Accelerating Gradients above 15MV/m in 3GHz Nine-cell Structures

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Abstract

Superconducting linear colliders with beam energies beyond 100 GeV require accelerating gradients between 15 and 25 MV/m. To achieve such high field strengths in nine-cell structures, we chose an optimized cell shape and high purity sheet niobium (RRR>280). Four nine-cell cavities were heat treated in UHV at 1350°C with a titanium shield. The results of test series on the achievable accelerating field and Q_0 values are reported. A high resolution temperature mapping system shows the local distribution of power dissipation and allows a better characterization of the loss mechanism. A movable x-ray diagnostic diagnostic system yields information about the character and the distribution of the emission sites.

INTRODUCTION

e^+e^--collision experiments in the energy range beyond LEP II should be explored by the use of linear colliders. The high Q-values of a linear collider based on superconducting (SC) cavities (TESLA [1,19]) give fundamental advantages to achieve the requirements in luminosity and gradient compared to linear colliders based on warm cavities. The design of TESLA is based on accelerating fields (E_{acc}) of 15 - 25MV/m at Q-values of $5 \cdot 10^9$ in 1.3 GHz nine-cell structures. Despite of the proposed frequency of 1.3 GHz, four nine-cell S-Band prototypes with an optimized ratio of $E_{peak}/E_{acc} = 2.1$ [18] were built, to develop and optimize usefull technologies for surface cleaning and dustfree mounting. This choice of frequency makes best use of the available infrastructure at Wuppertal and allows the application of the structures under high quality beam conditions in the 130 MeV recyclotron S-DALINAC at the TH Darmstadt [12].

The improvements of preparation, dust free assembly and processing techniques [2,3] shifted the limits of E_{acc}, caused by anomalous loss mechanisms like field emission and quenching at local defects, to values above 20 MV/m, even in multicell cavities. A proven procedure for good cavity performance is given by firing above 1200°C without pick-up of residual gases from the furnace vacuum [4,5,6]. The single-sided titanisation (SST) at 1350°C [7,8] of the cavities combines the increase of the thermal conductivity, preventing local and global thermal breakdown [4], with the reduction of fieldemission [9,10]. In addition, as shown at Cornell, the remaining field emission can be overcome during the cryotest by the use of short (< 1ms), high power RF-pulses (HPP) [11]. The application of these methods to multicell structures led to $E_{acc} = 22$MV/m and 17MV/m at Wuppertal without HPP in a five-cell cavity and a nine-cell cavity, respectively. After HPP $E_{acc} = 20$ MV/m in a 3 GHz nine-cell cavity was reached at Cornell [11].

FABRICATION, PREPARATION AND EXPERIMENTAL SETUP

The structures were manufactured by deep drawing and electron beam welding from Wah-Chang sheet Nb with RRR value of 270 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 our cleanroom (class 10-100). RF- and He-processing can be done with 400 W pulse and cw using an adjustable input power coupler. A rotatable, high resolution thermometry system for superfluid helium is available to detect the temperature distribution of the RF-losses on the outer side of the cavity. The system is supplemented by a rotatable frame of 54 X-ray detectors to detect the local distribution of the Bremsstrahlung in case of fieldemission.

EXPERIMENTAL RESULTS AND DISCUSSION

The detailed preparation procedures and results of the cavities T1 - T4 are summarized in Table1. Q(E)-curves are shown in Fig. 1.

To prevent hydride precipitation in the high purity niobium (RRR ≈ 270) [8,13], all structures, except cavity T1, have been heat treated before the first cryotest. This resulted in residual quality factors at low fields above $5 \cdot 10^9$, whereas cavity T1 was limited at 10^8 (T1-a) and needed outgassing at 900°C to achieve high Q-values (T1-b) [11].

The first heat treatments at 1350°C (T1-d, T2-b) caused a very unflat field profile due to mechanical creep of the structures. Additional fixings in the furnace reduced the problem significantly (T2-d, T3-a, T4-a). Nevertheless the low wall thickness of 1.6 mm makes the structures very sensitive against detuning during the whole preparation procedure (T2-c). Check and final tuning was performed in the class 1.000 - 10.000 area of our cleanroom.

All four structures are single-sided titanisated. This increased the RRR to values above 500. Due to the improved thermal conductivity, magnetic surface fields up to $H_p = 93$ mT were reached [18]. Only three of the over all 16 experiments were limited by a local thermal breakdown. In agreement with thermal model calculations, the achievable magnetic surface field showed no dependence on the bath temperature between 1.5K and 2.1K (Fig.1) [16,17].

Despite the heat treatment of the cavities, which should be very effective in the suppression of fieldemission, the dominant limitation was caused by local field emission. Though the gradient exceeded 7.9 MV/m in all experiments, which is significantly above today's design value of $E_{acc} = 5$ MV/m, the aimed $E_{acc} = 15$ MV/m could not be achieved reproducebly.

Analysis of the temperature and X-ray maps showed, that most of the field emission sites were found near the lower iris of the vertically prepared and tested cavities. As well known from single-cell experiments, very few or only one emitter could be localized as the source of the field emission. A typical example for the high resolution temperature and X-ray maps at an accelerating gradient of $E_{acc} = 17$ MV/m is given in Fig.2. The broad trace of increased signals is due to the impact of the electrons on the cavity wall, depositing their energy as heat and Bremsstrahlung. The peak at temperature sensor no.36 shows the location of the local thermal breakdown limiting the gradient in this experiment at $E_{acc} = 17.3$ MV/m. Characteristic for fieldemission loaded cavities is the distribution of the temperature increase and the X-rays as a trace over several cells with a more or less broad angle distribution. In addition, an under-

ground with a maximum at each iris, but not depending on the cell and the angle position, can be seen. Most probably this effect is due to processes of high order. Before the X-ray diagnostic system was available, the corresponding temperature signals were interpreted as dielectric losses by mistake.

The analysis of the local X-ray flux, the field emission induced RF-losses and the current of the detected free electrons confirmed the expected Fowler-Nordheim dependence to the electric surface field. The local field enhancement factor β was determined with the X-ray diagnostic system and varied in a typical range of $\beta = 100$ to $\beta = 500$.

No influence of the surface treatment of the cavity (SST at 1350°C, HTA at 850°C and 1000°C) on the field emission characteristic was observed in the first series of experiments (Table 1). This behaviour as well as the distribution of the field emitters indicated a contamination during the assembly. For the last two reported experiments, the assembly conditions and the procedure were improved in a number of details. This effort resulted in accelerating gradients of $E_{acc} = 13.5$ MV/m ($Q_0 = 2 \cdot 10^9$) (pulsed: $E_{acc} = 16$ MV/m) and $E_{acc} = 17.3$ MV/m ($Q_0 = 1 \cdot 10^{10}$), which are significantly improved compared to the average of the experiments in Wuppertal (Fig.3).These values were achieved after RF- or He-processing with a maximum RF-power of 400W. Processing in cw or long pulse (> 10ms) operation caused 10 - 30% progress in E_{acc} before the emission became stable.

In all experiments the residual Q-value at low fields started above $5 \cdot 10^9$. The lowest residual resistance $R_{s,res} = 8n\Omega$ ($Q_0 = 3 \cdot 10^{10}$) was measured in the last experiment T3-d, which is close to the sum of the BCS-resistance ($R_{s,BCS}(1.4K) \approx 2.5n\Omega$) and the losses due to frozen-in-flux ($R_{s,fif} \approx 3-5n\Omega$) in our cryostat. Beside the improvements of the final assembly, in this experiment special care was taken to avoid hydrocarbon contaminations of the vacuum system, which were shown to cause additional losses [16].

A significantly increased residual resistance was observed in the experiments after SST, compared to a preparation procedure without titanium. Probably titanium might diffuse into the cavity, because the niobium hats on the cavity ports are not completely closed. To avoid this drawback of the single sided titanisation, we added a separate vacuum system for the cavity to our furnace (Fig.4). A niobium tube is flanged to the cavity from the top. The niobium tube contains heat shields and ends with an adapter to the the standard CF 35 UHV-system at the (cold) top plate of the furnace. This vacuum system is pumped with a 180 ℓ/s turbo pump and controlled with a mass spectrometer. First tests of the system with single-cell cavities resulted in a pressure in the order of 10^{-7} mbar and the expected clean mass spectra. Though the connection of the cavity to the tube inside the furnace is not UHV leak tight, the additional vacuum system should prevent all contaminations of the inside of the cavity. The very first RF-test of a single-cell cavity resulted in a low field Q-value of $3 \cdot 10^{10}$ and an accelerating gradient $E_{acc} = 30.5$MV/m, which is new record in Wuppertal. Further experiments with single and nine-cell cavities are underway.

CONCLUSION

Advanced firing techniques and cleanroom assembly result in accelerating gradients above 15 MV/m in 3 GHz nine-cell structures with improved cell shape. Field limitation is still caused mostly by FE-loading. Together with a careful preparation, a cavity vacuum free of hydrocarbons contaminations allows residual resistances below 10 nΩ, even in multicell structures. Advanced diagnostic systems are used to localize and characterize the limiting anomalous losses. Further progress needs refined preparation and diagnostic techniques on single- and multi-cell cavities. As one step, the SST procedure was improved significantly and resulted in a new record gradient of $E_{acc} = 30.6$ MV/m in a single-cell cavity in Wuppertal. As concerns the cavities, a superconducting linear collider for beam energies beyond 100 GeV is within reach now.

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Table 1: Results of the cryotests of cavities T1 - T4

SST: single-sided titanisation; 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 in cleanroom

Cavity test	surface preparation	RRR	Q_0^{max} [10^9]	E_{acc}^{onset} [MV/m]	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	11	3.0	19.5	41.3	9.3	1.0	4.2	FE, power (C)
			8	13.0	31.5	66.6	15.0	5.0	6.8	Q, HPP (C)
T1-c	BCP 15 850°C, 4h	270	10	6.5	22.3	47.1	10.6	1.4	4.8	FE, power
T1-d	BCP 8; SST 1330°C, 20h	750	11	*(7.6)*	41.8	88.2	*(13.8)*	1.0	6.2	FE, power unflat
T1-e	BCP 5 870°C, 4h	550	12	10.5	33.6	71.0	16.0	1.0	7.2	FE, power
T1-f	BCP 5	550	20	8.0	29.4	62.2	14.0	2.0	6.3	FE, power (C)
			>10	17.0	41.0	86.6	19.5	4.0	8.8	FE, HPP (C)
T2-a	BCP 25 850°C, 4h	270	7	7.0	17.4	36.9	8.3	3.0	3.7	Q
T2-b	BCP 8; SST 1330°C, 23h	750	5.3	*(4.9)*	27.1	57.3	*(7.9)*	0.7	3.6	FE, power unflat
T2-c	BCP 57 850°C, 6h	550	11	*(6.5)*	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	23.9	50.6	11.4	0.8	5.1	FE, power
T3-b	HNO_3;BCP 6 880°C, 2h + 1000°C, 1.5h	550	7.0	5.5	17.2	36.4	8.2	0.5	3.7	FE
	RF-Proc.		7.0	9.5	28.4	59.9	13.5	2.0	6.1	FE, power
		Pulse operation:			34.7	73.3	16.5	0.2	7.4	
T3-c	300K		6.5	9.5	28.4	59.9	13.5	2.0	6.1	FE,power
T3-d	BCP 15 1190°C,1.2h water rinsing	<550	35	11.3	35.7	75.5	17.0	6.8	7.7	Q,(FE)
	He-Proc.		30	14.3	36.3	76.8	17.3	10	7.8	Q
T4-a	BCP 65; SST 1330°C, 15h Tun.,Meth.	750	5.6	8.5	22.0	48.6	11.0	1.0	5.0	FE, power
T4-b	HNO_3;BCP 12 900°C, 4h	550	1.4	5.0	18.9	40.0	9.0	1.0	4.1	FE

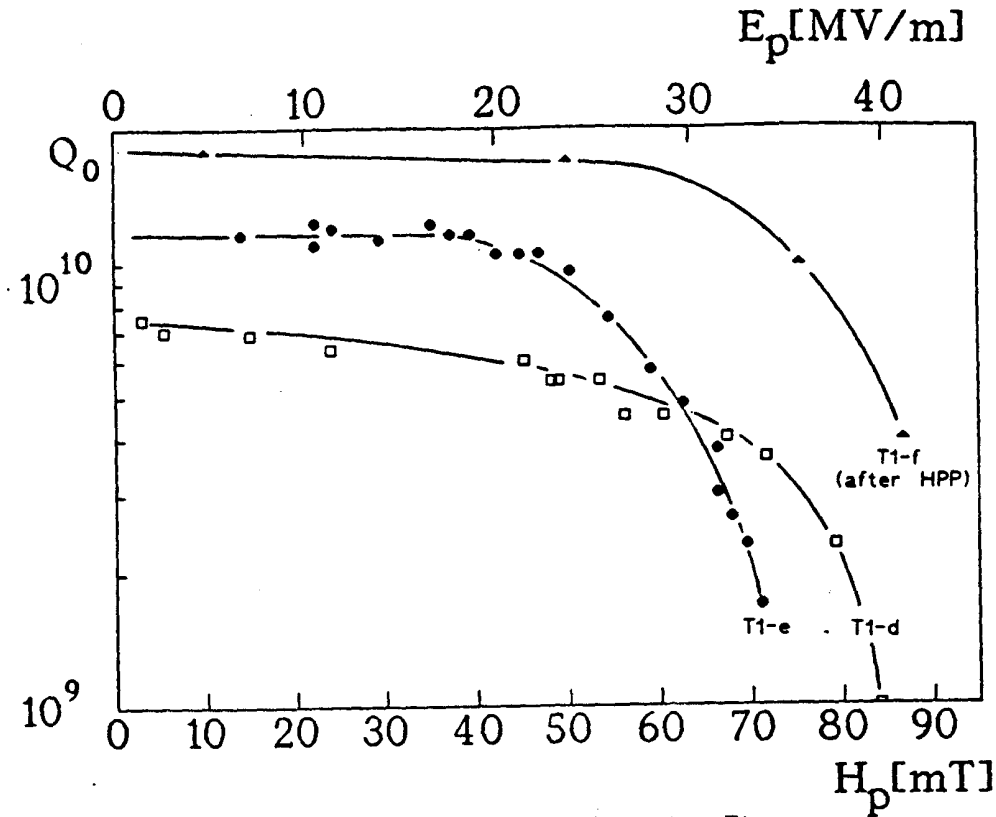


Fig.1a: $Q(H_p)$-performance of the nine-cell structure T1
Open symbols are used for experiments with unflat field profile

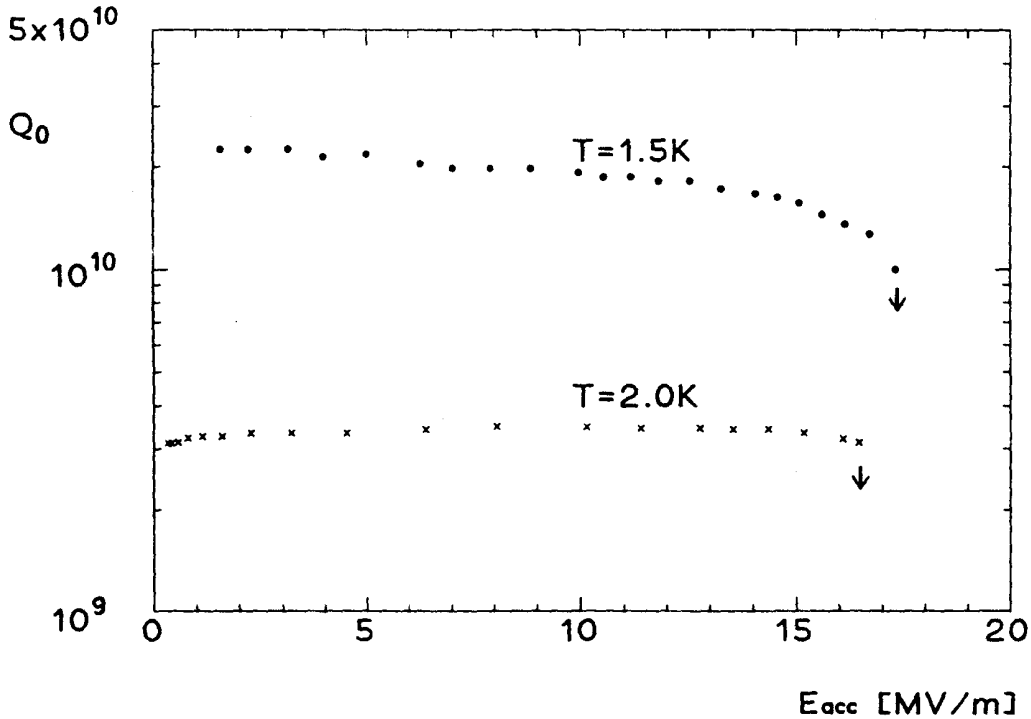


Fig.1b: $Q(E_{acc})$-curve of test T3-d after He-Processing
The two curves are for a Helium bath temperature of T = 1.5K and T = 2.0K.

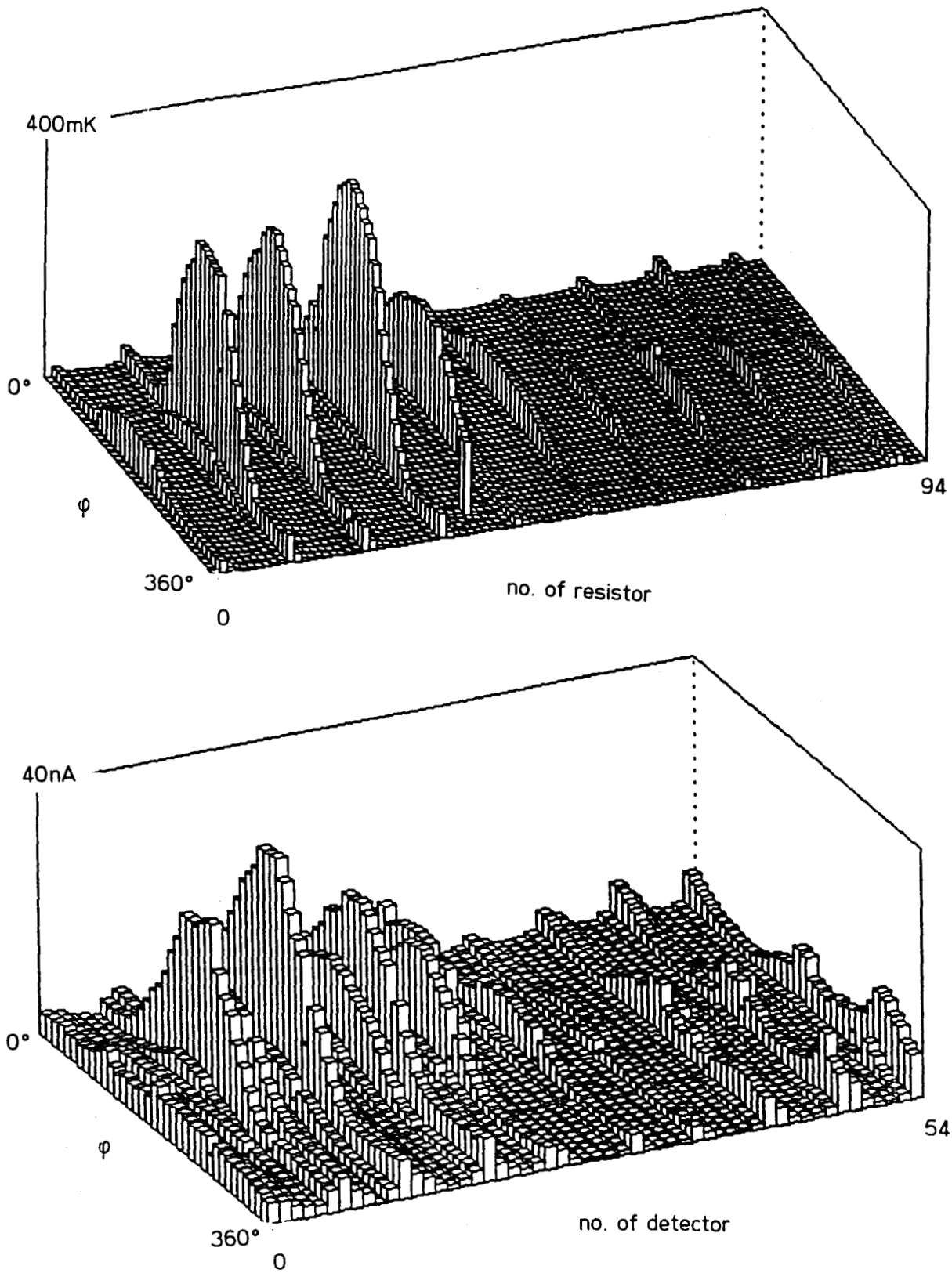


Fig.2a: Temperature map (top) and X-ray map (bottom) of test T3-d before He-processing at a gradient of E_{acc} = 17MV/m

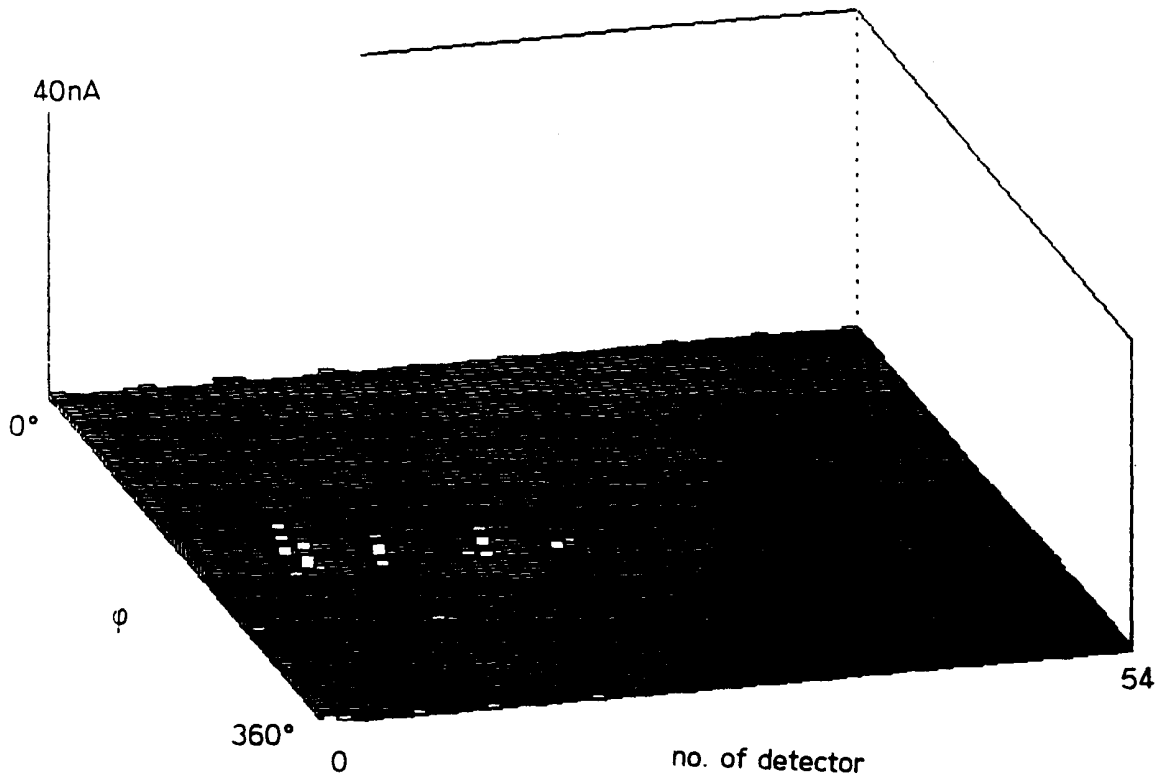


Fig.2b: X-ray map of the same test (T3-d) after He-processing at E_{acc} = 17MV/m

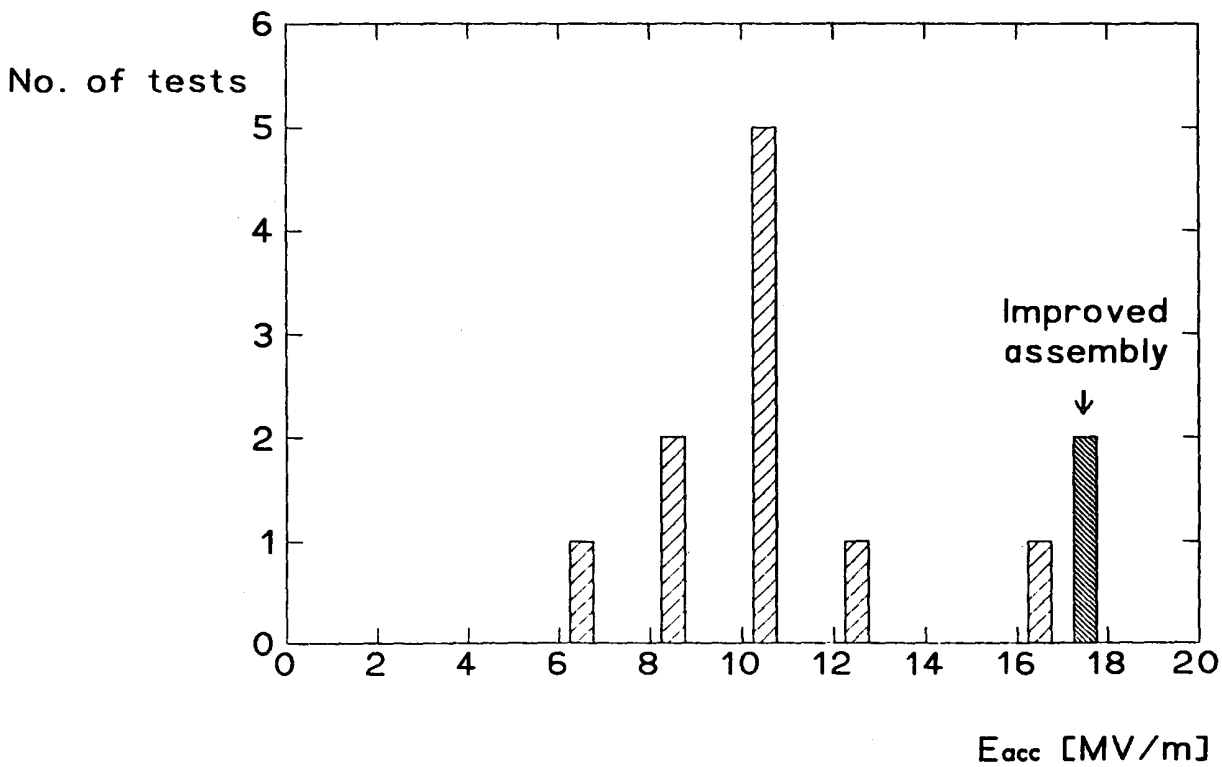
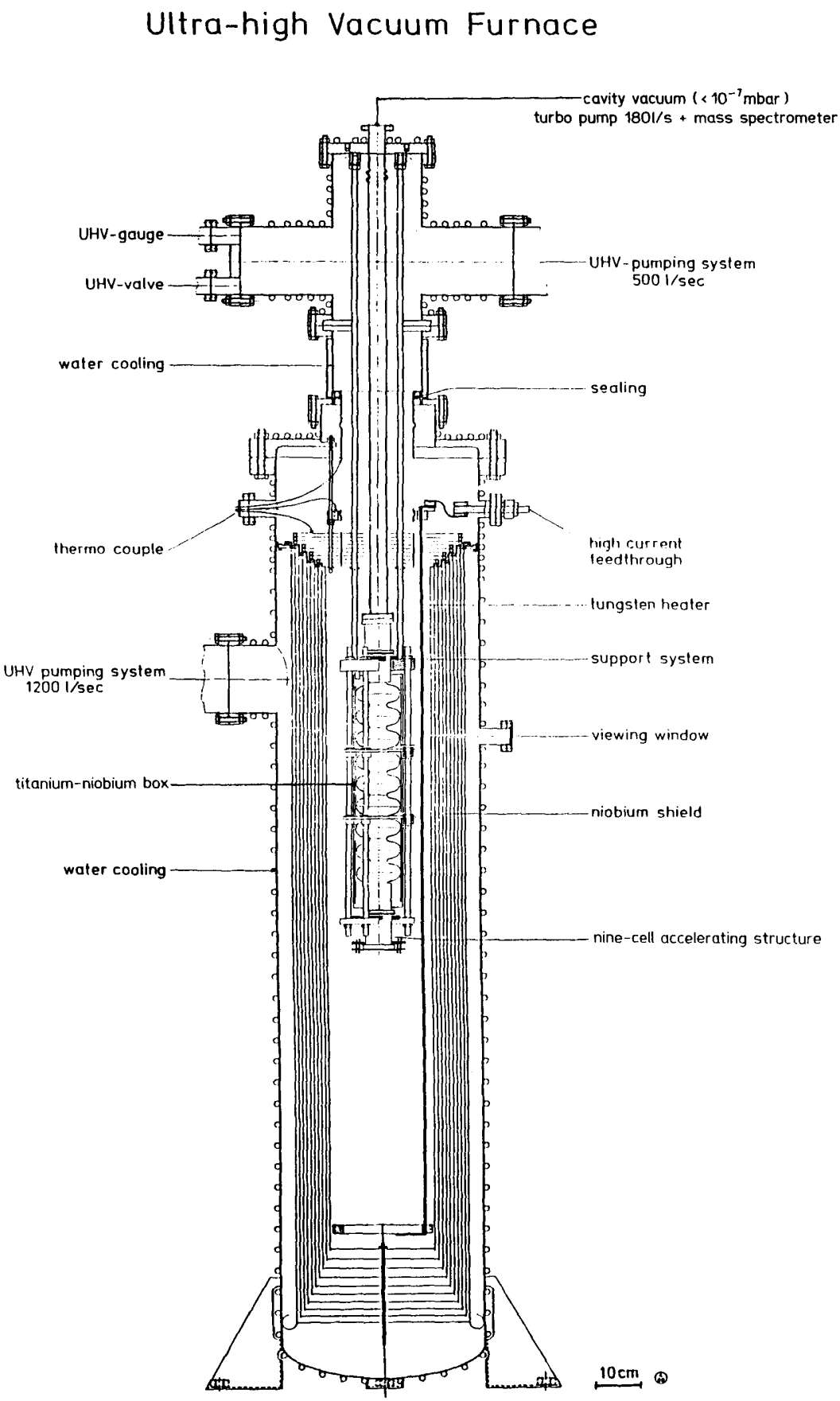


Fig.3: Maximum accelerating gradients of all nine-cell experiments at Wuppertal



Cross section of the UHV-furnace with the improved system for single-sided titanisation (T=1400°C