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A SUPERCONDUCTING Nb_3Sn COATED MULTICELL ACCELERATING CAVITY

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Abstract

We report on the first results, obtained with a five cell Nb_3Sn coated accelerating structure of 3 GHz. A uniform layer of Nb_3Sn was formed by processing a niobium structure in a tin atmosphere at 1170°C. At 4.2 K a resonator Q of $7 \cdot 10^9$ was measured. This corresponds to a residual surface resistance of 27 nΩ which is the lowest ever achieved with a Nb_3Sn cavity in the GHz range. The rf losses of this resonator are by a factor of 55 lower than those of an equivalent niobium cavity at 4.2 K. The maximum accelerating field at this temperature was 4.0 MV/m. It is similar to the quench field of the niobium structure before coating. The spatial distribution of the rf losses was measured at different field levels using the temperature mapping technique. We describe the characteristic features of the Nb_3Sn layer, we report on residual losses specific to Nb_3Sn coated niobium structures and we discuss the observed field limitations.

Introduction

Up to now niobium, the element with the highest critical temperature (T_c=9.2K) and the highest thermodynamic critical field (B_c=196 mT) is most frequently used for the construction of superconducting accelerating cavities.
Because of its high critical temperature (T_c=18.2 K) and its high thermodynamic critical field (B_c=535 mT) the A15 compound Nb_3Sn has gained attention as an alternative material. It should allow accelerating fields which are two times higher than those of niobium and it should show specifically a surface resistance which is about 150 times lower than the one of niobium. The high accelerating fields should therefore be obtainable at a low rf power already at 4.2 K. These promises make Nb_3Sn an interesting material for the very large superconducting linacs of future Linear Colliders [6] and also an economic choice for the realisation of Free Electron Lasers with energy recovery.
Most of the experimental work with Nb_3Sn cavities has been carried out at frequencies between 8 and 10 GHz[1-3] and improvement factors of the surface resistance between 40 and 70 have been measured at 4.2 K. The margin surface magnetic field of 89 mT reached at 10 GHz [2] is still lower but already comparable to the best results obtained with equivalent niobium cavities.

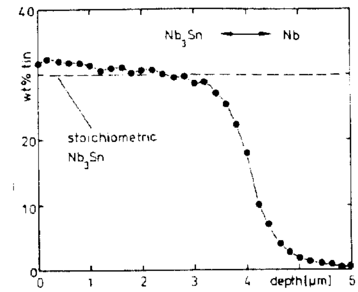
For the superconducting 3 GHz Recyclotron under construction at DARMSTADT (West Germany) [5], niobium five and 20 cell accelerating structures will be used at an operating temperature of 2 K in the first step. In the frame of this project investigations of single and five cell Nb_3Sn cavities at 3 GHz have been carried out and the first results of this work are reported in this contribution.

Experimental

For the fabrication of the Nb_3Sn structures the vapor diffusion technique including a prenucleation with $SnCl_2$ [2] was applied. The niobium cavities have been manufactured out of 2 mm sheet material of standard purity and have been tested several times before coated with Nb_3Sn. The coating procedure itself was carried out in a vacuum furnace in which the tin pressure can be adjusted independently of the cavity's temperature. As a result uniform Nb_3Sn layers of about 5 μm in thickness could be formed both on single and on five cell niobium cavities. A description of the coating procedure is given elsewhere [7,8]. In Fig. 1 a depth profile of a Nb_3Sn layer on a niobium sample which was tin processed together with a five cell structure is shown. The measurement was carried out using energy dispersive X-ray analysis in a scanning electron microscope of 0.2 μm resolution at CERN. The tin amount near the surface slightly exceeds that of stoichiometric Nb_3Sn but is still below the upper limit of the stable Nb_3Sn phase [9]. It is observed that removing the first 0.5 μm of the Nb_3Sn surface by oxipolishing [17] significantly reduces the residual rf resistence of a Nb_3Sn layer. Therefore, all cavities were oxipolished by this amount, rinsed with demineralized and filtered water and dust-free methanol before they were mounted to the test system.

Fig. 1:

Depth profile of the Nb_3Sn layer on a niobium sample which was treated by the vapor diffusion process together with a five cell cavity.



The superconducting structures were tested with standard techniques in an ambient magnetic field below 30 mOe. The rf parameters of the cavities are given elsewhere [10]. The spatial distribution of the rf losses was determined using the temperature mapping technique in subcooled helium [18]. In the case of the five (single) cell cavity the temperature signals of the outer cavity wall are detected with 11 (17) carbon resistor thermometers per cell rotating along the azimuth of the spherical cells. The conversion of the temperature signals into a heat flux density $\dot{Q}$ is carried out by a calibration described in ref. 11. In general the accuracy of the measured $\dot{Q}$ maps is better than ± 20 %.

Results and discussion

Up to now first experiments with one five cell and two single cell cavities (at 3 GHz) have been carried out. In both of the single cell cavities a Q of $4 \cdot 10^9$ and a maximum accelerating field of E_a=7.2 MV/m, corresponding to a maximum surface magnetic (electric) field of B_p=30 mT (E_p=18 MV/m) were measured at 4.2 K. In the five cell cavity a maximum accelerating field of 4.0MV/m was obtained in the π-mode. The Q value of this cavity was $7 \cdot 10^9$ at 4.2 K which corresponds to a residual resistance of 27 nΩ. In all cases the fields were limited by local thermal instabilities on the rf surface. The maximum fields of all cavities were independent of temperature between 4.2 and 1.8 K and comparable to those obtained in the niobium resonators before they were coated with Nb_3Sn. The dependence of the residual losses on the cool down cycle, the field dependence of the residual losses and the thermal instabilities observed have been studied using for the first time the technique of temperature mapping on superconducting Nb_3Sn cavities.

The surface resistance of Nb_3Sn:
The analysis of the temperature dependence of the surface resistance $R_s(T)$ measured in the five cell cavity between 1.8 and 4.2 K shows that the residual resistance R_{res} is constant in this range. The

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temperature dependent part $R_{BCS}(T)=R_S(T)-R_{res}$ agrees well with the theoretical expectations based on the BCS theory [4]. Because of the low R_{res} the surface resistance of superconducting Nb_3Sn could be determined rather accurately to $R_{BCS}=15\pm3n\Omega$ at 3 GHz and 4.2 K. Typical Q versus accelerating field curves of a single and the five cell cavity measured mostly at 2.2 K are shown in Fig. 2 and Fig. 3 respectively. Since $R_{BCS}(2.2K)$ of Nb_3Sn is only about $2\cdot10^{-12}$ Ω, these curves describe the field dependence of $R_{res}=G/Q_{res}$ ($G = 290$ Ω). The curves exhibit two features of Q_{res}: a dependence on the cool down rate of the cavity and a considerable degradation with increasing field.

Alternative to the commonly used "fast cool down" to temperatures below the T_c of Nb_3Sn by filling liquid helium into the cryostat, the cavity temperature was reduced very slowly (≈ 1 K/5 min) in the range between 20 K and 15 K with a technique, described elsewhere [7]. Both in the single and in the five cell structure the slow cool down resulted in a significantly increased residual cavity Q (Fig. 2 and 3). The reproducibility of this effect was demonstrated in many experiments. As seen from $\dot{Q}$ maps (Fig.4) the additional losses are uniformly distributed over the cavity surface. The spikes in the measured heat flux density are caused by local defects. Their rf losses are independent of the cool down rate. Analysing the uniform losses displayed in fig.4 further one observes that these uniform losses after a fast cool down are not only higher than after a slow one but they also are within errors proportional to each other. This indicates that a significant part of the residual resistance is caused by a cool down dependent mechanism and is not negligable even after the slow cool down practiced in our experiments. Up to now the origin of these losses is not clear. At present it is assumed, that magnetic flux, generated by thermoelectric currents in the Nb_3Sn-Nb interface and frozen in during the transition into the superconducting state of Nb_3Sn, is responsible. Similar effects have been observed in Pb coated Cu cavities [13,14].

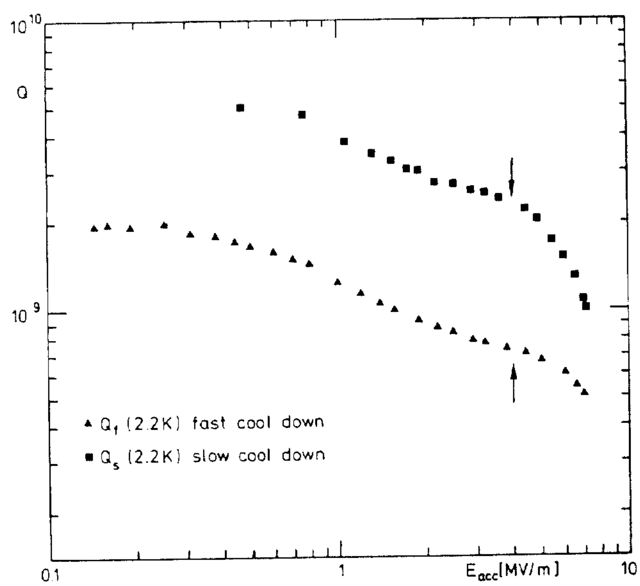

Fig.2: Plot of Q versus accelerating field of a Nb_3Sn coated single cell cavity after different cool down cycles.
Fast cool down: 77 K → 4.2 K, fast (by filling liquid helium into the cryostat)
Slow cool down: 20 K → 15 K, slow (≈1 K/5 min); 15 K → 4.2 K, fast
Above E_{acc} ≈ 4 MV/m electron field emission loading was observed (indicated by the arrows).

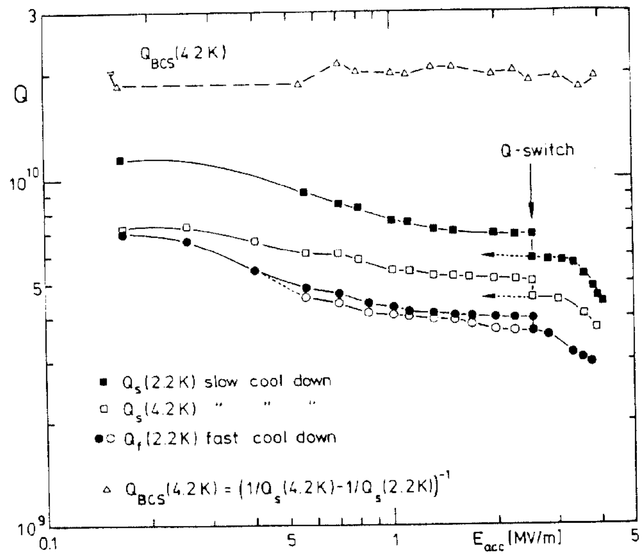

Fig.3: Plot of Q values of a five cell Nb_3Sn coated cavity as a function of the accelerating field. The hysteresis in the curves results from a Q-switch which appeared at E_a = 2.6 MV/m and disappeared far below the switching field.

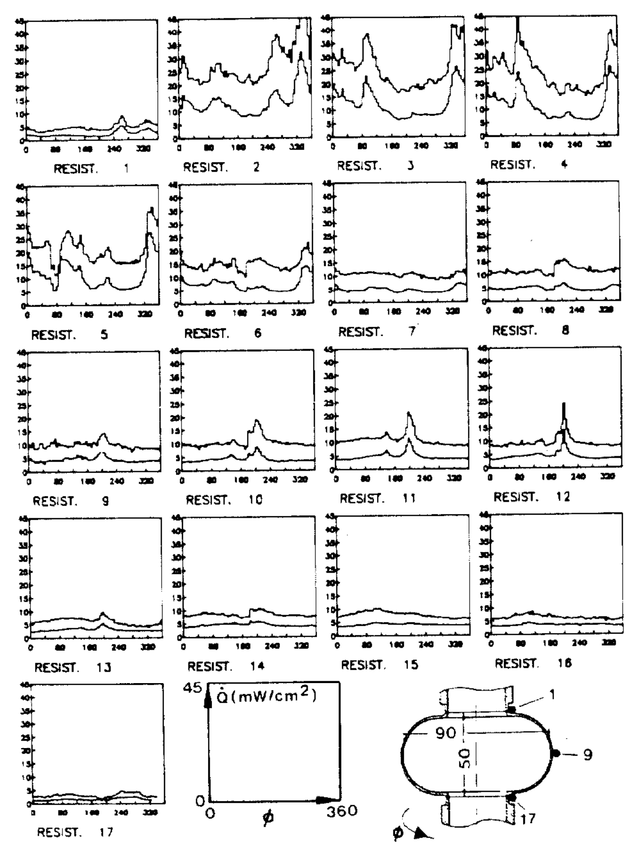

Fig.4: Spatial distribution of the rf losses in a single cell cavity after a slow cool down (lower curves) and after a fast cool down (upper curves), documented with 17 carbon resistors rotating on the outer cavity wall along the azimuth in subcooled He at 2.2 K. In both cases the accelerating field is 7 MV/m.

The reduction of Q with increasing field not only observed in Nb_3Sn cavities is of great practical importance. After analysing the field dependence of the measured rf losses one comes to the following conclusions:

1. Only the residual losses depend on the field level. (see Q_{BCS} plotted in fig.3)
2. The residual losses after the fast and the slow cool down have the same field dependence (this is seen from the equality of slopes of the corresponding Q versus E_a curves in fig. 2 and 3
3. From all these observations on rf losses in s.c. cavities coated with Nb_3Sn we conclude that the cool down dependent residual losses are of a significant importance and need further studies.

Weak spots in Nb_3Sn cavities: For accelerating fields above 2 MV/m one observes anomalous losses in addition to those discussed in the preceeding chapter. One notices for one non-resonant field emission loading (above E_a = 4 MV/m) like in other s.c. cavities [16].More specific to Nb_3Sn cavities are sudden increases in the rf losses at well defined fields [1] ("Q switches"). Fig.5 shows temperature maps of the five cell cavity at fields below and above such Q switches. It is clearly seen that small, maybe microscopic, regions of the cavity surface switch to a high loss state at a given field. We assume this to be a transition from the superconducting to the normal conducting state. The switching fields do not depend on temperature in the range between 2.2 and 4.2 K. From this we conclude that these weak superconducting spots have critical temperatures well above 4.2 K. One explanation is given by the existence of impurity inclusions in the niobium base material which disturb the uniform Nb_3Sn layer and which become weak superconductors by the proximity effect. The use of high purity niobium, which now is commercially available, is therefore planned as a next experimental step.

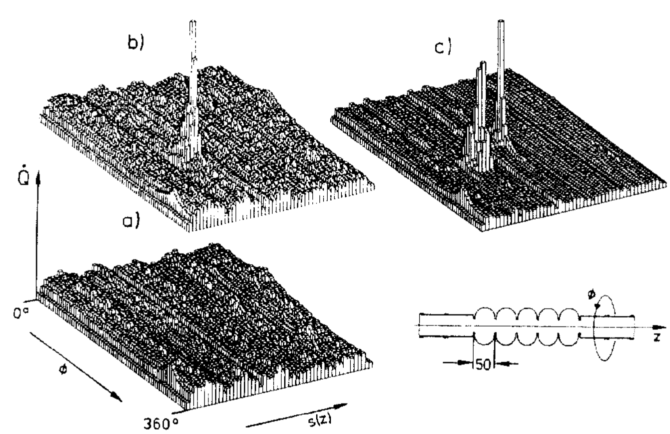

Fig.5: Spatial distribution of the rf losses in a Nb_3Sn coated five cell cavity taken at 2.2 K in subcooled He at E_{acc} = 2.55 MV/m (a), 2.6 MV/m (b) and 3.9 MV/m (c). With increasing field a few presumably microscopic regions switch into high loss areas. ($\dot{Q}$ in arbitrary units)

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Conclusions

It has been shown that uniform Nb_3Sn layers can be formed on 3 GHz multicell accelerating cavities. The quality factors and accelerating fields measured at 4.2 K are comparable to the results from niobium resonators of standard purity, obtained at temperatures below 2 K.
A significant part of the residual losses in Nb_3Sn structures was found to be dependent on the cool down rate of the cavity. This behavior is believed to be connected with thermoelectric currents, generated in the Nb_3Sn-Nb interface. The lowest residual surface resistance of R_{res} = 27 nΩ was obtained in a five cell structure after a slow cool down.
The surface resistance of Nb_3Sn at 4.2 K and 3 GHz has been determined to R_{BCS} = 15 ± 3 nΩ in agreement with theoretical expectations [4].
The fields were limited by local thermal instabilities on the rf surface. One cause of these instabilities are weak superconducting defects which switch into the normal conducting state far below the critical field of Nb or Nb_3Sn. Because impurity inclusions in the niobium base material are a possible explanation, the use of high purity niobium is planned for the fabrication of Nb_3Sn structures in the near future.

A comparison of the obtained results with those measured in X-band [1-3] and at 20 GHz [15] shows that the residual resistance increases with frequency. Q values in the few 10^{10} regime at 4.2 K can be expected already today for frequencies around 1 GHz. This frequency range is most interesting for future superconducting linear colliders.

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