Active magnetic shielding for cryomodules

Anton Ivanov

on behalf of SRF team

Outline

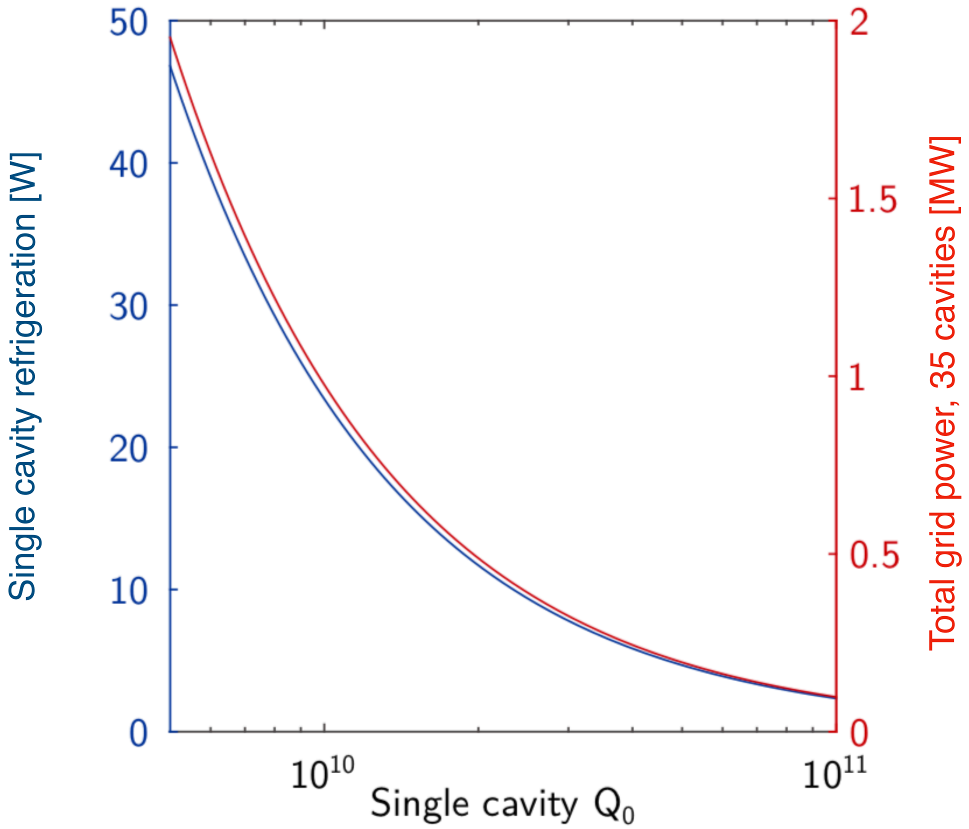
- Why B-filed shielding matters
  - Trapped flux in RF field
  - Residual resistance due to trapped flux

- Shielding
  - Design procedure
  - Study 1: Passive shielding — cryomodule design of HG
  - Study 2: Active shielding — vertical cryostat V6 in SM18
  - Study 3: Field mapping — vertical cryostat V4 in SM18

- Wrap-up

Why shield the magnetic field?

- Efficiency matters
  - SRF Nb vs RF -> dissipated power/m can be improved up to ≈ 10^6
  - Cryogenic losses: 1 W (RF) -> 1 KW (from the power grid)



Plot: LCLS-II, Linac Coherent Light Source Stanford, $Q{\sim}2.710^{10}$, $T = 2$ K, $E_{acc}= 15$ MV m^{-1}, *Surface Resistance Minimization in SRF Cavities by Reduction of Thermocurrents and Trapped Flux,* J-M Köszegi

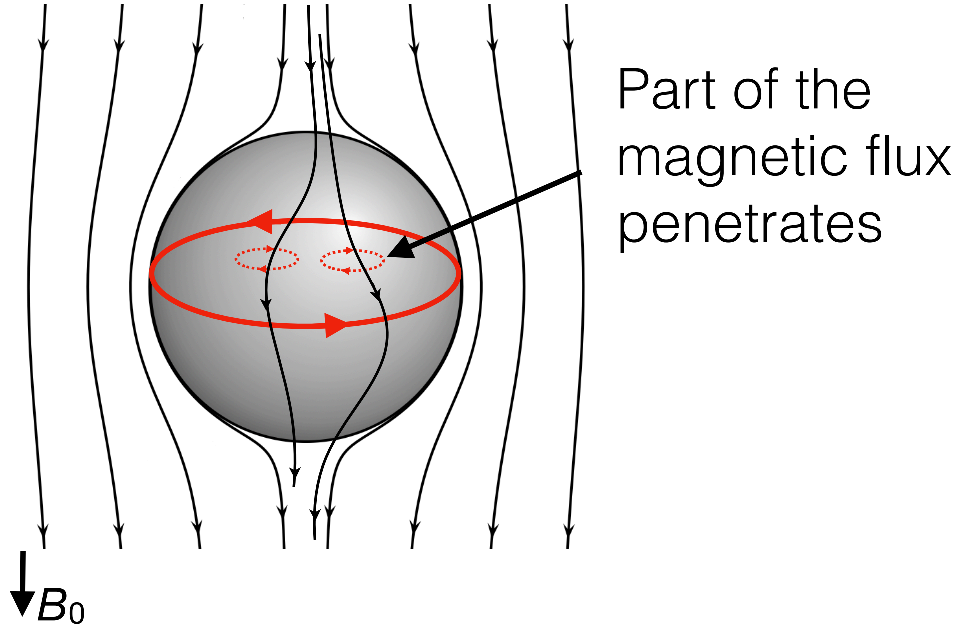
- Surface resistance

$$Q \propto \frac{1}{R_s} \qquad R_s = R_{BCS}(T) + R_B(B_0) + R_{res}$$

Takeaway: We need to decrease the residual resistance

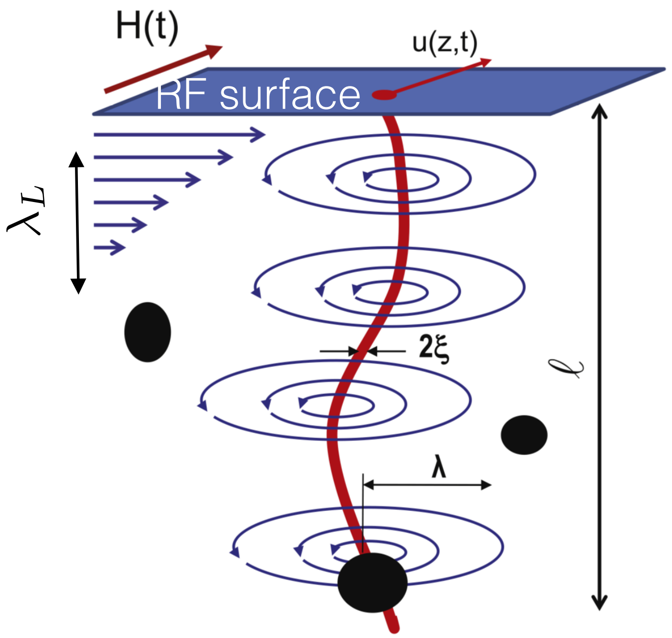
Trapped flux in RF field

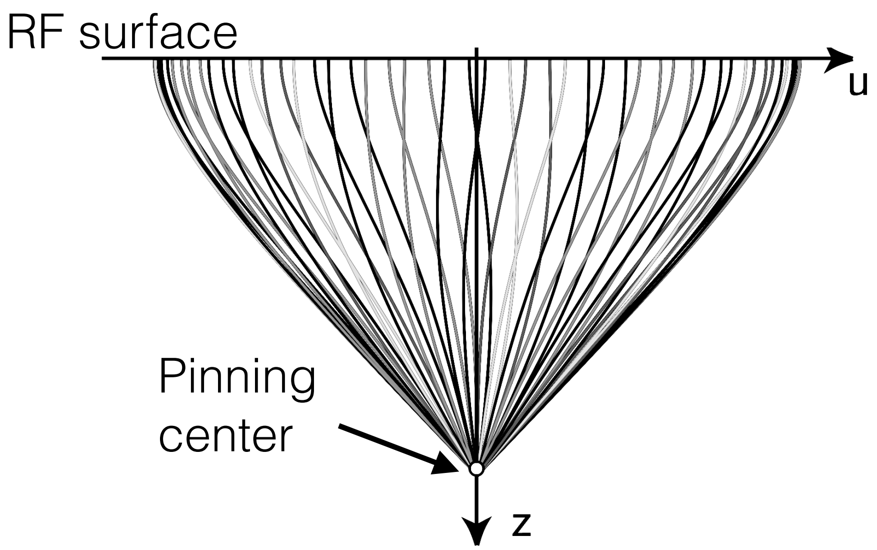
- Meissner effect in Nb: T < Tc, $B_0 \neq 0$



- Type-II superconductors can exhibit non-complete Meissner effect

- Single flux line string oscillations





Left image: Gurevich A and Ciovati G 2013 Phys. Rev

Right image: Surface Resistance Minimization in SRF Cavities by Reduction of Thermocurrents and Trapped Flux, J-M Köszegi

Residual resistance due to trapped flux

- How much contribution?

  - Model without oscillation - bulk Nb cavities

$$R_f(B_0) = \frac{B_0}{2B_{c2}} \left(\frac{\mu_0 \rho_n \omega}{2g}\right)^{1/2}$$

Relative amount of the flux line cores in a given volume

Rs in normal state

$$\boxed{R(1\ \mu\mathrm{T},\ 1.3\ \mathrm{GHz}) = 2.8\ \mathrm{n}\Omega}$$

$\longrightarrow$

For a bad Nb cavity that traps
Earth's field B ≈ 40 uT - not shielded

$$R_B \approx 110\ n\Omega \rightarrow Q \approx \ \mathrm{few} \times 10^9$$

- What knobs to decrease?

$$R_\mathrm{B} = B_0 \times \eta(\nabla T ...) \times S(f, B_{\mathrm{RF}...})$$

Remove the B-field

Expel all the flux

Reduce the sensitivity

Takeaway: trapped DC magnetic flux from insufficient shielding —> major residual contribution knob

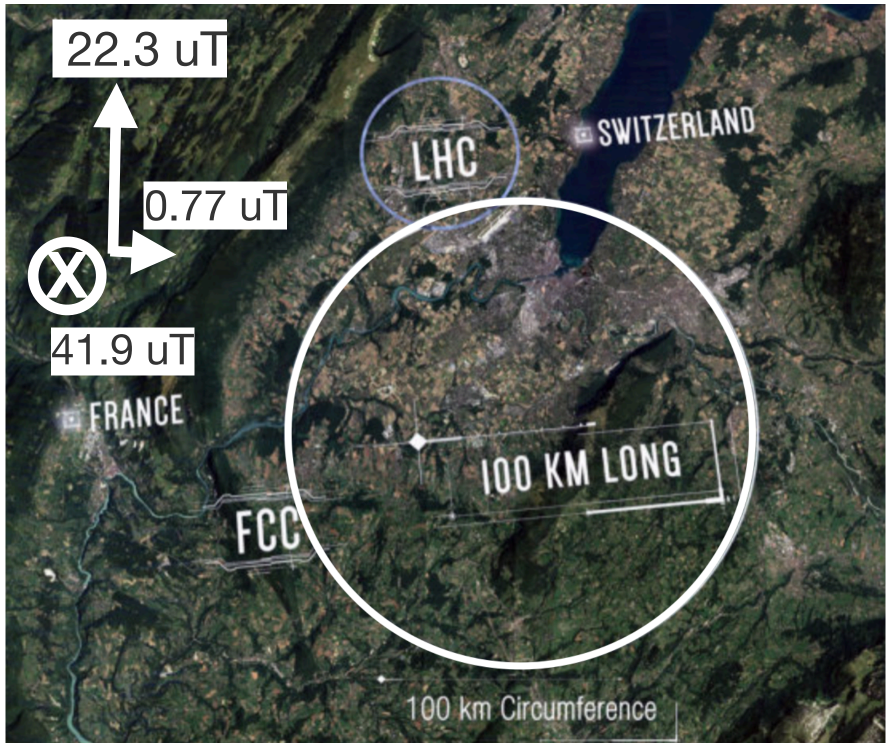
Design of the magnetic shield

- Sources of ambient magnetic field B_0
  - Earth -> homogeneous
  - Local -> magnetized parts — non homogeneous

- Shielding factor

$$S > |\frac{B_0}{B_{\rm in}}|$$

Earth’s field



- Lessons learned from three recent studies:

-> Passive + active shielding
(HG SPL, **Sotiris Papadopoulos)**
-> Active shielding
(V6 at SM18 , **Mικκο Karppinen**)
-> Mapping (V3 at SM18)

⟶

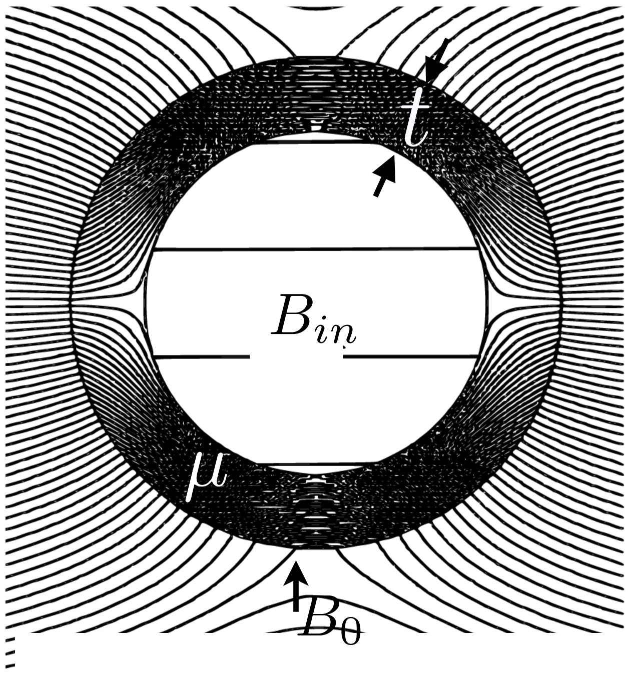
- Questions to answer

-> Passive or active shield?
-> How many shields?
-> Where to put?
-> Material?
-> Homogeneity?

Passive shielding

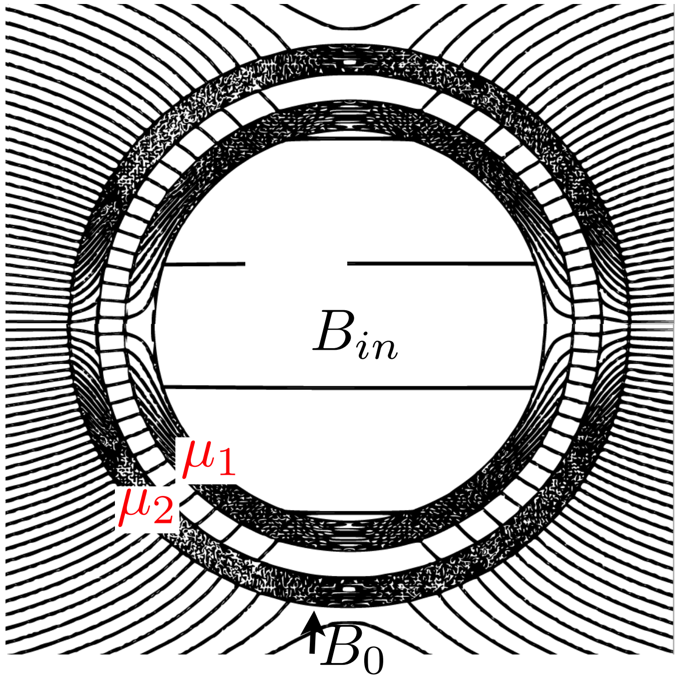
- Use high mu-material —> concentrate field inside material

Single layer



$$S = \frac{B_0}{B_{in}} \propto \mu t$$

Multi-layer



$$S = S_1 \times S_2 \propto \mu_1 t_1 \times \mu_2 t_2$$

- Multi-layer —> less material —> better performance
- Keep the layers spaced (decoupling)
- Spherical shells —> best shielding and homogeneity

Takeaway: best strategy is to shield the shield

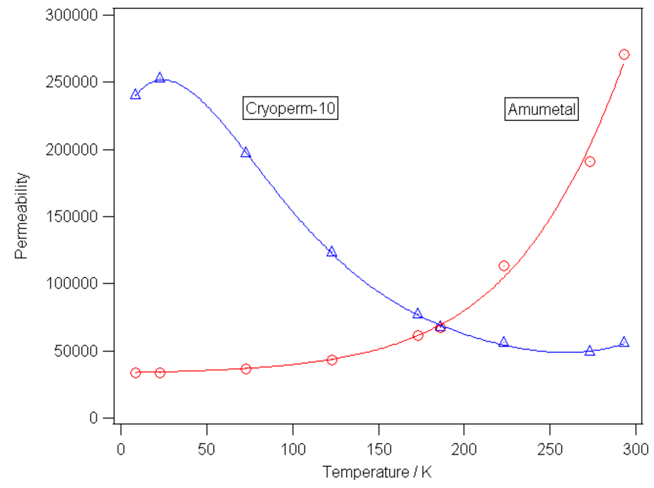
Passive shielding study — cryomodule design of HG SPL

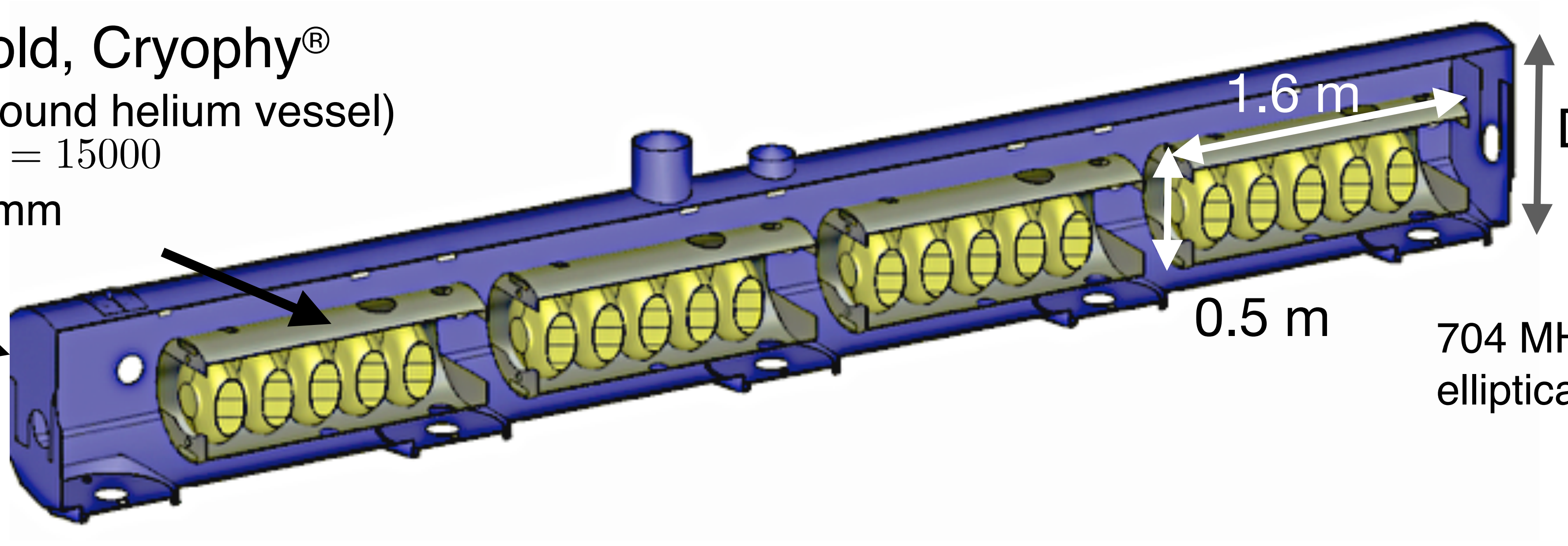
- Cylindrical passive shield — orientation dependent

Transverse factor $S_{\perp} = \frac{\mu t}{D}$ Axial factor $S_{\|} \approx \frac{2\mu t D}{L} + 1$

- Strategy:
  - First shield closest to cavity —> cold
  - Second shield, keep decoupled —> warm

Optimal to use 2 materials





Cold, Cryophy®
(around helium vessel)
$\mu_r = 15000$
1 mm

Warm
near the inner surface of vacuum vessel
$\mu_r = 50000$
3 mm

1.6 m

D = 0.7 m

0.5 m

704 MHz 5-cell elliptical cavities

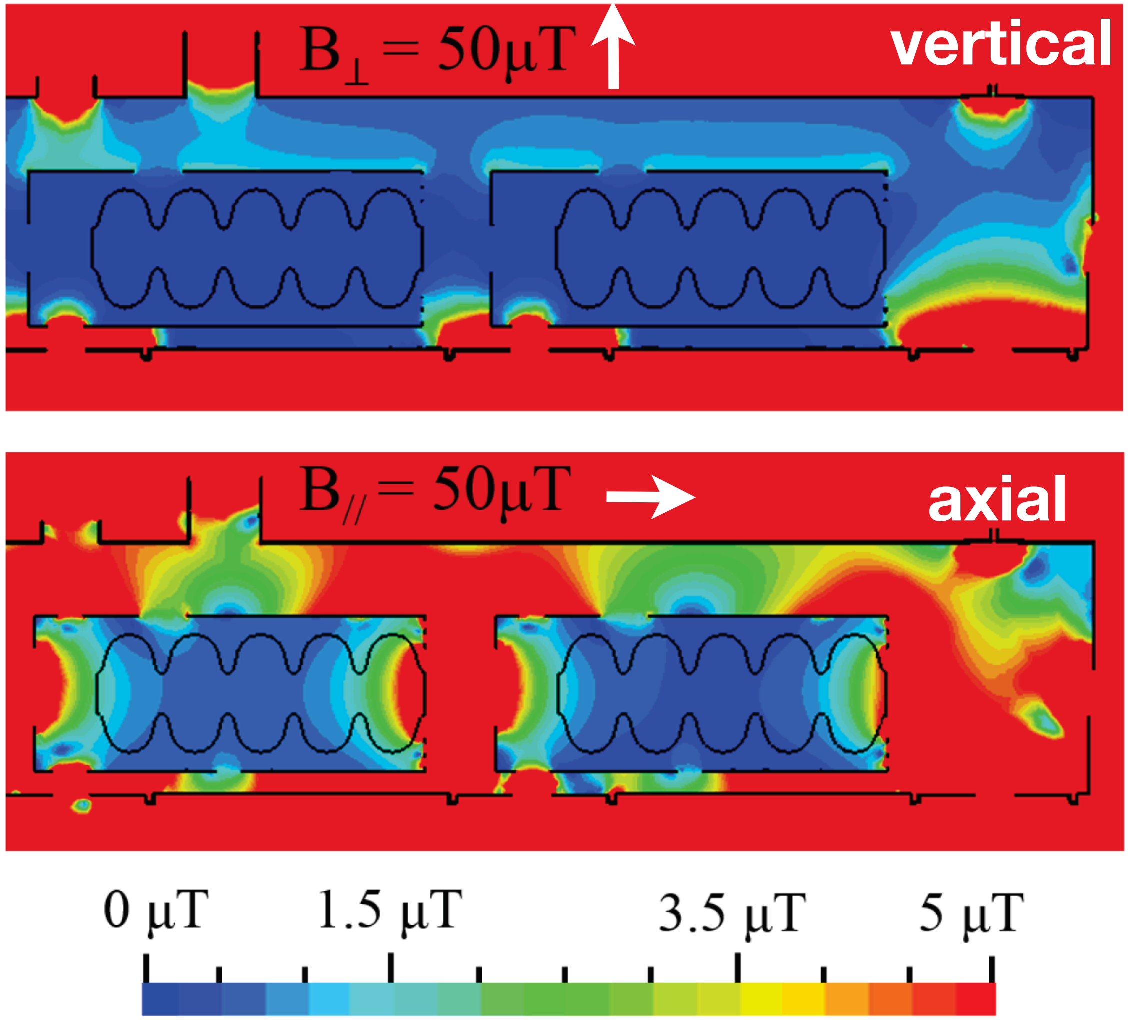
“SUB-MICRO-TESLA MAGNETIC SHIELDING DESIGN FOR CRYOMODULES IN THE HIGH-GRADIENT PROGRAM AT CERN”, S. Papadopoulos, SRF2017

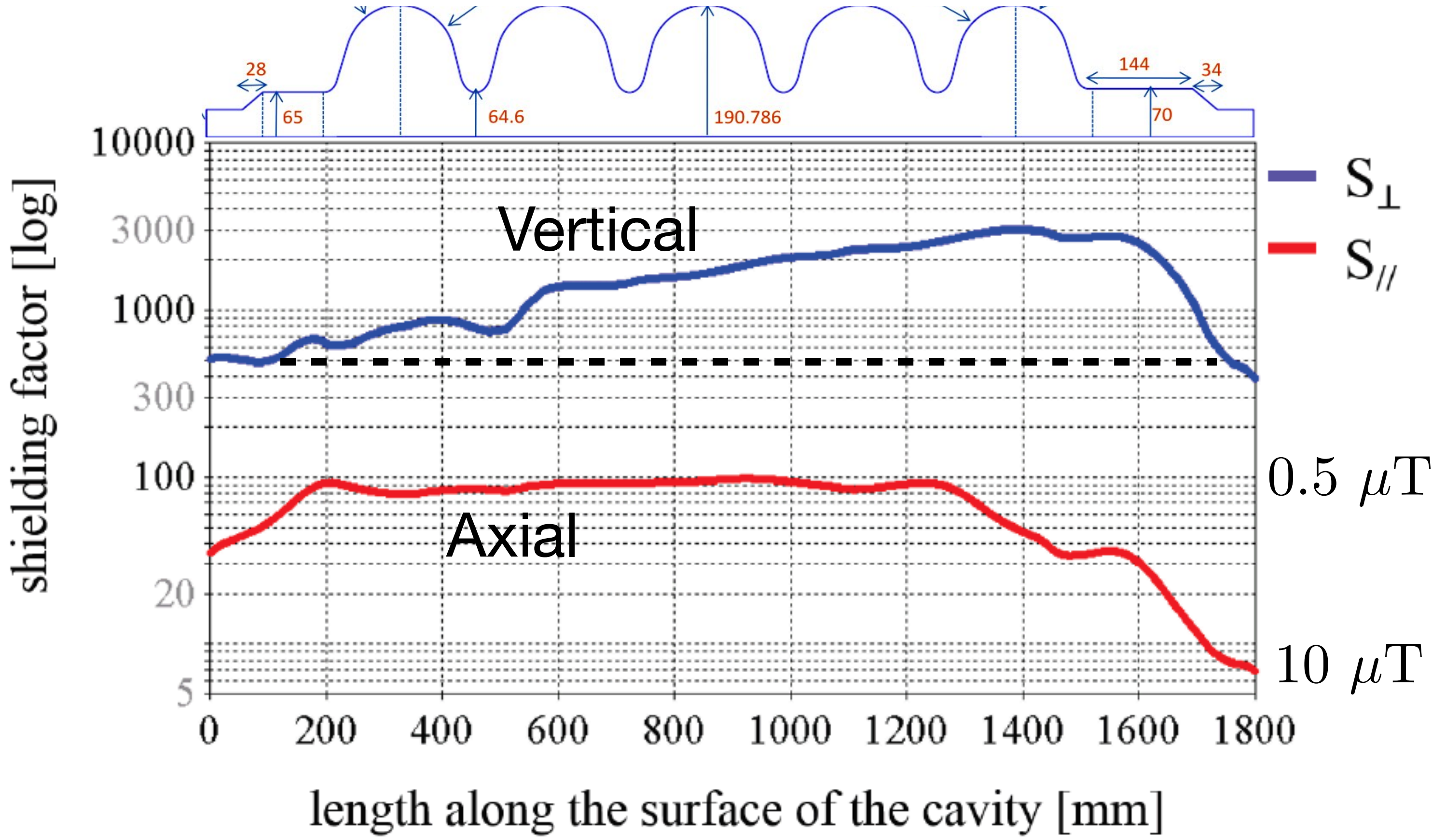
Passive shielding results

- Goal: reach shielding factor of S = 500 —> 0.1 µT for $B_{\|} = B_{\perp} = 50\ \mu\mathrm{T}$

$R_{\mathrm{B}} \leq 11\ n\Omega$

Field distribution - simulation





- Non-homogenous even for homogenous ambient field (leakage)

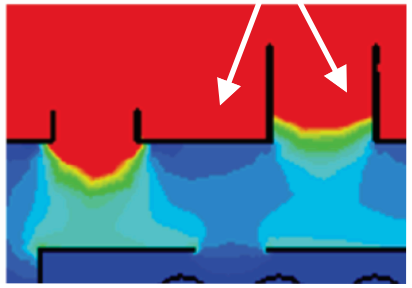
- Axial shielding cannot reach spec

Passive shielding — lessons learned

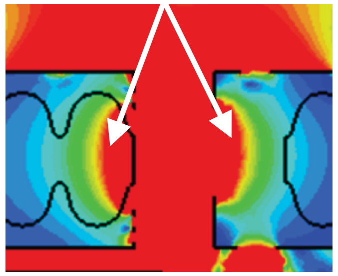
- Design:
  - **Axial field harder to shield** —> keep length small
  - **Homogeneity is challenging** (leakage from openings)
  - Bigger cavity —> thicker shield to obtain spec
  - Avoid axial coupling —> shorter length preferred
  - Computationally not trivial: thickness: ~ few mm, length: ~ few meter

Transverse leakage

Modifications can help



Axial leakage



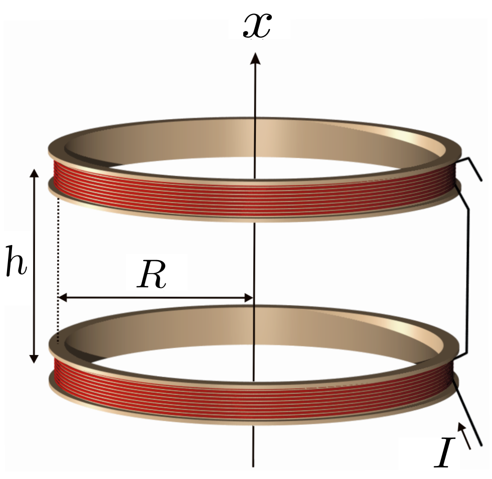
- Realisation:
  - **A lot of work needed**: press forming, welding, cutting
  - **Tradeoff: the more structural work the less the performance of material**
  - Heat treatment helps (ongoing studies) —> the higher the better but possible deformations
  - Cryogenic materials used: Cryophy/Cryoperm —> production might vary in performance
  - Cold shields —> need to cool properly

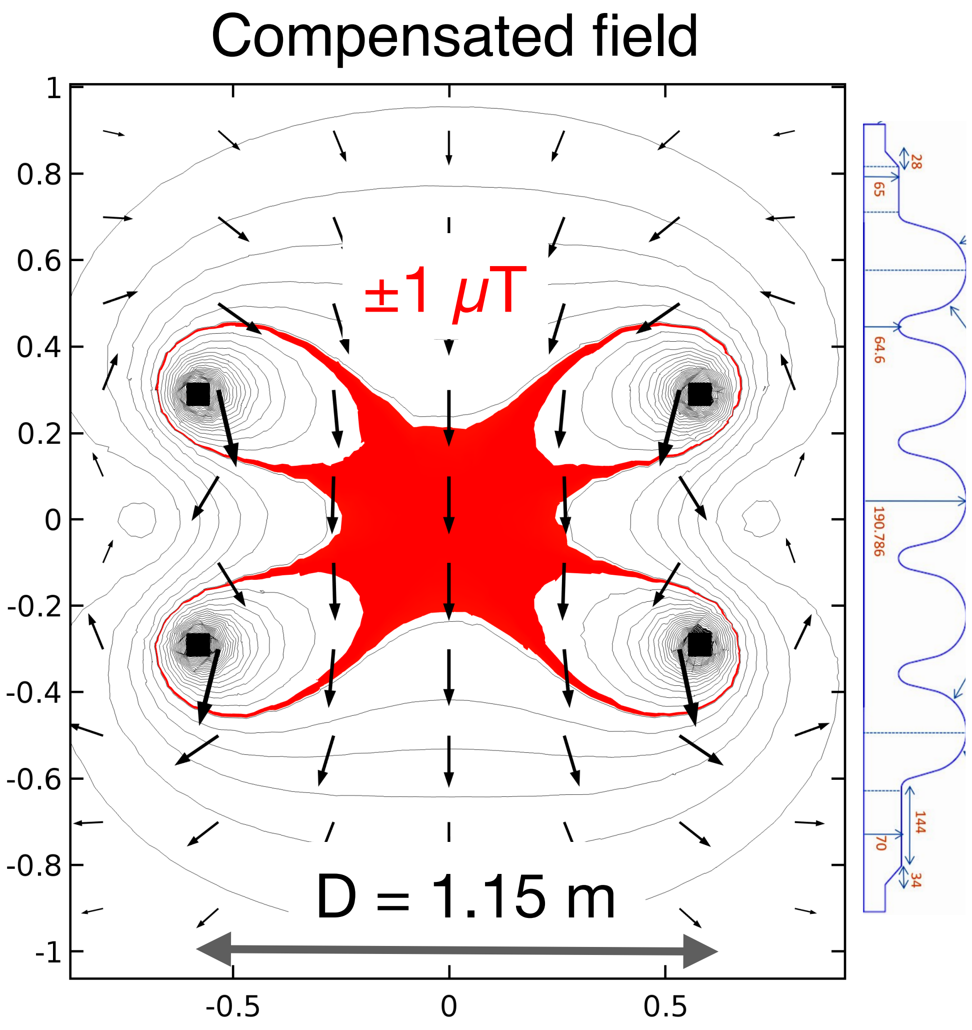
Takeaway: far from straightforward and cheap but quite efficient for simple and small volumes

Active shielding

- Active shielding —> generate opposing field inside the shielded volume
- Homogeneity and orientation —> superimpose fields of different coils

- Helmholtz pair

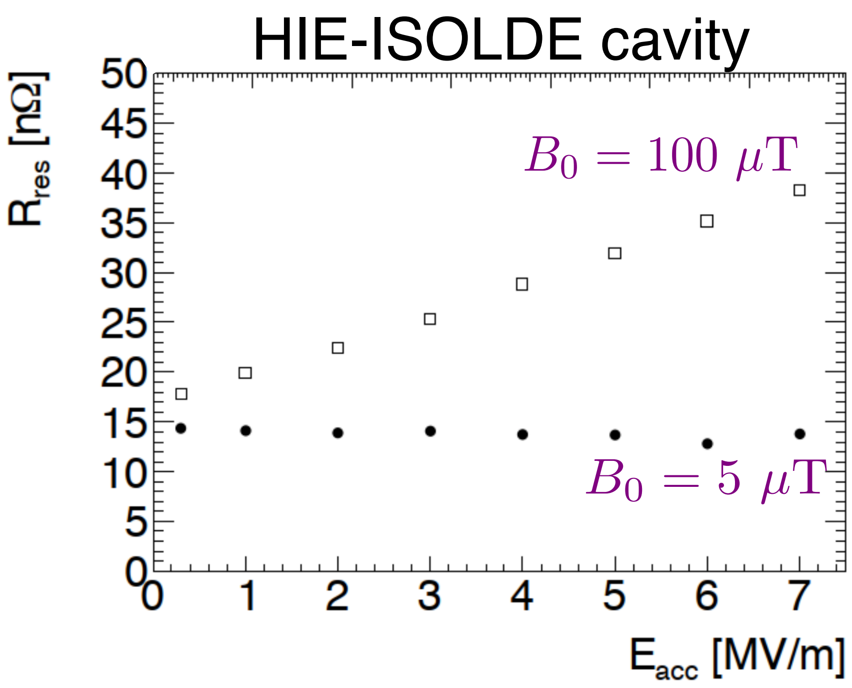




- Most homogenous central field —> $h = R$
- Large homogeneous region —> large coils needed
- Shown—> ~1.15 m (diameter of HG SPL vacuum vessel)

Takeaway: Helmholtz coil — good homogeneity for its simplicity, but insufficient

Active shielding study — V6 in SM18



- Goal: Control B-field in vertical cryostat V6 at SM18 used for 400 MHz studies

- Motivation:
  Study Q-slope due to external B-field in Nb/Cu cavities

- Provisional specs

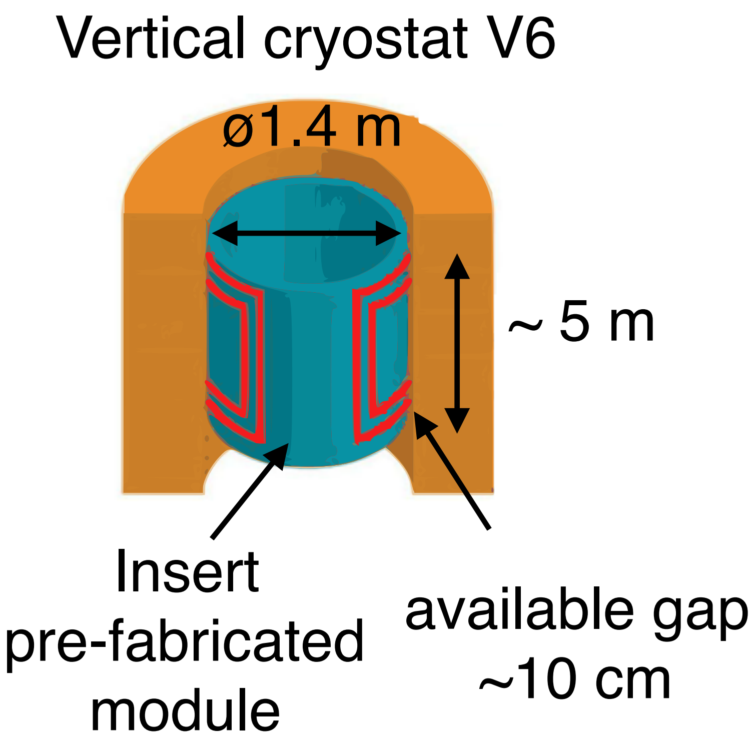
  - Field uniformity 0.5% —> ~ 0.25 μT in a volume of 400 MHz LHC cavity

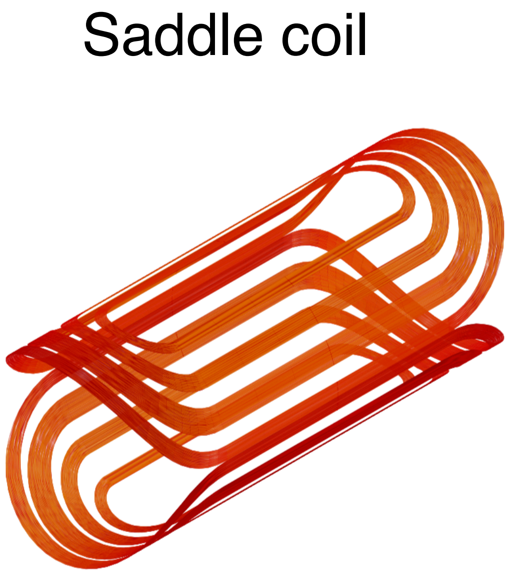
  - Trapping studies —> 100 μT with free orientation

  - Iron-free design

  - Cu-conductor — no active cooling

- Solenoid + 2 × cos theta saddle coils



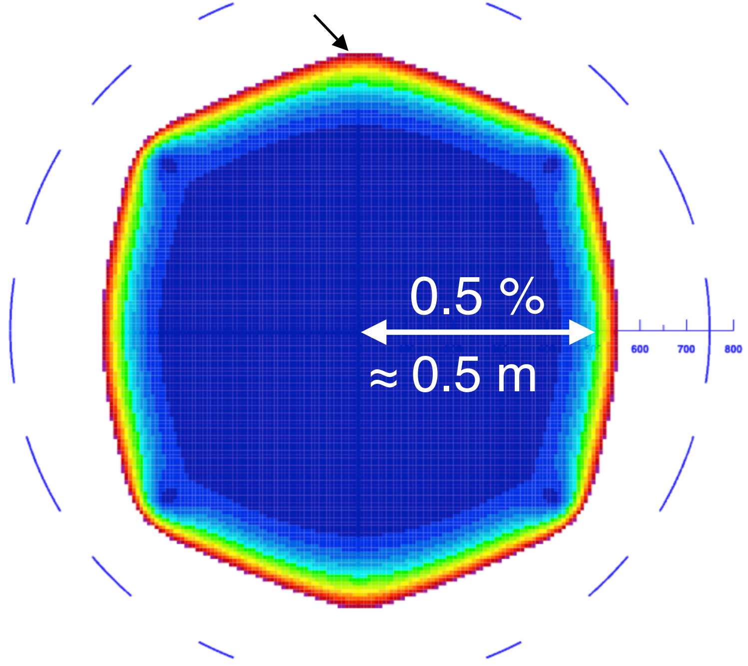


Active shielding results

- Transverse distribution

Saddle coil

2% variation

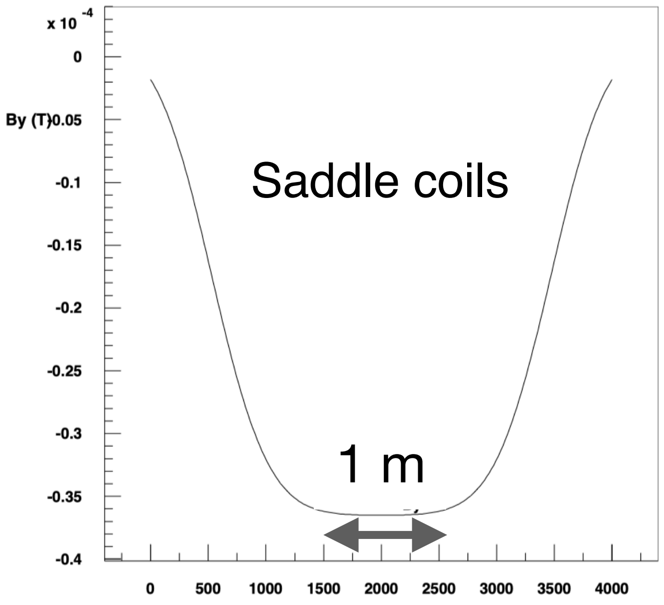


0.5 %

≈ 0.5 m

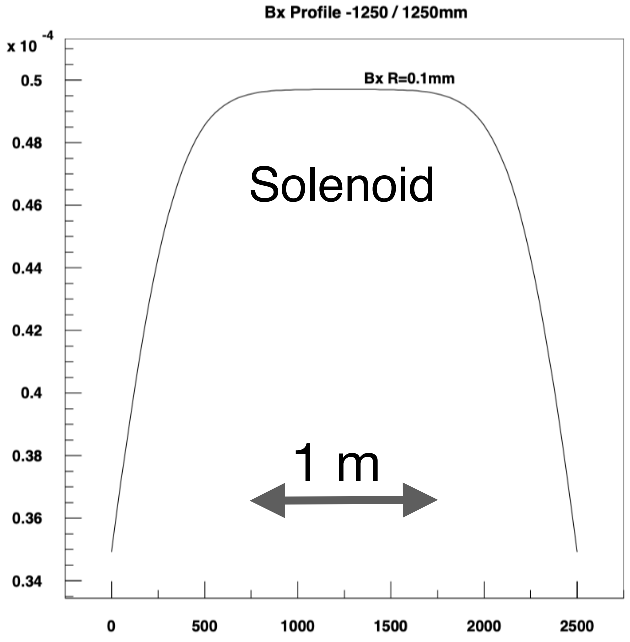
Cryostat wall

- Axial distribution



Saddle coils

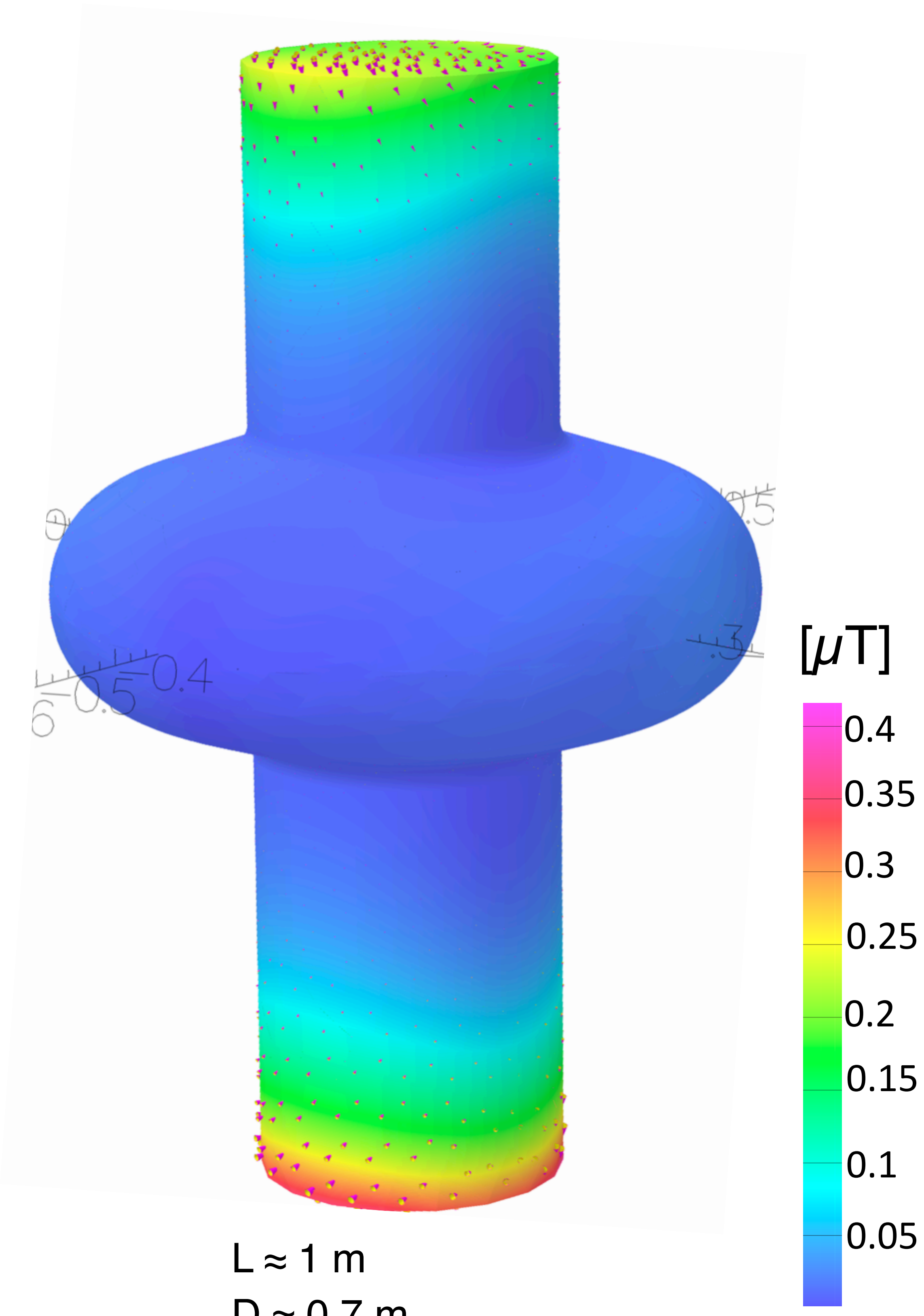
1 m



Solenoid

1 m

- Earth's field + coils ON



L ≈ 1 m

D ≈ 0.7 m

Active shielding - lessons learned

- **Field uniformity of 0.5% is achievable** —> no leakage with end openings
- Realization —> pre-fabricated fibre-reinforced composite
- Power not issue (low field ~ 50 µT)
- Good expertise —> magnet design and gradient coils for MR imaging
- Mapping needed —> Needs sensors

Fibre-reinforced composite

Takeaway:

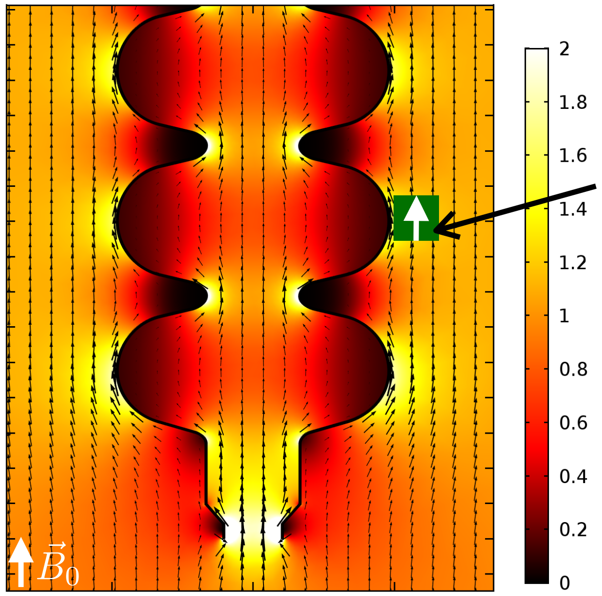
Seems sufficient for stand alone shielding solution

Compensate with respect to what?

B-field mapping of V4 in SM18

- Motivation: Flux expulsion measurements

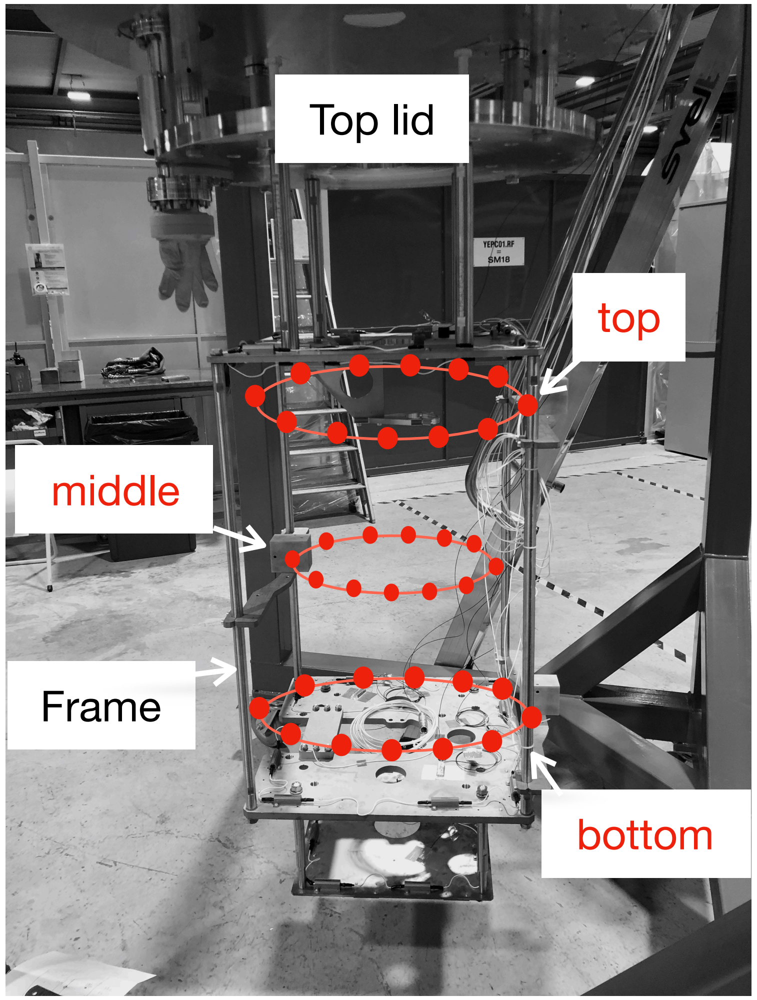
- Question: if we measure and compensate locally what is the role of inhomogeneity?



single axis-probe at the equator

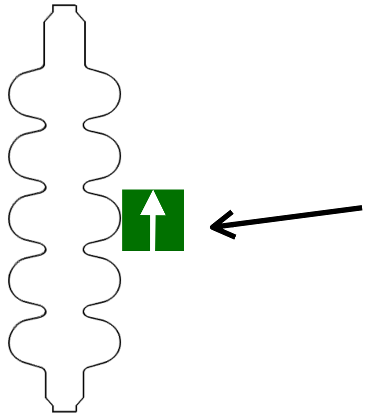
Assume homogeneity and tune current until Bt ≈ few nΩ

- B-field Mapping in Vertical Cryostat V4
  - Minimal passive shielding exists
  - Coils — unknown positions and geometry
  - 9 (single axis) sensors available
  - 12 azimuthal positions
  - 3 height levels



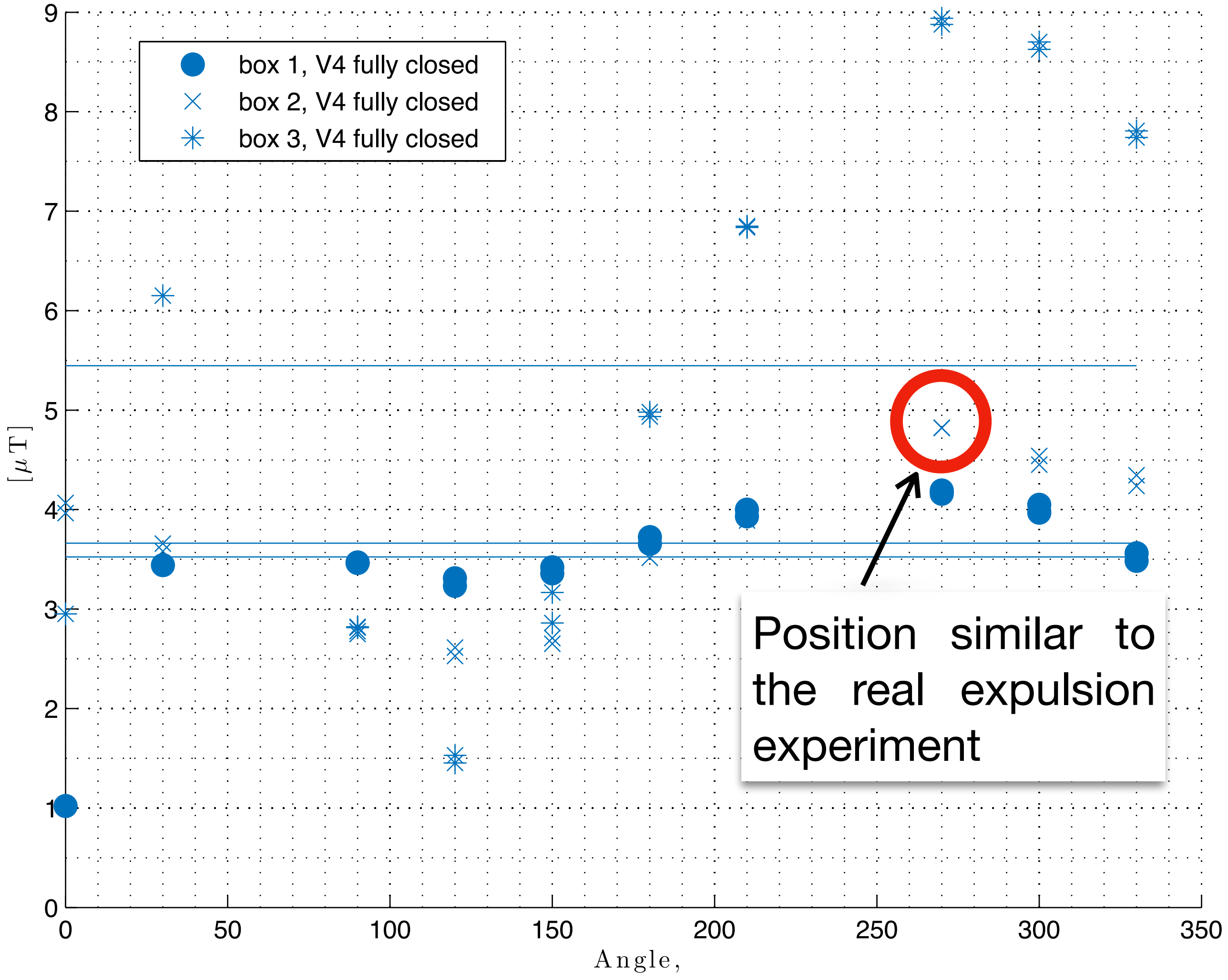
B-field mapping results

- How much field is left?



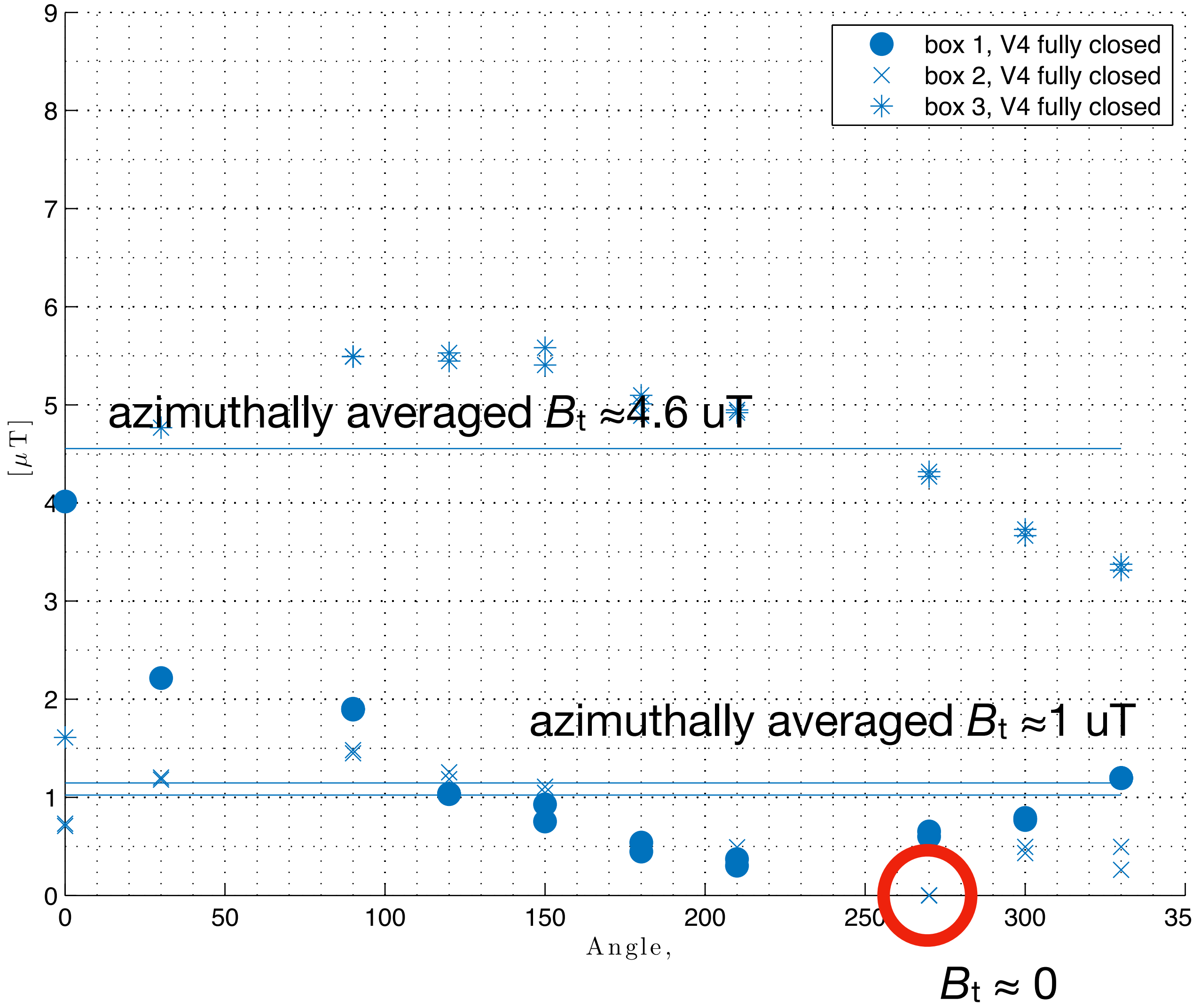
Local B-field compensation results in a non-negligible field in other points

Before compensation



Position similar to the real expulsion experiment

After compensation



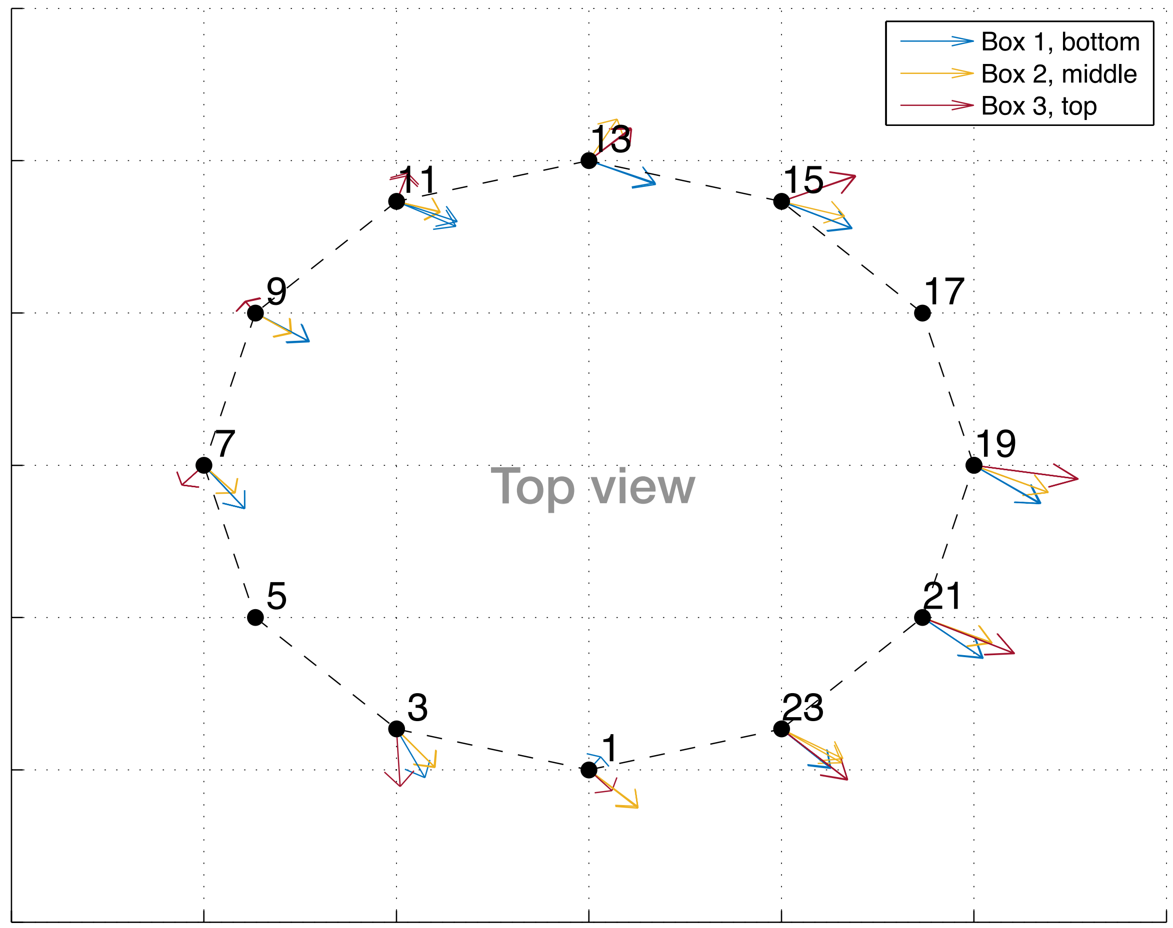
azimuthally averaged $B_t \approx 4.6$ uT

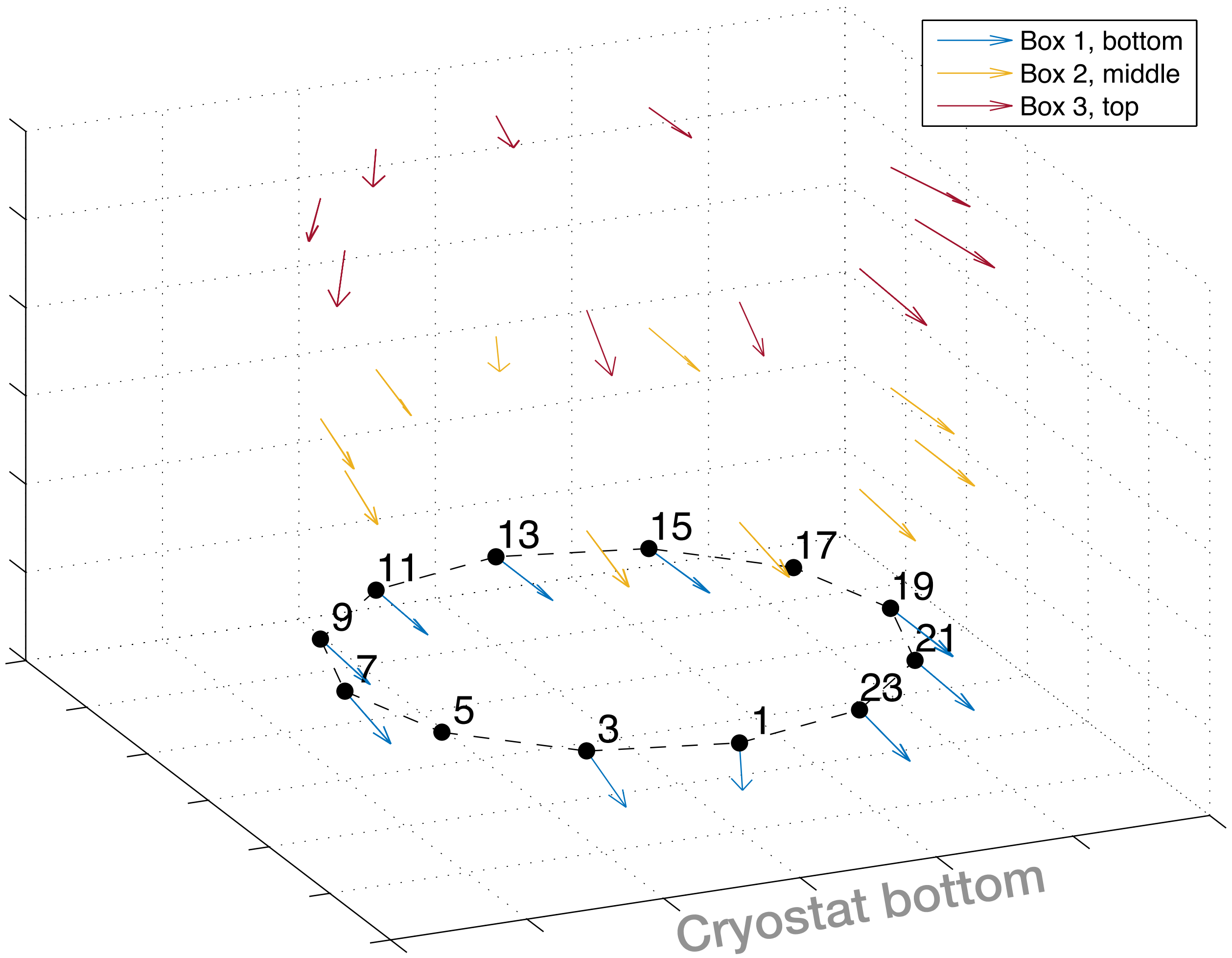
azimuthally averaged $B_t \approx 1$ uT

$B_t \approx 0$

B-field mapping results

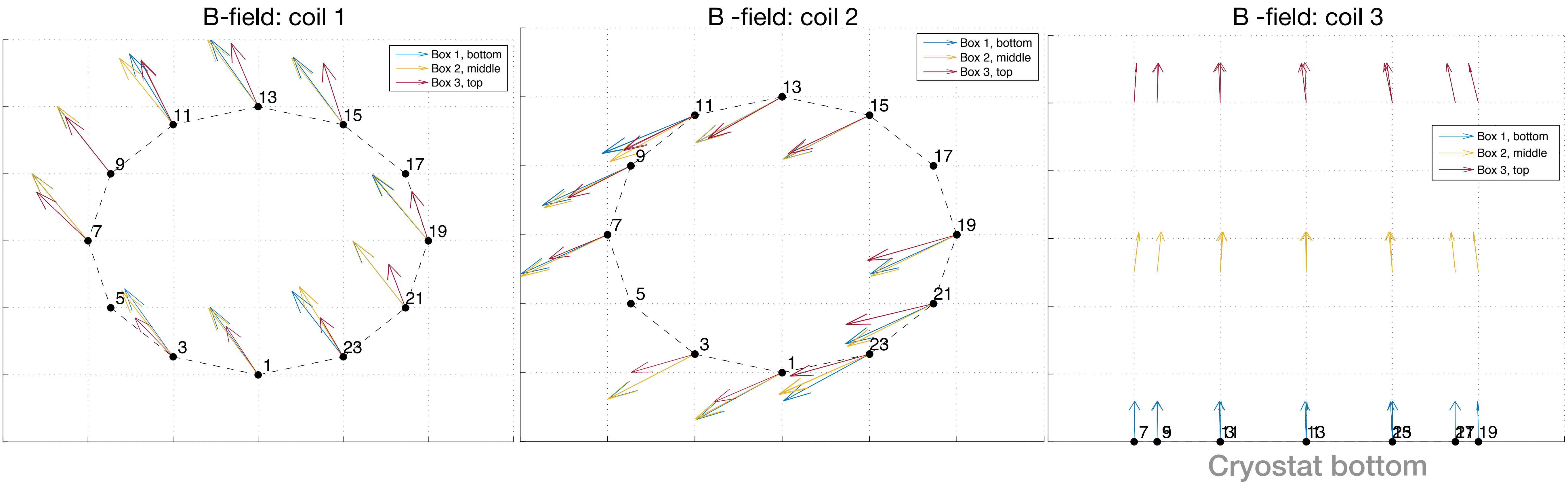
- ○ Ambient B-field inside V4





B-field mapping results

- B-field — compensation coils
  - Apply 1000 mA to each coil and measure separately

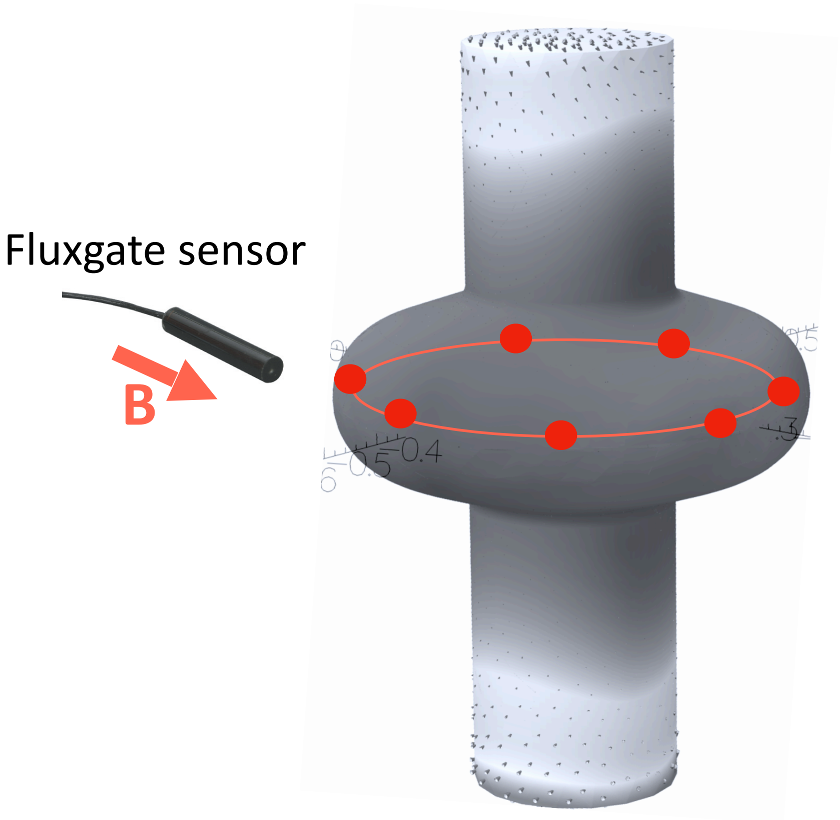


- Spatial average of the compensated field inside V4

B-field earth for Geneva: 46.9 μT $\xrightarrow{\text{passive} \approx 3.4 \text{ times reduction}}$ 13.9 μT $\xrightarrow{\text{active} \approx 4.2 \text{ times reduction}}$ 3.35 μT

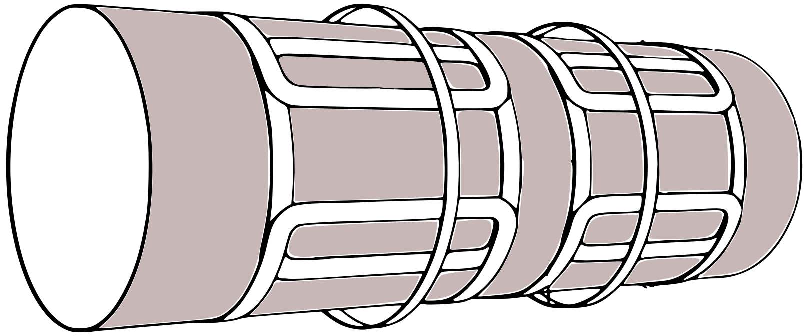
B-field mapping lessons learned

- Procedure to efficiently cancel the field:
  - Map the “hot spots” at least once —> verify homogeneity level
  - Minimize ensemble, not locally
  - Fluxgate Magnetometer



Wrap-up: Passive/Active shield?

- Passive
  - Transverse homogeneity is less of an issue, even if holes exist
  - More flexible and compact (thickness)
  - Can be used locally to homogenize
  - Axial homogeneity is an issue (end holes)
  - Field strength is an issue (saturation possible)
  - Reproducibility more challenging (not trivial to produce)
- Active
  - Field strength is not an issue
  - Power not issue (low field ~ 50 μT)—> switch on only just before SC transition
  - Reconfigurable —> long term “investment”
  - Homogeneity is less of an issue —> cylindrical openings don’t leak
  - Scaling for a cryomodules possible
  - B-field mapping: at least 3-axis per shield, but map hot spots first
  - Some components might be magnetized since active stronger fields
  - Circumferential apertures much more challenging than passive shield



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Thank you for your attention!

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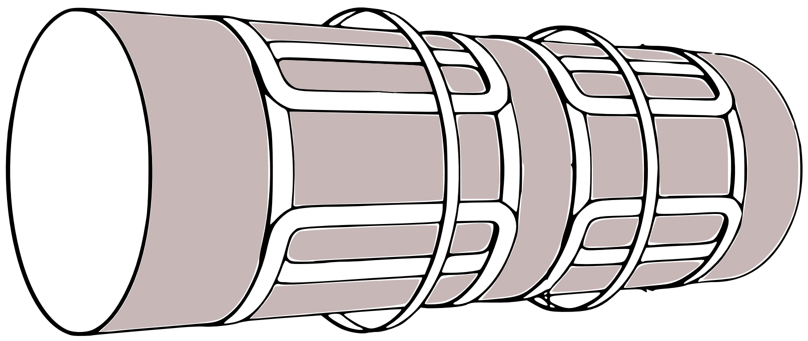
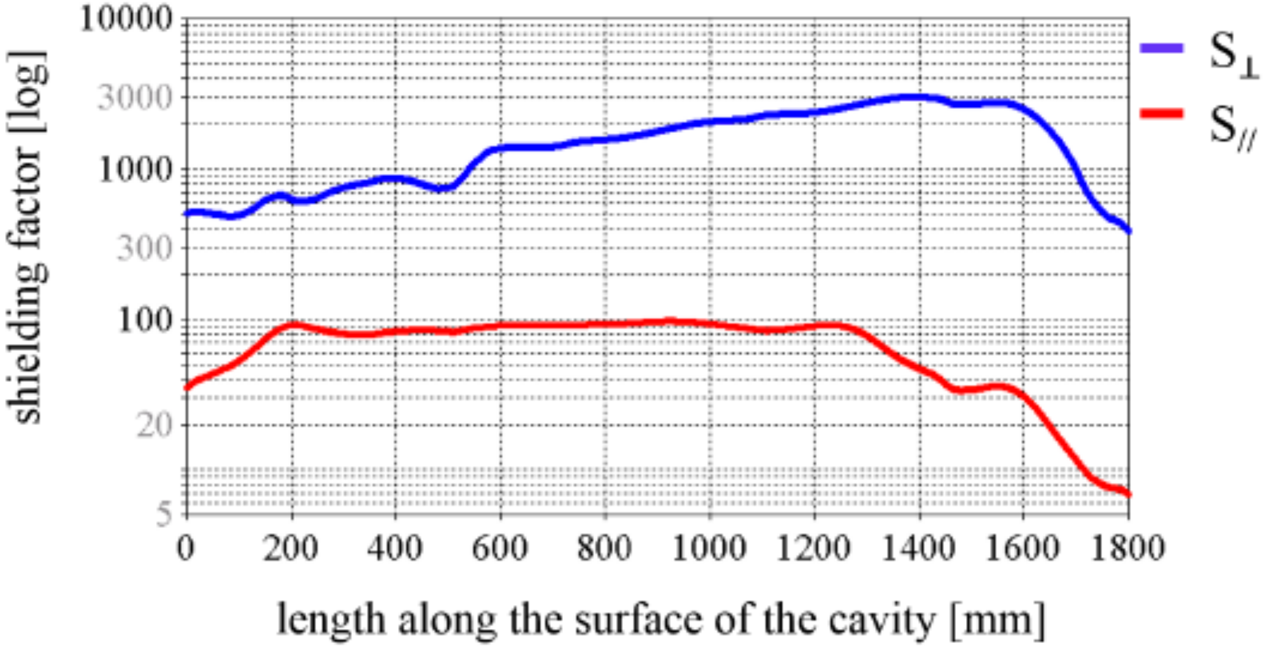
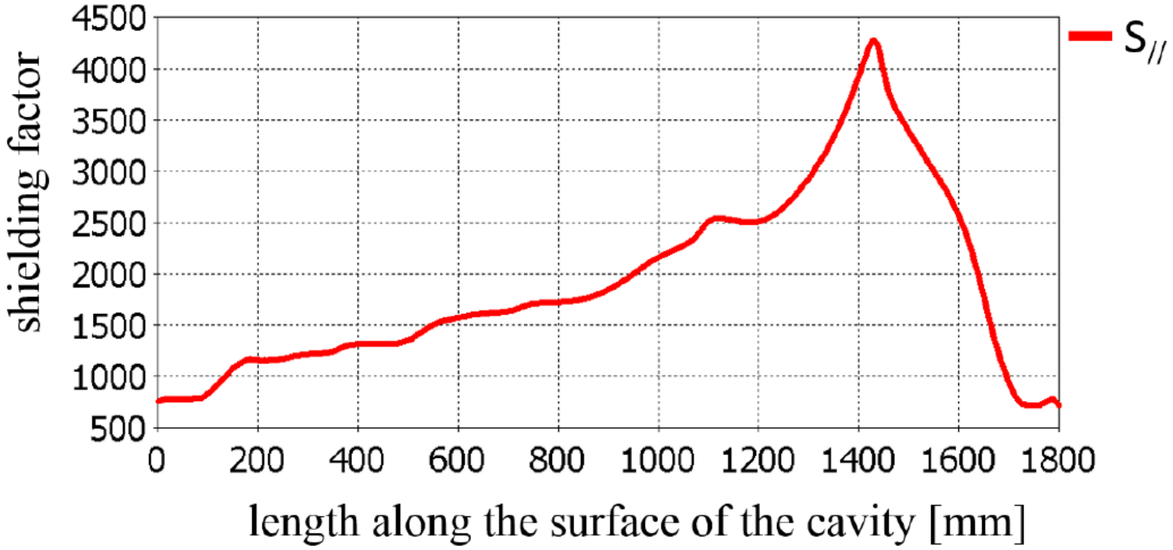


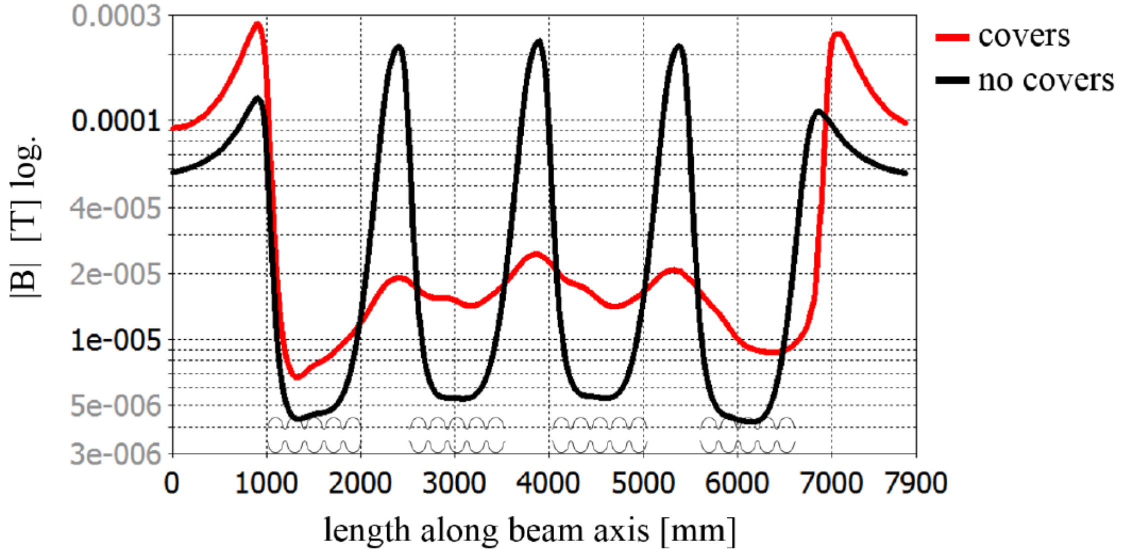
Backup: Passive + active shield

- Axial compensation can be compensated by solenoid


without solenoid


with solenoid

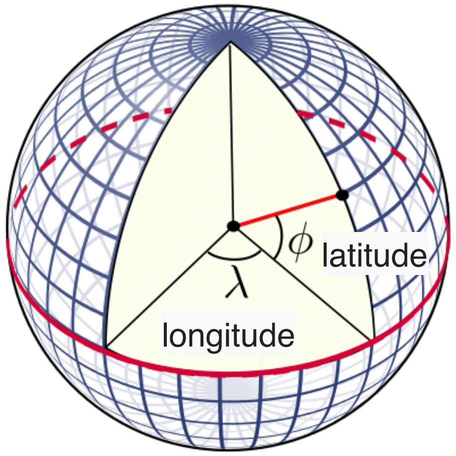
- Passive shield — homogeneity can be degraded —> more difficultly to shield with active shield



Earth’s magnetic field calculation

Geneva coordinates:

latitude: 46.204391° N
longitude: 6.143158° E



Geneva coordinates (Swiss projection LV03) :
East : 500013.259
North: 117819.944

https://www.swisstopo.admin.ch/en/maps-data-online/calculation-services/navref.html

B-field
Calculator 1

https://geomag.nrcan.gc.ca/calc/mfcal-en.php

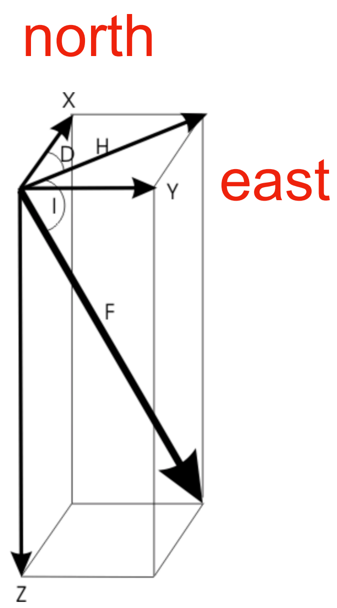
X = 22,257 nT
Y = 766 nT
Z = 41,934 nT

Total field = 47,481

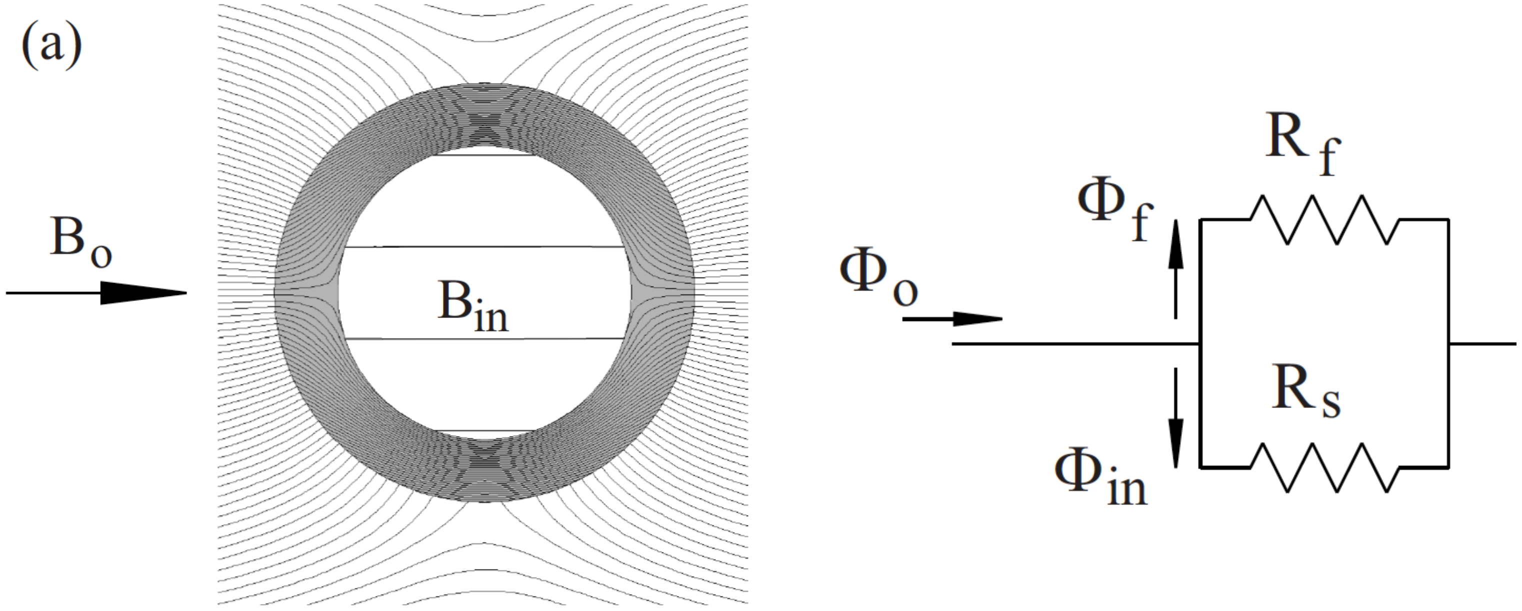
B-field
Calculator 2

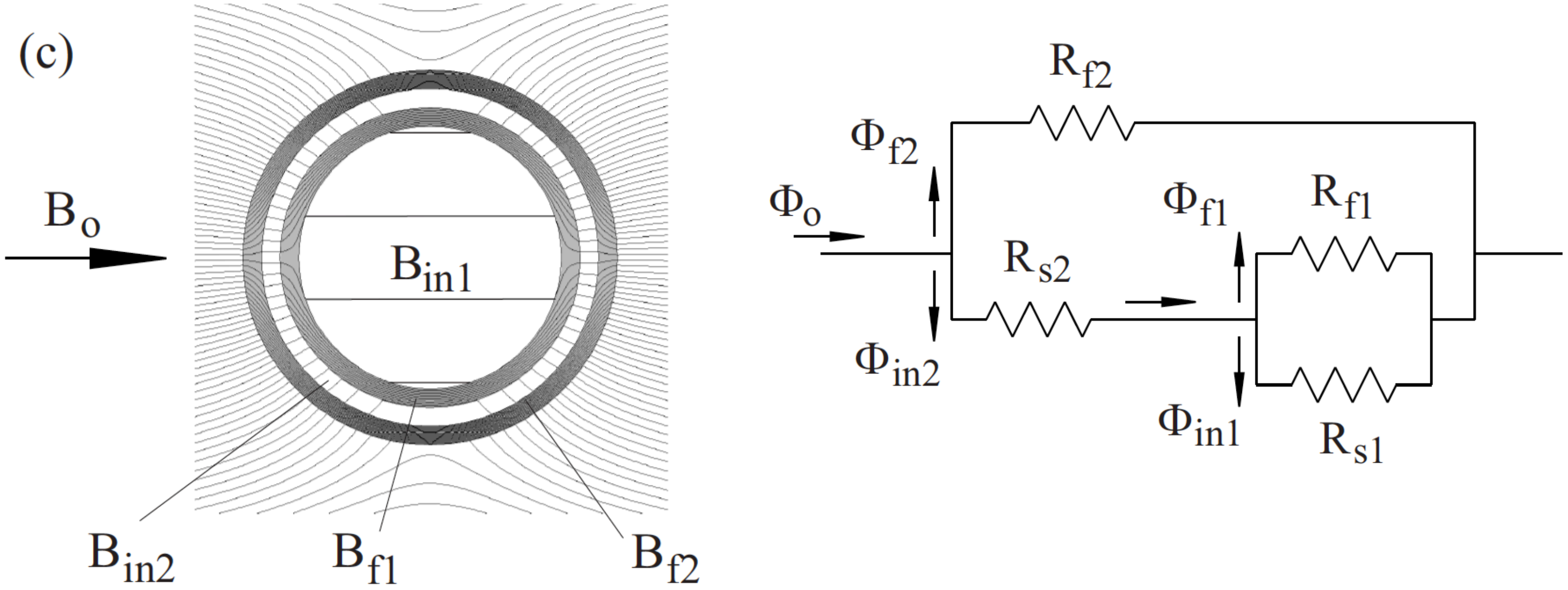
https://www.swisstopo.admin.ch/fr/cartes-donnees-en-ligne/calculation-services/deklination.html

Declination: 2.14425
Meridian convergence -0.94690
Inclination: 62.07666
Total field (F) [nT]: 47444



Passive shielding backup

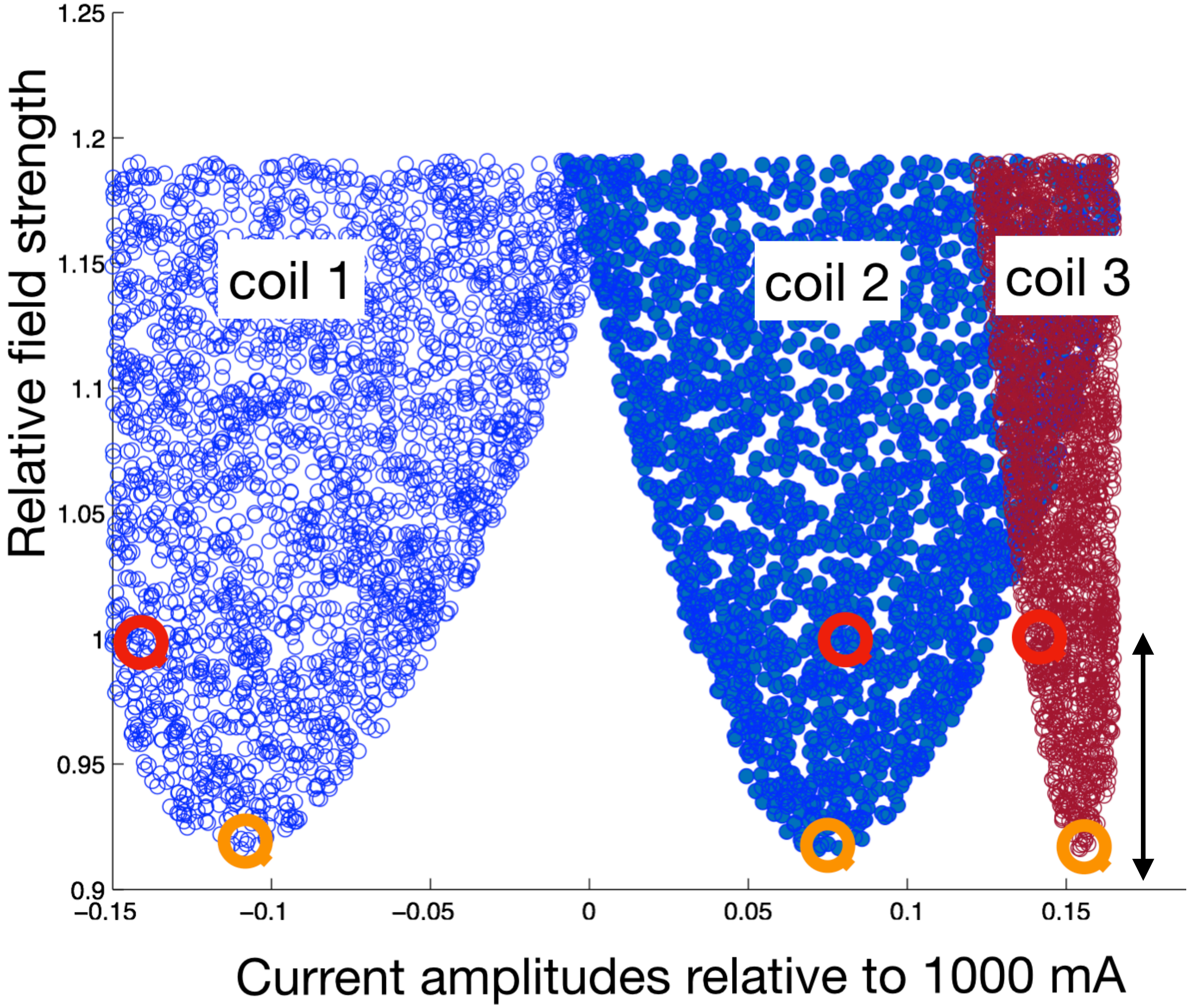




○ What is the maximum compensation that can be achieved?

- Strategy: find the coil currents which minimize the spatially averaged B-field

Set of random coil amplitudes → Obtain B-field, add to B_0 → Evaluate B-field averaged



- Numerically found currents [mA]:

-0.1095 0.0721 0.1544

Suppression of the spatially averaged field by additional 8.4 %

$B_{avg} \approx 3.025$ uT