CERN/EF/RF 84-3
29 March 1984

RF SUPERCONDUCTIVITY AT CERN
NEW RESULTS

C. Benvenuti, P. Bernard, D. Bloess, G. Cavallari, E. Chiaveri, N. Circelli, W. Erdt, E. Haebel, H. Lengeler, P. Marchand, R. Stierlin, J. Tückmantel and W. Weingarten

CERN, Geneva, Switzerland

and

H. Piel

University of Wuppertal, West Germany

ABSTRACT

During the last year efforts were concentrated in order to reach higher field levels in multi-cell and single-cell cavities. In a 500 MHz, 5-cell cavity an accelerating field E_{acc} = 5 MV/m and $Q_o = 0.74 \times 10^9$ at maximum field and 4.2 K were obtained. In view of the frequency choice for LEP a 350 MHz single cell cavity was constructed and tested and reached a field of 5.4 MV/m with an excellent $Q_o = 3 \times 10^9$ at 4.2 K. The programme of Cu cavities sputtered with a Nb layer allowed to reach accelerating fields in excess of 8 MV/m in a 500 MHz single cell cavity. No fast breakdown was observed up to the highest field level. Another 500 MHz cavity fabricated from Nb sheet material with increased thermal conductivity reached an acceleration field of 9 MV/m with $Q_o = 1 \times 10^9$. These results became possible largely because of improved cavity fabrication methods, surface treatments and inspection methods. A new improved design of SC cavities for LEP using a main coupler and higher order mode couplers located at the beam tubes was finalized.

2101G/HL/ed

In the following report the period from May 1983 onwards is covered. At this time a 2-month test of a 500 MHz, 5-cell cavity installed in PETRA/DESY had been finished [1]. Efforts were concentrated in order to reach in multi-cell and single-cell cavities higher fields and to achieve improved reliability of results. Therefore the facilities for cavity welding, for chemical treatments, rinsing with ultra pure water and for cavity inspection were improved. It had to be made sure that SC cavities with a frequency of 350 MHz for LEP did not show unexpected phenomena. The programme for Cu cavities sputtered with a thin layer of niobium was continued and a 500 MHz cavity fabricated with niobium material of improved thermal conductivity was tested. Computations for a new cavity design matched to the requirements of LEP were started.

1. MULTICELL 500 MHz CAVITIES

5-cell cavity

In March-April 1983 a 500 MHz 5-cell cavity had been installed and tested successfully in the PETRA storage ring at DESY [2,1]. The cavity was equipped with a main coupler [3] tested up to 70 kW, one hom coupler [3,4] on each cell and a mechanical tuning system matched to the operation conditions in PETRA. In tests at CERN the cavity had reached acceleration fields of 2.8 MV/m with $Q_o = 10^9$ at 4.2 K. The field was limited by a defect at cell 3. Due to a very tight time schedule it was not possible to retreat the cavity before installation in PETRA and to reach a higher field level. During the test at PETRA two more quenches were observed and limited the fields to 2.3 MV/m. As the cavity was not equipped with a T-mapping system but only with 40 fixed resistors it was not possible to locate these defects precisely.

After its return to CERN the cavity was carefully inspected. A stain was discovered at the bottom of cell 5, which could be correlated to the observed quench. Analysis of some scraped material from this stain with a Scanning Electron Microscope (SEM) showed mainly P and traces of K and Ca. A later analysis with SIMS(*) confirmed that this stain consisted mainly

(*) The SIMS analysis was done by Dr. C. Plog at Dornier System GmbH, Friedrichshafen.

of non-water soluble phosphates. At the bottom of cell 2 where another quench occurred a small dark spot was found. This spot was removed by a pneumatic chisel and was analyzed with a SEM. Cl, K, Ca and traces of Al and Pb were detected. It is probable that this contamination had fallen down from the hom coupler of this cell, which had been heated up accidentally to a very high temperature during the test. A number of small spots were also detected at the walls of the hom coupler port. An analysis revealed Pb, Cr, Fe and small amounts of Al, Si and Ti. At the quench region of cell 3 nothing particular was seen. Besides these localised spots large area stains were found in various regions of the cavity. An analysis with a SEM and SIMS revealed also non water soluble niobium phosphates. Tests on Nb samples have shown that such phosphates may be produced whenever a thin layer of our CP solution remains for a few minutes in contact with a Nb surface(*). It was shown that these phosphate layers cannot be dissolved by water or "mild" acids. They can be removed by a new CP, by concentrated HF (40%) or by H_2O_2 (with a strong formation of oxides).

During the test at PETRA the Q_o degraded from an initial 10^9 to 5×10^8 at the end of the run and could not be restored by a warm up to 300 K. It is hoped to find out in near future whether the Q degradations observed during the PETRA test can be explained by the observed phosphates or whether they have to be attributed to the large gas exposures of the cold cavity during the test (cf. chapter 7). It would be extremely useful in a future storage ring test to install a T-mapping system for monitoring such cavity degradations.

Before the next test the cavity was submitted for the first time to an integral chemical polish in a new surface treatment installation (fig. 1). After a first treatment where about 20 μm of Nb were removed the cavity was inspected. No more large stains were observed. The cavity was chemically polished a second time (30 μm Nb), rinsed with high purity, dustfree water (ρ = 18.2 MOhm x cm) and as usually dried in a horizontal position inside a dustfree hut.

(*) We believe that this situation occurred during the local treatments at the iris regions after the final weldings [2].

A T-mapping system using electronic multiplexers at LHe temperatures inside the cryostat was constructed and mounted. A new simplified support system was prepared which does not fix the intermediate irises. The original mechanical tuners acting on the two end-cells were replaced by a hydraulic tuner which changes the total length of the cavity (fig. 2). In this way it became possible to study variations of the field flatness due to non-uniform deformations of the 5-cells at cool-down or during tuning. As before the field distributions are monitored by an RF probe on each cell. The main coupler and the hom couplers needed for operation inside PETRA were removed. A small loop coupler at one hom-port was used as input coupler. The cavity was tuned flat at room temperature by inelastic deformation of the individual cells. Cold measurements were performed in our large vertical cryostat.

In contrast to the results of the two first tests before installation at PETRA the field could this time be raised without difficulties. It took only about 1 h to reach the maximum field level of 5 MV/m. Some low multipacting levels at 0.04, 0.09 and 0.3 MV/m and some quenches due to electron activity at 3.4, 3.7, 4, 4.2, 4.8 and 5 MV/m were overcome rapidly. No electron current was detected at the RF probes; some X-ray activity, monitored by an ionisation chamber at the side of the cryostat, was observed above 3.9 MV/m. We attribute this small electron activity, which was orders of magnitude smaller than in the first tests, to the improved chemical polishing and to the final rinsing with very clean water. This is the more remarkable as the cavity was measured in a vertical position where the cavity is more prone to electron activity than in the horizontal position [5].

At 2.5 K a low field $Q_o = 1.35 \times 10^9$ was reached. The field was limited at 5.2 MV/m by a defect located at one of the intermediate ring weldings of cell 2. At 4.2 K a low field $Q_o = 1 \times 10^9$ was measured and a maximum field of 5.0 MV/m was reached. The field was limited by a defect located at the main coupler port of cell 2.

The hydraulic tuner allowed a tuning range of 227 kHz; this corresponds to a change in total length of ~ 3 mm and exceeds by a large factor the tuning range considered necessary for LEP. The setting accuracy is estimated < 150 Hz. If the frequency tuner would act equally on all 5-cells no change of field distribution should be observed. However, we know from the measurements of individual cells that one cell showed a different mechanical behaviour from the other cells. This has been confirmed by the change of field distribution at maximum detuning and also by some change observed during cooldown. Finally we mention that the pressure dependence of the frequency is increased because the intermediate supports at the irises were suppressed. The previous -90 Hz/mbar was changed to -155 Hz/mbar.

This test has fully confirmed that the field limitations previously found were only due to the poor quality of the local chemical polishings applied before the test. No field limitations specific for multicell cavities were observed. In particular it was shown that with a high quality vacuum even the much feared multipactor levels in multicell cavities with many coupling ports were almost completely suppressed.

<u>4-cell cavity</u>

In 1981 a 4-cell, 500 MHz cavity had been constructed [6,7] in order to study problems specific for multicell cavities like e.g. multipactor, field flatness and frequency tuning [8]. Q_o values up to 1.6×10^9 at low field and acceleration fields E_{acc} = 2.8 MV/m were reached after the application of He-ion sputtering. This cavity is equipped with a tuning system [8] allowing an individual tuning of all 4 cells.

In May 1983 a new series of measurements were started with the aim to understand and cure the field limitations previously encountered. T-mapping had allowed to localise a lossy RF region which had caused the field breakdown in the 1981 measurements. An elemental analysis performed with a Scanning Electron Microscope (SEM) on material removed from this region showed mainly Pb (26%) and Zn (74%) with a possible presence of C and O_2 (not detectable by the SEM). The origin of this material at the cavity wall is not understood. The quench region was ground by a hard-metal tool followed by grinding with "emery paper" and by a standard Chemical Polishing (CP) of 20 µm. It was checked by a SEM on Nb samples that no grinding material inclusions were left at the Nb surface after this treatment.

The cavity was measured in a vertical position with a chicane added to the pumping line above the cavity to avoid dust particles falling inside the cavity.

In table 1 a few results are summarized. The initial period of a first test was characterized by the appearance of many multipactor-like levels and by large changes in the e^- landscape as seen on T-maps. At 1.7 MV/m a strong e^--source (with β = 26500!) causing a fast breakdown by heating of the cavity walls was observed. A short He processing reduced its activity considerably (β = 1450). Another fast breakdown was observed at 2.1 MV/m linked to an electron trajectory at the same azimuth [9].

At 2.7 MV/m and at <u>subcooled</u> LHe conditions a quench was observed at the equator of cell 1. This quench was also observed in other modes of the fundamental passband and could not be removed by a long He-ion sputtering. It showed a thermal hysteresis. A later inspection revealed a welding irregularity at the quench position (fig. 3). At 4.2 K another quench was observed at 2.2 MV/m located near the iris region of cell 3. This quench had no precursor and showed also a thermal hysteresis. A subsequent optical inspection revealed at first no anomaly at the quench region. Under improved illumination with a Xenon lamp an area of some cm^2 with a different brilliance was detected. It is suspected that this spot withstood a chemical polishing. The losses inducing the quench are reduced below 3.8 K to an undetectable amount so that the breakdown occurs below 3.8 K at the welding of cell 1. In fig. 4 the dependence of the breakdown field on bath temperature is shown.

Before the second test the quench region of cell 1 (at the equatorial weld) was ground and the cavity was submitted to chemical polishing of

~ 30 μm and rinsed with dustfree water. For the first time a slow pumpdown (1.5 h) was applied to avoid dust transport from the vacuum system to the cavity. The cavity was tuned flat in the π-mode to ± 5%. During the first field increase, a He-ion sputtering was applied to avoid surface damages due to heavy electron loading and the electron current (measured by the output antenna located in one beam tube) was always kept below 1 nA.

At 2.43 MV/m the reground region in cell 1 caused again a quench whose precursor could be seen on the T-map. Because of this quench, the cavity was detuned to reduce the field in cell 1. In this way a mean accelerating field $\overline{E_{acc}}$ = 3.4 MV/m was reached with a relative field distribution $E_1 = 0.65$; $E_2 = 1$; $E_3 = E_4 = 0.96$.

After the test the cavity was inspected. At the quench region of cell 1 fissures at the welding were discovered. It is suspected that these fissures, which were not visible after the grinding of this region were uncovered by the subsequent chemical polishing. Therefore we inspect reground regions from now on always after a first chemical polishing and look for irregularities which may have been hidden by the grinding itself. Only after this inspection the final chemical polishing is performed.

All tests confirmed earlier observations that no field limitations different from those observed in single cell cavities were found.

<u>2-cell cavity</u>

A 2-cell cavity was fabricated for investigating more closely the influence of the iris weldings on the RF-losses and mechanical deformations at the iris region. By keeping the beam tubes very short it was possible to measure this cavity also in a horizontal position in our big cryostat (fig. 5). Pumping is done by a pumping line connected to one of the beam tube covers. The cavity was equipped with a T-mapping system covering entirely the iris regions.

At low field and T = 4.2 K a quality factor $Q_o = 1.8 \times 10^9$ was measured (the Q_o is limited by the copper-plated lids of the beam tubes and by their joints). Many multipacting levels were observed (0.16, 0.37, 0.95, 1.1, 2.2, 2.3 and 3.7 MV/m). These levels were strongly influenced by the He gas pressure inside the cavity during He-ion sputtering. The maximum field reached by RF-processing was 4.7 MV/m. A first He-ion sputtering allowed to reach immediately 6 MV/m. At this level a breakdown almost certainly caused by e^- loading was observed. We infer this from the fact that the breakdown started only 1 sec after E_{max} had been reached and was accompanied by a strong X-ray burst. At 5.3 MV/m and 4.2 K a $Q_o = 1 \times 10^9$ was measured. The second passband mode ($\pi/2$-mode) was also measured and showed considerable multipacting.

During the second He-processing the cavity was exposed accidentally to a mixture of He-gas and non dustfree air ($p > 0.4$ mbar). The Q_o was not changed (cf. chapter 7) but the field was limited by a quench at the bottom of cell 2, probably caused by a dust particle dragged along during the gas exposure. On the T-maps of fig. 6 the additional RF losses can be clearly seen. An optical inspection of the cavity revealed nothing particular at the quench region; in particular no black spot with a halo due to the evaporation of a dust particle could be seen. The T-maps of fig. 6 show also that the equatorial weldings cannot be distinguished from their surrounding and that there are no additional (dielectric) losses at the iris regions. This has been confirmed up to the highest field levels reached.

The T-maps give us a possibility for determining the field flatness in a multicell cavity. In ref. [10] the relation

$$\Delta T \sim Q^{0.75} \sim H^{1.5}$$

has been established (ΔT: local T-increase; Q, local heat flow; H, local magnetic field. By integrating ΔT over some definite regions of the cells (e.g. along the equator region) one thus obtains the ratio of the magnetic fields in the different cells. For the 2-cell cavity we got $H_2/H_1 = 1.4 \pm 0.2$ in very good agreement with a direct perturbation measurement. By taking into account the measured field flatness the quench field level in cell No. 2 is 7 MV/m.

2. 350 MHz SINGLE CELL CAVITY

The fabrication and results from the first tests are described in ref. [11]. The cavity (fig. 7) reached a maximum field of 4.7 MW/m with $Q_o = 3.2 \times 10^9$ at 4.2 K and with $Q_o = 10^{10}$ at 2.7 K and low field. Electron loading was insignificant. The field was limited by a defect located at the equatorial weld (fig. 3(b)). Before the second test this region was reground and a new chemical polishing of 20 µm was applied. A few results are given in table 1 (for a discussion of Q_o-limiting effects see ref. [11]).

With a short HF processing it was possible to raise the field to 4.7 MV/m; as usual He-ion sputtering was applied afterwards in order to reduce the e^- activity and avoid surface damages. Some electron induced breakdowns located in the equator region were detected. However these activites were so quickly overcome so that no documentation by T-mapping was possible. Finally a defect located at the same position as before i.e. at the ground equator weld limited the field. The maximum field now depended on the bath temperature (table 1). An inspection revealed some fissures at the ground welding similar to the ones in the 4-cell cavity (see above).

This test shows that in 350 MHz cavities fields comparable to the ones in 500 MHz cavities can be reached. In addition, the Q_o values are very high, they were already dominated by losses due to the ambient magnetic field (130 mOe) and by losses of the copper plated lids of the beam tubes. Therefore we believe that the losses of the cavity walls correspond to Q_o values in excess of 5×10^9 and approach the theoretical values for BCS losses of 7.3×10^9 at 4.2 K.

3. Nb SPUTTERED Cu CAVITIES

In 1980 at CERN a programme was started for investigating the feasibility of sputtering niobium on copper cavities [12]. In fall 1983 a first monocell 500 MHz Cu cavity with our standard geometry was tested. Despite very poor weldings and many defects on the sputtered Nb layer a field of 2 MV/m with $Q_o = 8 \times 10^8$ at low field and 5×10^8 at 2 MV/m was reached. The field was limited by an overall warming up of the cavity and by strong e^- loading. Many Q switches caused by small parts of the Nb layers which are in poor thermal contact with the Cu wall were observed and could be well documented by T-maps. An inspection of the cavity at the quench region showed that a small part of the Nb layer had peeled of. Additional points of "broken" Nb layers with protruding spikes also were observed. The cavity was cut to pieces in order to study the defects in detail. These investigations are going on.

After this test a few improvements in the sputtering, cleaning and mounting procedures were applied and a second Cu-cavity was sputtered with a 1.5-5 µm layer of Nb (fig. 8). At low field Q_o values of 1.8×10^9 at 4.2 K and 7×10^9 at 2.2 K were found. The Q_o degraded at 1 MV/m to 1×10^9 (fig. 9). By RF processing it was possible to increase the field to 5 MV/m. The strong electron activity (with one typical $\beta = 560$) made it advisable to perform a He-ion sputtering. Finally a field of 8.6 MV/m was reached. The limit was set by a very strong field emission reducing Q_o to 3×10^8. It is remarkable that the cavity showed no sign of any thermal breakdown despite strong electron trajectories and despite the fact that up to 188 W were dissipated inside the cavity. We attribute this behaviour to the high thermal conductivity of the Cu wall (an estimated 300 W/m x K as compared to a typical 10 W/m x K for Nb at 4.2 K). The effect of the large conductivity is also clearly seen on the T-maps (fig. 10). Large areas with increased temperature are visible and the typical sharp T-peaks of Nb cavities are absent. An inspection of the cavity after the test showed two defects of the Nb layer at the centre of the areas with increased temperature. The analysis of the experimental results and of the cavity defects is still going on.

The absence of quenches up to the high field levels reached makes this development extremely interesting. This could be a big advantage once many SC cavities are operated in LEP. If a single cavity would deteriorate without reaching a quench the additional cryogenic losses due to a Q degradation may be well tolerable for some time and this may avoid switching off a whole array of SC cavities fed by one common RF generator.

In addition the high thermal conductivity of Cu may allow cooling by tubes or small He-tanks. This could considerably reduce the amount of the LHe inside the cryostat.

The future programme will aim at an improvement of Q_o values at high fields and at repair possibilities for the sputtered Nb layer.

4. A 500 MHz CAVITY FABRICATED FROM Nb SHEET MATERIAL WITH IMPROVED THERMAL CONDUCTIVITY MEASUREMENTS. CONDUCTIVITY MEASUREMENTS

The influence of the thermal conductivity λ of the Nb material on breakdown fields has been computed and it has been shown that for point-like defects $H_{max} \sim \sqrt{\lambda}$ [13]. A computer controlled set-up for measuring automatically the thermal conductivity λ as a function of the temperature between 2 K and 10 K was built [14] and is now used in a routine way. In fig. 11 the result of such an experiment is shown. The insight on the role of high thermal conductivity for SC cavities has already triggered some developments in the fabrication of Nb sheet material where λ is increased from a typical 10 W/K × m to 28 W/K × m (fig. 11) with a residual resistance ratio of 110(*). Before the construction of a cavity it was checked on electron beam welded Nb samples that λ is only decreased from 28 W/K × m to 21.5 W/K × m in the welding region.

A 500 MHz single cell cavity with a wall thickness of 2 mm was constructed, surface treated with our standard methods and tested. At 4.2 K, the field could be raised within 1 h to a remarkable 8.3 MV/M with a nearly field independent Q_o of 1×10^9 (fig. 12) and exceeds the performances of all Nb single cell cavities measured up to now. By applying RF-processing, He-ion sputtering and mode mixing it was possible to increase the field to 9 MV/m. At this field an electron induced quench is observed whose exact nature has still to be investigated. As expected lossy regions and electron trajectories produce temperature increases which are approximately twice as broad as in cavities fabricated from lower λ niobium. As for the Nb-Cu cavities (chapter 3) the improved thermal conductivity may allow operation with cavity walls only partially in contact with liquid helium. In order to check this possibility the

---

(*) Manufactured by W.C. Heraeus GmbH, Hanau, West Germany.

cavity was operated in subcooled He (where the evaporation is suppressed) while only partially immersed. In fig. 13 the result of this measurement is given. As for Nb-Cu cavities this may allow to device simpler cryostats for LEP.

5. RESULTS WITH OTHER MONOCELL CAVITIES

5.1 A TIG welded 500 MHz Nb cavity

A 500 MHz single cell cavity with an intermediate ring was assembled by TIG welding. The aim was to check the behaviour of TIG welded joints on cavity performances. In the course of the welding a large hole was produced at one of the welds and repaired by melting some additional Nb onto the weld.

Some results are given in table 1. The field was limited at 4.2 MV/m by a defect located at an equatorial weld but not at the repaired region. At a field just below the quench the repaired weld can be seen on a T-map, its maximum ΔT being 380 mK as compared to the 546 mK of the quench region itself. It is intended to remeasure this cavity after a grinding of the quench region and of the repaired region.

TIG welding may advantageously replace EB welding in Nb cavities. It is also more flexible if welds must be made on complicated geometries of auxiliary Nb parts like e.g. couplers. It was possible to master the problem of an adequate protection gas system and to avoid water vapour, particularly detrimental for Nb weldings. However, more studies will be necessary so to reach the reliability standard of EB weldings.

5.2 A 500 MHz cavity for coupler and tuning tests

A 500 MHz single cell cavity has been fabricated and has been equipped with coupling ports for a main coupler, hom couplers and RF probes. With this cavity all couplers needed for the operation of the 5-cell cavity in PETRA were tested and a total of 14 coupler tests have been performed.

The cavity showed an enhanced electron activity as compared to similar cavities without coupling ports. In particular many multipactor levels were observed in this cavity which are produced by resonant electrons in the hom coupling port regions. The resistance of these levels to processing depends strongly on the surface conditions; for clean and dustfree surfaces and good vacuum ($p < 10^{-8}$ mbar) the multipactor can be suppressed almost completely.

This cavity was submitted to a tuning by inelastic deformation of its length. With a force in excess of 0.5 t an irreversible tuning by 150 kHz was achieved. It was also shown that the pressure dependence of this cavity was nearly twice as big as for a cavity without main coupler port. This observation is of importance for the construction of multicell cavities. It is intended to tune these cavities by a change of their total length. In order to avoid a non-uniform change of cells resulting in field unflatness they should be made as much as possible of equal mechanical strength against tuning forces and pressure changes. Therefore large coupling ports located on the cells should be avoided (see chapter 9).

6. RESULTS WITH 3 GHz CAVITIES

Since the start of the programme in 1979, work with 3 GHz cavities (fig. 7) has always been continued and many problems have been investigated. In all 21 3-GHz single cell cavities have been tested and 9 of them have been cut to pieces to obtain additional information on lossy regions or weldings [15]. A large part of these tests have been devoted to improve the methods of the chemical treatments, rinsing and assemblying. A big proportion of quenches came from rinsing residues containing Na, Ca, K and Cl. This led us to push for an installation with ultrapure, dustfree water. Other quenches were related to defects containing Si, Al, S and Al and pointed to dust particles or to contaminations originating from other parts of the measuring system (e.g. joints). Some tests were devoted to the improvement of welding techniques; in particular holes observed in TIG weldings could be identified as the cause of quenches and led to improved systems for protective gas. Tests of cavities with Nb sputtered onto a Nb or Cu substrat were also first done at 3 GHz and the results were only then applied to 500 MHz cavities. We plan to continue the 3 GHz programme as a flexible back up of our main 350 MHz programme.

7. EXPOSURES TO AIR AND PROTECTIVE GASES

During the 2-month operation of the 5-cell cavity in PETRA the cavity was exposed to an estimated 2×10^{-8} mbar year of gases originating from warmer parts of the cavity (like couplers and beam tubes) and from the adjacent beam components in particular from the Cu cavities. At the final warm-up a considerable gas desorption from the cavity was observed, corresponding to about 200 monolayers of gas covering the inner cold walls. In the course of the test the Q_o degraded from 10^9 to 5×10^8 and could not be restored after a warm up to 80°C. We were not able to trace back the causes of this degradation and we therefore cannot exclude that the decrease was due to the cryopumping of large amounts of gases. We compare this result with a vacuum accident of the 2-cell cavity (cf. chapter 1) by which the cavity was exposed at 4.2 K to a mixture of He-gas and non dustfree air at a pressure $p > 0.4$ mbar. During warm up (with closed valves) a desorption corresponding to ~ 40 monolayers of air was measured. A mass spectrum revealed one order of magnitude higher CO and CO_2 signals than for air. In contrast to the PETRA test no change of the Q_o was observed.

A better understanding of cavity degradations will be of obvious importance for a later operation in LEP. Therefore it is intended to start more systematic tests on exposures to air (and dust particles) of <u>cold</u> SC cavities.

Of similar interest are exposures of cavities at <u>room temperature</u> to protective gases for "in situ" repairs. The 500 MHz cavity used for high power tests of main couplers and hom couplers (chapter 5.2) has been exposed 14 times to dry, dustfree N_2 and couplers were changed under dustfree laminar air conditions. No new chemical treatment nor rinsing was applied during this period. The initial performances ($Q_o = 1.1 \times 10^9$ at 4.2 K and low field, E_{max} = 4.1 MV/m at 4.2 K and 5.1 MV/m at 2.5 K) were not deteriorated.

8. IMPROVEMENTS IN SURFACE TREATMENTS; WELDINGS AND MEASUREMENT SET-UPS

A new installation (fig. 1) for a treatment of 500 and 350 MHz multicell cavities has been constructed and applied for a treatment of the PETRA cavity. The cavity is treated in a vertical position and acids are pumped in and out from below. The filling and emptying time is about 2 min. The temperature increase of the Nb surfaces can be kept below 3°C by cooling the outer walls by water. The neutralisation of acids is obtained by a water sprinkler placed inside the cavity, afterwards the cavity is rinsed with demineralized water. The final rinsing is done with high purity and dustfree water (ρ = 18 MOhm x cm, standard used in microcircuit fabrication) followed by a drying inside a dustfree hut. For mounting under clean conditions an additional laminar flow tunnel of $3 \times 4\ m^2$ cross section has been constructed. It will allow clean assembling of large multicell cavities and mountings inside horizontal cryostats.

All these improvements have not dramatically increased maximum field levels and Q_o values but they have allowed to reach in a much more reliable way satisfactory results, especially with large multi-cell cavities.

A great effort has been made together with the CERN workshops for improving the electron beam and TIG welding facilities. First tests with an internal electron beam welding gun(*) have been successful. A support is under preparation which will allow to assemble a multicell 350 MHz cavity by internal EBW, and avoid the use of tools inside the cavity. It is hoped to do in this way all iris weldings in one pumpdown cycle.

Some effort has also been made to improve and automatize measurements of SC cavities. There is now a computer controlled measuring set-up available which allows to measure and plot Q values, electron currents, coupling factors, etc. as a function of the accelerating field.

(*) Lent kindly to us by SIAKY, Paris, France.

The existing PETRA cryostat has been modified and will allow operation of a 4- or 5-cell cavity with a T-mapping system inside. A horizontal cryostat for testing 350 MHz multicell has been ordered and design work for dedicated LEP cryostats has been started.

9. DESIGN OF A LEP CAVITY

Tests on the SC 500 MHz 5-cell cavity for PETRA had shown that tuning the cell frequencies correctly for a flat fundamental π-mode does not guarantee a good tune for higher order modes (hom). The problem of sufficiently low Q_{ext} for the hom had been overcome by the use of one hom coupler on each cell. However, hom couplers located on a cell always present a risk for multipactor and in addition may not be an economic solution; therefore a cavity geometry was searched which would allow to put not only the main coupler but also hom couplers on the beam tubes of a multicell cavity. The new computer code URMEL [16], especially in its improved version URMEL 1.8 [17] gave us for the first time the possibility to compute in a fast way not only monopoles but also multipoles of multicell cavities.

In a first step an improved single cell cavity was designed. Ideally, one would like to combine an increased cell-to-cell coupling with no decrease in R/Q for the fundamental mode, no increase of E_p/E_{acc} and H_p/E_{acc}, together with no increase of the R/Q for hom.

A great number of geometries suitable for SC cavities were calculated and led to a compromise where the cell-to-cell coupling for the fundamental mode was increased from 0.9% to 1.76% with a 12% decrease of R/Q and with a 11% increase in E_p/E_{acc} (table 2). The R/Q of the hom could be decreased. It was possible to obtain this compromise without a radical change of our geometry using a circular boundary around the equator and slightly more inclined side walls (fig. 14).

In a second step a new multi-mode compensation scheme for the end-cells was applied involving a geometry change of the beam tube section adjacent to the end-cells (fig. 14). By choosing adequately their diameter and length and a slightly reduced cell length it was possible to compensate the end-cells not only for the TM_{010} but also for the two most dangerous hom, the TM_{011} and TM_{012} modes. In this way it was possible to reach sufficient coupling for the fundamental and hom modes with couplers located at the beam tubes (fig. 14). For reasons of simple manufacturing and in contrast with earlier designs the diameter of the end-cells was not changed. In fig. 14 and table 2 a few parameters of this new cavity design are given [18]. We intend to construct and test two 3-cell, 350 MHz cavities based on this design.

In connection with this design effort a new method [19] was developed to compute from URMEL and SUPERFISH data the RF power radiated from propagating cavity modes into the beam tubes and to determine thereby the Q_{ext} of hom corresponding to such an energy loss.

10. CONCLUSION

The results described have shown that field levels above 5 MV/m can be reached in multicell cavities by applying improved cavity fabrication methods and surface treatments. No field limitations different from those found in single cell cavities were observed and it was shown that under dustfree, high vacuum conditions electron loading can be suppressed almost completely up to these field levels. At 350 MHz fields comparable to the ones obtained at higher frequencies are reached and have invalidated the long belief that the maximum obtainable fields decrease with frequency. This together with the excellent Q_o values of 3×10^9 decided us to start now the fabrication and testing of 350 MHz multicell cavities for LEP.

The results obtained with Nb sputtered Cu cavities show great promise, mainly because of the absence of fast breakdowns even at field levels as high as 8 MV/m. A future programme will aim at an improvement of Q_o values at high fields and at repair possibilities for the Nb layer. A 500 MHz cavity fabricated from Nb sheet material with increased thermal conductivity allowed to reach at the first cooldown accelerating fields of 9 MV/m together with a Q_o value of 1×10^9 which showed nearly no degradation up to the highest field levels. Tests with this cavity showed also that high fields can be reached if the cavity is only partially immersed in the LHe-bath. These results open the way for new and simpler cooling layouts and will simplify the cryostat design.

The application of improved computer programmes to cavity calculations lead to a new cavity design for LEP which takes into account, besides the fundamental mode, the properties of higher order modes and makes the use of couplers located at the beam tubes envisageable.

Acknowledgements

We would like to thank all technicians of our group for their help. We also would like to thank the cryogenic group, BEBC and the Workshop of EF Division, the vacuum group of LEP Division as well as the SB workshops for sheet metal work, chemistry, EB welding, brazing and surface inspection.

REFERENCES

[1] Ph. Bernard et al., CERN/EF 83-12, to be published in Proc. 12th Int. Conf. High Energy Acc., Fermilab 1983.

[2] Ph. Bernard et al., IEEE NS-30 (1983) 3342.

[3] E. Haebel, IEEE Trans. Nucl. Sc. NS-30, 4 (1983) 3345, and CERN/EF/RF 83-4.

[4] E. Haebel, CERN/EF/RF 83-4.

[5] Ph. Bernard et al., Nucl. Instr. & Meth. 206 (1983) 47.

[6] Ph. Bernard et al., CERN/EF/RF 81-2.

[7] Ph. Bernard et al., CERN/EF/RF 81-7.

[8] E. Haebel and J. Tückmantel, CERN/EF/RF 81-5.

[9] Ph. Bernard et al., Nucl. Instr. & Meth. 190 (1981) 257.

[10] R. Romijn, W. Weingarten and H. Piel, CERN/EF 83-1 and IEEE MAG 19, 3 (1983) 1318.

[11] Ph. Bernard et al., CERN/EF/RF 83-6.

[12] C. Benvenuti, N. Circelli and M. Hauer, to be published in Appl. Phys. Letter.

[13] H. Padamsee, CERN/EF 82-5 and IEEE MAG 19, 3 (1983) 1322.

[14] A. Schopper and W. Weingarten, CERN/EF/RF 83-7.

[15] H. Padamsee, J. Tückmantel and W. Weingarten, CERN/EF 82-17 and IEEE MAG 19, 3 (1983) 1308.

[16] T. Weiland, DESY report 82-015 (1982) and M-82-24 (1982).

[17] J. Tückmantel, CERN/EF/RF 83-5.

[18] E. Haebel, P. Marchand and J. Tückmantel, CERN/EF/RF 84-2.

[19] E. Haebel, P. Marchand and J. Tückmantel, CERN/EF/RF 84-1.

TABLE 1

Some experimental results

Type of cavity	Q_o (x 10^9) at low field 4.2 K	~ 2.3 K	Q_o (x 10^9) at E_{max} 4.2 K	E_{max} (MV/m) 4.2 K	2.3 K	Field limitation	Remarks
500 MHz - 5 cell (PETRA cavity)	1	1.35	0.74	5	5.2	Defect at welding	1 quench at hom coupling port (e^- - induced?)
500 MHz - 4 cell	1.5	5	1.5	3.4	-	Defect at welding	2 T-dependent quenches
500 MHz - 2 cell	1.8[(a)]	2.7	1	6	6	Defect after vacuum accident	Dust particles
350 MHz - 1 cell	4[(a)]	18[(a)]	3	5.4	6.4	Defect at welding	Fissures at welding
500 MHz - 1 cell Nb-Cu	1.8[(a)]	7[(a)]	0.3	8.6	-	Q degradation by by e^- loading	No fast quench observed (P_{diss} ≤ 188 W!)
500 MHZ - 1 cell high λ niobium	1.3[(a)]	1.7[(a)]	1	9	-	e^- induced quench	
500 MHZ - 1 cell TIG welded	1.3[(a)]	5.4[(a)]	1	4.2	4.2	Defect at welding	
3 GHz - 1 cell TIG welded	0.2	4	4	-	9.3	Defect at welding	12 MV/m for a short period

(a) Values limited by Cu-covered lid and RF joints of beam tubes.

TABLE 2

Some parameters of a 352 MHz, 4-cell cavity with improved geometry for LEP and of the cavity tested in PETRA (scaled to 4 cells at 352 MHz)

Fundamental mode	LEP geometry	PETRA geometry
Frequency	352 MHz	352 MHz
Iris diameter	24.2 cm	21.3 cm
Effective length	1.7 m	1.7 m
R/Q	469 Ohm	532 Ohm
E_p/E_{acc}	2.3	2.05
H_p/E_{acc}	39.5 G/(MV/m)	37.7 G/(MV/m)
Q (Cu, 300 K)	57650	56000

Higher order modes		f (MHz)	R/Q (Ohm)	Q_{ext} (a)		f (MHz)	R/Q (Ohm)	Q_{ext} (b)
TM_{011}-mode	0	639	108	57000	π/5	648	84	17000
	π/4	636	48.5	35000	2π/5	646	56	15000
TM_{012}-mode	π	1005	22.7	39000	?	1033	28	5×10^6
	2π/4	999	22.8	87000				
Dipole mode with highest R/Q (3.5 cm off axis)		687	25.6	-		723	60	2×10^5
Quadrupole mode with highest R/Q (3.5 cm off axis)		875	1	-	-	-	-	-

(a) Estimated for one beam tube hom coupler.

(b) Measured at PETRA tests.

FIGURE CAPTIONS

Fig. 1 The new installation for chemical polishing and rinsing of multicell cavities. Acids are pumped and emptied from below, rinsing is done by a sprinkler tube located inside the cavity.

Fig. 2 The 500 MHz, 5-cell cavity equipped with a T-mapping system and a hydraulic tuner (double plate below). The tuner is actioned by a membrane with GHe and changes the length of the cavity. Pumping is done from below.

Fig. 3 (a) 500 MHz, 4-cell cavity. A welding irregularity causing a fast quench (cell 1).

(b) 350 MHz, 1-cell cavity. Quench region at welding overlap; the steel ball is used for localising the quench region.

Fig. 4 500 MHz, 4-cell cavity. Dependence of breakdown field on LHe-bath temperature. At ~ 3.8 K the cavity "switches" over from one quench to another.

Fig. 5 The 500 MHz 2 cell-cavity with its T-mapping system using cold multiplexers. Pumping is done from one side of the beam tube.

Fig. 6 500 MHz, 2-cell cavity. Temperature map of cell 2:

(a) before vacuum accident at E_{acc} = 4.7 MV/m.

(b) after vacuum accident at E_{acc} = 4.1 MV/m.

The large local increase of RF losses at the equator region of cell 2 can be clearly seen and is probably due to a dust particle dragged along (note change of T-scale!).

Fig. 7 Photo of the 350 MHz cavity fabricated from 3 mm sheet niobium with its temperature mapping system. The small 3 GHz cavity is used for studying surface properties.

Fig. 8 500 MHz Nb-Cu cavity with the cathode used for sputtering.

FIGURE CAPTIONS (Cont'd)

Fig. 9 500 MHz Nb-Cu cavity. The unloaded Q_o at 4.2 K as a function of accelerating field. This plot is produced by the new computerized measuring set-up. The steep decrease above 8 MV/m is due to electron loading. The points correspond to the first RF measurement and show that the cavity was degraded by the high power measurements.

Fig. 10 Temperature map of the Nb-Cu cavity at 5.07 MV/m. Note the broad area with increased temperature which may be compared with the typical peaks of Nb cavities (fig. 6(b)).

Fig. 11 Thermal conductivity as a function of temperature for (a) a standard and (b) for an improved Nb material. This plot is produced by a fully automatised measuring set-up.

Fig. 12 500 MHz cavity fabricated from high λ niobium. Q_o as a function of accelerating field at 4.2 K.

Fig. 13 500 MHz cavity fabricated from high λ niobium. Maximum acceleration field as a function of immersion in a slightly subcooled He bath.

Fig. 14 Main dimensions of the new cavity with multimode compensation for LEP. The possible location of a main coupler and a hom coupler is indicated.

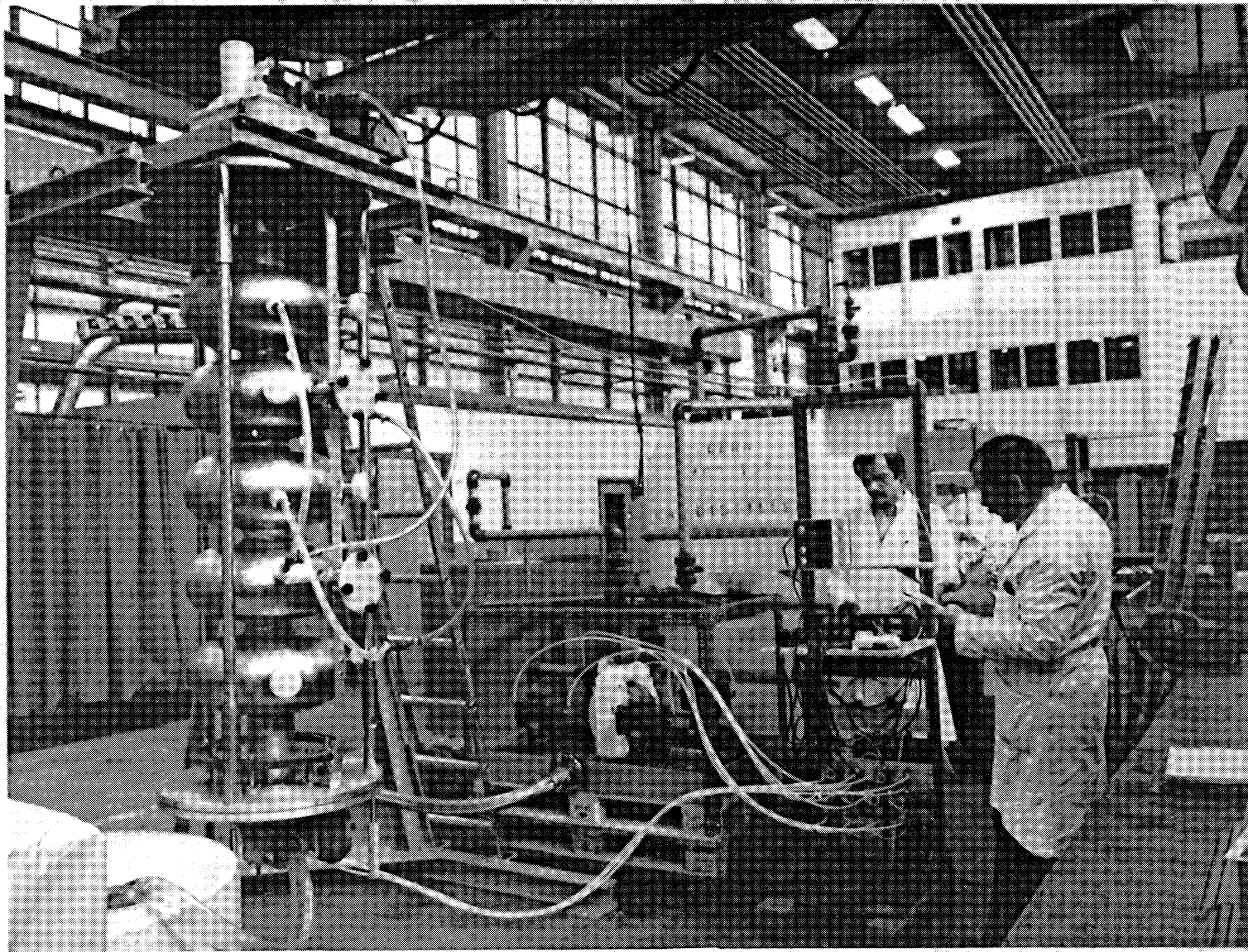


Fig. 1

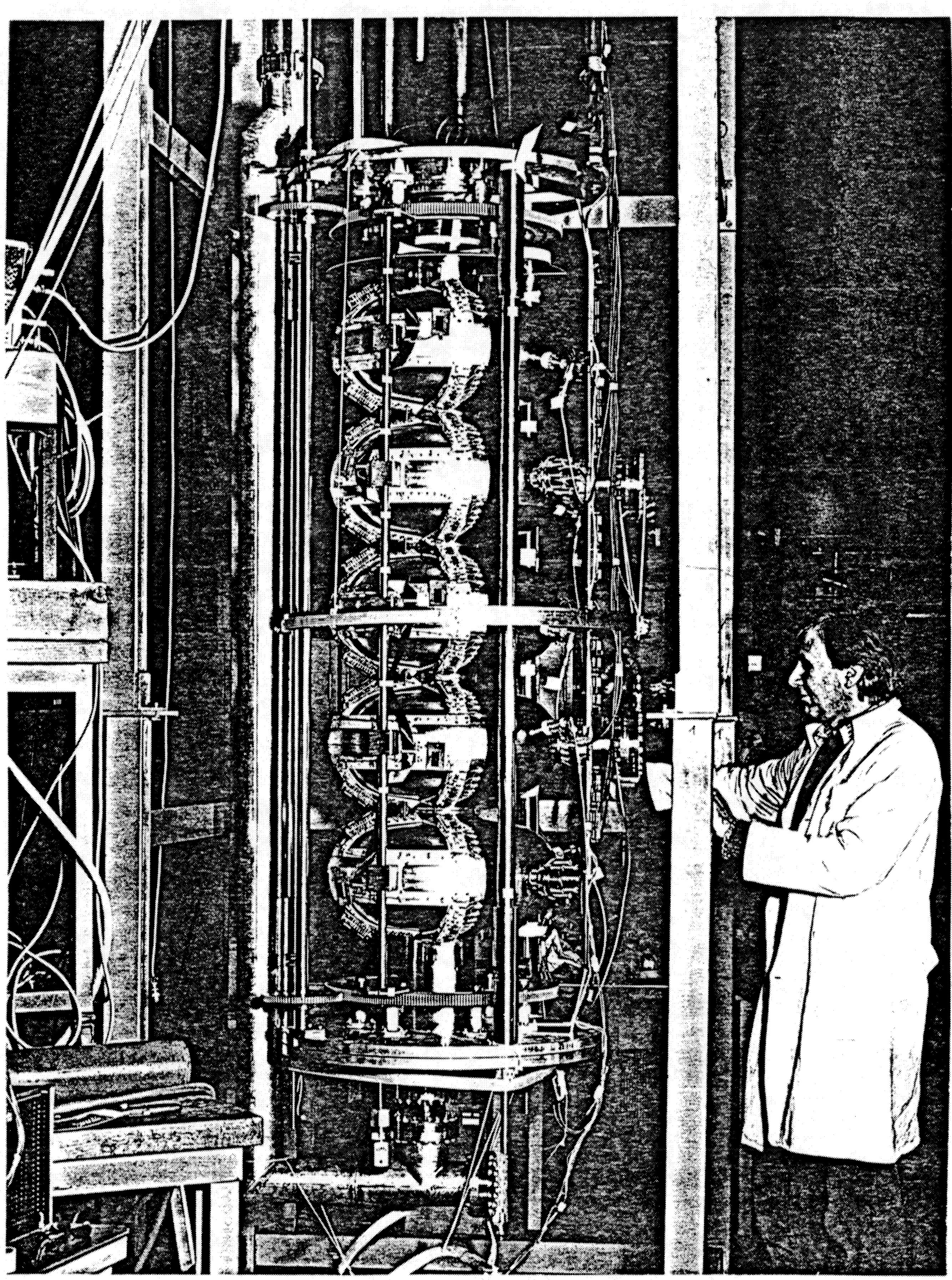
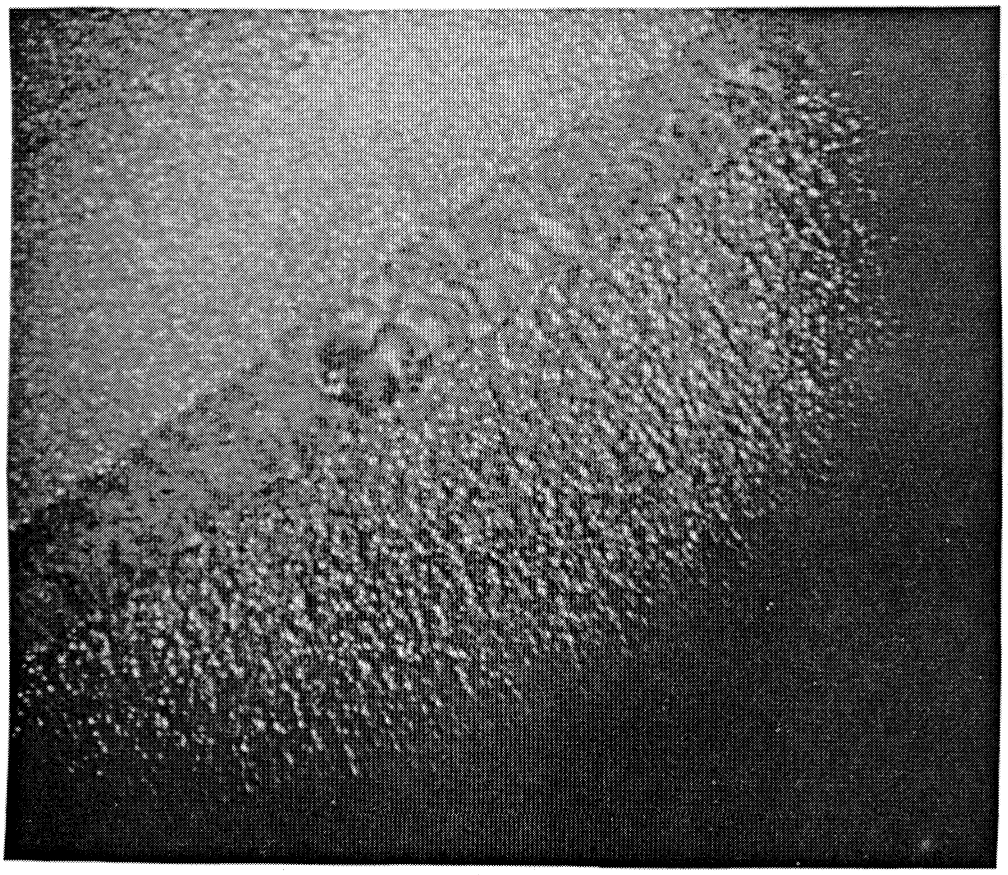


Fig. 2

(a)



(b)

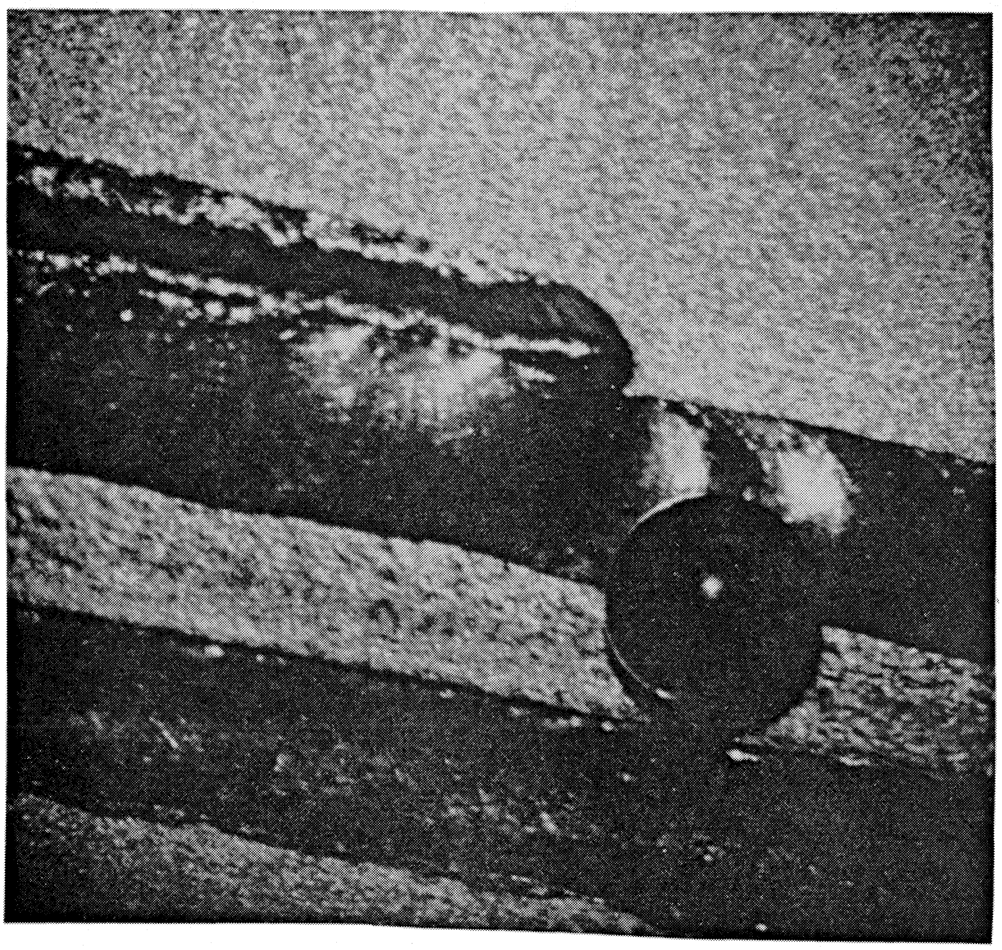


Fig. 3

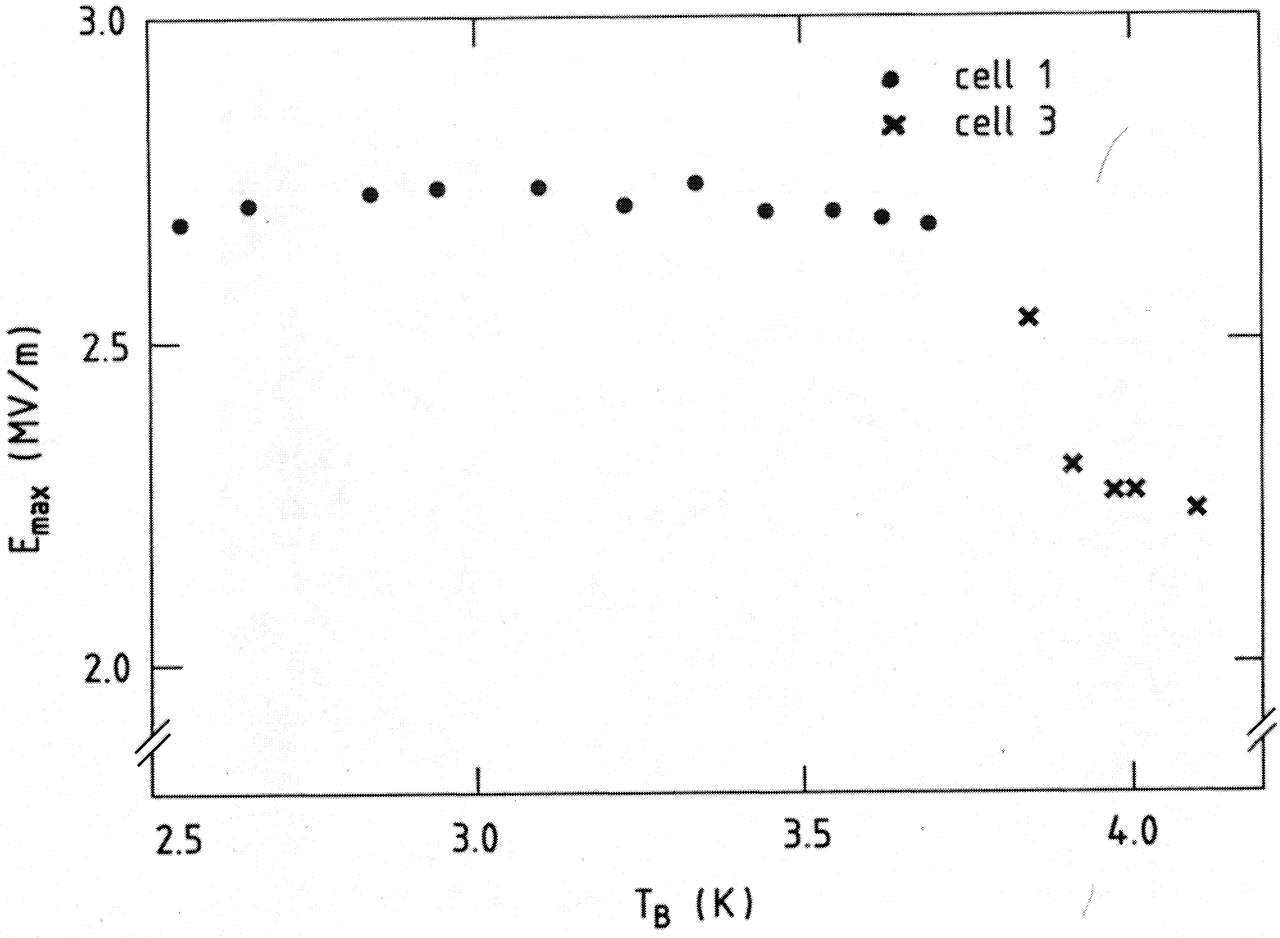


Fig. 4

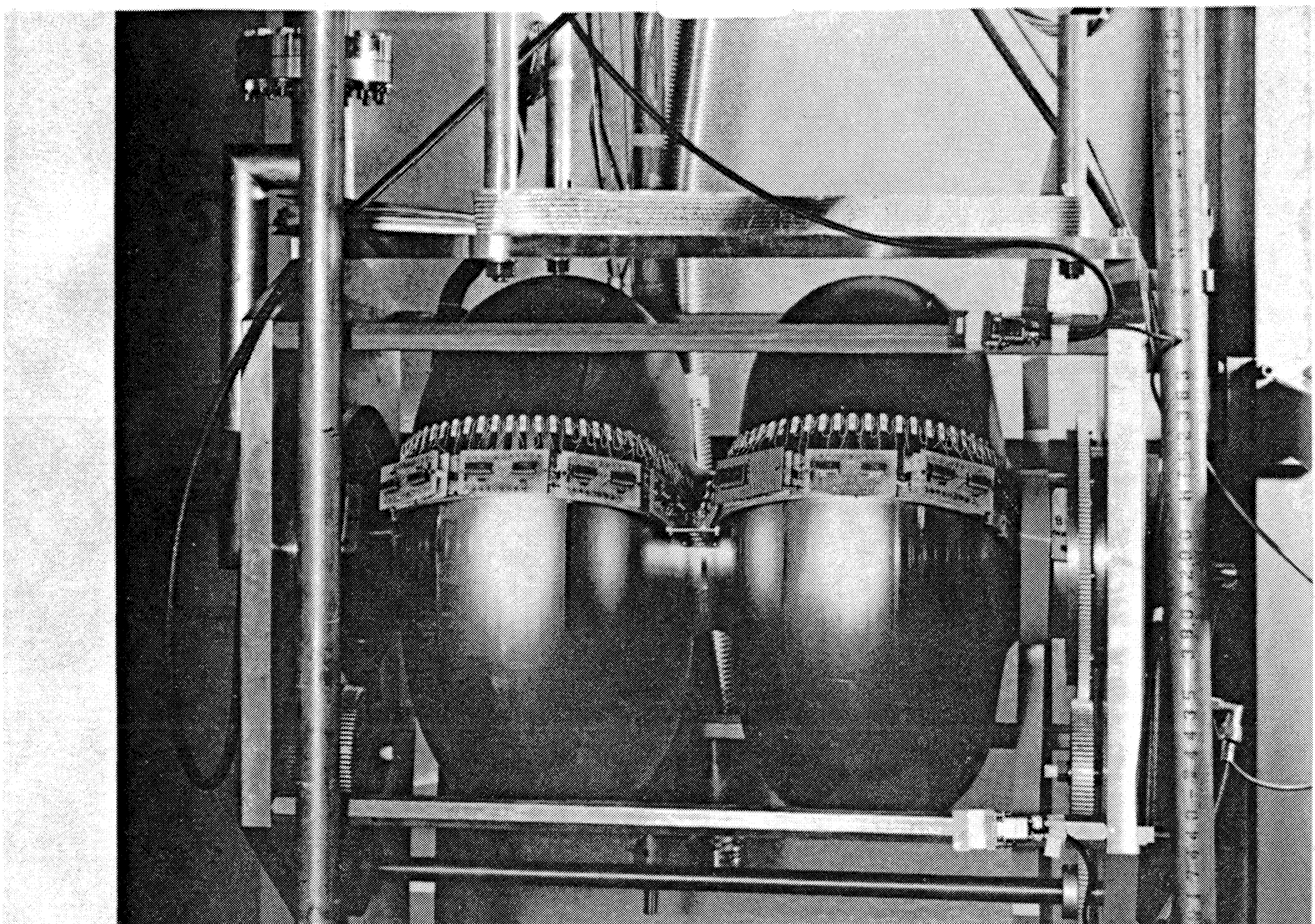
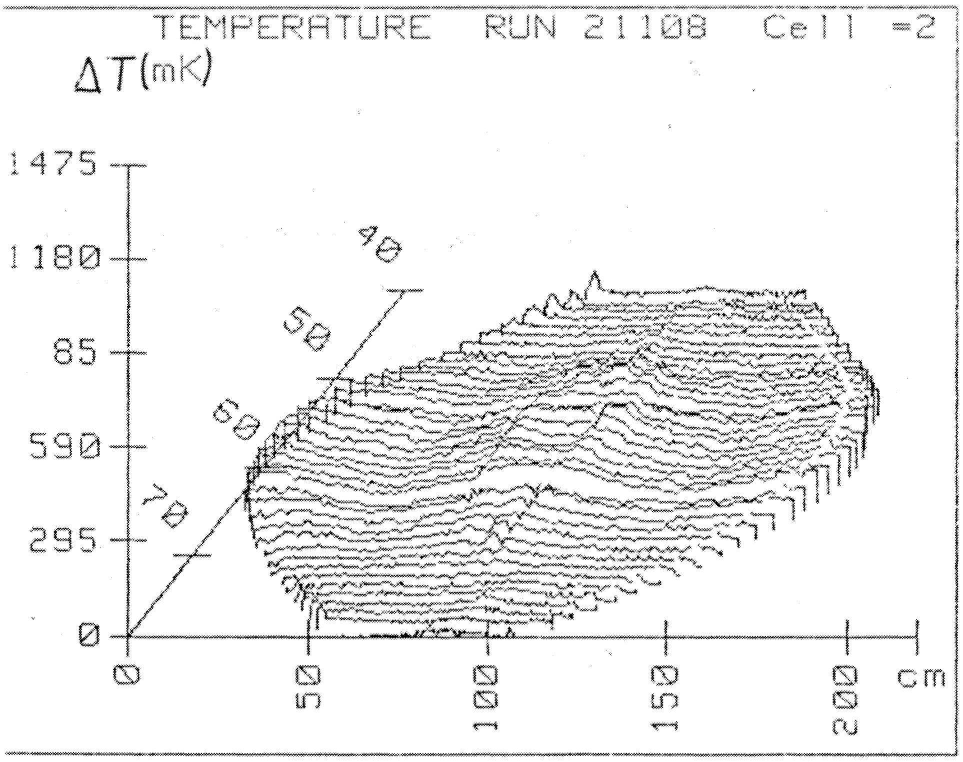


Fig. 5

(a)


TEMPERATURE RUN 21108 Cell =2
ΔT(mK)
1475
1180
85
590
295
0
40
50
60
70
0
50
100
150
200
cm

(b)

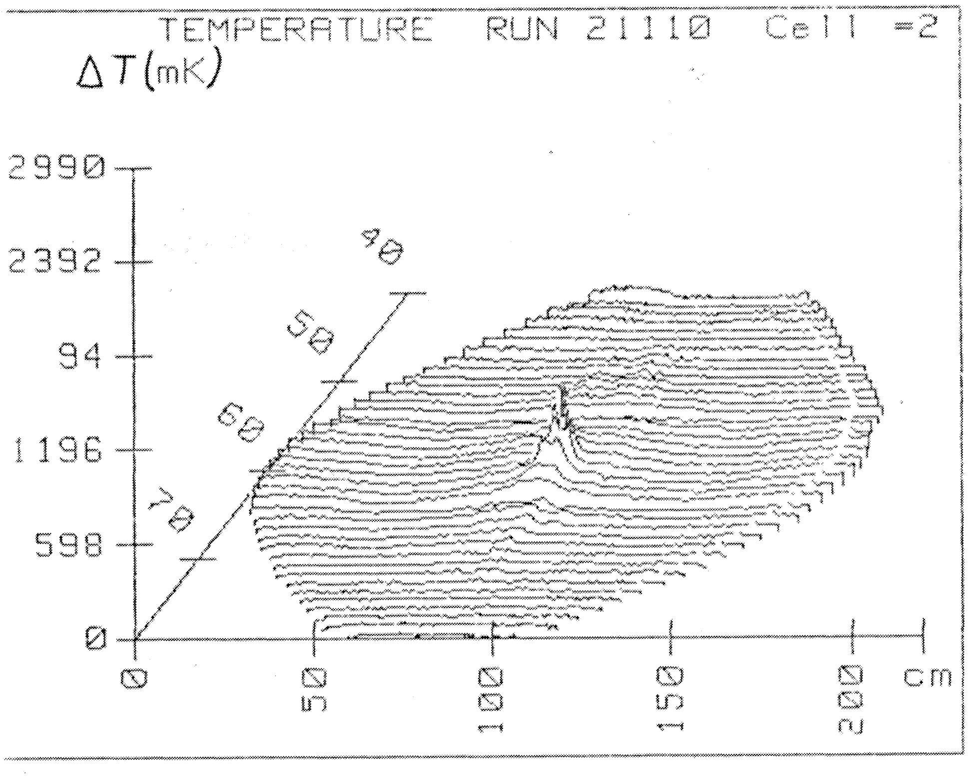

TEMPERATURE RUN 21110 Cell =2
ΔT(mK)
2990
2392
94
1196
598
0
40
50
60
70
0
50
100
150
200
cm

Fig. 6

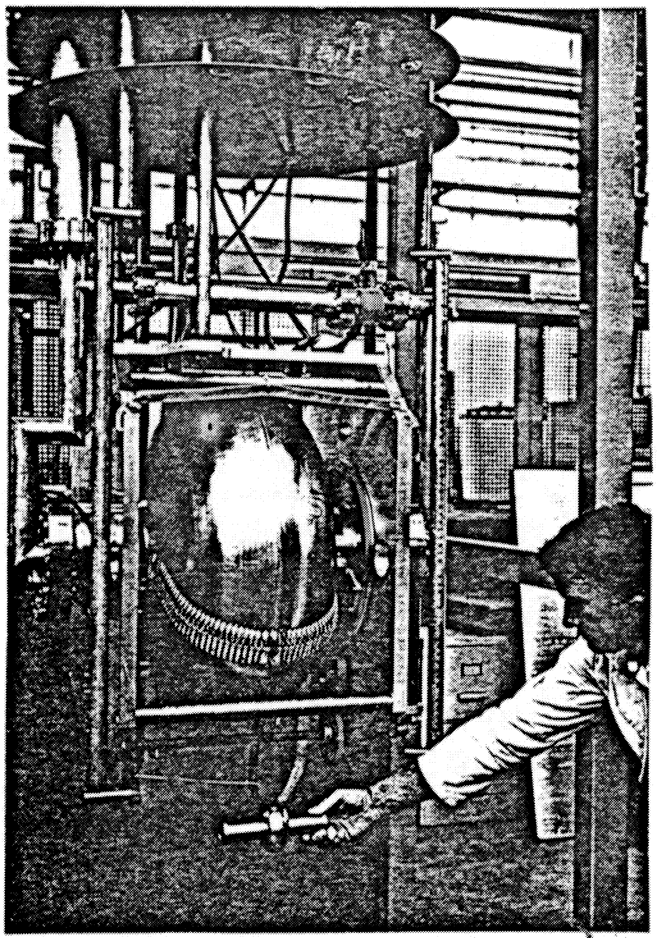


Fig. 7

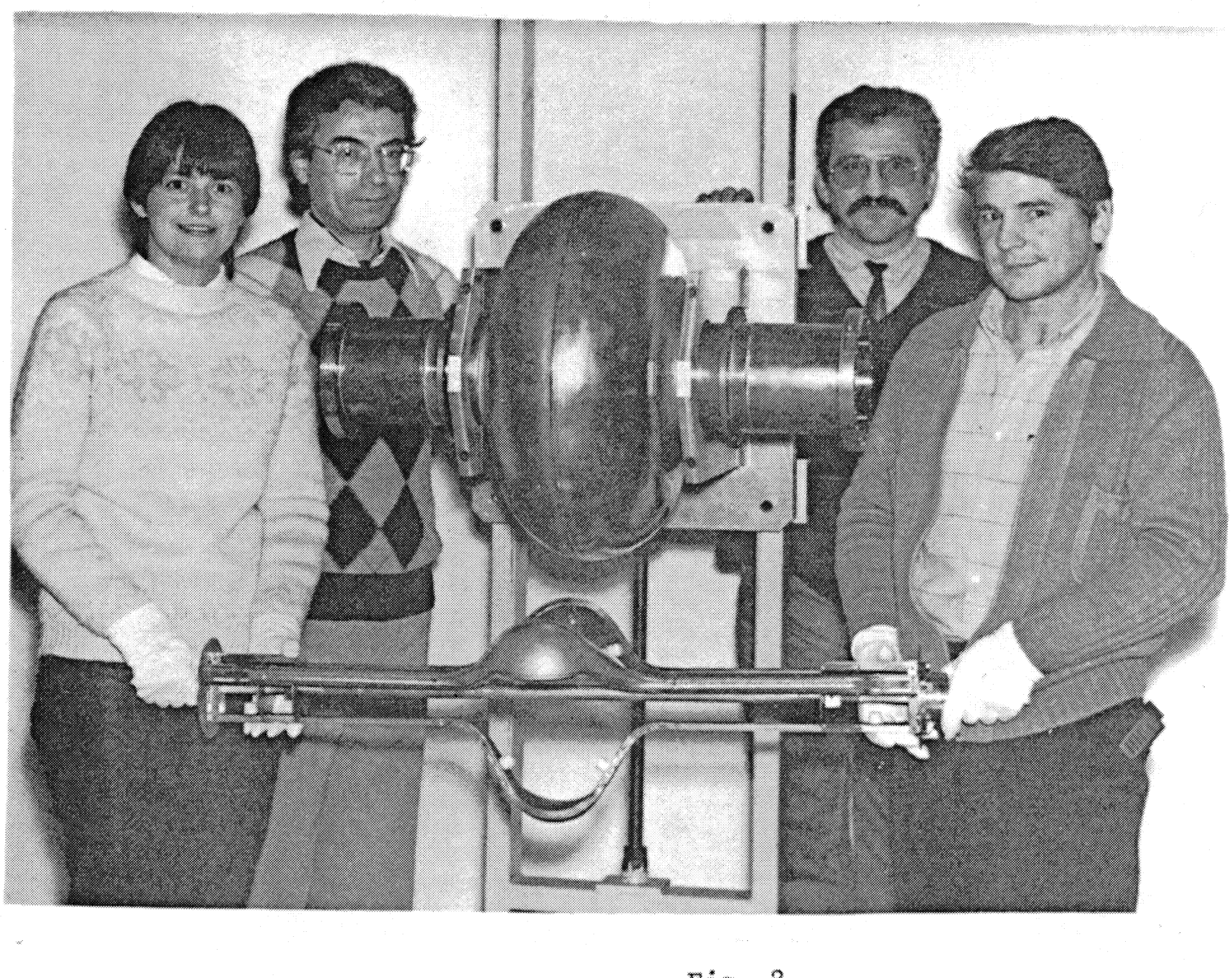


Fig. 8

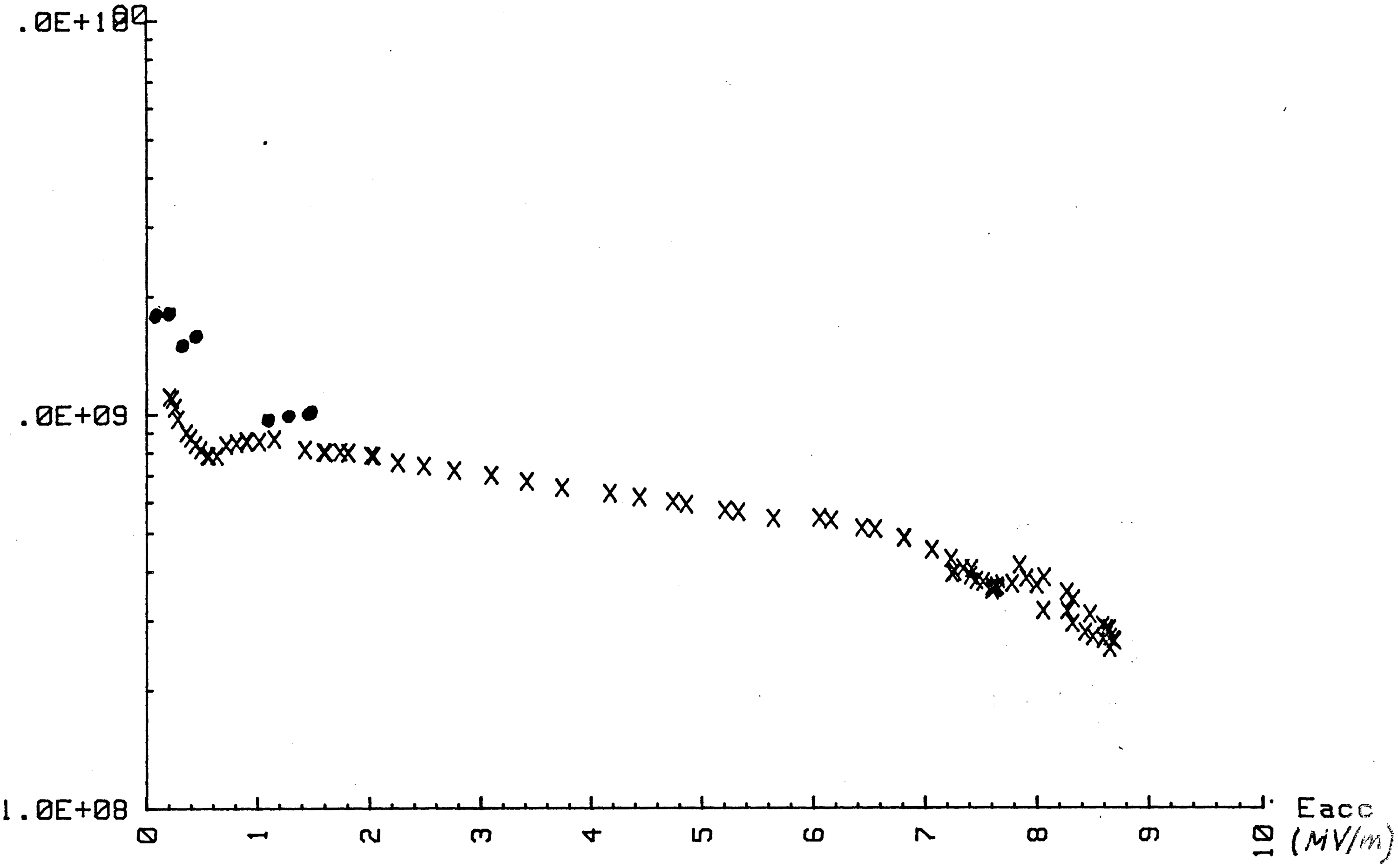

.0E+10
.0E+09
1.0E+08
0
1
2
3
4
5
6
7
8
9
10
Eacc
(MV/m)

Fig. 9

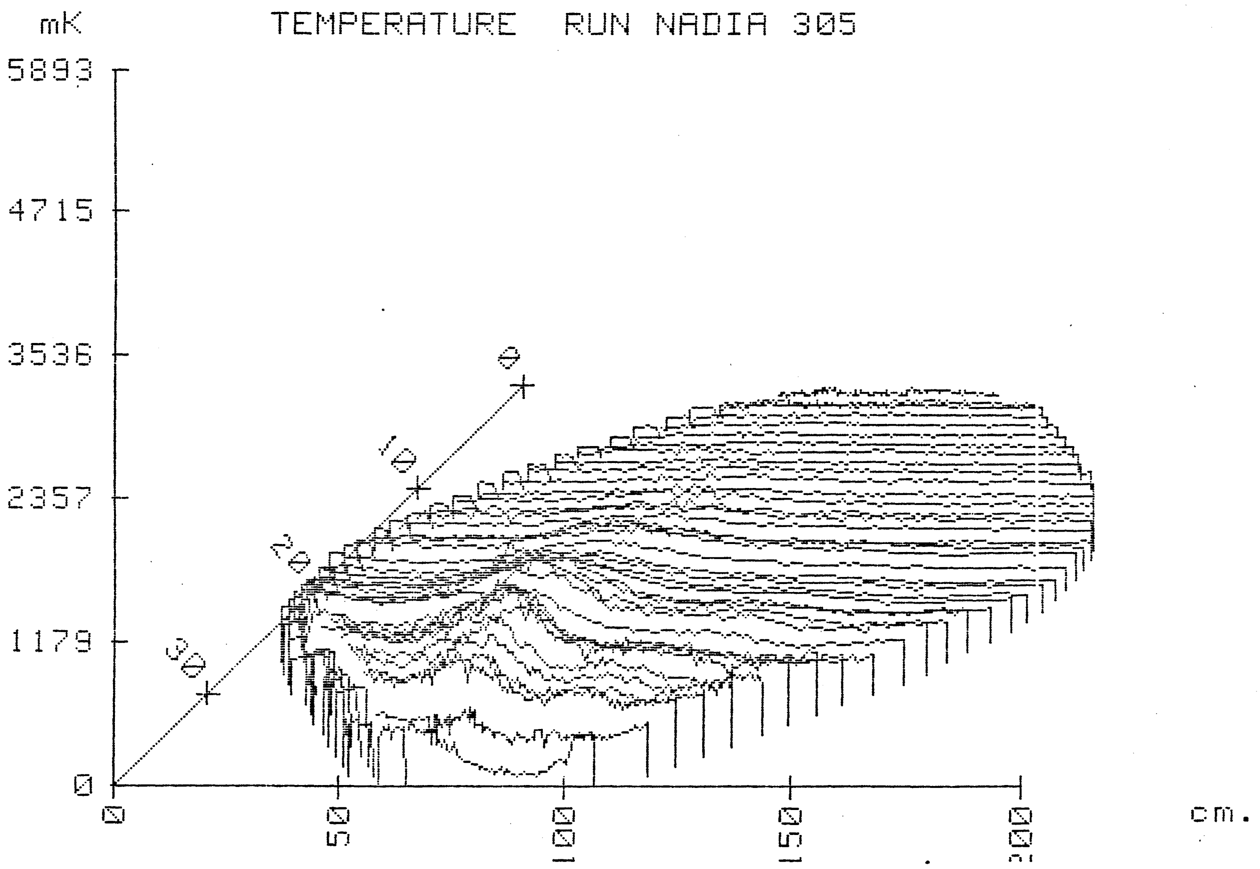
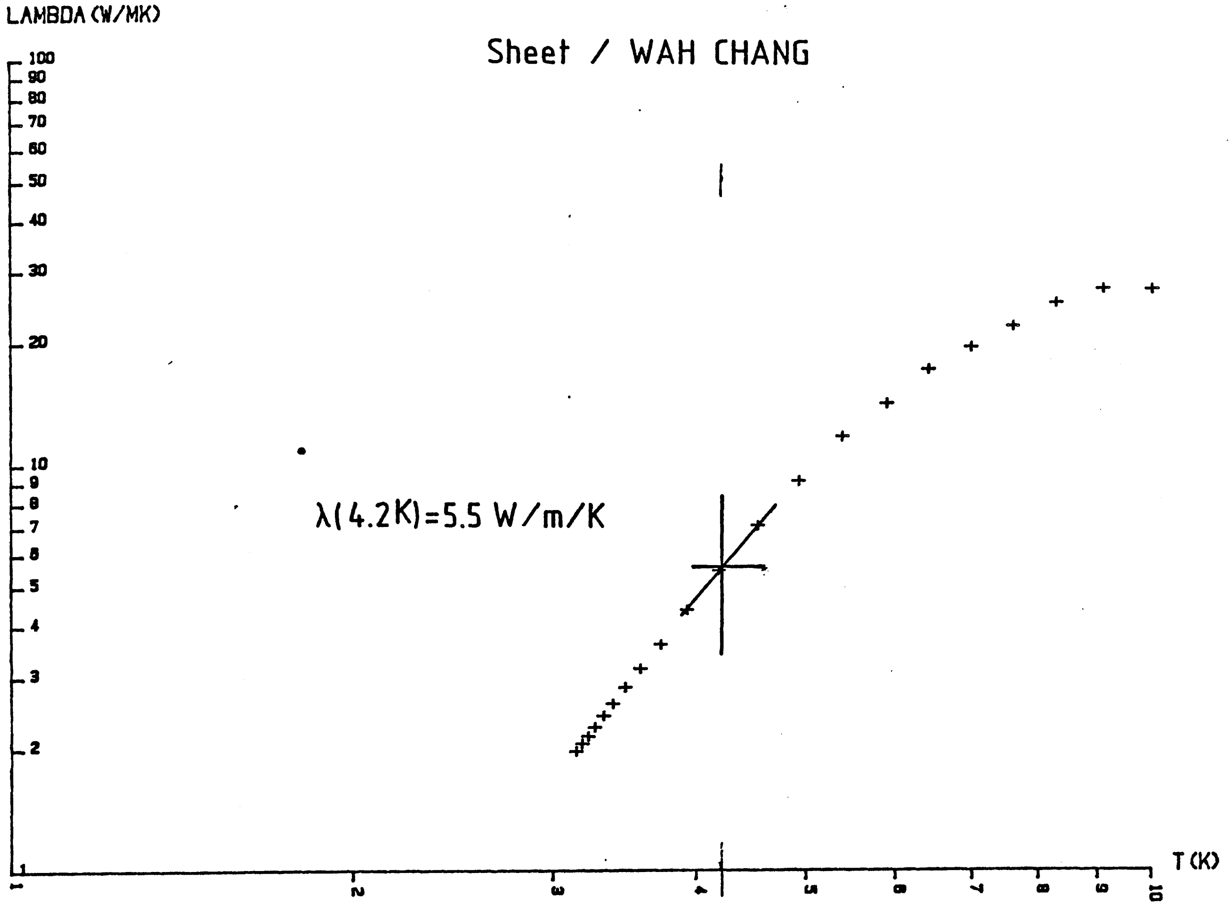

mK
TEMPERATURE RUN NADIA 305
5893
4715
3536
2357
1179
0
0
10
20
30
0
50
100
150
200
cm.

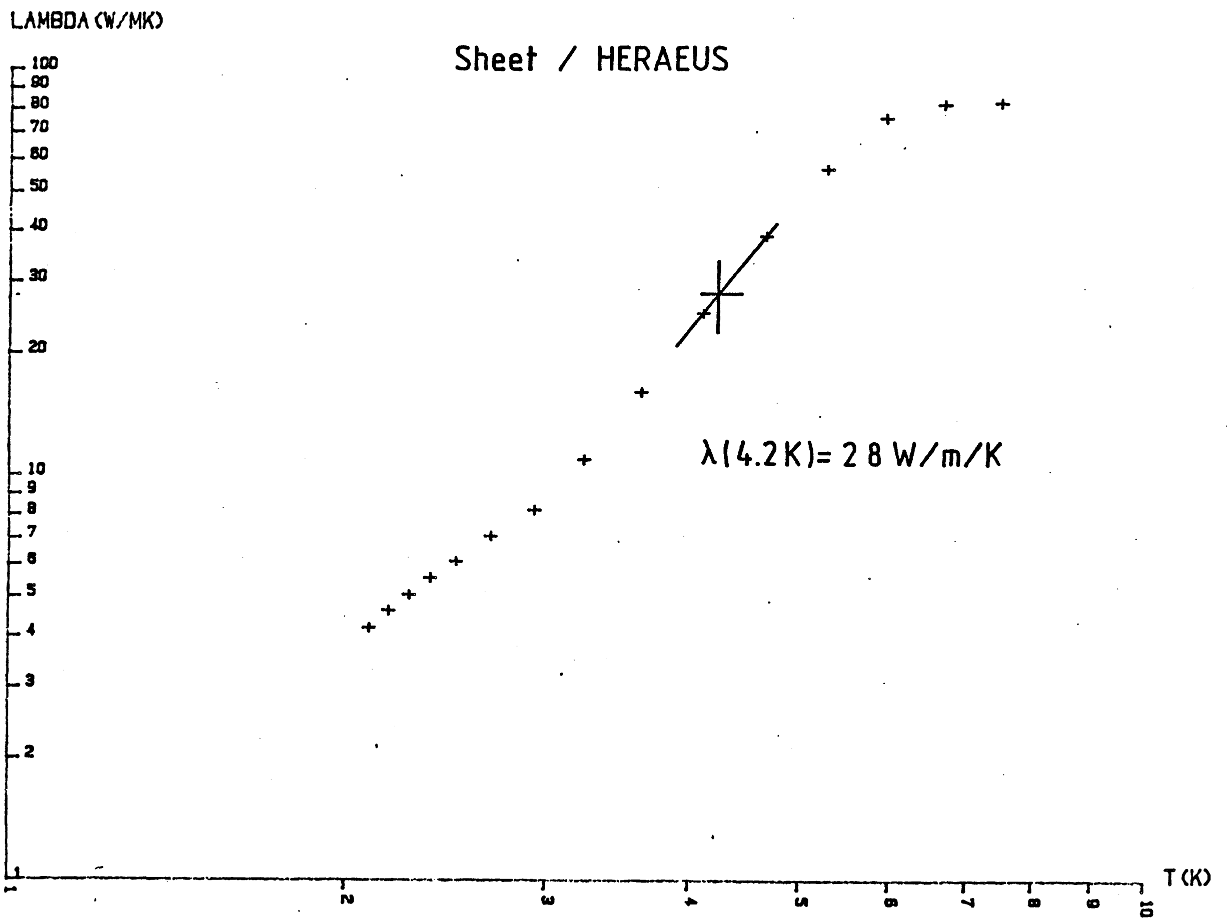
Fig. 10

(a)



LAMBDA (W/MK)
Sheet / WAH CHANG
λ(4.2K)=5.5 W/m/K
T (K)

(b)



LAMBDA (W/MK)
Sheet / HERAEUS
λ(4.2K)= 28 W/m/K
T (K)

Fig. 11

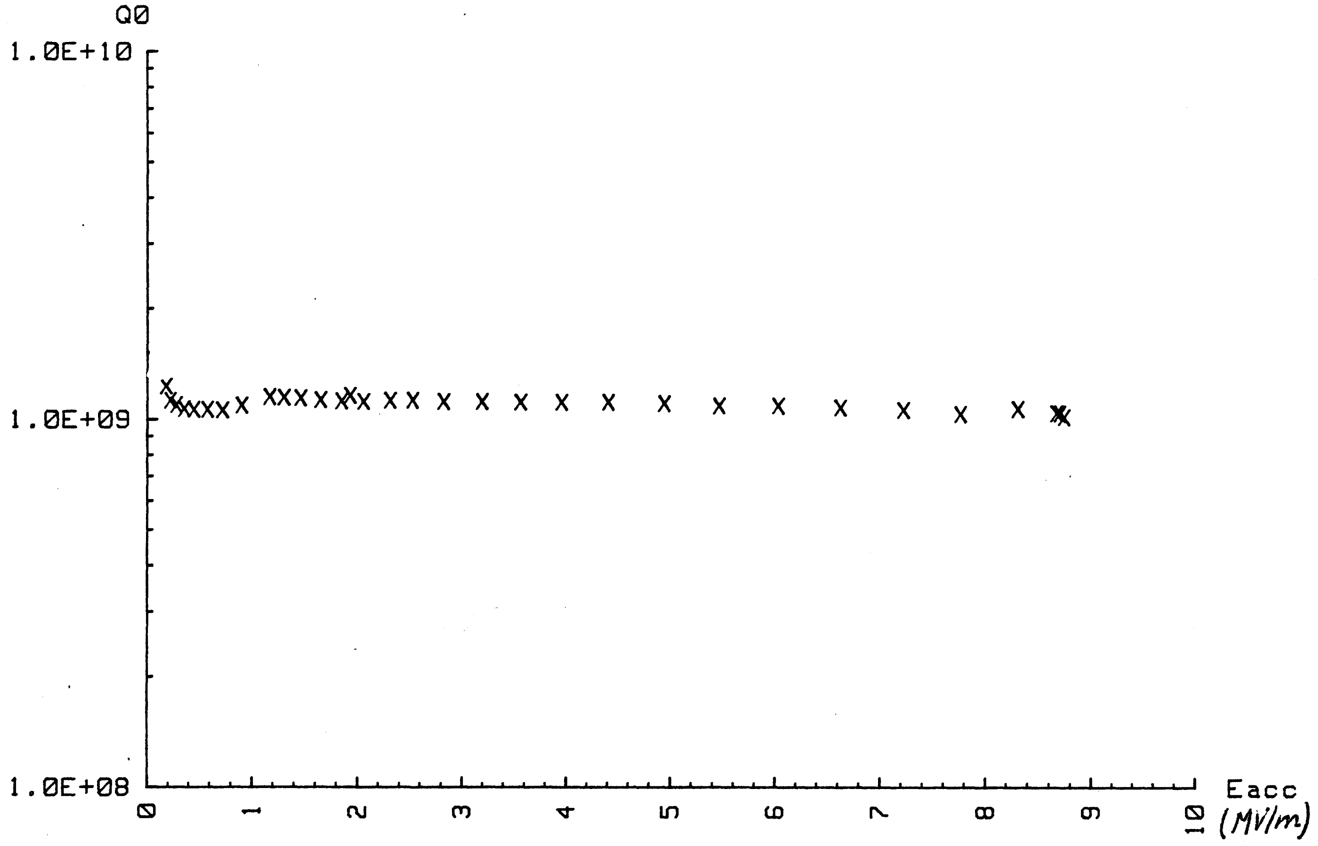

Q0
1.0E+10
1.0E+09
1.0E+08
0
1
2
3
4
5
6
7
8
9
10
Eacc (MV/m)

Fig. 12

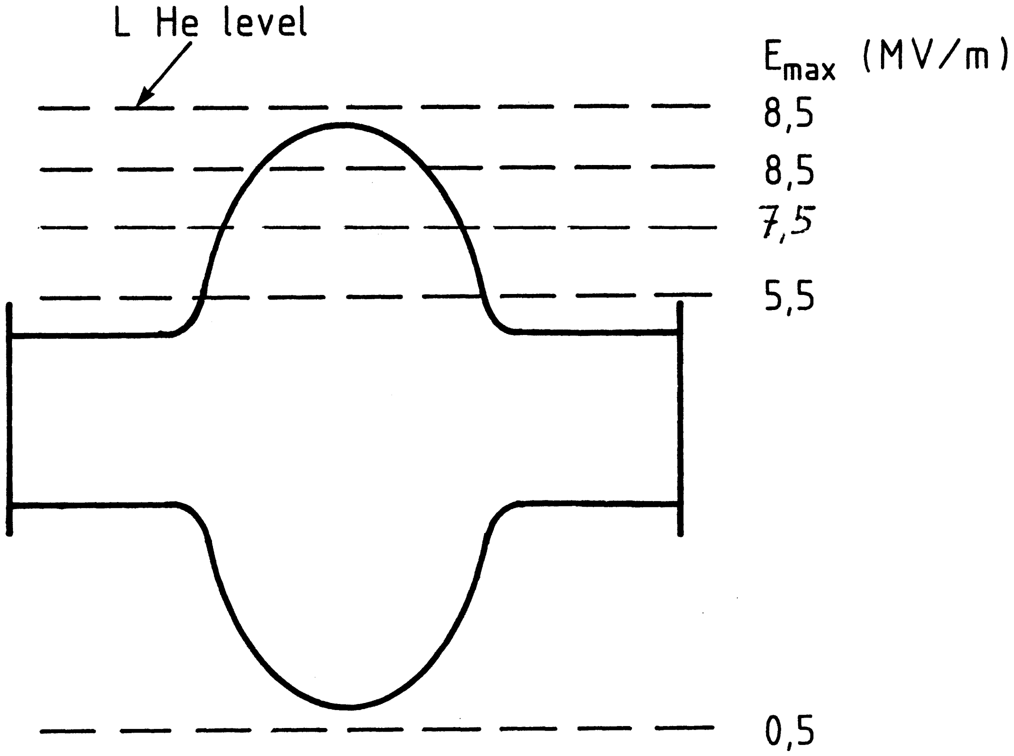

L He level
Emax (MV/m)
8,5
8,5
7,5
5,5
0,5

Fig. 13

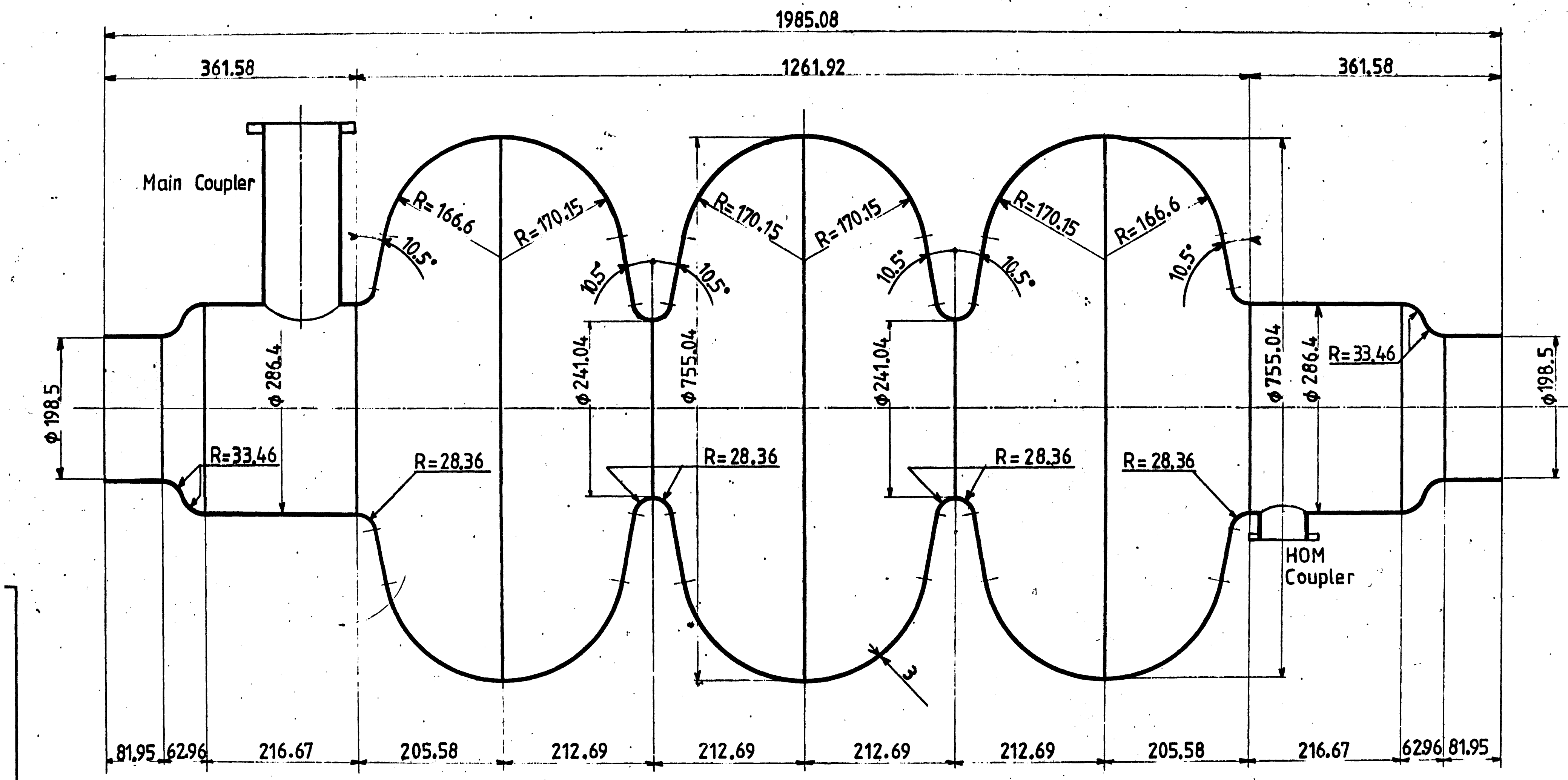
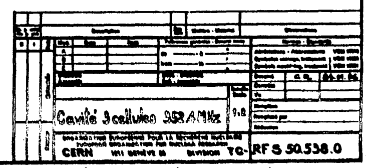

1985.08
361.58
1261.92
361.58
Main Coupler
HOM
Coupler
R=166.6
R=170.15
R=170.15
R=170.15
R=170.15
R=166.6
10.5°
R=33.46
R=33.46
R=28.36
R=28.36
R=28.36
R=28.36
ϕ 198.5
ϕ 198.5
ϕ 286.4
ϕ 286.4
ϕ 241.04
ϕ 241.04
ϕ 755.04
ϕ 755.04
3
81.95
62.96
216.67
205.58
212.69
212.69
212.69
212.69
205.58
216.67
62.96
81.95

Fig. 14


CERN
RF S 50.538.0