Generation of 25 T with an all-superconducting magnet system

field profile and field quality measurements of a 4 T REBCO insert coil for a 21 T LTS magnet

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Motivation

Towards all-superconducting 30-T solenoid magnets

Funded by FNSNF Fonds national suisse Schweizerischer Nationalfonds Fondo nazionale svizzero Swiss National Science Foundation *in collaboration with* Bruker BioSpin

- **Today:** commercial systems: B_{max} = 23.5 T @ 2.2 K
- **Scope:** high resolution NMR , laboratory magnets

Towards 20 T accelerator magnets for HEP

EuCARD² *Funded by* 7 Capacities *coordinated by* CERN

- **Today:** record collision energy of 8 TeV
- **Scope:** future circular colliders with up to 100 TeV
  physics beyond the Standard Model

Motivation

Call for high magnetic fields:

- LTS (background) + HTS (highest field region)
- REBCO tapes currently most promising for high fields
  - mechanical, electrical properties
  - commercial availability

Project: magnet field booster:

- Layer wound REBCO insert for existing 21 T LTS magnet
- ≥ 25 T combined center field, ≥ 15 mm Ø usable bore
- Has to fit in the magnet’s VTI (48 mm max. diameter)

Insert coil

Conductor selection:

- SuperPower (3 mm wide), Kapton insulation

Insert coil design:

- 20 mm min. Ø, 48 mm max. Ø, 175 mm length
- 1820 turns in 50 layers, 180 m conductor
- 19.2 mH, 220 A op. current, 423 J stored

BUT: screening currents

- Tape geometry & radial field component
  → field changes induce screening currents

GOAL: understanding field profile & screening current effects

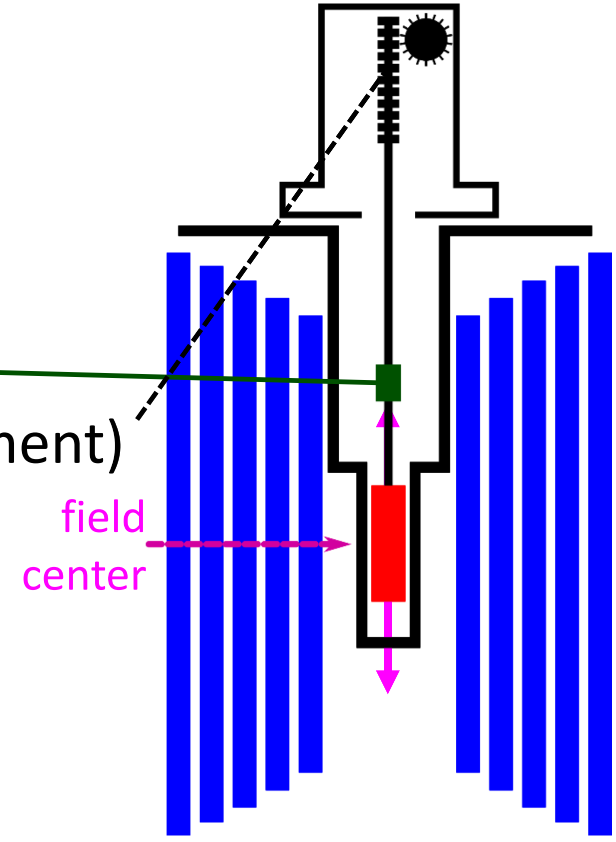
Operation of the insert coil

Christian Barth

Coupled coils

Outsert & insert: inductively coupled

- Misalignment results in high forces
- Movable insert coil
  - load cell to detect the forces
  - stepping motor + gearbox (µm displacement)



- Outsert quench → induces high over current in insert
- Quench detection and protection
  - monitors insert & outsert
  - dissipate >> the insert's stored 423 J

Quench detection & protection

Quench analysis:

- 2 Ω dump resistor, 100 ms max. reaction time
- 8 kW max. load, dissipate 1.5 kJ

Quench detection:

- Hardware QD: ΔU of both halves of the outsert
- Agilent 3457A with limit function: U of the insert

Quench protection:

- 1k A switch to bypass dump resistor in normal operation

  → 19 ± 8 ms reaction during tests ✓

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reached 25 T (all-superconducting):

- European record
- 4th highest worldwide

http://www.manep.ch/switzerland-winds-up-superconductivity/

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Field profile measurements

Christian Barth

Experimental details

Hall sensor array:

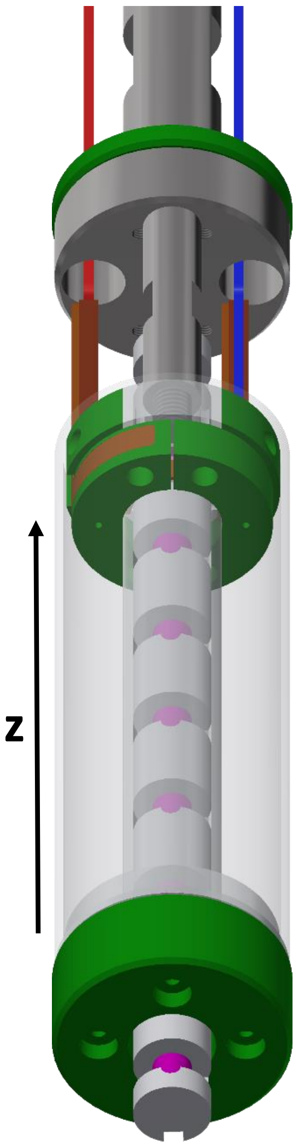
- 9 hall sensor (Arepoc, 30 T), 25 mm separation
- Feed in series, read in parallel, z direction

Calibration:

- Insert coil dummy: use outsert field profile as reference

Experimental procedure:

- Ramp outsert to field, wait for relaxation (600s)
- Charge insert, wait for relaxation (1200 s)
- Discharge insert, wait for relaxation (600s)



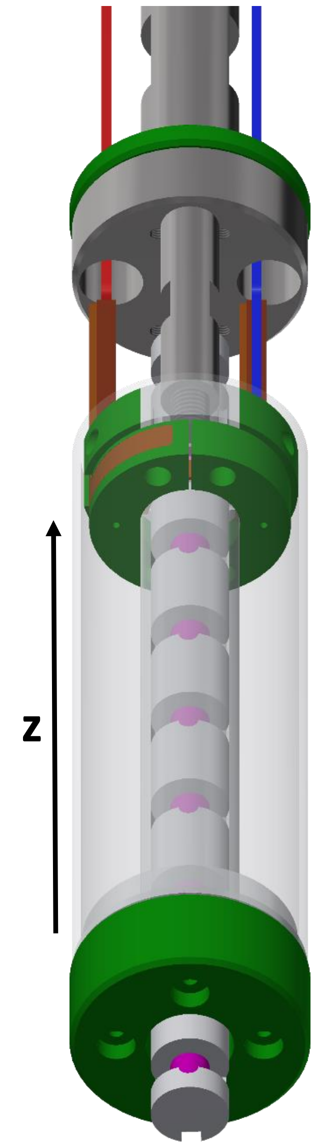
Performed experiments

Hall sensor array:

- 9 hall sensor (Arepoc, 30 T), 25 mm separation
- Feed in series, read in parallel

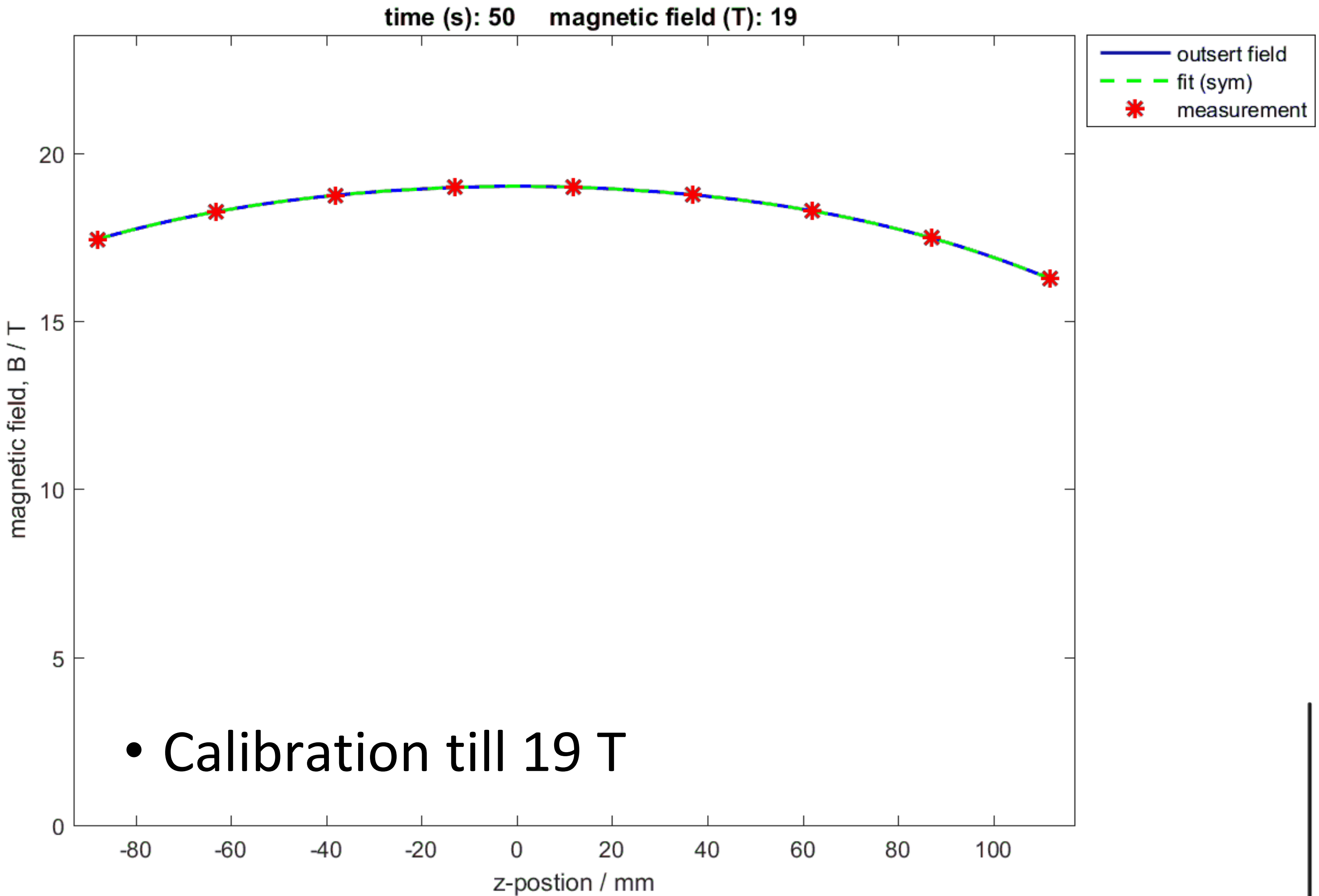
calibration only experiment

	Outsert	Insert
Insert dummy	Ramping to 19 T	n.a.
Insert dummy	Ramping to 0 T	n.a.
Insert	0 T	charging to 4 T - relaxation - discharging
Insert	5 T	charging to 4 T - relaxation - discharging
Insert	10 T	charging to 4 T - relaxation - discharging
Insert	15 T	charging to 4 T - relaxation - discharging
Insert	19 T	charging to 4 T - relaxation - discharging



Calibration

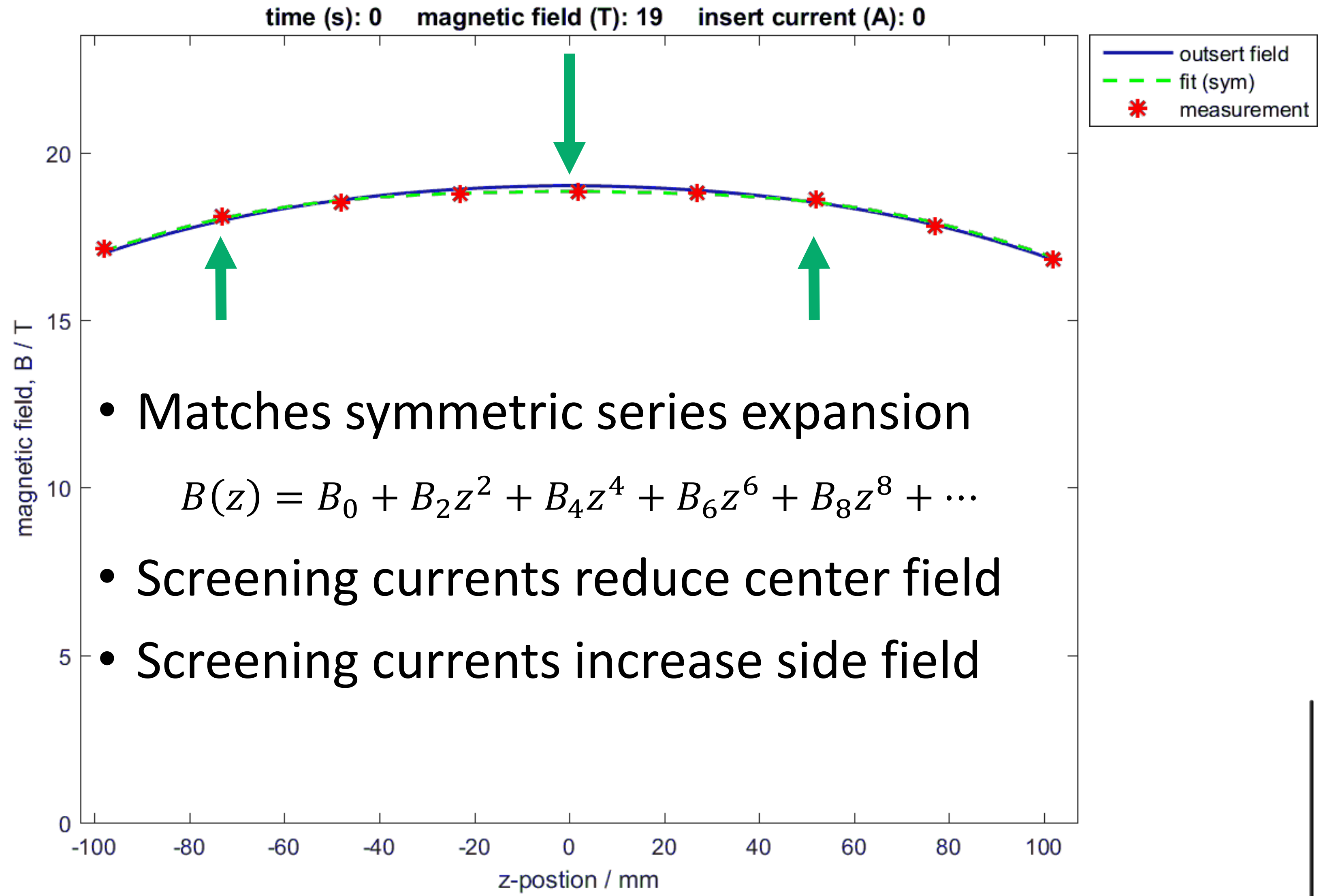
outsert +
dummy



- Calibration till 19 T

Charging of the outsert

outsert
+ insert



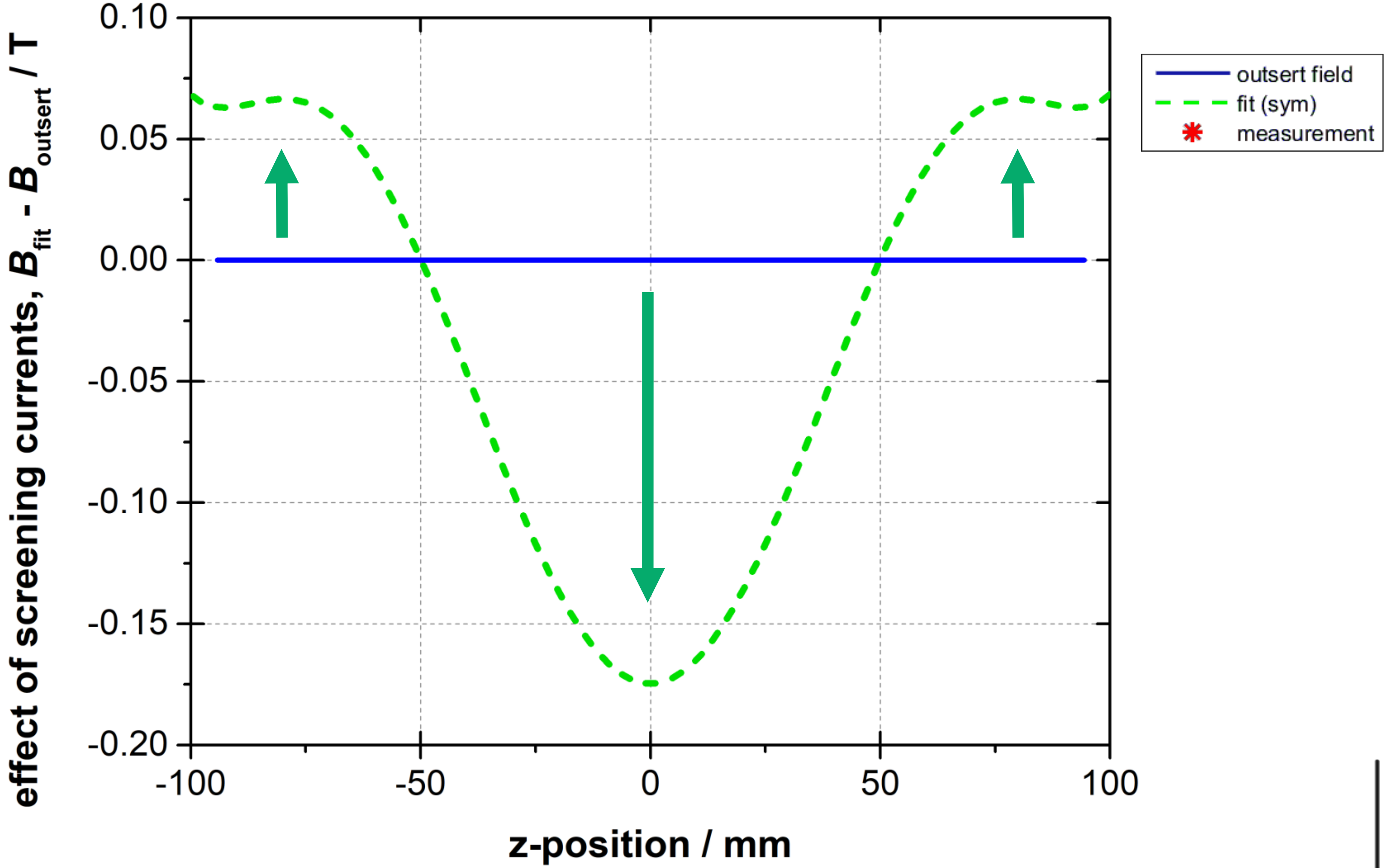
- Matches symmetric series expansion

$$B(z) = B_0 + B_2 z^2 + B_4 z^4 + B_6 z^6 + B_8 z^8 + \cdots$$

- Screening currents reduce center field
- Screening currents increase side field

Charging of the outsert

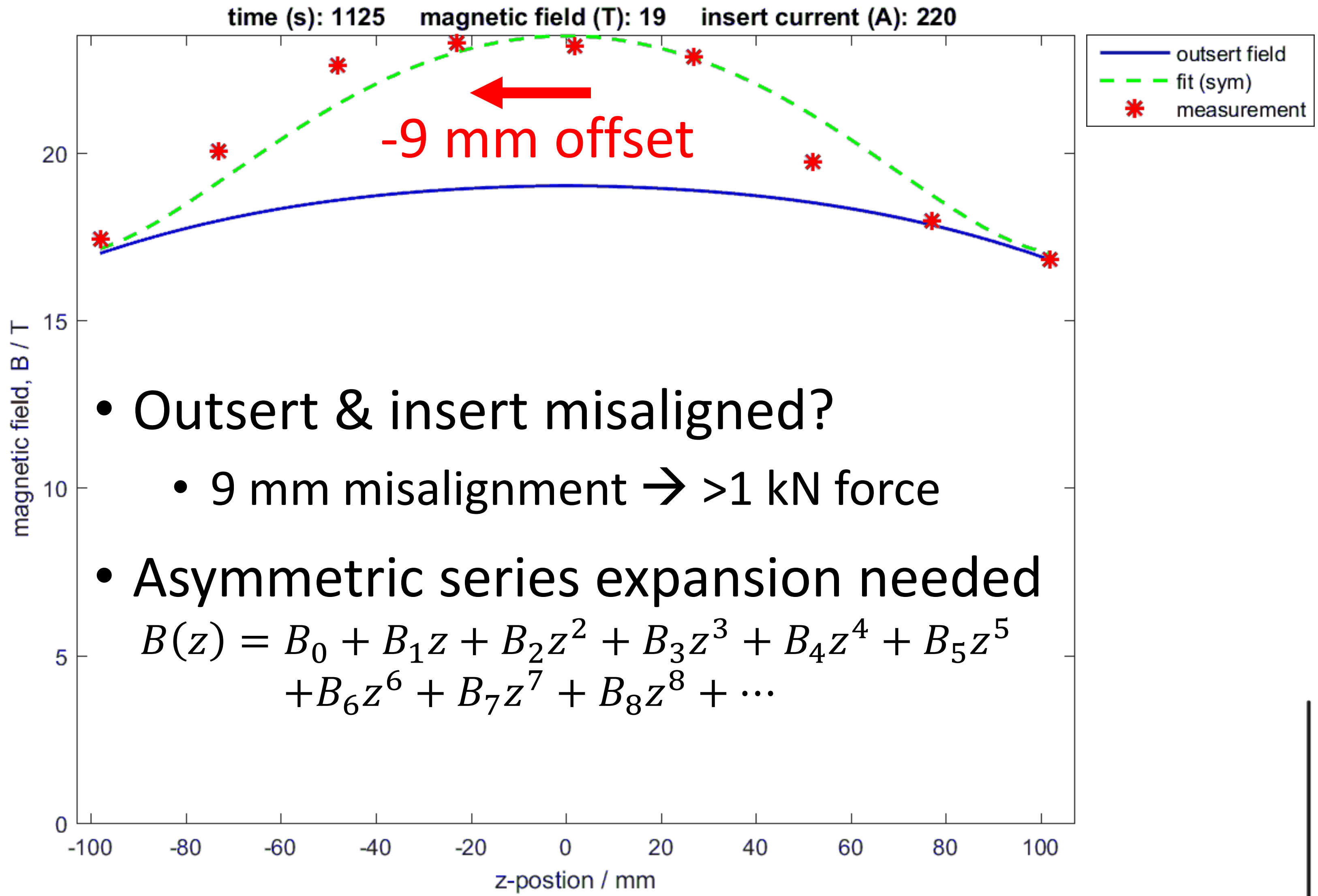
outsert
+ insert



→ expected behavior

Charging of the insert

outsert + insert

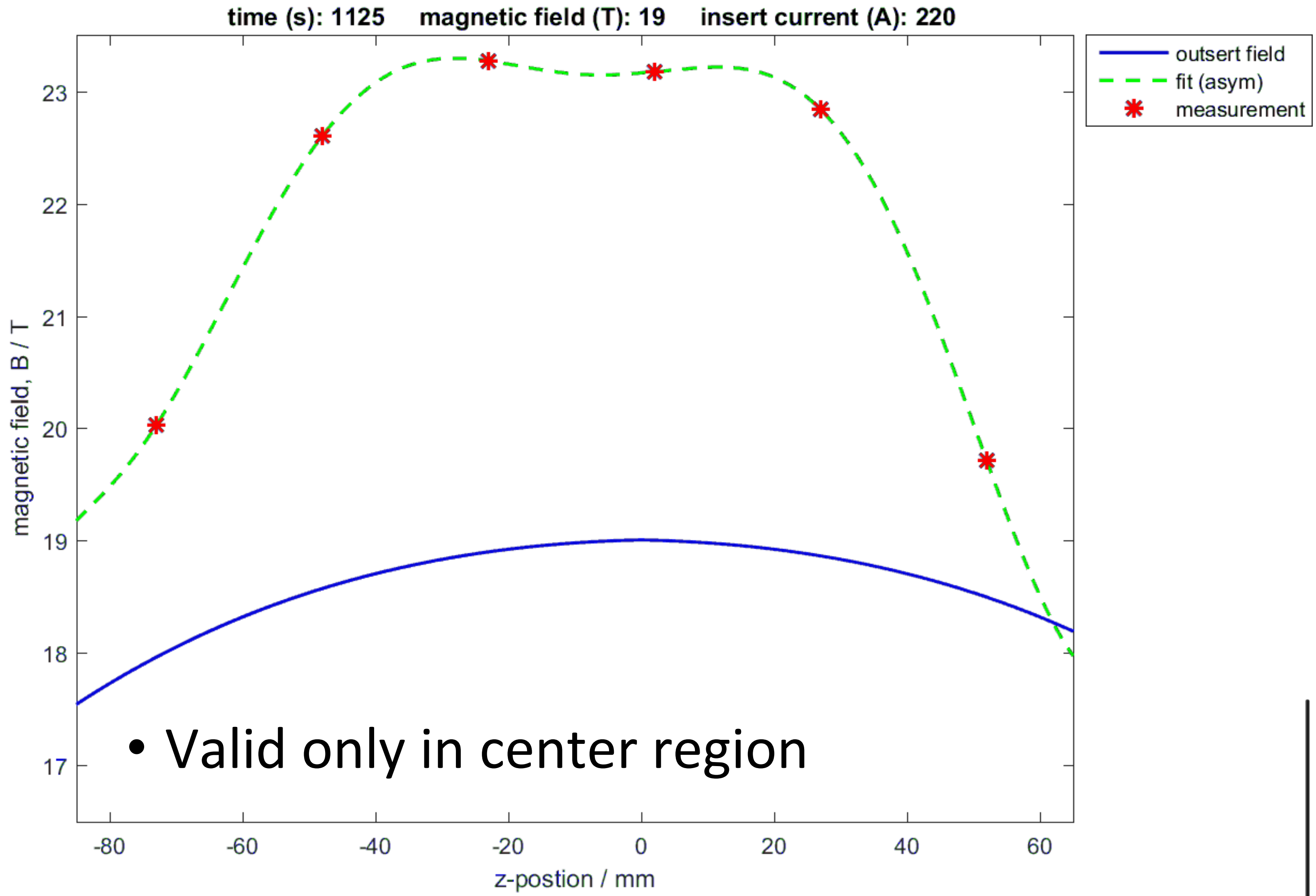


- Outsert & insert misaligned?
  - 9 mm misalignment → >1 kN force
- Asymmetric series expansion needed

$$B(z) = B_0 + B_1 z + B_2 z^2 + B_3 z^3 + B_4 z^4 + B_5 z^5 + B_6 z^6 + B_7 z^7 + B_8 z^8 + \cdots$$

Asymmetric series expansion

outsert
+ insert



- Valid only in center region

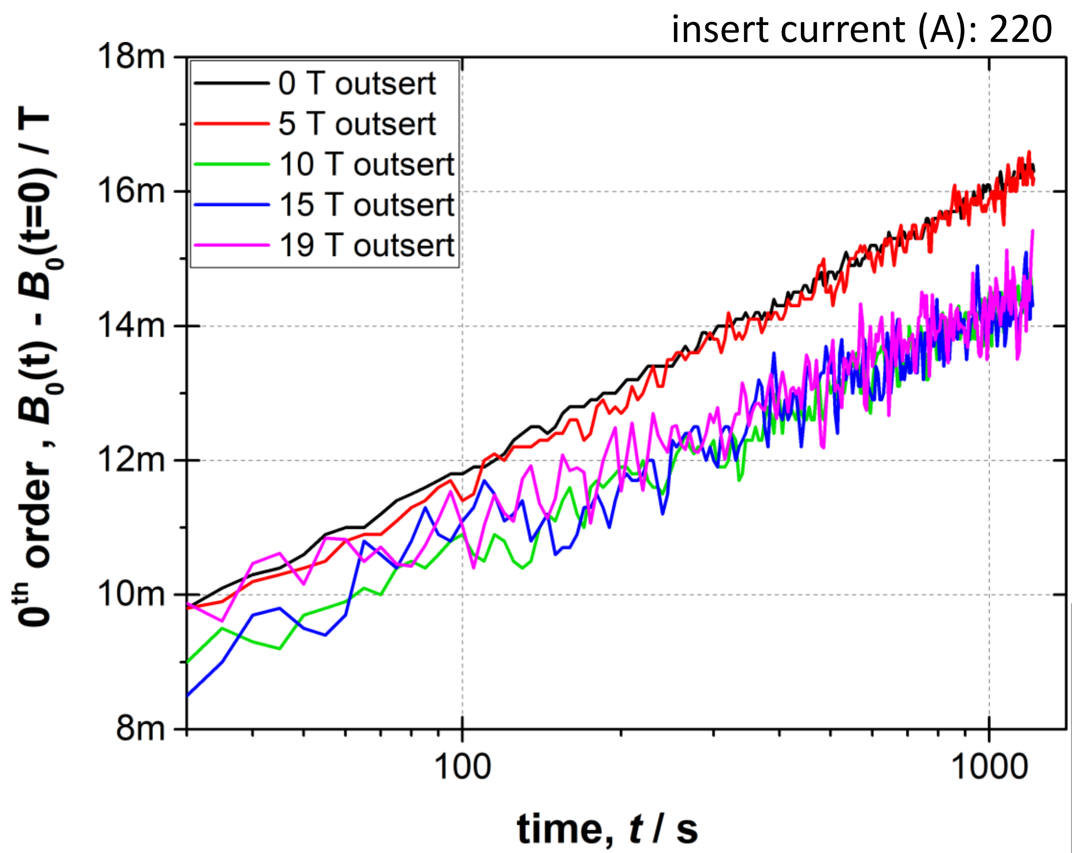
Screening current decay

Evolution of series expansion after charging: 0th order

$$B(z) = \boldsymbol{B_0} + B_1 z + B_2 z^2 + B_3 z^3 + B_4 z^4 + B_5 z^5 + \cdots$$

Main field:

- Increases after charging
- Independent of outsert field
- 4 mT / decade → 0.1 % / decade



→ expected behavior

Screening current decay

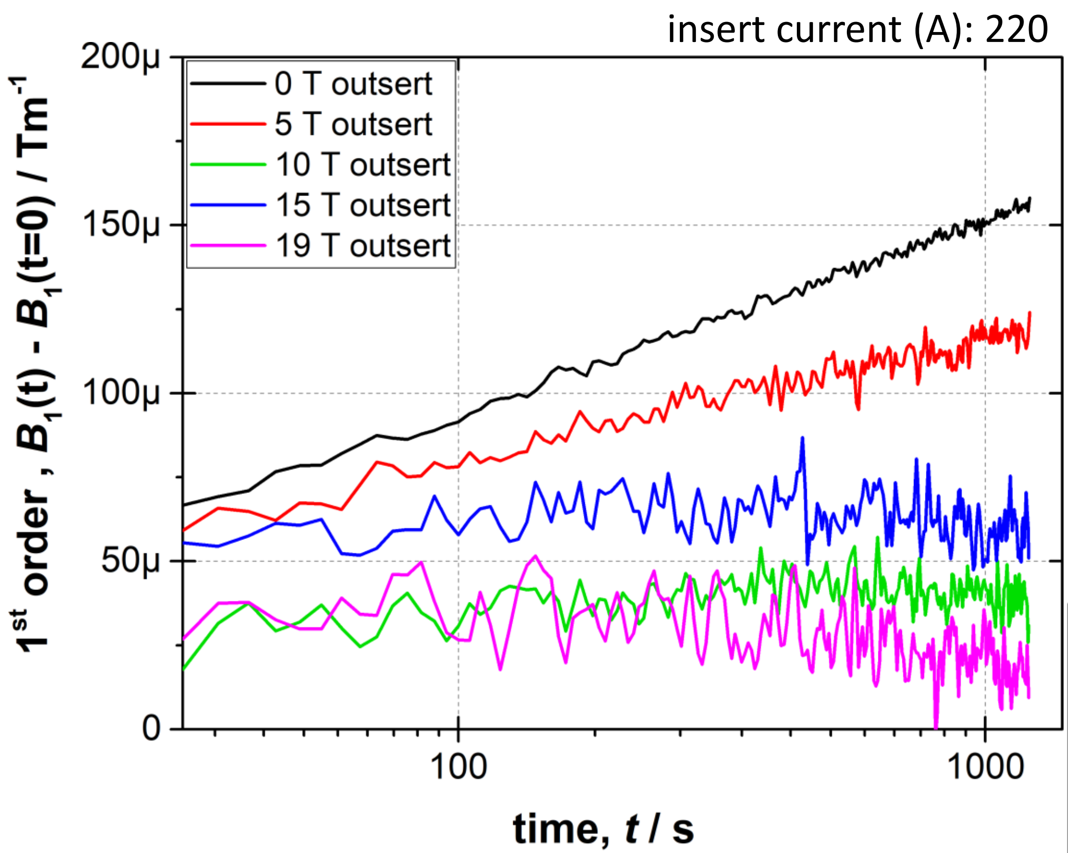
Evolution of series expansion after charging: 1st order

$$B(z) = B_0 + \mathbf{B_1} z + B_2 z^2 + B_3 z^3 + B_4 z^4 + B_5 z^5 + \cdots$$

1st field harmonics:

- Measure of field asymmetry
- Asymmetry drifts at low outsert fields
- Constant from 10 T

→ further investigation needed



Screening current decay

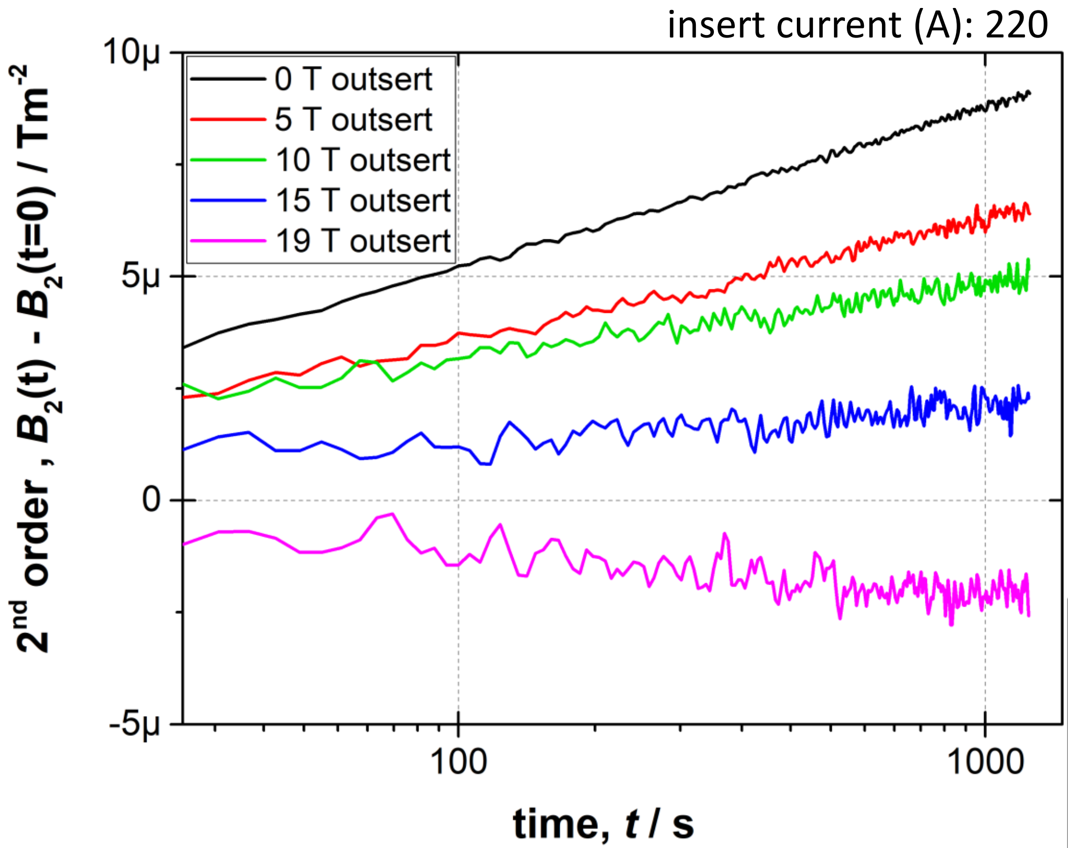
Evolution of series expansion after charging: 2nd order

$$B(z) = B_0 + B_1 z + \mathbf{B_2} z^2 + B_3 z^3 + B_4 z^4 + B_5 z^5 + \cdots$$

2nd field harmonics:

- Measure of field curvature
- Drifts towards more positive values (= less screening curr. effect)
- Lower drift at high outsert fields

→ expected behavior



Insert offset

Load cell readout during outsert & insert charging:

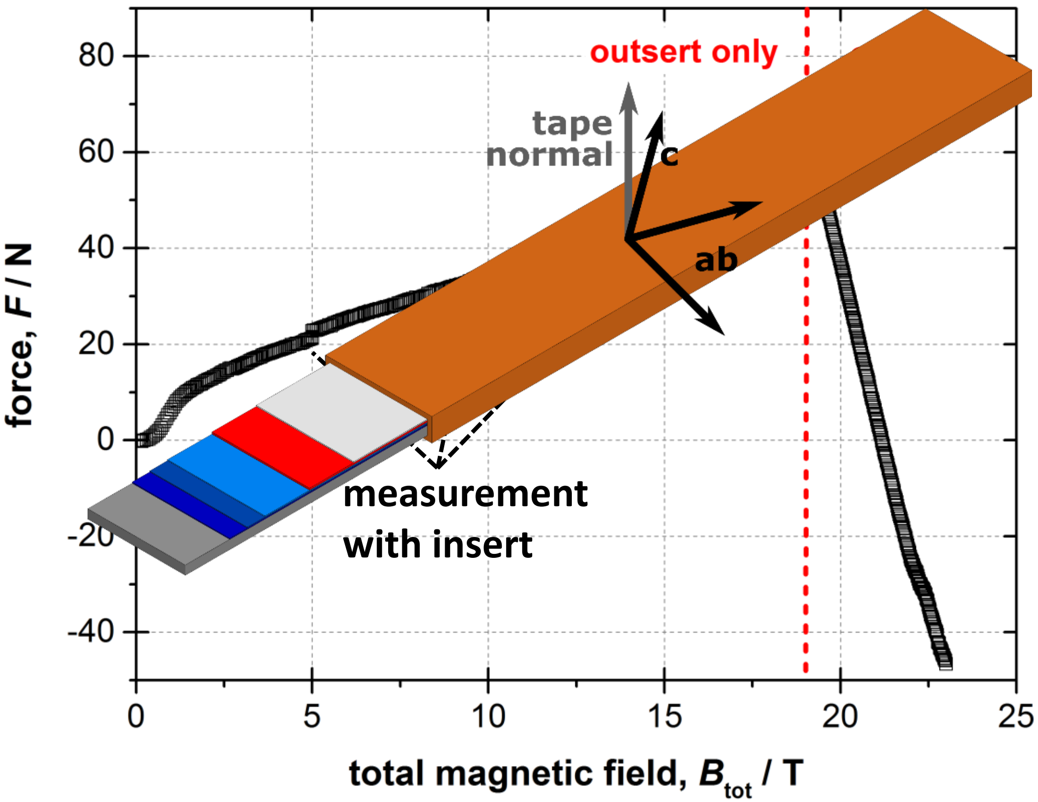
- 115 N centering force ≠ -9 mm misalignment

Other explanations?

- Force measure error?
- Asymmetric screening current induction?
  - tilt of the insert coil?
  - tilt of the REBCO layer?

→ offset should decay after charging

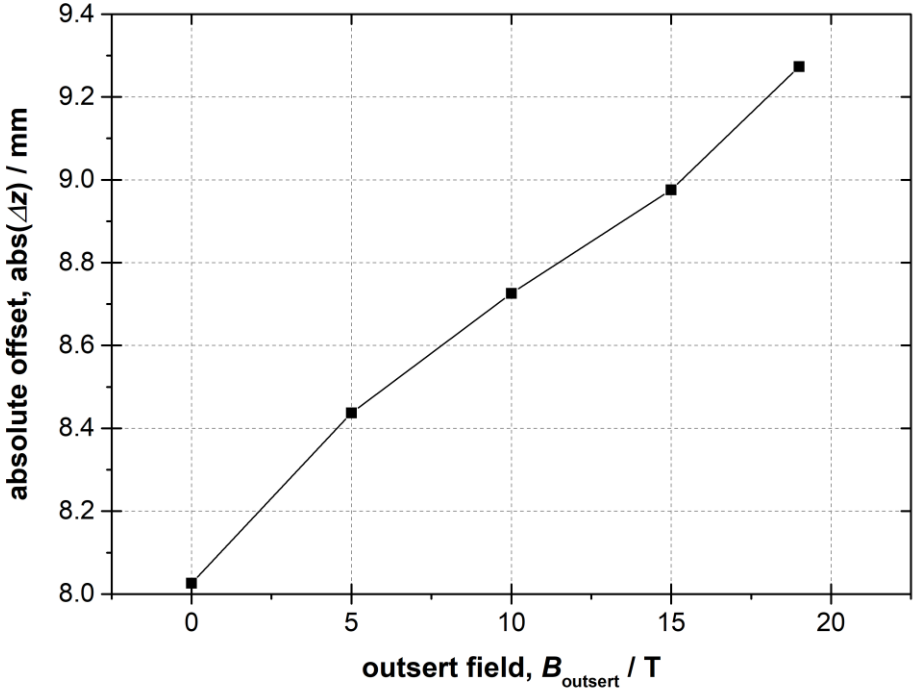
→ offset should in-crease with field

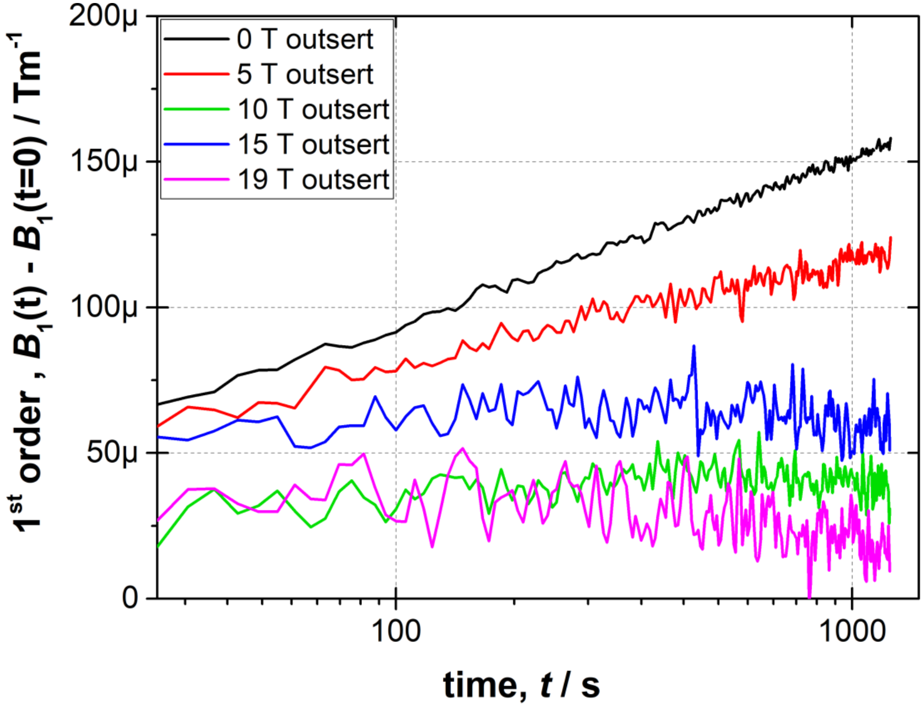


Insert offset

Tilt of the REBCO layer → asymmetric screening curr.:

- Absolute value of offset increase with field ✓
- Offsets decay after charging ?





Summary & outlook

Outlook

- Repeat experiment with less hall probe separation
  → more data points in field center → better for fitting
- Investigate why insert field offset ≠ measured force
  - main field increases independent of outsert field
    → expected, magnetic relaxation of REBCO is field independent
  - 1st harmonics (field asymmetry) drifts only at low outsert fields
    → needs further investigation
  - 2st harmonics (field curvature) drifts towards positive values (= less screening curr. effect), lower drift at high outsert fields
    → expected, high outsert fields homogenize field alignment
    → I/I_c more homogeneous → homogenous screening curr.

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Thank you for your attention

http://supra.unige.ch
https://www.bruker.com/

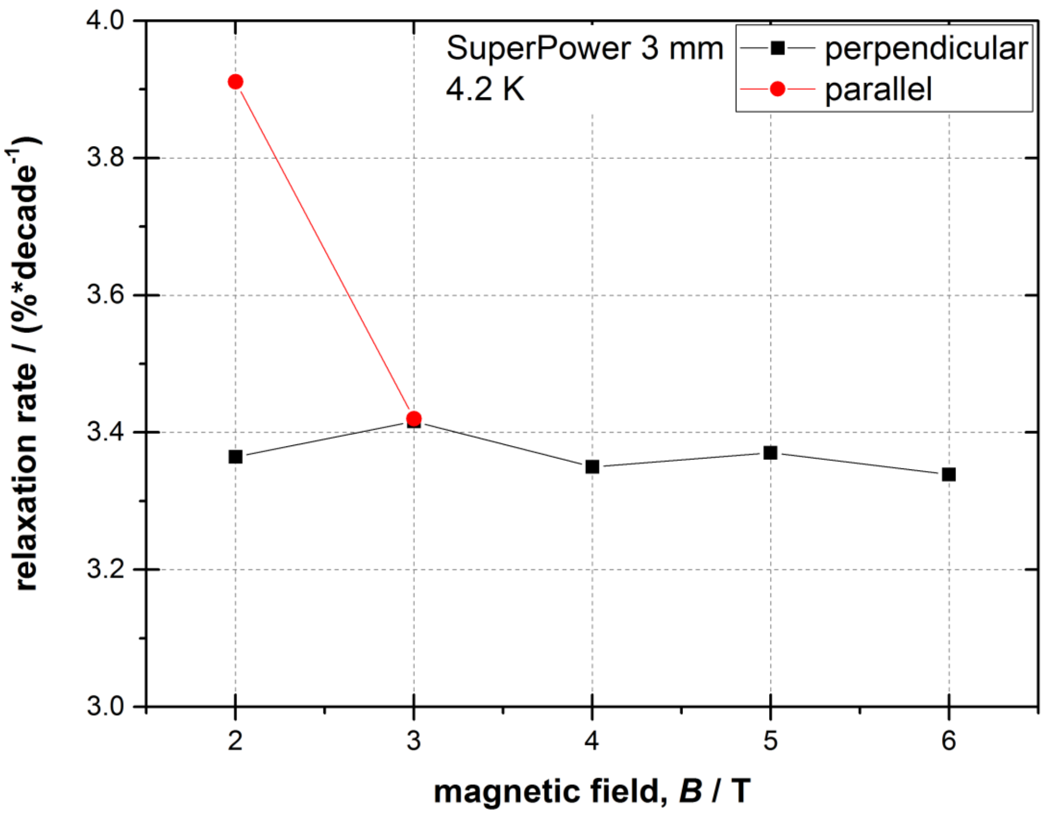
REBCO magnetic relaxation

3 mm wide SuperPower REBCO tapes:

- Logarithmic magnetic relaxation
- Independent of field
- ≈3.4 % / decade

→ 33x the main field Drift (0.1% / decade)

???



perpendicular: B || c

parallel: B || ab

Decay of the screening currents

<u>Relaxation of the central magnetic field:</u>

- Logarithmic decay
- Independent of field
- 0.08 % / decade

→ close to calculated main field drift (0.1% / decade)