \cdot 10^9$ was achieved at 1.5 K, a leak in superfluid helium made it necessary to measure the Q versus E_{acc} behaviour above the lambda point. At 2.2 K the gradient was limited at $E_{acc} = 11.3$ MV/m by available RF power and field emission. In summary, tests on this cavity so far did not yield the desired performance due to the technical problems described above. Most of these problems are overcome right now, so that we are optimistic to improve the results on this structure in future tests.

The preparation procedure of structure T3 summarized the experience of the former tests: 60µm BCP, SST with additional fixings, check of field profile and tuning in class 1.000-10.000 area, rinsing and mounting in class 10-100. This yielded the best starting performance of the three structures tested so far with $Q_0 = 8 \cdot 10^9$ and $E_{acc} = 11.5$ MV/m (Fig.4a). With the exception of some pre-checks during test T2-d, the thermometry system was applied for the first time. Fig.4b-d show the temperature signals of the 90 thermometers at 73 angle positions detected in superfluid helium. The first map was taken at $E_{acc} = 7.9$ MV/m ($E_p = 16.6$ MV/m) and $Q_0 = 7.5 \cdot 10^9$, and only electronic noise of about $\Delta T \approx 1.5$ mK was detected. At $E_{acc} = 9.3$ MV/m ($E_p = 19.5$ MV/m) the Q_0 degraded to $3.0 \cdot 10^9$ and the electron probe measured a current of 80 nA. Correspondingly, the second map (Fig.4c) shows a signal near the lower iris of the sixth cell of the vertically assembled structure. As expected for field emission, the temperature signal rises stronger than $\sim H^2$. An additional signal appears at $E_{acc} = 10.5$ MV/m ($E_p = 22.1$ MV/m) (Fig.4d) near the upper iris of the fifth cell, most probably due to a new emitter. After RF- and He-processing the field emission loading decreased only slightly, still limiting the achievable gradient. It is remarkable, that the nine-cell structure results correspond to those of single-cell cavities [15], where the field strength is limited by only one or very few local defects and/or field emitters. Therefore, the next step will be the inspection and guided repair of this structure.

It is remarkable how the achievable quality factor depends on the cavity preparation technique. The experiments, where the cavities have been tested without an additional chemical surface treatment after SST, lead to a significantly higher residual resistance than after a procedure without titanium (Table 1). Therefore contamination of the inner surface with titanium traces is very probable [15]. This should be prevented by niobium hats on all cavity ports. These covers are not completely closed, because they must not limit the pumping speed too much. In case of strongly reduced pumping, residual losses may be caused by the interaction of the cavity surface with the residual gas atmosphere. Thus, the single sided solid state gettering procedure has to be optimized with respect to the residual resistance.

In the near future we plan to continue our test series with the cavities T2 - T4 with priority to the suppression of field emission. In Wuppertal a movable x-ray diagnostic system inside the cryostat is under construction now, which will yield additional information about the character and distribution of the emission sites. Some of the nine-cell structures will be installed in the S-DALINAC to determine whether it is possible to maintain $E_{acc} > 15$ MV/m from laboratory results in an accelerator with electron beam.

CONCLUSION

The improvements in clean-room assembly and firing techniques, made in the last years on single-cell Nb cavities, were successfully applied to nine-cell structures with improved cell shape. After single-sided titanisation, accelerating gradients of 11 - 16 MV/m were achieved frequently. The additional application of an advanced RF processing (HPP) resulted in an E_{acc} up to 20 MV/m. Further progress needs refined preparation and diagnostic techniques on single- and multi-cell cavities. Nevertheless, a superconducting electron collider with high gradients for beam energies beyond 150 GeV seems to be within reach now.

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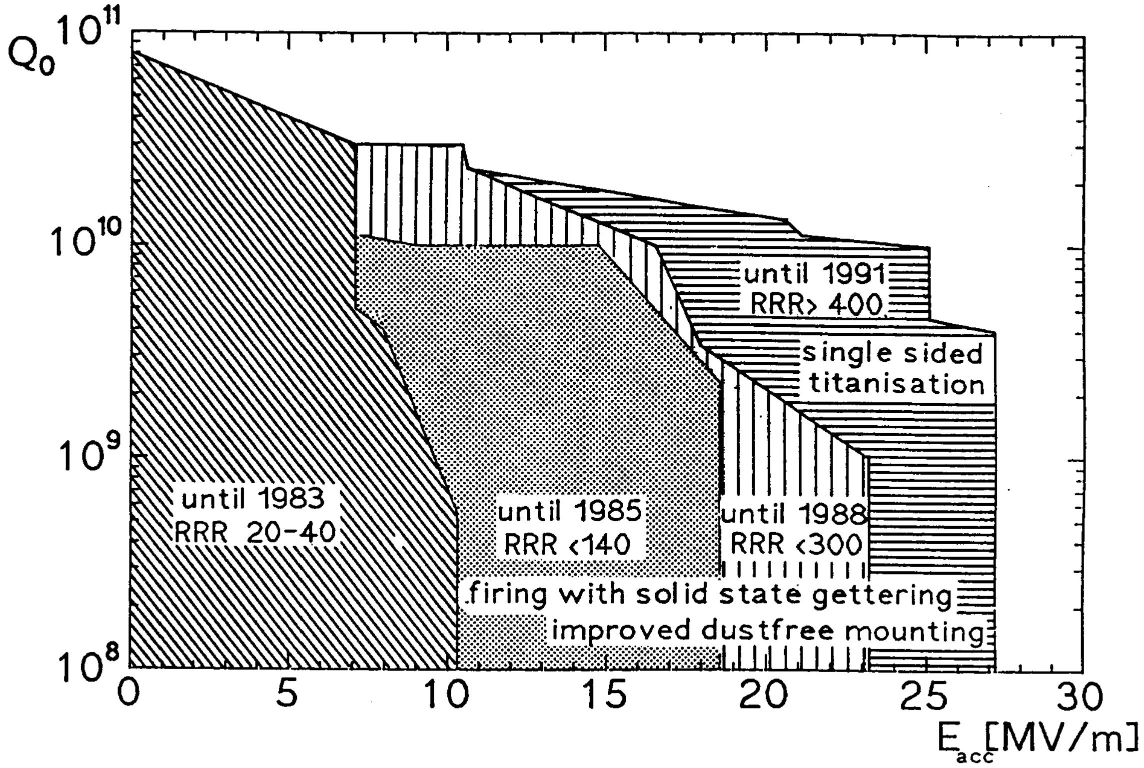
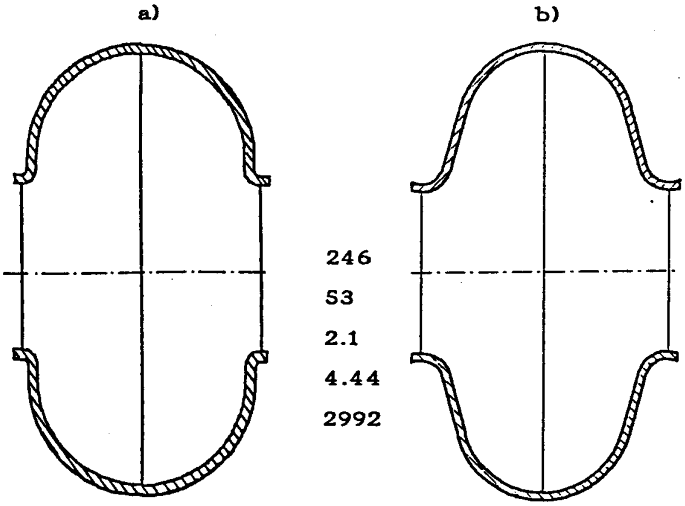


Fig.1: Performance limits of 3-GHz single cell cavities at Wuppertal (T_{Bath}= 1.5 K) [4]. Similiar results have been obtained at 1.5 GHz [16].



			a)	b)
G	[Ω]	:	293	246
R/Q	[Ω]	:	50	53
E_p/E_{acc}		:	3.1	2.1
H_p/E_{acc}	[nT/(V/m)]	:	4.18	4.44
f	[MHz]	:	2992	2992

Fig.2: RF-parameters of a) multicell cavity for SDALINAC b) 9-cell TESLA prototype

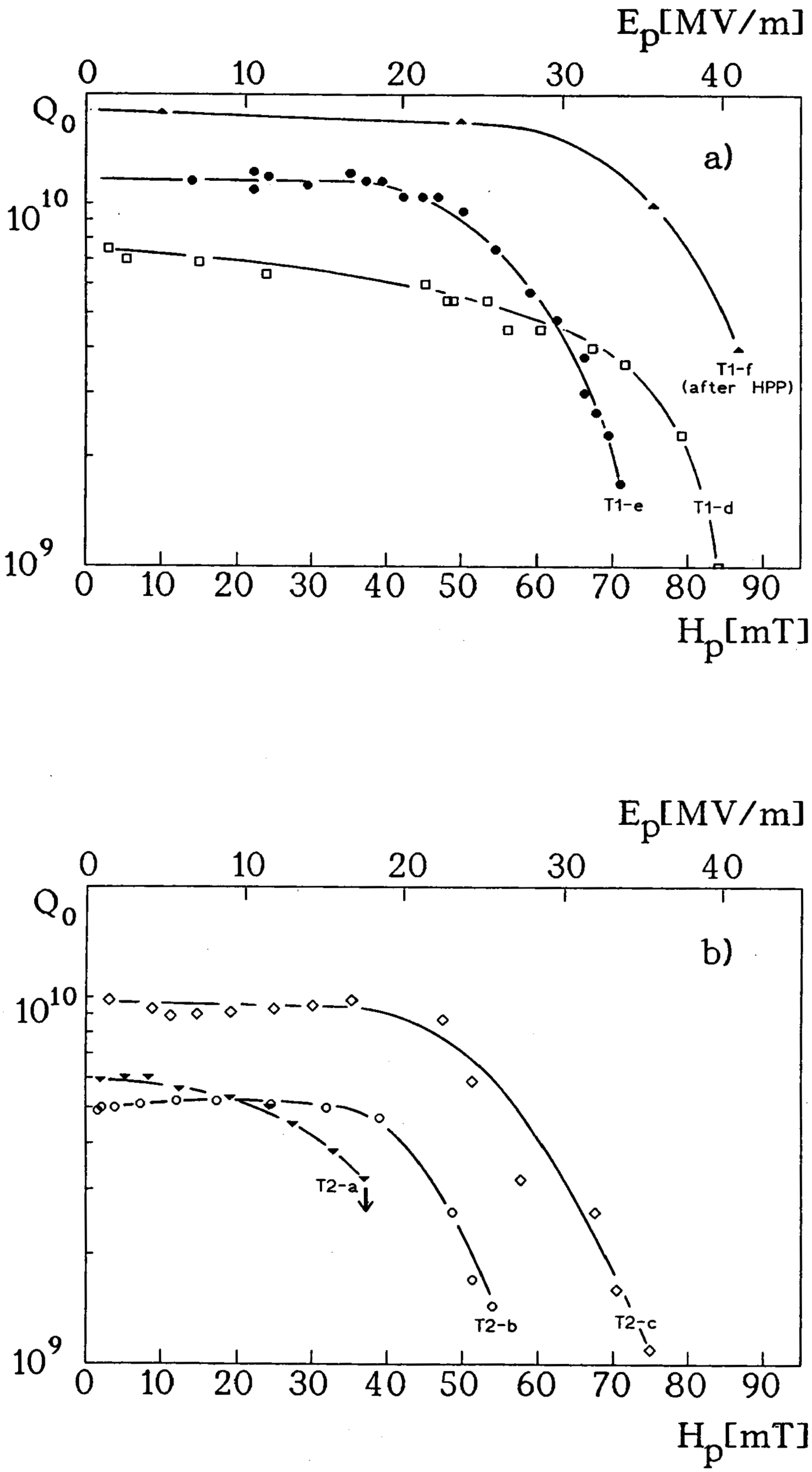


Fig.3: Q(H_p)-performance of the nine-cell structures a) T1 ; b) T2
Open symbols are used for experiments with unflat field profile.

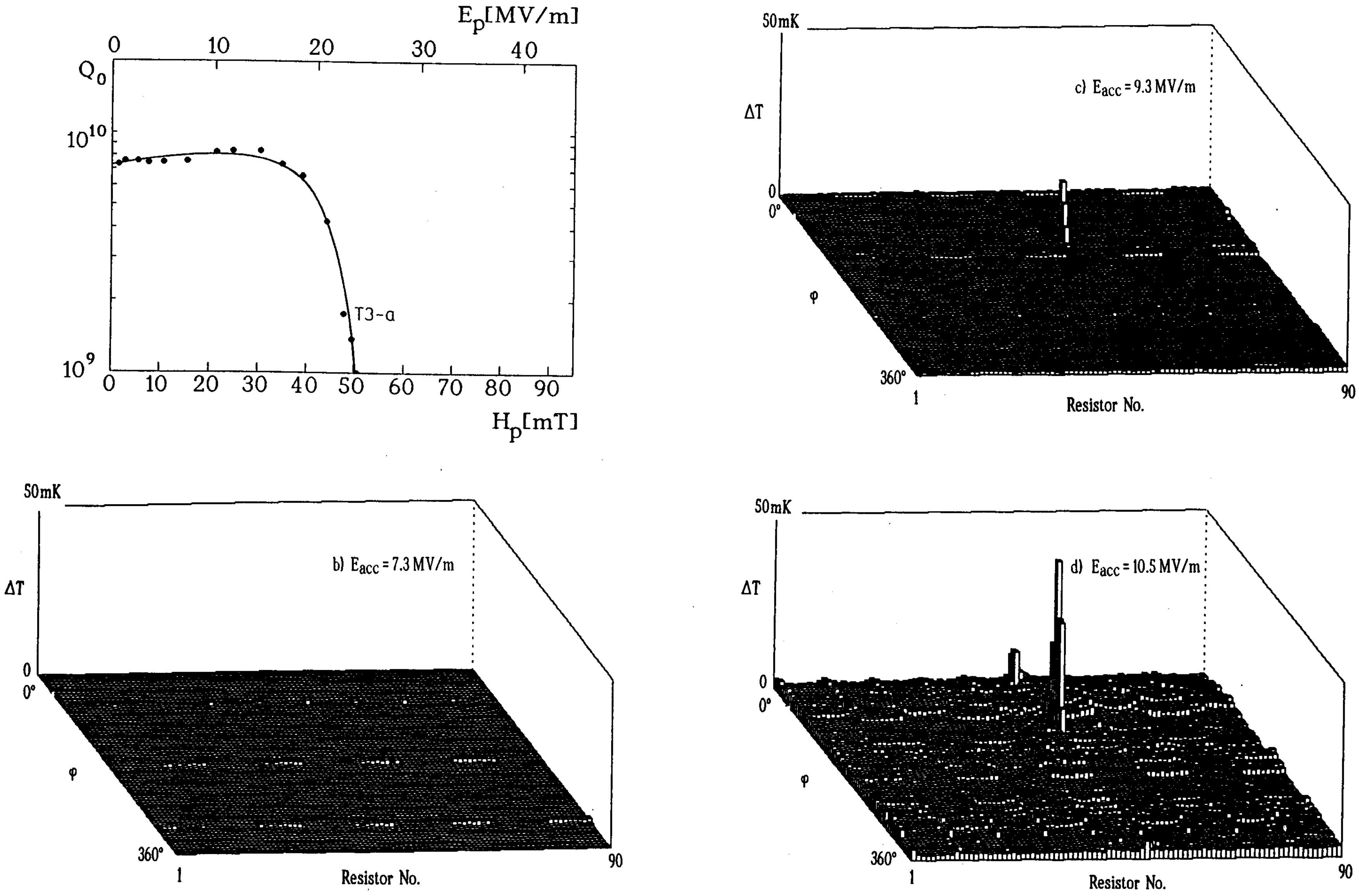


Fig.4: Results on structure T3: a) Q(H_p)-performance

b)-d) Temperature maps in superfluid helium (T_b = 1.6K) at different field levels

Cavity test	surface preparation	RRR	Q_0^{max} [10^9]	E_{acc}^{onset} [MV/m]	$Q_0(E_{acc}^{onset})$ [10^9]	E_{peak} [MV/m]	H_{peak} [mT]	E_{acc}^{max} [MV/m]	$Q_0(E_{acc}^{max})$ [10^9]	U [MV]	limitation (comments)
T1-a	BCP 80	270	0.1	-	-	-	-	-	-	-	hydrids (C)
T1-b	900°C, 2h	270	15	8.5	12	-	-	-	-	-	
			11	3.0	11	19.5	41.3	9.3	1.0	4.2	FE, power (C)
			8	13.0	7	31.5	66.6	15.0	5.0	6.8	Q, HPP (C)
T1-c	BCP 15 850°C, 4h	270	10	6.5	7	22.3	47.1	10.6	1.4	4.8	FE, power
T1-d	BCP 8; SST 1330°C, 20h	750	11	*(7.6)*	9	41.8	88.2	*(13.8)*	1.0	6.2	FE, power unflat
T1-e	BCP 5 870°C, 4h	≤750*	12	10.5	10	33.6	71.0	16.0	1.0	7.2	FE, power
T1-f	BCP 5	≤750*	20	8.0	20	29.4	62.2	14.0	2.0	6.3	FE, power (C)
			>10	17.0	10	41.0	86.6	19.5	4.0	8.8	FE, HPP (C)
T2-a	BCP 25 850°C, 4h	270	7	7.0	6	17.4	36.9	8.3	3.0	3.7	Q
T2-b	BCP 8; SST 1330°C, 23h	750	5.3	*(4.9)*	5.1	27.1	57.3	*(7.9)*	0.7	3.6	FE, power unflat
T2-c	BCP 57 850°C, 6h	≤750*	11	*(6.5)*	8	34.0	71.9	*(10.3)*	1.0	4.6	FE, power unflat
T2-d	BCP 8; SST 1330°C, 23h; Tun., Meth.	750	6.5 (1.5 K)	3.5	-	23.7	50.2	11.3	-	5.1	FE, power at 2.2 K (s.f. leak)
T3-a	BCP 60; SST 1330°C, 18h; Tun., Meth.	750	8.5	8.0	7	23.9	50.6	11.4	0.8	5.1	FE, power

Table 1: Results of cryotests of the cavities T1 - T3
SST: single-sided titanification; BCP 70: 70 µm etching; onset: start of field emission loading; U: energy gain of accelerated electron; Q: quench; FE: field emission; power: maximum available input power; (C): measured at Cornell; unflat: very unflat field profile; *(...)*: corrected for effective energy gain; Tun., Meth: tuning and methanol rinsing with ultrasonic agitation;
*: RRR value may be reduced by diffusion of the oxygen from the Nb_2O_5 layer into the sheet Nb [19]