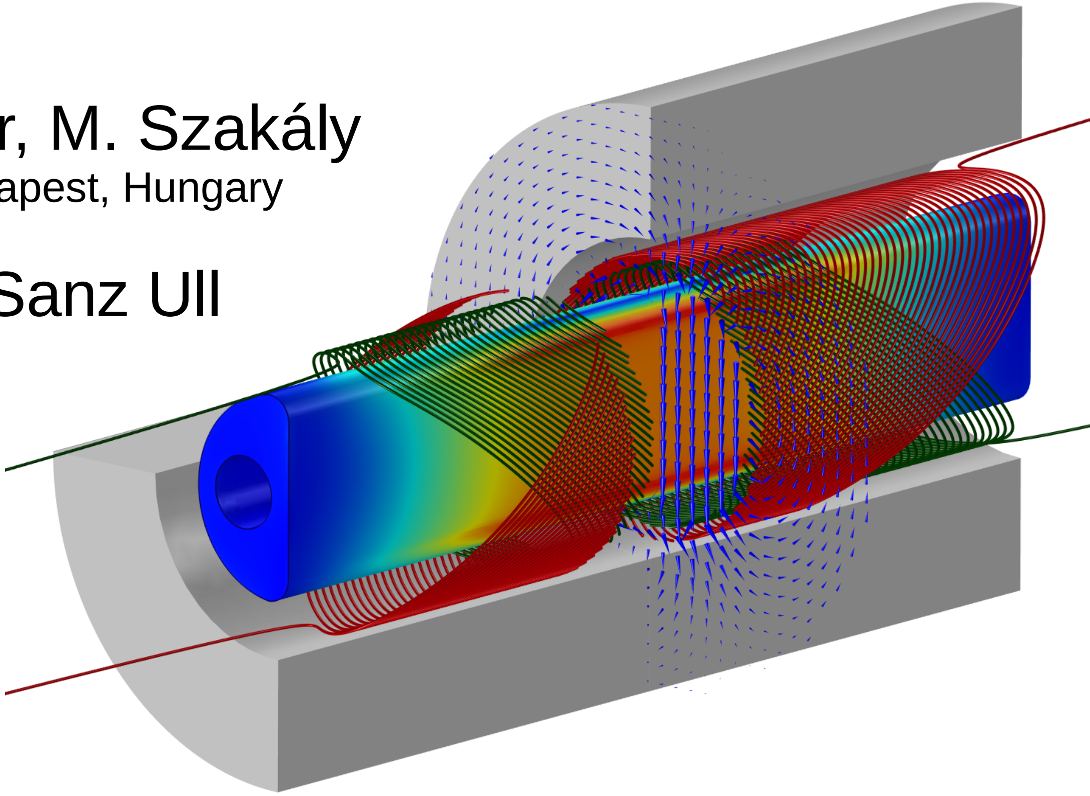
Superconducting Shield (SuShi) septum: towards a full prototype

D. Barna, M. Novák, K. Brunner, M. Szakály
Wigner Research Centre for Physics, Budapest, Hungary

Miroslav Atanasov, Alejandro Sanz Ull
CERN



Outline

- Motivation
- The SuShi idea – review
- Possible materials – review
- Full prototype concept: CCT magnet & shield
  - 2D optimization, field quality
  - 3D simulation, field patterns
  - Max field, stresses, conductor performance
  - Comparison to Hi-Lumi CCT corrector
  - Project proposal

Motivation: extraction parameters

Deflection by extraction septa	1.14 mrad
Integrated field	190 Tm
Available space	120 m

- Required field: > 2 T to include valves, pumps, fringe fields, etc
- Higher is better → more compact, especially in high-energy LHC

Goal: ≥ 3 T field, +/-1 % homogeneity

The SuShi idea

- **Passive** superconducting **shield** around circulating beam
- **Cool** below T_c **in zero field**
- Ramped-up external field induces **persistent shielding currents**
- Which exclude field and completely shield the interior

Pros & Cons

PROS

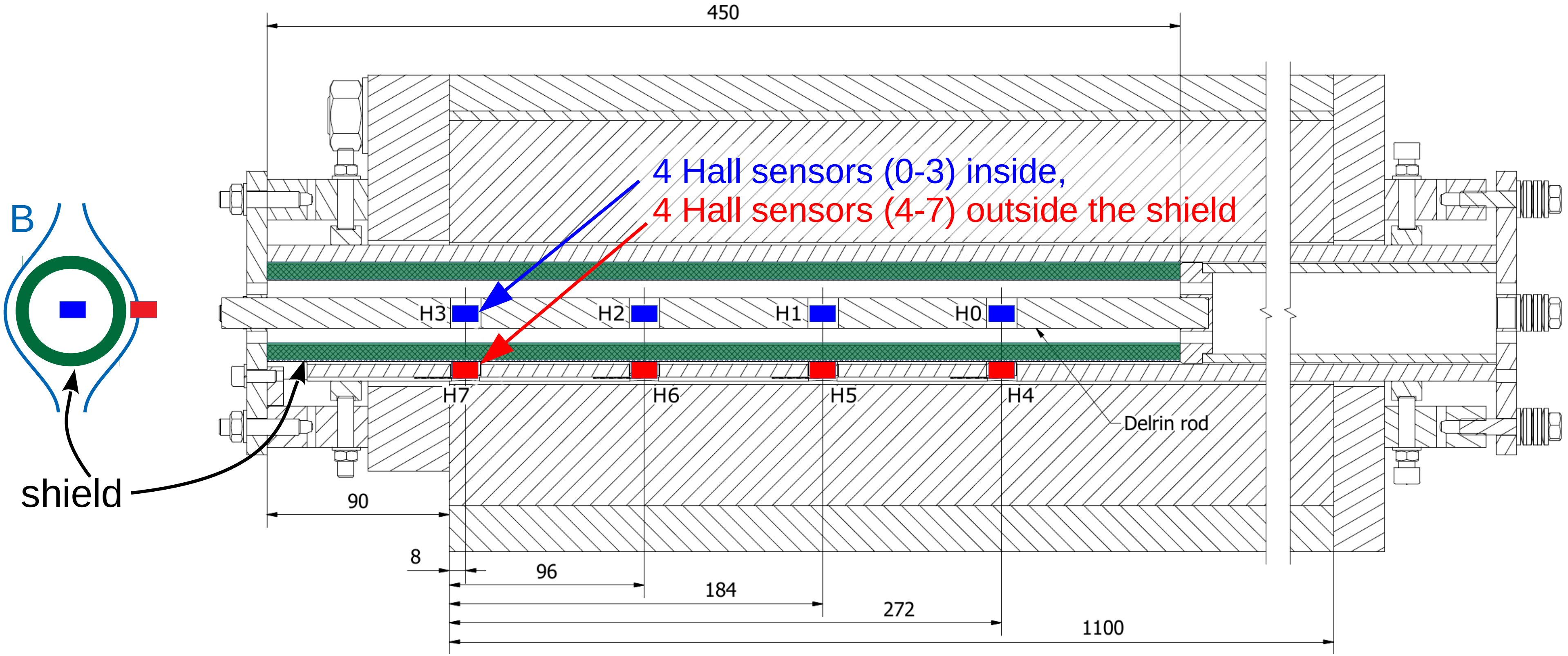
- Shielding currents are continuous in 2D, and not discrete
- No quench-protection needed in the shield
- Bulk superconductor
  - No insulation
  - Better heat conductivity
  - Mechanically stronger
- Critical state model: $J_{shielding} = J_c$ → thinnest shield

CONS/ISSUES

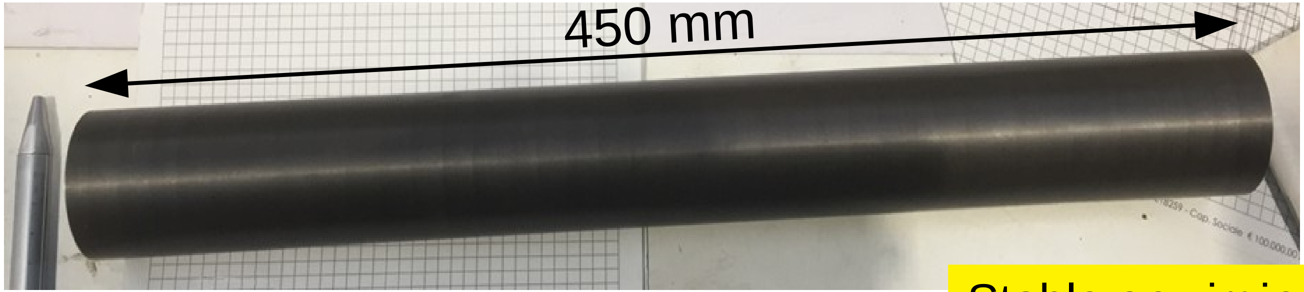
- Trapped field? Will it distort field homogeneity?
- Needs “thermal reset” to
  - eliminate trapped field?
  - in case of flux jump

Shield material tests

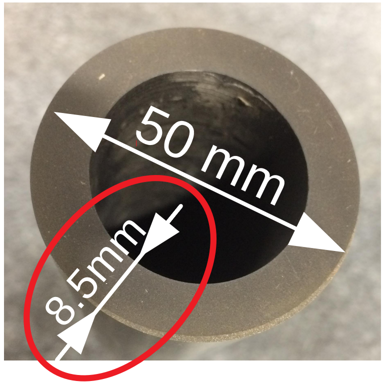
- Shield: 450 mm long tube
- Magnet: LHC spare MCBY dipole (length: 1100 mm, bore: 70mm)

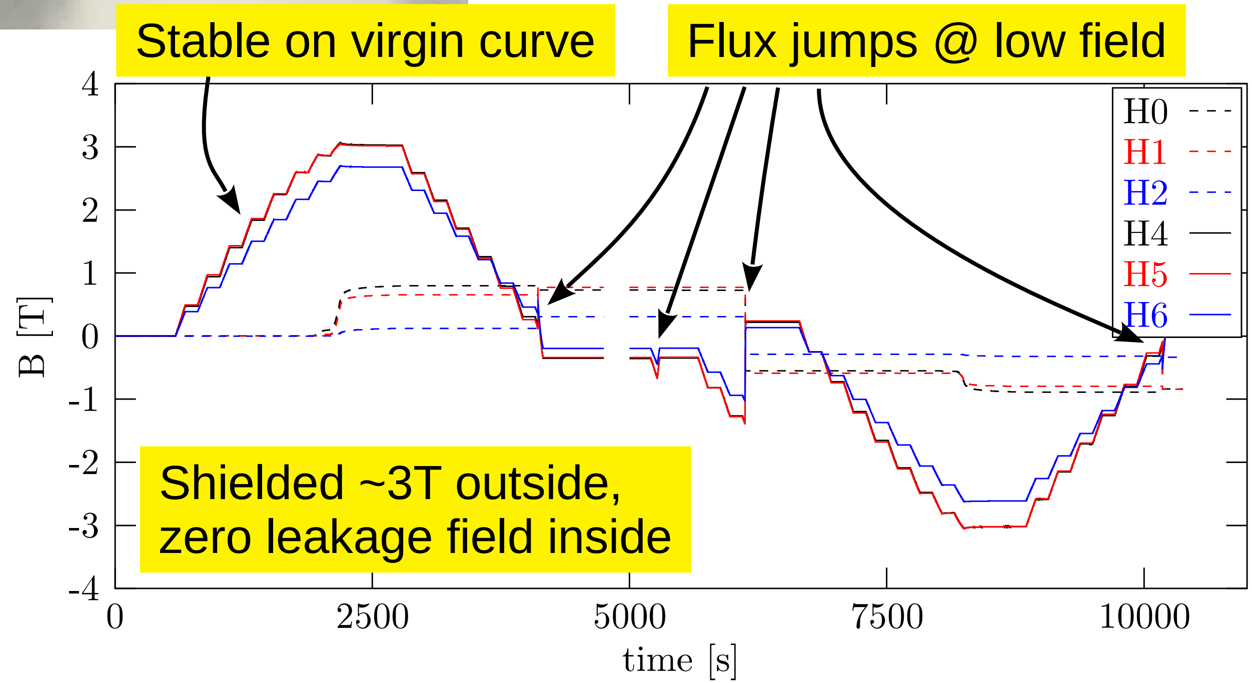


Materials 1: MgB_2



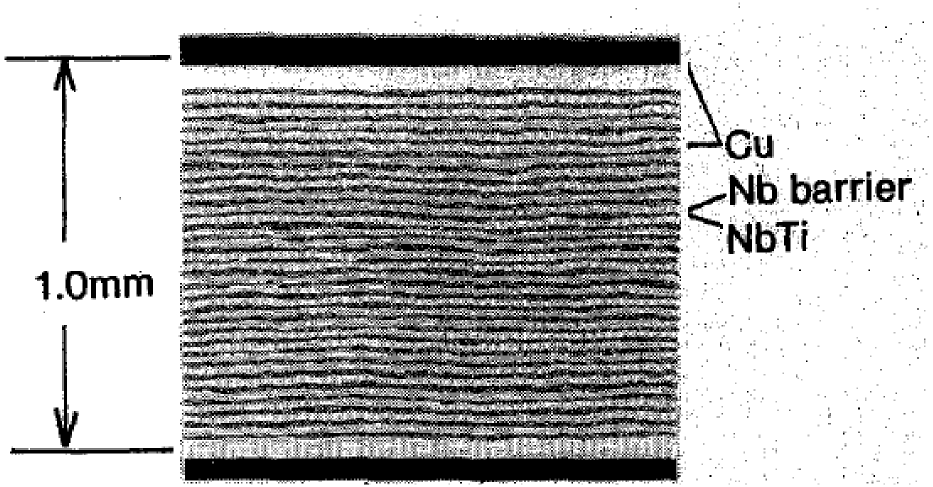
Reported @ FCC Week '17





- 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)

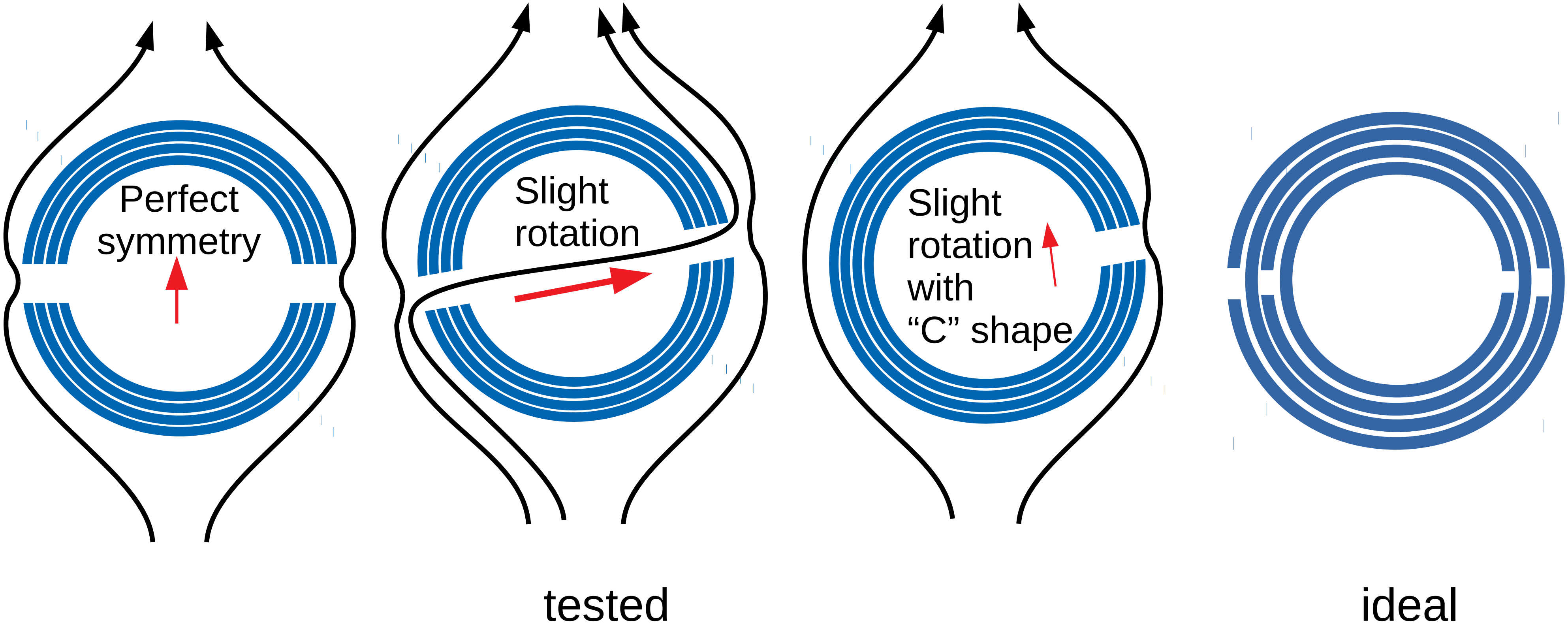
Materials 2: NbTi/Cu multilayer



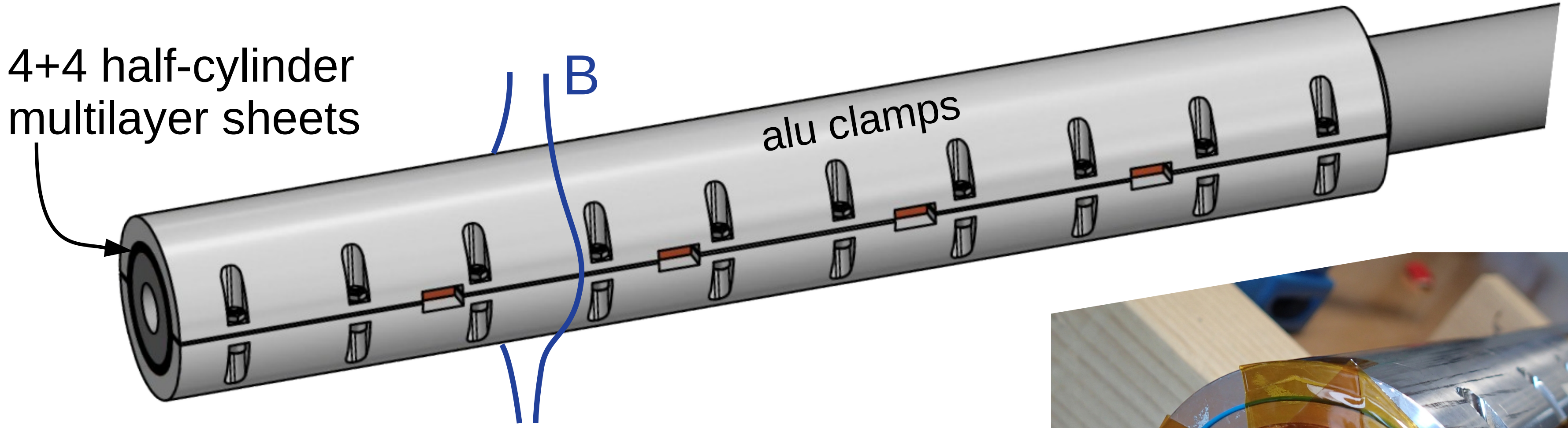
30 layers of NbTi, 8-10 micron thick, alternated with Cu for stabilization

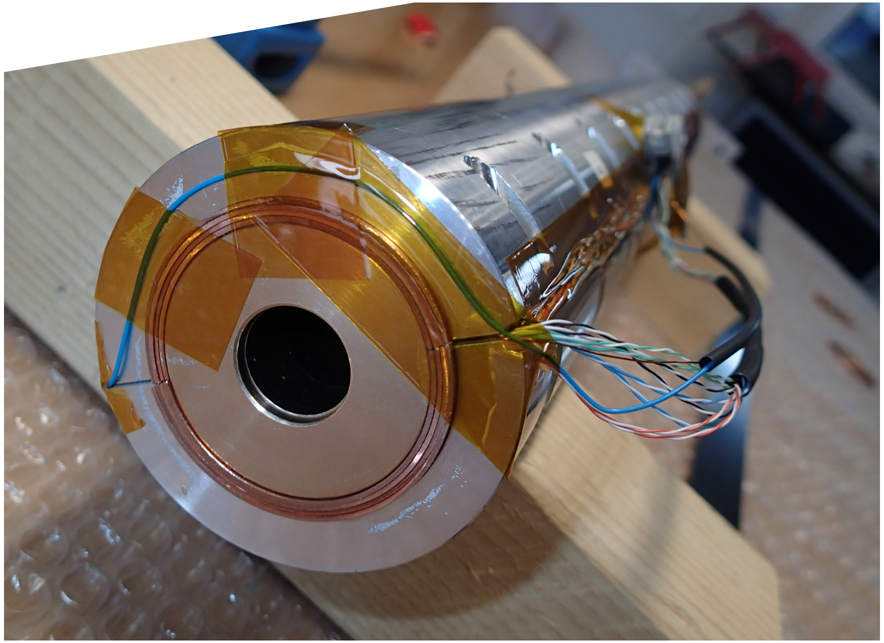
I. Itoh, T. Sasaki: Magnetic shielding properties of NbTi/Nb/Cu multilayer composite tubes, IEEE.Trans.Appl.Supercond.3 (1993), 177

Materials 2: NbTi/Cu multilayer - geometry



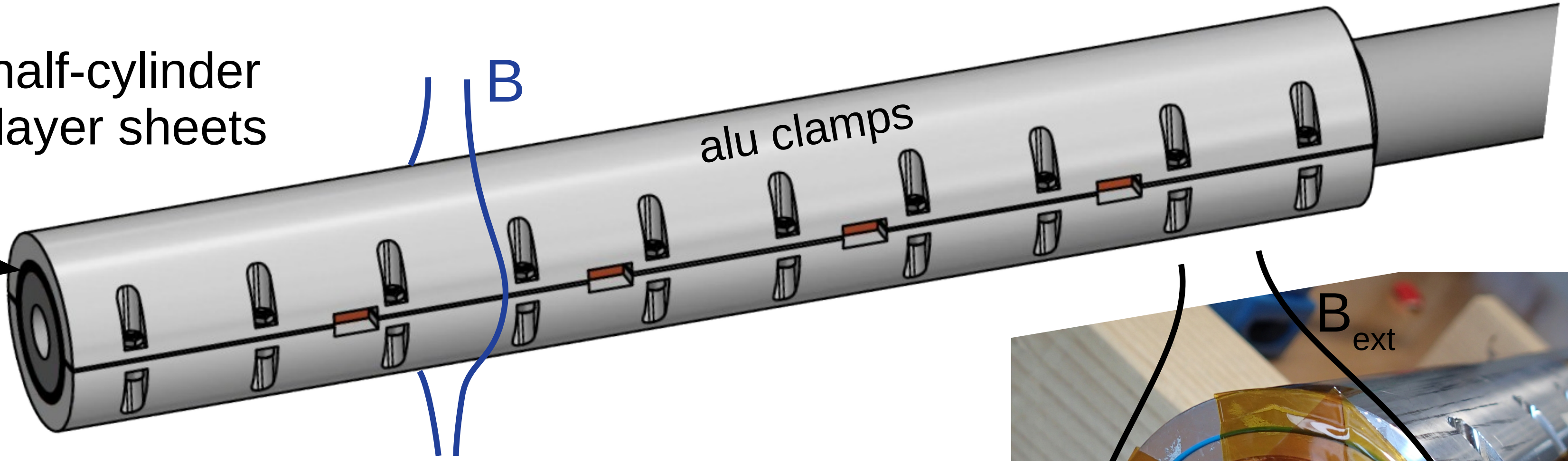
Materials 2: NbTi/Cu multilayer - results

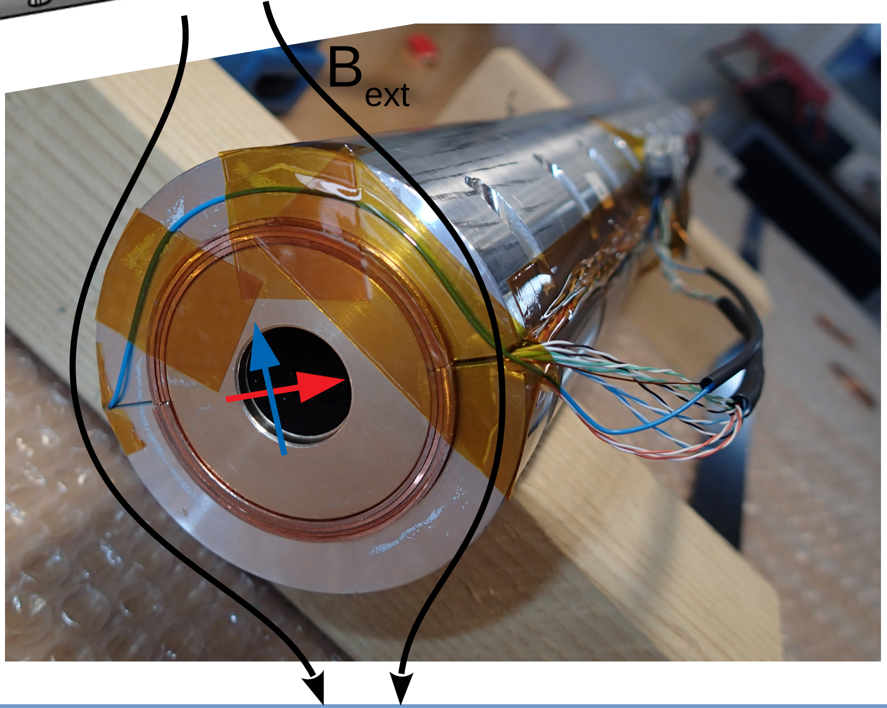




Materials 2: NbTi/Cu multilayer - results

4+4 half-cylinder multilayer sheets





- Very stable! No flux jumps!
- B_{ext} = 3.1 T before full penetration
- Below this, leakage field:
  - 10 mT ⊥ to external field ($3 \cdot 10^{-3}$)
  - 0.2 mT ∥ to external field ($<10^{-4}$)
  - Simulation: due to cuts on both sides

See poster: M. Novák, 2AMSP06

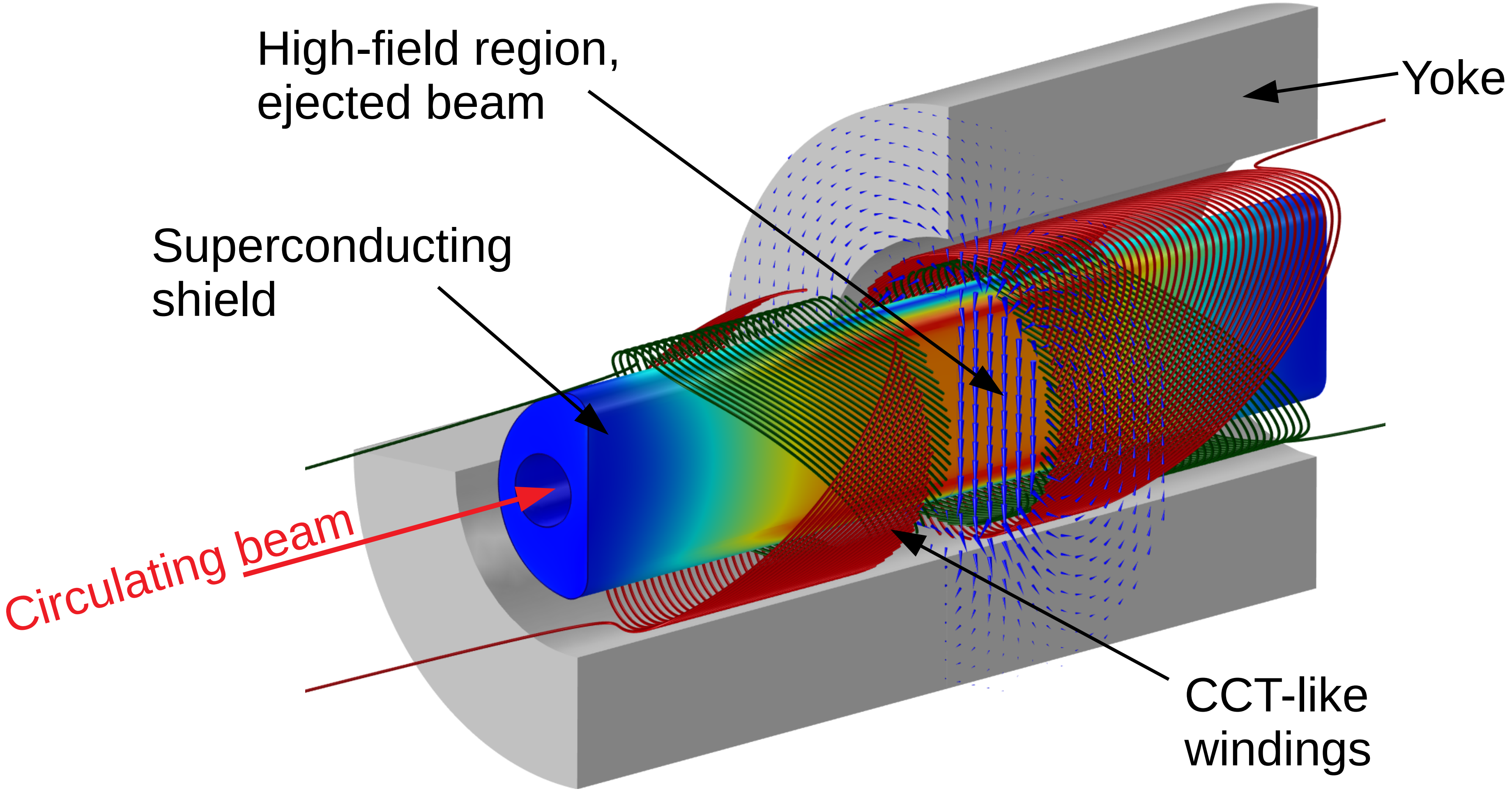
Materials: summary

	MgB2	NbTi/Cu
Thickness [mm]	8.5	4
Shielded field [T]	3	3.1
Flux jumps	yes (@ low fields after exposure to high field)	no

What we can safely promise:

- **3.2 T** field (maybe higher with NbTi/Cu)
- **15 mm** shield thickness
  - 15 mm bulk MgB_2 is self-supporting (if flux jumps eliminated)
  - 5 mm NbTi/Cu + 10 mm support

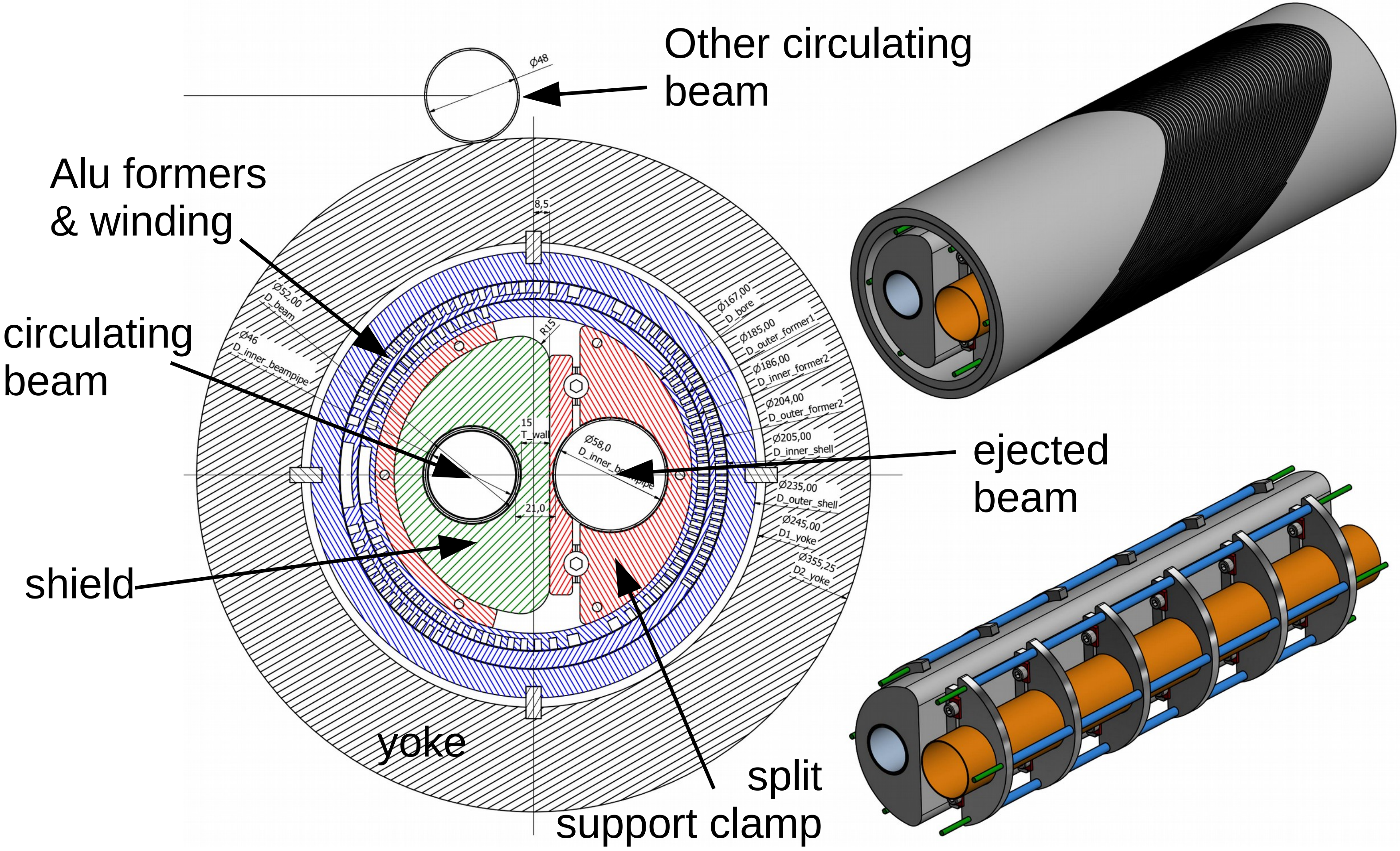
The CCT-SuShi idea



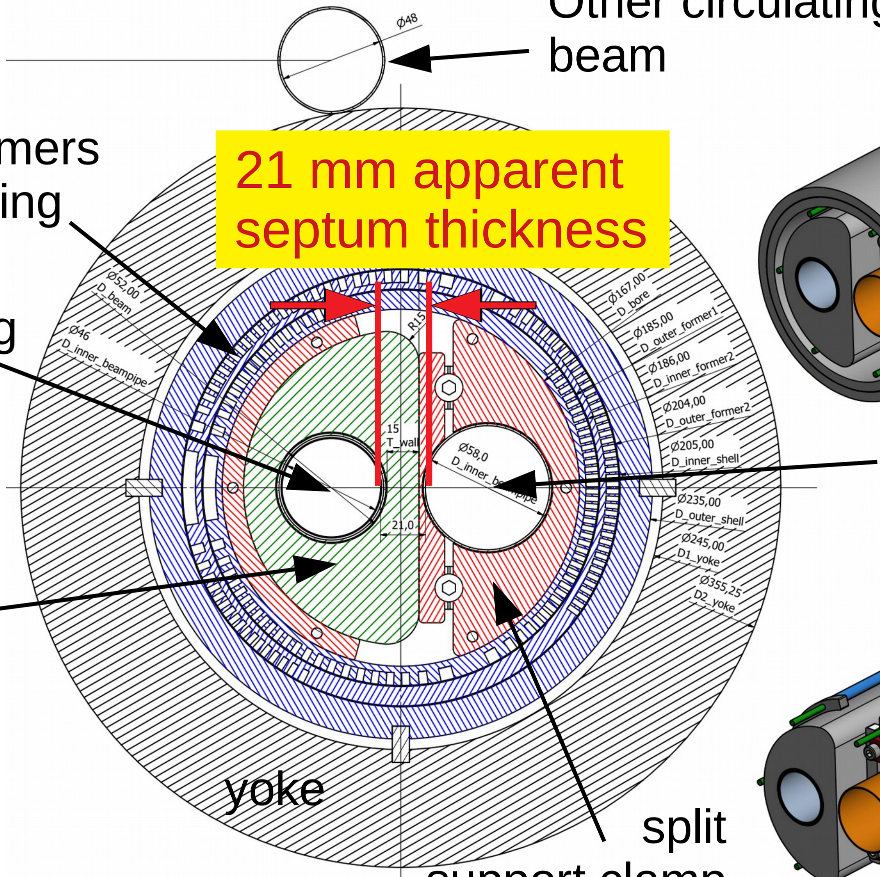
Why a CCT-like magnet?

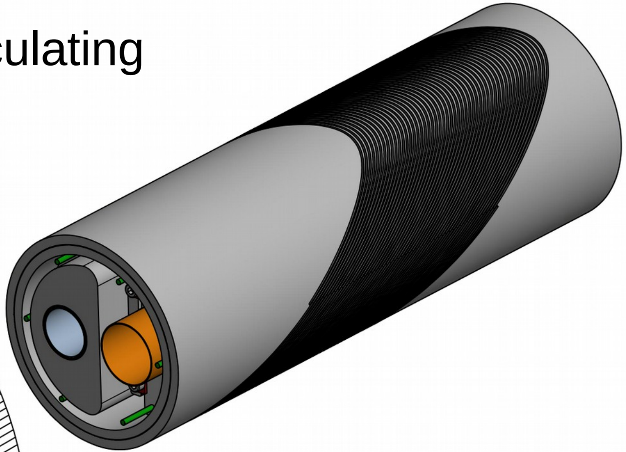
- Very easy to design and optimize
- Very simple, cheap to build
- Few parts, minimal tooling
- Very low stresses, robust, quick (or no) quench training
- Simple quench-protection system
- Active R&D @ CERN: Hi-Lumi CCT corrector magnets
  https://www.researchgate.net/project/LHC-hi-Lumi-orbit-corrector-5Tm-CCT
- Parameters fall close to this – reusing design or even test hardware makes project cheaper

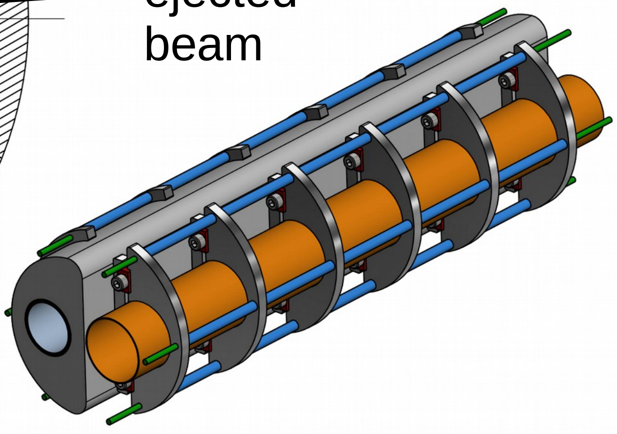
Design concept (very preliminary concept)



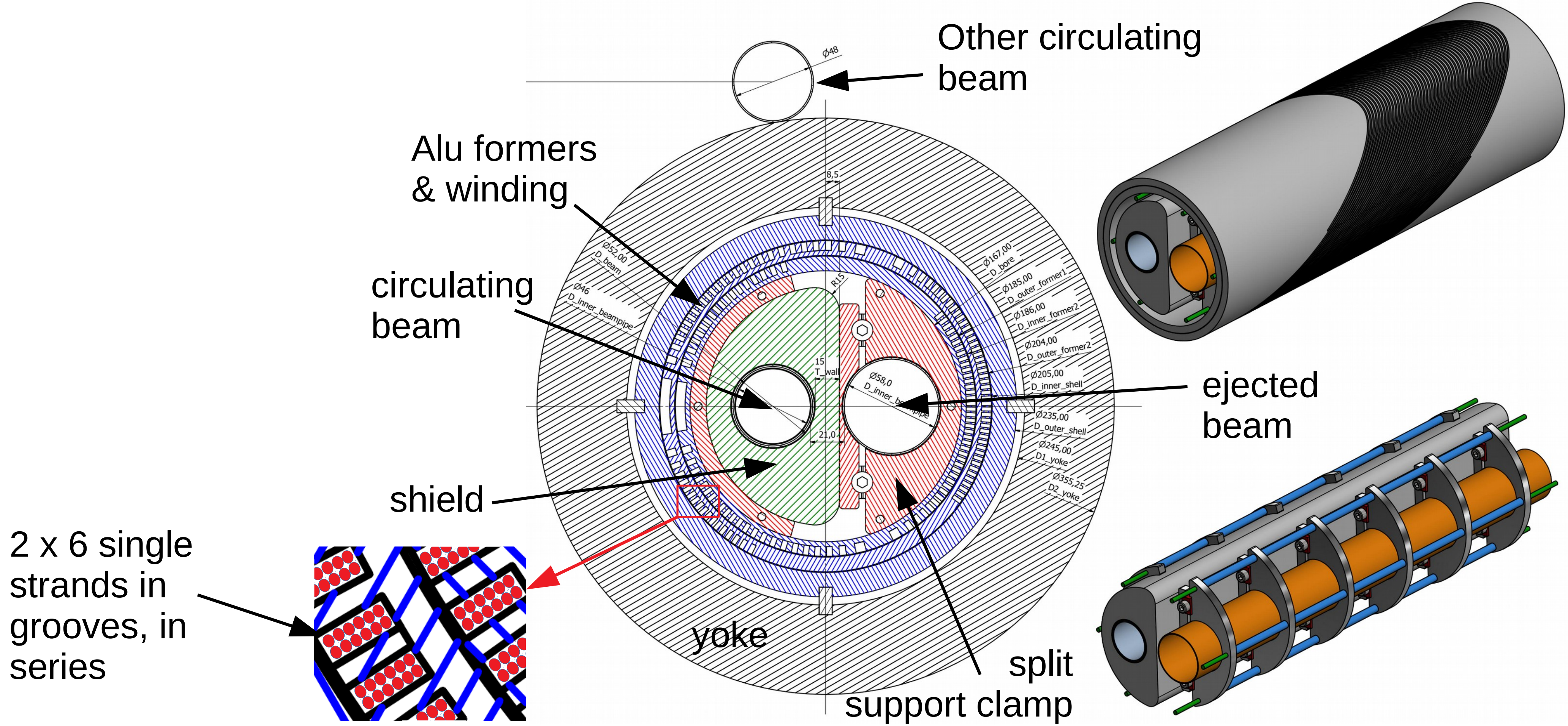
Design concept (very preliminary concept)







Design concept (very preliminary concept)

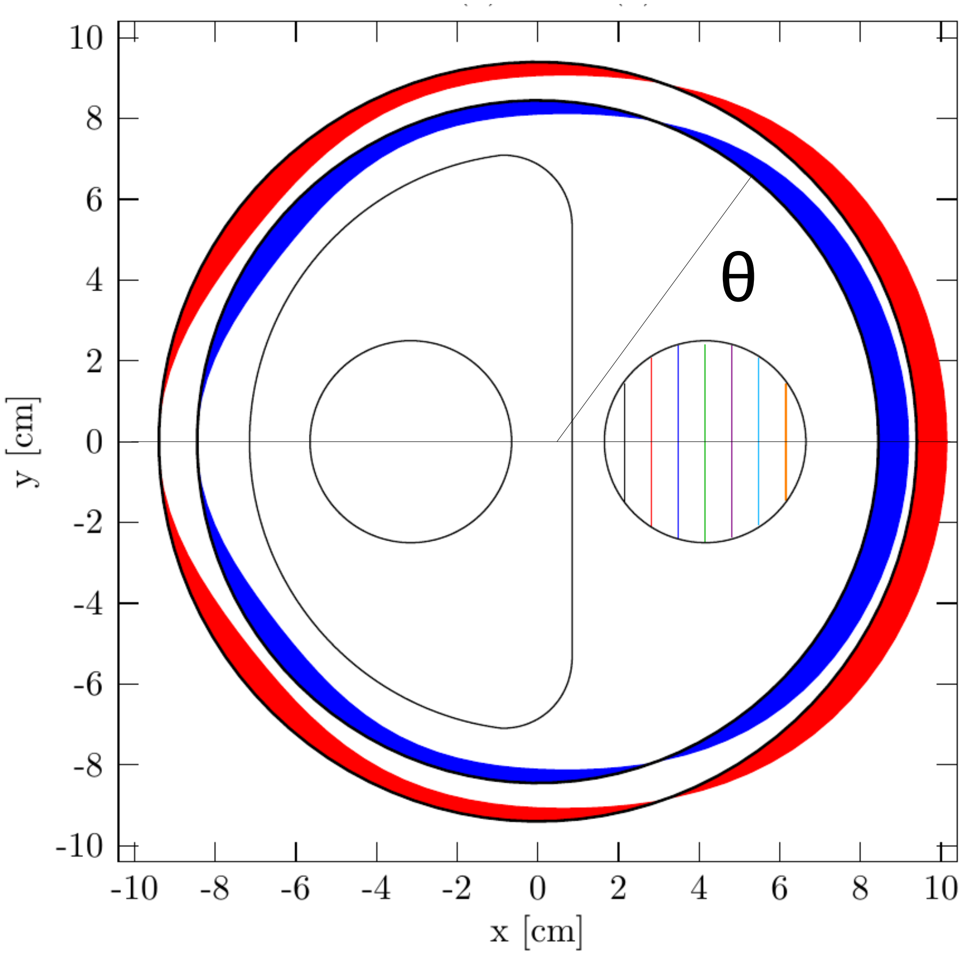


CCT-SuShi parameters

	CCT-SuShi	Hi-Lumi CCT (ref)	Reason
Good field region [mm]	50		Giga-size, accomodate full beam displacement
Bore diameter [mm]	167	105	
Nominal current I_0 [A]	420	422	Keep margin to I_c
# wires in groove n_1 x n_2	2 x 6	2 x 5	More than ref to keep I_0 low
Nominal field [T]	3.2	2.6	
Peak field [T]	(<4 T)	3.1	
Pitch	5	5.22	
SC cable length [km/L_w]	4		
Inductance [mH]	1400 (2 m length)	101 (0.5 m proto) 820 (2.2 m final)	
Apparent septum thickness [mm]	21 (25)		Septum thickness of 15 [mm] + beam pipes & screen

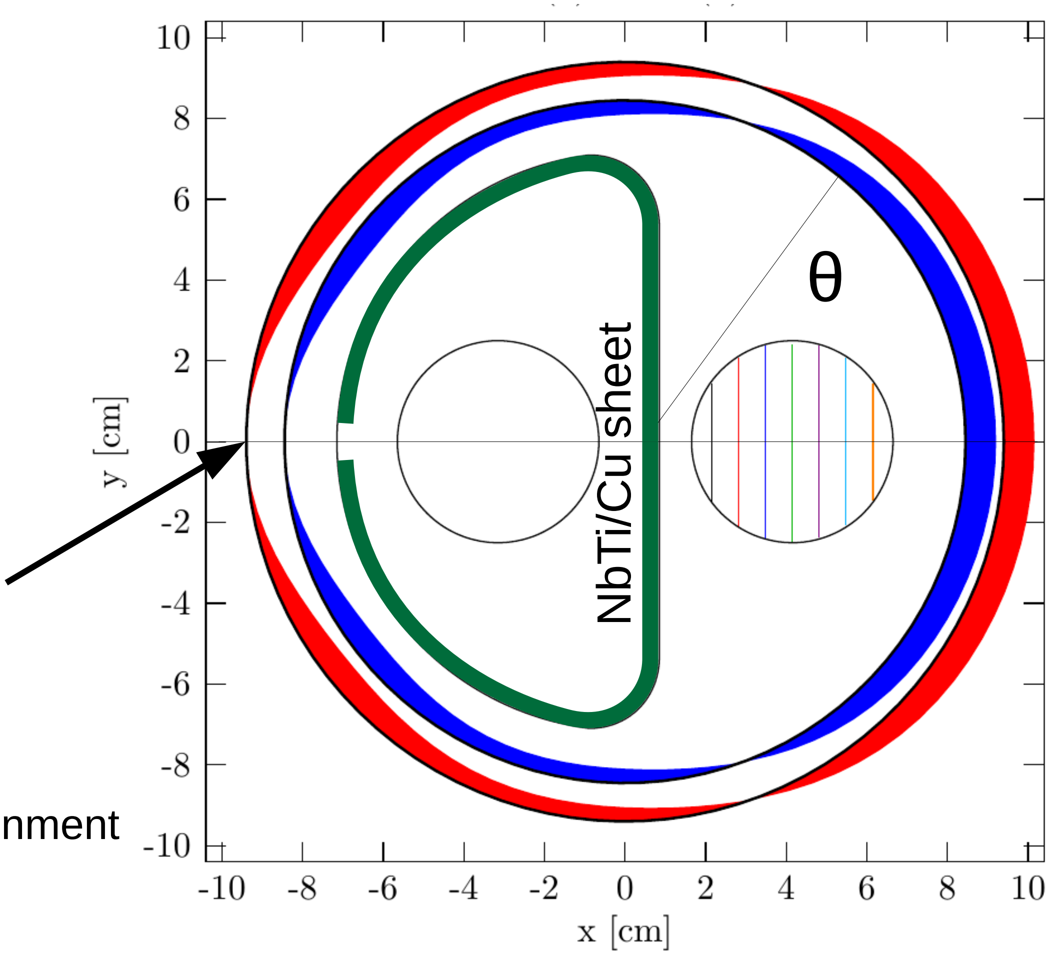
2D optimization for homogeneous field

- Assume that shield is perfect diamagnet
- Find best excitation current pattern synthesized from multipoles:
  $J_z(\theta) = \Sigma J_k \cos(k\theta)$
- Simulate and Fourier-analyze field (B_n) for individual current multipoles $\cos(k\theta)$
- Linear problem: $B_n = M_{nk} \cdot J_k$



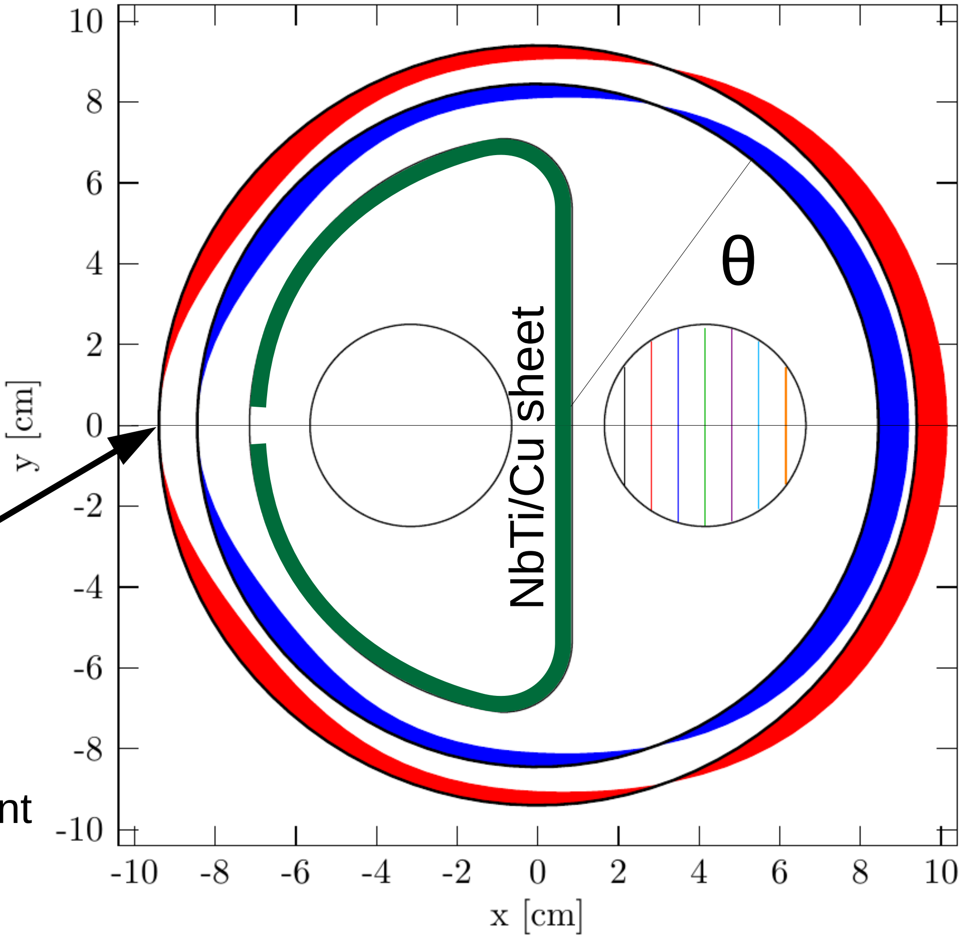
2D optimization for homogeneous field

- Assume that shield is perfect diamagnet
- Find best excitation current pattern synthesized from multipoles: $J_z(\theta) = \Sigma\, J_k \cos(k\theta)$
- Simulate and Fourier-analyze field (B_n) for individual current multipoles cos(kθ)
- Linear problem: $B_n = M_{nk} \cdot J_k$
- One can add further linear constraints, e.g. $J_z(\theta=180^o)=0$
  - Shield from NbTi/Cu sheet needs a cut
  - Best position is here
  - Small field here decreases sensitivity to alignment



2D optimization for homogeneous field

- Assume that shield is perfect diamagnet
- Find best excitation current pattern synthesized from multipoles:
  $J_z(\theta) = \Sigma J_k \cos(k\theta)$
- Simulate and Fourier-analyze field (B_n) for individual current multipoles $\cos(k\theta)$
- Linear problem: $B_n = M_{nk} \cdot J_k$
- One can add further linear constraints, e.g. $J_z(\theta=180^o)=0$
  - Shield from NbTi/Cu sheet needs a cut
  - Best position is here
  - Small field here decreases sensitivity to alignment
- Invert the problem using singular value decomposition (SVD) to get J_k



2D → 3D

- 3D wire path is straightforward from $J_z(\theta)$

$$x(\theta) = R\cos(\theta)$$

$$y(\theta) = R\sin(\theta)$$

$$z(\theta) = \frac{\pm R D_w P}{I_0 n_1} \int J_z(\theta')\,\mathrm{d}\theta' + P\frac{\theta}{2\pi}$$

pitch

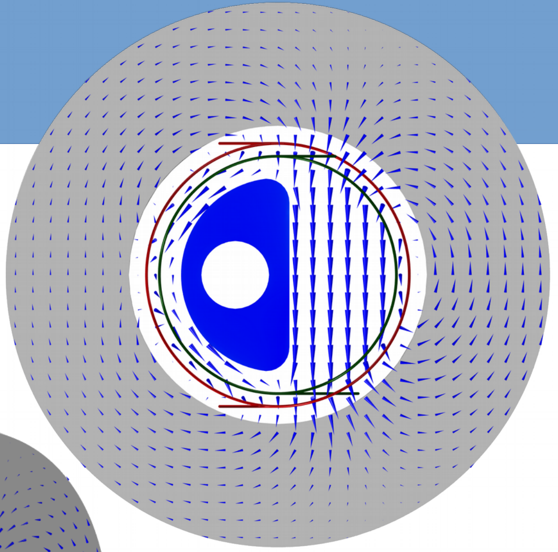
wire diameter

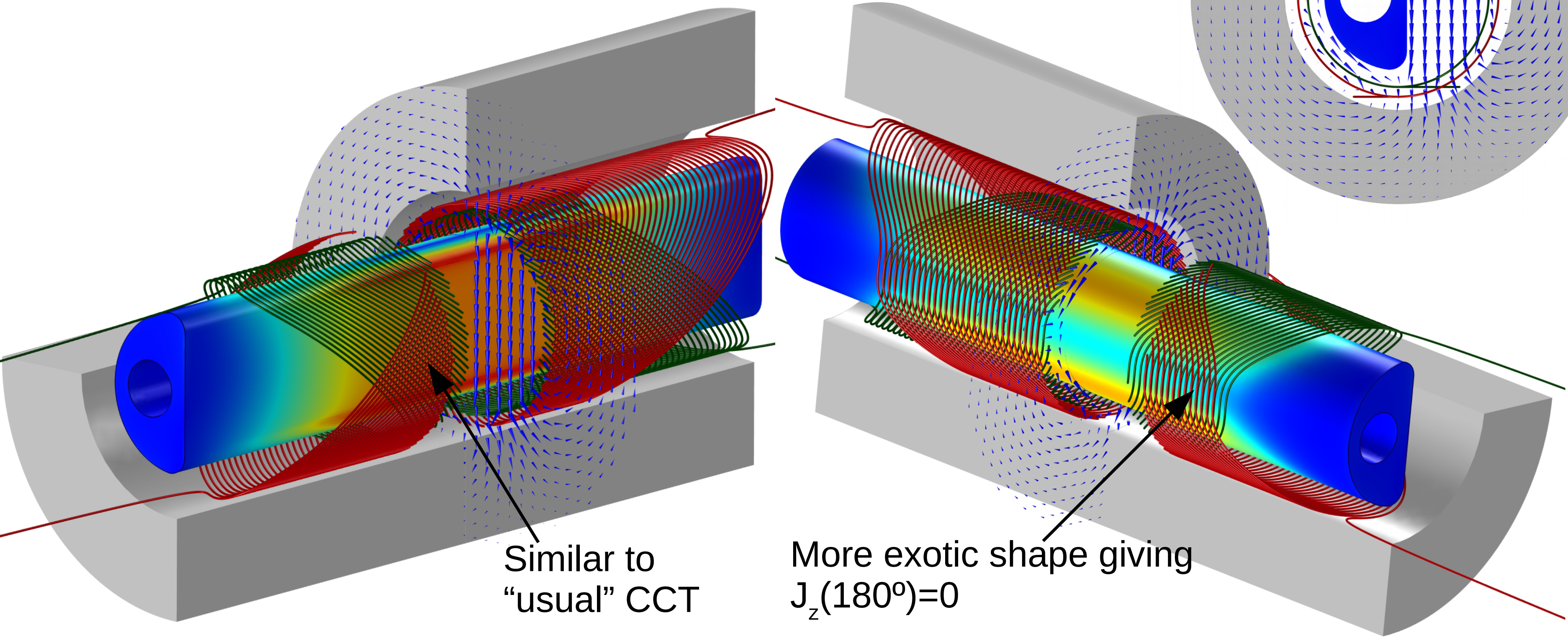
Number of neighbouring wires in groove (=2)

$\Sigma\, J_k \cos(k\theta)$

Closed analytical formula for 3D path of winding

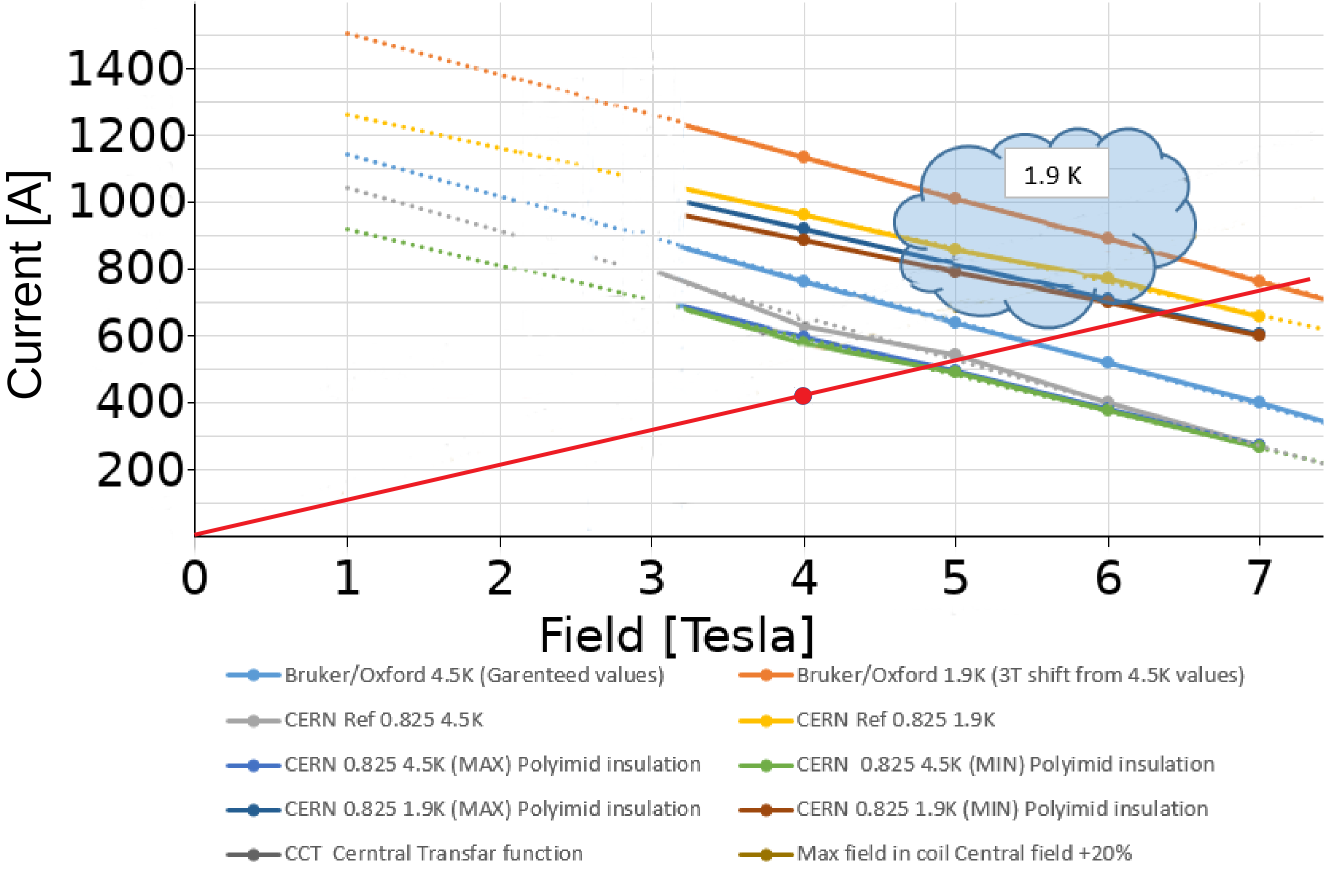
3D winding





SC wire performance

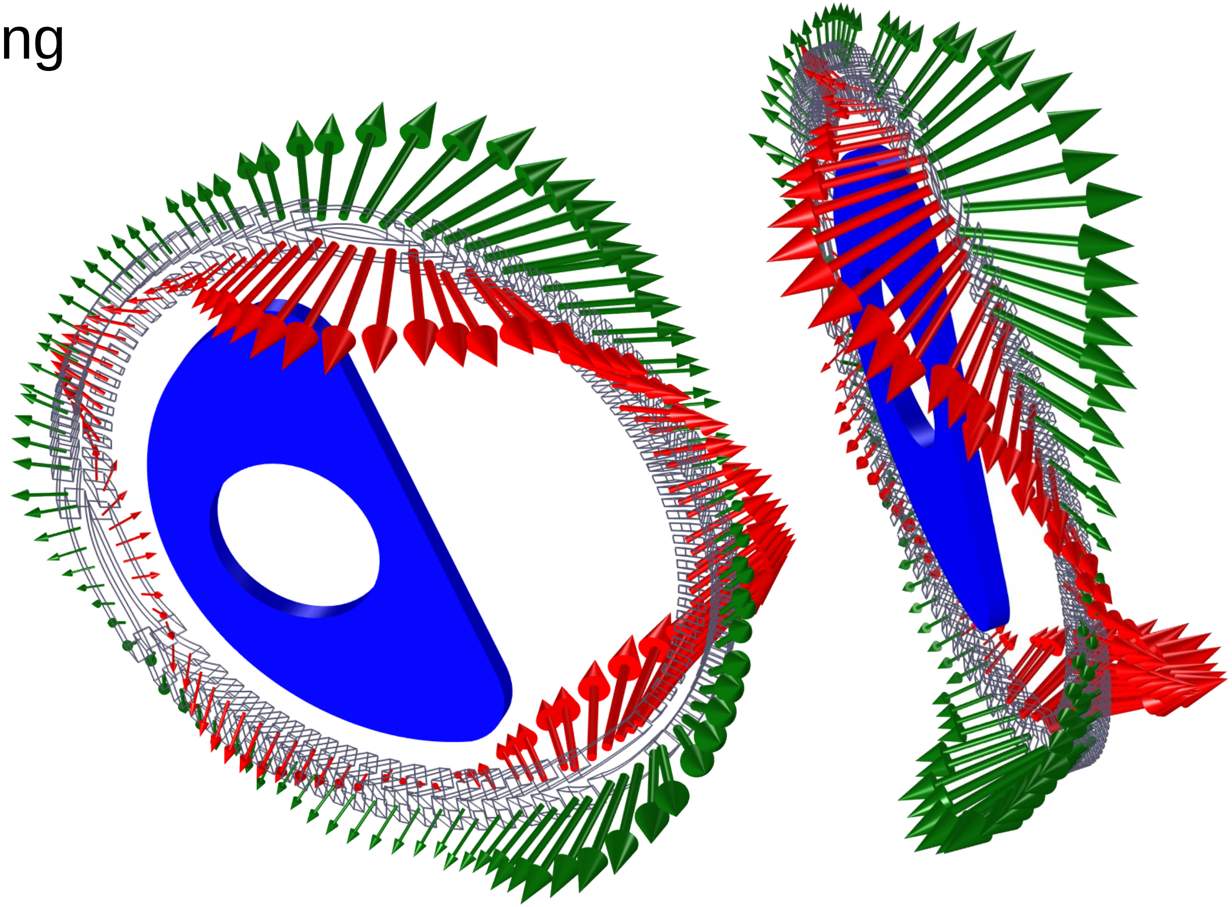
- Peak field: assume 4 T (see backup slide)
- Commercial SC conductors have ≥40% margin
- Wire length for 1 m winding: ~ 4 km
- 4 kEuro, Negligible cost



https://www.researchgate.net/project/LHC-hi-Lumi-orbit-corrector-5Tm-CCT/update/592db3cf1042bfac8917475f

Mechanical stresses

- Assume the winding is a floating block
- Force/m = $N \cdot I_0 \cdot B_{max}$ = 12 · 420 A · 4 T = 20 kN/m
- Take smaller side: 2 mm
- P = 10 MPa
- Very conservative!!! Largest forces are tangential (larger surface of wire block)



Stresses are OK!

Issues: trapped field & thermal “reset”

- When SC is cycled to high field and back, trapped field remains
- Can disturb homogeneity at low fields

- Flux jump – collapse of the shielding effect
- Field penetrates suddenly
  - Field freezes back into SC shield

Need “thermal reset” to eliminate?

- Heat above T_c
- Cool down in zero field
- Causes a lot of deadtime!

Issues: trapped field & thermal “reset”

- When SC is cycled to high field and back, trapped field remains
- Can disturb homogeneity at low fields

- Not significant
- Can be eliminated

- Flux jump – collapse of the shielding effect
- Field penetrates suddenly
  - Field freezes back into SC shield

Need “thermal reset” to eliminate?

- Heat above T_c
- Cool down in zero field
- Causes a lot of deadtime!

Issues: trapped field & thermal “reset”

- When SC is cycled to high field and back, trapped field remains
- Can disturb homogeneity at low fields

- Not significant
- Can be eliminated

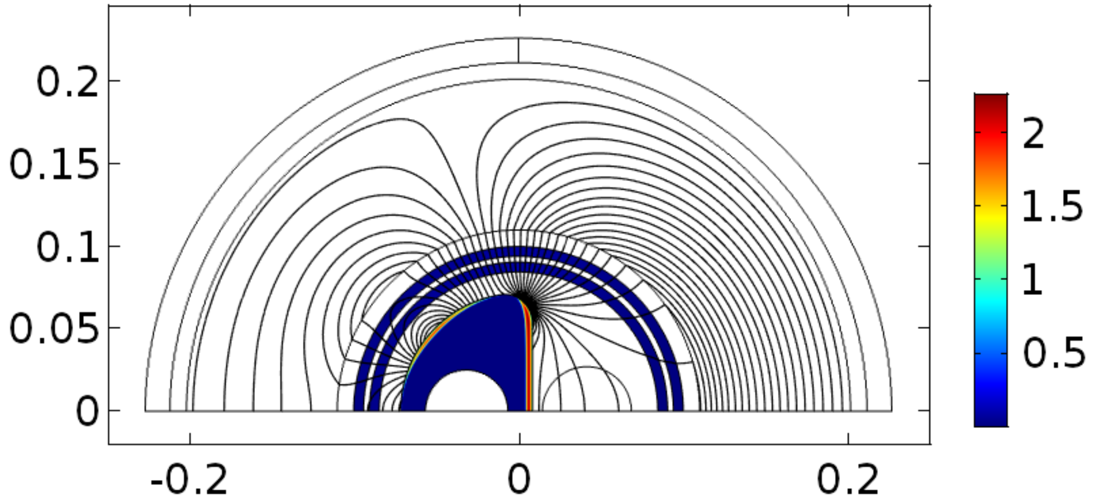
- Flux jump – collapse of the shielding effect
- Field penetrates suddenly
  - Field freezes back into SC shield

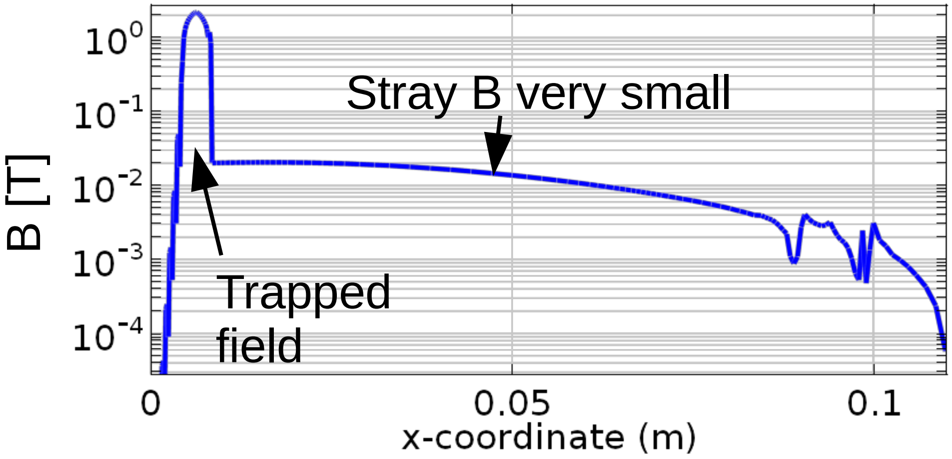
- Shield is stable
- Only if beam actively quenches the shield

Need “thermal reset” to eliminate?

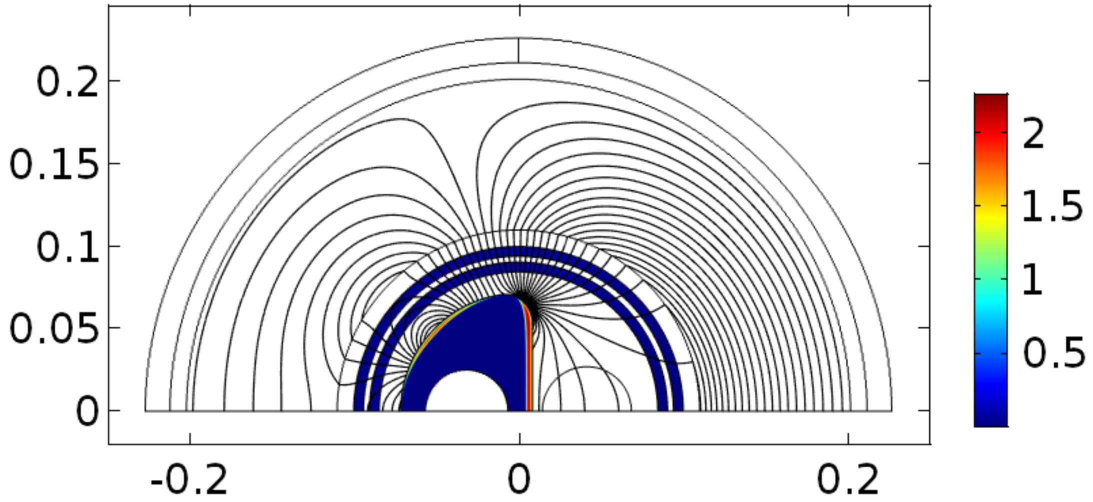
- Heat above T_c
- Cool down in zero field
- Causes a lot of deadtime!

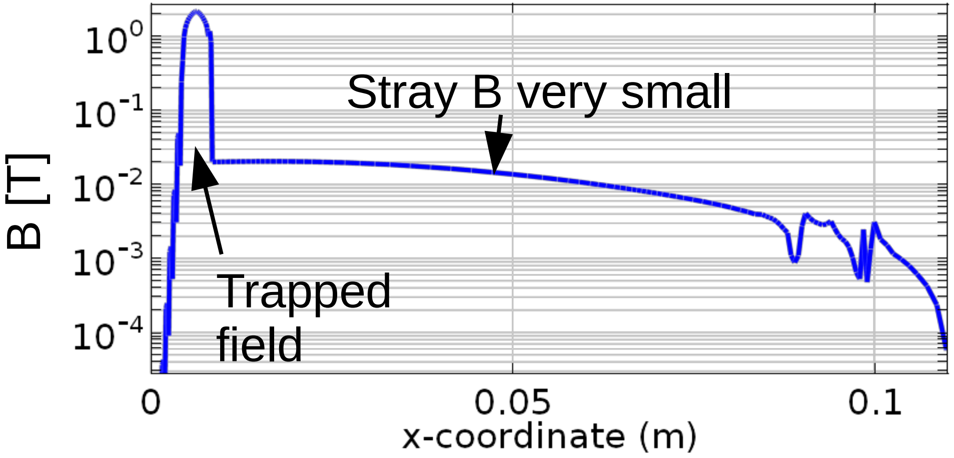
Trapped field

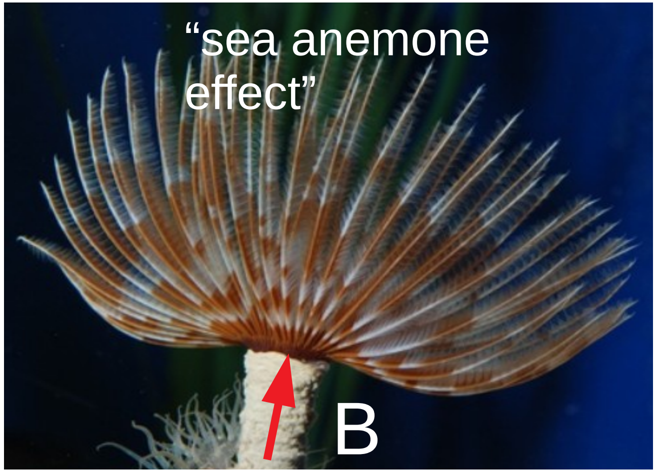




Trapped field



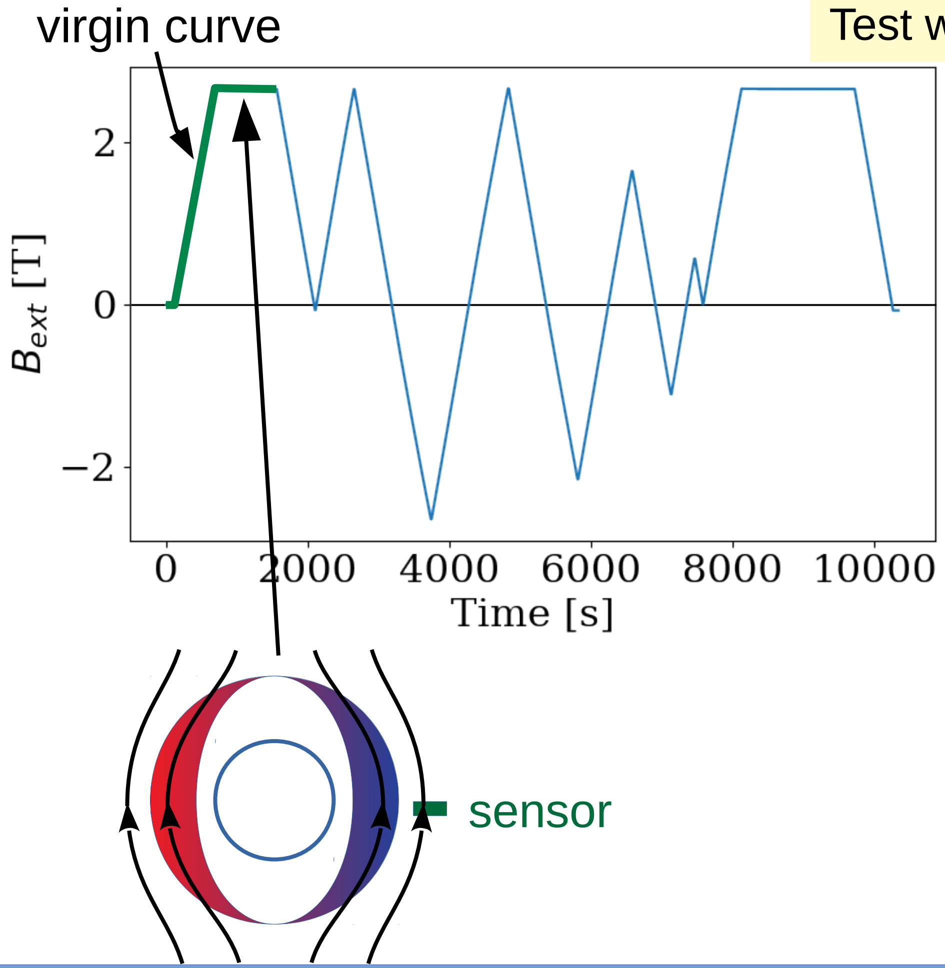


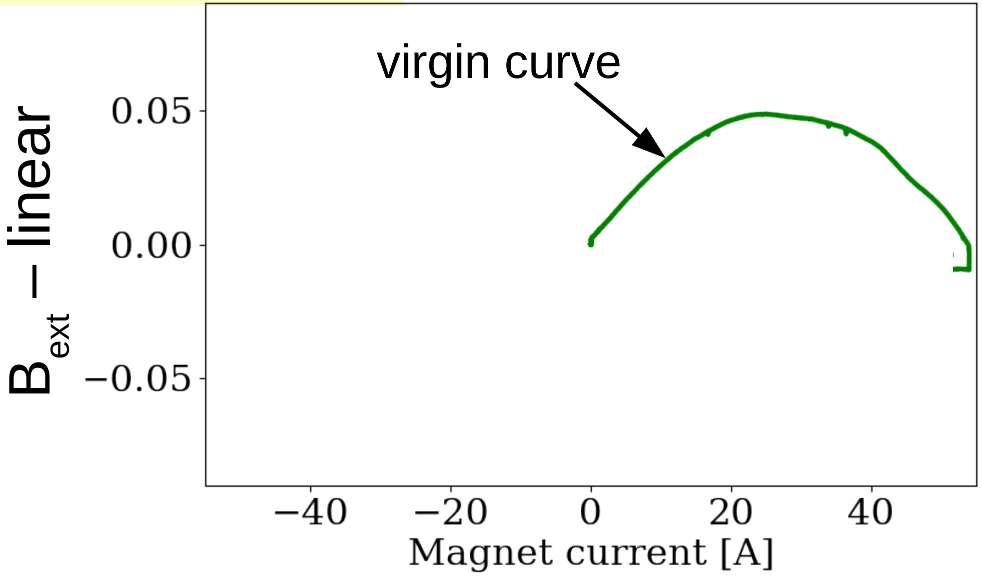


- Magnetic field in long narrow region
- B-lines exit at two ends
- Captured by the nearby yoke

Eliminating trapped field: demagnetization

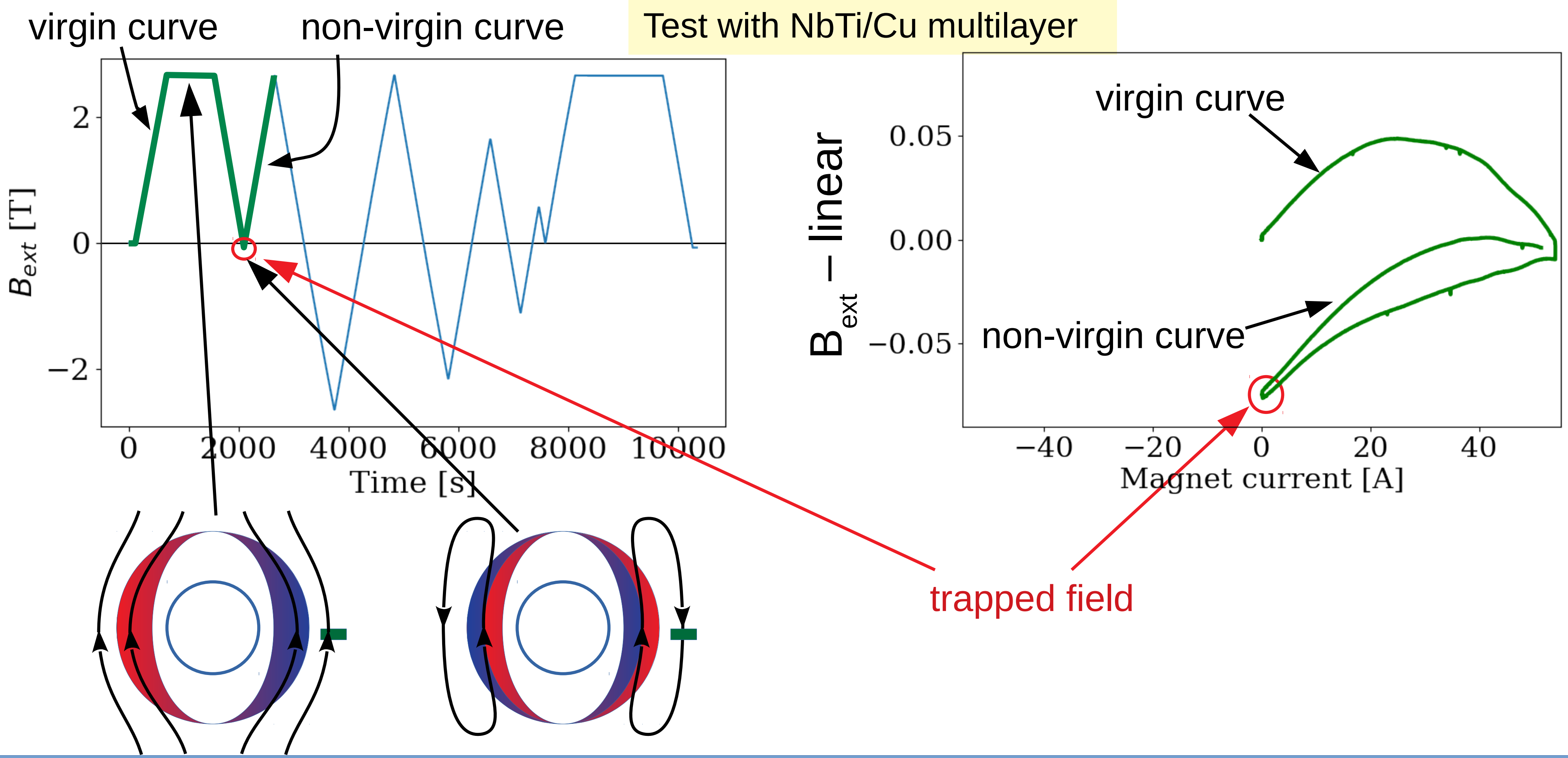
Test with NbTi/Cu multilayer





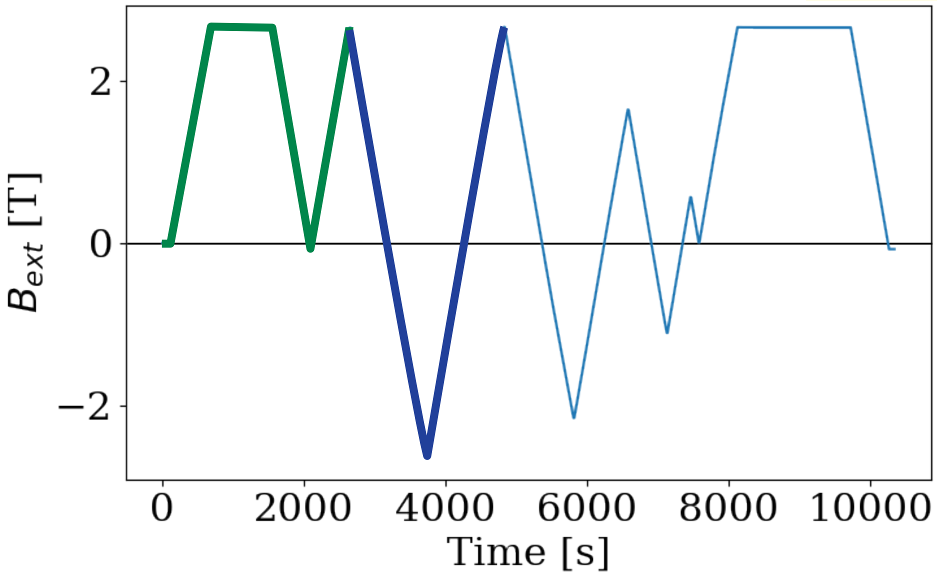
Eliminating trapped field: demagnetization

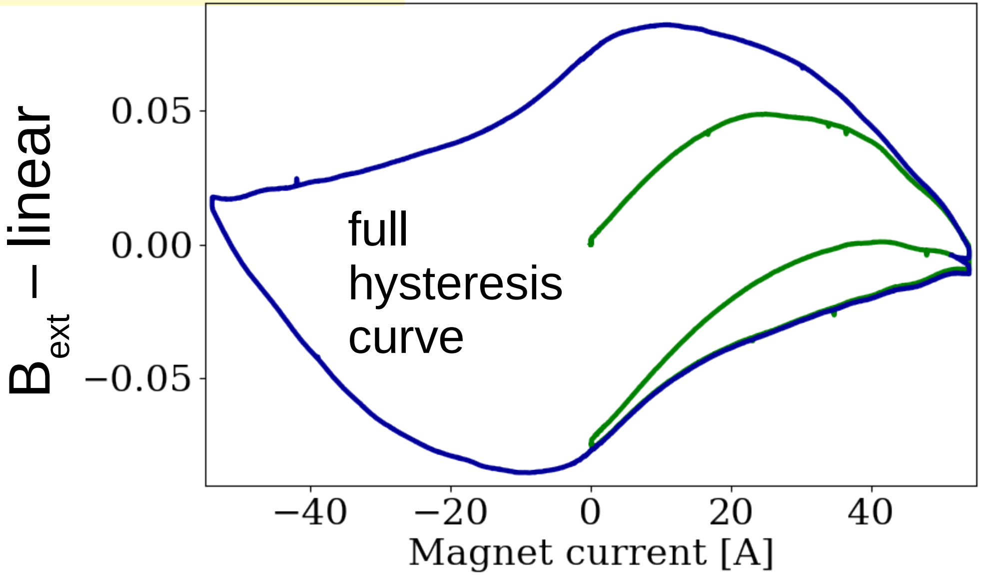
Test with NbTi/Cu multilayer

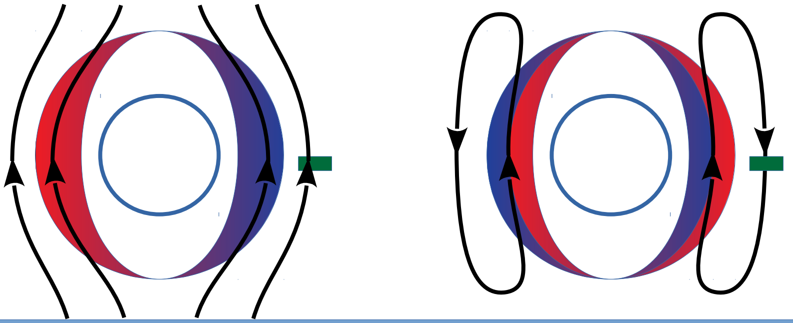


Eliminating trapped field: demagnetization

Test with NbTi/Cu multilayer

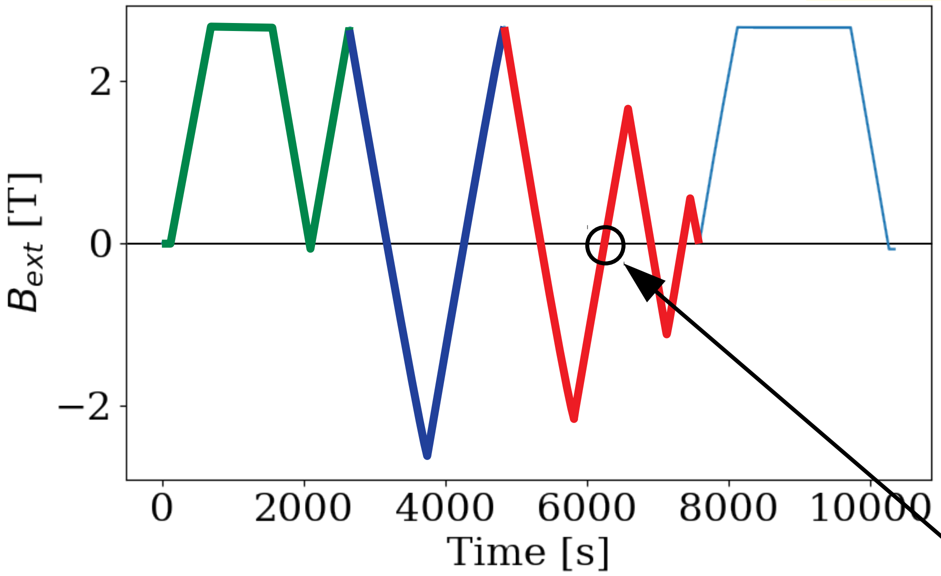


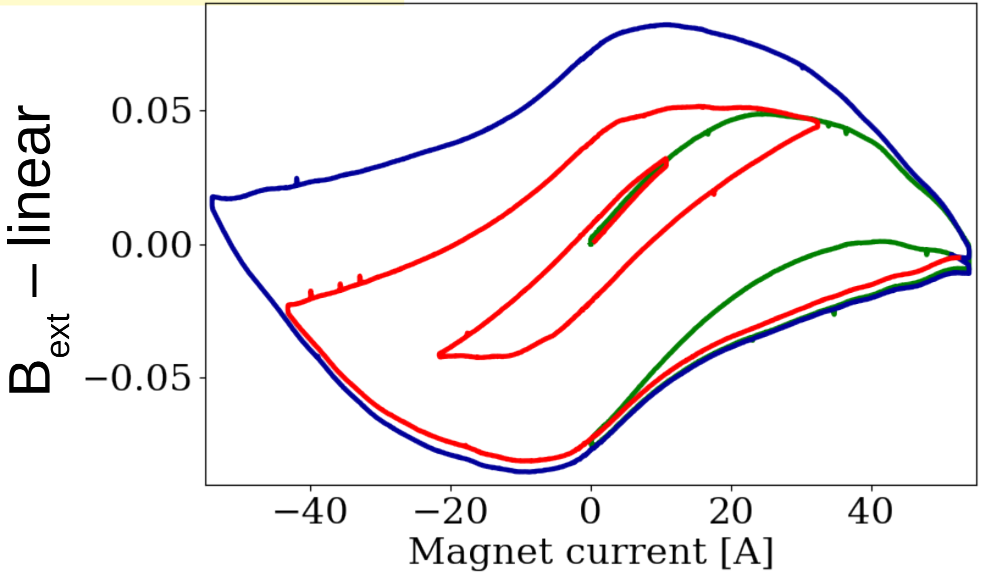


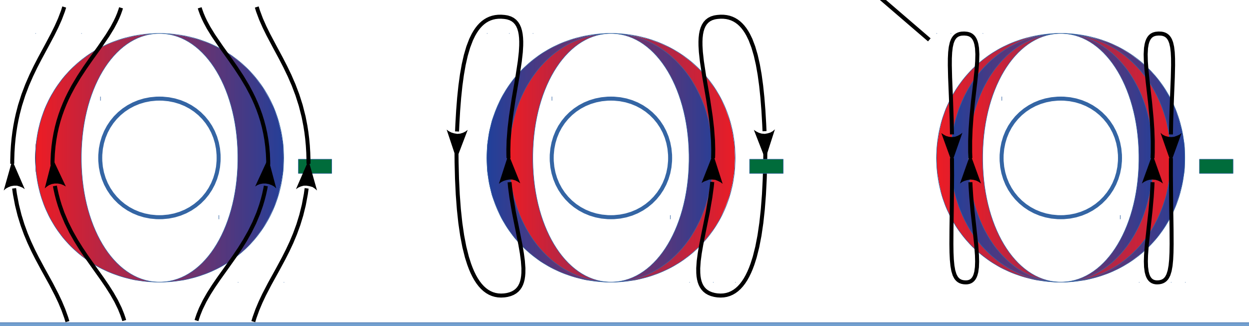


Eliminating trapped field: demagnetization

Test with NbTi/Cu multilayer

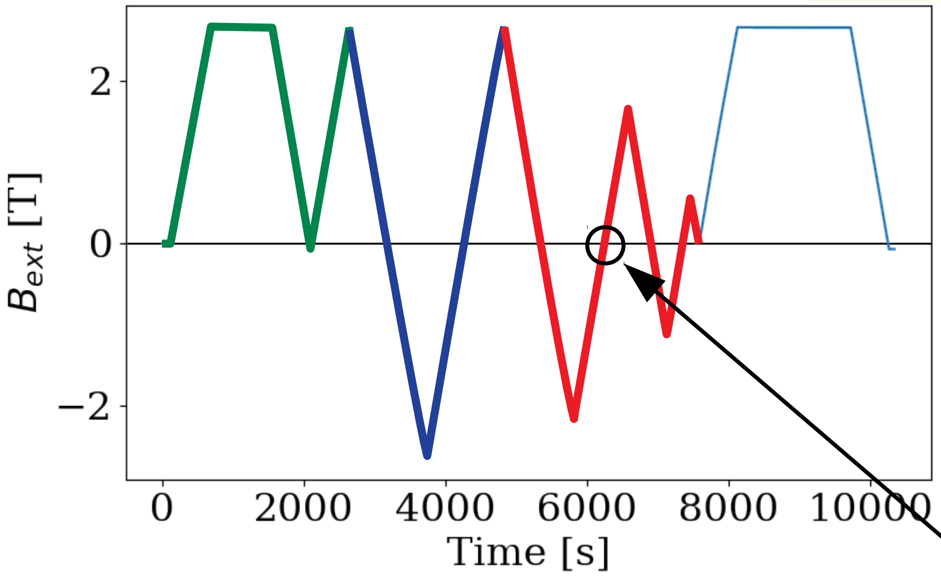


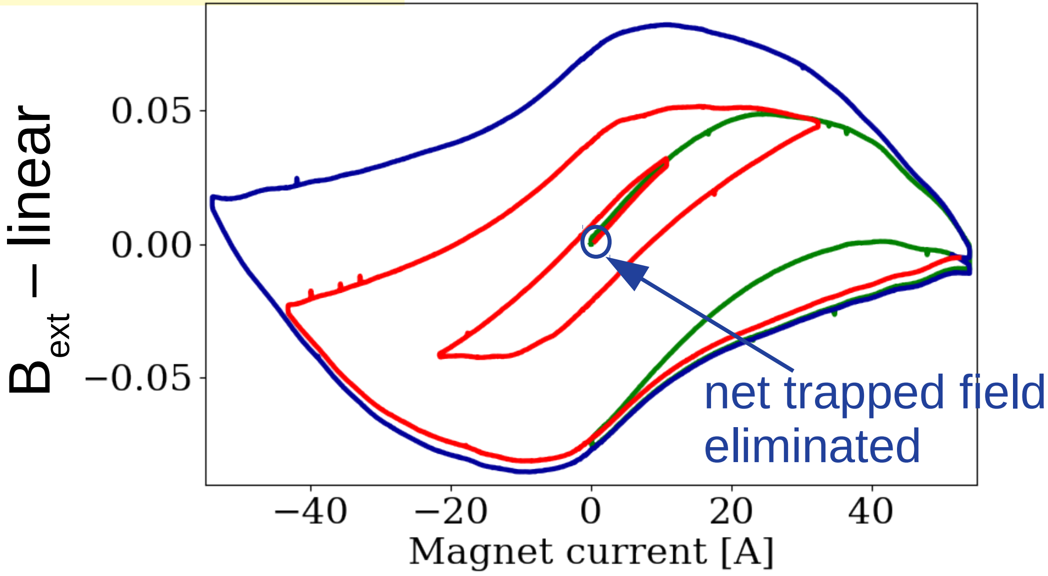


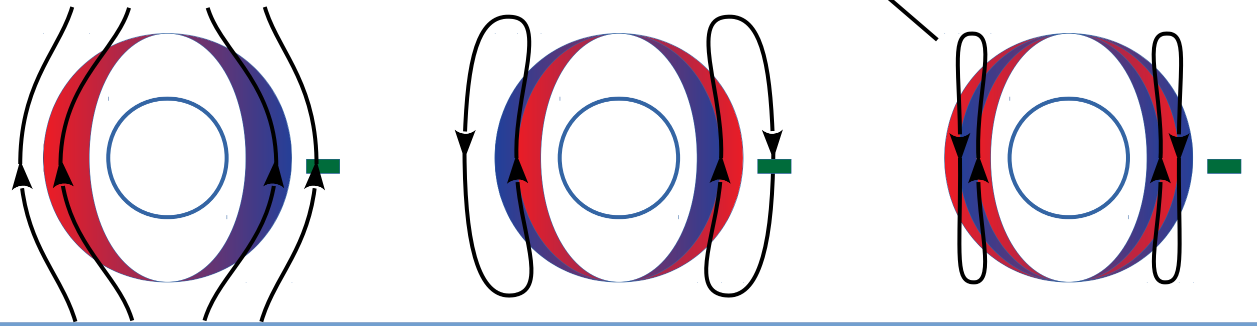


Eliminating trapped field: demagnetization

Test with NbTi/Cu multilayer







- Trapped field is not an issue
- No “thermal reset”

Project proposal: demonstrator prototype

- Short length
  - 80 turns, L_w = 400 mm
  - Total winding length: ~600 mm
  - Shield length: 700 mm
- Scale transverse geometry down to D_{bore} = 105 mm (Hi-Lumi corrector)
- GFR = 30 mm – sufficient to use a rotating coil to measure field quality
- Inductance: 150 mH (~ 100 mH of REF) → Can use existing test hardware (power supply and quench protection system)

Staged approach:

1. Manufacture MgB_2 shield (half-moon shape) – cheap & quick
2. Put it into Hi-Lumi CCT prototype (no homogeneous field yet) – by end of 2018, early 2019
3. If all goes well: Construct dedicated CCT magnet, MgB_2 shield, measure field qual. – by end of 2019
4. If all goes well: discuss about the purchase of NbTi/Cu multilayer

Conclusions & Outlook

- Both MgB_2 and <u>NbTi/Cu</u> could safely shield **3.2 Tesla**
- Septum thickness of 15 mm (**apparent septum thickness of 21 mm**) – use conservatively 25 mm for baseline design
- Trapped field is not an issue, no need for “thermal reset”
- CCT-like magnet can generate required field quality, and it is simple & cheap
- Scaled-down demonstrator prototype project is proposed:
  - Conceptual model exists
  - Simulations (both 2D and 3D) are underway
  - Magnetic & mechanical design seems straightforward
  - Parameters close to Hi-Lumi CCT system → use existing hardware (QPS, PS, etc)
  - Timescale: 2 years

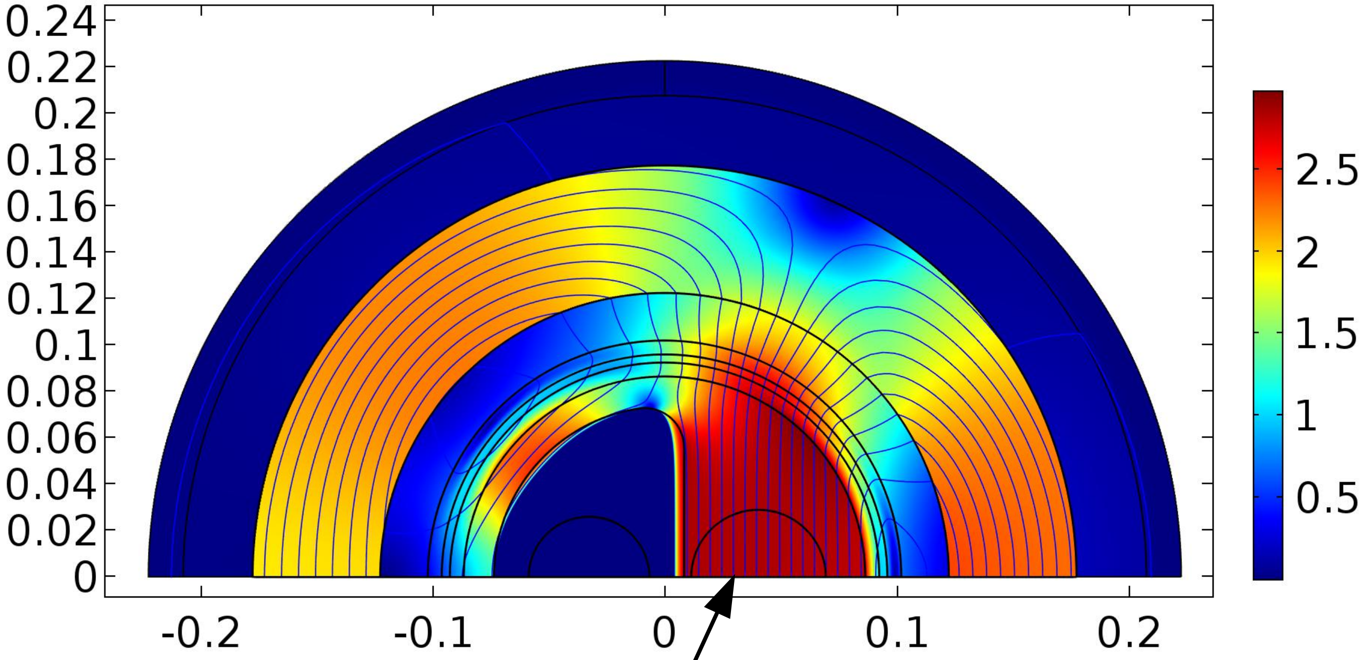
Acknowledgements

- Glyn Kirby & his team – (hi-lumi CCT design & construction) for discussions, ideas, brainstorming, knowledge sharing
- Márta Bajkó, Max Pascal, Jerome Feuvrier, Franco Mangiarotti, Frederic Rougemont, Yannick Thuau & the rest of the CERN SM18 team – SC shield tests (Aries TNA)
- Carlo Petrone – Magnetic diagnostics of the tests
- European Union’s Horizon 2020 research and innovation programme (ARIES) under grant agreement No 730871
- Hungarian National Research, Development and Innovation Office under grant #K124945
- FCC Study Group

BACKUP SLIDES

2D with realistic superconductor

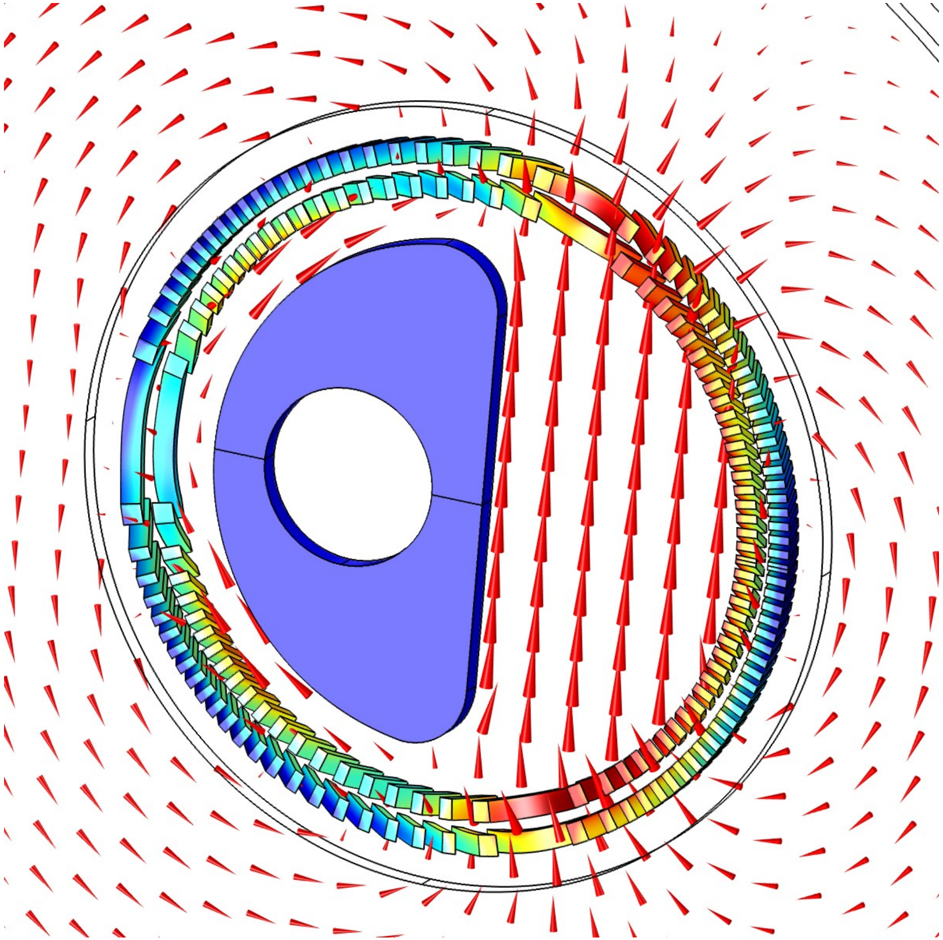
- At high fields: field penetrates → nonlinearities
- Use Campbell's method in COMSOL
- Flat wall of shield → parallel penetration, minimal field distortion



Homogeneity in a 50 mm good-field-region: within +/-1%, without further optimization

Peak field

- Inside the structure: periodic symmetry
- Simulate one cell with fine mesh
- Peak field inside coil: ~3.5 T
- TODO: peak field at coil ends
  - assume: 4 T
  - simple scaling from hi-lumi CCT gives 3.8 T



Quench protection

- Aluminium formers → induced currents
  - part of energy is dissipated there
  - helps heating the winding everywhere (quench-back)
- Hi-Lumi CCT magnets use a simple QPS:
  - *M. Mentink, et al: Quench Behaviour of the HL-LHC Twin Aperture Orbit Correctors, Proc. 25th Int. Conf. Magn. Techn. (MT25)*
- Our coil geometry is very similar to REF
- Device inductance:
  ~3.5 mH/5 mm → 1400 mH for 2 m device
- Try to bring close to REF (820 mH),
  use similar QPS