Investigation on intense axial magnetic field shielding with Bi-2212 tube

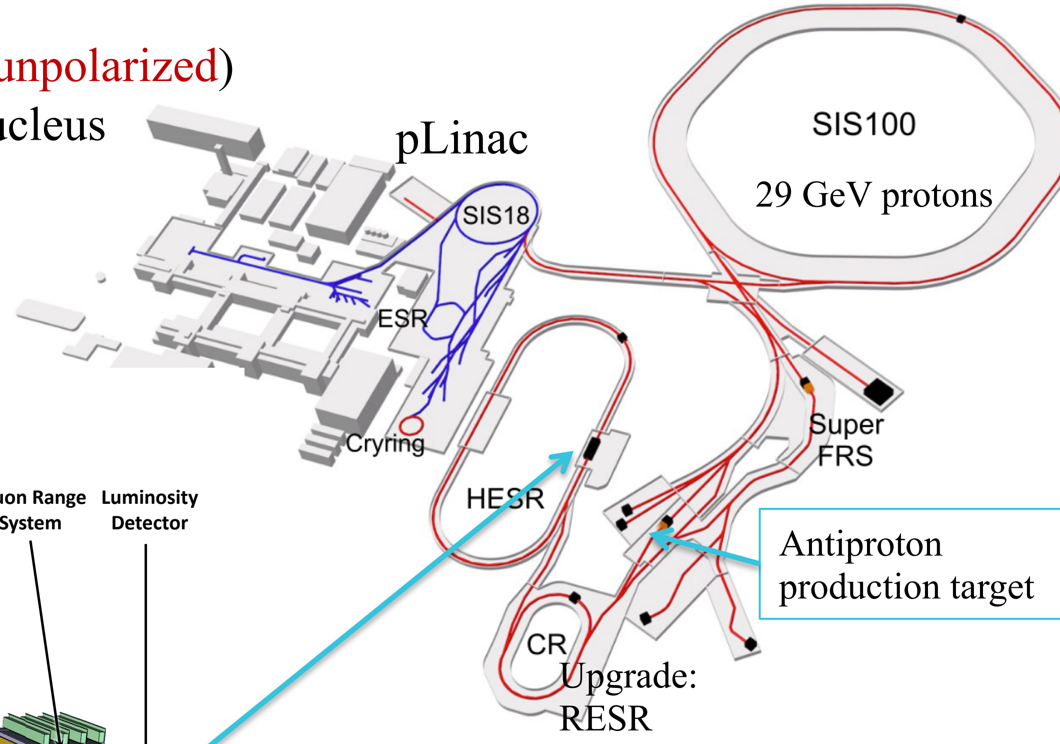
HIM
Helmholtz-Institut Mainz

L. Capozza, A. Dbeyssi, **F. Maas**, B. Froelich, M. C. Mora Espi, O. Noll, Y. Wang, D. Lin – 22.09.2022, Mainz

Helmholtz-Institut Mainz, Institute of Nuclear Physics, Johannes Gutenberg University, Prisma Cluster of Excellence

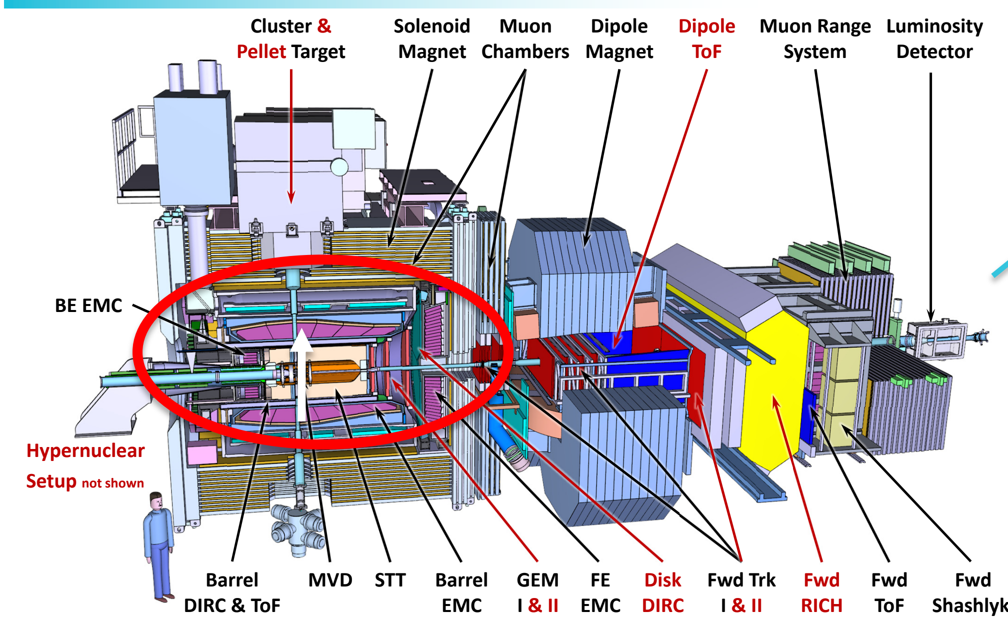
The PANDA experiment at FAIR

- Antiproton beams (1.5 – 15 GeV/c, unpolarized)
- Antiproton-proton and antiproton-nucleus interactions



Phase 3 (+RESR)

- High Luminosity (**HL**) Mode
  - $L = 2 \times 10^{32}\ cm^{-2}\ s^{-1}$
  - $\Delta p/p \leq 2 \times 10^{-4}$



Solenoid: 1T or 2T longitudinal magnetic field

Transversally polarized target at PANDA

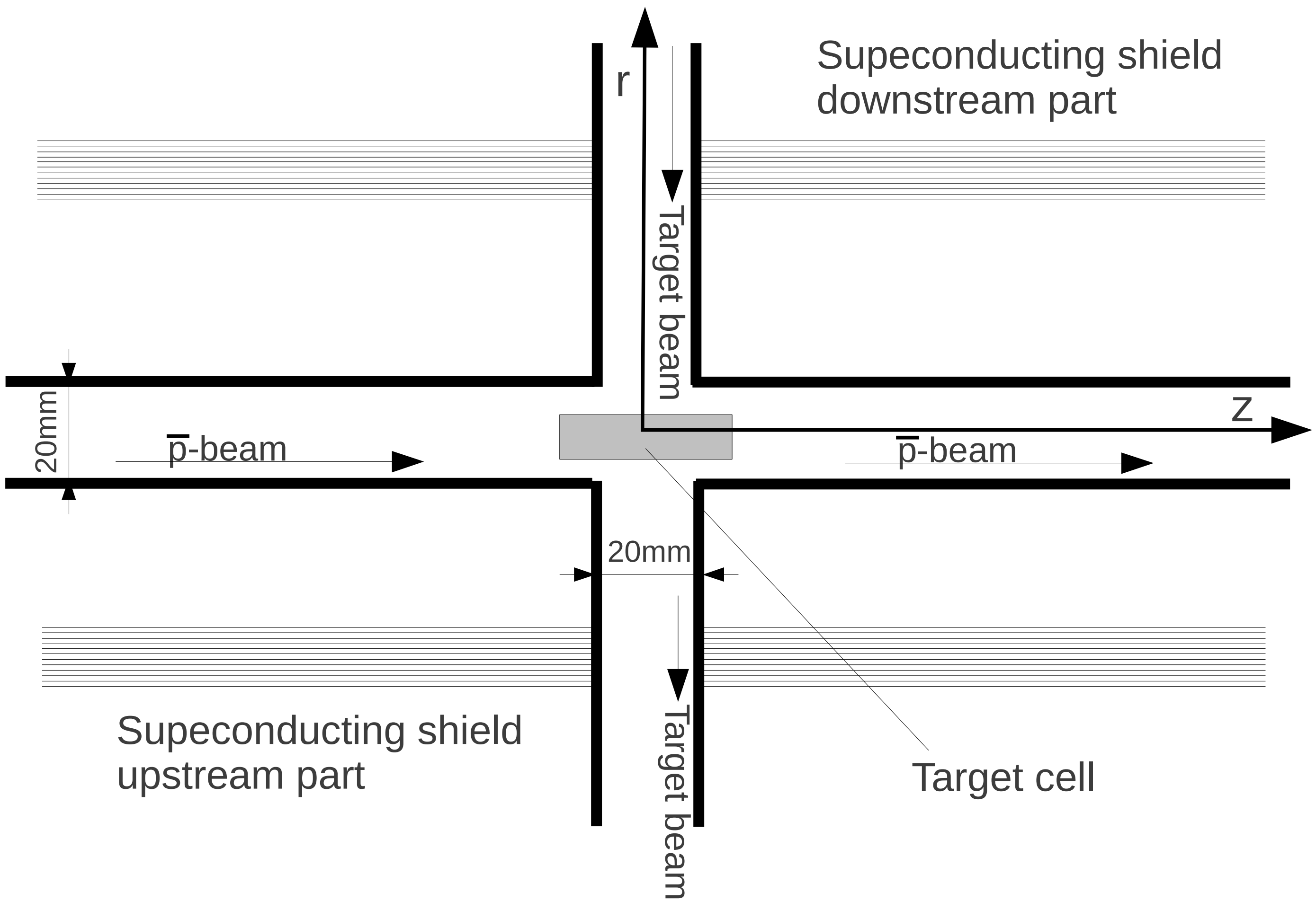
Shielding the longitudinal solenoid field

No space around the target region

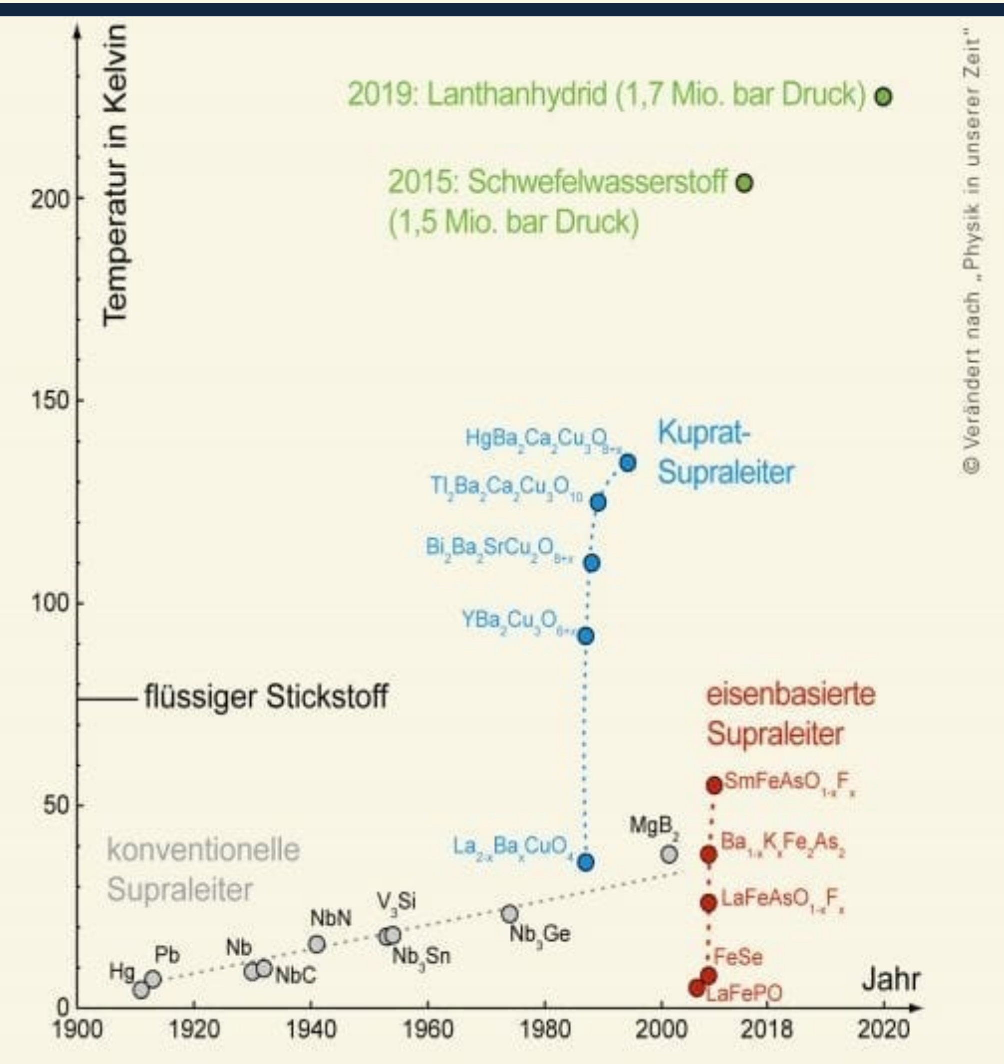
Impact on tracking of particles

How to bring in polarized hydrogen

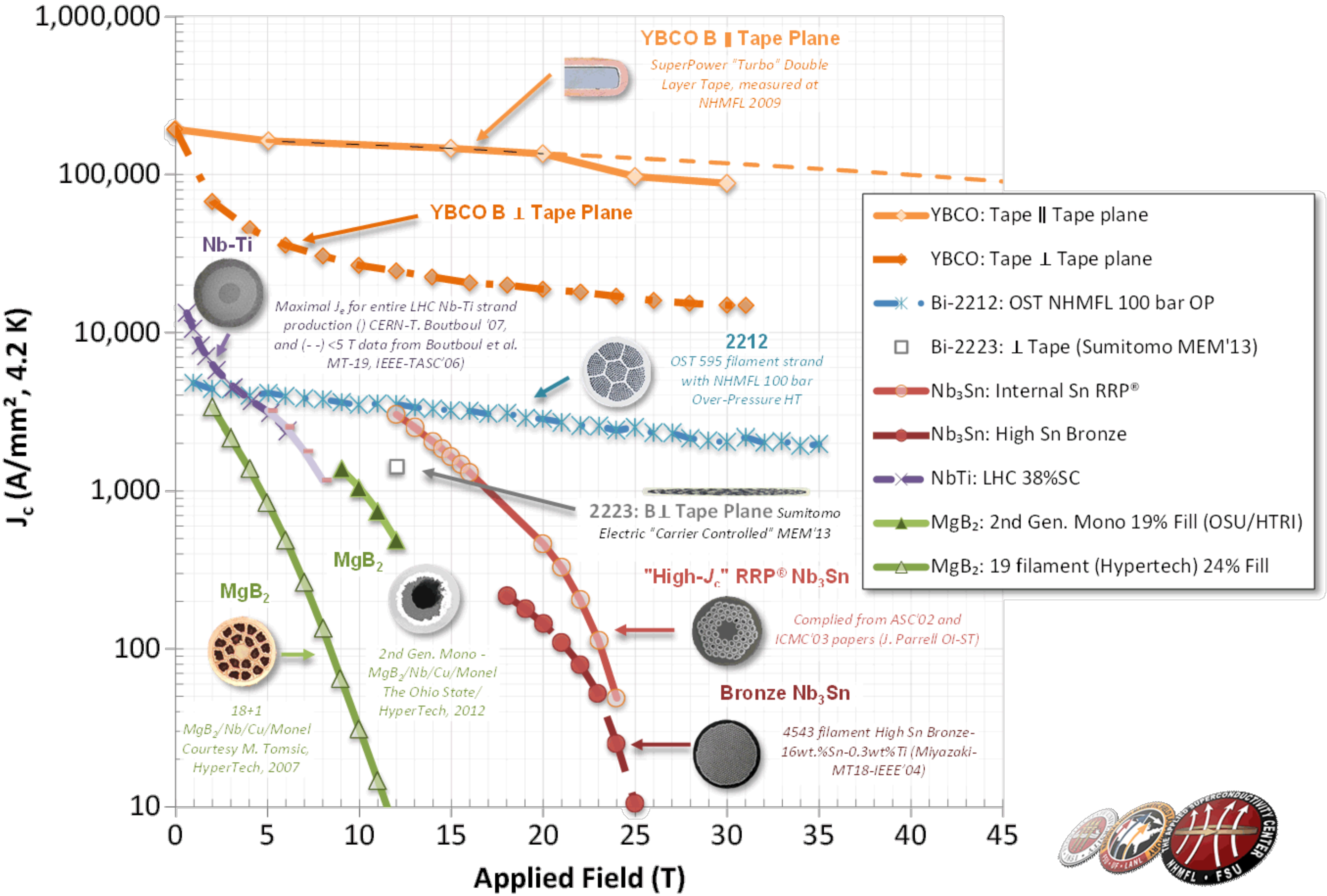
PANDA polarized target challenges

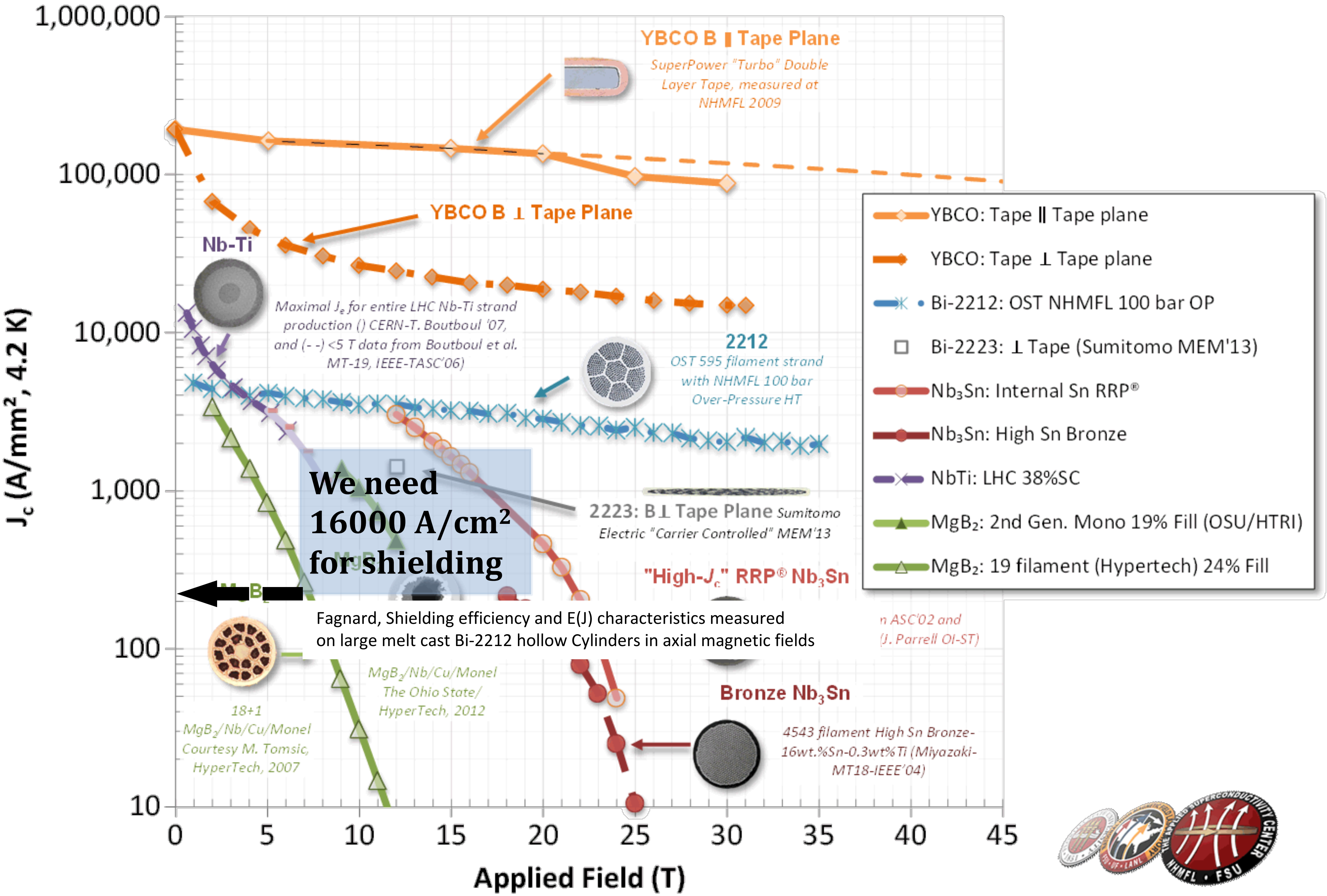


High Temperature Superconductors



Ab 1986 ließen die neuen Hochtemperatur-Supraleiter die Rekorde purzeln.


YBCO B ‖ Tape Plane
SuperPower "Turbo" Double Layer Tape, measured at NHMFL 2009
YBCO B ⊥ Tape Plane
Nb-Ti
Maximal J_e for entire LHC Nb-Ti strand production () CERN-T. Boutboul '07, and (- -) <5 T data from Boutboul et al. MT-19, IEEE-TASC'06)
2212
OST 595 filament strand with NHMFL 100 bar Over-Pressure HT
2223: B⊥Tape Plane Sumitomo Electric "Carrier Controlled" MEM'13
MgB$_2$
2nd Gen. Mono - MgB$_2$/Nb/Cu/Monel The Ohio State/ HyperTech, 2012
MgB$_2$
18+1 MgB$_2$/Nb/Cu/Monel Courtesy M. Tomsic, HyperTech, 2007
"High-J_c" RRP® Nb_3Sn
Complied from ASC'02 and ICMC'03 papers (J. Parrell OI-ST)
Bronze Nb_3Sn
4543 filament High Sn Bronze-16wt.%Sn-0.3wt%Ti (Miyazaki-MT18-IEEE'04)
YBCO: Tape ‖ Tape plane
YBCO: Tape ⊥ Tape plane
Bi-2212: OST NHMFL 100 bar OP
Bi-2223: ⊥ Tape (Sumitomo MEM'13)
Nb_3Sn: Internal Sn RRP®
Nb_3Sn: High Sn Bronze
NbTi: LHC 38%SC
MgB$_2$: 2nd Gen. Mono 19% Fill (OSU/HTRI)
MgB$_2$: 19 filament (Hypertech) 24% Fill
J_c (A/mm², 4.2 K)
1,000,000
100,000
10,000
1,000
100
10
0
5
10
15
20
25
30
35
40
45
Applied Field (T)



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MgB2/Nb/Cu/Monel The Ohio State/ HyperTech, 2012
18+1 MgB2/Nb/Cu/Monel Courtesy M. Tomsic, HyperTech, 2007
We need 16000 A/cm² for shielding
Fagnard, Shielding efficiency and E(J) characteristics measured on large melt cast Bi-2212 hollow Cylinders in axial magnetic fields
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10,000
1,000
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35
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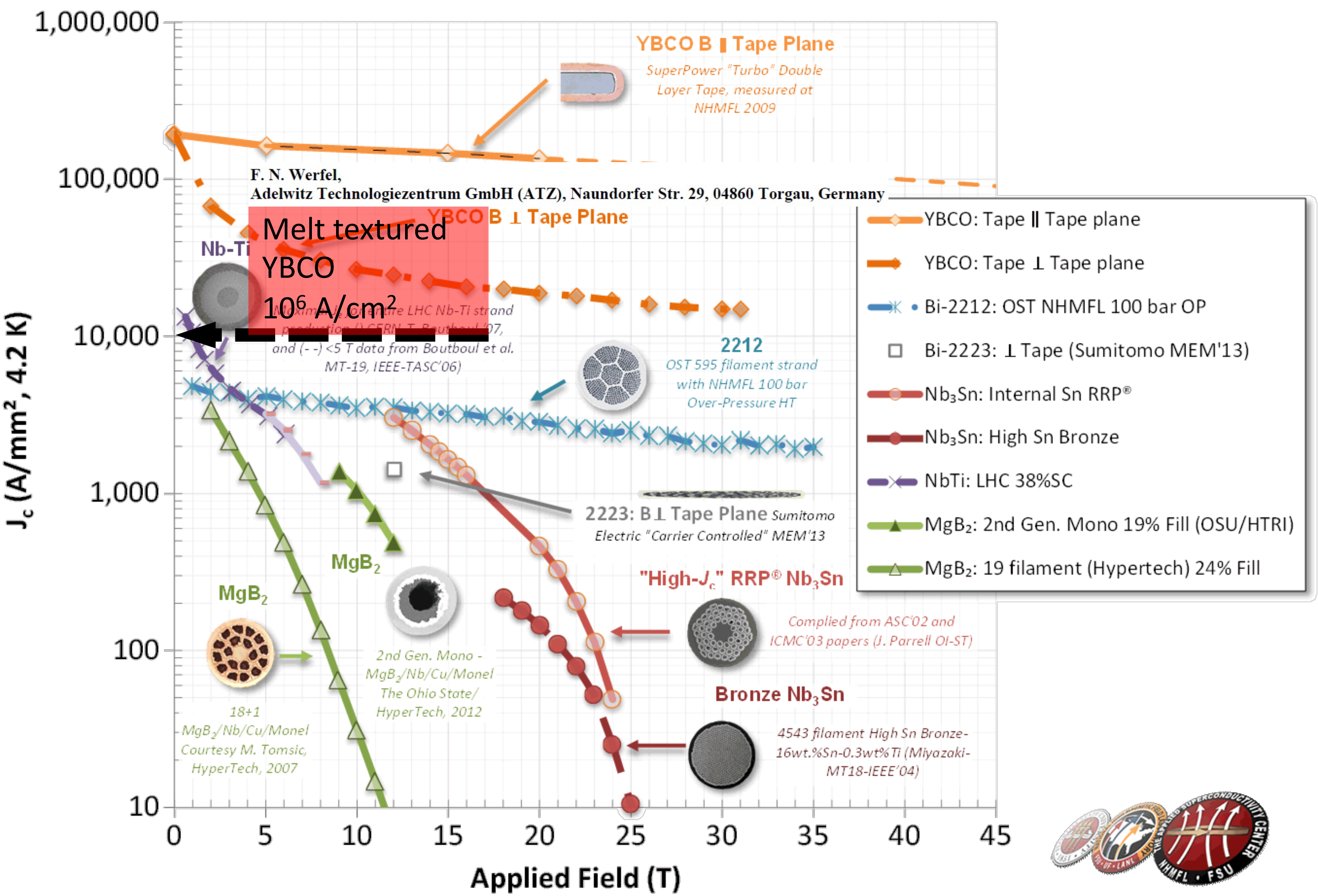
45
Applied Field (T)


F. N. Werfel,
Adelwitz Technologiezentrum GmbH (ATZ), Naundorfer Str. 29, 04860 Torgau, Germany
Melt textured
YBCO
10^6 A/cm^2
YBCO B ‖ Tape Plane
SuperPower "Turbo" Double Layer Tape, measured at NHMFL 2009
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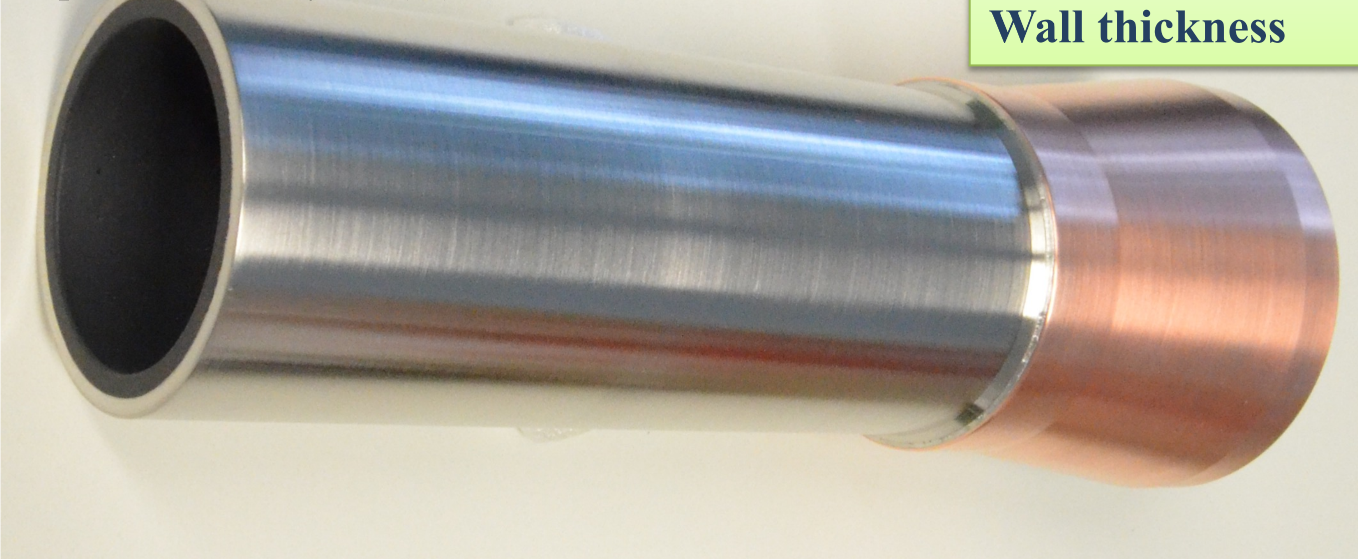
35
40
45
Applied Field (T)

Bi-2212 schielding tube

- High temperature superconductor
- A large melt cast Bi2 Sr2 CaCu2 O8 hollow cylinder (from Nexans); manufactured with centrifugal technique

[J. Bock, S. Elschner, P. Herrmann, IEEE Transactions on Applied Superconductivity 5 (2) (1995) 1409-1412]

Length	150 mm
Outer radius	25 mm
Wall thickness	3.5 mm

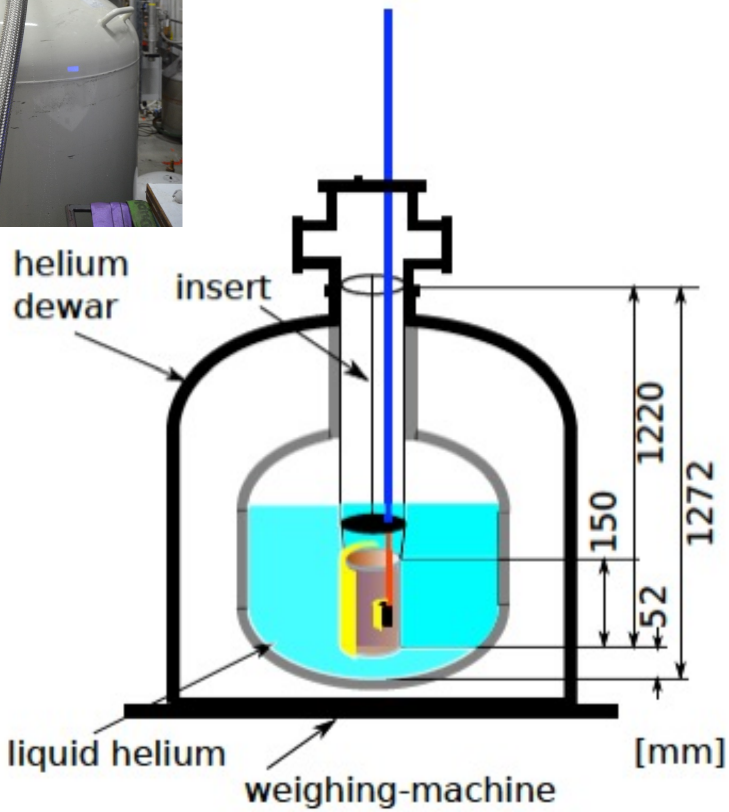


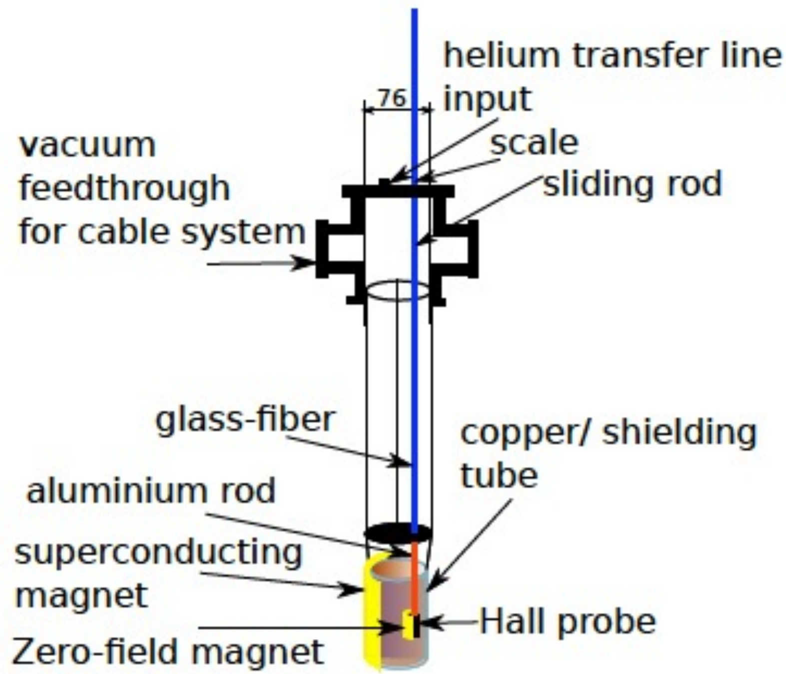
- **At 10 K**, a 1 T magnetic field is shielded with **a shielding factor of 10^3 with** Bi-2212 tube (80 mm length, 8 mm inner radius and 5 mm wall thickness)

J.-F. Fagnard, et al., Superconductor Science and Technology 23 (9) (2010) 095012

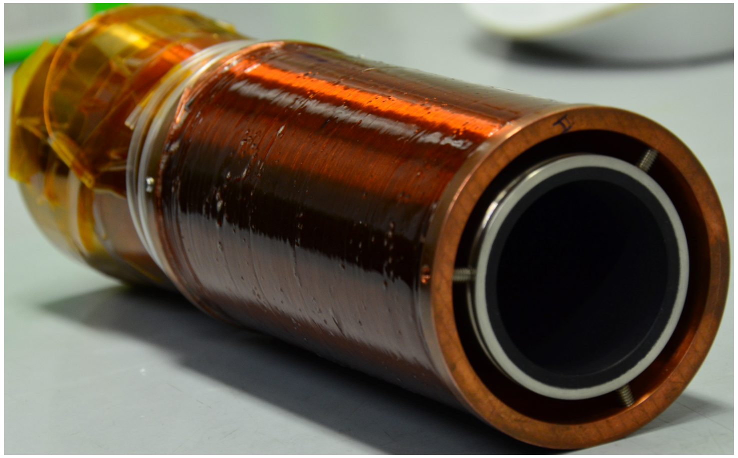
Experimental Setup

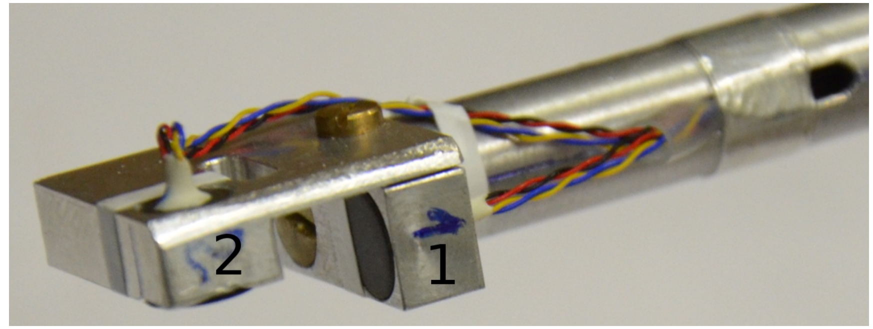
- **Measurements at 4.2 K**
- A dedicated apparatus has been built for these measurements
- A dedicated DAQ system has been developed

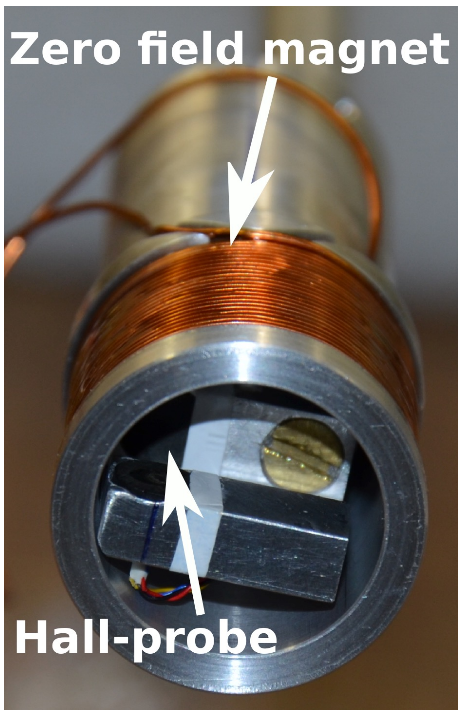




Experimental Setup





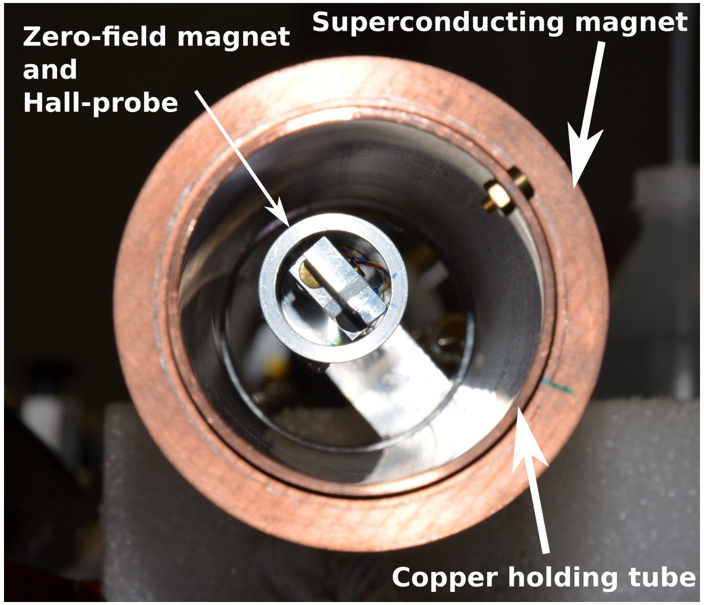


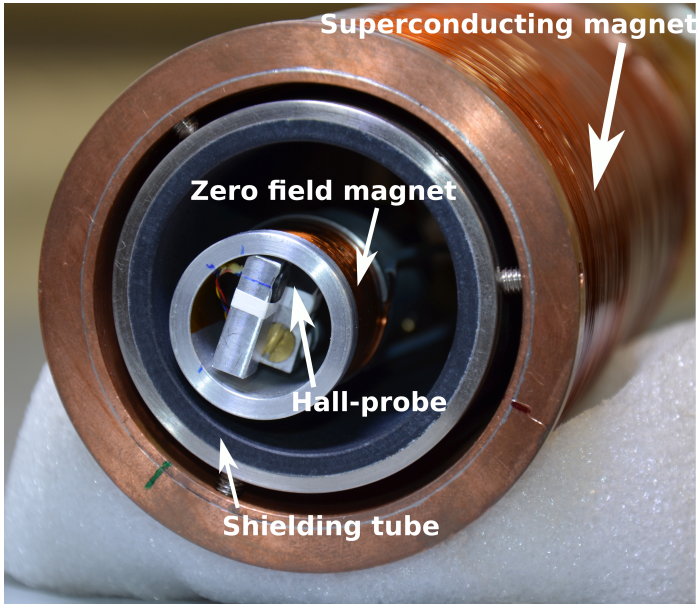
External magnet: designed to provide intense magnetic fields of at least 2 T. Wires made of NbTi with a transition temperature around 9 K

Hall probe from Lake Shore (HGCA-3020); temperature range from 1.5 K to 375 K. Accuracy better than 0.1% up to 2 T. Digistant 64256 T for current supply and Prema 5017 for voltage readout

Zero-field magnet: normal conducting coil on an aluminum; current supply by the Instek PSP 603 from GW-INSTEK. At 1 A, the magnetic field at the center is 22.10^{-4} T

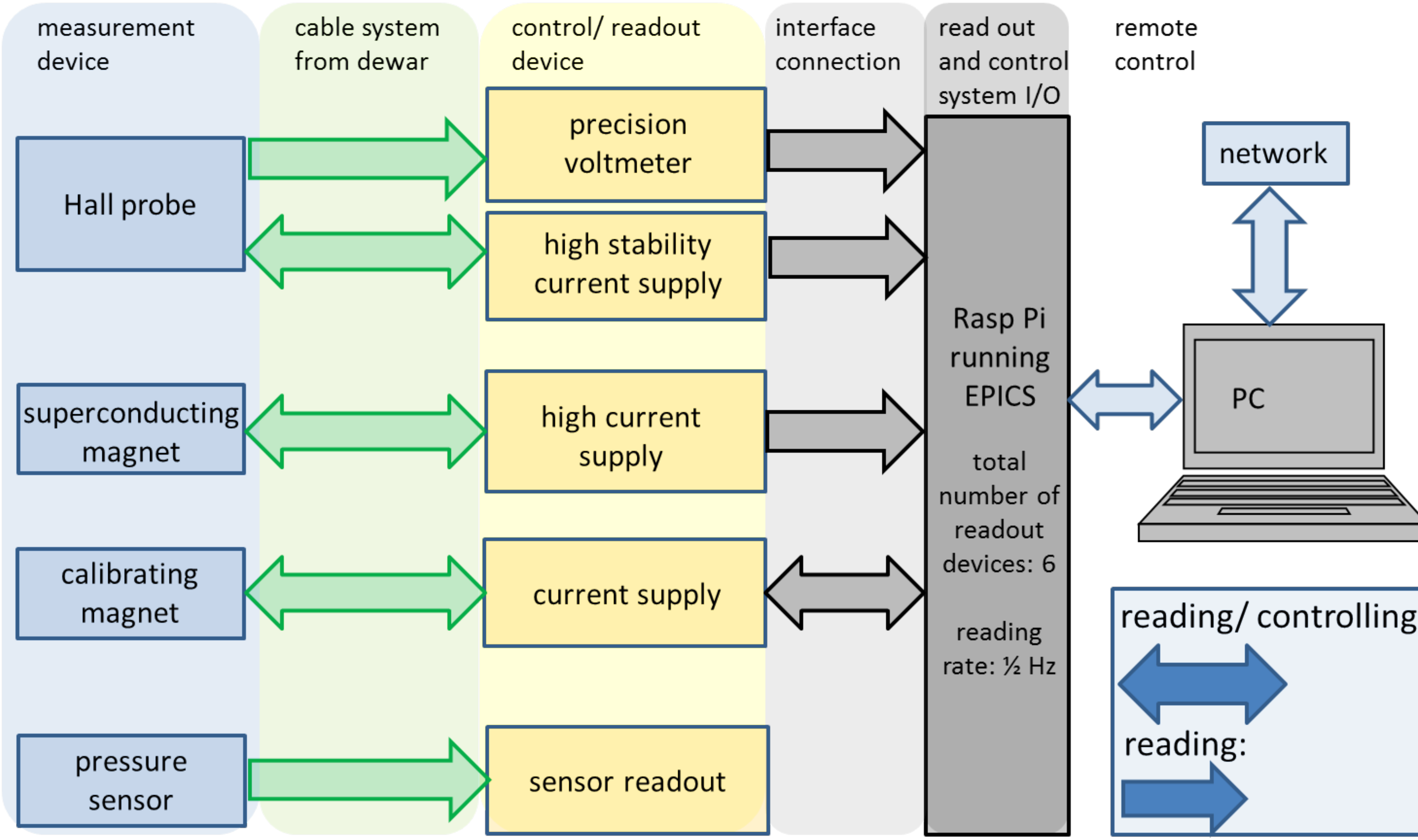
Experimental Setup





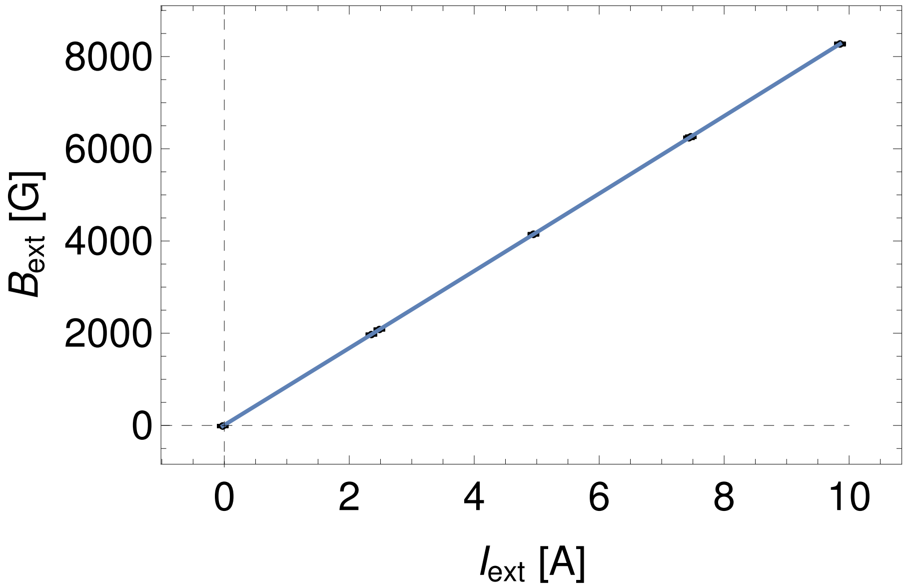
✧ SETUP-A (without Bi-2212)	SETUP-B (with Bi-2212)
✧ Measurements of B_{ext} as a function of I_{exr} ✧ Measurement of B_{ext} along the axis of the external magnet at fixed I_{exr}	✧ Measurement of B_{res} up to 1 T and 1.4 T, at the center of Bi-2212 ✧ Measurements of B_{res} along the axis of Bi-2212 ✧ Stability measurements of B_{res} ✧ Measurements with the Zero-field magnet

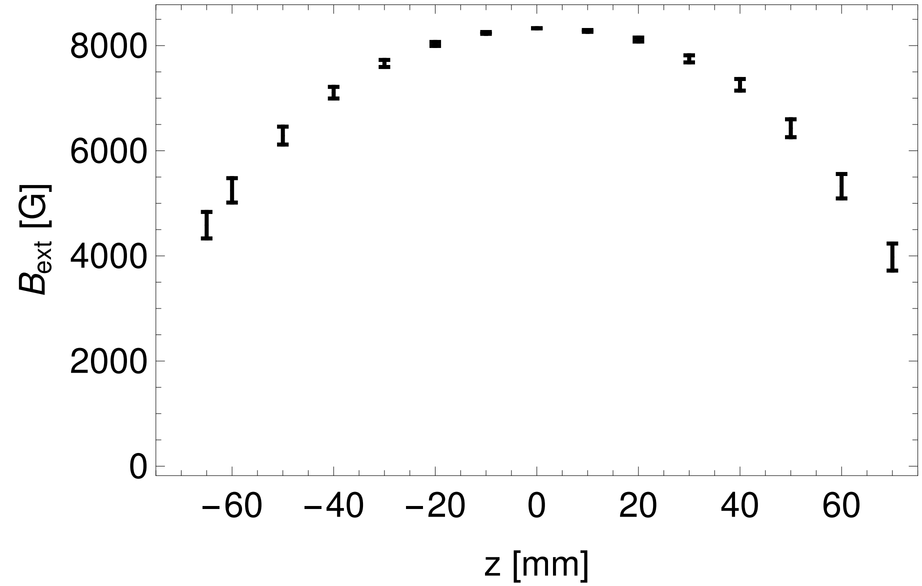
Experimental Setup Data Acquisition System



Measurement of the external magnetic flux density (B_{ext})

[Setup-A]





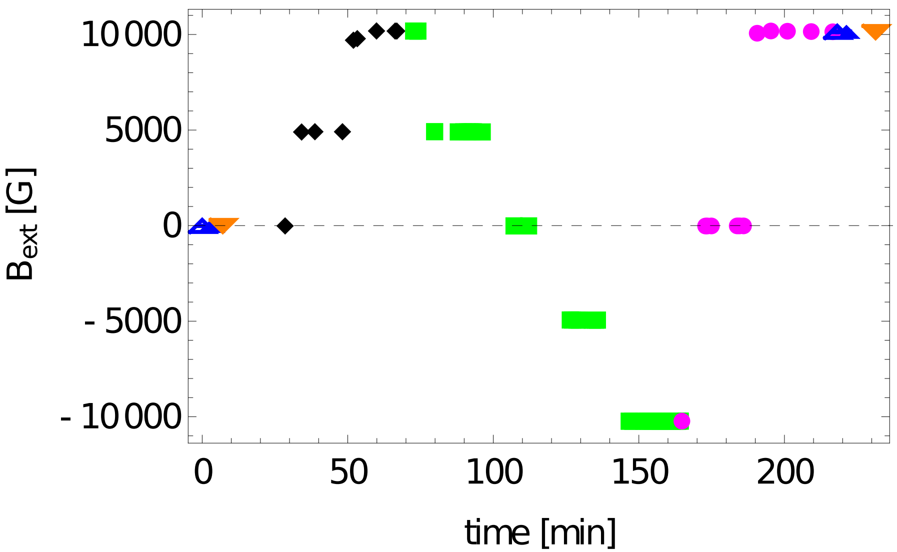
- ✧ Measurement of B_{ext} at the center of the magnet
- ✧ Each point is the mean value of data collected at a stable current I_{ext}
- ✧ Uncertainty mainly from the setting of I_{ext}
- ✧ Data are well described by a second order polynomial function (χ^2/ndf=0.2)

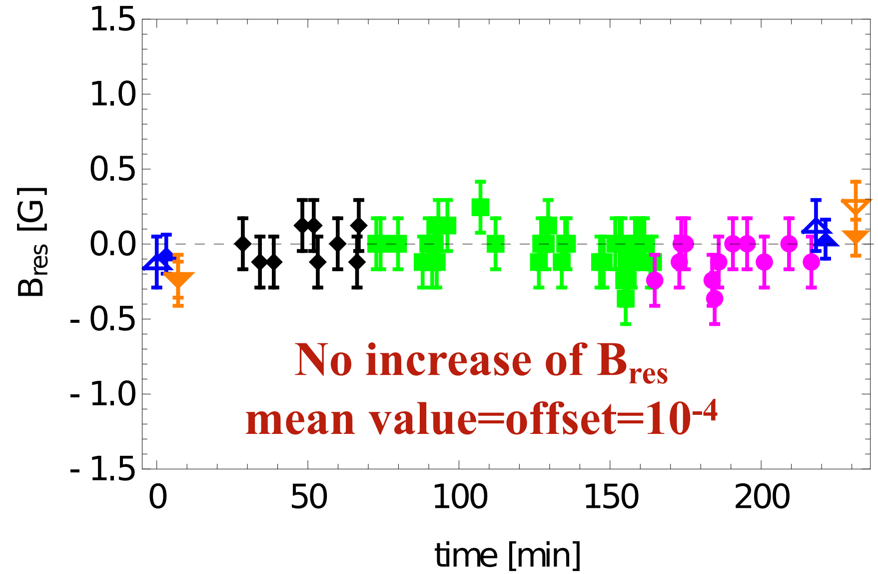
- ✧ Measurement of B_{ext} along the axis of the magnet
- ✧ During these measurements uncertainty on I_{ext} is within 0.1%
- ✧ Mean value I_{ext} = (9.88 ± 0.01) A, and B_{ext} at the center is (828 ± 1) 10-3 T

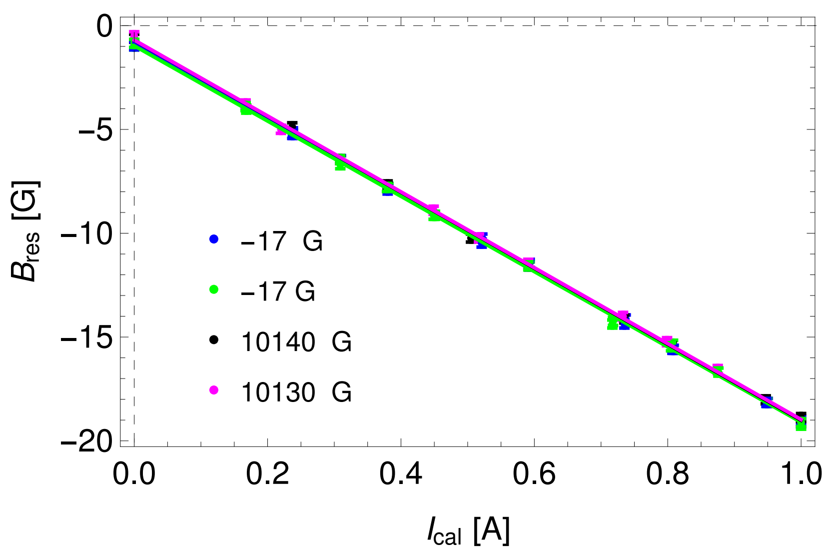
✧ **Quench (measured)= (24150 ± 90) G**

Measurement of the residual magnetic flux density (B_{res}) at 1 T

✧ Measurement of B_{res} at the center of the Bi-2212 tube [Setup-B]





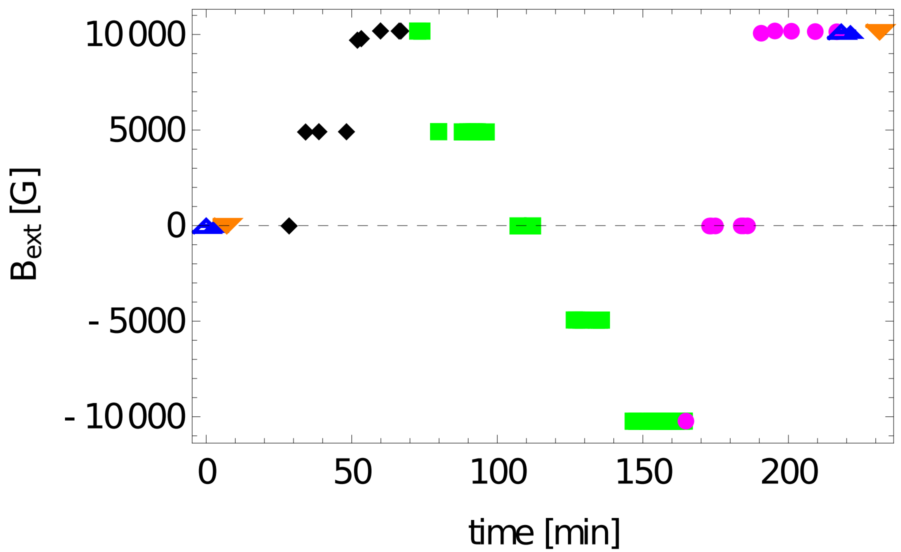


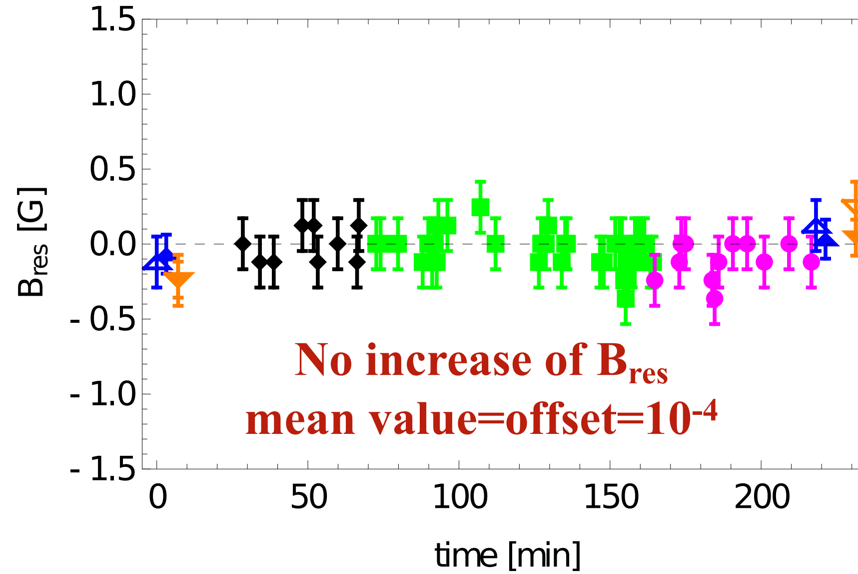
B_{ext} is 1) increased up to 1 T (black points);
2) decreased down to -1 T (green squares);
3) increased again up to 1 T (magenta points).

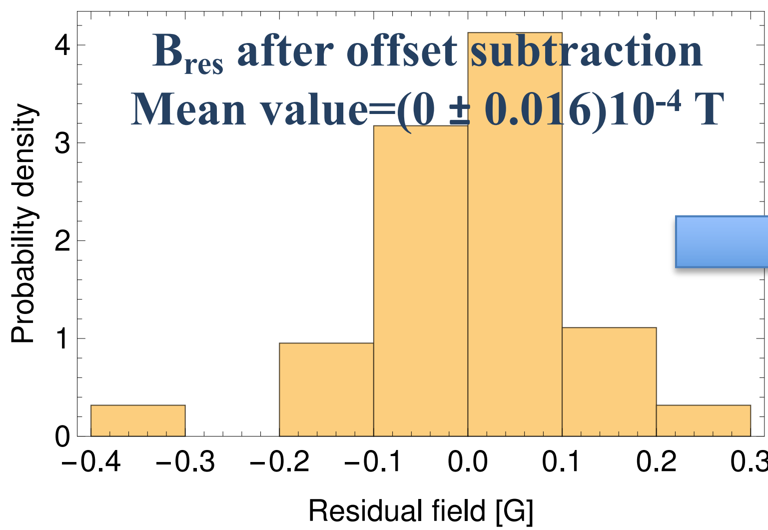
Data obtained from the the Zero-field magnet:
Blue triangles (inc. values), orange triangles (dec. values)

Measurement of the residual magnetic flux density (B_{res}) at 1 T

✧ Measurement of B_{res} at the center of the Bi-2212 tube [Setup-B]





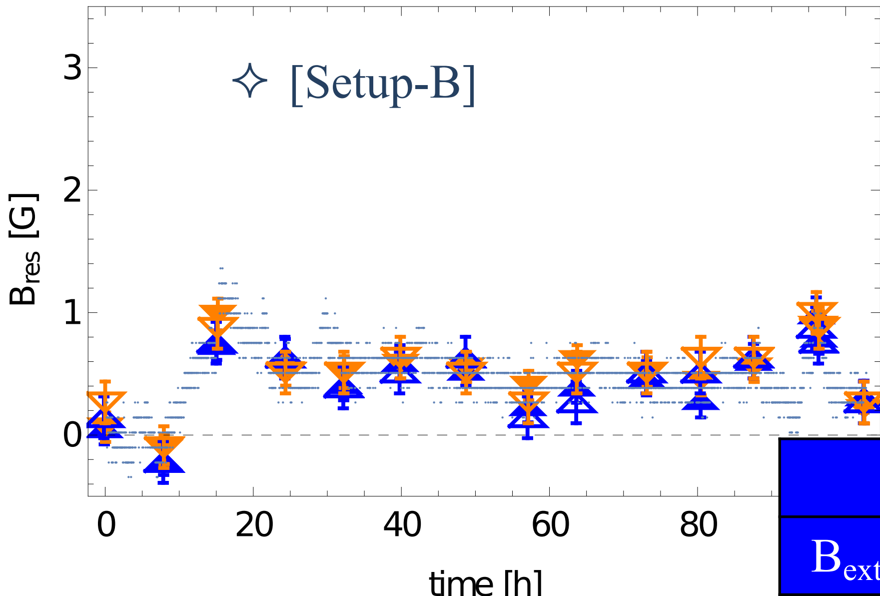


B_{ext} = (10140 ± 14)10^{-4} T

B_{res} = (0 ± 0.016)10^{-4} T

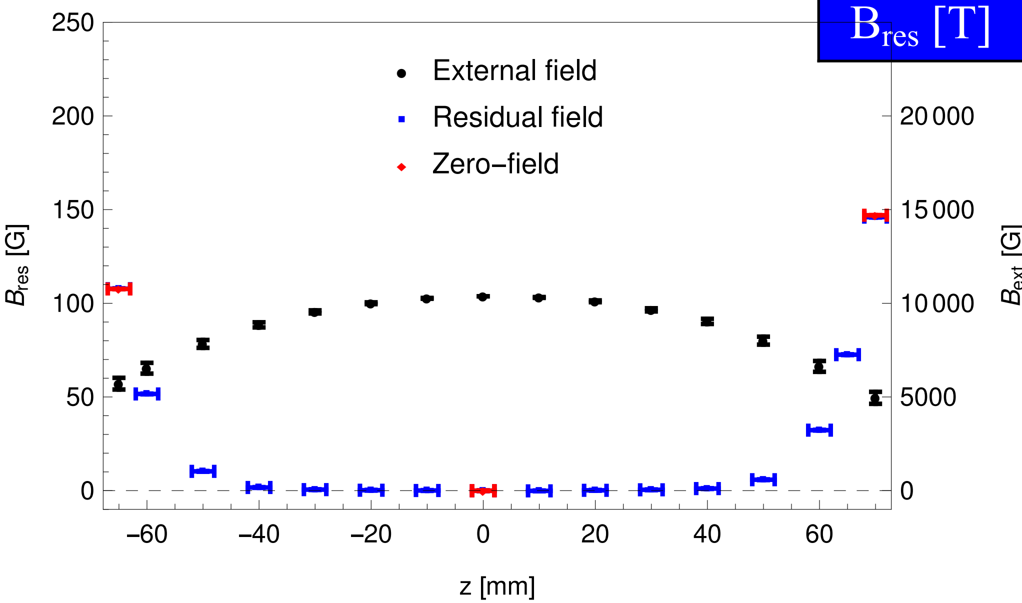
Shielding factor ($SF=B_{ext}/B_{res}$)= 3.2 10^5 at 95% confidence level

Stability and field-map measurements of B_{res} at 1 T



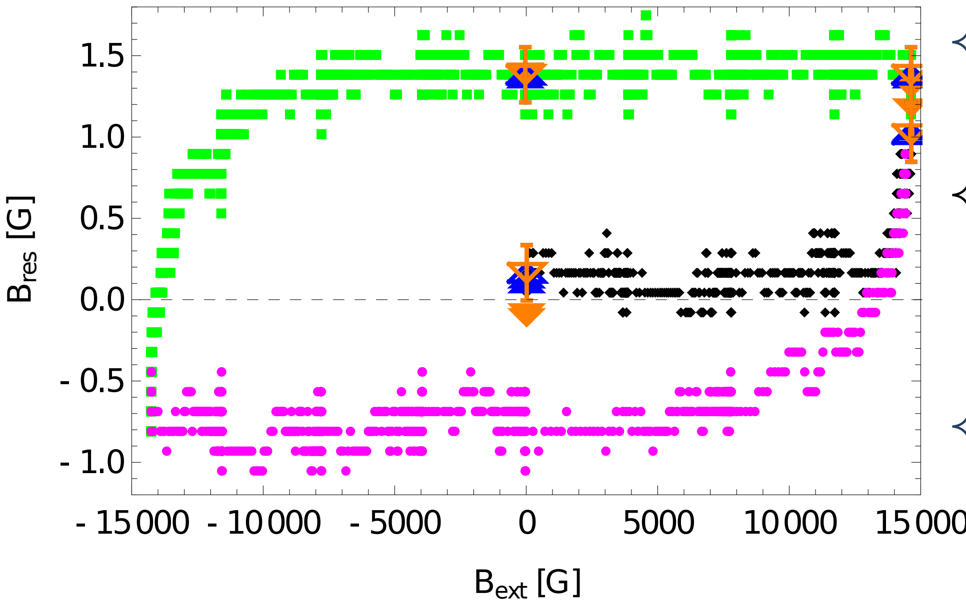
- ✧ 4 days of B_{res} measurement at B_{ext} =1 T (at the center of Bi-2212)
- ✧ An increase step of B_{res} is observed after 9 hours followed by a stable behavior
- ✧ B_{res} is stable (no penetration of B_{ext})

	0 to 10 h	20 h to 100 h
B_{ext} [T]	**$(10081 \pm 14)10^{-4}$**	**$(100 \pm 2)10^{-1}$**
B_{res} [T]	**$(0.000 \pm 0.008)10^{-4}$**	**$(0.499 \pm 0.003)10^{-4}$**



- ✧ A shielded length of 80 mm from 150 mm, where B_{res} is lower than 10^{-4} T, is observed

Measurement of B_{res} at 1.4 T



- ✧ Measurement of B_{res} at the center of the Bi-2212 tube [Setup-B]
- ✧ B_{ext} 1) increased up to 1.4 T; 2) decreased down to -1.4 T; 3) increased again up to 1.4 T.
- ✧ A slight increase of B_{res} observed above ~1.2 T

$$B_{res} = B_{res}^{max} - B_{res}^{0} = (1.22 \pm 0.06) \times 10^{-4} T;$$

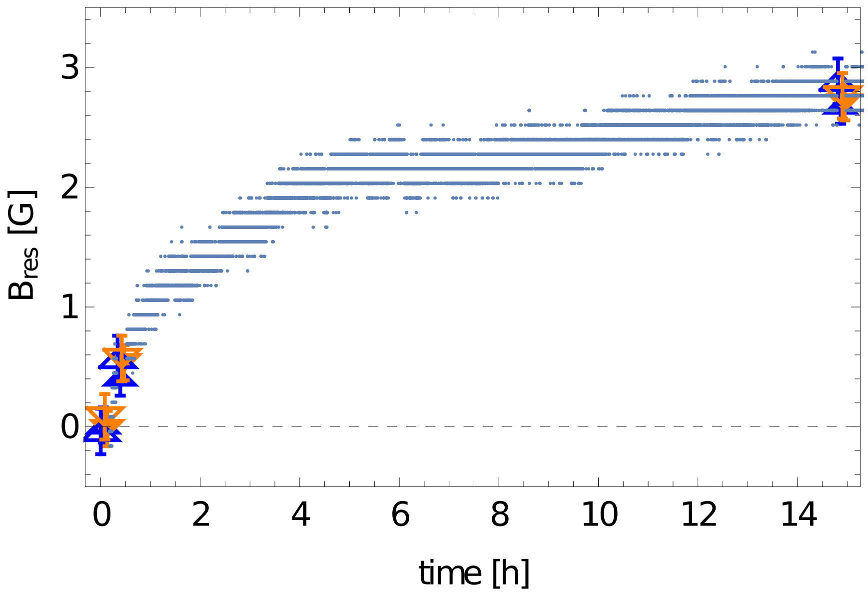
$$B_{res}^{max} @ B_{ext} = (14640 \pm 30) \times 10^{-4} T;$$

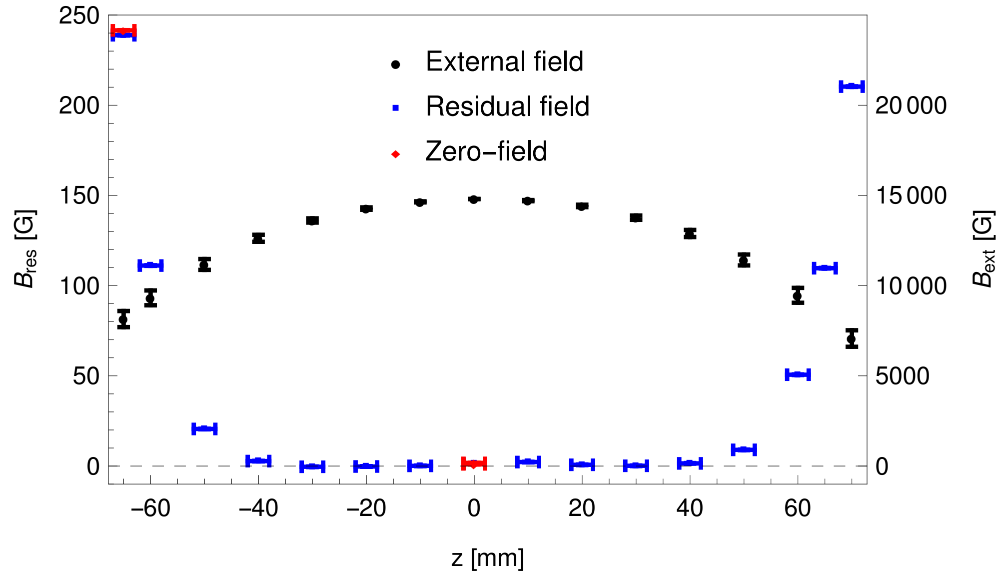
$$B_{res}^{0} @ B_{ext} = (17 \pm 2) \times 10^{-4} T;$$

$$SF @ 1.4T = B_{ext} / B_{res} = 122 \times 10^{2};$$

- ✧ The values of external, maximal and minimal residuals fields are determined from the fit to the Zero-field magnet data

Stability and field-map measurements of B_{res} at 1.4 T



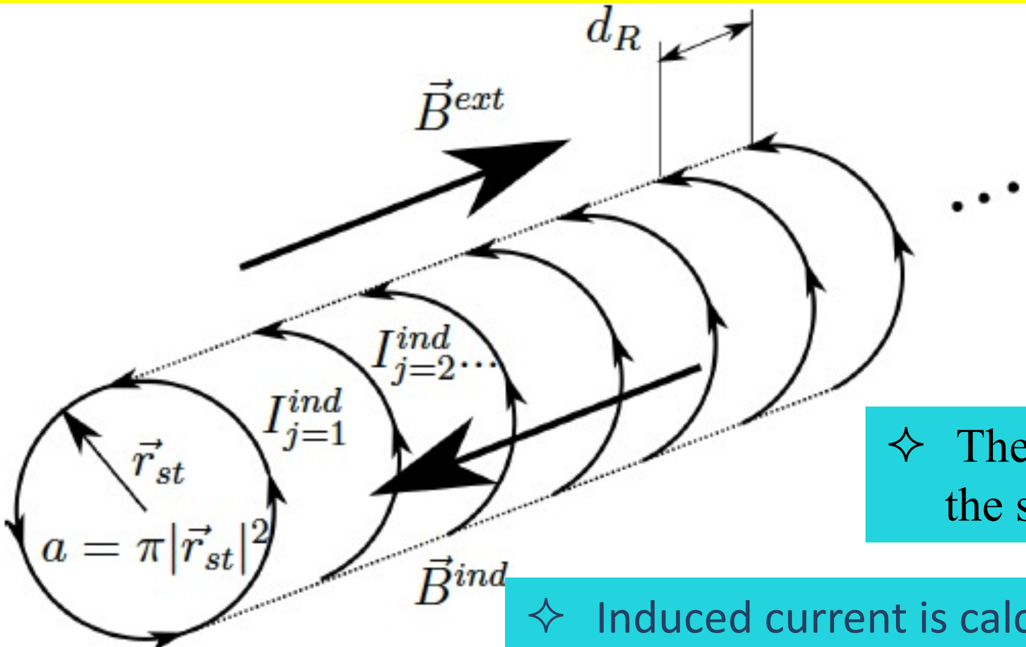


- ✧ 14 hours of B_{res} measurement at B_{ext} =1.4 T (at the center of Bi-2212)
  - ✧ B_{res} increased up to observed up to **(2.7± 0.15)10^{-1}**
- ✧ A shielded length of 80 mm from 150 mm, where B_{res} is lower than 2.10^{-4} T, is observed

Numerical simulations

✧ Design a prototype of geometrical characteristics that fits the PANDA spectrometer

✧ Optimize the shielding length as a function of the geometrical parameters of the tube



✧ The method is based on the discretization of the shielding tube into rings

✧ Induced current is calculated using the exact forms of the Maxwell equations in integral form and the Biot-Savart law

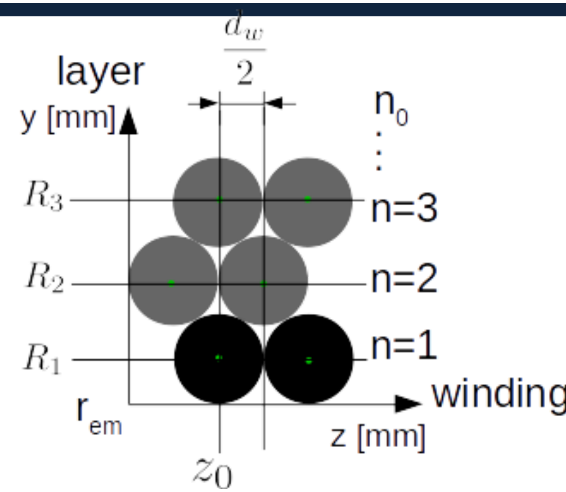
✧ The assumption of ideal circular conducting rings is used ($F_{ext}=F_{ind}$)

✧ The model can only be applied to magnetic fields equal or less than 1 T

Numerical simulations

External magnet
- Length, Radius
- Layers
- Windings
- Ext. current

Calculate external flux F_j^{ext}



$F^{ind} = -F^{ext}$

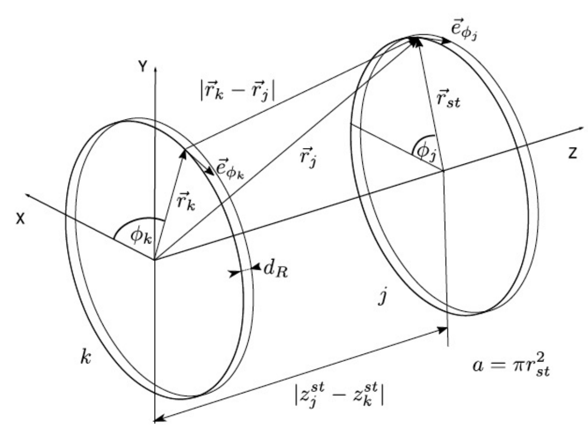
Solve
$M_{kj} I_k^{ind} = -F_j^{ext}$

Result
I^{ind}

Calculate B_{ind} via Biot-Savart
$B^{res} = B^{ext} + B^{ind}$

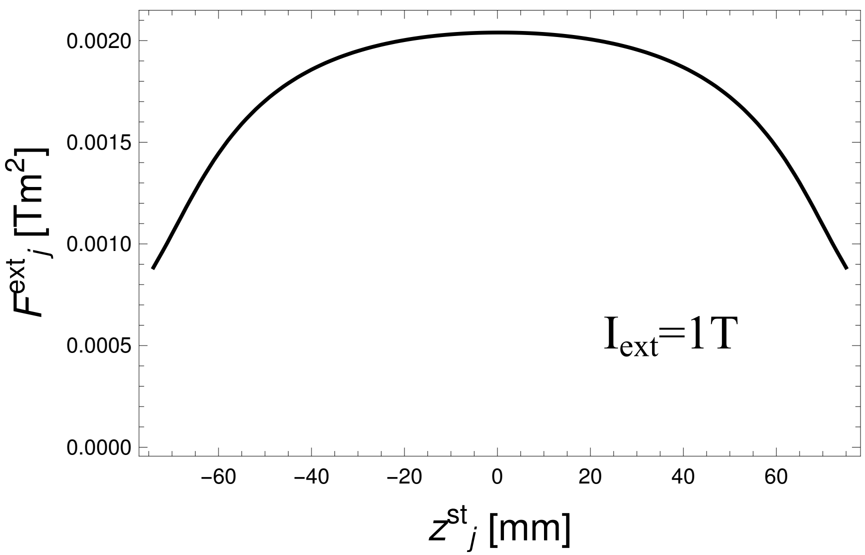
Shielding tube
- Length, Radius
- Rings

Calculate inductance matrix elements M_{ij}

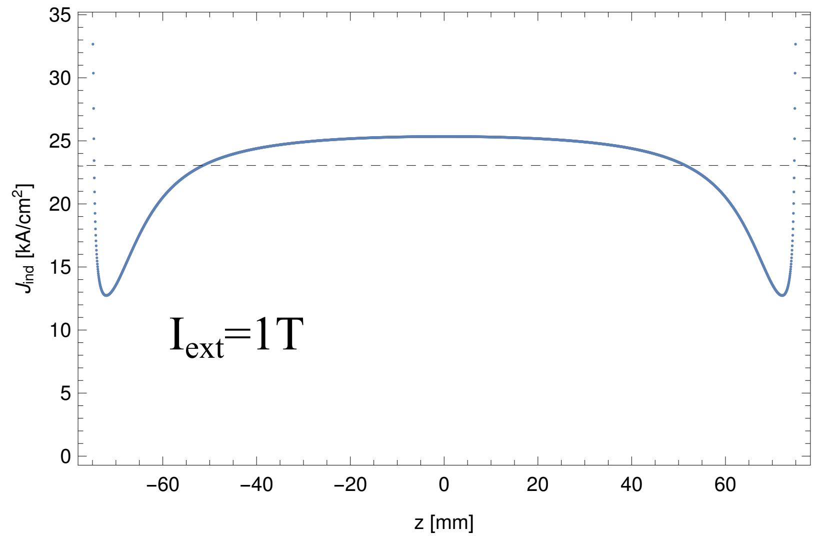


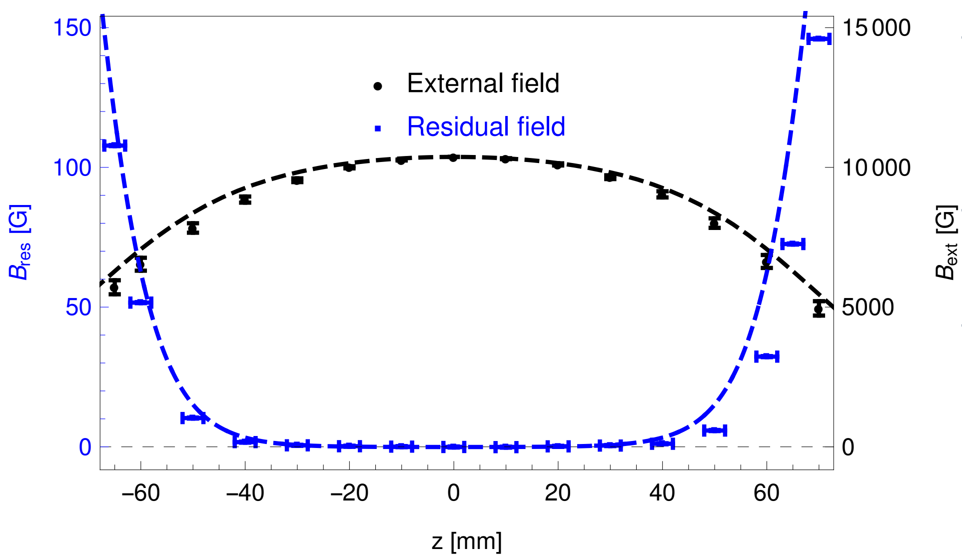
Numerical simulations and data

- ✧ Calculated magnetic flux of the external magnet in the shielding tube ring “j“



- ✧ Calculated magnetic flux of the external magnet in the shielding tube





- ✧ Comparison of B_{ext} and B_{res} values between the data and the numerical simulations (1T)
- ✧ Data and simulations are consistent
- ✧ A small deviation is observed due to the manual positioning of the sliding rod and the Hall-probe

Experimental Setup Data Acquisition System

External field	1 T	1.4 T
Shielding factor	32×10^4 (95%$C.L.$)	$(12 \pm 1) \times 10^3$
Induced current density J_{ind} [A/cm^2]	$(23 \pm 2) \times 10^3$	$(33 \pm 3) \times 10^3$
Shielded length [mm] (tube length 150 mm)	80 ± 2	80 ± 2
Residual field after 9 h at 1 T and 14 h at 1.4 T	$(0.0 \pm 2.4) \times 10^{-7}$ T	$(2.70 \pm 0.15) \times 10^{-4}$ T
Residual field in the range of 20 to 80 h	$(0.499 \pm 0.003) \times 10^{-4}$ T	

[arXiv:2205.00727 [physics.ins-det]]

- The shielding performance of a large melt cast Bi-2212 tube in axial magnetic fields is tested at a temperature of 4.2 K
- A dedicated apparatus built and a data acquisition system is developed for the measurements
- A magnetic flux density at the center of the tube of 1.014 T can be completely shielded
- A large volume within the Bi-2212 tube, 80 mm from 150 mm length can be homogeneously shielded.
- High attenuation of the longitudinal magnetic field at 1.4 T is observed
- The results show a high shielding performance of the Bi-2212 tube up to 1.4 T