Status of the SuShi septum project

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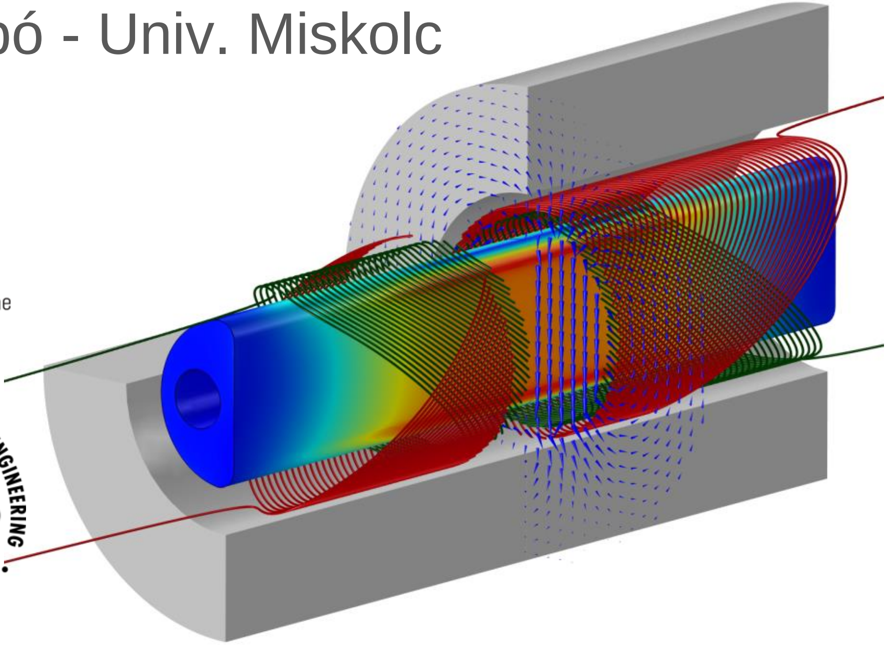
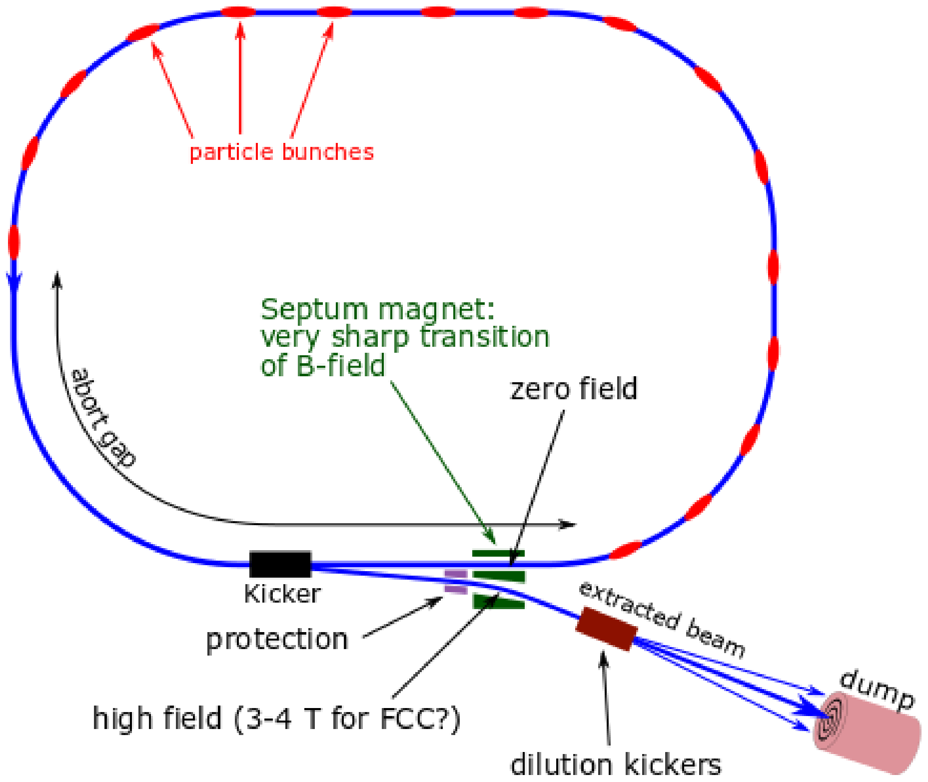


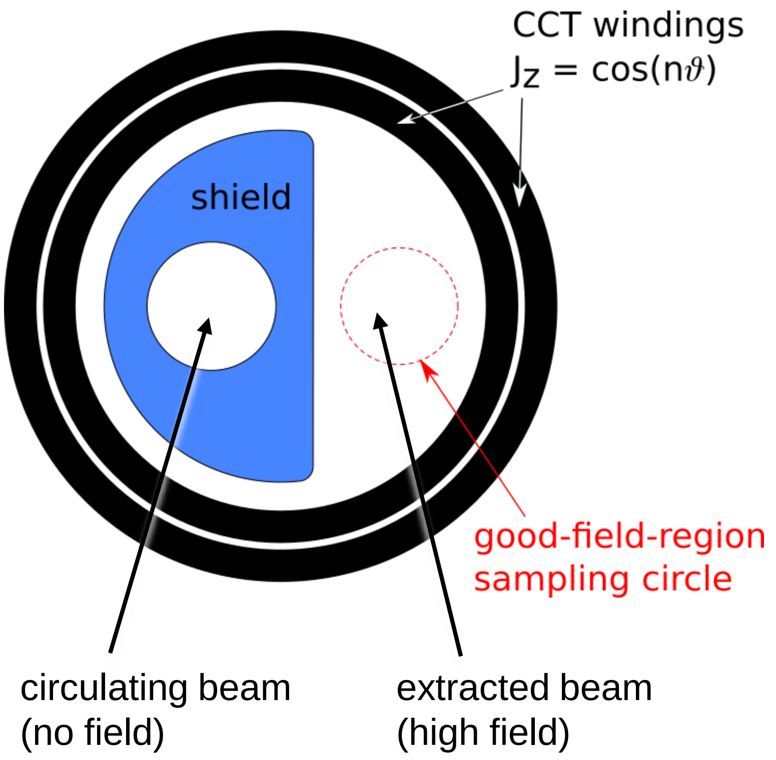
Introduction



- LHC uses Lambertson septum
- Conventional technologies
- Reliable
- Limited ~ 1.5 T
- For FCC it would be too long
- High energy consumption
- Goals:
  - Demonstrator prototype
  - Septum with 3+ T field
  - <25 mm apparent thickness
  - CCT magnet with a bulk sc. shield inside of it

2D optimization

1. Simulate the field around the half-moon shaped shield (perfect diamagnet) for $J_z=\cos(n\vartheta)$ (n=1..6) using COMSOL
2. Sample field around GFR, calculate multipole composition for each n
3. Invert the problem (linear algebra) to get weights J_n of multipole current $J_z(\vartheta) = \sum J_n * \cos(n\vartheta)$ which gives pure dipole field



Review of Scientific Instruments, 90 (2019) 053302, doi: 10.1063/1.5096020

3D geometry of coils from 2D optimization

3D winding path:

- $x(\vartheta) = R\cos(\vartheta)$
- $y(\vartheta) = R\sin(\vartheta)$
- $z(\vartheta) = \pm T \; P \left(\frac{RG}{n_1 n_2}\right) \int_0^{\vartheta} J_z(\vartheta')\, \mathrm{d}\vartheta' + P\frac{\vartheta}{2\pi}$

Coil radius, groove depth, # of wires

Current from 2D optimization

transfer function, only free parameter

pitch - choose smallest possible for a given T

Study magnet parameters, field pattern etc. as a function of the transfer function T

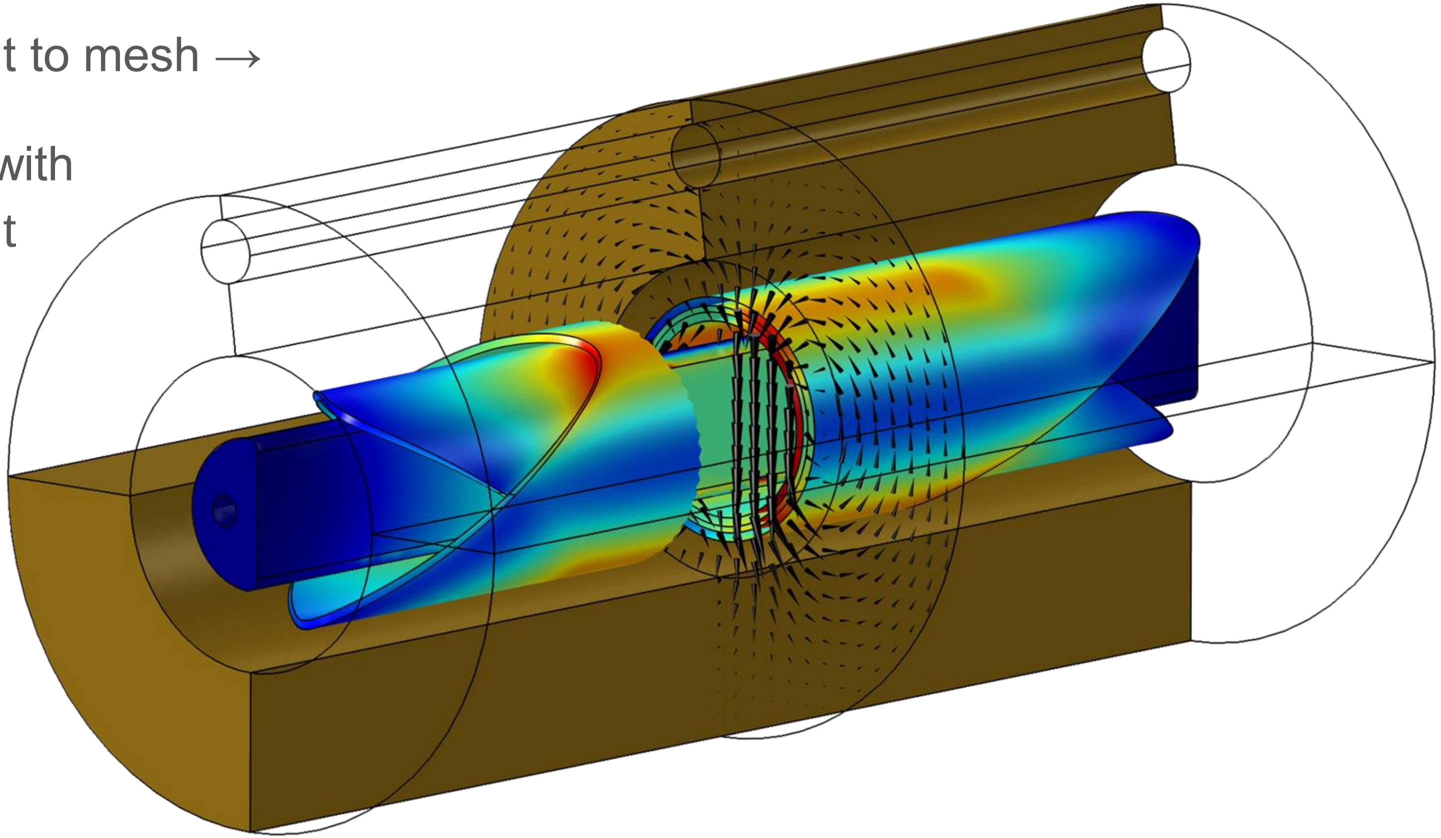
Design goals

- Keep in mind: proof-of-concept prototype for a shield+magnet septum, and not a CCT-magnet R&D project →
- CCT magnet as standard as possible, use same parameters, concepts (even test hardware) from the HL-LHC CCT corrector project, as much as possible
- Key element: shield !
- Reach **3.2 Tesla central field**
- Over a plateau of at least **10 cm**
  (to measure field homogeneity, required: ±1.5%)
- **80 cm device/shield length** (gives feasible parameters, see later)
- **105 mm bore diameter** (= hi-lumi CCT corrector)
- Do **not** try to **maximize ∫ B dz** (it will only be important in a ring)
- If the shield works → experts can tune up the magnet to maximize ∫ B dz

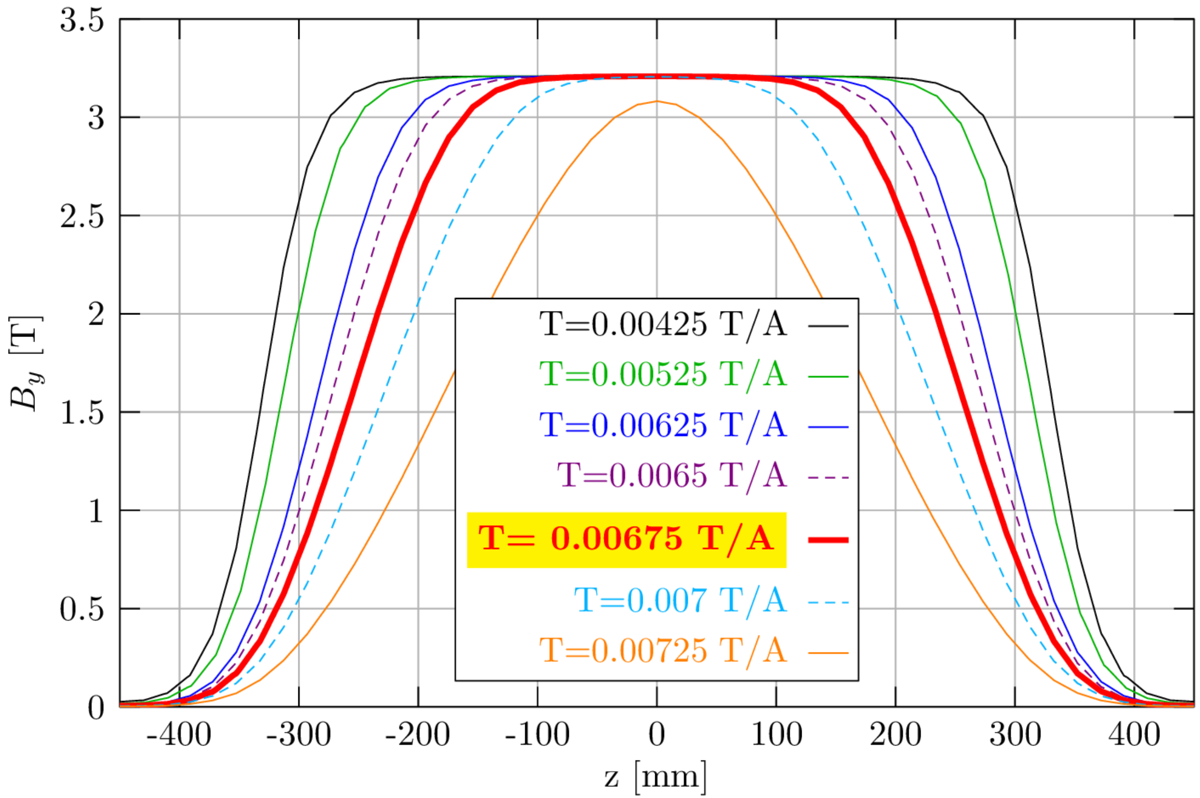
3D simulation

Winding is difficult to mesh →

use “block coils” with distributed current



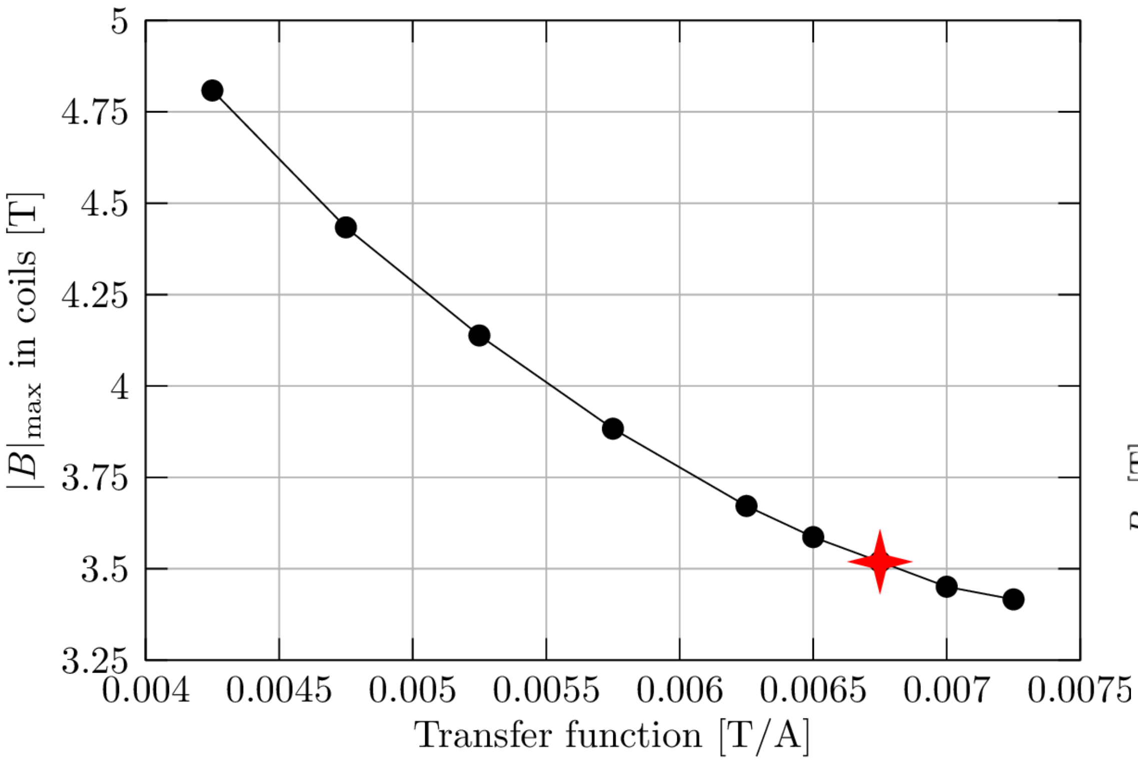
Min. 10 cm central plateau of B_y



- T = 0.00675 T/A gives > 10 cm plateau
- I_0 = **475 A** for B_0=3.2 T

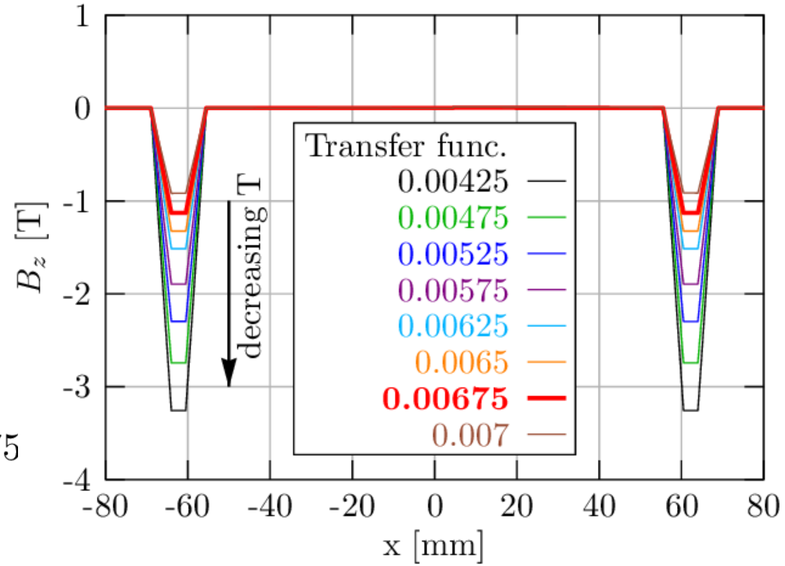
Geometry fixed

Max |B| in coils for B_0=3.2 T

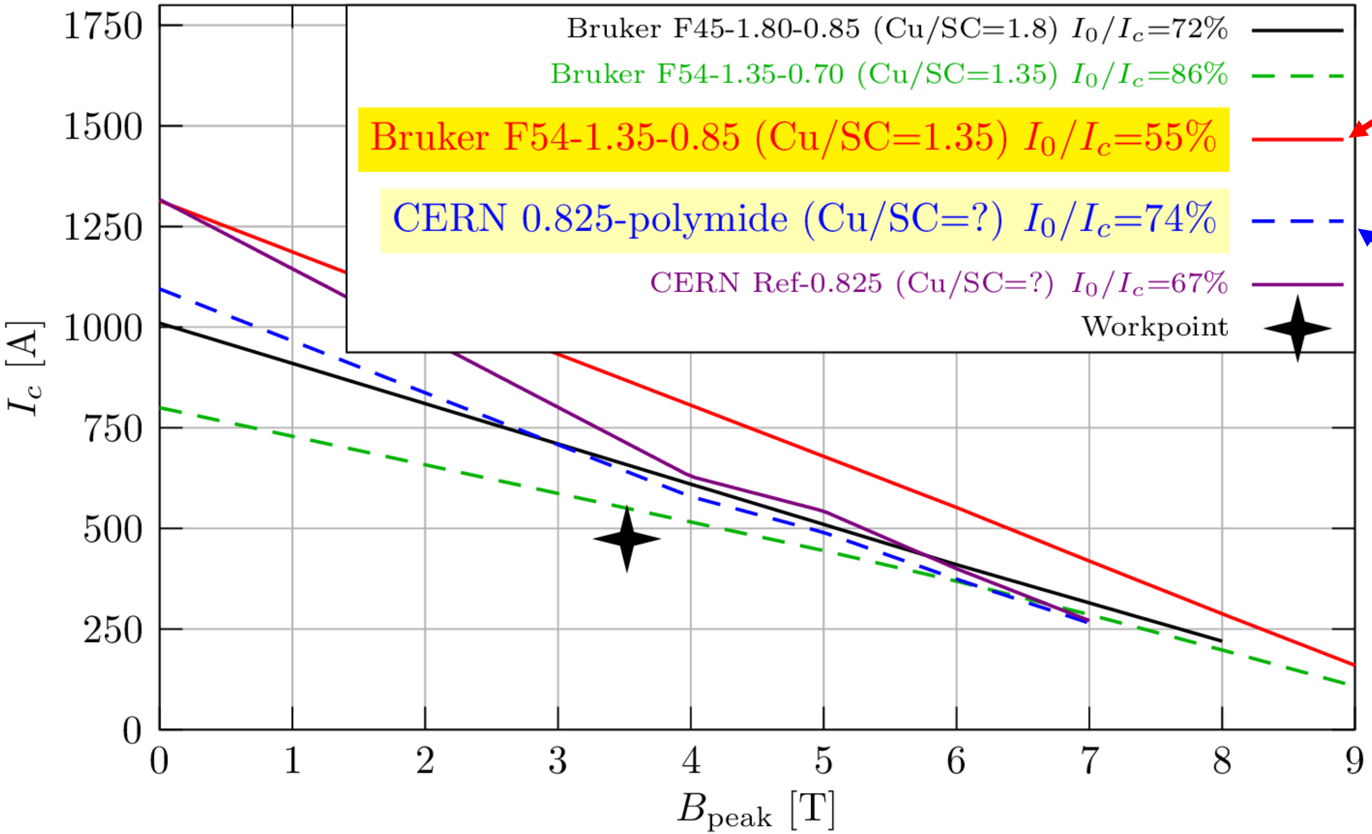


B_{peak} = 3.52 T in the coils

Reason: for low T the coils "straighten up", producing more B_z between coils



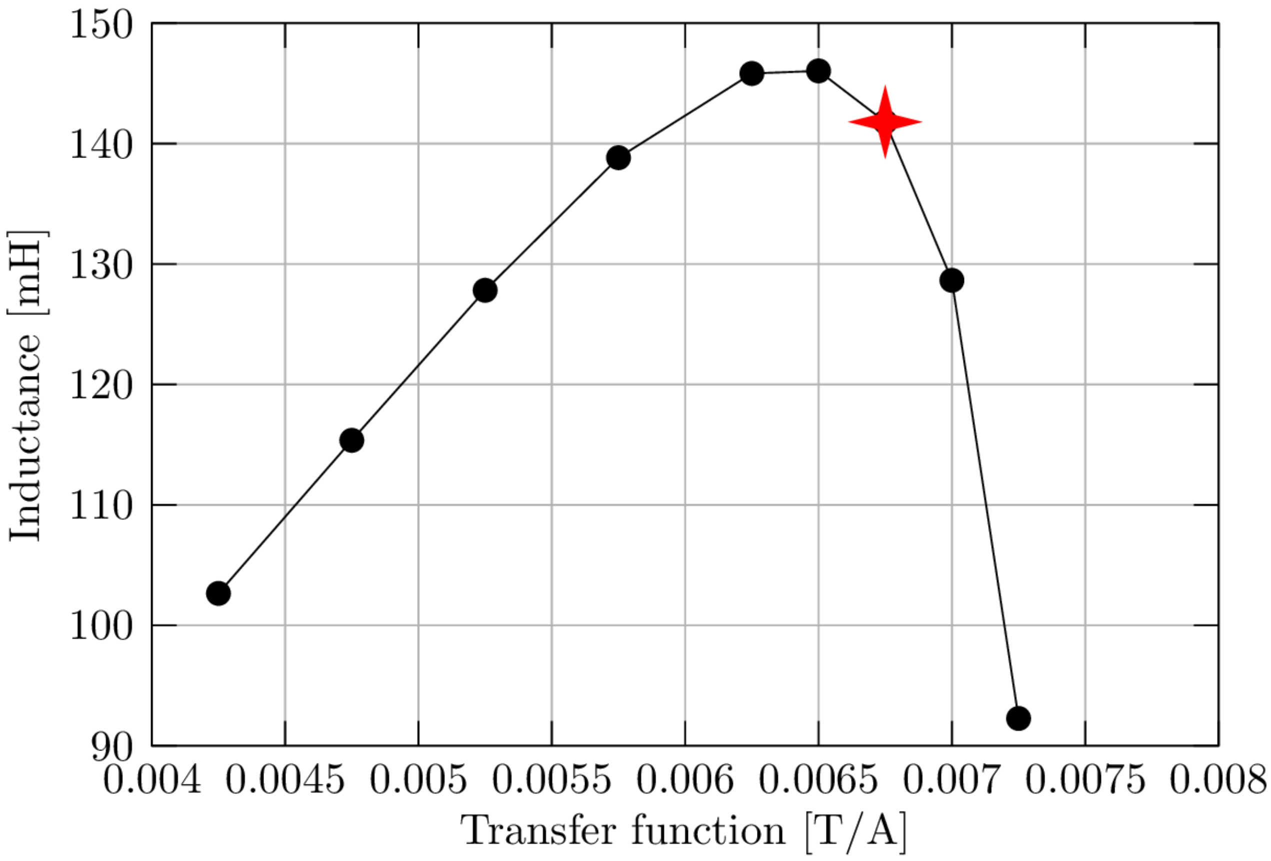
Choice of SC wire



Largest current margin

Available in CERN stocks

Inductance



L = ∫ B·H / I^2 = **142 mH**

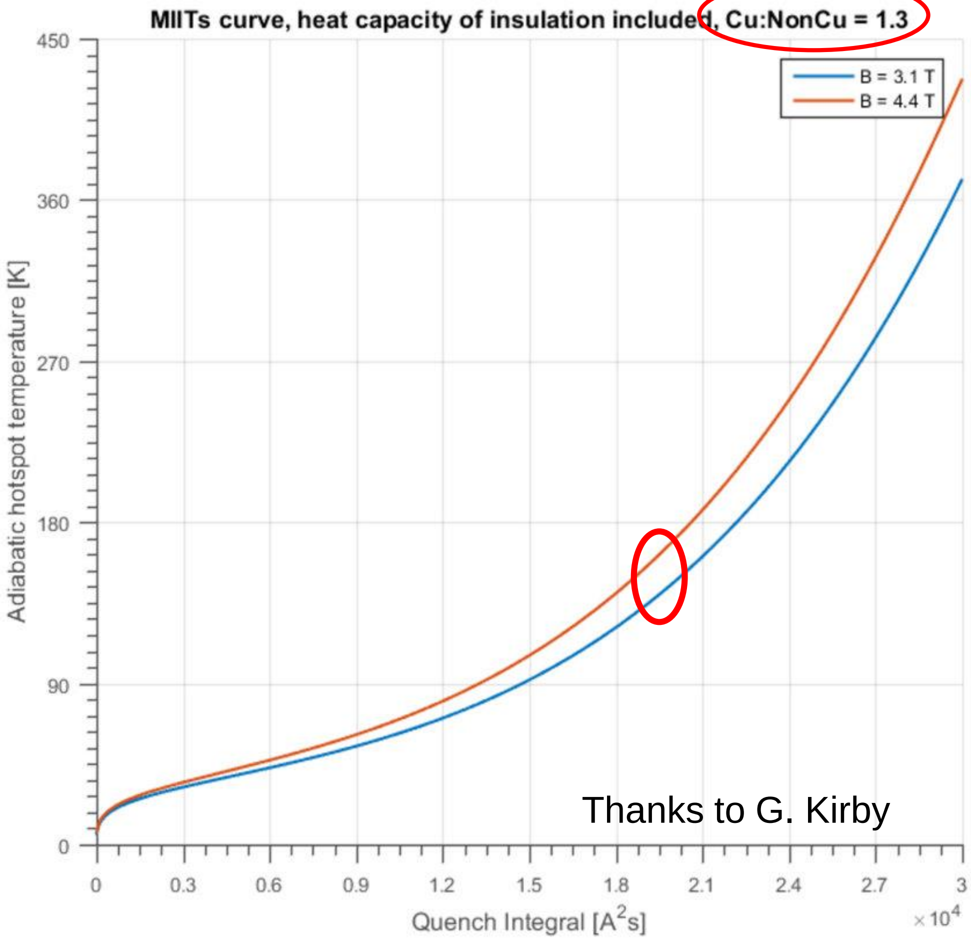
Compare to hi-lumi CCT corrector prototypes:

- 0.5 m: 102 mH
- 2.2 m: 820 mH

Quench protection

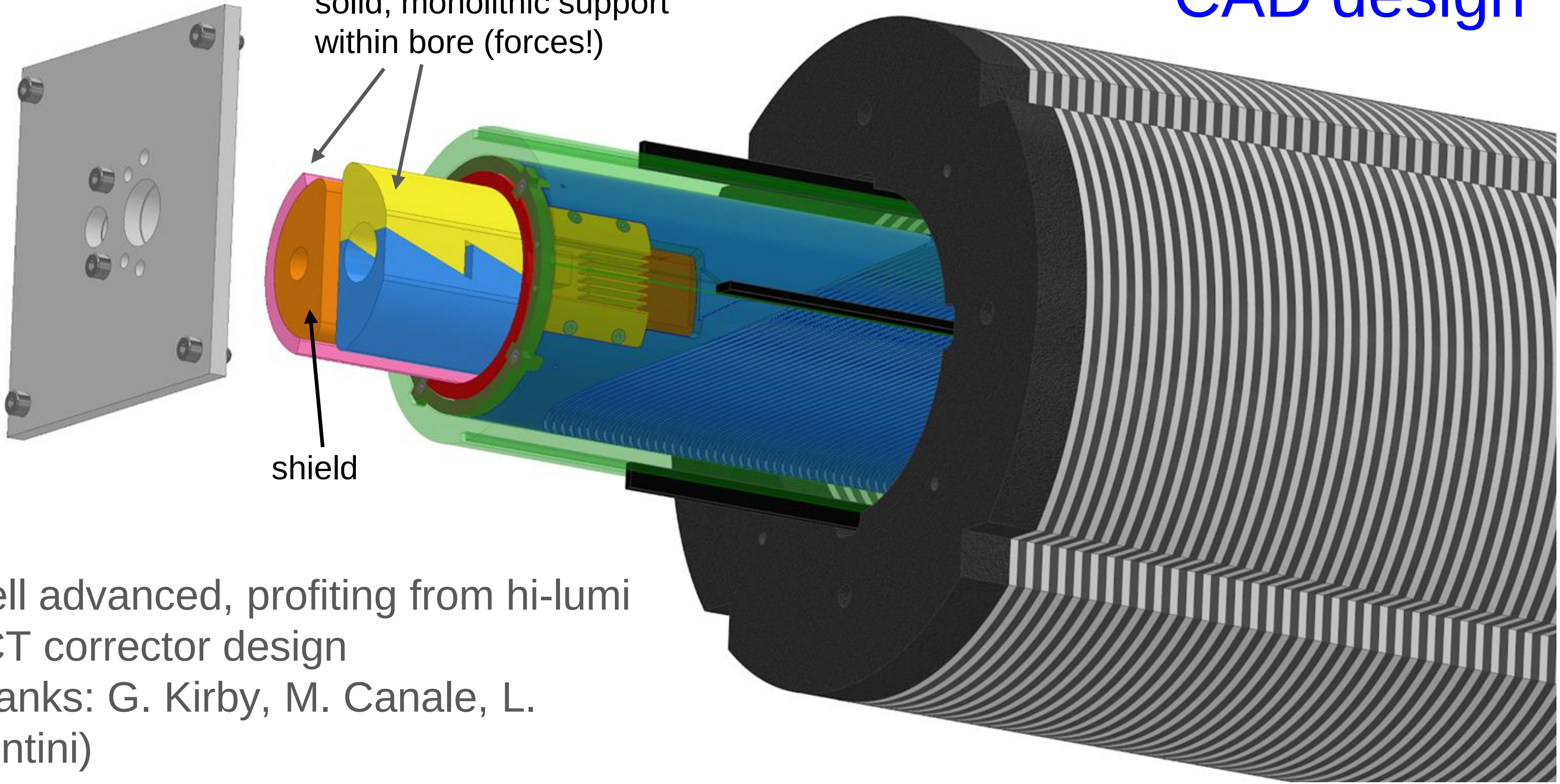
Goal: try with simple external damp resistor, as for HL-LHC CCT corrector magnets [IEEE TAS 28, 4004806]

- Set max voltage: U_0=400 V
- Damp resistor: $R_d=U_0/I_0$=843 mΩ
- τ = 168 ms
- $\int I^2\,dt$ = 18885 A^2 s
- $T_{hotspot} \approx$ 160 K
- Overestimation
  - Neglects quench back
  - Shield acting as a quench fuse (please ask…)



Thanks to G. Kirby

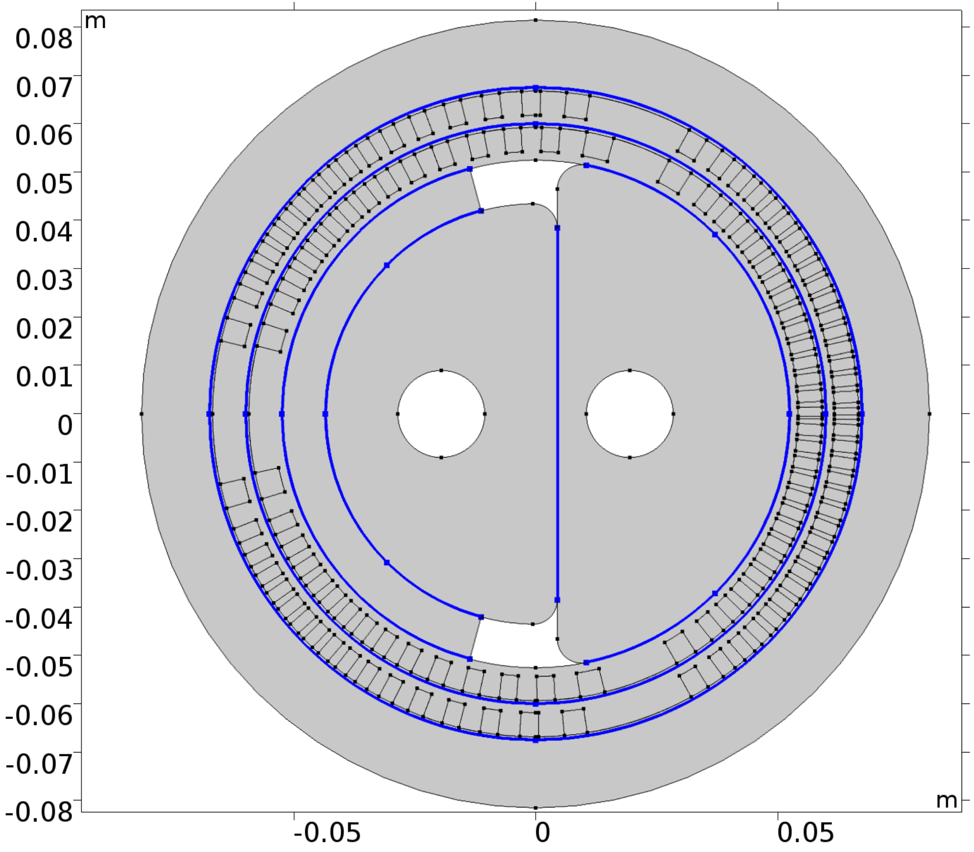
CAD design



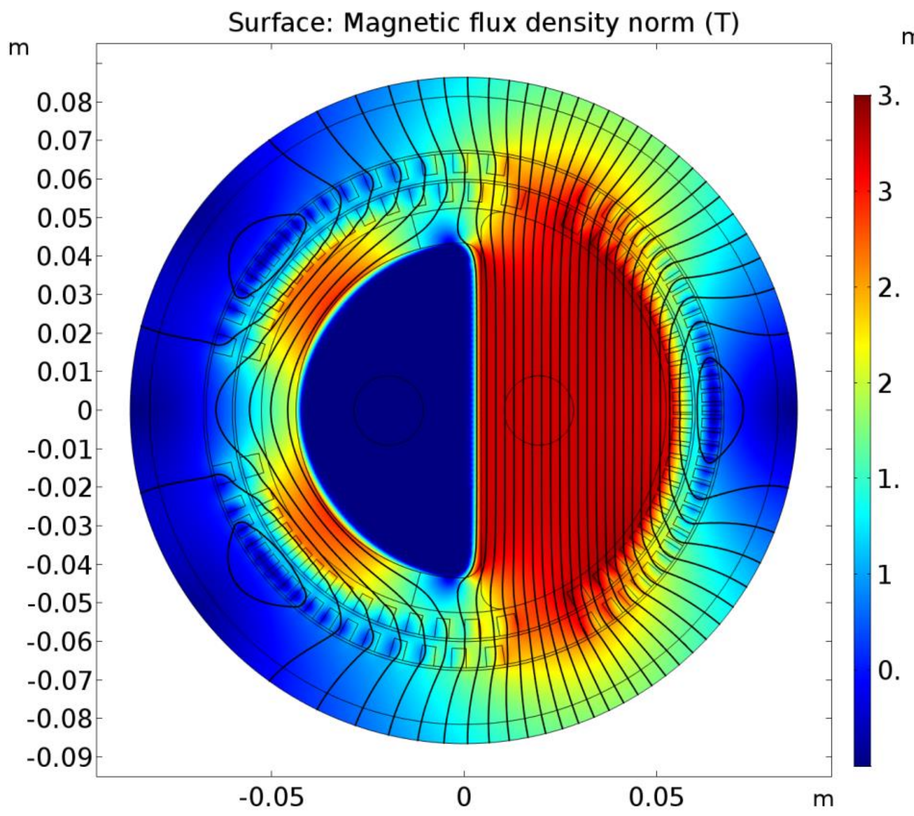
Well advanced, profiting from hi-lumi CCT corrector design (thanks: G. Kirby, M. Canale, L. Gentini)

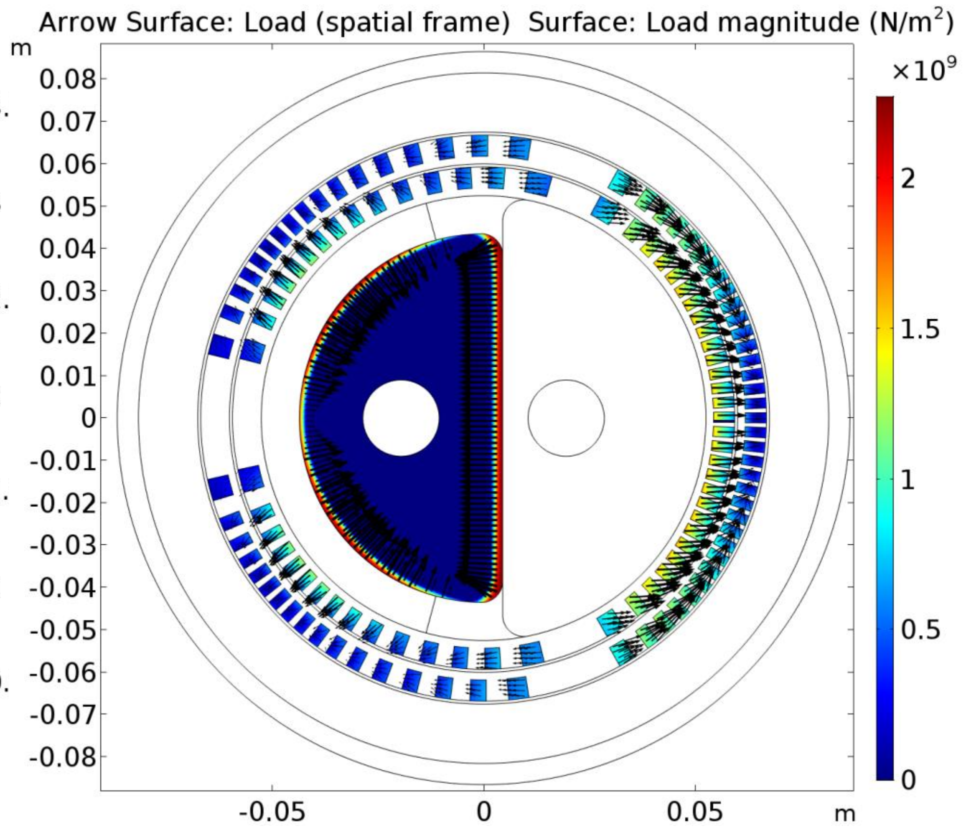
Mechanical simulations, forces

- Model the 3D coil (only)
- Using ‘Coil’ feature, calculate the current distribution in it
- Create 2D slice of the coil, and build the rest of the geometry (formers, etc)
- A-formulation in 2D → Magnetic fields, currents
- The shield is modelled with Campbell’s model
- Multibody mechanics simulation
- Prescribed displacement constraint In x=0 and y=0 planes to eliminate rigid body modes
- The applied loads are the Lorentz forces

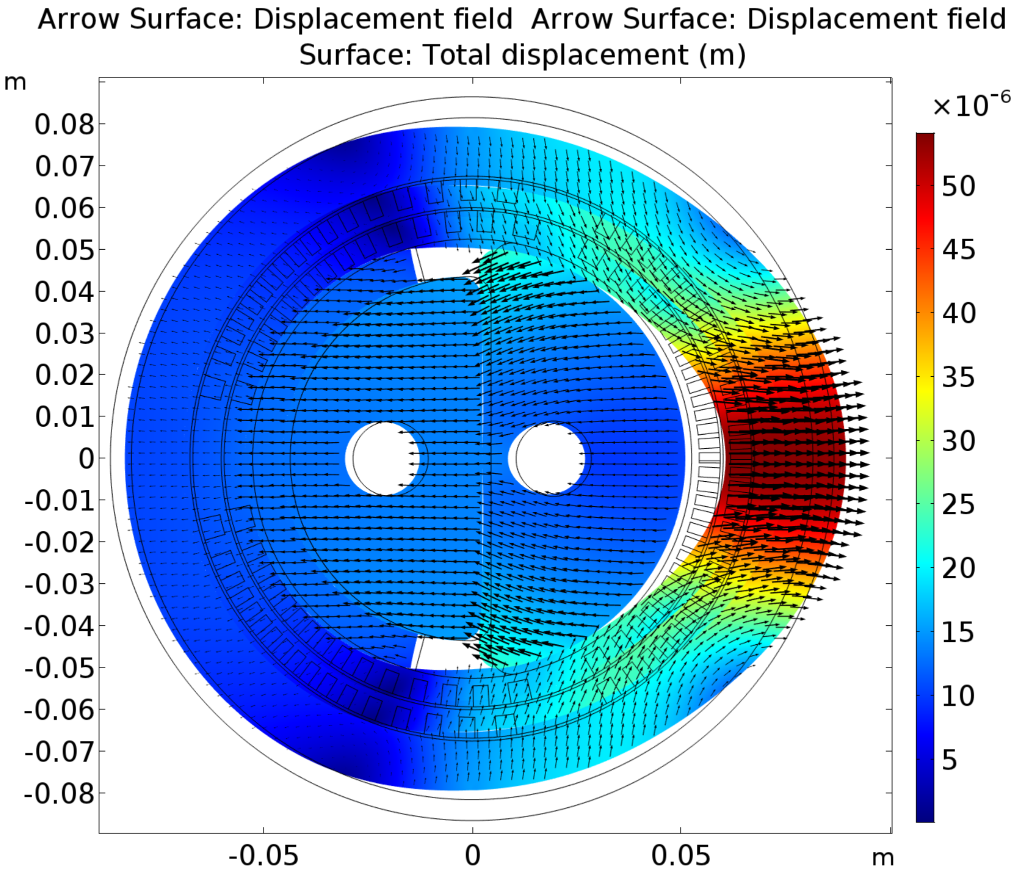


Mechanical simulations, forces



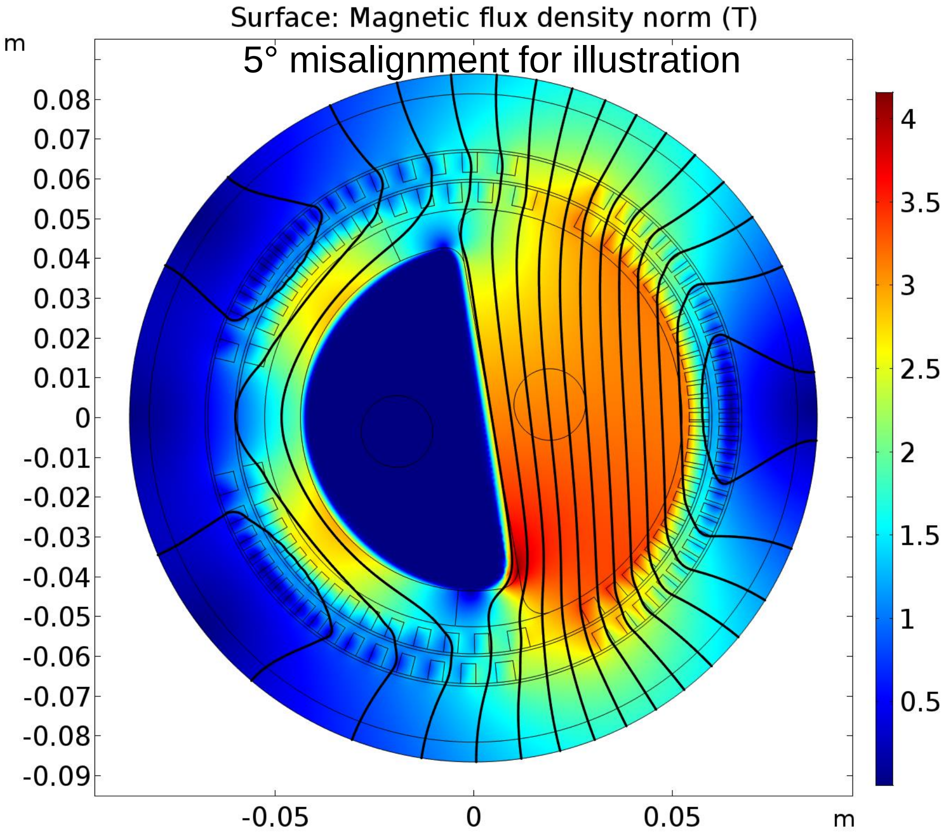


Mechanical simulations, forces



- Vertically asymmetric deformation
- Right support element pushes the shield against the former
  - Reduces the possibility of wobbling
- Forces acting on the shield:
  - $F_x = -\int B_y * J_z \, dA = -1.45e5$ N/m
  - $F_y = \int B_x * J_z \, dA = 321$ N/m (numerical error, should be 0)

Mechanical simulations, forces



- Misalignments of the shield cause distortion in the field pattern
  - x component of B appears
  - $B_x \sim \tan(\alpha) \sim 40$ mT for 1°
  - The requirements on field quality determine the assembly precision
- Torque on the shield
  - $\tau_z = -235.19$ (N*m)/m for 1°
- Even for 1° it is quite large
- Luckily, stabilizing

MgB_2 shield

- Tubular MgB_2: shielded 2.75 T with a thickness of 8.3 mm
  [To appear in IEEE Trans. Appl. Supercond. https://doi.org/10.1109/TASC.2019.2920359]
- Worse than NbTi/Cu, but can be manufactured quickly
- Half-moon shaped shield ordered in May 2019
- To be tested this year, in the hi-lumi CCT prototype

NbTi/Cu multilayer shield

- Excellent performance (no flux jumps, can be demagnetized, 3 T shielded by 3.2 mm thickness)
  IEEE Transactions in Applied Superconductivity 29 (2019), 4900108
- Best candidate so far
- Expensive, availability unclear even on short term
- Material R&D is explicitly out-of-scope for FCC project

↦ Collaboration with the University of Miskolc started (unofficial yet) http://www2.mak.uni-miskolc.hu/en/

- von Roll experimental rolling mill
- ovens for hot rolling
- sophisticated material characterization (XRD for texture analysis and residual stress measurement, pole figures, Scanning Electron Microscopy, EDXS, etc.)

NbTi/Cu multilayer rolling @ Miskolc
(Infrastructure snapshots)

von Roll experimental rolling mill

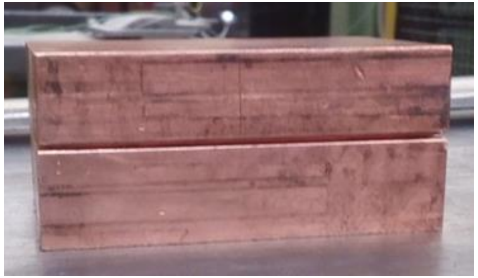
Robotized texture measurements

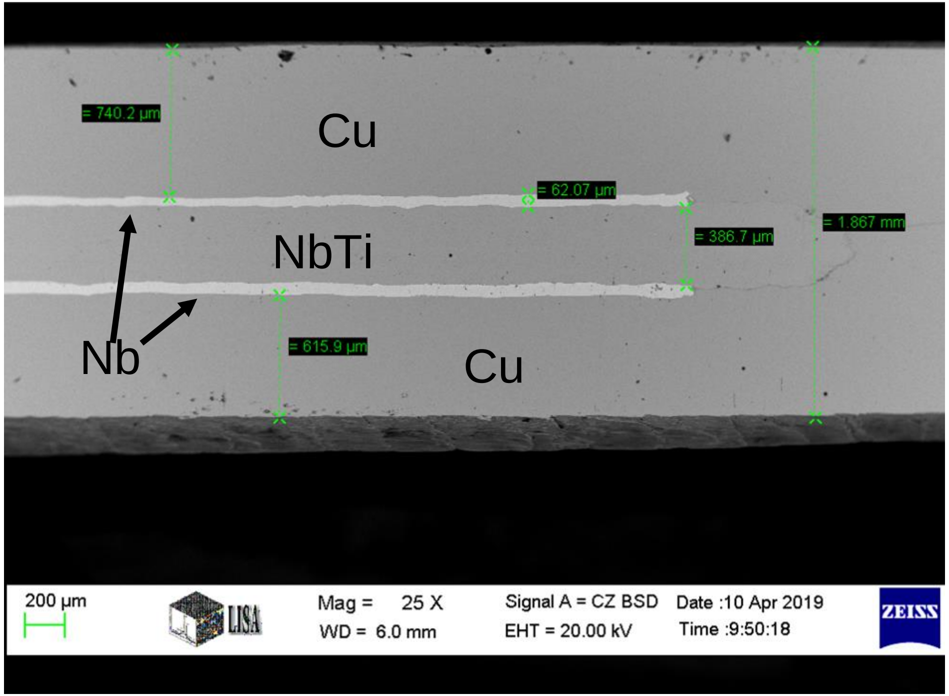
NbTi/Cu multilayer - first rolling tests

Single sequence: Cu-Nb-NbTi-Nb-Cu

Assembled in a Cu cassette in Argon, closed by a 70-ton press

Good metallic bond, no traces of oxygen.





Infrastructure

Vacuum epoxy impregnation system, winding machine being prepared

Conclusions

- Most of the pre-prototype studies progress according to schedule
  - Detailed quench simulation still a TODO
- The first measurement with the actual half-moon shaped shield in a “regular” CCT magnet (hi-lumi corrector prototype) is on its way, hopefully will be performed until the end of this year
- The first rolling experiments were successful
- The manufacturing of the magnet expected to start next year

Acknowledgements

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- János Bolyai scholarship

Backup slides

References

- Basic idea: "High field septum magnet using a superconducting shield for the Future Circular Collider" - Phys. Rev. Accel. Beams 20, 041002 (2017)
- First experimental tests: Talk at FCC Week, Berlin, June 1st, 2017, 13:48
- CCT+SuShi concept & exp. results: Talk presented at FCC Week 2018, 09-13 April, Amsterdam
- NbTi/Cu shield test results: IEEE Transactions in Applied Superconductivity 29 (2019), 4900108
- MgB2 shield test results: IEEE TAS early access, 10.1109/TASC.2019.2920359
- CCT 2D geometry optimization: Review of Scientific Instruments, 90 (2019) 053302, doi: 10.1063/1.5096020

Quench protection - extra

- Field pattern around the shield is quasi-stable
- Quench will induce eddy currents in the shield, causing flux jump
- Reorganization of the full field pattern
- Induces currents in the formers and windings
- Helps to quench the windings
- Shield is acting as a kind of “quench fuse”

Project goal

- FCC-hh extraction septum magnet demonstrator prototype
- > 3 Tesla field
- < 25 mm apparent septum thickness
- Concept: canted-cosine-theta (CCT) magnet with a superconducting shield

Project history:

- Successful proof-of-concept experiments:
  - MgB_2 shield - 2.75 Tesla with 8.3 mm wall thickness - flux jumps after first cycle
  - NbTi/Nb/Cu multilayer shield - 3 Tesla with 3.2 mm wall thickness - no flux jumps
- FCC Week 2018: presentation of the concept of the complete device (CCT-like magnet & shield)
- 2019 March: CERN-Wigner collaboration agreement signed to construct a demonstrator prototype

Project overview - milestones

- 2019 Dec: test a half-moon shaped MgB_2 shield in Hi-Lumi CCT magnet prototype (cheap, gain experience before constructing a SC magnet)
- 2020 March: CCT magnet design report
- 2020 June: CCT magnet prototype
- 2020 July: NbTi/Cu shield design report
- 2020 October: NbTi/Cu shield
- 2021 July: tests of MgB_2 and NbTi/Cu shields in magnet

Design, simulation & construction @ Wigner RCP
With supervision/help from CERN
CCT construction training is foreseen @ CERN for Wigner personnel