Concept and development of the superconducting shield (SuShi) septum for the FCC

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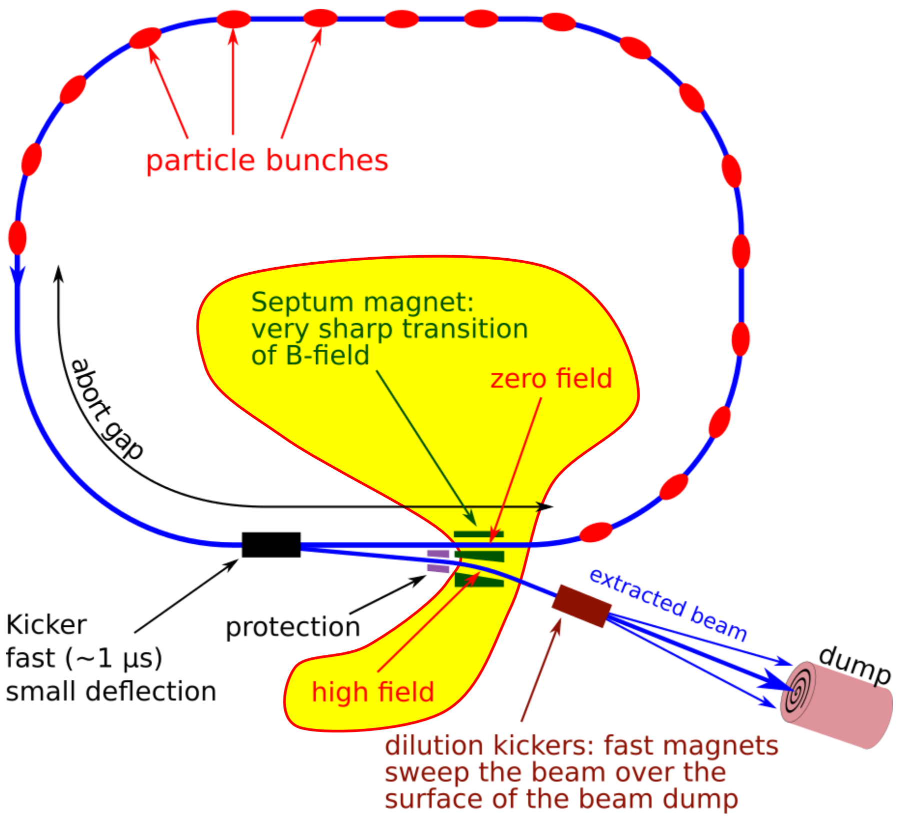
https://www.youtube.com/@wignerrcp-acceleratorresea7995/videos

Overview

- Particle extraction scheme
  - Importance of the septum magnet
  - Introducing the SuShi concept
- Proof-of-concept experiments with shields
  - NbTi/Nb/Cu multilayer sheet
  - Bulk MgB2
- The SuShi prototype
  - Concept
  - Simulation
  - Design
  - Construction status
- Development of NbTi/Cu multilayer sheet in-house

Introducing the SuShi concept

Extraction from an accelerator

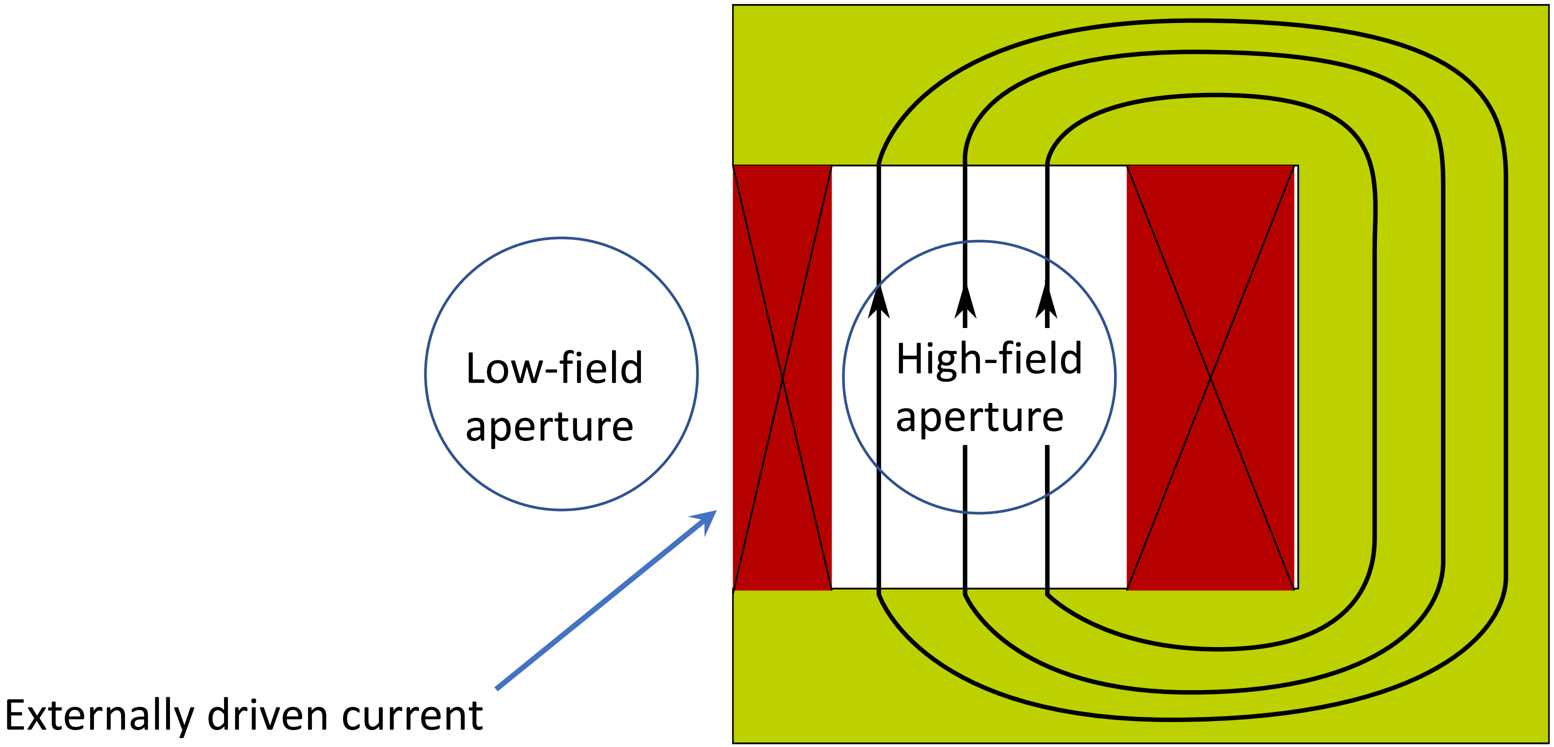


<u>General extraction scheme:</u>

- The **<u>kicker</u>** magnet can ramp from 0 to max field while no particles are passing it by
- But the kicker only provides a small deflection
- The **<u>septum</u>** has strong, stationary magnetic field
- Sends the extracted beam towards the beam dump

Septum configurations

"Active" septum wall



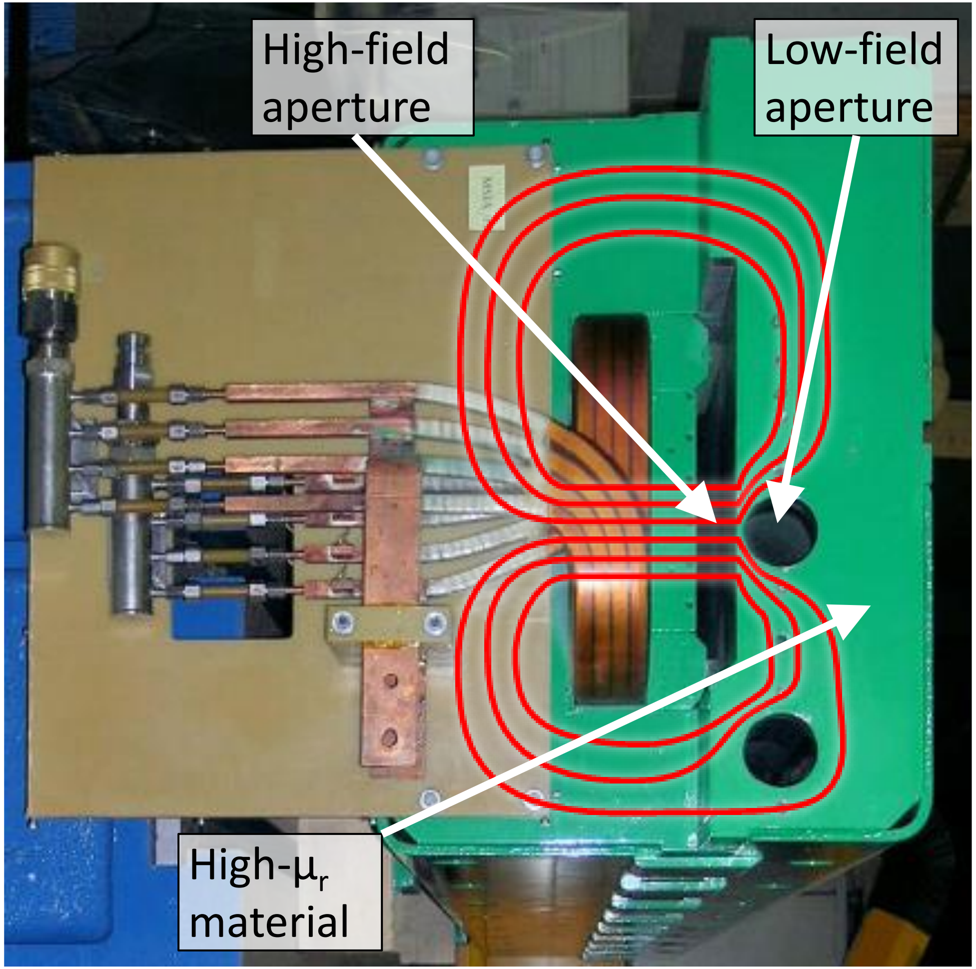
Example septum configuration

"**Passive**" septum wall – **high μ_r**

LHC Lambertson septum

- No externally driven current between the two domains

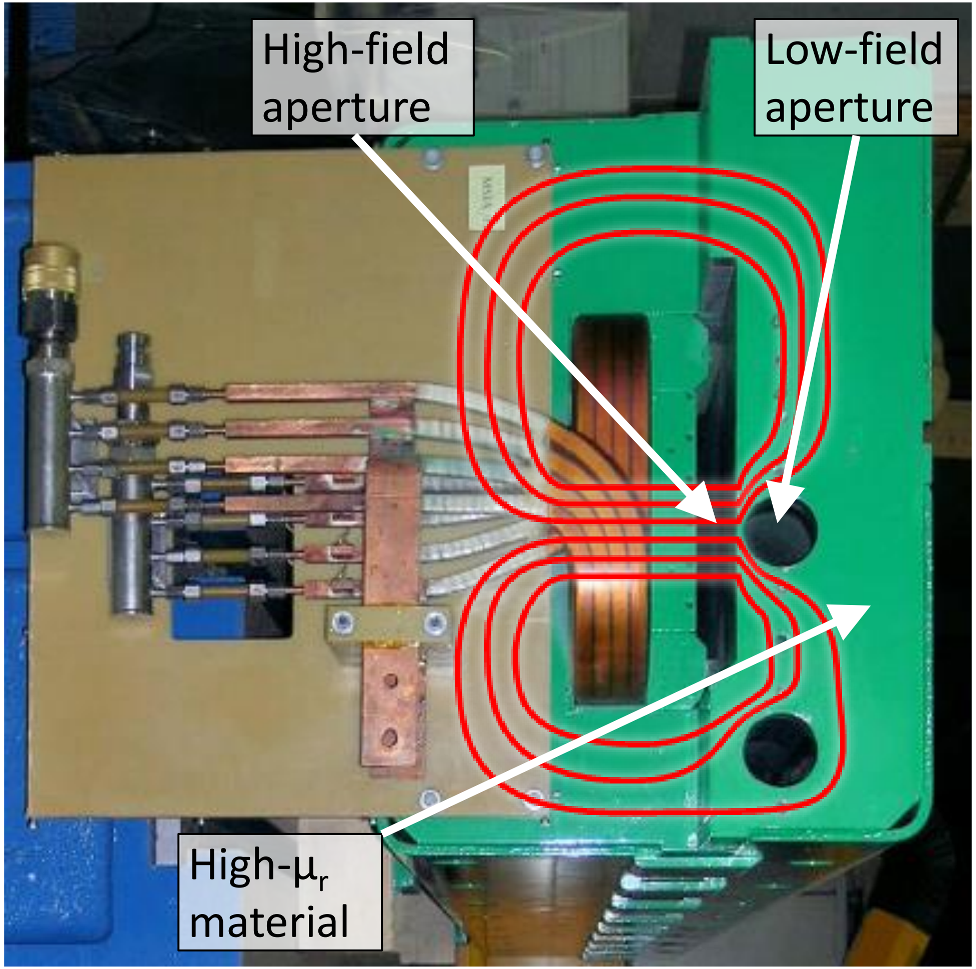
- High-μ_r (iron) yoke "**sucks out**" the induction lines from the low-field aperture
- Even higher μ_r (mu-metal) shields the circulating beam from the residual field



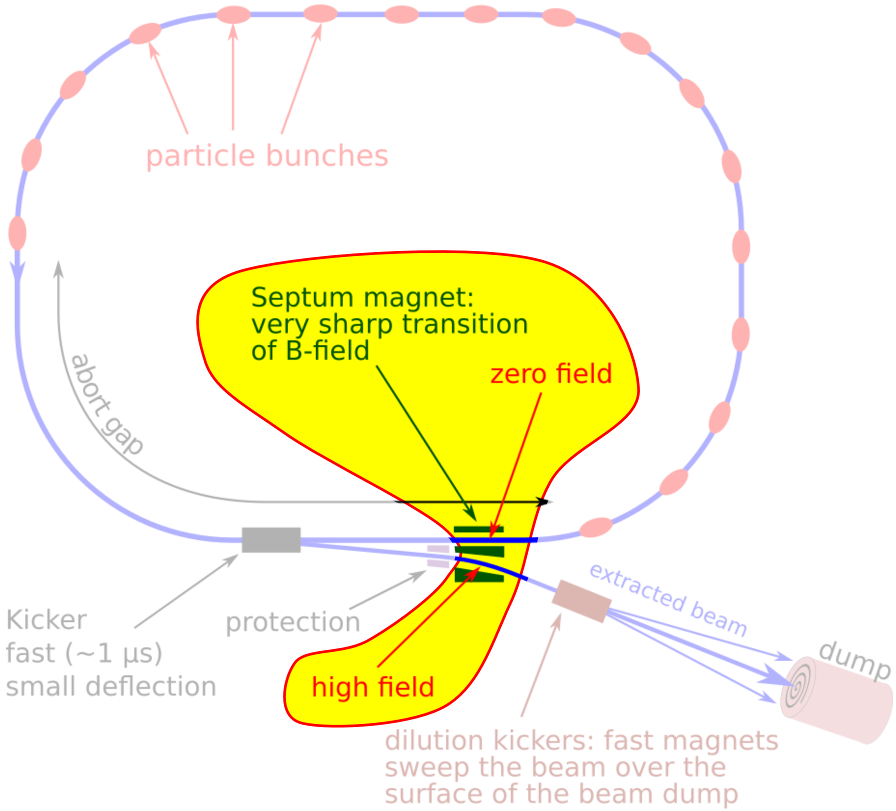
Septum configurations

Limitation:

- Gap field is limited to around 1.2 T due to the saturation of iron at higher fields



Extraction from the FCC-hh



Requirements:

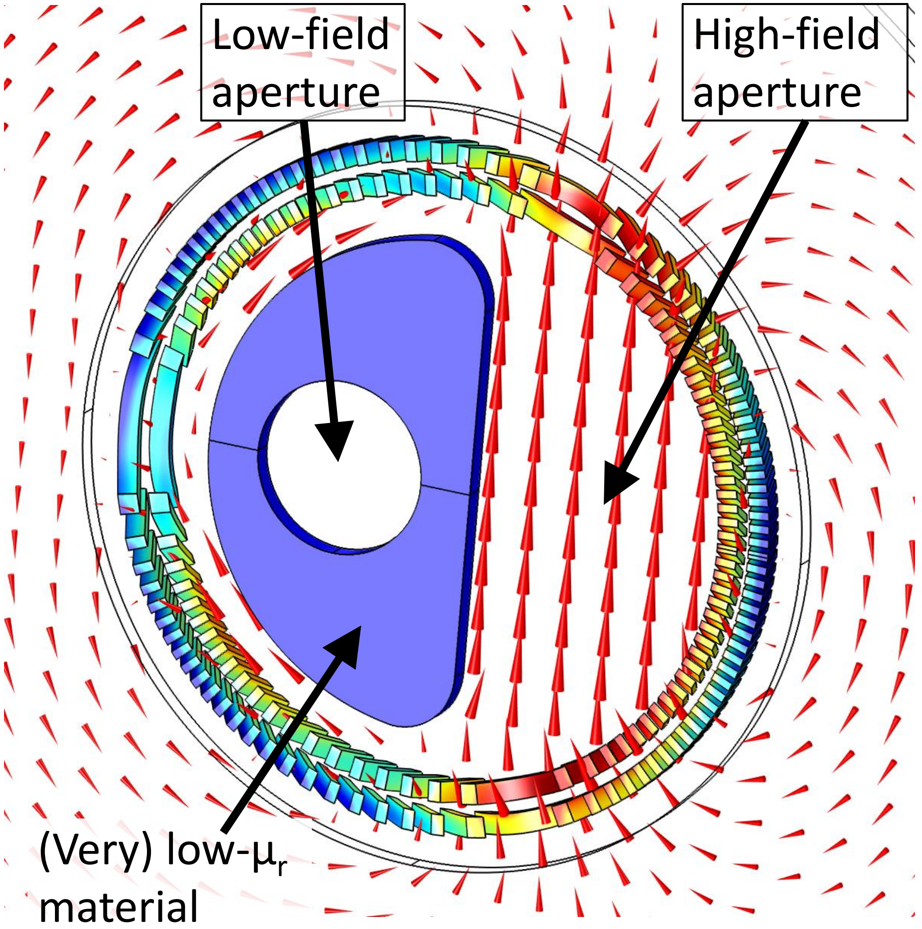
- Large difference in magnetic field between the two apertures (FCC: > 3 Tesla) → strong separation of two beams, next ring magnet can come close
- Thin wall between two apertures (FCC: < 25 mm) → kicker can be closer, or weaker

Septum configurations

"**Passive**" septum wall – **low μ_r**
Superconductin **Shi**eld (SuShi)

- No externally driven current between the two domains

- Low-μ_r shield "**pushes out**" the induction lines from the low-field aperture

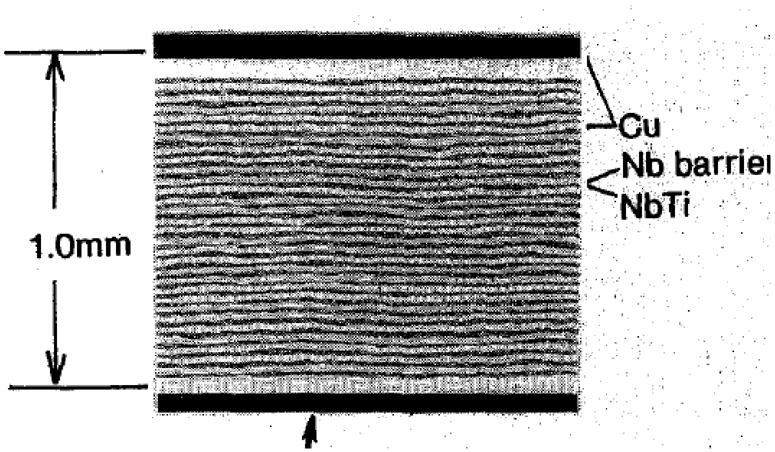


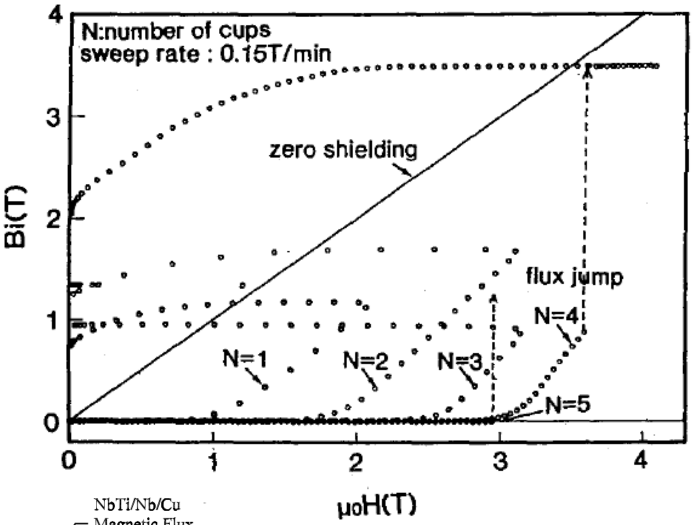
The SuShi concept

- Very low μ_r = superconductor (induced persistent currents)
- Advantages
  - **Continuous 2D current distribution** (in contrast to discrete wires in windings), no leaking field
  - **Perfect shielding** by nature
  - **Shield can be a bulk** material, no epoxy, no cracking
  - Partially self-supporting, smaller total thickness (high forces!)
  - Bean (critical state) model: optimal, automatically graded current density - everywhere $J_c(B)$, the highest possible → thinnest possible
- Disadvantages
  - No external control over the persistent currents
  - Sensitive to beam loss
  - Needs a “reset” in case of the collapse of the shielding currents (warm up and cool down in zero field)

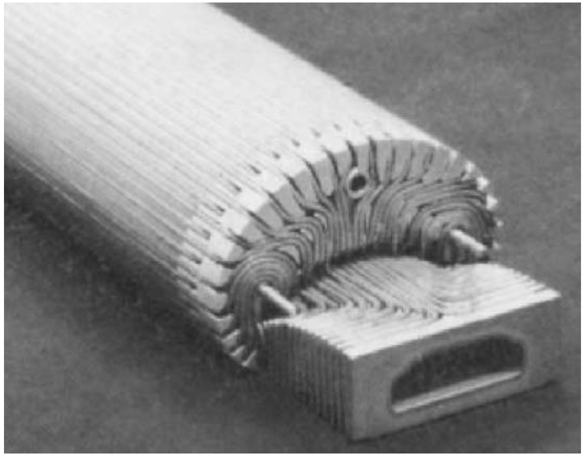
Proof of concept experiments of shields: NbTi/Nb/Cu multilayer sheet

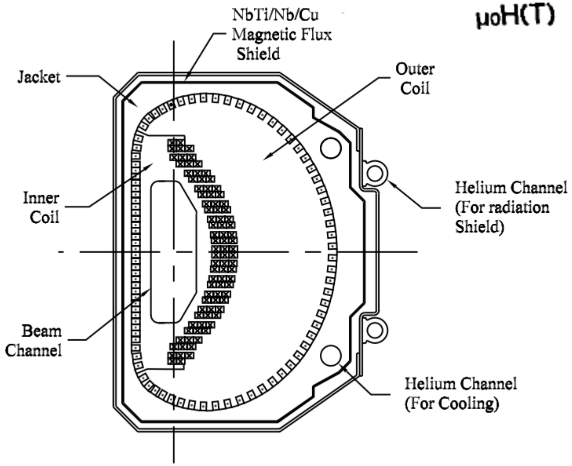
NbTi/Nb/Cu multilayer sheet





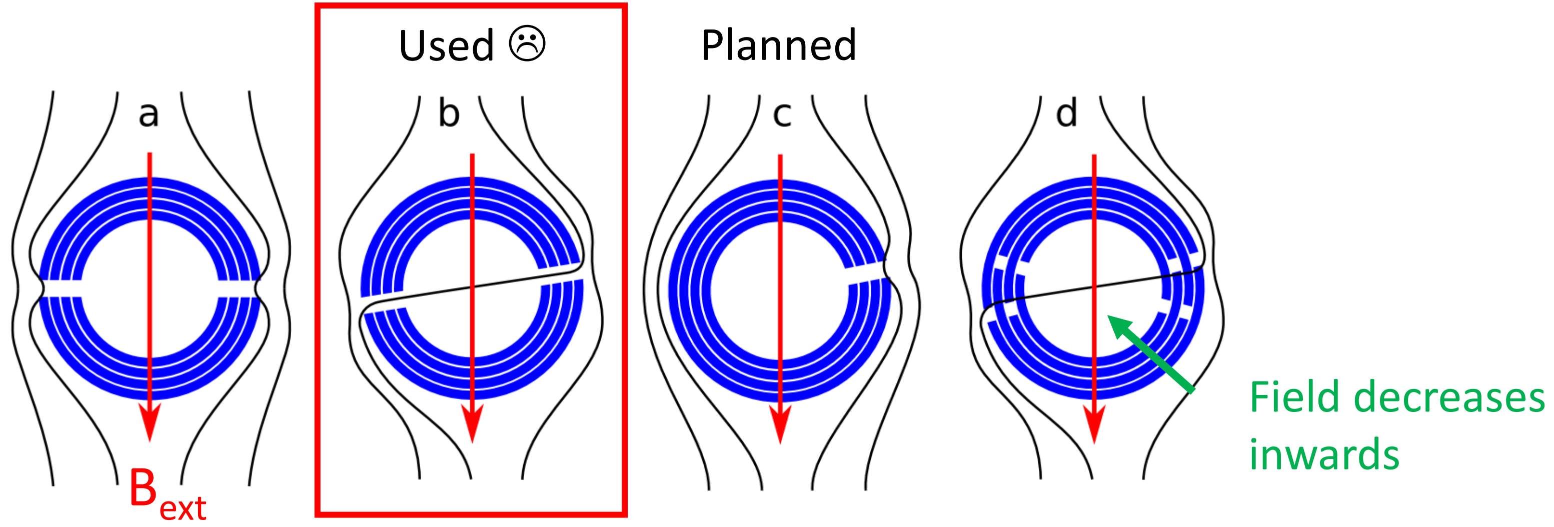
I. Itoh, T. Sasaki: Magnetic shielding properties of NbTi/Nb/Cu multilayer composite tubes, IEEE.Trans.Appl.Supercond.3 (1993), 177





A. Yamamoto, et al: The superconducting inflector for the BNL g-2 experiment, NIM A 491 (2002) 23–40

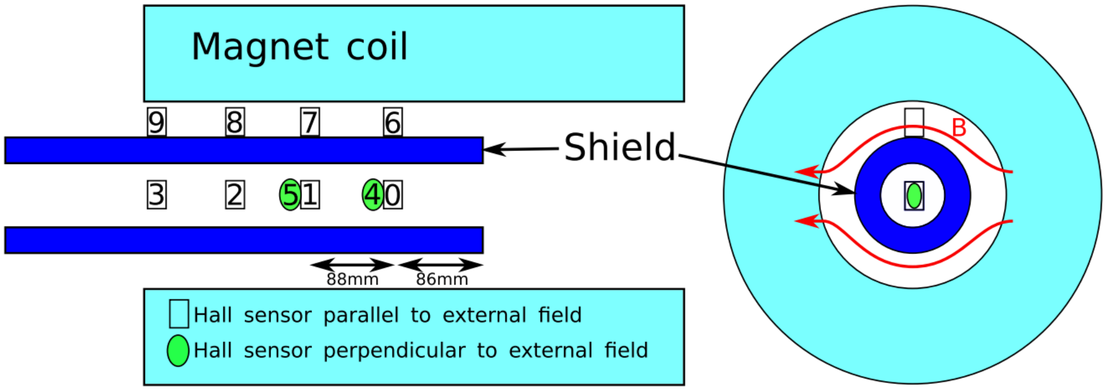
NbTi/Nb/Cu multilayer sheet

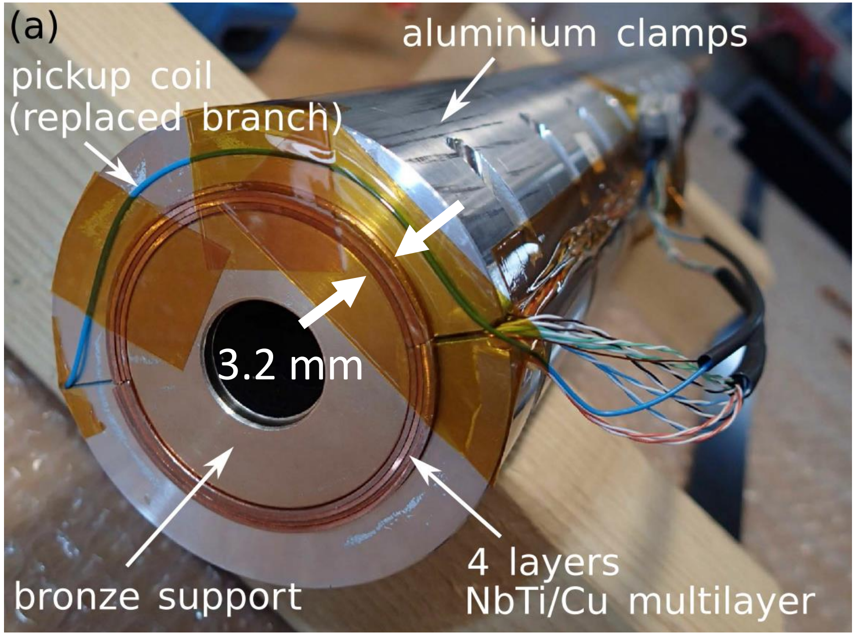


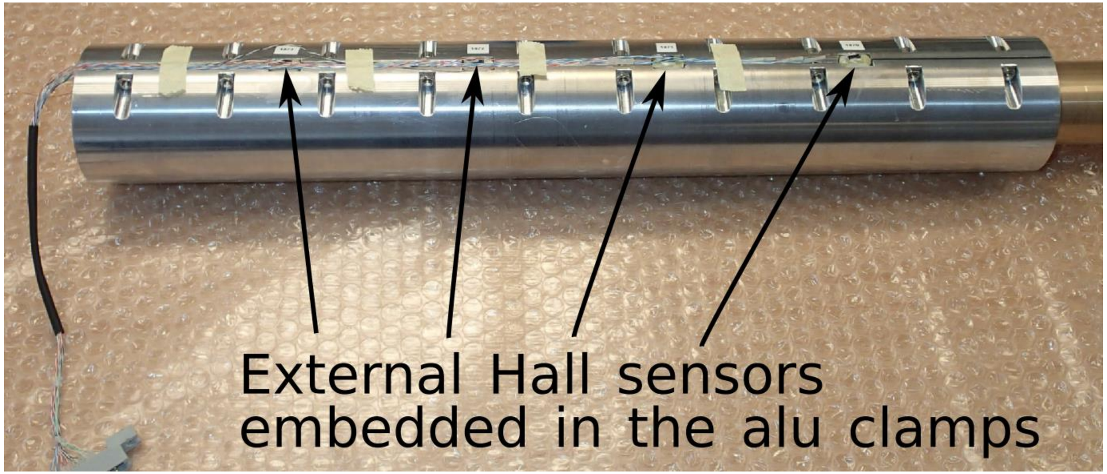
Half cylinders in perfect alignment – small parallel leakage field through cuts	Half cylinders slightly misaligned – transverse leakage field through cuts	C profiles – very low parallel leakage field even if misaligned	Half-cylinders with alternating, intentional rotation – transverse leakage field

NbTi/Nb/Cu multilayer sheet

Measured in the bore of an MCBY magnet in SM18







NbTi/Nb/Cu multilayer sheet

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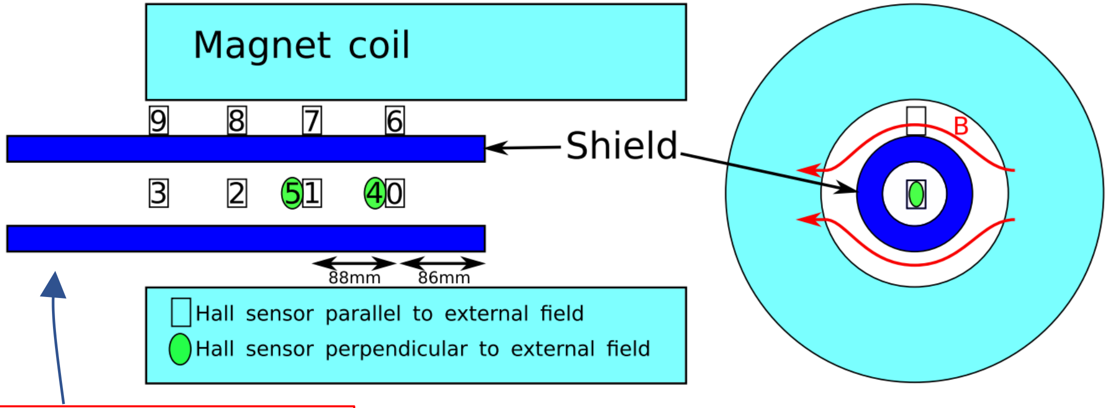
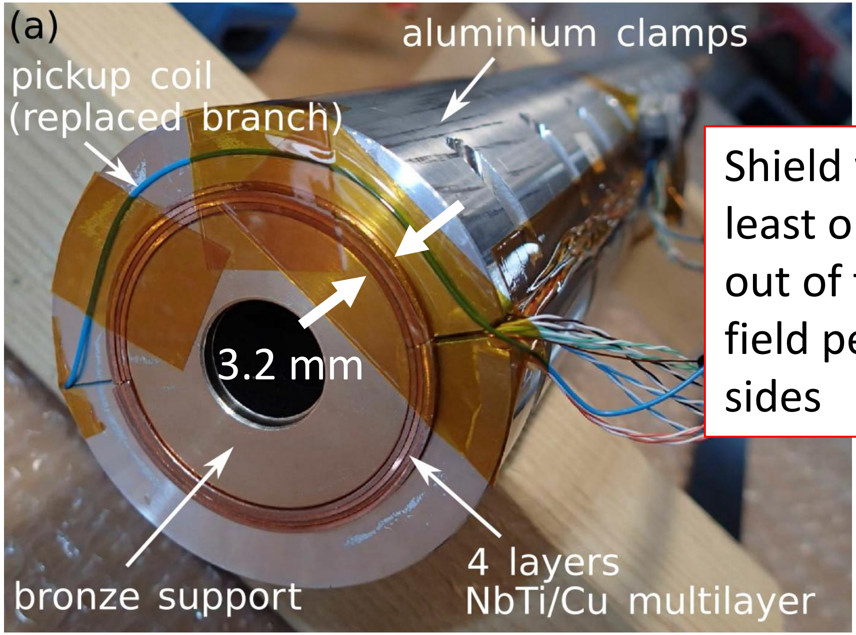
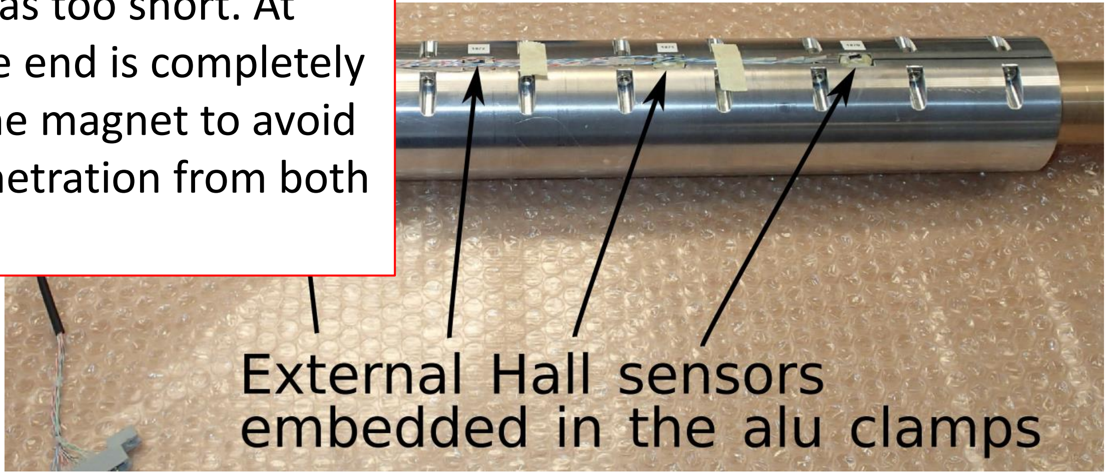


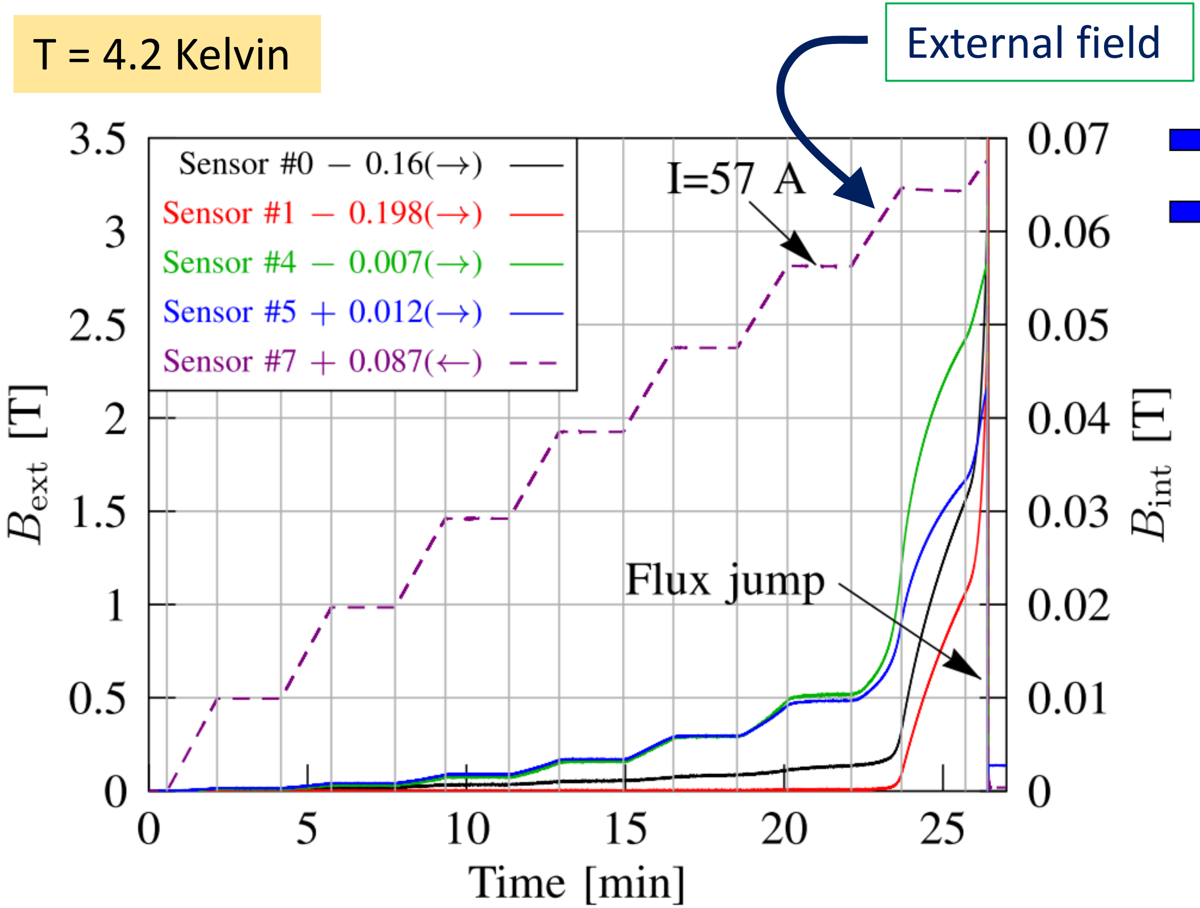


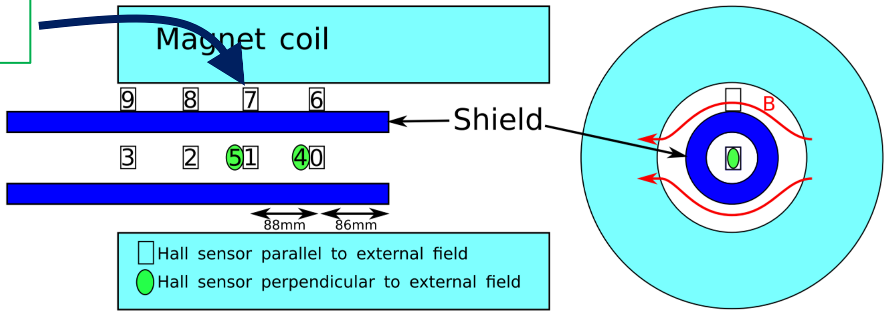
Shield was too short. At least one end is completely out of the magnet to avoid field penetration from both sides



NbTi/Nb/Cu multilayer sheet - results

T = 4.2 Kelvin





NbTi/Nb/Cu multilayer sheet - results

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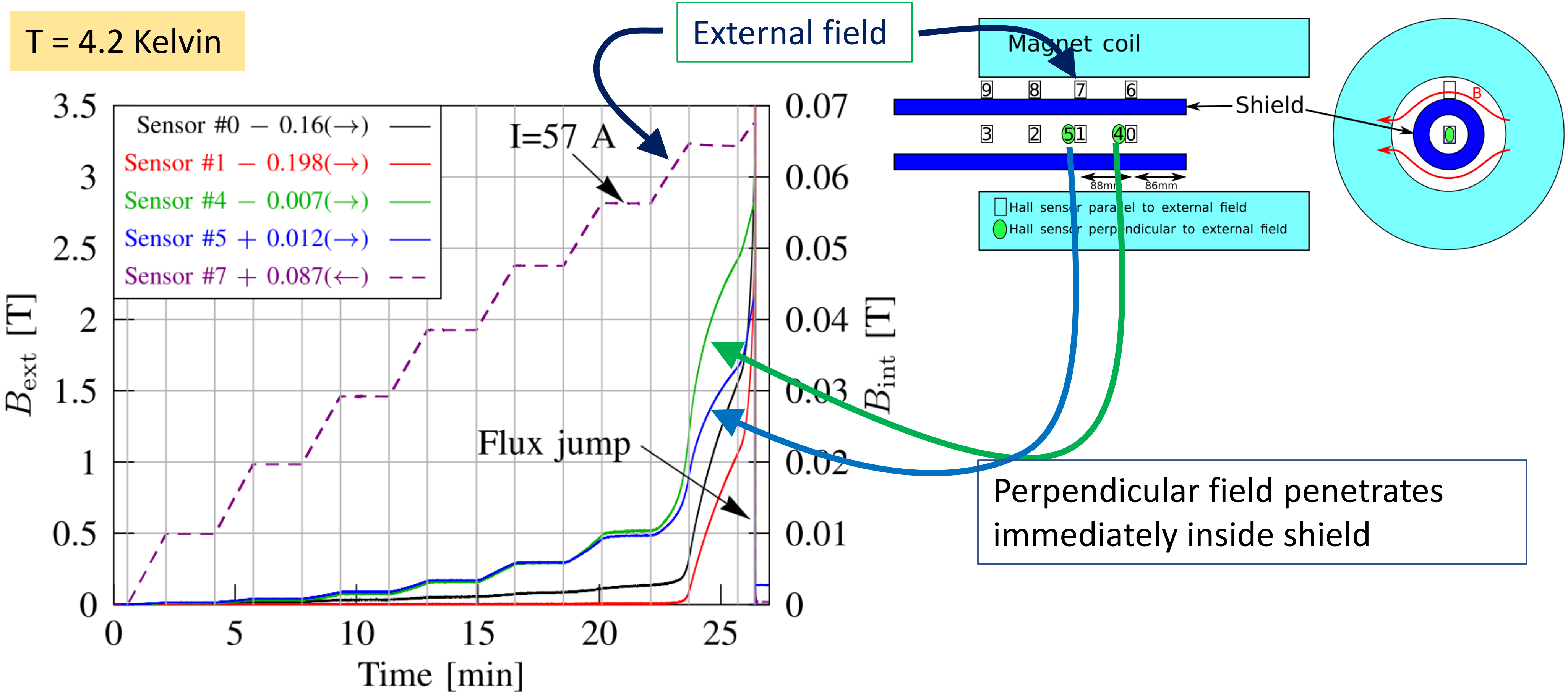
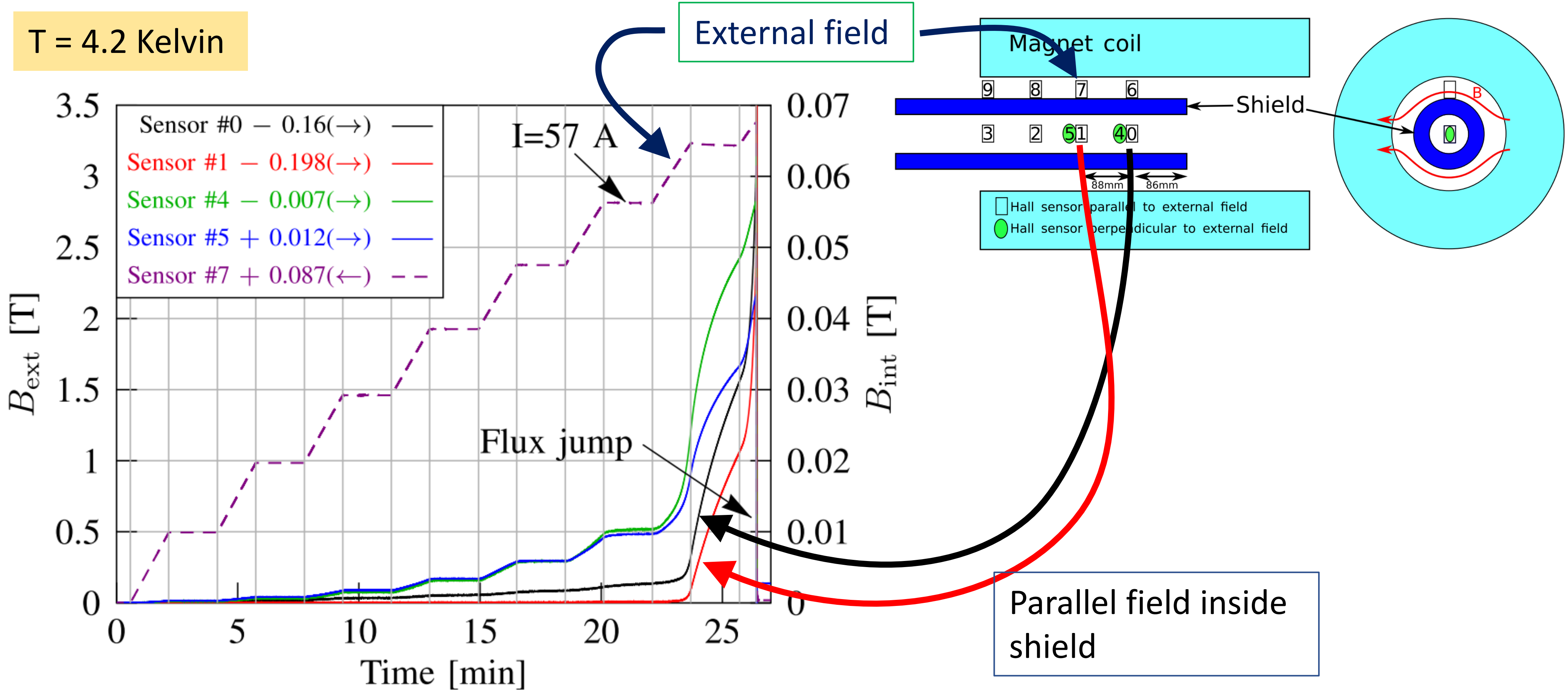


Perpendicular field penetrates immediately inside shield

NbTi/Nb/Cu multilayer sheet - results

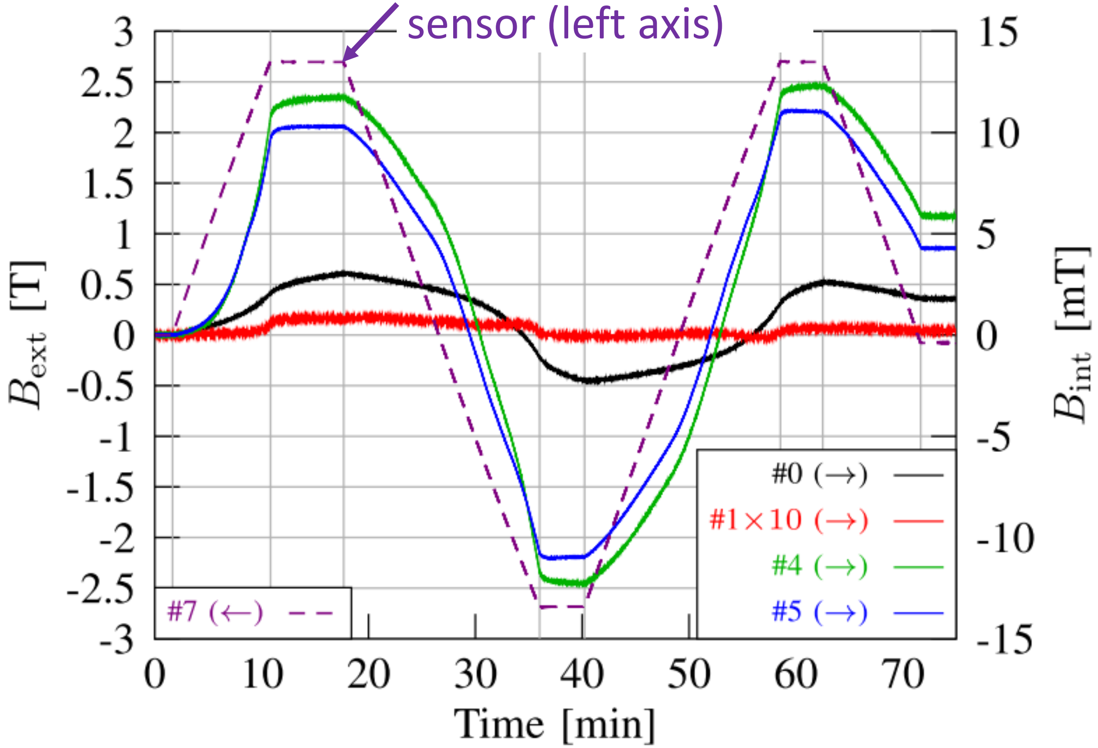
T = 4.2 Kelvin



NbTi/Nb/Cu multilayer sheet - results

T = 4.2 Kelvin, virgin state

External field at the sensor (left axis)



NbTi/Nb/Cu multilayer sheet - results

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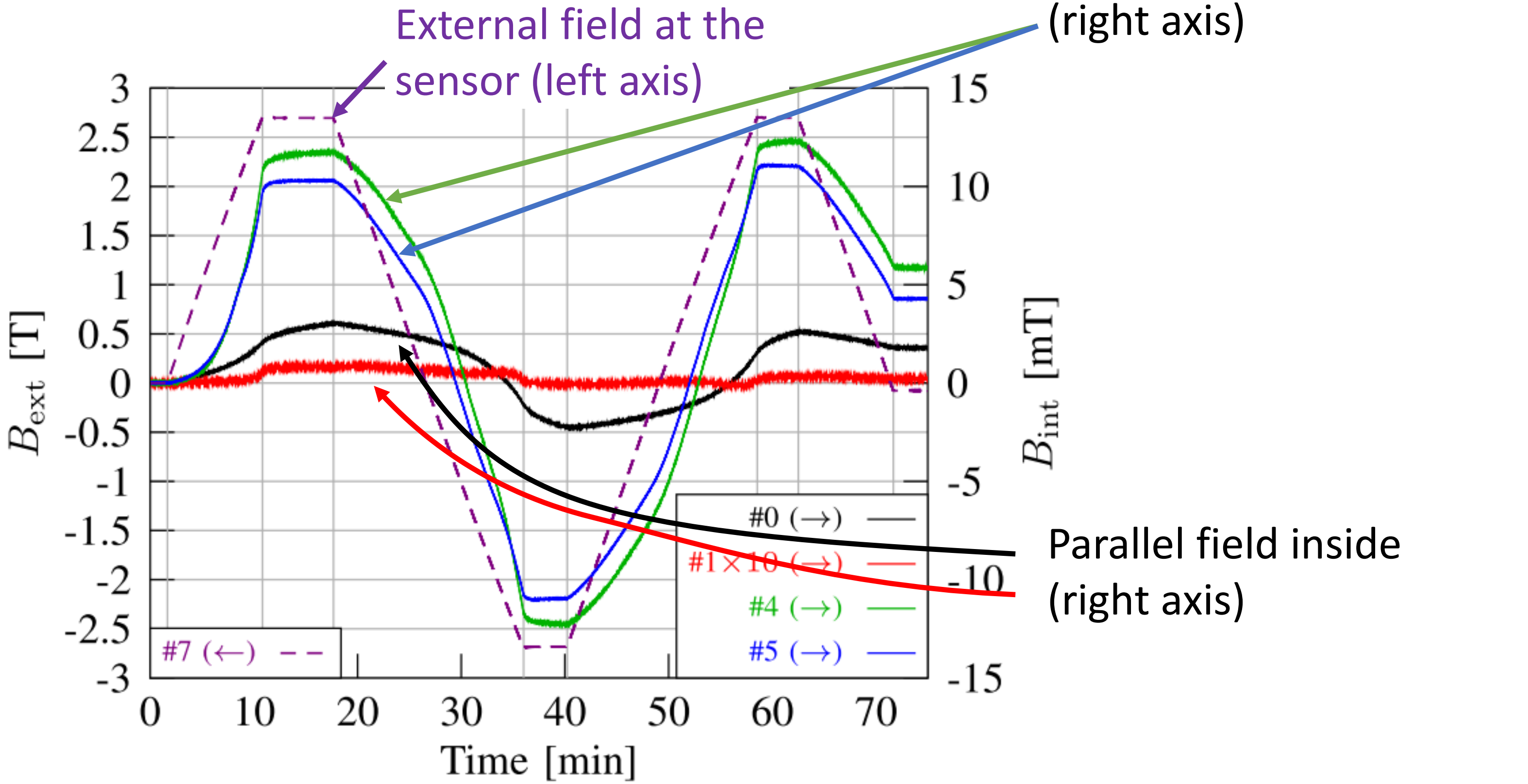

NbTi/Nb/Cu multilayer sheet - results

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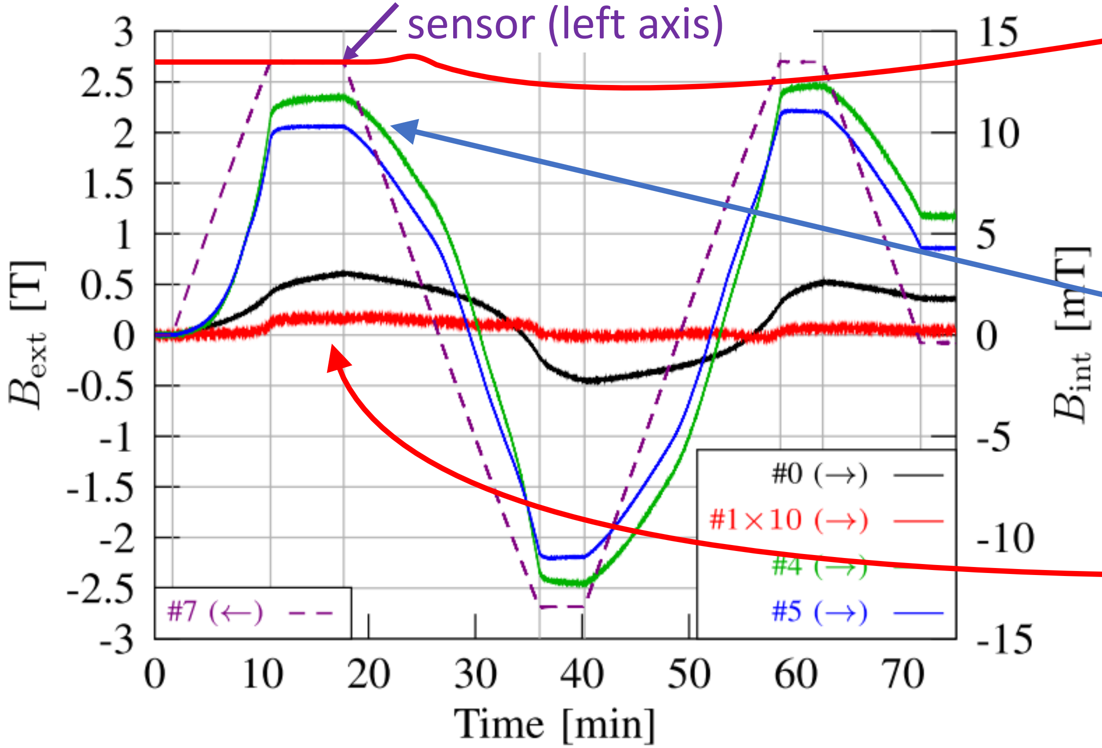


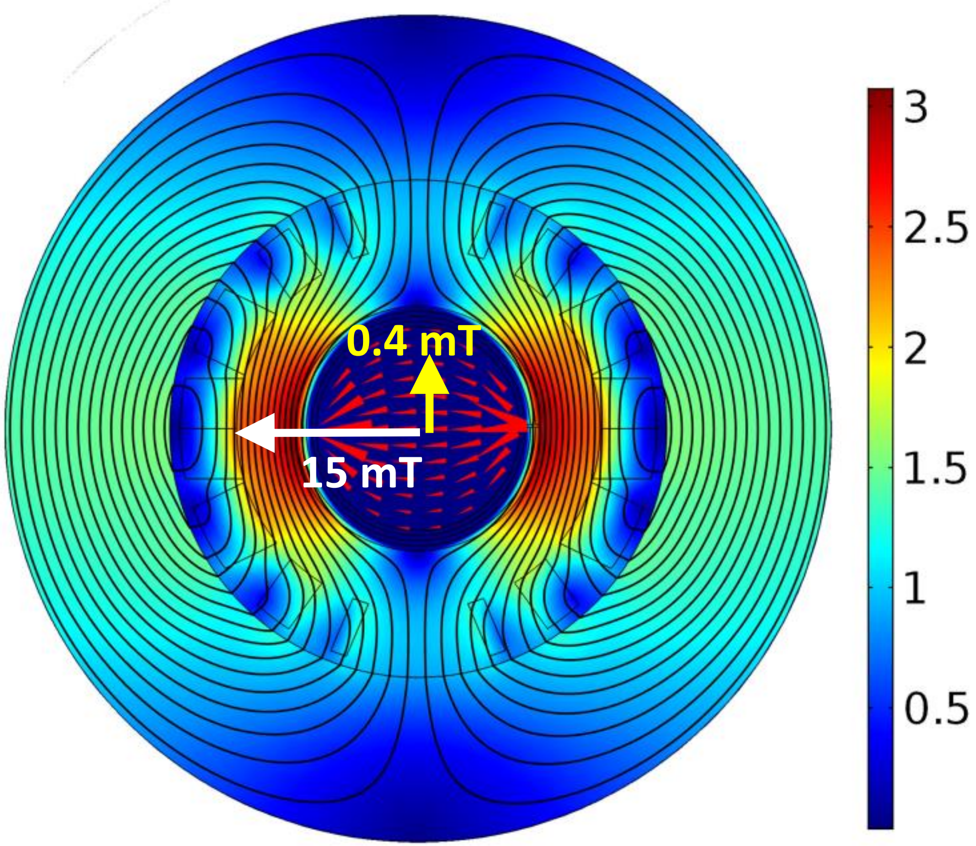
2.7 Tesla at the location of the Hall sensor → **3.1 Tesla** at the shield's surface

3 Tesla shielded by 3.2 mm thickness

~12.5 mT perpendicular field inside

0.1 mT parallel field
4×10^{-5} attenuation

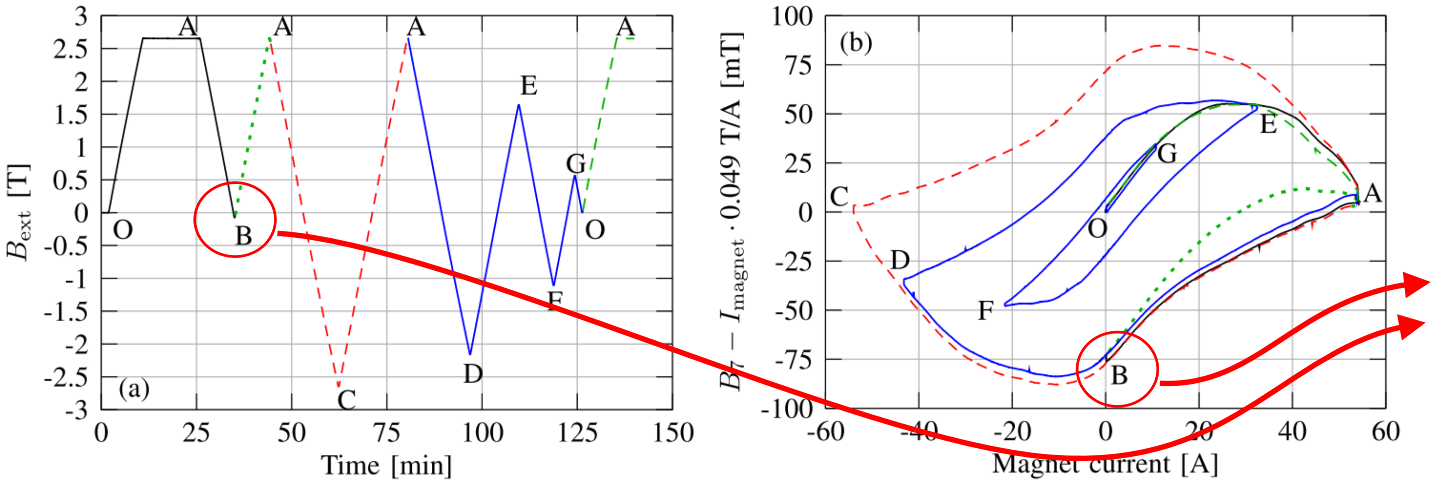
NbTi/Nb/Cu multilayer sheet - results



- 2D simulation using Campbell's method [1] and experimental $J_c(B)$ of sheet
- 4 layers, 0.5 mm cut, 1.5° misalignment
- Realistic input parameters give similar results to experiment

[1] A. M. Campbell, "A new method of determining the critical state in superconductors," Supercond. Sci. Technol., vol. 20, pp. 292–295, 2007. https://doi.org/10.1088/0953-2048/20/3/031

NbTi/Nb/Cu shield – trapped field & degaussing

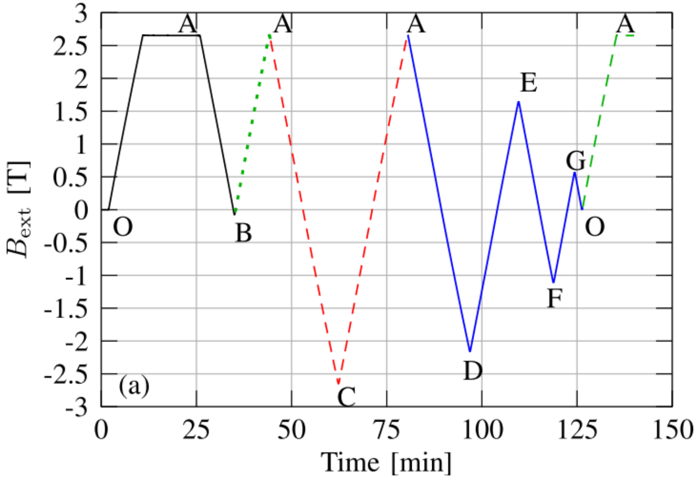


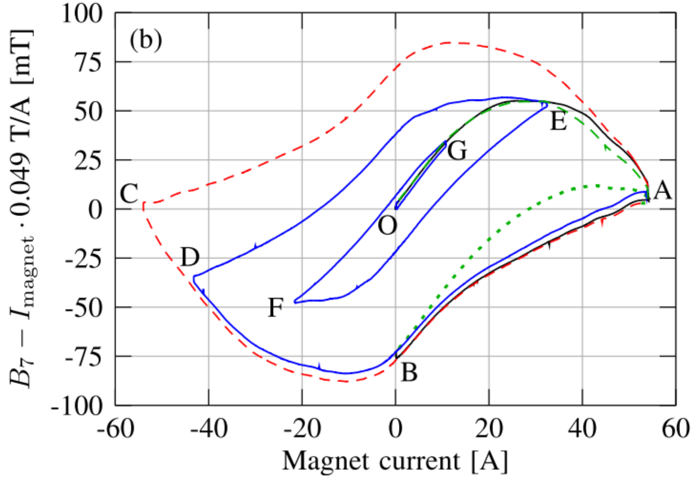
Experiment

If not in a virgin state, field is trapped in the shield.

At zero magnet current there is some field outside the shield (i.e. at circulating beam) → problem

NbTi/Nb/Cu shield – trapped field & degaussing



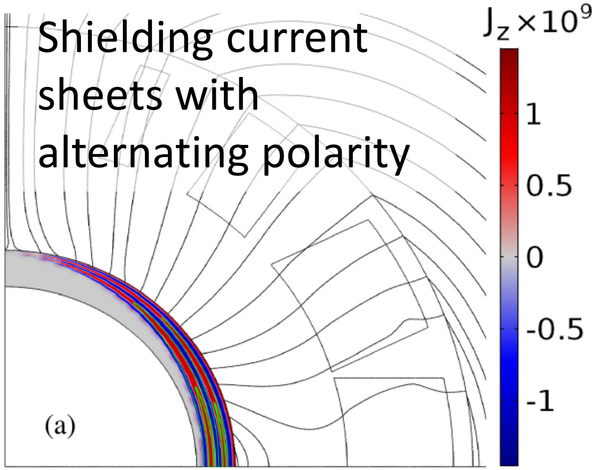


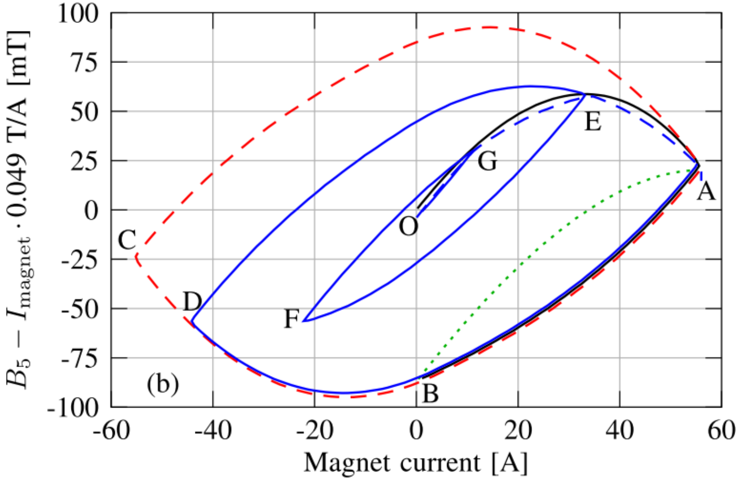
Experiment

Beautiful qualitative agreement between experiment and simulation

Degaussing can decrease trapped field at beam to minimum.

Shielding current sheets with alternating polarity

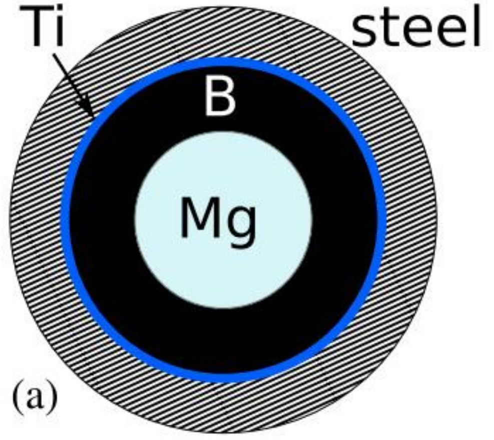


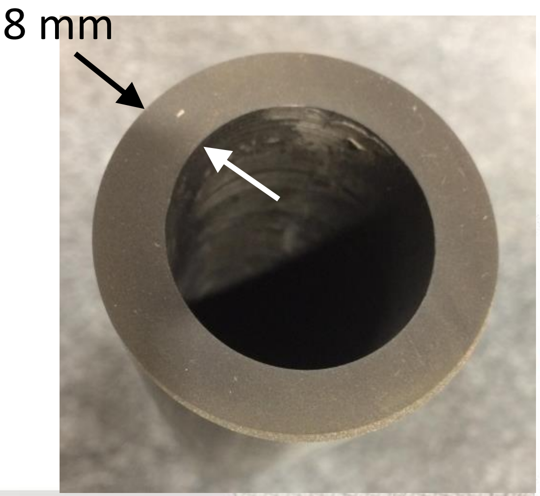


2D time-dependent simulation, power-law E-J

Proof of concept experiments of shields: MgB_2 bulk tube

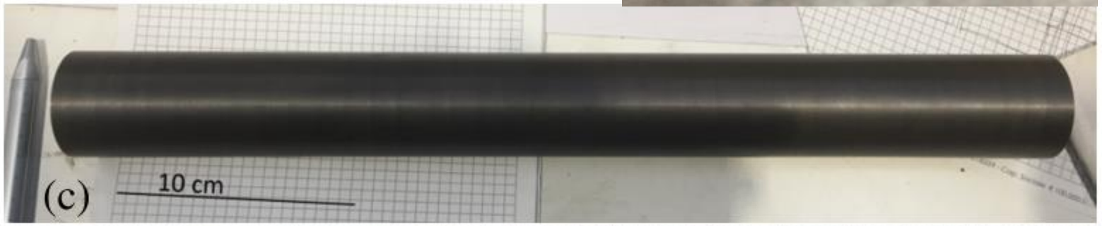
MgB_2 bulk shield

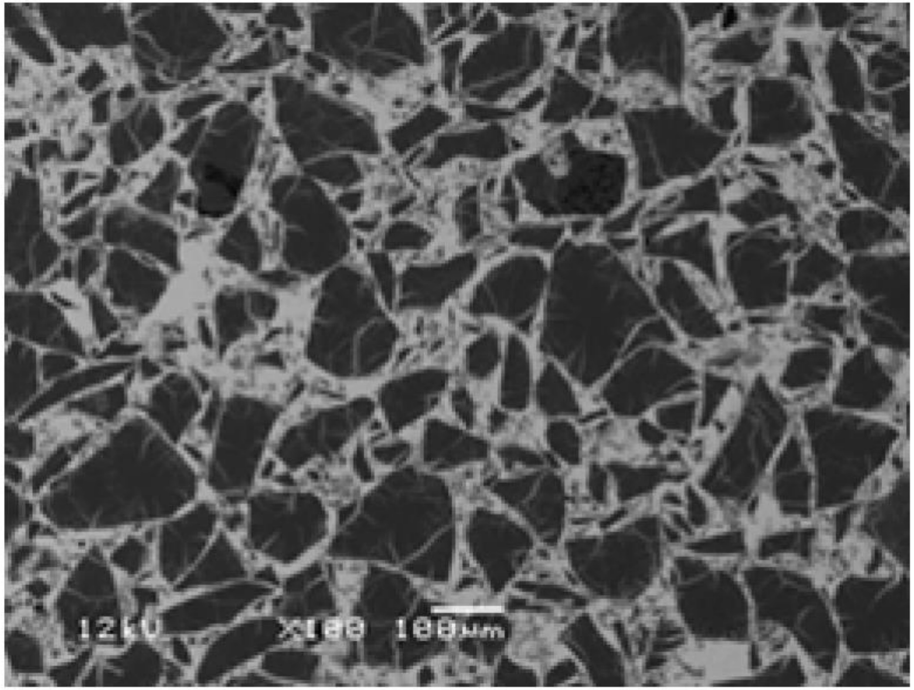




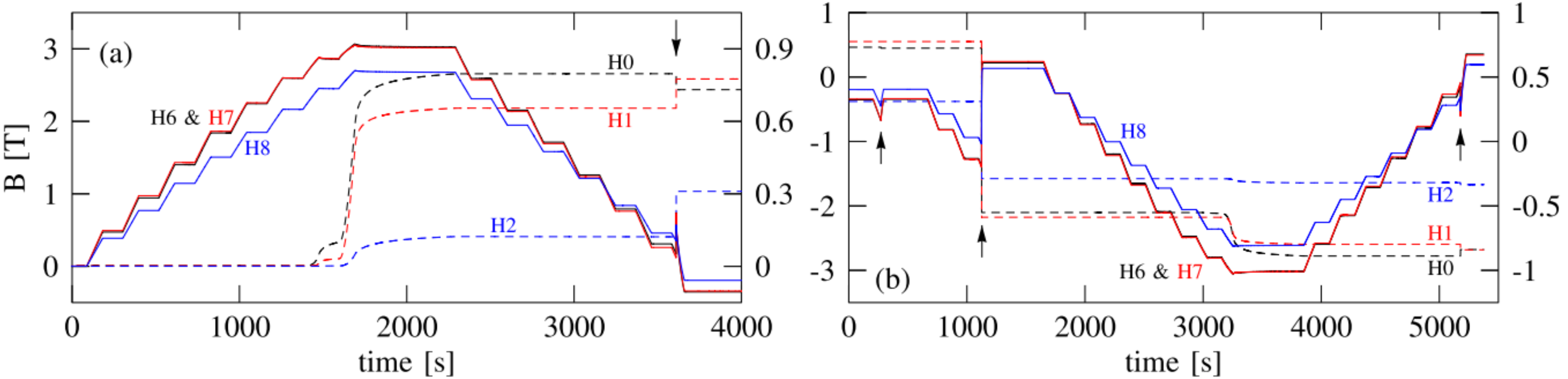
RLI – Reactive Liquid Infiltration process
(developed by Giovanni Giunchi @ Edison)

160 µm boron powder (large → less flux jump)

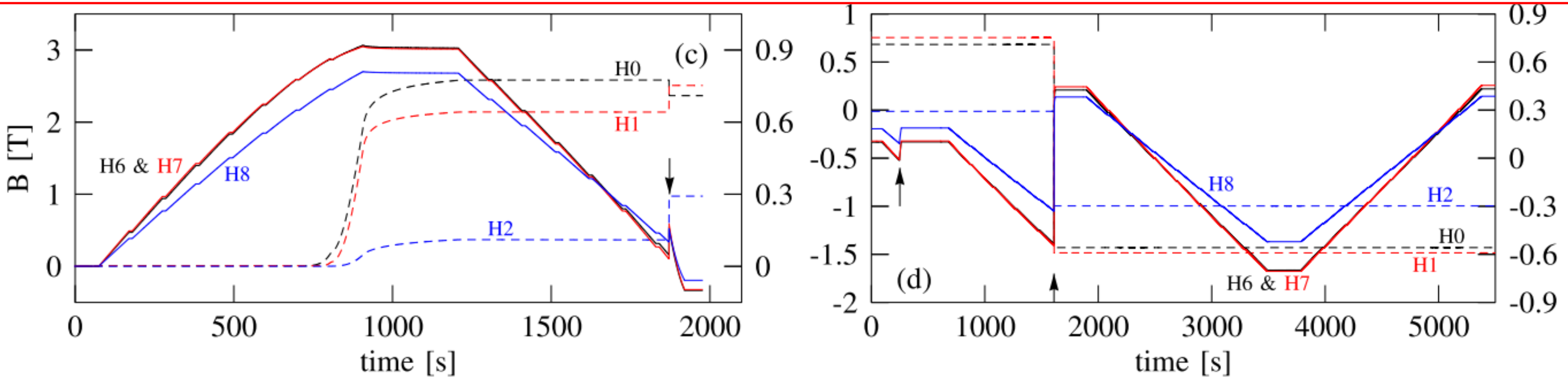




MgB_2 shield – magnetization cycles



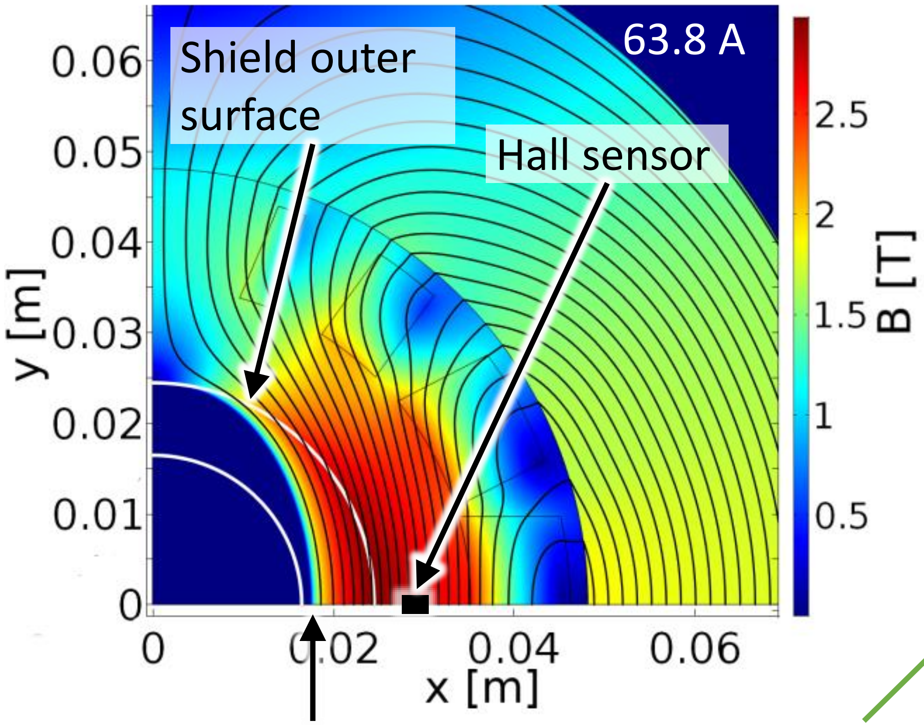
Same bipolar cycle

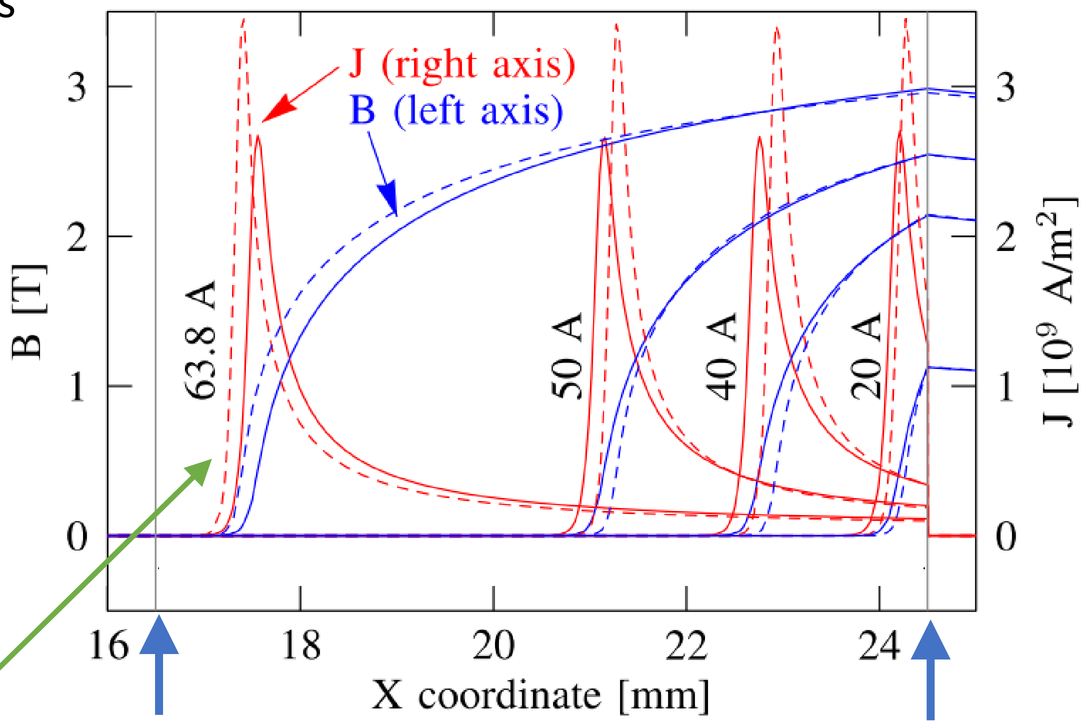


Same bipolar cycle

MgB_2 – shielding performance

Static simulation, Campbell's method, using $J_c(B)$ as determined before

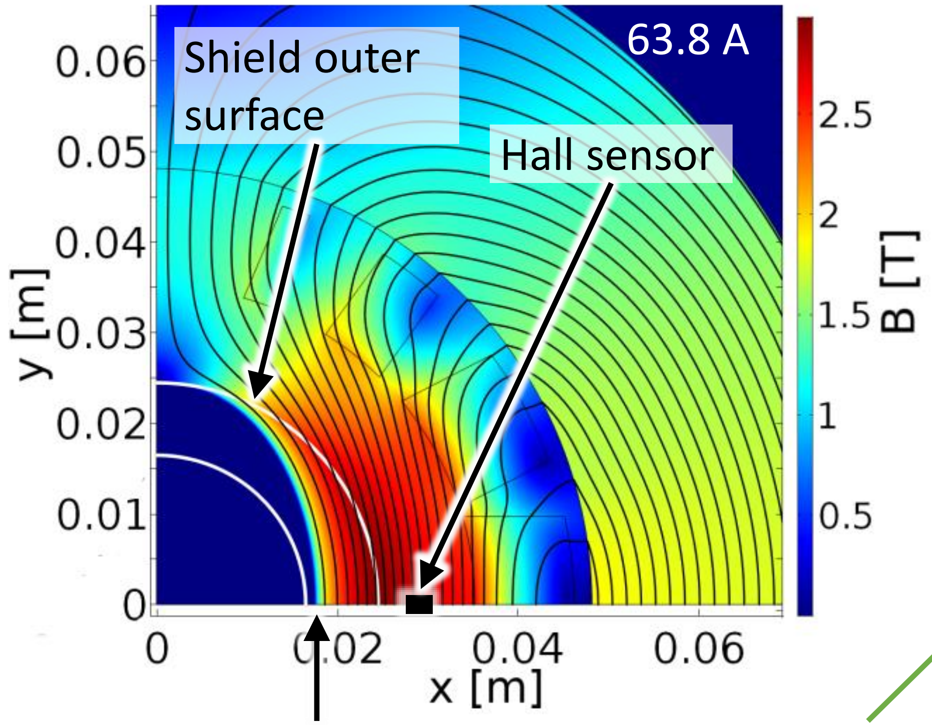


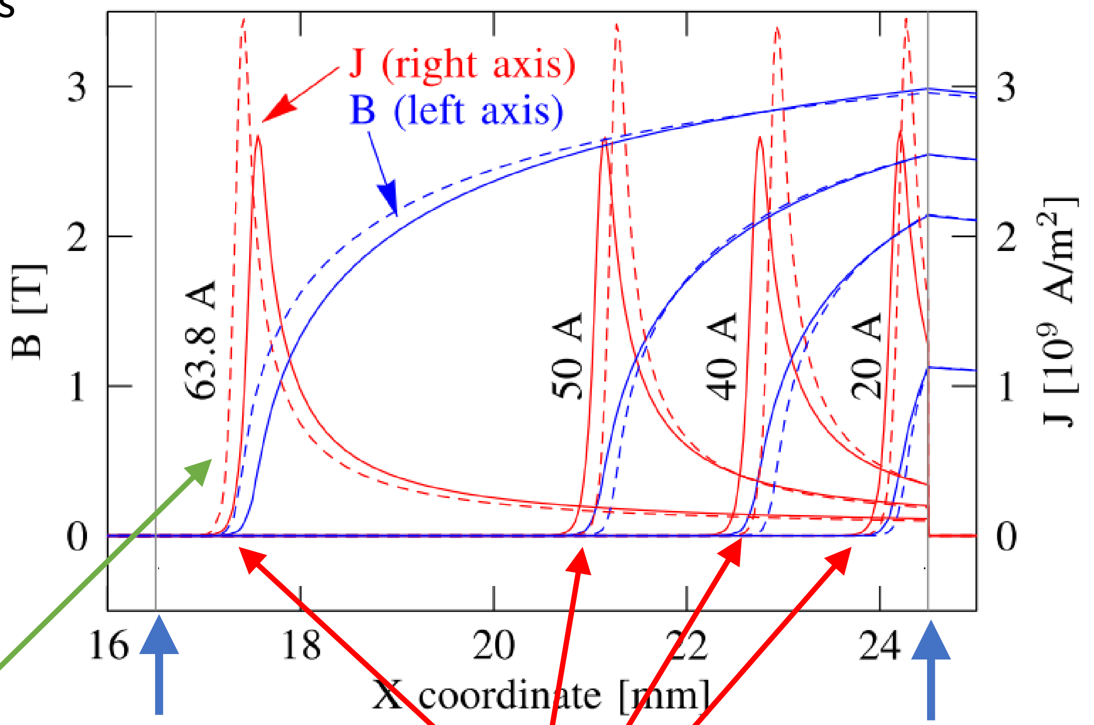


63.8 A – just before experimental penetration, within 1 mm to inner surface

MgB_2 – shielding performance

Static simulation, Campbell's method, using $J_c(B)$ as determined before



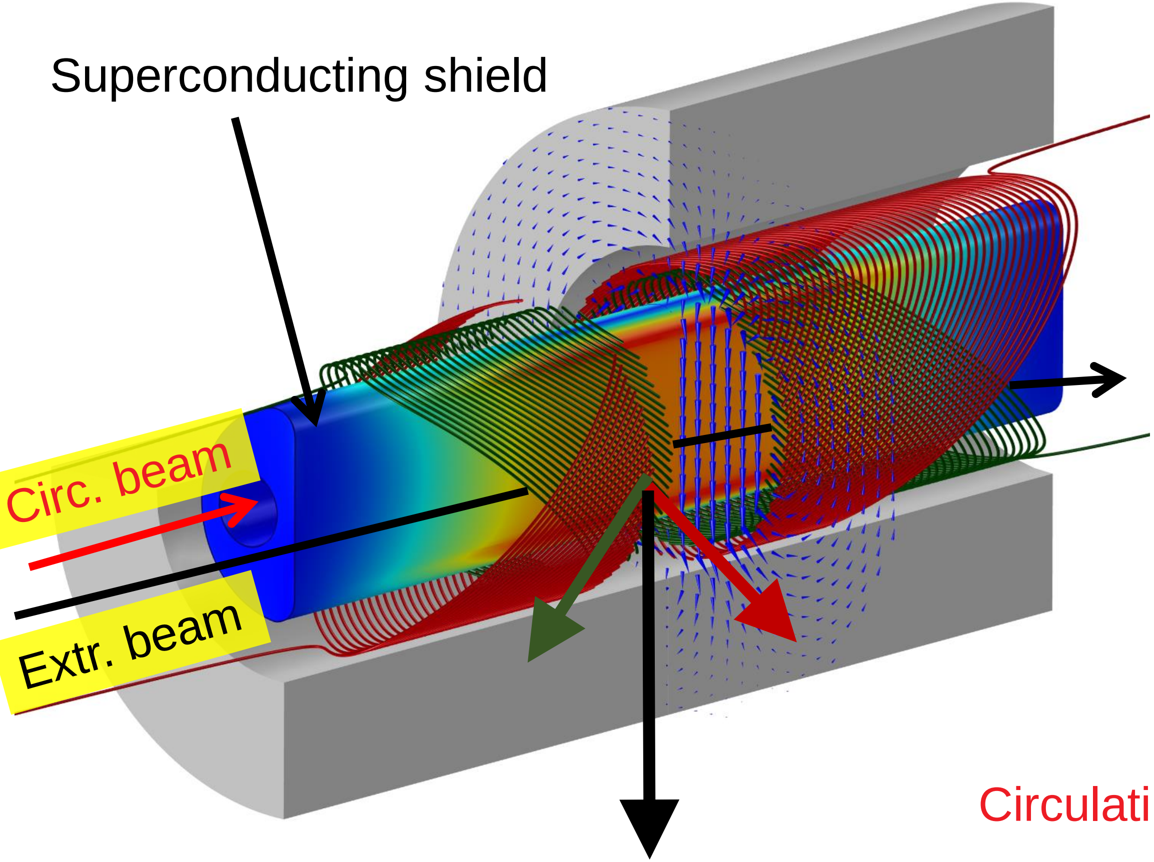


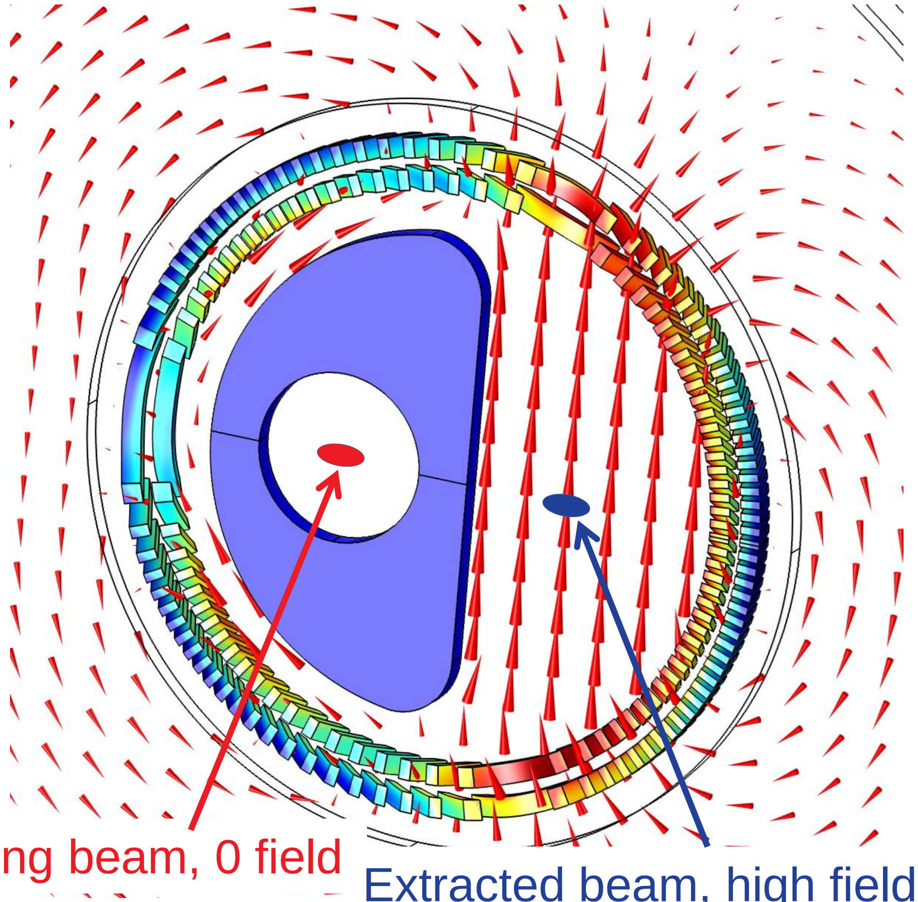
63.8 A – just before experimental penetration, within 1 mm to inner surface

Effective shielding surface drifting inwards

The magnet

The SuShi magnet - CCT

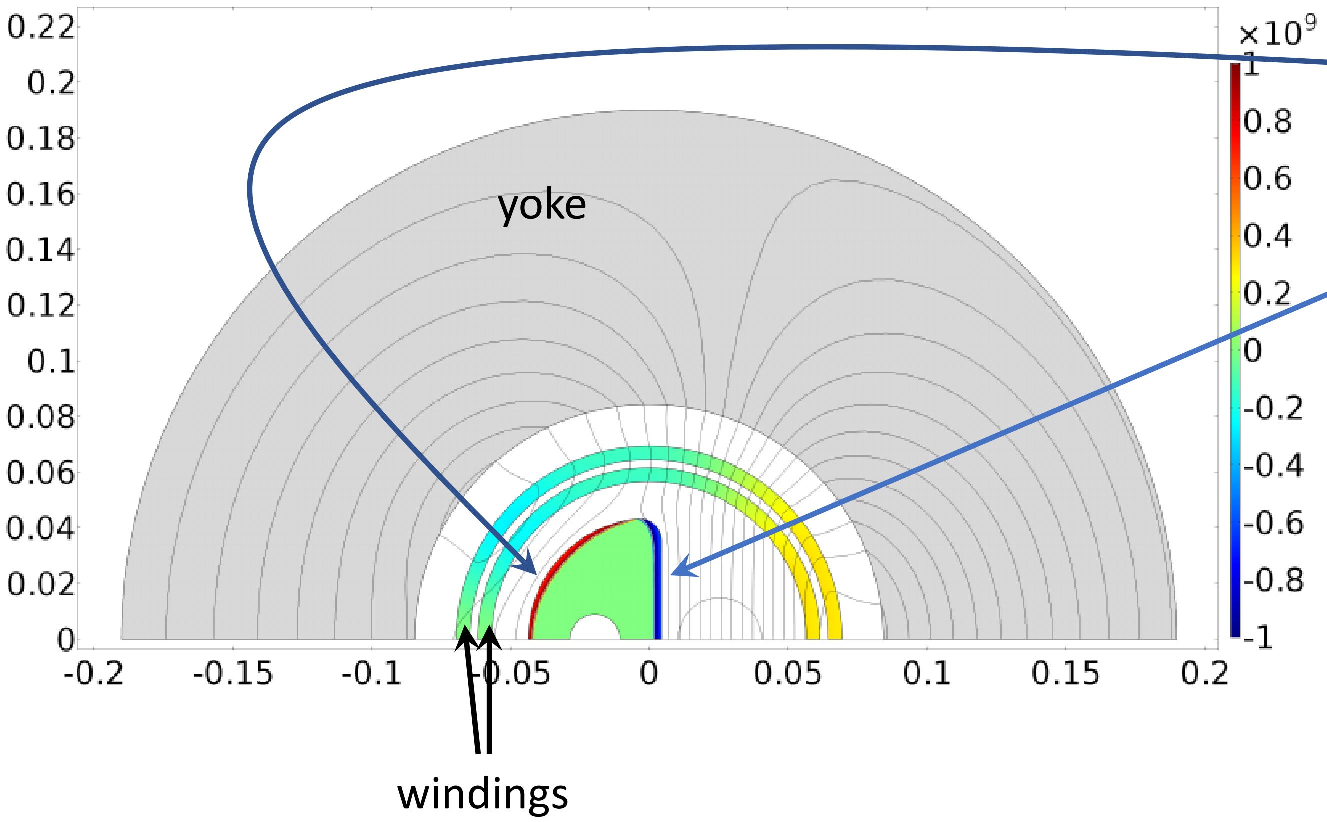




Why a CCT?

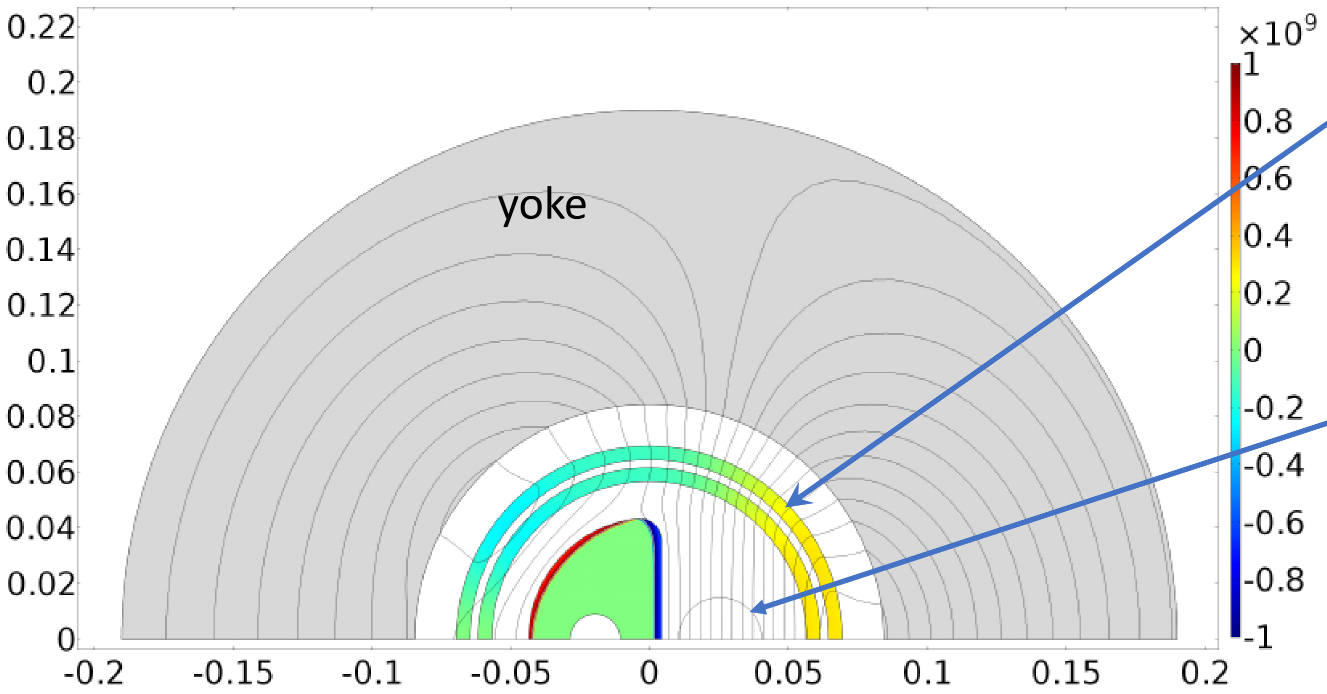
- Cheap and simple construction
- Target field is in the right range (~3 T)
- Very easy winding/field optimization
- General interest and momentum in the community

Shield shape optimization



- Back-face should follow aperture (arc)
- Active side be straight – renders induction lines straight

Winding geometry optimization



- Assume current density as

$$J_z = \sum J_n \cos(n\vartheta)$$

- Simulate for each n

- Fourier analysis of the field around the beam

⇓

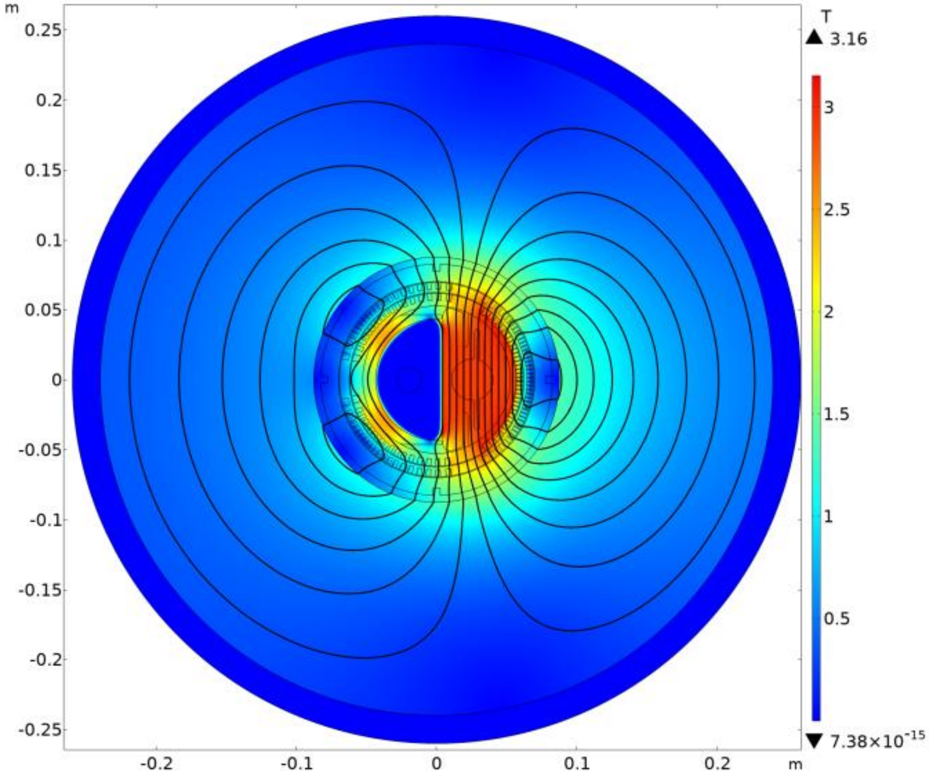
J_n coefficients

⇓

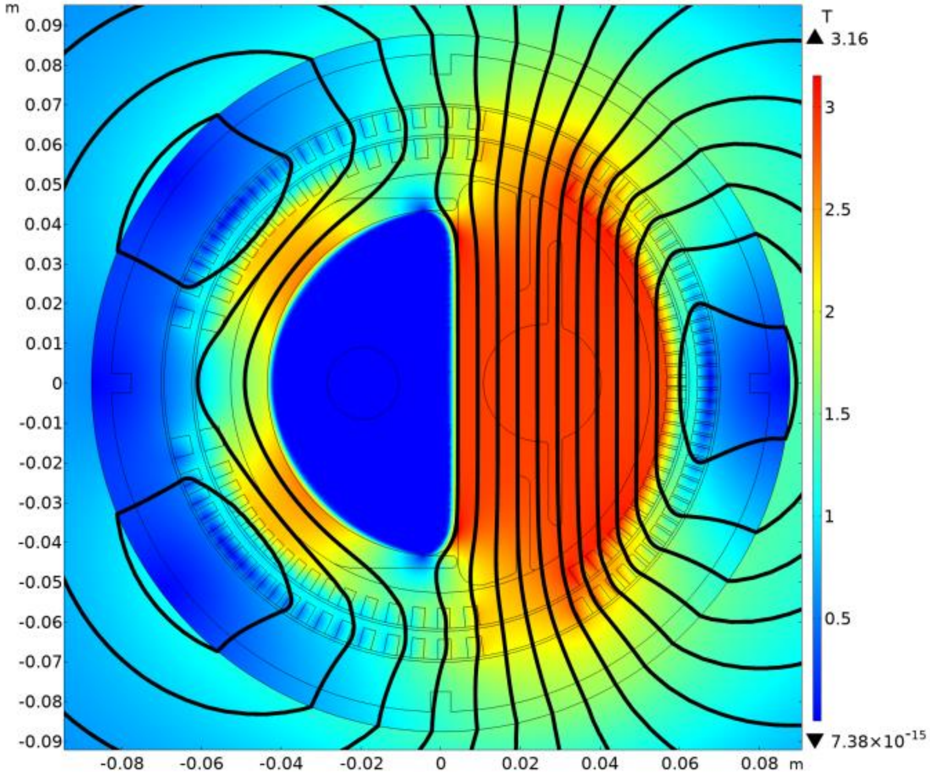
Inverse linear problem

This is a linear algorithm, not accounting for the nonlinear behaviour of the shield – a-posteriori check is needed

SuShi field quality – 2D field map



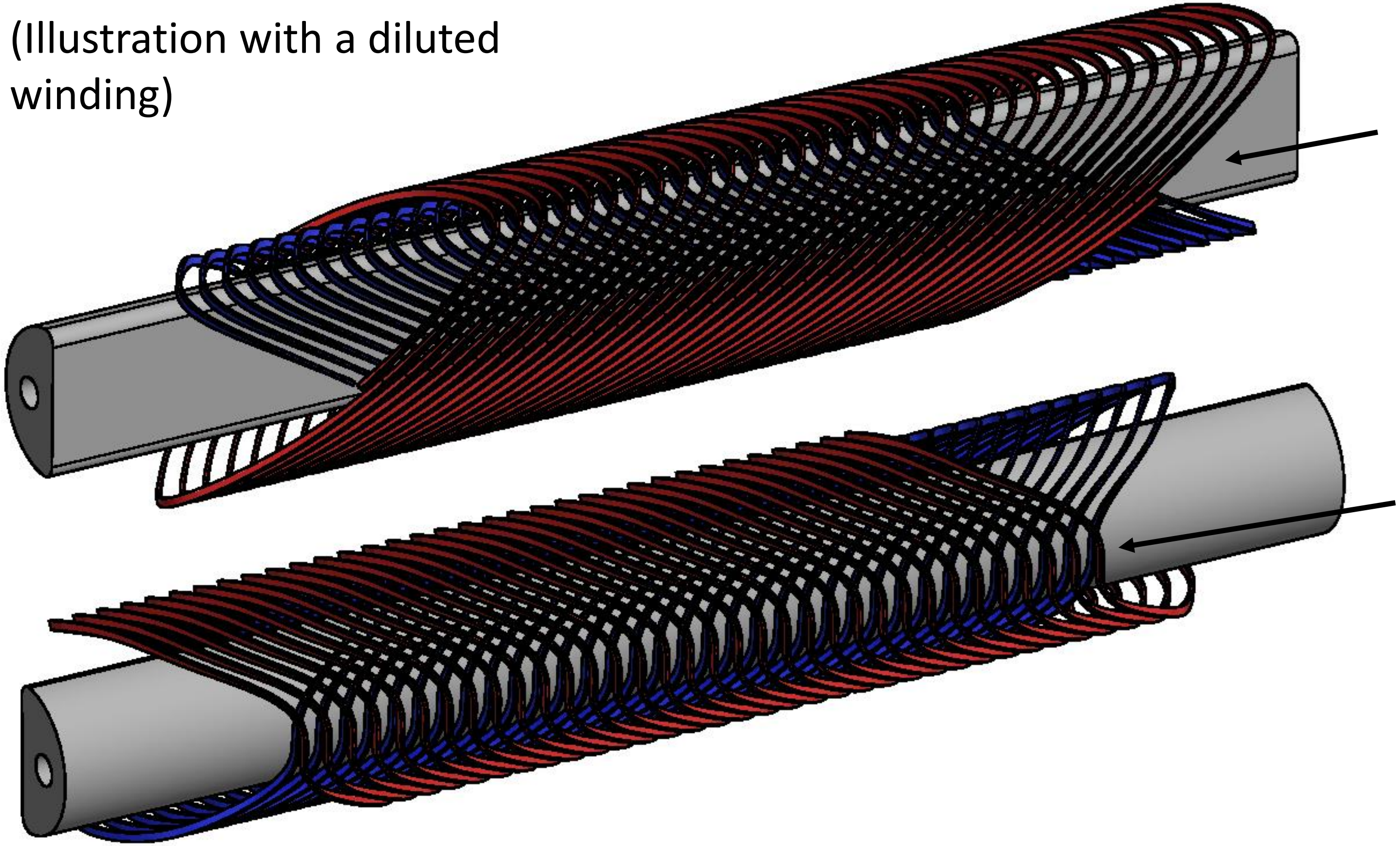
(a) Result in the full geometry



(b) Solution inside the yoke

SuShi optimized winding geometry

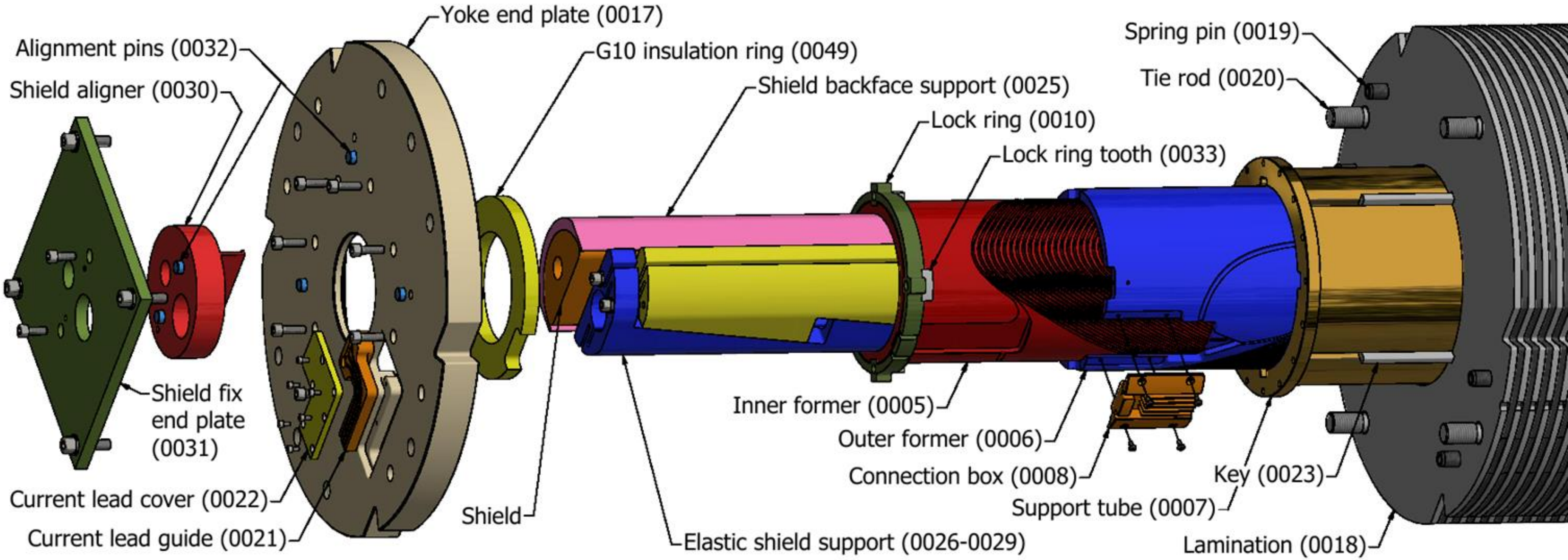
(Illustration with a diluted winding)



On the active side it seems to be a usual dipole (it is NOT)

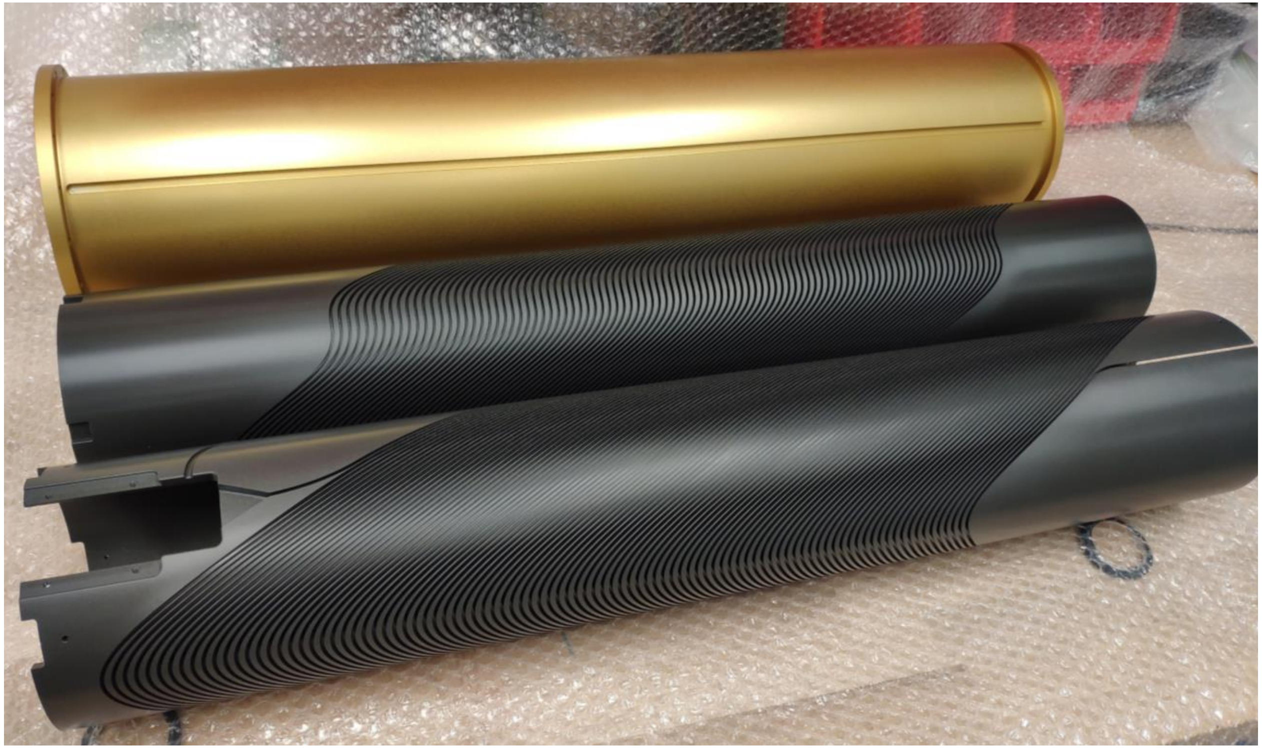
Backside:
$J_z(\vartheta = 180^o) = 0$ constraint leads to exotic S-shape
(and to a much more difficult winding process)

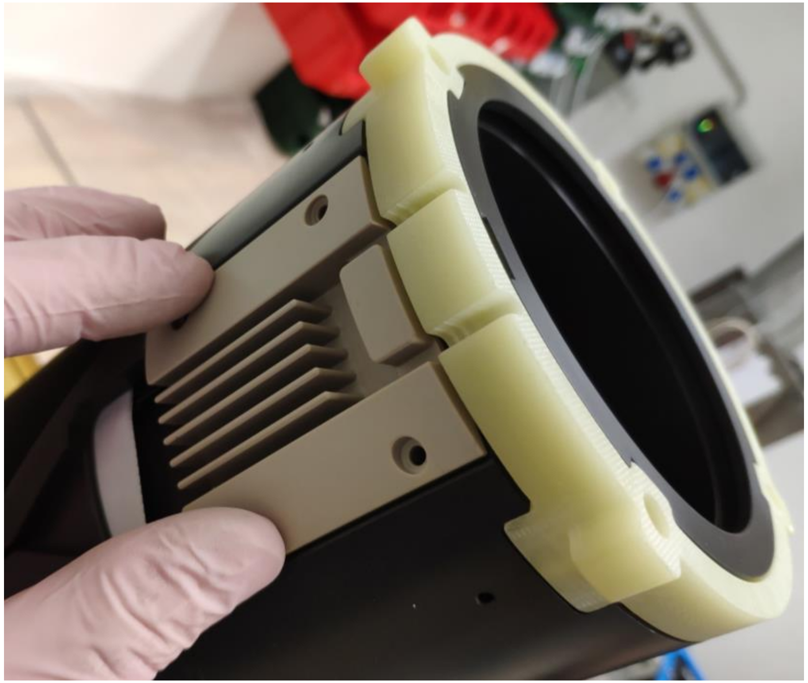
SuShi CAD modell



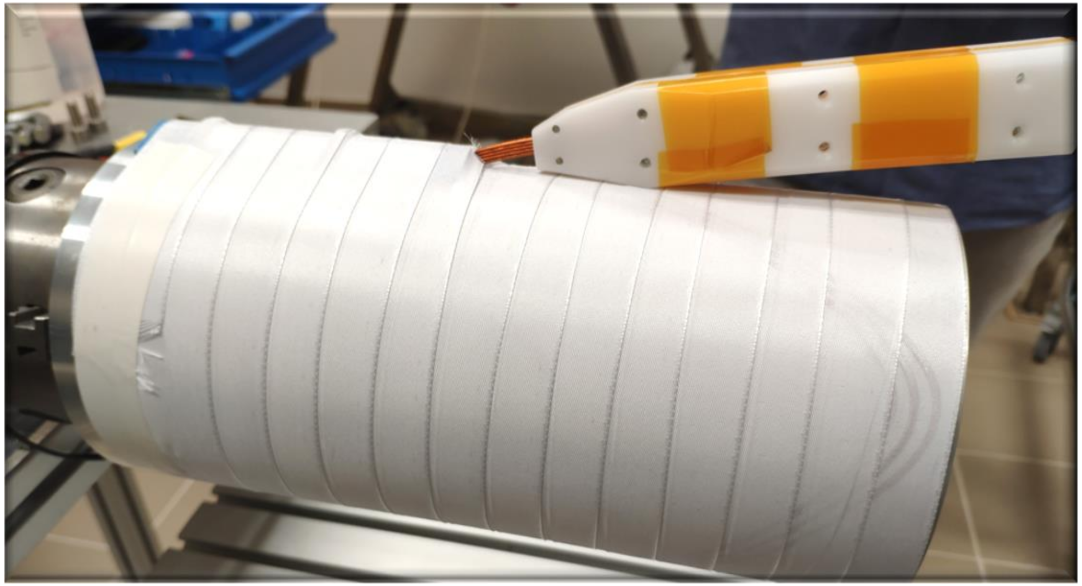
SuShi winding and assembly

SuShi formers and splice box



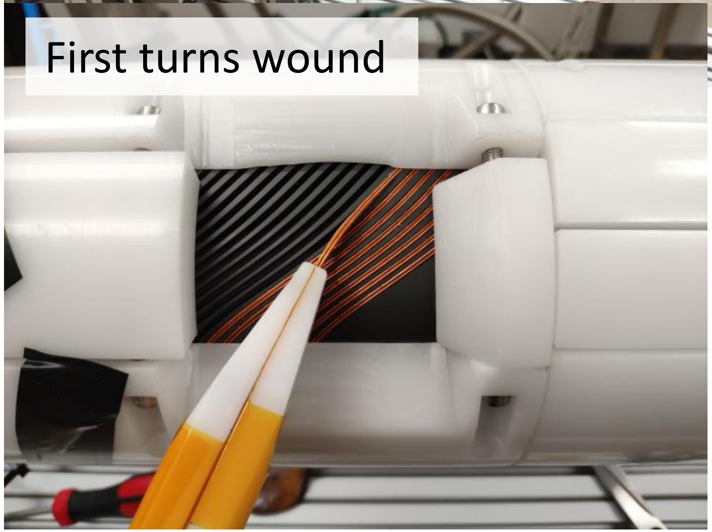


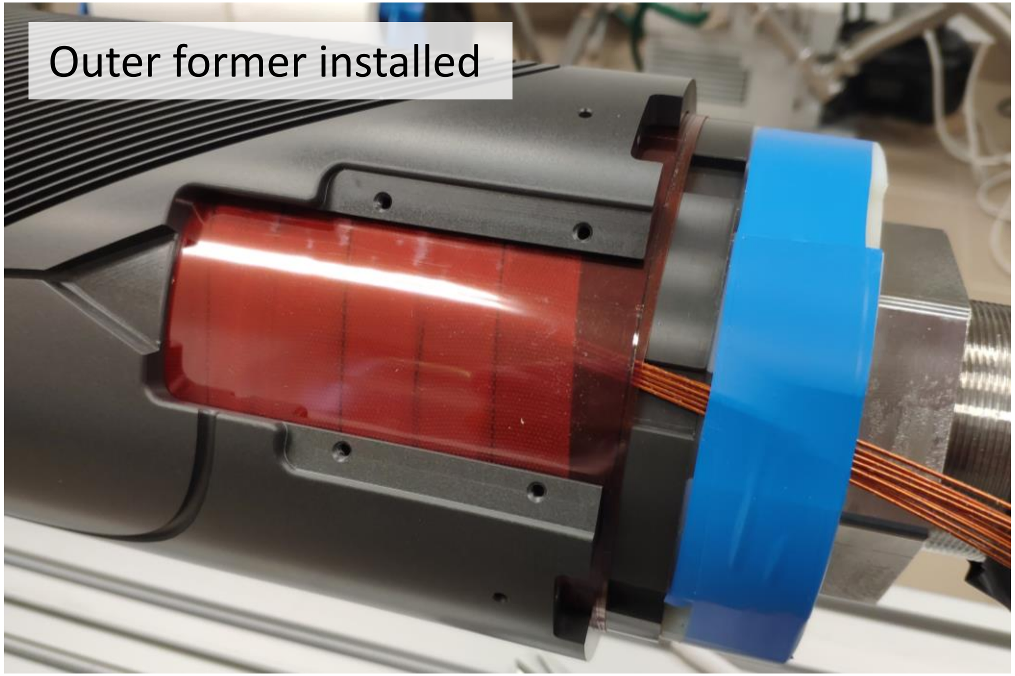
SuShi winding test @ Wigner RCP



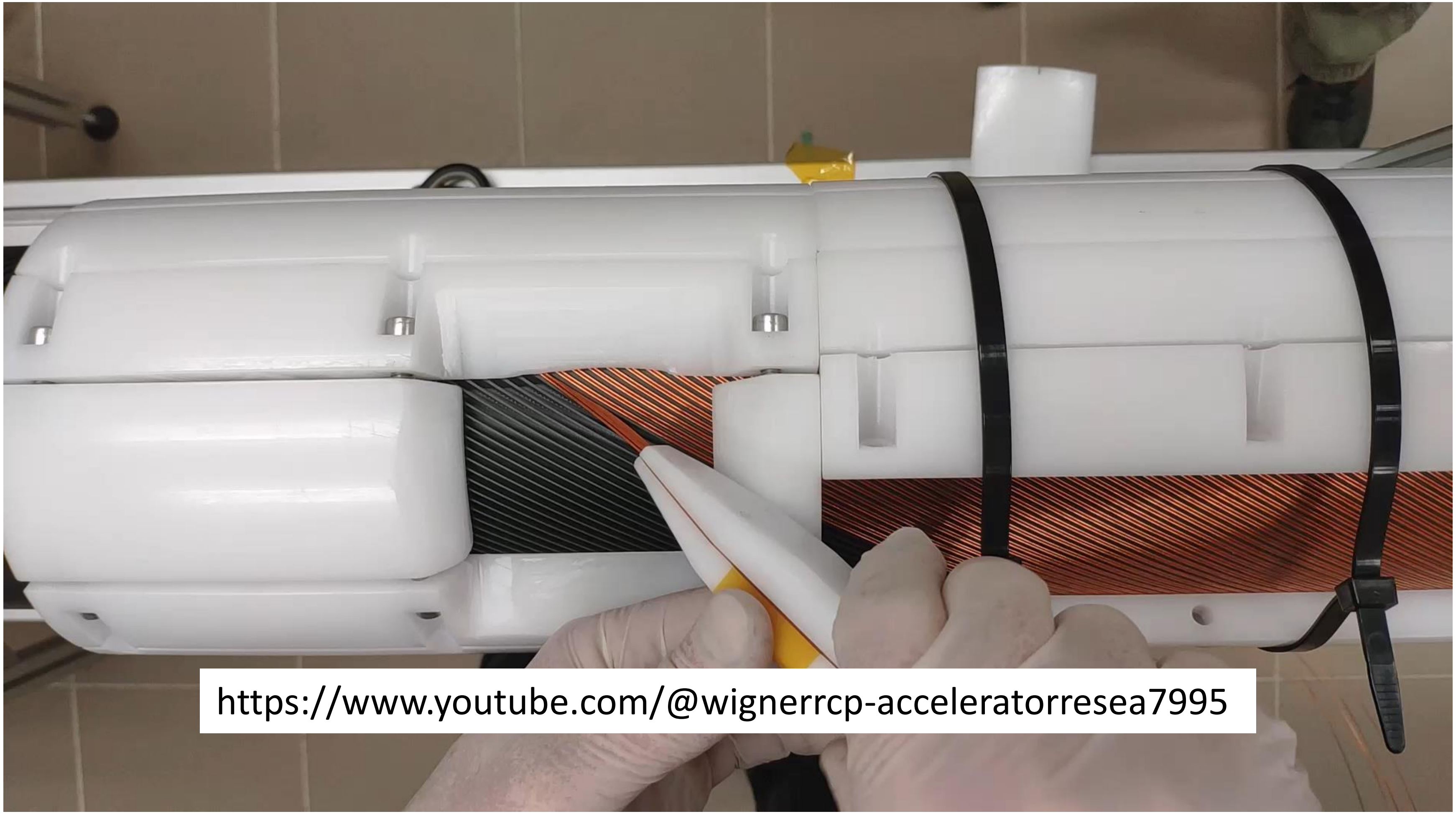
S-curve: difficult at the beginning, needs continuous support (pops out)
Now quite some experience…

SuShi winding @ Wigner FK



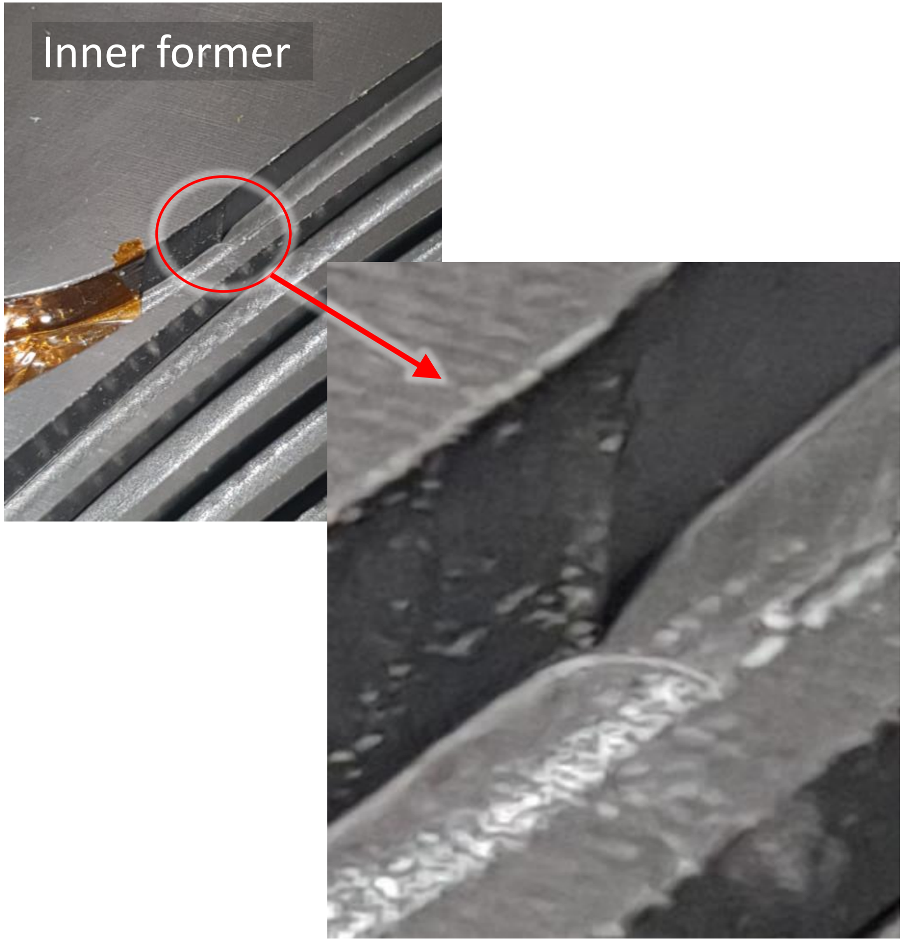


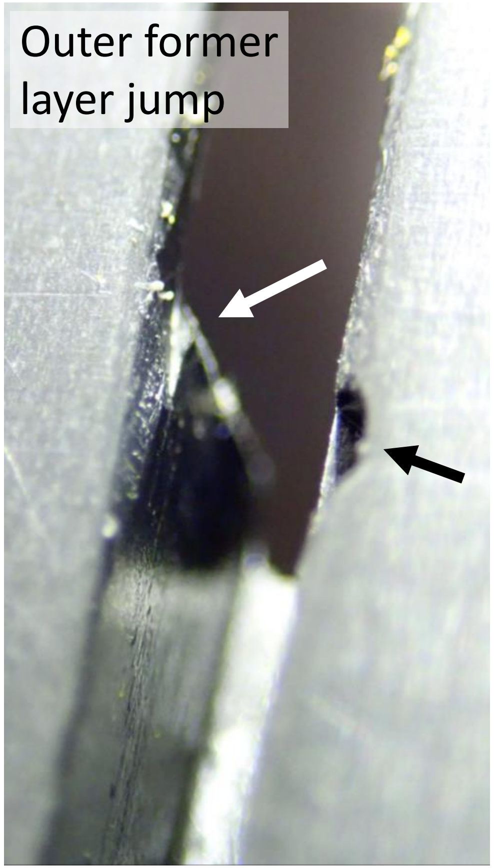
SuShi – winding

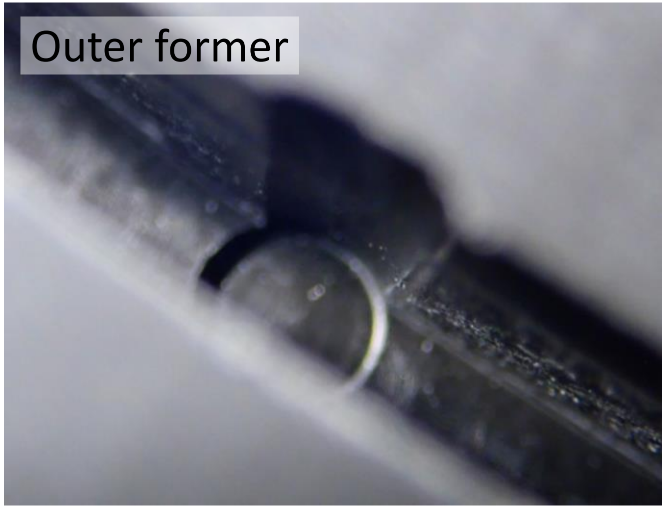


https://www.youtube.com/@wignerrcp-acceleratorresea7995

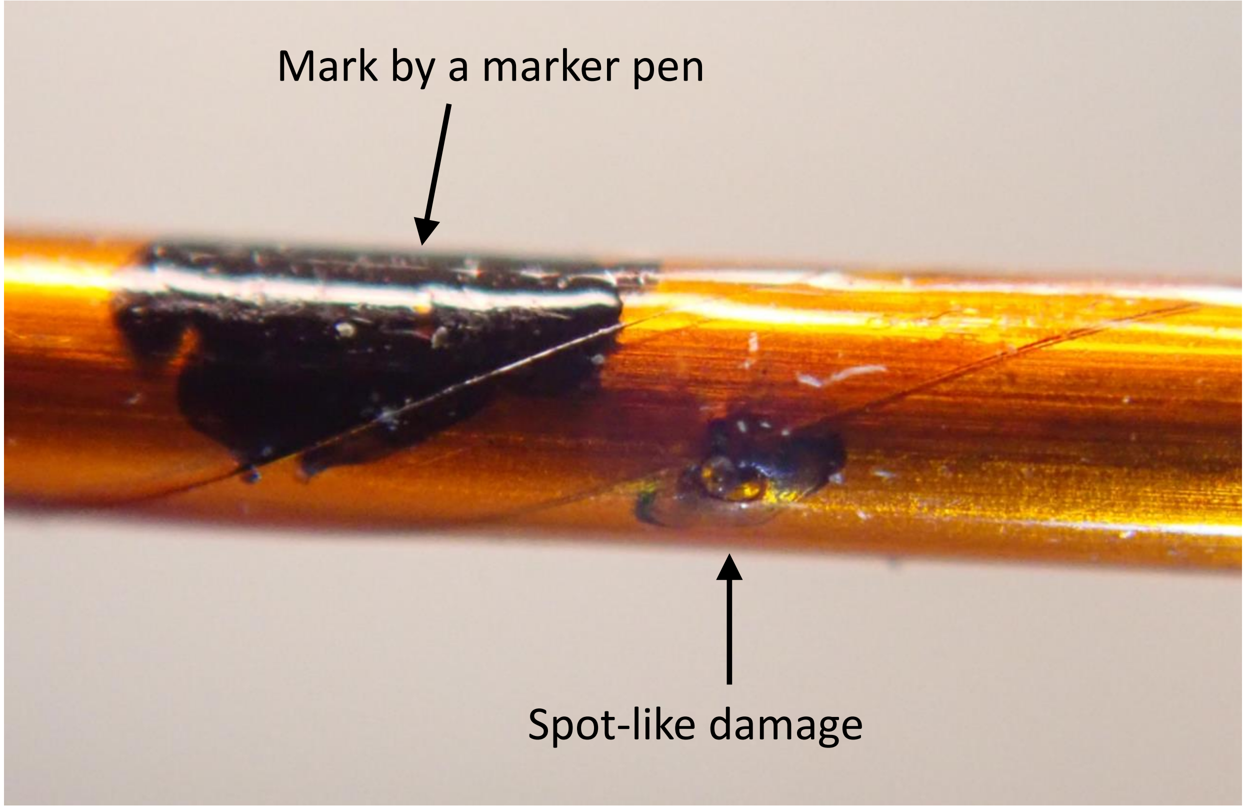
Former machining errors





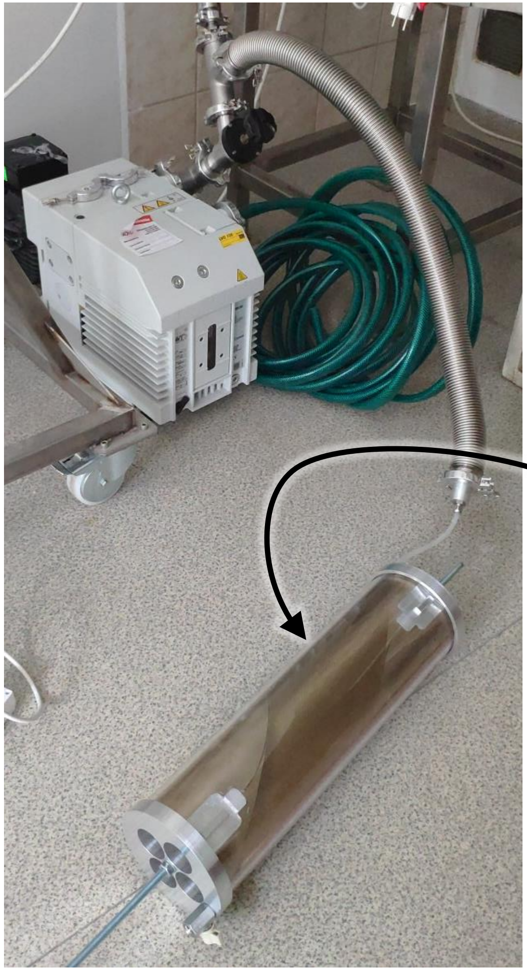


Insulation problems



- Wire at bottom of groove (no way to damage it installing)
- Survived 15 HV tests before breakdown
- Spot-like, displaying no damage at all due to winding (i.e. by the edge of the groove)
- Had some other similar cases, random late occurrence of sparks (outer former), not associated with former machining errors

WAX impregnation tests



BOX experiment @ PSI: wax-impregnated test sample showed no training!

SuShi prototype is in the best phase for testing this on a real magnet.

M. Daly, et al: Improved training in paraffin-wax impregnated Nb3Sn Rutherford cables demonstrated in BOX samples, https://arxiv.org/abs/2201.11039

0.5 m long test Alu-bronze CCT former (thanks to Glyn Kirby) in a plexi tube

- To be impregnated with wax
- Develop a method to master the 10-15% volume reduction of wax upon solidification
- Tests going on in these days…

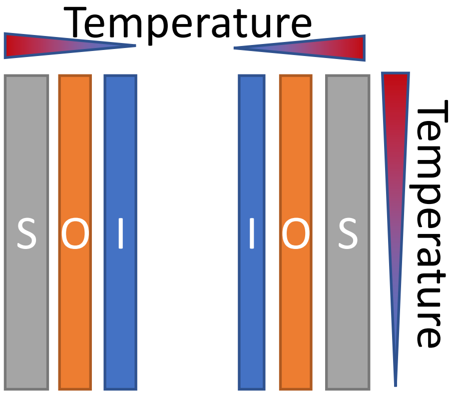
Pressurizable pot

WAX impregnation tests

- Wax melts at 55 °C and has viscosity similar to water
  - This makes wax significantly easier to use than epoxy
- During solidification it shrinks ~15% which needs to be accounted for

⬇

- We implement a reservoir on top, and create a temperature gradient in the wax from bottom to top, and inside to outsideo

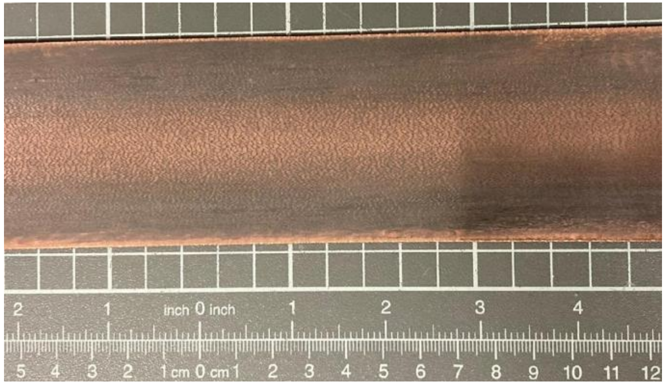


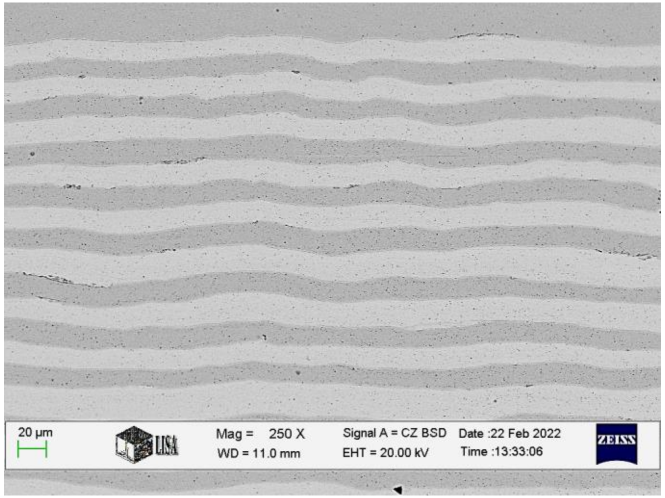
Shield development

NbTi/Cu sheet development – Nb-free

- Nipon Steel have stopped the production of the NbTi/Nb/Cu sheet
- To not let the knowledge be forgotten the University of Miskolc have took over resurrection and further development of the technology
- One of the goals is to eliminate Nb from the multilayer, thus reducing the price, and increasing the current density

NbTi-Cu – sample states





- 10 NbTi layers sandwiched with Cu

- Tests are ongoing, they did not yet manage to reproduce the behavior of the Nipon sample

MISKOLCI EGYETEM
UNIVERSITY OF MISKOLC

Conclusions

- Phantastic support by CERN: financial, professional and mental – THANK YOU!!!
- Many years spent on this project (more than foreseen), but by now have gained experience in a wide spectrum of topics
  - Mechanical, magnetic design, simulation of bulk SC in external field
  - Quench simulation
  - Analytic calculations
  - Impregnation
  - Metallurgy, NbTi
- Developed a network of collaborators, got new players on board (Univ. of Miskolc → FCC, HL-LHC), joined new projects (HITRIplus, I.FAST)
- Special efforts on transparent workflow, on-line e-logbooks, budget planning and monitoring, project documentation – everything constantly and instantaneously shared with colleagues
- Trying to contribute by ideas, improvements

Closing words

- If any of these grabbed your attention, feel free to contact for more info, discussion:
  - Many people and groups contributing
  - Starting contact:

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    brunner.kristof@wigner.hu

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Winding geometry optimization

Required multipole (Fourier) components

Part describing the field pattern

$$
\begin{pmatrix} B_0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} & \dots & M_{1N} \\ M_{21} & M_{22} & \dots & M_{2N} \\ \vdots & \vdots & \dots & \vdots \\ M_{K1} & M_{K2} & \dots & M_{KN} \\ \cos(\vartheta_0) & \cos(2\vartheta_0) & \dots & \cos(N\vartheta_0) \end{pmatrix} \begin{pmatrix} J_1 \\ J_2 \\ \vdots \\ J_N \end{pmatrix}
$$

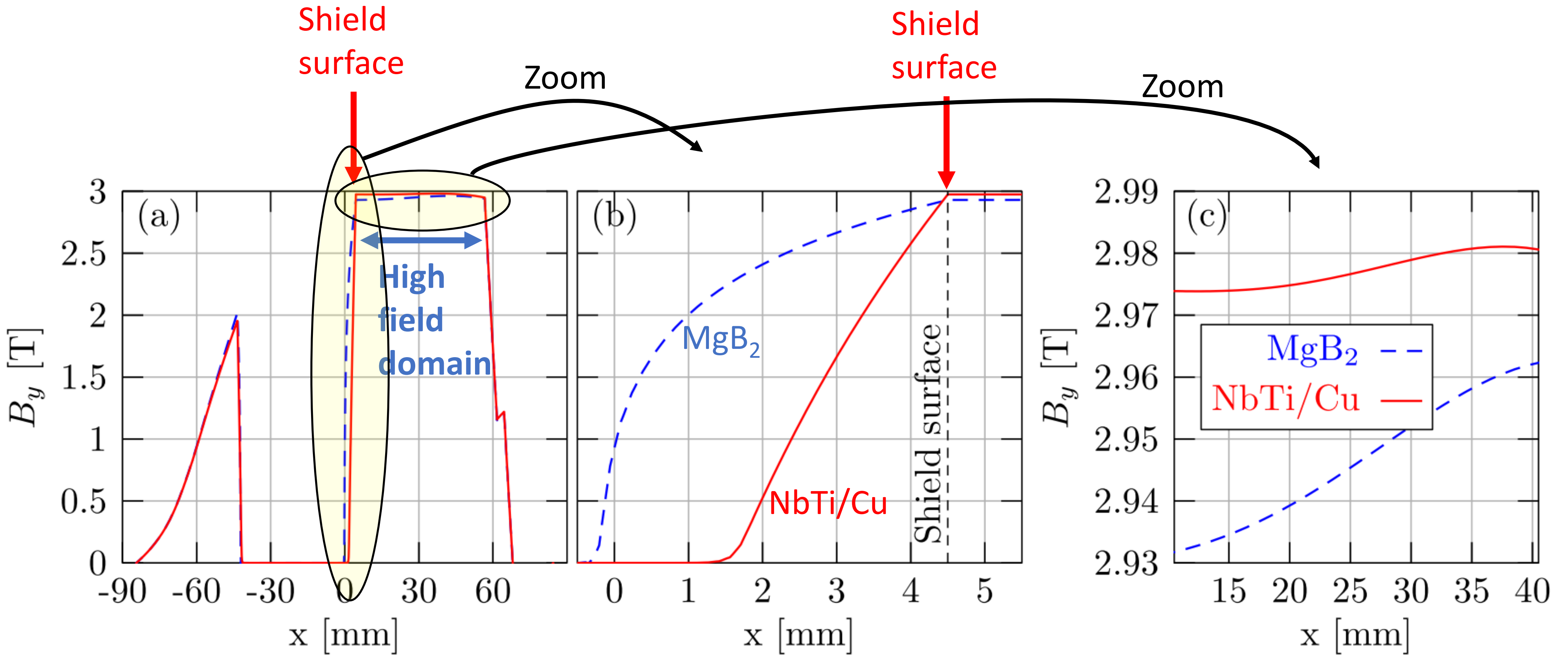
For ex.: dipole Fourier-component due to unit quadrupole current

Matrix would be diagonal, and this element be zero without the shield!

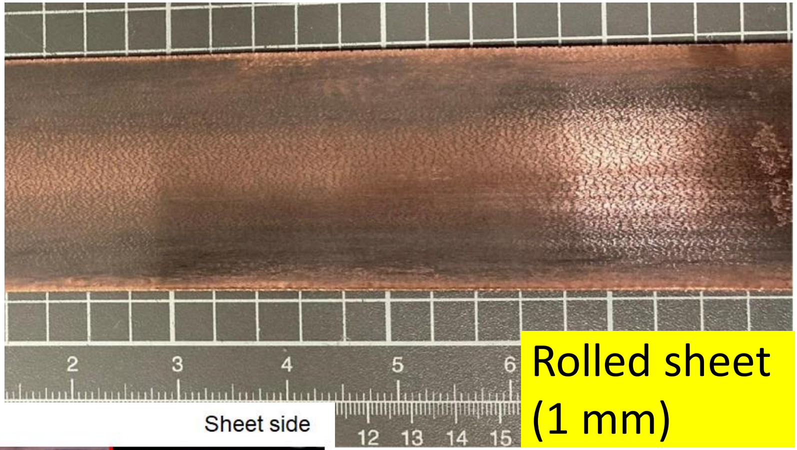
Constrains $J(\vartheta_0) = 0$

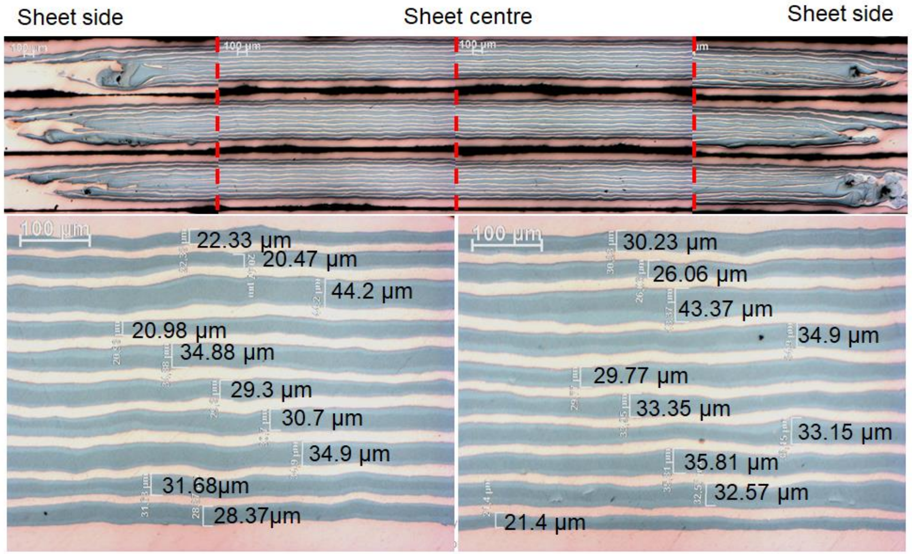
For us: $\vartheta_0 = 180^o$

SuShi field quality – penetration profile



NbTi/Cu sheet development





These are the nice examples.

There are many failed attempts (delamination, broken/uneven layers, Cu-Ti, warping, etc)

Not as easy as it seems.