First experimental results with the SuShi septum prototypes

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Outline

- Motivation
- The SuShi concept
- Simulation
  - Field homogeneity
  - Massless septum
- Experimental results:
  - MgB_2
  - HTS
- Outlook

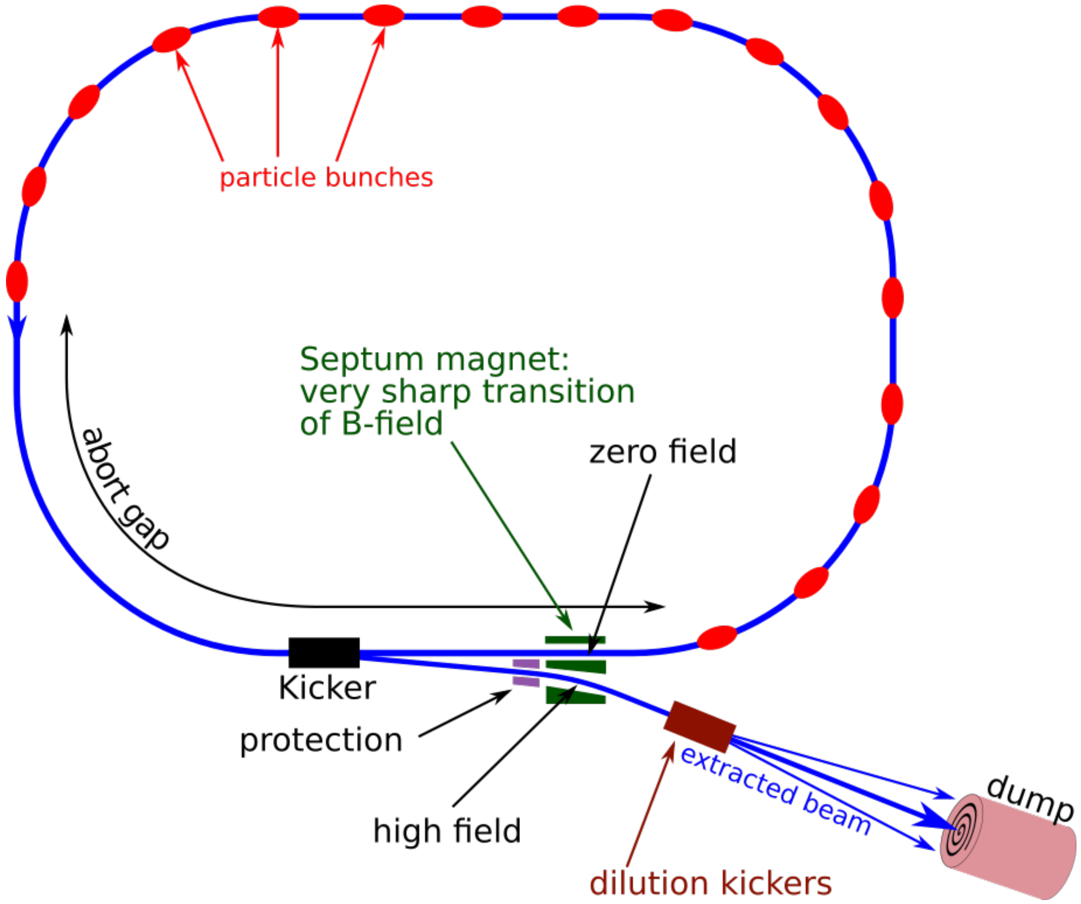
Kristóf Brunner, Anikó Német (Wigner RCP)

Miro Atanasov, Márta Bajkó, Hugues Bajas,
Carlo Petrone (CERN)

Giovanni Giunchi

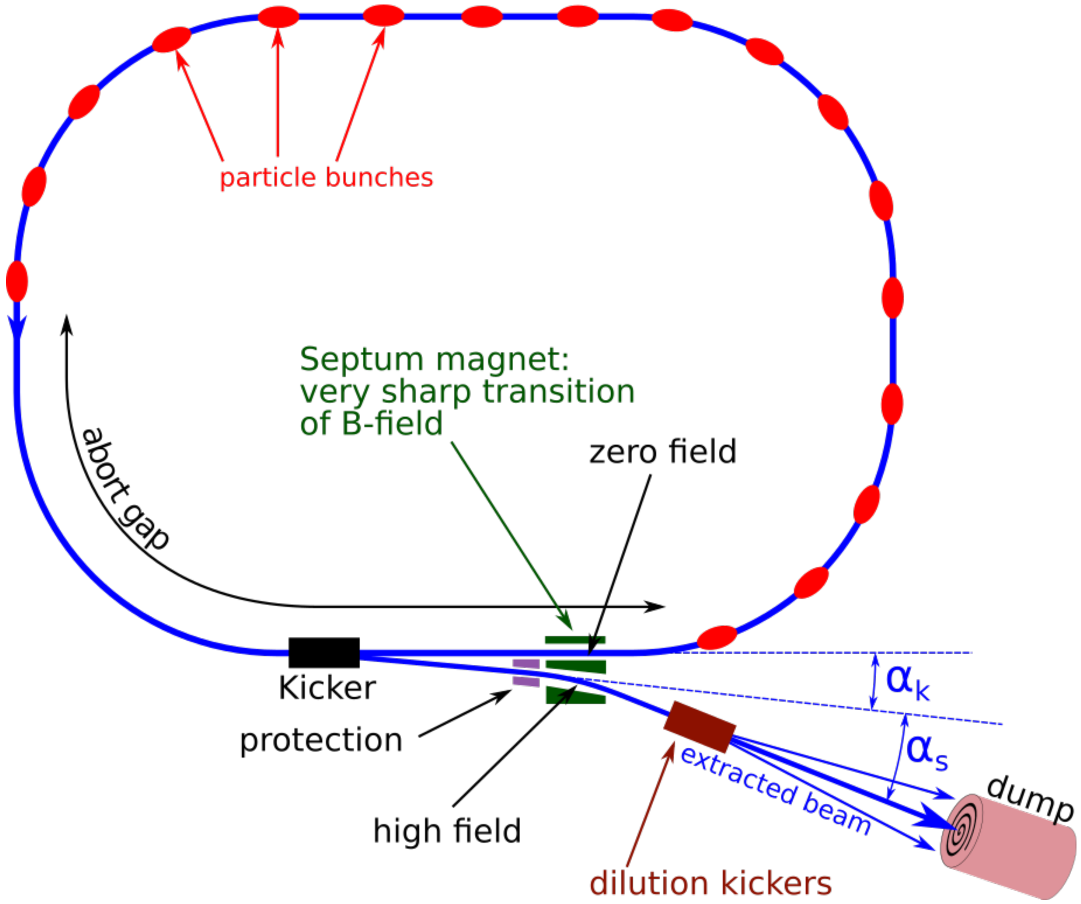
Alexander Molodyk (SuperOx)

FCC extraction scheme & parameters



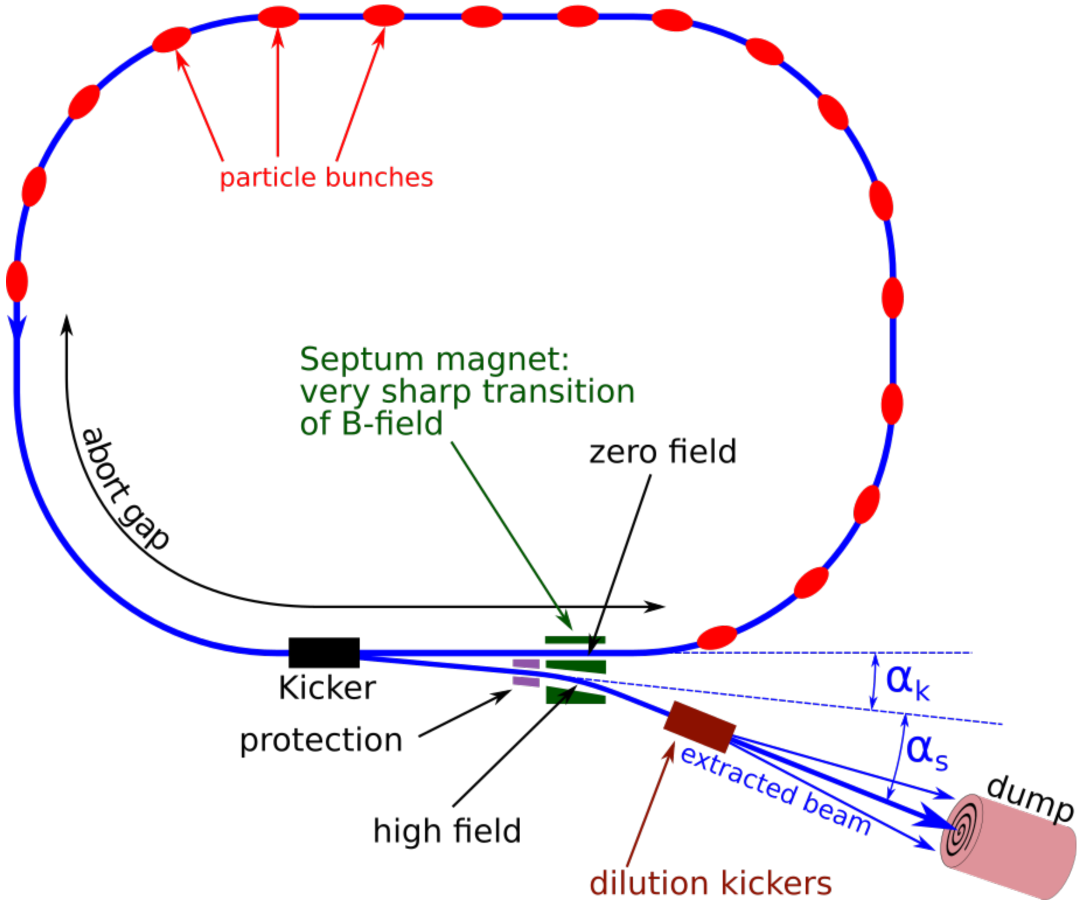
Injection is OK with LHC technology
(Lambertson septa)

FCC extraction scheme & parameters



Kicker angle α_k	0.045	mrad
Septum angle α_s	1.2	mrad
Septum integrated field	190	T m
Available space for septum	120	m

FCC extraction scheme & parameters



Kicker angle α_k	0.045	mrad
Septum angle α_s	1.2	mrad
Septum integrated field	190	T m
Available space for septum	120	m

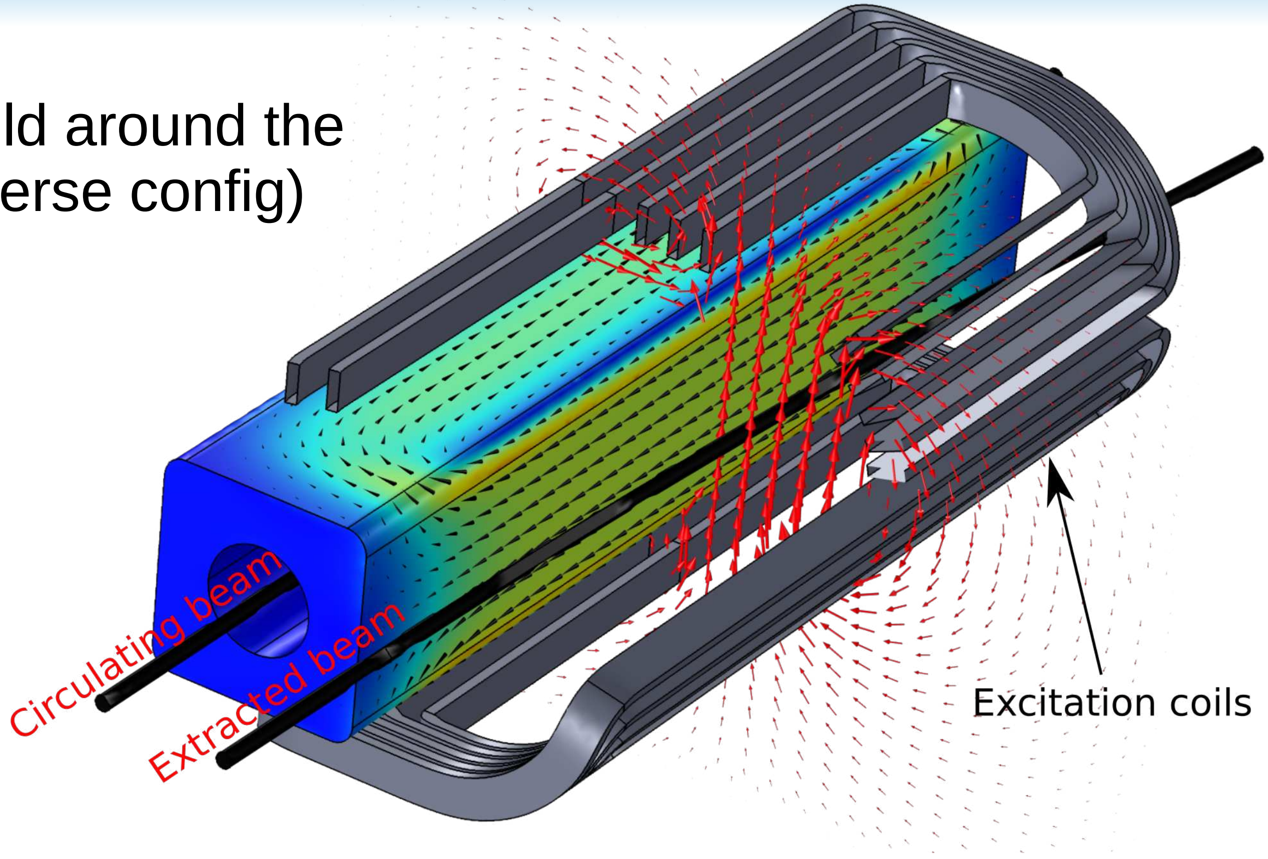
Need ≥ 2 T field
(to accomodate gate valves, pumps, etc)

Motivation, requirements

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

SuShi = **Su**perconducting **Sh**ield

- Put a superconducting shield around the circulating beam (or the inverse config)
- Cool below T_c in zero field
- Ramp up an external field
- Induced persistent eddy currents cancel the field inside
- Like an eddy current septum, but can work in quasi-DC mode



For details: D. Barna, PRAB 20 (2017), 041002
http://cern.ch/sushi-septum-project

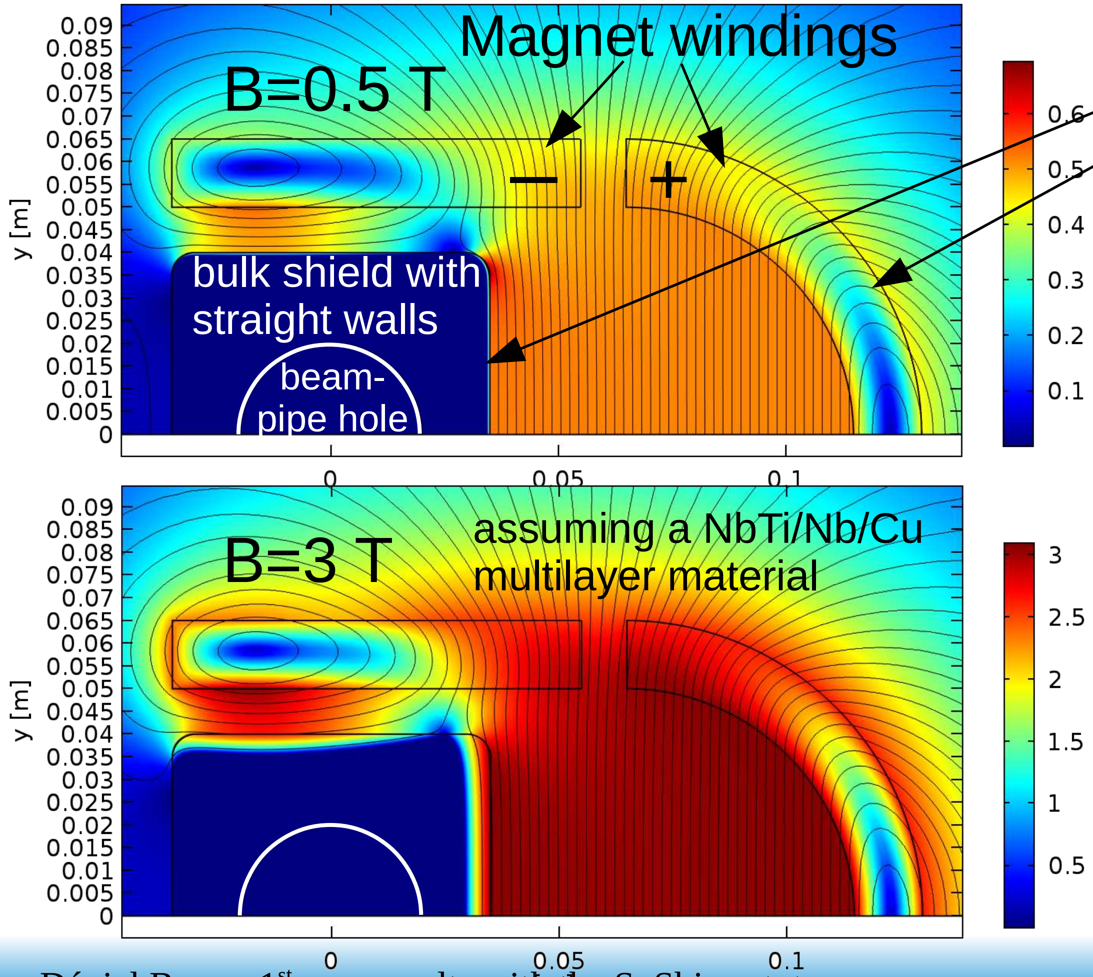
Pros & Cons

- Pros
  - Shielding currents arranged by nature precisely, not by us
  - Continuous 2D current distribution, with no leak (in contrast to a magnet's winding)
  - Critical state model: currents flow at J_c (i.e. highest possible value, thinnest possible septum blade)
  - Bulk superconductor, no windings, no interleaving insulation (better mechanical and thermal stability)
  - No quench heater needed
- Cons
  - Superconductors in potentially high rad zone → quench? (for all SC solutions)
  - Passive shield - hysteretic behaviour
  - Shield's state is not a unique function of the controllable parameters T and B_{ext} → must start from a 'virgin' state for each accelerator cycle.

Challenges compared to usual shielding applications

- Aimed field is high: >2 T (3-4 Tesla for a more compact system?)
- Must simultaneously **shield** the circulating beam, and **shape** a homogeneous field outside
- Coupled optimization of superconductor's shape and external magnet's geometry
- Homogeneity must hold independently from field strength, spanning a range of a factor 15 between injection/extraction

How to make a homogeneous field



Magnet windings

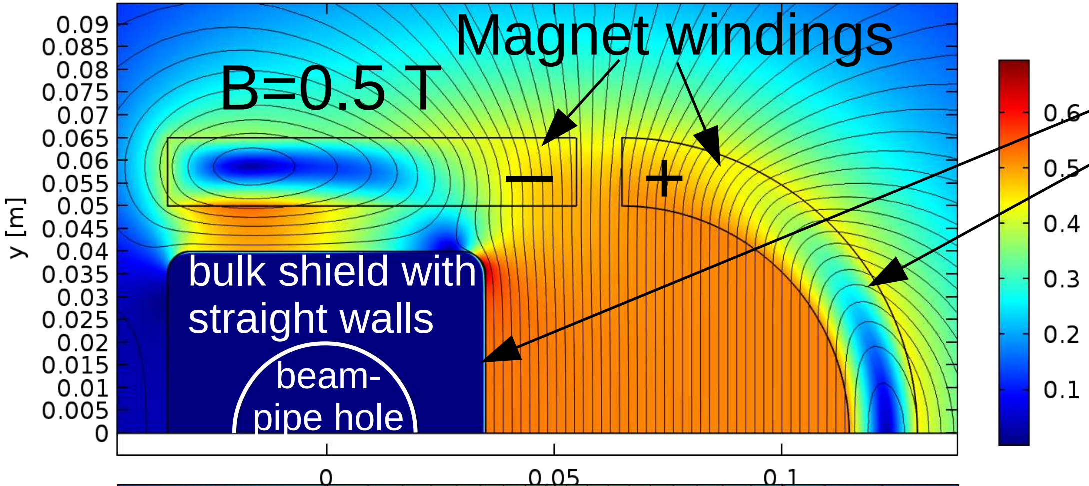
bulk shield with straight walls

truncated cos-θ-like configuration

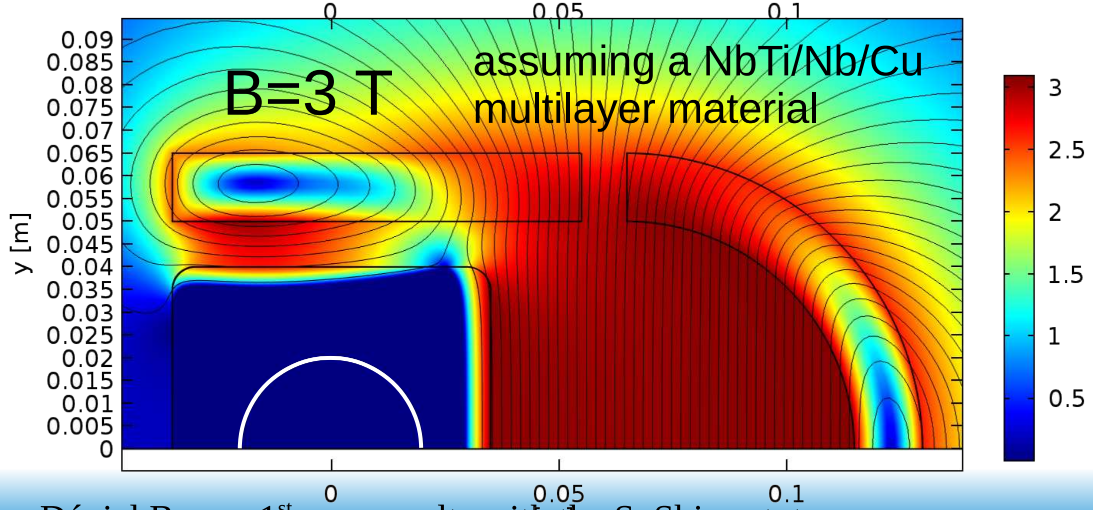
assuming a NbTi/Nb/Cu multilayer material

For details:
D. Barna, PRAB 20 (2017), 041002

How to make a homogeneous field

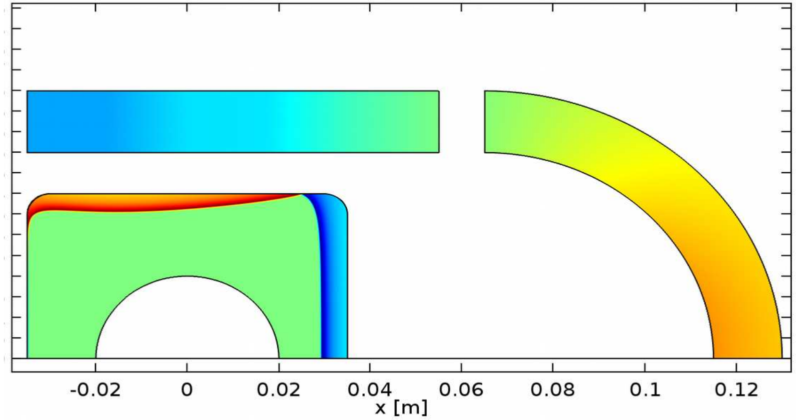


truncated cos-θ-like configuration



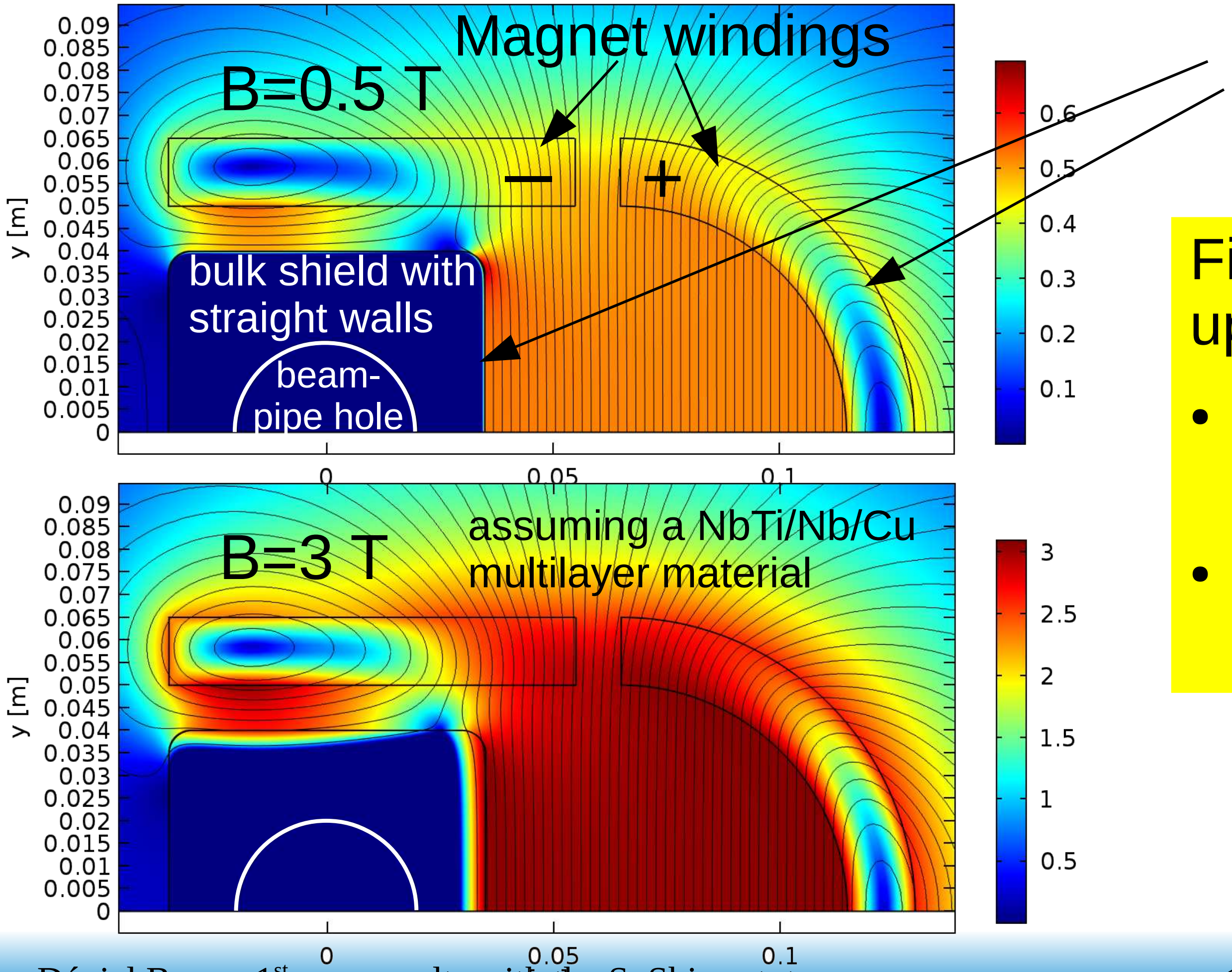
assuming a NbTi/Nb/Cu multilayer material

Excitation & shielding currents @ 3T (< 400 A/mm^2 in windings)



For details:
D. Barna, PRAB 20 (2017), 041002

How to make a homogeneous field


Magnet windings

bulk shield with straight walls

beam-pipe hole

assuming a NbTi/Nb/Cu multilayer material

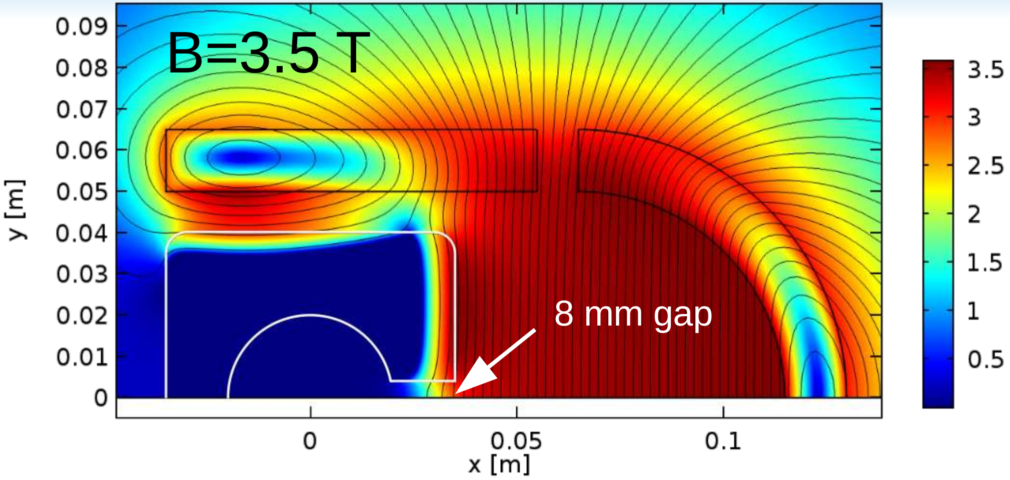
truncated cos-θ-like configuration

Field homogeneity: ΔB/B~1-2% up to 3 Tesla, over a 5 cm GFR

- despite different penetration depths
- with different SC materials

For details:
D. Barna, PRAB 20 (2017), 041002

Massless septum



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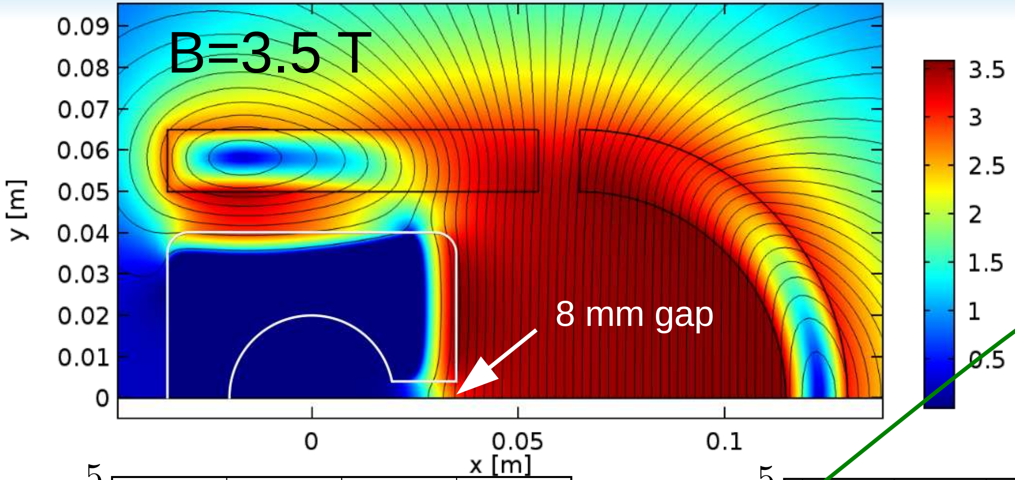
Massless septum



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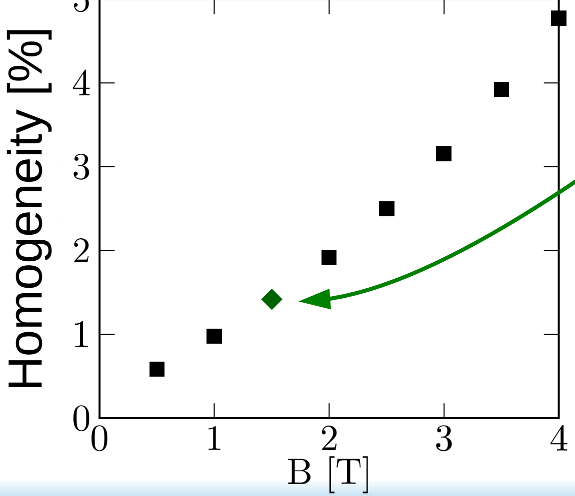
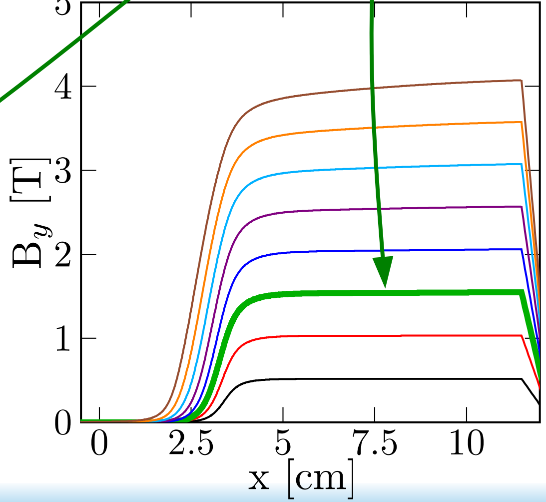
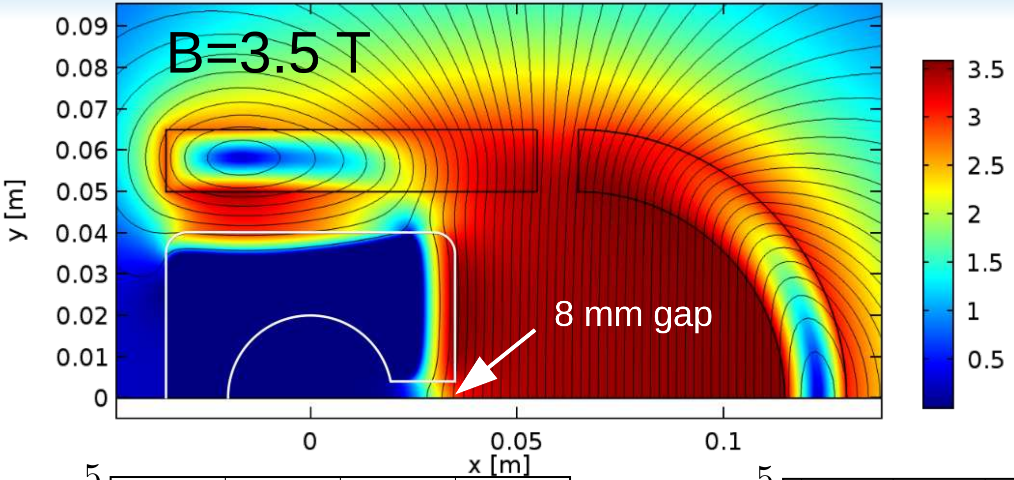
“Quite good” up to ~1.5 T:

- Homogeneity: 1.5%





Massless septum



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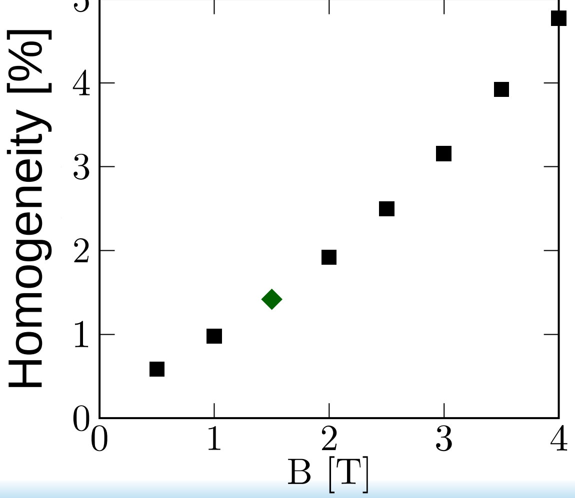
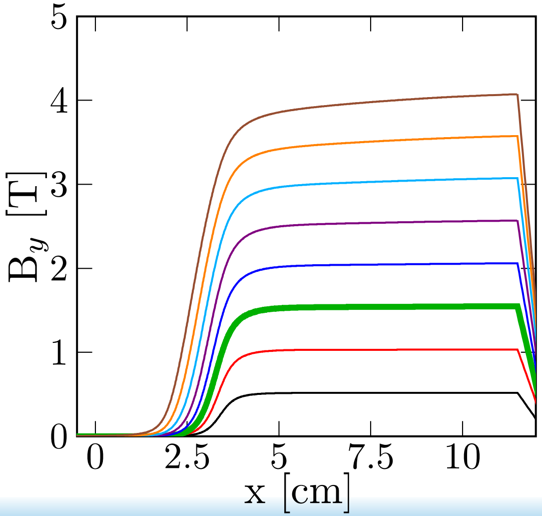
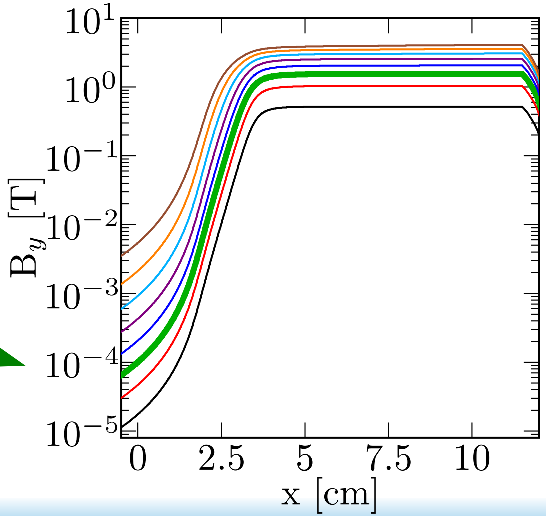
“Quite good” up to ~1.5 T:
- Homogeneity: 1.5%
- Attenuation: 10^{-4}





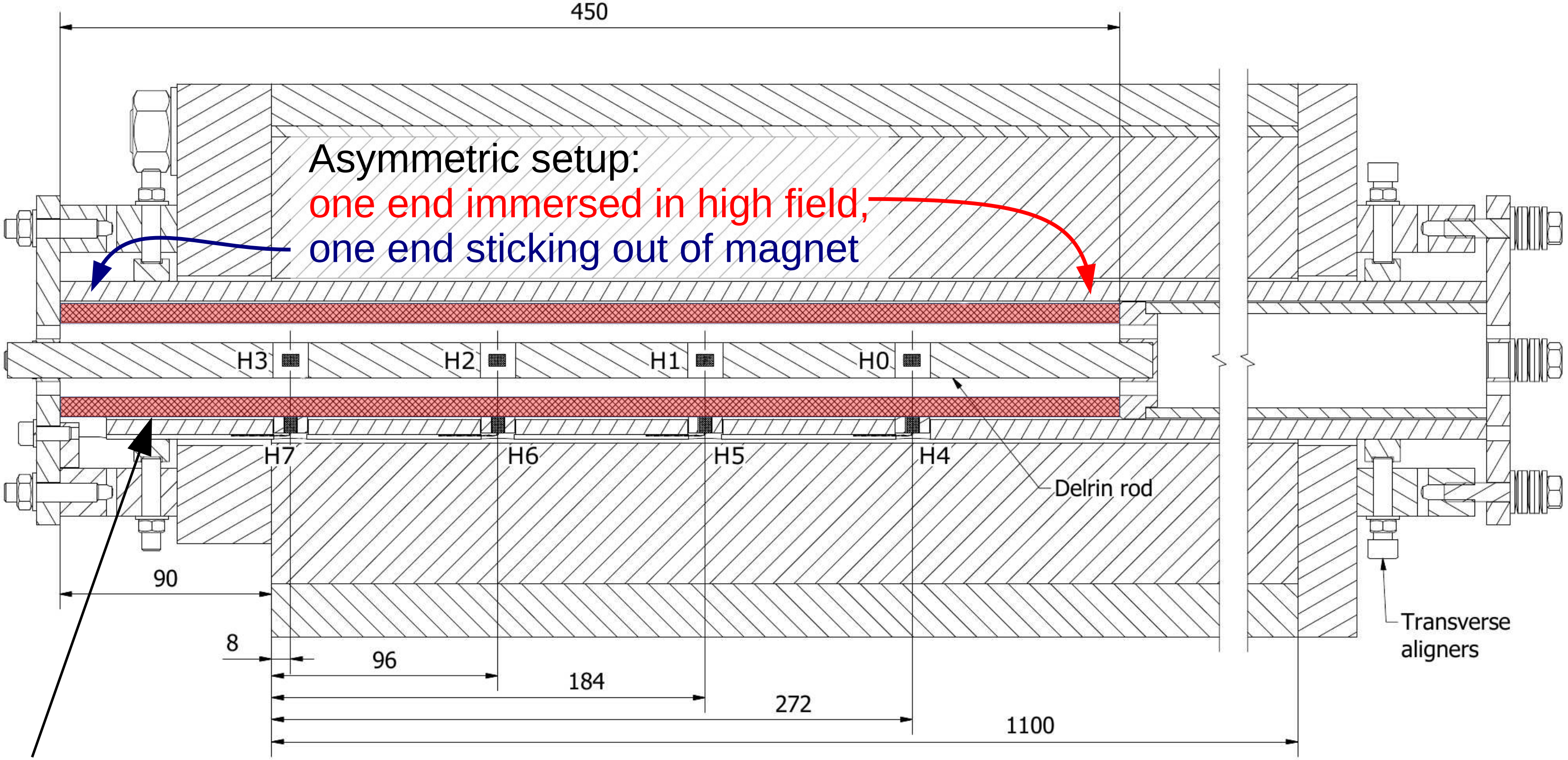


3 planned prototypes

- Quick and simple experiments → cylindrical shield in an existing magnet
  - Check highest shielded field
  - Check flux creep (slow relaxation of shielding currents)
  - Identify best material/technology for more sophisticated tests/prototypes
- Prototypes:
  - **MgB_2**
  - **HTS**
  - NbTi/Nb/Cu multilayer
- Shield parameters:
  - 450 mm length (to exceed the originally planned LHC MQSX magnet's length)
  - 50 mm outer diameter (to easily fit into the 70 mm bore of the magnet)

Experimental setup

MQSX was not available. Used magnet: MCBY (length: 1100 mm, bore: 70 mm)

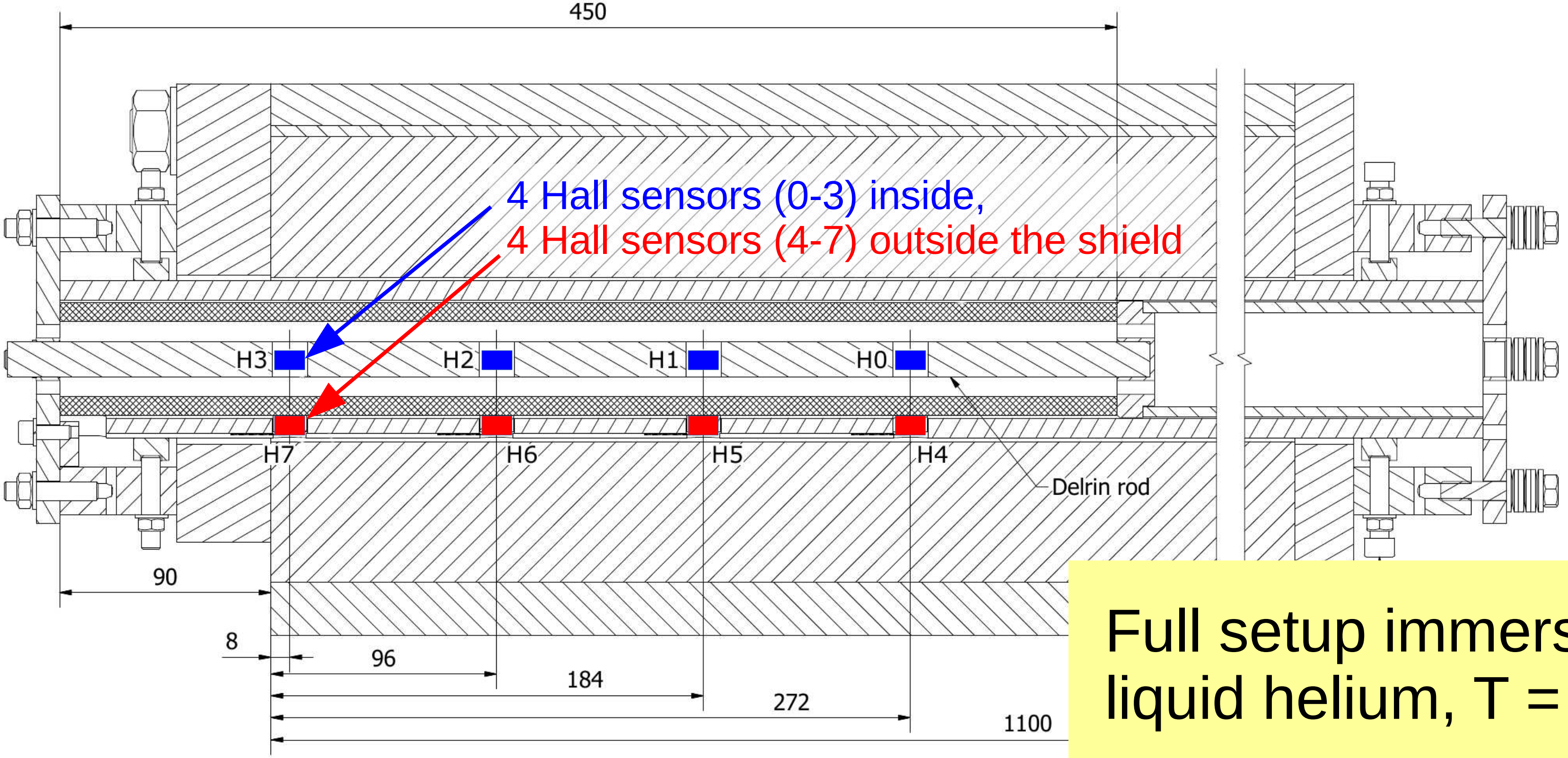


Asymmetric setup:
one end immersed in high field,
one end sticking out of magnet

Superconducting shield

Experimental setup

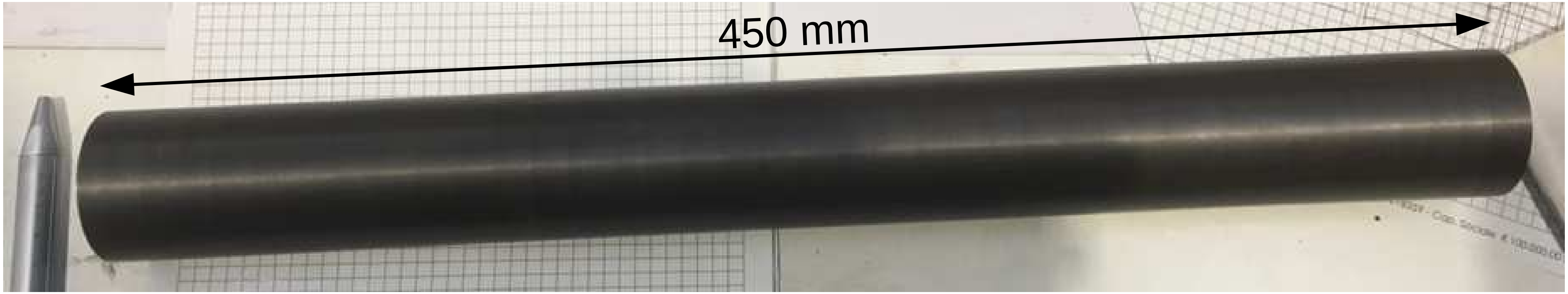
MQSX was not available. Used magnet: MCBY (length: 1100 mm, bore: 70 mm)

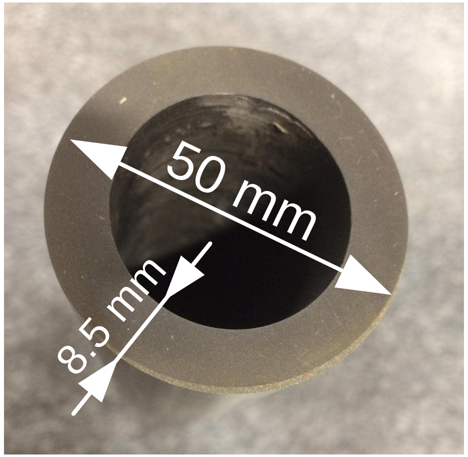

4 Hall sensors (0-3) inside,

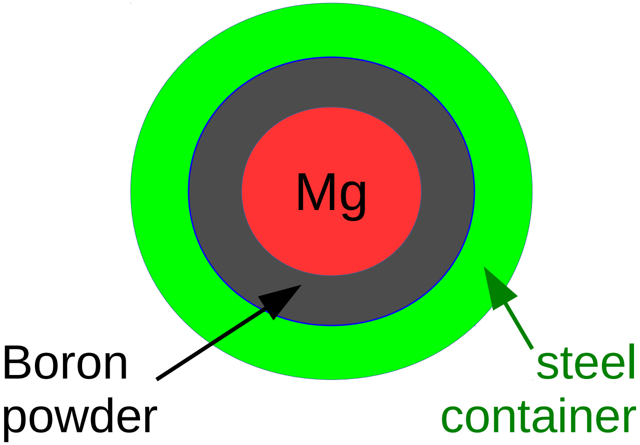
4 Hall sensors (4-7) outside the shield

Full setup immersed in liquid helium, T = 4.2 K

The MgB_2 shield

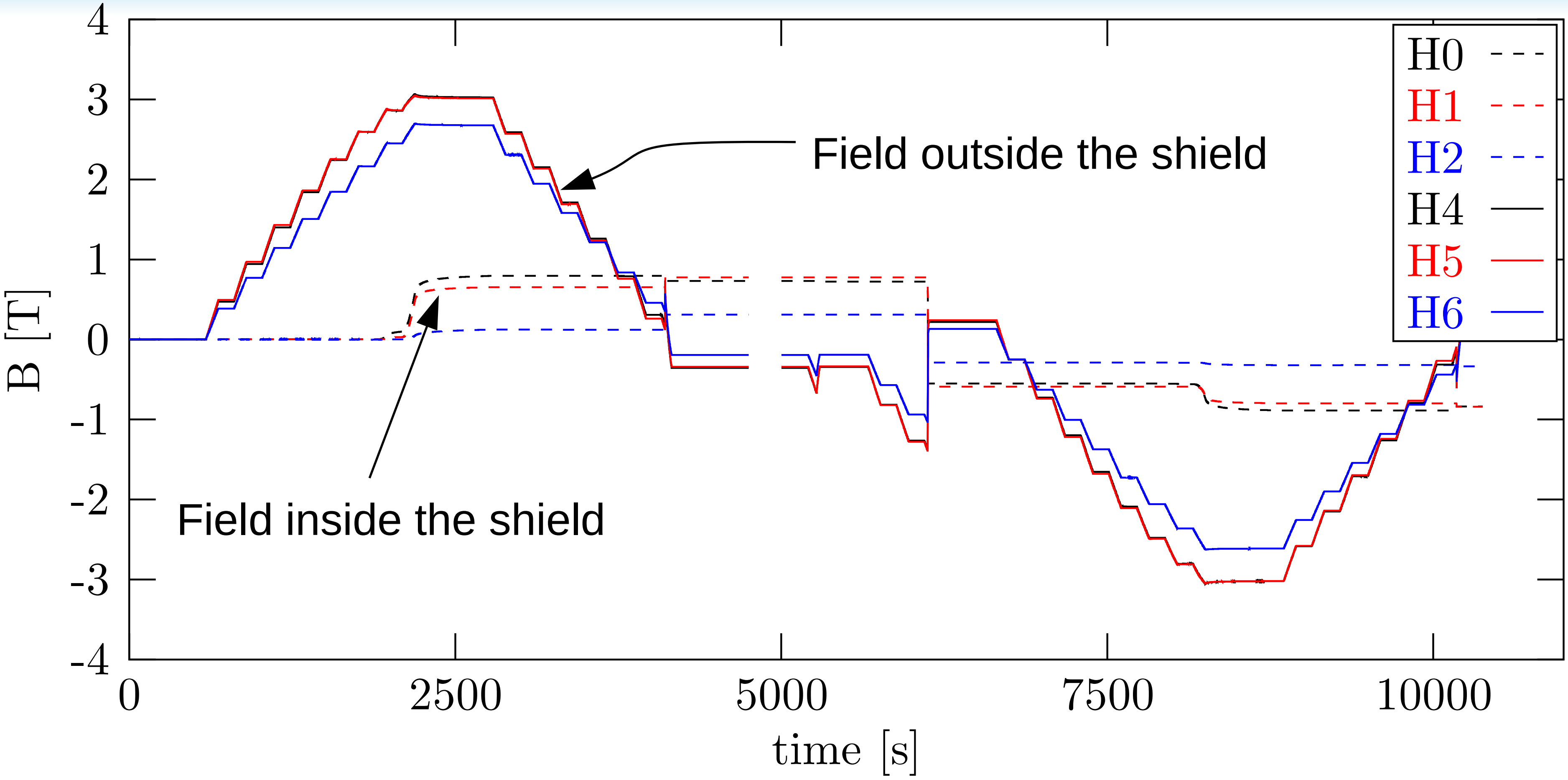






- Produced by the Reactive Liquid Magnesium Infiltration (RLI) process (G. Giunchi, Int.J.Mod.Phys.B17,453)
- Extra large boron grainsize (160 µm) to be stable against flux jumps (G.Giunchi et al, IEEE Trans. Appl. Supercond. 26, 8801005)

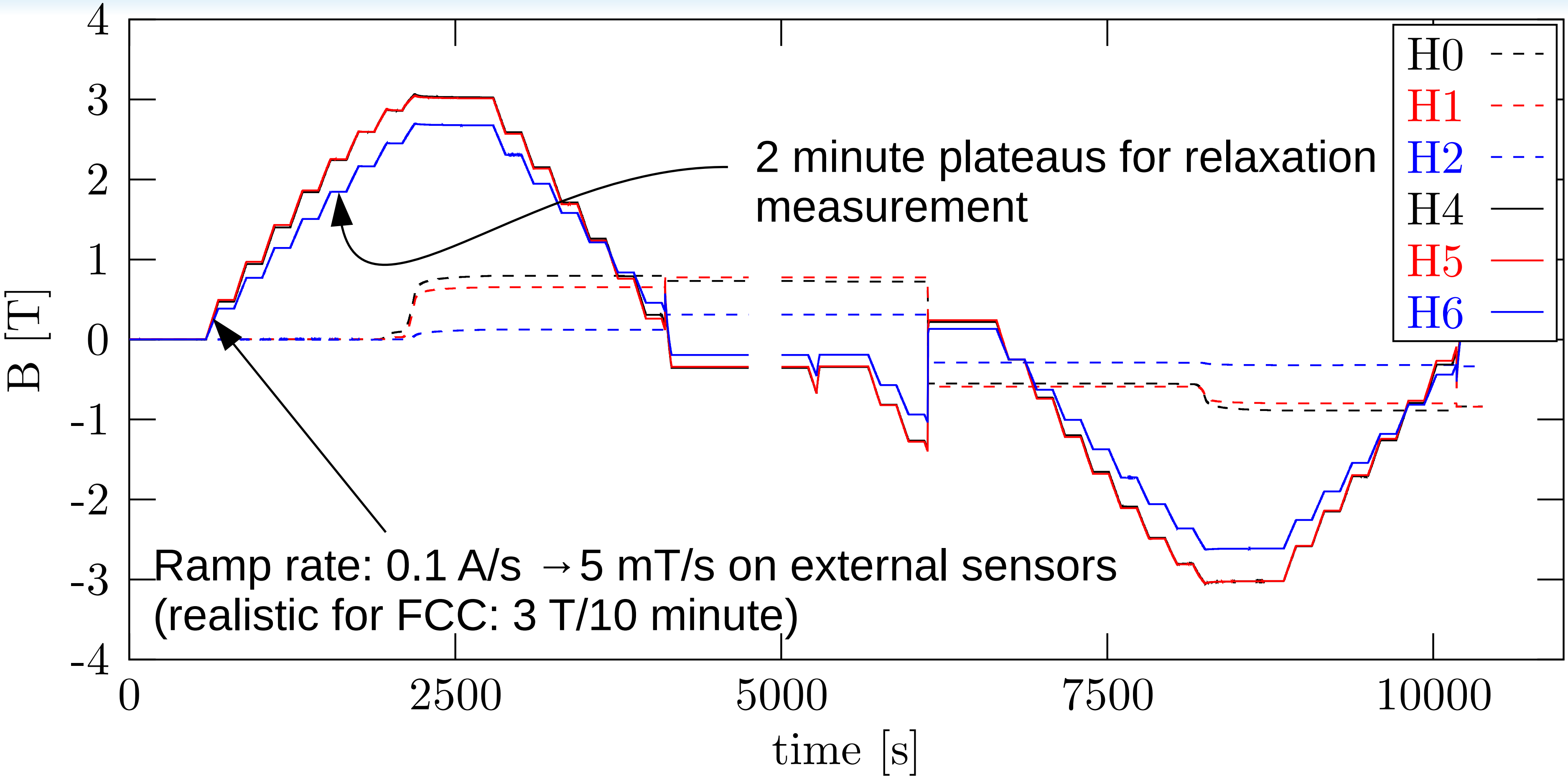
MgB_2 magnetization cycle



Field outside the shield

Field inside the shield

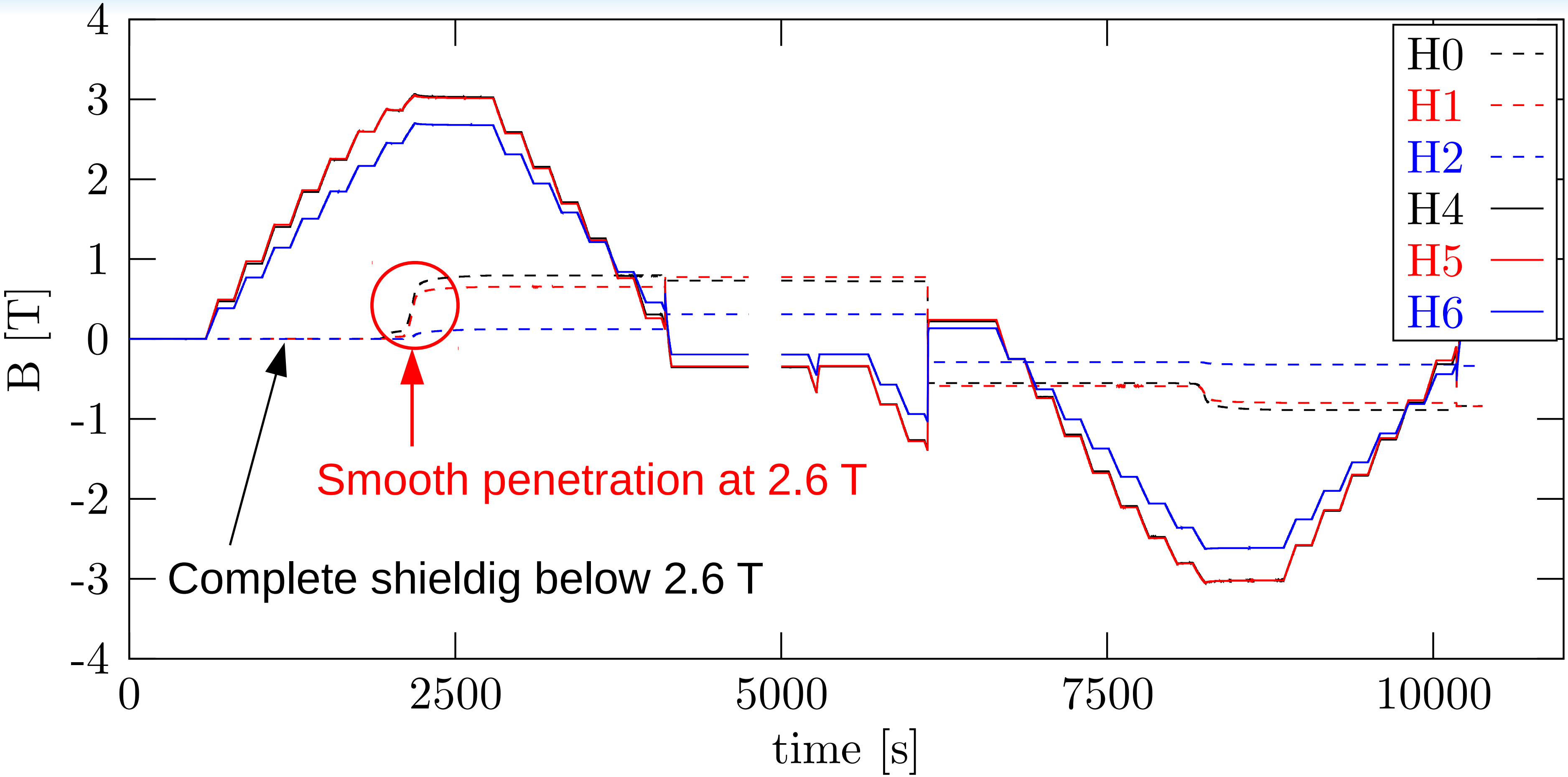
MgB$_2$ magnetization cycle



2 minute plateaus for relaxation measurement

Ramp rate: 0.1 A/s → 5 mT/s on external sensors
(realistic for FCC: 3 T/10 minute)

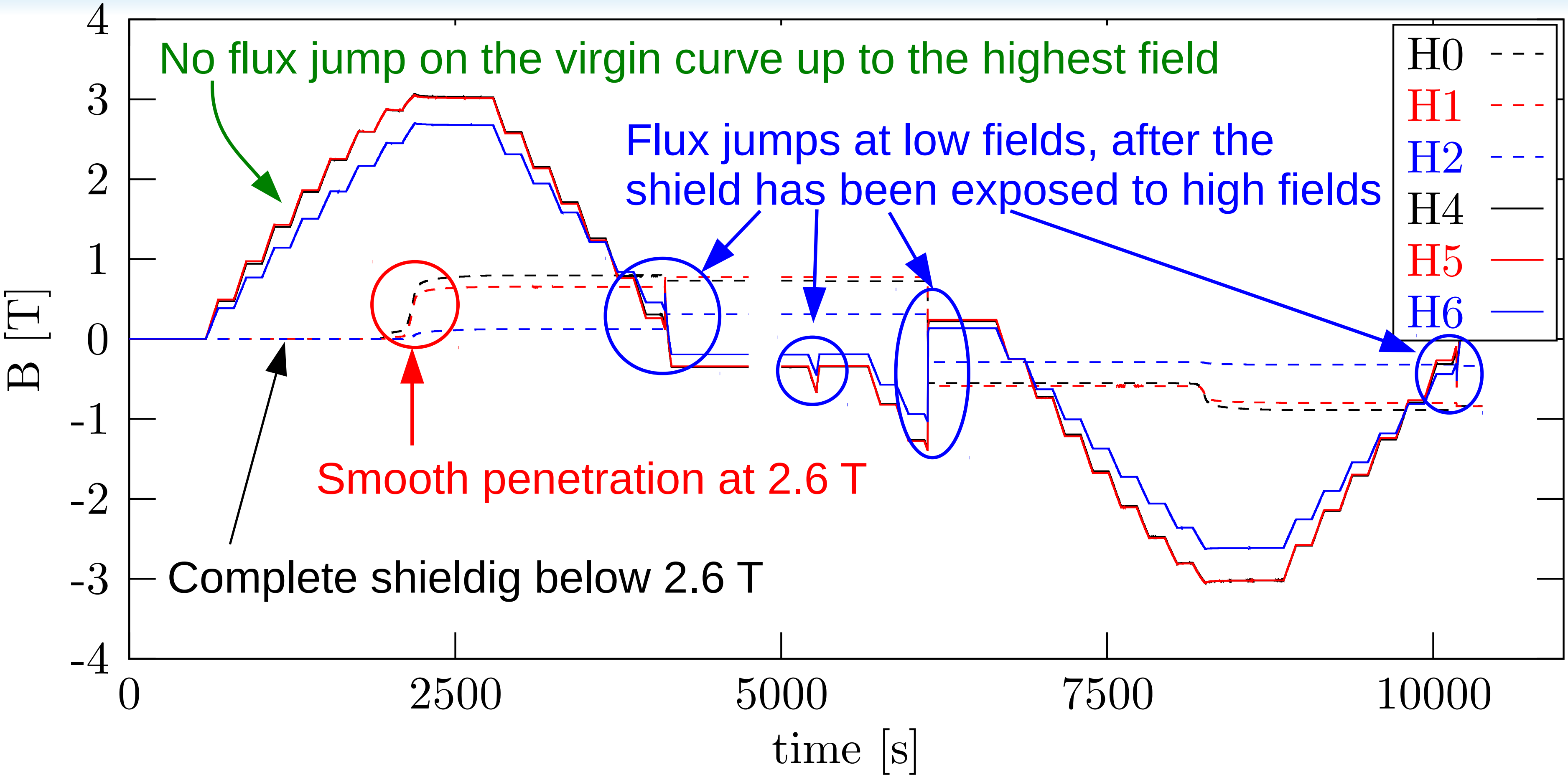
MgB$_2$ magnetization cycle



Smooth penetration at 2.6 T

Complete shieldig below 2.6 T

MgB_2 magnetization cycle



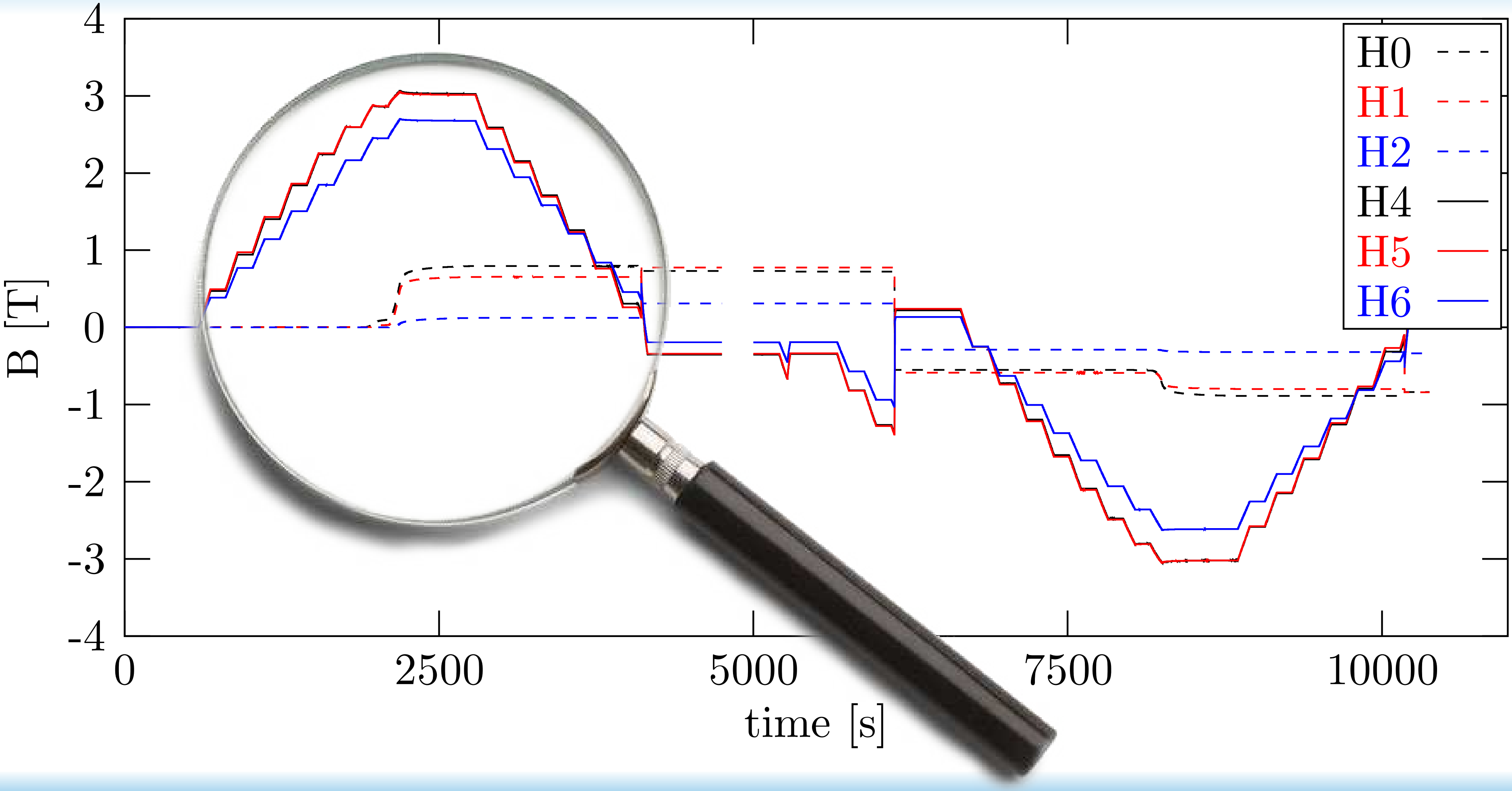
No flux jump on the virgin curve up to the highest field

Flux jumps at low fields, after the shield has been exposed to high fields

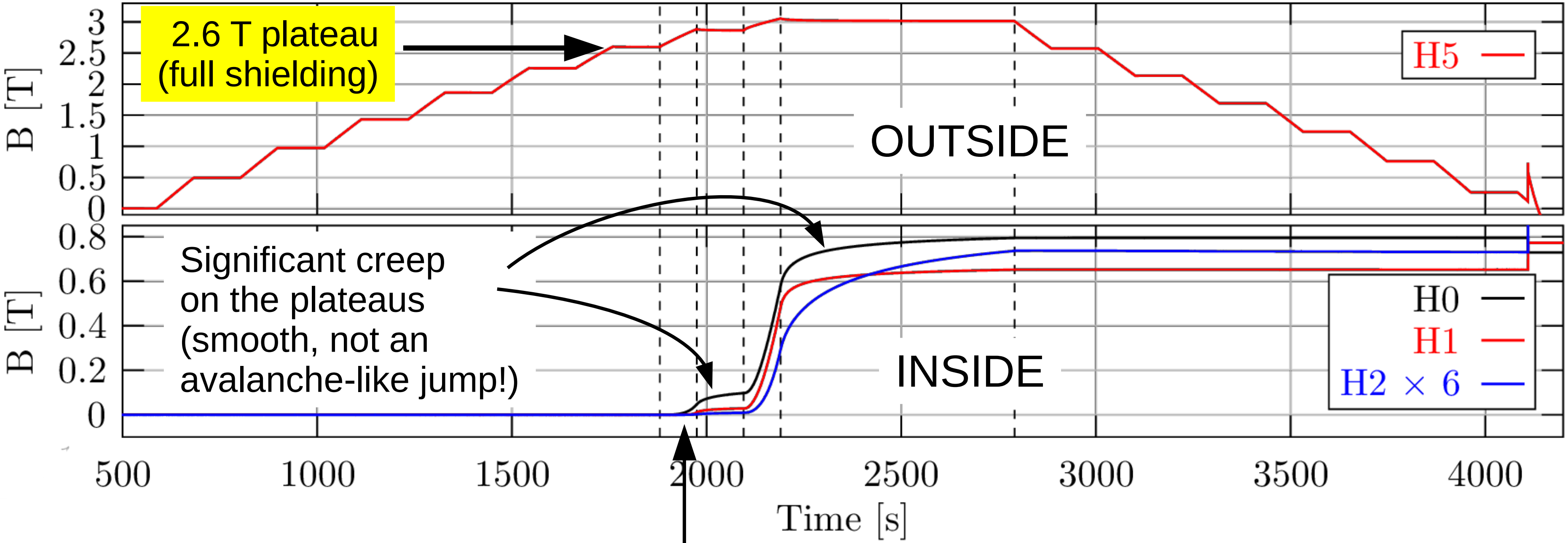
Smooth penetration at 2.6 T

Complete shieldig below 2.6 T

MgB_2 magnetization cycle



MgB$_2$: field penetration



2.6 T plateau
(full shielding)

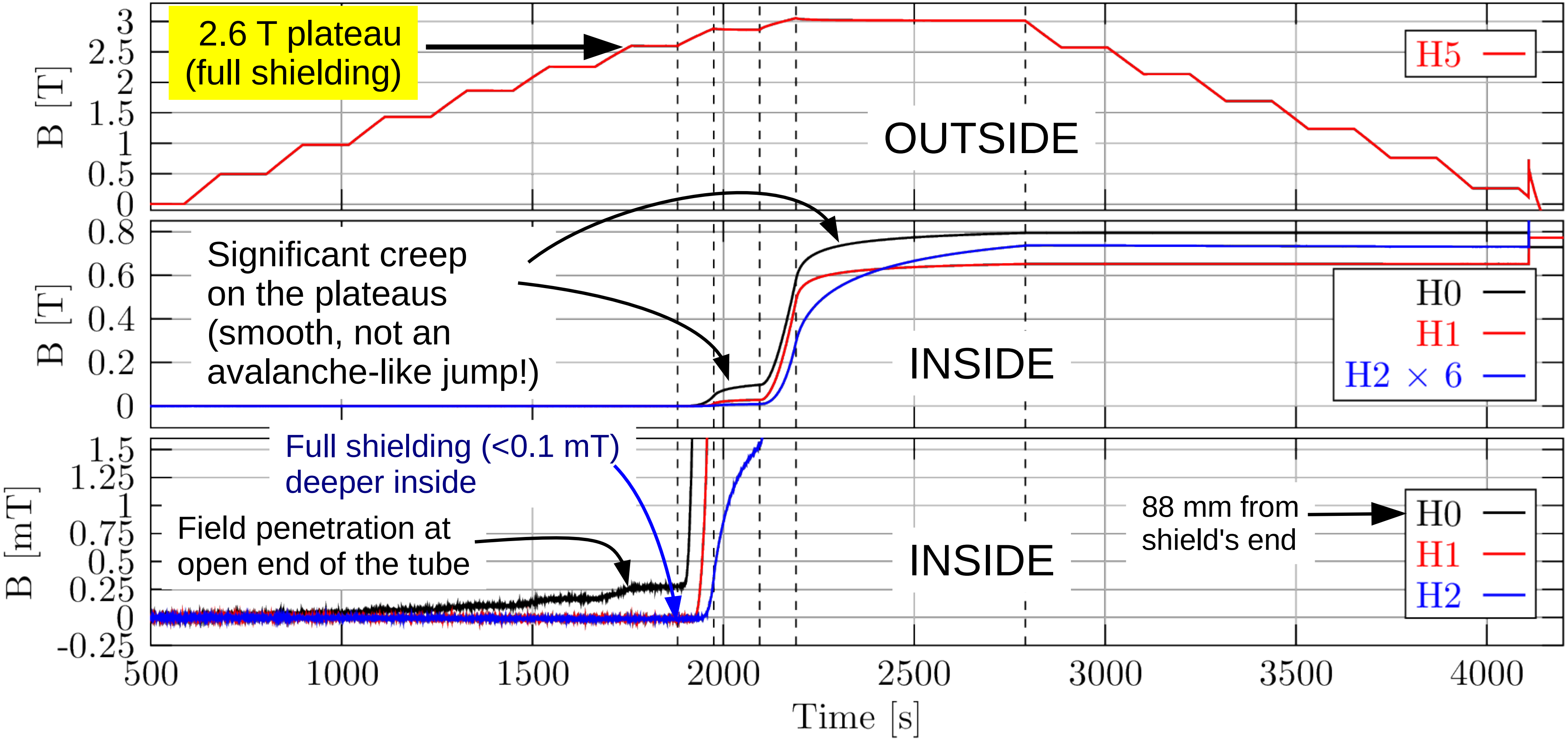
OUTSIDE

Significant creep
on the plateaus
(smooth, not an
avalanche-like jump!)

INSIDE

64 A magnet current

MgB_2: field penetration



2.6 T plateau
(full shielding)

Significant creep
on the plateaus
(smooth, not an
avalanche-like jump!)

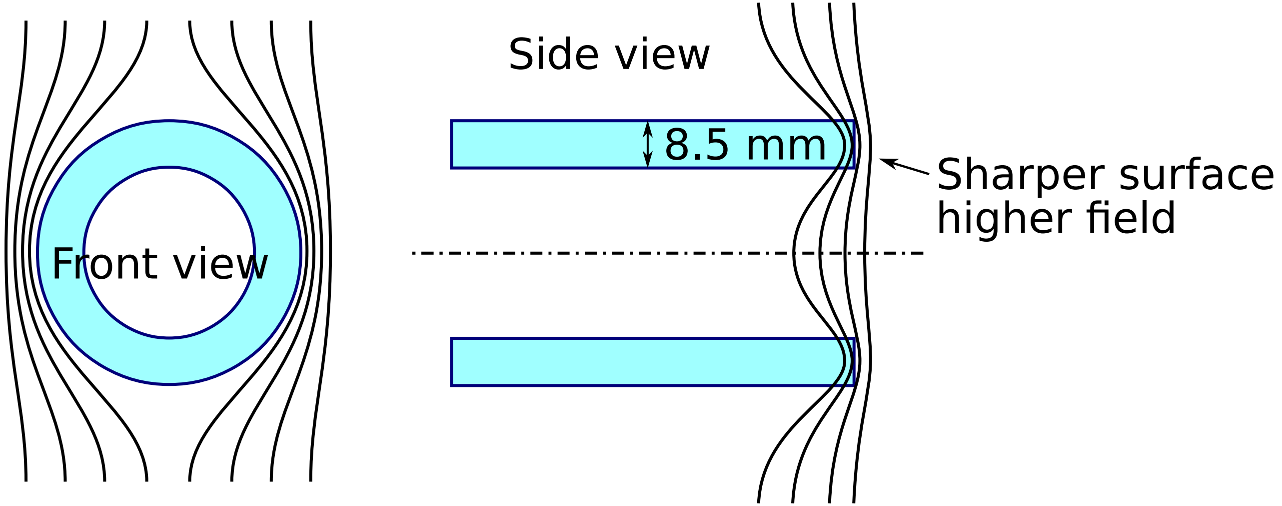
Full shielding (<0.1 mT)
deeper inside

Field penetration at
open end of the tube

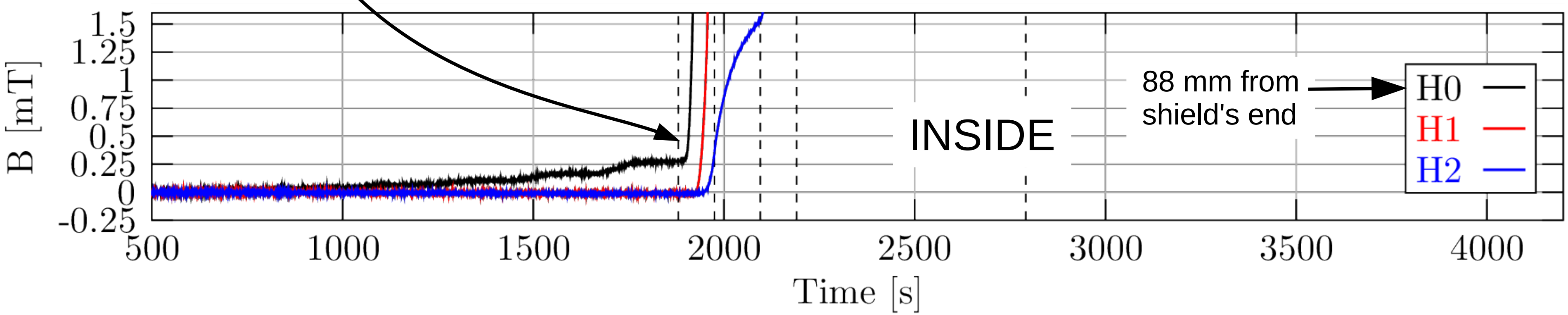
88 mm from
shield's end

MgB$_2$: field penetration

Breakdown proceeds from the end? End effect?

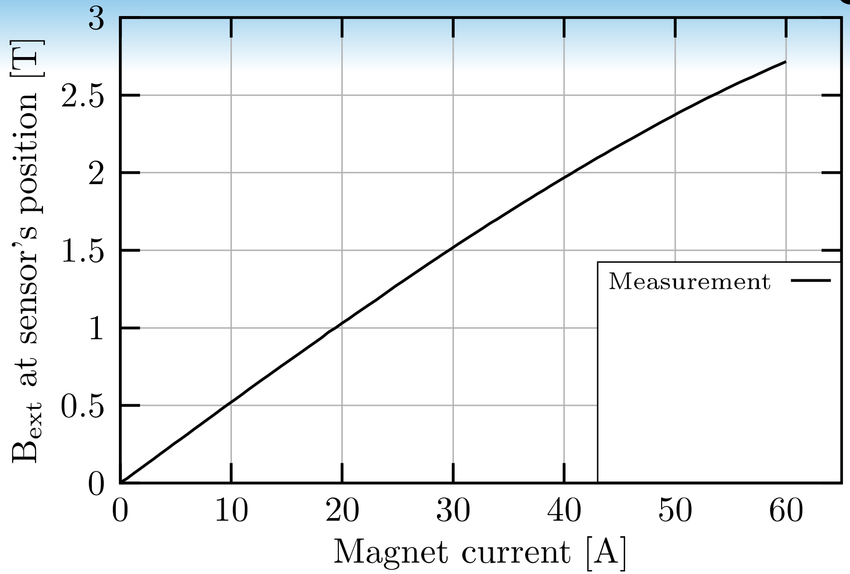


Sharper surface higher field



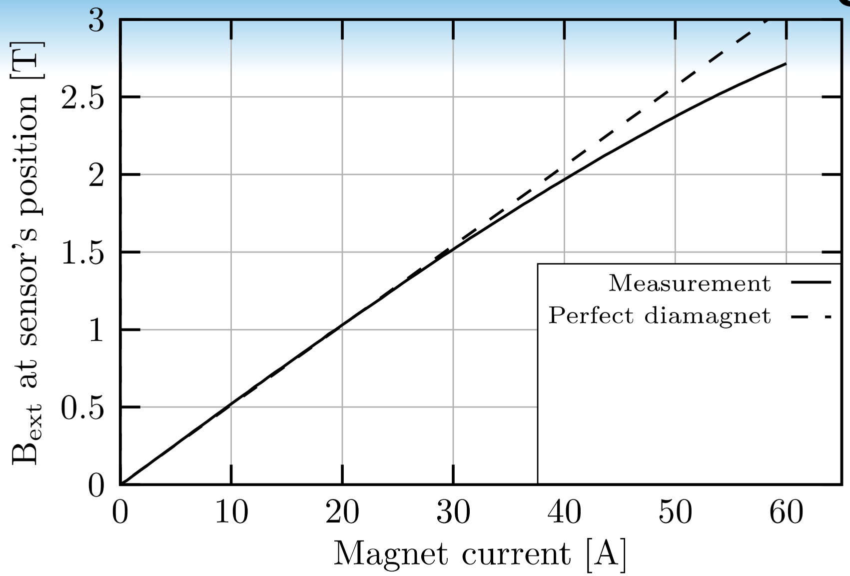
88 mm from shield's end

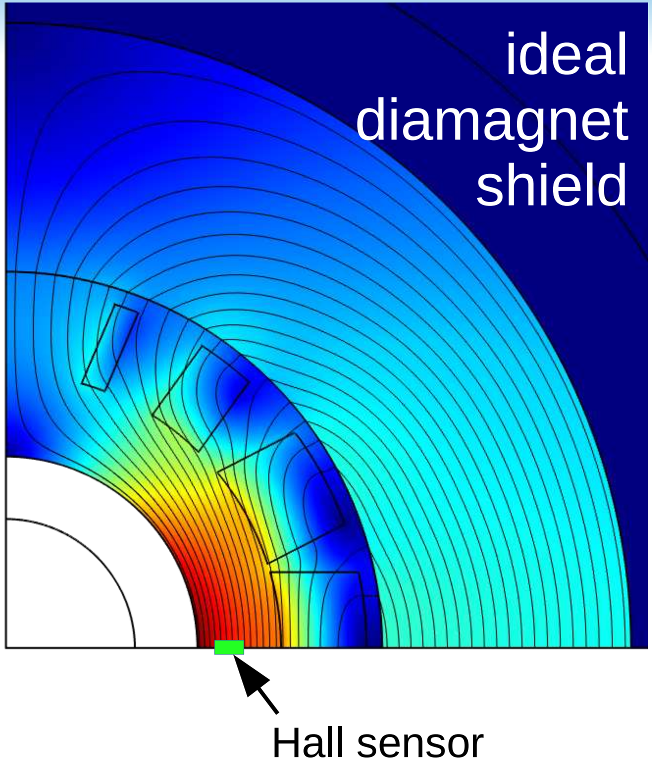
MgB_2: linearity



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

MgB_2: linearity

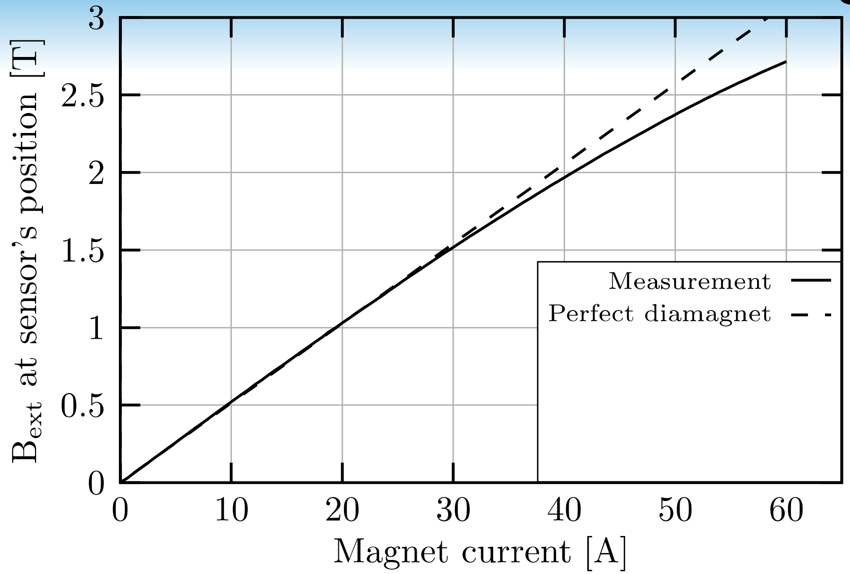


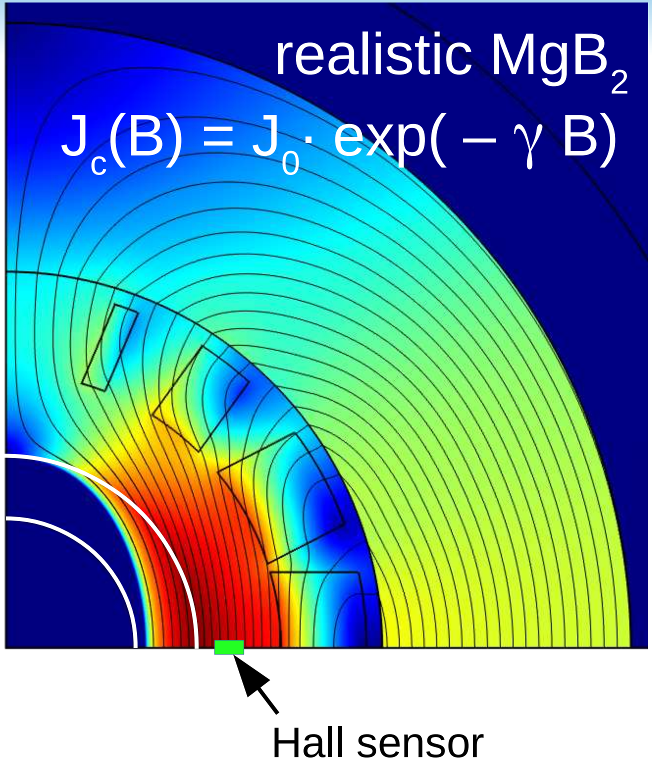


COMSOL simulation in precise model of MCBY magnet

Observed nonlinearity is not due to MCBY's iron

MgB_2: linearity

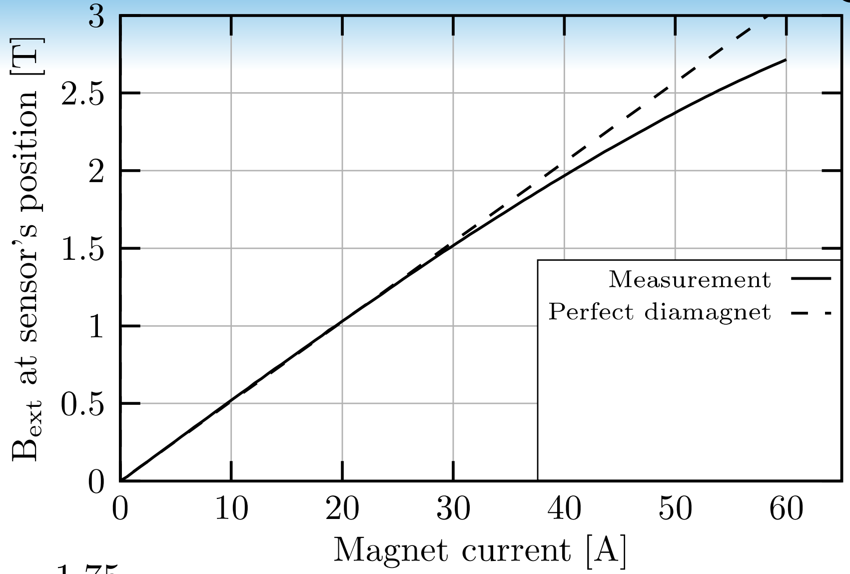


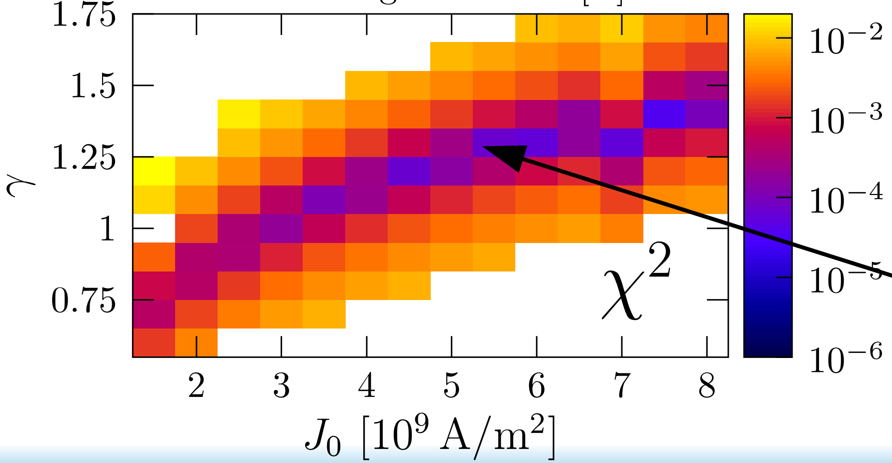


COMSOL simulation in precise model of MCBY magnet

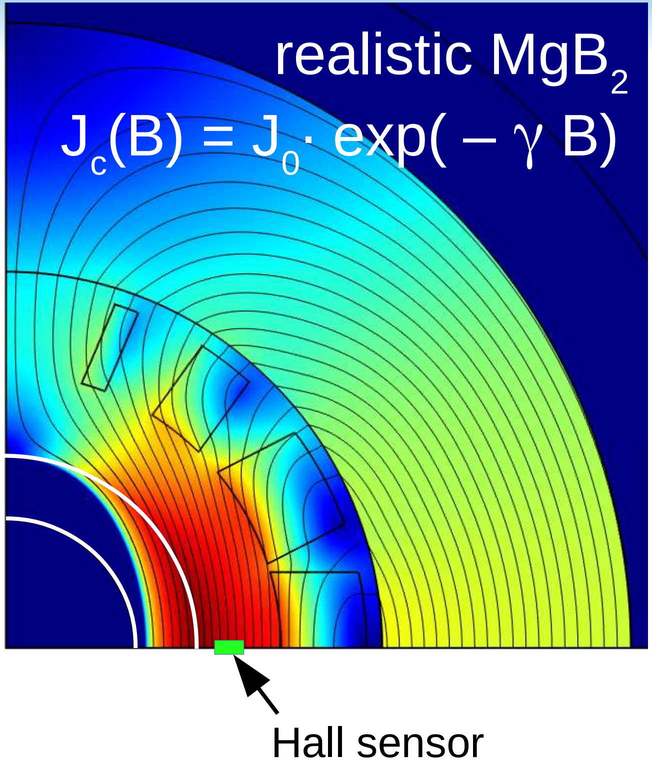
- Increasing field → more penetration
- Effective shielding surface drifts away from Hall sensor
- Less field concentration at sensor

MgB$_2$: linearity



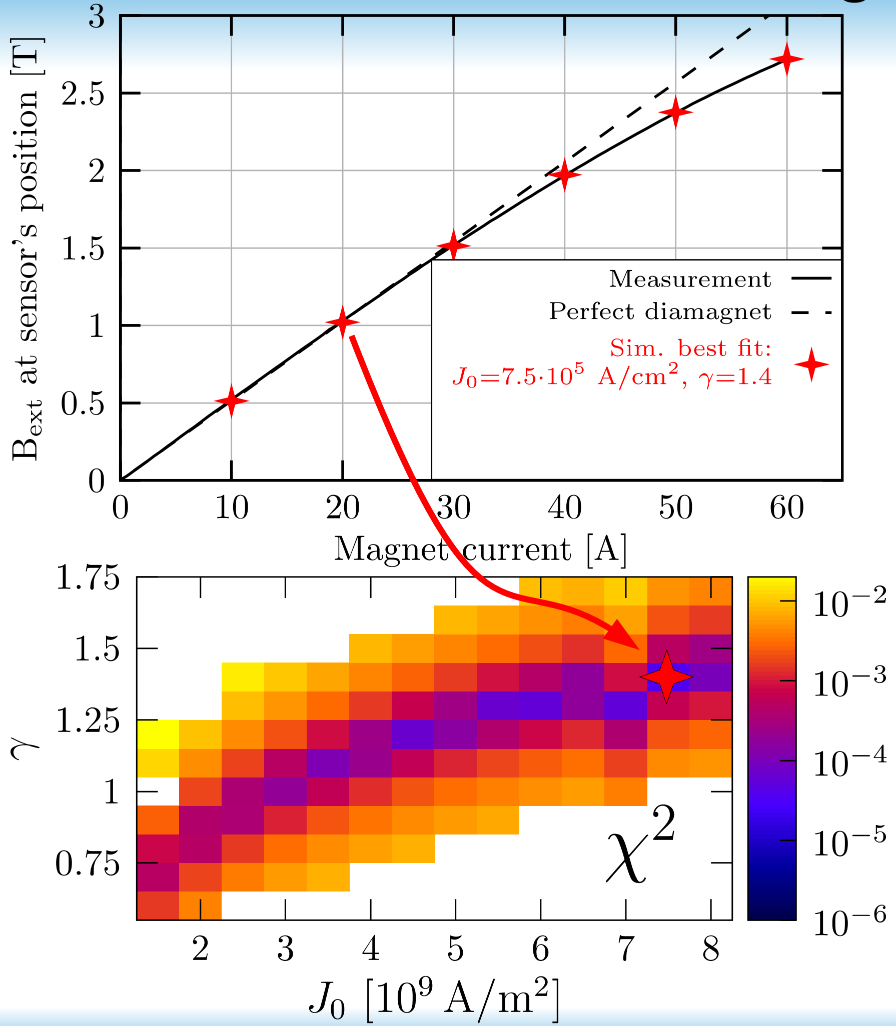


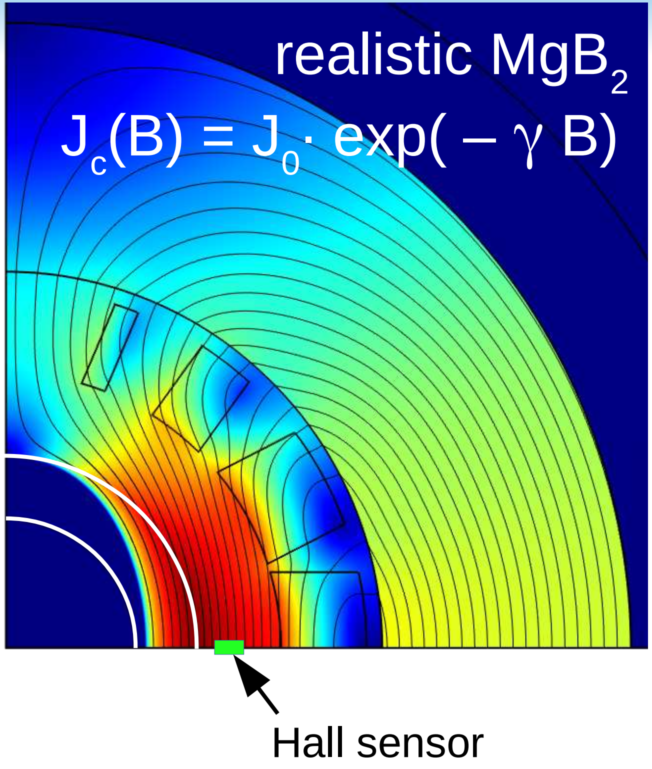
J_0 and γ are strongly correlated



COMSOL simulation in precise model of MCBY magnet

MgB_2: linearity





COMSOL simulation in precise model of MCBY magnet

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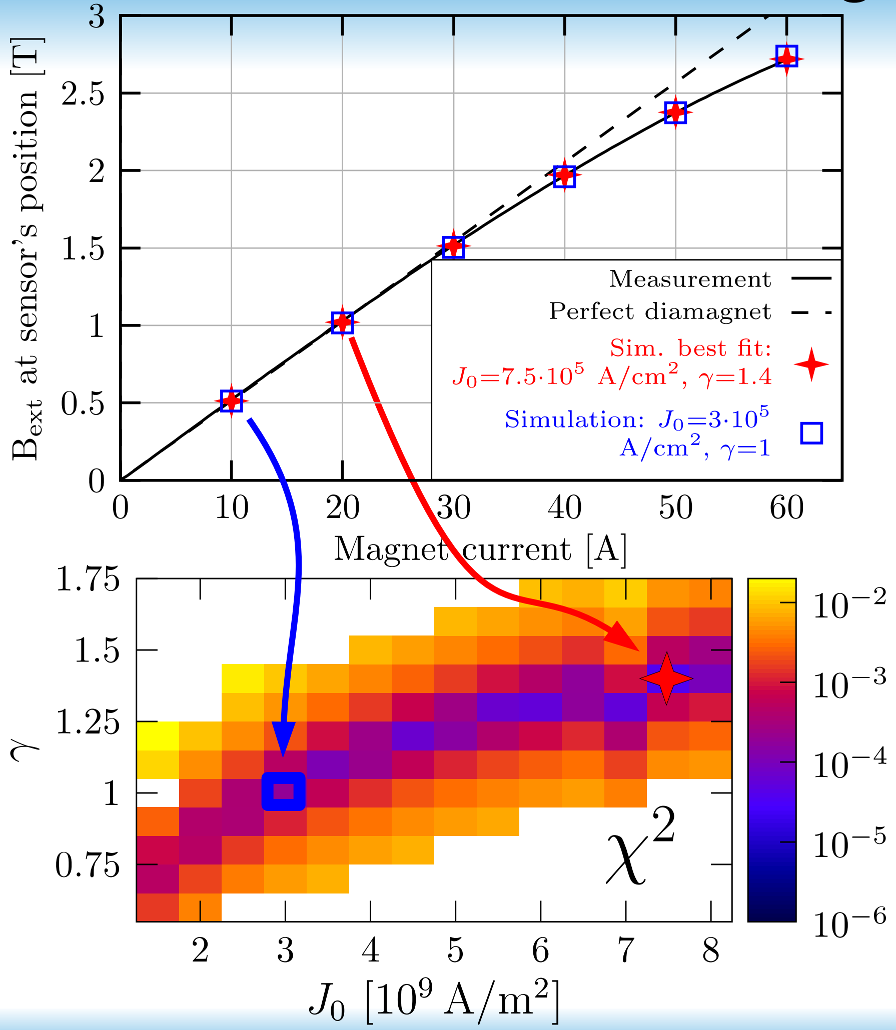
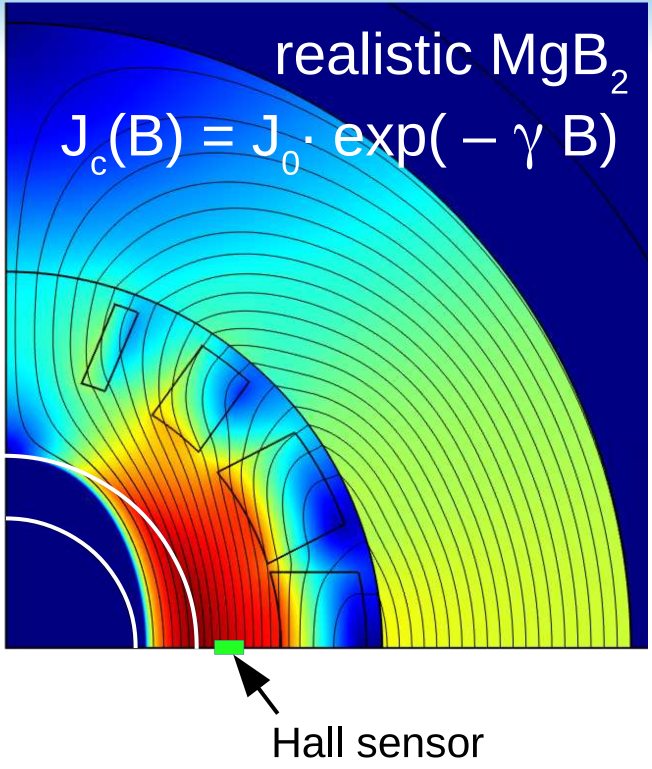
MgB$_2$: linearity



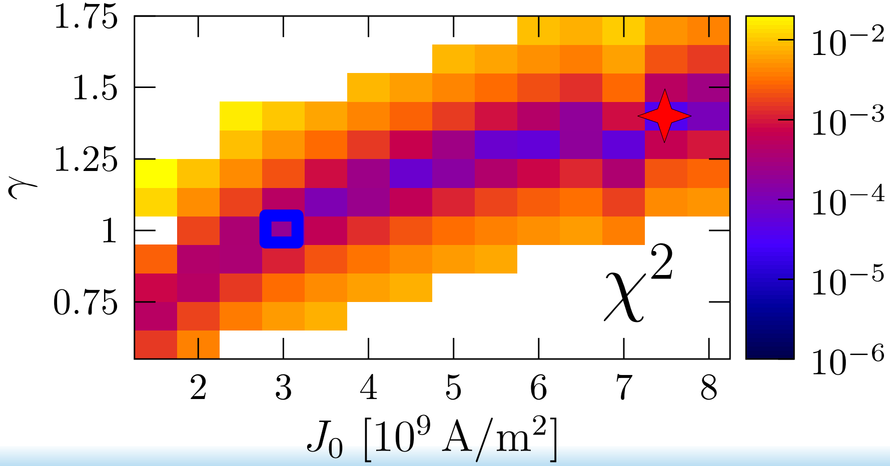


COMSOL simulation in precise model of MCBY magnet

J_0 and γ are strongly correlated

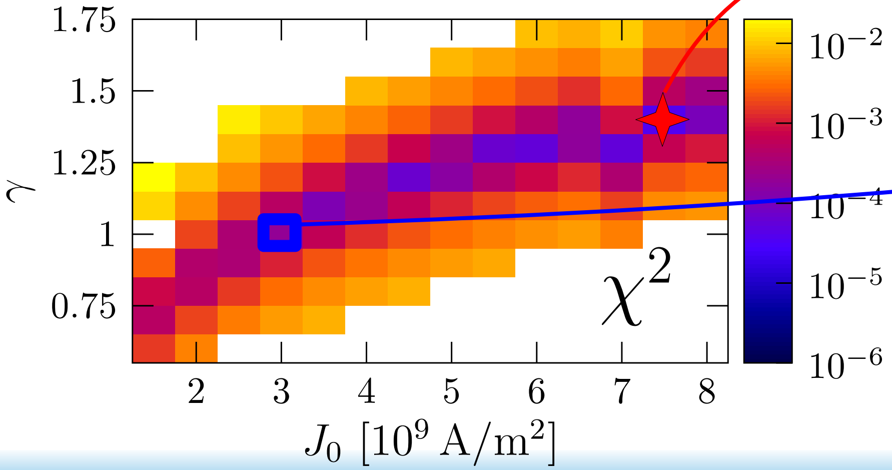
MgB_2: linearity

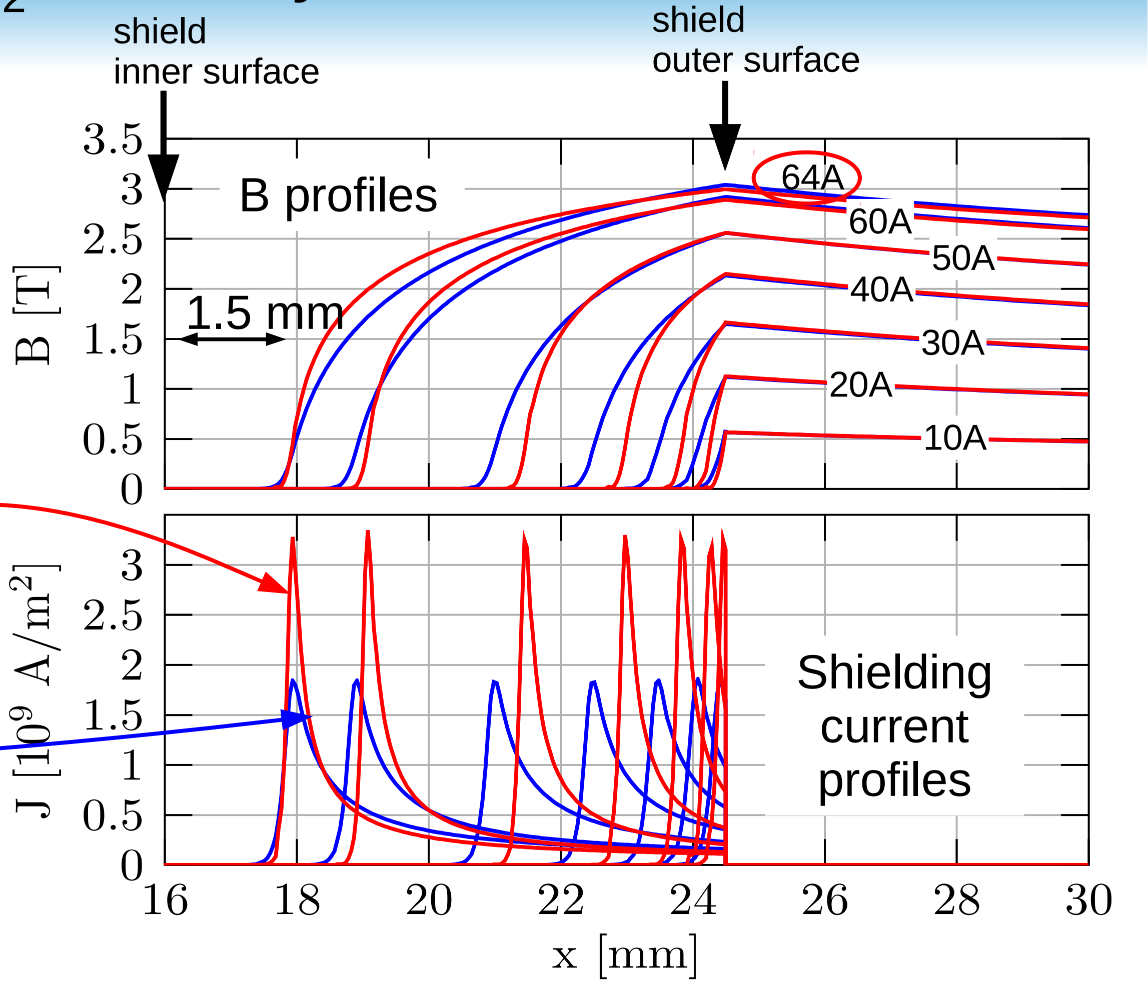
- From observed nonlinearity one can get **some** info on $J_c(B)$



MgB_2: linearity

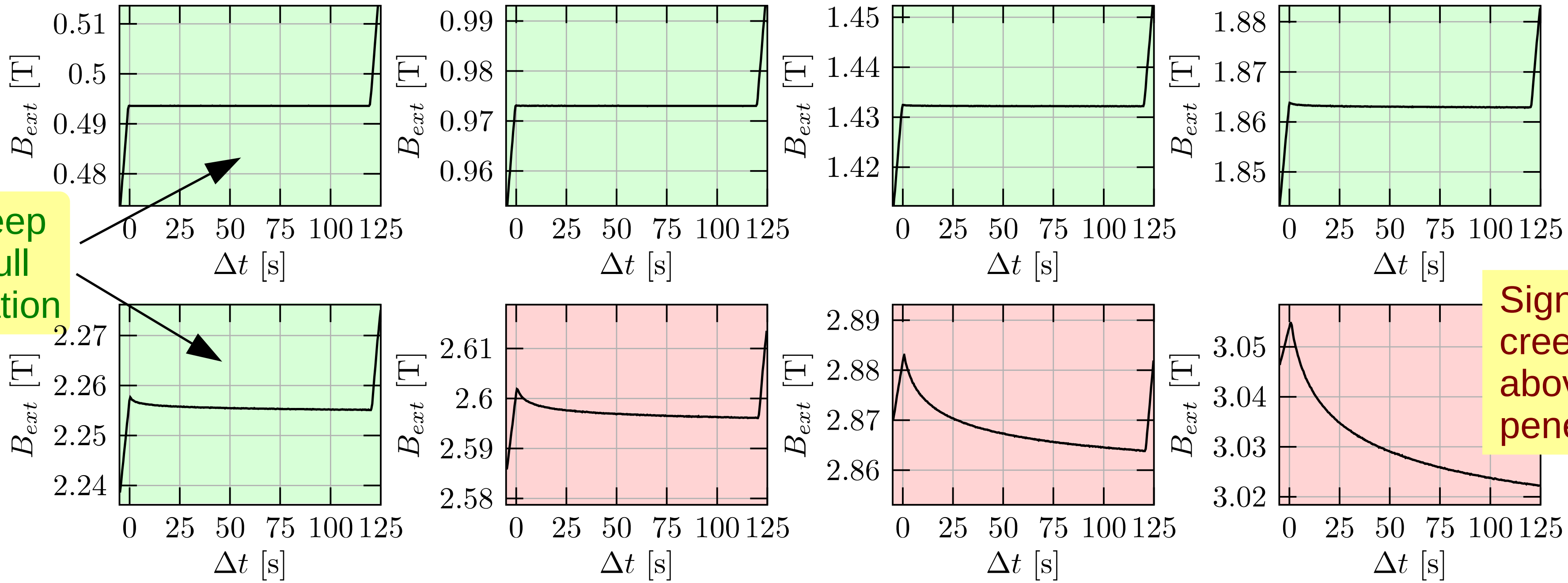
- From observed nonlinearity one can get **some** info on $J_c(B)$
- At 64 A different parameters give B penetration profiles with same, almost full depth
- Small discrepancy – end effect?
- **..but ultimate limiting factor is thickness (and/or J_c)!**





MgB$_2$: relaxation

- External field on the plateaus (magnet's current is constant)
- Same vertical scale on all plots

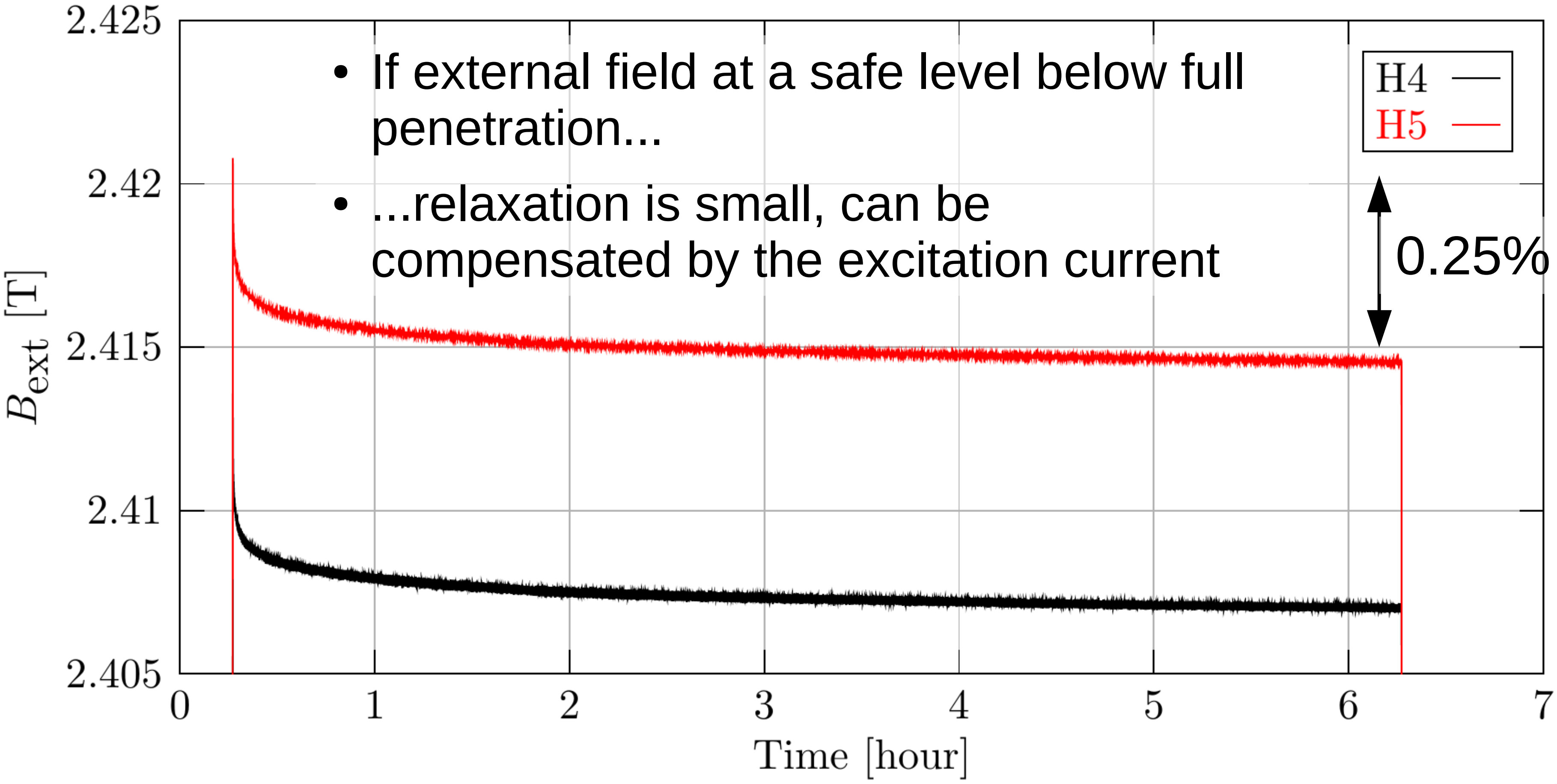


Low creep below full penetration

Significant creep near/ above full penetration

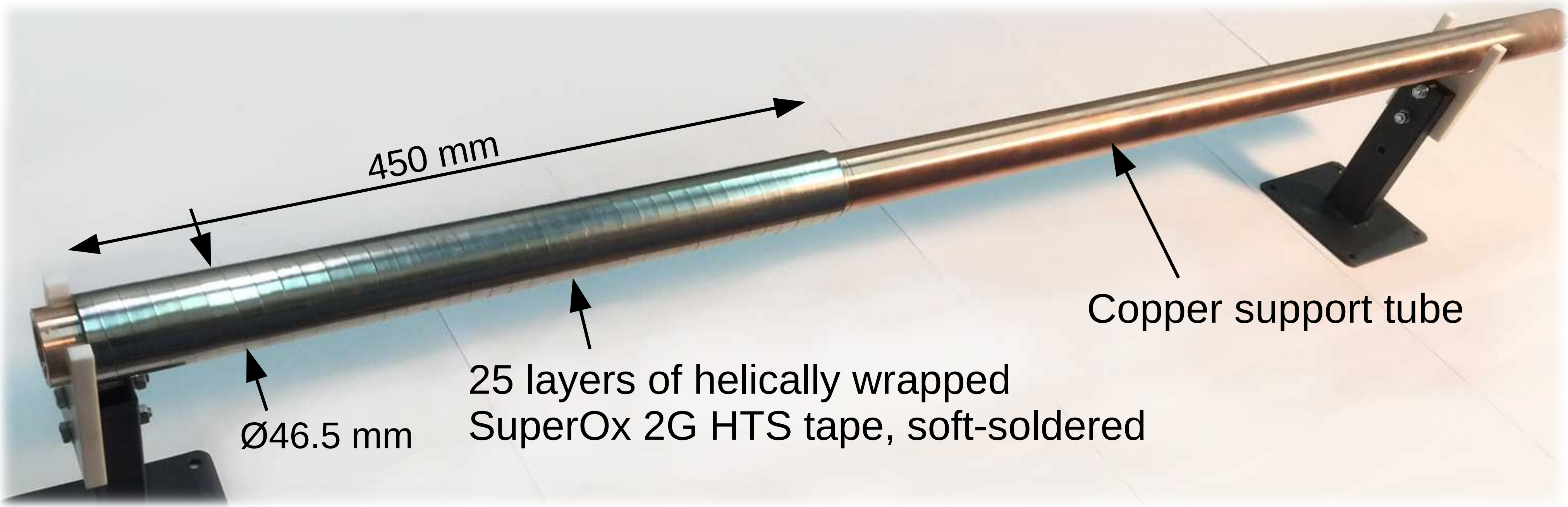
Interplay between geometry and shielding currents' dynamics (shielding currents decay → effective shielding surface drifting away from Hall sensor)

MgB_2: long-term relaxation



- If external field at a safe level below full penetration...
- ...relaxation is small, can be compensated by the excitation current

The HTS Shield

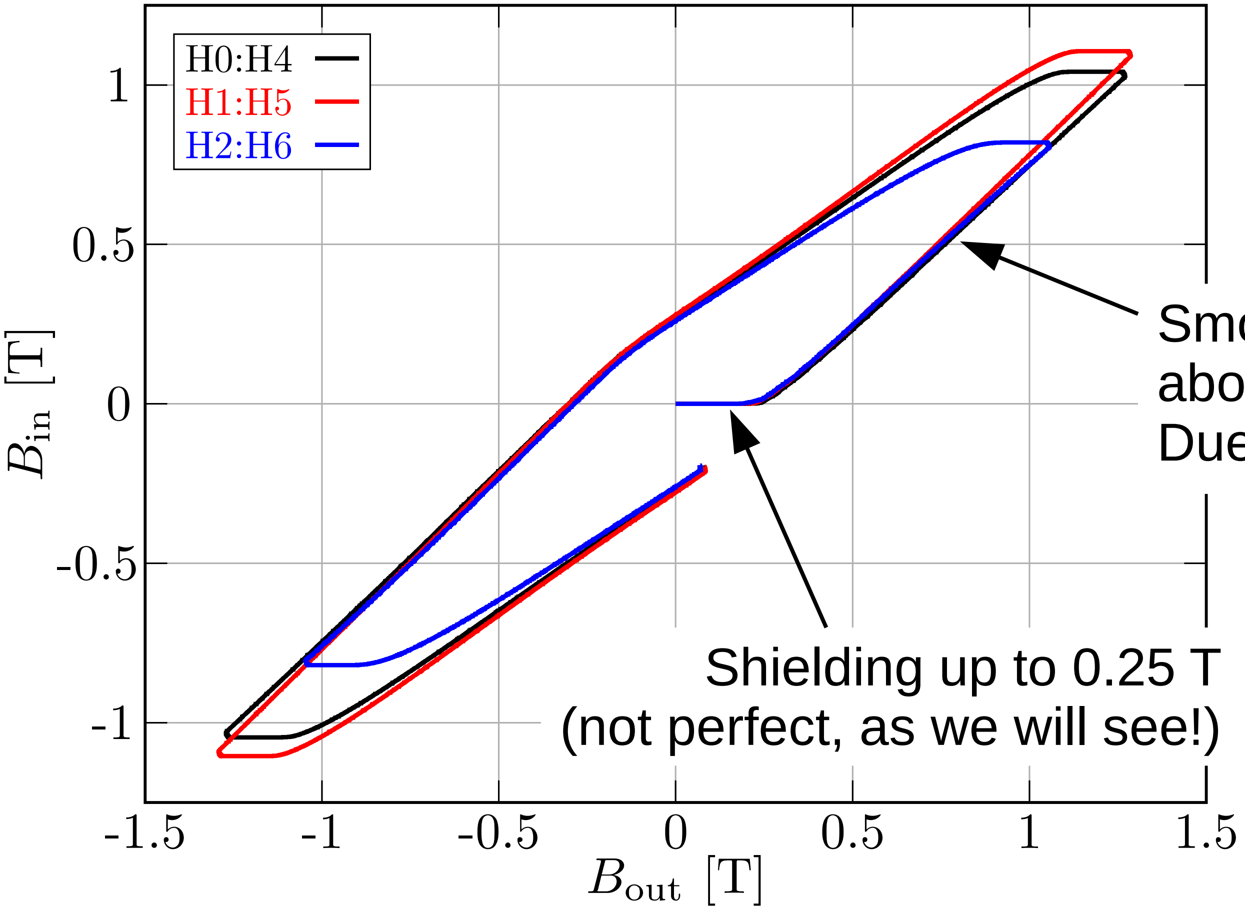


HTS: expectations

- SuperOx 2G HTS Critical Current:
  I_c = **250**-500 A/cm in self-field, T=77 K
- Our moderate B field does not change much...
- Lift factor (improvement at 4.2 K w.r.t. 77 K)
  > 4 for B<1 T
- n=25 layers

$$\boxed{\Delta B = \mu_0 * I_c * n = 0.8 \text{ Tesla}}$$

HTS: Shielding performance

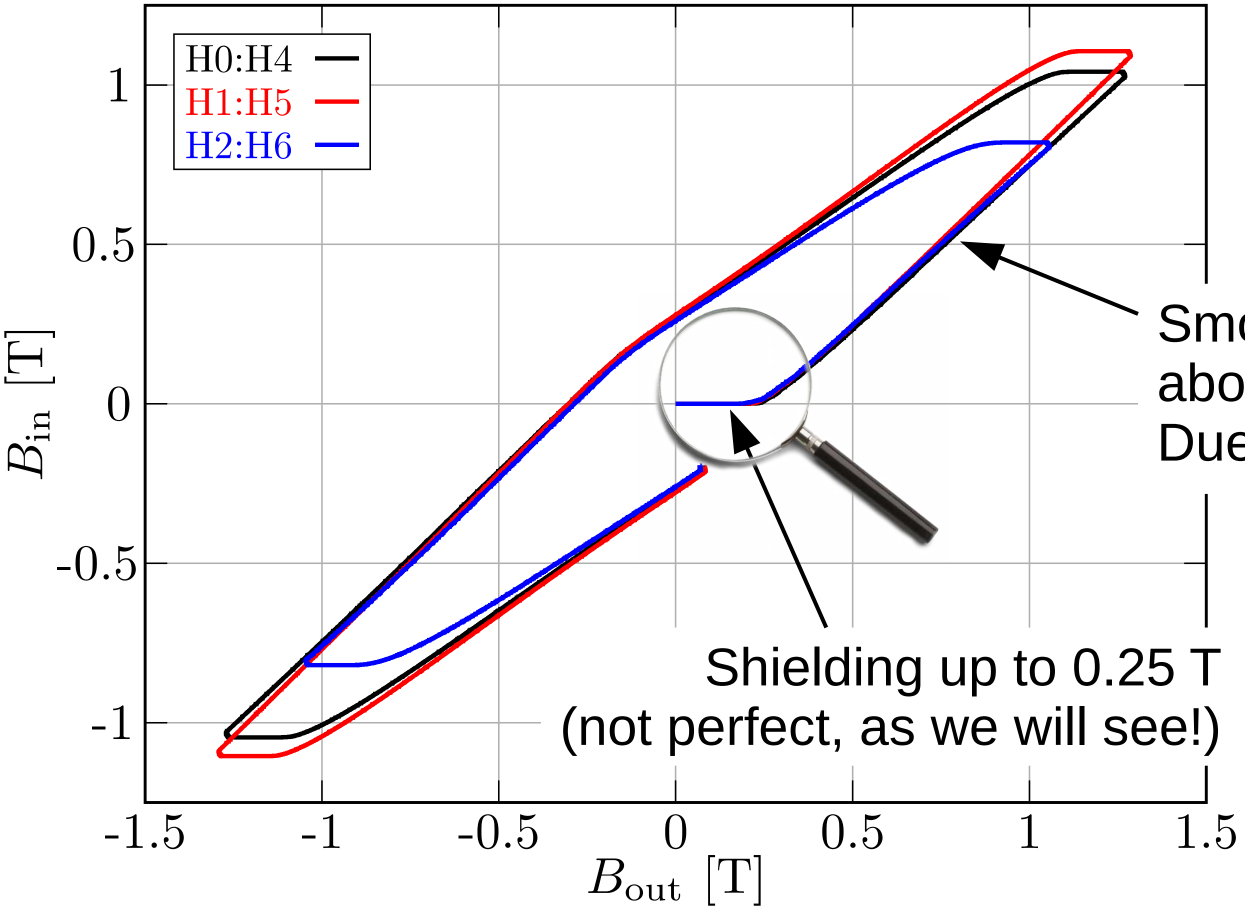


No flux jumps!

Smooth, full penetration
above 0.25 T
Due to limited J_c?

Shielding up to 0.25 T
(not perfect, as we will see!)

HTS: Shielding performance

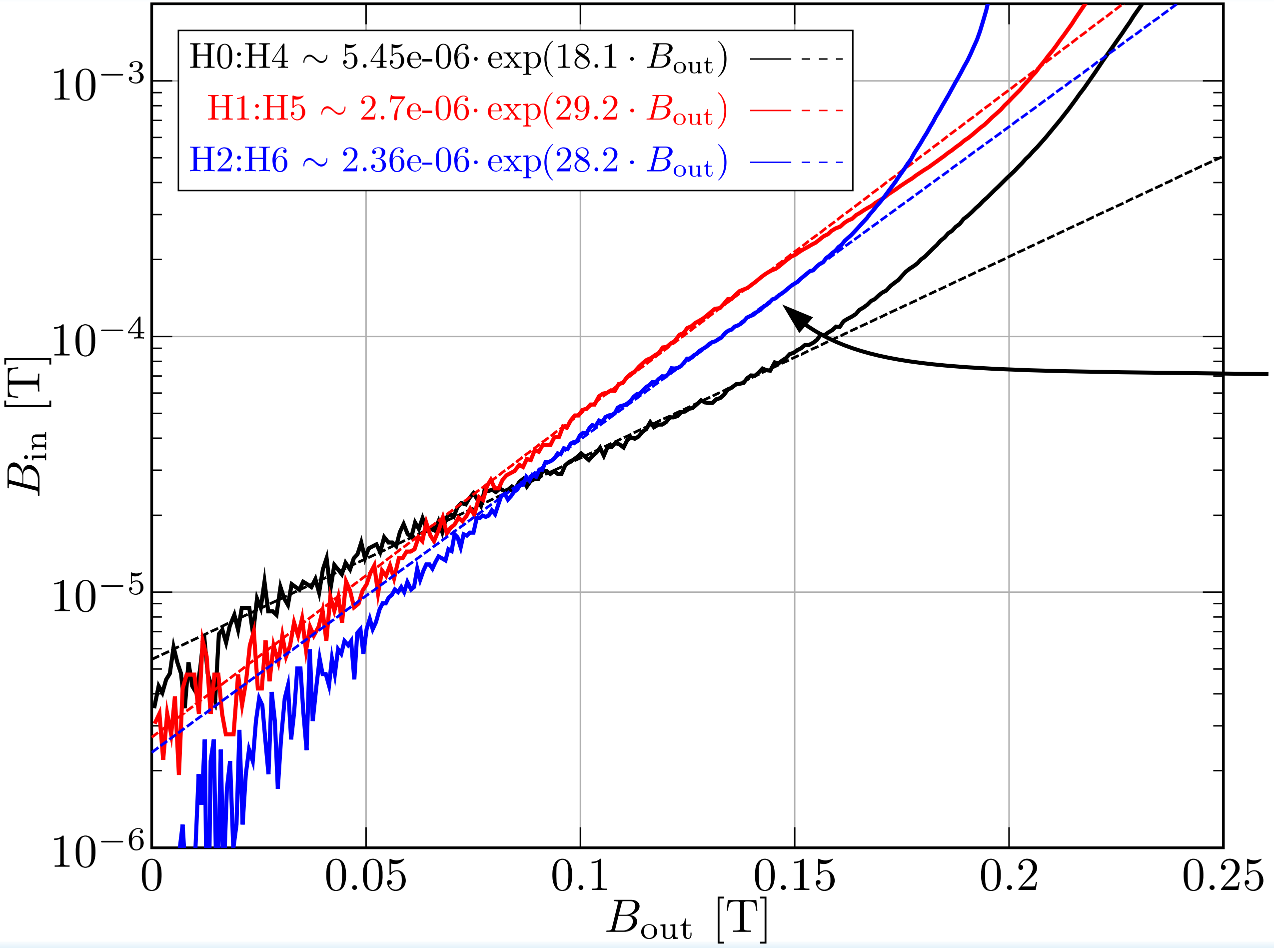


No flux jumps!

Smooth, full penetration
above 0.25 T
Due to limited J_c?

Shielding up to 0.25 T
(not perfect, as we will see!)

HTS: penetration at low field!

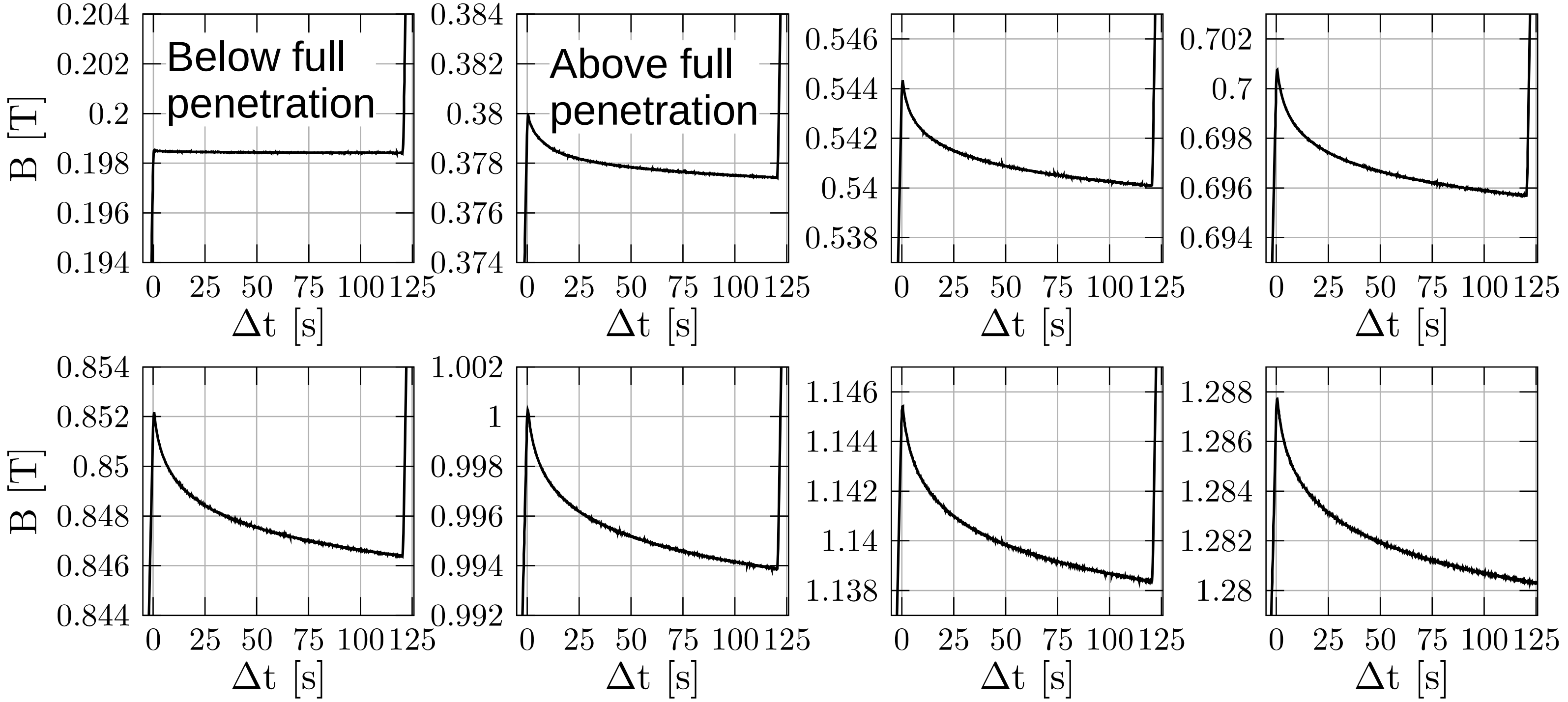


Continuous penetration from zero field!

Attenuation is about 10^{-3} here

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

HTS: relaxation

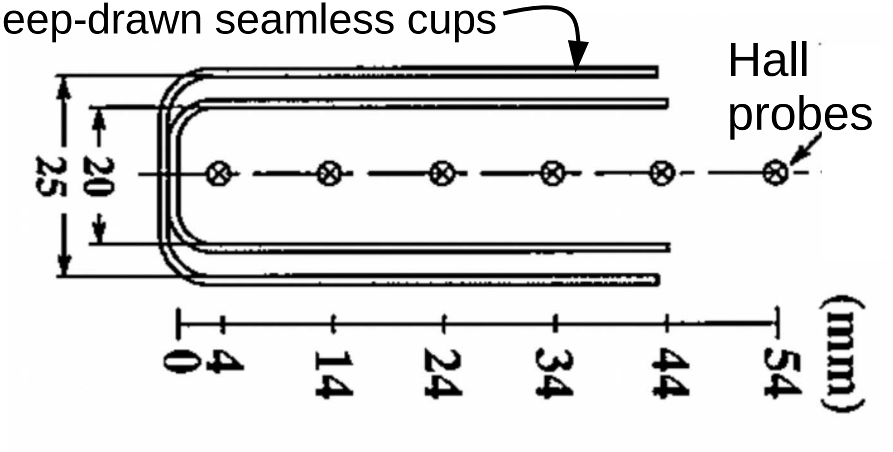

Relaxation of external field on the plateaus (H5)

- Same absolute scale on all plots
- Negligible below full penetration, significant above it.

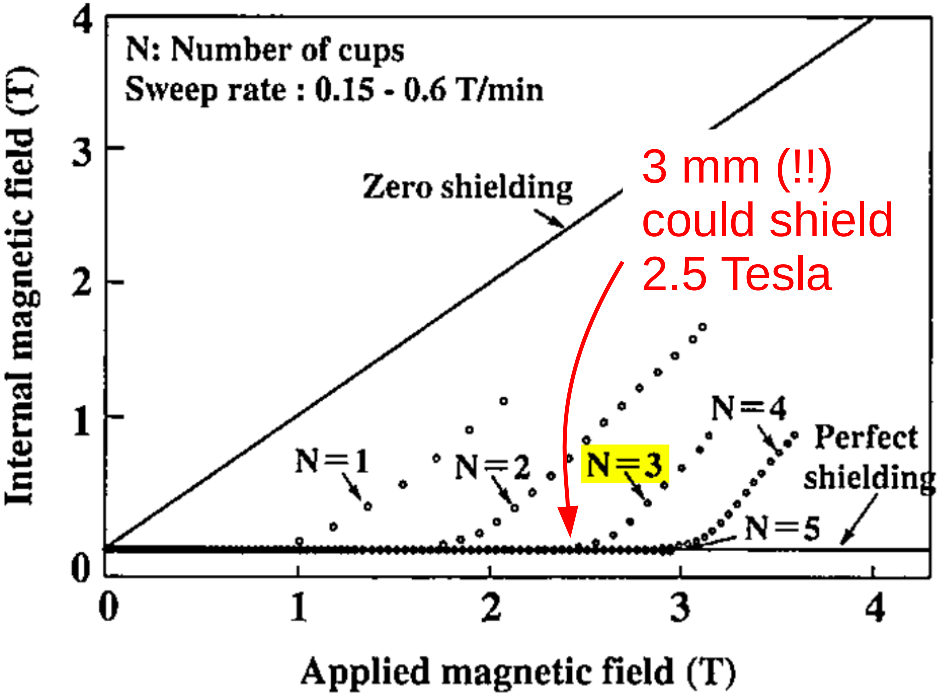
3rd prototype – stay tuned!

NbTi/Nb/Cu multilayer sheet

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


Deep-drawn seamless cups

Hall probes


3 mm (!!) could shield 2.5 Tesla

- Seems very promising
- Sheet material waiting for shipment
- Some R&D to fabricate the prototype

Prototype comparison

	MgB_2	HTS	NbTi/Nb/Cu
Price	1	4 x MgB_2	5 x MgB_2
Manufacturing	simple (baking 950 °C), diamond or spark machining	easy (from commercial tapes), scalable	heavy machinery (rolling & heat treatments)
Mechanical	hard and brittle	robust	most versatile, ductile, robust
Performance	good	insufficient	best (anticipated from literature)
Comments	manufacturing of long (2-3 m) tubes needs R&D (can be joined...)	very wide tapes to avoid helical wrapping?	can the price be reduced drastically?

Conclusions

- Simulation: optimized geometry produces homogeneous field at different field strengths, with different superconductor characteristics
- Massless septum configuration is promising up to moderate levels (1 T)
- MgB_2 prototype ✔
  - No flux jumps on the virgin curve
  - Perfect shielding up to 2.6 T with 8.5 mm wall thickness
  - 0.25% relaxation of external field over 6 hours, @ 2.4 T (ok for FCC)
  - Cheap and simple
- HTS tape prototype (helical, multilayer wrap) ✗
  - Field penetrates already at very low fields (due to geometry?)
  - Full penetration above 0.25 T – much below expectations. Degraded J_c?
  - Relaxation...
- NbTi/Nb/Cu multilayer ? (this year...)

Outlook

- Candidate #1 so far is MgB_2
- With the best candidate:
  - Test fast & reliable detection of flux jumps/quench
  - Test massless configuration
  - Develop a dedicated SC coil & shield to produce a homogeneous field

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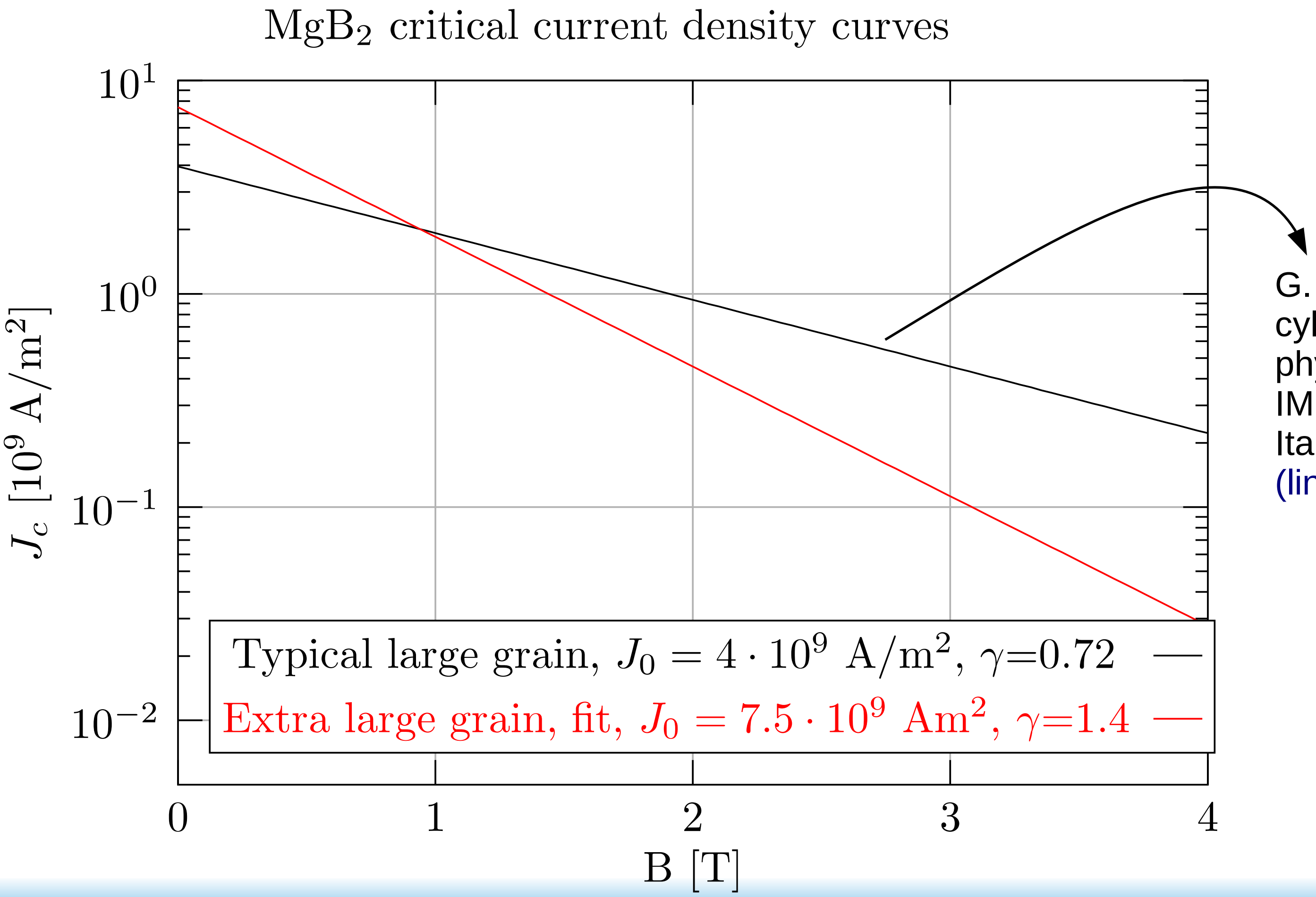
Backup slide #1



G. Giunchi, “The MgB 2 bulk cylinders as magnetic shields for physical instrumentation” in 20th IMEKO TC4 Int. Symp., Benevento, Italy, pp. 1033–1037, 2014. (link)