Mariusz WOŹNIAK[1], Simon C. HOPKINS[1], Bartłomiej A. GŁOWACKI[1,2]

University of Cambridge (1), Institute of Power Engineering (2)

Characterisation of a MgB_2 wire using different current pulse shapes in a pulsed magnetic field

***Abstract**. A pulse field - pulse current system for critical current measurements has been modified to allow control of the current pulse shape. Regression analysis of the voltage vs. current behaviour has been used to determine the critical current and n value using a specified electric field criterion from a single measurement cycle, in place of the previous qualitative approach from a series of pulses. The results for a superconducting magnesium diboride wire agree well with conventional DC measurements in a constant magnetic field.*

Streszczenie.** System do pomiarów prądu krytycznego przy użyciu impulsowego prądu i pola magnetycznego został zmodyfikowany, aby umożliwić kontrolę kształtu impulsu prądu. Prąd krytyczny i parametr n określono z przebiegu napięcia od prądu używając analizę regresji i kryterium pola elektrycznego z pojedynczego cyklu pomiarowego w zastępstwie poprzednio używanego jakościowego sposobu opartego na serii impulsów. Wyniki otrzymane dla przewodu z dwuborkiem magnezu dobrze zgadzają się z konwencjonalnymi pomiarami stałym prądem i polem magnetycznym.* (Charakteryzacja przewodu MgB_2 w impulsowym polu magnetycznym przy użyciu różnych kształtów impulsu prądu***).

Keywords: pulse measurements, magnesium diboride, critical current.
Słowa kluczowe: pomiary impulsowe, dwuborek magnezu, prąd krytyczny.

Introduction

The pulse field – pulse current (PFPC) technique is a promising method for the transport critical current $I_c(B)$ characterisation of short superconductor samples, allowing high fields and high currents to be achieved economically and without excessive sample heating. However, for some samples discrepancies in measured $I_c(B)$ between this and the standard constant field direct current (CFDC) technique arise. The PFPC method often slightly overestimates the CFDC results in higher magnetic fields, as reported recently for an MgB_2/Cu wire [1]. Larger discrepancies, typically an underestimate of I_c at low fields, can occur in some conductor architectures (e.g. those with a large number of filaments) due to flux jumps arising from the non-uniform current distribution resulting from the transient magnetic self-field [2]. A model for the intrinsic stability of a multifilamentary Nb-Ti/Cu-Mn/Cu wire was recently shown to describe quite well the PFPC measurement [3]. The PFPC technique may also underestimate $I_c(B)$ due to difficulties in current transfer from the current leads to the superconducting region through the resistive matrix of short samples, as has been shown by finite element analysis [4].

In all reported measurements [1-4] the critical current $I_c(B)$ was determined by comparing qualitatively the shape of the voltage vs. time response of the sample from a series of approximately sinusoidal current pulses of increasing amplitude, each delivered during a plateau of magnetic field. The qualitative nature of this analysis and the relatively high noise level for high sampling rate data acquisition meant that a low and strictly defined electric field criterion could not be applied. The near-sinusoidal current pulse shape also meant that the rate of change of current, and hence the induced voltage, was time dependent, further complicating analysis. For the measurements reported here, the capacitive discharge current source used previously has been replaced by one capable of delivering accurately any arbitrary shape and length current pulse (Fig.1). In this contribution, regression analysis is applied to the voltage vs. current response to allow the critical current to be determined using a 1 μV cm^{-1} criterion for sinusoidal and linear current pulse shapes, and the differences between them and CFDC measurements are discussed.

Experimental methods

A 0.58 mm diameter wire with the MgB_2 core occupying 47 % of its cross-sectional area was manufactured using the powder-in-tube (PIT) method with an oxide dispersion strengthened copper (Glidcop™) sheath (Fig.1). The starting core composition was Mg+2B+0.09Cu, i.e. with copper powder additions to minimise the diffusion of copper from the Glidcop sheath and thus maximising the fraction of MgB_2 in the core [5,6]. A 7 cm long wire sample was heat treated with a 20 °C min^{-1} heating rate at 700 °C for 5 min in a flowing 95 % Ar + 5 % H protective atmosphere (Fig.1).

Sample 18 mm in length were measured perpendicular to the magnetic field and in liquid helium by the CFDC technique in a Bitter magnet (type Bitter 100, BM1 [7]) in the ILHMFLT (Wrocław, Poland), with a voltage tap spacing of 6 mm and a current ramp rate up to 2 A s^{-1} (Fig.2 a)).

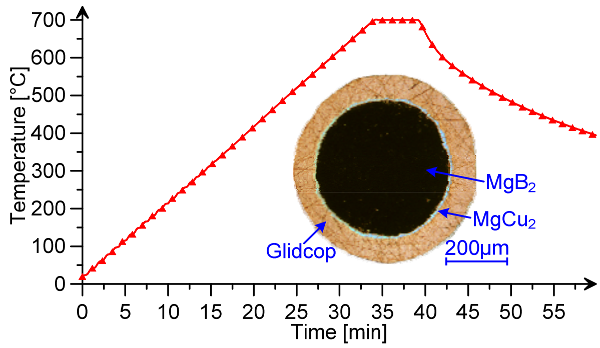


Fig.1 Temperature profiles of the heat treatments of the wire. Insert shows an optical microscope micrograph of the wire cross-section.

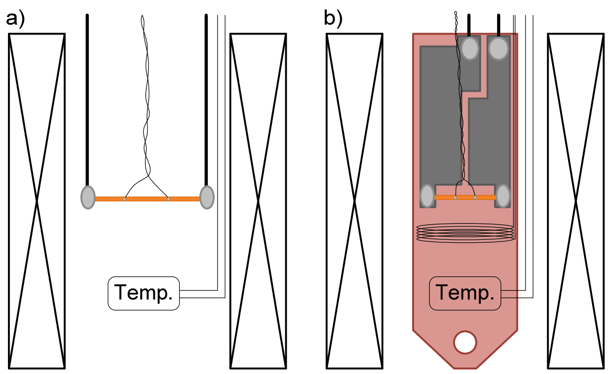


Fig. 2 Schematic diagrams showing the mounting of wire samples for: a) constant field direct current (CFDC) and b) pulse field pulse current (PFPC) measurements. In fig. b), the coil below the sample is used to measure the voltage induced by the pulsed magnetic field, so that this contribution to the sample voltage can be cancelled. Temperature sensors and magnetic field coils are not shown to scale.

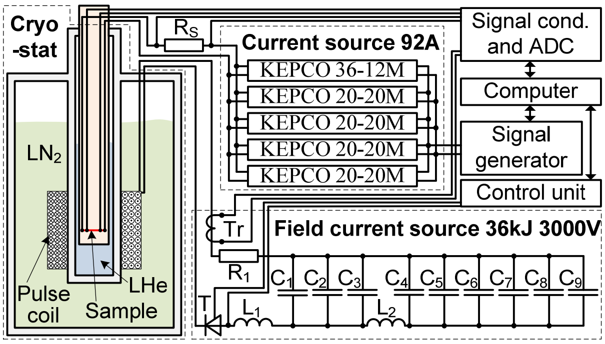


Fig.3. Schematic diagram of the modified Cryo-BI-Pulse system.

An 11 mm long straight sample was measured by the PFPC technique by placing it perpendicular to the magnetic field and in liquid helium (Fig.2 b)). The voltage from taps separated by 2.6 mm was amplified (10× gain), summed with a voltage proportional to the cancellation coil (Fig.2 b) signal to correct for the induced voltage, and recorded by a high sampling rate ADC system (Fig.3).

A signal generator was used to control the current delivered by a current source consisting of 5 power supplies (4 × KEPCO 20-20M + 1 × KEPCO 36-12M) in parallel (Fig.3). A current of 92 A (4 × 20 A + 12 A) with a minimum rise or fall time of 35 µs (10%-90% I_{max}) could be achieved. 4 ms long current pulses with sinusoidal and linear shapes were delivered during the plateau of the magnetic field pulse (Fig.4).

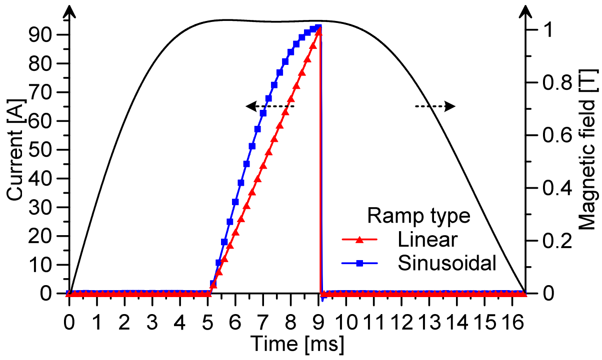


Fig.4. Magnetic field and current pulses used for testing at 4.2 K.

Signal processing

Two types of voltage signals were recorded from the voltage taps of the sample before proceeding to the actual $I_c(B)$ measurements. Firstly, the voltage responses to a series of current pulses with increasing amplitude without an applied magnetic field were recorded as reference signals corresponding to the voltage induced by the change of the sample current with time (an example is shown in Fig.5). Secondly, the voltage responses to a series of magnetic field pulses with increasing amplitude without passing a sample current were recorded as reference signals corresponding to the voltage induced by the change of the magnetic field with time. Most of this voltage had already been removed by correcting with the signal provided by the cancellation coil, but a small signal remained. These voltage components were subtracted from the voltage signal recorded from the sample during simultaneous pulses of magnetic field and current for I_c determination: for example, the sample voltage due to a current pulse with an amplitude of 92 A during a magnetic field pulse with a 1 T plateau was corrected by the subtraction of the separate voltage responses to (i) a 92 A current pulse without magnetic field and (ii) a magnetic field pulse with a 1 T plateau without sample current (Fig.5).

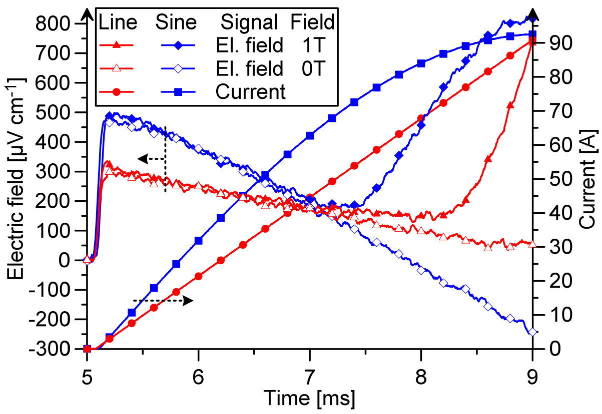


Fig.5 Electric field (left ordinates) signals recorded from the sample during sinusoidal and linear current pulses (right ordinates) without applied magnetic field and during a 1 T magnetic field pulse.

The resulting voltage vs. current response was further processed by subtracting a linear fit to the low-current behaviour, to eliminate any slope in the signal, and then scaled by the separation of the voltage taps.

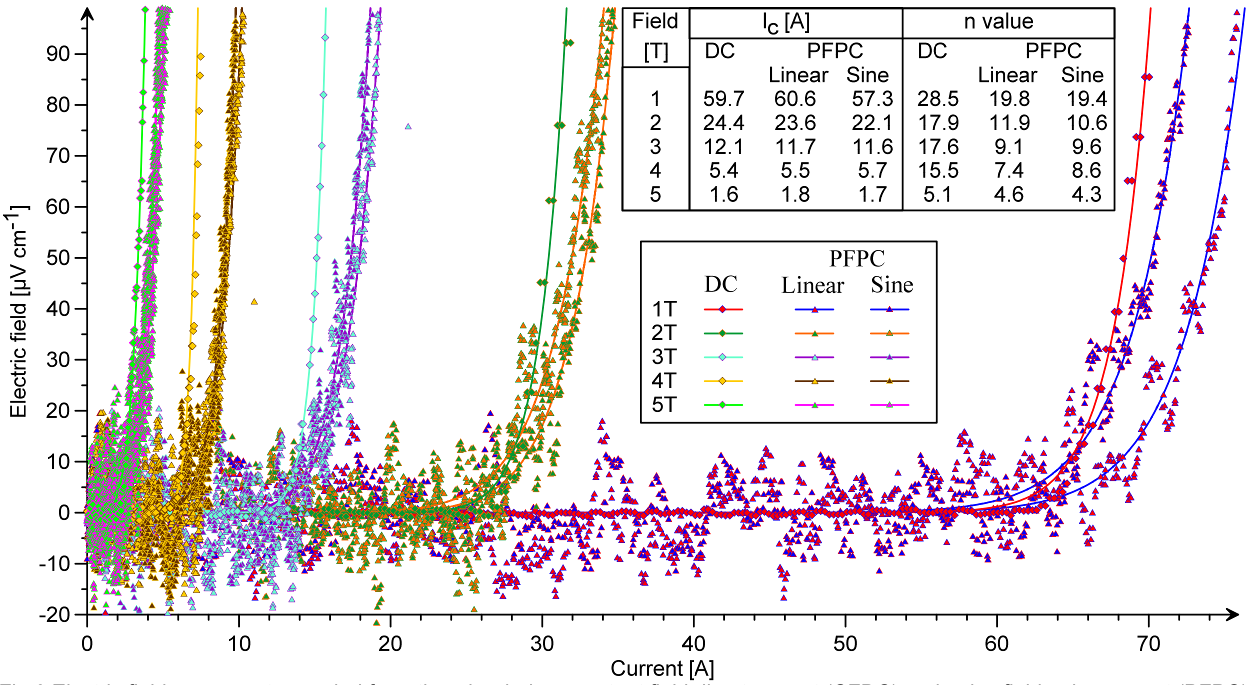
An example of the electric field vs. current (E vs. I) behaviour at 1 to 5 T is shown in Fig.6. $E=E_c\cdot(I/I_c)^n$ curves were fitted using the Levenberg-Marquardt method in the range of electric field up to 100 µV cm^{-1}, and the resulting I_c and n values are tabulated in Fig.6 based on a E_c=1 µV cm^{-1} criterion.

Results and discussion

The MgB_2/Glidcop wire prepared for this comparison of measurement techniques achieved a critical current density, J_c, of 10^4 A cm^{-2} at 3 T and 4.2 K, which is about three times lower than for recently reported wires in a copper sheath and with copper powder additions [5,6]. However, this and the small wire diameter (0.58 mm) helped to achieve a relatively low value of I_c, which was very desirable because it allowed measurements to be performed in low magnetic fields with the available current supplies. The use of a low resistivity metal sheath (Glidcop) and its thin wall also helped to minimise current transfer voltages during measurements on such short wire samples with closely-spaced current contacts and voltage taps. Any contribution of a very thin $MgCu_2$ reaction layer (Fig.1) to the current transfer is also believed to be small as in CFDC measurements no resistive slope in the sample voltage due to current transfer was observed.

With the aim of better differentiating between the resulting E-I curves from linear and sinusoidal current ramps in Fig.6, the amplitude of current pulses for each magnetic field pulse was selected in such a way that the maximum electric field (after corrections) from the sample at maximum current was close to 200 µV cm^{-1}. This ensured that the knee of the E-I curve for the sinusoidal ramp was measured when the rate of change of sample current was decreasing to zero.

Critical currents obtained by regression analysis of the voltage vs. current behaviour from both CFDC and PFPC techniques are in good agreement (Fig.6 and Fig.7). Linear and sinusoidal pulse shapes resulted in very similar estimates of I_c, without any systematic trend in these values. The noise level for voltage measurements without software averaging was on the level of 20 µV, so it is likely that the previously-reported qualitative approach [1-4] would correspond to an electric field criterion at least one order of magnitude higher. Adopting the same criterion may therefore account for ~10% $I_c(B)$ of the discrepancy between the previously-reported PFPC and CFDC techniques. Clearly, when using the same criterion, some I_c



Field [T]	I_c [A] DC	I_c [A] PFPC Linear	I_c [A] PFPC Sine	n value DC	n value PFPC Linear	n value PFPC Sine
1	59.7	60.6	57.3	28.5	19.8	19.4
2	24.4	23.6	22.1	17.9	11.9	10.6
3	12.1	11.7	11.6	17.6	9.1	9.6
4	5.4	5.5	5.7	15.5	7.4	8.6
5	1.6	1.8	1.7	5.1	4.6	4.3

Fig.6 Electric field vs. current recorded from the wire during constant field direct current (CFDC) and pulse field pulse current (PFPC) measurements with two shapes of current ramp (Fig. 2). The inset table presents the critical current I_c and n values obtained for each curve.

discrepancy remains. Most of these discrepancies arise from the fact that the E-I curves from PFPC are shifted to higher currents due to the high current ramp rate as was reported in [8], but with much lower n values. The n values measured in PFPC are lower than those from CFDC measurements, but quite similar for both sinusoidal and linear current pulse shapes.

The current source used in the present work restricts the range of currents which can be achieved but provides a very high degree of flexibility in controlling the current pulse shape and duration. This is essential for optimising PFPC $I_c(B)$ characterisation, particularly in the high field region where the previously explained heating and stability effects are less significant [2-4]. A systematic study of the effect of ramp rate, as controlled by pulse duration, is under way.

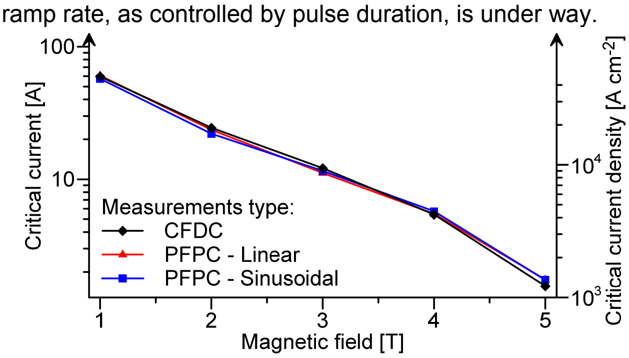


Fig.7. Critical current (density), $I_c(B)$ ($J_c(B)$), vs. magnetic field from constant field direct current (CFDC) and pulse field pulse current (PFPC) measurements for MgB_2 wire (Fig.1) at 4.2 K.

Conclusions

A refinement of the PFPC technique for $I_c(B)$ measurement has been demonstrated, in which I_c can be determined at a chosen electric field criterion from a single current pulse. I_c and n values are in good agreement with CFDC results, with little dependence on the current pulse shape, and most of the differences being caused by the much higher ramp rate for the PFPC technique.

Acknowledgments

M Woźniak gratefully acknowledges Siemens Magnet Technology for financial support.

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***Authors**: mgr inż. Mariusz Woźniak, dr Simon C. Hopkins and prof. dr Bartłomiej A. Głowacki, Department of Materials Science and Metallurgy, University of Cambridge, Pembroke Street, Cambridge, CB2 3QZ, UK, prof. dr Głowacki also Institute of Power Engineering, Augustówka 6, 02-981 Warsaw, Poland. E-mails: mw477@cam.ac.uk, sch29@cam.ac.uk and bag10@cam.ac.uk.*