CERN

Studies of the cool-down dynamics around T_c using a flux expulsion lens

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Thanks for the support from:
Cryolab team — *Cryogenics Group CERN*
Tommi Mikkola, Simon Barrière — *Mechanical and Materials Engineering Group CERN*

Research context

Why improve expulsion efficiency?

Main goal: mitigate residual resistance RB due to trapped flux

$$R_B = B_0 \times S(f, B_{RF}, ...) \times \eta(\nabla T, ...)$$

Remove external field — Reduce sensitivity — Increase expulsion efficiency

What impacts flux expulsion?

History of material preparation

Flux trapped in **defects**:
Impurities, dislocations, grain boundaries

Consensus:

Recrystallization by heat treatment improves expulsion

History of cool-down

Observed from: Q_0 and **magnetometry**
Correlated to: Cooling rate, SC front speed, ∇T …

Consensus:

$\uparrow \nabla T \quad R_B \downarrow$

Bare cavities
Improves by “fast” cool-down
Intrinsic to material

$\downarrow \nabla T \quad R_B \downarrow$

Thermoelectric-prone setups
Improves by “slow” cool-down
Related to the setup

What is a useful experiment to study flux expulsion?

Relate material preparation to cool-down dynamics near T_c

What have we done?

A standalone magnetometry instrument to measure expulsion efficiency prior to cavity production — proof of concept reported at TTC 2020

What is the goal of this study?

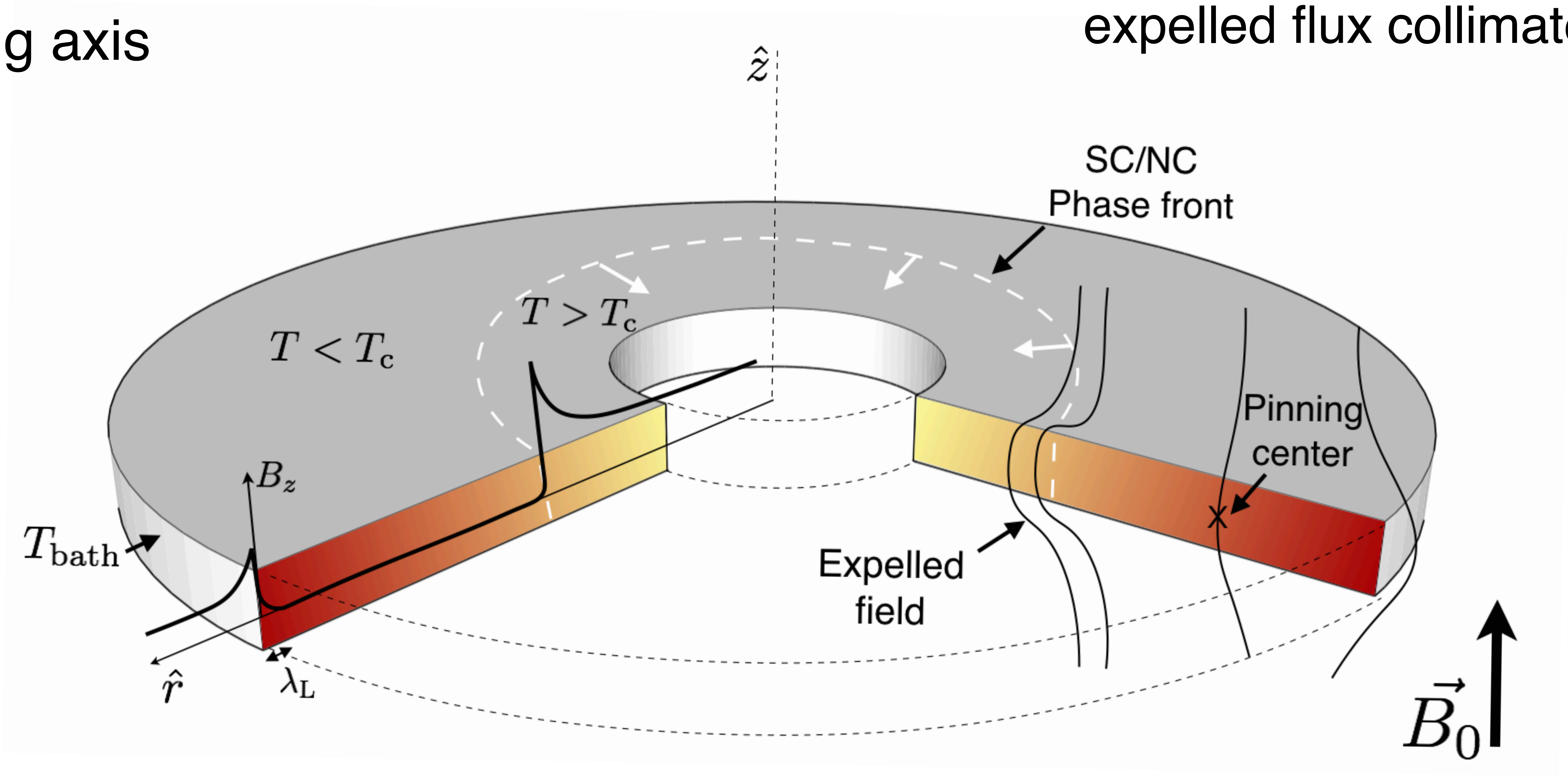
Can we correlate trapped flux to the cool-down dynamics around T_c?

Outline

- Magnetic Flux Lens Concept
- Measurement and control of the cool-down dynamics
- Results from measurement campaigns
- Summary and contributions

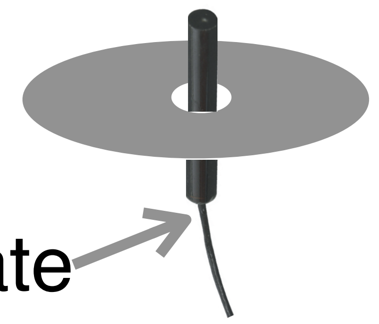
Concept

- Sample: sheet Nb disc
- Magnetic field: Along axis and homogeneous
- Cool-down on a closed thermal topology: expelled flux collimated at aperture



- Flux expulsion efficiency η with $0 < \eta < 1$ obtained from:

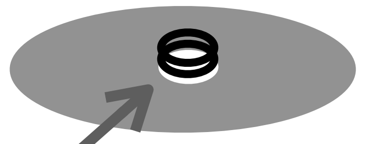
Flux density measured with a fluxgate:



$$\eta = \frac{B_{sc}^{meas}/B_0 - 1}{B_{sc}^{sim}/B_0 - 1}$$

Simulated

Expelled flux measured with a search coil:



$$\eta = \Delta\Phi_{\text{coil}}/\Phi_0$$

$$\Delta\Phi_{\text{coil}} = -\int_{t_{NC}}^{t_{SC}} V_c dt$$

$$\Phi_0 = B_0 A_{Annulus}$$

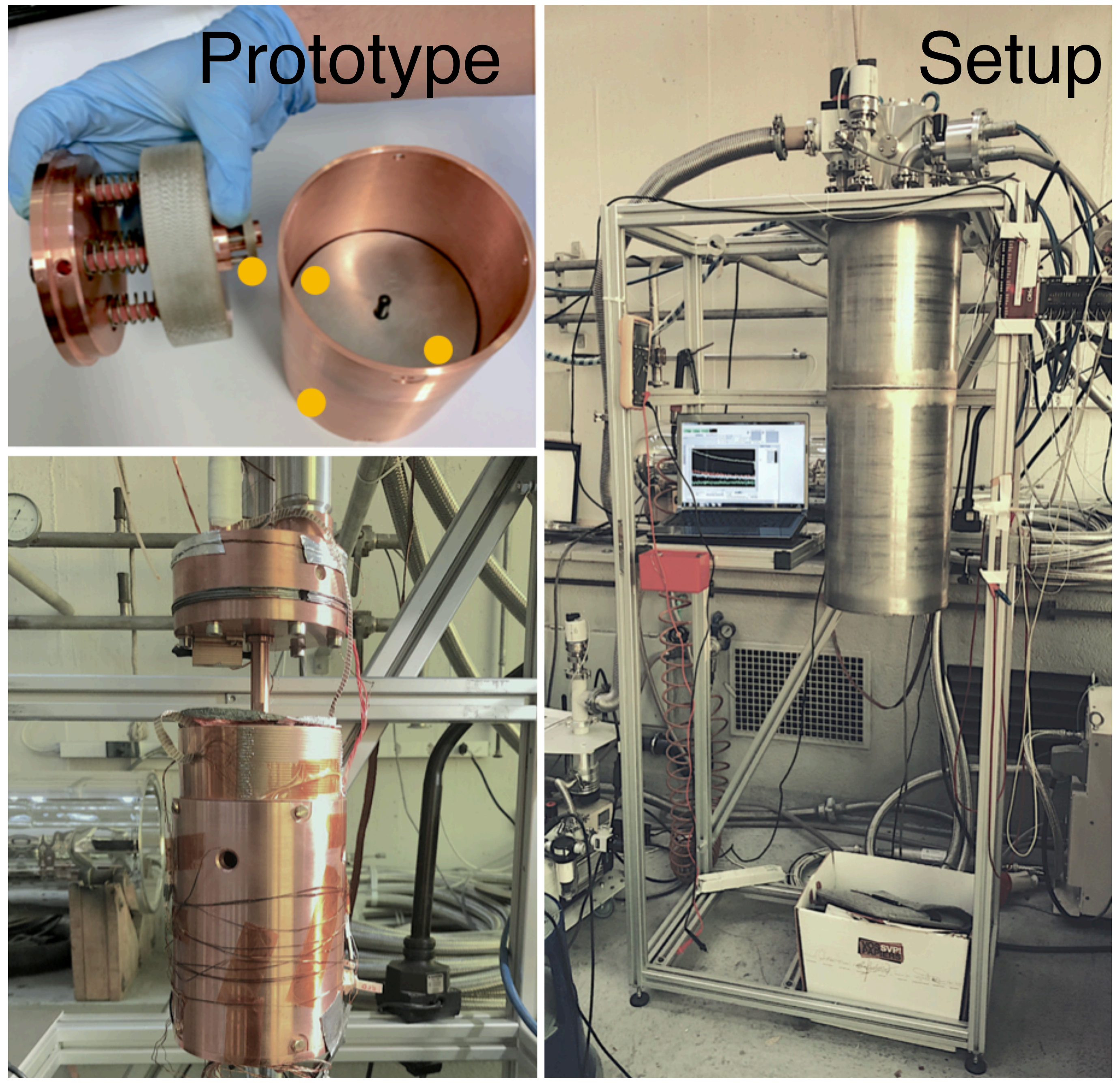
Instrument design and setup

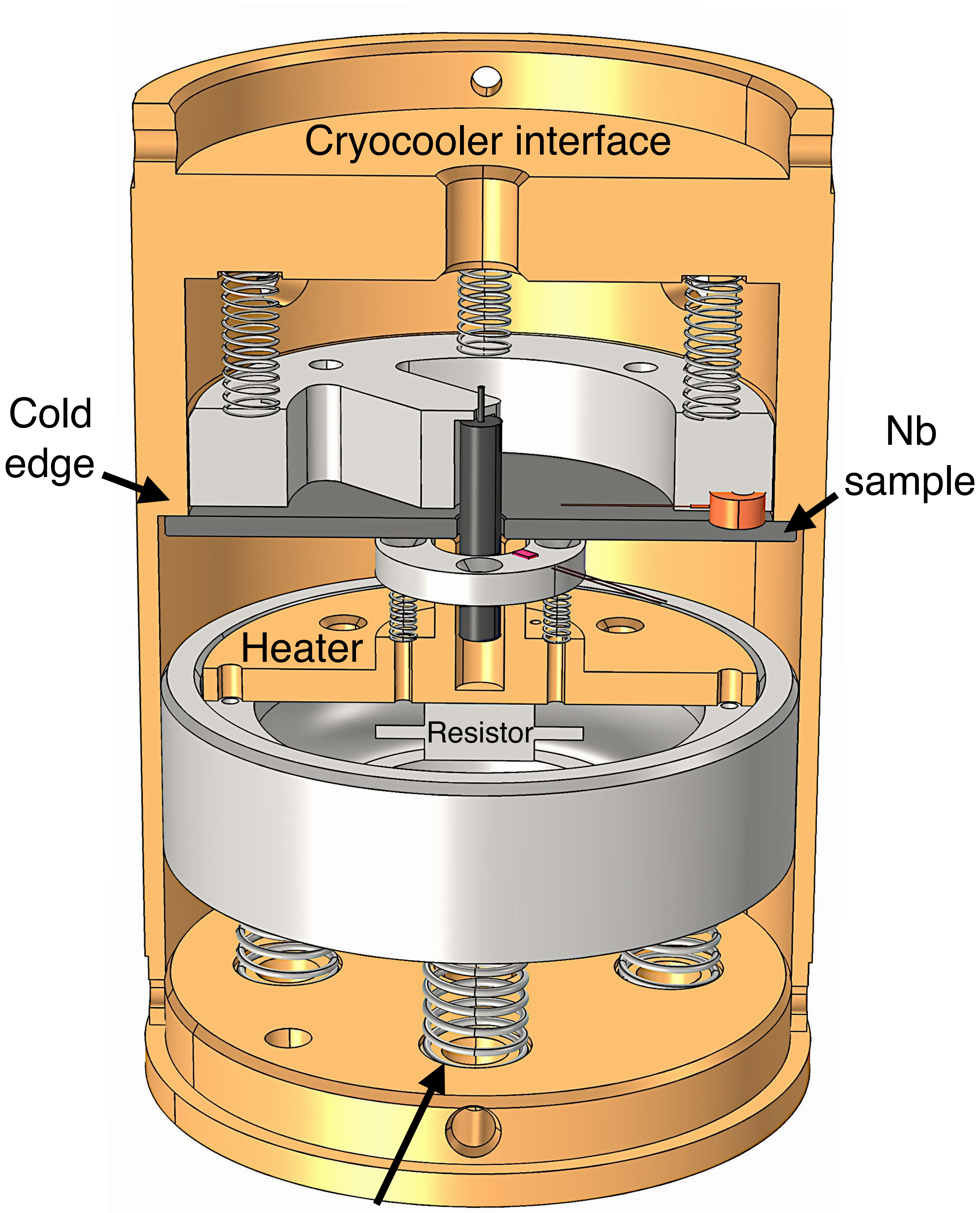
- Flux density measurement
  - Bartington Mag-F

- Sample
  - Diameter = 9 cm
  - Aperture = 0.6 cm

$B_{SC}^{sim}/B_0 \approx 2$

- Earth's magnetic field used
  - Small setup — homogeneous field





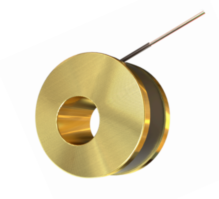
Spring loading for the cold contact

- Conduction cooling in vacuum
- Cryocooler
  - Cooling power ≈ 1 W at 10 K
- Thermoelectric current mitigated by symmetry

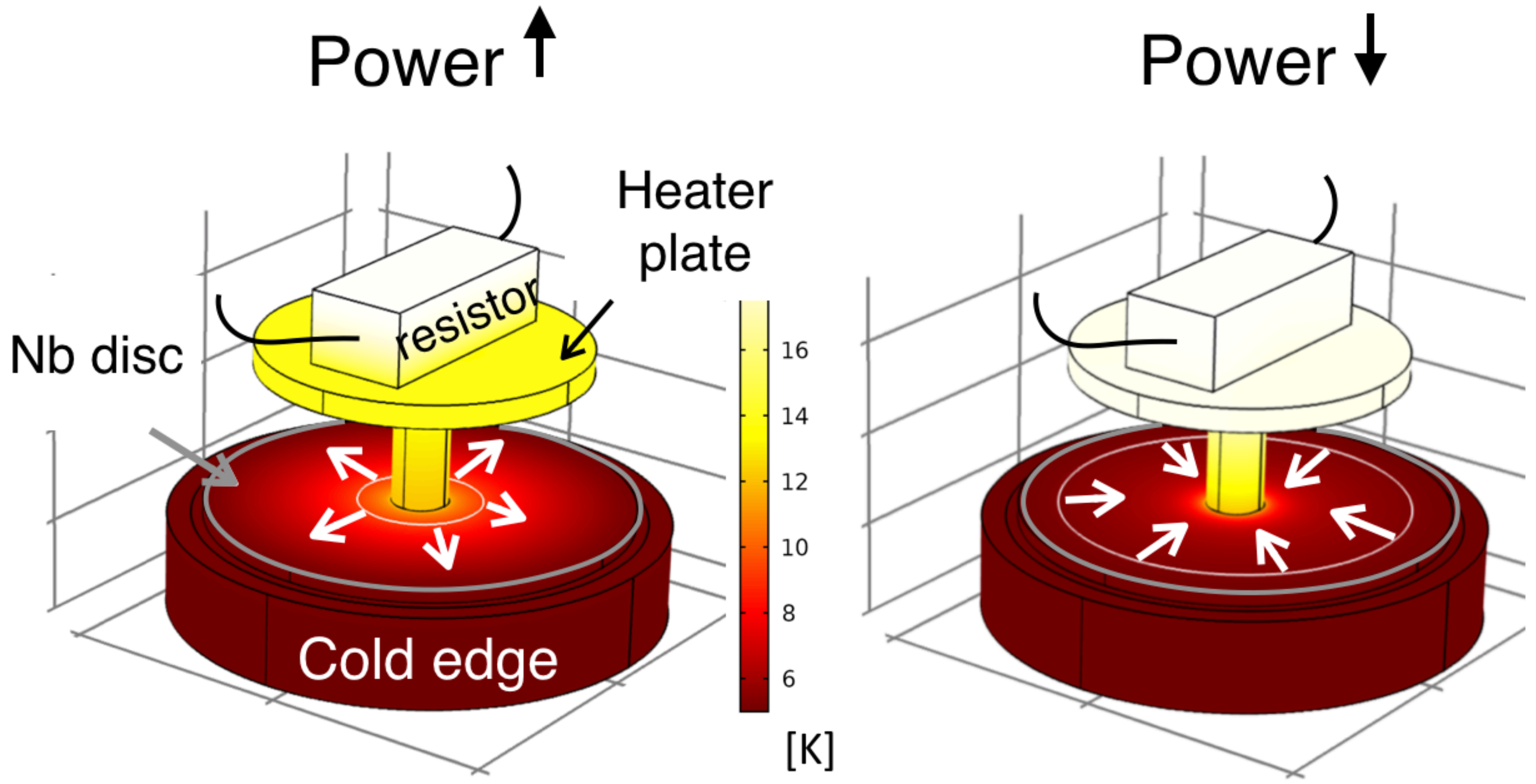
- Contact thermometry

SD-type CERNOX

CU-type CERNOX

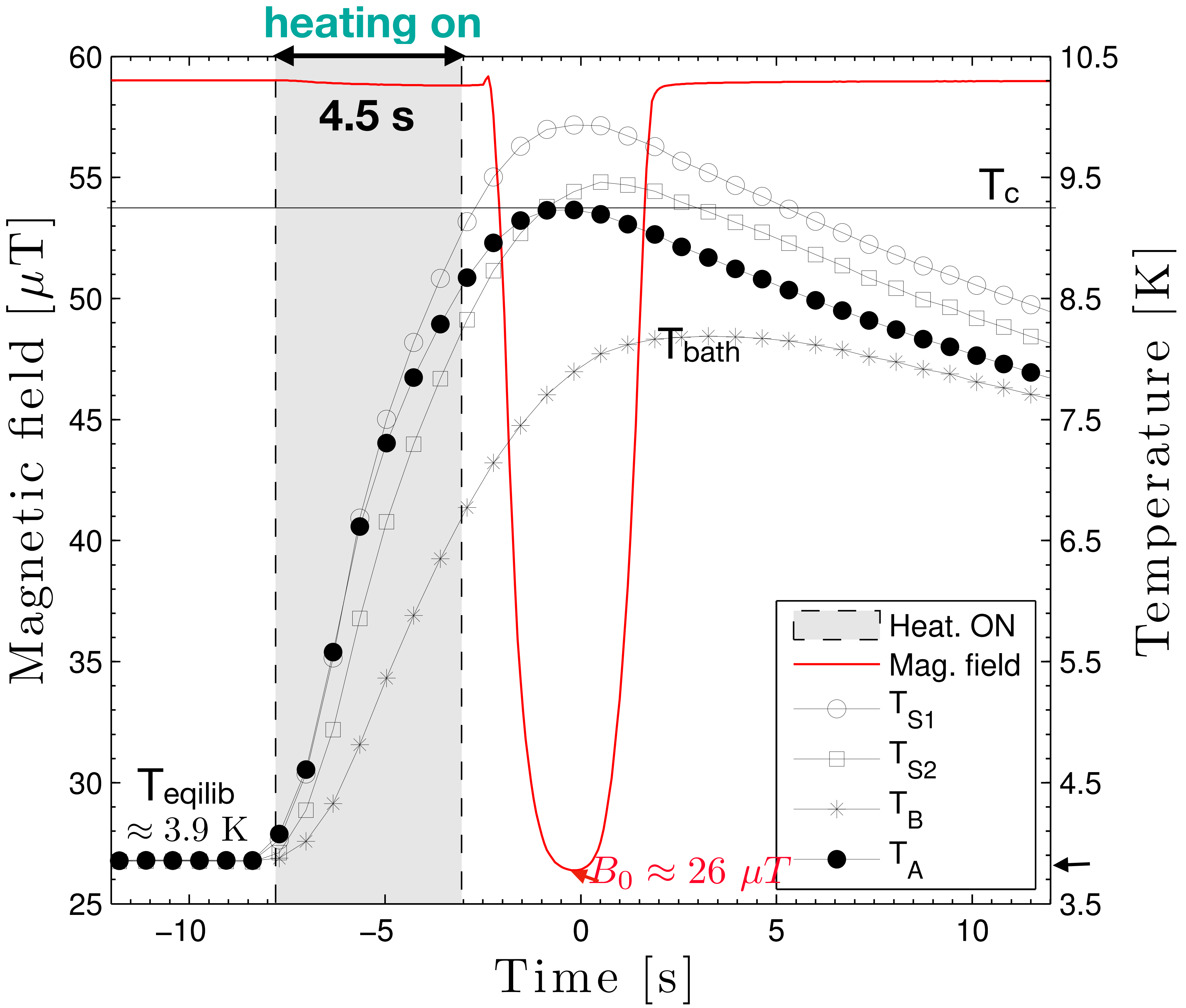


- Control of the SC transition

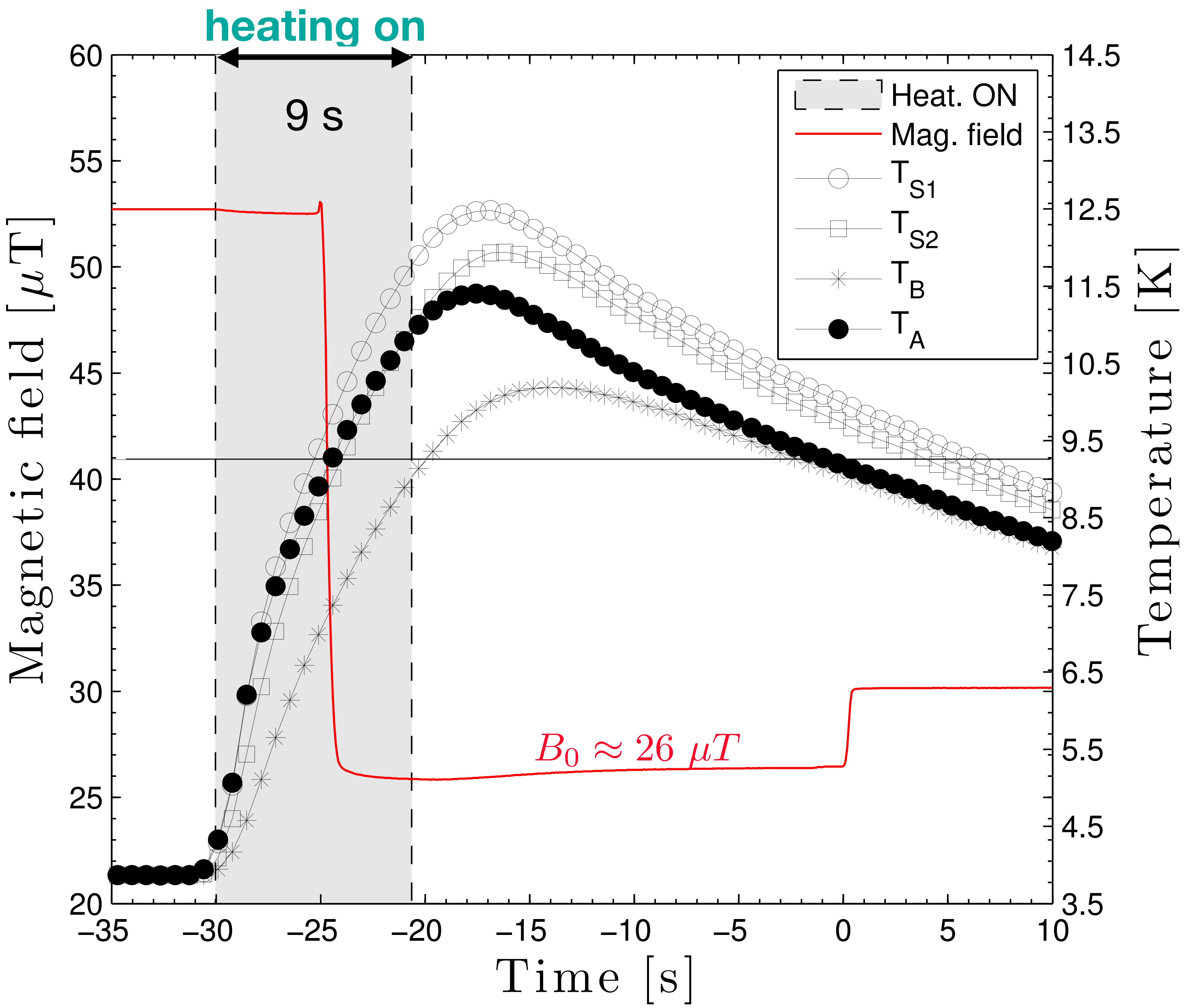


Control of cool-down dynamics near T_c

Short heating pulse — **strong** expulsion



Long heating pulse — **weak** expulsion

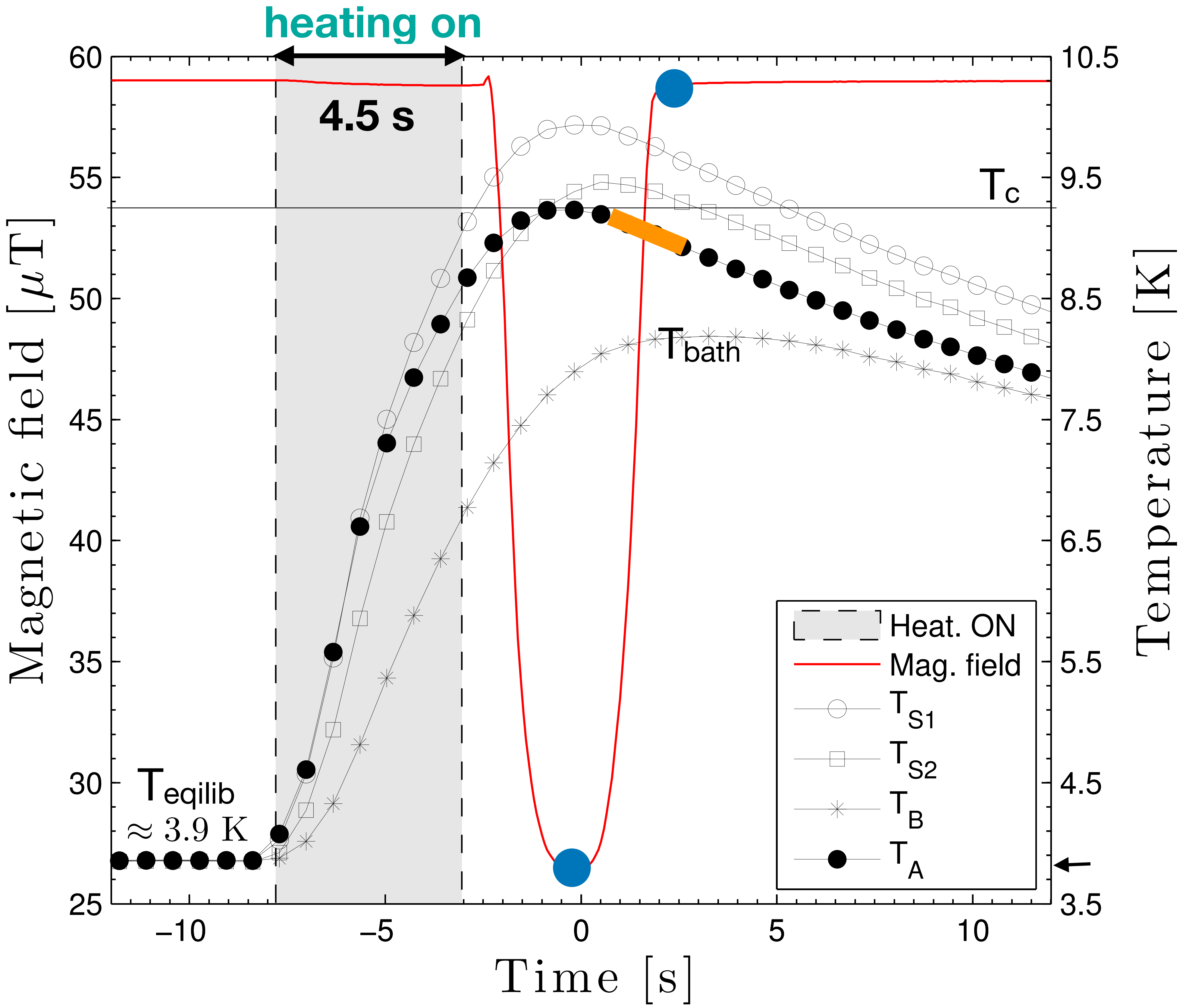


- **Control** of the NC/SC transition via sample heater

Heating pulse length ↑ B_{SC}/B_0 ↓ $\Longrightarrow$ ∇T ↓

Measurement of cool-down dynamics near T_c

Short heating pulse — **strong** expulsion



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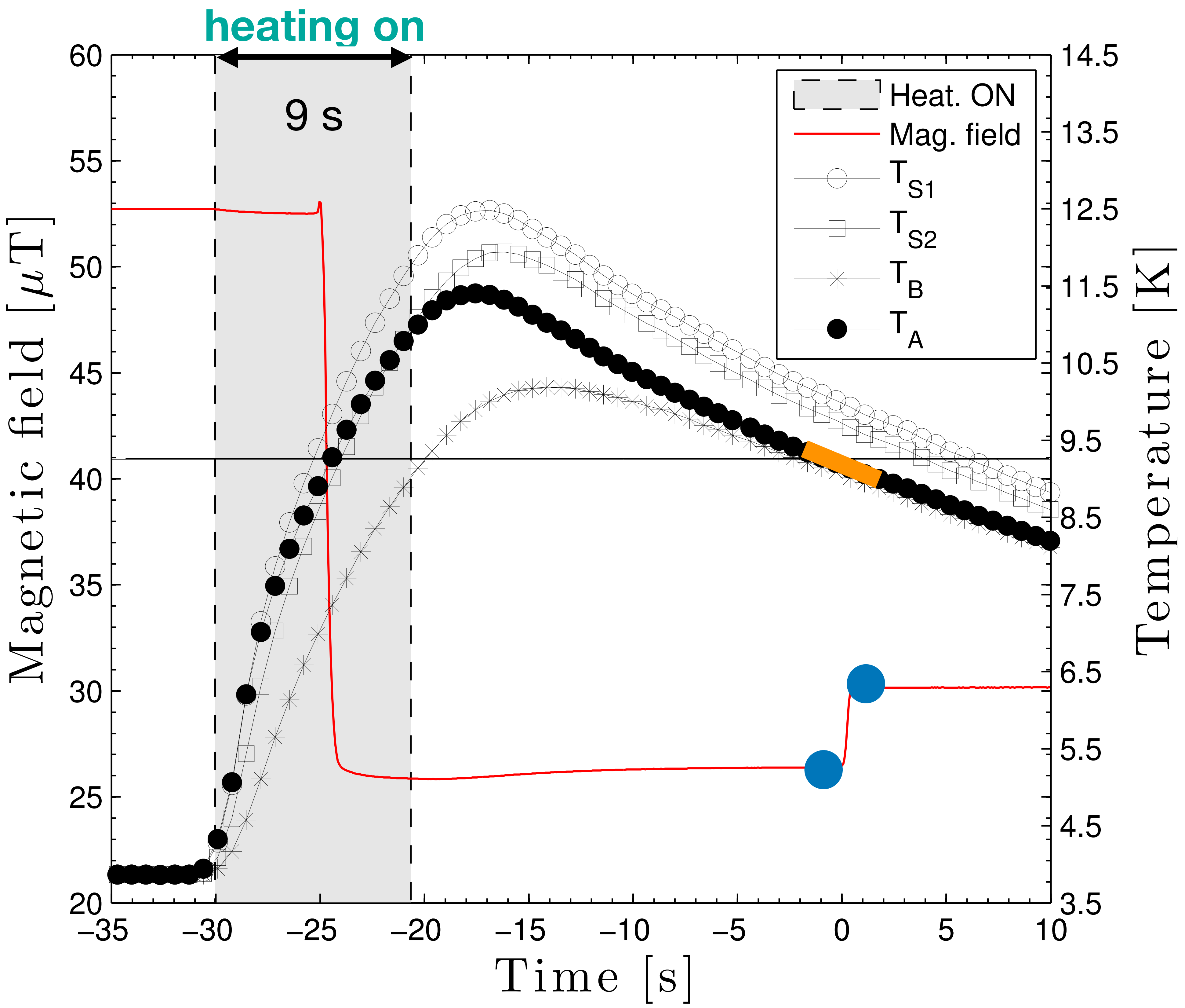
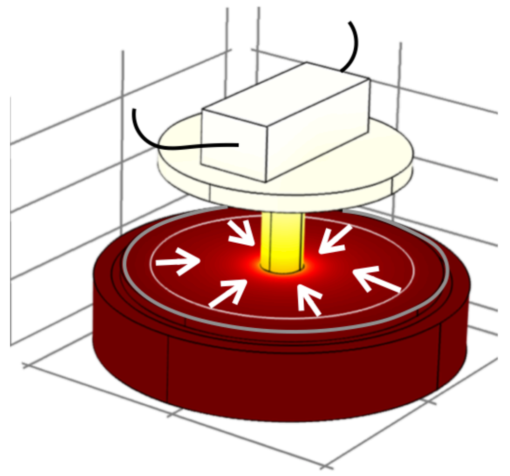


○ **Measurement** of spatial temperature gradient:*

1D problem



$$\nabla T = \frac{dT}{dr} = \frac{1}{\nu_{SC}} \frac{dT}{dt}$$

From B(t) signal

From T(t) signal

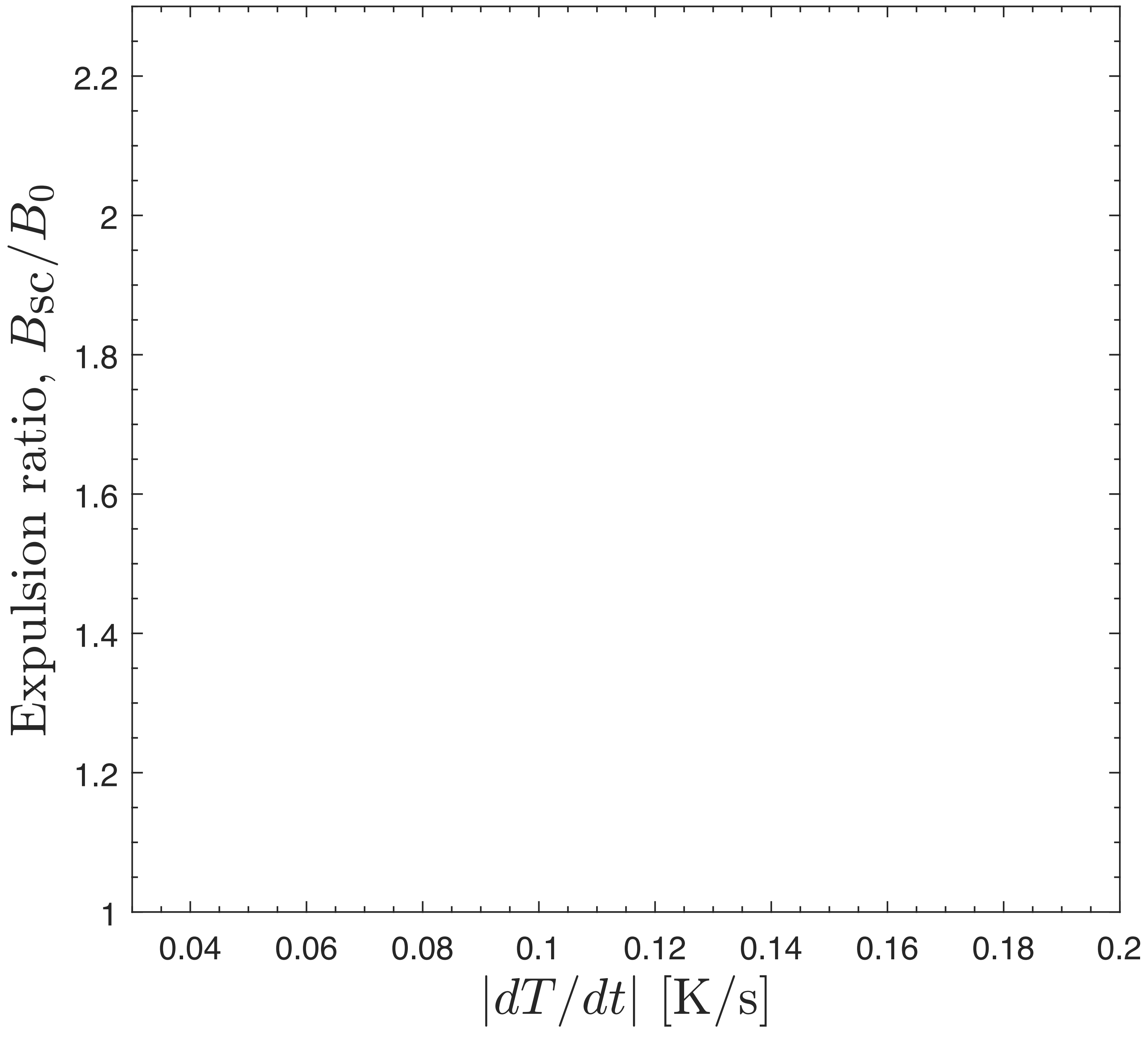
Cooling rate: 0.04 to 0.2 K/s
SC front speed: 2 to 18 cm/s

*S. Huang, T. Kubo, and R. L. Geng, Phys. Rev. Accel. Beams 19, 082001 (2016)

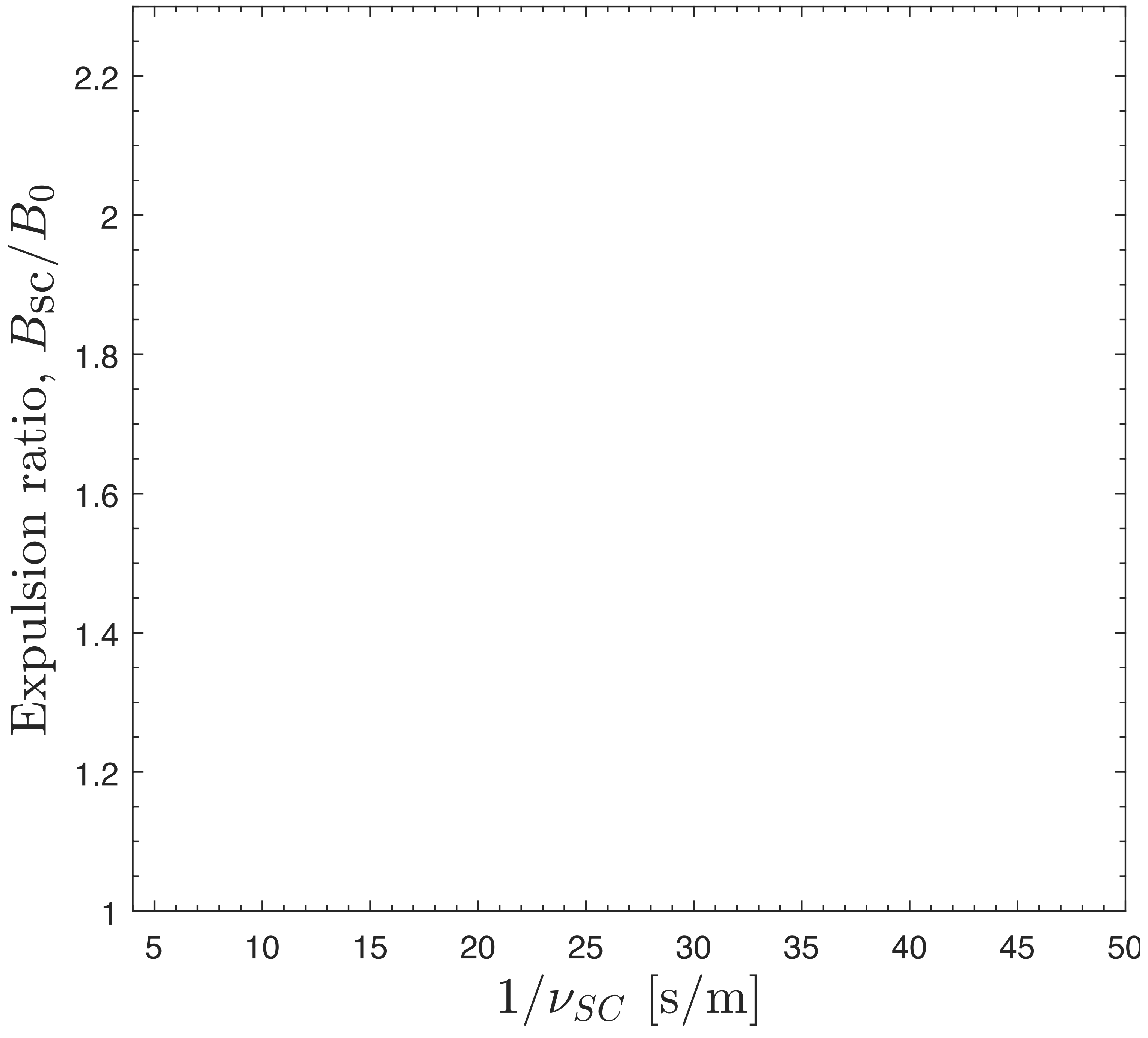
- Measurement procedure:

Assemble and initial cool-down → Perform expulsion for a given pulse length → Thermalize ~20 min → Repeat

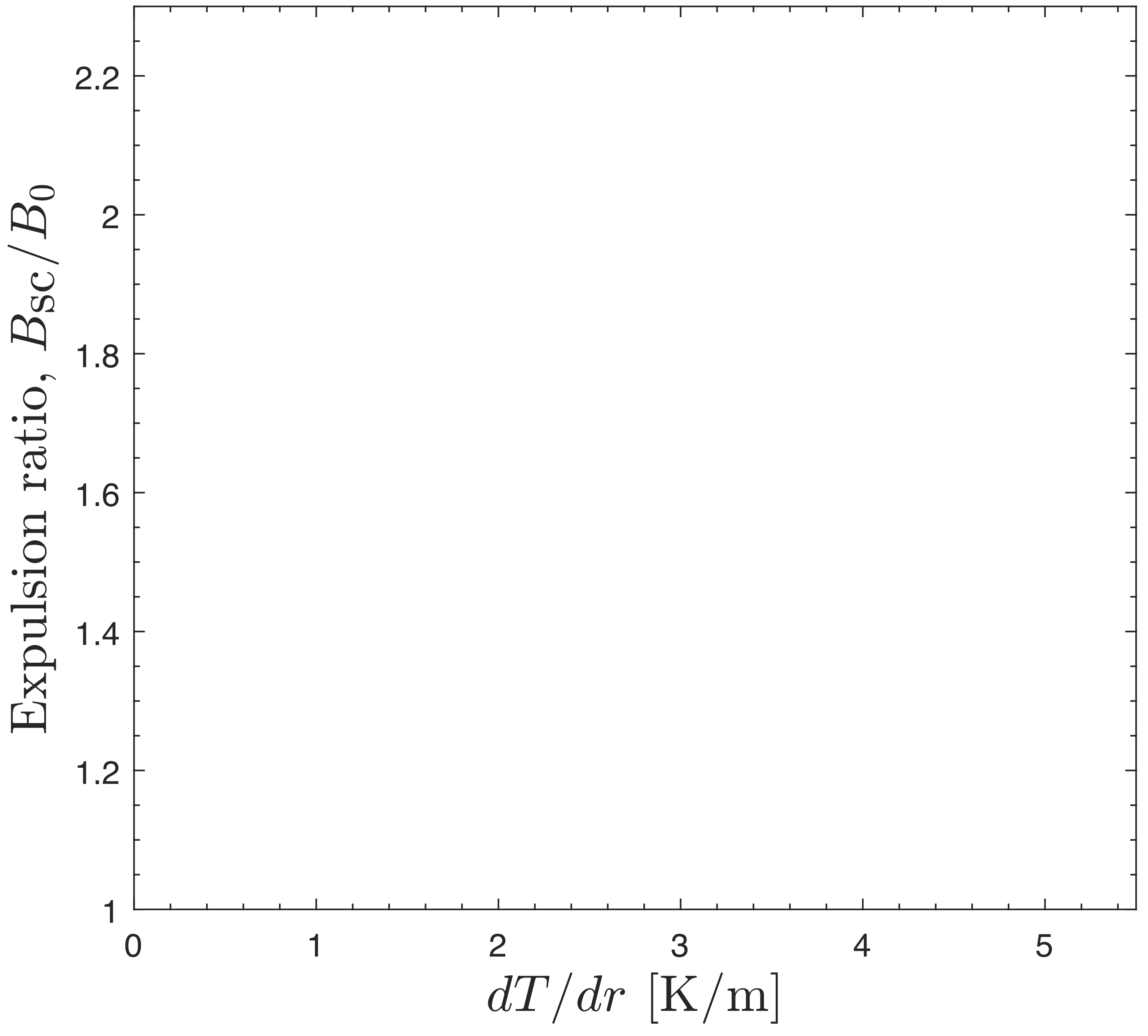
- A total of 669 expulsion measurements over 7 measurement campaigns
- Tested sample: benchmark cavity-grade RRR = 300 niobium (unworked sheet material)



Cooling rate



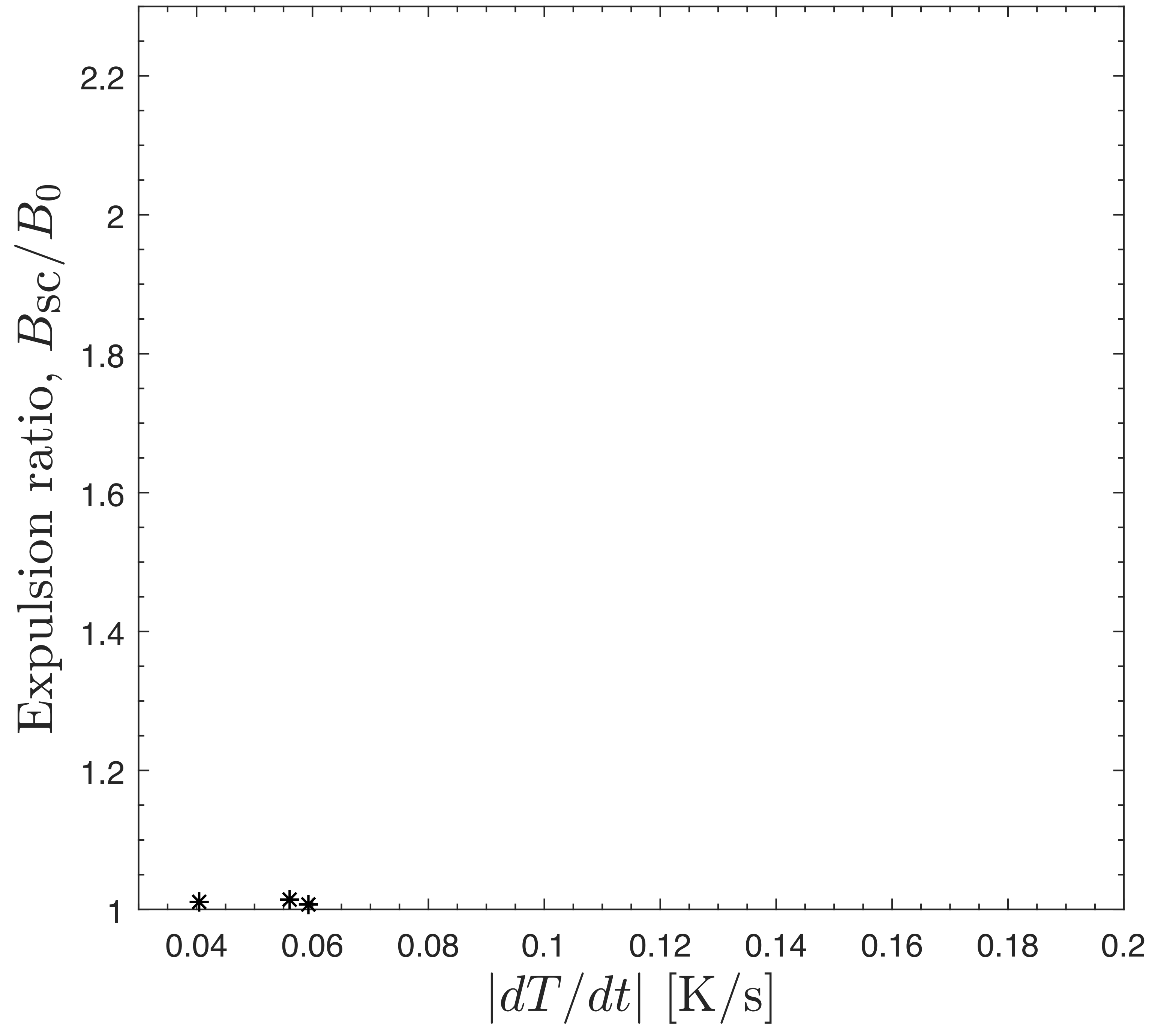
(SC front speed)$^{-1}$



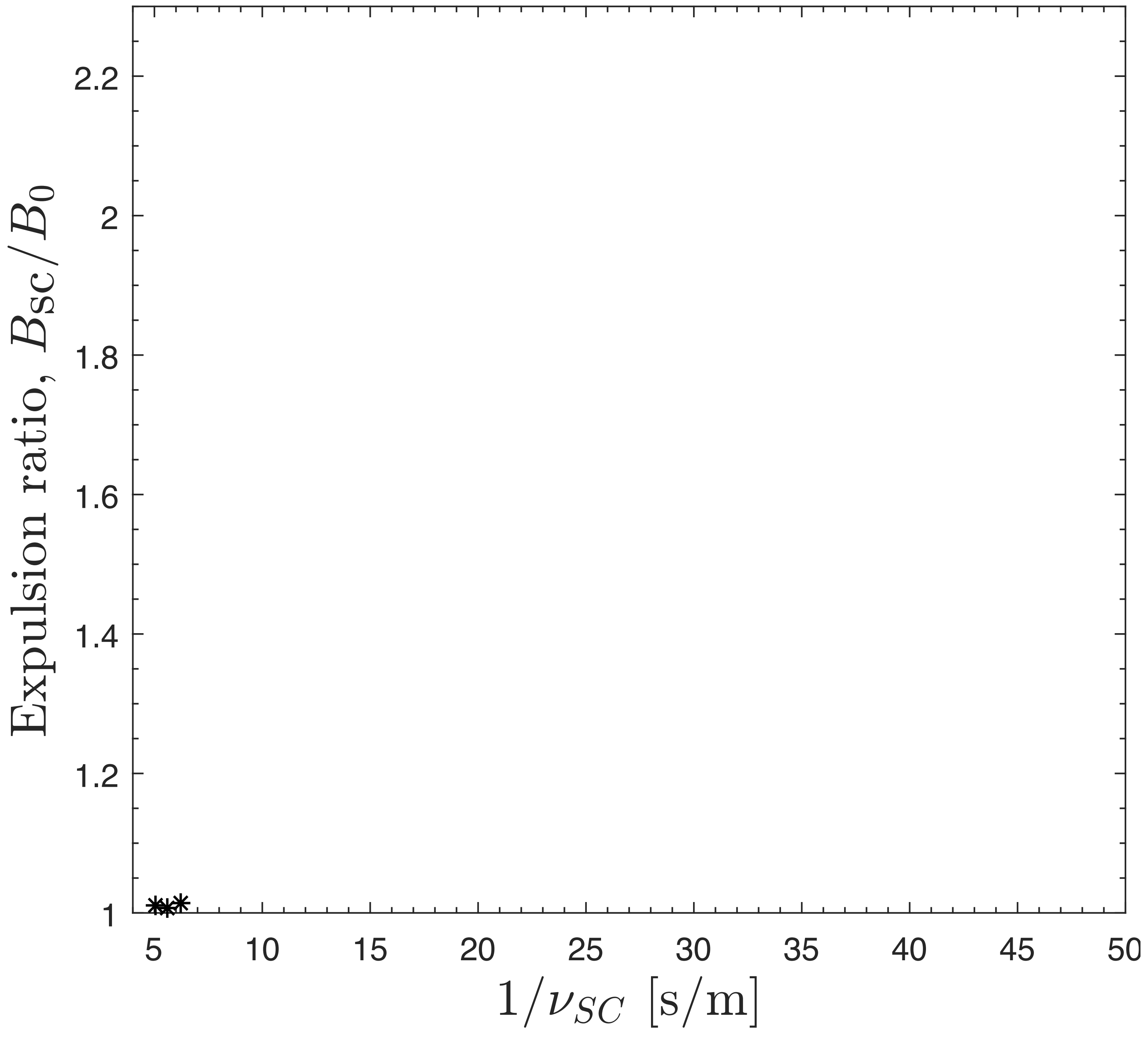
Spatial gradient

Results from measurement campaigns

* C1 Poor thermal contact



Cooling rate



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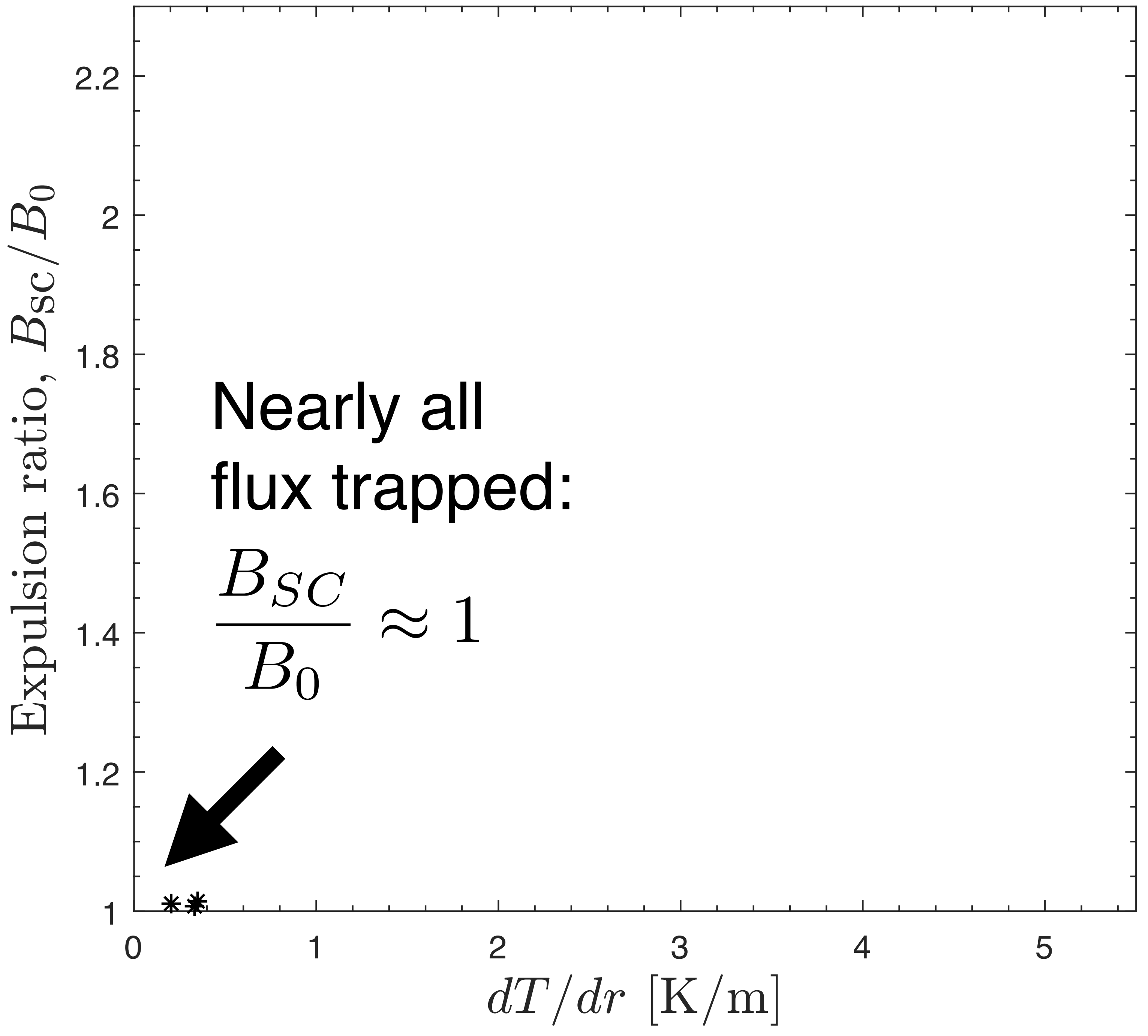


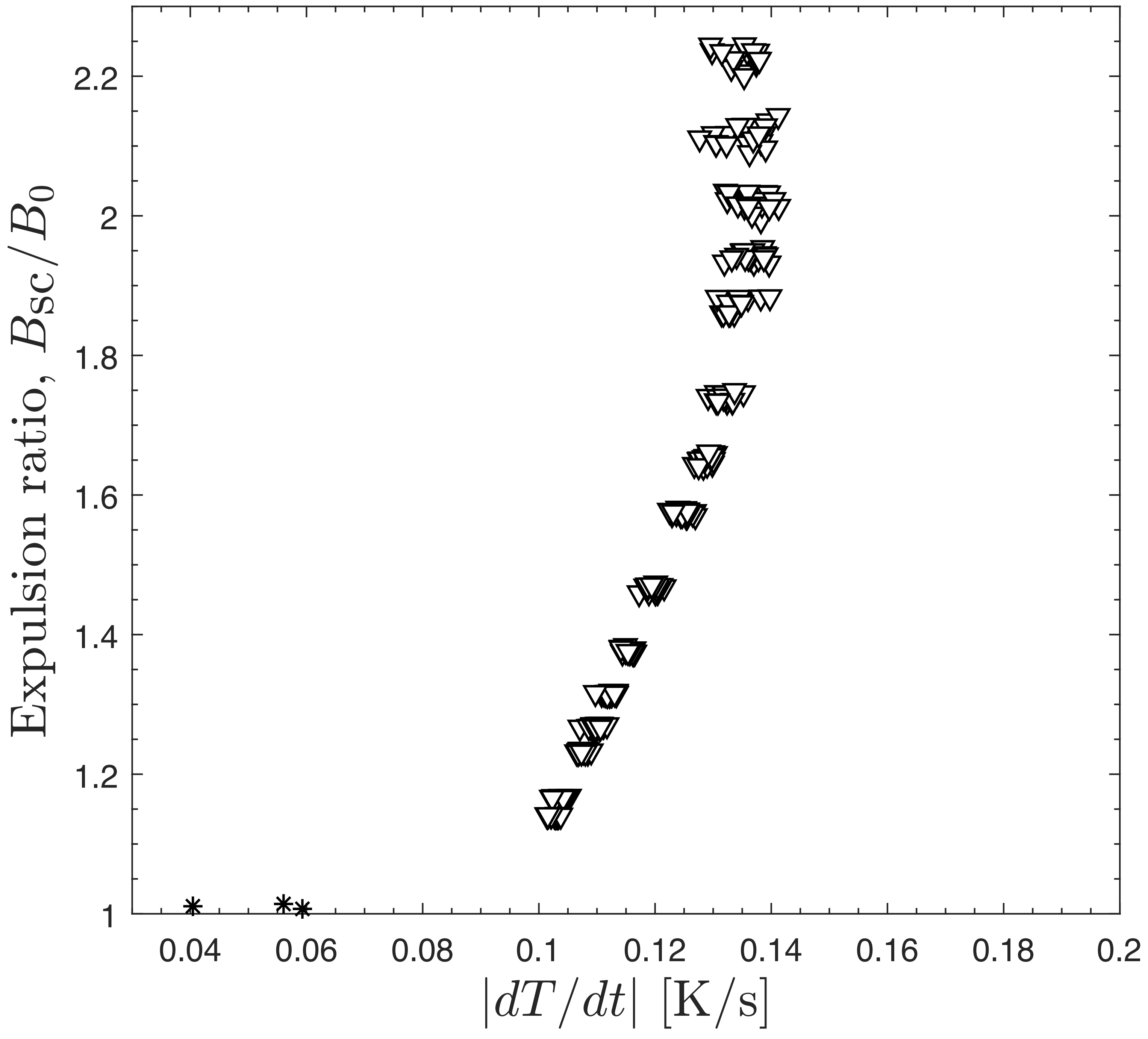
Spatial gradient

Results from measurement campaigns

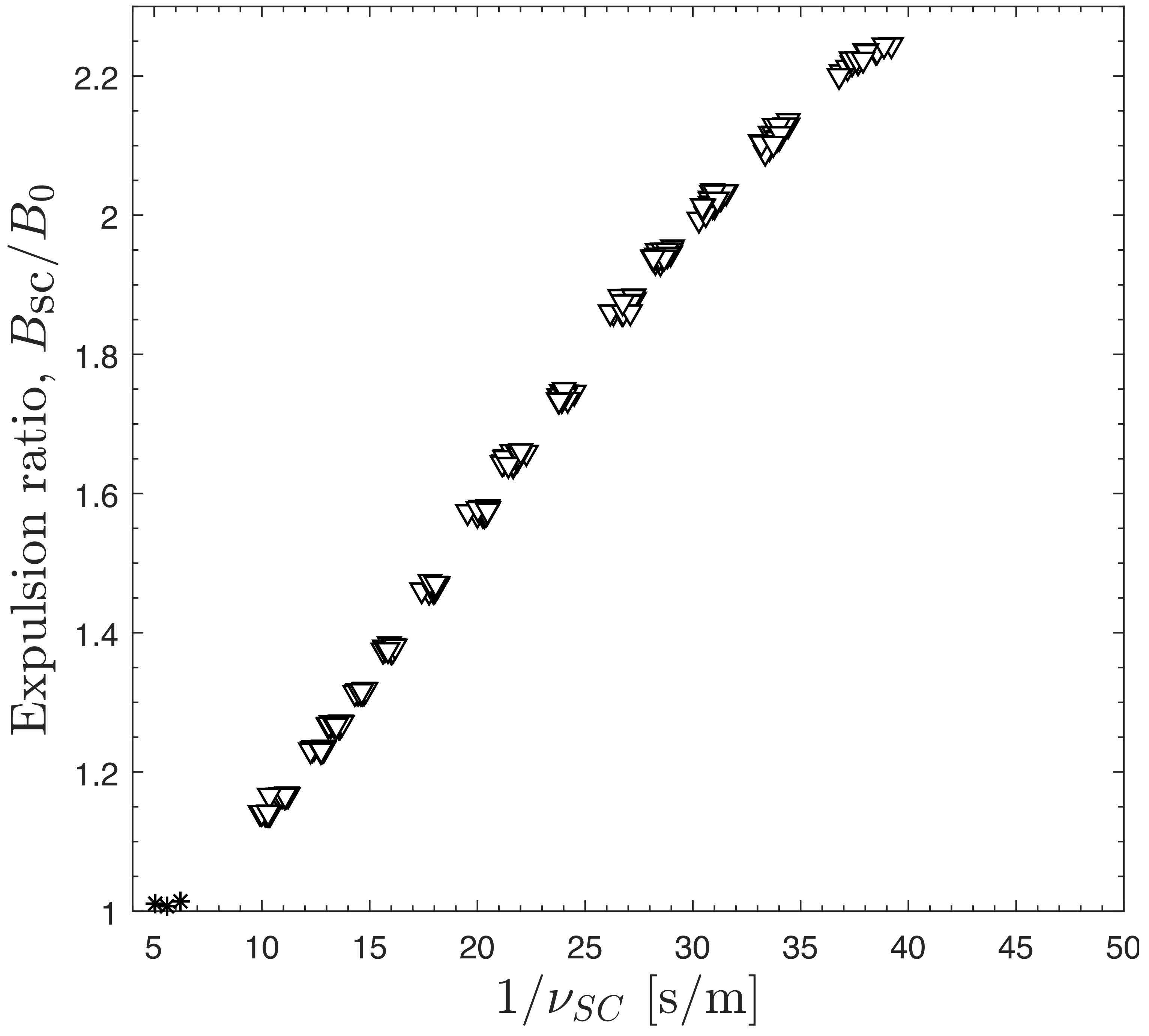
∗ C1 Poor thermal contact

▽ C2 Indium gasket added

Predicted from simulation: $\frac{B_{SC}^{sim}}{B_0} \approx 2$



Cooling rate



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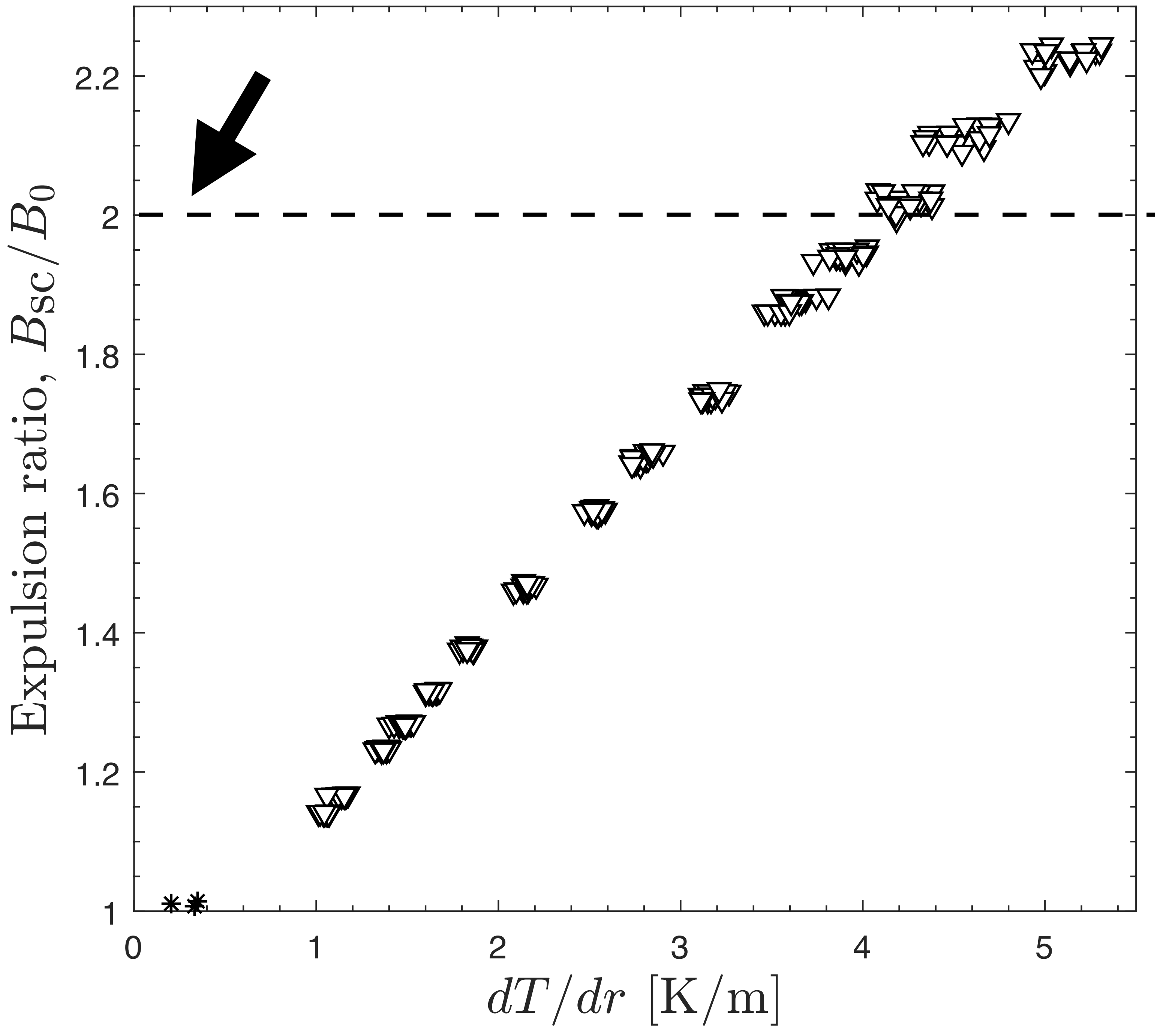
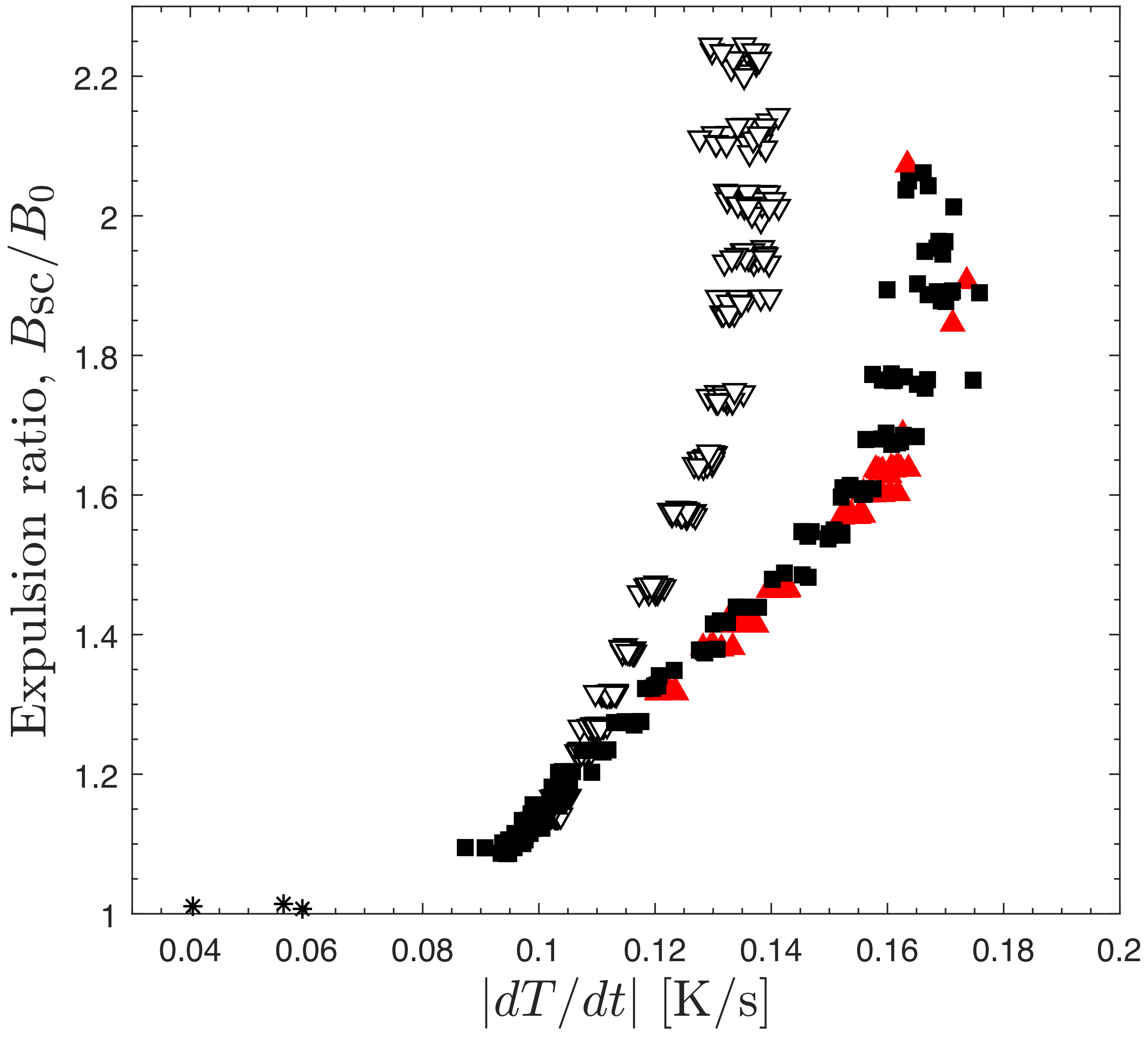


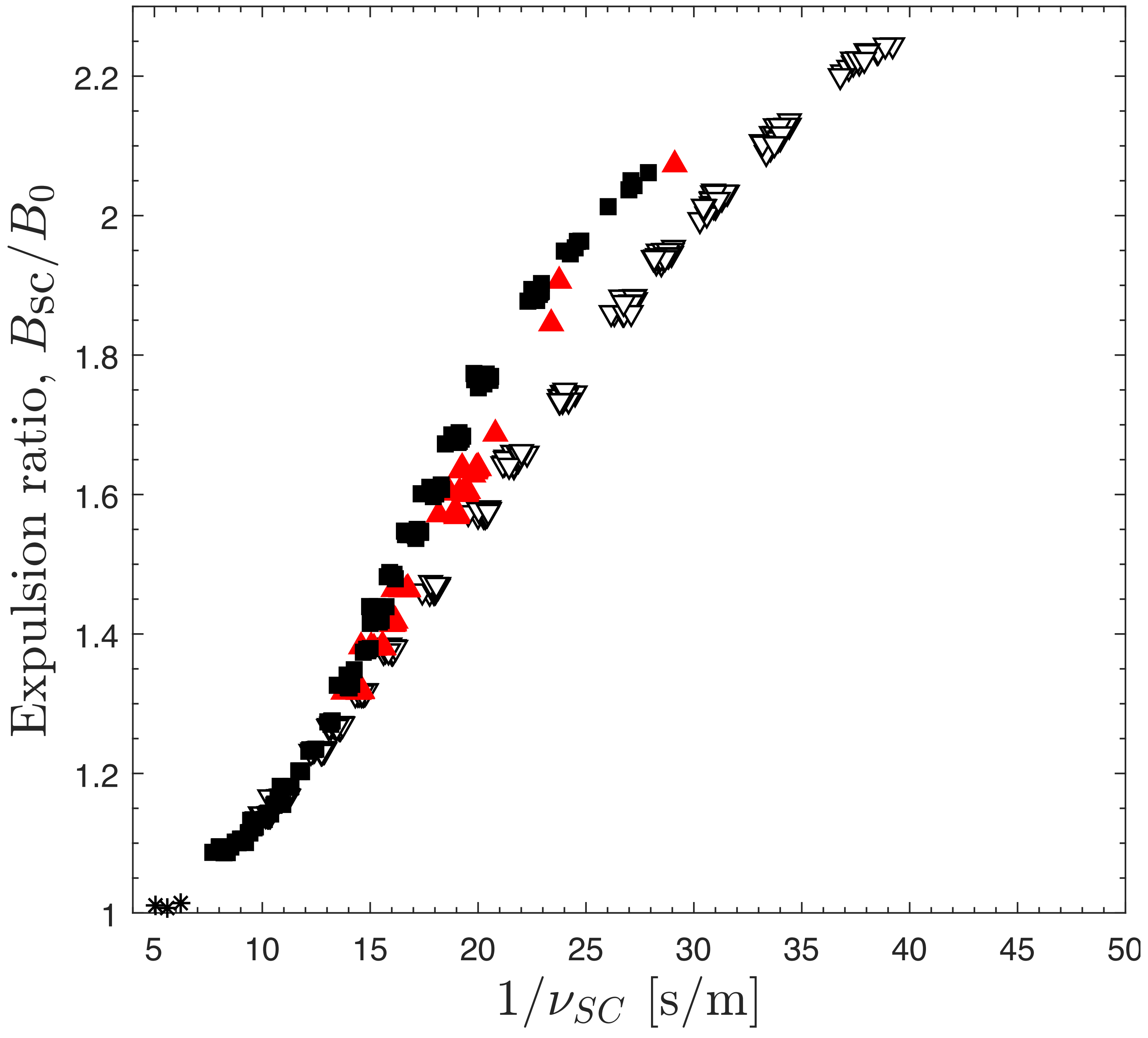
Spatial gradient

Results from measurement campaigns

- ✱ C1 Poor thermal contact
- ▽ C2 Indium gasket added
- ▲ C3, ■ C4 Indium gasket reused, C4 repeated without disassembly



Cooling rate



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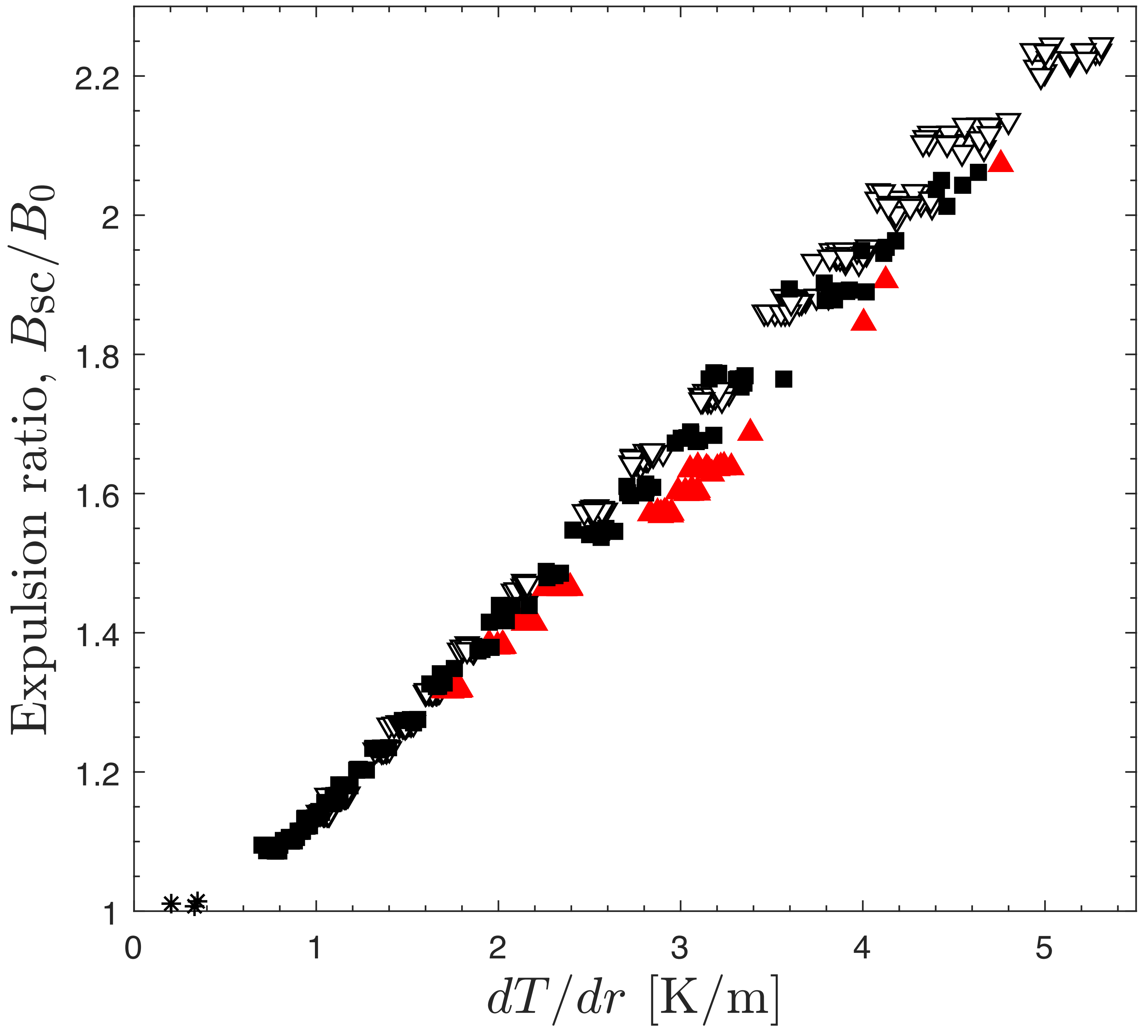

Spatial gradient

Results from measurement campaigns

- ∗ C1 Poor thermal contact
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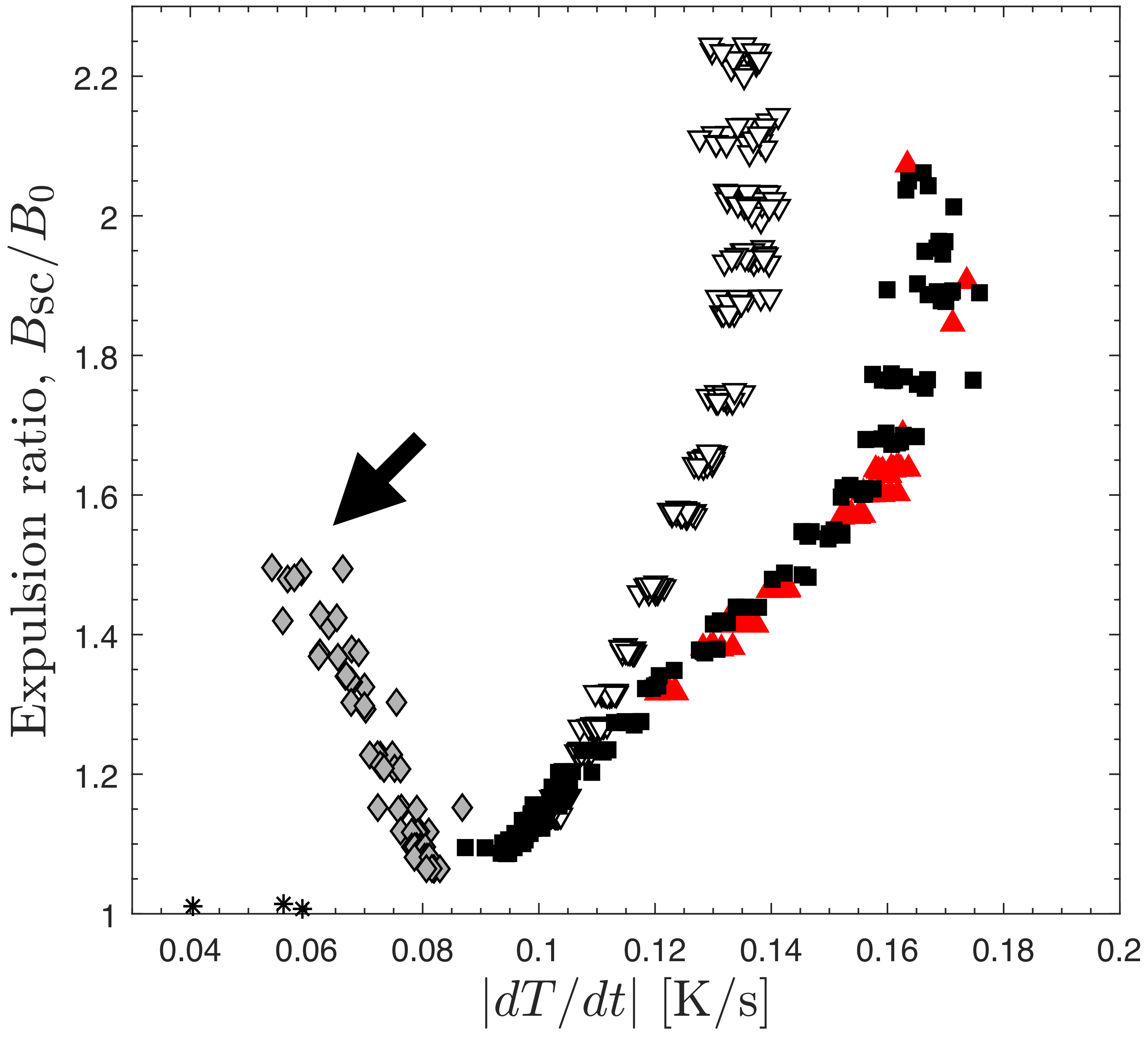
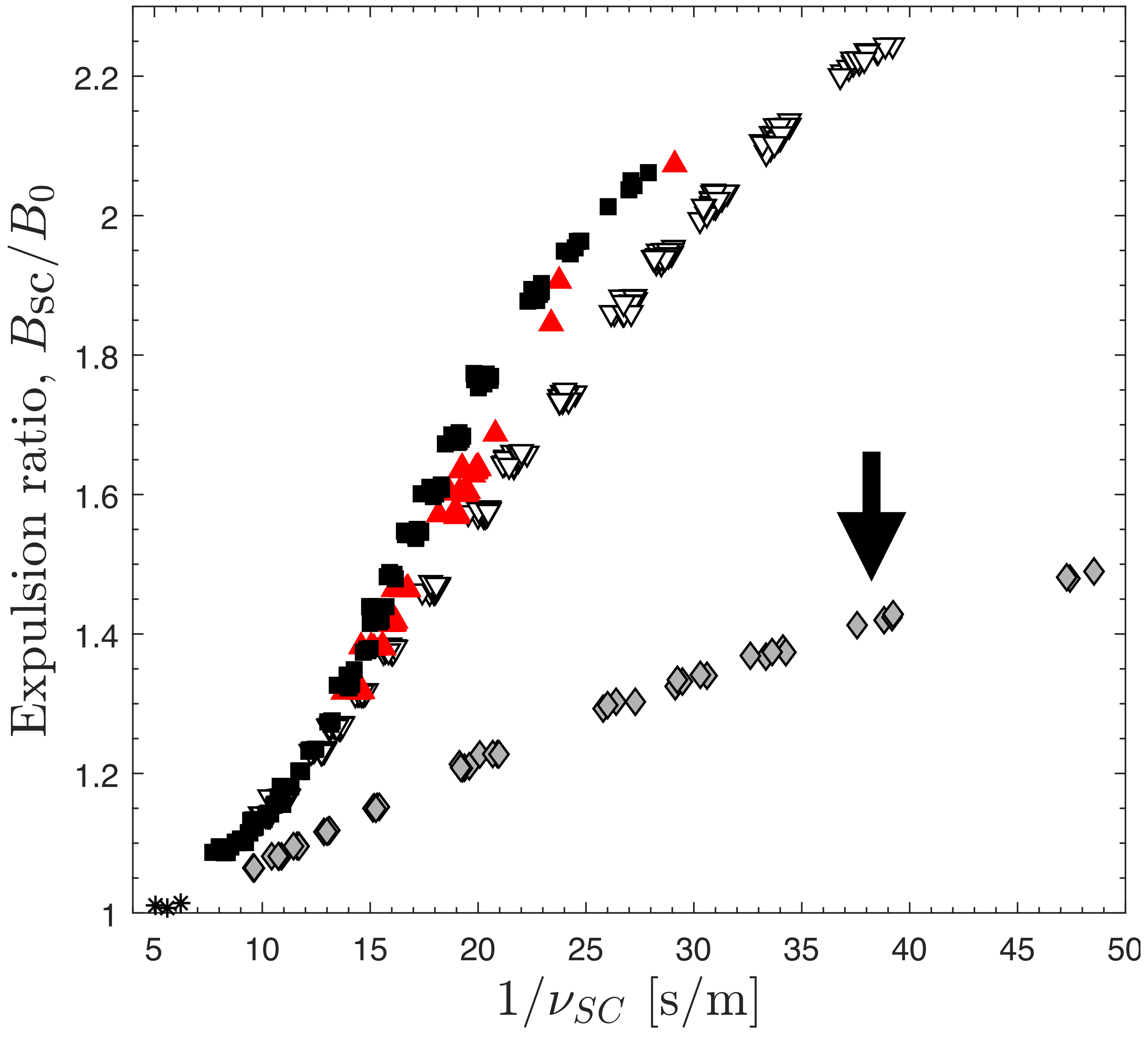
- ▲ C3, ■ C4 Indium gasket reused, C4 repeated without disassembly
- ◆ C5 Force at cold contact tripled —> affects thermal contact resistance



Cooling rate



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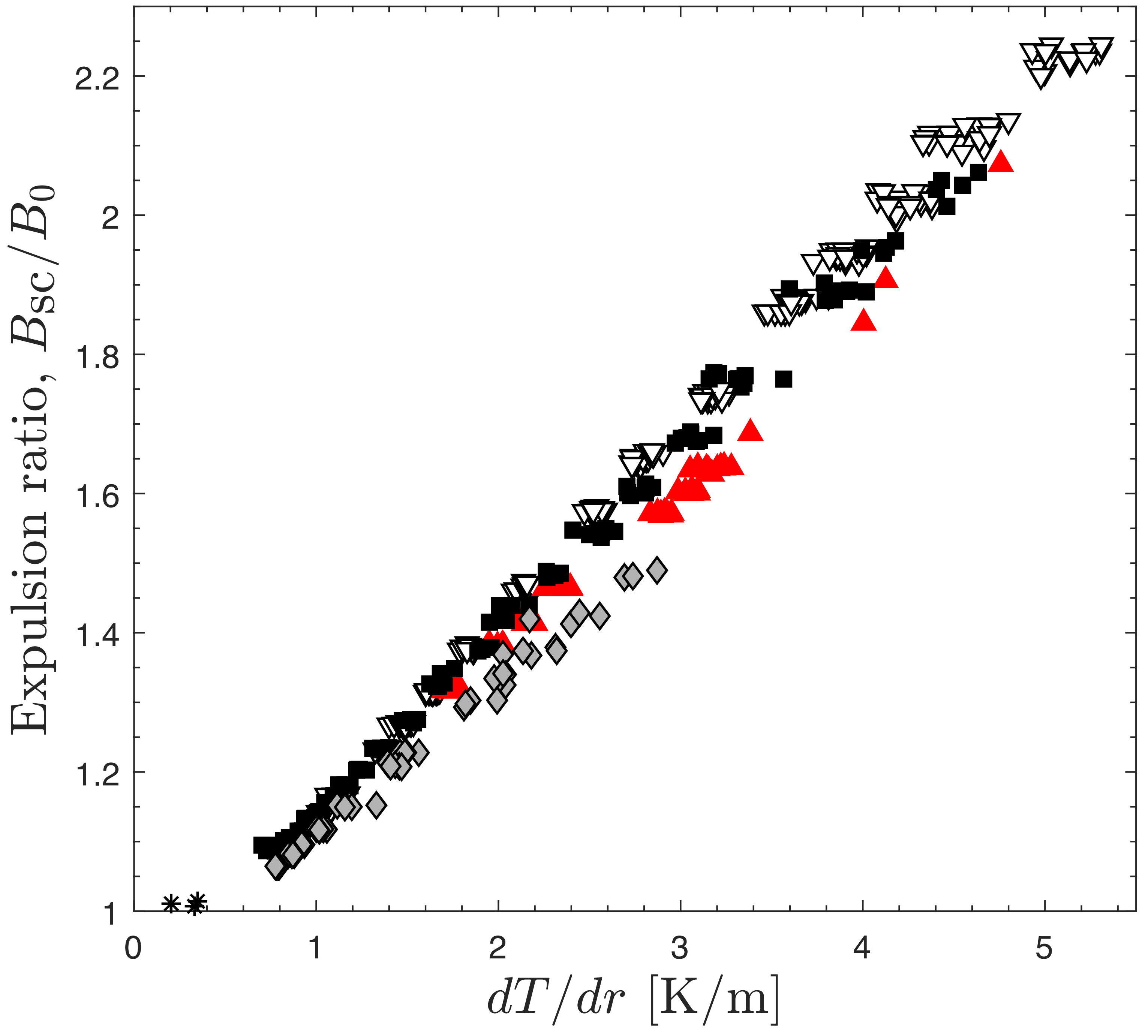
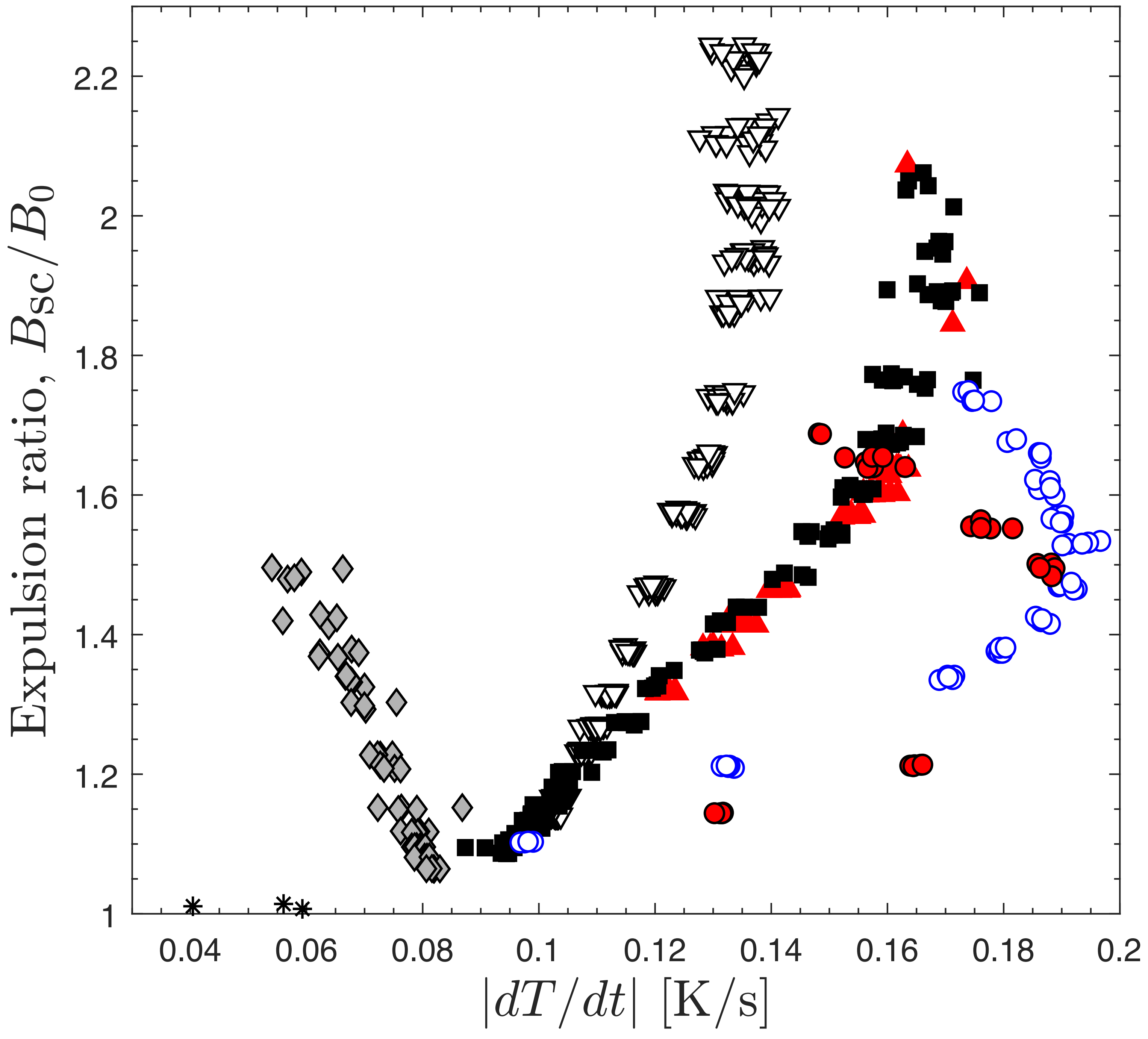


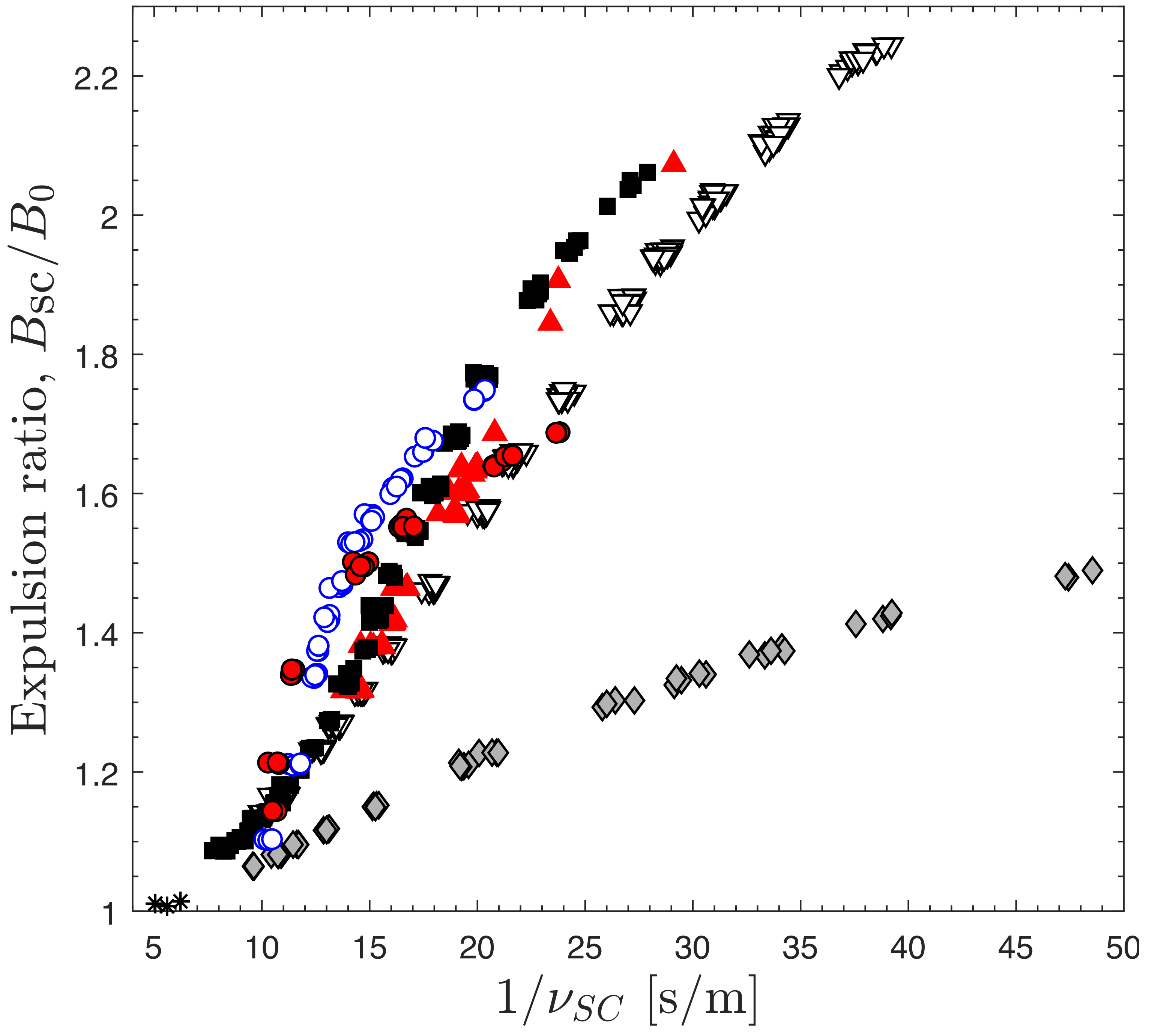
Spatial gradient

Results from measurement campaigns

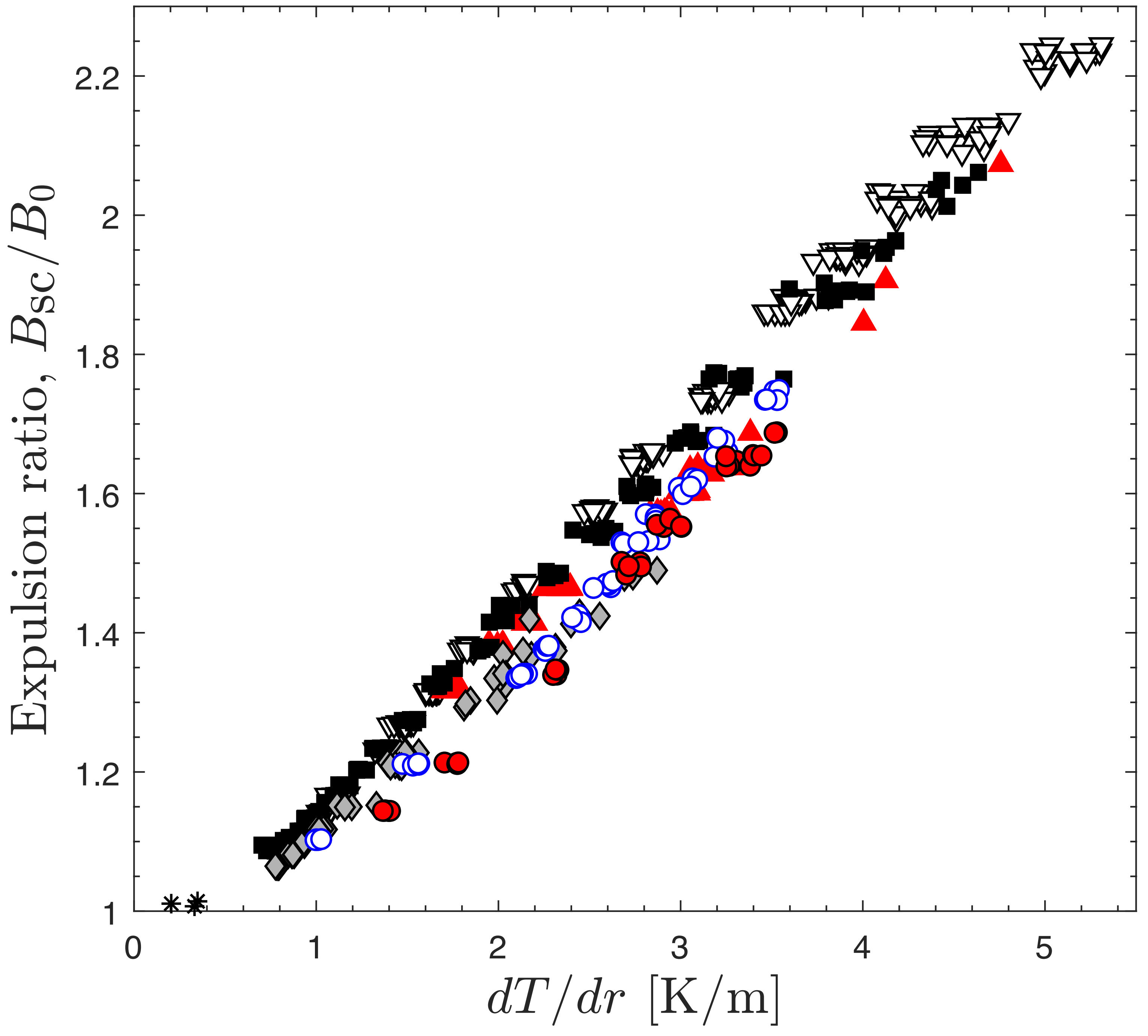
- ∗ C1 — Poor thermal contact
- ▽ C2 — Indium gasket added
- ▲ C3, ■ C4 — Indium gasket reused, C4 repeated without disassembly
- ◆ C5 — Force at cold contact tripled —> affects thermal contact resistance
- ○ C6, ● C7 — Design change: fixed gasket —> improved assembly



Cooling rate



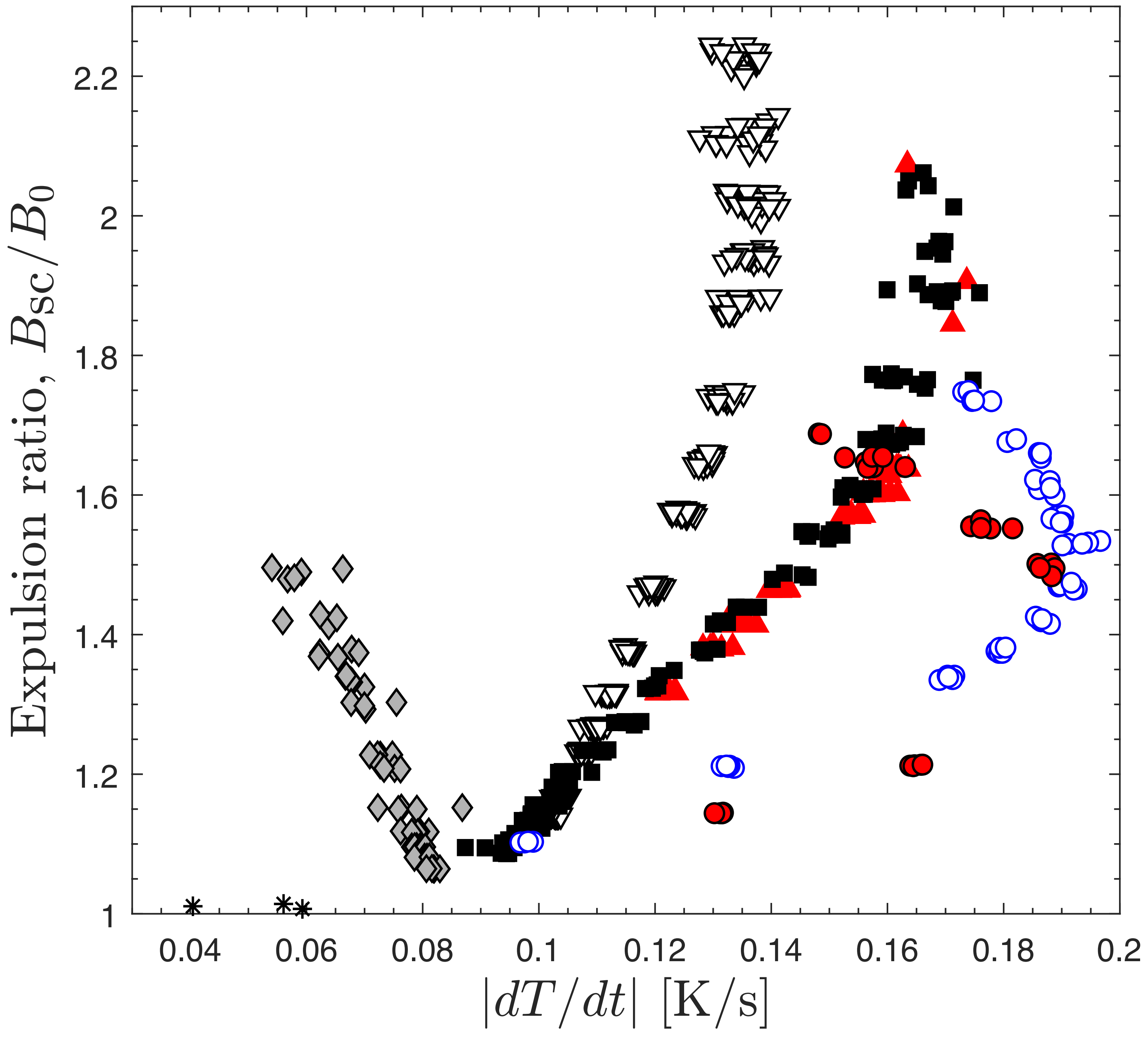
(SC front speed)$^{-1}$



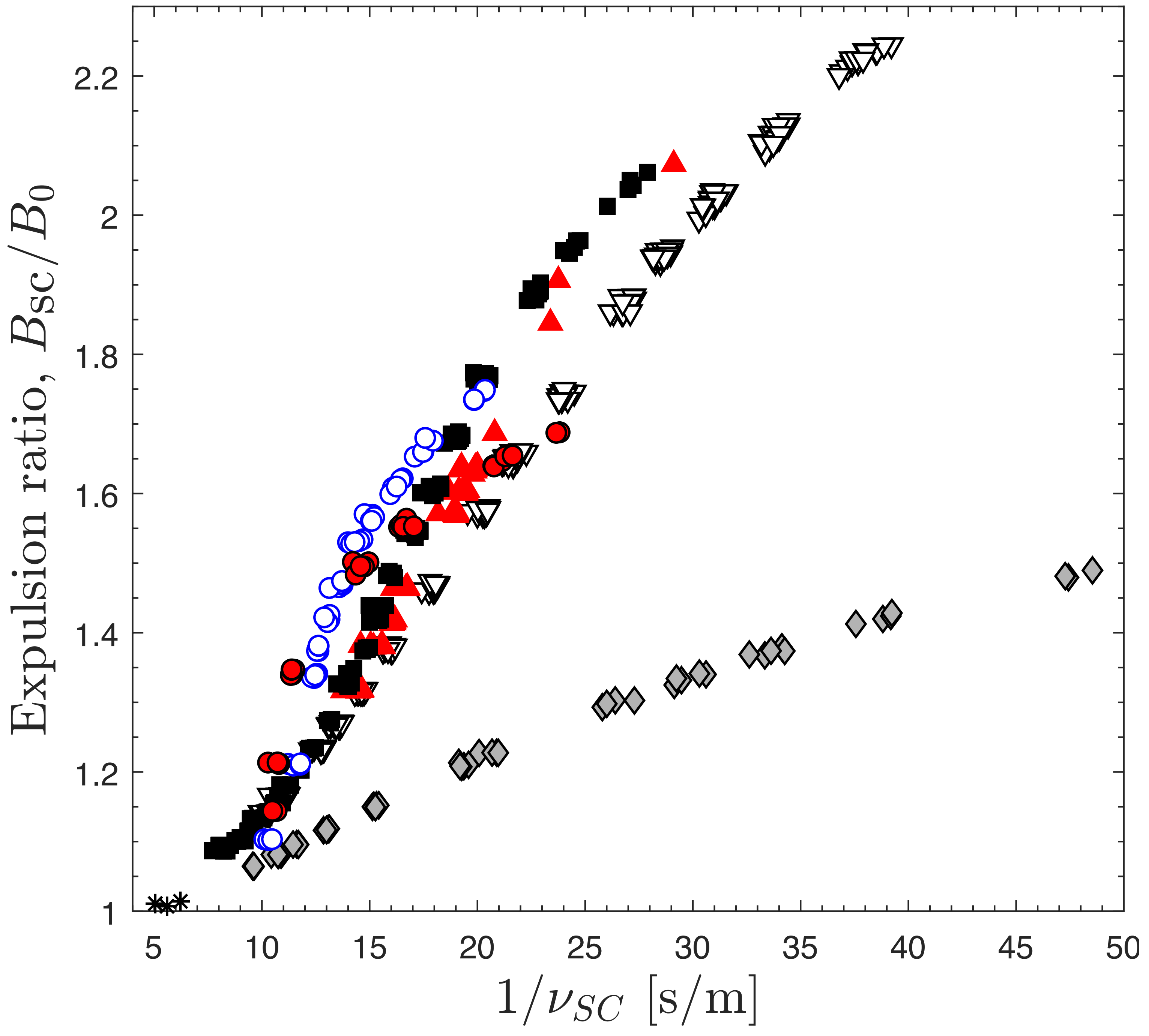
Spatial gradient

Observations

- Cool-down conditions are **repeatable within a given campaign** and can be controlled by the heating pulse length
- Cool-down Conditions **vary from campaign to campaign** — thermal contact resistance varies
- Cooling at high rate not uniquely related to high ER



Cooling rate



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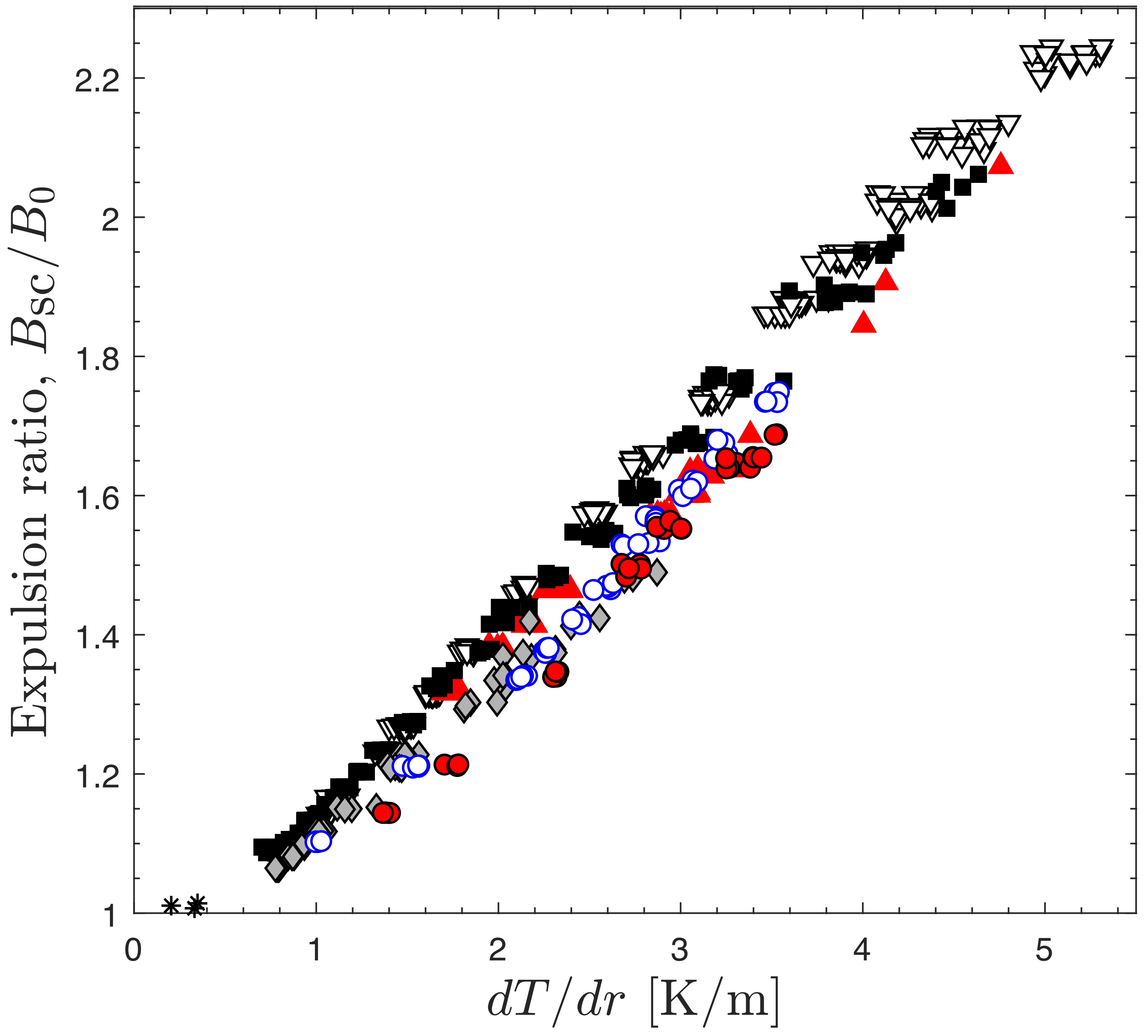


Spatial gradient

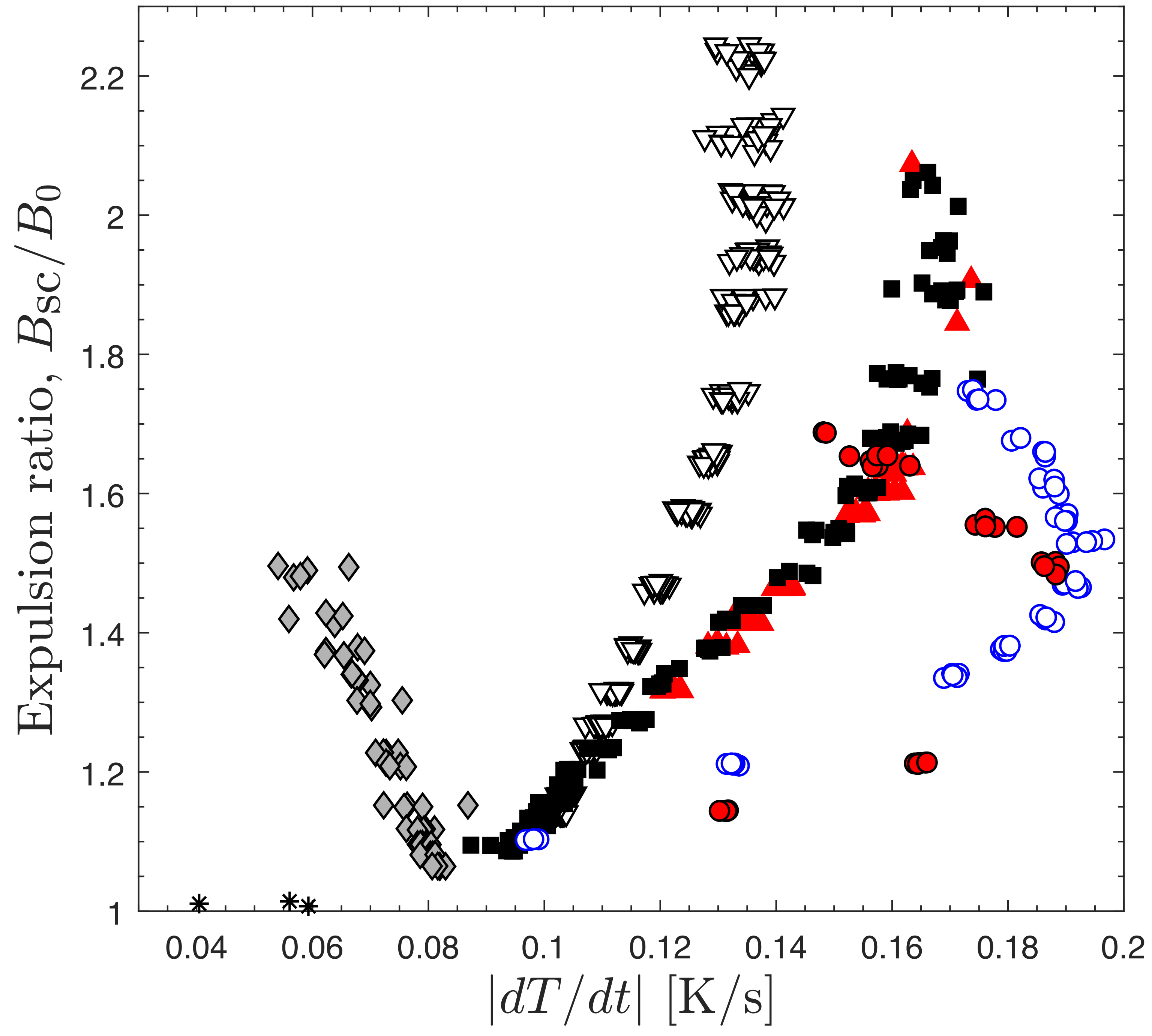
Observations

- Cool-down conditions are **repeatable within a given campaign** and can be controlled by the heating pulse length
- Cool-down Conditions **vary from campaign to campaign** — thermal contact resistance varies
- Cooling at high rate not uniquely related to high ER

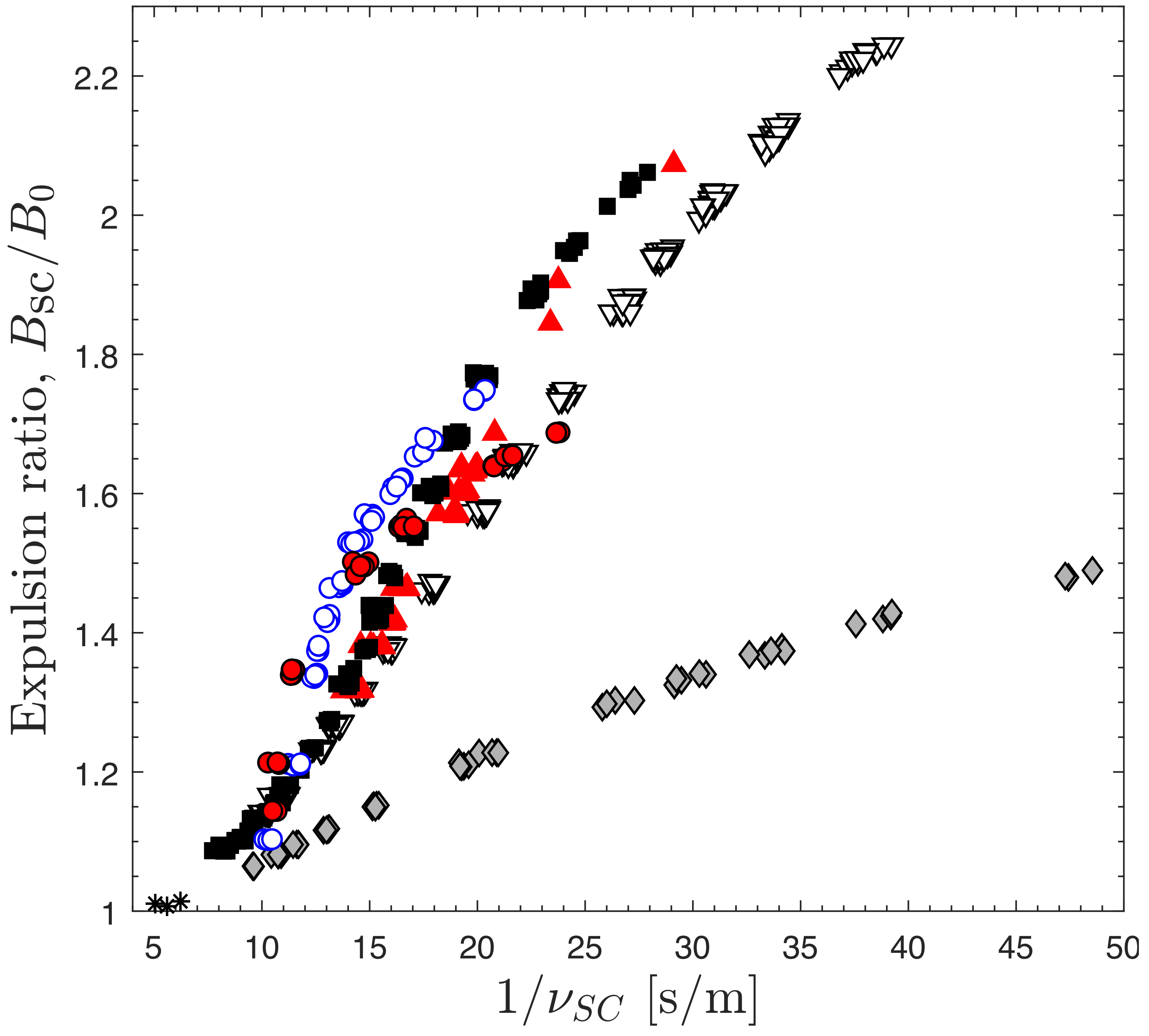
- ER vs grad T is insensitive on the thermal contact resistance and **reproducible across campaigns**

↓

Allows to characterize expulsion efficiency



Cooling rate



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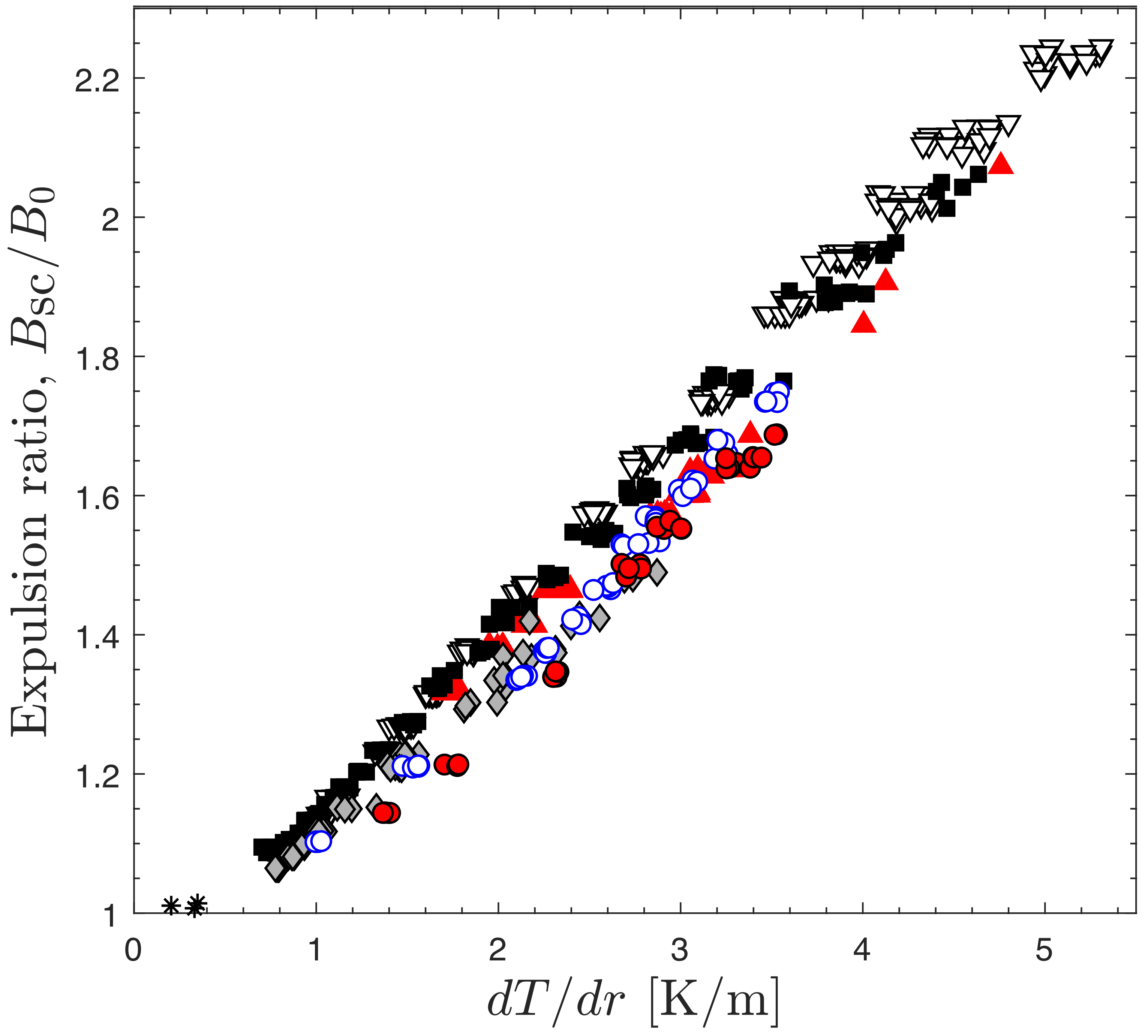


Spatial gradient

Summary and contributions

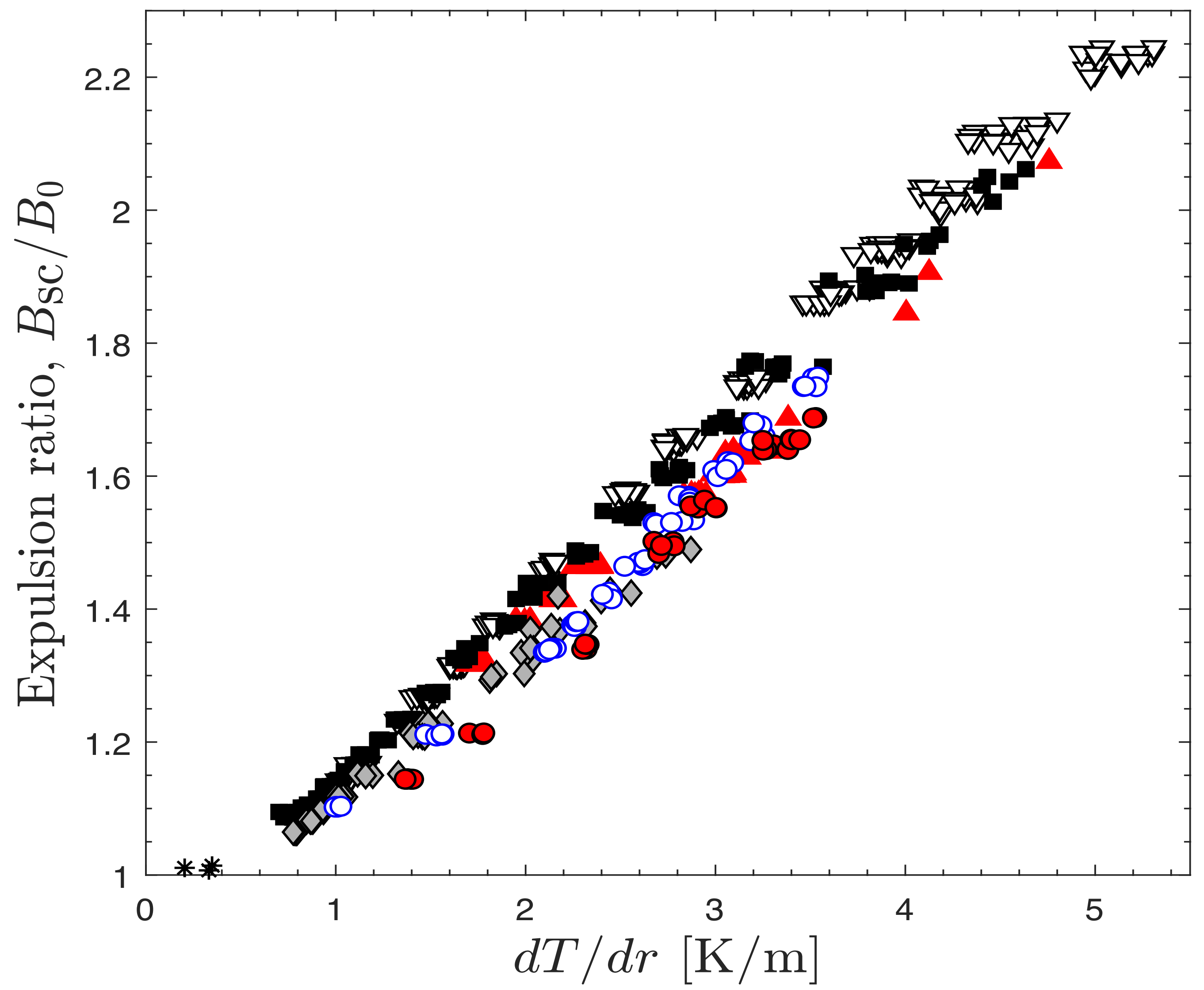
Anton Ivanov *anton.ivanov@cern.ch*
Torsten Koettig,
Alick Macpherson

- Strategy to control and resolve the cool-down dynamics near T_c in the flux Lens developed

- Amount of **trapped flux linked to the cool-down dynamics** near Tc

Campaign	N expulsions	$\max\{\nabla T\}$ [K/m]	$\max\{\frac{B_{sc}}{B_0}\}$	Slope [a]
C1	3	0.4	1.01	–
C2	300	5.3	2.24	0.27
C3	75	4.8	2.07	0.23
C4	144	4.8	2.06	0.26
C5	57	2.9	1.5	0.22
C6	55	3.5	1.75	0.26
C7	35	3.5	1.69	0.27

- **Reproducible result** for $\frac{B_{SC}}{B_0}(\nabla T)$ allows to characterize material



- **Independent confirmation** of studies performed on bare cavities:
  - Cooling at high rate is not uniquely related to high expulsion
  - Expulsion improves for cooling at high temperature gradients