Lead-Free Persistent Mode Joints Between NbTi Wires

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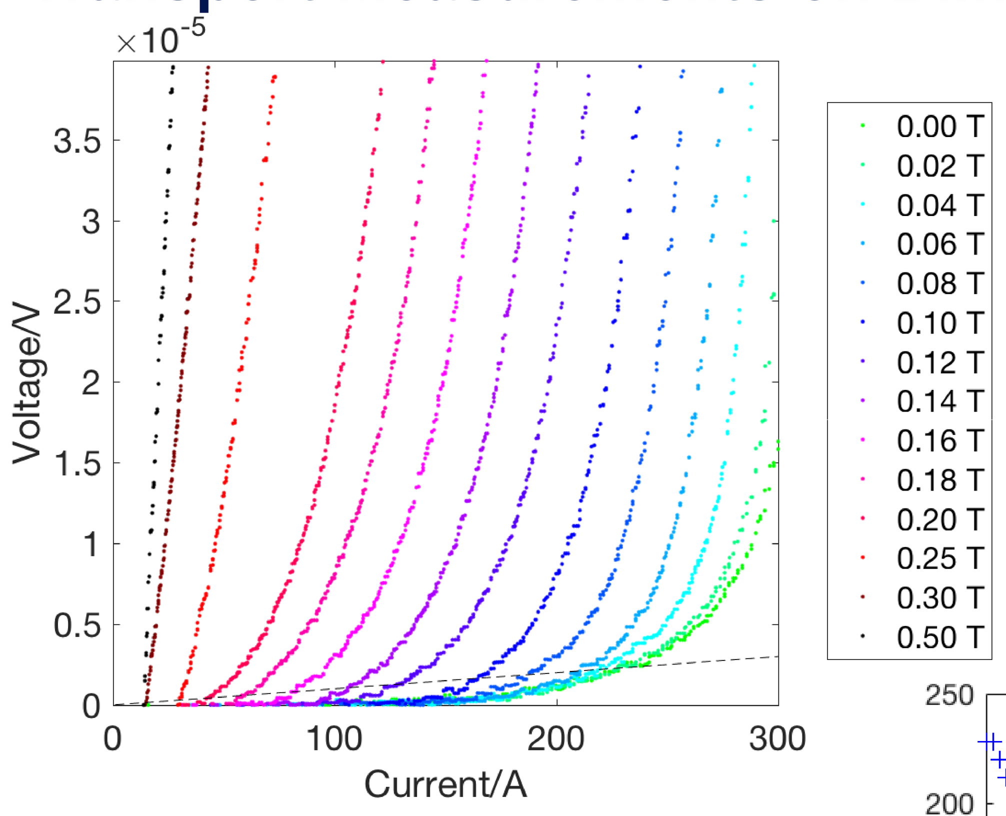
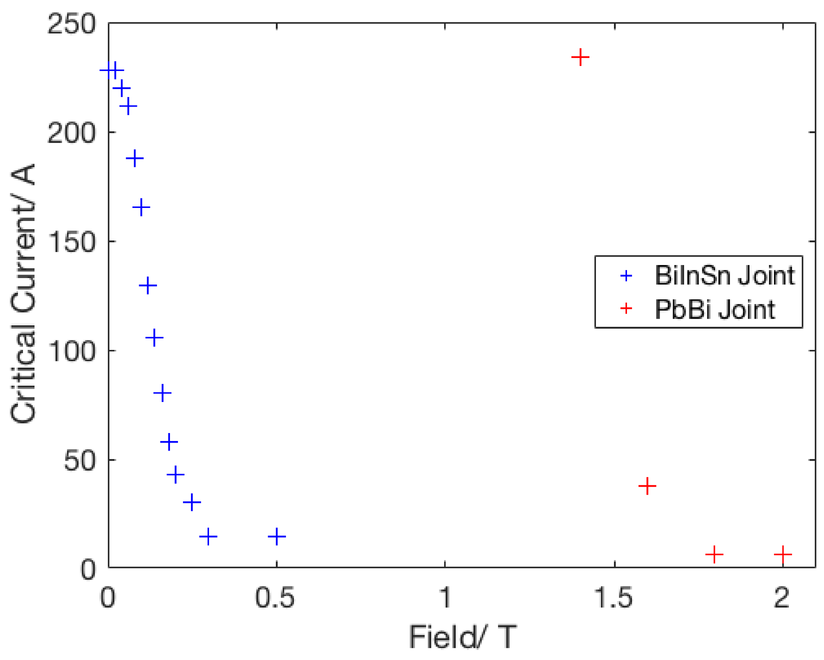
Introduction

- Persistent mode magnets are entirely dependent on the existence of high-quality superconducting joints between superconducting wires.
- For the NbTi wires in commercial MRI scanners, well known techniques rely on a PbBi solder. There is currently legislative pressure to remove lead from magnets; for industry this would ideally involve a lead-free replacement solder.
- The best known lead-free solder is $Bi_{15}In_{50}Sn_{35}$, which has been shown by magnetisation measurements to have the highest T_c and $B_{c,2}$ of any lead-free material with low melting temperature[1]. The first measurements on the performance of joints made from this material are presented below
- A novel composite technique that dramatically increases the in-field performance of this lead-free solder is also presented

Transport Measurements on BiInSn Solder Joints



Two 0.5 m sections of multifilamentary NbTi were joined using a solder matrix replacement method[2] with $Bi_{15}In_{50}Sn_{35}$ solder. The NbTi wires were placed in liquid tin to dissolve the copper matrix, and then in the liquid solder to coat the filaments in solder. They were then cast into a 2 x 20 mm cylinder

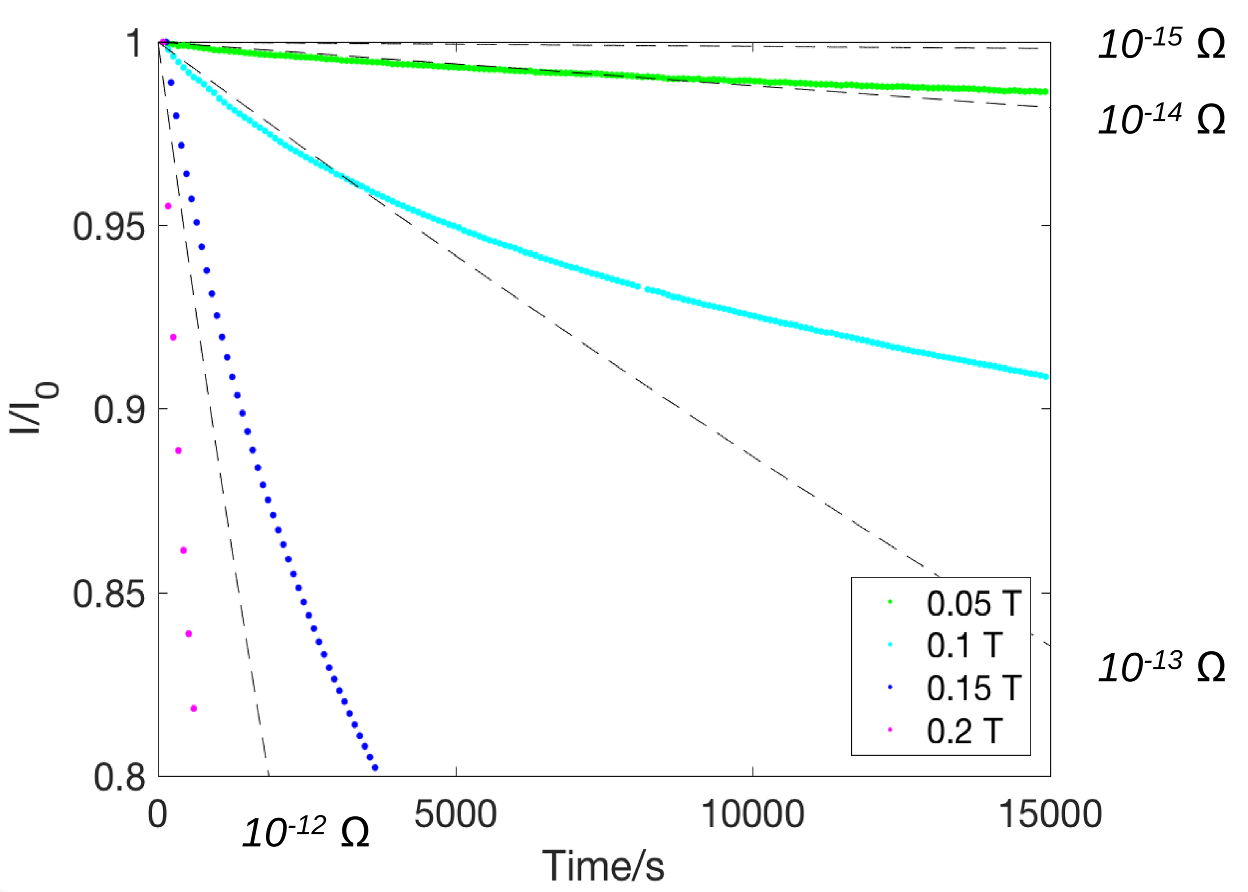


IV measurements in varying applied field at 4.2 K (above) were used to determine the critical current as a function of field (right) by applying a 10 nΩ resistance criteria (dashed line above).

In zero field the critical current is high, but the low $B_{c,2}$ limits in-field performance

Persistence Measurements on BiInSn Solder Joints

A $Bi_{15}In_{50}Sn_{35}$ solder joint was made by matrix replacement between the ends of a 10 cm piece of NbTi wire. From this a 4.2 mm single turn loop was wound around a G10 former, and the decay of currents in this loop at 4.2 K was tested in a commercial SQuID magnetometer using the decay technique devised by Brittles *et al.* [3]



After an initial settling period of increased resistance, this revealed resistances of <10^{-14} Ω at 0.05 T, and <10^{-13} Ω at 0.1 T, promising for persistent mode operation. Above 0.15 T the performance was significantly worse as expected from the measured bulk $B_{c,2}$ value of the solder

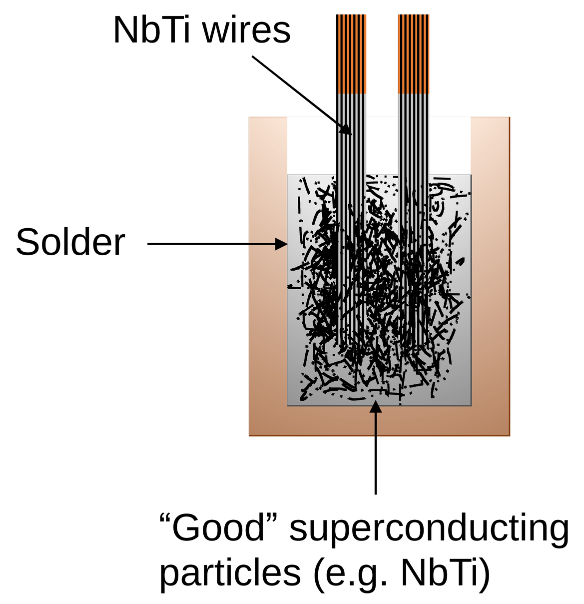
Conclusions

- **$Bi_{15}In_{50}Sn_{35}$ solder joints** have been shown to carry significant currents at zero field and demonstrate persistent behaviour at low fields
- Whilst $B_{c,2}$ may be too low for a 'drop-in' replacement for commercial MRI magnets, it has potential for use in smaller magnet systems
- **Composite lead-free solders** demonstrate significantly improved magnetisation performance compared to their equivalent matrix
- Work is ongoing to understand the physics behind this and to further improve the performance of joints made from this composite material

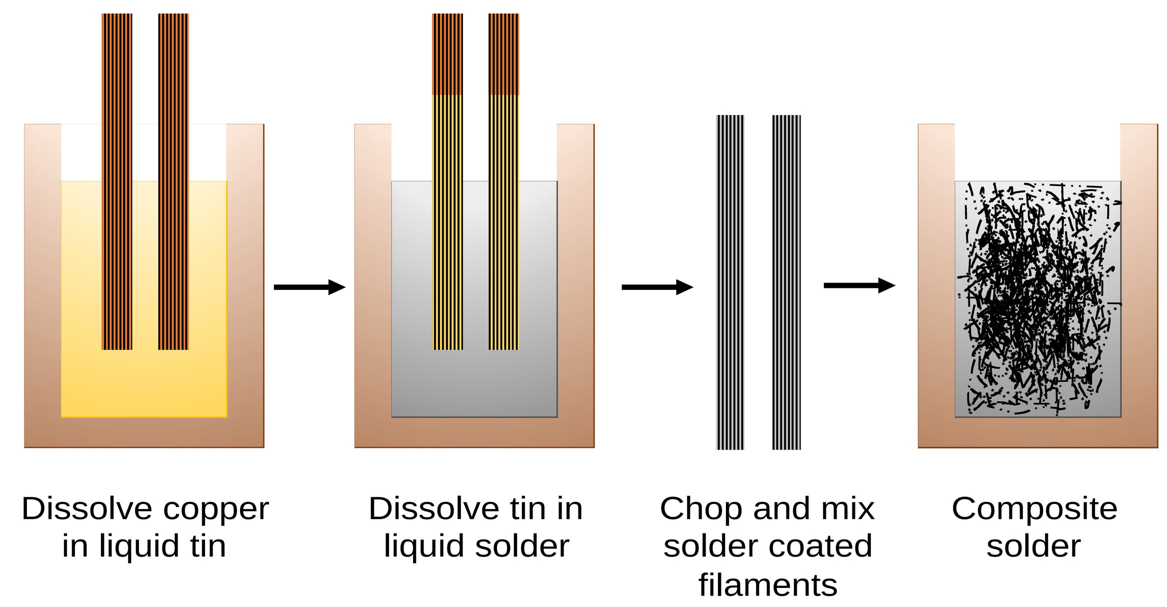
References [1] Mousavi et al, SuST **29** (2016) 015012; [2] Thornton, US Patent 4907338; [3] Brittles et al, SuST **27** (2014) 122002.

Composite Solder Concept

No known lead-free solder has a critical field high enough to replace PbBi joints for MRI scanners above 0.1 T. NbTi and many other superconductors have a much higher critical field, but cannot be melted at low temperatures. By providing NbTi superconducting paths through a solder, performance approaching that of a wire might be achieved. The filaments of very fine superconducting wire are perfect for this, with a large aspect ratio to help create a 3D percolation path.

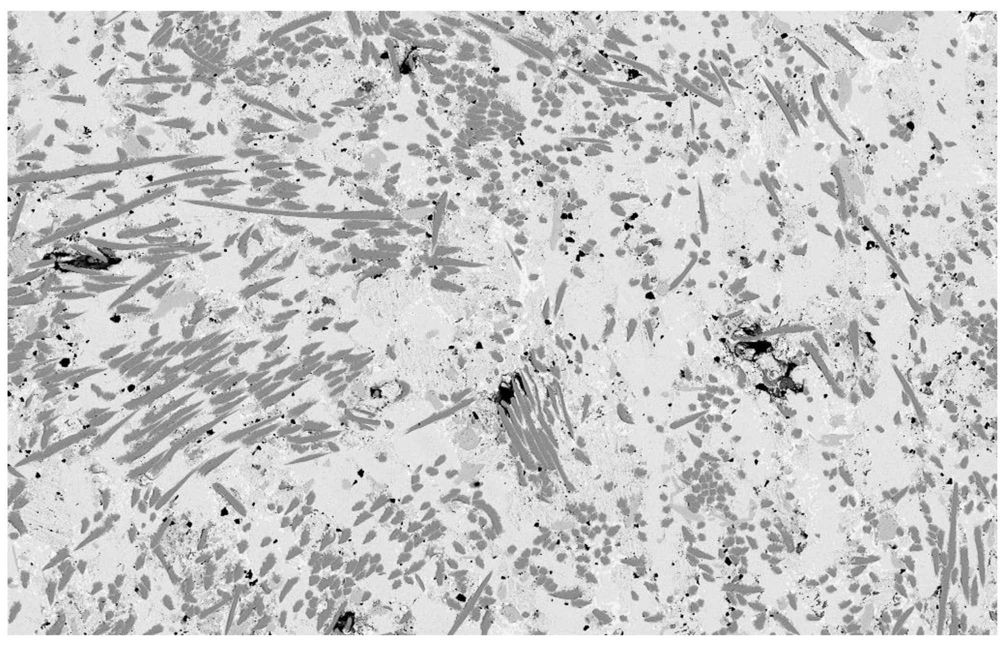


Composite Solder Production



Composite $Bi_{15}In_{50}Sn_{35}$/NbTi solders are made from NbTi wire containing ~12,000 filaments each 3 μm in diameter. This wire is placed in liquid tin for 90 minutes at 370°C to replace the copper matrix with tin. The tin coated filaments are then placed in liquid $Bi_{15}In_{50}Sn_{35}$ solder at 250°C for 60 minutes to coat them in solder. The wire is then chopped and the pieces melted together and agitated to form the composite solder.

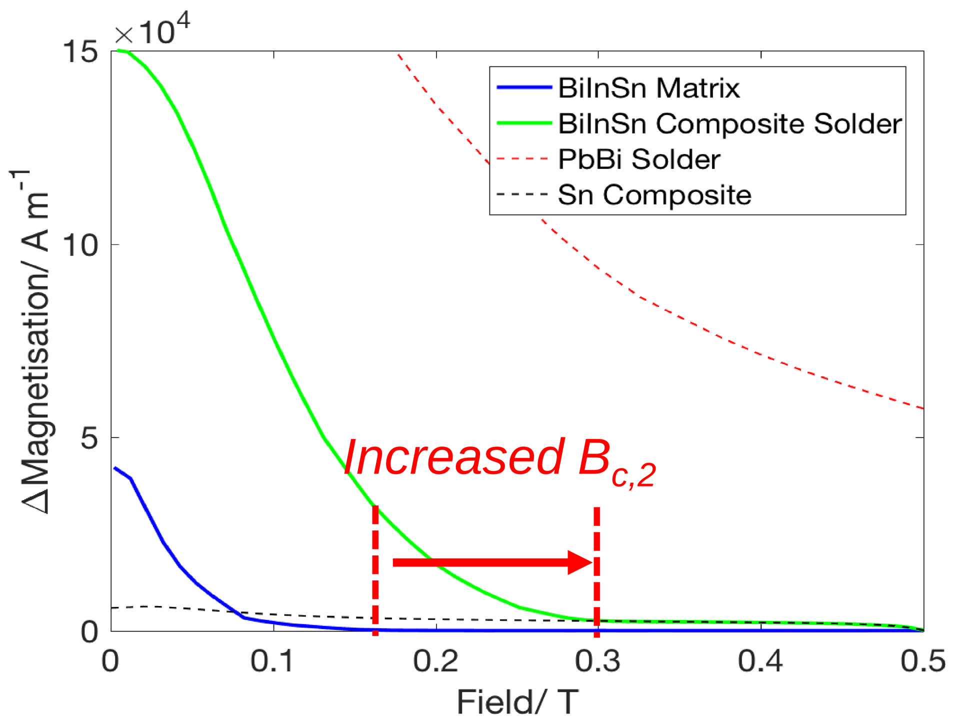
Composite Solder Microstructure



Scanning electron microscopy (SEM) of the composite reveals little sign of the original filament bundle structure and good randomisation of the filament structure. There is no evidence of preferential nucleation of one of the solder phases onto the NbTi filaments

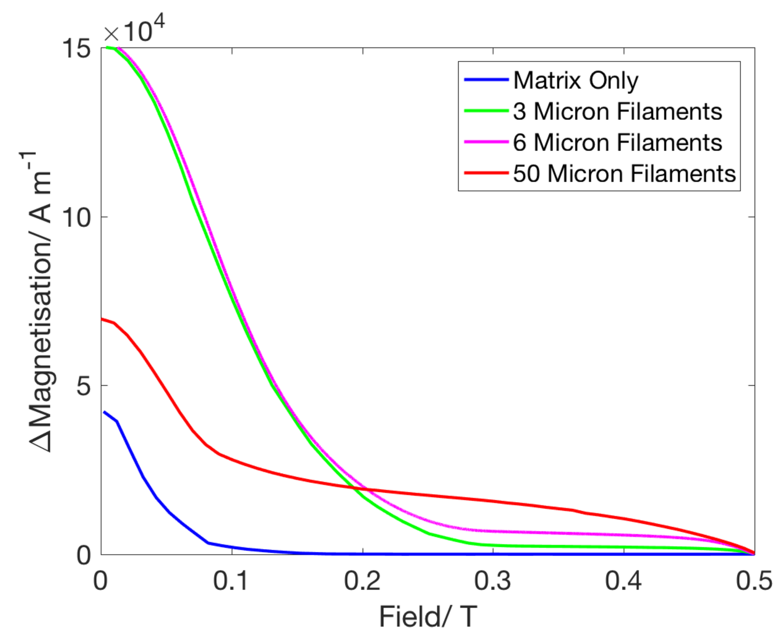
Composite Solder Magnetic Properties

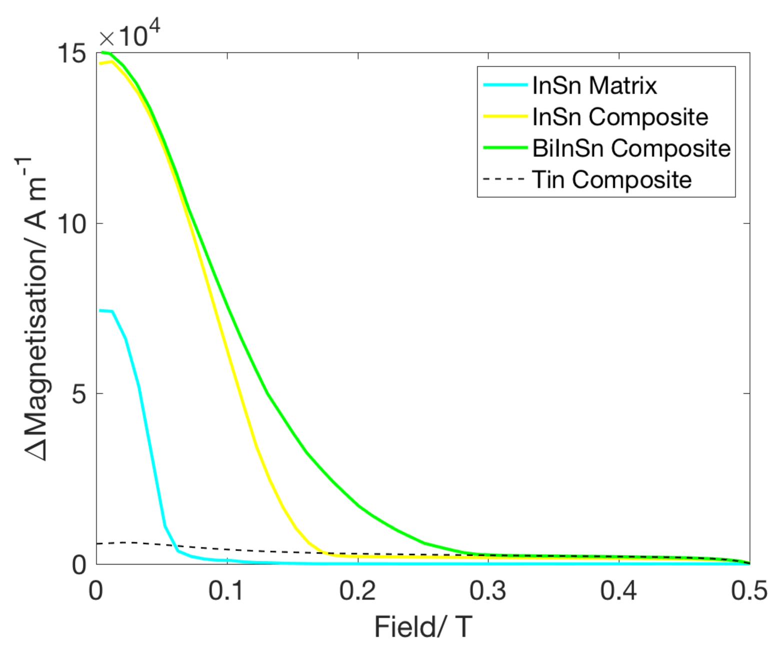
SQuID magnetometry of bulk superconducting solders allows critical temperatures, currents and fields to be investigated quickly and efficiently. All measurements below show hysteresis loop width (ΔM) against applied magnetic field at 4.2 K



The composite solder demonstrates a significant increase in $B_{c,2}$ compared to the matrix material. It also demonstrates considerably higher ΔM, indicating higher critical current, but it is still worse than lead-bismuth solders. There is some magnetisation at higher fields due to current loops in the NbTi filaments.

Changing the filament size (below, left) has limited effect on the critical field for the same loading until filaments become very large. Similar enhancements in higher field performance have been observed with other lead-free solders (InSn), but the matrix must be superconducting to see this effect (below, right).





It is expected that the reason for this improvement is weak-link type coupling between the NbTi filaments in the composite, and work is ongoing to confirm this.

Acknowledgements
Kieran McCall (Department of Physics, Oxford University) for assistance with transport measurements. Clara Barker and Rob Gresham (Department of Materials, Oxford University) for technical support.
Funding from an EPSRC Industrial CASE studentship with Siemens Magnet Technology

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