Magnetic Shielding and the SuShi Magnet

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Overview

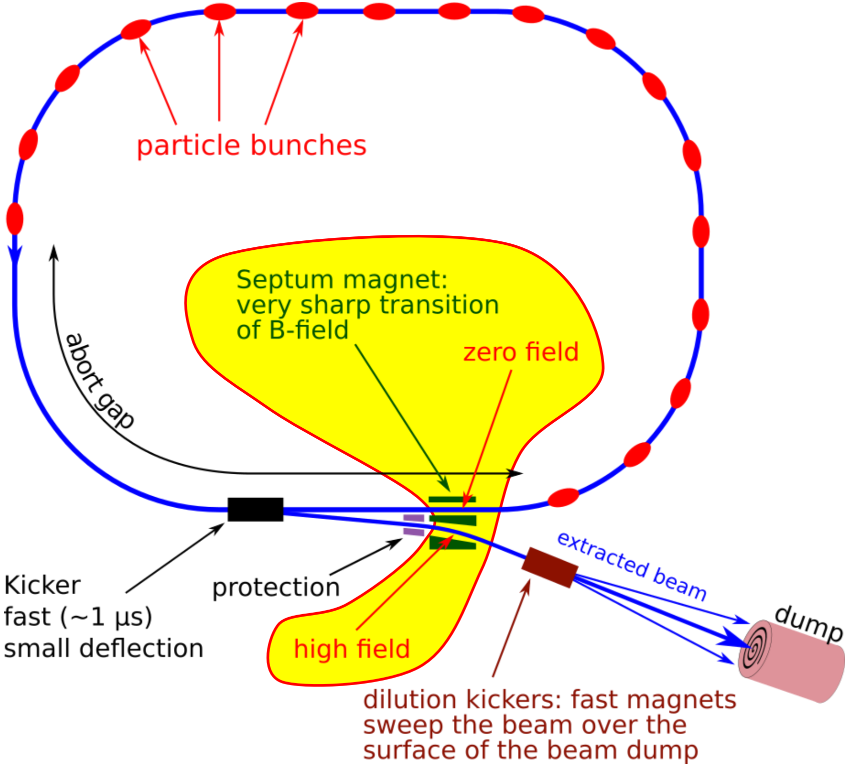
- The SuShi septum magnet
    - Beam extraction in the FCC-hh: septum magnets
    - The SuShi concept – overview of other applications
    - Proof-of-concept tests
    - Magnet design
    - Magnet construction
    - Magnet testing
    - Development of NbTi/Cu multilayer shielding material
- Teaser: the I.FAST HTS CCT magnet prototype
    - Project overview
    - Highlights of the R&D

Disclaimer: slides have animations, their absence in the PDF version hides some content and hinders understanding

Beam extraction from the FCC-hh

Septum magnet concepts

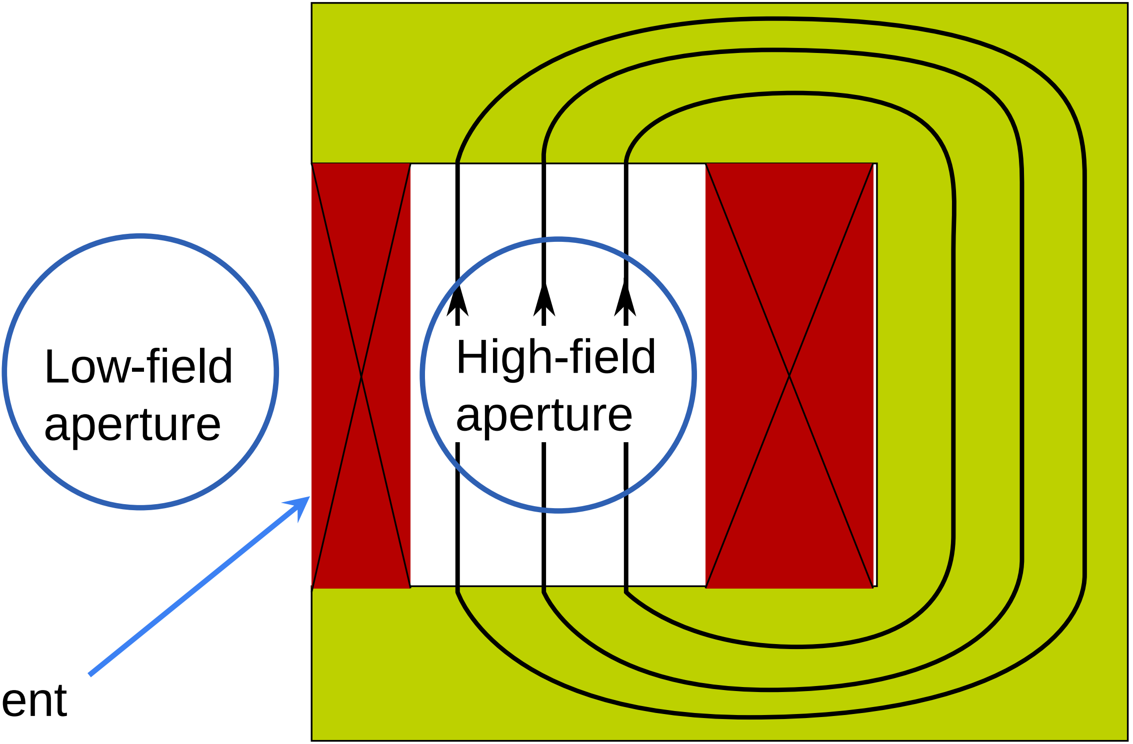
Future Circular Collider: beam extraction



- Fast extraction of the **8 GJ** proton beam from FCC-hh (programmed, or safety abort)
- Need **thin** wall…
- … yet high field (≥ 3 T)
- Quasi-DC (following beam energy), but avoid high power consumption

⇒ Superconducting solution

Septum configurations – active wall



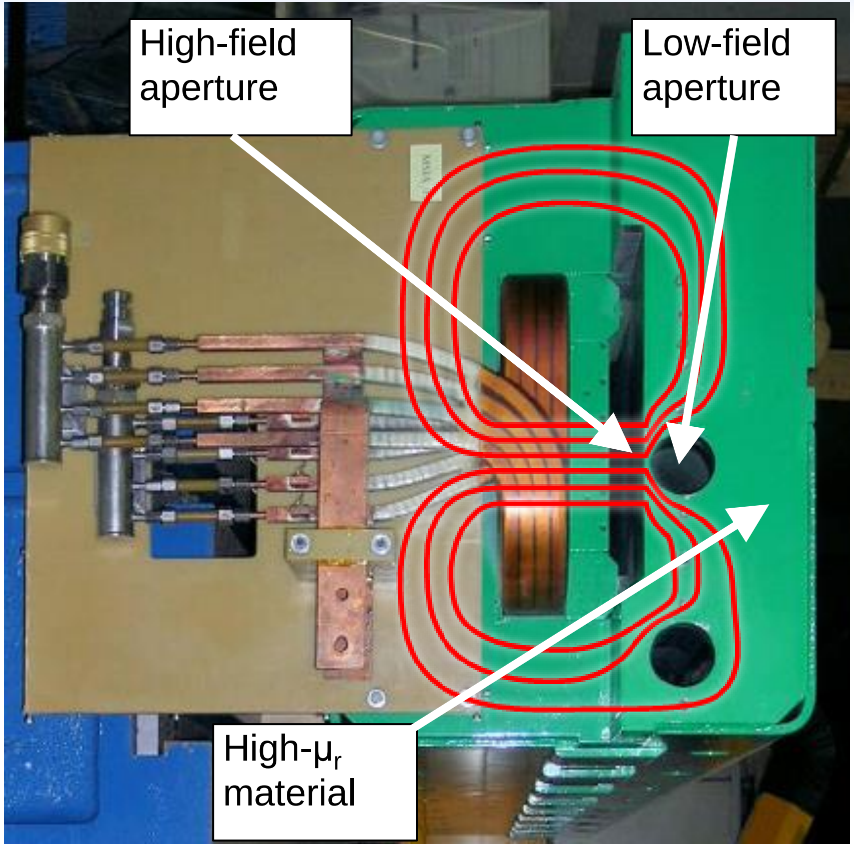
Externally driven current

Septum configurations – passive wall

No externally driven current between the two domains

- **Ferromagnetic, high μ_r**
  LHC Lambertson septum

- **High-μ_r** shield “**sucks out**” the induction lines from the low-field aperture



Septum configurations – passive wall

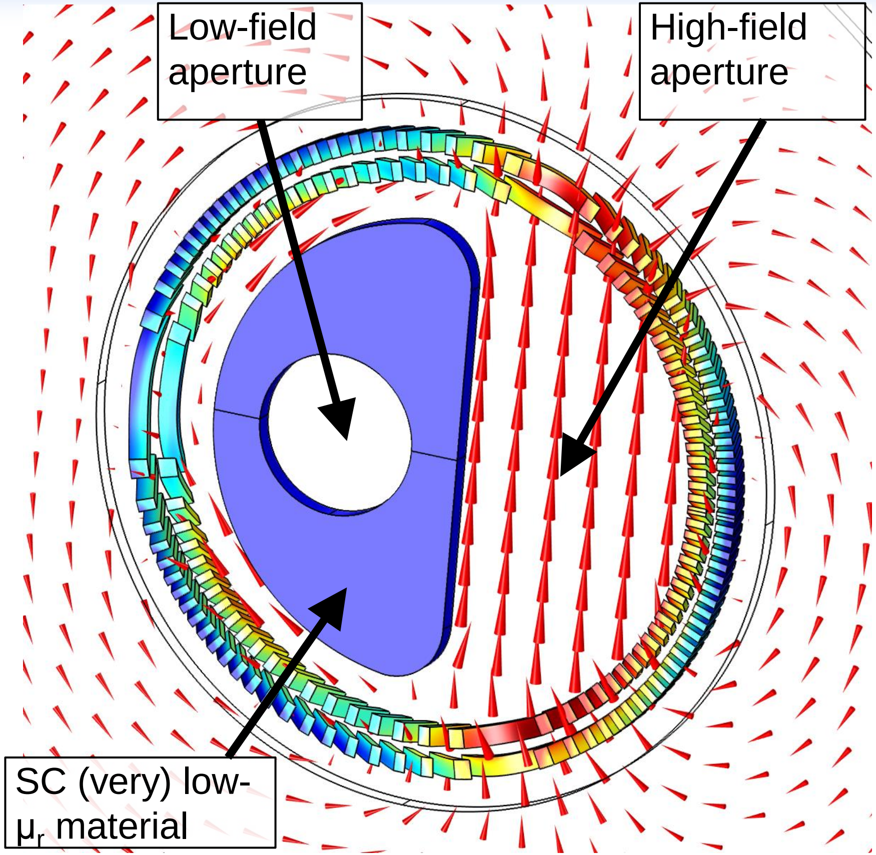
No externally driven current between the two domains

- **Diamagnetic, very low μ_r** (SC) SuShi septum

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

Under the hood (diamagnetism of SC-II):

- Eddy-current septum: transient currents shield the aperture
- Transients last "forever" (persistent currents)



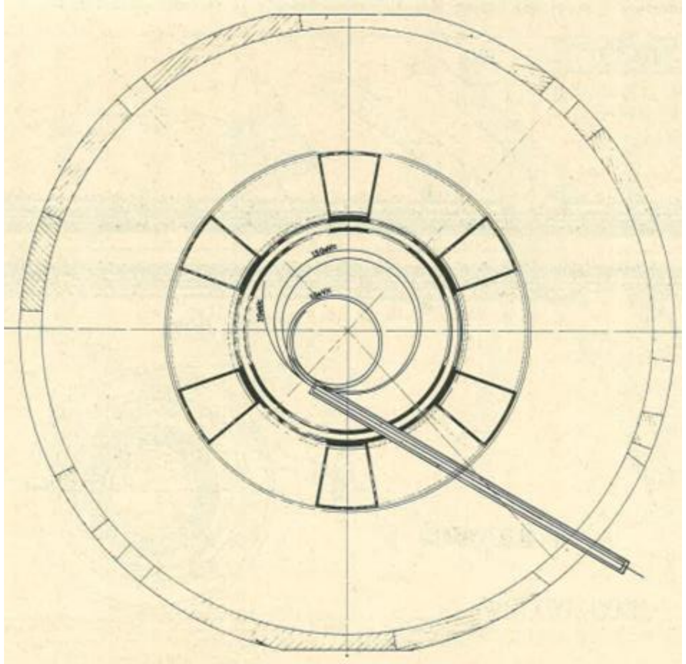
Pros and cons

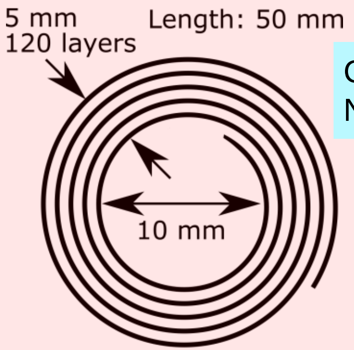
- Advantages
  - Continuous 2D current distribution (in contrast to discrete wires in windings), no leaking field
  - Perfect shield by Nature
  - Shield can be a bulk material, no epoxy, no cracking
  - Partially self-supporting, smaller total thickness (high forces!)
  - Bean (critical state) model: everywhere $J_c(B)$ - optimal, automatically graded current density, 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)

Other applications of the SuShi concept

CERN bubble chambers

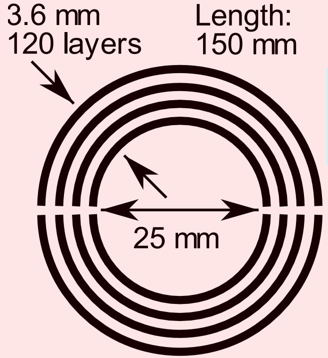
Goal: field-free channel to enter low-momentum particles





Cu-cladded Nb_3Sn foil

Shielded 4.2 T transverse field

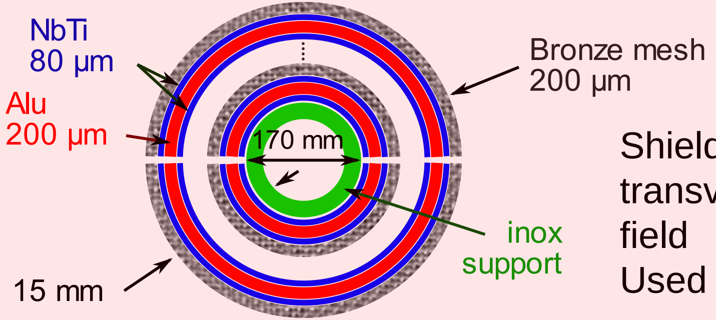


Cu-cladded Nb_3Sn foil

Shielded 3.3 T transverse field

Pure NbTi foil

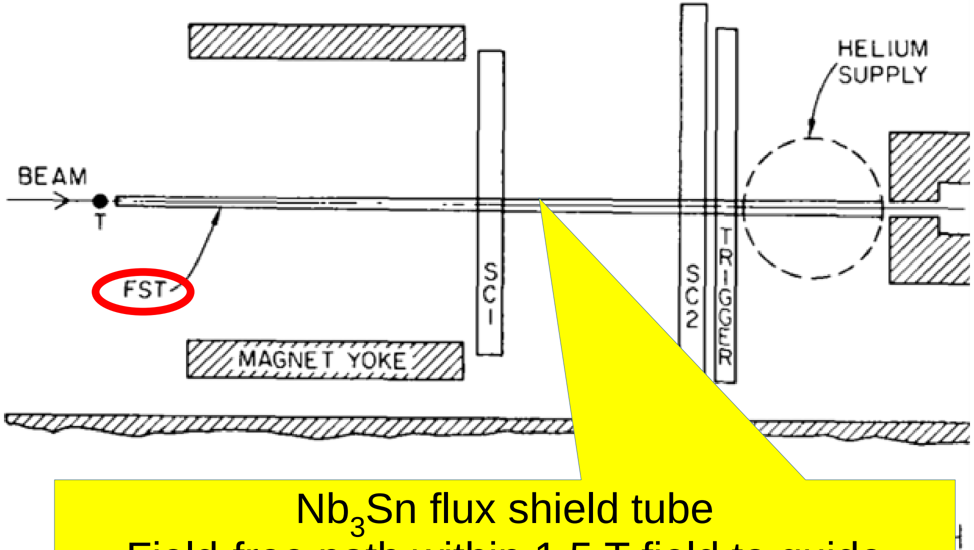
Only mechanically clamped



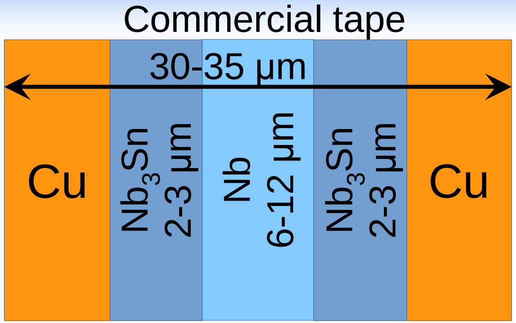
Shielded 1.2 T transverse field
Used in exp.

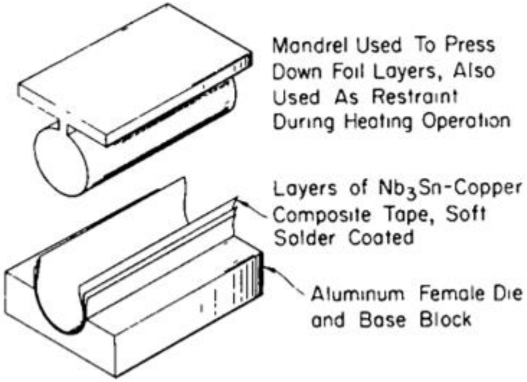
M.Firth, L.Krempasky, F.Schmeissner: Preliminary work on field-free particle beam paths from hollow superconducting shielding tubes – Proc. 3rd. Int. Conf. Magn. Tech. (1970) 1178
M.Firth, E.U.Haebel, L.Krempasky, F.Schmeissner: Performance of the superconducting field shielding tube for the CERN 2 meter hydrogen bubble chamber

Flux exclusion tube @ SLAC



Nb_3Sn flux shield tube
Field-free path within 1.5 T field to guide out low-momentum particles from the magnet, avoiding detector saturation





A. Lamination, Bonding with Solder and Shaping Operation

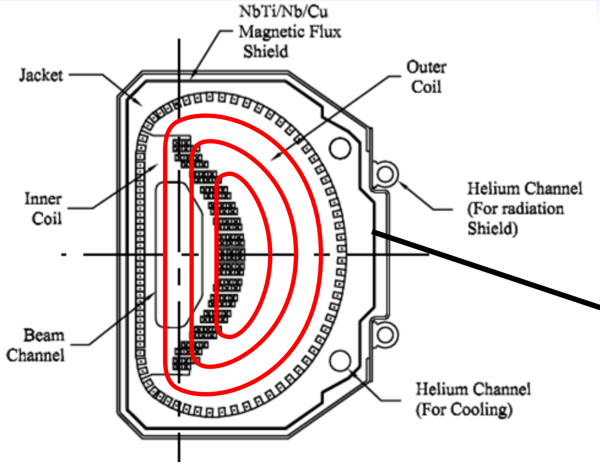
Pb-Sn solder bonded half cylinders

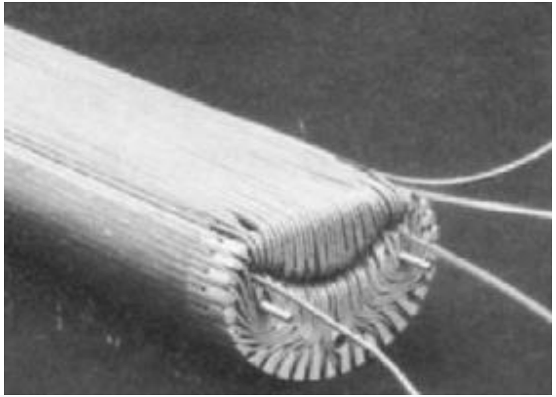
80 layers
2.4 mm thickness

Shielded
1.7 T field

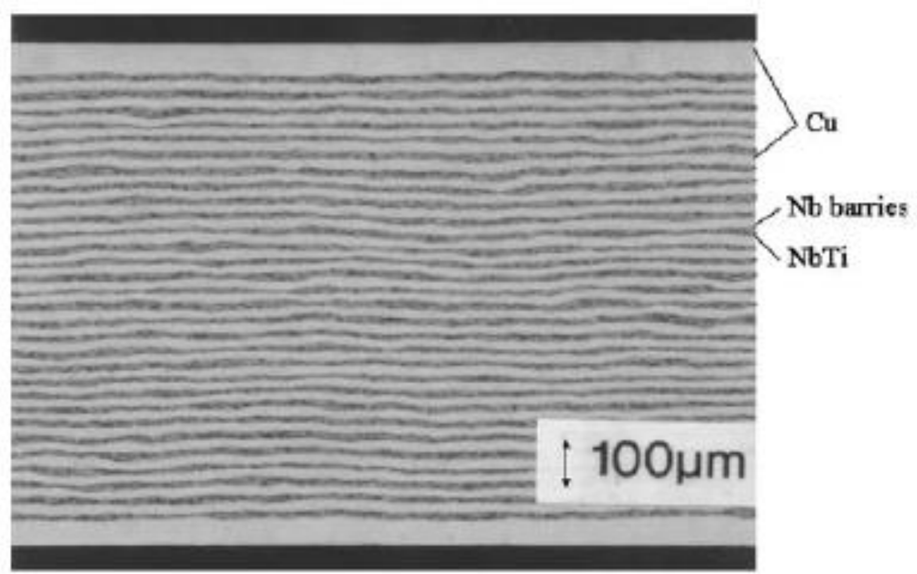
F.Martin, S.J.St.Lorant, W.T.Toner: A four-meter long superconducting magnetic flux exclusion tube for particle physics experiments, NIM 103 (1972) 50
S.J.St. Lorant: Superconducting Shields for Magnetic Flux Exclusion and Field Shaping, SLAC note

BNL g-2 inflector



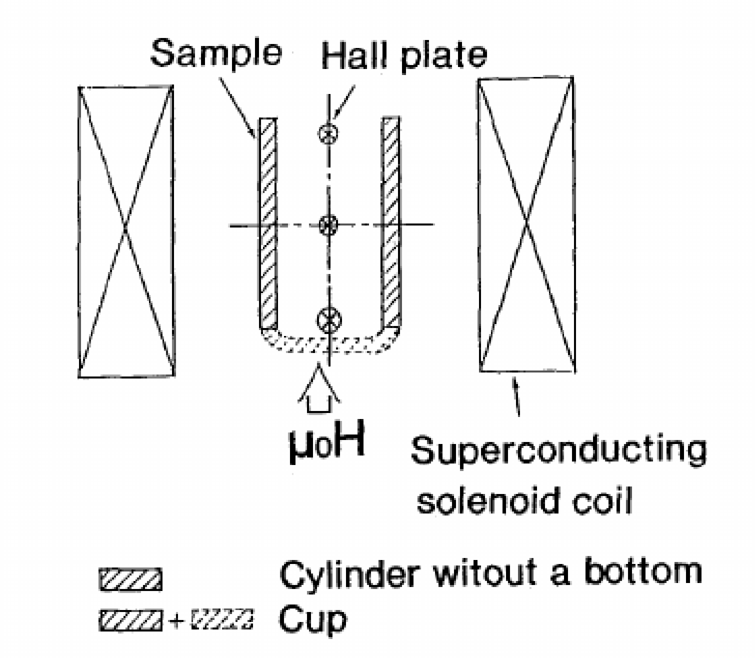


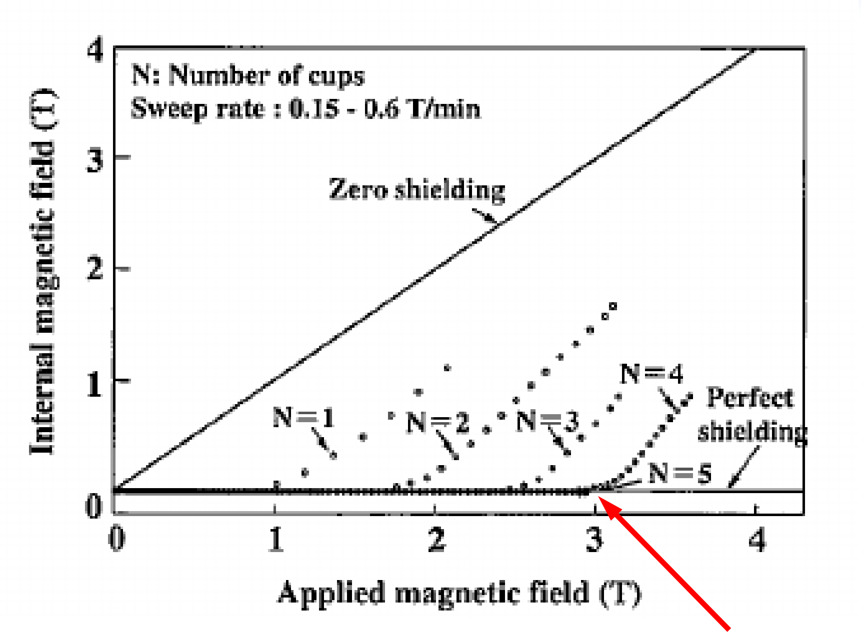
30 NbTi layers (10 μm) between Cu
SC shield to contain stray field (0.1 T)



A.Yamamoto, et.al., The superconducting inflector for the BNL g-2 experiment, NIM A491 (2002) 23-40

The NbTi/Nb/Cu multilayer shield (Nippon Steel Ltd)





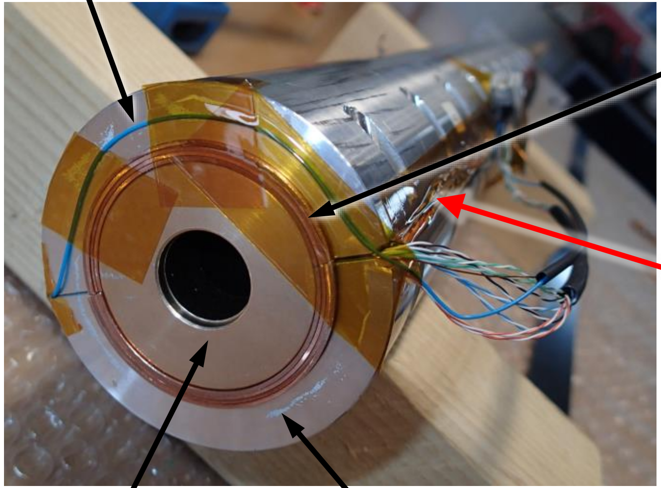
4 cups (4 x 0.8 mm)
could shield 3 Tesla

I.Itoh,K.Fujisawa,H.Otsuka: NbTi/Nb/Cu multilayer composite materials for superconducting magnetic shielding, Nippon Steel Technical Report No. 85, January 2002
And many others…

Proof of concept tests

NbTi/Nb/Cu multilayer (Nippon Steel Ltd)

Saddle-shaped pick-up coil

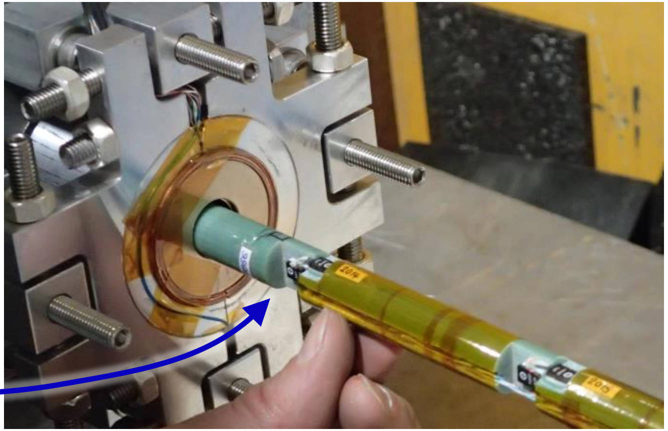


Bronze support

Alu clamp

4 x 0.8 mm
2 half cylinders

Hall sensors
outside and
inside



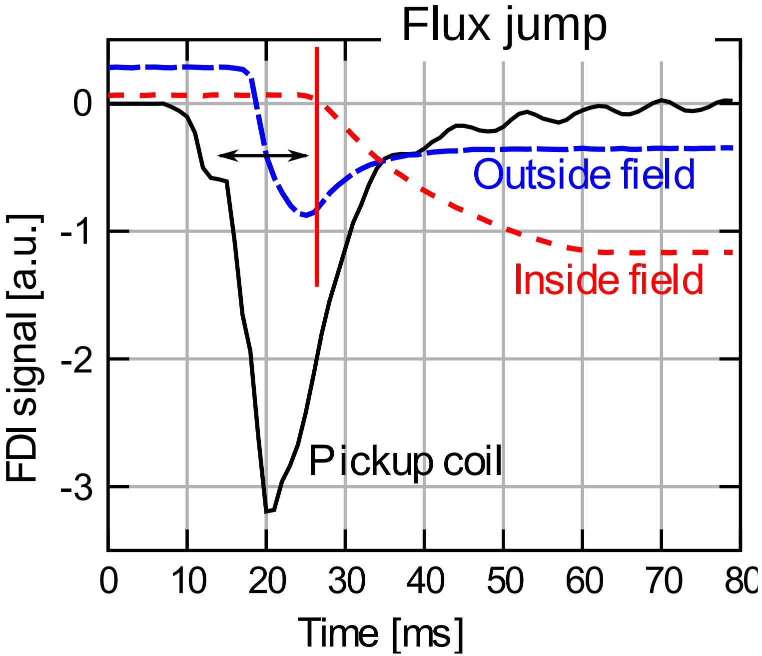
Shield in MCBY magnet

D. Barna, et al: NbTi/Nb/Cu multilayer shield for the superconducting shield (SuShi) septum, IEEE TAS 29 (2019), 4900108

NbTi/Nb/Cu multilayer (Nippon Steel Ltd)

Performance:

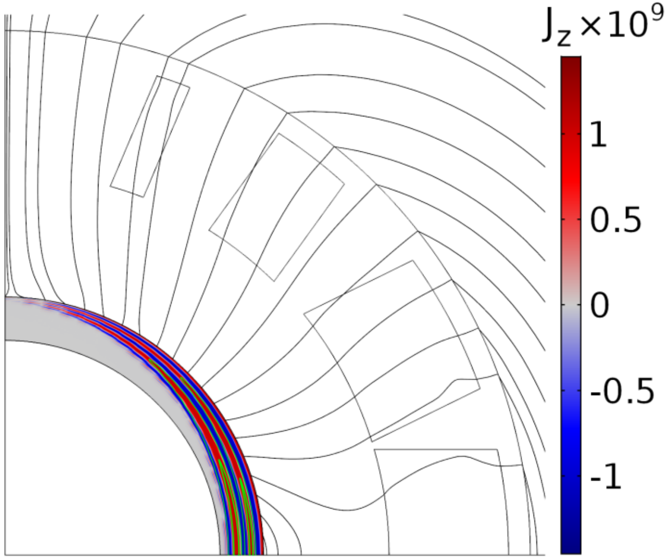
- 3.1 Tesla on-surface field shielded
- 4.2 K: no flux-jumps
- 1.9 K: unstable, flux jumps

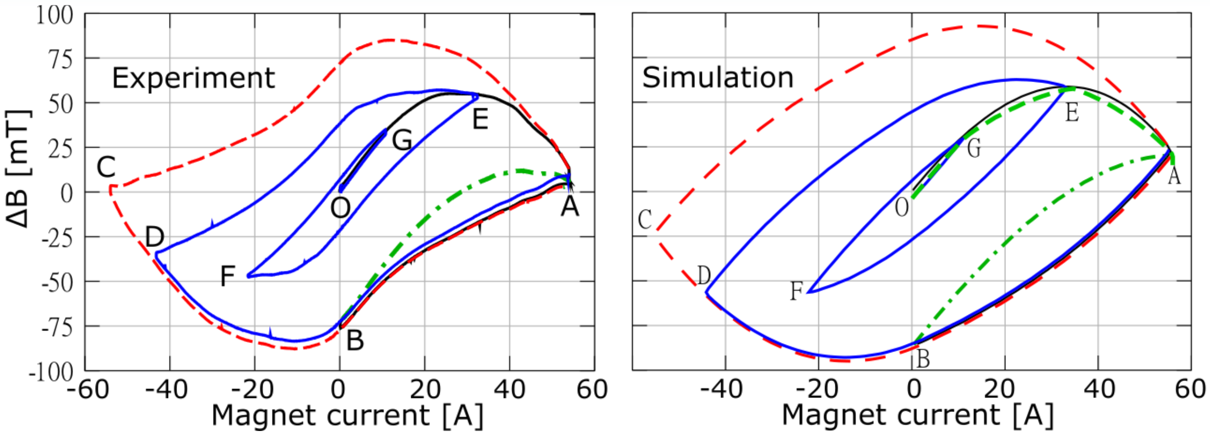


Sufficient time (~10 ms) to extract the beam

D. Barna, et al: NbTi/Nb/Cu multilayer shield for the superconducting shield (SuShi) septum, IEEE TAS 29 (2019), 4900108

NbTi/Nb/Cu multilayer – trapped field



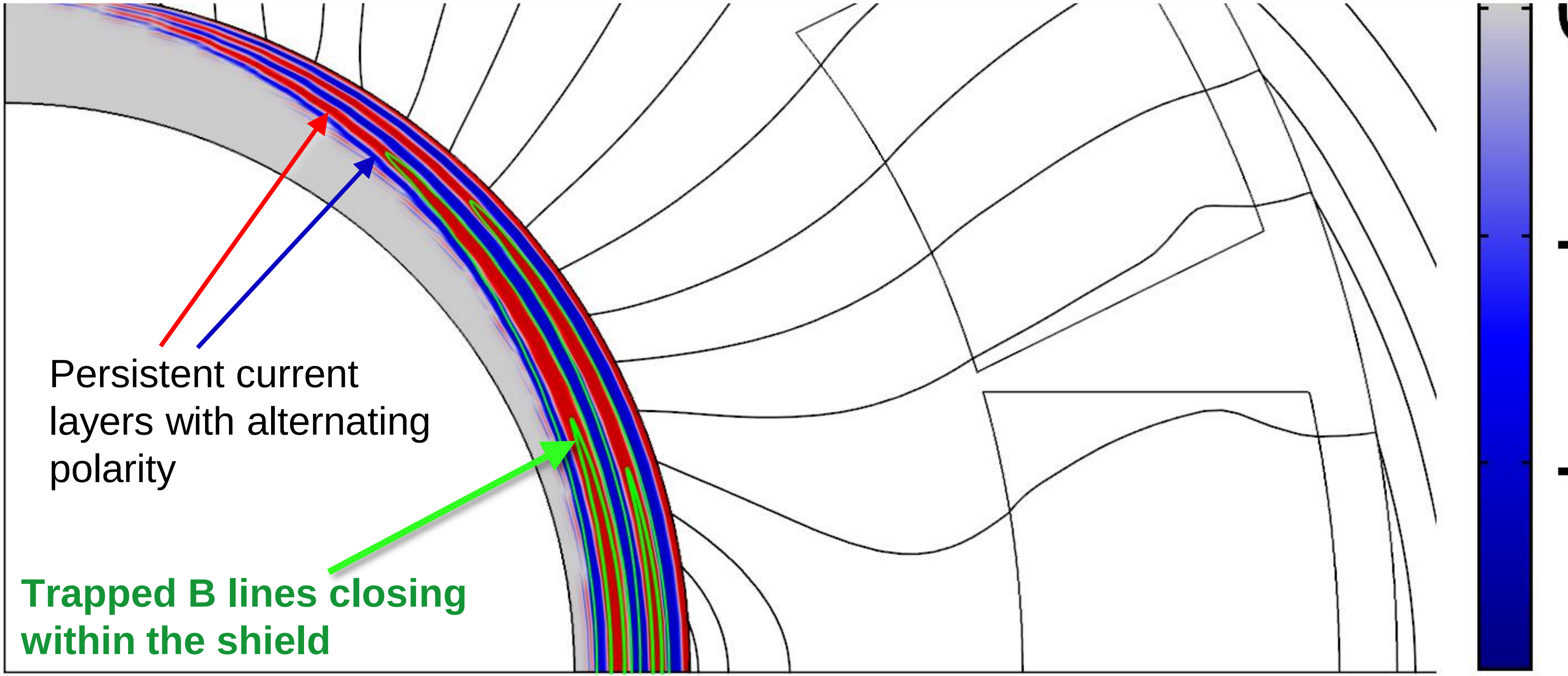


Did we restore the virgin state?
The shield shows no trapped field…

No! Micro-structure of persistent currents, partially cancelling out

D. Barna, et al: NbTi/Nb/Cu multilayer shield for the superconducting shield (SuShi) septum, IEEE TAS 29 (2019), 4900108

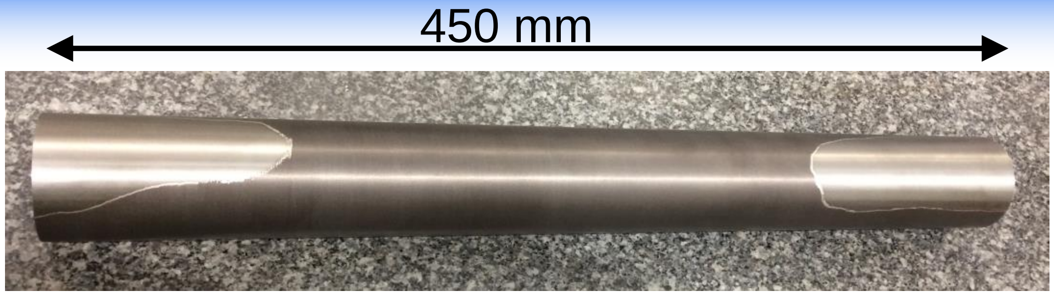
NbTi/Nb/Cu multilayer – trapped field

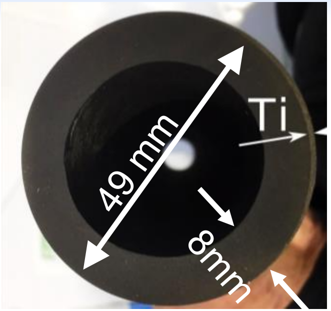


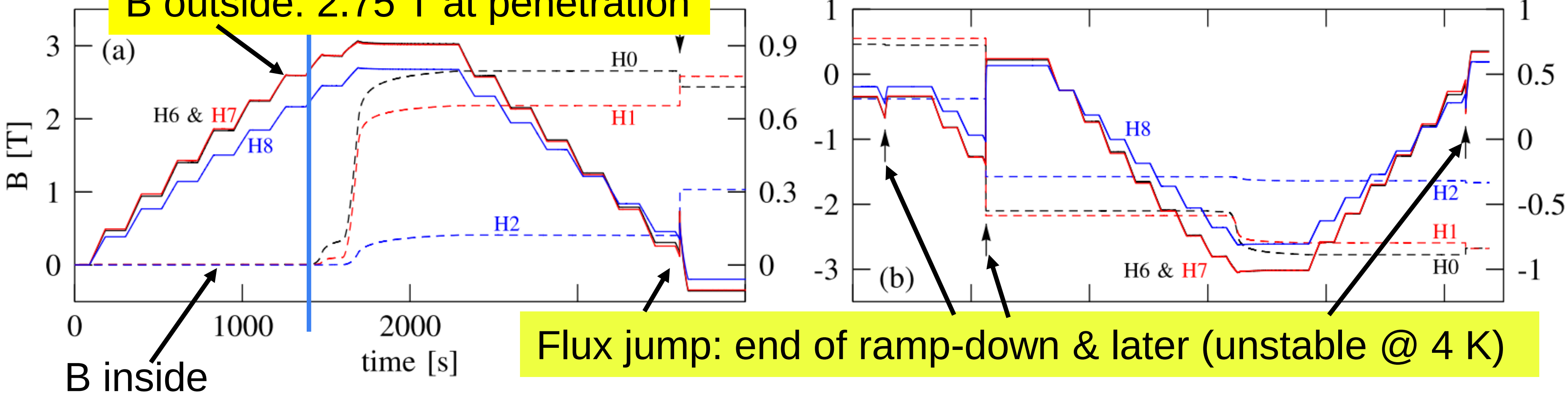
Persistent current layers with alternating polarity

Trapped B lines closing within the shield

MgB$_2$ tube







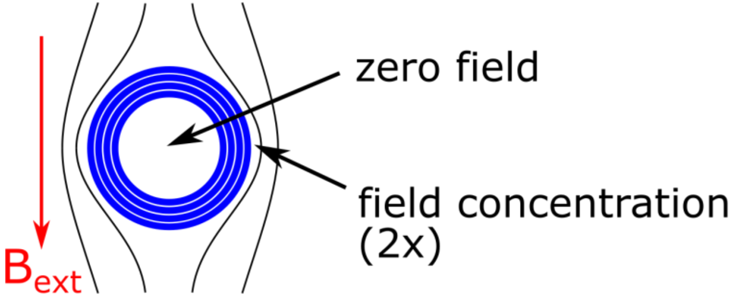
B outside: 2.75 T at penetration

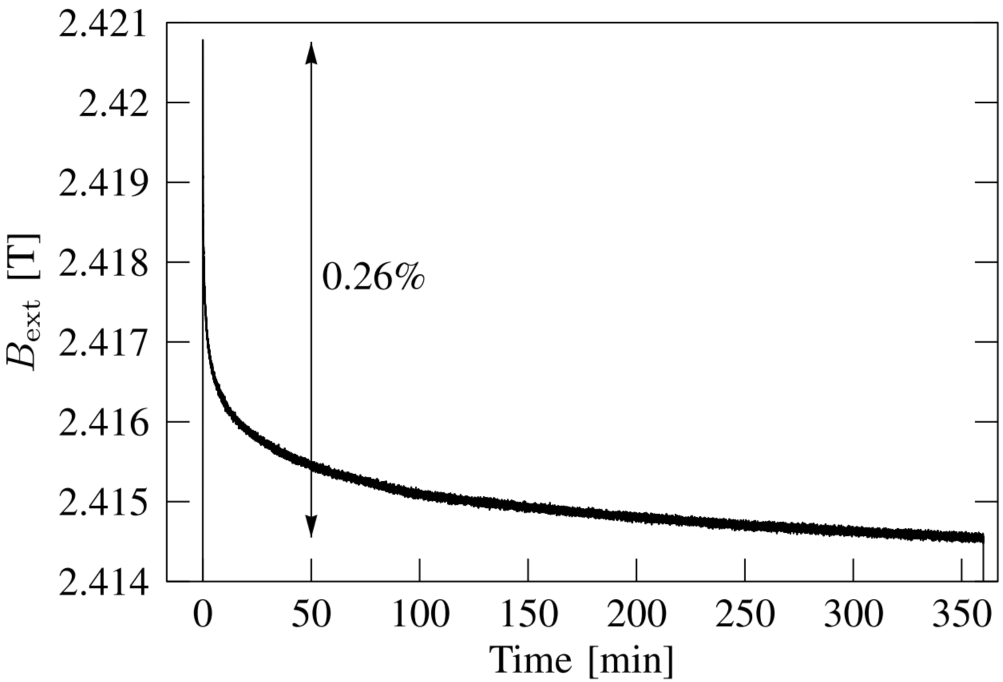
B inside

Flux jump: end of ramp-down & later (unstable @ 4 K)

D. Barna, G. Giunchi, M. Novák, K. Brunner, A. Német, C. Petrone, M. Atanasov, H. Bajas, J. Feuvrier: An MgB2 superconducting shield prototype for the Future Circular Collider septum magnet. IEEE Transactions in Applied Superconductivity, 29 (2019) 4101310

MgB_2 – persistent current relaxation



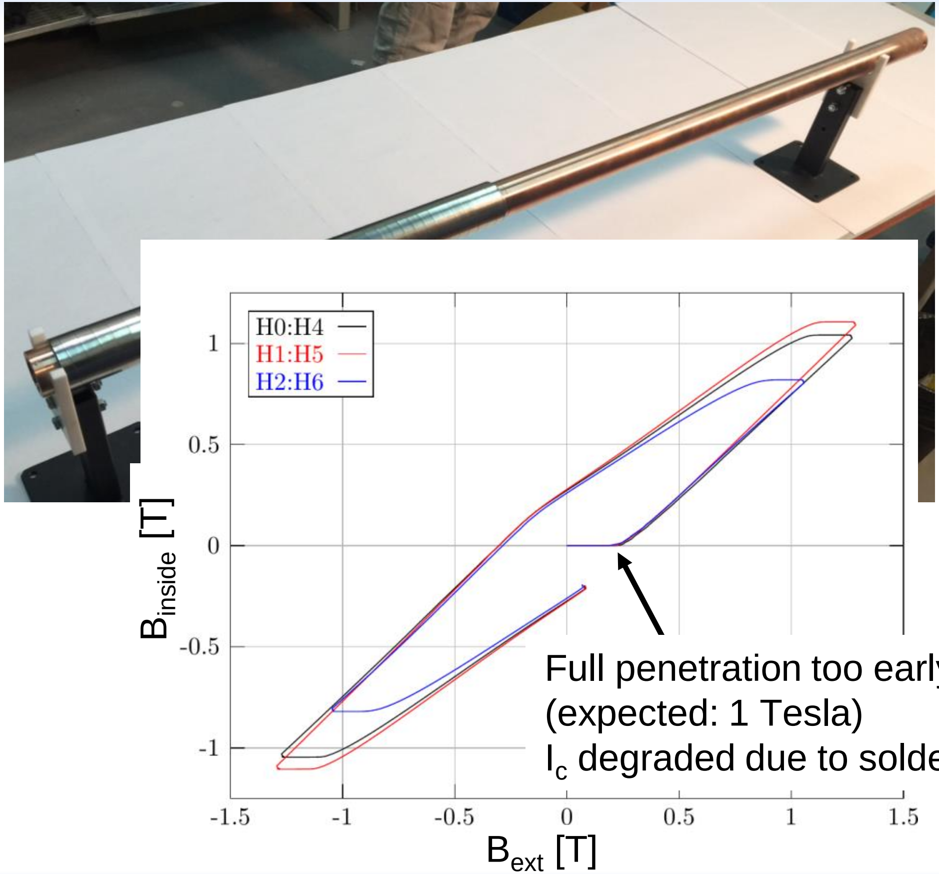


- Decaying currents → smaller B-field concentration on the surface

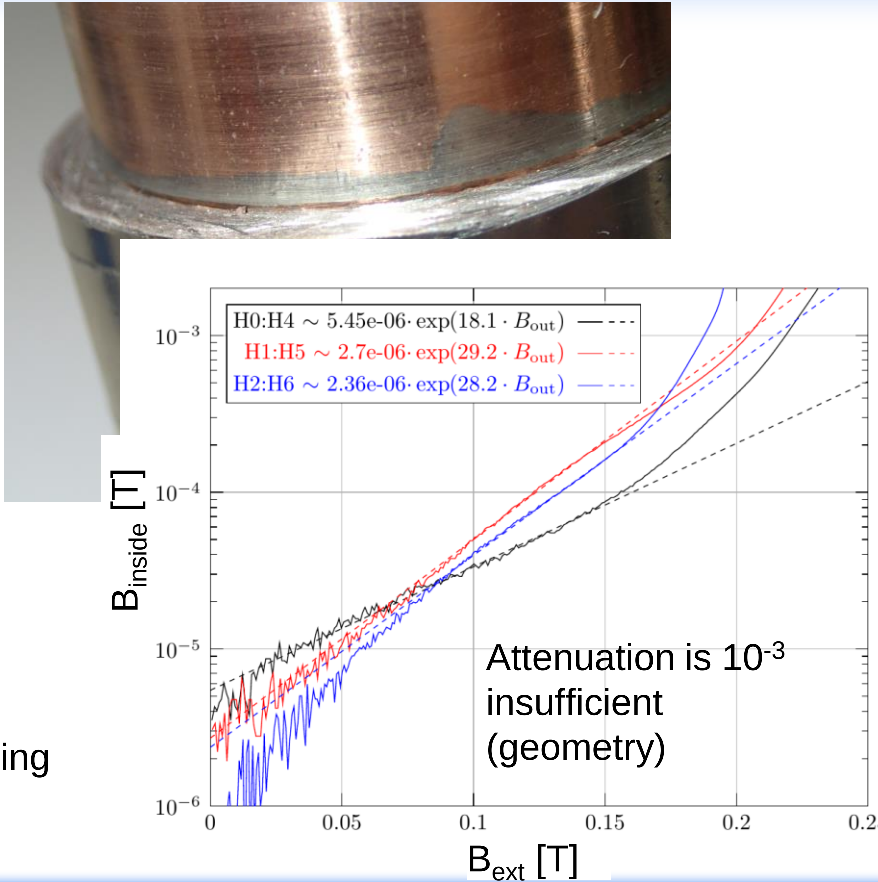
- Long-term relaxation is ok
- (similar in NbTi)
- Per-mill level over 6 hours

D. Barna, G. Giunchi, M. Novák, K. Brunner, A. Német, C. Petrone, M. Atanasov, H. Bajas, J. Feuvrier: An MgB2 superconducting shield prototype for the Future Circular Collider septum magnet. IEEE Transactions in Applied Superconductivity, 29 (2019) 4101310

HTS shield (SuperOx 2G HTS tape)

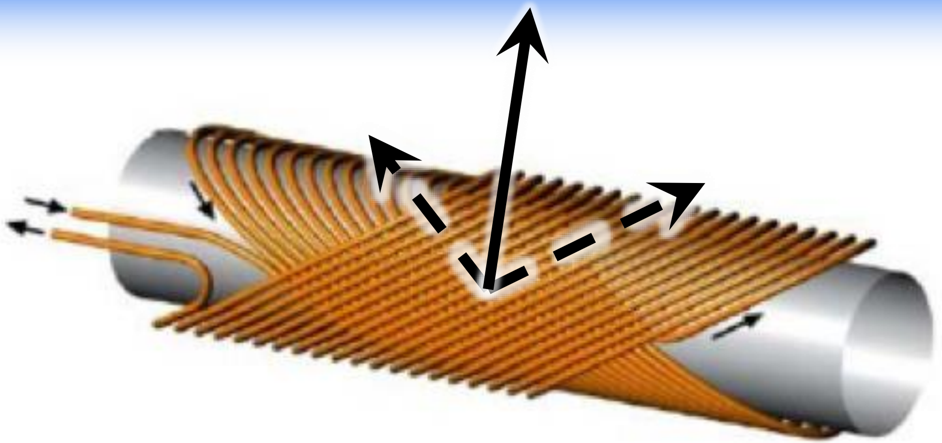


Full penetration too early
(expected: 1 Tesla)
I_c degraded due to soldering



Attenuation is 10^{-3}
insufficient
(geometry)

The magnet: canted cosine theta (CCT) concept



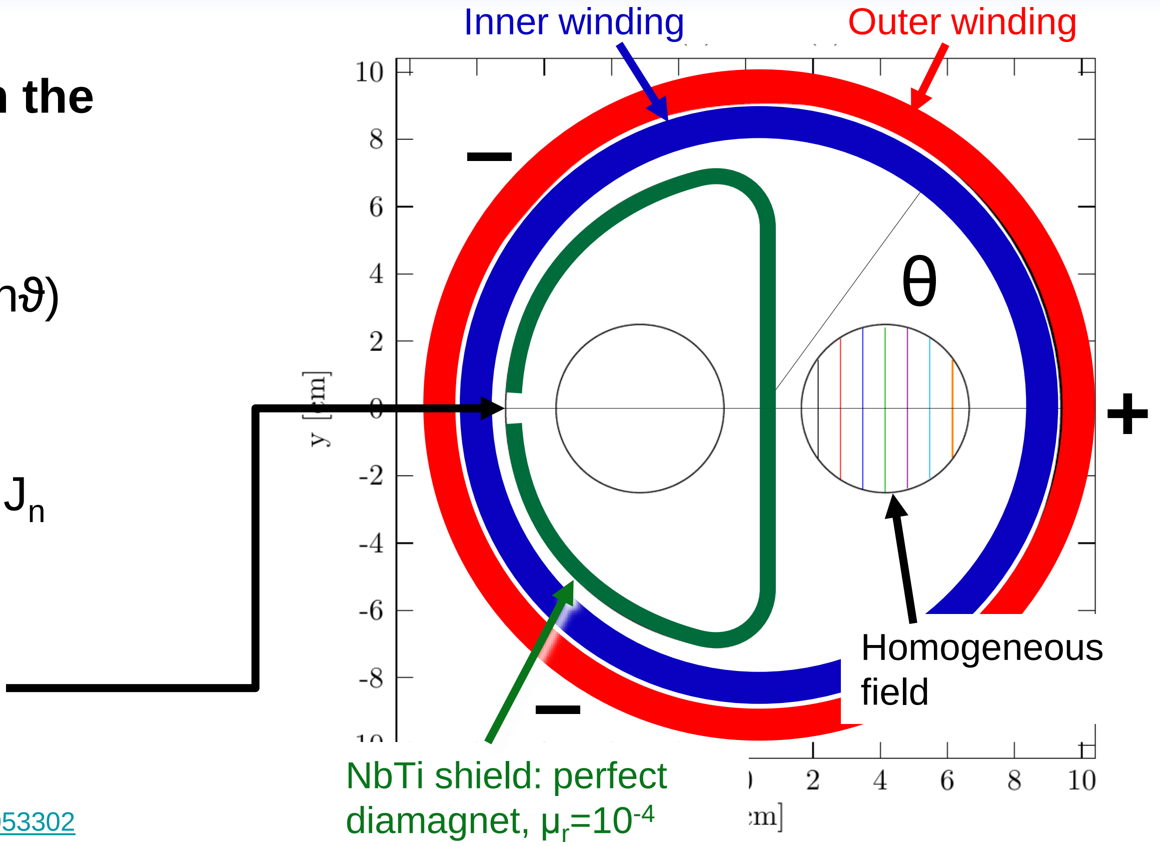
- Two canted solenoids
- Resulting field: transverse
- Regular, simple geometry
- Naturally open aperture for the beam

- Machining grooves in a cylinder
- **Easy** and **precise** in these days (modern CNC machines)
- **Each turn is individually supported** by a mechanical structure ("stress managed") - robust

Original idea: D.I. Meyer and R. Flasck, Nucl. Inst. Meth. 80 (1970) 339

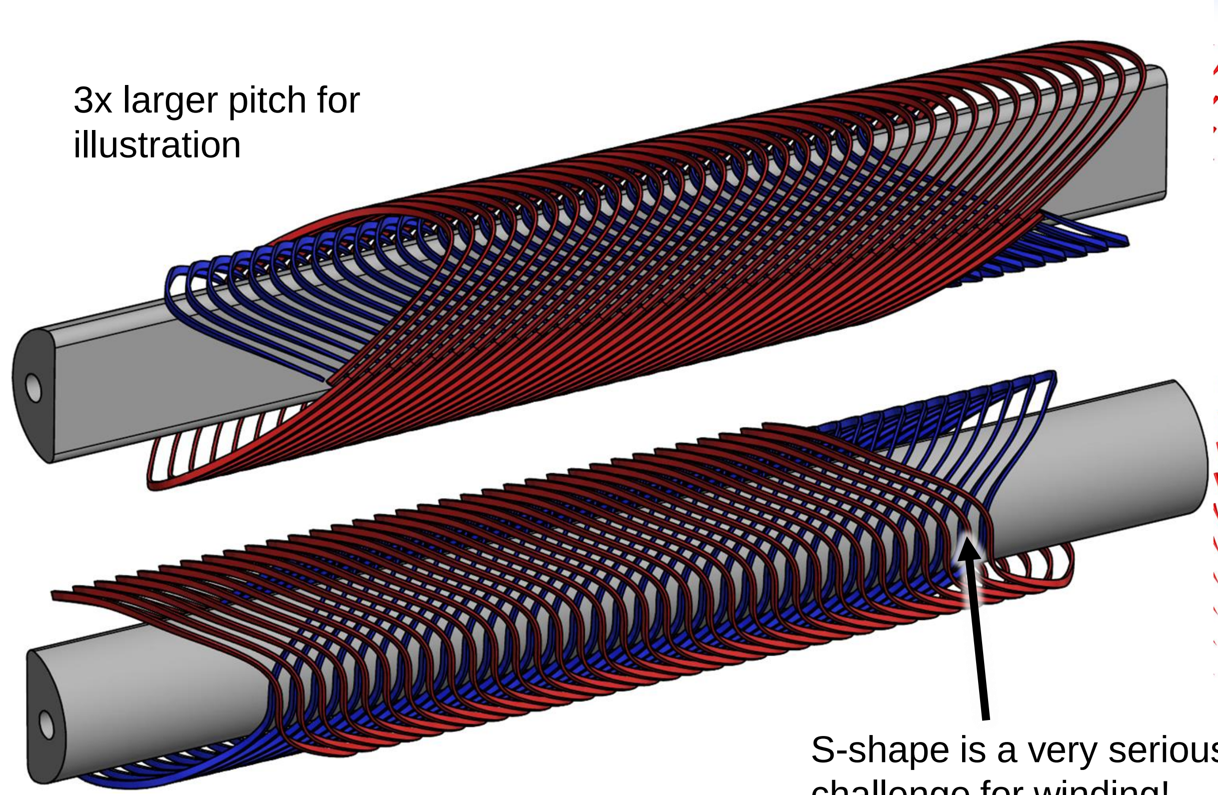
Coil design in 2D

- Goal: homogeneous field **in the presence of the shield**
- Assume perfect diamagnet
- Simulate with $J_z(\vartheta)=J_n\cdot\cos(n\vartheta)$ (n=1..6)
- Multipole analysis
- Invert linear problem to get J_n producing dipole-only field
- Reduce B at 180^0, require $J_z(180^o)=0$ (an extra linear constraint on J_n)



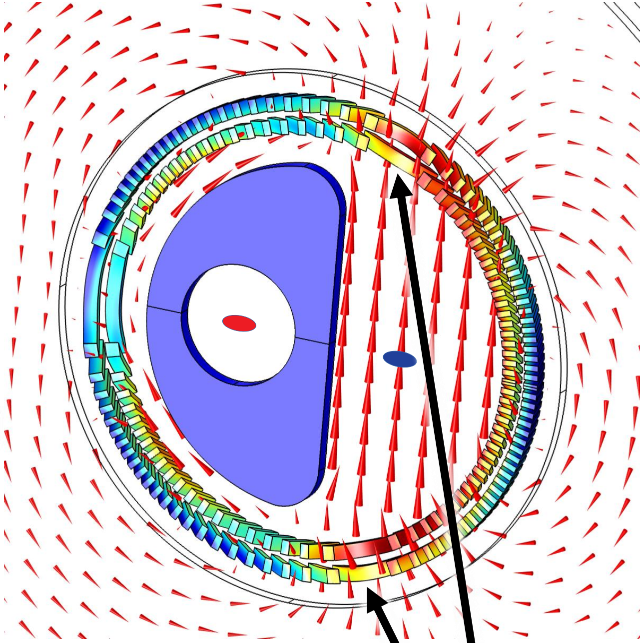
D. Barna et al, Review of Scientific Instruments, 90 (2019) 053302

Coil geometry in 3D



3x larger pitch for illustration

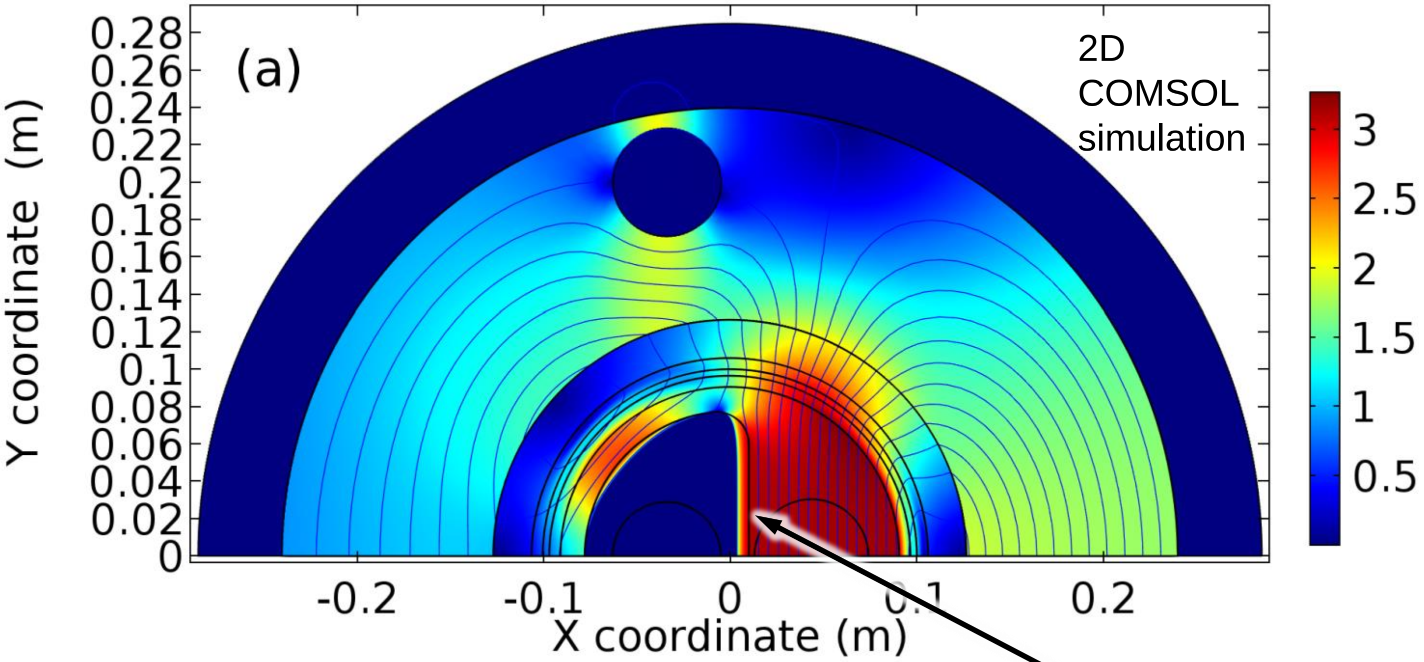
S-shape is a very serious challenge for winding!



Poles displaced w.r.t. pure dipole

D. Barna et al, [Review of Scientific Instruments, 90 (2019) 053302]

Check field quality with realistic shield (not a perf. diamagnet)



2D COMSOL simulation

Homogeneity remains within required +/- 1.5% for full range

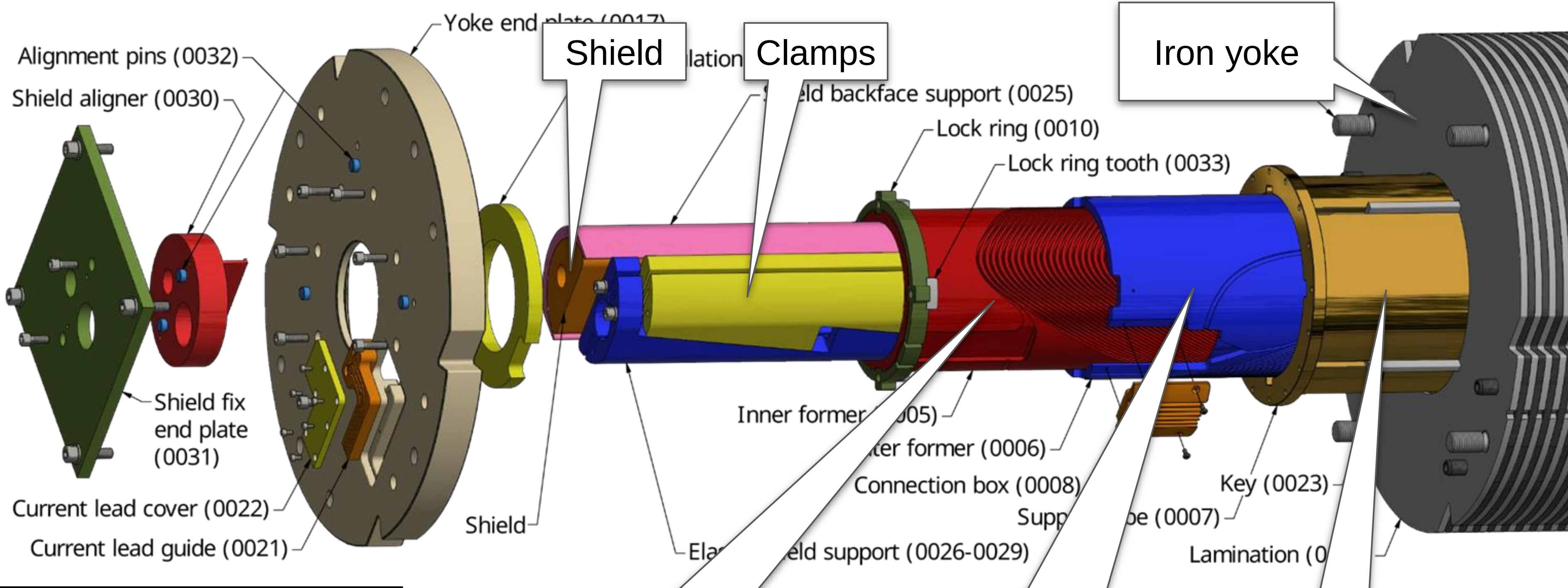
Field penetration increases with current → distortion

D. Barna et al, Review of Scientific Instruments, 90 (2019) 053302

Magnet properties

Conductor	2 x 5 LHC dipole strands (0.85 mm)
Groove dimens.	2.1 x 5.1 mm
Inductance	148/189 mH (with/without shield)
Nominal current	430 A
Nominal field	3 T
Peak field	3.6 T
Turns	102
Minimum rib thickness	0.35 mm
Load line current	75% of I_c

SuShi septum 3D model



Shield

Clamps

Iron yoke

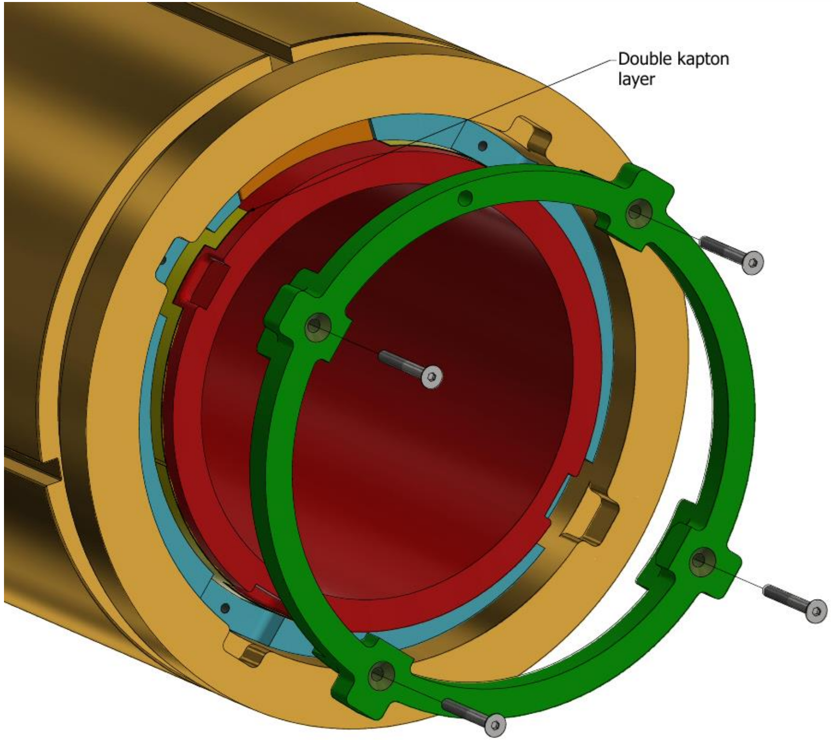
Inner former/winding

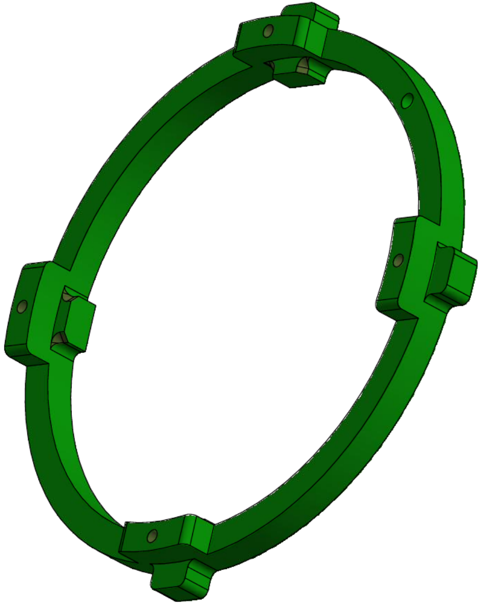
Outer former/winding

Support tube

Reference design:
High-lumi CCT corrector

Magnet design features

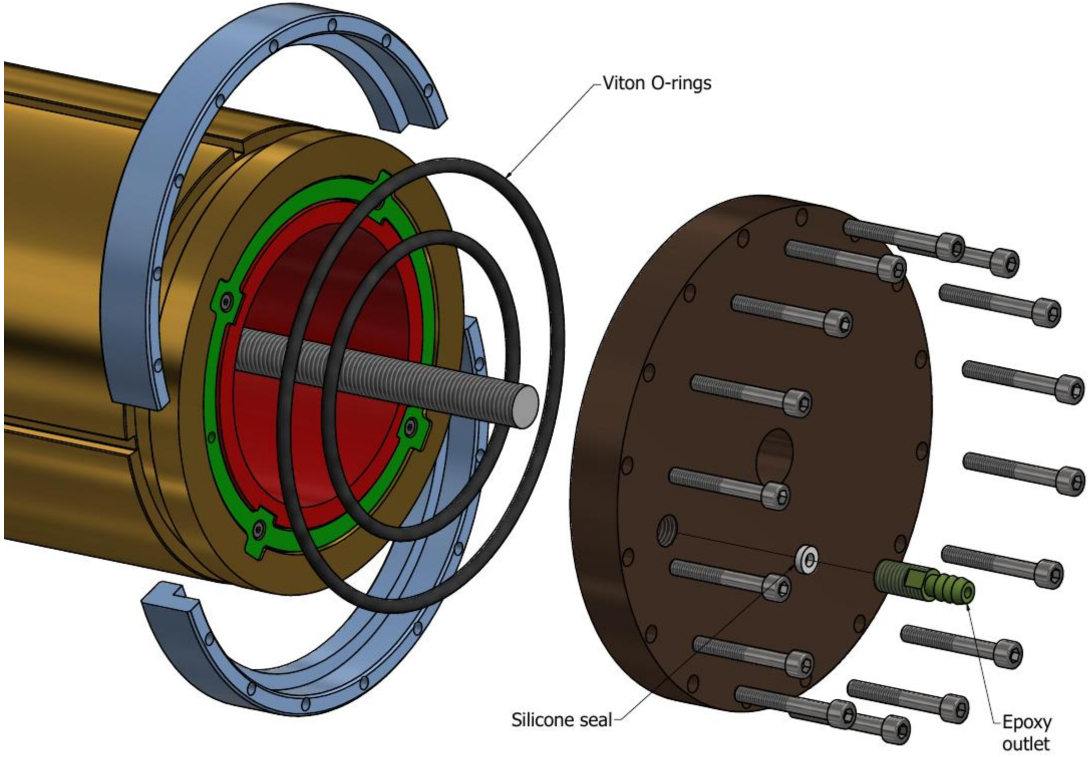




Azimuthal lock ring at magnet end

Avoid holes through tube walls

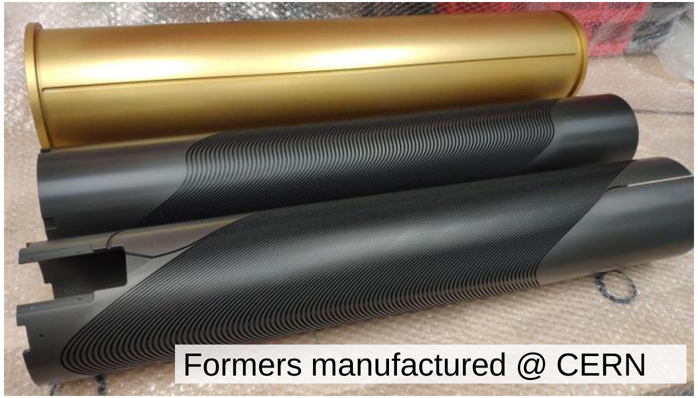
Magnet design features

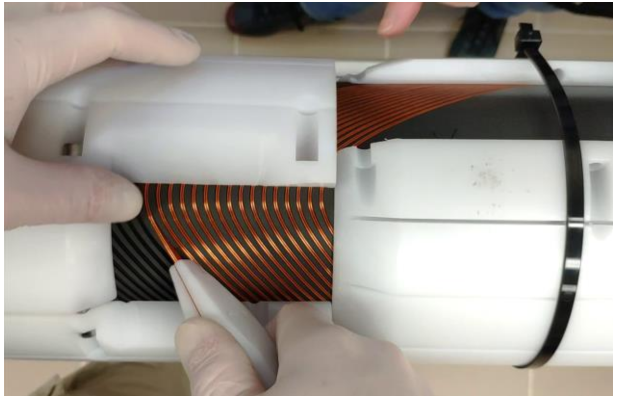


Impregnation

- No autoclave system
- Magnet is its own vacuum chamber
- Avoid long tie rods, locally tighten seals

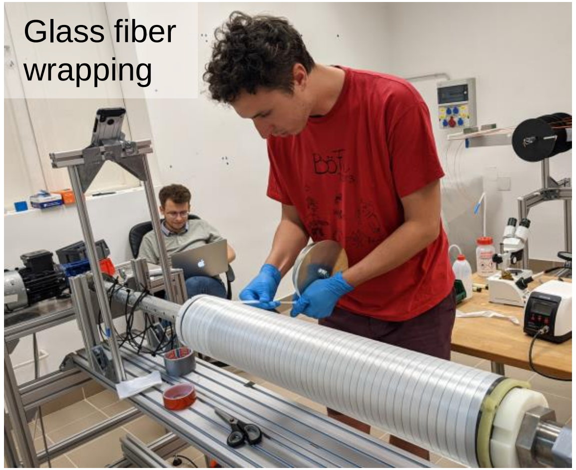
Construction – winding

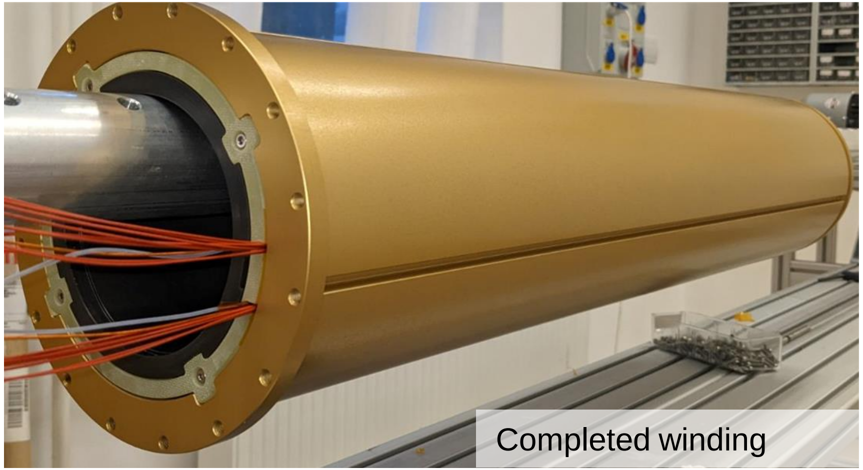

Formers manufactured @ CERN

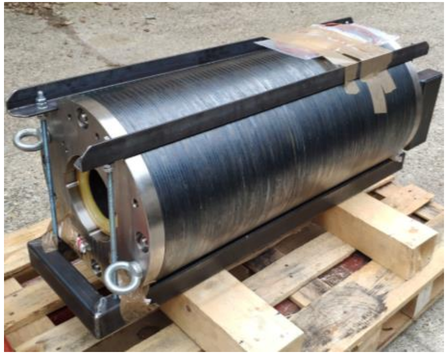


Winding in-house, gaining **experience** → HITRIPlus & I.FAST projects

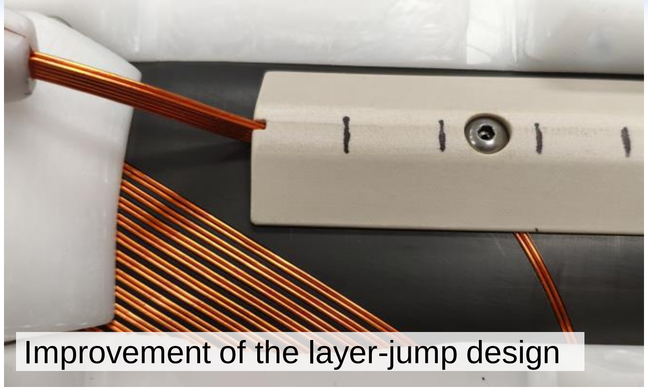
Several insulation problems - unwind, find, fix (kapton tape)

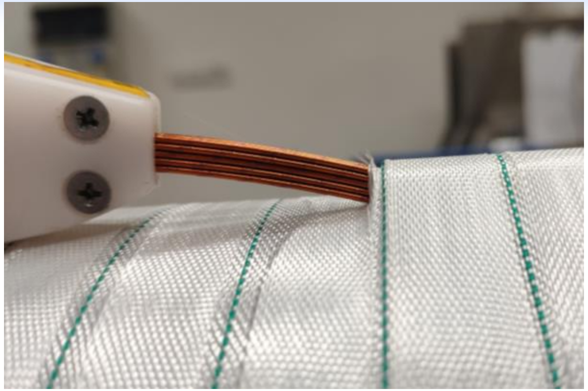

Glass fiber wrapping

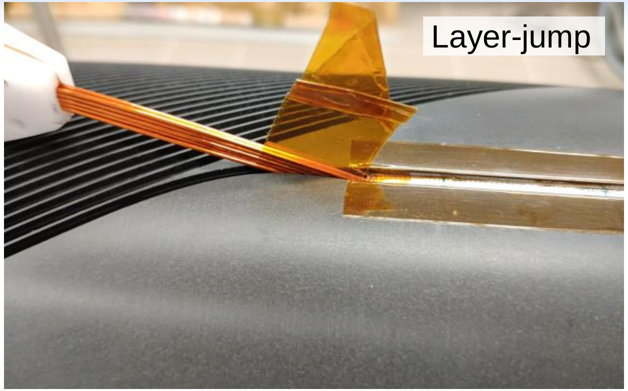

Completed winding



Construction – winding (“layer jump”)

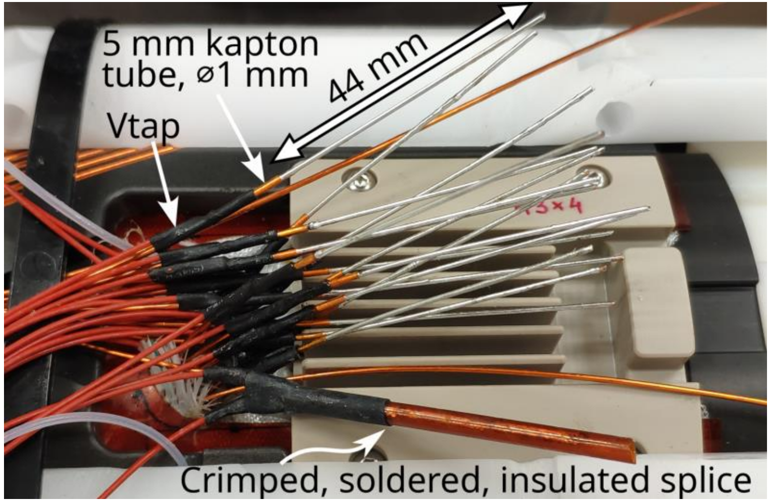

Improvement of the layer-jump design

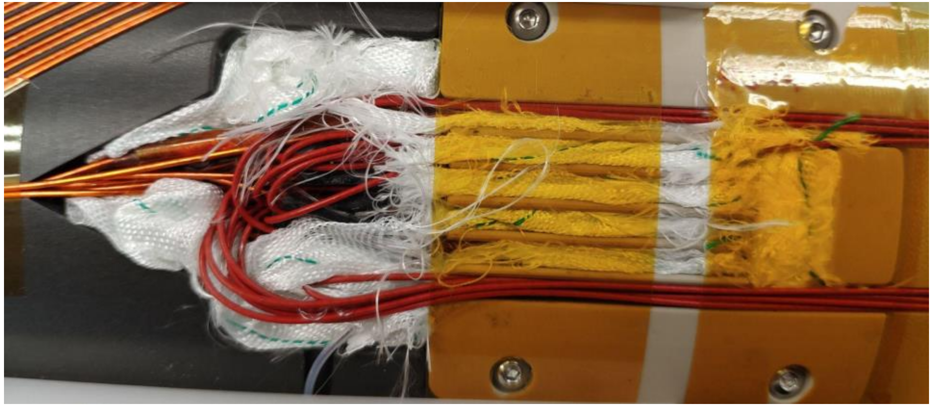



Layer-jump

This design is inherited into the HITRIplus and I.FAST NbTi CCT prototypes

Construction - In-magnet soldered joints





Strands connected in series

Shaking-hand crimped/soldered splices

Consistently 5-8 nΩ resistance

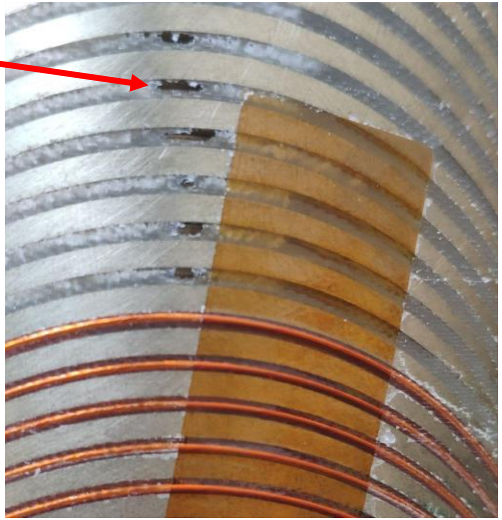
Construction - Wax impregnation R&D

- About to impregnate with CTD101K epoxy, when PSI “BOX exp.” reported on **no training with wax (short samples)**

  → **Consider wax! Fast change of track…**

- **Problem**: 15% volumetric contraction on freeze-out → **voids**, especially in complicated narrow channels

- Launched a few-months R&D campaign @ Wigner RCP



Need controlled freeze-out

Controlled progress of liquid-solid interface

IEEE TAS (Proceedings of MT-28), 10.1109/TASC.2024.3354223

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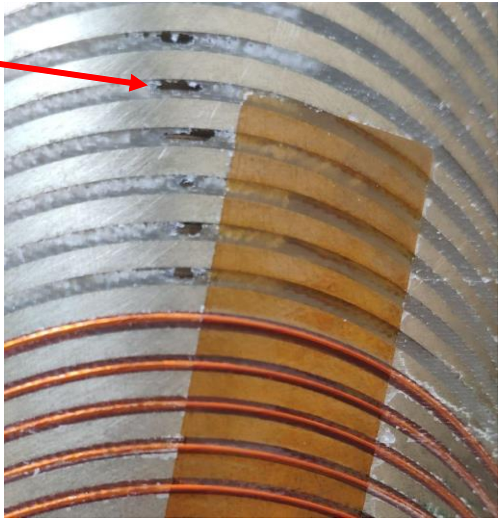
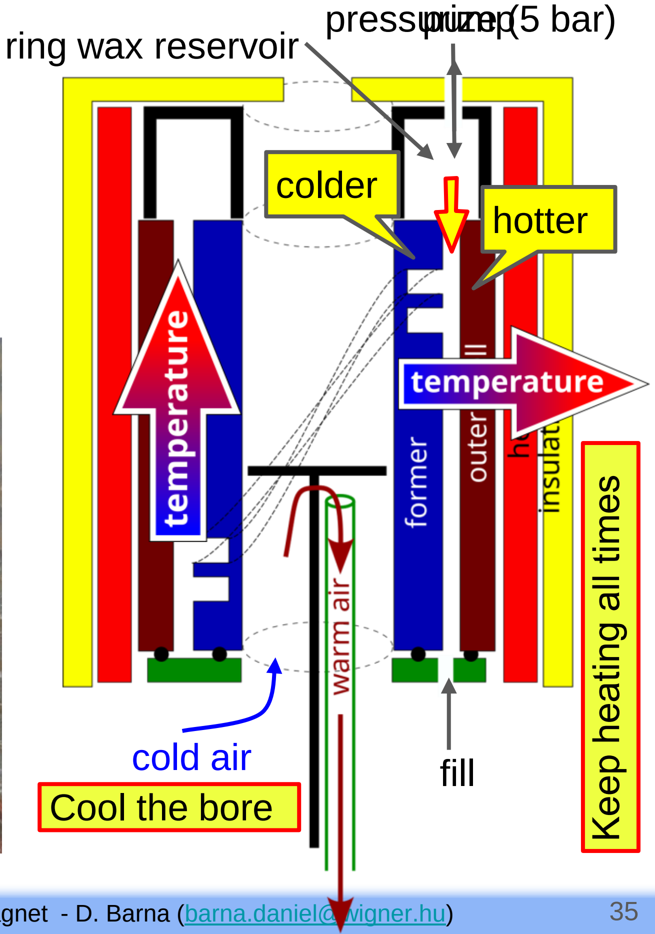
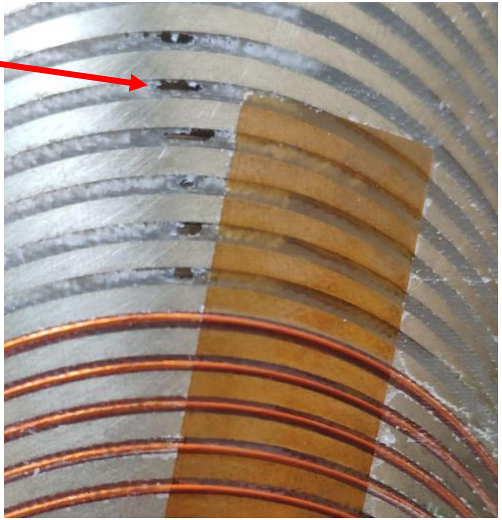


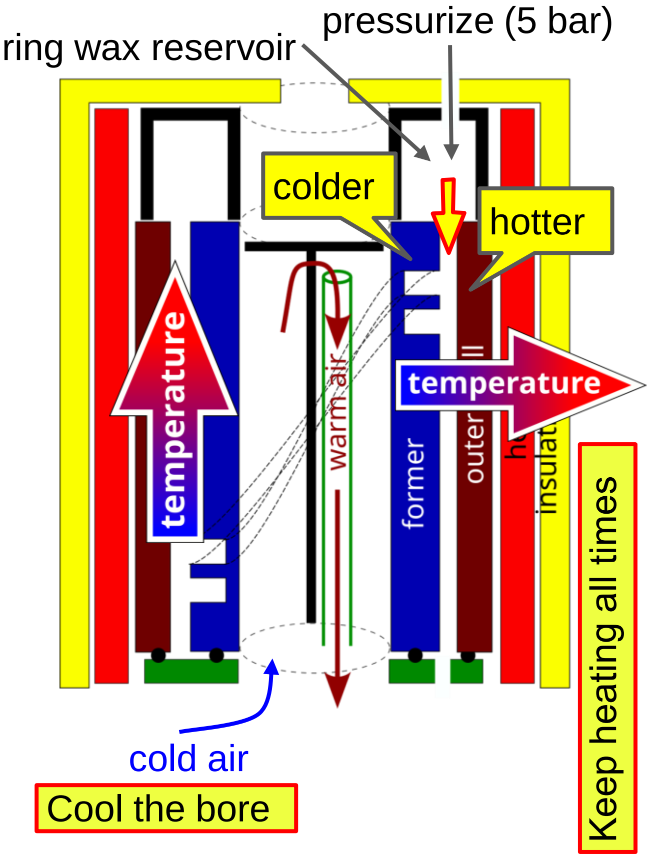
IEEE TAS (Proceedings of MT-28), 10.1109/TASC.2024.3354223



Construction - Wax impregnation R&D

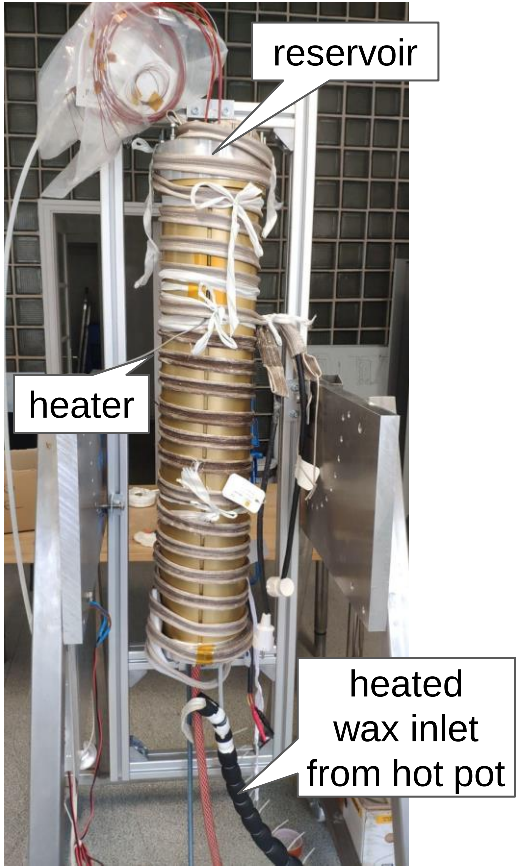
- About to impregnate with CTD101K epoxy, when PSI “BOX exp.” reported on **no training with wax (short samples)**
  → **Consider wax! Fast change of track…**
- **Problem**: 15% volumetric contraction on freeze-out → **voids**, especially in complicated narrow channels
- Launched a few-months R&D campaign @ Wigner RCP

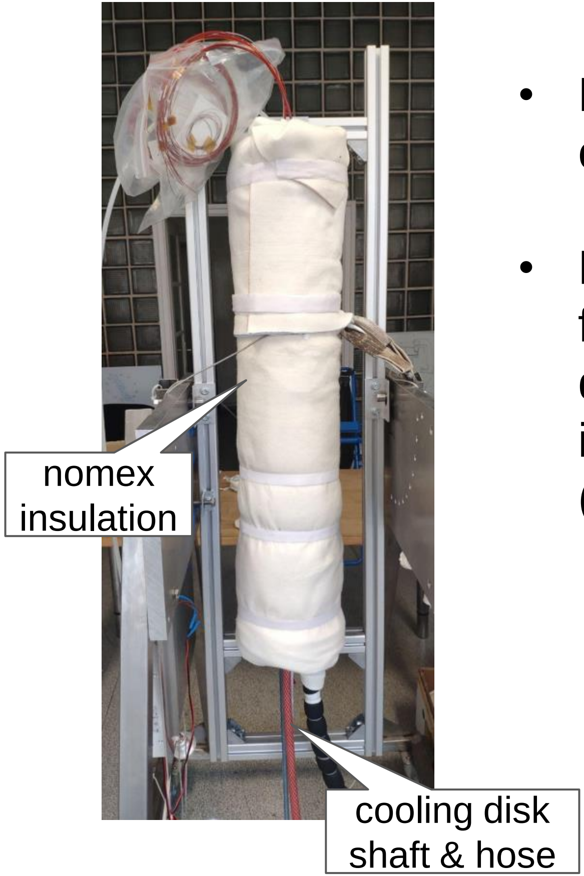




IEEE TAS (Proceedings of MT-28), 10.1109/TASC.2024.3354223

Construction - Wax impregnation of the magnet





- Extremely simple and cheap setup
- Know-how → FCC-ee final focus CCT quadrupole wax impregnation (M. Koratzinos, PSI)

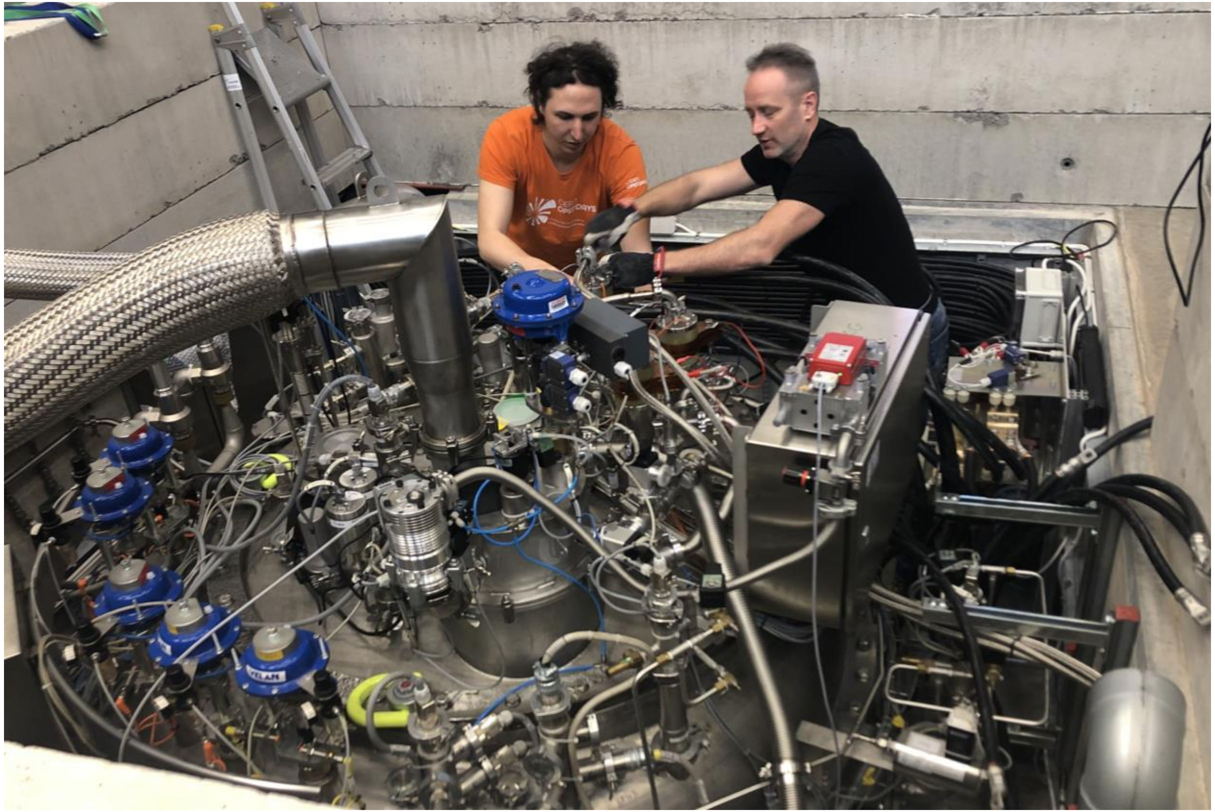
Further info on manufacturing the SuShi magnet

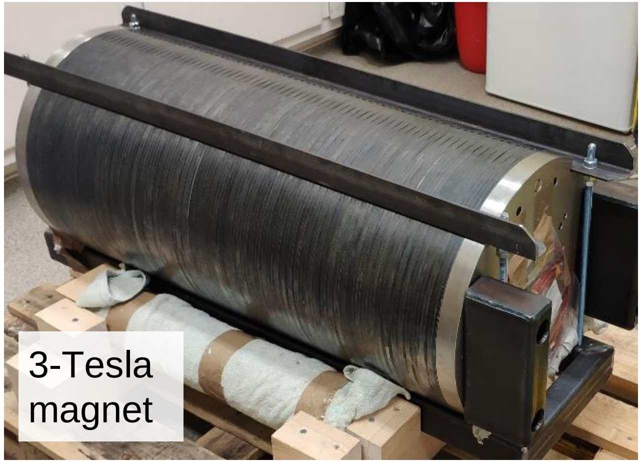
- Winding videos (timelapse/explanation) on YouTube: https://www.youtube.com/watch?v=1BVQtau7L5w&list=PLeC-OFQnTJU_-4SBEik2P-025CHFe9ZzN

- Wax impregnation development and testing on YouTube: https://www.youtube.com/watch?v=PfkMnblAhGo&list=PLeC-OFQnTJU_WG1woGvIBHH3dHW06fohE

- Papers
  - https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.20.041002
  - https://ieeexplore.ieee.org/document/8478800?arnumber=8478800
  - https://doi.org/10.1109/TASC.2019.2920359
  - https://doi.org/10.1063/1.5096020
  - https://doi.org/10.1088/1361-6668/ad2981
  - https://doi.org/10.1109/TASC.2024.3354223

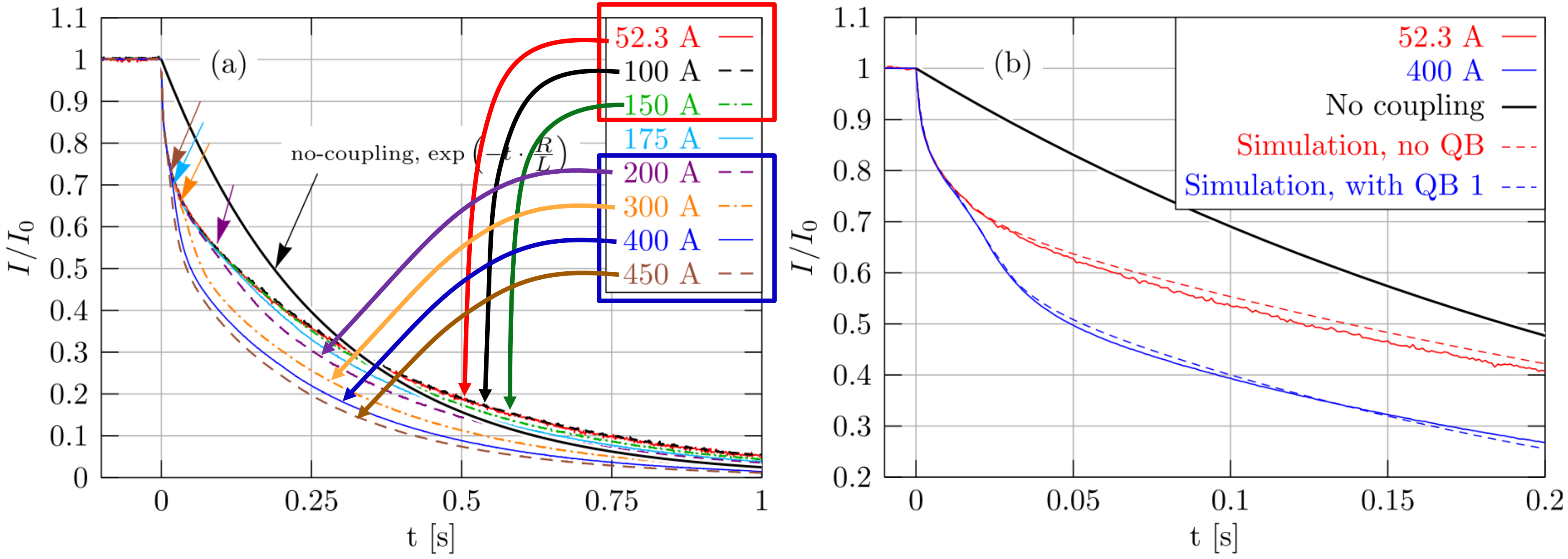
First testing @ FREIA (Uppsala University) – 2023 April





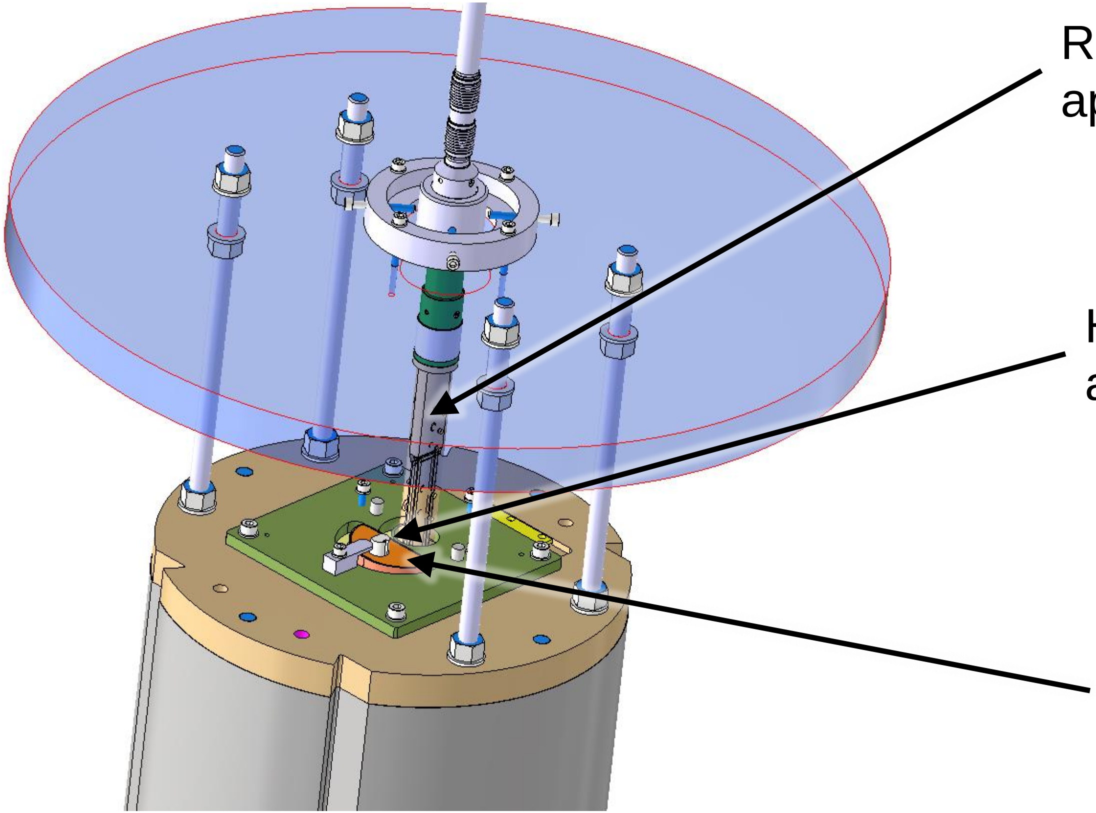
- Empty magnet reached nominal current **without training**
- **Not a single quench** during entire testing period

Energy extraction, quench-back



D. Barna et al, Superconductor Science and Technology 37 (2024) 045006

Test with shield @ CERN SM18 soon



Rotating coil in high-field aperture

Hall probes in zero-field aperture

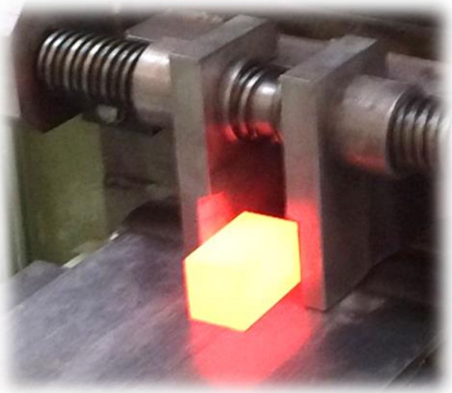
Shield.
#1 – two layers of Nippon
#2 – 7 layers of Miskolc

NbTi/Cu multilayer sheet development

University of Miskolc
Wigner RCP
CERN
Ikuo Itoh (ex Nippon)

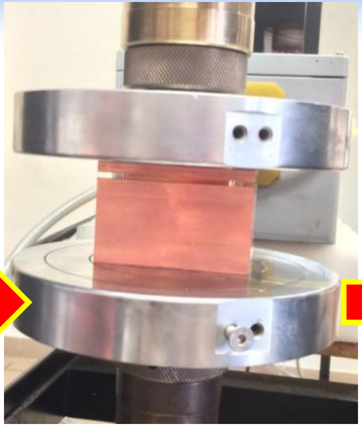
Superconducting material R&D @ Miskolc (HU)

- Key component of SuShi: the shield
- Best candidate: NbTi/Nb/Cu multilayer (Nippon Steel, Japan)
  - Very expensive
  - Discontinued, experts retired, know-how disappearing
- Keep the technology – started an R&D collaboration (many thanks to Akira Yamamoto)
  - CERN
  - Wigner RCP (HU)
  - University of Miskolc (HU)
  - Ikuo Itoh (ex Nippon Steel)

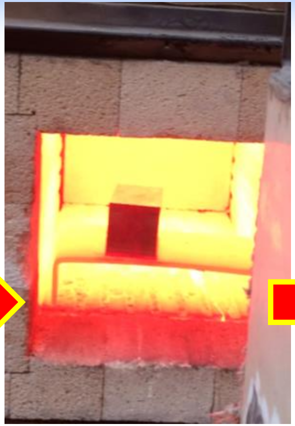


Production of NbTi/Cu multilayer composite sheet

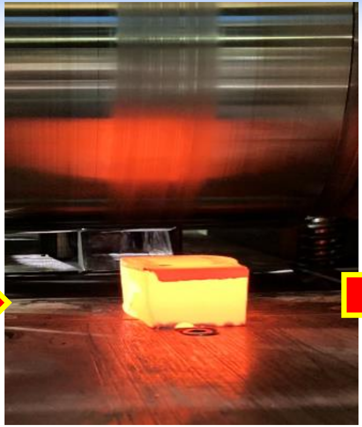
Assembling



Pressing + EB welding



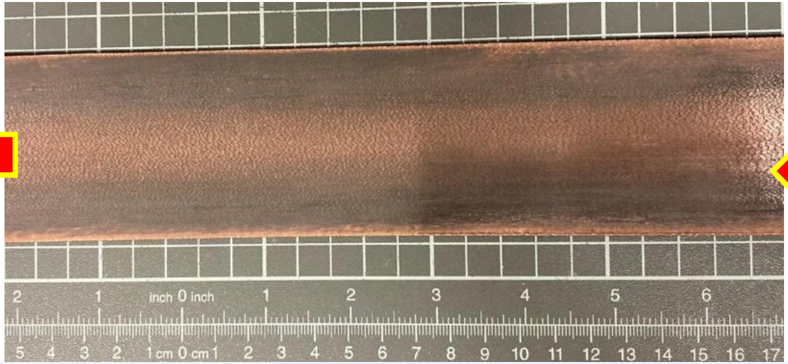
Preheating



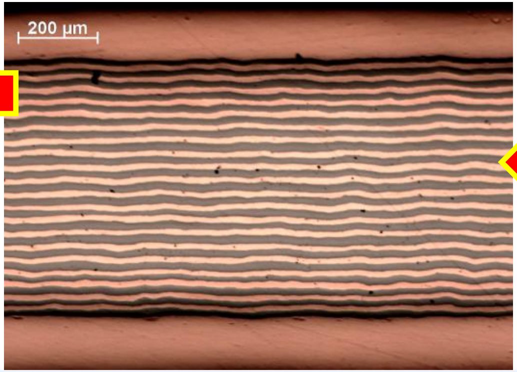
Hot rolling

Cold rolling

Rolled composite sheet



Multilayer NbTi/Cu composite

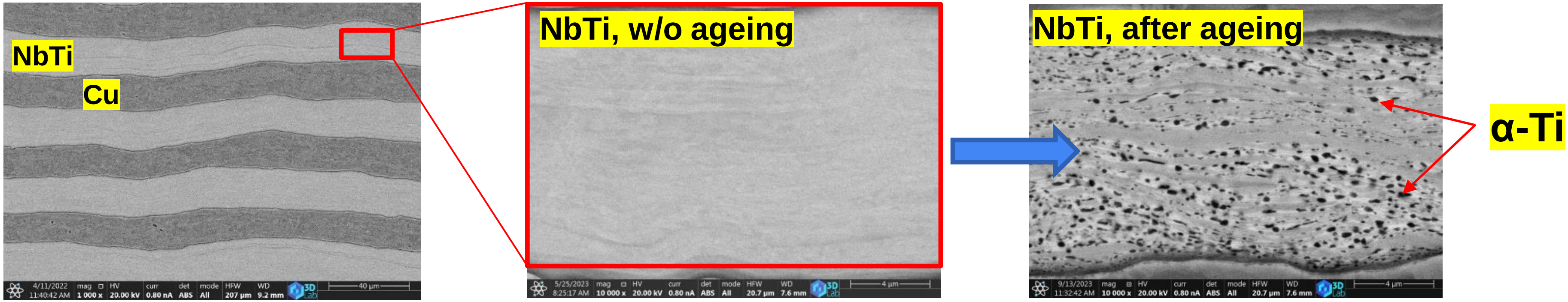


Final HT!
Ageing!

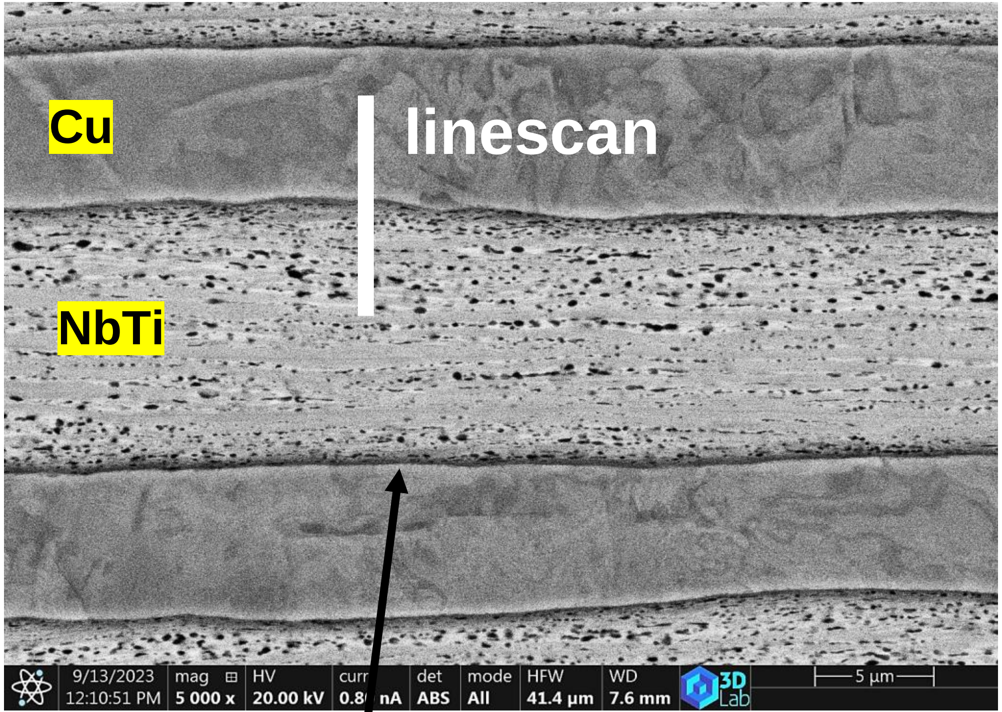
3DLab

Ageing of the NbTi/Cu composite

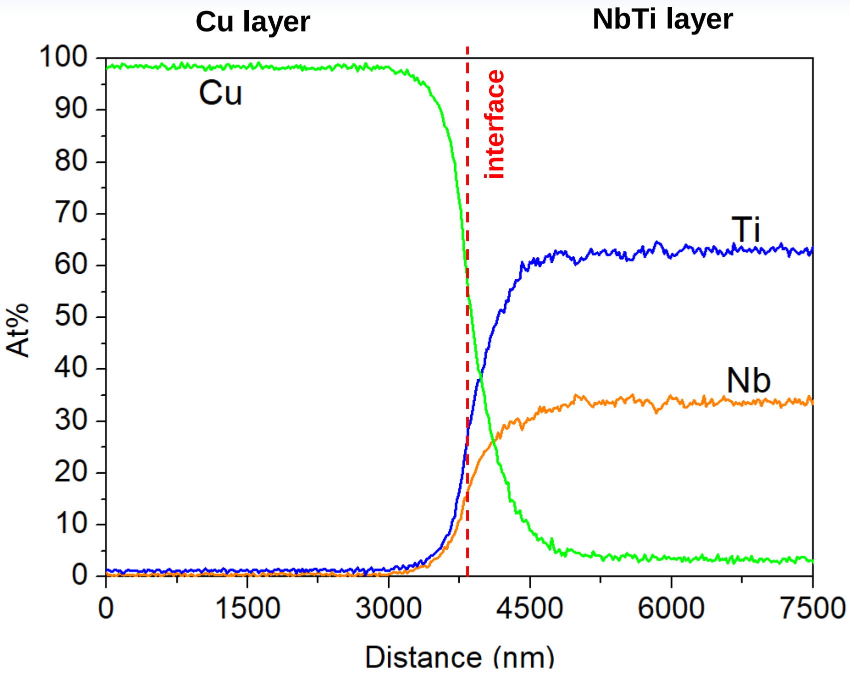
Cold work + heat treatment
  → α-titanium precipitates
    → pinning centers
      → high Jc



NbTi/Cu multilayer – layer interface

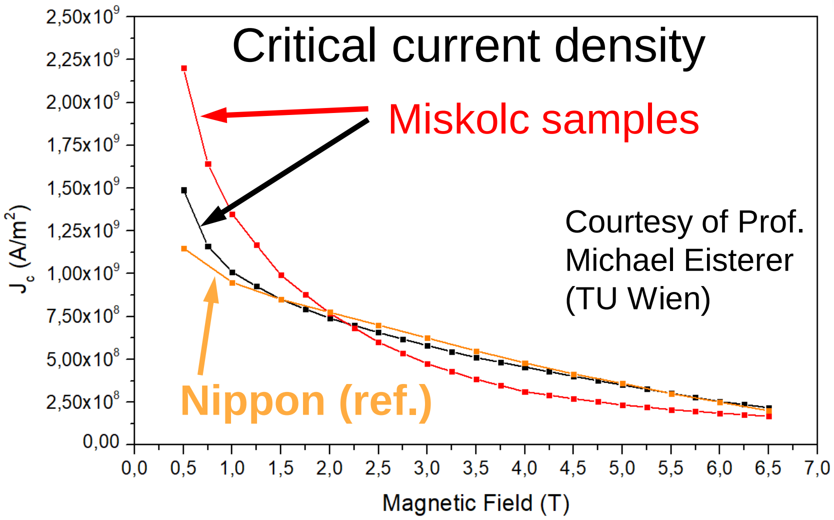


Eliminated Nb diffusion barrier



No intermetallics at NbTi-Cu interface even after > 100 hours of ageing

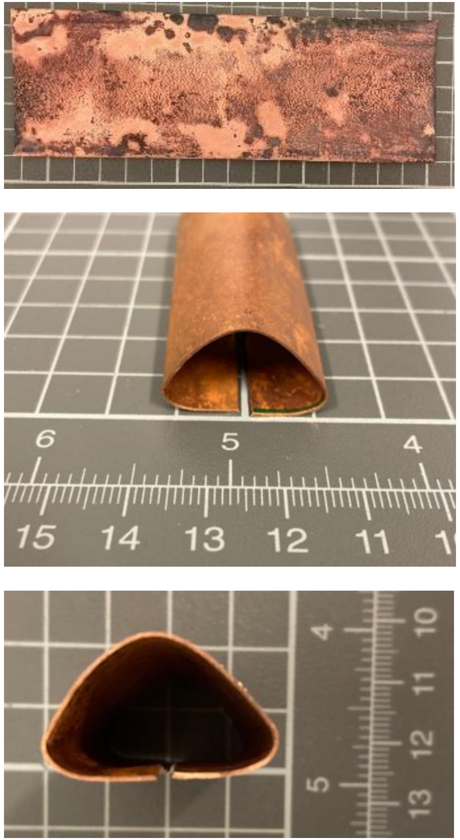
NbTi/Cu multilayer performance

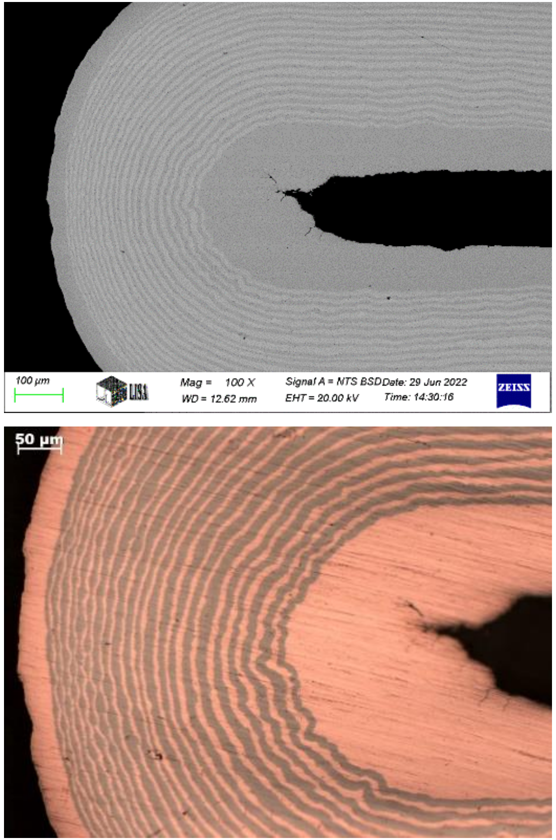

Critical current density

Miskolc samples

Courtesy of Prof. Michael Eisterer (TU Wien)

Nippon (ref.)





Manufacturing the final sheets for SuShi

Manufacturing in progress

Hot… (picture from yesterday)

Hot-rolled sheets
(4 mm thickness)
@ University of Miskolc

To be rolled further to 0.7 mm

I.FAST project

Innovation Fostering in Accelerator Science and Technology

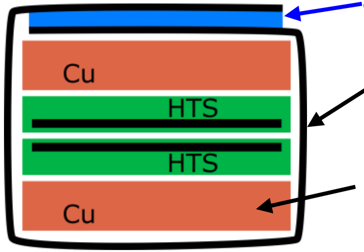
Involve industry, improve European capabilities

(https://ifast-project.eu)

The I.FAST HTS CCT prototype

- 4 Tesla central field
- Length: ~ 1 meter
- Current: ~ 0.9 kA
- Operating temp: ~ 20 K
- Cooled by He gas
- Stacked flat cables

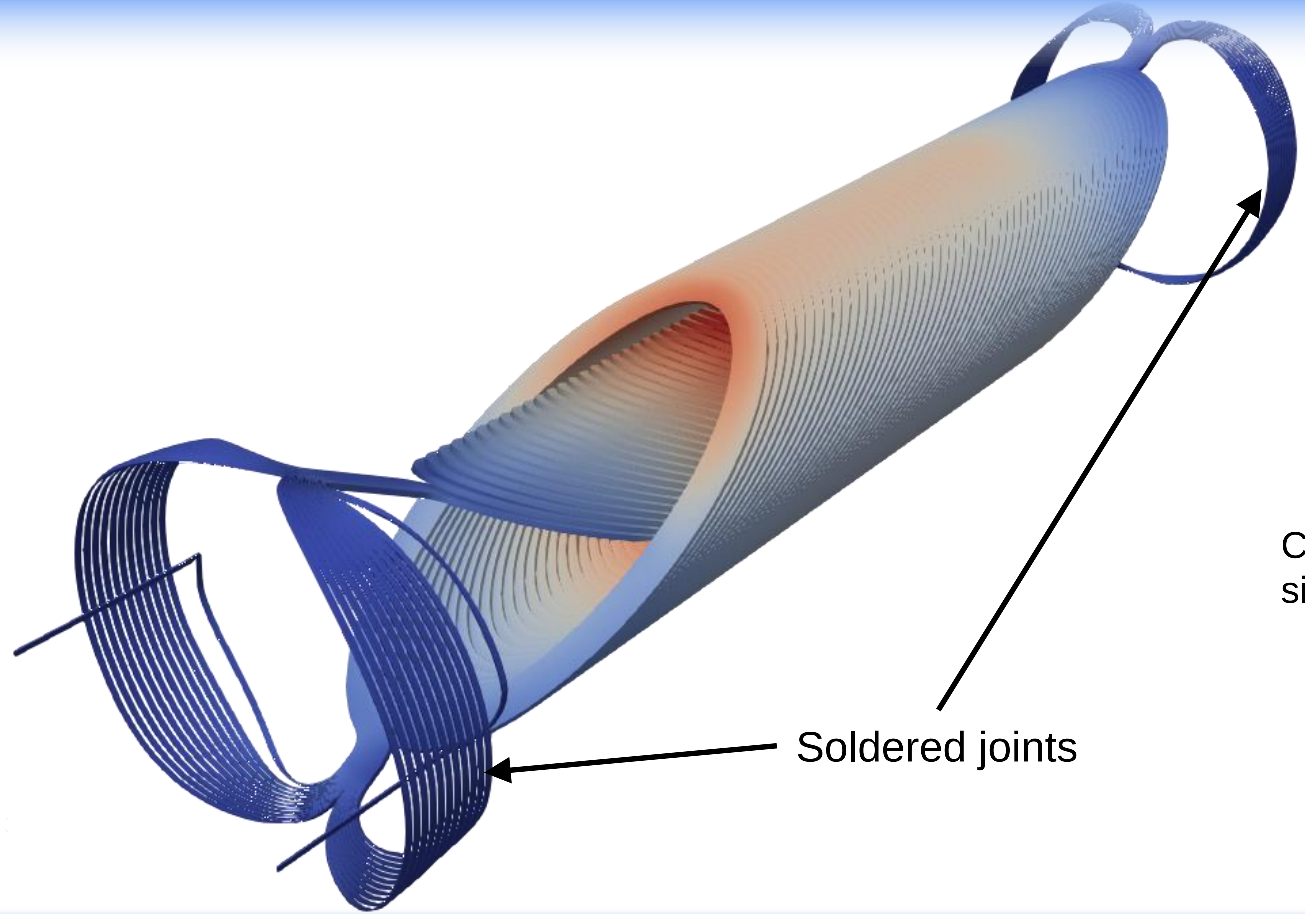
- Tape routing is highly non-trivial (no “hard-way” bends!)
- Developed C++ code to describe, optimize and design winding



Composite, soldered cable

($In_{52}Sn_{48}$)

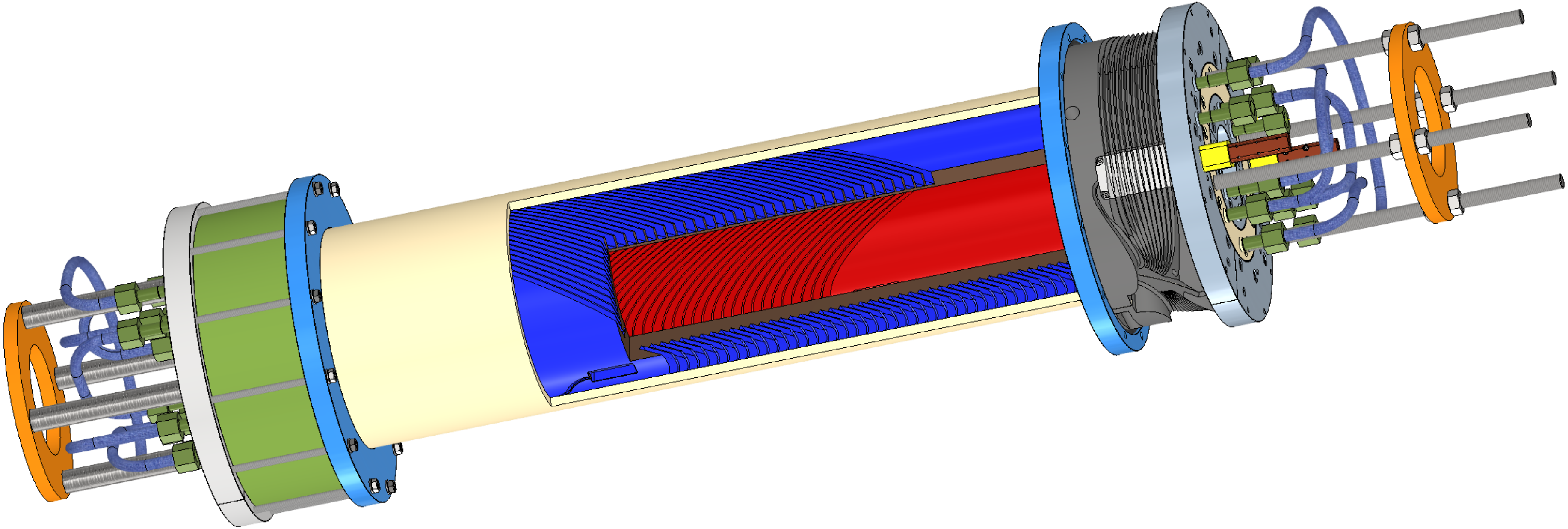
HTS CCT challenges – tape routing



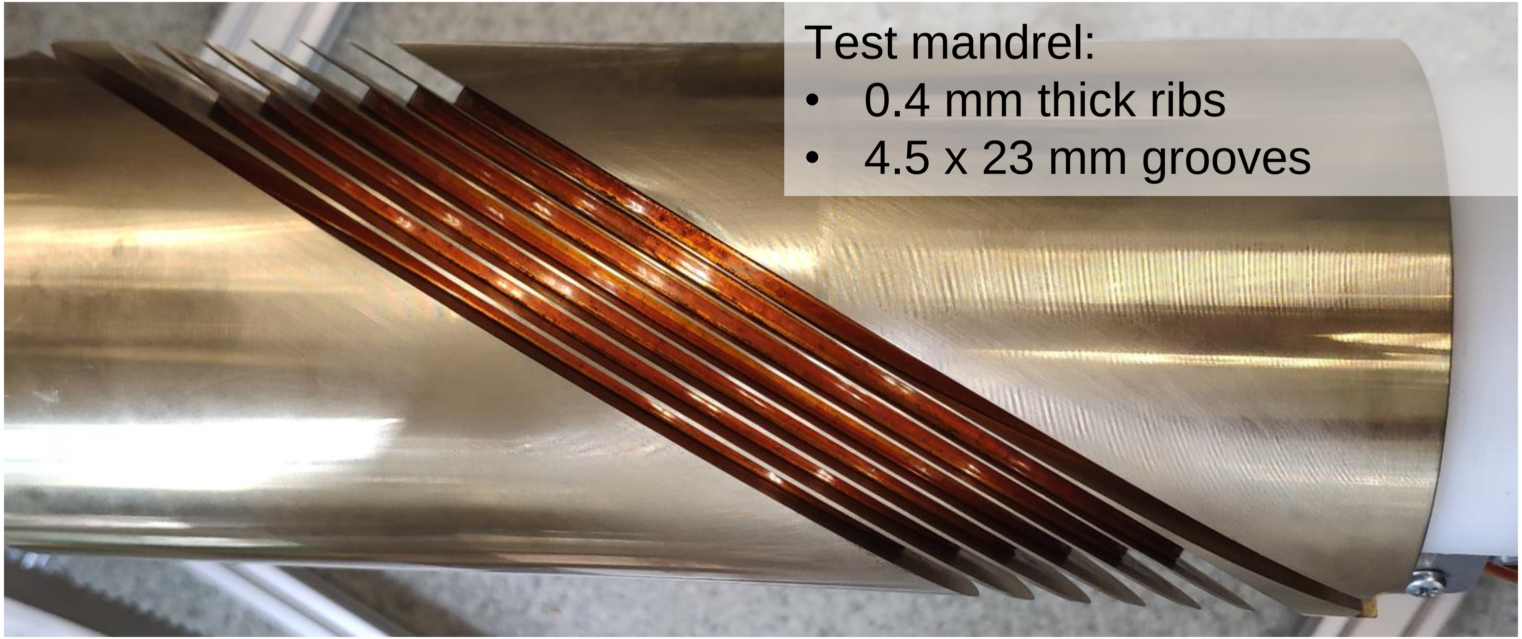
Soldered joints

Cable-by-cable simulation by RAT/C++

CAD design



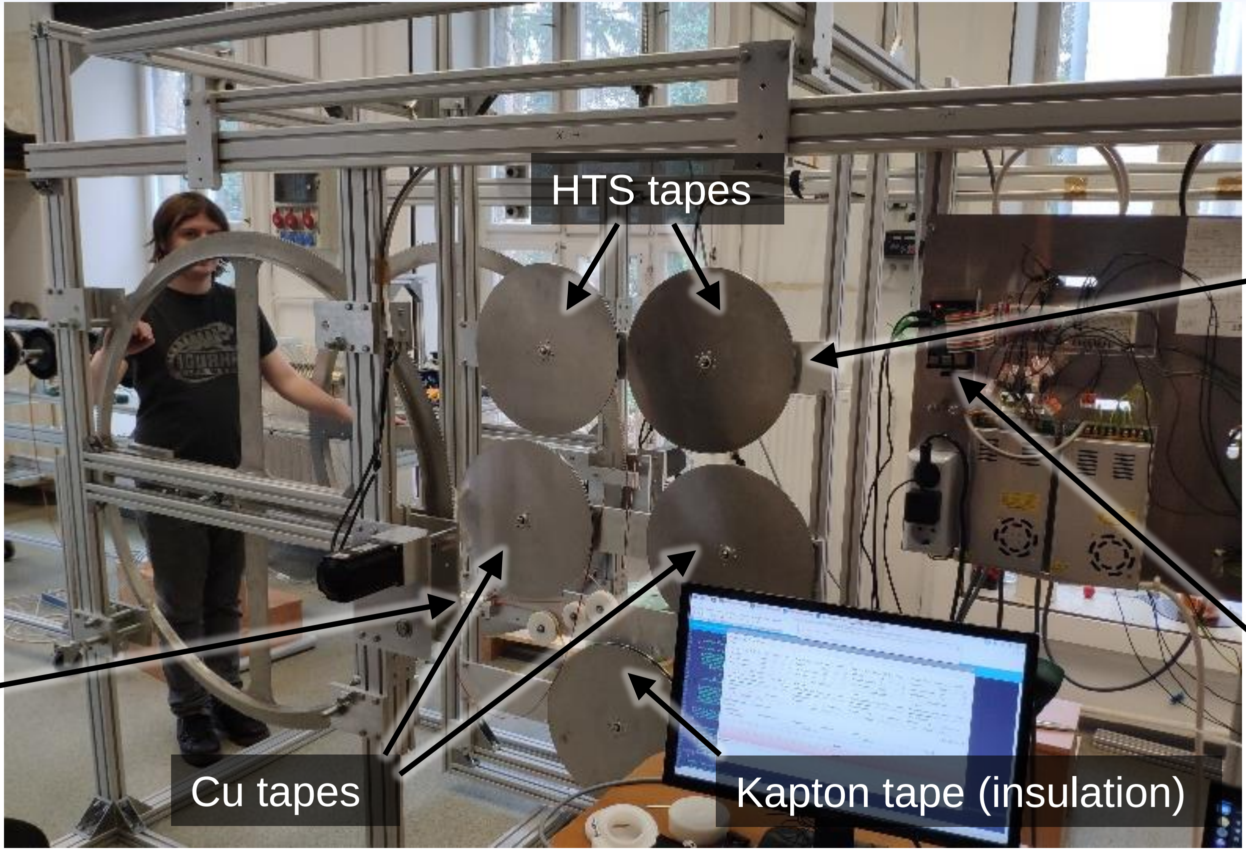
Mandrel: a challenge on its own



Test mandrel:

- 0.4 mm thick ribs
- 4.5 x 23 mm grooves

Infrastructure constructed in-house: winding machine



Mandrel mounted-rotated with 30º inclination

Insulation wrapping tool

HTS tapes

Cu tapes

Kapton tape (insulation)

Tape spools on a moving frame, following mandrel rotation

Raspberry PI controlling the 5 stepper motors

Winding machine

(DIY – entirely in house)

Acknowledgments

- FCC Study Group
- CERN SY septa section (Jan Borburgh, Miro Atanasov, Louise Jorat, Friedrich Lackner et al)
- Glyn Kirby (CERN)
- Akira Yamamoto
- Márta Bajkó (CERN)
- CERN Bldg. 927 team
- CERN SM18 team
- Mathieu Canale, Luca Gentini (CERN)
- Uppsala University, FREIA lab. team, Tommaso Bagni
- INFN/LASA (Milano) team
- Ciemat (Madrid) team
- Elytt Energy
- … and many others
- Grants:
  - Hungary: OTKA K124945, 2019-2.1.6-NEMZ KI-2019-00008, TKP-17-1/PALY-2020
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