Shielding magnetic fields of several Tesla: the FCC SuShi project

http://cern.ch/sushi-septum-project

Kristóf Brunner, Dániel Barna
Wigner Research Centre for Physics, Budapest, Hungary

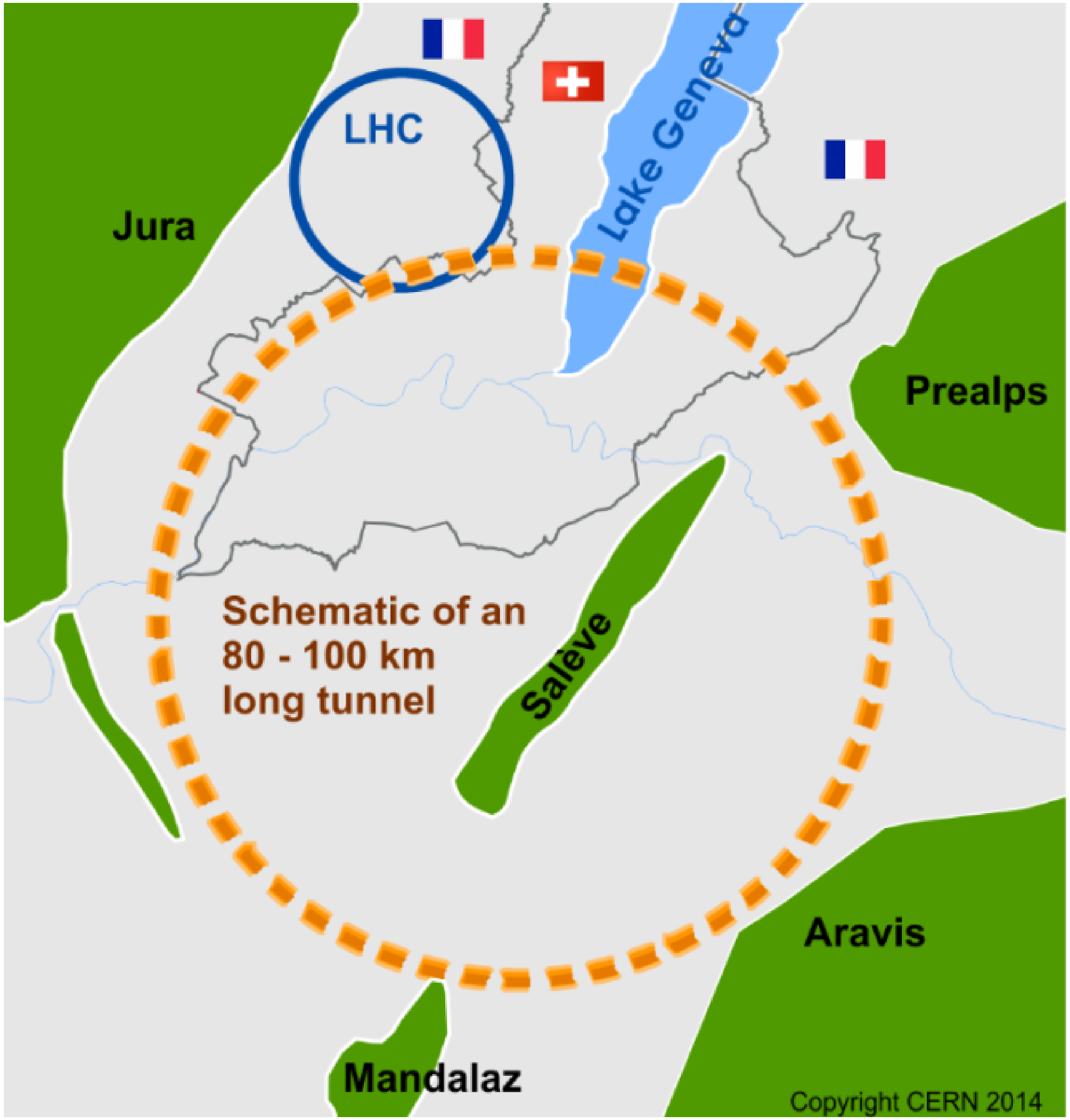
Miro Atanasov, Alejandro Sanz-Ull
CERN

The Future Circular Collider

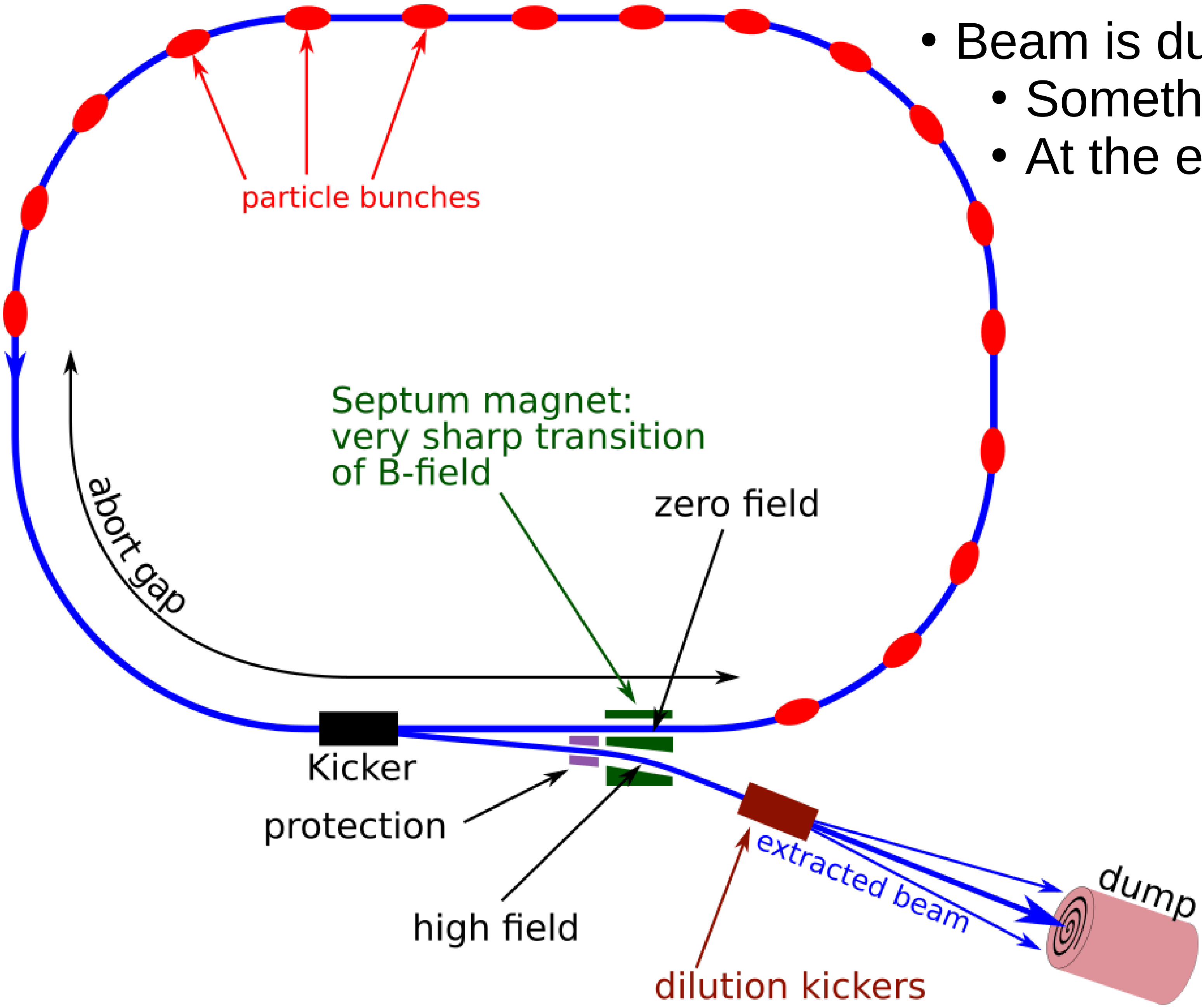
Baseline:

- 50+50 TeV proton-proton collider
- 100 km ring
- Using existing CERN infrastructure as injector

Targeted problem: extraction of the 50 TeV beam towards the beam dump

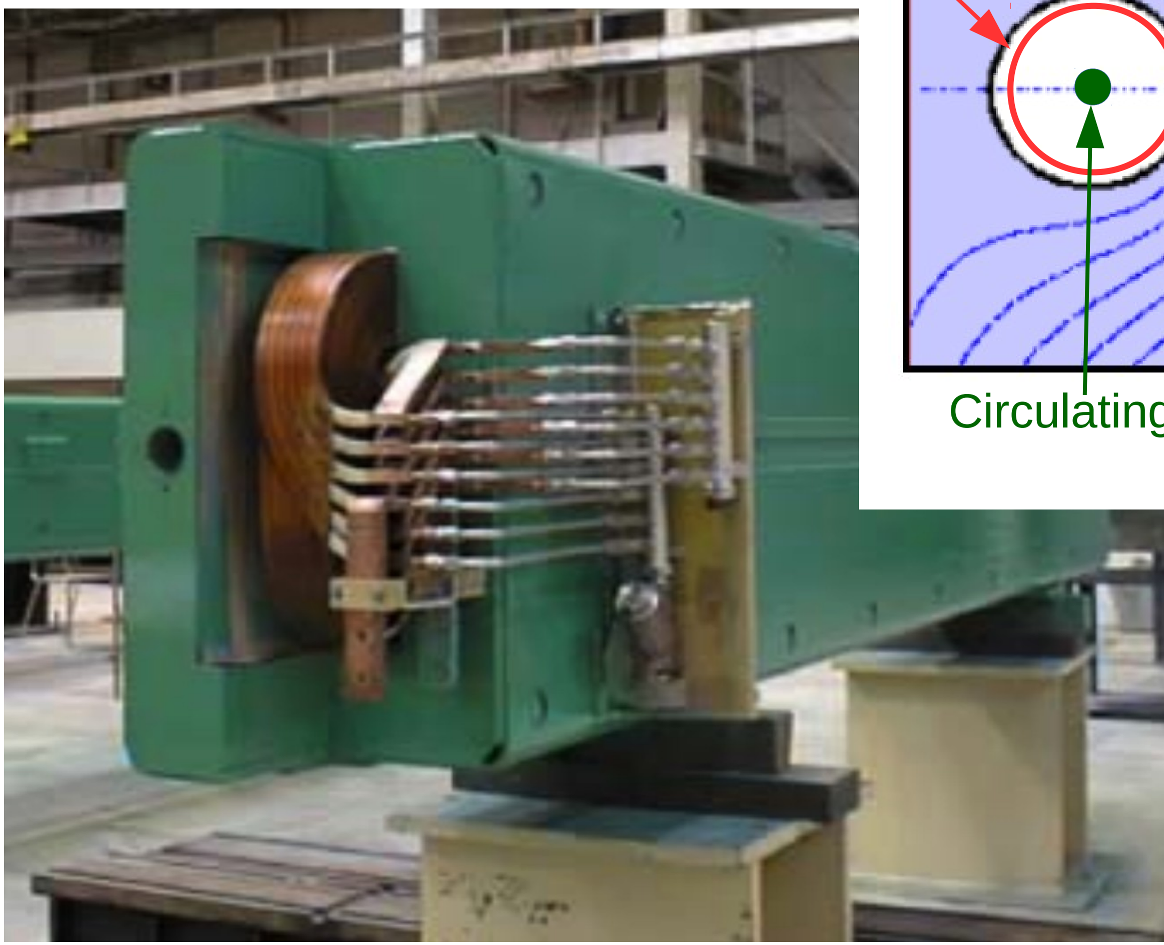


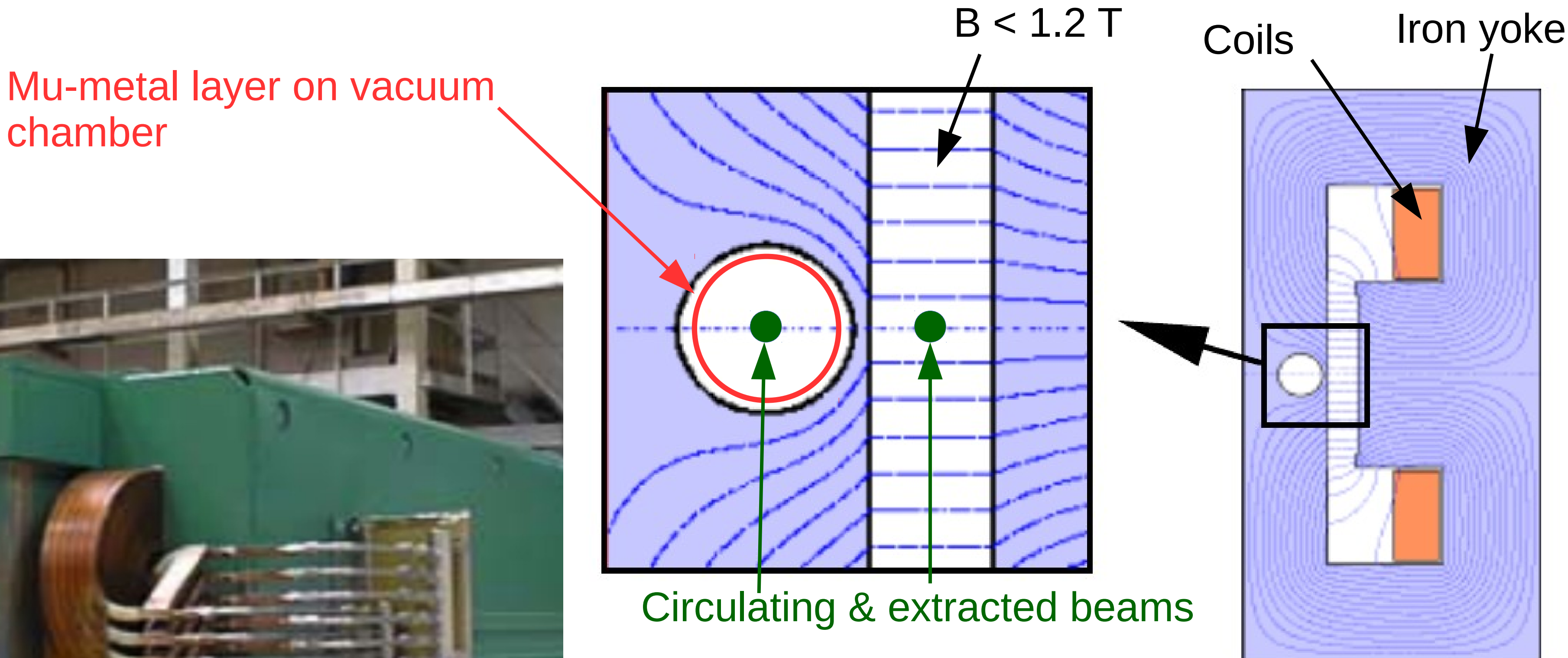
Extraction scheme



- Beam is dumped when:
  - Something misbehaves
  - At the end of the cycle

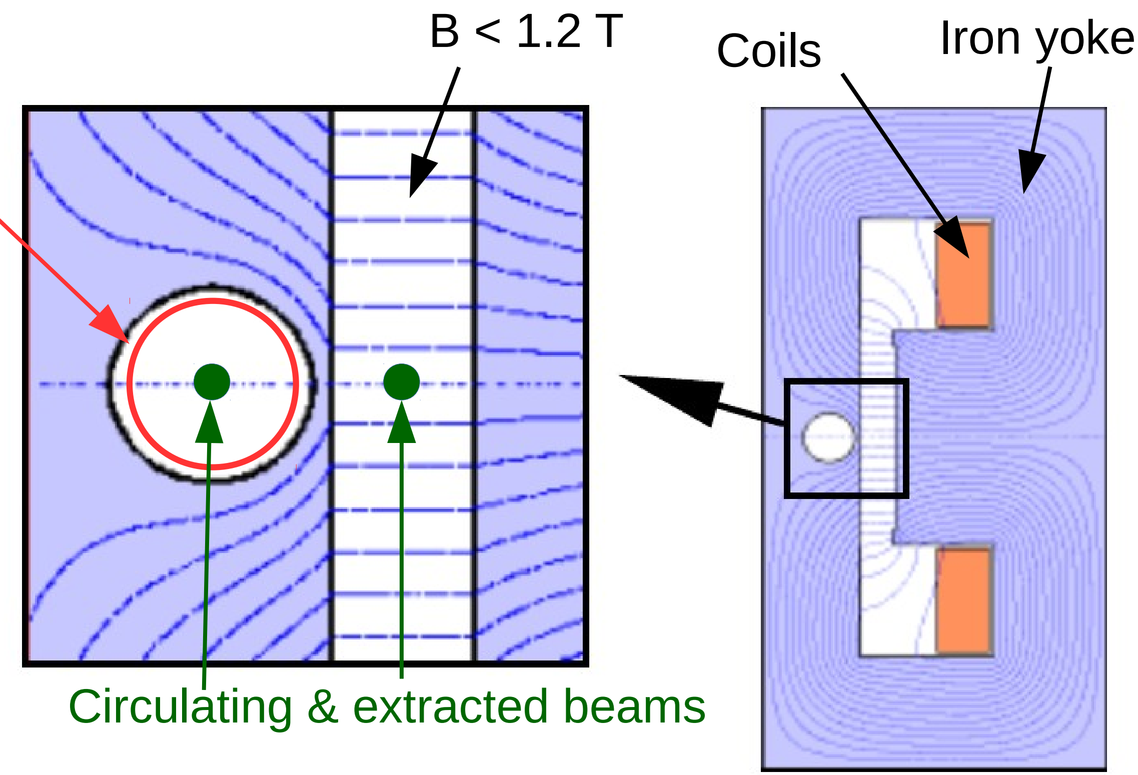
Doing it at the LHC: the Lambertson septa

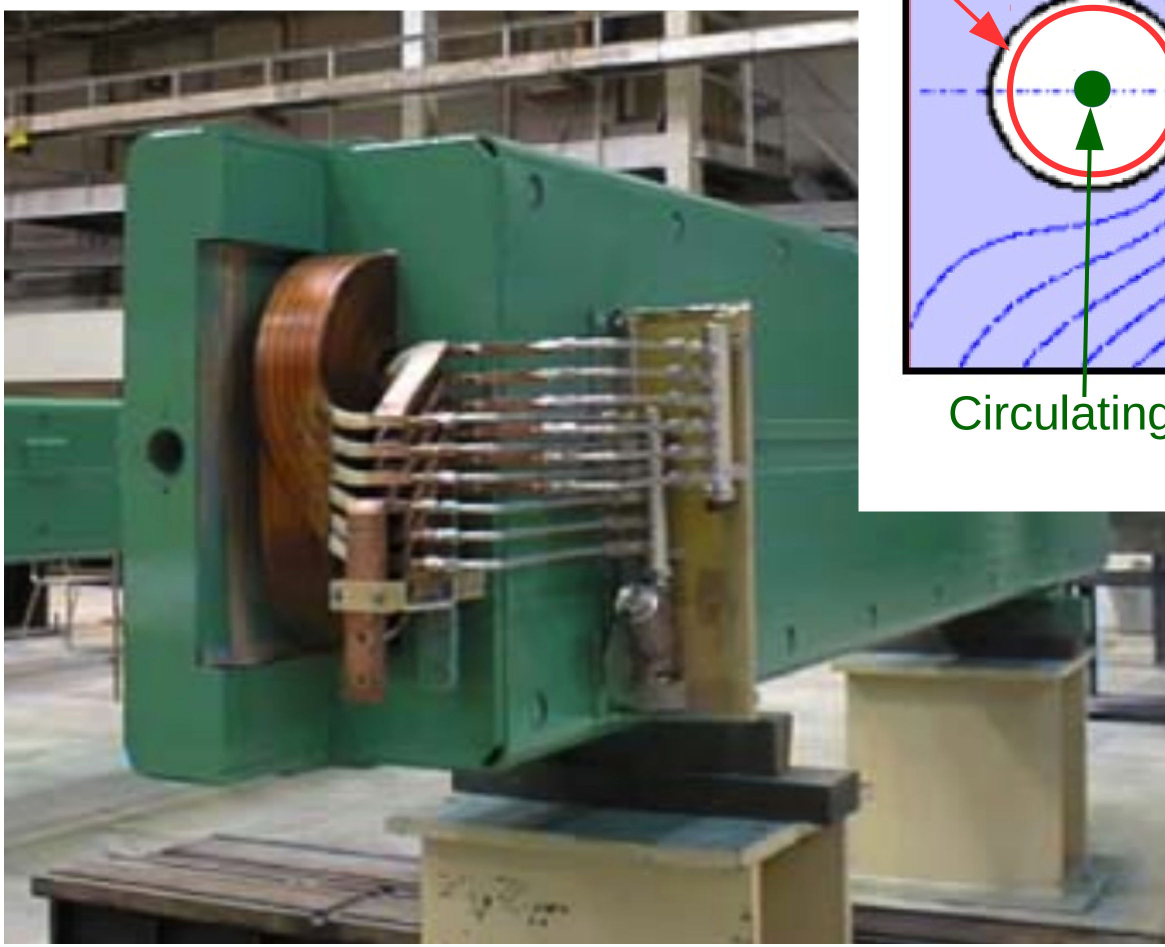




S. Bidon, et al: Steel septum magnets for the LHC beam injection and extraction, Proc EPAC 2002

Doing it at the LHC: the Lambertson septa





Using $\mu_r \gg 1$
to „suck out" the field lines from the circulating beam

Can't go above ~1.5 T due to saturation of iron

S. Bidon, et al: Steel septum magnets for the LHC beam injection and extraction, Proc EPAC 2002

FCC parameters for extraction

At top energy (most difficult):

Septum integrated field	190	T m
Available space for septum	120	m

→ Need ≥ 2 T field (to accomodate gate valves, pumps, etc)

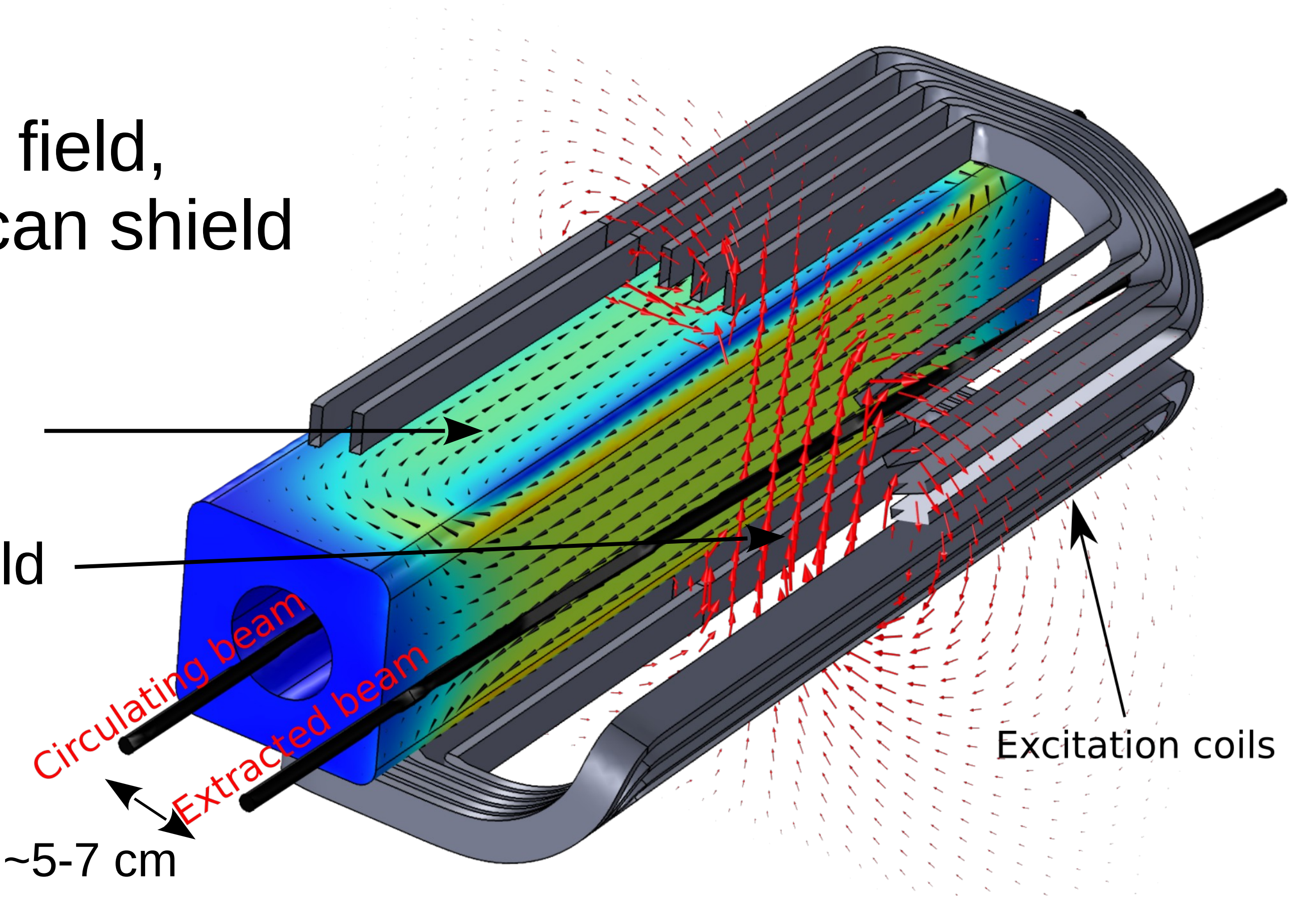
(Space would be even more tight in the „high-energy LHC" - LHC tunnel with FCC technology)

- B > 2 T (target: 3 Tesla)
  - Not easy with normal-conducting devices
  - need superconductors?
- Must follow the ring energy to be ready for beam-abort at any time (quasi-DC mode)
- Field homogeneity: ~1%
- Leakage field at circulating beam: < 10^{-4} relative

Doing it at the FCC: the SuShi idea

- If cooled down in 0 field, a superconductor can shield the outside field
- Persistent currents

Homogeneous high field

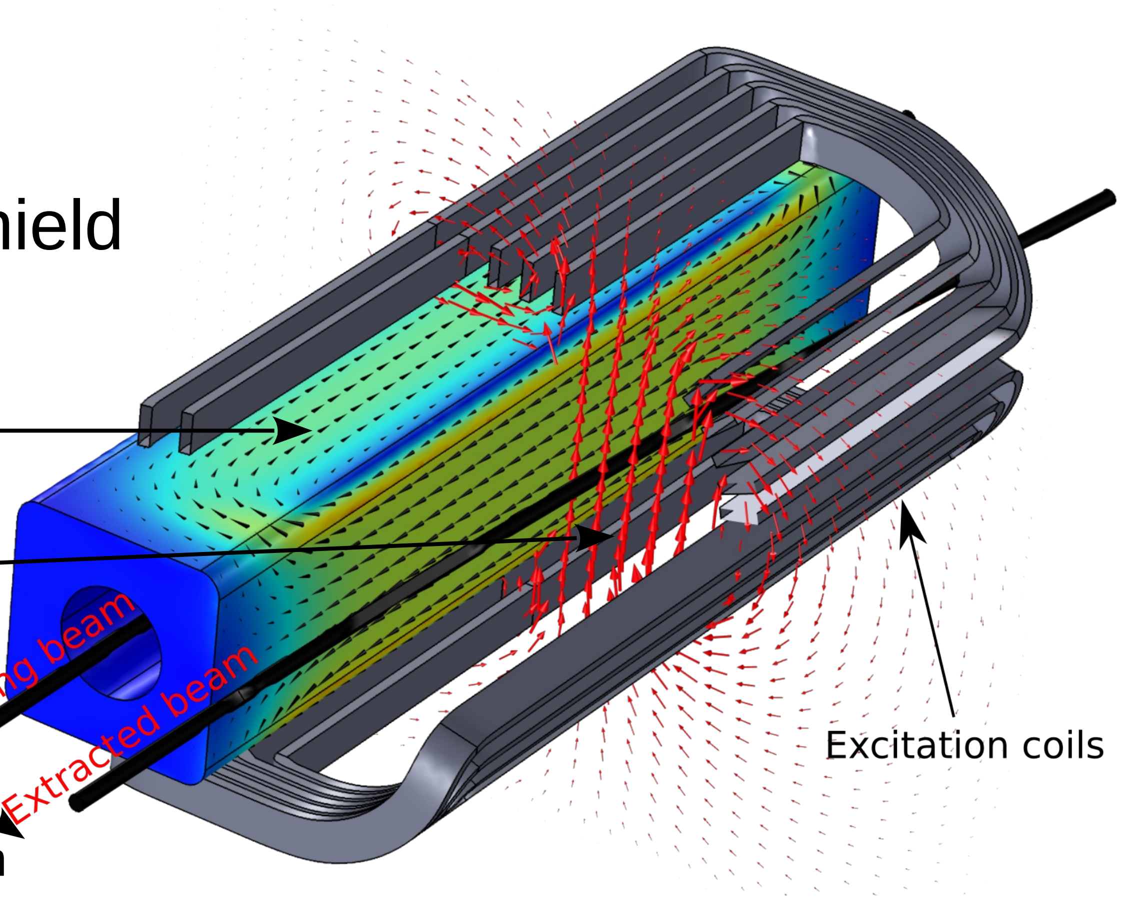


- Concept is similar to eddy current septum, but can work in DC mode, (because the eddy currents are persistent)

Doing it at the FCC: the SuShi idea

- If cooled down in 0 field, a superconductor can shield the outside field
- Persistent currents

Homogeneous high field



- Concept is similar to eddy current septum, but can work in DC mode, (because the eddy currents are persistent)

Using $\mu_r \ll 1$ material to expel the field lines

Pros & cons

Pros

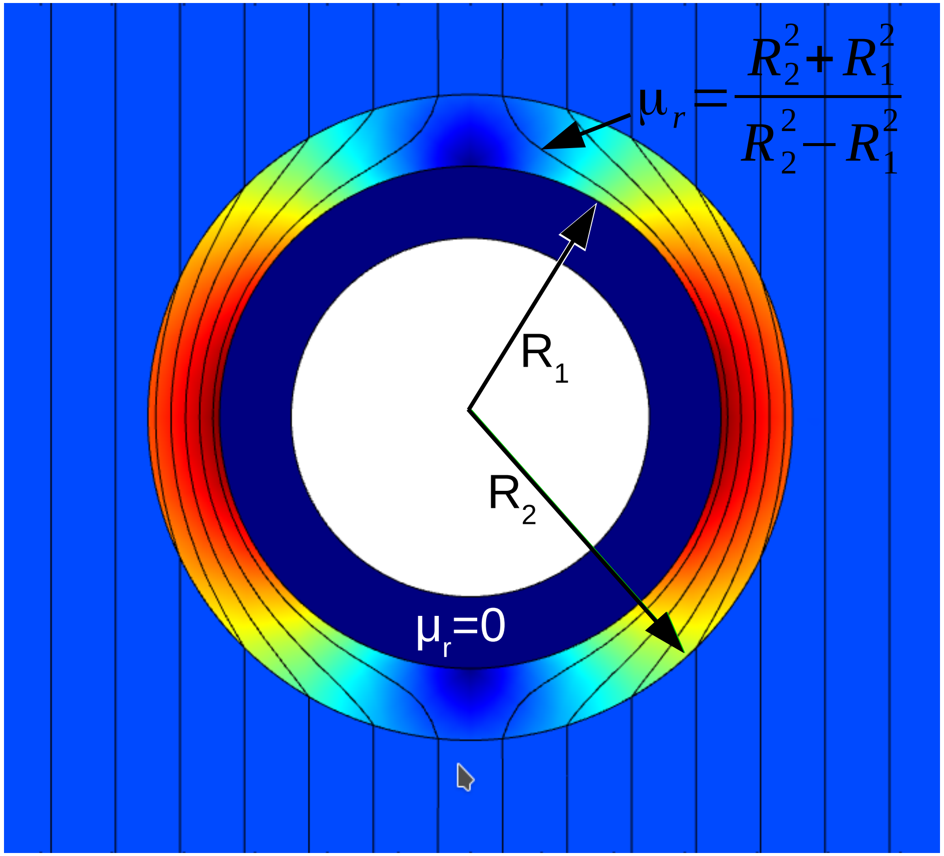
- Shielding currents arranged by nature (high precision zero field)
- Continuous 2D current distribution (unlike a winded magnet) → perfect shielding
- Bulk shield, better mechanical, and thermal stability
- Highest possible current density(critical state model) →thinnest shield

Cons

- Superconductor in high rad zone (quench)
- Hysteretic behavior, always have to start from virgin state
- To erase ‘memory’ of shield, temperature has to be increased

Combining $\mu_r \gg 1$ and $\mu_r \ll 1$

The „magnetic cloak”



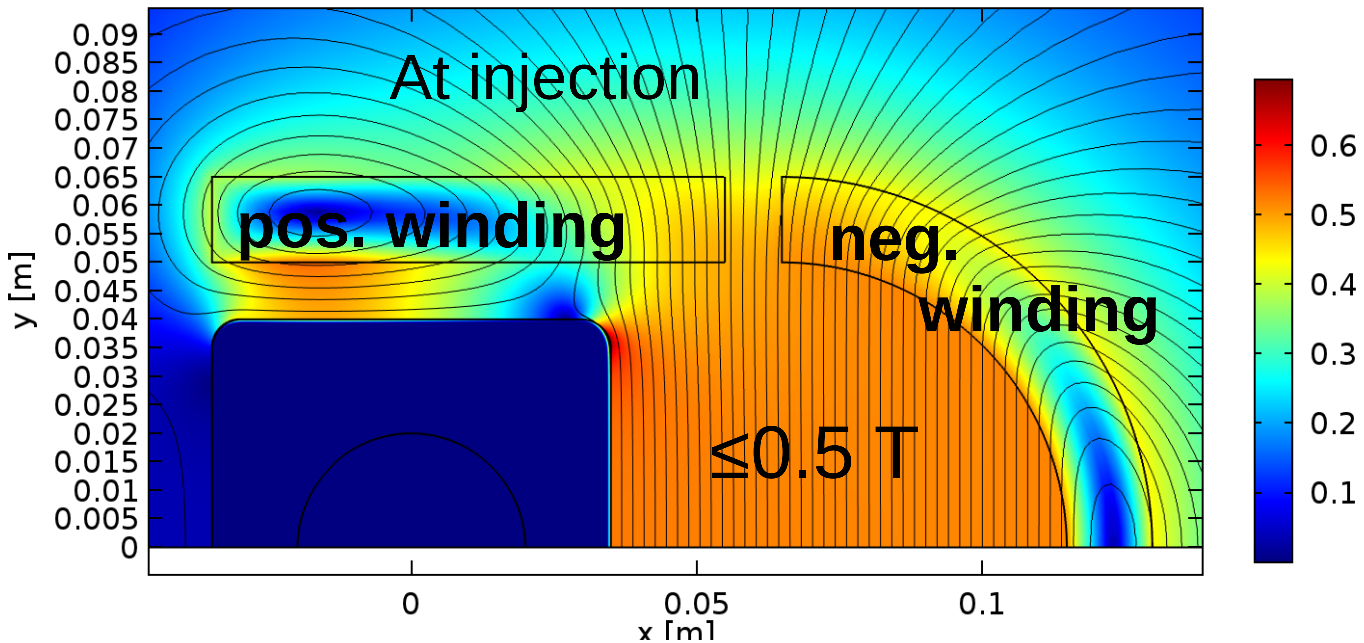
- Ferromagnet absorbs the induction lines expelled by the superconductor
- Seems a natural choice, since it does not distort the external field

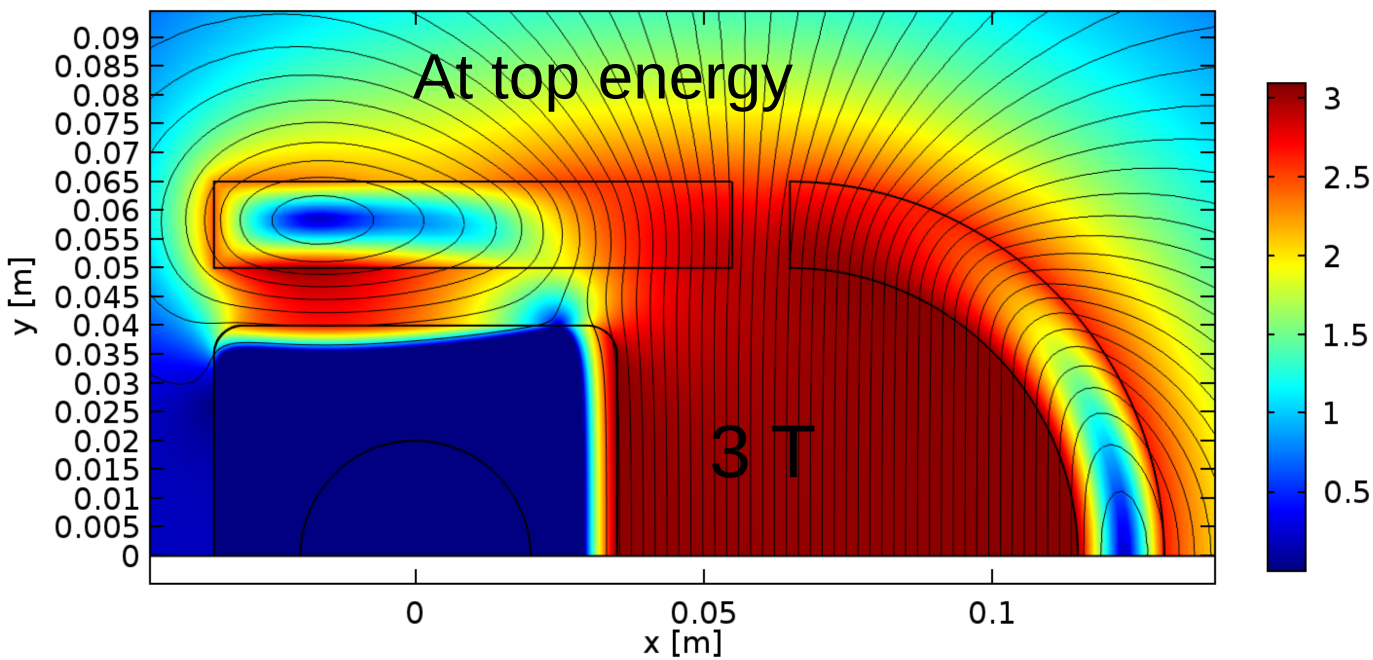
Does not work for FCC with realistic geometrical parameters:

field in ferromagnet would be too high: ~13-18 T

Homogeneity at various field strengths

Flat wall → homogeneity despite significantly different penetration depths





CERN Bubble chambers

- In the '70ies: superconducting tube to shield high magnetic field
- To introduce low-momentum particles into the high field of the bubble chamber
- Different materials, and techniques could bring the shielded field strength from 2 T up to 5.9 T

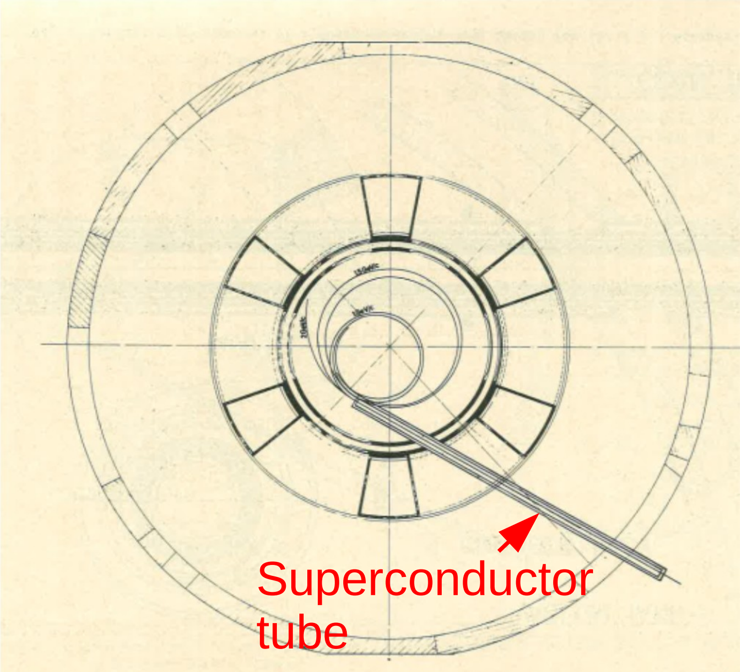
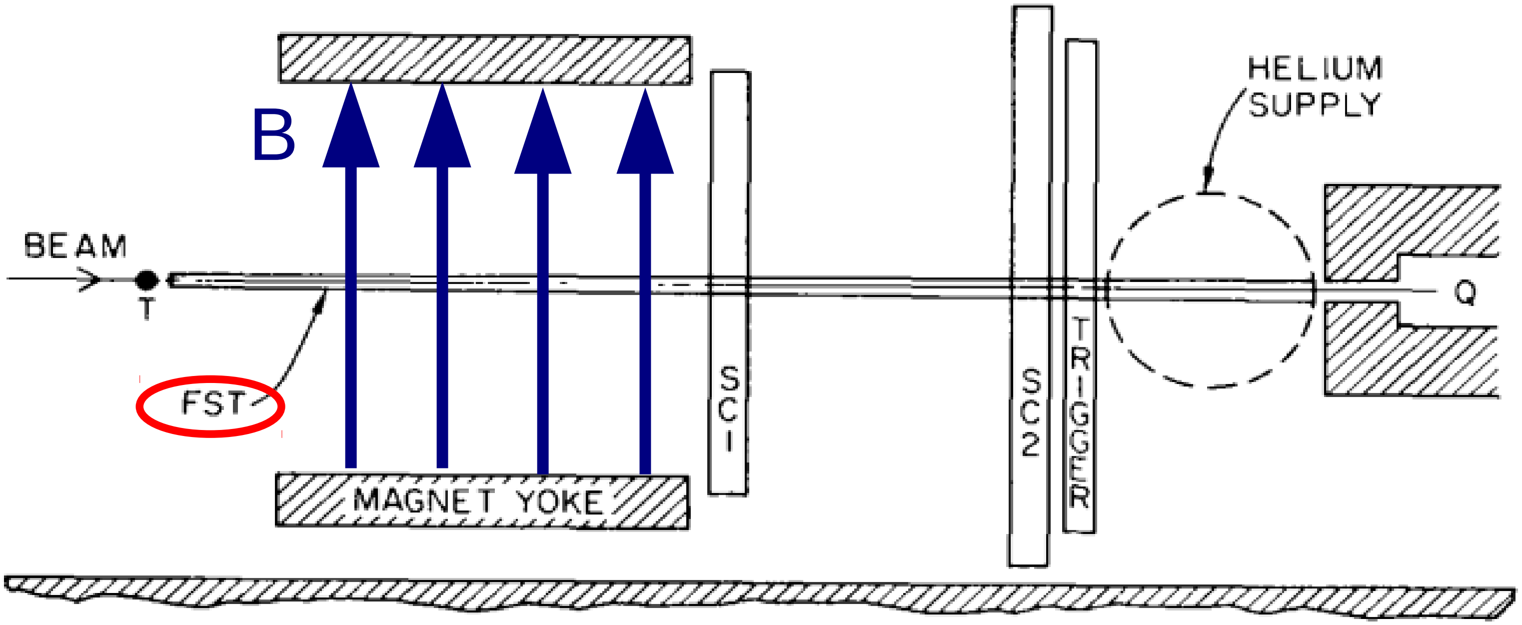


Fig. 2 Trajectories of Low Momentum Particles Emerging from a Field Free Path.

- M.Firth, et.al.: Performance of the superconducting field shielding tube for the CERN 2m hydrogen bubble chamber
- 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
- http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/46/027/46027030.pdf

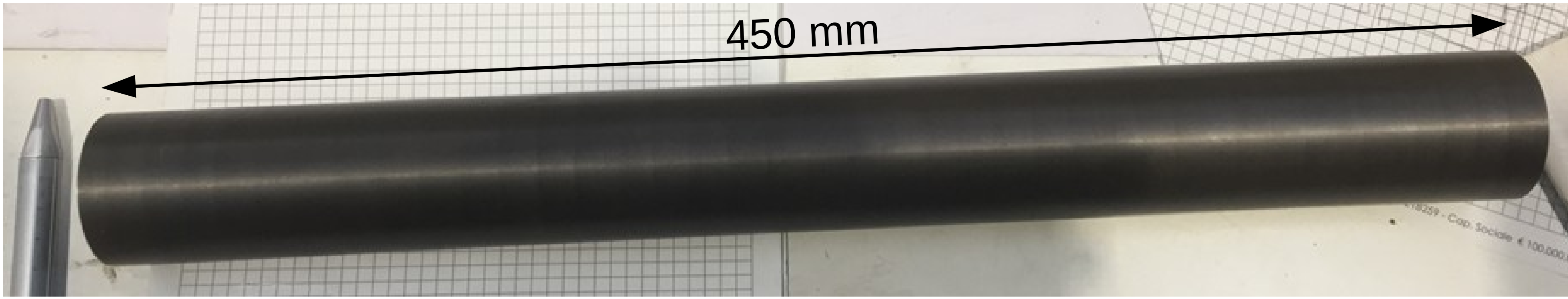
SLAC

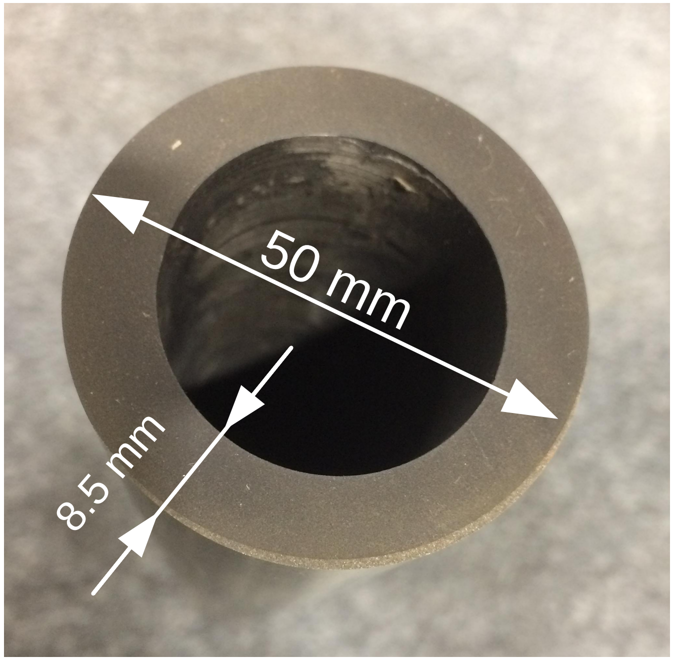


BEAM. $e^{+(-)}$ 2×10^4/pulse.
T: Liquid H_2/D_2 target. 4cms long
FST · Superconducting flux shielding tube
SCI, SC2 Optical spark chambers.
TRIGGER: Lead-lucite shower counters.
Q · Quantameter

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

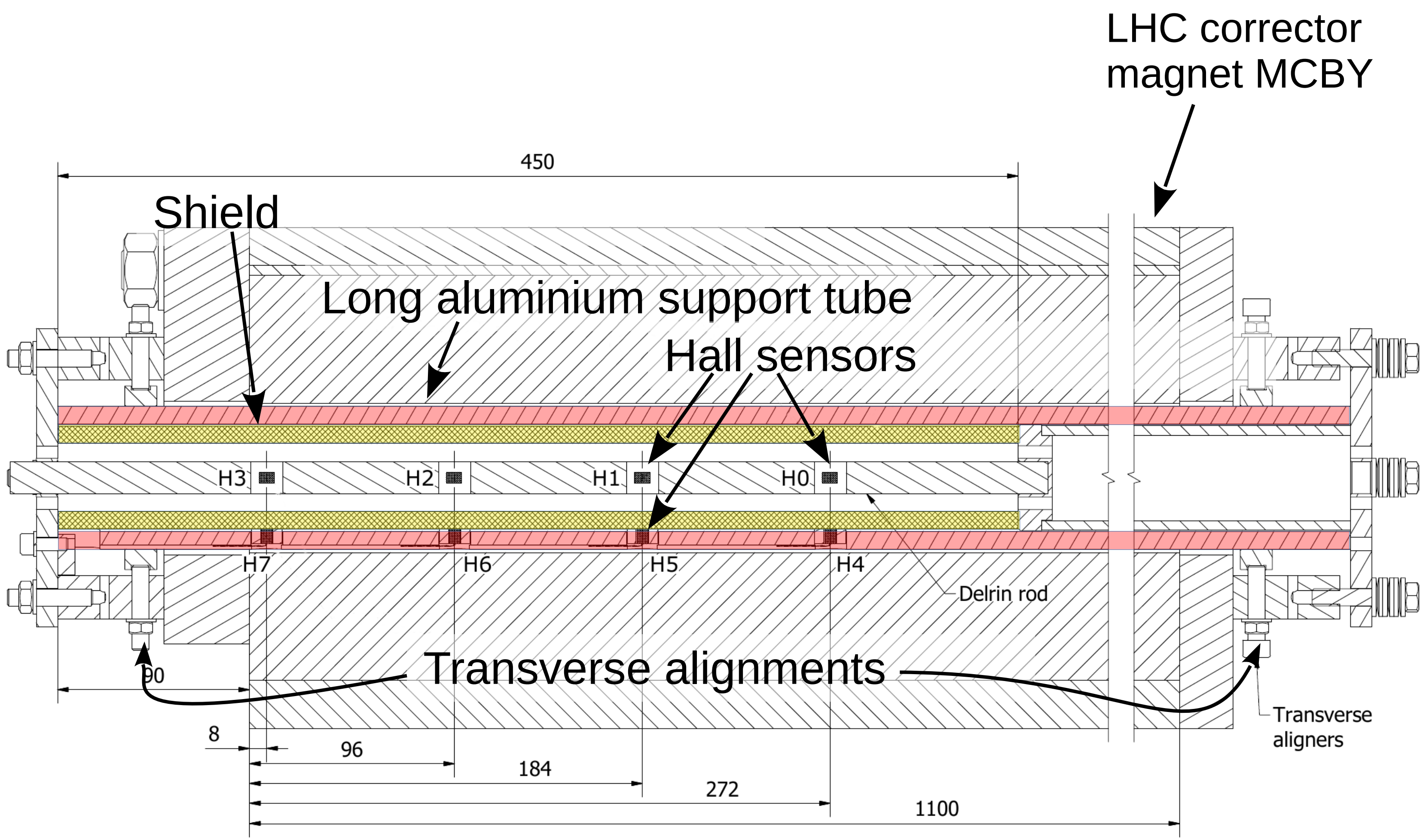
MgB_2



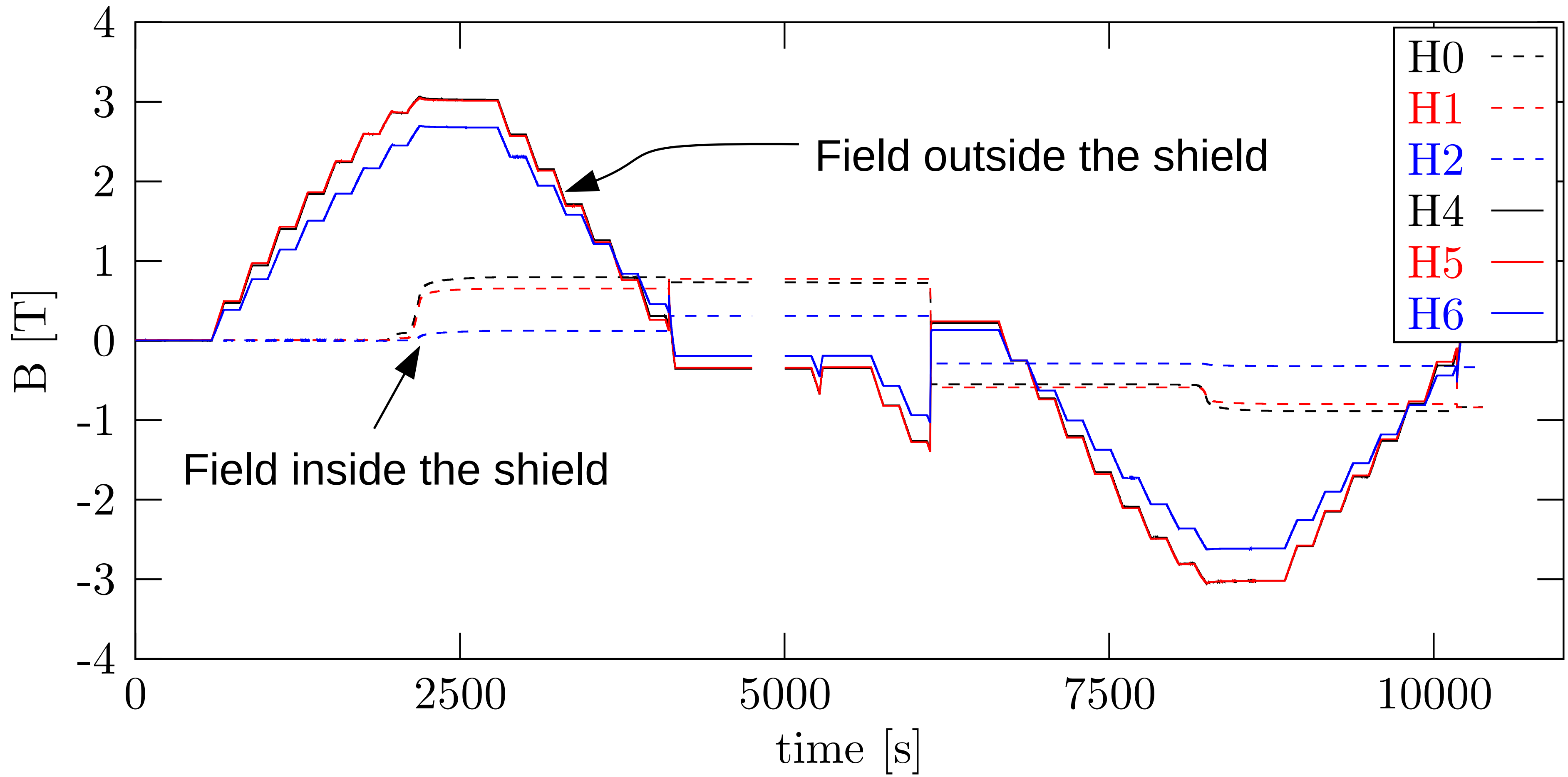


- Produced by the Reactive Liquid Magnesium Infiltration (RLI) process (G. Giunchi, Int.J.Mod.Phys.B17,453)
- Extra large boron grainsize (160 μm) to be stable against flux jumps (G.Giunchi et al, IEEE Trans. Appl. Supercond. 26, 8801005)

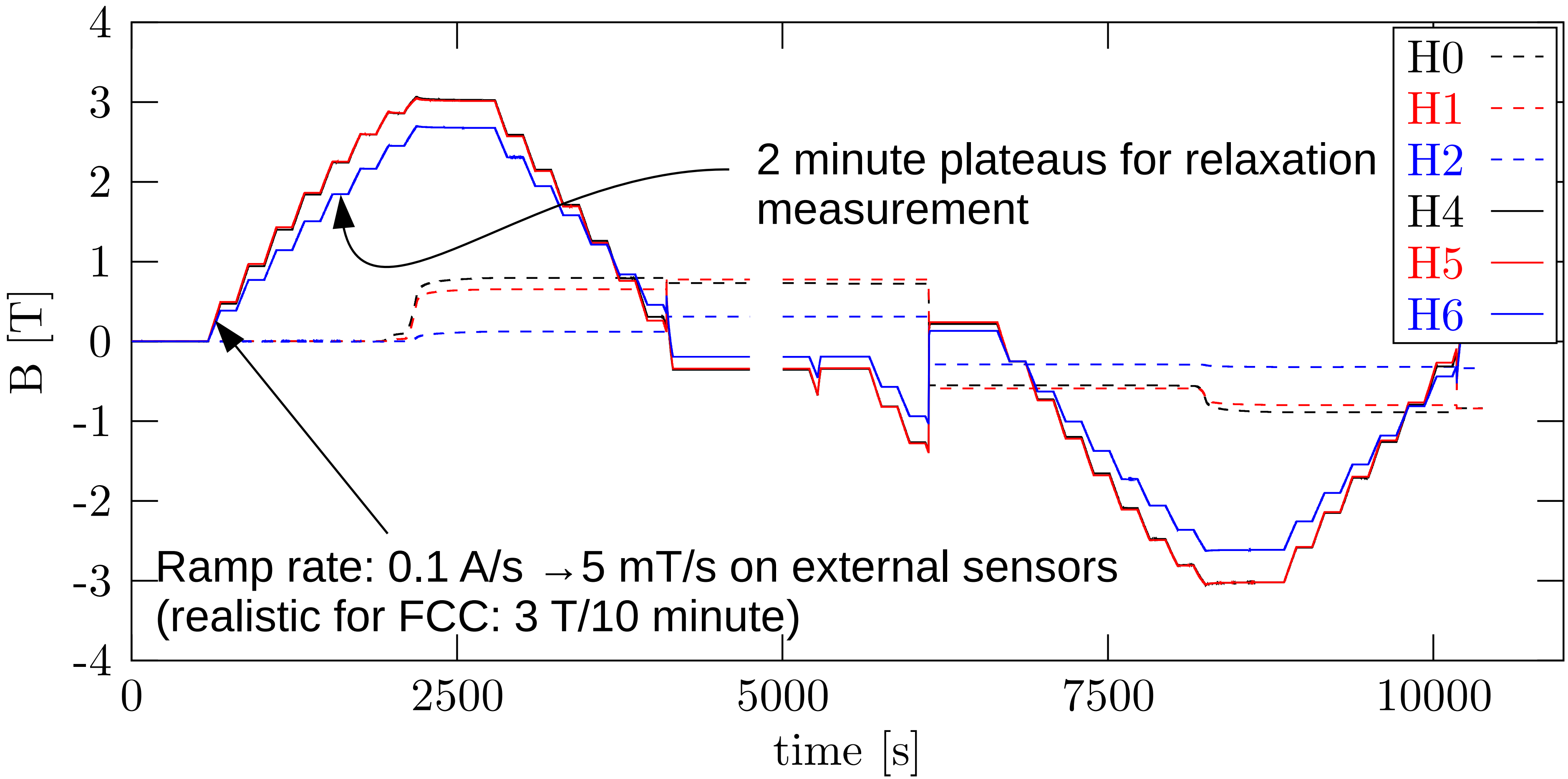
Testing of prototypes at SM18



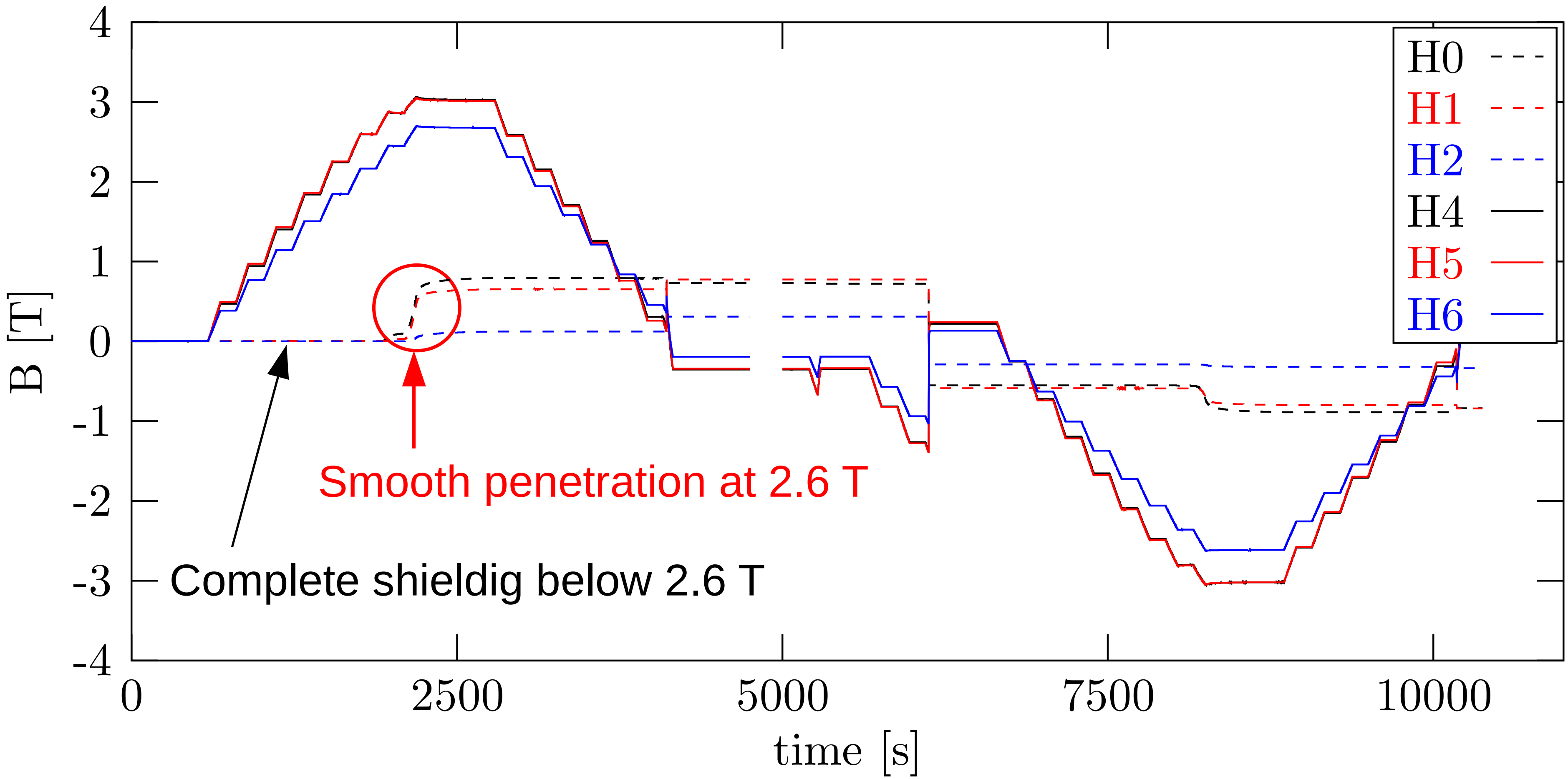
MgB_2 magnetization cycle



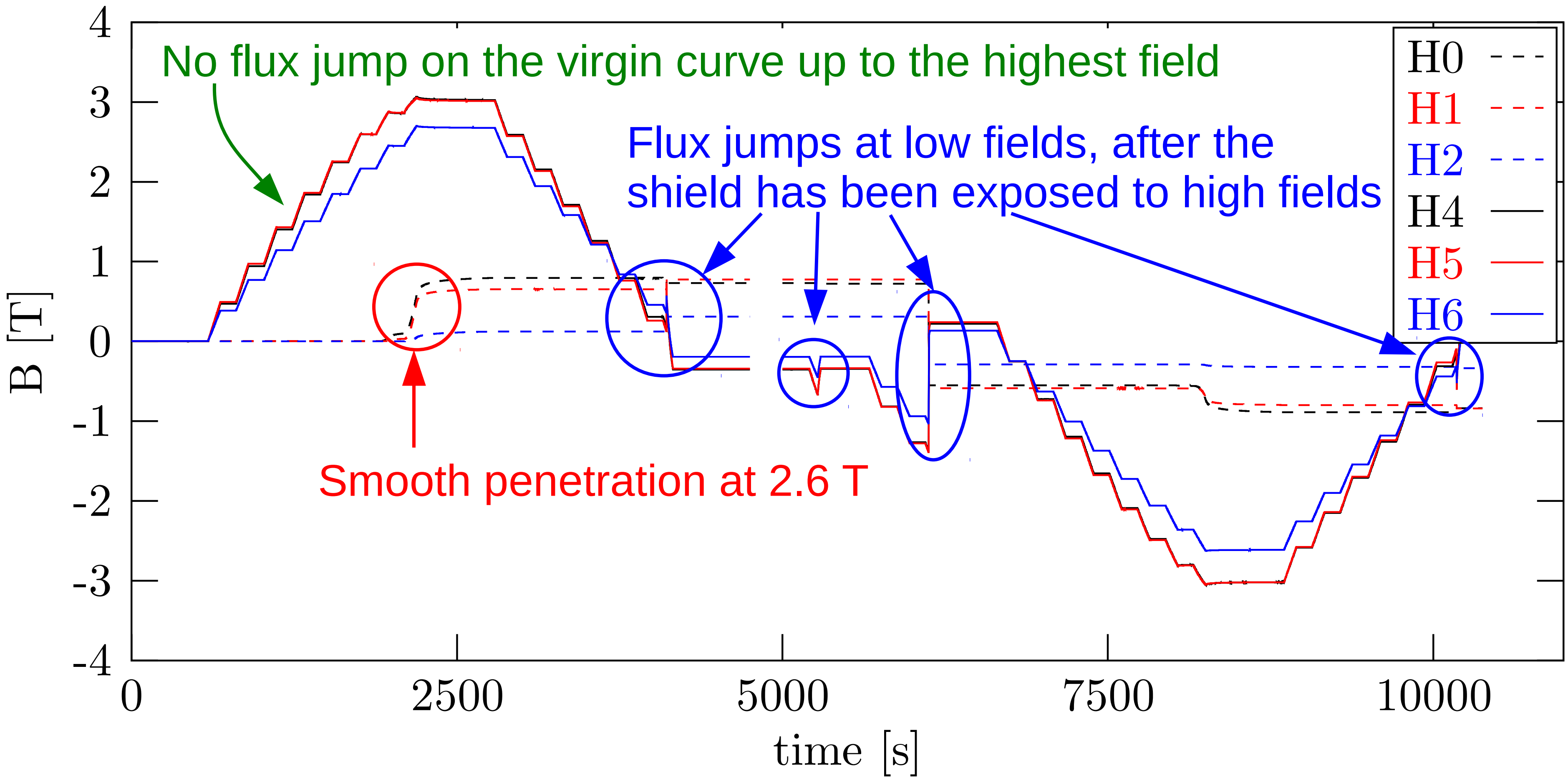
MgB_2 magnetization cycle



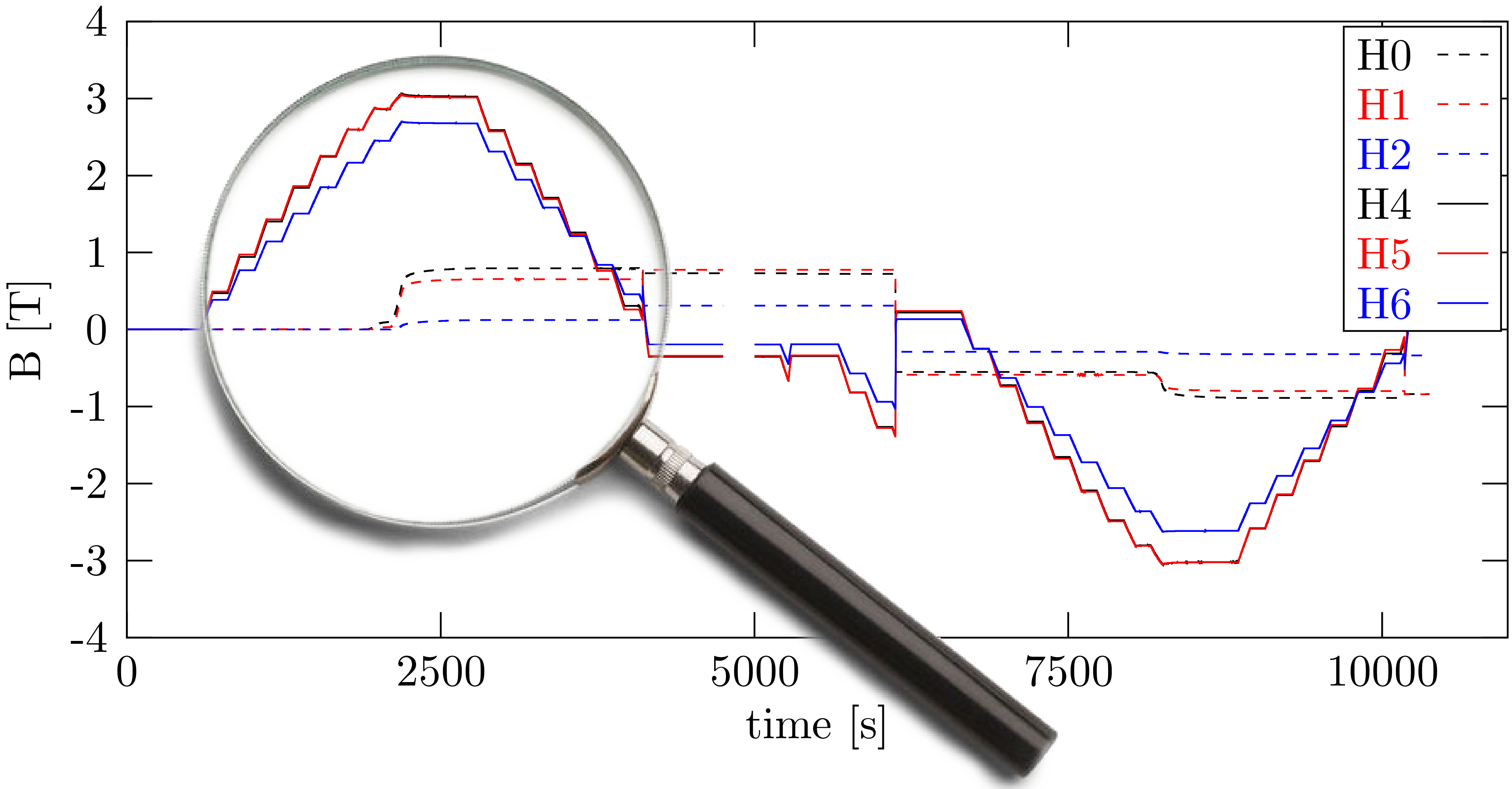
MgB_2 magnetization cycle



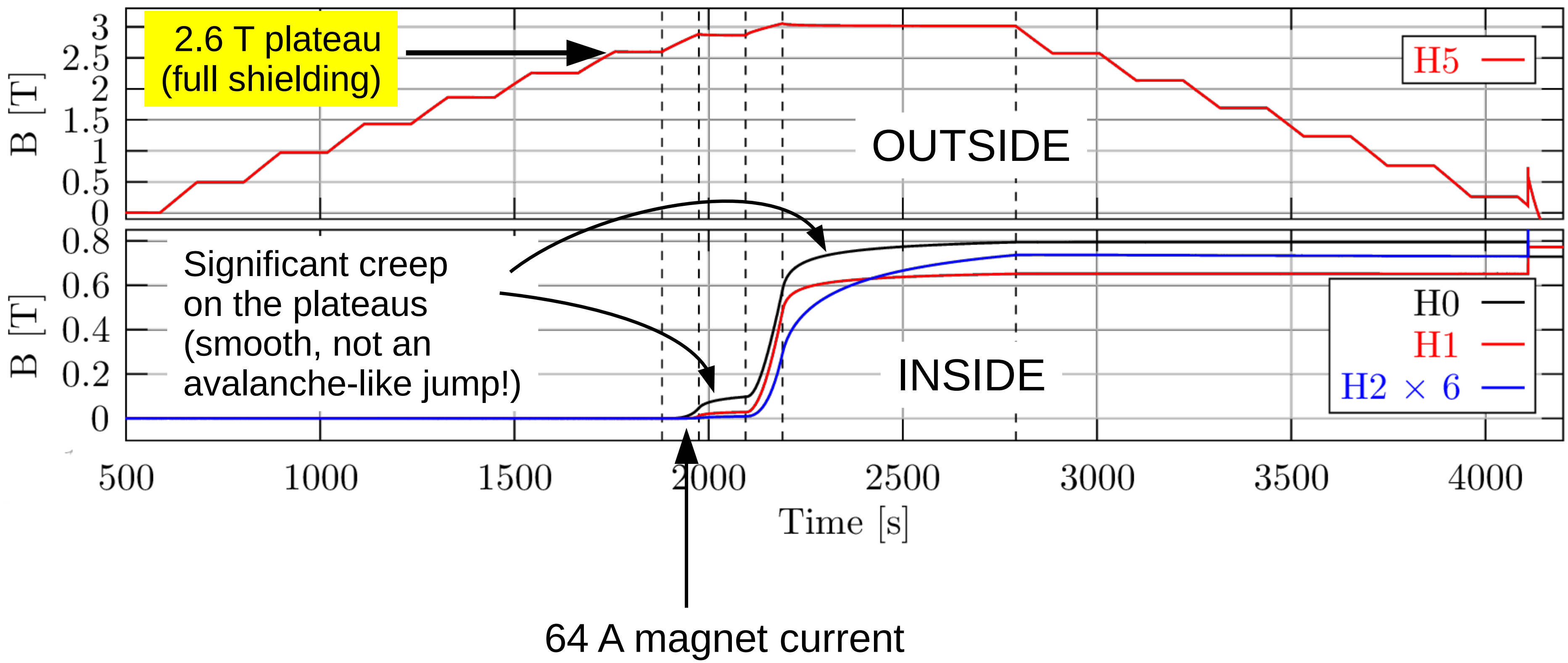
MgB_2 magnetization cycle



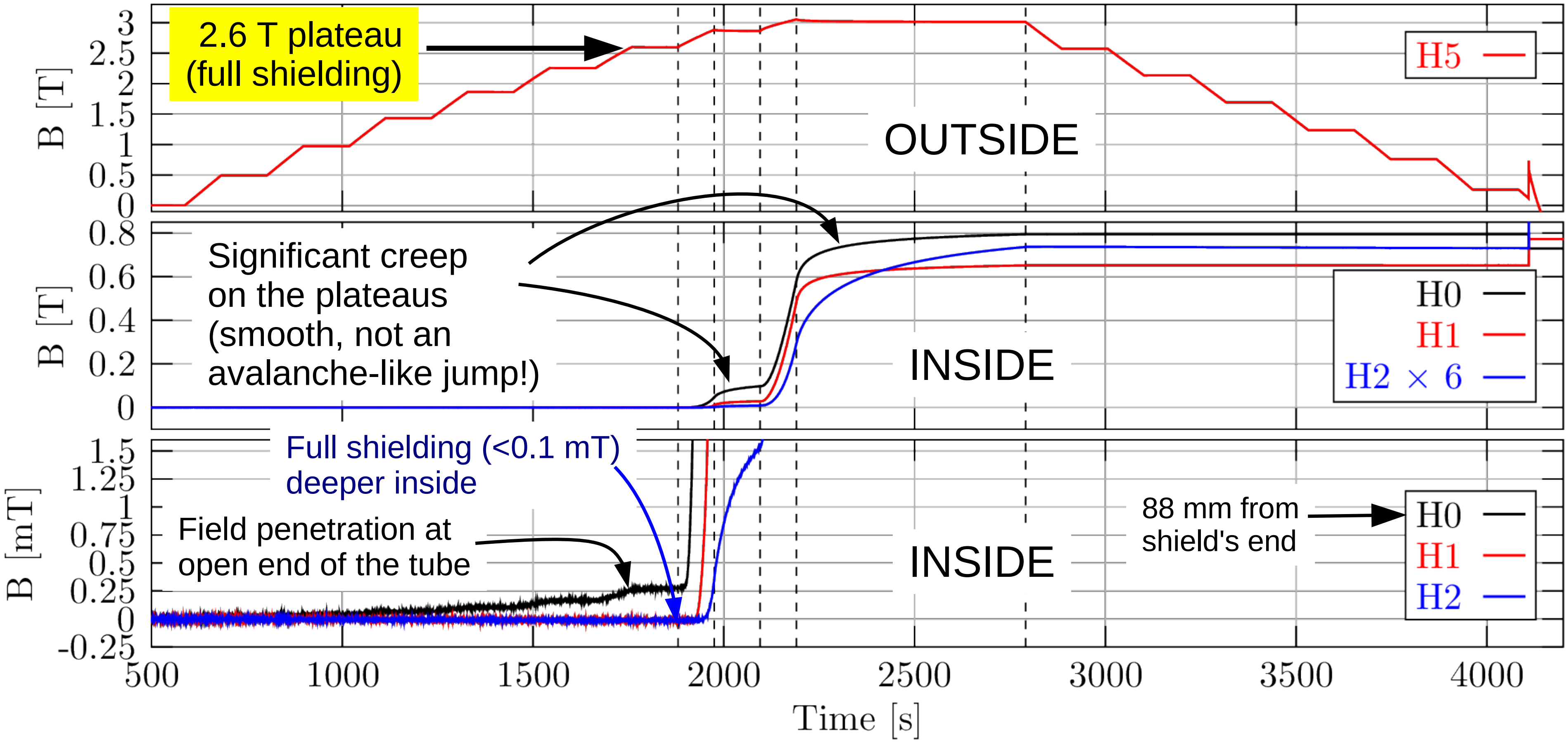
MgB_2 magnetization cycle



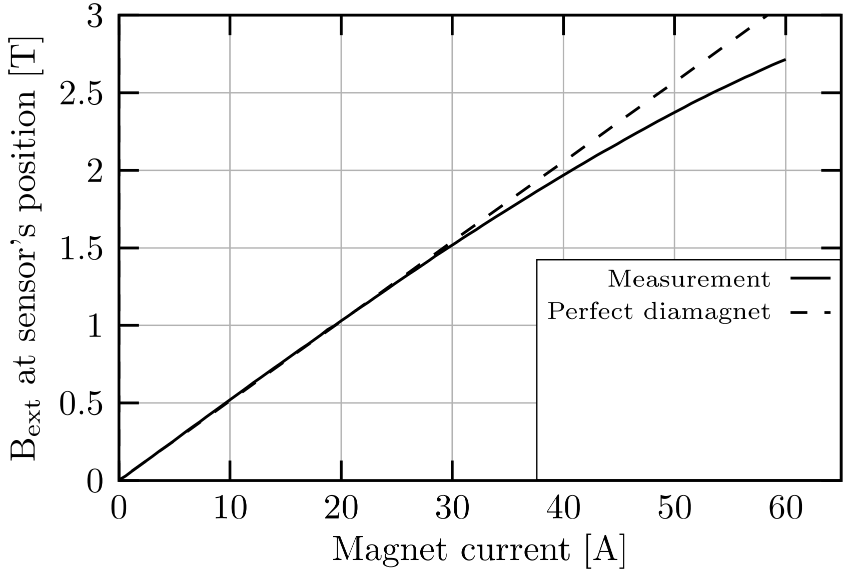
MgB_2: field penetration



MgB_2: field penetration

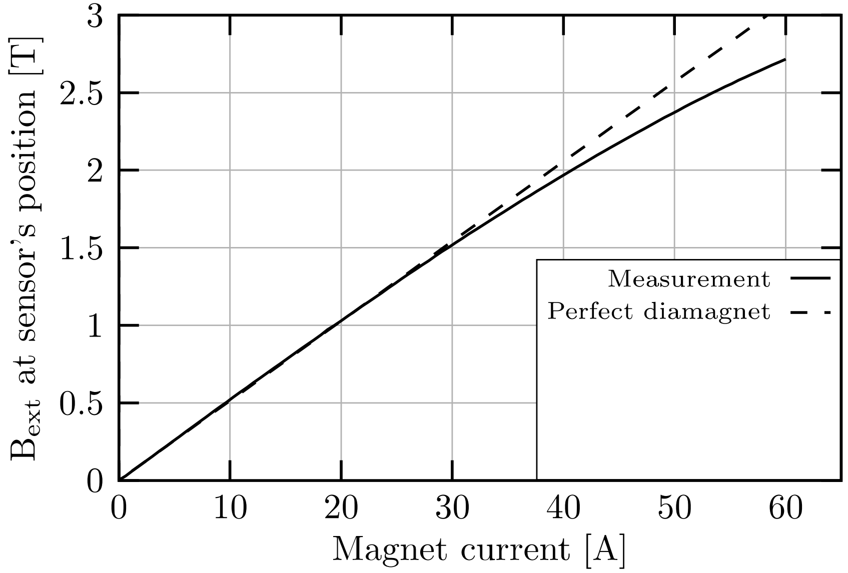


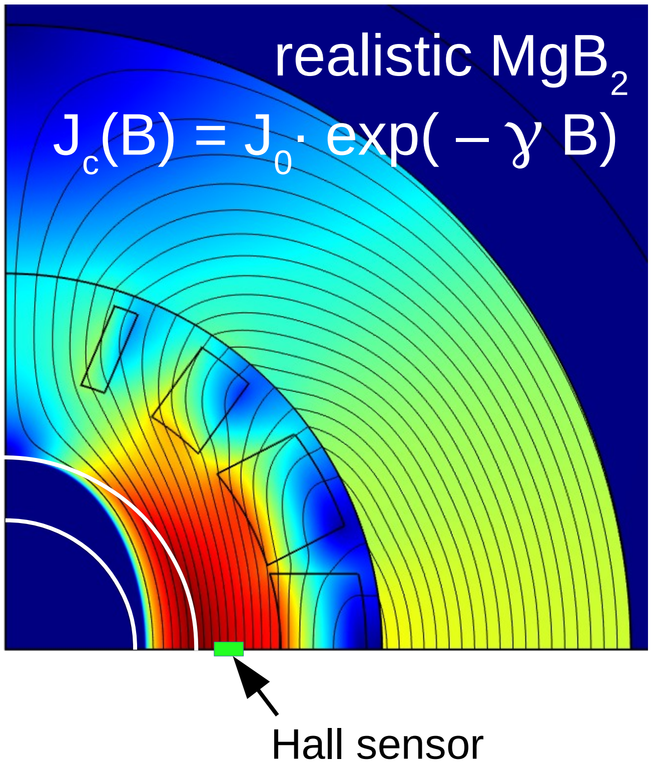
MgB_2: linearity



Measured external magnetic **field is non-linear as a function of magnet current**!

MgB_2: linearity

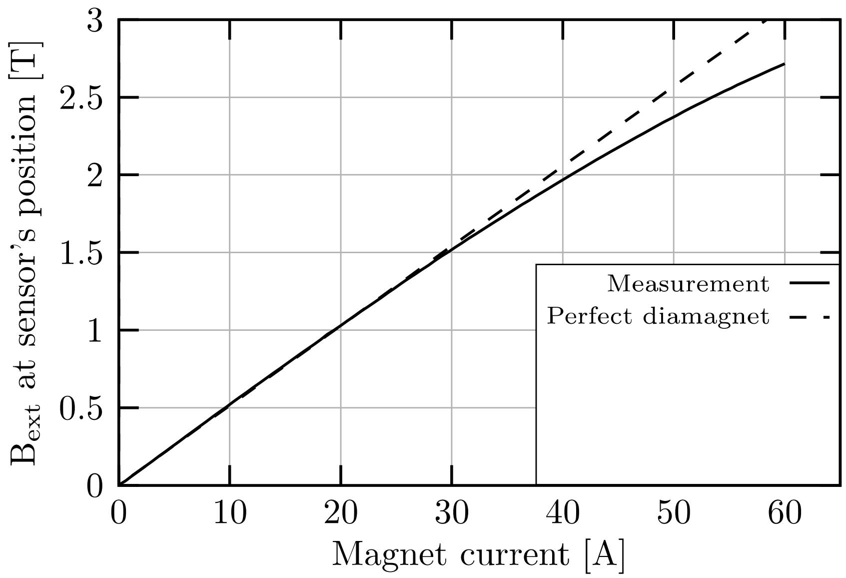


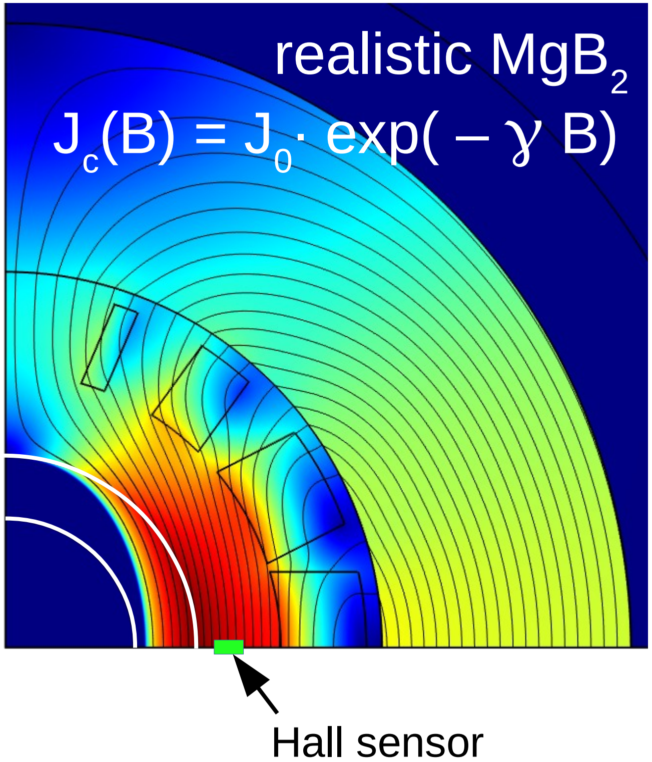


COMSOL simulation in precise model of MCBY magnet

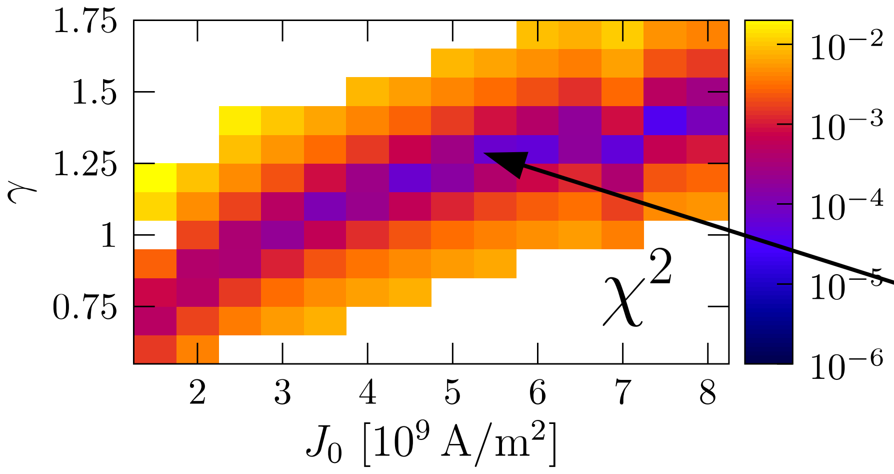
- Increasing field → more penetration
- Effective shielding surface drifts away from Hall sensor
- Less field concentration at sensor

MgB_2: linearity



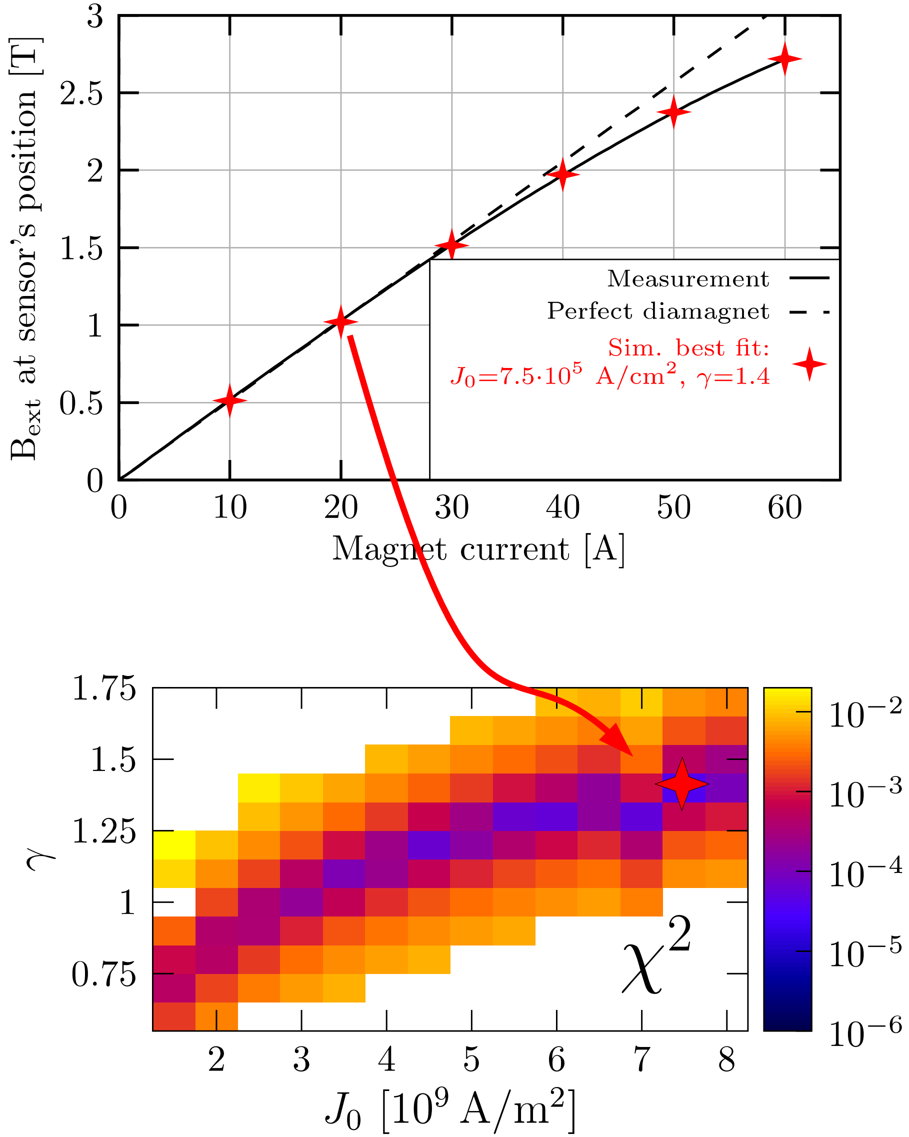


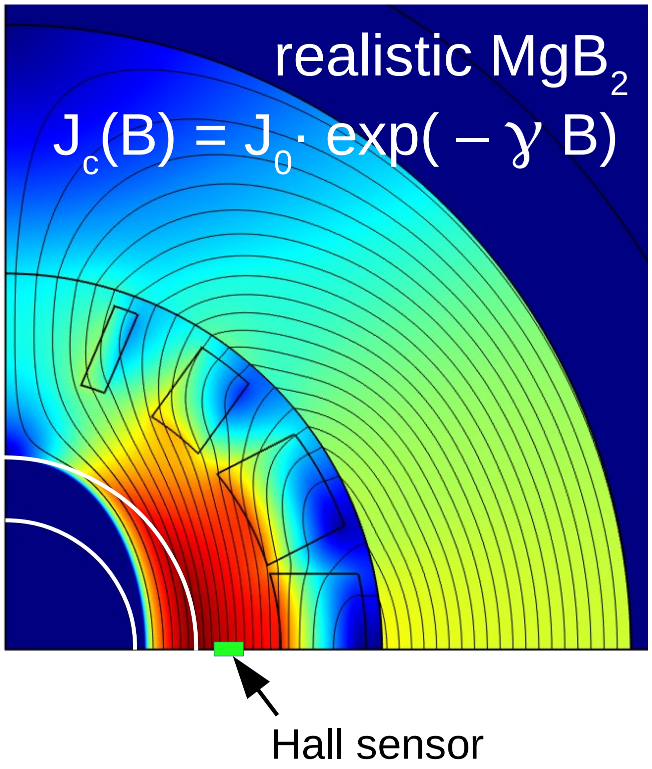
COMSOL simulation in precise model of MCBY magnet



J_0 and γ are strongly correlated

MgB_2: linearity

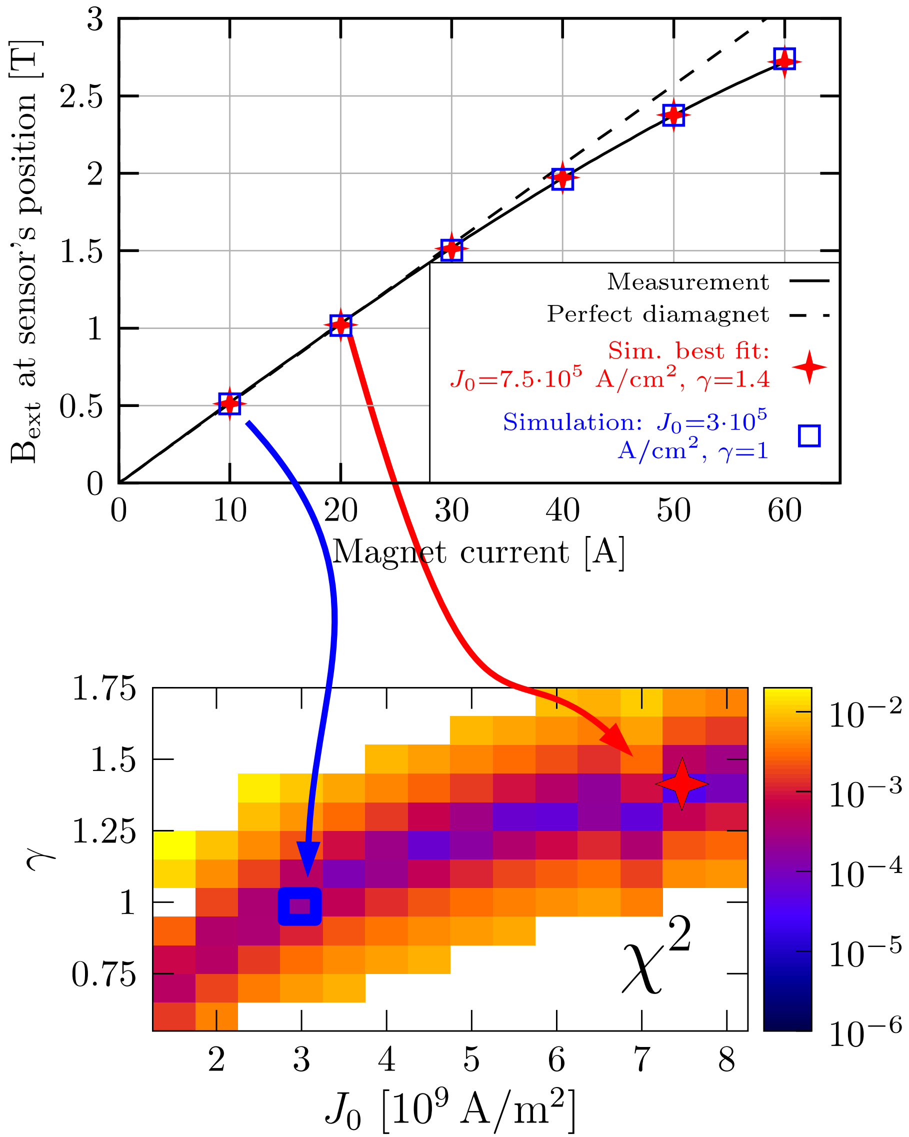


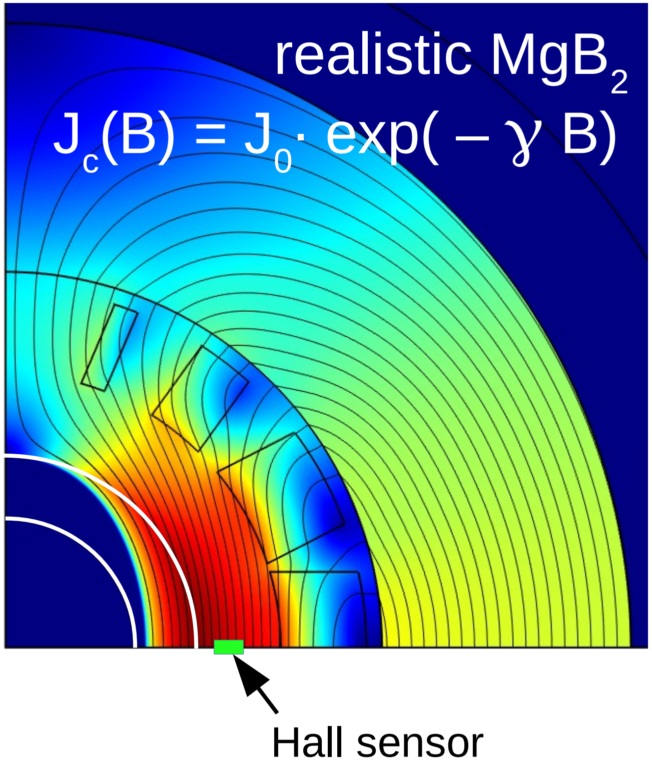


COMSOL simulation in precise model of MCBY magnet

J_0 and γ are strongly correlated

MgB_2: linearity



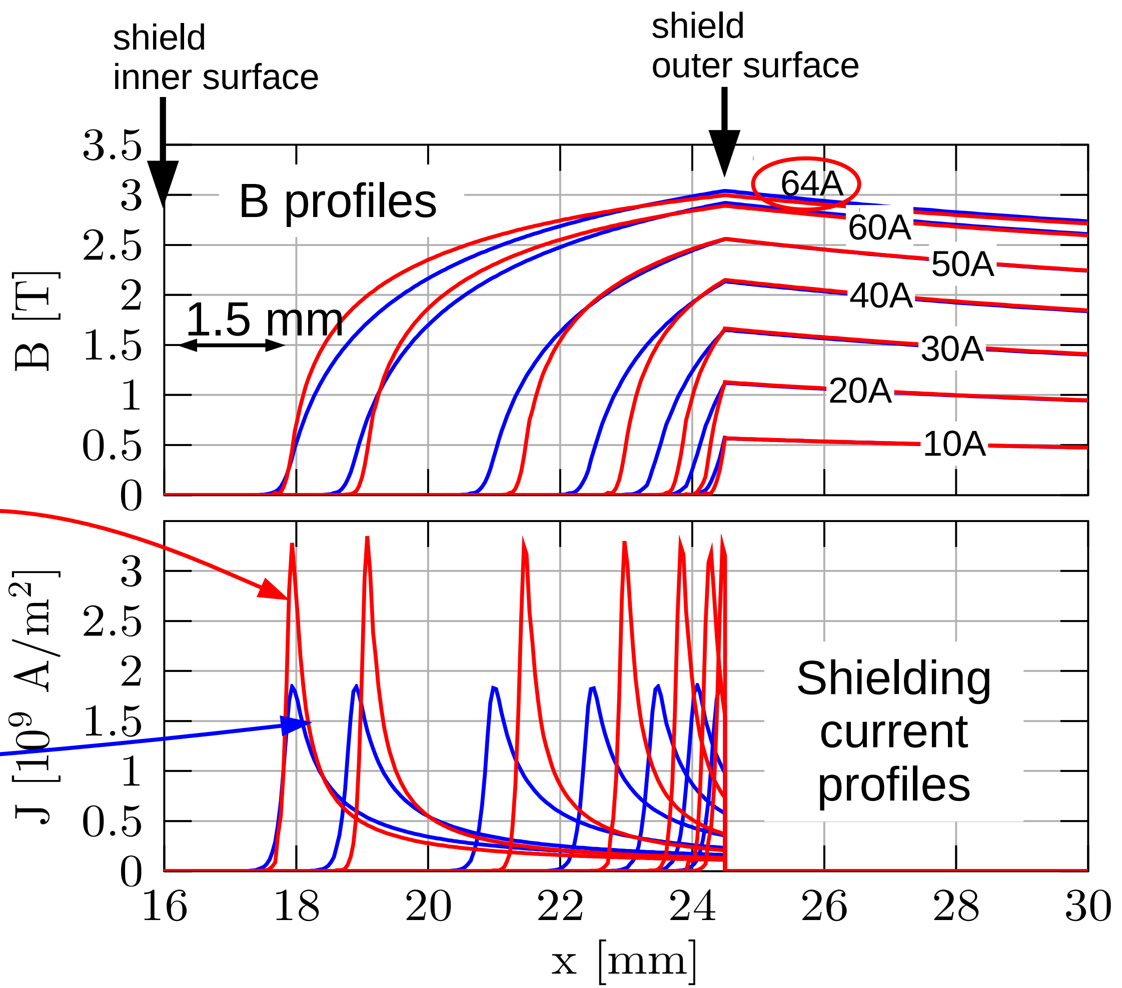


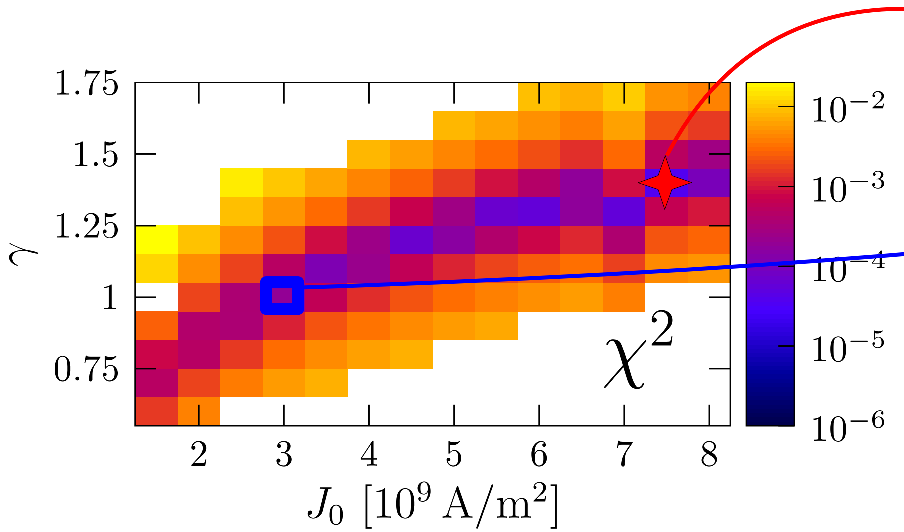
COMSOL simulation in precise model of MCBY magnet

J_0 and γ are strongly correlated

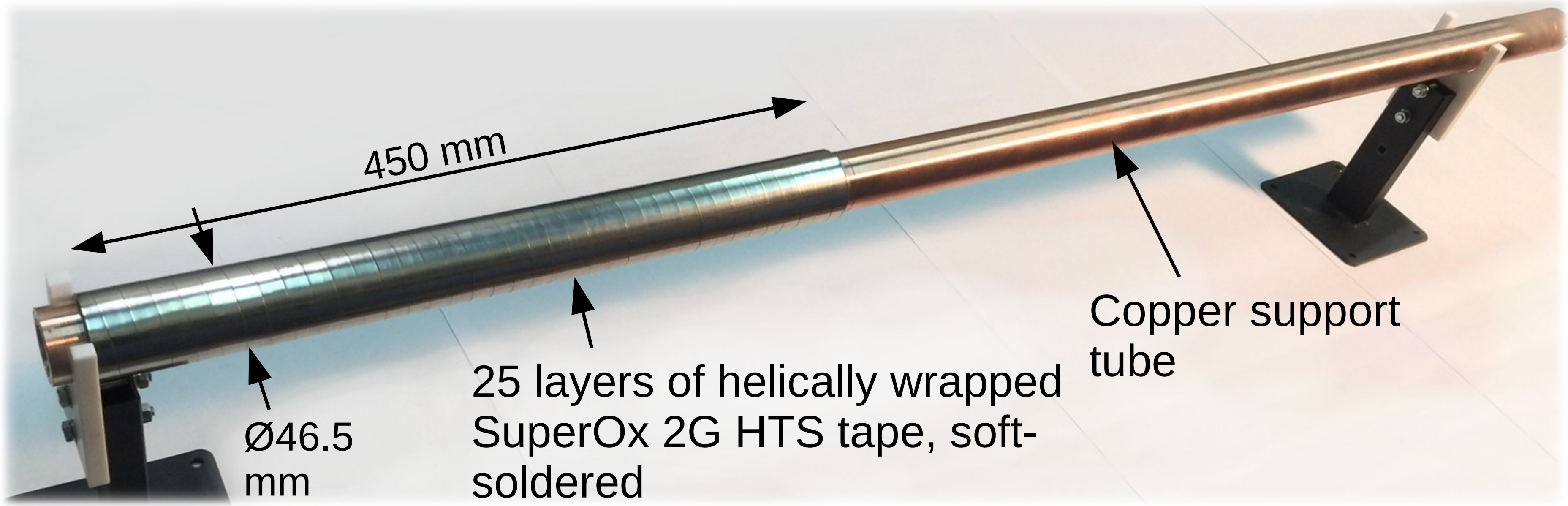
MgB_2: linearity

- From observed nonlinearity one can get **some** info on $J_c(B)$
- At 64 A different parameters give B penetration profiles with same, almost full depth

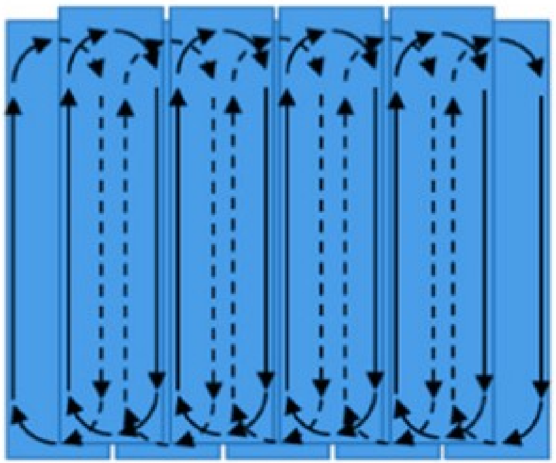




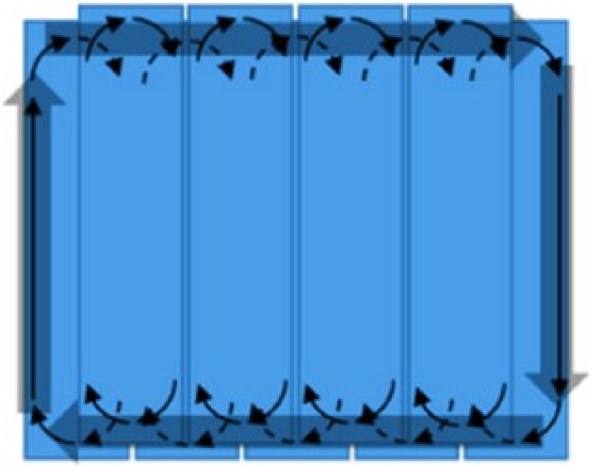
HTS tape covered tube



Layers overlapping

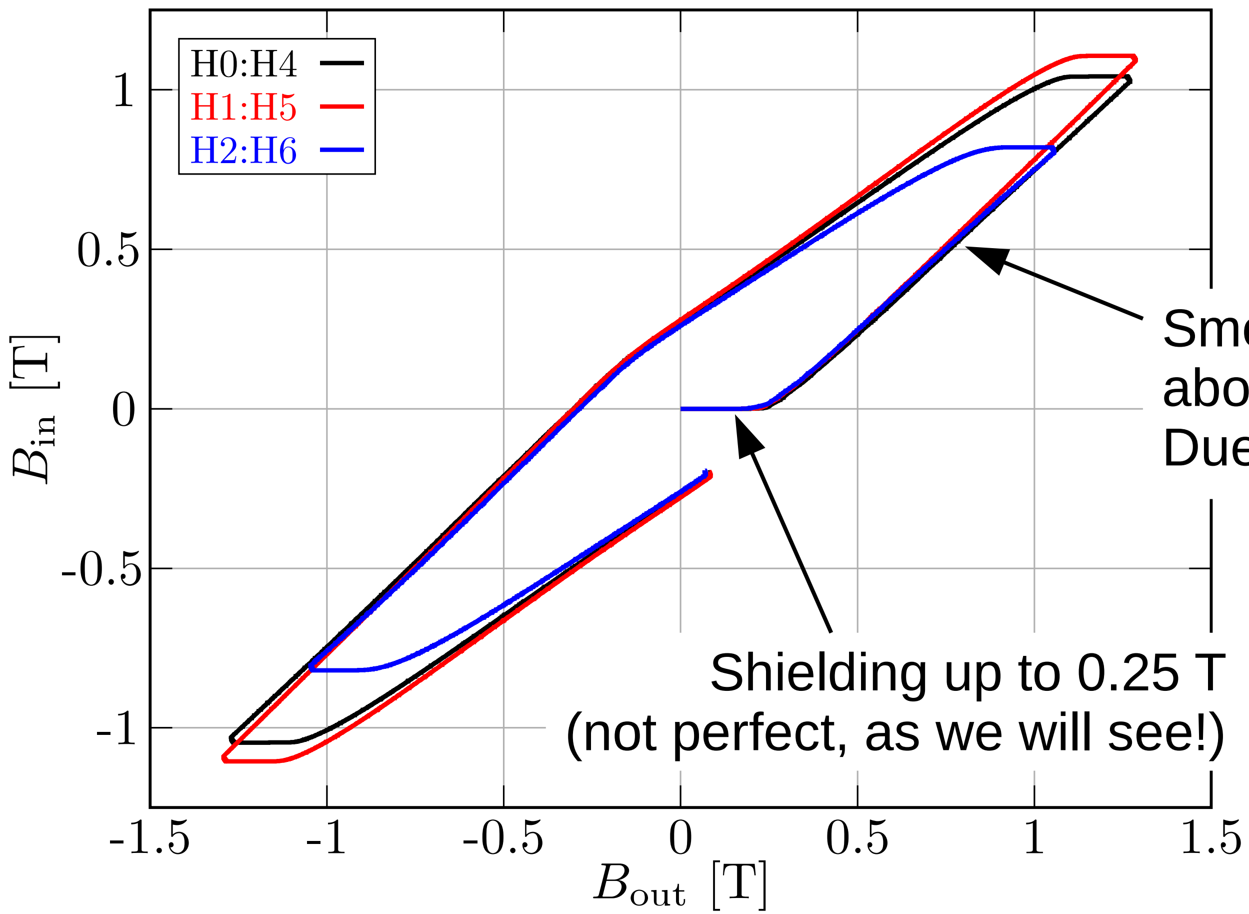


Little current loops



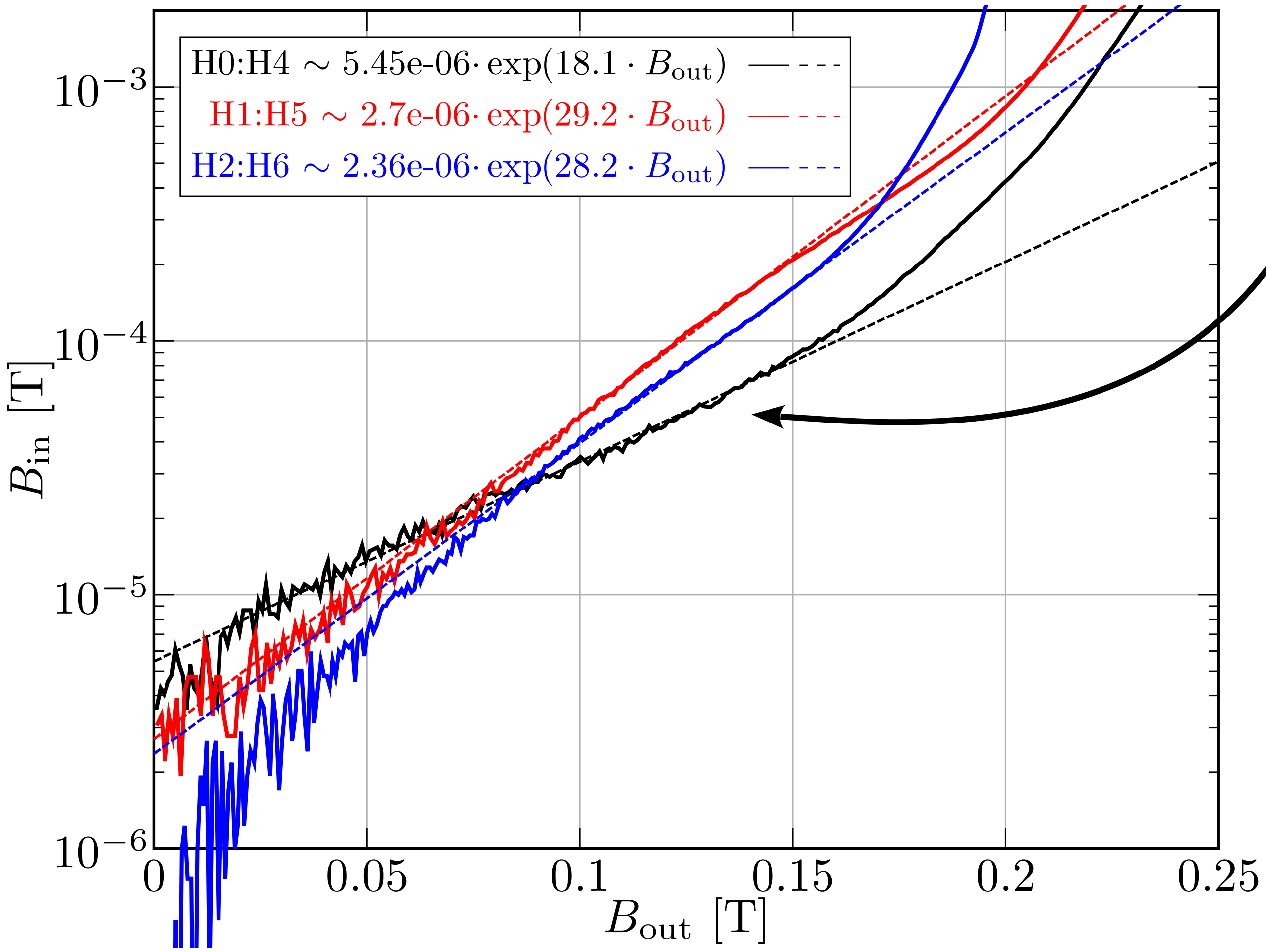
Superposition

HTS: Shielding performance



No flux jumps!

HTS: penetration at low field!



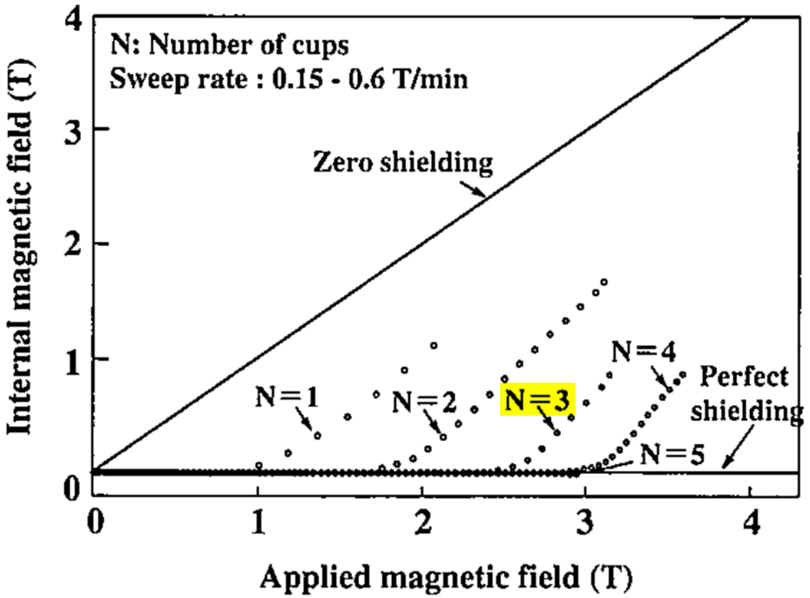
Continuous penetration from zero field!

Attenuation is about 10^{-3} here

Due to geometry?
(non-continuous geometry, small gaps between tape layers, small current loops)

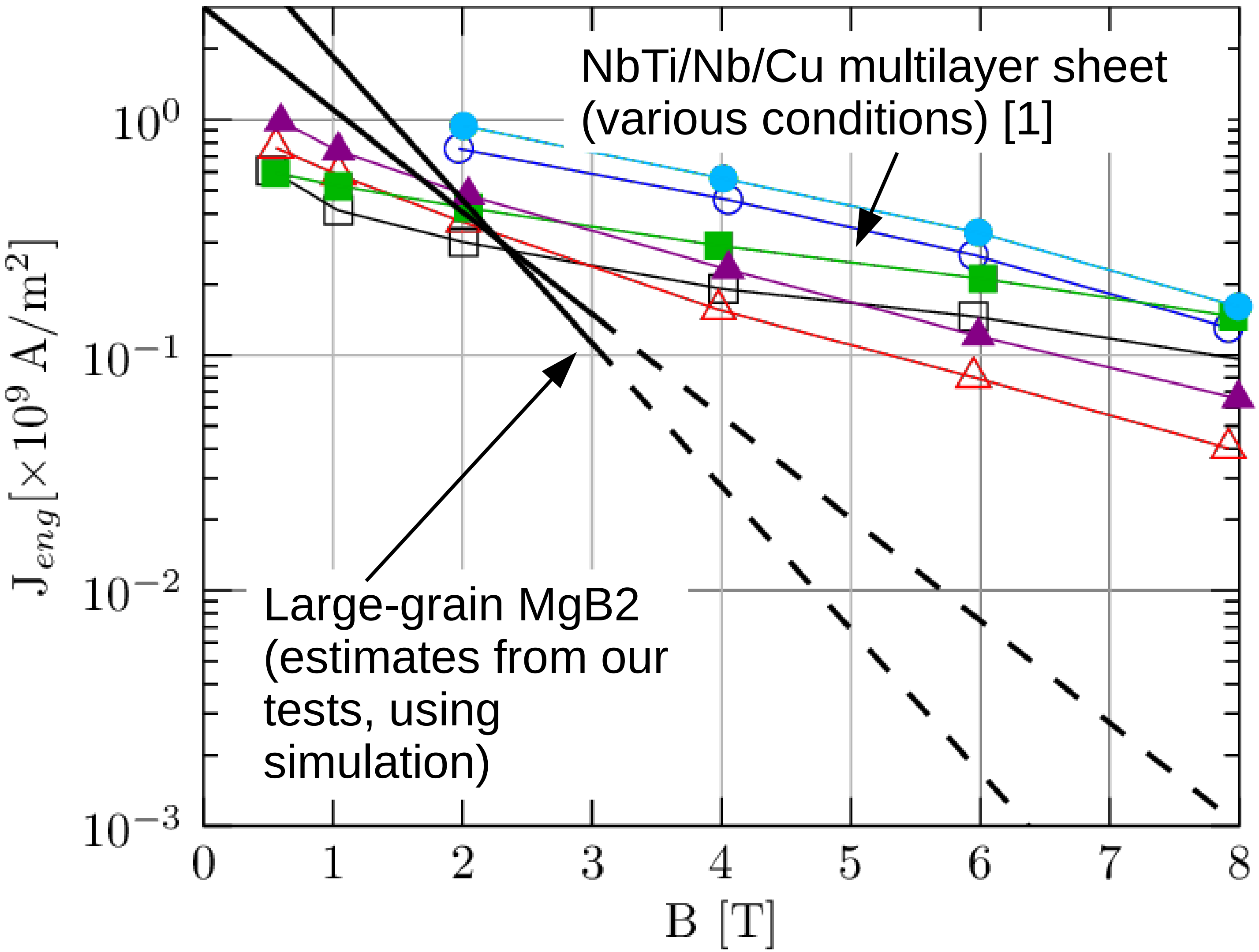
NbTi/Nb/Cu multilayer shield

- Consists of multilayer sheets of ~0.8mm, containing 30 layers of 9 µm NbTi
- From previous tests it seem possible to shield 2.5T field with 3 sheets (~2.4mm)
- A 4-sheet shield will be tested in the beginning of next year



- I.Itoh, K.Fujisawa, H.Otsuka: NbTi/Nb/Cu Multilayer Composite Materials for Superconducting Magnetic Shielding, Nippon Steel Technical Report No. 85, January 2002

Shielding performance



Exponential

$J_c(B)=J_0 \cdot \exp(-\gamma B)$

leads to exponential increase of required thickness:

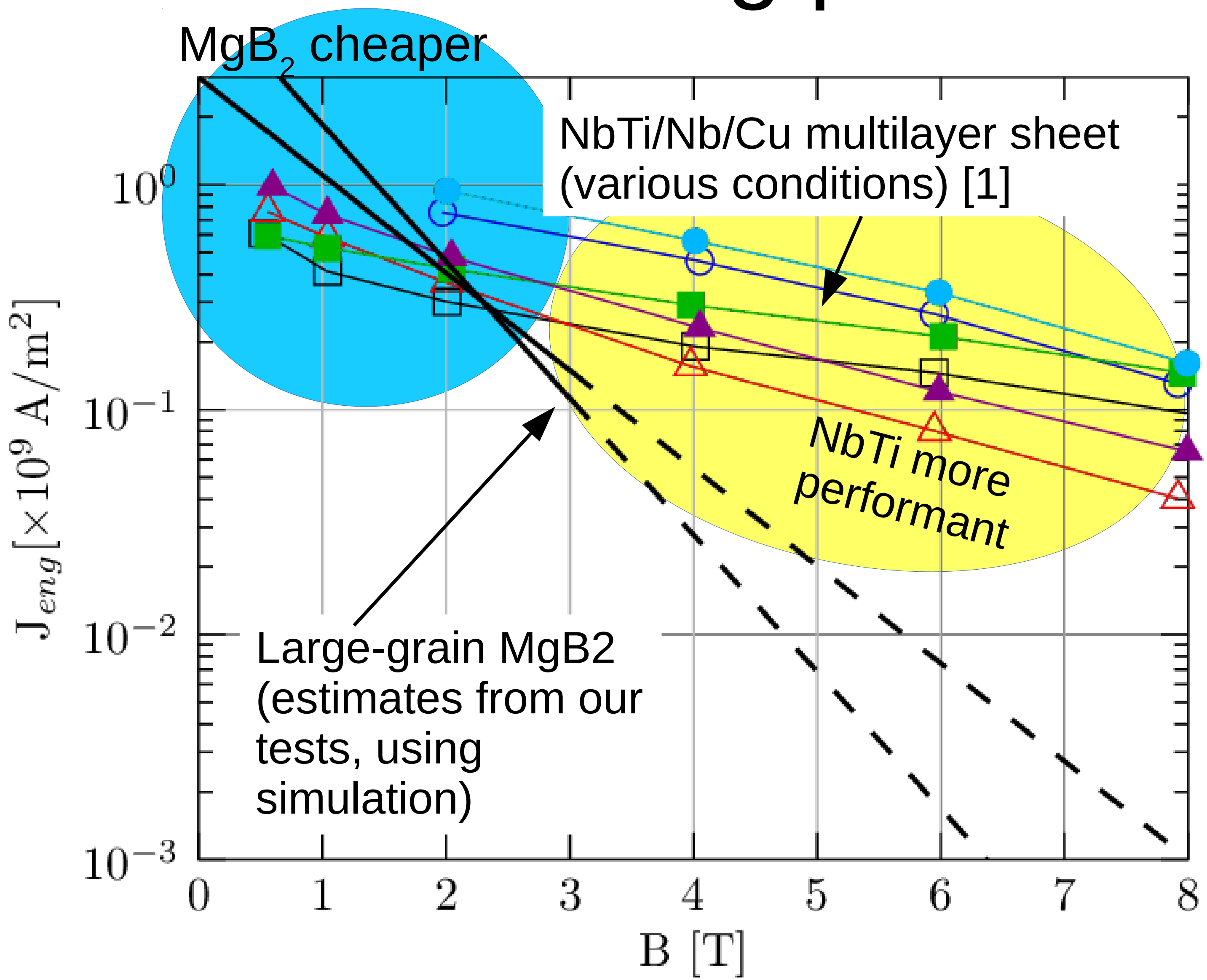
$d = d_0 \cdot \exp(\gamma B)$

with $d_0 = 1/\gamma\mu_0 J_0$

For MgB_2: roughly x3 increase for +1 T

[1] I.Itoh, T.Sasaki, Cryogenics 35 (1995) 403

Shielding performance



Exponential

$J_c(B) = J_0 \cdot \exp(-\gamma B)$

leads to exponential increase of required thickness:

$d = d_0 \cdot \exp(\gamma B)$

with $d_0 = 1/\gamma \mu_0 J_0$

For MgB_2: roughly x3 increase for +1 T

[1] I.Itoh, T.Sasaki, Cryogenics 35 (1995) 403

Outlook

- Passive superconductors:
  - Perfect shielding if thickness is sufficient
  - Up to very high fields
  - DC and AC mode
  - Very attractive if space is tight
  - Very versatile:
    - MgB_2: large bulk, complex shapes, EDM machining, cheap
    - NbTi multilayer: ductile, robust, formable
- Future plans:
  - Measurement of third prototype
  - Construct a full demonstrator

Thank you for your attention!

Acknowledgements

- FCC Study group
- CERN SM18 (M. Bajko, H. Bajas, M. Strychalski)
- CERN TE-MSC-MM (C. Petrone, M. Buzio)
- CERN TE-ABT (B. Goddard, J. Borburgh, M. Atanasov, A. Sanz-Ull)
- G. Giunchi (MgB_2)
- A. Molodyk (SuperOx)
- European Commission (FP7/EUCARD-2, grant agreement no. 312453)
- Hungarian Academy of Sciences
- Wigner Research Centre for Physics, Budapest

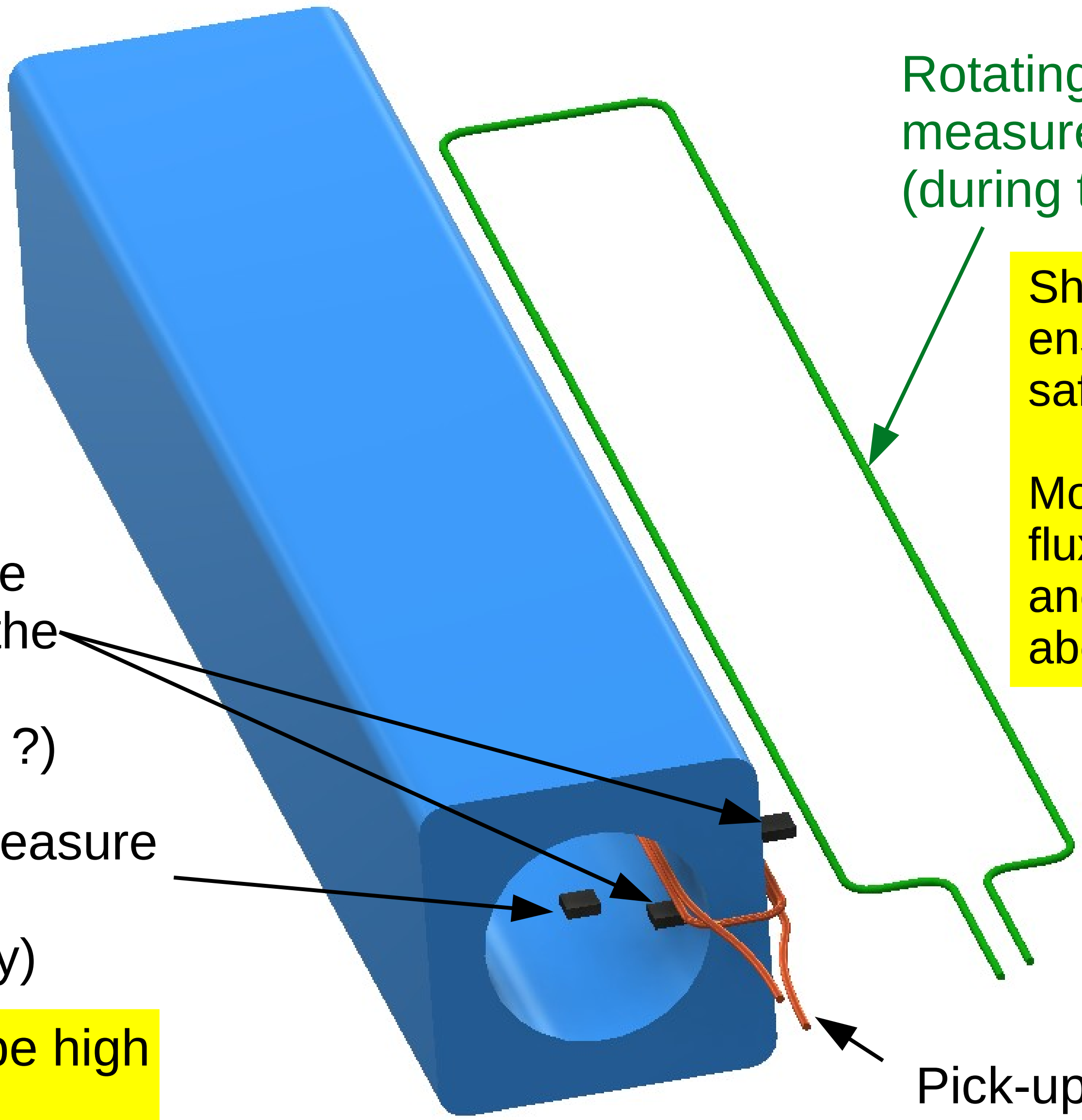
Additional slides

Measurement possibilities

Rotating coil to measure field quality (during tests only)

Shield thick enough to ensure **perfect shielding** safely...

Most important: detect flux-jumps (very quickly and reliably) → beam abort



Hall sensors close to the shield (off the mid-plane) (tests & real app. ?)

Hall sensor to measure the „zero field" (during tests only)

Do not need to be high precision

Pick-up coil to detect flux-jump (tests & real app.)

MgB_2: long-term relaxation