On Enhanced Flux Expulsion in Superconductors

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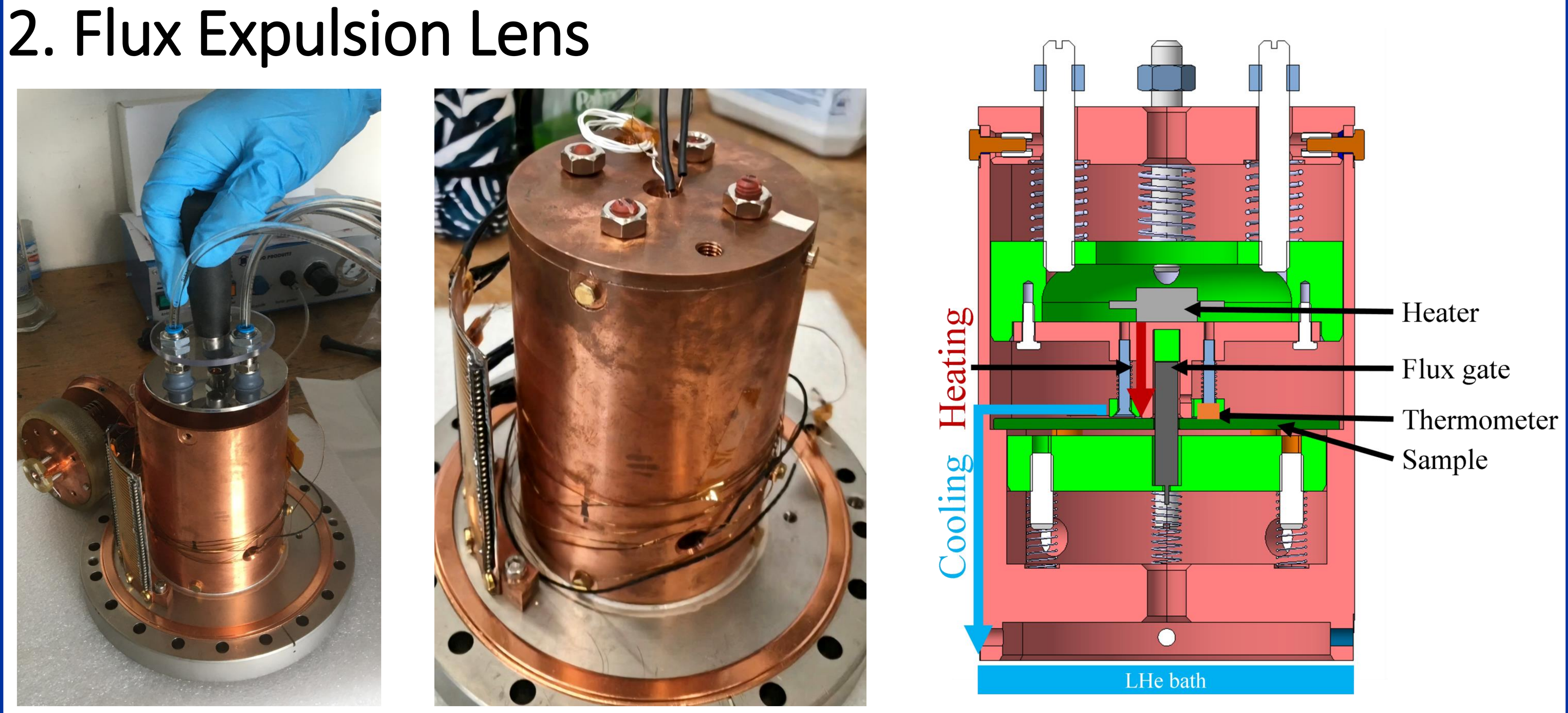
1. Overview

A magnetic flux expulsion lens (MFEL) has been designed and built at CERN. This device uses topological conduction cooling of samples to quantify magnetic flux expulsion of superconductors. This device allows for repeatable and systematic measurements of the cooling dynamics and magnetic response to identify the influence of thermo-electric effects and screening currents at the superconducting transition.

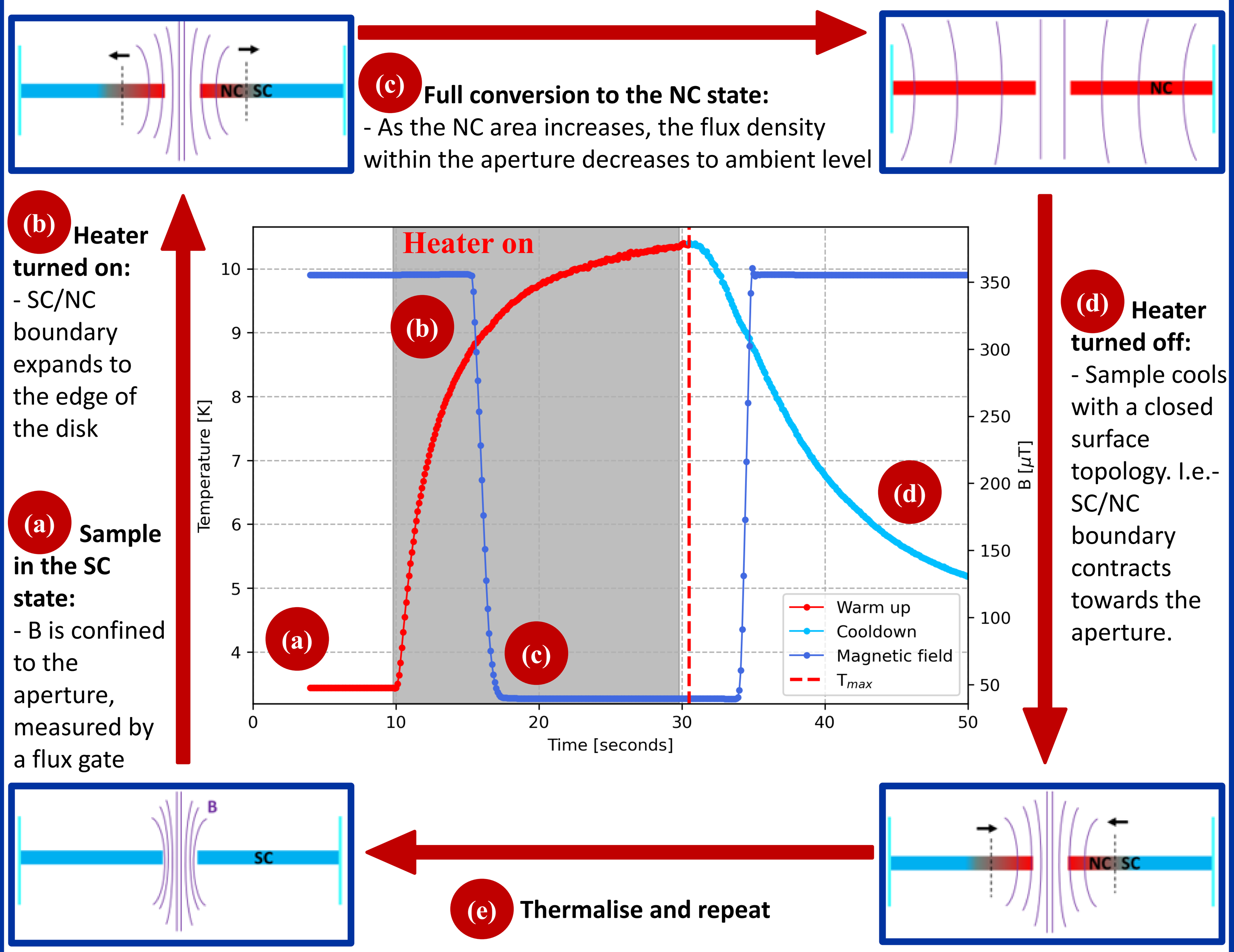
The MFEL is applicable to both bulk and layered superconducting samples, and offers both material qualification and investigation of the magneto-thermal behaviour of the RF layer. Measurement results for bulk Nb, cold worked Nb, Nb thin films on Cu deposited by HIPIMS at CERN, and multilayer SIS structures produced by plasma enhanced atomic layer deposition (PEALD) at DESY are reported, including preliminary results on flux pumping using SIS samples for cavity applications.

2. Flux Expulsion Lens

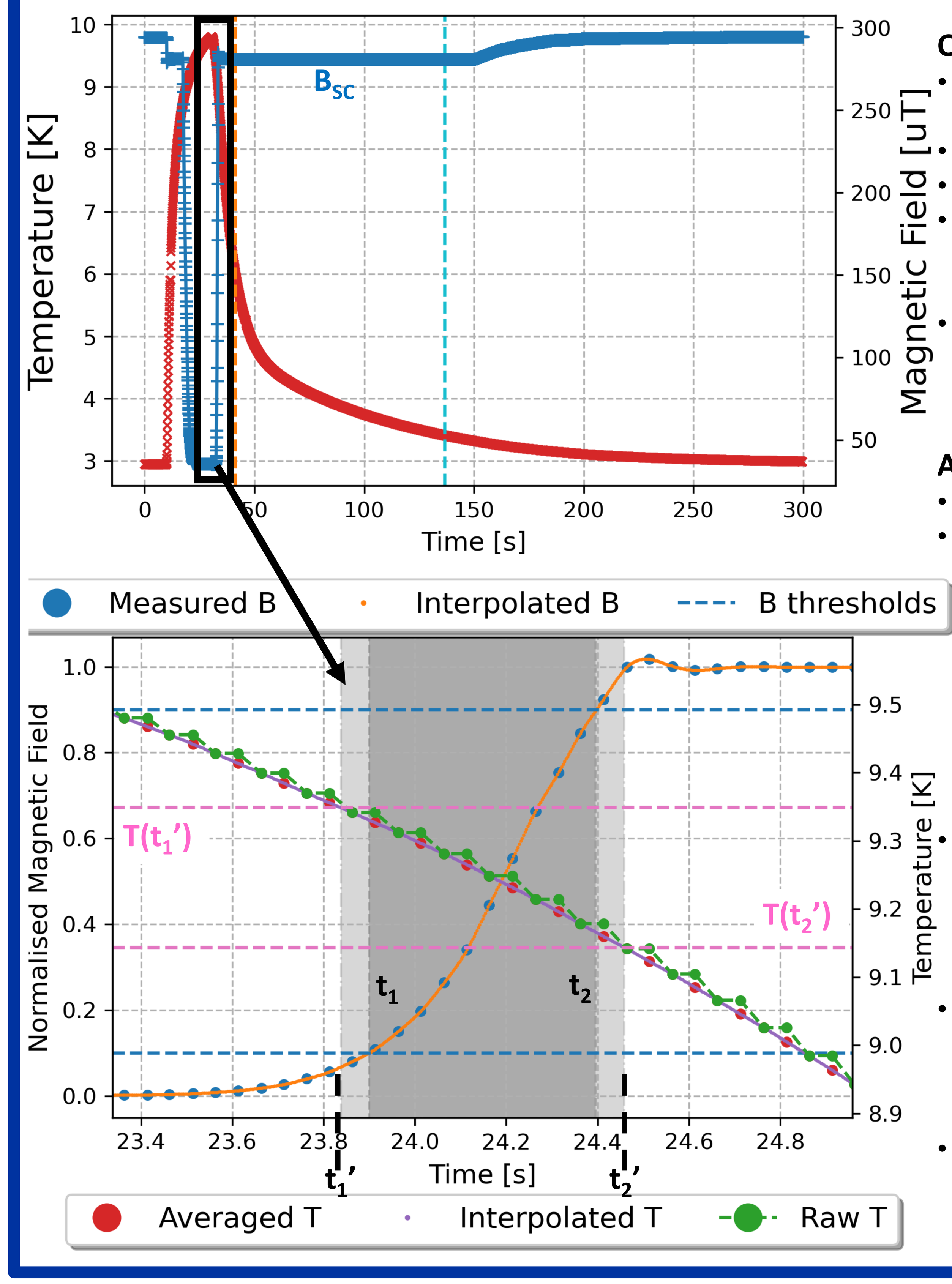


- The Flux expulsion lens cooled by a LHe bath.
- A heat pulse applied by a heater
  - Heat must move through the sample to the Cu shell
- The B field response is measured by a flux gate situated in the aperture of the disk.

Measurement sequence



3. How is the analysis performed?



Observables

- Analysis performed on NC -> SC transition.
- B_{SC} is the final magnetic field.
- B_{NC} is the ambient B field.
- T is temperature at the aperture

- Readout :T at 10 Hz, B at 20 Hz.
  - B and T and interpolated.

Analysis

- $t_1 = B(10\%)$, $t_2 = B(90\%)$.
- Extended time is found by accounting for the thresholds, finding t_1' and t_2':

$$Full\ time = \frac{t_2 - t_1}{0.9 - 0.1}$$

$$dT = T(t_1') - T(t_2')$$

- Transition spatial thermal gradient:

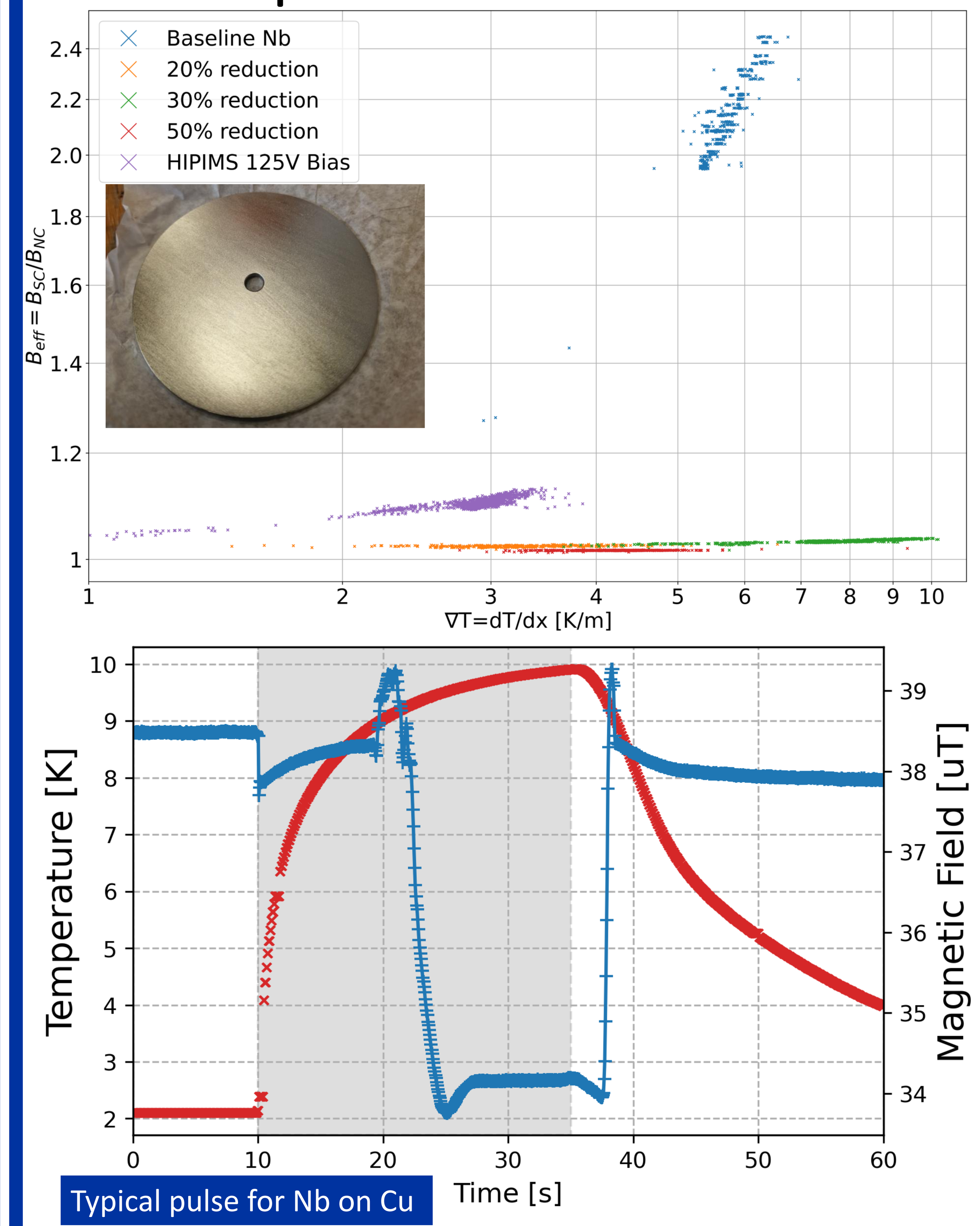
$$\nabla T = \frac{dT}{dx}$$

- Flux expulsion defined as:

$$B_{eff} = \frac{B_{SC}}{B_{NC}}$$

- Material performance quantified by B_{eff} vs T

4. Flux Expulsion in Nb



Bulk Nb

- All samples machined from the same RRR300 Nb sheet.
- Different levels of plastic strain were introduced by cold rolling. Samples are labelled by thickness reduction after cold work.
- Samples are labelled by the reduction in sample thickness due to cold rolling.

Sputtered Nb

- A micron thick Nb film sputtered on Cu by HIPIMS with a 125V bias.
- The Cu substrate acts as an alternative heat path, limiting dT/dx.
  - Heat does not all go through the Nb.

Observations

- Large reduction in B_{eff} found for cold rolled samples.
- A similar B_{eff} for samples with 20 and 30% reduction.
- Almost no expulsion for 50 % reduction.
- Sputtered Nb has more expulsion than cold worked Nb but less than un-annealed Nb.

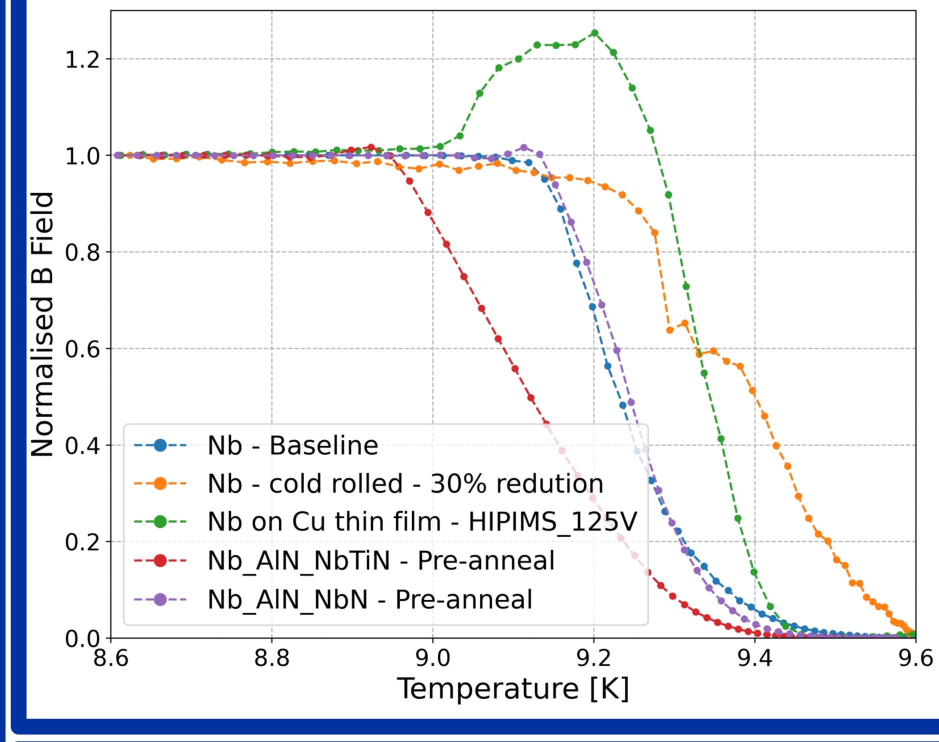
- Sputtered Nb shows clear signatures of magnetic effects from thermo-electric currents.
  - This includes dynamics at the superconducting transition of the film.

Future work

- Cold worked Nb samples are to be annealed (by high temperature heat treatments, range: 600 to 1000°C) to see how performance is enhanced/recovered.
- 2 more HIPIMS samples have been deposited with a 80V and 150V bias.
  - Objective to determine an optimal coating process with respect to flux trapping.
- Nb_3Sn sample to be deposited on Cu is to be prepared and tested at CERN.

6. Cooldown dynamics

Studying the B(T) also provides insight into the behaviour of the samples.



Observables

Bulk Nb

- Bulk Nb (RRR=300): typical smooth curve.
- Cold worked Nb: Distinct B field step.
  - Re-arrangement of trapped flux.

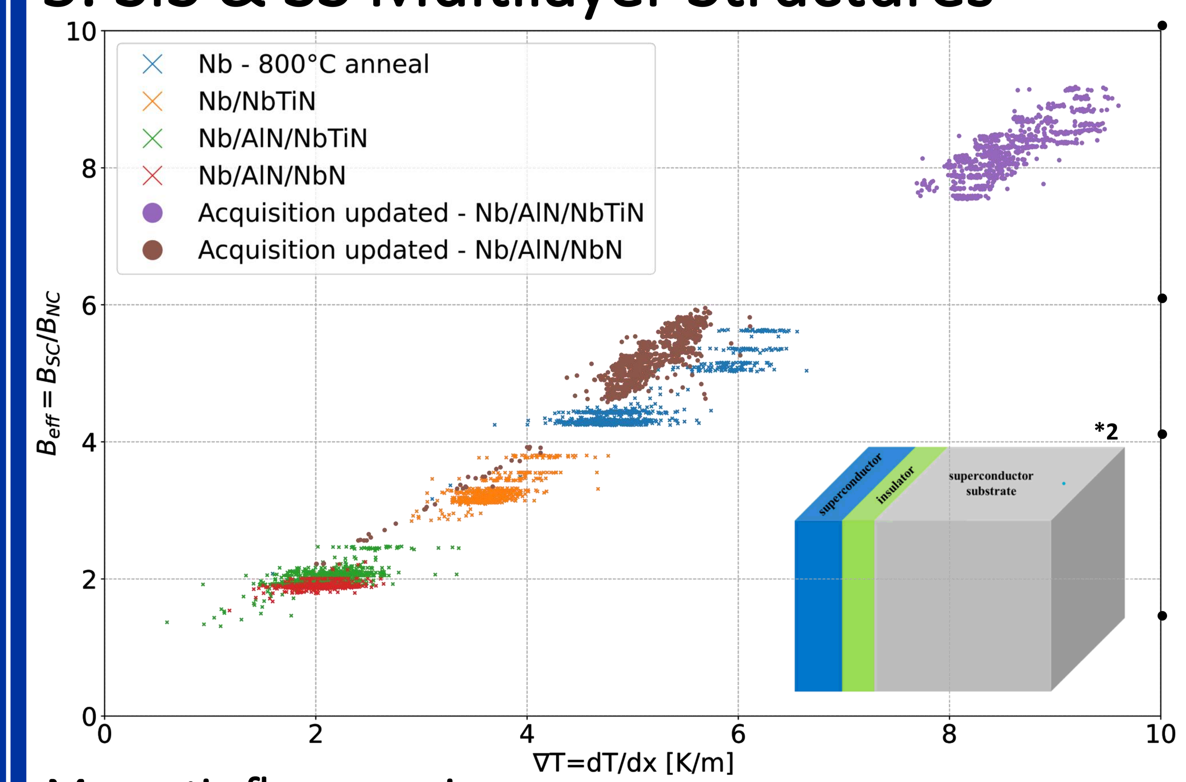
Nb on Cu

- Large change in B - Likely due to thermo-electric effects producing B.

SIS

- Small self induced B field at transition, only visible in NC→SC transition. This could be due to the thin films on the surface causing thermo-electric effects.

5. SIS & SS Multilayer Structures

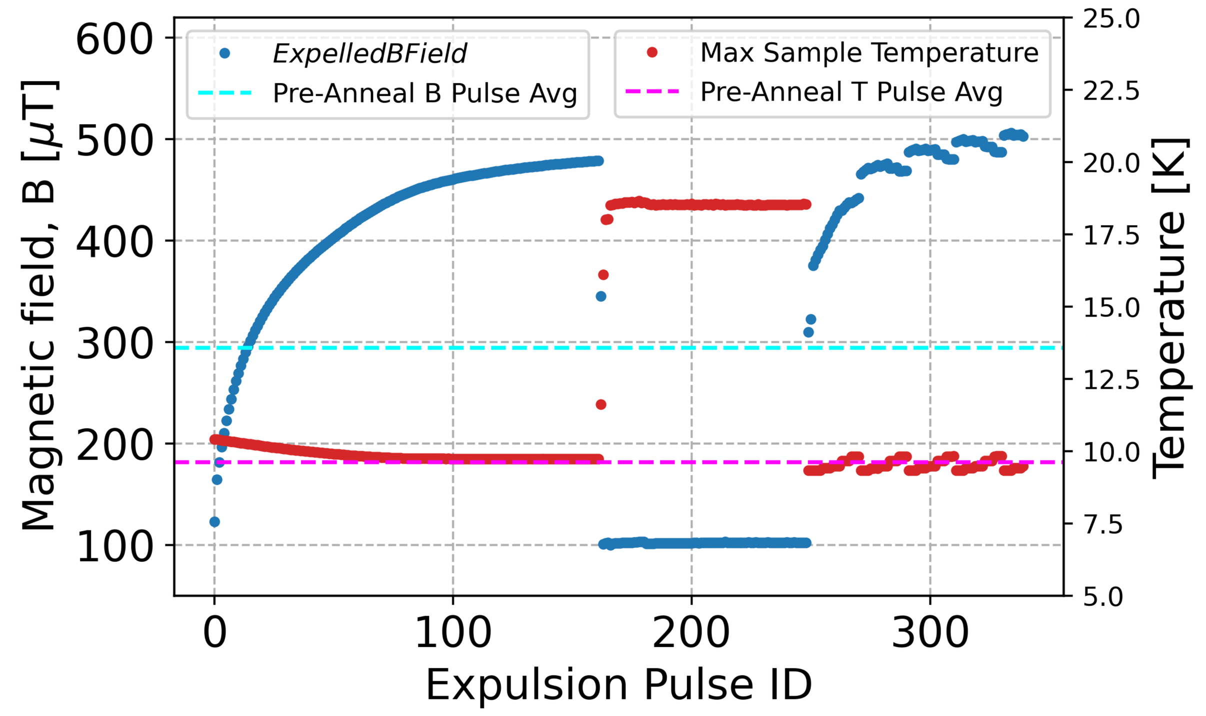


- A collaboration with University Hamburg has allowed SIS and SS multilayers deposited by PEALD to be tested.
  - S layers = NbN or NbTiN.
  - I layer = AlN.
- Nb substrates annealed at 800°C to remove stress' in the Nb **before** coating starts.
- The Nb is 2.8 mm thick, if present the AlN is 15 nm, and the superconducting thin film is 60nm.

- It has been found that after deposition the thin films have a low T_c – typically around 7 K[1].

Magnetic flux pumping

- Annealed SIS sample enhances thin film T_c to ≈ 15 K → thin film stays SC above Nb transition.
  - Opens possibility for flux pumping in $T_{c,Nb} < T < T_{c,NbTiN}$.
- **Flux pumping**: Repeated thermal cycle to $T_{c,Nb} < T < T_{c,NbTiN}$, progressively expels more flux.
  - Expelled flux is 'reset' by increasing $T > T_{c,NbTiN}$.
  - Progressive expulsion has potential for improving performance of SRF cavities.



Observation

- Re-starting pulses with a T in range of $T_{c,Nb} < T < T_{c,NbTiN}$ recovers enhanced expulsion.
  - Pulses post $T > T_{c,NbTiN}$ further increases the expelled B field.

Left, annealed Nb/AlN/NbTiN sample

7. Executive Summary

- Reproducible magnetic flux expulsion in bulk, thin film & multilayer samples.
- Improved flux expulsion over conventional techniques.
- Flux pumping offers potential for improved SRF cavity performance.

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