PROGRESS REPORT ON THE INVESTIGATIONS OF SUPERCONDUCTING STRUCTURES AT KARLSRUHE

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In this short survey I can only briefly describe the recent work of our group investigating superconducting structures and details can be obtained from the reports refered to.

1. Preparation of Superconducting Surfaces

The main effort was directed to the preparation of lead surfaces by electroplating cylindrical cavities. In order to obtain good layers organic macro-moleculs have to be added to the galvanic bath. Various kinds of glue are usually used. Since their chemical composition is not known and reproducibility therefore is very often poor various well defined chemical substances have been used instead e.g. alicarin, aniline, polyethylene glycol, starch and commercially available substances LPW 1203 and S. Unsatisfactory results were obtained with most chemicals. They could also not be improved by varying the concentrations and the current density over a wide range.

The best Q-values were obtained with LPW 1203. For this substance a systematic investigation of the influence of its concentration in the bath and of the current density was undertaken. The best results were achieved with a concentration of 0.4 g/liter and a current density of 1.5 A/dm^2. It was found that surfaces plated with a fresh bath gave lower Q-values than those prepared after several hours of electroplating. In order to obtain good surfaces it is also important to move the structure during the plating process and to shape the anode in such a way that the current density does not differ too much for different points of the structure.

Besides electroplating evaporation was used to prepare lead and indium layers and in addition lead, niobium and tantalum surfaces were produced by sputtering. Satisfactory results will be reported below for indium layers whereas in all other cases no success was achieved so far.

2. Measurements and Results of Q-values

Losses in the coupling system might lead to errors in the determination of very high Q-values. Therefore such losses were investigated in some detail. If a coupling loop is used the overall Q-value Q_M can be decomposed in the following manner1)

$$\frac{1}{\omega\tau} = \frac{1}{Q_M} = \frac{1}{Q_o} + (G_o + K_L)e^{-2\alpha z} = \frac{1}{Q_o'} + G_o e^{-2\alpha z}$$

where τ is the measured decay time, Q_o is the unloaded Q-value of the cavity, G_o and K_L are parameters characterizing the losses by radiation and by heat production in the coupling loop, respectively. The exponential takes into account the decay of the cutoff fields in the coupling tube. By plotting $1/\omega\tau$ as a function of the loop position z one can extrapolate to Q_o (fig. 1). In this way Q_o can be determined without a knowledge of the coupling coefficient ß. In previous experiments it was found that a reliable determination of ß is rather difficult2). If $1/Q_o$ is subtracted from the measured values of $1/\omega\tau$ the exponential contribution can be isolated. The experimental slope is in good agreement with the theoretical value for a cutoff mode(fig.1)

G_o and K_L can be found separately, if $ß(z) = G_o e^{-2\alpha z} x\ Q_o'(z)$ is derived independently e.g. from the standing wave ratio. For our particular arrangement it was found that $G_o \simeq K_L$.

With this extrapolation technique the Q-values of cylindrical cavities excited in the TE_{011} mode were measured for temperatures between 1.8° and 4.2°K. Results for lead surfaces at a frequency of 2.5 GHz have been reported before1,2). For a linear accelerator the frequency range below 1 GHz is of interest, however, and since the precise frequency dependence of the surface resistance is not known measurements at about 800 MHz were performed3).

For this purpose two types of resonators were used. A coaxial cavity with an outer diameter of 15 cm was excited in the TEM_{001}-mode. This offered the advantage that the cavity dimensions were comparable to those at 2.5 GHz and the same plating technique could be used. In addition a cylindrical cavity (diameter 53 cm, height 37 cm) was measured in the TE_{011}-mode. The main aim was to get some experience in the electroplating and cooling down of large structures. Preliminary results for the TEM_{001}-cavity are $Q = 2 \times 10^8$ at $4.2^{o}K$ (improvement factor $I \approx 1.7 \times 10^4$) and for the TE_{011}-cavity $Q = 1 \times 10$ at $4.2^{o}K$ ($I \approx 10^4$) and $Q = 3 \times 10^9$ ($I \approx 3 \times 10^4$) at $2^{o}K$. The low improvement factor for the cylindrical cavity is probably caused by the fact that its parts could not be moved in the electroplating bath because of their size.

The surface resistance deduced from the Q-values is shown in fig. 2 together with results from other laboratories. They can be fitted by a straight line with the slope 1.77. The residual resistance as determined from the temperature dependence of R becomes more important at lower frequencies. At 800 MHz it might amount to 20 t0 30% of the total resistance. Correcting for the residual resistance would bring the slope close to 2. This corresponds to Pippard's limiting case (penetration length small compared to coherence length) which is somewhat surprising since it should not hold for lead. Indeed a more detailed comparison with theory[5] leads to discrepancies. To solve this problem improved experimental results are necessary.

We have also investigated the behaviour of indium layers produced by electroplating. For this purpose the base plate of a cylindrical lead cavity was covered by an indium layer. In another experiment the whole cavity was electroplated with indium, but this surface was contaminated by impurities. The results are shown in fig. 3 together with theoretical curves. The slope of the experimental curves is in agreement with theory and corresponds to a gap $\Delta(0) = 1.75\ kT_c$. However, the measured values of R are lower than the predicted ones and it seems that even with different assumptions this discrepancy cannot be avoided.

Of course, indium surfaces are hardly of interest for accelerating cavities since their surface resistance is more than two orders of magnitude higher than that of lead. However, it has the remarkable property that it does not age appreciably. Whereas the Q-values of lead surfaces at $4.2^{o}K$ deteriorate by factors of 5 and more within several weeks practically no change was observed for indium layers. One could benefit from this fact for the protection of superconducting lead layers from oxidation. If the indium layer is thin enough superconductivity can be induced in this metal by the superconducting lead even above the critical temperature of indium $T_c = 3.4^{o}K$ by the proximity effect[4]. To investigate this possibility an indium layer was evaporated onto a 7µ thick lead layer (thickness below 1000 Å). A Q-value of 1.3×10^8 at $4.2^{o}K$ and 2×10^8 at $2^{o}K$ was found at 2.5 GHz. After 3 weeks no appreciable decrease of Q was found. No sudden change was observed near the critical temperature of indium. Whether this indicates the existence of the proximity effect or whether an alloy was formed by diffusion is not yet known.

3. Effects at High Electric Fields

The Q-values measured with low electric and magnetic fields may not be valid for the high power levels in practical applications. Additional losses will occur which depend on the field strength. Multipactoring starts already at field strengths of a few kilovolts/cm but it can be suppressed to a large extend, if closely spaced, parallel surfaces normal to the electric field are avoided.

In the region of a few MV/m field emission may become important. From the Fowler-Nordheim relation for the field emission current one derives an expression for the power consumed by field emission

$$P_{FE} = C_1 E^3 \exp(-2.7 \times 10^7 \varphi^{3/2} / \alpha E)$$

where C_1 is a constant that depends on the emitting area and the gap length. φ is the work function and E is the maximum macroscopic field. The enhancement factor α takes into account microscopic projections.

P_{FE} can be measured in two different ways. In the first method the total loading power $P_t \sim 1/Q$ is measured as a function of the electric field strength. From this the cavity wall losses as determined from the unloaded Q-values at low power levels are subtracted. The remaining losses are identified with P_{FE}. This procedure has been used at Stanford[11] for E between 2 and 5 MV/m and similar measurements have been performed at Karlsruhe[12] which were extended up to 10 MV/m. If one plots $\log P_{FE}/E^3$ versus $1/E$ one indeed obtains straight lines up to about 6 MV/m. The slopes of the various experiments(cp.fig.4 of [12]) differ by factors 2 to 4 but this may be attributed to different surface condition. However, the absolute values of these slopes require enhancement factors α larger than 6000. The highest α values that have been observed with DC fields are about 200. This raises some doubts whether field emission is the proper explanation. An interpretation of these results meets the difficulty that other field dependent effects are included in the determination of P_{FE}.

Therefore it seems important that P_{FE} can also be derived from a measurement of the dose rate in the vicinity of the cavity. Of course, the conversion of the dose rate into the power loss is complicated by absorption effects of the γ rays and other corrections. As a consequence this method is less reliable than a direct measurement of P_{FE} but at least a determination of the slope should be possible. On the other hand systematic effects of field dependent wall losses should not matter and therefore a measurement of the dose rate can give independent information. Such an experiment[13] has been carried out at Stanford on a normal copper structure for fields between 13 and 16 MV/m. At Karlsruhe[14] a superconducting lead structure has been investigated for fields between 20 and 35 MV/m. The results are plotted in fig. 6. It is remarkable that the Fowler-Nordheim relation is very well fullfilled and that the slopes of the two kinds of measurements agree. The fact that one single line fits both results may be a coincidence, however. We note that the slope in fig. 6 is about 194 MV/m (corresponding to [illegible] 200) compared to values of the order of 10 MV/m as deduced from a direct measurement of P_{FE}. The value [illegible] 200 is in nice agreement with the results obtained with DC fields. We may conjecture therefore that the dose rate measurements are predominantly sensitive to the field emission whereas the Q-measurements include some wall effects.

The nature of these latter effects is not yet understood but there exist various possible explanations for field dependent wall losses. Since the heat conduction is not perfect the temperature of the lead layer can rise at high power levels. A change of 0.5°K will increase the surface resistance by a factor 2. Another explanation is offered by nonlinear losses in the superconductor. As was shown[15] the surface resistance is given by $R = R_o[1 + k(H/H_c)^2 + \ldots]$ where the constant k can be as high as 5. Hence for magnetic fields still well below the critical field H_c additional losses occur which could simulate a Fowler-Nordheim relation. These losses could be reduced by shaping the resonators in such way that only the electric field is concentrated whereas the magnetic field should be kept low by distributing it as uniformly as possible.

It is encouraging to note that the loading power deduced from the dose rate is several orders of magnitude lower than those derived from the loaded Q-values. This implies that field emission is perhaps not the limiting effect for the accelerating field. The additional losses are not yet well understood but one might hope to find ways to reduce them. No doubt much more work is required before a definite value for a practically accelerating field can be given.

4. Work on Structures

The structures developed for normal linear accelerators cannot in general be adapted to a superconducting accelerator since they must be suitable for the deposition of a superconducting layer. The Los Alamos side-coupled structure is geometrically too complicated for plating. A slotted bi-periodic iris structure seems to combine the advantages of a resonance-coupled structure with geometrical simplicity. Hence the work to optimize such a structure for the acceleration of protons has been continued.

From a simple theory[6] the optimum value of g/L (g = gap, L = cell length) was deduced. The shunt impedance exhibits a flat maximum at $g/L \approx 0.3$ whose position is practically independent of v/c. Using this information a structure with rounded edges was designed. Computed shunt impedances for a copper structure at room temperature give approximate values of 32 MΩ/m for $v/c \approx 1$ and 20 MΩ/m for a proton energy of 50 MeV ($\beta = 0.3$).

Since coupling effects cannot be computed with available programmes the dependence of the coupling coefficients as a function of the geometrical parameters of the cavities was investigated experimentally. The dispersion curves can very well be represented by a relationship which we write

$$\begin{aligned}2(\omega_o^2-\omega^2)\omega^{-2} = {} & K_1(1+\varepsilon_1) + K_2(1+\varepsilon_2) \\ & -(\varepsilon_1 K_1 + \varepsilon_2 K_2)\cos 2\phi \\ \mp\Big\{ & [K_1(1+\varepsilon_1) - K_2(1+\varepsilon_2) - K_2(1+\varepsilon_2) \\ & -(\varepsilon_1 K_1 - \varepsilon_2 K_2)\cos 2\phi]^2 + 4\, K_1 K_2 \cos^2\phi\Big\}^{1/2}\end{aligned}$$

From the measured dispersion curves the coupling constants can be derived. K_1 and K_2 describe the coupling from an accelerating to a coupling cell and vice versa. $\varepsilon_1 K_1$ and $\varepsilon_2 K_2$ represent the coupling of alternate cells. Since this coupling is provided by cutoff modes one expects $\varepsilon_1 = e^{-\alpha L_B}$ 0 and $\varepsilon_2 = e^{-\alpha L_K}$ are the lengths of accelerating and coupling cell, respectively. Neglecting phase factors[10] the surface integrals can be written

$$\int_{S^+} \vec{E} \times \vec{H}_o \times \vec{n}\,ds = K_1(1+\varepsilon_1)\int_B \vec{E} \times \vec{E}_s\,dv + \varepsilon_2 K_2 \int_K \vec{E} \times \vec{E}_o\,dv$$

$$\int_{S^-} \vec{E} \times \vec{H}_o \times \vec{n}\,ds = K_2(1+\varepsilon_2)\int_K \vec{E} \times \vec{E}_o\,dv + \varepsilon_1 K_1 \int_B \vec{E} \times \vec{E}_o\,dv$$

One can get an approximate expression for the coefficients K_1 and K_2 by noting that the total energy in the cavity can be decomposed into the energy without coupling elements and the coupling energy. Since the volume integrals are proportional to the lengths of the cells one has $\int_B \vec{E} \times \vec{E}_o dv \sim (L_B + L_i^+)$,

$$\int_K \vec{E} \times \vec{E}_o dv \sim (L_K + L_i^-), \int_{S^\pm} \vec{E} \times \vec{H}_o \times \vec{n} dS \sim L_i^\pm \quad .$$

Here it is assumed that the coupling energy is essentially characterized by the lengths $L_i^\pm$. This leads to the relations (with $\varepsilon_1 \ll 1$)

$$1/K_1 = (1 + L_B/L_i^+) \times [1 - \varepsilon_2 K_2 (1 + L_K/L_i^-)]^{-1}$$

$$1/K_2 = (1 + \varepsilon_2)\ (1 + L_K/L_i^-) \quad .$$

The experimental values of $1/K_1$ and $1/K_2(1+\varepsilon_2)$ are plotted in fig. 4 together with the theoretical lines. With $L_i^+ = 7.5$ mm and $L_i^- = 11$ mm one obtains a very good agreement. ε_1 was found to be very small whereas ε_2 is shown in fig. 5. It can be seen that ε_2 is practically independent of L_B and the experimental slope $2\alpha = 0.33\ \text{cm}^{-1}$ is not too different from the theoretical slope $2\alpha = 3.68/R = 0.26\ \text{cm}^{-1}$ for a cutoff mode in a cylindrical tube.

Since mode stability and flattness are determined by the coupling it seems advisable to have the same coupling for different parts of the accelerator. With the information given above it should be possible to achieve this over a large range of v/c values.

A full size structure consisting of 6 cells with tuning devices and a cryostat has been built for a frequency of about 760 MHz. Measurements of the shunt impedance and a study of beam loading effects will be accomplished with an electron beam in an analog experiment. So far only measurements at room temperatures have been performed 8).

In the case of a proton linac it is very important to keep the energy gain constant since otherwise the synchronous condition would soon be violated. Therefore the variation of energy gain ΔW caused by various errors was investigated for the case of heavy beam loading 7).

The beam loading is characterized by b = (power absorbed by beam)/(power dissipated in cavity), ß is the usual cavity coupling coefficient and $\text{tg}\,\psi = -2Q_L(\Delta\omega/\omega_o) = -y/(1+\beta)$ describes the detuning of the cavity. Then it can be shown that for $b \gg 1$ the variations $\Delta W/\Delta\Theta$, $\Delta W/\Delta y$ and $\Delta W/\Delta\beta$ are practically zero if $\beta \approx b$ and $\text{tg}\,\psi \simeq \text{tg}\,\phi$. Here Θ is the phase of the generator current and ϕ the phase of the particles with respect to the accelerating voltage. It seems therefore that by a proper matching and tuning of the cavity the most dangerous changes of ΔW can be avoided. Also the dynamical behaviour of ΔW was studied under sudden changes of parameters. Fig. 7 shows the time dependence of $\Delta W/W$, if the beam current i_b is changed by 3% and fig. 8 is an example for a sudden frequency jump $\Delta\omega$.

5. Superconducting Particle Separator

A superconducting particle separator seems to be a convenient first step towards the construction of a superconducting accelerator as in this case some difficulties are absent. Beam loading is of no importance and since the total length of the structure is only a few meters improvement factors below 10^5 are tolerable from an economic point of view. Therefore the work on structures at Karlsruhe was restricted to deflecting structures so far.

Iris-loaded cavities with 8 cells were electroplated with lead. It was found that the shape of the anode influences the quality of the surfaces considerably since one has to try to obtain an appropriate current density also in the corners of the structure. Another difficulty which is being fought against at present is the uncomplete deposition of lead on soldered joints. The best results obtained for the $\pi/2$ mode at 2.9 GHz are $Q_o = 16 \times 10^6$ at 4.2°K ($I_3 = 1.6 \times 10^3$) and 70×10^6 at 2°K ($I = 7 \times 10^3$). The temperature dependence corresponds to the theoretical expectation but the absolute values are still a factor of about 10 below what one might hope to obtain. It is expected that a removal of the mentioned difficulties will lead to improved results.

A series of experiments was performed in order to study various types of end cells. Full and half cells have been tried. If the joints are placed at a position without current it is difficult to deposit the lead in the narrow end cell. Therefore indium joints at a position where currents flow have also been tried. A jump of the Q-value at the critical temperature of indium was observed, but the overall Q-values were still low. No definite conclusion on the best design of end cells can yet be drawn.

Our plans are to construct a 2-cavity separator for 10 GeV/c Kaons at CERN. In order to get experience in operating a superconducting deflecting cavity a simple cavity separator for momenta around 1.5 GeV/c is envisaged. For a deflector length of 3.25 m the necessary cooling power would be about 20 W at 2°K, if an improvement factor of 10^5 is assumed.

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DISCUSSION

(H. Schopper)

VAN STEENBERGEN, BNL: You stated that the maximum fields obtainable will be higher at superconducting temperatures than normal temperatures. Are these maximum field strengths dependent on frequency?

SCHOPPER, KARLSRUHE: No systematic investigation has been performed so far. But, from all that is known, all of the extra losses, except the ohmic wall losses, do not seem to depend upon the frequency. You would not expect the field emission to depend upon frequency, but if you have local heating it should depend upon frequency. Very little is known, but from what is known, I would say that frequency dependence is not important.

LEISS, NBS: I would expect that the character of a plated surface would depend upon the substrate. Have all of these experiments been done with copper as the substrate or has other material been tried? Most experiments have been done on copper but I think one group has tried aluminum, but I am not quite sure. It might be worth contacting the people in the thin film business. They have been playing these games 20 to 30 years and know the crazy thing that can happen with thin films.

SCHOPPER, KARSRUHE: Our films are probably not as thin as that. They are about 2 to 20 microns.

LEISS, NBS: I think that is still classified as thin.

SCHOPPER, KARSRUHE: From all available experiments so far, there is no correlation between structure of the films and the Q values. You can get high Q values when the surface exhibits large crystal structure and also high Q values with films of fine structure.

LEISS, NBS: I was thinking particularly of niobium which might not plate on copper as well as lead.

WEAVER, MIT: With regard to your comment on plating at Stanford, there was some work done on copper structures in which lead or tin was first put on. This was immersion tin, which is very thin, then lead was put on afterward. This was done mainly to get a better "throwing power". The lead would plate better on tin than copper. However, some recent checks on the resultant surface under a high power microscope X200 or X500 seemed to indicate that the lead (plated over tin) exhibited more whiskers and bumps etc. This whole problem of thin films and surfaces has not been looked into at Stanford. They are beginning to study the microscopic nature of these surfaces. The results as you suggest are hard to correlate because you can only look microscopically at a small part of the surface you are testing.

SCHOPPER, KARSRUHE: We have evaporated a thin film of indium on the copper first and on top of this lead but it didn't make any difference. We have also evaporated indium on lead to protect the surface of the lead. It seems to prevent oxidation without decreasing the Q value.

WEAVER, MIT: G. Loew suggested that I mention that there is some question, if you start to superimpose layer upon layer each has a different thermal expansion coef. Since this is done at room temperature, then cooled you introduce stresses which are significant. It is hard experimentally to check this.

Stanford is now working on niobium electroplated on copper. Then they etch the copper out because they have to anneal and outgas at 2200°C.

SCHOPPER, KARLSRUHE: In order to avoid stresses we once made a cavity of solid lead. It gave bad Q values, probably for other reasons, maybe the surface was not good enough.

WEAVER, MIT: When you quote fields, do you refer to fields at the surface or accelerating fields?

SCHOPPER, KARLSRUHE: In the Fowler Nordheim plot, it was the field on the surface of the lead.

WEAVER, MIT: What was the ratio of the Q at 10 MeV/meter compared to a fraction of MeV/meter.

SCHOPPER, KARLSRUHE: It goes down by a factor of 3 or so.

WEAVER, MIT: We found in some cavities at Stanford the ratio of field at the surface to an accelerating field for a typical biperiodic structure was an additional ratio of 3. A factor of 2 for a standing wave accelerator.

SCHOPPER, KARLSRUHE: A factor of 2 for a standing wave accelerator is not right vs. traveling wave. It is true only if there are no drift tubes. If you have drift tubes with a very small gap, the factor is one.

WEAVER, MIT: Yes, if you can realize that structure.

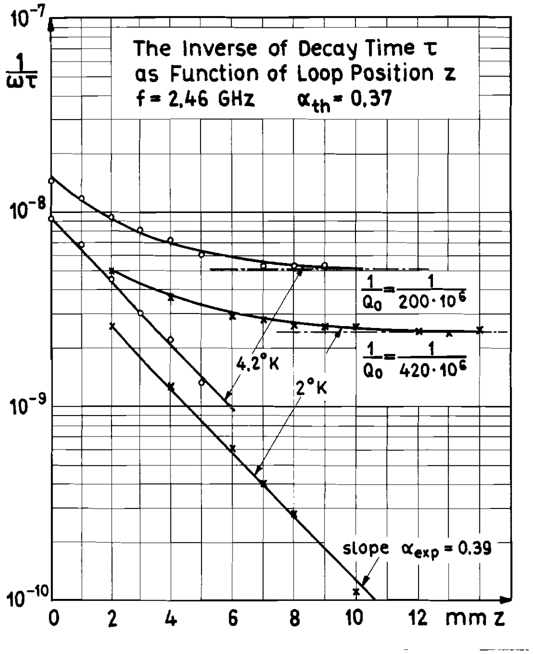

Fig. 1) The reciprocal of the decay time τ as function of the coupling loop position z

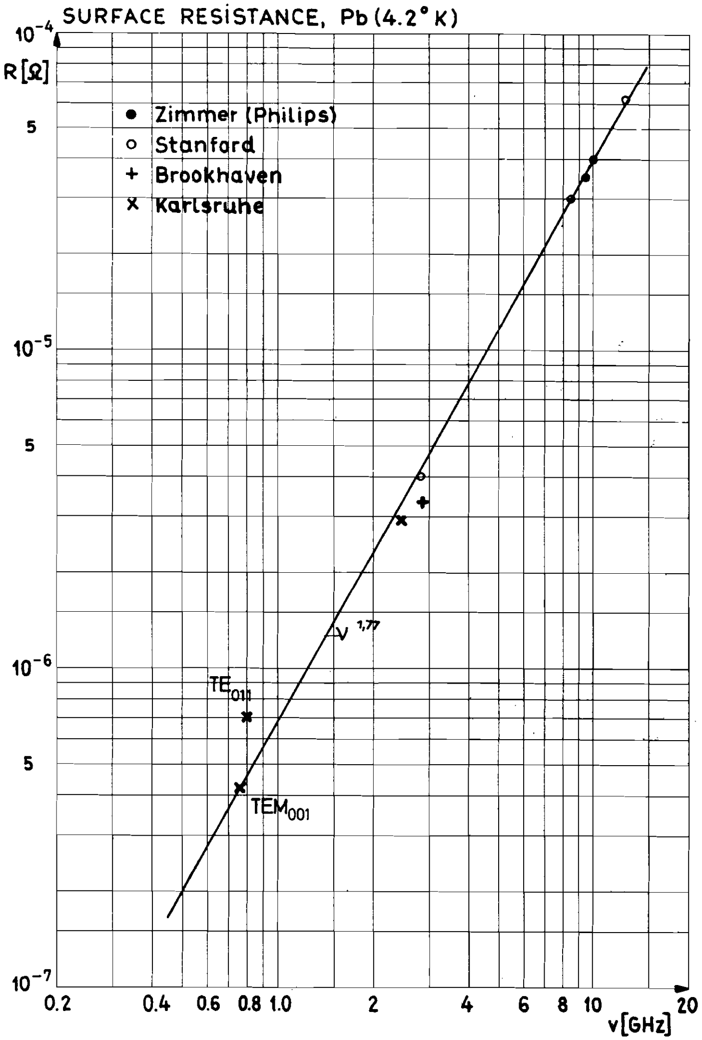

Fig. 2) Surface resistance of lead at 4.2°K as function of the frequency ν

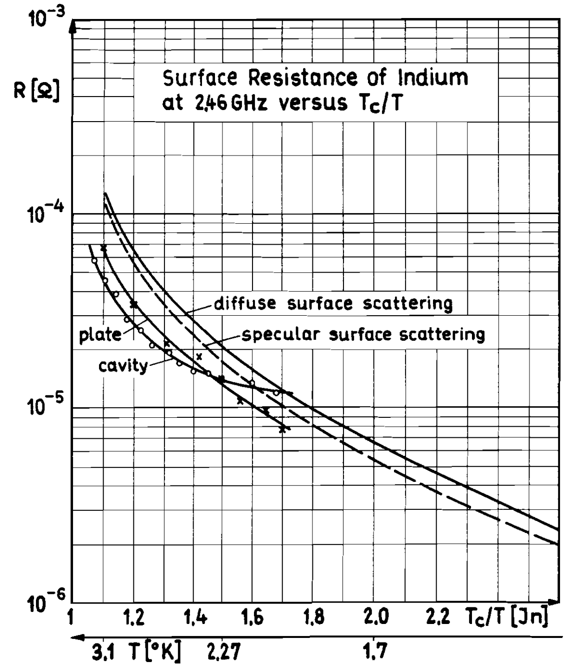

Fig. 3) Surface resistance of indium at 2.46 GHz as a function of temperature

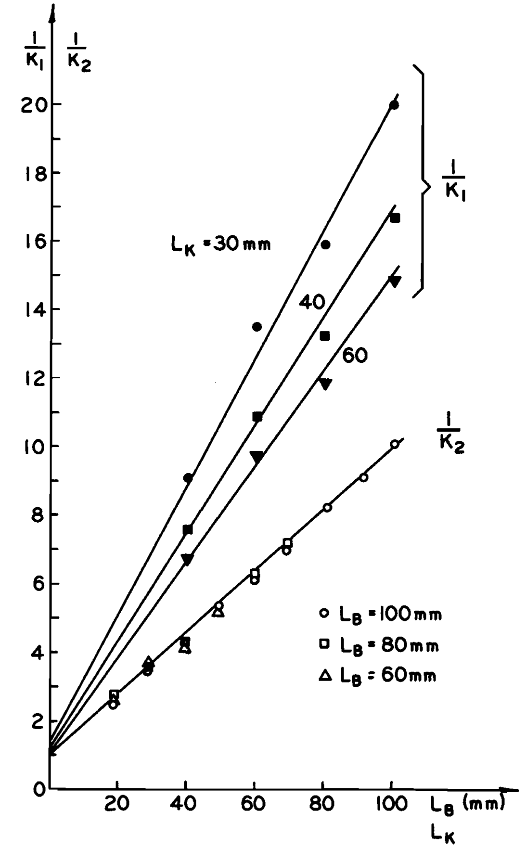

Fig. 4) The dependence of the coupling coefficients on the length of accelerating cell L_B and of coupling cell L_K. The straight lines are computed with $L_i^+ = 7.5$mm and $L_i^- = 11$ mm

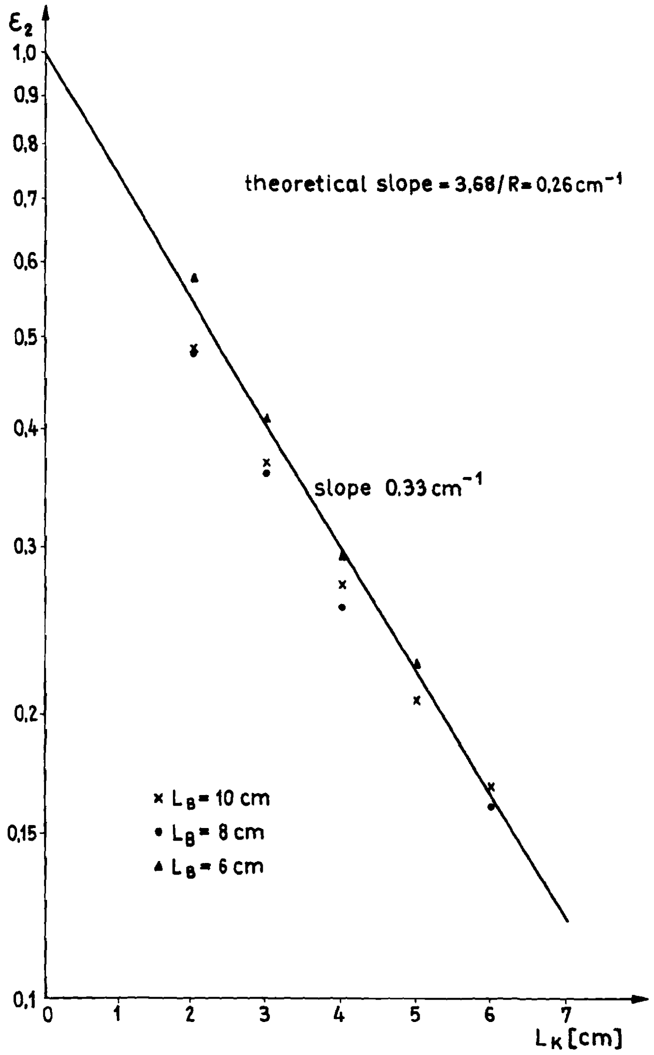

Fig. 5) The coefficient ε_2 for the coupling between alternate accelerating cells.

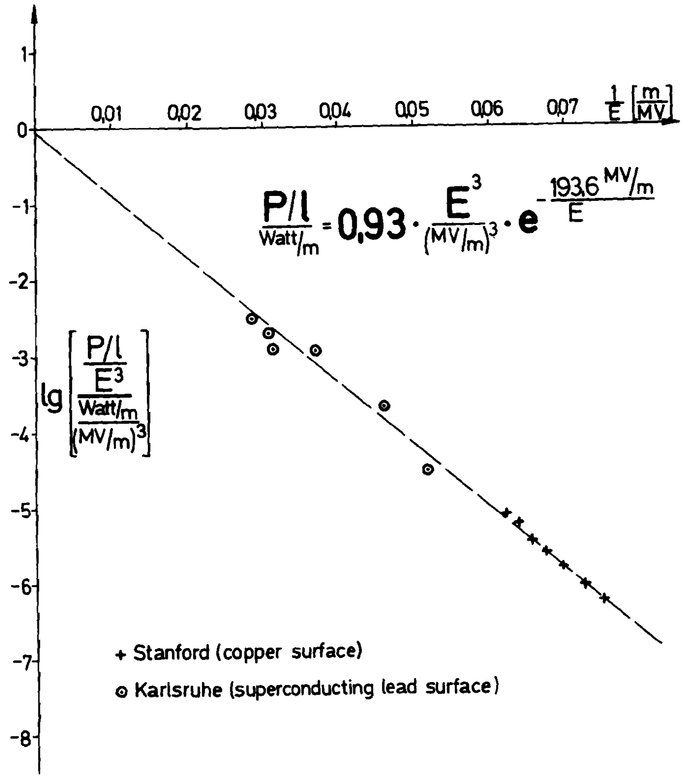

Fig. 6) The power loss due to field emission determined from the dose rate as a function of maximum field strength 14)

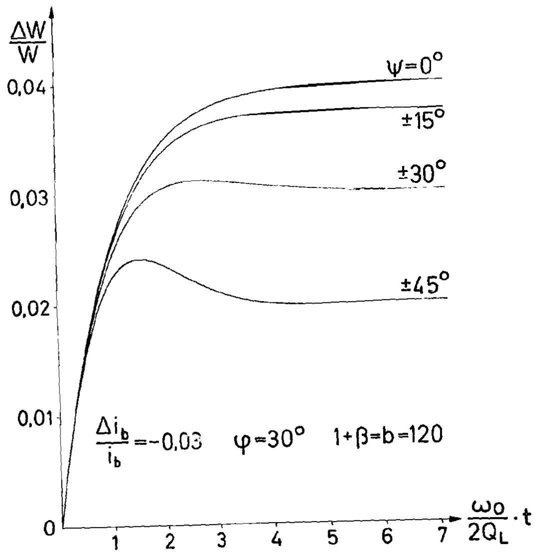

Fig. 7) The variation of energy gain with time for a sudden change of beam current i_b (ϕ phase angle, Ψ tuning angle, b beam loading parameter).

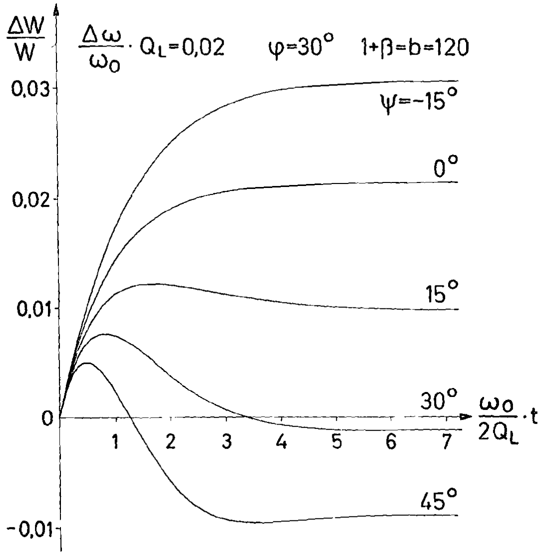

Fig. 8) The variation of energy gain with time for a sudden frequency jump $\Delta\omega$