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SUPERCONDUCTORS FOR PULSED RF ACCELERATORS*

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INTRODUCTION

The choice of superconducting materials for accelerator RF cavities has been determined in the past only in part by basic properties of the superconductors, such as the critical field, and to a larger extent by criteria which include fabrication processes, surface conditions, heat transfer capabilities and so on.[1] For CW operated cavities the trend has been toward choosing materials with higher critical temperatures and lower surface resistance, from Lead to Niobium, from Niobium to Nb_3Sn. This trend has been dictated by the specific needs of storage ring CW system and by the relatively low fields which could be reached without breakdown.

The work performed at SLAC on superconducting cavities using microsecond long high power RF pulses has shown that in Pb, Nb, and Nb_3Sn fields close to the critical magnetic fields can be reached without magnetic breakdown.[2] In Table 1 and Fig. 1 the major results of the tests on the three technical superconductors are illustrated. From these measurements comes the demonstration that for sufficiently short pulses there is no specifically predetermined critical field, and it is possible to exceed, depending on the material, even the superheated critical field.

Table I. Maximum instantaneous fields reached with low losses. The temperature indicated is the highest for which the field value was reached. A saturation process, yet to be explained, makes the fields almost constant below the given temperature (see Fig. 1). The accelerating gradients are computed under the assumption that they can be maintained over a suitable length of time and should be understood as upper limits. (SW= Standing Wave, TW= Traveling Wave).

Material	$H(T)$ (Oe)	$T_{\max}$ (K)	$E_a(SW)$ (MV/m)	$E_a(TW)$ (MV/m)
Pb	1175	1.4	25	38
Nb	1330	4.2	29	43
Nb_3Sn	1200	11	26	39

These results have led to considering the possibility of applying pulsed RF superconductivity to systems suitable for high-energy pulsed electron accelerators, such as in low loss accelerator structures[3] or delay lines for efficient power multiplication by means of pulse compression.[4]

The new picture of the short-pulse, peak field properties of the superconductors tested so far, together with the special needs of the pulse power superconducting systems, has led us to reevaluate the parameters of superconducting cavities which are of importance in this context and to reconsider which material would be best suited for pulse power applications.

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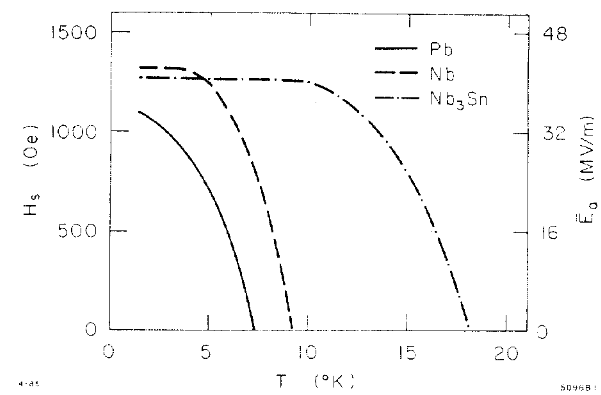

Fig. 1. Temperature dependence of the pulse breakdown fields for the superconductors indicated. A large degree of superheating is observed in Lead, some in Nb, none in Nb_3Sn. The accelerating gradient is for a traveling-wave structure.

CAVITY PARAMETERS

The most important parameters which are used to characterize the properties of accelerator cavities are the average accelerating gradient and the fraction of the stored energy that is dissipated in the cavity walls.

The Accelerating Gradient.

The maximum accelerating gradient in a superconducting cavity is limited by the corresponding maximum surface magnetic field which can be sustained by the superconducting material without increased losses. Typical standing wave cavities have a ratio of H/E_a=45 Oe/MV/m, whereas traveling wave structures can reach H/E_a=31 Oe/MV/m.

The question of the maximum attainable gradient seems, at first sight, easy enough to answer, since the critical magnetic fields of many superconductors have been known for a long time. This is actually not the case, for the following reasons: First, the behavior of superconductors in RF fields of amplitude comparable to the critical fields is not well understood and experimental results indicate that the ultimate limits strongly depend on the time scale over which the fields are maintained. Second, CW RF superconductivity must contend not only with the fundamental properties of the materials, but also with the less predictable and harder to control properties of the cavity surface, its impurities, defects, chemical and physical conditions, *etc.* These effects limit the maximum attainable fields, and make the choice of the proper material more complex, because the superconductor's properties per se do not necessarily determine the overall performance of the cavity. For instance, type I and type II superconductors have been employed thus far with similar results and the characteristics of the thermodynamic or superheated fields have made little or no difference in the performance. The gradients now available (about 10 MV/m) are more than adequate for most accelerator

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applications, especially for CW circular machines, in which low RF losses constitute the most important attraction of superconductivity.[5]

For pulse applications the situation is different: The high field properties of the superconductors do play a major role in the selection of the materials to be used under pulsed conditions. As discussed by Halbritter[6] and experimentally observed at SLAC,[7,8,9] the peak field properties of each material can be clearly distinguished from those of the others.

The ultimate field limits have not been completely determined even by using the pulse technique, but it is clear from the measurements that a higher degree of superheating is observed in Pb[9] (a type I material) than in Nb[7] (moderately type II) and no superheating is observed in Nb_3Sn[2] (extreme type II).

In pulsed RF superconductivity one must assess the ability to reach high gradients based on considerations other than those so far used to obtain low losses. For instance, the fabrication tolerances necessary for cavities used with short pulses are much less stringent than for CW cavities, since the external coupling factor is much higher under pulsed conditions and the bandwidth is larger; the superconductors could be deposited on substrates that are either less expensive or easier to machine, and the quality of the current-carrying surfaces need not be as finely controlled as in the CW case.

Unlike the CW operation, the pulsed technique differentiates more sharply among materials based on the critical field properties, so that the maximum gradients become the most important parameter in choosing the material to be used.

Losses

The losses in RF cavities can be alternatively characterized by the unloaded quality factor Q_0 or by the unloaded time constant, defined as

$$T_0 = \frac{2U}{P_d} = \frac{2Q_0}{\omega} \qquad (1)$$

where U is the stored energy and P_d is the power dissipated. In pulsed superconductivity, it is more convenient to use the unloaded time constant, since it can be compared directly to the other relevant characteristic times of the system.

In CW operated superconducting cavities, a decrease in the losses has the important effect of proportionally decreasing the heat load to the refrigeration system and increasing the operating gradient. In the pulsed case the internal time constant can drop by several orders of magnitude, even within a pulse, without adversely affecting the operation of the system, as long as the average refrigeration power requirements do not increase significantly. The small duty cycle usually enables the cavity to recover between pulses even if T_0 varies from, say, 10,000 μs down to 100 μs or so, as long as the cavity is still superconducting. If a fraction of the cavity surface should become normal, it is still possible to choose operating conditions which would put a limited load on the refrigeration system. Fig. 2 shows that operating field levels can be chosen, at least in liquid Helium, such that they can be maintained even though a slight increase in the losses is observed.

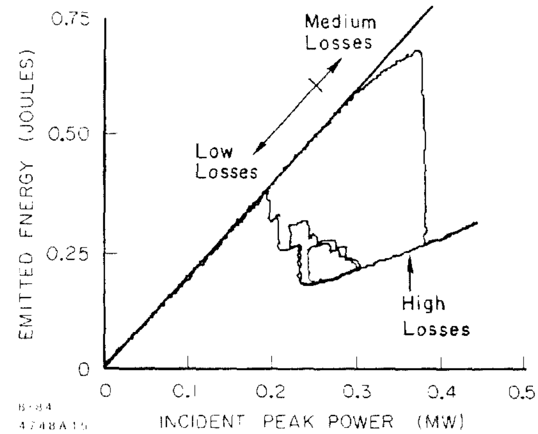

Fig. 2. Emitted energy U_e versus incident peak power for a cavity operated in the pulse mode. The peak magnetic field is H_s (Oe)=$1440\sqrt{U_e\ (\mathrm{J})}$. The fields in the cavity can still be increased in the medium losses region, which is not possible in CW superconductivity. In that region, superconductivity is recovered from pulse to pulse.

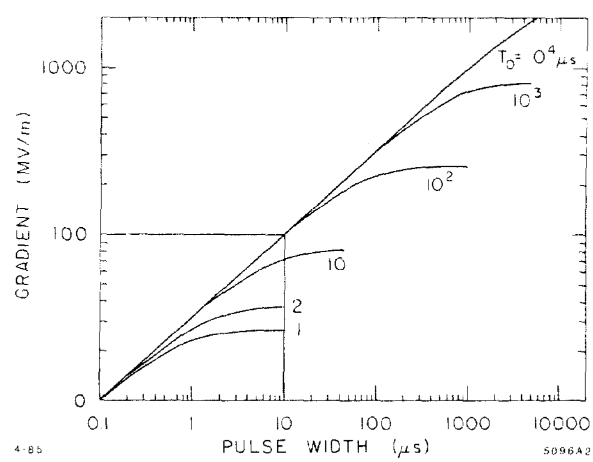

Fig. 3. Average accelerating field for a TM_{010} cavity resonating at 2856 MHz. The input power is fixed at 1 MW. Normal conditions of operation are in the lower left corner, where there is no decrease in field amplitudes, as long as $T_0 > 100$ μs.

Other Considerations

The roles of the critical field and of the losses are somewhat reversed in CW and in the pulse case: whereas in CW one can accept a compromise in lowering the operating field level well below the critical one, as long as the losses are as low as possible, in the pulsed case one can operate at relatively low internal time constants without compromising the maximum attainable field. This fact is illustrated in Fig. 3: for a given input power (in this case 1 MW), for field levels in the neighborhood of those that have been instantaneously reached in single-cell test cavities, and for pulse lengths which are available in high power RF systems, even a sharp drop in T_0 still allows one to reach the highest gradients possible. The reason for this lies in the fact that the efficiency with which the field builds up in a superconducting cavity starts to decrease significantly only when the internal time constant decreases below the value of the pulse length. For a TW section the accelerating gradient is given by the equation

$$E_a = \sqrt{\frac{\eta_s s P_o T_f}{L}} \qquad (2)$$

where

η_s = section efficiency = $1 - (T_f/T_0)$ for $T_0 \gg T_f$
s = elastance per unit length (MΩ/μs/m)
P_o = power input into the section (MW)
T_f = section fill time (μs)

This equation implies that if the efficiency is held constant by fixing the ratio T_f/T_0, then an increase of filling time requires a decrease of the losses to maintain the efficiency unchanged. This is true from the microwave engineering point of view, whereas the physical properties of the superconducting cavities make the losses increase with increasing filling time. Then for each superconductor an optimum ratio T_f/T_0 must exist which maximizes the efficiency. Such ratio will have to be determined experimentally. In any case, it is not advantageous to increase the filling time beyond T_0 because the increase in gradient is only marginal. Under these conditions, the accelerating field is proportional to the square root of T_0 which, for a superconducting section, is proportional to the improvement factor.

CHOICE OF MATERIALS

The question of the appropriate pulse length in pulsed RF superconductivity is not just a matter of microwave parameters or accelerator properties. The physics of the superconductor and other phenomena determine the choice of the length of time over which the RF can be sustained. It is not as yet clear which optimal pulse length should be used for each material, but from the experiments it appears that the pulse length does affect the maximum fields even at the microsecond time scale. How these fields depend on the pulse length is very difficult or impossible to predict. Tests in this direction will be performed in the near future using transmission cavities, but already by using the existing data it is possible to predict a set of operating conditions and make a choice of suitable materials.

The RF sources available at high power have pulse lengths of up to 5-10 μs, depending on the peak power. The operating conditions in Fig. 3 are therefore limited to the region to the left of the abscissa $T_p = 10\ \mu$s. On the other hand, the highest gradients which can be reached are around 50 MV/m or less, with theoretical expectations as high as 100 MV/m. As shown in Fig. 3, the gradients under consideration can be reached only with a superconductor for the given input peak power, whereas a much higher power would be needed to reach it with a normal conducting structure ($T_0 = 1\ \mu$s).

The losses in the material are of minor importance, since at that field level (50 > MV/m) all the curves for $T_0 >$ 100 μs coincide. Therefore the choice of the material must be dictated by the economy of construction and by the refrigeration efficiency. From the latter point of view the obvious choice is Nb_3Sn, because it can be used at high temperatures (T = 10 K) in vapor and at high field. Although the technology of Nb_3Sn does not always guarantee uniformity of results, this does not seem to affect the pulsed performance almost at all.

An easier approach from the point of view of technology consists in building structures for pulsed RF superconductivity with a lead-plated substrate, which need not be copper, since the thermal conductivity is of marginal importance in this case. Lead can just be plated without any further processing, even on relatively complicated surfaces and the substrate could be built with conventional methods used for manufacturing copper structures, rather than with the more complicated techniques employed in superconducting cavity construction.

To illustrate this point, we can consider building a low loss delay line, suitable for pulse compression and power multiplication, out of cylindrical waveguides of an appropriate length and possibly folded to make the delay line more compact. For a structure of this sort, the power-carrying capabilities depend on the surface magnetic field H as[10]

$$P\ (\text{MW}) \simeq 4700\ \text{H}^2\ (\text{kOe}) \qquad (3)$$

for a 10 cm diameter TE_{11} waveguide operating at 2856MHz. Power levels as high as several gigawatts could be handled with low losses even by a lead-plated waveguide which would be easier to construct than one built out of Niobium.

From the above example it appears that Niobium, so far the favorite material in RF superconductivity and accelerator cavity construction, is probably the least attractive for applications in pulsed RF systems. Materials with a smaller Ginzburg-Landau parameter seem to be favored for pulsed applications, as the tests performed at SLAC indicate.

CONCLUSIONS

Practical systems can be built out of superconductors for various uses in high energy pulsed linear accelerators using existing technology. For the pulsed case less stringent tolerances and manufacturing methods are needed than for CW, which makes the use of pulsed systems attractive. The criteria used in the choice of superconducting materials are also different from those used in evaluating CW systems.

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