Modelling the record trapped field by pulsed field magnetisation of a composite bulk MgB_2 superconducting ring

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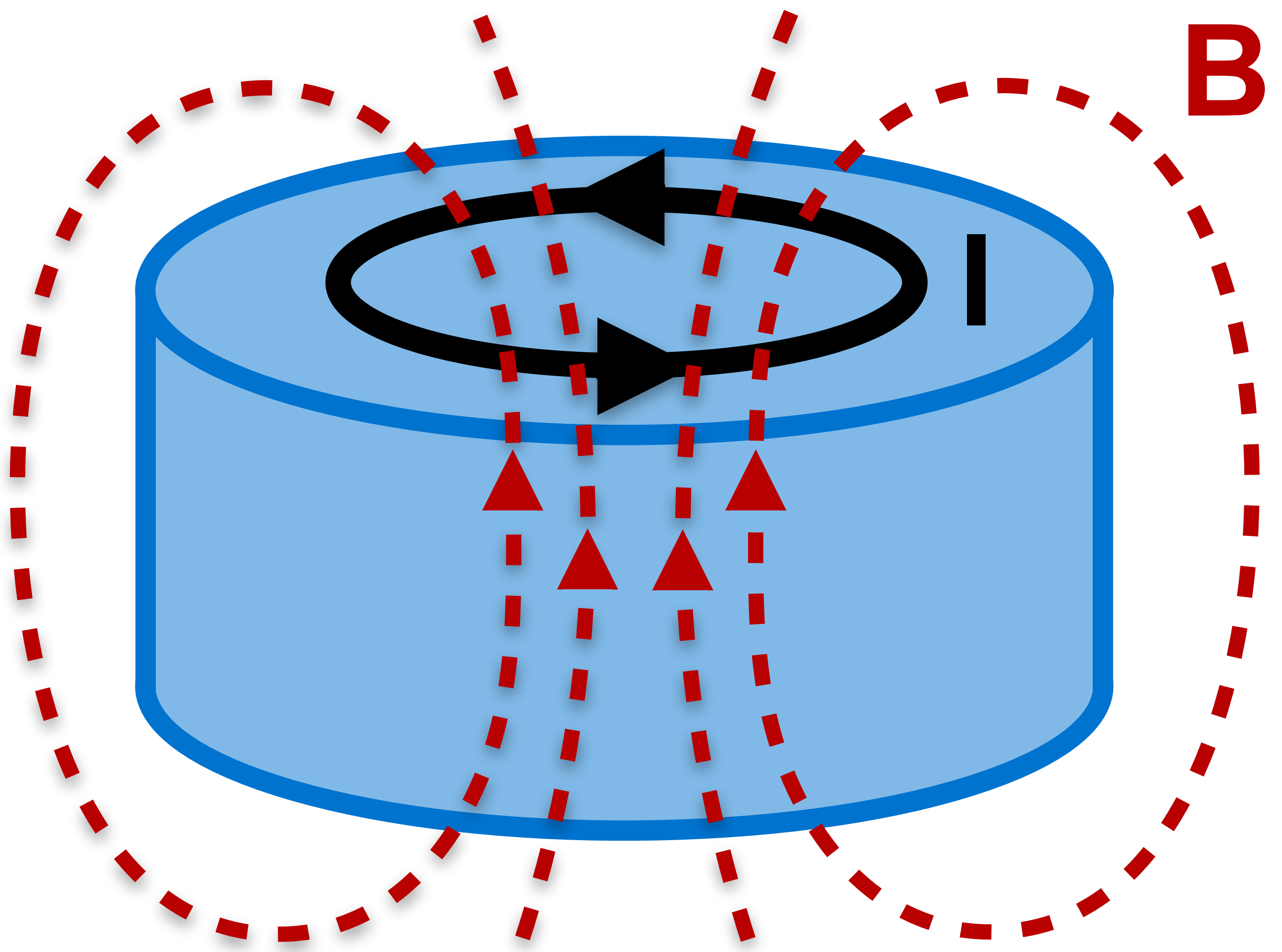
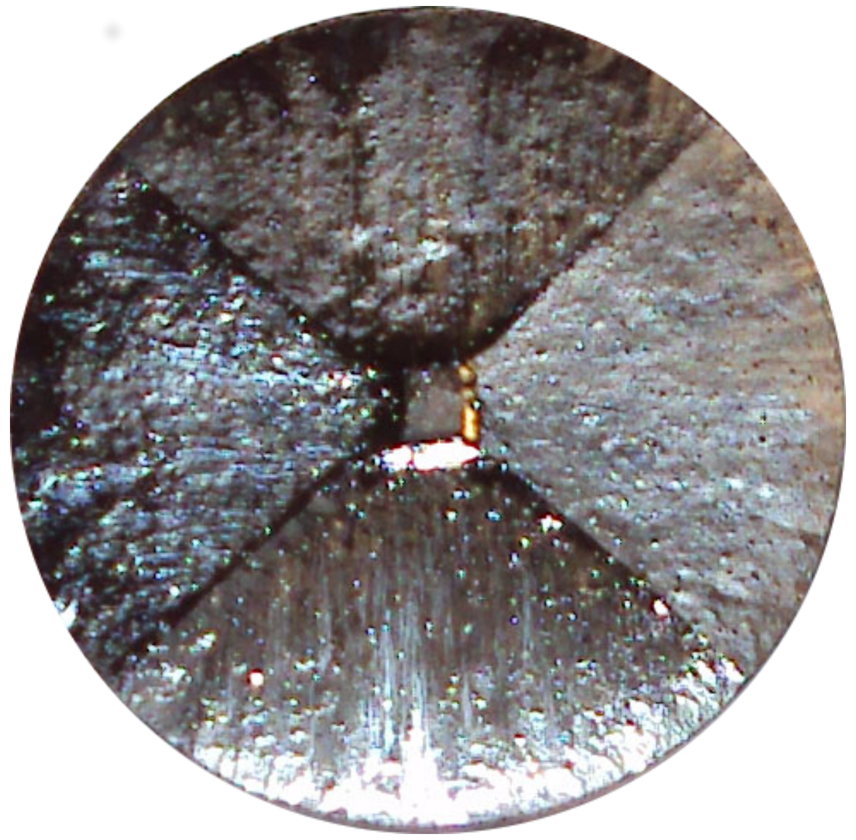
Introduction
Bulk Superconductors

- Bulk Superconductors are fabricated to 'trap' large fields; in excess of 17 T
- Magnetising currents are 'pinned' by the mixed state of superconductivity
- Larger bulks = greater magnetisation



Circulating 'super currents' are pinned within the bulk, resulting in a trapped magnetic field.



(RE)-BCO

MgB_2

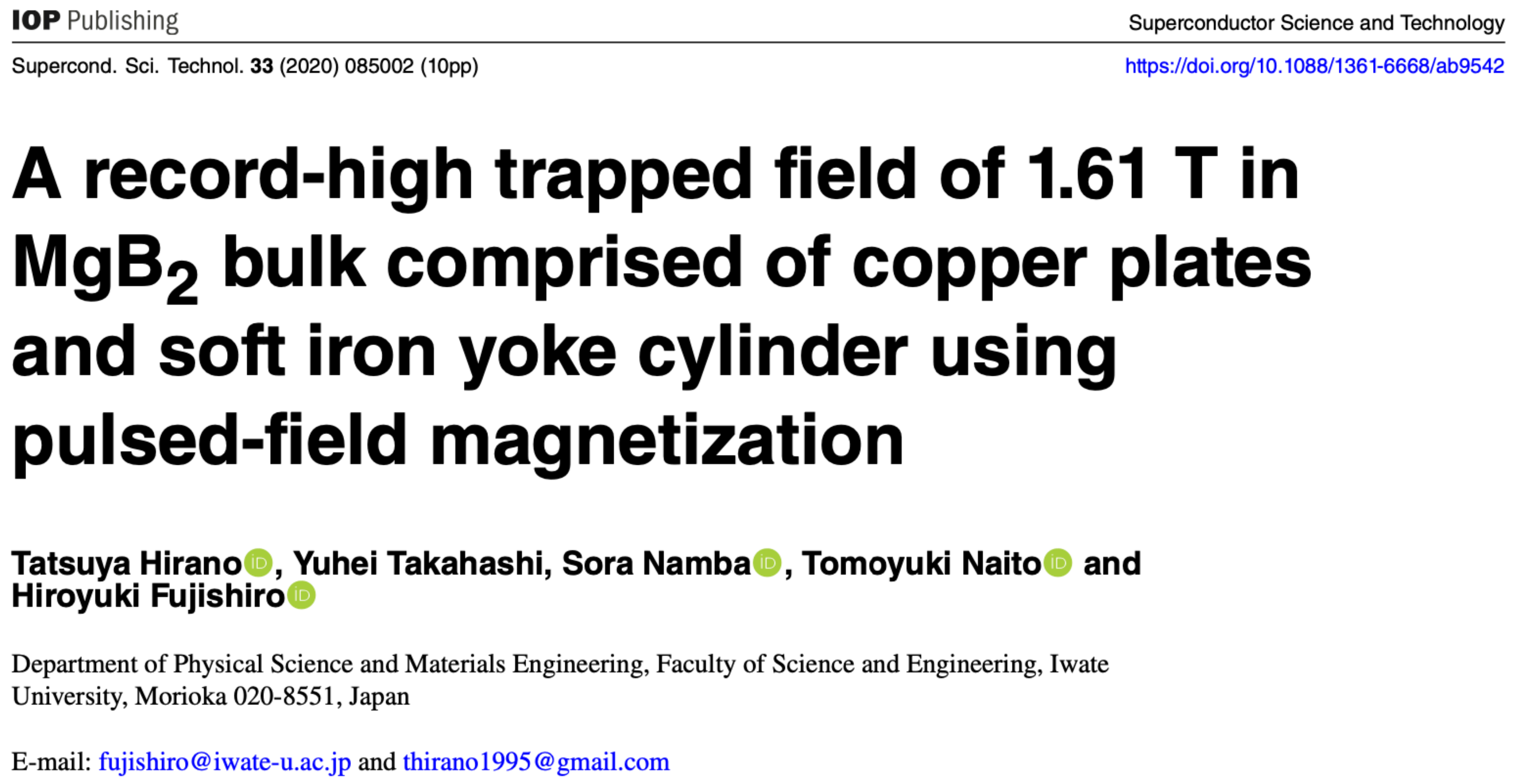
- MgB_2 is not quite HTS: T_c = 39 K
- Very uniform J_c; polycrystalline form
- An important alternative to HTS due to lightweight structure and manufacturability

Motivation

Record-High Trapped Field

- Hirano et al. achieved a record-high trapped field in 2020
- Earlier studies show split-coil, multiple pulsing, and pulse elongation can enhance trapped field
- Previous record of 1.1 T at 13 K was beaten with 1.61 T at 20 K using PFM
- Our numerical investigation was motivated by the results of Hirano et al. [1]

[1] Article published by Hirano and Fujishiro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A record-high trapped field of 1.61 T in MgB_2 bulk comprised of copper plates and soft iron yoke cylinder using pulsed-field magnetization

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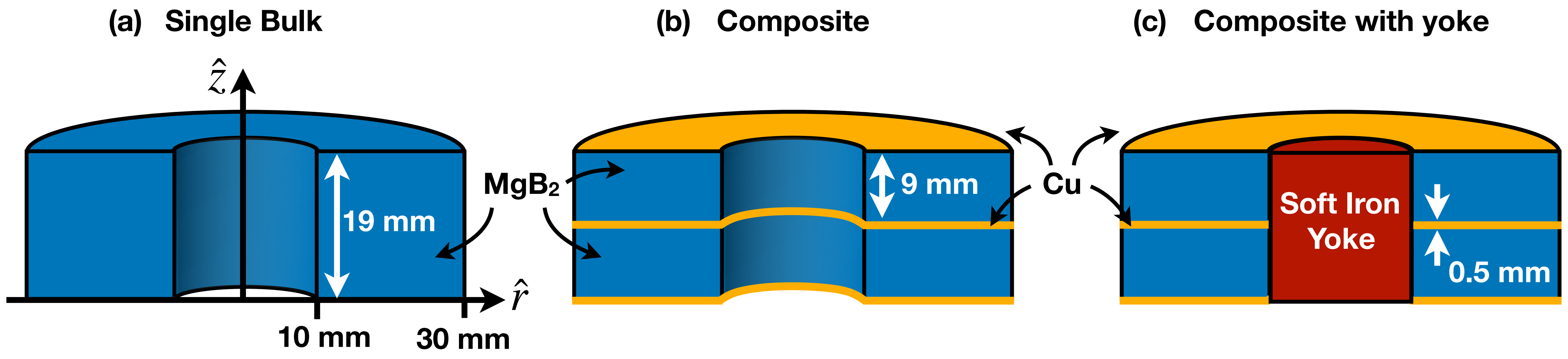
Sample configurations investigated by Hirano et al.

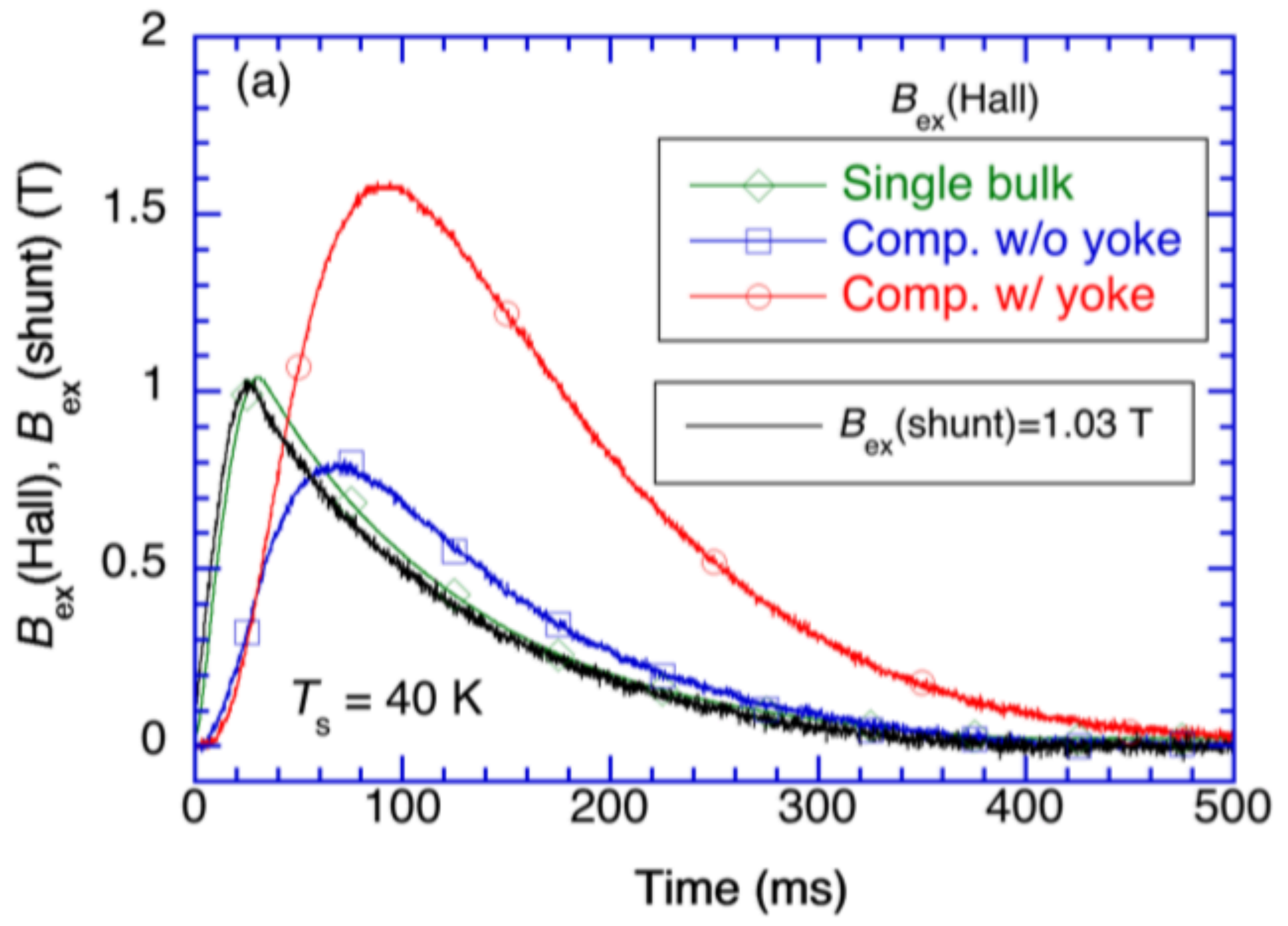


Motivation

Goals of Work

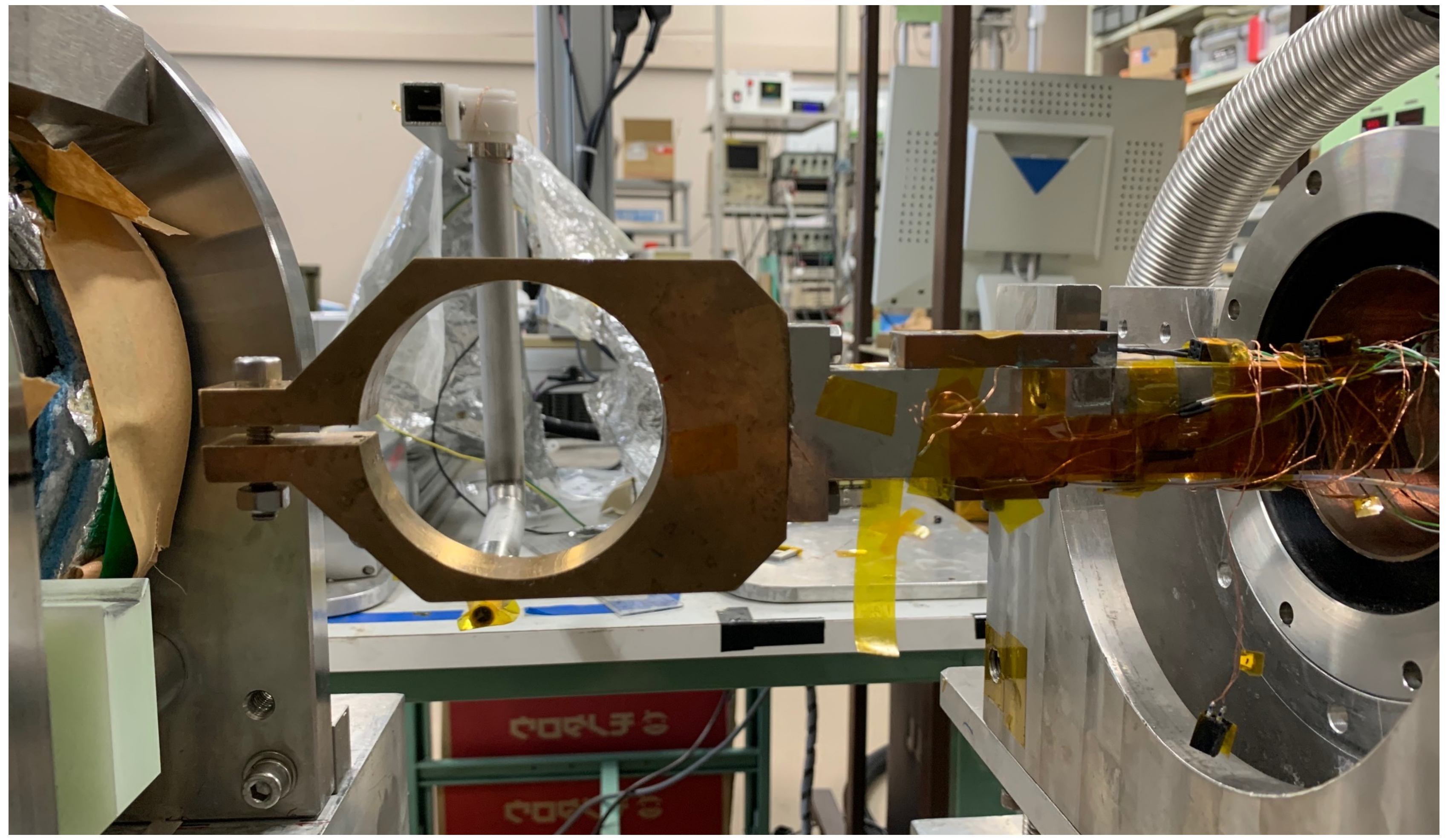
1. Accurate replication of geometry & experimental setup
2. Simulation of thermomagnetic properties and experimental results
3. Extend study for insights and interesting new findings

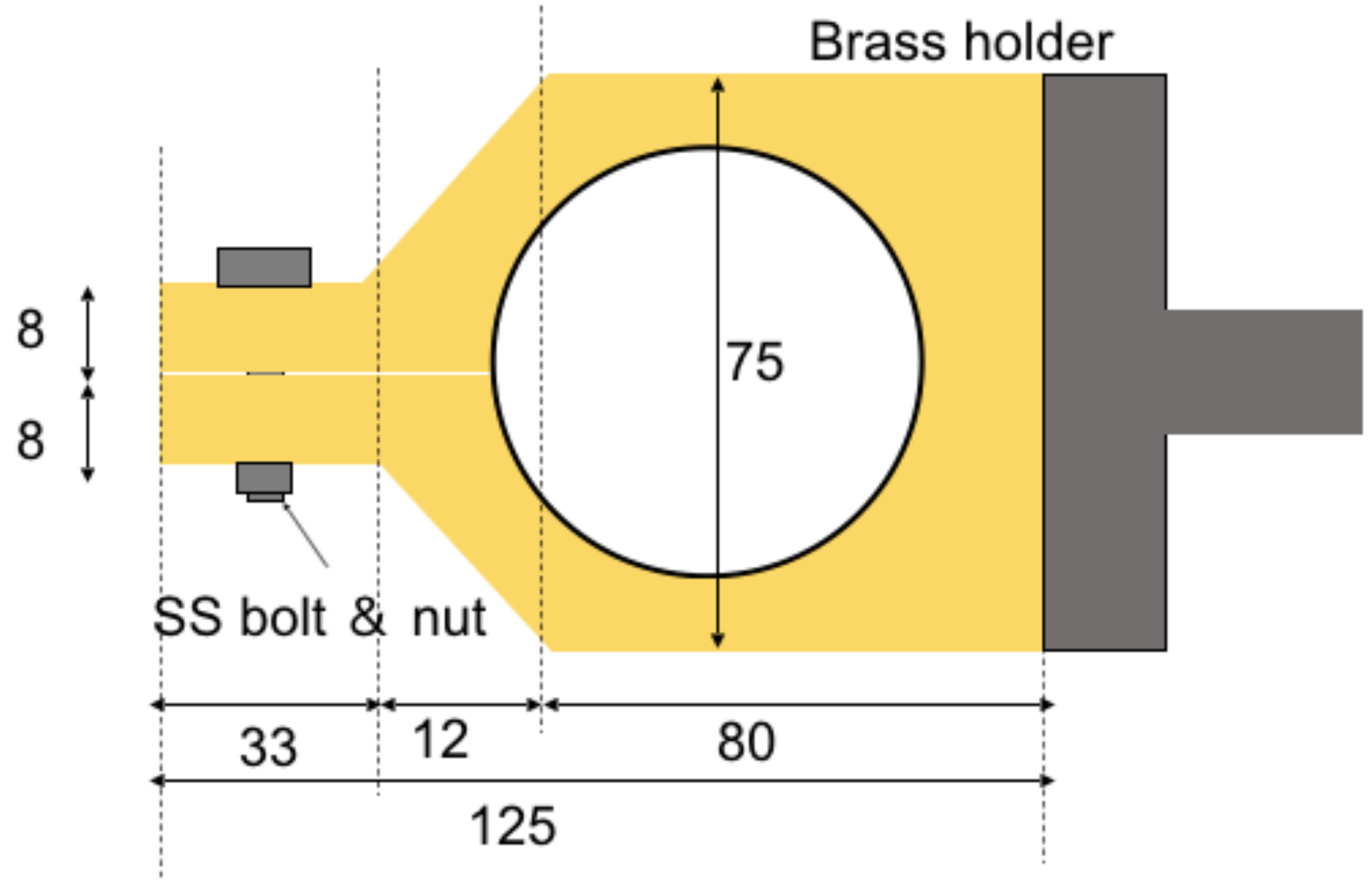
Calibration pulses from original paper. We need to reproduce these exactly.



Replicate with FEM

Photo of the original sample holder, used to hold the MgB_2 superconducting ring



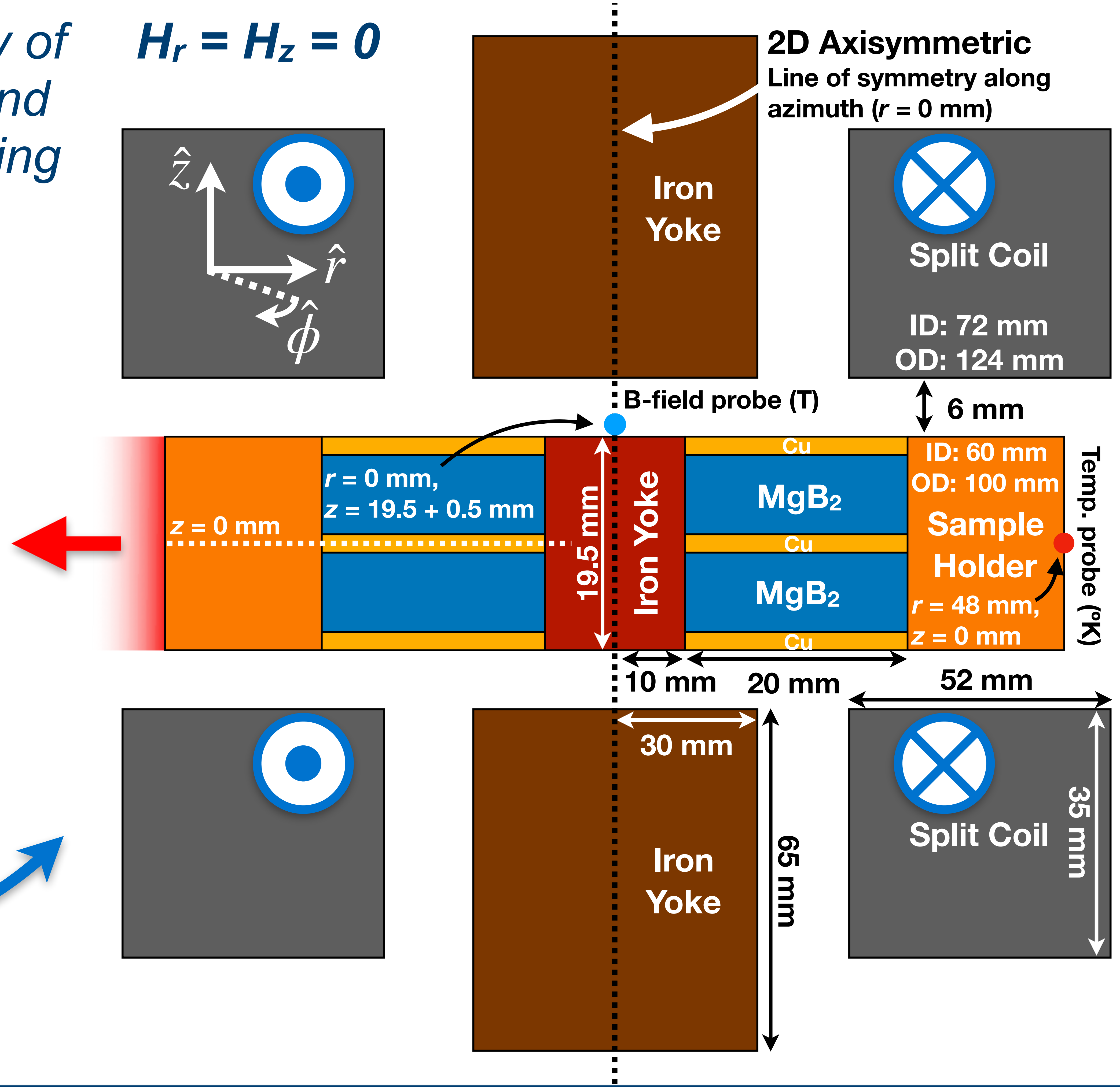


Modelling Details

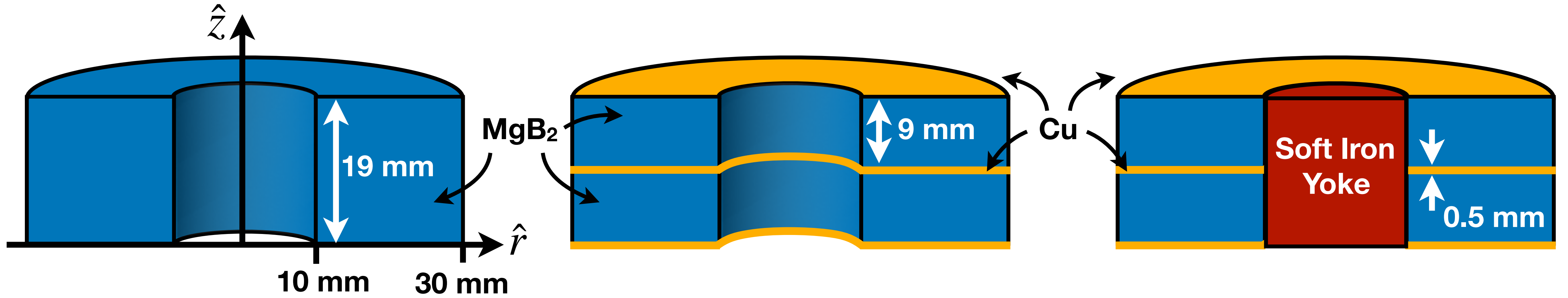
Formulation

- 2D axisymmetric model used
- Sample holder and magnetising fixture modelled with experimental data
- Current applied via split coil subdomain to generate pulse
- Cooling from boundary condition at sample holder periphery

Geometry of sample and magnetising fixture



Each configuration modelled with fixture



Modelling Details

Electromagnetic Formulation

- Finite Element Method with commercial package COMSOL utilised
- Governing equations use ***H-formulation***
- Applied pulse typical of PFM

Maxwell's Equations

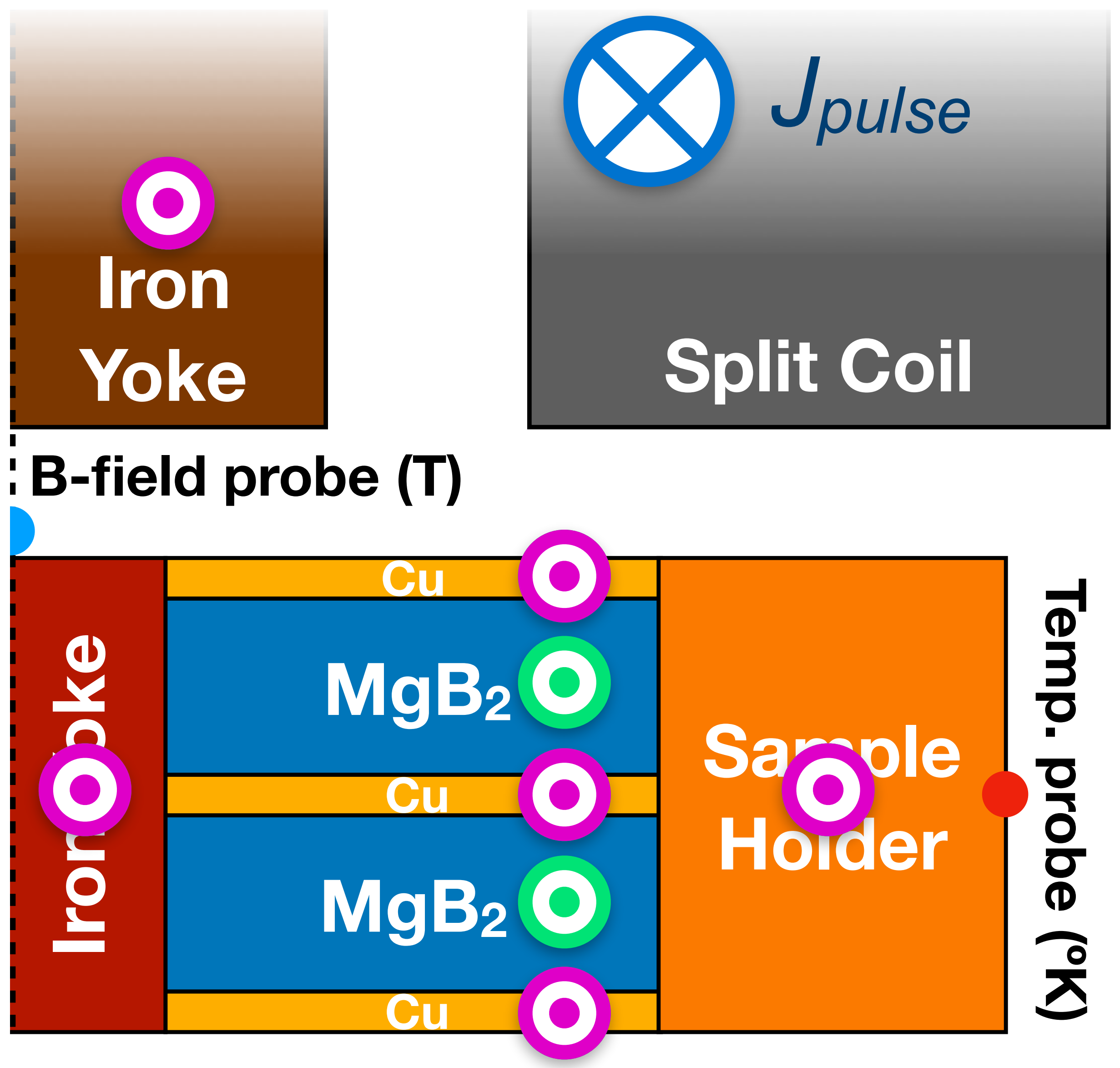
Faraday's Law / Ampere's Law

$$\begin{cases} \nabla \times \mathbf{H} = \mathbf{J} \\ \nabla \times \mathbf{E} = -\dfrac{\partial(\mu_o \mu_r \mathbf{H})}{\partial t} \end{cases}$$

Electrical conductivity defined via experimental data and calibration pulses

Lenz's Law

Induced Currents



Current Density

$$J_{pulse} = H_{ext} A \left(1 - e^{-\frac{t}{t_s}}\right)\left(e^{-\frac{t}{t_d}}\right)$$

Calibration pulses: 1.03 T

➡ *A is field dependent correction factor*

Modelling Details
Thermal Considerations

- Coupled problem of EM and thermal
- Heat equation with conductive loss and boundary conditions

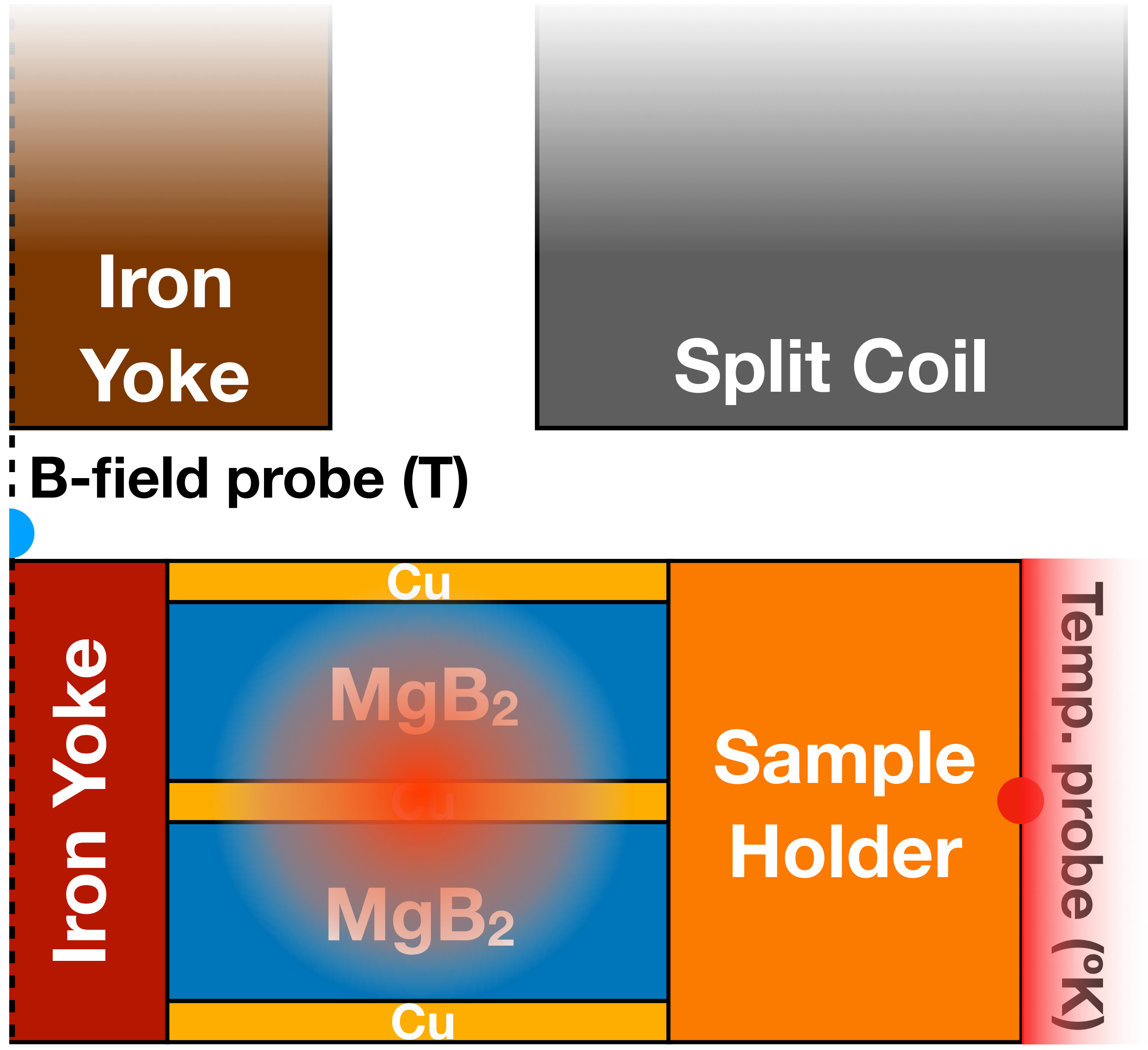
Heat Equation

$$\rho c_p \frac{\partial T}{\partial t} = \kappa \nabla^2 (T_r - T_{ri}) + Q$$

$$Q = E \cdot J$$

ρ = mass density, c_p = specific heat, κ = thermal conductivity, Q = heat source

Q generated in bulk & sample holder



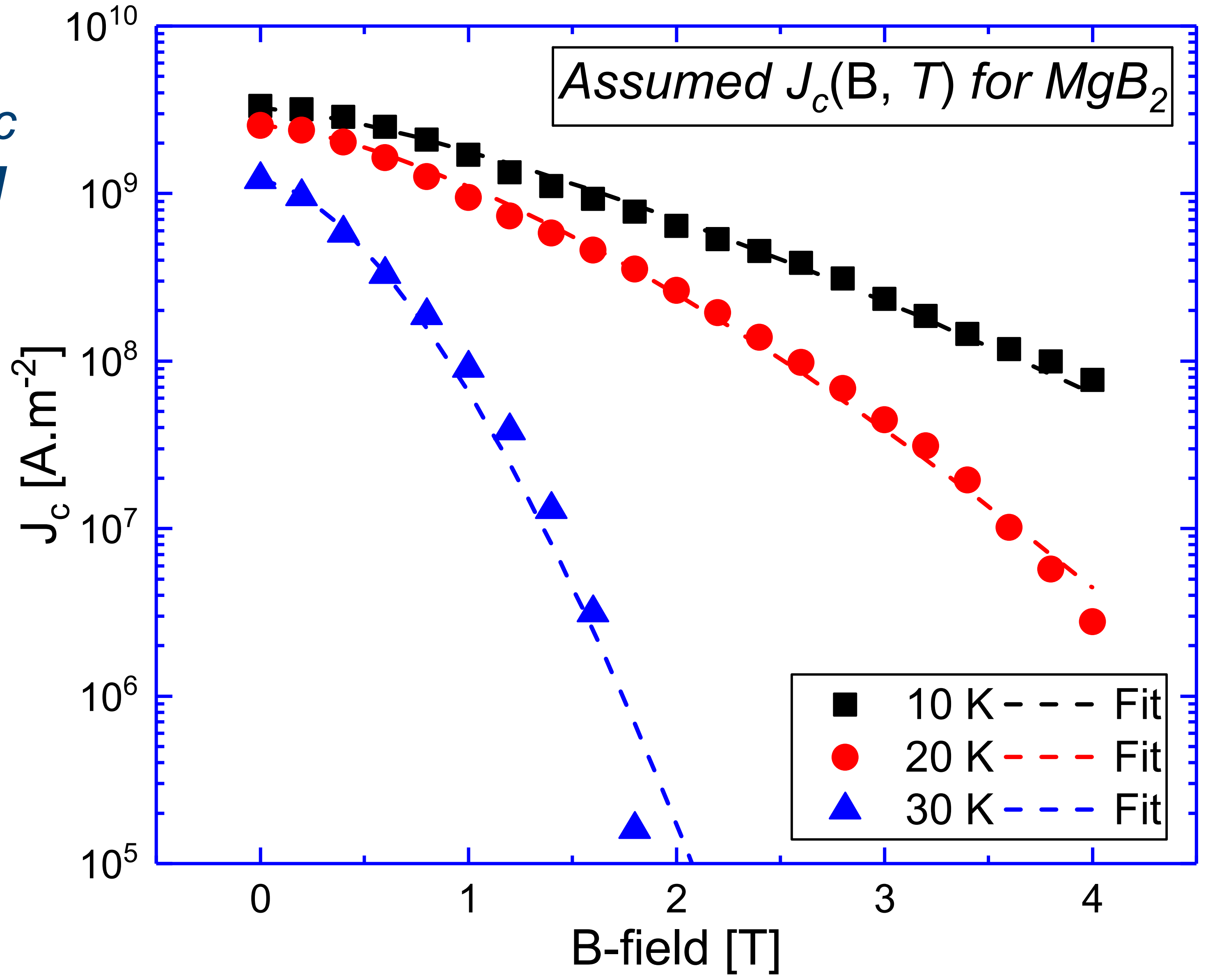
$$-K(T_r - T_{amb})$$

Cooling bulk via cold stage modelled through Fourier's law. Constant K was determined through iterative adjustment

Modelling Details
MgB_2 Considerations

- $J_c(B, T)$ interpolated from sample data
- Non-linear resistivity modelled via the E-J power law
- n-value assumed constant below 39 K

Interpolated J_c distribution [2]



[2] A. Ogino, T. Naito, and H. Fujishiro, "Optimization of infiltration and reaction process for the production of strong MgB_2 bulkmagnets," *IEEE Transactions on Applied Superconductivity* **27**, 1–5 (2017)

Critical Current Density

$$J_c(B,T) = \alpha \left(1 - \left(\frac{T}{T_c}\right)^2\right)^{0.5} e^{-\frac{B}{B_o\left(1-\left(\frac{T}{T_c}\right)^2\right)^{0.5}}}$$

E-J Power Law

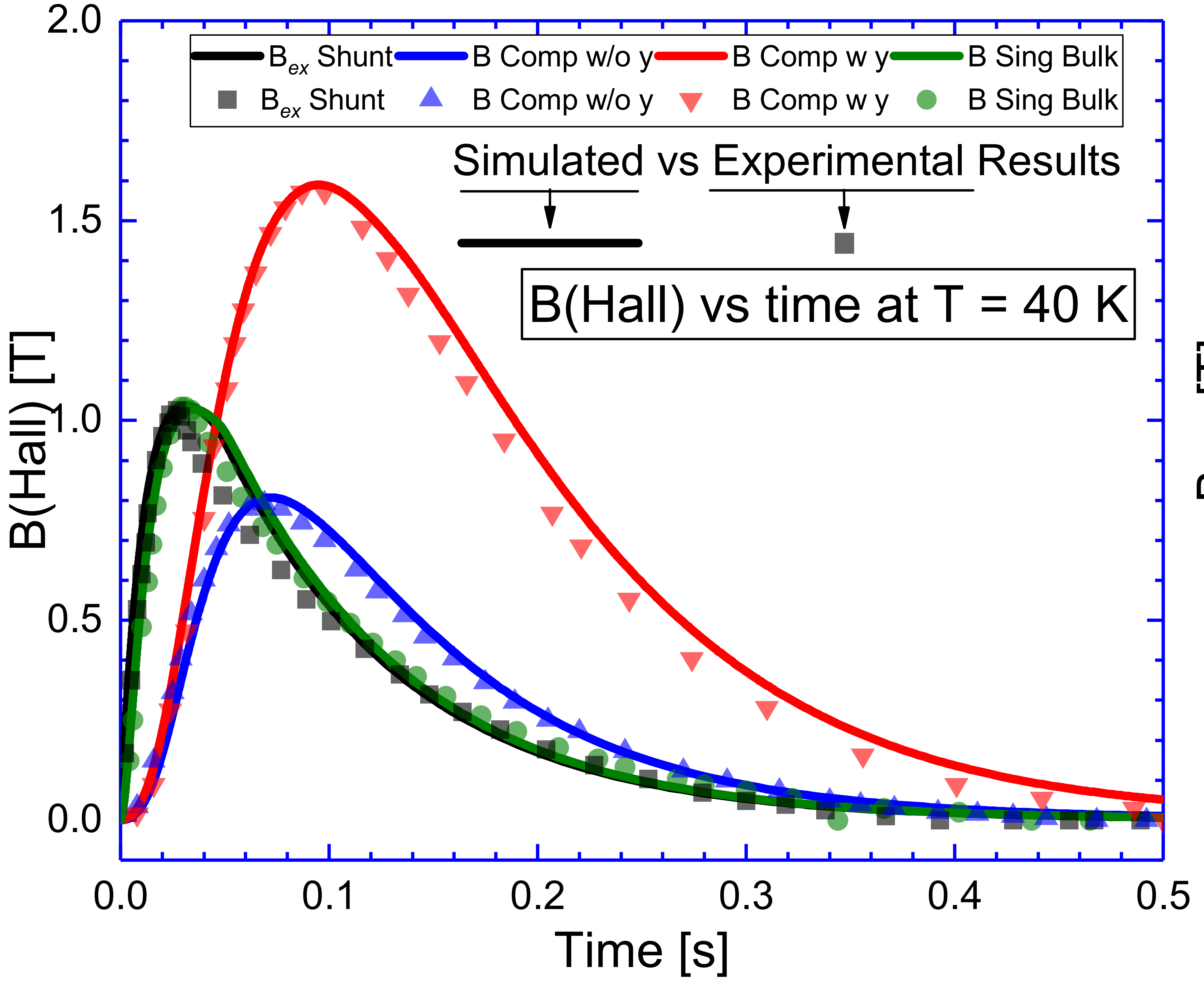
$$E = E_o \left(\frac{J(B,T)}{J_c}\right)^n \qquad n = \begin{cases} 45 & B < 4\text{ T},\ T < 39\text{ K} \\ 1 & \text{else} \end{cases}$$

$\alpha = J_{co}(B = 0\text{ T}, T = 10\text{ K})$, $T_c = 39$ K, $B_o = 0.85$ T, $E_o = 1\text{x}10^{-4}$ V.m^{-1}

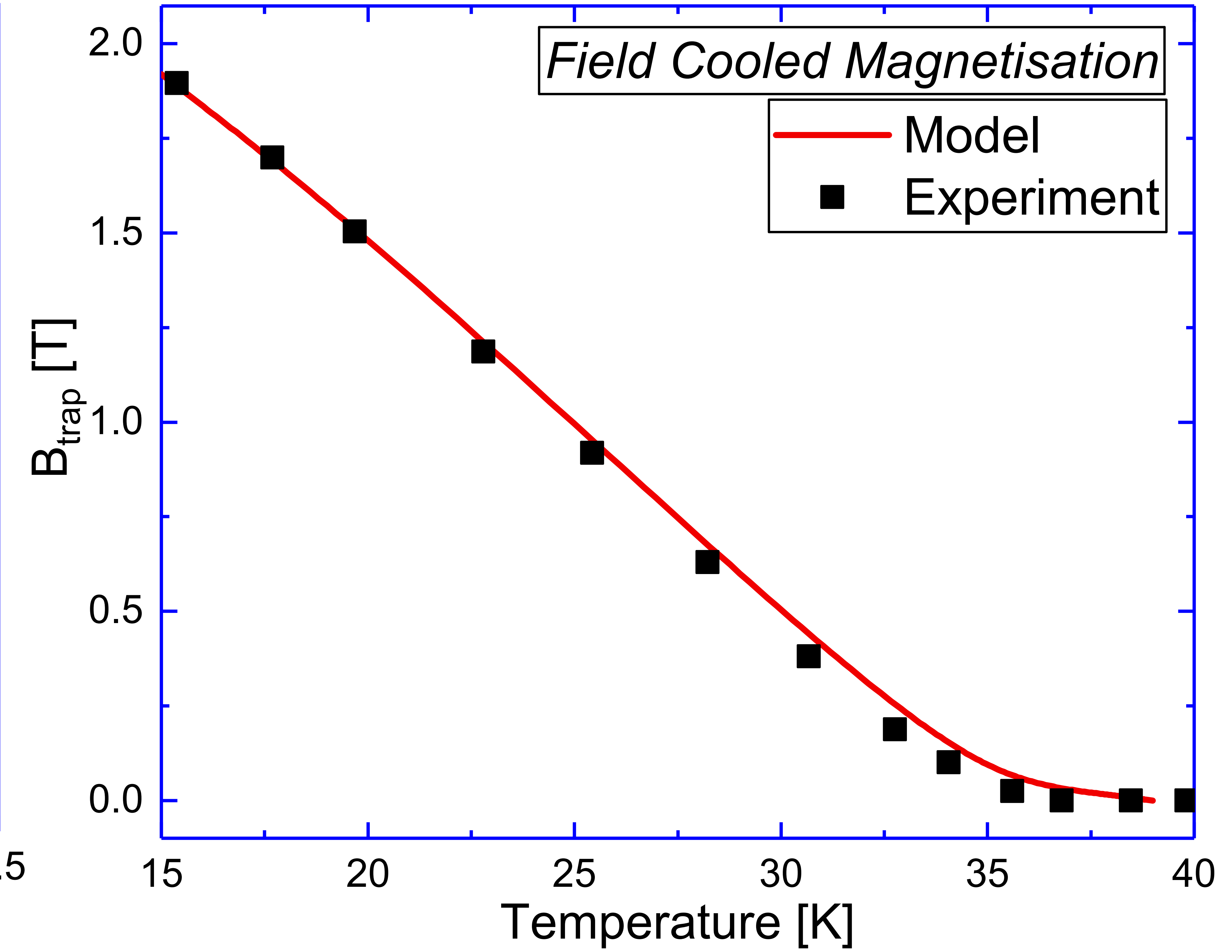
Modelling Results

Calibration & FCM Results

- Applied pulses calibrated to agree with experiment
- FCM of bulk performed to gauge properties and reliability of models



Calibrated pulses, illustrating how careful choice of material properties and experimental constants produce excellent agreement

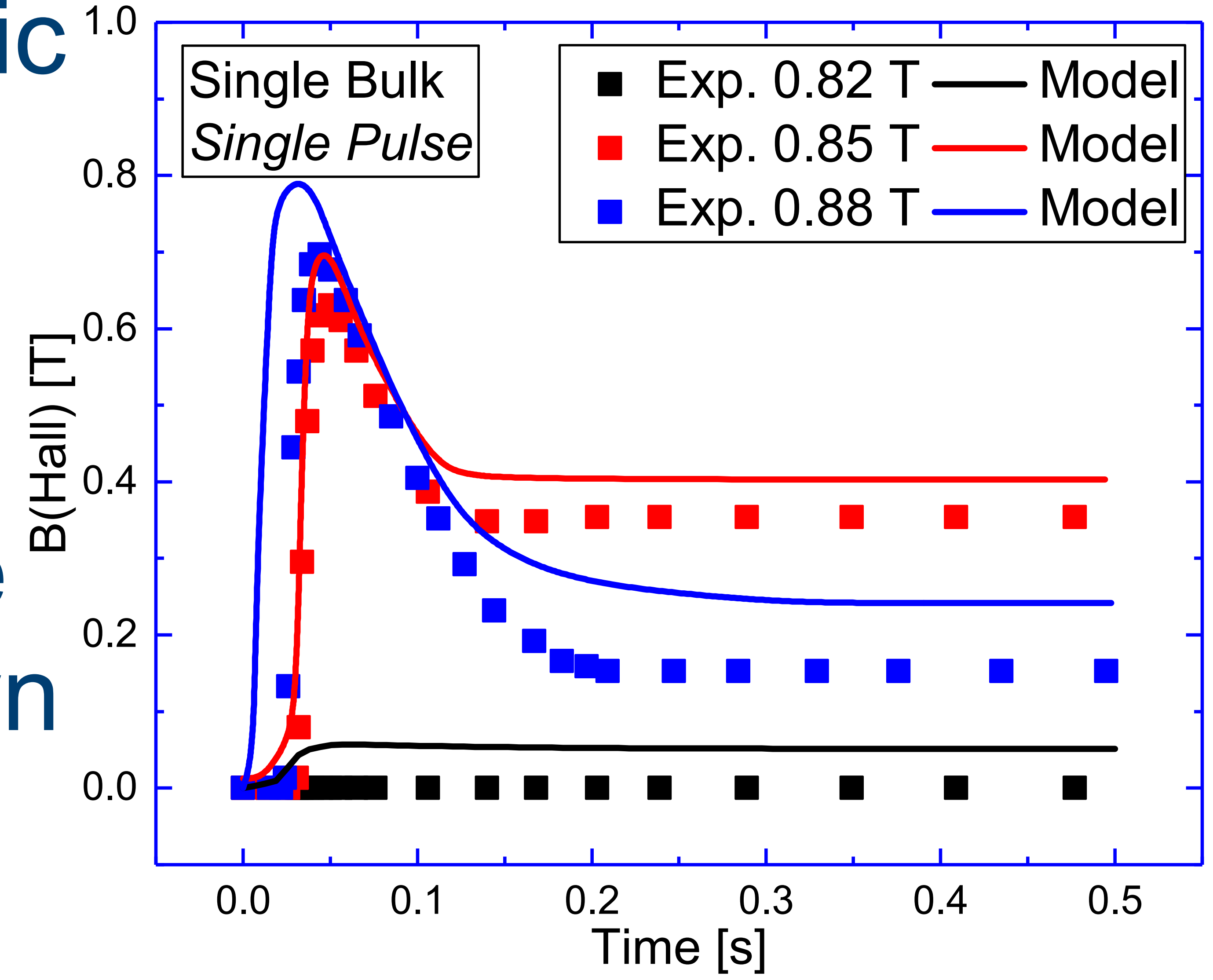


Field Cooled Magnetisation results for the modelled MgB_2 sample

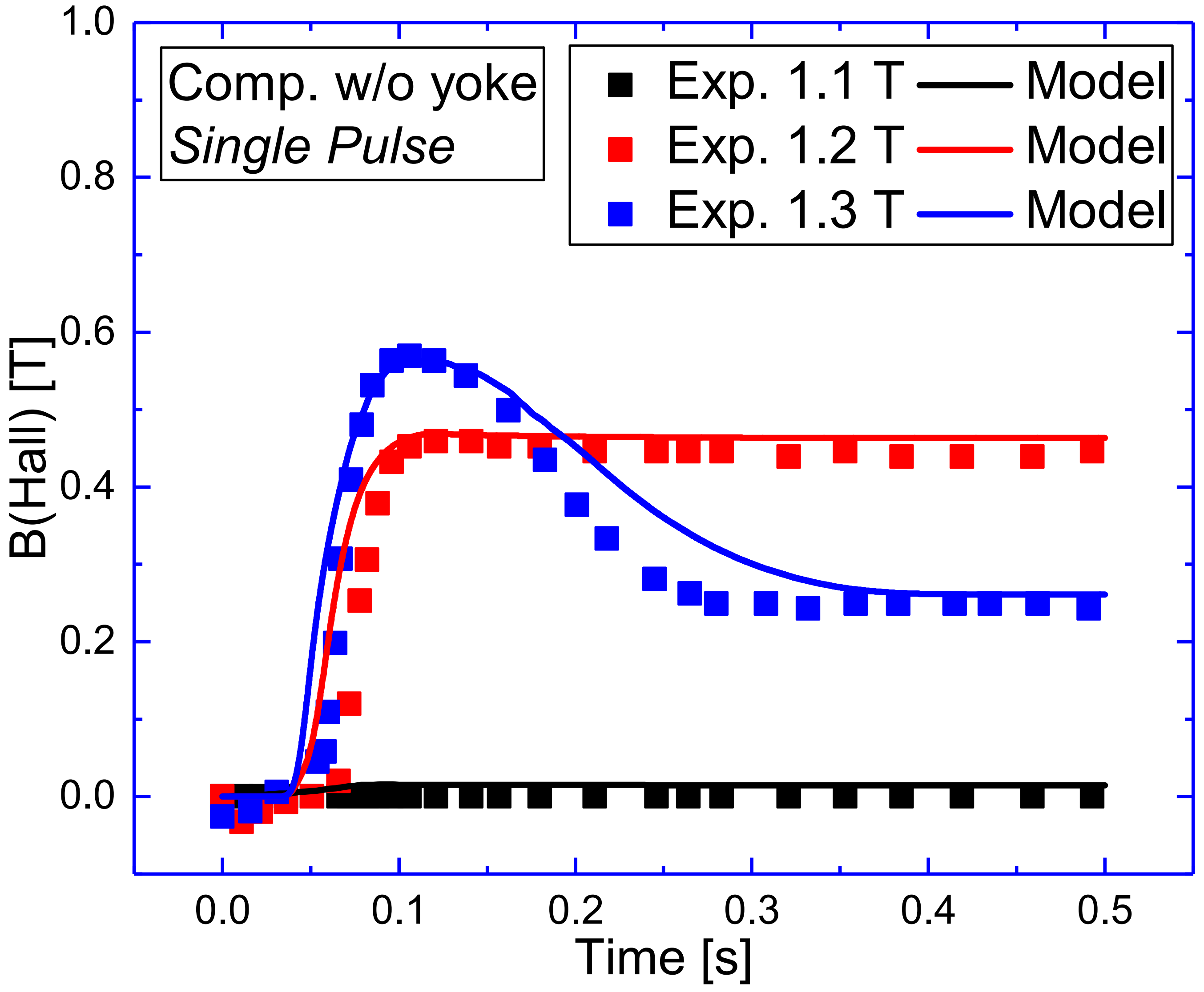
Modelling Results
Single Pulse Results

- Applied a single magnetic pulse to samples
- Graphs from left to right are samples shown
- Magnitude of trapped field quantitatively agrees

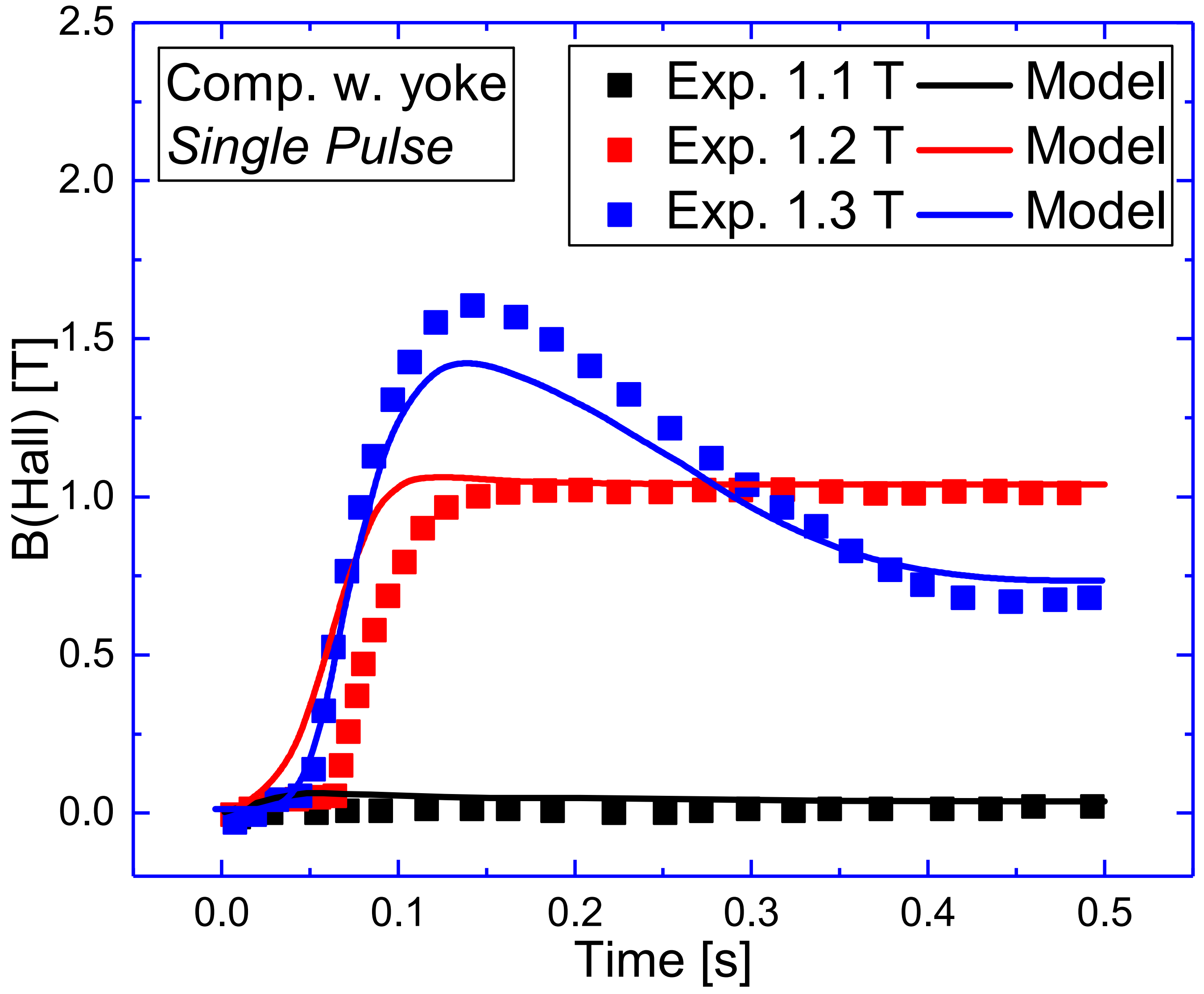
Single Bulk

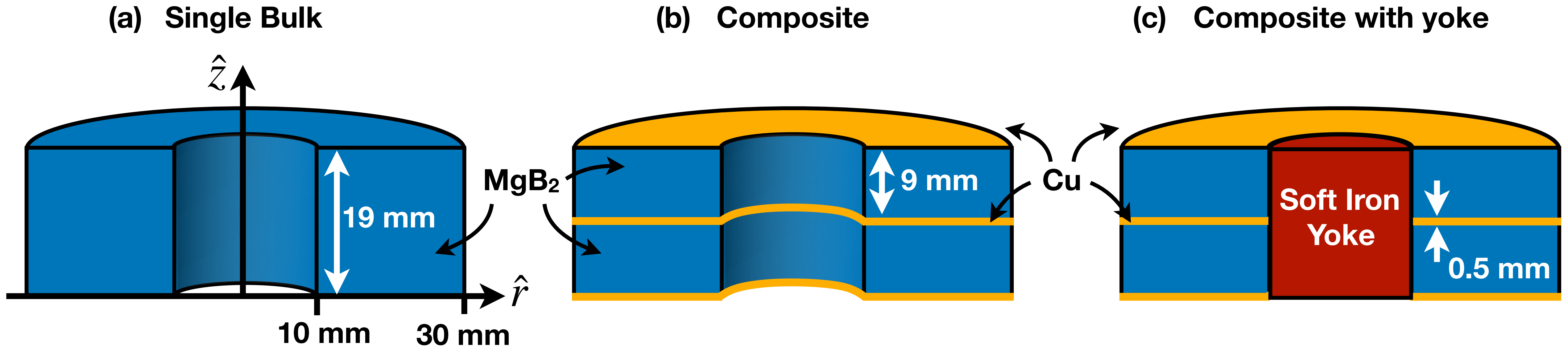


Comp. w/o. yoke



Comp. w. yoke

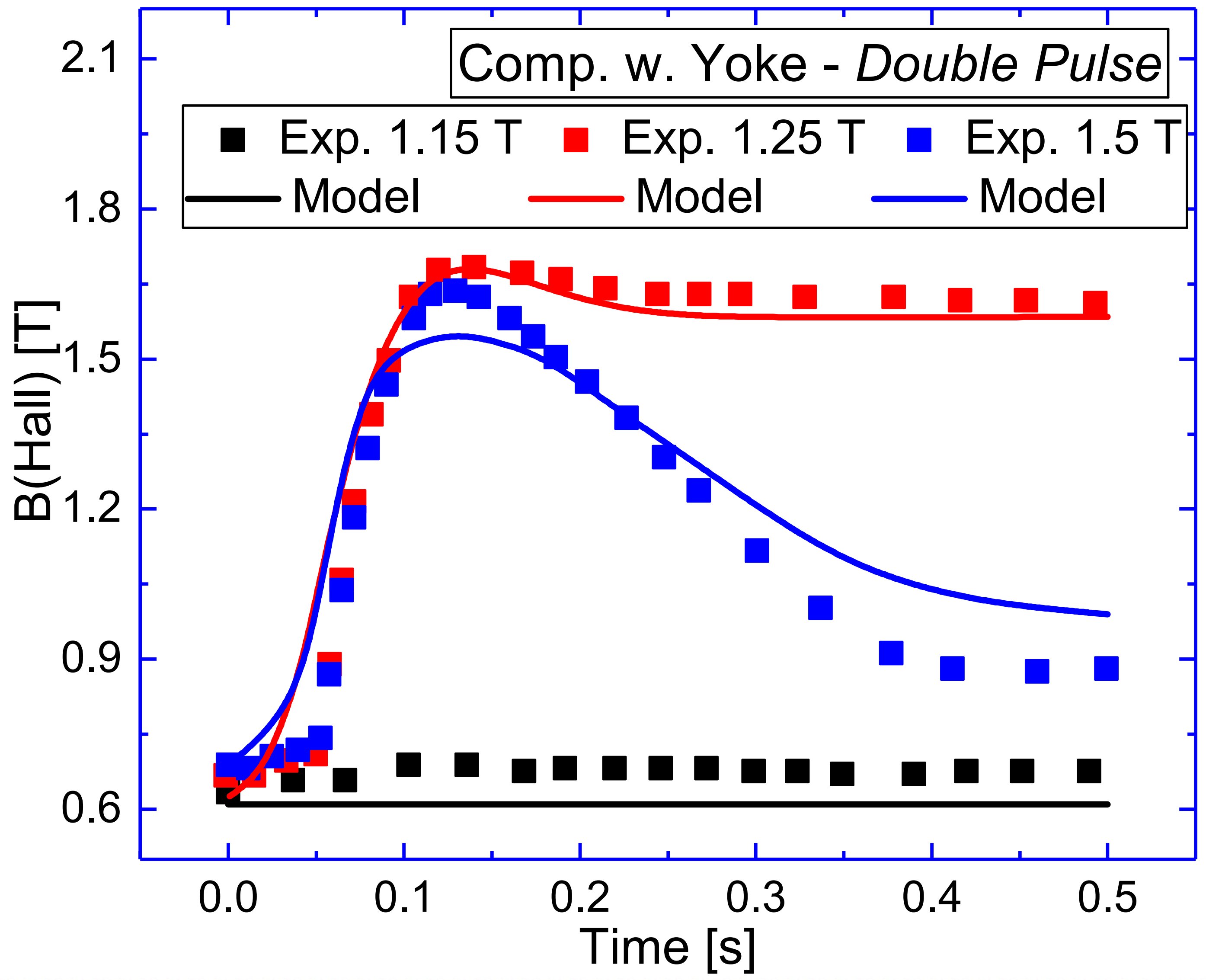




Modelling Results
Double Pulse Results

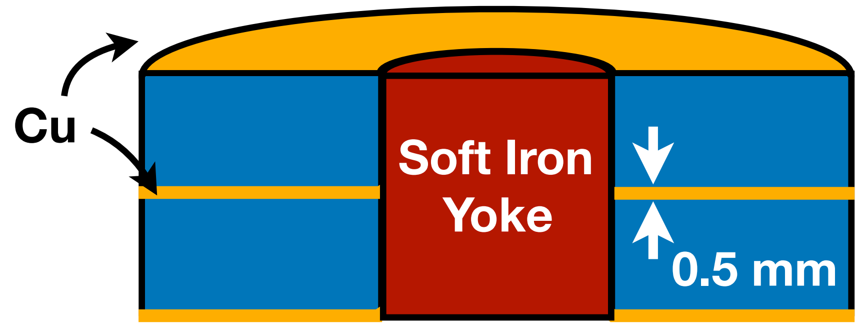
- Sample pulsed after an initial 1.3 T pulse
- Pre-magnetised state with 0.6 T trapped
- Successfully modelled record breaking trapped field; multi-pulse successfully aids trapped field

Modelled results

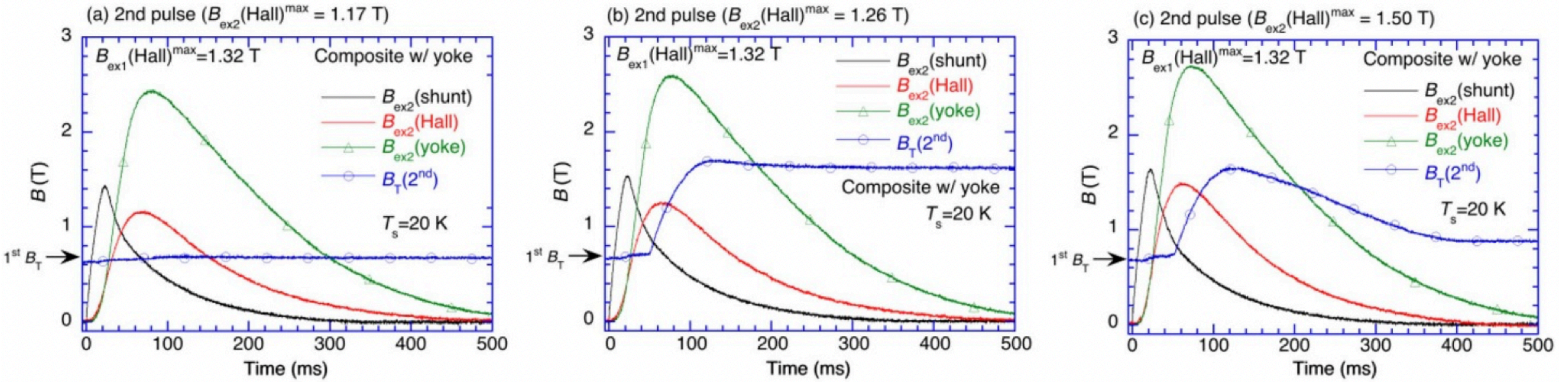


Comp. w. yoke

(c) **Composite with yoke**



Experimental data from [1]



Modelling Results

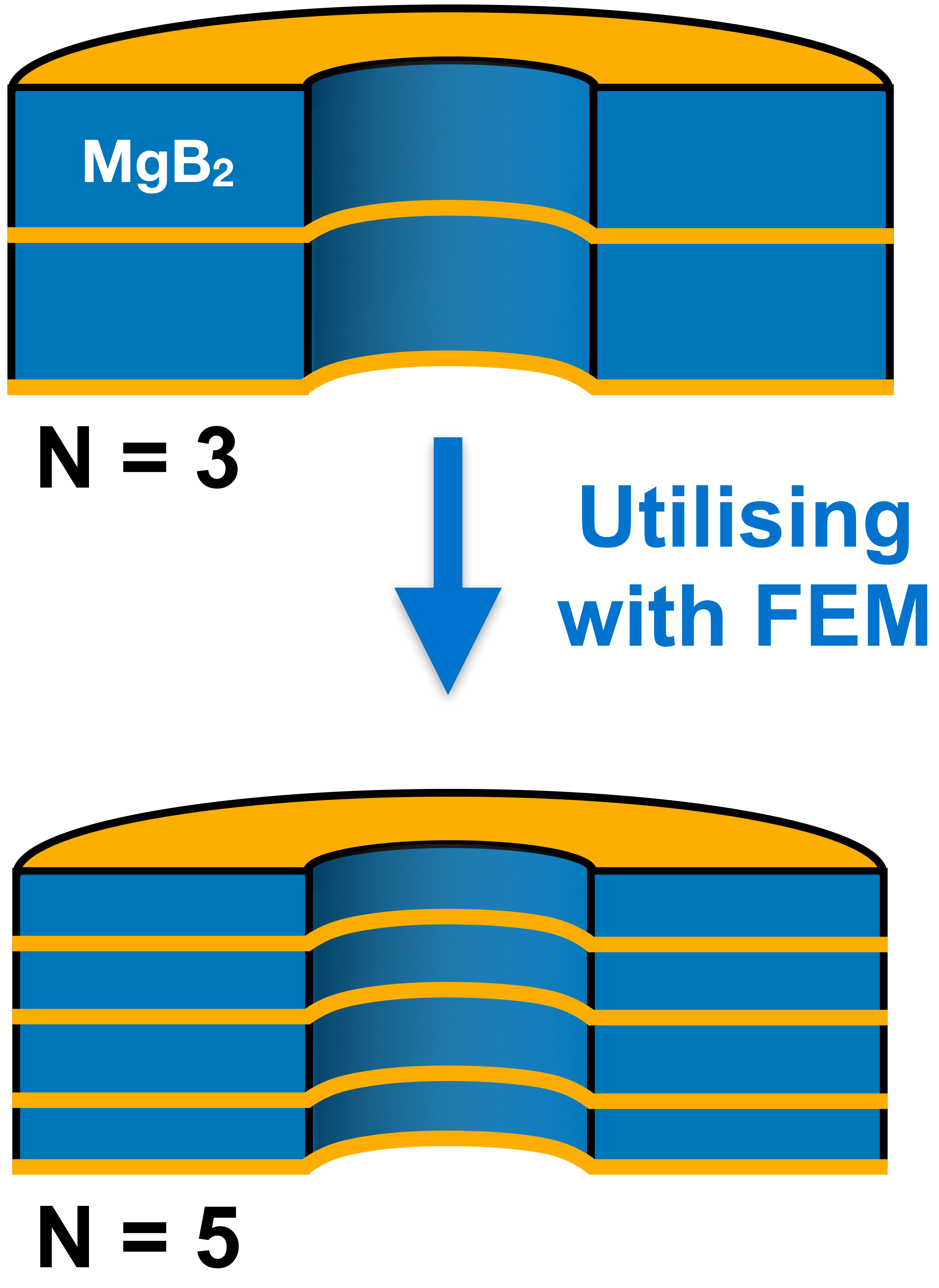
Extension Studies: Copper Layers

- Hirano et al. [1] illustrated effect of three inserted copper layers
- As layer number increases, MgB_2 media decreases and copper layer increases
- The number of layers utilised is hard to vary experimentally but easy with FEM

↑ **Increase N** { **MgB_2** ↓ / **Cu** ↑

Composite bulk created by Hirano et al. [1] with three layers

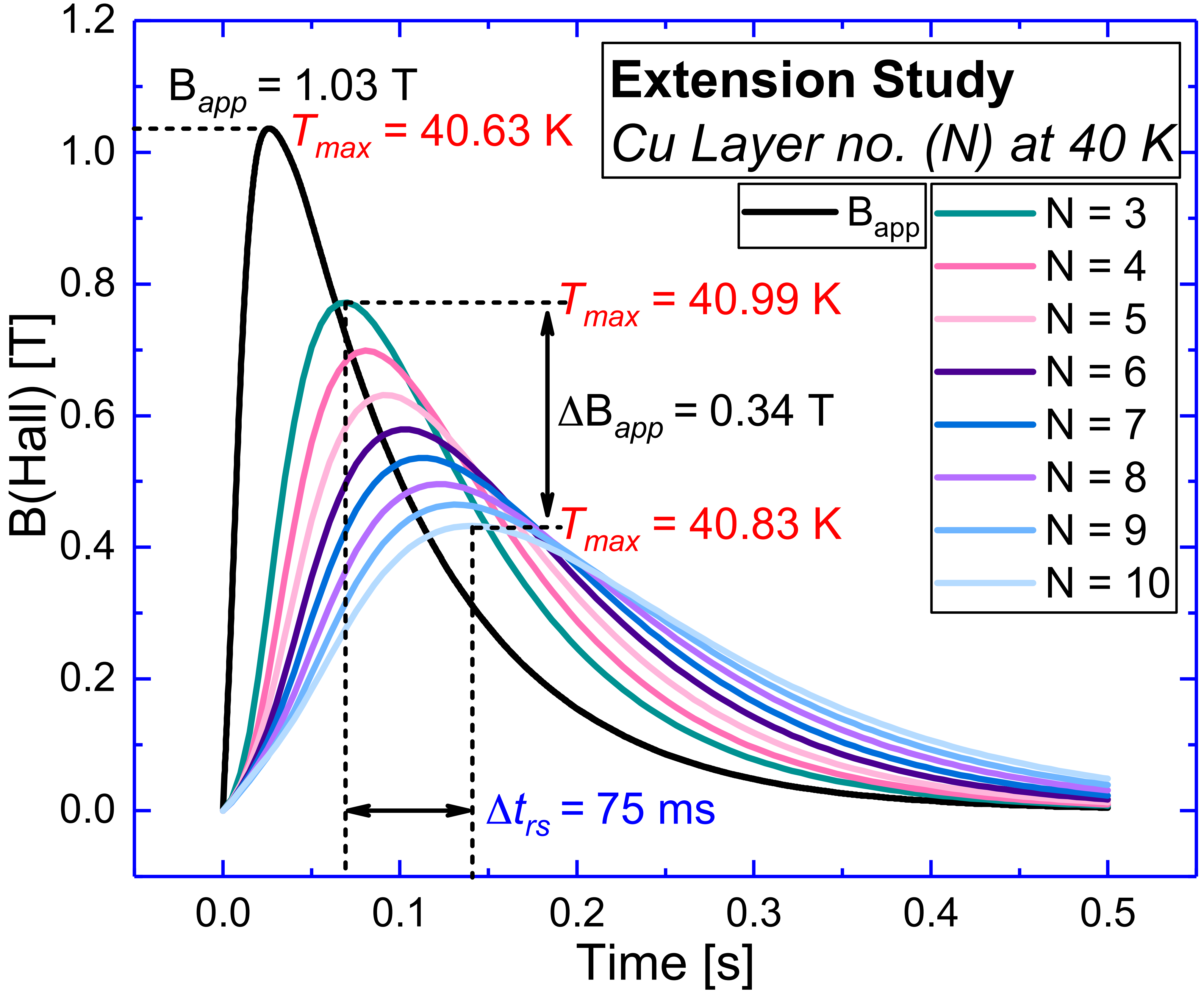
Composite bulk with N = 5 layers



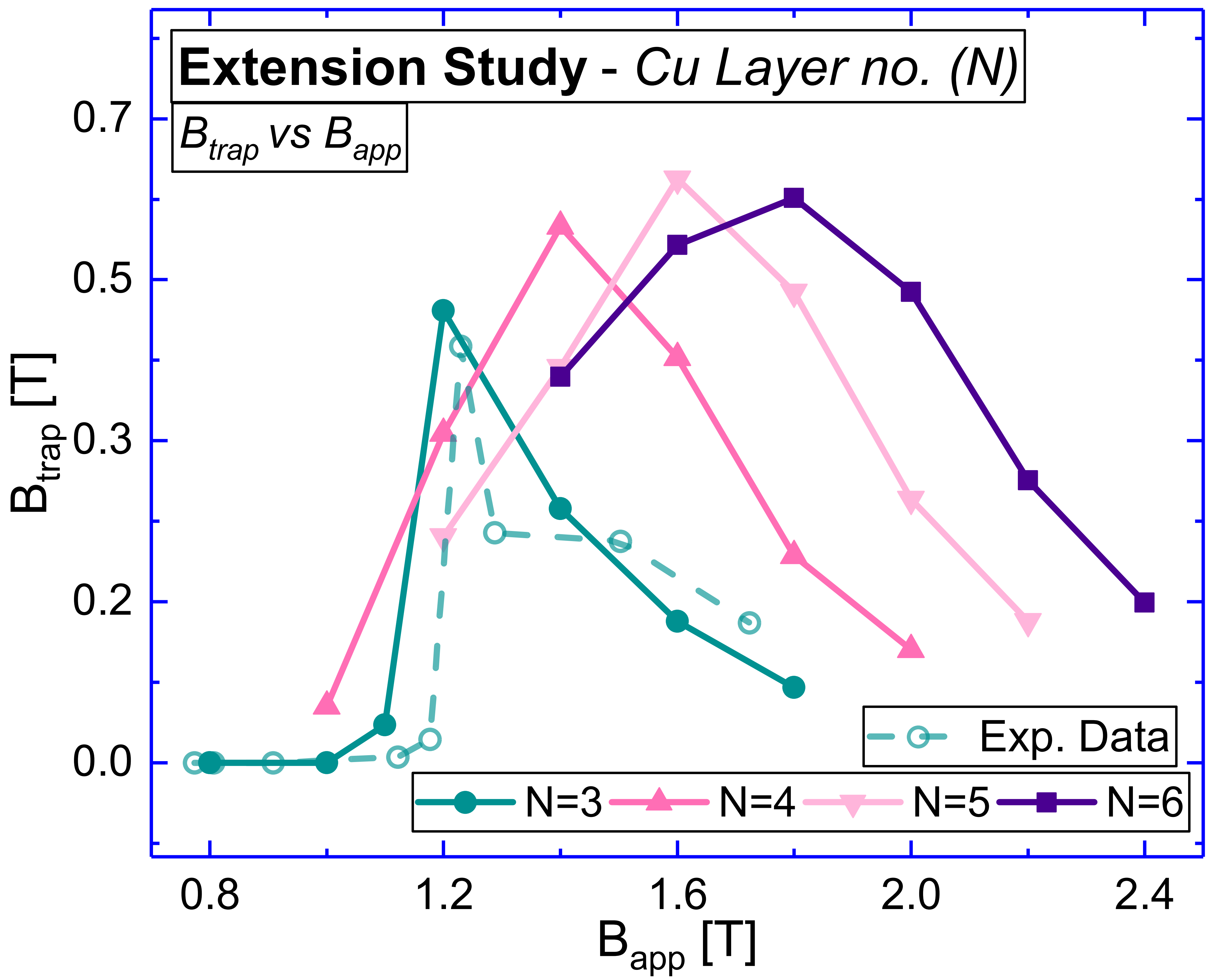
Modelling Results

Extension Studies: Copper Layers

- Effect of layers on pulse modification illustrated
- How trapped field varies with applied field for various layers shown



Effect of layer number on pulse magnitude and rise time

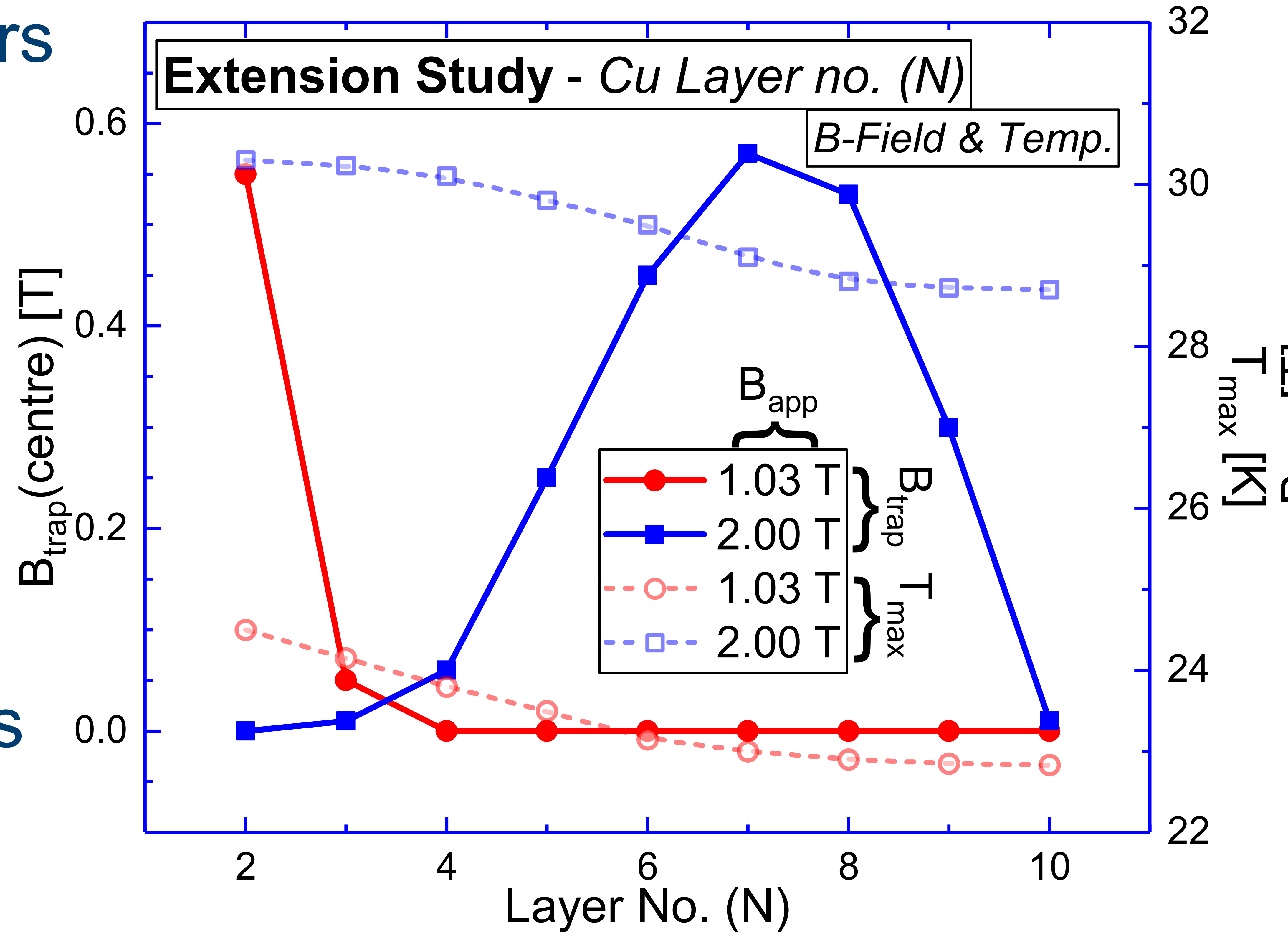


Effect of layer number on maximum trapped field

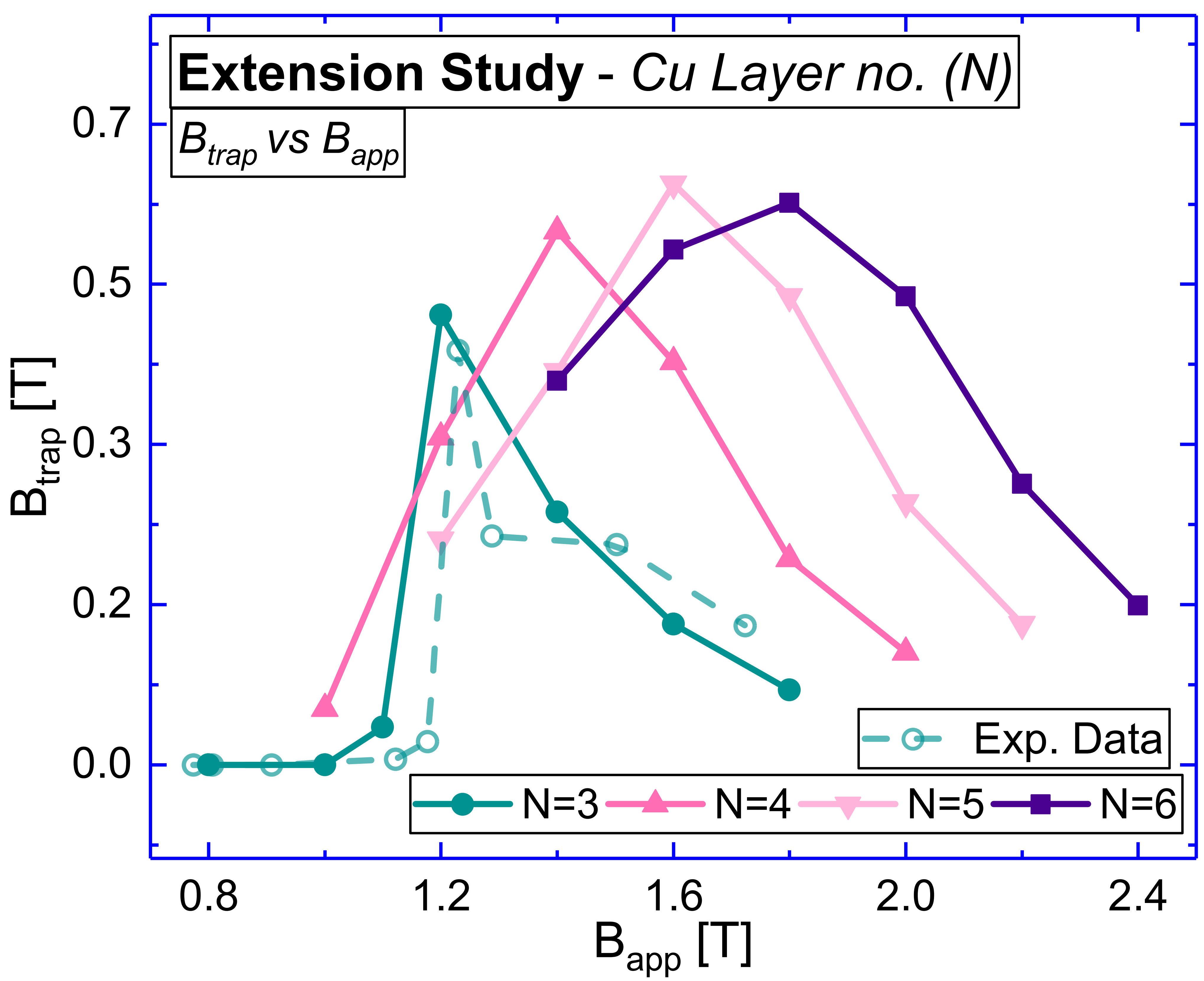
Modelling Results

Extension Studies: Copper Layers

- Effect of layers on pulse modification illustrated
- How trapped field varies with applied field for various layers shown



Layer number versus trapped field and maximum temperature



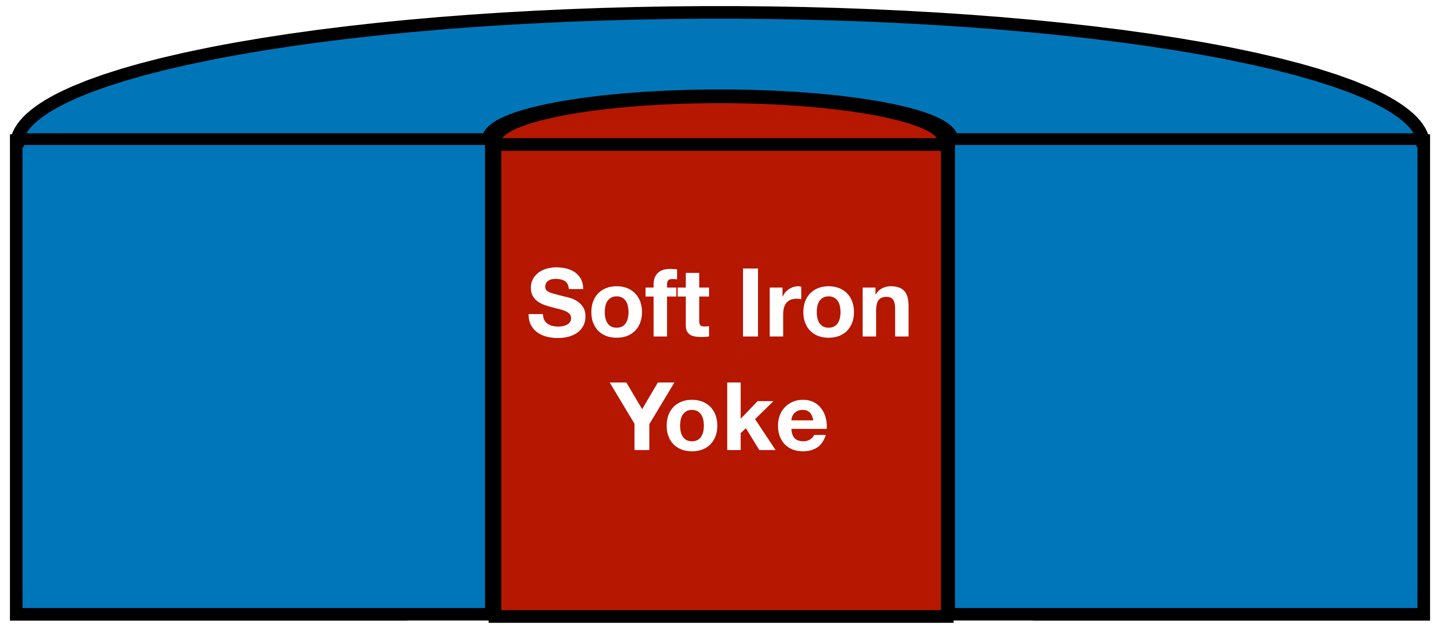
Effect of layer number on maximum trapped field

Modelling Results

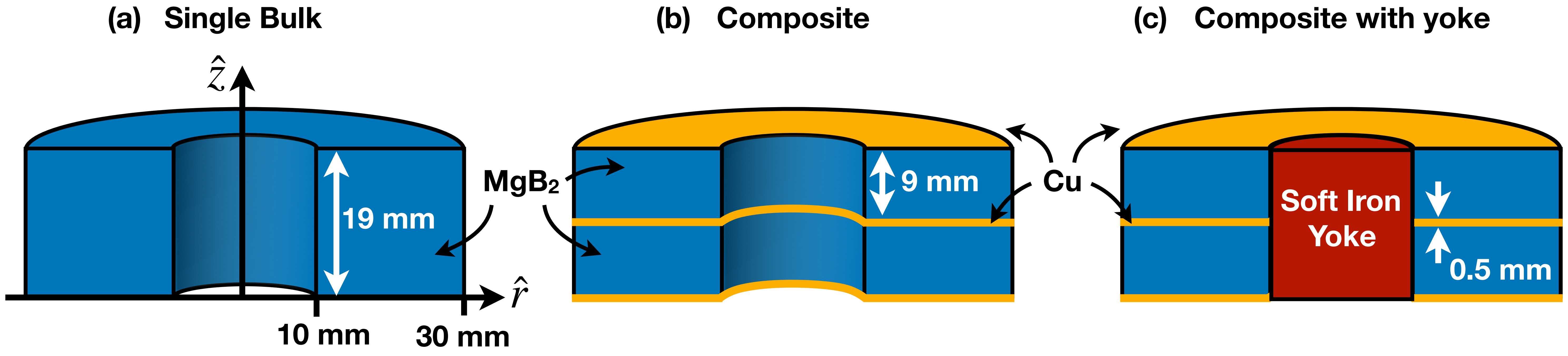
Extension Studies: Effect of Yoke

- Hirano et al. [1] illustrated effect of yoke inserted to composite bulk only
- Effect of yoke is therefore only observed with combined effect of copper layers
- Investigation of how the 'Single Bulk' was affected by an inserted soft-iron yoke

Modelled sample investigating the effect of the yoke with the single bulk



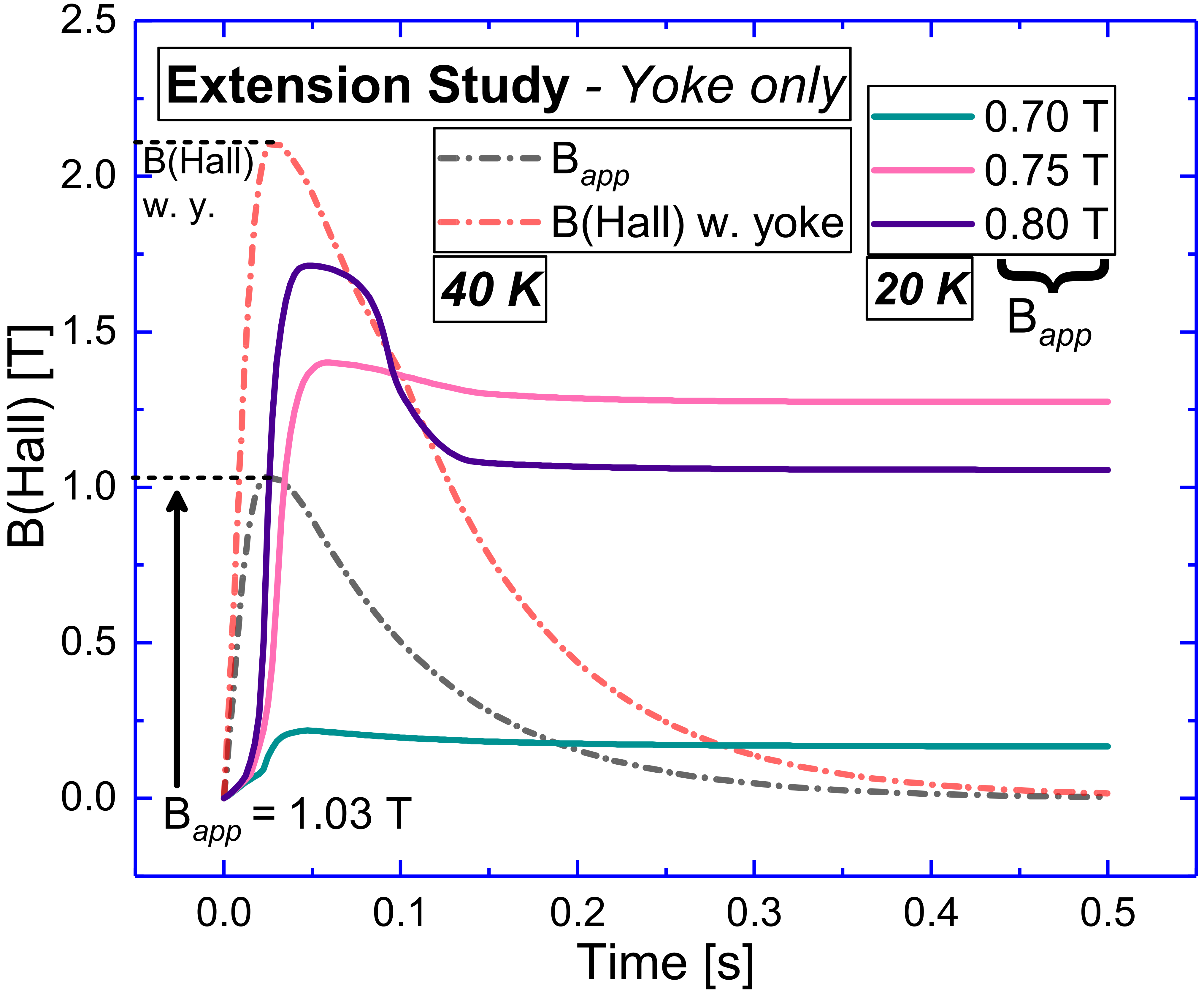
Sample configurations created by Hirano et al. [1]



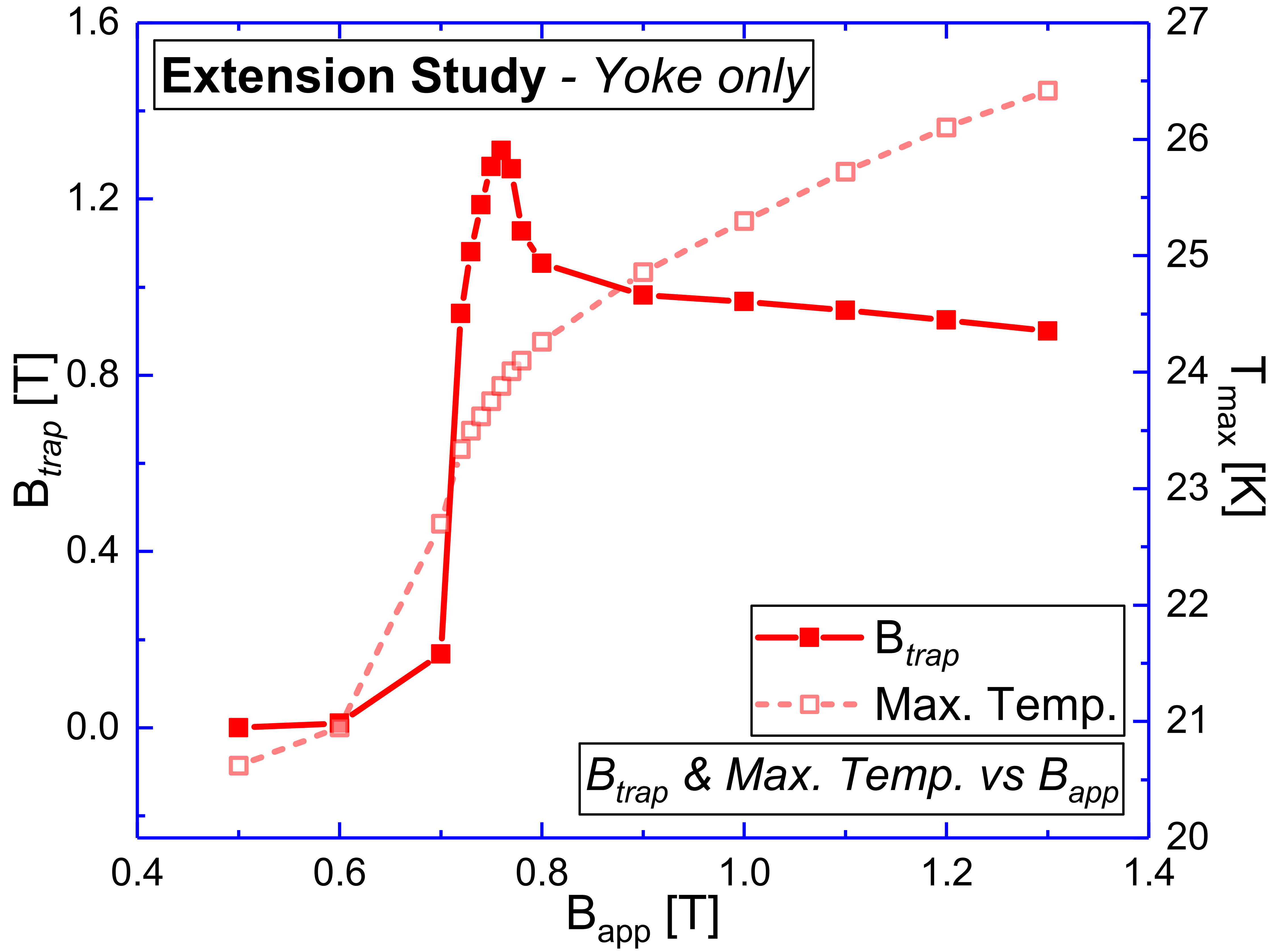
Modelling Results

Extension Studies: Effect of Yoke

- Large enhancement of applied field
- Yoke significantly enhanced trapped field with ‘activation’ at 0.76 T



Effect of adding the yoke to the single bulk; trapped field

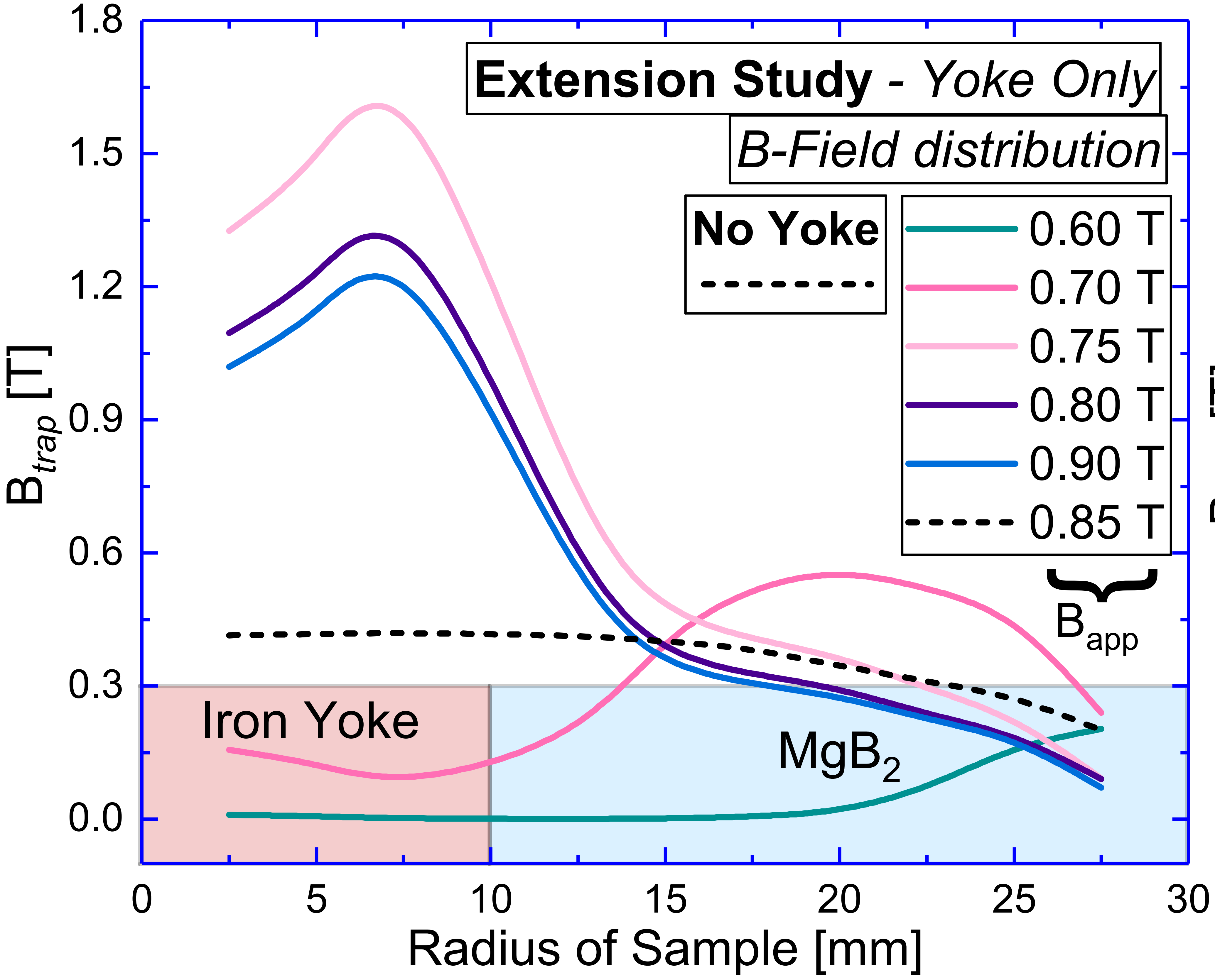


Applied field versus trapped and associated max. temperature

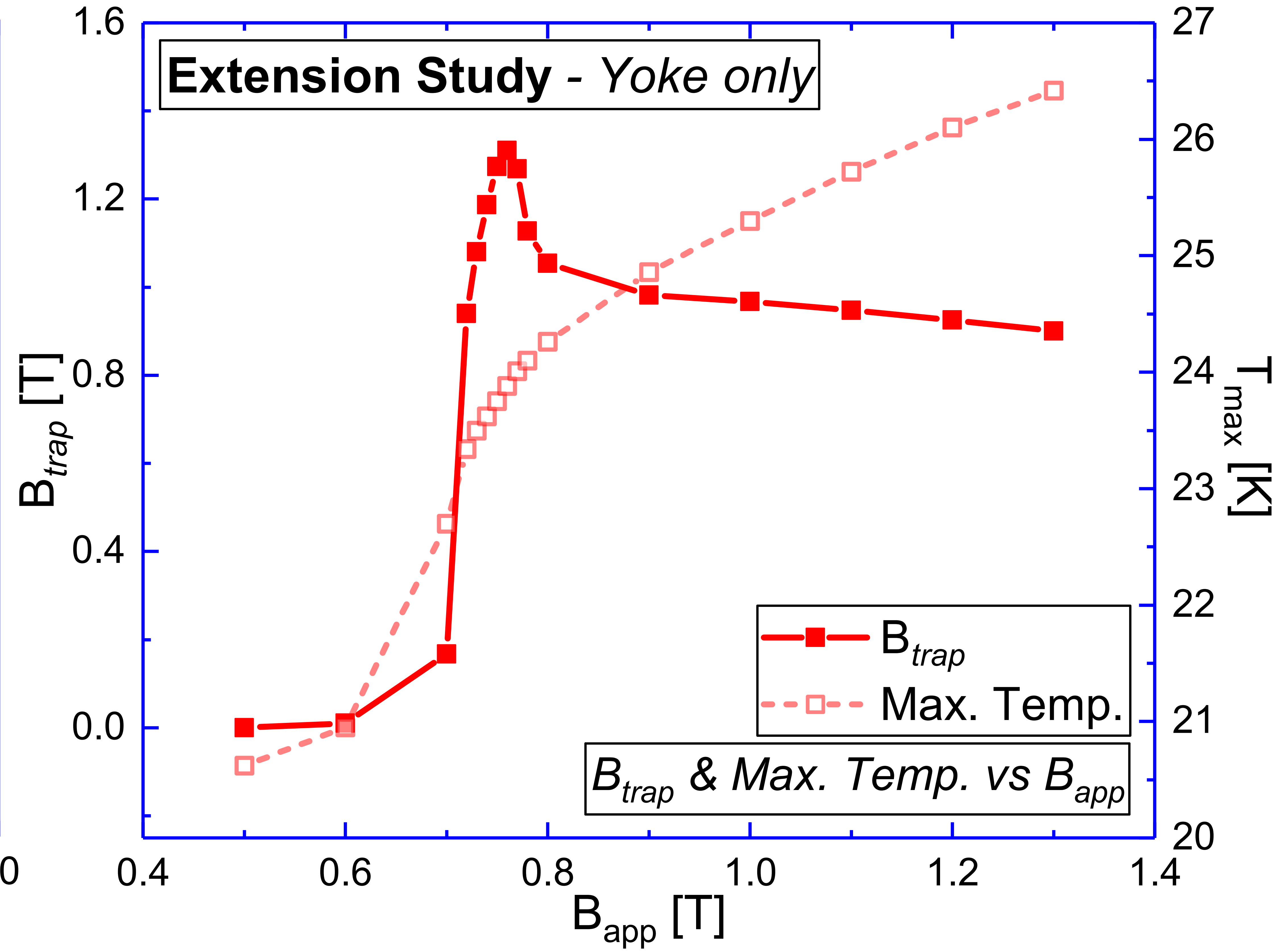
Modelling Results

Extension Studies: Effect of Yoke

- Large enhancement of applied field
- Yoke significantly enhanced trapped field with 'activation' at 0.76 T



Radial field distribution of 'Single bulk' with iron yoke



Applied field versus trapped and associated max. temperature

Conclusions

- With careful calibration, utilisation of experimental data and material constants, excellent agreement of modelling composite MgB_2 bulks can be achieved
  - Copper layers effectively retard pulse, but diminish magnitude significantly
  - Optimal layer number was between 3 and 5 to balance maximum trapped field and reduced field penetration
  - Iron yoke significantly enhanced applied field locally
  - Soft-iron yoke magnetisation assisting magnetisation of MgB_2

EPSRC

Thank you for watching

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