HTS COATINGS FOR IMPEDANCE REDUCTION OF BEAM-INDUCED RF IMAGE CURRENTS IN THE FCC

S. Calatroni[#], CERN, Geneva, Switzerland

Abstract

The FCC-hh presently under study at CERN will make use of 16 T superconducting dipoles for achieving 100 TeV p-p center-of-mass collision energy in a 100 km ring collider. A copper coated beam screen, like in the LHC, is envisaged to shield the 1.9 K dipole cold bores from the 28 W/m/beam of synchrotron radiation. Operating temperature should be in the 50 K range, as best compromise temperature in order to minimize the wall-plug power consumption of the cryogenic system. However, preliminary studies indicate that copper at 50 K might not provide low enough beam coupling impedance in the FCC-hh. It has then been proposed to reduce the beam impedance by a thin layer of a High-Temperature Superconductor (HTS), which will thus effectively shield the beam-induced RF image currents. Purpose of this paper is to define the basic requirements for an HTS film in the RF field induced by beam image currents and exposed to a high magnetic field, and to identify the best candidate materials and coating processes.

INTRODUCTION

The FCC-hh is a study for a next-generation large p-p collider aiming for a 100 TeV center-of-mass collision energy in a 100 km circumference ring [1]. Superconducting magnets at 16 T cooled at 1.9 K will steer the beam which will emit 28 W/m/beam of synchrotron radiation. A beam screen held at around 50 K will shield the magnets from it, thus allowing for a better overall cryogenic efficiency and power consumption. A similar screen in the presently running LHC makes use of a copper coating to minimize impedance for beam image currents. However the surface resistance of copper at 50 K might not be sufficiently low for the FCC-hh beam stability. The goal of this paper is to study the feasibility [2] of using High-Temperature Superconductor (HTS) coatings in order to minimize the surface impedance.

The operating conditions of HTS in the proposed FCC-hh beam screen are extremely challenging. The beam screen of about 30 mm diameter would operate in a temperature window between 40 K and 60 K, and the coatings will have to remain superconductive (in the mixed state) up to a field of 16 T. Although the beam average current is of the order of 1 A, the 8 cm long bunches of 10^{11} protons would induce in the HTS film peak currents of the order of 25 A, with a frequency spectrum extending from DC up to well above 1 GHz (Fig. 1) [3]. Assuming a thickness of 1 µm which is typical in thin films technology, this would mean that the HTS material should have a critical current density J_c of about 25 kA/cm^2 at 50 K and 16 T, of course with a reasonable safety margin, and have surface resistance in these conditions better than copper.

Several HTS have been discovered in the last 25 years having a critical temperature much larger than the classical technological superconductors. Two main families have been identified as having the highest potential for applications: the REBCO family, thus called to include several Rare Earths such as Y, Gd, Sm; and the BSCCO family, which includes not only the Bi- but also the Hg- and Tl-based compounds. Key properties of the most commonly used YBCO and BSCCO compounds used for SC cable manufacturing are listed in table 1 [4], compared to classical LTS materials.

In the following, we will analyse the RF behaviour of superconductors in such extreme conditions, identify what are the required performances and possible benefits for the FCC-hh making use of YBCO as an example, and finally underline the research needed for identifying the best possible material and ways to characterize it.

RF PROPERTIES OF A SUPERCONDUCTOR

The field and temperature dependent surface resistance of a superconductor is usually experimentally described in the following form [5]:

$$R_s(H_{rf},T,B) = R_{BCS}(H_{rf},T,0) + R_{res}(H_{rf},0,0) + R_{fl}(H_{rf},T,B) \quad (1)$$

where $R_s(H_{rf},T,B)$ indicates the total surface resistance as a function of the RF field H_{rf}, the temperature T and the external applied flux density B. In our case H_{rf}

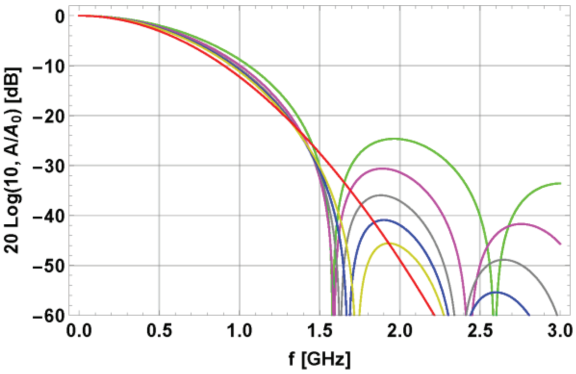

Fig. 1: frequency spectrum for 8 cm long bunch of 10^{11} p$^+$ of various shapes. Peak bunch current is about 25 A. [3]

[#] sergio.calatroni@cern.ch

Table 1: Basic Superconducting Quantities and Normal State Resistivity for a few Selected Superconductors [4]

Material	Crystal structure	Anisotropy	T_c (K)	H_{c2}	H^*	In-plane coherence length $\xi(0)$ (nm)	In-plane penetration depth $\lambda(0)$ (nm)	Depairing current density (A cm^{-2}), 4.2 K	Critical current density (A cm^{-2})	$\rho(T_c)$ (μΩ cm)
Nb47wt%Ti	Body-centred cubic	Negligible	9	12 T (4 K)	10.5 T (4 K)	4	240	3.6×10^7	4×10^5 (5 T)	60
Nb_3Sn	A15 cubic	Negligible	18	27 T (4 K)	24 T (4 K)	3	65	7.7×10^8	$\sim10^6$	5
MgB_2	*P*6/*mmm* hexagonal	2–2.7	39	15 T (4 K)	8 T (4 K)	6.5	140	7.7×10^7	$\sim10^6$	0.4
YBCO	Orthorhombic layered perovskite	7	92	>100 T (4 K)	5–7 T (77 K)	1.5	150	3×10^8	$\sim10^7$	~40–60
Bi-2223	Tetragonal layered perovskite	~50–100	108	>100 T (4 K)	~0.2 T (77 K)	1.5	150	3×10^8	$\sim10^6$	~150–800

comes from the beam induced image currents. R_{BCS} can in principle be calculated from theory [6], in particular for LTS materials, although its H_{rf} dependence is still the object of debate.

The residual term R_{res} is by definition independent from temperature, but depends on H_{rf}, and its origin is usually attributed to lattice defects, grain boundaries, hydrogen trapping and more generally to "defects" [7]. The effect of an external magnetic field is usually expressed by R_{fl} with a loss mechanism related to trapped fluxons which may result either from an imperfect Meissner flux expulsion at low field, or from proper mixed state behavior above H_{c1}, and is found to depend on both H_{rf} and T [8].

The BCS and the Residual Surface Resistances

The BCS surface resistance R_{BCS} can be calculated from theory [6] for traditional low-temperature superconductors. The results match very well with experimental data, however the calculation is based on a perturbation theory approach which is valid at zero H_{rf}.

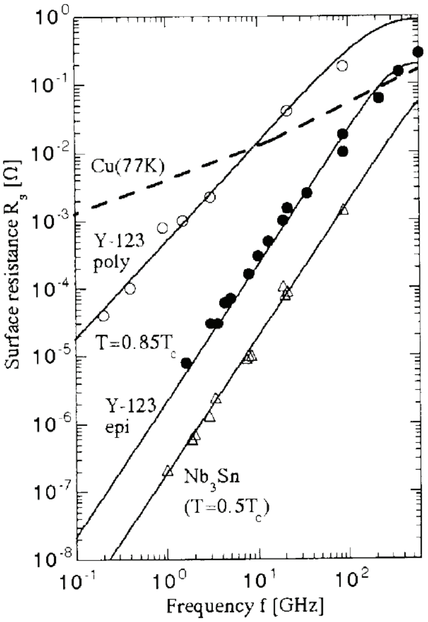

Fig. 2: Surface resistance at 77 K of YBCO films, polycrystalline (empty circles) and epitaxial (full circles) compared with Cu (dashed line) and Nb_3Sn films (triangles). [10]

No established theory exists for nonzero fields, although some progress in modelling has been performed recently for LTS [9]. Calculations for HTS face even larger difficulties, because of d-wave pairing, non-isotropic gaps and other effects discussed extensively in [10]. The situation for the residual resistance is even more complex: even for LTS there is no predictability, although established recipes exist for minimizing it in the case of niobium. HTS face even stronger problems due to non-isotropy, grain boundary orientation mismatch, low ξ and so on. The best approach is thus to analyse existing experimental data.

YBCO has been the best-studied HTS for RF device applications, and relevant data are summarized in Fig. 2. It is apparent that, below 1 GHz and at 77 K, epitaxial YBCO films have an enormous potential compared to Cu, allowing at least three orders of magnitude gain. Even polycrystalline films would allow at least one order of magnitude gain compared to copper.

The Fluxon-Induced Surface Resistance

The additional surface resistance R_{fl} in flux-flow regime for a superconductor thin film, of thickness comparable with the skin depth, can be described as:

$$R_{fl} = R_n \frac{H}{H_{c2}} \tag{2}$$

where R_n is the surface resistance in the normal state, $H = B/\mu_0$ is the external magnetic field and H_{c2} is the upper critical field of the material [11-13]. Intuitively, this can be related to the ratio of normal conducting (NC) to super conducting (SC) surface area in the mixed state, where the NC surface is within the flux cores (Fig. 3).

In this simple picture the NC normal cores would have the surface resistance of the material in its normal conducting state. Following basics of superconducting theory, for $H=0$ all the surface is SC, for $H = H_{c2}$ all surface is NC, and for any H value in between, the ratio of NC/SC surface is equal to H/H_{c2}. For HTS materials H_{c2} can be in excess of 100 T (Table 1), so in the FCC-hh at maximum energy one could suppose that 16% of the surface (16 T/100 T) would dissipate according to R_n, thus accounting for R_{fl}, and the remaining 84% of the surface would be superconducting, accounted for by $(R_{BCS} + R_{res})$.

More realistically [12, 13], the behaviour depends strongly on the relative strengths of the pinning potential of the flux-tube lattice, and the Lorentz force experienced by the fluxons in the RF field. Equation (2) is in fact the upper pessimistic limit for RF frequency much larger than the so-called de-pinning frequency. Without going into details, at low enough frequency R_{fl} can become negligible according to the modelling, see Fig. 4 [12]. It is worth noting that the depinning frequency has been estimated being as high as ~100 GHz for YBCO [10].

As mentioned earlier, both R_{res} and R_{fl} have been found experimentally to depend on H_{rf}, resulting in surface resistances much larger than at zero-field. It is not the object of this paper to describe this phenomenology and its theoretical modelling which are discussed extensively for example in [5, 7, 10]. However it is important to mention that this behaviour has been seen both in LTS and HTS, and is influenced among other by the specifics of the deposition of the thin film, including the technology, the geometry, the substrate and many others. In most cases theoretical modelling or interpretations are missing or fail, thus precise values can be obtained only through direct experimental verification.

SURFACE RESISTANCE OF FCC-hh BEAM SCREENS

We will estimate in the following the surface resistance of a FCC beam screen in the mixed state at zero H_{rf}, thus in the limit of zero beam induced image currents, and compare it to that of plain copper. For the sake of this estimate and to demonstrate the evaluation method we will make use of polycrystalline YBCO as reported in Fig. 2. According to the preceding discussion, we need to evaluate the surface resistance $R_{BCS} + R_{res}$ of the HTS in the superconducting state, and that of the HTS in the normal state, the latter representing the contribution R_{fl} of the normal cores as a function of the external field, and add them in the proper proportion.

Surface Resistance of Cu at 700 MHz and 50 K

The frequency of 700 MHz has been chosen as being approximately the mid-point of the FCC bunch spectrum, and is similar to the existing LHC spectrum mid-point. Copper with RRR=100 has been chosen for the simulation, as is typical for beam screen manufacturing. Calculations show [14] that in the temperature range of interest Cu is in the normal skin effect regime. Magnetoresistance effects are not needed to be considered here [15, 16], since these would simply extend the normal skin effect region down to even lower temperatures. The surface resistance of copper at 50 K and 700 MHz in the normal skin effect regime is 1.36 mΩ.

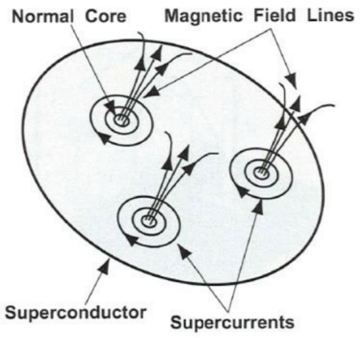

Fig. 3: pictorial illustration of the fluxons whose NC core is embedded in the SC matrix. In the mixed state above H_{c1}, all external flux is concentrated in the material into N=H/Φ fluxons, where Φ is the flux quantum.

Surface Resistance of HTS Films in the Normal State on Copper

HTS in the normal state have a fairly large electrical resistivity (Table 1), likely resulting in a skin depth much larger that the thickness of the HTS film itself. For example 1 µm-thick films of HTS on top of copper have a surface resistance indistinguishable from copper if they have a resistivity larger than 10 µΩcm, as illustrated in Fig. 5. For large enough electrical resistivity the HTS film thus becomes effectively "transparent" to the RF currents.

Taking now the specific case of YBCO as an example, we can assume a resistivity in the normal state of 50 µΩcm at 50 K (Table 1). We can demonstrate that its surface resistance is still roughly equivalent to that of copper for thickness up to about five microns (Fig. 6).

Surface Resistance R_{fl} of HTS as a Function of B

We follow (2) for a first crude estimate of the surface resistance R_{fl} due the fluxons' normal cores as a function of the applied B. This can be performed by multiplying the surface resistance of a HTS film 1 µm thick on Cu in the normal state (precisely 1.39 mΩ) by the fraction of surface, proportional to $\frac{H}{H_{c2}}$, which is within the fluxons' normal cores.

The result is illustrated in Fig. 7. Simple arithmetic indicates that at the maximum FCC-hh field of 16 T, R_{fl} would be equal to 0.22 mΩ. It should be underlined that this is the most pessimistic estimate and much lower

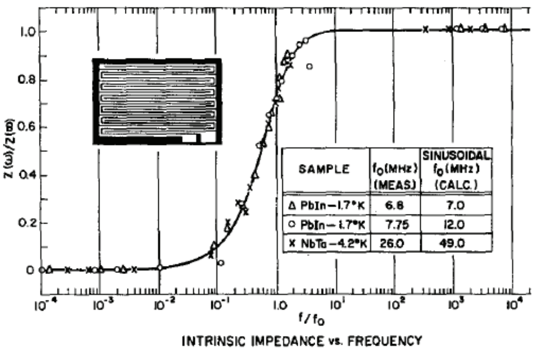

Fig. 4: frequency dependence of R_{fl} using LTS materials for illustration at $H = {}^{1}\!/_{2}\,H_{c2}$. The shape of the plot has general validity, for a given material-dependent depinning frequency f_0 [12]. Equation (2) corresponds to the high-frequency limit of this plot.

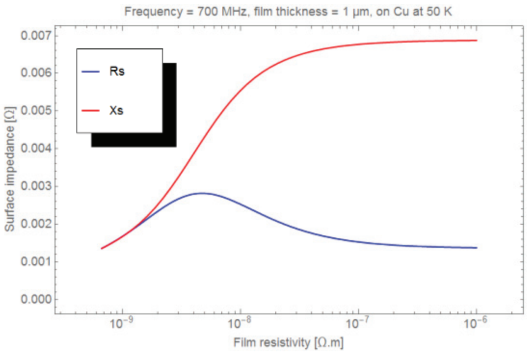

Fig. 5: Re and Im parts of the surface impedance of a 1 μm thick film of arbitrary resistivity, on top of Cu at 50 K and 700 MHz. The lowest resistivity limit of the curves corresponds to Cu at 50 K.

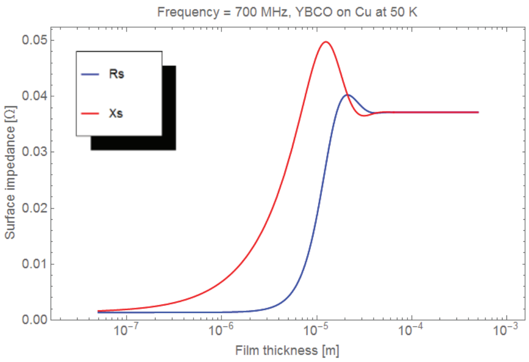

Fig. 6: Re and Im parts of the surface impedance of a YBCO film on top of Cu at 50 K, as a function of its thickness. For thickness << 10^{-7} m we obtain the surface impedance of Cu, for thickness > 10^{-4} m we have the surface impedance of bulk YBCO.

values might be possible, as indicated when discussing Fig. 4. It should be noted that beam impedance is more critical at injection [17], where the magnetic field is about 2 T only, thus greatly improving R_{fl}.

Surface Resistance of FCC Beam Screens with HTS Films

Following (1) we should now add the experimental values of $(R_{BCS} + R_{res})$ to our estimate for R_{fl}. At 700 MHz for polycrystalline YBCO (Fig. 2) we can expect 0.3 mΩ for $(R_{BCS} + R_{res})$ in the worst case, remembering that values two orders of magnitude lower have been reported for epitaxial films.

R_{fl} can range from 0 mΩ in absence of external field up to 0.22 mΩ at 16T. Adding it to the 0.3 mΩ of $(R_{BCS} + R_{res})$ gives us a total surface resistance R_s of 0.52 mΩ for HTS films at 16 T (see Fig. 7).

These values should be compared with the surface resistance of 1.36 mΩ of plain copper at 50 K. HTS films would thus allow a reduction of surface resistance of about 4.5 at 0 T and 2.5 at 16 T compared to copper.

It should again be underlined that few experimental results are available of RF surface resistance measured at such large applied B fields: our modelling is a broad extrapolation of the established behaviour at lower fields (see for example [18]), assuming a pessimistic dynamic regime. Direct experiments in the required operating conditions are thus needed.

Our estimates are also based on a pessimistic estimate of $(R_{BCS} + R_{res})$, and for the specific case of YBCO for sake of illustration. If this is reduced as it appears experimentally possible, for example through another HTS material, and become negligible compared to R_{fl}, we would obtain a larger reduction of surface resistance compared to copper.

These results apply close to zero H_{rf}. Experimental data at larger RF field do exist for HTS [19], but at frequencies not simply scalable to our case. It should thus be expected that some increase in R_s could take place which has to be experimentally verified in the appropriate conditions.

MATERIAL CHOICE

Possible candidates for this application lie clearly in the extended YBCO or BSCCO families (see Table 1).

YBCO thin films have already been demonstrated having good quality maintaining high effective critical field H^* (threshold for flux flow in presence of an applied current density J_c) and a promising set of (J_c, H_{c2}, T_c) when measured in DC. For example [20] have measured (8x10^5 A/cm^2, >6 T, 50 K), where the maximum field was limited by the capabilities of the experimental test station. In particular the critical current seems to be in excess of the peak value foreseen for the FCC, thus reducing the risk of a strong H_{rf} dependence of the surface resistance. However YBCO films are known to suffer from strong limitations due to grain boundary misorientation, thus the growth of good quality films at the large scales of interest for FCC is far from being proven.

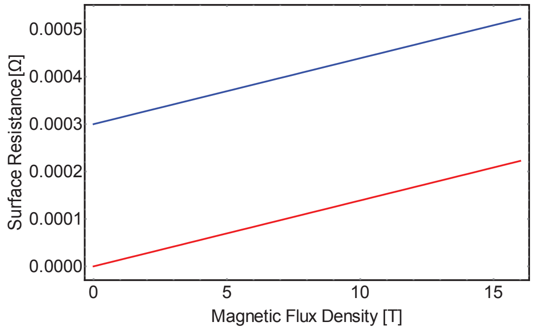

Fig. 7: Calculated R_{fl} (red) and total $R_s = (R_{BCS} + R_{res} + R_{fl})$ (blue) as a function of applied external magnetic field B for polycrystalline 1-μm thick YBCO films, at 700 MHz, 50 K and zero H_{rf}

(Bi, Hg, Tl, Pb)-SCCO allow the highest critical temperatures, and can maintain good quality when grown non-epitaxially. However in practical cases in particular for BSCCO the effective critical field H^* can be much smaller than H_{c2} (see Table 1). It is not clear if this results in a strong limitation as for high-field magnets: our estimates of the previous paragraph have been done in fact modelling the full flux-flow regime. Encouragingly, considerable improvements have recently been reported on this aspect for HTS cables [21].

An ideal compromise could however come from Tl-SCCO. Tl based materials are crystallographically similar to the bismuth-based HTS, and are known to have the tendency to establish a uniaxial texture when grown on untextured Ag [22]. The low anisotropy of thallium-based compounds results in flux pinning properties akin to those of YBCO [23], which together with their high Tc values (~130 K for Tl-1223, depending on stoichiometry and doping) makes them ideal candidates for this undertaking. Moreover, it is known that the thallium compounds can be overdoped easily, which provides a good strategy for further increasing the inter-granular critical current density. In the case of Tl-1223 the Tc reduction resulting from overdoping would be much less significant than it is in the bismuth- and rare earth-based compounds due to the very high critical temperature of this material. Electroplating has also been demonstrated for producing good quality Tl-1223 films [24], the main advantage of this technology being its easy scalability to large dimensions.

CONCLUSIONS

The main features of the behaviour of a superconductor in RF have been described, in the optics of applying HTS thin films inside the beam screens of the FCC-hh, with the goal of guaranteeing an impedance lower than that of copper at 50 K. The main findings, based on modelling performed with literature data for YBCO as an example are:

- The combined $(R_{BCS} + R_{res})$ from available experimental data, obtained on small scale samples, indicate that a surface resistance much lower than that of Cu can be achieved.
- Extrapolation of known RF behaviour of LTS and HTS when immersed in Tesla-scale external magnetic fields, indicates that the added R_{fl} surface resistance is large, but still allow considerably smaller total R_s compared to copper for the best-quality HTS films, at the full 16 T field. R_{fl} would proportionally be lower at lower fields (i.e. at injection), thus allowing for a greater reduction factor.
- The above mentioned behaviour is valid in the approximation of zero H_{rf} (i.e. zero beam current, thus zero induced RF field). No data is available allowing a safe extrapolation to non-zero H_{rf}. An increase should reasonably be anticipated, whose magnitude compared to R_{BCS}, R_{res} or R_{fl} at zero field remains to be identified.

A strong thin films and material development and characterization is needed in order to achieve the goals of HTS coatings for a large scale facility such as the FCC-hh.

A necessary first step in this direction would be to develop a surface impedance measurement facility for small-scale HTS films, able to operate in the temperature range 4.2÷77 K, up to 16 T external applied magnetic field and at < 1 GHz frequency. This would serve the purpose of validating existing HTS thin film coating technologies and select the most promising materials, and promote the developments needed for the FCC-hh.

ACKNOWLEDGEMENTS

The author would like to thank Lucio Rossi (CERN) for the privilege of sharing with him the idea of HTS coatings for beam screens at a very early stage of development. The author would also like to thank Elias Métral (CERN) for kindly providing Fig. 1, Gennady Stupakov (SLAC) for several productive conversations on beam impedance, and Marina Putti (CNR – SPIN) for providing much information regarding the choice of materials.

REFERENCES

[1] https://edms.cern.ch/document/1342402/1.0
[2] Lucio Rossi, *Priv. Comm.*
[3] E. Métral, Proc. of the IBIC2013 Conference (Oxford, UK, 2013) and *Priv. Comm.*
[4] D.C. Larbalastier, Nature 414 (2001) 368.
[5] C. Benvenuti et al., Physica C 316 (1999) 153-188.
[6] J. Halbritter, Zeit. Physik 238 (1970) 466.
[7] H. Padamsee, T. Hays, J. Knobloch, “RF Superconductivity for Accelerators”, Wiley.
[8] G. Arnolds-Mayer and W. Weingarten, IEEE Trans. Mag. 23 (1987) 1620.
[9] B. Xiao et al., Physica C 490 (2013) 26-31.
[10] M. Hein, “High-Temperature Superconductor Thin Films at Microwave Frequencies”, Springer.
[11] M. Rabinowitz, Lett. Nuovo Cimento 4 (1970) 549.
[12] J.I. Gittleman, B. Rosenblum, J. Appl. Phys. 39 (1968) 2617.
[13] J.R. Clem, M.W. Coffey, J. Supercond. 5 (1992) 313.
[14] S. Calatroni, unpublished.
[15] F. Caspers et al., LHC Project Report 307.
[16] E. Métral and S. Calatroni, Proc. of the HE-LHC 2010 Workshop.
[17] M. Benedikt, *Priv. Comm.*
[18] J. Krupka et al., APL 104 (2014) 102603.
[19] J.R. Powell et al., JAP 86 (1999) 2137.
[20] C.M. Friend et al., Supercond. Sci. Technol. 16 (2003) 65–70.
[21] D.C. Larbalastier, Nature Materials 13 (2104) 375.
[22] S. Tönies et al., IEEE Trans. Appl. Supercond. 13 (2) (2003), 2618-2621.
[23] C. Deinhofer und G. Gritzner, Supercond. Sci. Technol, 17 (10) (2004), 1196-1200.
[24] E. Bellingeri et al., IEEE Trans. Appl. Supercond. 11 (1)(2001), 3122-3125.