

RF SUPERCONDUCTIVITY

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Summary

Superconductors used for the microwave accelerating structures held the promise of a drastic reduction in RF power requirement at comparable or higher field strengths with respect to conventional ones. Technically applied accelerating structures have sufficiently low RF losses at high fields, whereas the maximum achievable RF field is still below expectations. However, the theoretical limit for the RF field has nearly been reached in some test resonators at a laboratory scale. Further improvement in high RF fields is expected.

Introduction

The new technology of RF superconductivity originally developed, as in the case of many other things, out of the field of accelerator research. Conventional linacs with high beam intensities for the acceleration of electrons, protons and heavy ions have been built (e.g. Stanford, Los Alamos, GSI-Darmstadt). They are expensive in operation because of the very high RF power requirements and must be pulsed, in general. Superconductors used for the microwave accelerating structures held the promise of a drastic reduction in RF power requirement and hence a reduction in operating cost due to the much lower RF losses at comparable or higher field strengths. In addition, continuous beam acceleration is available which results in higher beam quality and more abundant production of secondary particles. Therefore, nearly ten years ago, some enthusiastic physicists started to develop the new technology of RF superconductivity.

Some milestones in the history are:

- 1964 electrons were accelerated for the first time with a superconducting lead plated test-resonator by a group at Stanford¹. The existence proof for a superconducting linear accelerator (SCA) had been given.
- 1967 the construction of prototype components for an electron SCA was first begun at Stanford².
- 1968 the attention was directed towards Nb as a superconductor which had been shown to be superior to Pb by the Stanford group^{3,4}.
- 1970 the construction of prototype components for a proton SCA was first begun by a group at Karlsruhe⁵.
- 1971 electron beam tests with the first part of the Stanford SCA were carried out successfully⁶. The first part of an electron SCA as part of a microtron was operated as an accelerator by a group at the university of Illinois⁷.
- 1972 proton beam tests with the first part of the Karlsruhe SCA were carried out successfully⁸.

Today, in the field of accelerator technology, about 8 technical projects with superconducting RF devices are well underway. Among them are superconducting cavities for electron and proton acceleration⁹⁻¹² and for heavy ion acceleration^{13,14}. Moreover, superconducting particle separators¹⁵⁻¹⁷ are under construction for the separation of pions and kaons. A superconducting RF separator is the only economic possibility for particle separation above a certain particle momentum, especially for long beam pulses^{15,16}.

More than 10 other laboratories view their work as applied research on RF superconductivity. Unfortunately, detailed information about the work in this field which is going on in the UdSSR has not come to the authors attention.

This broad interest in RF superconductivity is motivated not from accelerator technology alone. Beyond basic nuclear research superconducting RF accelerators with its high beam current and continuous operation offer novel possibilities in biomedical research¹⁸⁻²². Basically, the use of particle accelerators in radiotherapy and radiodiagnostic has the advantage, that the global radiation exposure of the patient is reduced to a large extent, if pions or protons are used instead of X-rays, gamma rays or electrons. The existence of RF superconductivity held the promise of energy economized accelerators. It thus may contribute to the production of more useful particles for medical applications.

Small and compact SCA's in the MeV range could also be used advantageously in high voltage electron microscopes²³.

Superconducting cavities for high field applications must have low losses R (high Q-values) as well as high peak RF surface fields, E_{max} and B_{max} . However, the high Q-value alone permits various interesting low field applications. I am referring to the field of measurement of extremely small quantities (dielectric losses, small frequency shifts, small changes in length etc.). Recently at Stanford²⁴ another milestone has been achieved. A superconducting cavity stabilized a Gunn-effect oscillator with a short term frequency stability of 10^{-15} .

In principle, the scope of application of this new technology is nearly the entire field of electrical engineering. The additional expenditures for cryogenics limits the application of RF superconductivity, however, to problems where superconductivity offers particular advantages. For example, in the field of communications applications include low noise receivers of extremely weak signals, extremely narrow bandwidth, RF filters, and low loss delay lines. A particular example is the application of superconducting coaxial cable for communications²⁵. Superconducting transmission lines are nearly lossless and have low distortion. They are superior to conventional coaxial cables, but have a competitor in the glass optical waveguides²⁶.

There have been several summary papers in recent years concerning RF superconductivity and its application to particle accelerators at different conferences²⁷⁻³⁰. In this paper I would like to discuss the present situation with superconducting RF cavities and the currently operating superconducting accelerator prototypes. Fabrication and processing techniques being utilized for the production of superconducting structures have been summarized two years ago in the excellent paper by J.P. Turneaure²⁷. Progress in this field since that time will be summarized in this paper.

Present situation with superconducting RF cavities

The behavior of superconductors at high frequencies can be characterized by the following facts:

1. In contrast to dc fields ac fields still cause losses which are lowest in the Meissner state.
2. In the Meissner state shielding currents flow only near the surface and the RF losses are concentrated within this very thin surface layer of about 50 nm thickness.

According to the BCS-theory³⁸ the ac losses should vanish exponentially with temperature (see Fig. 1). Experimentally the losses in superconducting RF cavities have been reduced to the theoretical value at all temperatures above 1.5 K. This progress can be seen from Fig.1. At temperatures below 1.5 K a constant residual resistance, R_{res} , is obtained. The origin of this R_{res} is not completely understood, although surface effects which are localized directly at the metal oxide interface³⁹ are thought to be responsible.

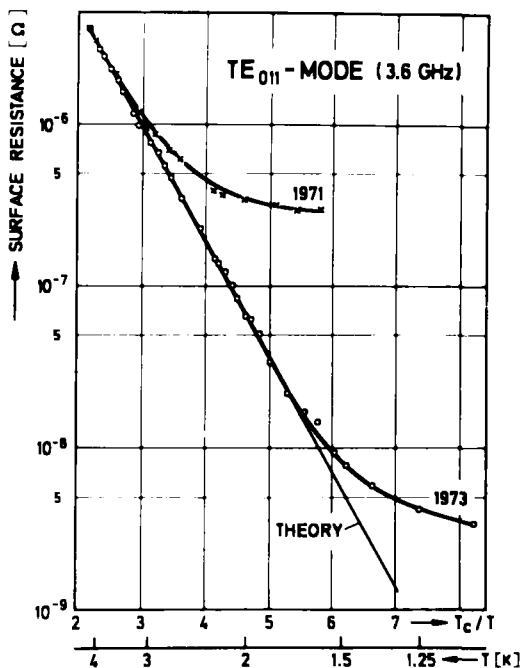


Fig. 1: Surface resistance as function of temperature for a TE-mode Nb cavity.

Obviously surface preparation and protection techniques are of great significance. The improvement of these techniques has led to the present situation with RF losses on the order of 10 nΩ (Fig.1). Results of simple cavities at 1.5 K are given in Table I^{36,37}.

Table I: Results of simple Nb cavities at 1.5K

Frequency	Mode	R	B _{max}	E _{max}	Reference
GHz		nΩ	mT	MV/m	
9.6	—	20	193	—	BCS-Theory
9.6	TE ₀₁₁	39	160	—	Siemens
9.6	TM ₀₁₀	140	150	70	Siemens
3.6	—	5	193	—	BCS-Theory
3.6	TE ₀₁₁	8	81	—	Karlsruhe
2.1	TM ₀₁₀	50	38	29	Karlsruhe
0.09	—	0.008	193	—	BCS-Theory
0.09	Helix, π	10	100	24	Karlsruhe

The residual resistance is sufficiently low, though it is sometimes an order of magnitude higher than the theoretical limit, especially in modes which have strong electric fields terminating on the cavity surface. Even in actual accelerating structures the RF losses at high fields do not exceed thermal insulation losses of the cryogenic system. For example, at an energy gradient of 3.0 MeV/m in a 6 m long 1300 MHz Nb accelerating structure at Stanford⁹ the RF power dissipated at helium temperature was 8.6 watts. The total insulation loss of the cryogenic system was on the order of 10 watts.

The situation, in general, with respect to RF losses hence is satisfactorily even on a technical scale. However, the situation with respect to maximum achievable RF field is different. The theoretical limit is thought to be the thermodynamic critical magnetic field B_c . With the type I superconductor Pb this limit has been reached at RF frequencies^{44,45}. For type II superconductor Nb the thermodynamic critical magnetic field is $B_c = 193$ mT at 1.5 K, while the lower critical field is $B_{c1} = 127$ mT at 1.5 K.³⁷ With simple Nb cavities the measured RF peak values at 1.5 K, B_{max} , are slightly lower than the thermodynamic limit (see Table I), but clearly higher than B_{c1} . This is in agreement with expectations of Halbritter^{36,40}, according to which the value of B_{c1} is meaningless within the microwave range, because the generation and penetration of magnetic flux takes too much time. Therefore, other hard superconduc-

tors such as Nb₃Sn or NbN become interesting for superconducting RF cavities due to their substantially higher B_c.

There exists, however, especially with respect to peak fields, a discrepancy between simple cavities and large Nb structures. In actual Nb accelerating structures the standard surface RF fields obtained are much lower than the best values obtained in these structures³¹⁻³⁵. This is shown by the results given in Table II, which summarizes standard values, best values and standard energy gradients for large Nb structures.

Table II: Results of actual niobium accelerating structures.

TYPE OF STRUCTURE	FREQUENCY	SURFACE STANDARD	RF-FIELDS BEST VALUE	ENERGY GRADIENT STANDARD	REFERENCE
	GHz	MV/m/mT	MV/m/mT	MeV/m	
SINGLE λ/2-HELIX	0.1	15 / 60	25 / 100	2 - 3	KARLSRUHE ^{31,32}
REENTRANT CAVITY	0.35	12 /	26 /	-	STANFORD ³³
IRIS	1.3	10.8 / 16.2	18 / 27	3 - 4	STANFORD ^{3,34}
DEFLECTOR IRIS	2.8	14.5 / 40	30 / 85	2.6 - 5.5	KARLSRUHE ³⁵
SINGLE CELL OPEN CAVITY	3.0	-	-	6	CORNELL ¹¹
TM-CAVITIES	2.1	-	29 / 38	-	KARLSRUHE ³⁶
	2.9	20 /	35 /	-	STANFORD ³⁴
	8.6	40 / 61.5	70 / 108	-	STANFORD ⁴
	9.6	-	70 / 150	-	SIEMENS ³⁷

The situation with respect to accelerator applications is indicated in Fig.2. Peak electric fields and energy gradients are given for different types of accelerating structures. Further improvements in the achievable energy gradient seem possible.

For all the real progress in superconducting RF cavity work the essential requirement for high RF fields and Q's have still not been determined with assurity. Still one gets varying results for B_{max} and Q with resonators which have been fabricated and treated in a similar way. In particular, in real accelerating structures the results fluctuate for identical resonators as a result of similar repeated surface preparation procedures. This points to different surface states which we are not yet able to parameterize.

Two problems which are related to the surface condition are the following^{36,41}. One problem is magneto-thermal breakdown. Precipitates of bad superconductors or surface roughness, for instance, will locally lower the critical magnetic field and thus lead to a premature magneto-thermal breakdown. Already at medium macroscopic field levels the spot goes normal conducting. Due to a factor of 10⁶ higher

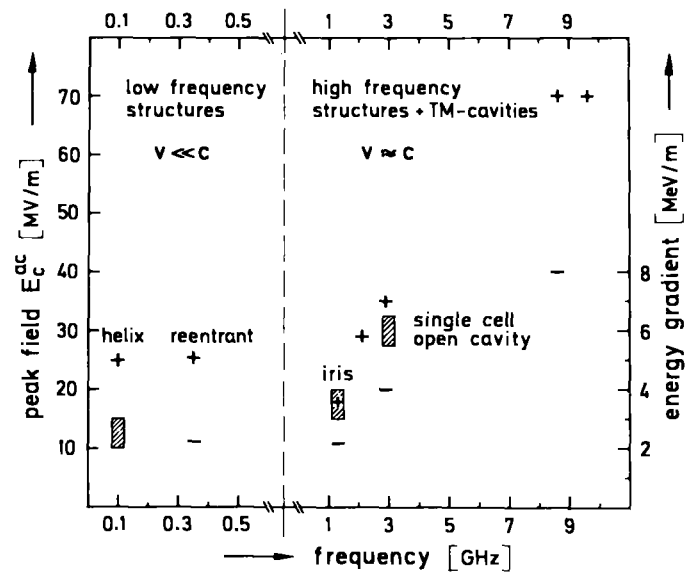


Fig. 2: Peak electric field (±) and achievable energy gradient (▨) for different types of accelerating structures. Standard values are indicated with dash (-), best values are indicated with cross (+).

losses the normal conducting nucleus is heated up and spread out within microseconds until at least a large part of the resonator surface goes to the normal-state.

Another problem which has become apparent in recent years is that of electron loading^{41,43} for cavity modes which have strong electric fields terminating on the cavity surface, as is the case for all accelerating modes. Electron loading is a primary reason for field limitation and degradation in accelerating structures. In particular, surface damage due to electron impact can cause RF breakdown. Furthermore charging of the oxide coating by electron impact will change the residual losses and will enhance the secondary electron emission⁴¹. The experimental evidence is taken from the big difference in obtainable peak magnetic RF fields in TE- and TM-mode cavities. TM-mode cavities- subjected to electron loading- have significantly lower breakdown fields than TE-mode cavities. Results of B_{max}(TE₀₁₁) = 80 mT and B_{max}(TM) = 40 mT in a S-band cavity show⁴¹, that the hypothesis of an area²⁷ or frequency-dependent²⁸ B_{max} cannot describe the experiments. Instead, a model derived on electron loading can explain B_{max} ∝ ω in similar shaped cavities, e.g. the value B_{max} (2.2 GHz) = 40 mT corresponds to B_{max} (9.6 GHz) = 150 mT, which has in fact been measured in a 9.6 GHz Nb cavity³⁷.

Current activities in RF superconductivity

<u>Laboratory</u>	<u>SCA projects underway</u>
Stanford University (High Energy Physics Lab) ref. 9	electron linac (4 orbit recirculation system), 350 MeV, >100 μ A superconducting structure: 4x6 m long 1300 MHz niobium structure of the iris-loaded type (multiperiodic)
University of Illinois ref. 10	electron microtron (recirculation of beam for 6 turns), 600 MeV, 10 μ A superconducting structure: 4.6 m long, 1300 MHz Nb structure of the iris-loaded type (multiperiodic)
Cornell University ref. 11	electron synchrotron, 25 - 40 GeV superconducting structure: 10 - 500 m, 3000 MHz Nb structure which is completely open in the horizontal mid-plane
Rutherford High Energy Lab. ref. 17	RF-separator for pions and kaons with a central momentum of 4GeV/c superconducting structure: 2x1.25 m long lead-plated cavities separated by a distance of 7.5 m and operated at 1.3 GHz
Karlsruhe / CERN ref. 15, 35	RF-separator for kaons and antiprotons up to a momentum of 30GeV/c superconducting structure: 2x2.7 m long Nb deflectors of 10 ⁴ cells each and separated by a distance of 90 m and operated at 2.855 GHz
Karlsruhe Institut für Experimentelle Kernphysik ref. 12, 30	proton linac (2-stage-pilot accelerator) 10 - 15 MeV, >100 μ A superconducting structure: 4.8 m long 90 MHz Nb helices, 2 m long 720 MHz Nb structure (eventually of Alvarez-type)
Argonne National Lab. ref. 13	heavy-ion postaccelerator 10 MeV/N superconducting structure: 90 MHz niobium helices
California Institute of Technology ref. 14	heavy-ion postaccelerator superconducting structure: niobium spiral resonator
<u>Laboratory</u>	<u>applied SCA research</u>
Stanford University ref. 34	niobium TE- and TM-mode cavities at 1.3 GHz, 2.6 GHz and 8 - 10 GHz (stable oscillators)
Stanford University/ Weizmann Institute of Science ref. 33	niobium reentrant cavities at 433 MHz
Karlsruhe/Heidelberg (Max-Planck-Institut für Kernphysik)	niobium single $\lambda/2$ -helix resonators at 50/100 MHz
Karlsruhe ref. 36	niobium TE- and TM-mode cavities at 2-5 GHz
Siemens (Erlangen) ref. 37	niobium TE- and TM-mode cavities at 8-10 GHz
Bonn	niobium cavities at 8-10 GHz
DESY	niobium cavities at 1.3 GHz
Orsay (Institut d'Electronique Fondamentale)	niobium cavities at 2-3 GHz
Tokyo (National Lab. for High Energy Physics)	niobium cavities at 6.5 GHz
Osaka University ref. 46	lead-plated cavities at 3.8 GHz

The listing presented here does not pretend to be complete. For example, many laboratories are interested in developing superconducting cavities if they can possibly increase the energy of their accelerator. In the past there has been work on superconducting cavities at SLAC⁴⁷.

Fabrication and surface preparation of Nb cavities

Nb products can be supplied commercially with low enough impurity content, free of voids and inclusions, and annealed. The standard specification is now named "Stanford grade"²⁷. The price per kg still is constant at about 80 \$/kg. Drawn tubing for helices are mechanically polished, solid ingots are forged and sometimes prerolled or premachined. Generally, Nb products can be formed by most of the standard forming techniques.

The method of cavity fabrication depends very much on the type of cavity. The most direct way to fabricate cavities is to machine the parts from solid Nb bar and join the parts with either demountable seals or electron beam (EB) welds. This method is used for 3 GHz and 10 GHz test-cavities³⁶ and even for 3 GHz particle separator structures¹⁵. It has been used for 720 MHz test cavities for proton acceleration. This method is relatively expensive for a long SCA, and therefore HEPL has used another approach to manufacture Nb cavities for their bigger structures. 20 cm diameter cavities are fabricated from Nb square sheets about 5 mm thick. Half cells are made by hydroforming into cups and then machining. These cups are finally EB welded together to form the cavity^{9,27}.

But what decides the matter above all, is the preparation of the niobium surface. The surface preparation procedures are chemical polishing, electropolishing with subsequent anodizing, and ultra-high-vacuum (UHV-)firing.

Chemical polishing: The usual surface treatment after final machining is chemical polishing with a mixture of HNO₃ and HF. Up to about 100 μm are to be removed from the surface to get rid of the damage layer and smooth the surface.

Electropolishing: The best surface smoothness is obtained by electropolishing with a H₂SO₄ and HF solution⁴⁹. Starting at a certain dc voltage current oscillations occur, due to a repetitive process which involves the formation of oxidation products (SO₄ ions etc.) in a thin oxide layer of high resistance, which is then dissolved by HF. Because of the high resistance layer peaks are preferentially removed. As a result, a surface roughness as low as 30 nm has been achieved.

Anodizing: The electropolished Nb surface is very often subsequently covered with a dense (about 0.1 μm thick) layer of amorphous Nb₂O₅. This is done by anodic oxidation⁵⁰ in a NH₃- or H₂SO₄-solution. Anodizing results in an increase of B_{max} and Q, even if the resonator has not been handled before under particularly clean conditions. The reason for this improvement is thought to be that, when the oxide layer is grown, the Nb surface is shifted to a deeper and cleaner niobium layer. In addition, this method allows to get rid of a large amount of chemicals. Handling under particularly clean conditions is not always possible with the relatively large accelerating structures, therefore anodizing seems to be advantageous. At least transportation and storage of Nb structures may be much easier with anodized cavities. The only disadvantage of the oxide layer seems to be its sensitivity

to electron loading and its enhanced secondary electron emission. These effects have to be studied in more detail.

UHV-firing: UHV-firing the Nb cavity at temperatures in the range of 1400°C to 1800°C for several hours not only removes gaseous contaminations, mainly oxygen, but it also stress relieves and dissolves precipitates. Especially, if the surface has been anodized first, UHV-firing can remove some carbon^{36,47}, because CO can be evaporated. Again UHV-firing is necessary for welded and complicated Nb structures because welds always need some annealing and complicated structures are otherwise difficult to clean from chemicals. In addition, rapid cooldown of the UHV furnace and ventilation with nitrogen at 400°C has shown to give better results in small test cavities⁴¹.

Other performance considerations

We are able to design and manufacture superconducting Nb cavities with similar or better CW energy gradients than with conventional RF cavities. We maintain the required deflecting and accelerating fields continuously, because the power loss on the surface of the cavities is reduced up to a factor of 10⁶ compared to normal-state conductors. Although some improvements still remain to be made, especially increasing the energy gradient in Nb accelerating structures, the major difficulty has been shifted to the economy and reliability question of the compound system of superconducting electrical engineering with cryogenics.

Nb RF structure: As already indicated, the fabrication and processing of large Nb cavities is sometimes expensive because a rather complex surface preparation technique is needed. Simplifying the processing procedure and developing new methods for mass production will essentially contribute to a more economic solution.

Further SCA development should be towards

- improved surface preparation techniques to achieve higher fields,
- simplified surface preparation techniques for mass production,
- surface protection for long term stability,
- radiation resistivity,
- other superconducting materials with higher T_c.

RF-system: In general, unless very high beam currents are required, the RF system of a SCA is simpler than conventional ones. Conventional RF transmitters in the range of 50 W to 1 kW are needed, only. The only problem which will remain in some cases is probable tuning of individual cavities with extremely narrow bandwidth. In particular, for a high current proton accelerator one major problem is to couple adequately the microwave power out of the cavity to an external tuner⁵¹ without large dissipation into the helium.

Cooling: The power loss on the surface of superconducting accelerating structures is in the order of W/m. One must remember, however, that this heat loss must be removed at 1.8 K. When the Carnot efficiency and the refrigerator efficiency are taken into account, the refrigerator must have a power input of about 2000 W per W of power dissipated at 1.8 K.

It seems clear, that the cost of the refrigerator and that of the cryogenic appendages play a major role in the total cost of a superconducting accelerator. These cost are dominated by the necessary size of the refrigerator, which in turn must be adequate to handle the total power dissipated at 2 K. The latter is composed of the RF power loss on the cavity surface, the RF dissipation into the helium down the RF transfer lines, and the insulation loss of cryostats, helium transfer lines and fittings. Optimization with respect to economy and reliability of cryogenic components must be given particular attention. The choice of operating temperature and the design of an adequate cooling system have to be taken seriously into account.

Refrigerators and cryostats: Rapid progress has been made in cryogenics, and the state of cryogenic engineering permits the manufacture of helium refrigerators in the range of very small (<1 W) up to large (> 1 kW) machines. However, refrigerators so far have not been particularly optimized to special applications and continuous operation at a constant heat load. It seems to be clear, that an optimization of refrigerator, cryostat and transfer lines for every special application is necessary.

Helium cryostats and transfer lines do have insulation losses, at this time, in the range of 0.2 W/m² up to 0.7 W/m^{2.52}. With the rapid progress in reduced RF power losses on the surface of superconducting structures in recent years, it seems to be clear, that a reduction in insulation losses also will contribute to a more economic superconducting solution. The cost for cryostats^{4,6} (3-6 m³) are nowadays in the range of 8000 \$/m³ up to 40000 \$/m³.

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Discussion

T. Khoe, Argonne National Laboratory: When you anodize the accelerating cavities, do you have any problems with multipactoring ?

M. Kuntze: We had problems with multipactoring but so far we have always been able to overcome it. But electron loading seems to limit the cavities at high fields. We have not gone completely through it up to now, but what will happen at the surface will happen with or without anodizing, because there is a 40 to 50 Angstrom thick oxide layer on the niobium surface. What happens on the surface will happen in the first 10 or 15 Angstroms, so an oxide layer of 500 Angstroms makes no difference. It will enhance electron secondary emission a little, but I don't think that that is a problem.

M. White, Princeton University: Do you have any problems with whiskers ?

Kuntze: No, we have developed a surface preparation method called "electro-polishing" which is extremely sensitive just to whiskers, so we can get a very plane surface. I think that this was the real progress of the last two years.

A. Schwettman, Stanford University: I'd like to respond briefly to the last two questions. There are still field emission problems in superconducting cavities but these problems appear at higher energy gradients than are achieved in large-scale structures at the present time. If we make progress in the magnetic breakdown problem and reach higher and higher fields, we are still going to be confronted with the problem of field emission which is enhanced both by geometrical projections and by an absorption of gases on the surfaces of the cavity and consequent resonant tunneling.

The first question had to do with multipactoring and I'd like to point out that there is one effect of multipactoring which we at Stanford had not clearly perceived before. Multipactoring is usually looked upon as a barrier in getting to high field levels and if you once get through the multipactoring levels you don't worry about them any longer. We have found upon occasion, however, in our electron accelerator tests at Stanford that you can have small-level multipactoring taking place which couples r.f. energy from the accelerator mode into one or another of the longitudinal modes of the accelerator structure. If you are trying to achieve very high energy resolution such as in one part in 10^4 , it is possible to excite these other modes by the secondary electron currents, despite the fact they don't represent a limitation to the field itself. I don't think that's a serious problem, but it is only one aspect of multipactoring that we have only recently become aware of.

H. Hahn, Brookhaven National Laboratory: Why don't most cavities reach H_{c1} ?

Kuntze: There is a difference between the results one gets with small test resonators and with actual accelerating structures. In actual accelerating structures one has electron loading which does damage to the surface lowering the breakdown below H_{c1} . But the proof you can go above H_{c1} has been given by a small test resonator.

Hahn: But you have not reached H_{c1} ?

Kuntze: It depends on the H_{c1} of the material.

J. Blewett, Brookhaven National Laboratory: I have the impression that H_{c1} is not that clearly defined.

B. Cork, Lawrence Berkeley Laboratory: Is there an application of r.f. superconductivity to high-voltage electron microscopes ?

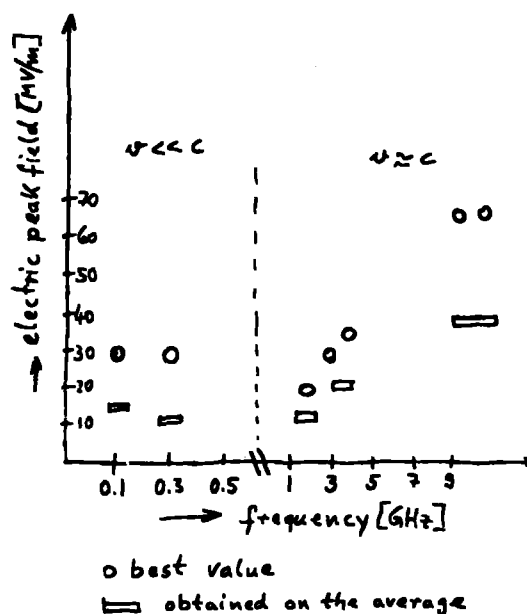
Kuntze: Yes. One thinks about a 10 MeV electron microscope that uses a superconducting accelerator structure and superconducting lenses. The ultimate goal is to achieve a very good energy resolution and spatial resolution on the order of 1 Angstrom.

R. Wideroe, Swiss Institute for Nuclear Research: Could you say something about the surface treatment of the niobium ? Must there still be a bake at 1800°C or more in vacuum ?

Kuntze: It's a very critical procedure. I will come back to this in the second part of my talk.

D. Gray, Rutherford High Energy Laboratory: Would you give some numbers for the magnetic fields you reach at various frequencies in large-scale structures ?

Kuntze: As you can see from the drawing, for low- β structures the best values are around 30 MV/m, but the average standard value is about a factor of 2 lower. In the S- or L-band structures, the normal gradient is about 10 MV/m peak field, and one has reached nearly 20 MV/m. In X-band test cavities, peak fields as high as 70 MV/m have been seen, but on the average they are about 40 MV/m.



Gray: These are peak fields ?

Kuntze: Yes. You can derive from the peak fields the possible energy gradient vs frequency. In the low- β region the accelerating field is between 2 and 4 MV/m, and in the electron structure Cornell obtained nearly 6 MV/m at 3 GHz. The energy gradient obtained at Stanford is between 3 and 4 MV/m. This is where we are now. We have peak values which are roughly a factor of 2 higher.