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HIGH FIELD RF SUPERCONDUCTIVITY: TO PULSE OR NOT TO PULSE?*

ISIDORO ENRICO CAMPISI
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94305

SUMMARY

Experimental data on the behavior of superconductors under the application of RF fields of amplitude comparable to their critical fields are sporadic and not always consistent. In many cases the field level at which breakdown in superconducting RF cavities should be expected has not been clearly established.

Tests conducted with very short ($\sim 1\ \mu s$) RF pulses indicate that in this mode of operation fields close to the critical values can be consistently reached in superconducting cavities without breakdown.

The advantages and disadvantages of the pulsed method are discussed compared to those of the more standard continuous wave (cw) systems.

INTRODUCTION

Ever since a phenomenological theory of superconductivity was proposed,[1] it has been known that a finite, although very small, surface resistance should be observed in superconductors when subjected to alternating electromagnetic fields. The BCS theory[2] was applied to this problem[3,4] but the theory was able to make predictions on the properties of superconductors only in the weak field approximation ($H \ll H_c$).

The existence of well-defined dc critical magnetic fields motivated the accelerator community to investigate whether superconductors could be used for microwave cavities in linear accelerators:[5,6] the combination of the clear, established advantages of the low RF losses together with the possibility of reaching fields of amplitude comparable to the dc critical fields, made the construction and operation of high-gradient, high-energy, large duty-cycle linear accelerators very attractive. For that goal in particular, measurements were undertaken on various superconductors to determine their RF properties and to establish the field limits at which they could be operated. In the late 60's and early 70's a great deal of work was done on superconducting RF cavities of different materials (Sn, Pb, Nb, Nb_3Sn), frequencies and modes to establish the limits as well as the fabrication technologies and preparation procedures for such cavities.[7,8] In many instances carefully prepared cavities were able to sustain fields close to[9] or up to the thermodynamical dc critical field.[10] In one instance[11] the data indicated that in specially designed Pb cavities not intended for acceleration, fields close to the superheated critical field could be reached without breakdown. The superheated field is the value of the magnetic field up to which the Meissner state can still exist in a metastable condition, and it is defined in terms of the thermodynamical critical field H_c and of the Ginsburg-Landau parameter κ as $H_{sh} \simeq \frac{1}{\sqrt{\kappa}} H_c$.

Table 1 shows the critical fields that theoretically should be attainable in cavities manufactured out of the most commonly used superconductors and the corresponding accelerating gradients typical for TM_{010} accelerator cavities, both for standing-wave and travelling-wave structures.[12]

Obviously the maximum benefits of operating accelerators with superconducting cavities would come not so much from the high gradients which could be reached but mostly from the possibility of maintaining those field levels with a large duty cycle and with low losses.

High-energy linear electron accelerators should be operated at the maximum possible gradient in order to benefit the most from the single passage of the particles through the accelerating fields. In normal-conducting accelerators such as the one at the Stanford Linear Accelerator Center (SLAC) the requirement of a relatively high gradient demands that a compromise be made for the duty cycle, which is less than 10^{-3}, in order for the average energy dissipated to be of a reasonable amount.[13] It is therefore in such structures that the potential of superconductors could be best used.

Table 1. Theoretical zero temperature critical fields and accelerating gradients (from H_{sh}) for TM_{010} RF superconducting cavities. The average accelerating gradient E_a is assumed to be ~ 2.5 times smaller than the peak surface field E_s for the standing wave (SW) and ~ 1.65 times for the travelling wave (TW) case.[12] (H in Oe, E in MV/m)

Material	H_{C1}	H_{C2}	H_C (therm.)	H_{sh}	E_s	E_a (SW)	E_a (TW)
Sn	—	—	306	765	41	16.5	25
Pb	—	—	803	1200	65	26	40
Nb	~ 1950	~ 2050	1985	2400	130	51	77
Nb_3Sn	~ 310	2.3×10^5	5400	4000	215	87	132

Unfortunately the expectations that had built up from the theoretical estimates or from the experiments on selected cavities could not be realized in the vast majority of the cavities and extended structures built out of superconducting materials. Whereas cw-operated structures can still be highly valuable for RF cavities for storage rings where the gradient requirements can be relaxed, or in heavy-ion linear accelerator cavities for which the particular shape allows one to reach high magnetic fields in certain parts of the surface, the idea of building high-gradient, cw-operated, 100% duty-cycle superconducting linear accelerators has been almost abandoned.

From the point of view of the basic physics of the superconductors exposed to high-level RF fields, the experimental data are definitely not complete. The difficulties encountered in reaching high fields for practical applications have limited also the harvest of data which could clarify the role of the various critical fields in the RF and microwave frequency range.

Recently at SLAC a number of measurements performed on superconducting cavities at about 3 GHz with short ($\sim 1\ \mu s$) pulses of RF from a high-power klystron have shown that high fields can be reached in TM_{010} cavities consistently and repeatedly.[14,15,16] Although these results are not yet complete and the high fields can be reached only for a very short time, they have been obtained in cavities which had not received a particularly sophisticated treatment. For accelerator applications it is clear that this mode of operation is not as appealing as a low-loss cw system, but in specialized cases it should be possible to make a good use of the low-loss high gradients when a high duty cycle is not of vital importance.[17] These measurements can also indicate which limiting fields are ultimately attainable in superconducting cavities. From this point of view the operation of cavities with pulsed power could allow a better understanding of the fundamental properties of superconductors, especially their non-equilibrium properties.

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It will be clear, from the data presented in this paper, that the operation in cw (not to pulse) and with short pulses (to pulse) each presents its advantages and disadvantages: in a certain way, they are complementary, each providing information and applications which the other cannot provide. In this sense the concepts developed for the pulsed measurements and the results obtained from them cannot be transferred to the cw case and *vice versa*: the cavities under test are the same, but the physical systems tested by each method are different.

THE CW PICTURE

The highest surface magnetic fields reached without breakdown in superconducting RF cavities are approximately 1600 *Oe* in a *Nb*, TE_{011} mode cavity and about 1500 *Oe* in a *Nb*, TM_{010} cavity, both in X-band and at temperatures lower than 4.2°K.[18] Field values of 1100-1200 *Oe* have been reported by other authors for *Nb*-cavities of various types.[19,20]

The above results constitute the best performance ever which required particular care and attention in the preparation of the cavities, especially in regard to the surface treatment. Even so, the fields were significantly below the thermodynamical critical field and as mentioned, only in the case of *Sn* and *Pb* were clear physical limits reached and established. The experimental work on Nb_3Sn has not been as exhaustive as for *Nb*, but fields as high as 1000 *Oe* have been reached in a TE_{011} cavity:[21] this value is well above the first critical field but well below both thermodynamical and super-heating fields. In TM_{010}, Nb_3Sn cavities, fields of the order of 400-500 *Oe* can now be consistently reached.[22]

The general picture of the performance of practically obtainable superconducting cavities gives breakdown fields definitely lower than the results quoted above. Table 2 summarizes the results obtained reliably and routinely in various laboratories until 1983.[23,24]

Table 2. Representative results of *Nb* TM_{010} cavities until 1983.

Laboratory	Cavity Shape	Frequency (MHz)	Best Q_0	E_s (MV/m)	H_s (*Oe*)
KEK	spherical	500	$5 \cdot 10^{10}$	7.0	~ 350
CERN	spherical	500	$5 \cdot 10^{9}$	6.5	~ 325
KfK	elliptical	1500	10^{11}	13.5	~ 675
Wuppertal	spherical	3000	$\sim 10^{10}$	10.3	~ 515
SLAC	cylindrical	2856	$5 \cdot 10^{9}$	9.5	~ 480

It is clear that the typical cavity performance is nowhere near the limits set by the theoretically expected critical fields. As in the cases for which great care was used in the cavity preparation high fields were indeed reached, the reasons for the generally lower breakdown fields must not be of fundamental nature but must be associated with accessory causes. This appears to be true especially when the data for multi-cell structures are considered (Table 3): in this case the results are only at about 50% of the field levels reached in single-cell cavities.

During the past ten years the work of many researchers in several laboratories around the world has been concentrated on the task of determining and eliminating the causes of the discrepancy between the theoretical expectations and the actual experimental results. From all this work diagnostic tools have been developed together with theoretical and computational models, which have allowed people to locate, identify and, at least in part, correct the causes of premature breakdown. Among the various problems that have been identified as being of primary importance are electron loading and surface defects.

Table 3. Typical results for multi-cell *Nb* cavities.

Laboratory	Cavity	No. of cells	Active Length m	Freq. MHz	$E_{s\,max}$ MV/m	H_s *Oe*	Q_0
CERN	spherical	4	1.2	500	2.7	125	$5 \cdot 10^{8}$
HEPL	cylindrical	20	2.4	1300	2.3	110	$9 \cdot 10^{8}$
Cornell	muffin tin	10	1.0	1500	2.1	100	$1 \cdot 10^{9}$
HEPL	cylindrical	7	0.37	2856	5.5	250	$1.4 \cdot 10^{10}$
Cornell	muffin tin	6	0.3	2856	6.9	320	$3.9 \cdot 10^{9}$
Wuppertal	spherical	5	0.25	3000	~ 5	230	$\sim 5 \cdot 10^{9}$
Genoa	spherical	3	0.2	4500	8	370	$5 \cdot 10^{8}$

Electron Loading

Electron loading can be caused by two different phenomena: field emission and multipacting. The effects in both cases are the subtraction of energy from the stored fields by unwanted electrons and a possible heating by the same electrons impinging onto the cavity surface, with consequent depression of the local critical field and premature breakdown.

Field emission loading and its sources are not very well understood, but in general there seems to be a close correlation between the presence of "dust" particles in high electric field regions of TM_{010} cavities and the extent of the phenomenon. Under the influence of the fields these particles may become hot electron emitters. RF processing[25] or *He* sputtering[26] seem to have a beneficial effect on the problem.

Recent systematic studies of field emission have lead to the development of new, more reliable tools to diagnose the fundamental causes of this phenomenon.[27] Even so, not in every instance it seems possible to associate an identifiable feature with each field emission source. Consequently more work will be necessary to study the fundamental properties and the causes of the phenomenon in order to eliminate it or to decrease its consequences.

Multipacting is a much better understood phenomenon[28,29] and it has been almost entirely eliminated as a consistent source of breakdown, although it occasionally still creates problems.[30]

In the late 70's the work of Turneaure and others clarified and explained the nature of multipacting: at certain power levels and at certain locations in a RF cavity it is possible for some electrons to gain energy from the fields, impinge onto the same or a different region of the cavity surface with an appropriate energy and, on the average, extract more than one electron which in turn would repeat the process of resonant build-up. This process also limits the field levels by direct energy extraction from the fields and by indirect heating of the surface.

It has been demonstrated that by a proper choice of the cavity geometry[31] or by coating the cavity or parts of it with superconducting films which decrease the secondary electron emission coefficient[32,33] multipacting can be virtually eliminated.

Defects

The other major cause of field limitation in cw operated cavities is the presence of defects. In general defects are "irregularities of a real cavity surface which leads to additional RF power losses compared to those of an ideal superconducting surface."[34] In practice the surface conditions of superconducting cavities (and of superconducting extended structures even more so) are often far from being ideal. A great deal of work has been done over the past few years to identify and eliminate various classes of defects. Among the most successful techniques employed in this process is temperature mapping:[35] a set of resistor thermometers is spun around the cavity filled with RF at various power levels, creating a map in which the position of defects can be clearly identified (Fig. 1). The defects are subsequently located, studied and possibly eliminated, usually through mechanical grinding. This work has demonstrated that the sources of enhanced losses are often correlated with bad welds, microfissures, welding beads, inclusions, drying stains, chemical spots and so on. It is generally accepted that, although this process of systematically identifying and eliminating defects is very powerful and has contributed to the understanding of the underlying problems, for practical large-scale applications other methods are necessary. One of these methods consists of allowing ceramic beads to tumble for hundreds of hours inside the structure, thus performing a random removal of the cavity surface layer.[36]

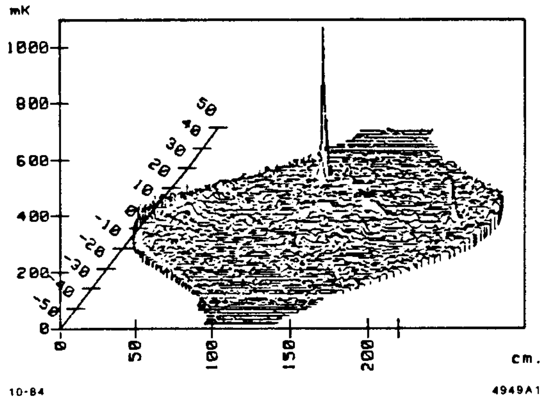

Fig. 1. Temperature map of a CERN 350 MHz Nb cavity. The large temperature spike indicates the presence of a defect.[34]

Another approach is to thermally stabilise the defects by using materials with high thermal conductivity: the effects can thus dissipate higher power without causing thermal run-away.[37,38] Recently cavities manufactured out of high thermal conductivity Niobium have been operated at magnetic field levels of about 800 Oe at 1.5°K, greatly improving the typical cavity performance of just a year ago.[39,40,41] At CERN cavities have been manufactured by sputtering Nb onto a copper substrate,[42,43] a technique which also has great potential for thermal stabilization and would allow the use of simpler refrigeration techniques, since the copper cavity can easily be cooled by a forced flow of helium.[44]

Table 4. Recent results obtained in high-thermal conductivity cavities.

Laboratory	Cavity Material	E_s (MV/m)	H_s (Oe)
CERN	low-λ Nb	5.4–6.4	320
CERN	$NbCu$	8.6	430
CERN	high-λ Nb	9	450
Wuppertal	high-λ Nb	~ 18	785
Cornell	high-λ Nb	~ 18	850

The results obtained during the past year in Wuppertal, CERN and Cornell have improved the overall picture of the performance of cw operated Nb cavities (Table 4).

Diagnostic tools and techniques exist nowadays which should allow the RF superconductivity physics community to steadily improve the performance of the cavities and to ultimately reach fields closer to the theoretical limits than has been possible so far. In the meanwhile, the present performance is considered good and reliable enough to be used in existing and future accelerators.[45,46,47,48,49,50]

THE PULSE PICTURE

Short pulses of RF power have been used for quite some time in connection with research in superconducting cavities. Pulses with a length of the order of a millisecond were used by Turneaure to obtain the results on the limiting fields in Sn.[10] Other authors have occasionally shortened the RF pulse length together with an increase of coupling and observed a sizeable improvement of the field they could reach.[51,11,52,53] Even in these cases the use of pulsed RF was mostly aimed at limiting the average thermal load in the superconductor, as was done in the normal structures at SLAC, and no meaningful practical use of the pulsed technique was envisioned. Moreover the typical imprecision associated with transient measurements made the method not very attractive for systematic physics studies.[51]

Apart from the previous reasons for not extending systematically the pulsed method to the study of superconductors, the main limiting cause is the fact that in most laboratories it is easier to find low-power cw RF sources than to find short-pulse length, high-peak power amplifiers which could provide enough energy to fill the cavity to field levels comparable to or exceeding the critical fields in a short time. At SLAC the necessary RF sources are available for high power tests and the outcome of the measurements is of interest for possible practical applications to the existing pulsed accelerator.

The measurements presented here are an outgrowth of some early tests which indicated that fields considerably higher than those obtained with cw could be reached in a Nb cavity by using short pulses and strong coupling.[14] Since then the program has been extended and currently it is directed at testing cavities manufactured out of various superconducting materials in order to compare their behavior against the known cw properties, and at developing actual structures and devices which could be of practical interest in pulsed accelerators.

The Pulsed RF Measuring System and Apparatus

To obtain sufficiently high fields in a cavity in a short time, a strong coupling is necessary. In order to transfer the maximum energy from the incident RF pulse into a cavity operated in the reflection mode, one must satisfy the condition ($\beta \gg 1$):

$$Q_e \simeq 2.5\, f\, T_p \qquad (1)$$

where Q_e is the external Q of the cavity, f is the resonance frequency and T_p is the pulse length. This condition guarantees that about 80% of the incident pulse energy will be transferred to the cavity by the end of the pulse provided that during the pulse the losses are negligible.[54,15] This is true in the case of a superconducting cavity with $Q_0 \geq 10^7$. The ratio between the energy dissipated during the pulse and the energy stored at the end of it is of the order of $Q_e/Q_0 = 1/\beta$. For our system $f = 2856$ MHz, 1 $\mu s \leq T_p \leq 2.5$ μs and $Q_e \sim 10^4$, so that the error made by neglecting the losses in the estimate of the energy stored in the cavity is of the order of 10^{-3} or less.

To determine the fields existing in the cavity at the end of the charging pulse it is necessary to know the energy stored in it:

$$H_s = k\sqrt{U} \qquad (2)$$

where U is the energy stored and k is a cavity-dependent constant, which can be obtained by computation. One possible way to determine U is by means of a transient measurement: these types of measurement are difficult to perform and there are often discrepancies between values obtained from one pulse to the other. At SLAC we have adopted an average power measurement method which provides automatically a statistical averaging and gives the field levels in the cavity with a typical error of ±1%.[15]

The method consists of integrating the emitted power decaying as a function of time from the cavity, using an average power meter and a properly positioned PIN diode modulator gate (Fig. 2 and Fig. 3).

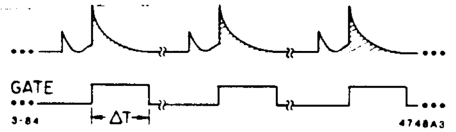

Fig. 2. The integrated emitted power (shaded area) gives, for low losses, the energy stored at the end of the RF pulse. The integration is performed by an average power meter.

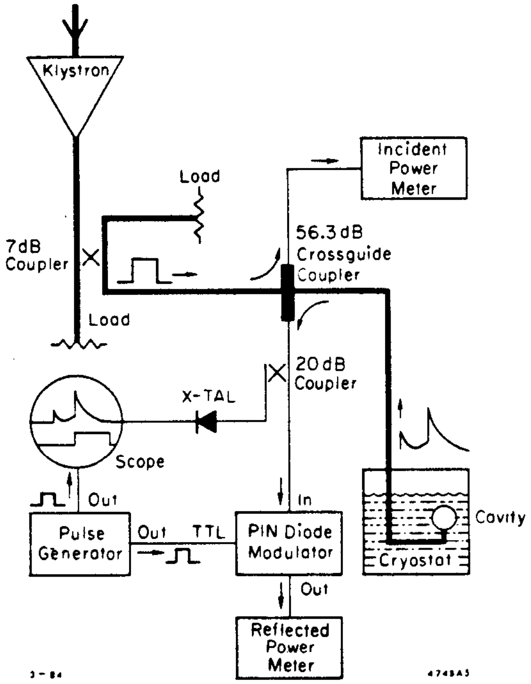

Fig. 3. Schematic of the system used for pulsed RF measurements. The power emitted from the cavity is sampled by a cross-guide coupler and separated from the reflected power using a properly gated PIN diode modulator.

The fields can then be determined as

$$H_s = k\sqrt{\frac{P_e}{f_r}} \qquad (3)$$

where f_r is the pulse repetition frequency and P_e is the average integrated emitted power. Apart from the error in timing the gate of the PIN diode modulator this method only has errors deriving from the measurements of the attenuation of the line between the cavity and the power meter. As long as the cavity has small losses ($Q_o \gg Q_e$) the determination of the fields in the cavity is extremely simple and requires the measurement of only one quantity, the average emitted power.

By plotting the average emitted power (proportional to the emitted energy, in turn proportional to the stored energy in the low-loss case) versus the average incident power (proportional to the incident peak power) graphs like the one shown in Fig. 4 will be obtained. These graphs are extremely compact and provide a greater amount of information about the breakdown field level than that obtained through other methods.

Because the cavities are so heavily coupled the breakdown cannot be determined by a slight decrease in Q_0, as is done in the cw case. Here small changes of Q_0 cannot be observed by looking at the decay curve, so that only when Q_0 is less than approximately 10^5 the change can be detected. One way to locate the level of the onset of RF losses in the cavity at 4.2°K consists of observing the increase in the boil-off rate: our system allows us to measure an increase of dissipated power of about 15 mW. This method has various sensitivities depending on the repetition rate: for the best conditions a drop in the average Q_0 of the cavity below the 10^8 level can be detected. It should be stressed that this method only allows a measurement of the average Q_0 during the pulse, so that it is not known how Q_0 varies as the field increases and decreases in the cavity.

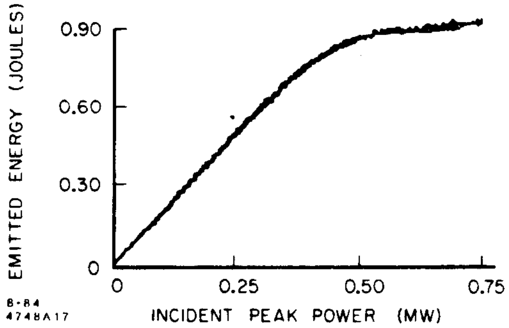

Fig. 4. Raw data for a test on a Nb cavity, the emitted energy (proportional to the reading of the emitted power meter) is plotted against the incident peak power (proportional to the reading of the incident power meter). The deviation from linearity is taken as the indication that the critical field is being exceeded at the cavity surface.

Another method used to determine the fields in the cavities makes use of a linear receiver to measure the transmitted field as a function of the incident power level. This method is accurate but it requires several independent measurements in order to pinpoint the breakdown level.

The final method determines the breakdown field from the level at which the emitted power curve of Fig. 5 deviates from linearity. This deviation from linearity is taken as the signal of increased losses. It should be stressed that all the other methods lead to slightly higher values of the breakdown fields, including those obtained with the boil-off method, which sets a limit on the range of applicability of the pulsed power technique in terms of thermal loads into a real refrigerator, and with the transmitted power method, which gives peak field readings useful for fundamental investigations of fields at the surface of superconductors.

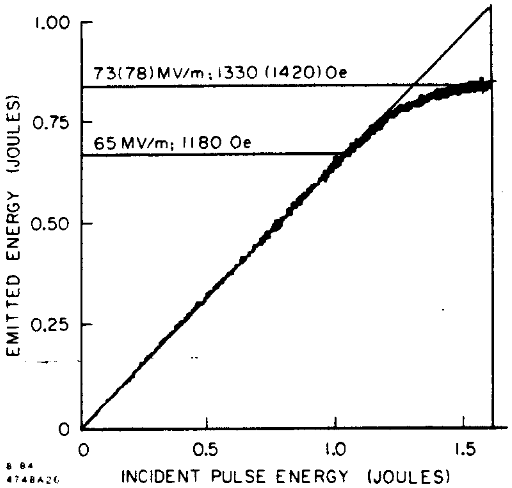

Fig. 5. Determination of the breakdown level in a *Nb* cavity operated under pulse conditions. The lower horizontal line indicates the highest fields reached without losses. The upper horizontal line gives the fields reached under breakdown conditions by taking (values in parentheses) or not taking into account the losses. Similar curves have been obtained for cavities of different geometries, various materials, at various temperatures and for several pulse lengths and repetition rates.

Tests on the *Nb* Cavities

Four *Nb* cavities were tested with the pulse method at SLAC.[15] The cavities were also tested in cw. The results of the cw tests indicated that the surface conditions greatly varied from cavity to cavity, since a wide spectrum of breakdown field levels was observed from 80 *Oe* up to about 450 *Oe*. These values were not particularly good compared to the state-of-the-art results, but the cavities had not undergone any particularly sophisticated surface treatment, and surface defects such as welding beads were clearly present in some of them. One of the best cavities was also subjected to an Indium removal treatment after the test and then retested: the breakdown field had degraded from about 450 *Oe* down to about 220 *Oe* and instead of a quench a gradual Q_0 degradation was observed as the cause of breakdown. On the contrary, the tests performed with short pulses gave extremely uniform results with fields ranging from about 1100 *Oe* up to 1300 *Oe*, depending on the cavity and on the pulse length. Repetition rate (up to 360 pps) and temperature (from 4.2°K down to 1.4°K) did not seem to have a measurable effect on the values of the breakdown fields.

The degradation of performance initially seemed to be correlated with the onset of x-rays, so that it was thought that field emitted electrons could have been the cause of indirect heating of the surface above a certain field level. A more careful analysis indicated that various cavities had totally different x-ray emitted intensity varying over two or three orders of magnitude, so that field emission alone could not be the cause of breakdown.

The independence of the breakdown field from temperature below 4.2°K suggests that there must be some heating mechanism which acts very quickly, so that the inner surface of the cavity warms up to a common value irrespectively of the external bath temperature. At present it is not clear whether this heating is fundamental in nature or if it is inherent in the system and can be eliminated by a proper design.

Tests on the Lead-plated Copper Cavities

Preliminary tests of two lead-plated copper cavities have been performed recently. The cavities were coated with 6 μm and 15 μm thick layers of lead respectively. It should be stressed that the cavities were only electroplated and that no further processing of the surface was performed. This was not the case in the earlier measurements on lead: field levels close to the superheated fields were reached only for the best polished cavity surfaces.[11]

The results of the measurements show that at any temperature in the range 1.5-7.2°K the fields that can be reached without an increase in the losses are very close to the superheated field. This is true for a pulse length of 2.5 μs, while for a 1 μs pulse length even the superheated field seems to be exceeded without losses.[55] It is not clear whether this effect is real or due to the insensitivity of the measuring method to the actual breakdown level. For practical applications the highest field of interest is the one that can be reached without an increase of the thermal load into the refrigerator: whether or not that particular field level is consistent with the theoretical expectations is not of primary importance. In any case theories exist which might explain the observed surpassing of the superheated fields for a short time.[56,57]

These preliminary results indicate that uniformly high fields can be reached in cavities with different *Pb* thicknesses with a well controlled and relatively simple deposition technique.

One clear advantage of the lead on copper technology is that when new materials become available, possibly with higher T_c or H_c, or new deposition techniques are developed, the existing copper structures for accelerators could be stripped and recoated without a large investment in materials and fabrication.

Other Materials

A major interest lies in Nb_3Sn, both for the high critical temperature and the theoretically high critical fields. A collaboration between SLAC and the University of Wuppertal, West Germany is under way to test the behavior of some *Nb* cavities fabricated at SLAC and coated with Nb_3Sn at Wuppertal.

Preliminary results indicate that the maximum fields that can be reached are essentially the same as for *Nb* (1200-1300 *Oe*) even at lower temperatures. This seems to indicate a saturation observed also in *Nb*, which could be due to some unforeseen problem in the coupling system, rather than to a fundamental property of the two materials. Although the limit of 1300 *Oe* has not yet been exceeded, almost the same field can be reached in the Nb_3Sn cavity at 11°K : this result makes practicable the operation of superconducting cavities at temperatures higher than 4.2°K .

Another material to be tested in the near future is a $Pb-Sn$ alloy which is being used at Stony Brook in the heavy-ion superconducting accelerator.[50] This material seems to be simpler to deposit on copper and it may be of technological importance for practical applications. Since no data are available on the critical field of this alloy, the possibility exists of characterizing it for the first time without bias from cw or dc measurements.

Tin is another material to be tested soon: it has been studied extensively[10,11] so that a comparison with other data will be possible. Its superheated critical field should be much larger than the thermodynamical field (~2.5 times), so that it will be very clear which limiting field can be reached. Both critical fields should be at a level lower than that which seems to be the saturation field for our system, so that spurious effects from the coupling are not expected. Moreover, as the critical temperature of tin is lower than 4.2°K , much more reliable temperature measurements are possible by operating in a bath rather than in vapor, was done for *Pb*, *Nb*, Nb_3Sn to study the properties of the limiting fields all the way to the critical temperature.

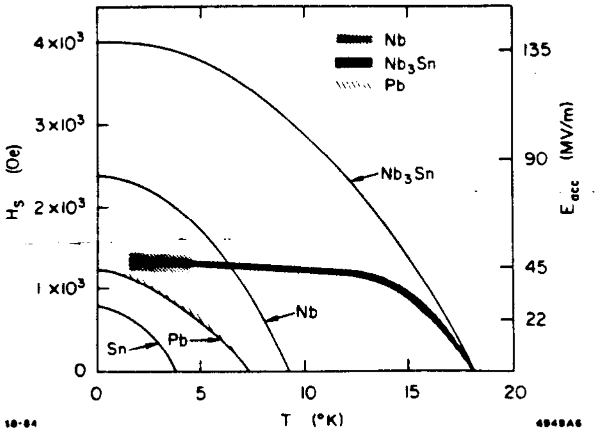

Fig. 6. Experimental breakdown fields reached in pulsed operation. The solid lines indicate the theoretical superheated fields for the given materials; for simplicity the Ginzburg-Landau parameter is assumed to be constant. The area under the *Nb* region represents several tens of measurements performed on several cavities and various repetition rates and pulse lengths. Two lead cavities were tested and the curve for Nb_3Sn represents the data for a single cavity. The scale on the right represents the average accelerating gradient attainable in a travelling-wave structure.

Features Derived from Pulsed RF Measurements

The tests so far performed on superconducting cavities indicate that the typical properties which are important for cw operation are not crucial under pulsed conditions.

Multipacting does not constitute a problem in pulsed operation, because the typical multipacting field levels are exceeded too quickly for the resonant phenomenon to build up or to subtract enough energy from the fields.

Field emission still exists in pulsed operation, but the varied amount of *X* radiation emitted by different cavities with similar breakdown fields indicates that it cannot be solely responsible for the breakdown field levels observed.

One of the benefits of the pulse method is that RF processing (elimination of the field emission sources through the application of RF power) is much more effective and faster than in cw; in the latter case small increases of power over a long time are necessary in order not to load the cavity, whereas with pulses electron loading is not a limitation and a few seconds of increased power seems to eliminate the majority of the field emitters. Even when the cavity is normal, the field level in it can still be increased and the field emission sources eliminated well beyond the possible cw field operating levels.[30]

Surface defects, surface finish and surface conditions do not greatly affect the performance of cavities operated with short pulses.

Thermal conductivity should not be important in the pulsed operation as it is in cw since the typical times over which heat is created within the pulse are much shorter than the total thermal relaxation time of the system, including thermal boundaries. The heat capacity of a thin layer of the cavity interior should be important as far as limiting the temperature rise during the fast pulse.

The fact that the results obtained in the pulse mode were uniform and that the fields were consistently higher than those reached in cw has two implications: the first is that the properties that are being tested through short pulses are not the same as those tested in cw so that a new way of looking at superconductors is opened by this method. The second is that common minimal results can be obtained without excessive development efforts, so that technological applications should be possible on an extended scale without unpleasant surprises and at moderate cost.

APPLICATIONS OF PULSED RF SUPERCONDUCTIVITY

Schemes are under study by which pulsed RF superconductivity could be applied to particular accelerator systems, thereby both improving the average accelerating gradients and significantly decreasing the average power consumption even with the refrigeration costs taken into account.[58] In particular, a scheme exists[17] which would improve the performance of an accelerator similar in type to the Continuous Electron Beam Accelerator Facility planned by the Southeastern Universities Research Association.[59] Studies are still needed to investigate in detail for how long a flat high-power RF pulse, necessary for the accelerator operation, can be maintained at the surface of a superconductor.

Other possible applications of these pulsed RF superconducting structures include the construction of lossless delay lines which could be used to multiply by pulse compression the peak power of existing high power, pulsed RF sources. The almost lossless structure in this scheme allows true peak power doubling which is impossible to achieve through normal conducting structures with pulse lengths of 1 μs or longer.[60]

One scientific application that comes to mind is the study of the dynamical behavior of superconductors close to the critical field: at this frequency (~3 GHz) very few data exist which are not masked by the interference of surface effects.

CONCLUSIONS

The potential of pulsed RF superconductivity is still far from being fully appreciated.

The uniformity of results, independent of the surface conditions, suggests that the method is able to test properties of superconductors other than those which can be studied with cw techniques. From this point of view it might be important to correlate certain features of the pulsed results to those of the cw measurements to complete the picture of the properties of superconducting RF cavities and of superconducting materials under the influence of RF fields.

The question of whether pulsing or not pulsing is better for RF superconductivity cannot be answered at present. There are applications in which the low surface resistance of the superconductors is more important than the fact of reaching the critical fields.

The relative simplicity with which pulsed results can be obtained should constitute an incentive to investigate practical applications of this technique, which does not require the highly expensive refrigeration systems necessary for the cw operation.

Rather than answering the question of whether it is better to pulse or not to pulse to obtain high fields in superconductors, it is perhaps more useful to ask more questions which could lead to the application of this method to the study of the properties of superconductors and to the design of systems for high-gradient linear accelerators.

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