Assessment of the Potential of Iron-based Superconductors for Large Scale Applications

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***Abstract* - This paper is adapted from the final report for the Seventh Framework Programme FP7 European project SUPER-IRON (Grant Agreement No. 283204), which was focused on the worldwide progress in the research on iron-based superconductors (FeSCs) for large scale applications. SUPER-IRON was a coordinated EU-Japan research project, which lasted from 2011 to 2015, and was funded within the call FP7-NMP-2011-EU-Japan on Fundamental Properties of Novel Superconducting Materials (NMP.2011.2.2-6). The European consortium was led by Prof. Marina Putti and the Japanese consortium was led by Prof. Jun-ichi Shimoyama. The project webpage can be found at http://www.super-iron.eu/.**

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I. INTRODUCTION

Soon after the discovery of superconductivity in iron-based superconductors (FeSCs), their very high upper critical fields, low anisotropy and large J_c values, which are only weakly reduced by magnetic fields at low temperatures, have suggested considerable potential in large scale applications, particularly at low temperatures and high fields. Among the different families, the 122 compounds appear to be the most promising, as they are the least anisotropic, have fairly large T_c up to 38 K, close to that of MgB_2, and exhibit large critical current densities. However, 122 compounds contain toxic As and reactive alkaline earth metals, which may be a problem for large scale fabrication processes. In this respect, also the 1111 compounds present problems, as they contain volatile F and O, whose stoichiometry is hardly controlled. The 11 compounds have lower T_c up to 16 K, but they contain no toxic or volatile elements. It is worth mentioning that new iron-based superconducting families and compounds are steadily discovered. Among these, (Ca,*RE*)$FeAs_2$ (Ca112: *RE* = La,Ce,Pr,Sm,Eu,Gd) with T_c up to ~40 K [1*], $RE_4Fe_2As_2Te_{1-x}O_4$ (42214) with T_c ~45 K (*RE* = Gd) [2*] and [(Li,Fe)OH]FeSe with T_c up to ~40 K [3*] have been discovered within the SUPERIRON project [1].

[1] References with * denote work supported by the SUPER_IRON project.

Thanks to the coherence length values of few nm, iron-based superconductors are particularly sensitive to the inclusion of nanoparticles as pinning centers to enhance the critical current density. For example, self-assembled $BaFeO_2$ nanorods have proven to enhance the pinning force in 122 films above that of optimized Nb_3Sn at 4.2 K [4]. Critical current densities up to 6 MA/cm^2 at 4.2 K in zero field have been measured in 122 films [5,6] and up to 20 MA/cm^2 at 4.2 K in zero field in 1111 single crystals irradiated with heavy ions [7*]. Furthermore, nanometer scale disorder has proven to suppress T_c only very weakly [4,7], suggesting that further improvements of flux pinning are yet achievable. In the following, basic properties of iron-based superconductors are reviewed and compared with established results on other superconductors. Moreover, an assessment of the application potential of FeSCs conductors is attempted, based on properties and promising results measured on short specimens. Certainly, the issue of upscaling preparation procedures must be certainly faced in the future, but at the moment the iron-based wire technology is by far not as mature as other technologies such as that of $YBa_2Cu_3O_7$ coated conductors.

II. BASIC PROPERTIES

A. Transition Temperature

The basic properties set the final performance limits of a superconducting material in terms of temperature, magnetic field, and critical current. These properties of the most relevant iron-based superconductors will be reviewed in this section and compared to those of established technical superconductors.

The highest transition temperature of all iron-based superconductors was found in the 1111 compound (up to 58K [8*], Table 1), which places this compound in between the cuprates and MgB_2.The transition temperature, T_c, is defined as the temperature up to which superconductivity persists. However, applications are restricted to lower temperatures, since superconductivity becomes very weak close to T_c. As a rule of thumb, the operation temperature T^{op} should be about half of T_c or lower in applications requiring high currents and/or fields. However, strong thermal fluctuations of the vortex lattice reduce the critical currents significantly in highly anisotropic materials, restricting appropriate operation conditions to much lower temperatures. Bi-2212 is an extreme example that provides useful current densities only at temperatures below about 20 K despite its high transition temperature of 85 K. Anticipated maximum operation temperatures of the FeSCs are given in Table 1 together with values for other superconducting compounds. Note that the higher the required magnetic field, the lower must be the operation temperature. Since the 1111 compounds are the most anisotropic of all considered FeSCs, the estimated value for the maximum T^{op} has to be confirmed when conductors become available and may be restricted to low magnetic fields. In any case, all FeSCs discovered so far are obviously no alternative to *RE*-123 coated conductors or Bi-2223 tapes at high temperature (>50 K), in particular for use with nitrogen as the coolant.

K-doped Ba-122 has a transition temperature of around 38 K, nearly the same as MgB_2. From this viewpoint, the two materials are direct competitors for applications at intermediate temperatures, which do not rely on liquid helium as a coolant. P- or Co-doped Ba-122 has lower T_cs of about 30 K and 24 K, respectively, which makes a helium free operation questionable. The 11 compound has the lowest T_c, even below that of the readily available Nb_3Sn, thus helium cooling is the only option.

Although many new iron-based compounds were discovered during the past few years, T_c was not significantly increased since the starting of the project. However, Ge et al. [9] demonstrated superconductivity above 100 K in a single layer of FeSe on top of doped $SrTiO_3$. Although the high transition temperature results from a charge transfer between the superconducting layer and the substrate, it fuels hope that higher T_cs are achievable in iron-based compounds with yet unknown interlayers.

Table I. Relevant iron-based compounds and technical superconductors. The highest T_c found in the respective family is given. T^{op} refers to a typical or expected operation temperature.

Compound	Code	max. T_c (K)	T^{op} (K)	
$Ln\mathrm{FeAsO}_{1-x}\mathrm{F}_x$	1111	58	≤40 (?)	*Ln*=Sm, Nd, La, Pr,….
$BaFe_2As_2$**	122	38	≤25	K, Co, or P doping
$FeSe_{1-x}Te_x$	11	16	≤4.2	
Nb-Ti	-	10	≤4.2	
Nb_3Sn	-	18	≤4.2	
MgB_2	-	39	≤25	
$RE\text{-}\mathrm{Ba_2Cu_3O_{7-x}}$	*RE* -123	95	≤77	*RE*=Y, Gd, Sm, Nd, Yb,…
$Bi_2Sr_2CaCu_2O_{8-x}$	Bi-2212	85	≤20	
$Bi_2Sr_2Ca_2Cu_3O_{10-x}$	Bi-2223	110	≤77	

** Ba can be replaced by Sr or Ca

B. Upper Critical Field

The upper critical field, B_{c2}, limits the field which can be generated using the respective superconductor, maximally about $0.75 \cdot B_{c2}$ can be effectively achieved. Since superconducting wires are used nowadays predominantly for magnets, B_{c2} is certainly a key parameter for applications and restricts available magnets using conventional (niobium based) conductors to fields below 25 T. Novel conductors for the next generation of NMR, accelerator, research, and fusion magnets are urgently needed. While MgB_2 is unsuitable for high field magnets, cuprate- and iron-based superconductors have upper critical fields in the 50-100T range (and even higher) at 4.2 K, thus not imposing any realistic limitations for high-field magnets operating at low temperatures. However, B_{c2} decreases with temperature and converges to zero at T_c, thus a high B_{c2}(0 K) is, beside a high T_c, a prerequisite for cryocooled magnets operating at intermediate fields (e.g. medical MRI magnets). In this respect, FeSCs are clearly more suitable than MgB_2, which is already applied in low field MRI systems.

An important point to mention is the low anisotropy of the upper critical field in the FeSCs. It makes flux pinning more effective than in the highly anisotropic cuprates by reducing flux cutting effects and thermal fluctuations. In particular, the 11 and 122 compounds are nearly isotropic at low temperatures. Although the anisotropy increases with temperature in these compounds reaching values up to about 3 close to T_c, it remains well below that of *RE*-123 coated conductors (≈5) and Bi-tapes (>20) also at high temperatures.

C. Critical Current Densities

The critical current density in a superconducting wire is either limited by flux pinning or granularity (see next subsection). Flux pinning is an extrinsic effect, which can be tuned by generating a suitable defect structure. The maximally achievable loss-free DC currents are, however, not independent from the basic material parameters, since J_c amounts to maximally 10-20% of the de-pairing current density, J_d, in optimized materials. J_d is a material property, and can reach up to $3 \cdot 10^8$ A/cm^2 in the cuprates, about $1.8 \cdot 10^8$ A/cm^2 in Nb_3Sn and $2 \cdot 10^8$ A/cm^2 in MgB_2. It is similar in Sm-1111 and K-doped Ba-122 (about $1.7 \cdot 10^8$ A/cm^2), but smaller in the P- and Co-doped 122 system (≈5 and $9 \cdot 10^7$ A/cm^2, respectively) and only around $2 \cdot 10^7$ A/cm^2 in the 11 system; thus at least some compounds can compete with the high values in the cuprates, MgB_2 and Nb_3Sn.

Efficient pinning can be realized comparatively easily in the iron-based materials, as demonstrated by irradiation experiments [7*,10*] and by the successful introduction of nano-particles [5] or nano-rods [4,11]. Moreover, irradiation with Au ions [12] and neutrons [13] and introduction of artificial ab plane pins [14] have emphasized that the introduction of pinning defects does not affect T_c appreciably. This indicates that FeSCs tolerate a higher density of defects without a significant decrease in T_c than cuprates. That makes these superconductors ideal candidates for high field applications, since the density of pinning centers is of crucial importance at high fields.

D. Grain Coupling

All superconductors with a T_c above 30 K exhibit magnetic granularity, which limit the macroscopic currents [2]. While secondary phases residing at the grain boundaries and voids reduce the cross section over which the current effectively flows in MgB_2, high angle grain boundaries intrinsically limit the currents in untextured, polycrystalline cuprates. For misalignment angles between adjacent grains above 3°, J_c drops exponentially. Unluckily, such an exponential decay of the current as a function of the misalignment angle between grains has been measured in the FeSCs as well, namely in 122 films grown onto bicrystal substrates. However, the suppression of J_c is not as strong as in high-T_c cuprates [15,16]. Also, it has been suggested that “real” grain boundaries can often show much better transparency than the planar grain boundaries of the bicrystals [17], because the misorientation angle is not the only parameter that determines whether or not grain boundaries are transparent to the supercurrent. In addition, the orientation of the field with respect to the grain boundary has to be taken into account, because the inter-grain J_c degrades the most when a significant portion of the vortex lies in the grain boundary. When the vortex obliquely crosses the grain boundary, the suppression of the inter-grain J_c is much weaker.

Magnetic granularity in the cuprates has been (at least partly) overcome by texturing. A high degree of texture ensures a small density of high-angle grain boundaries that would reduce the macroscopic current. The corresponding production techniques, however, involve multiple steps with related costs.

Texturing might not be necessary for the FeSCs. In particular, results on K-doped 122 wires are encouraging, since current densities that approach the requirements of applications were demonstrated (see Section *Wire development*). A combination of the more favorable

[2] Grains have their own magnetic signal, generated by current loops shielding the grain only, not the entire sample. Magnetic "grains" are not necessarily the real grains of the material, but can be also clusters of well connected grains.

grain coupling and nano-sized grains enable current densities in granular iron-based materials, which are higher by orders of magnitude than the best results achieved in untextured cuprates.

Overdoping has a beneficial effect on the intergrain transport in cuprates, specifically Ca doping in YBCO. Analogously, it is found that Sn addition largely improves intergrain J_c in $SmFeAs(O_{1-x}F_x)$, whose self-field value exceeds 1 x 10^4 A cm^{-2} at 5 K [18*]. Also intergrain J_c of $Ba(Fe_{1-x}Co_x)_2As_2$ sintered bulk is enhanced by low temperature synthesis reaction and Co-overdoping up to x = 0.12, resulting in similarly high intergrain J_c at 5 K [19*].

III. APPLICATION PROSPECTS

One may conclude from the basic properties discussed above, that the FeSC can hardly compete with the superior properties of cuprates. The transition temperature, the upper critical field, and the depairing current density are higher in *RE*-123, on which the coated conductor technology is based, than in any iron-based compound. However, the smaller J_d may be balanced by smaller anisotropy and higher tolerance by FeSC of high defect concentrations and the, both favoring high critical currents at high fields; thus they may become an alternative for high field conductors at low temperatures.

From an economical point of view, the FeSC have a great potential, if the grain coupling could be enhanced further in polycrystalline materials, thus making possible a cheap Powder-In-Tube (PIT) wire production. Such wires could outperform MgB_2, Nb-Ti and Nb_3Sn conductors at a comparable or even lower price and result in a cost-effective technology of magnets operating in the temperature range between 20 K and 30 K, where cryocoolers can be used for cooling instead of liquid helium. If texture is necessary, FeSC conductors will be more expensive but possibly cheaper than cuprate- based coated conductors, due to relaxed requirements on texture quality. For example, a much simpler conductor architecture, with only one buffer layer, was already demonstrated (see below).

The possible operation conditions for applications requiring an engineering current density[3] above 10^4 A/cm^2 are summarized in Figure 1. The performance of the FeSC is extrapolated to thick-coated conductors or well-connected polycrystalline wires and was not demonstrated yet. However, it shows the potential of the iron-based compounds to replace other materials and push upwards the current limit of superconducting high field magnets. The range of $B(T)$ where FeSC could be economically favorable is the entire region below the red line in Figure 1, assuming that PIT wires could attain sufficiently high performance. Were coated conductor technology necessary for high performance then the red-marked area would still be of economical interest.

[3] Engineering critical current density, J_e, is the ratio of critical current I_c to the whole cross-sectional area of conductor.

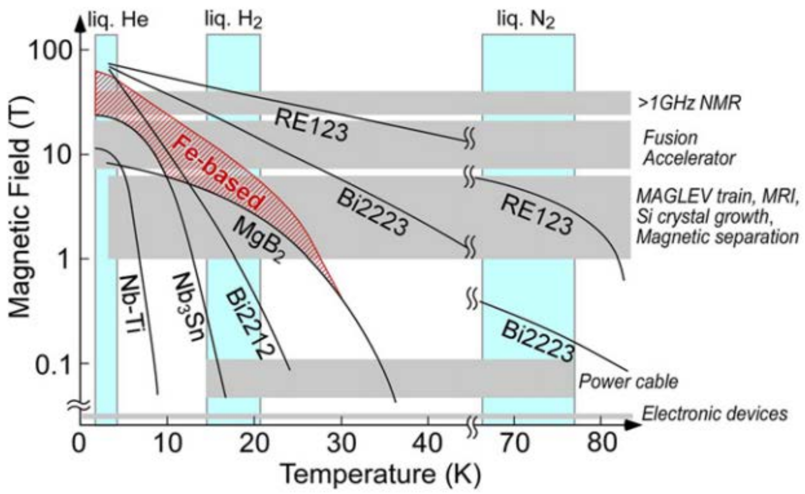

Fig. 1. Possible operation conditions for applications requiring engineering J_e>10^4 A/cm^2 for various superconducting tapes and wires (from [20], copyright 2014 by Institute of Physics). The lines show the limiting fields as a function of temperature. Engineering critical current density, J_e, is the ratio of critical current I_c to the whole cross-sectional area of conductor.

IV. CONDUCTOR DEVELOPMENT

A. Powder- in-tube Processed Conductors

Wires and tapes of all iron-based superconductor families have been fabricated by the powder-in-tube (PIT) method. Wires prepared by *ex-situ* PIT generally have higher J_c than those prepared by *in-situ* PIT [21], as the former process offers more options of optimizing the powder reaction, even by multiple steps. The quite isotropic character of J_c with respect to the crystalline direction and the better coupling between misaligned grains suggest that the texturing may not have to be as rigorous as in cuprates. This could mean that cables in the form of untextured wires may provide the required performance, without the need of texturing processes used for fabrication of coated conductors.

The best transport critical current values among iron-based superconductor wires and tapes, exceeding 10^5 A/cm^2, have been so far obtained in the 122 family [22,23,24,25]. For for both conductor geometries, Ag rather than Ta, Nb and Fe, has turned out to be the best sheath material and it has been used since, even in combination with an outer Fe sheath which reduces cost and improves the mechanical strength. Chemical additives are a well-established route to improve grain crystallization, add pinning centers, and enhance the metallic character of grain boundary secondary phases, thus promoting inter-grain coupling. It has been proved that 10%-20% Ag substitution significantly improves inter-grain connectivity and reduces porosity of 122 tapes, resulting in a three times increase of the global J_c up to high fields [26,27]. Pb addition, on the other hand, promotes grain growth and improves grain connectivity for contents up to 10%, yielding an enhancement of the global J_c in the low field regime [26]. Sn addition has a similar beneficial effect in 122 [28,29].

Nonetheless, with respect to the role of chemical additives in promoting grain growth, we observe that grain growth is not necessarily the right direction to pursue. Indeed, it has been shown that untextured polycrystalline $(Ba_{0.6}K_{0.4})Fe_2As_2$ bulks and round wires with high grain boundary density, i.e., small grains, prepared by *ex situ* PIT, have transport critical current densities well over 10^5 A/cm^2 in self-field at 4.2 K [22,23]. The enhanced grain connectivity has been ascribed to their much improved phase purity while the effectiveness of high density of grain boundaries (GBs) as pinning centers has been explained in terms of low anisotropy and consequent enhanced vortex stiffness in 122 compounds.

Densification of the superconducting core by uniaxial pressing under high pressure ~2GPa before sintering has yielded self-field J_c values above 10^5 A/cm^2, still as high as $8.6\cdot10^4$ A/cm^2 at 10 T [24]. This result can be attributed to a change in the crack structure and more uniform deformation achieved by pressing rather than rolling. Indeed, as already observed in Bi-2223 tapes, cracks run transverse to the tape length for rolled tapes and parallel to the tape length for pressed tapes [30]. An optimization of the cold deformation process has to attain the optimal tradeoff between improvements in density and initiation of micro-cracks, which cannot be healed by a subsequent heat treatment.

A further improvement in this direction has been achieved by a hot pressing technique, which makes the grains more flexible to couple with each other without producing a large number of crashed grains, thus significantly reducing the voids and cracks and leading to a denser superconducting core of the PIT tape. More specifically, by pressing K-doped 122 tapes at ~30 MPa and temperature T_{HP}, higher homogeneity, texture and grain connectivity have been obtained, yielding J_c above 10^5 A/cm^2 at 10 T for T_{HP}=850 °C [25] and even at 14T for T_{HP}=900 °C [31]. However, it should be pointed out that practical application of uniaxial pressing for the manufacture of long length wires requires specialized machines for continuous pressing of the tape. An easy and simple process is required to balance the high performance versus the production cost of the superconducting tapes. Yet, by scalable and cheap rolling processes, long-length iron-based superconducting tapes with high transport J_c~$5.4\cdot10^4$ A/cm^2 [32] – $7.7\cdot10^4$ A/cm^2 [33] at 10 T and 4.2 K have been obtained.

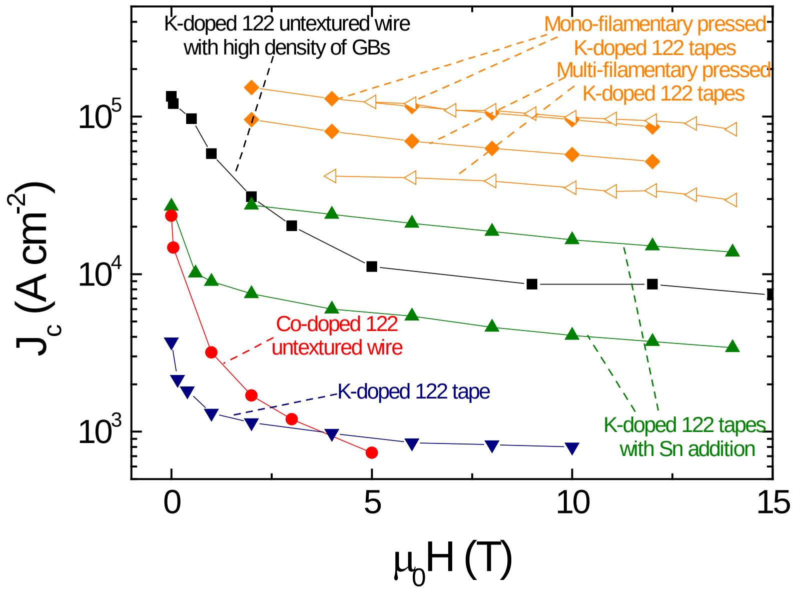

Fig. 2. Transport critical current densities of K-doped 122 textured tapes with and without chemical additives and prepared by different methods [28,29] as a function of applied magnetic field at 4.2 K.. Uniaxially pressed mono- and multi-filamentary K-doped 122 tapes [24], hot pressed mono- and multi-filamentary K-doped 122 tapes (open symbols) [25,31], K-doped 122 untextured wire with high density of GBs [22], and of a Co-doped untextured wire [22].

Texturing methods have also given very good results in achieving a high transport J_c above 10^4 A/cm^2 [28,34,35] up to fields as high as 14 T [29]. Indeed, at high fields, textured tapes perform better than the best untextured wires [29] (Figure 2). The beneficial effect of texturing has led to the idea of preparing iron based superconductor coated conductors (see below, IV,B).

For multifilamentary 122 iron-pnictide wires and tapes, the highest J_c values reached so far are $6.1 \cdot 10^4$ A/cm^2 and $3.5 \cdot 10^4$ A/cm^2 at 4.2 K and 10 T, respectively for hot pressed 7- and 19-core Sr-122 tapes [25].

Lesser effort has been devoted to the fabrication of 1111 wires and tapes, due to the difficulty in controlling O and F stoichiometry during heat treatments at high temperatures. The commonly used sintering temperature for 1111 wires is 1200 °C, but sintering at 850 °C-900 °C has yielded similarly high T_c and J_c up to 1300 A/cm^2 in self-field [36]. Low temperature sintering prevents FeAs liquid phases from forming, but many unreacted precursors remain in the 1111 bulks after long sintering as the reaction rate at low temperature is relatively low. Moreover, tapes cannot endure long-time sintering without fluorine loss. Also in the case of 1111 wires and tapes, Ag has been found to be the best sheath and metal additives are also beneficial. Indeed, the loss of fluorine is reduced and the intergranular coupling enhanced in tapes with added Sn prepared by *ex situ* PIT, exhibiting J_c as large as $2.2 \cdot 10^4$ A/cm^2 at 4.2 K in self-field [37]. Pre-sintering of Sn-added powders allows to reduce the FeAs wetting phase and fill the voids between Sm-1111 grains, yielding improved grain connectivity and J_c up to $3.45 \cdot 10^4$ A/cm^2 at 4.2 K in self-field [38]. However, J_c rapidly decreases with increasing magnetic field, dropping to around 10^2 A/cm^2 at 8 T [38, 39], possibly as a consequence of the anisotropy of the 1111 compounds higher than that of the 122 family.

Wires and tapes of the 11 family are appealing for applications as well, despite their lower T_c and J_c, as they do not contain toxic elements. However, several obstacles have been encountered due to chemical reactions between the superconductor and the sheath during thermal treatments and it is difficult to obtain high density of the powder inside the tube. For this reason, Fe has turned out to be the best choice for the sheath, as it allows a diffusion process, where Fe-free precursors are sealed inside Fe tubes and the final 11 phase is formed with the supply of Fe from the sheath during the thermal treatment [40]. This diffusion process has yielded a significant improvement in the transport J_c reaching self-field values up to 10^3 A/cm^2 in FeSe wires [41]. In optimizing thermal treatment, it was found that the superconducting properties of FeSe wires improve with increasing annealing temperature up to 1000 °C, where the phase formation is complete [42]. Proper thermal treatment of *ex situ* PIT Fe(Te,Se) wires allows to enhance the packing density of the core inside the sheath, thanks to the expansion of the lattice volume by the transformation from high-density hexagonal $Fe(Te_{0.4}Se_{0.6})_{1.4}$ to low-density tetragonal $FeTe_{0.4}Se_{0.6}$, thus yielding enhanced J_c up to $3 \cdot 10^3$ A/cm^2 at 4.2 K in self-field [43]. Combined melting and annealing processes allow to obtain homogeneous and denser Fe(Te,Se) samples, characterized by large and well interconnected grains [44*]. The resulting samples exhibit enhanced global critical current density, reaching about 10^3 A/cm^2.

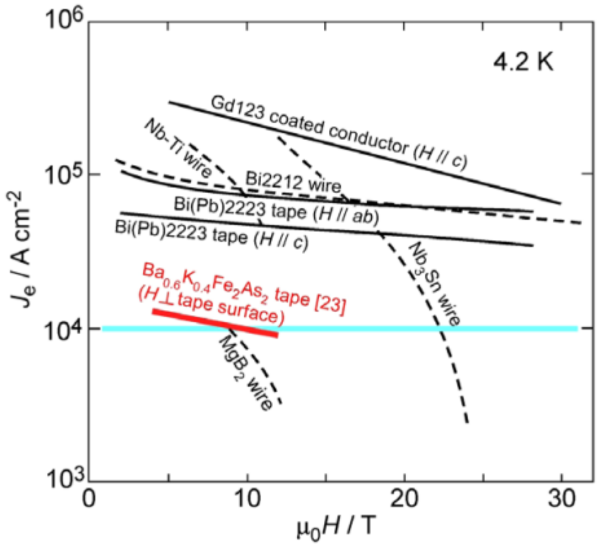

Fig. 3. Engineering critical current density J_e as a function of field at 4.2 K for various superconducting tapes and wires (from ref. [20], copyright 2014 by Institute of Physics).

In summary, the highest transport critical current in iron based superconducting wires and tapes have been obtained so far with the 122 family, namely up to 10^4-10^5 A/cm^2. Moreover, in 122 wires the J_c field dependence is quite flat, with a decrease of one order of magnitude from self-field to a field well above 10 T. For the 1111 family, the transport self-field J_c values found in wires and tapes prepared by *ex situ* PIT reach $3.45 \cdot 10^4$ A/cm^2 [38], but the field dependence of J_c is steeper than in 122 wires and tapes [39]. Wires and tapes of the 11 compounds obtained by *in situ* PIT exhibit the lowest transport J_c values up to $3 \cdot 10^3$ A/cm^2 in self-field [43,45], but they have the advantages of containing no toxic arsenic and having the simplest crystal structure.

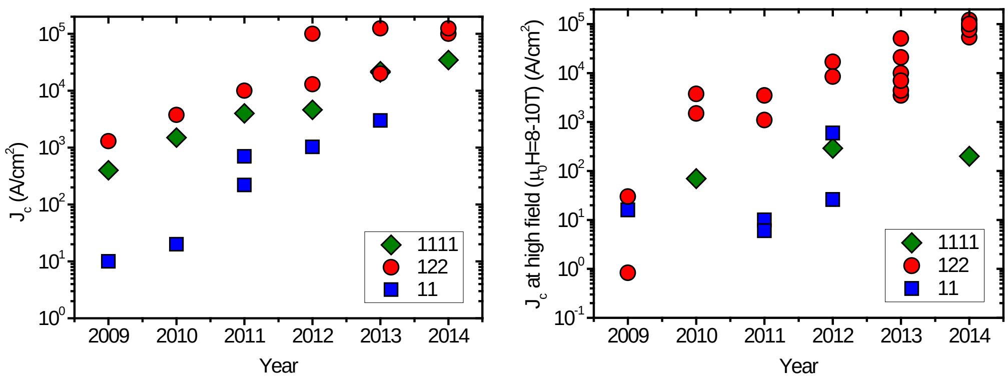

Fig. 4. Transport J_c values obtained in iron based polycrystals, wires and tapes versus the year of publication. In the left panel, data at T=4-5K and self- field are reported while data at T=4-5K and field of 8-10T are shown in the right panel. References for the left panel are [46] (2009), [unpublished datum of a polycrystal from CNR-SPIN] (2010), [47] (2011), [41,44] (2012), [43] (2013) for the 11 family; [48] (2009), [49] (2010), [21,28] (2011), [22,50] (2012), [23,35] (2013), [24,33] (2014) for the 122 family; [51] (2009), [36] (2010), [52] (2011), [39] (2012), [37,53] (2013), [38] (2014) for the 1111 family. References for the right panel are [58] (2009), [45,54] (2011), [44*,41] (2012) for the 11 family; [46] (2009), [55] (2010), [27,28] (2011), [22,29] (2012), [56,23,34,35,57,30] (2013), [24,25,31,32,33] (2014) for the 122 family; [36] (2010), [39] (2012), [53] (2013), [38] (2014) for the 1111 family.

It can be inferred from the state-of-the art results that iron based superconductor (122) wires and tapes have good possibilities for magnet applications at 20-30 K, where the niobium-based superconductors cannot play a role owing to their lower T_cs and J_c is rapidly suppressed by the applied field in MgB_2, as depicted in Figure 3. Moreover, the steady improvements of J_c values achieved in wires and tapes based on 11, 122 and 1111 iron based superconductors in the last years do not seem to be approaching any saturation (Figure 4). This positive trend suggests on one hand that the intergrain current in real conductors may behave better than that in epitaxially grown bicrystals, as mentioned above [17], and on the other hand that there exists of a considerable edge of improvement yet achievable with these materials.

B. Coated Conductors

As mentioned above, weak-linked behavior in 122 thin films grown onto bicrystals has suggested to deposit iron-based superconductor films on textured metal substrates with buffer layers, in analogy to techniques successfully developed for second-generation cuprate wires. Ion-beam assisted deposition (IBAD) coated-conductor templates are manufactured in two steps. First, an Y_2O_3 layer is made on unpolished Hastelloy by sequential solution deposition to reduce the roughness of the tape surface, then a biaxially textured MgO layer is deposited on top by IBAD. By this technique, biaxial texture is achieved by means of a secondary ion gun that orients the oxide film buffer layer while it is being deposited onto the polycrystalline metallic substrate. Alternatively, the RABiTS^{TM} process[4] for coated-conductor templates achieves texture by mechanical rolling of a face-centered cubic Ni–W alloy and subsequent heat treatment. On such metal substrates a series of biaxially textured buffer oxides, such as Y_2O_3, YSZ and CeO_2 is grown.

The 122 films have been grown on IBAD substrates [58,59,60*]. In-plane misorientation of 3°-5° has been measured with self-field J_c values at 4 K above 10^6 A/cm^2 and above 10^5 A/cm2 in 9 T field. This route has turned out to be encouraging for the 11 family as well. Fe(Se,Te) thin films deposited on IBAD-MgO-buffered Hastelloy substrates have been able to carry transport critical current up to $2 \cdot 10^5$ A/cm^2 at low temperature and self-field, still as high as 10^4 A/cm^2 at a field of 25 T [61]. Even more remarkable results have been obtained for Fe(Se,Te) thin films deposited on RABiTS substrates, namely critical currents up to $2 \cdot 10^6$ A/cm^2 at low temperature and self-field, still as high as 10^5 A/cm^2 at a field of 30 T [62].

Fabrication of coated conductors has also been tried with 1111 iron-based superconductors [63]. NdFeAs(O,F) thin films grown on IBAD-MgO-Y_2O_3 Hastelloy substrates by molecular beam epitaxy have shown high c-axis texture, but not complete in-plane texture. The magnetic J_c measured in self-field at 5 K is $7 \cdot 10^4$ A/cm^2, larger by one order of magnitude than J_c of 1111 PIT tapes, but significantly smaller than J_c of 122 and 11 coated conductors. Also the field and temperature dependence of J_c is much stronger than that of coated conductors of the other families, as a consequence of the weak link behavior related to incomplete biaxial texture. Record data of transport J_c in coated conductors are reported in Table II.

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[4] Rolling assisted biaxially textured substrates is a technique originally developed at Oak Ridge National Laboratory (ORNL).

In the assessment of the potential of coated conductors, it must be pointed out that the thickness of the superconducting layers in coated conductors is currently less than 150 nm. Thicker layers were not attempted so far but are not expected to be difficult to achieve. Considering the very low engineering critical current density J_e, no advantageous points can be found for the iron-based coated conductors compared to the PIT processed tapes and wires at the present stage. Moreover, higher production cost and low production rates of coated conductor technology must be taken into account when assessing the application potential of this field as compared to that of the PIT technology. However, the elaborate oxide buffer structure, partially designed to protect the metal template from oxidation for cuprates wires may not be needed at all for Fe(Se,Te) wires, deposited in vacuum. Growing a Fe(Se,Te) coating directly on textured metal tapes may be possible, thus greatly simplifying the synthesis procedure, reducing production costs and avoiding possible uncontrolled oxygen diffusion into the intermetallic superconductor.

Table III. Transport and magnetic J_c record values of iron-based superconductors coated conductors of different families, measured at low temperature (2.5-5K) in self-field and high magnetic field.

FeSC family	J_c in self-field (A/cm^2)	J_c at $\mu_0H_{\perp ab}$=10T (A/cm^2)	J_c at $\mu_0H_{\parallel ab}$=10T (A/cm^2)	Type of measurement	Ref.
122	$3.5\cdot10^6$	$1.0\cdot10^5$	$2.0\cdot10^5$	transport	[59]
1111	$7\cdot10^4$	$5.0\cdot10^3$ at $\mu_0H_{\perp ab}$=4T		magnetic	[63]
11	$2.0\cdot10^6$	$9.0\cdot10^5$	$1.0\cdot10^6$	transport	[62]

V. CONCLUSIONS

The performance of the iron-based superconductors in terms of the highest possible operating temperature as well as achievable fields and currents is between those of the cuprate superconductors and the conventional superconductors (Nb_3Sn, MgB_2 and Nb-Ti)[5]. Thus they have to be either cheaper than the cuprate coated conductors or outperform the conventional superconductor wire technology. Both scenarios seem to be realistic. The performance of inexpensive PIT wires and tapes steadily increases and iron-based wires might be applicable at higher temperatures than those of Nb_3Sn and Nb-Ti or at higher fields than MgB_2. Ultrahigh field magnets may be made of iron-based coated conductors, since they could be cheaper than their cuprate counterparts, thanks to a simpler architecture and less stringent texture requirements.

[5] By conventional superconductors we understand here those with phonon-mediated superconductivity mechanism.

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