# Nb<sub>3</sub>Sn FOR SUPERCONDUCTING ACCELERATORS AT 4.2 K

M.Peiniger<sup>\*</sup>, G.Müller, H.Piel, P.Thüns<sup>\*</sup>

Fachbereich Physik, Bergische Universität-Gesamthochschule Wuppertal, D- 5600 Wuppertal, FRG

Abstract: Nb3Sn is a promising material for superconducting (s.c.) accelerators because of its high critical temperature of 18.2 K and high thermodynamic critical field of 535 mT. Compared to Nb significantly reduced rf losses and higher accelerating fields should be possible at operation temperatures of about 4.2 K especially for frequencies between 1 and 6GHz. The presently used Nb accelerating structures can be coated with a Nb<sub>3</sub>Sn layer by the vapour diffusion technique. We have formed uniform Nb3Sn layers on 1 and 3 GHz singleand multicell accelerating structures in specially constructed UHV furnaces. At 4.2 K and low rf fields quality factors of  $10^{10}$  (1 GHz) and 7.10<sup>9</sup> (3 GHz) have been achieved which are reduced by a factor of about three at the maximum accelerating fields between 4 and 7.2 MV/m. The BCS surface resistance as well as anomalous loss mechanisms and field limitations investigated by multimode measurements and temperature mapping will be discussed. First results obtained in a Nb<sub>2</sub>Sn coated 3 GHz single-cell cavity made of high purity niobium are promising.

### Introduction

The use of s.c. cavities is planned in an increasing number for storage rings, linear accelerators and for free electron lasers at frequencies between a few hundred MHz and several GHz.<sup>1</sup> Typical design values are accelerating fields of  $E_a = 5 \text{ MV/m}$  at cavity Q values of a few 10<sup>9</sup> which are routinely reached by using s.c. niobium of high purity as cavity material. Unfortunately for frequencies above 500 MHz niobium structures have to be operated at temperatures below 4.2 K in order to reach the required Q values. Especially this disadvantage should be overcome by using the A15 compound  $\rm Nb_3Sn$  instead of niobium. Due to the critical thermodynamical field and critical temperature both about twice as high as those of niobium, maximum accelerating fields two times higher and Q values with  $6 \cdot 10^{11}$  at 500 MHz and 2:1010 at 3 GHz a factor of about 150 larger than those in niobium cavities are theoretically expected for Nb<sub>2</sub>Sn at 4.2 K. These expectations make Nb<sub>3</sub>Sn an interesting material for applications in future s.c. linear colliders<sup>2</sup>

Since 1974 Nb<sub>3</sub>Sn cavities have been developed in different laboratories mainly by using the vapour diffusion process.<sup>3-7,14</sup> This technique profits from the fact that the Nb<sub>3</sub>Sn layer can be formed on pure niobium cavities with already optimised rf performance. The formation of Nb<sub>3</sub>Sn layers on 3 GHz single- and five cell accelerating cavities made of low purity niobium has been described earlier.<sup>7,8</sup> This paper reports on first experiments with 1 GHz accelerating structures with correspondingly larger surfaces. Furthermore first experiments are reported on a Nb<sub>3</sub>Sn coated 3 GHz cavity made of high purity niobium.

#### **Experimental Procedures**

The 1 and 3 GHz niobium cavities were made of low purity niobium (RRR = 20 - 40). The vapour diffusion process was carried out at temperatures between 1100 and 1200 °C in

special ultra high vacuum furnaces in which the tin pressure can be adjusted independently of the cavity's temperature. In general homogenous Nb<sub>3</sub>Sn layers were formed by applying a prenucleation with SnCl<sub>2</sub> and by performing the coating process with a temperature gradient between the tin source and the cavity. <sup>7</sup> Furthermore a first successful coating experiment was carried out on a postpurified 3 GHz single-cell cavity with a RRR of 150.<sup>9</sup> A uniform, 0.6  $\mu$ m Nb<sub>3</sub>Sn layer was formed without reduction of the purity of the niobium base material.

After the Nb<sub>3</sub>Sn formation typically 0.1 to 0.3  $\mu$ m of the Nb<sub>3</sub>Sn layer was removed by oxipolishing. Finally the cavities were rinsed with demineralised and filtered water and (in some cases) dustfree methanol before they were mounted to the test system.

Rf tests have been performed on a 1 GHz single-cell accelerating structure (fig.1) and on the high purity 3 GHz cavity by using standard microwave techniques and the temperature mapping technique which enables the determination of the spatial distribution of the rf losses.<sup>10,11</sup> The cavity temperature could be varied between 1.5 and 300 K. The 1 GHz accelerating cavity (fig.1) is equipped with a variable, coaxial beam pipe coupler which allows the determination of the cavity Q over several decades and the exitation of higher order modes. Between 1 and 3.4 GHz 8 modes were found exhibiting Q values higher than  $10^9$ . They were unambiguously identified by comparing the experimentally found frequencies, geometry factors and field distributions with values, calculated with the computer codes SUPERFISH<sup>12</sup>, URMEL and URMEL T<sup>13</sup>.



Fig.1:

1 GHz Nb $_3$  Sn cavity with microwave couplers and vacuum connection as it is mounted in its cryostat.





In all excited modes of high Q the surface resistance

Now at Interatom GmbH, Accelerator and Magnet Technology. D-5060 Bergisch-Gladbach, FRG

1296

 $\rm R_s$  was determined as a function of temperature T at low field levels. In fig.2 the  $\rm R_s(T)$  curves of the fundamental mode and the 3-EE-3 mode (URMEL notation) at 3.4 GHz, both measured in the 1 GHz accelerating cavity are given. The "steps" in the  $\rm R_s(T)$  curve of the fundamental mode at about 9 K and 3.4 K are not caused by rf losses inside the cavity cell. They were found to be due to the rf losses on the niobium flanges (T\_c= 9.2 K) and the indium seals (T\_c= 3.4 K) closing the short beampipes (fig.1). These flange losses are comparably less pronounced in the 3.4 GHz mode.

At temperatures below  ${\rm T_c}/2$  the experimental surface resistance is well described by the relation

$$\mathbf{R_s}(\mathbf{T}) = \frac{\mathbf{A}}{\mathbf{T}} \exp \left(-\frac{\Delta}{\mathbf{kT}}\right) + \mathbf{R_{res}} = \mathbf{R_{Nb_3Sn}}(\mathbf{T}) + \mathbf{R_{res}}$$

The surface resistance of Nb<sub>3</sub>Sn R<sub>Nb<sub>3</sub>Sn</sub> at 4.2 K and the reduced energy gap  $\Delta/kT_c$  ( $T_c$  was measured to 18 K) were obtained by fitting this relation to the data. In fig.3 R<sub>Nb<sub>3</sub>Sn</sub>(4.2K) and the residual resistance R<sub>res</sub> are given as a function of frequency. With regard to data obtained at



Table 1: Summary of test results

Surface resistance of  $Nb_3Sn$ as a function of reduced temperature measured in the same cavity for two different modes

Fig.2:



<u>Fig.3</u>: Surface resistance  $R_s$  of Nb<sub>3</sub>Sn at 4.2 K. The measured parts  $R_{Nb_3Sn}$  (full circles) and  $R_{res}$  (full triangles) are compared to the data of other laboratories (open symbols) and to the surface resistance of niobium at 4.2 K (dashed line)<sup>15</sup>.

frequencies between 8 and 22  $\text{GHz}^{3-8}$  we come to the following conclusions:

- 1. All the  $R_{Nb_3Sn}$  (4.2 K) data between 1 and 22 GHz are fitted well by an  $f^2$  dependence which is expected from the two fluid model.
- 2. Below 10 GHz  $R_{Nb_3Sn}$  (4.2 K) is a factor of about 150 lower than the surface resistance of niobium (RRR = 40) at the same temperature. As a consequence, Nb<sub>3</sub>Sn accelerating cavities with quality factors of about 6  $\cdot$  10<sup>11</sup> at 500 MHz

Cavity/treatme	ent mode	frequency [GHz]	temp. [K]	Q <sub>0</sub> (H <sub>p</sub> ) /10 <sup>9</sup>	max. surface fields E <sub>p</sub> [MV/m] H <sub>p</sub> [mT]		max.acc. field [MV/m]/lim.			Abbreviations:
multi mode ca Nb <sub>3</sub> Sn 3.8 μ oxipol. 0.2 μ RRR = 20 - 4	vity TM010 m 2-ME-1 m " 40 2-EE-1 " TE0-ME-2 2-EE-3 " 3-ME-2 " 3-EE-3 "	1.00 1.83 u 1.83 d 1.87 u 1.87 d 2 2.97 2.98 u 2.98 d 3.07 u 3.07 d 3.39 u 3.39 d	4.2 2.1 2.1 2.2 2.2 2.2 2.2 2.2 2.3 2.3 2.3 2.2 2.2	3.8 1.4 3.0 1.2 1.7 3.2 1.0 1.7 0.9 1.45 2.1 1.65	8.7 5.6 5.5 5.4 8.0 3.2 5.1 6.9 6.5 7.4 4.2	24.0 40.9 39.9 18.8 28.8 11.7 14.0 23.0 23.0 21.6 32.2 18.2	5.4	/ Q / Q / Q / Q / P / Q / Q / MP / Q / Q / Q	Nb <sub>3</sub> Sn Oxipol. RRR Q, P, M	<ul> <li>thickness of the Nb<sub>3</sub>Sn layer</li> <li>removal of Nb<sub>3</sub>Sn surface layer by oxipolishing</li> <li>residual resistance ratio of the Nb base material</li> <li>rf field limitation by Quenching, rf input power, elec-</li> </ul>
3 GHz cavity Nb <sub>3</sub> Sn 0.6 μ oxipol. 0.1 μ RRR = 150	m TM010 m	2.92	3.1	0.6	25.2	41.4	9,9	/ Q	u, d	tron multipacting : multipole partner of upper (u), lowe (d) frequency

and 2  $\cdot$  10<sup>10</sup> at 3 GHz are theoretically obtainable at 4.2 K. 3. There is no apparent frequency dependence of  $\Delta/kT_c$ . Its average value is 2.2  $\pm$  0.1 showing the strong coupling

## Anomalous Losses and Field Limitations

behaviour of Nb<sub>2</sub>Sn.

As shown in fig.3 the residual resistance  $R_{res}$  is significantly larger than  $R_{Nb3Sn}$  at 4.2 K and exhibits a strong frequency dependence. On the other hand  $R_s$  at 4.2 K measured at low field levels is at least a factor of ten lower than the surface resistance of niobium at the same temperature.

<u>Cool down dependent rf losses</u>: As in the earlier 3 GHz tests <sup>8</sup> both in the 1 GHz accelerating structure and in the high purity 3 GHz cavity a significant part of the rf losses were found dependent on the cavity cool down rate. Lowest  $R_{res}$  values were achieved after a very slow cool down of the cavity ( $\approx$  1 K/S min) below  $T_c$  of the Nb<sub>3</sub>Sn layer. The additional rf losses caused by a faster cool down are uniformly distributed over the cavity surface. Furthermore local regions of enhanced residual losses were found by thermometry created by a thermal breakdown. These losses vanished after a warm up of the cavity above  $T_c$  of the Nb<sub>3</sub>Sn layer. Both effects are presently interpreted to be due to frozen in magnetic flux generated by thermoelectric currents in the Nb/Nb<sub>3</sub>Sn interface.

<u>Cavity performance at high fields</u>: In table 1 the rf data of the 1 GHz accelerating structure and the high purity 3GHz cavity are summarised. Due to the dominating residual losses between 2 and 4.2 K the rf data of the different modes were found nearly independent on temperature in this range. In fig.4 the cavity Q versus accelerating field curves are given for both cavities. The strong reduction of  $Q_0$  at low fields in case of the 1 GHz structure (curve a) is presently not understood. A similar behaviour was observed in earlier 3 GHz tests on Nb<sub>3</sub>Sn coated cavities of low purity.<sup>8</sup> On the other hand this phenomenon is not observed in the same structure at higher order modes above 2 GHz and in the high purity cavity (curve b).

Maximum surface magnetic fields between 18.8 and 41.4 mT were obtained in nearly all cases limited by quenching. In the 1 GHz structure four different quench locations were found by multi mode excitation. In the fundamental mode the quench location caused a sudden drop in cavity Q by switching over into a high loss state at a well defined field level significantly below the breakdown field (fig.4). Q switches are observed frequently in Nb<sub>2</sub>Sn cavities.<sup>8</sup>

After the measurements the Nb<sub>3</sub>Sn layer of the 1 GHz structure was stripped off and the pure niobium cavity was subsequently tested. As in the coated state the cavity quenched at  $E_a = 5$  MV/m and also the quench location was found to be the same. This phenomenon of nearly equal maximum field in the pure Nb and Nb<sub>3</sub>Sn coated state is generally observed.<sup>7,8</sup> This confirms the assumption that the fields achievable in Nb<sub>3</sub>Sn cavities are in general limited by impurity inclusions in the niobium base material. As a consequence Nb<sub>3</sub>Sn coated cavities made of high purity niobium should therefore give higher breakdown fields. The first result obtained in the 3 GHz cavity of high purity (fig.4, curve b) can be interpreted in this direction. For the first time an accelerating field of nearly 10 MV/m was achieved in a Nb<sub>3</sub>Sn coated 3 GHz structure.



<u>Fig.4</u>: Cavity Q as a function of accelerating field taken in the low purity 1 GHz (a) and the high purity 3 GHz (b) accelerating cavities

# Conclusion

Uniform Nb<sub>3</sub>Sn layers have been formed on 1 GHz accelerating structures. First results on a single-cell accelerating cavity at this frequency have demonstrated, that the design values for current s.c. accelerator projects can be obtained in Nb<sub>3</sub>Sn cavities already at 4.2 K, now. The surface resistance of Nb<sub>3</sub>Sn at 4.2 K was determined as a function of frequency in the GHz range. The results correspond to limiting Q values at 4.2 K of  $6 \cdot 10^{11}$  at 500 MHz and  $2 \cdot 10^{10}$  at 3 GHz if the residual resistance can be improved. In a first experiment Nb<sub>3</sub>Sn was coated successfully on a 3 GHz cavity made of high purity niobium. A maximum accelerating field of .9.9 MV/m was obtained which is by a factor of 1.4 larger than ever achieved in a 3 GHz cavity of low purity.

#### Acknowledgement

We are very grateful to the Deutsches Elektronen Synchrotron (DESY) for their technical and financial support. Special thanks are given to R.Fleck and D.Dasbach for their devoted work during all the 1 GHz and 3 GHz experiments, respectively. This work was funded in part by the German Federal Minister for Research and Technology (BMFT) under the contract number 054 WT 85 I (1).

### References

- Proc.of the 3rd Workshop on RF Superc., edited by K.W.Shepard, Arg. Nat.Lab., Argonne, Illinois (1988)
- [2] U.Amaldi, CERN/EP/79-136 (1979) and M.Tigner, CBN 82-22, Cornell University (1982)
- [3] H.Diepers et al., Forschungsbericht BMFT-FBT 74-19
- [4] J.B.Stimmel, thesis, Cornell University (1978)
- [5] P.Kneisel et al., IEEE Trans.Mag-15, 21 (1979)
- [6] G.Arnolds et al., IEEE Trans.Mag-15, 27 (1979)
- [7] M.Peiniger et al., ibid [1], 503
- [8] M.Peiniger and H.Piel, IEEE Trans. NS-32, 3612 (1983)
- [9] D.Dasbach et al., to be pres. at the Appl.Superc.Conf., San Francisco (1988)
- [10] H.Piel and R.Romijn, CERN/EF 80-3, Geneva (1980)
- [11] G.Müller, Proc. 2nd Workshop on RF Superc., 377. CERN, Geneva (1984)
- [12] K.Halbach and R.F. Holsinger, Part.Acc.7, 213 (1976)
- [13] T.Weiland, IEEE Trans.Nucl.Sci., NS-32, 2738 (1985)
- [14] G.Arnolds-Meyer, E.Chiaveri, CERN/EF/RF 86-2 (1986)
- [15] U.Klein, thesis, WUB-DI 81-2, Univ.of Wuppertal (1981)