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Towards optimisation of multi-pulse, multi-temperature pulsed field magnetisation of bulk high-temperature superconductors

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Outline

- **Pulsed field magnetisation (PFM)**
- **Modelling trapped field capability**
  - Simulating field-cooling (FC) & zero-field-cooling (ZFC) magnetisation
- **Modelling PFM & multi-pulse PFM**
  - Electromagnetic & thermal considerations
  - Simulating multiple magnetic field pulses
- **Main results & conclusions**

Pulsed Field Magnetisation

- **PFM technique: compact, mobile, relatively inexpensive**
- **Issues: B_{trap} [PFM] < B_{trap} [FC], [ZFC]**
  - Temperature rise ΔT due to rapid movement of magnetic flux
- **Record PFM trapped field: 5.2 T @ 29 K**
  Top surface of 45 mm diameter Gd-Ba-Cu-O
  Fujishiro et al. *Physica C* 2006
  - Record trapped field by FC: 17.6 T @ 26 K
    Centre of 2 x 25 mm diameter Gd-Ba-Cu-O
    Durrell et al. *Supercond. Sci. Technol.* 2014

Pulsed Field Magnetisation

- **Many considerations for PFM:**
  - Pulse magnitude, pulse duration, temperature(s), number of pulses, type of magnetising coil(s), use of ferromagnetic materials
  - Dynamics of magnetic flux during PFM process

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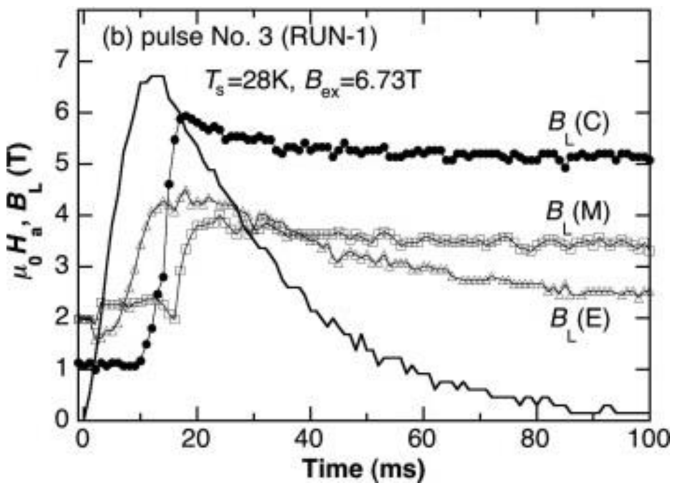
  - Dynamics of magnetic flux during PFM process
- **Multi-pulse PFM: effective in increasing trapped field/flux**



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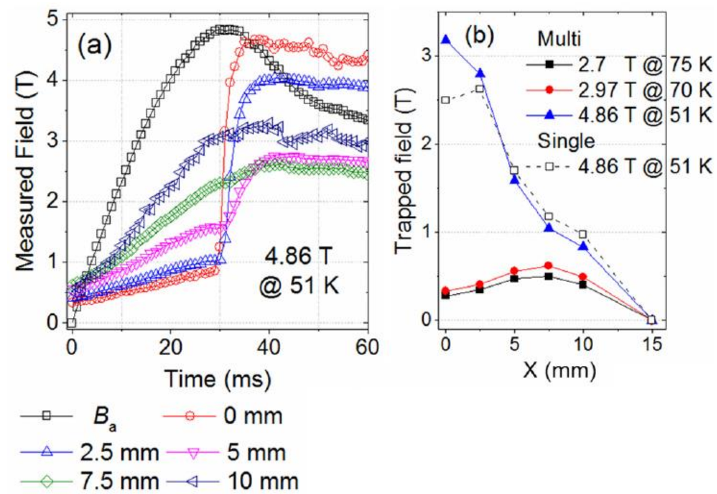
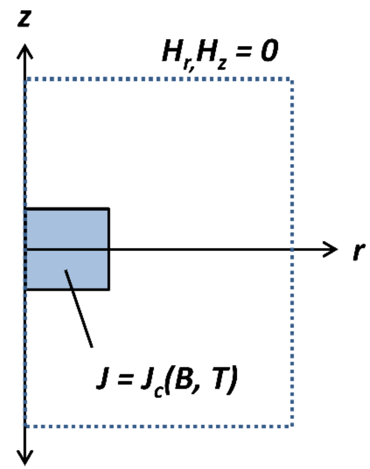


Zhou et al. *Appl. Phys. Lett.* 2017

Modelling Trapped Field Capability

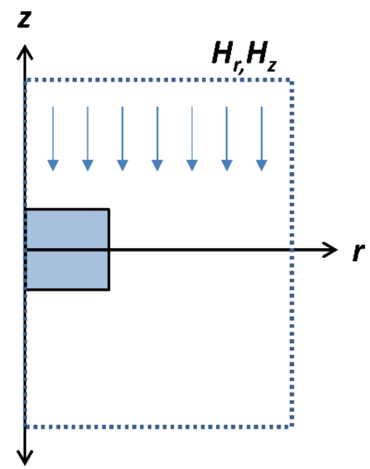
Model #1

- Stationary
- Comsol Multiphysics 5.2a
  - 2D axisymmetric
  - AC/DC module
  - Magnetic Field (mf) interface
  - External Current Density node
- No flux creep
- Time taken: ~ 2-3 seconds



Model #2

- Time-dependent
- Comsol Multiphysics 5.2a
  - 2D axisymmetric
  - AC/DC module
  - Magnetic Field Formulation (mfh) interface
- *E*-*J* power law, $E \propto J^n$ (flux creep)
- Apply + remove background field
- Time taken: ~ 1-2 hours

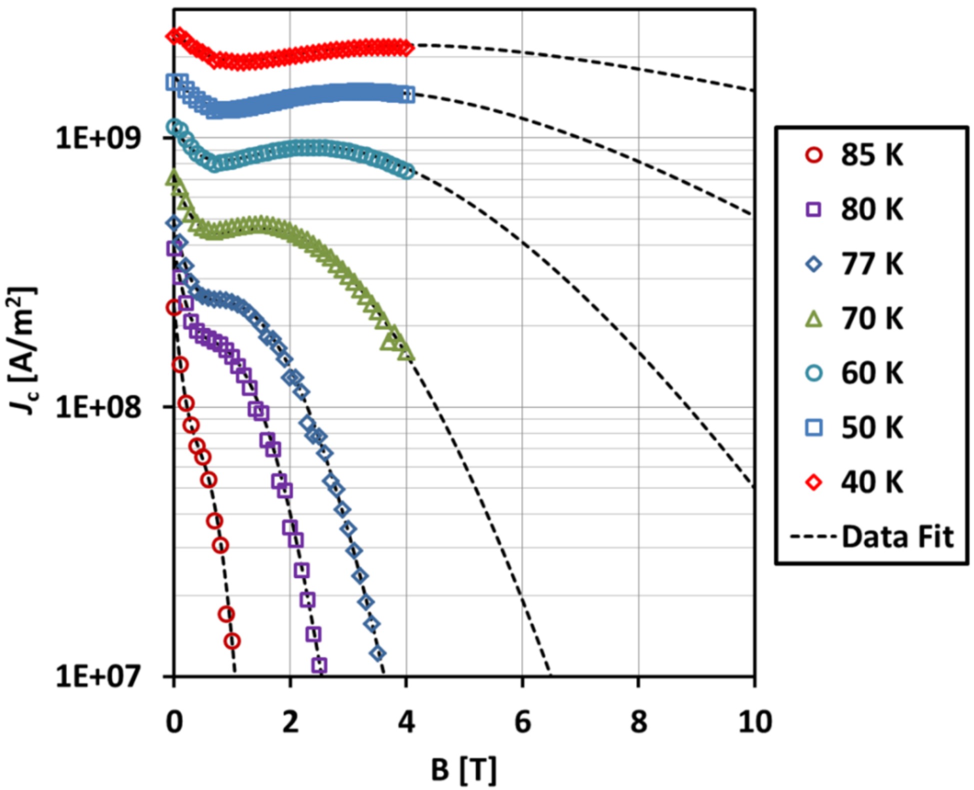


Modelling Trapped Field Capability

$J_c(B, T)$ characteristics

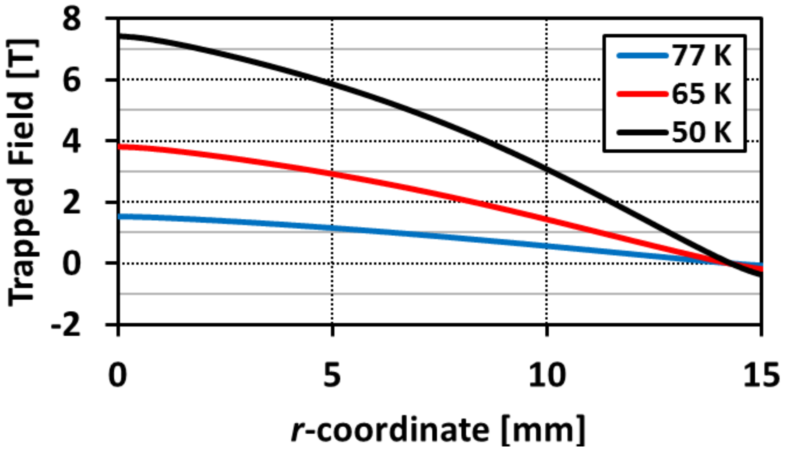
- Measured from a small specimen taken from representative sample: $GdBa_2Cu_3O_7$ (15wt% Ag)
- Input into model using direct interpolation of experimental data, i.e., look-up table
- Can dramatically speed up model
- Can also use fitting equation for fishtail effect in (RE)BCO materials:

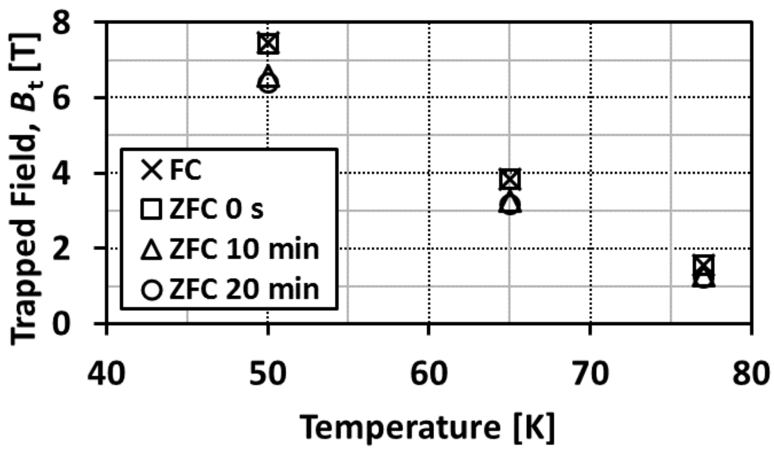
$$J_c(B) = J_{c1}\exp\left(-\frac{B}{B_L}\right) + J_{c2}\frac{B}{B_{\max}}\exp\left[\frac{1}{y}\left(1-\left(\frac{B}{B_{\max}}\right)^y\right)\right]$$



Modelling Trapped Field Capability

Results





Magnetisation	Time	Trapped Field	
77 K			
FC	---	1.544 T	
ZFC [5 T]	t = 0 min	1.546 T	
	t = 10 min	1.263 T	
	t = 20 min	1.223 T	**79%**
65 K			
FC	---	3.826 T	
ZFC [10 T]	t = 0 min	3.827 T	
	t = 10 min	3.256 T	
	t = 20 min	3.158 T	**82.5%**
50 K			
FC	---	7.449 T	
ZFC [20 T]	t = 0 min	7.422 T	
	t = 10 min	6.577 T	
	t = 20 min	6.405 T	**86%**

PFM Modelling Framework

Electromagnetic properties modelled as Model #2 (ZFC); magnetising fixture assumed as solenoid coil:

$$I_{pulse}(t) = N \cdot I_0 \frac{t}{\tau} \exp\left(1 - \frac{t}{\tau}\right) \qquad \tau = 15\text{ ms}$$

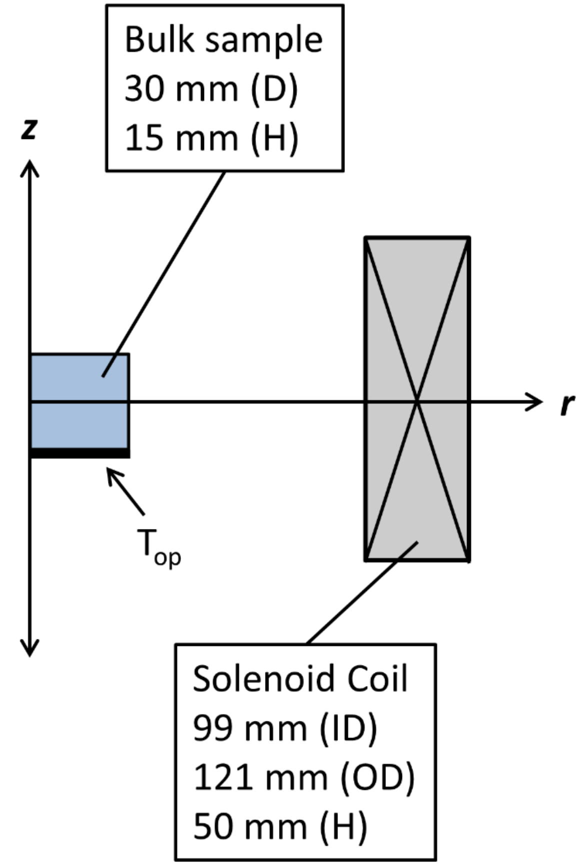
Thermal behaviour needs to be modelled during PFM; governing equations:

$$\rho \cdot C \frac{\mathrm{d}T}{\mathrm{d}t} = \nabla \cdot (k \nabla T) + Q$$

$$Q = E \cdot J$$

Heat source,
coupling with EM model + $J_c(B, T)$

ρ = mass density (bulk 5900 kg/m^3, indium 7310 kg/m^3)
C = specific heat (measured, temperature-dependent)
κ = thermal conductivity:
κ_{ab} = 20 W/(m·K), κ_c = 4 W/(m·K), κ_{indium} = 0.5 W/(m·K)

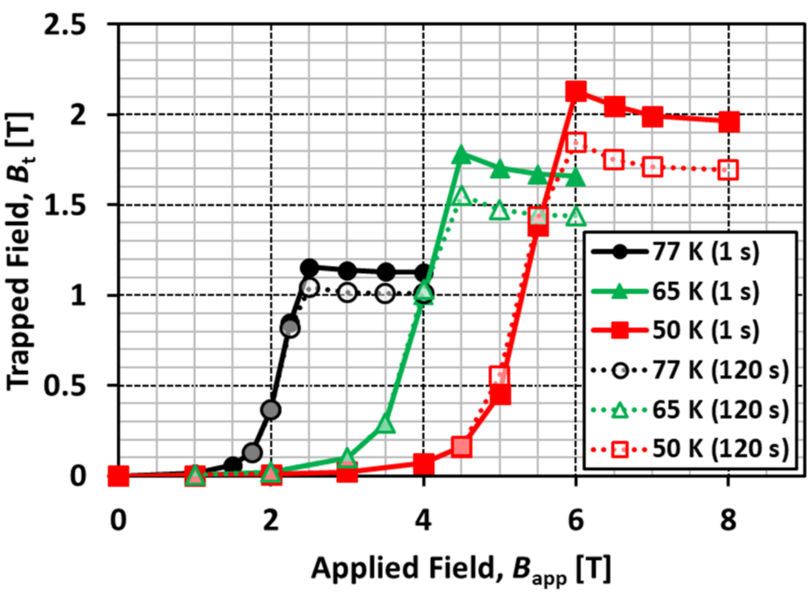


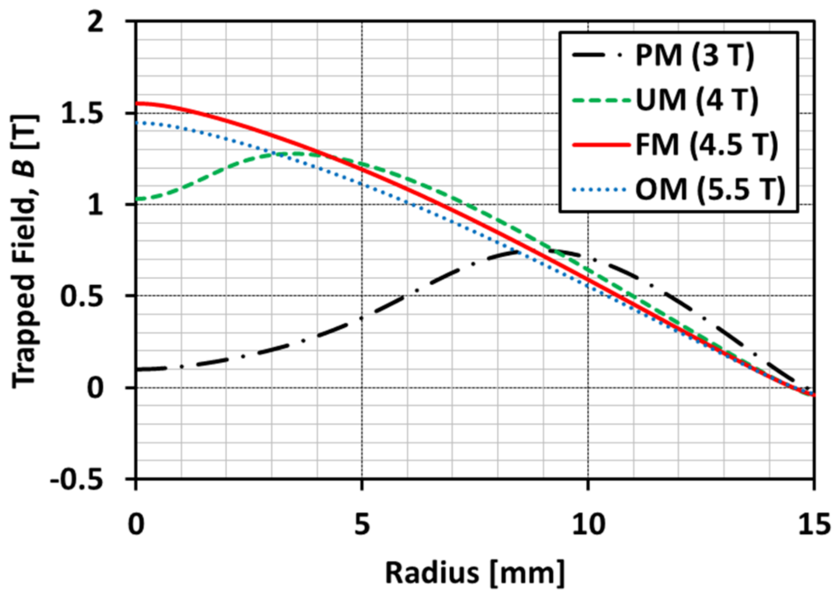
PFM Single Pulse Results

- *t* = 120 s → flux creep relaxation & cooling back to operating temp.

- Percentage of ZFC(*t* = 20 min):
  - 77 K 85%
  - 65 K 49%
  - 50 K 29%

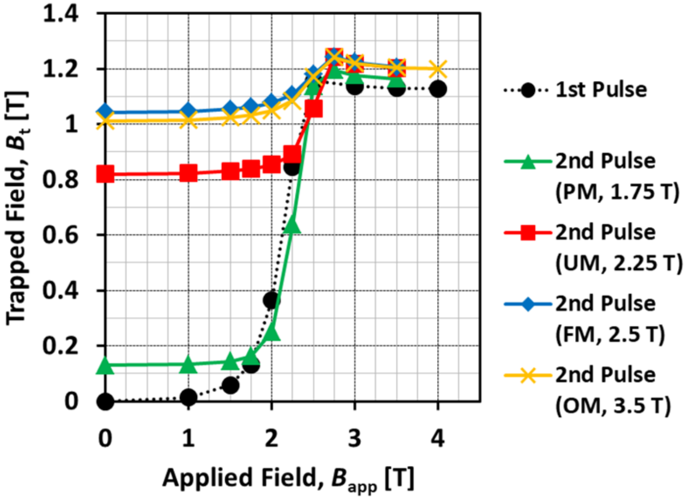
- Four specific cases as initial conditions for 2nd pulse:
  - Partially-magnetised (PM), so-called 'M-shaped' profile
  - Under-magnetised (UM)
  - Fully-magnetised (FM)
  - Over-magnetised (OM)



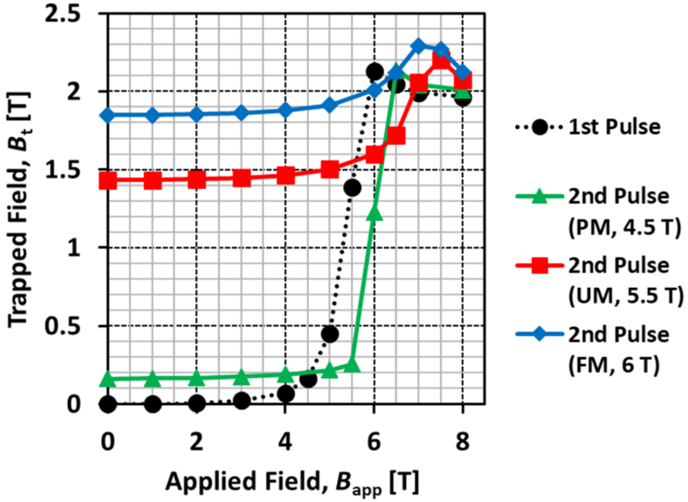


PFM 2nd Pulse Results

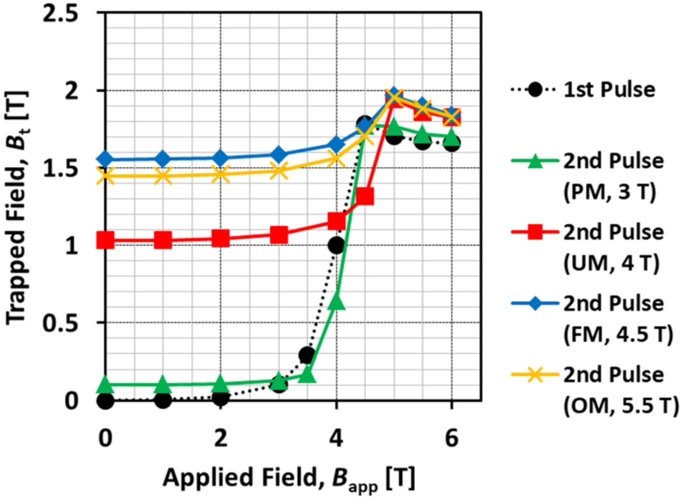
77 K



50 K



65 K

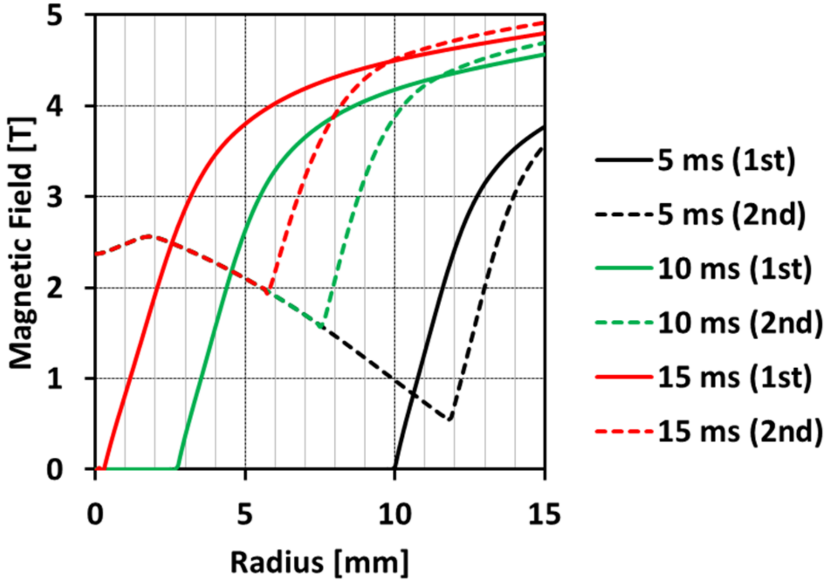


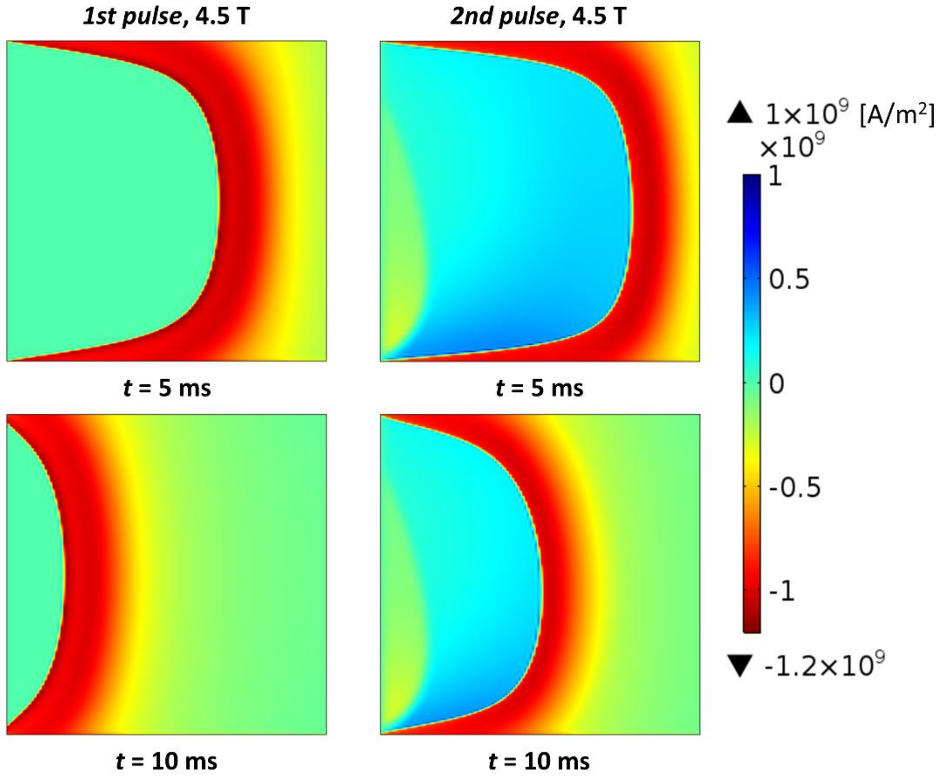
For all *T*, trapped field after 2nd pulse exhibits two particular characteristics:

1) Increased trapped field, B_t, when the bulk is fully magnetised; maximum value when the 1st pulse results in full magnetisation
2) Increased activation field: applied field, B_{app}, required to fully magnetise the sample

PFM 2nd Pulse: Magnetic Flux Penetration

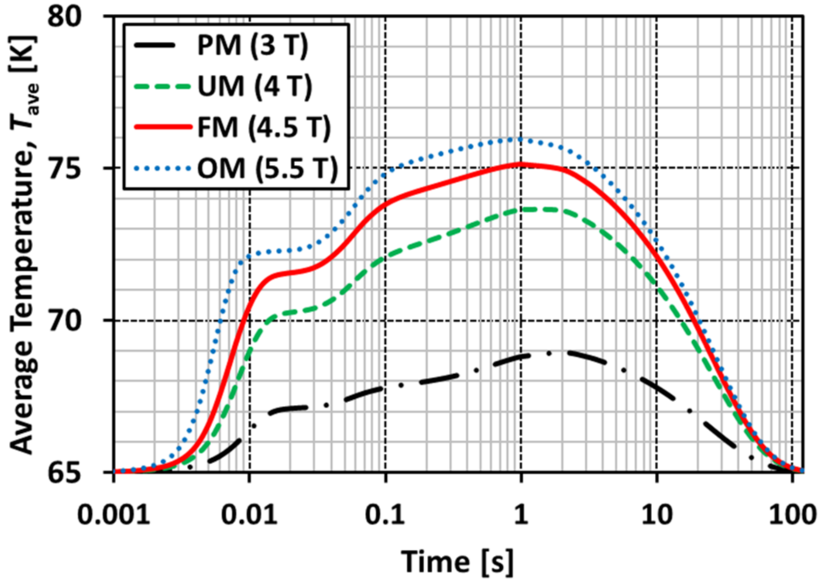
- Why does this occur?
  - More difficult for magnetic flux to penetrate the sample due to existing trapped field
  - Existing, induced supercurrent flows in opposite direction

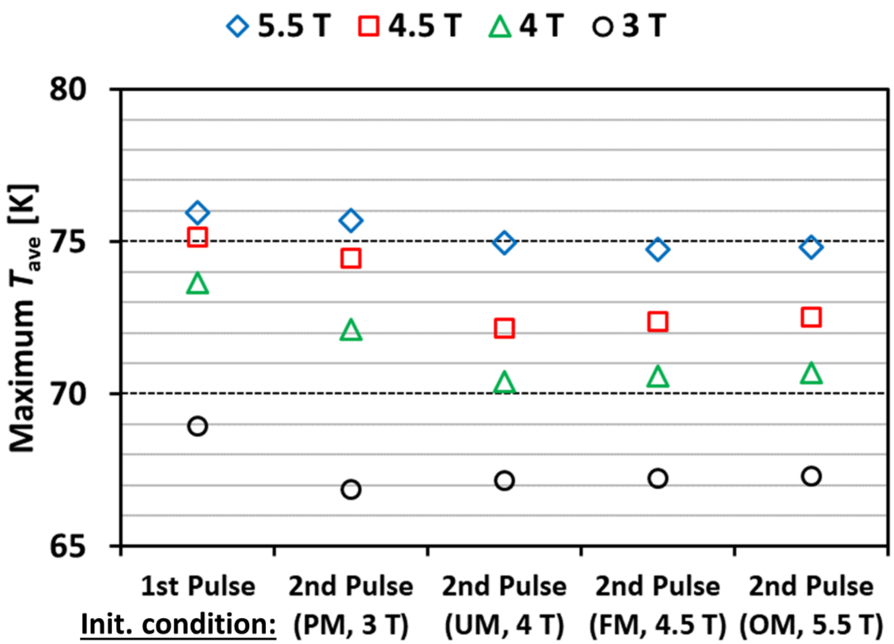




PFM 2nd Pulse: Thermal Behaviour

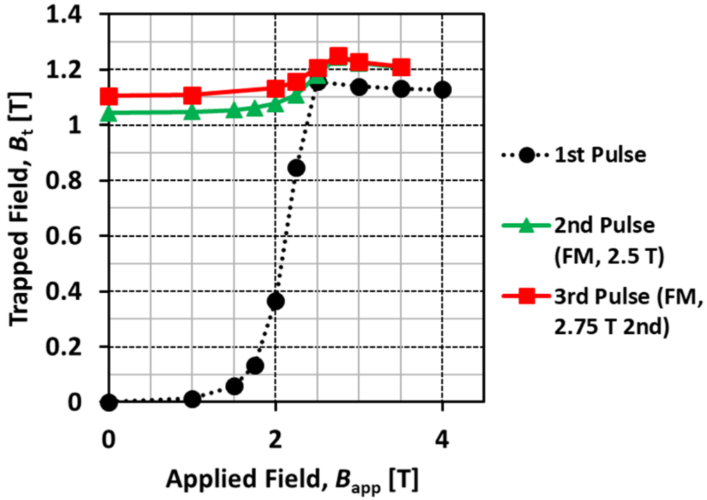
- Why does this occur?
  - Reduced dynamic movement of flux = lower temperature rise for equivalent next pulse
  - Can examine the average temperature, T_{ave}, during & after PFM:



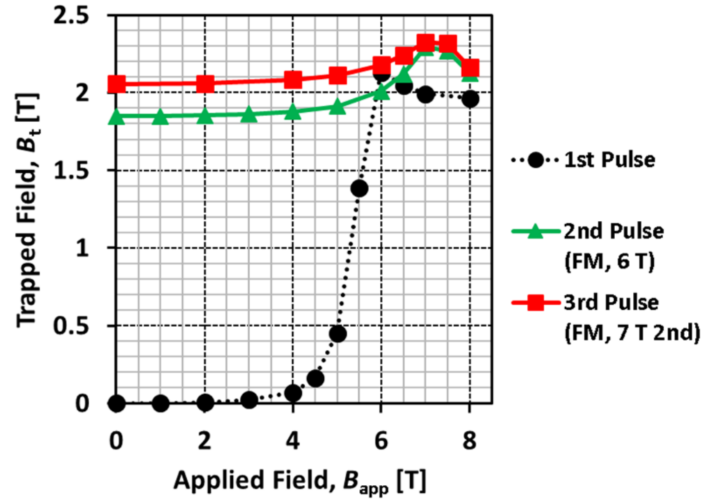


PFM 3rd Pulse Results

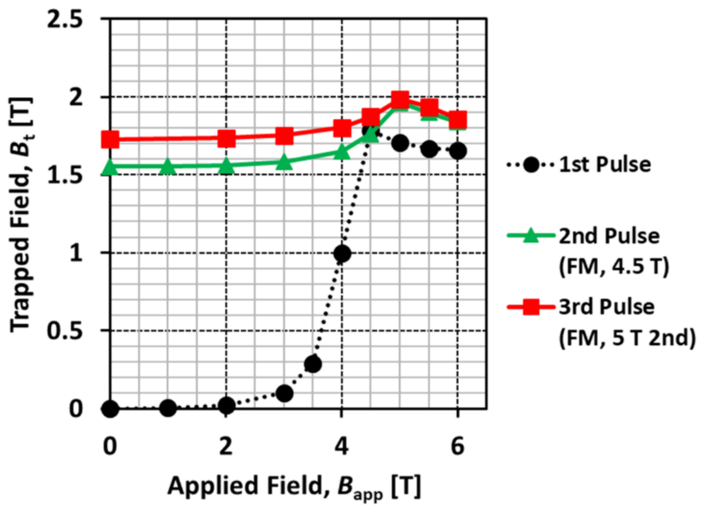
77 K



50 K



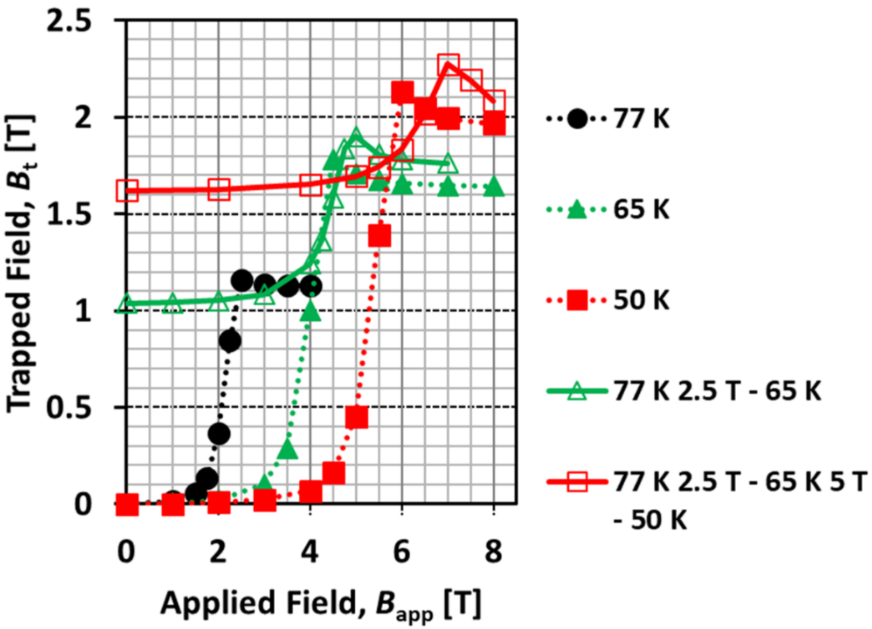
65 K



Similar results are found for the 3rd pulse; however, increase in B_t is marginal, suggesting saturation has been reached

PFM: Towards Multi-Pulse, Multi-Temperature

77 K → 65 K → 50 K



- At t = +120 s, temperature is lowered to next temperature (–0.5 K/s)
- Fully magnetised (FM) cases as initial conditions
- Maximum trapped field, $B_{t,max}$, slightly less than for multiple pulses at constant T
- More investigations & optimisation needed!

Summary

- **A 2D axisymmetric finite element method based on the *H*-formulation was extended to investigate multi-pulse PFM**
- **An increase in the trapped field, B_t, can be achieved after a 2nd pulse:**
  - This is maximised when the 1st pulse results in full magnetisation; and
  - An increased applied field is necessary for the 2nd pulse
- **This occurs because:**
  - It is more difficult for the magnetic flux to penetrate the already-magnetised sample
  - There is a lower temperature rise from the reduced dynamic movement of flux
- **A 3rd pulse results in a marginal increase in B_t**
- **Preliminary multi-pulse, multi-temperature investigation showed similar, but slightly lower, B_t**