Marco Calvi :: ID group :: Paul Scherrer Institut

Superconducting Undulator Design

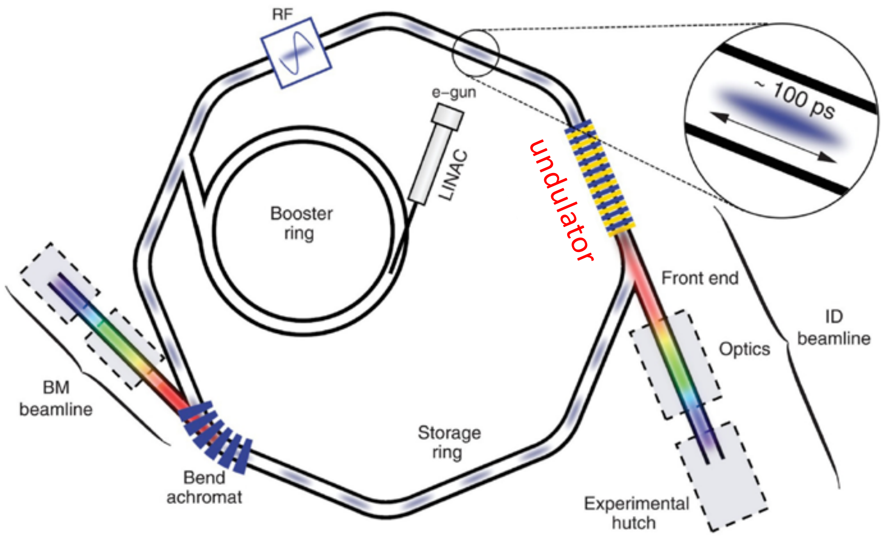
Porthos Working Group
PSI, 27 Oct 2020

PAUL SCHERRER INSTITUT

Overview

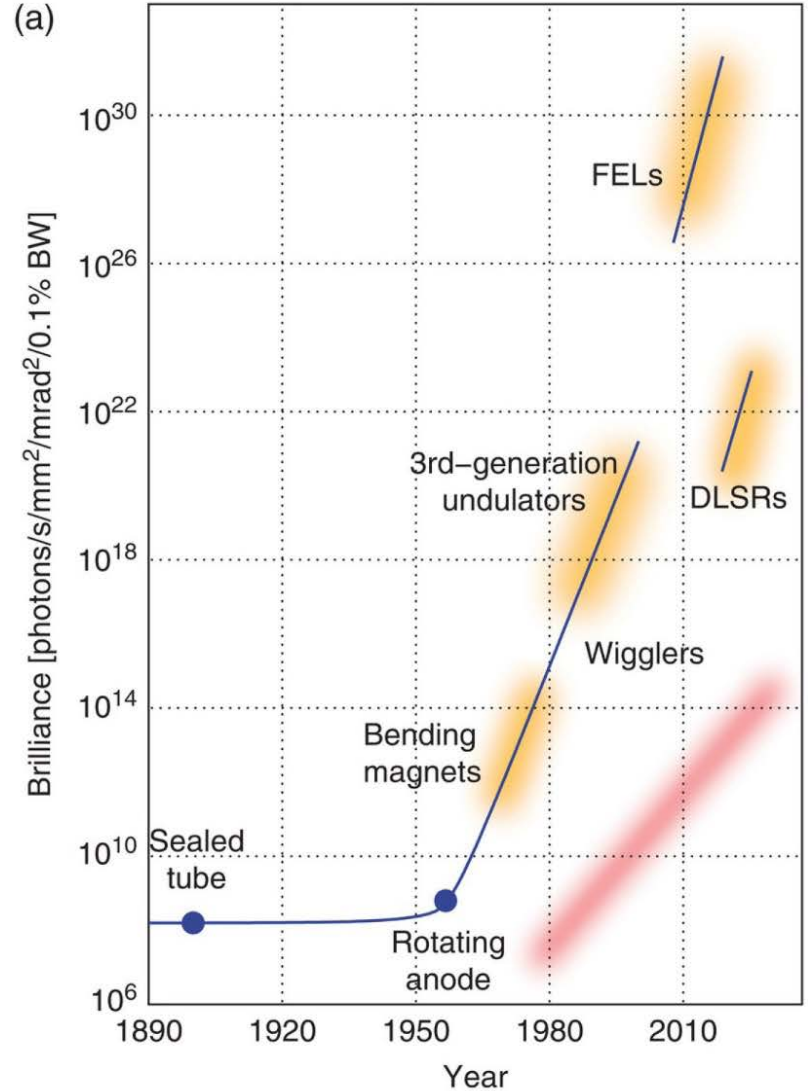
- Synchrotrons & FELs
- The (HTS) Staggered Array Undulator
- An example of application:
  - μ-tomography beamline
- Research activities already done :
  - Simulation of the HTS magnetisation process
  - First TEST campaign (Aug 2019)
  - Second campaign (Oct 2020)
- Next actions
- Conclusions

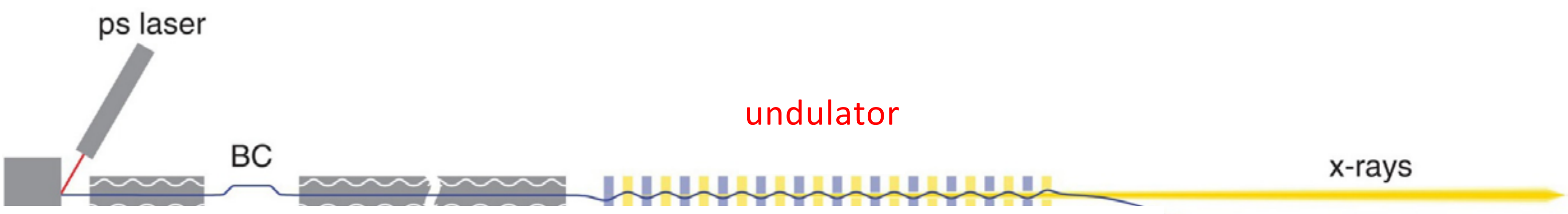
Synchrotrons & FELs



$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{1}{2}K^2\right)$$

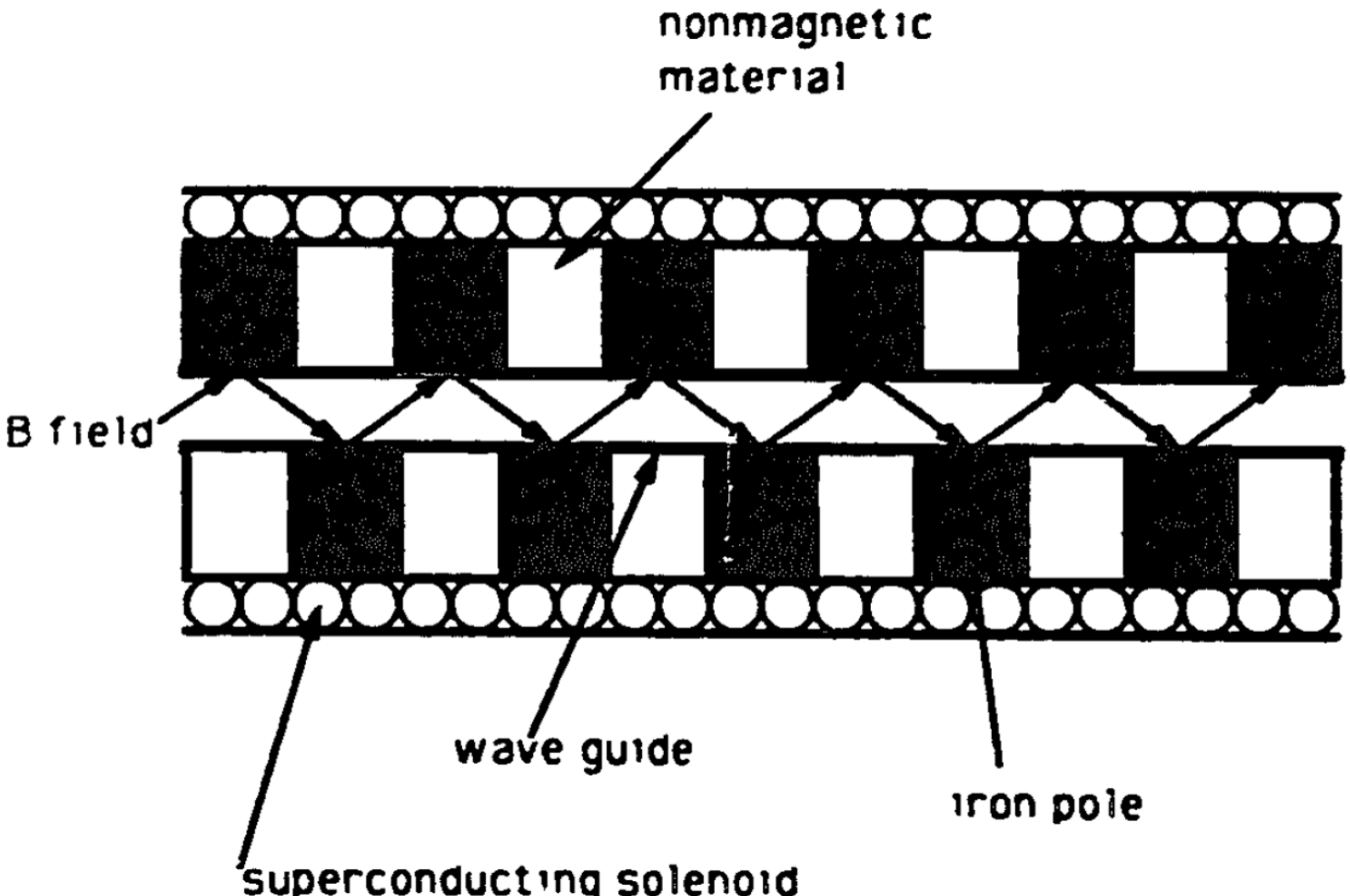
$$K = \frac{B_0 e}{mc}\frac{\lambda_u}{2\pi}$$





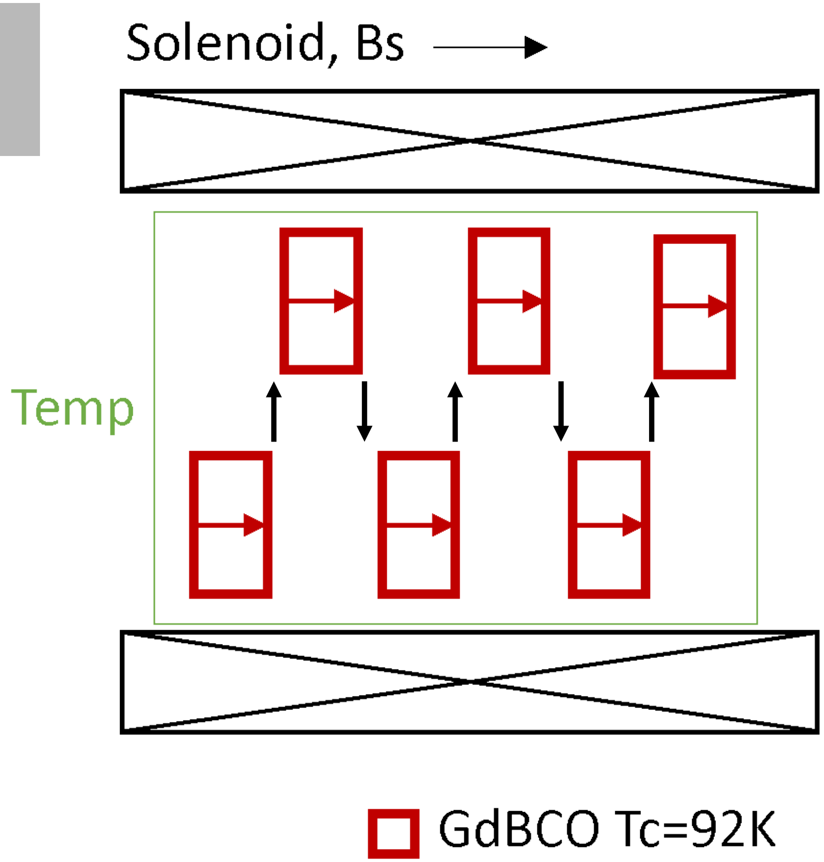
The Staggered Array Undulator

- *Y. C. Huang, et al., “COMPACT FAR-IR FEL. DESIGN”, NIMA318 (1992):*

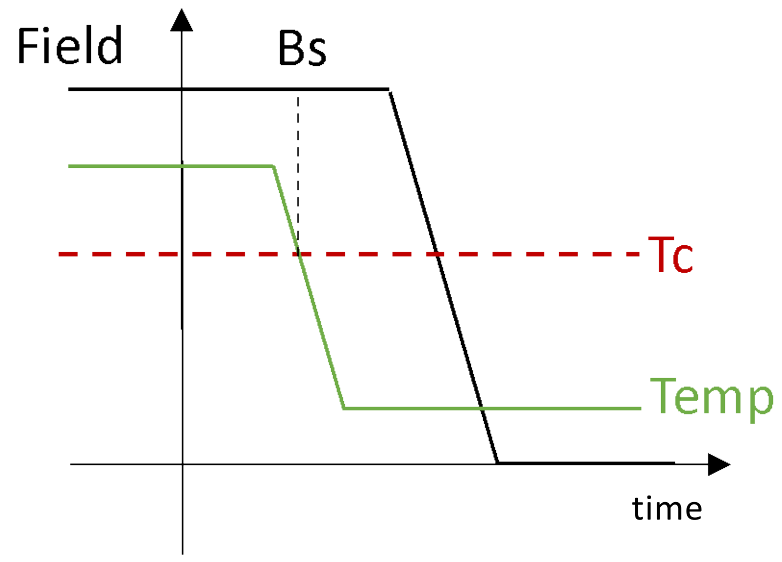


[source: Y. C. Huang et. al.]

Superconducting Staggered Array Undulator

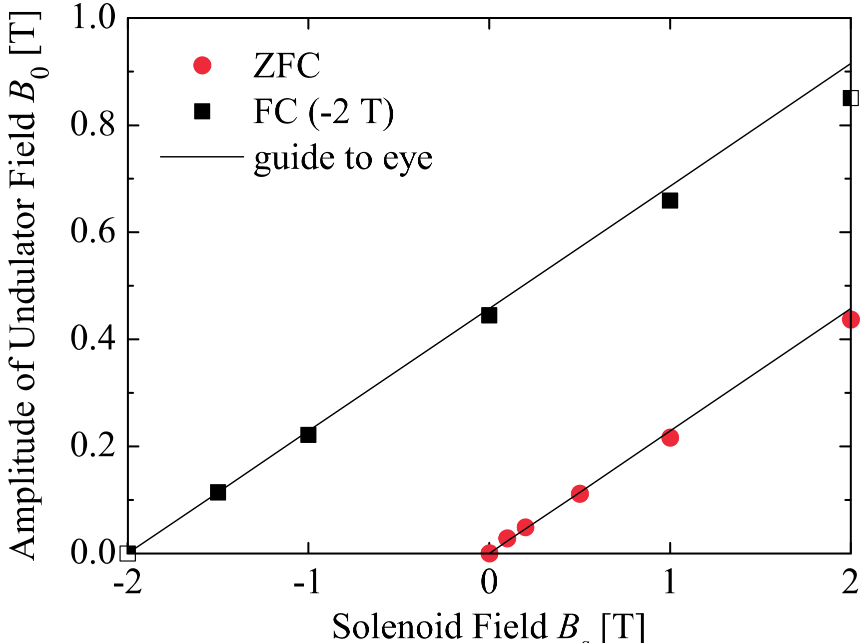


Exampe of *field cooling*

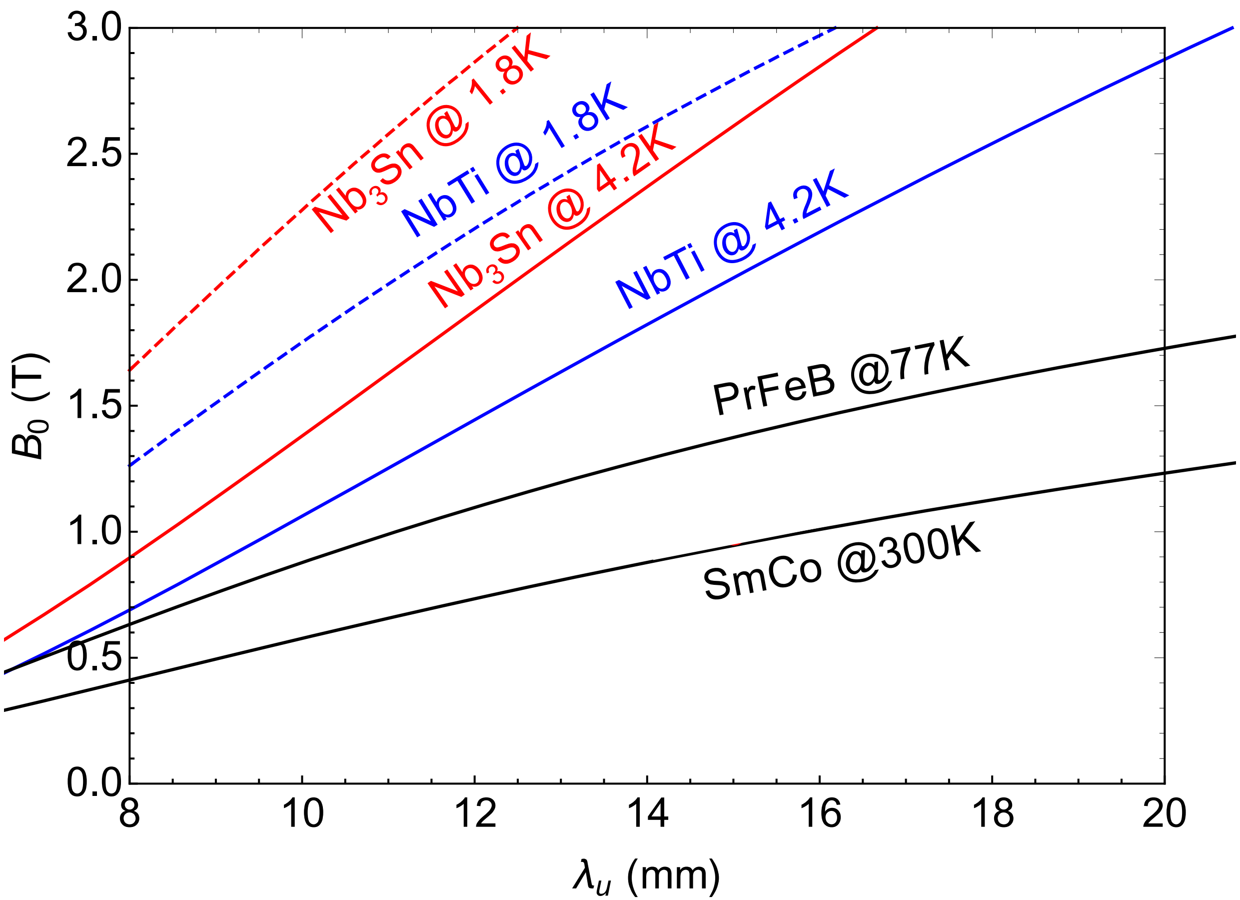


Superconducting Staggered Array Undulator

R.Kinjo et al. Appl.Phys. Express 6 (2013)



Comparison among different technologies

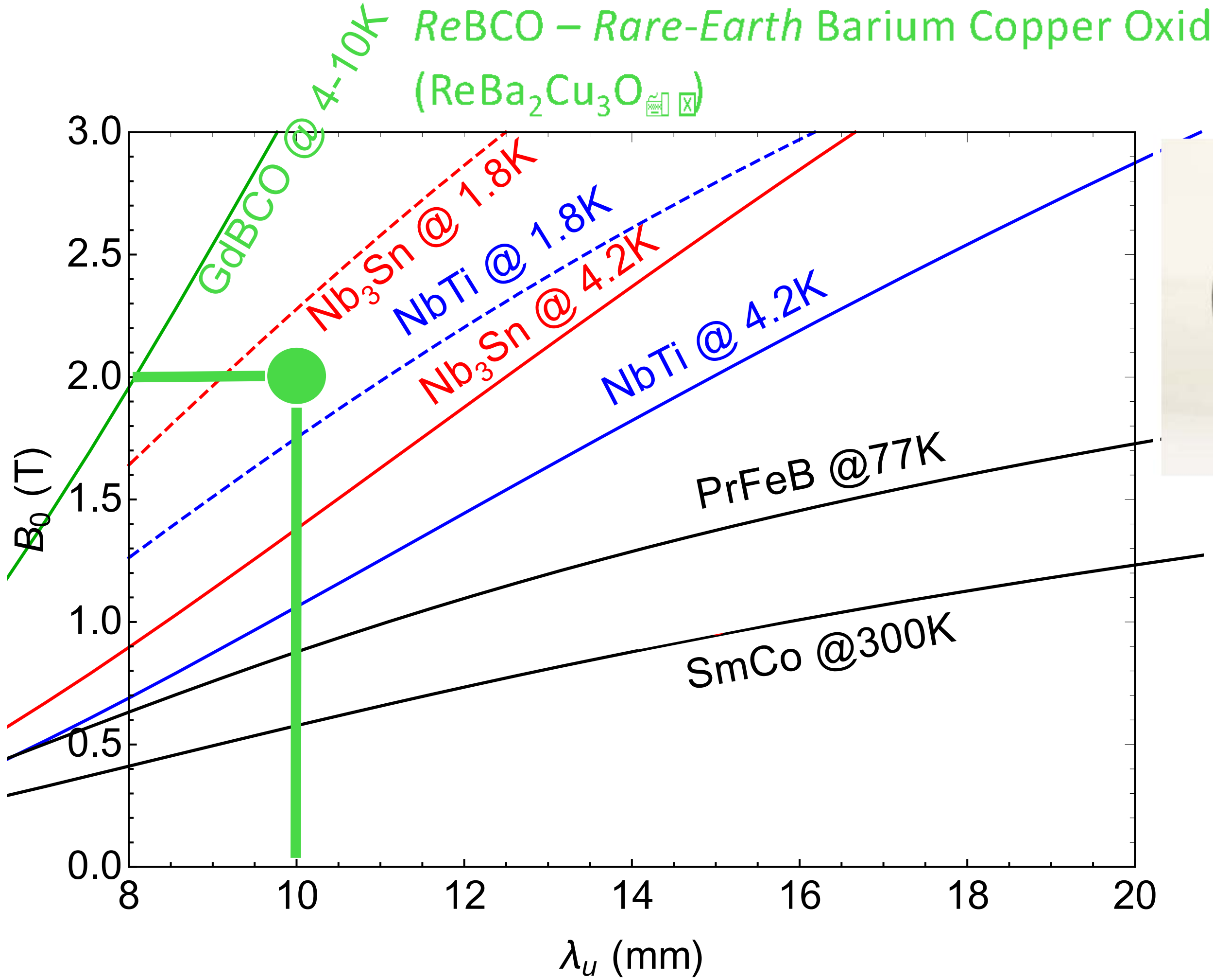


[Scaling laws: E.R. Moog, R.J. Dejus, and S. Sasaki , Light Source Note: ANL/APS/LS-348
James Clarke, FLS 2012, March 2012, Ryota Kinjo Physical Review Special Topics, Accelerator and Beams 17, 022401 (2014)]

Comparison among different technologies

ReBCO – Rare-Earth Barium Copper Oxide

($ReBa_2Cu_3O_{[illegible]}$)



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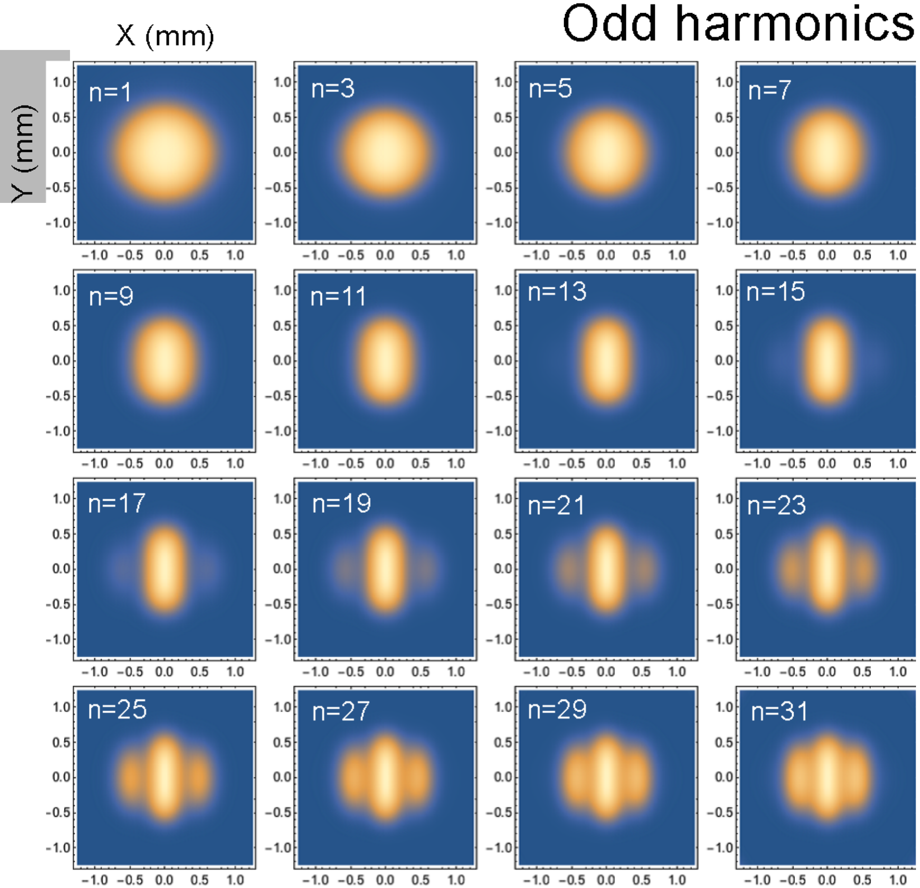
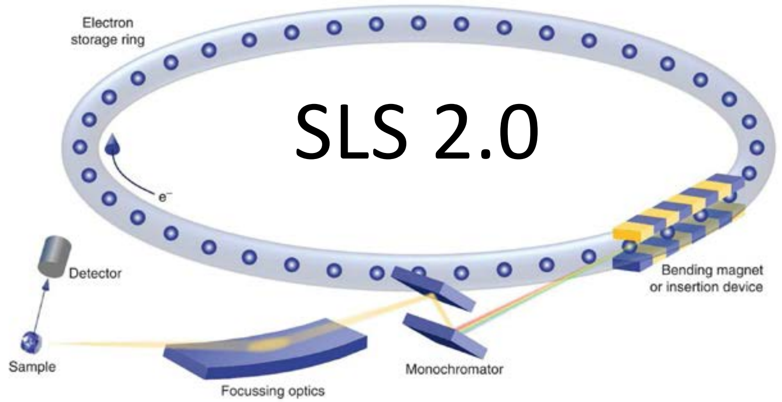
James Clarke, FLS 2012, March 2012, Ryota Kinjo Physical Review Special Topics, Accelerator and Beams 17, 022401 (2014)]

HTSU10 with B_0=2.0 T

Odd harmonics

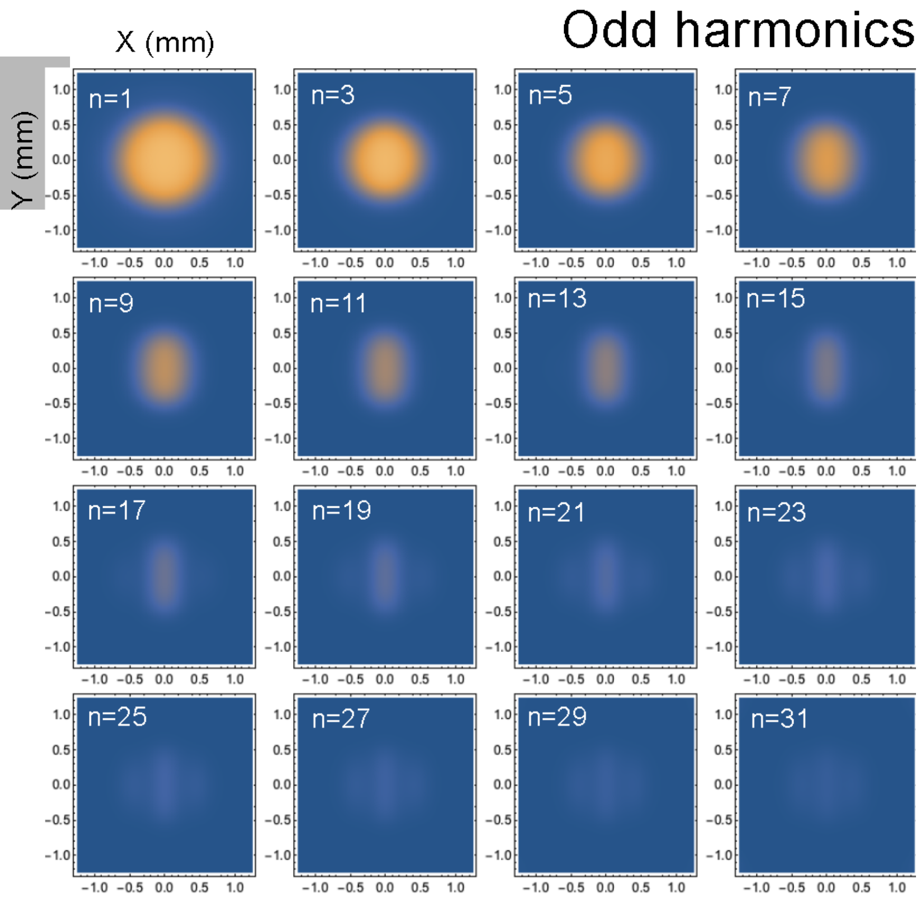




Calculations done for the future iTOMCAT beamline, dedicated to micro-tomography

Flux at 30m from the source
to illuminate a sample of about 1mm^2

CPMU14 with B_0=1.3 T – ABSOLUTE SCALE



Flux at 30m from the source
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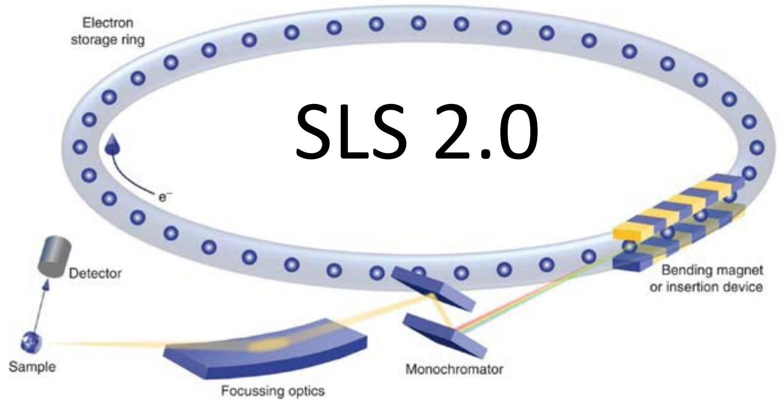

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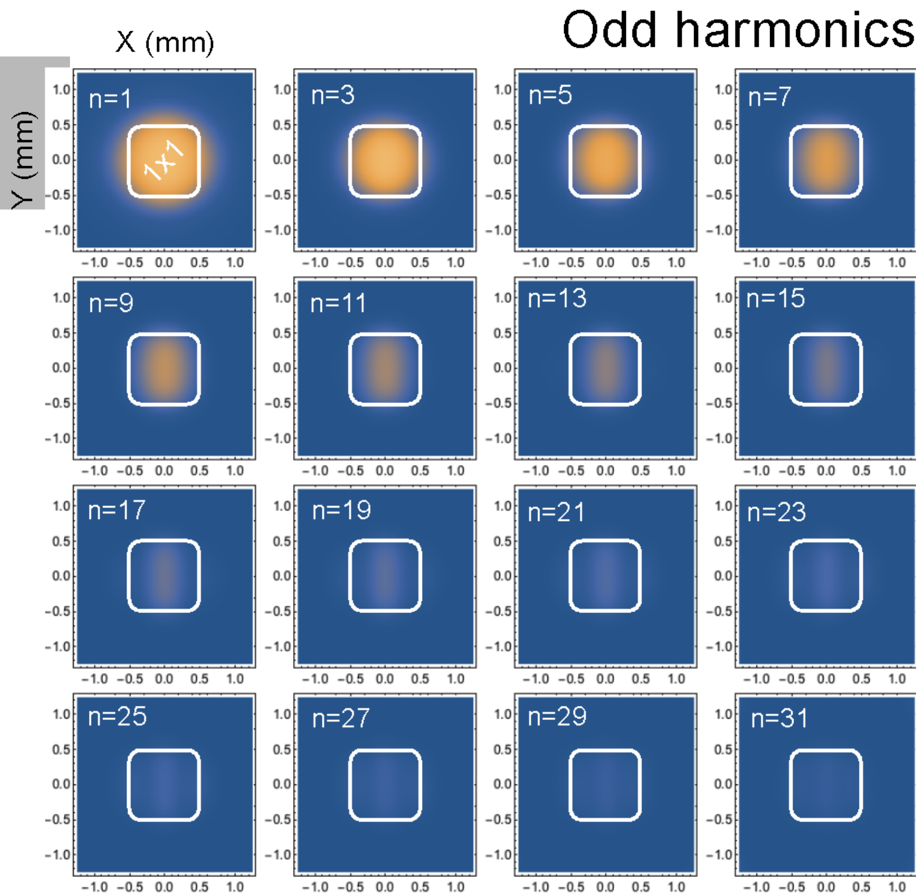

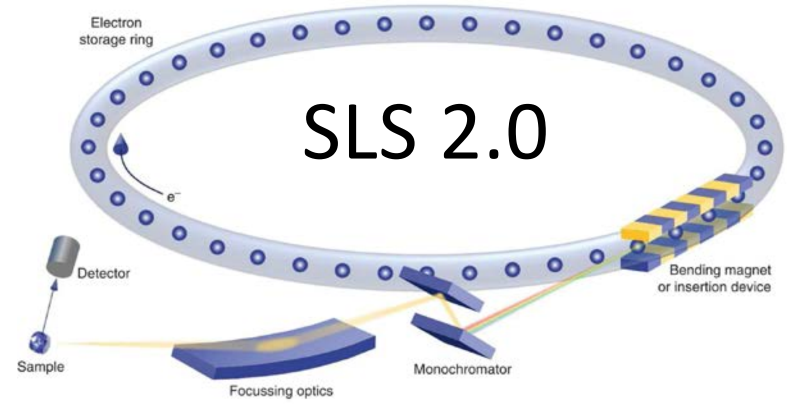

Flux at 30m from the source
to illuminate a sample of about 1mm^2

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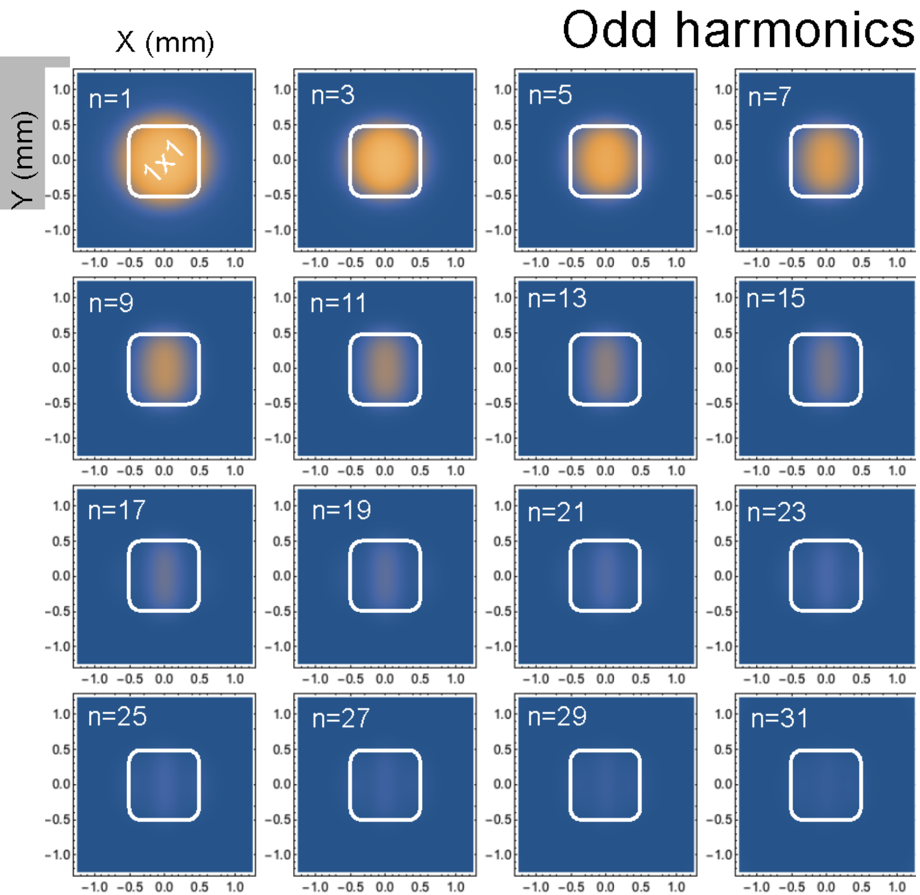

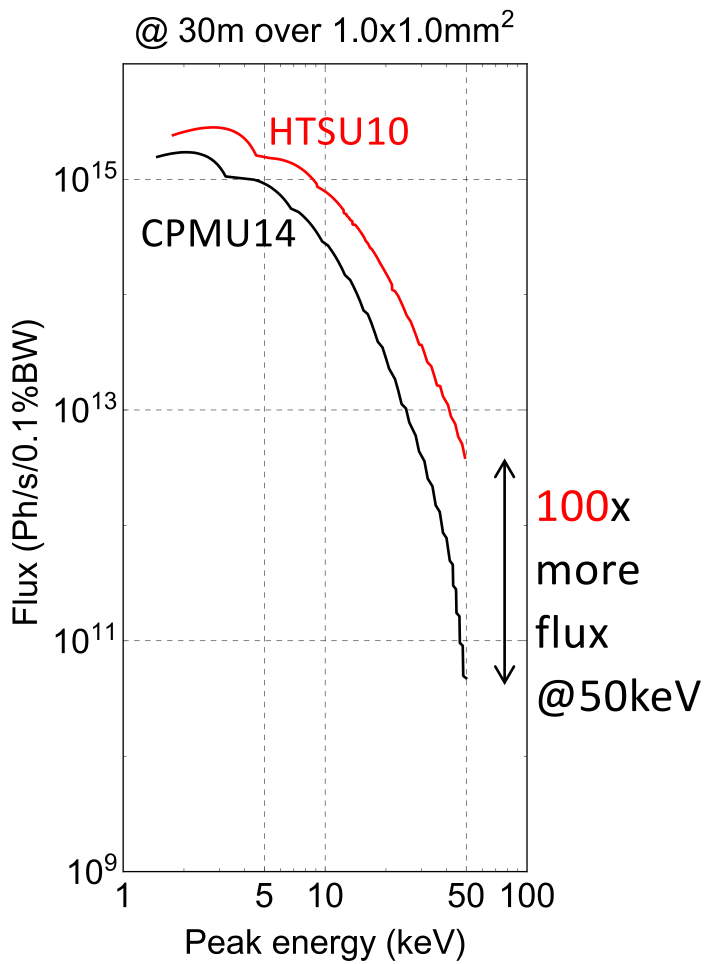

Flux at 30m from the source
to illuminate a sample of about 1mm²

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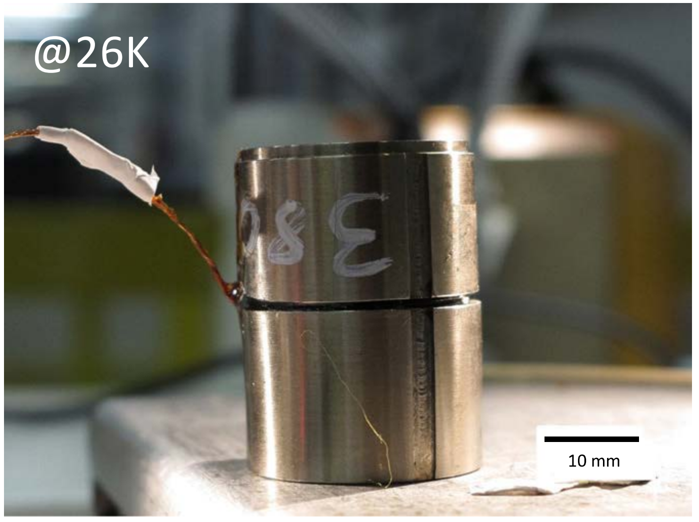
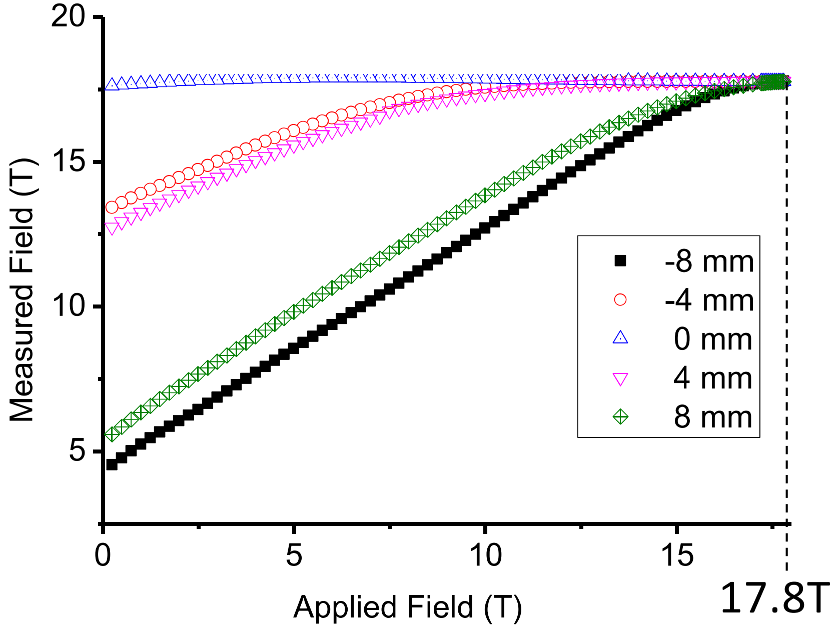
Example of Field Cooling (FC)

The Magnetisation record

J.Durrel et al. Supercond. Sci. Technol. 27 (2014) 082001



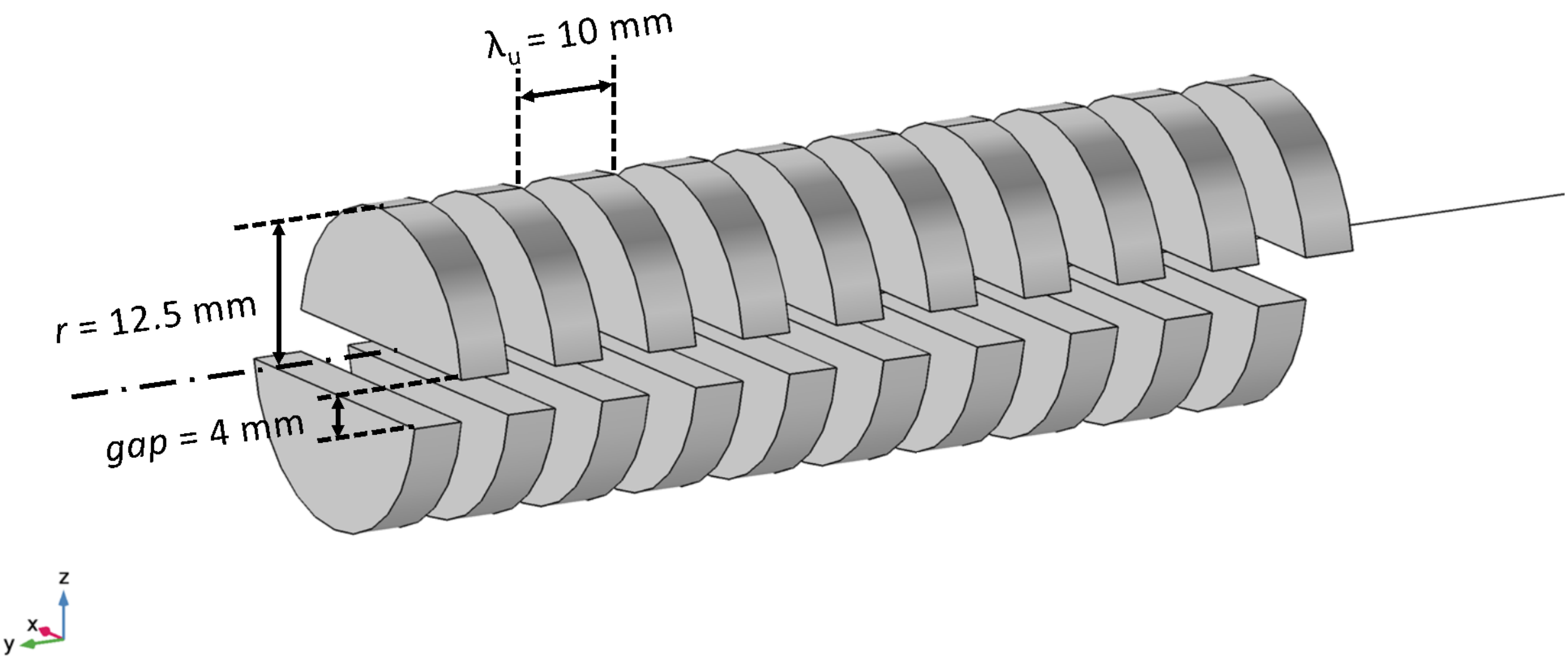
The assembled stack of two GdBCO bulk samples, each 24.15 mm in diameter and 15 mm high. The samples were reinforced with a 3 mm thick ring fabricated from 304 Stainless Steel.



The Trick

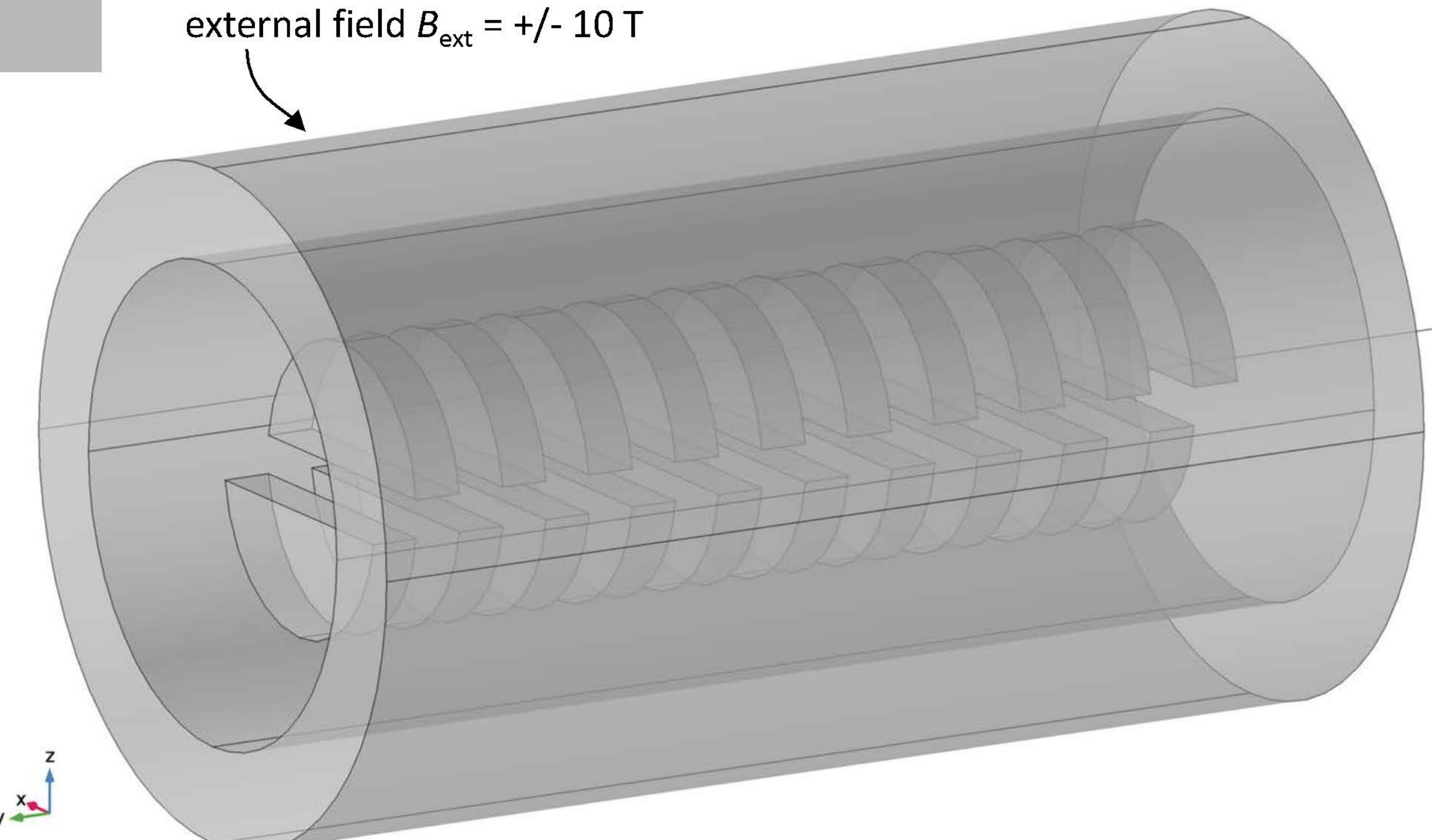
The rings were heated to >300 °C to enable them to fit onto the superconductor. This configuration was calculated to provide a pre-stress of ∼250 MPa, which is a significant improvement on the stress achieved from simple steel banding.

Superconducting Staggered Array



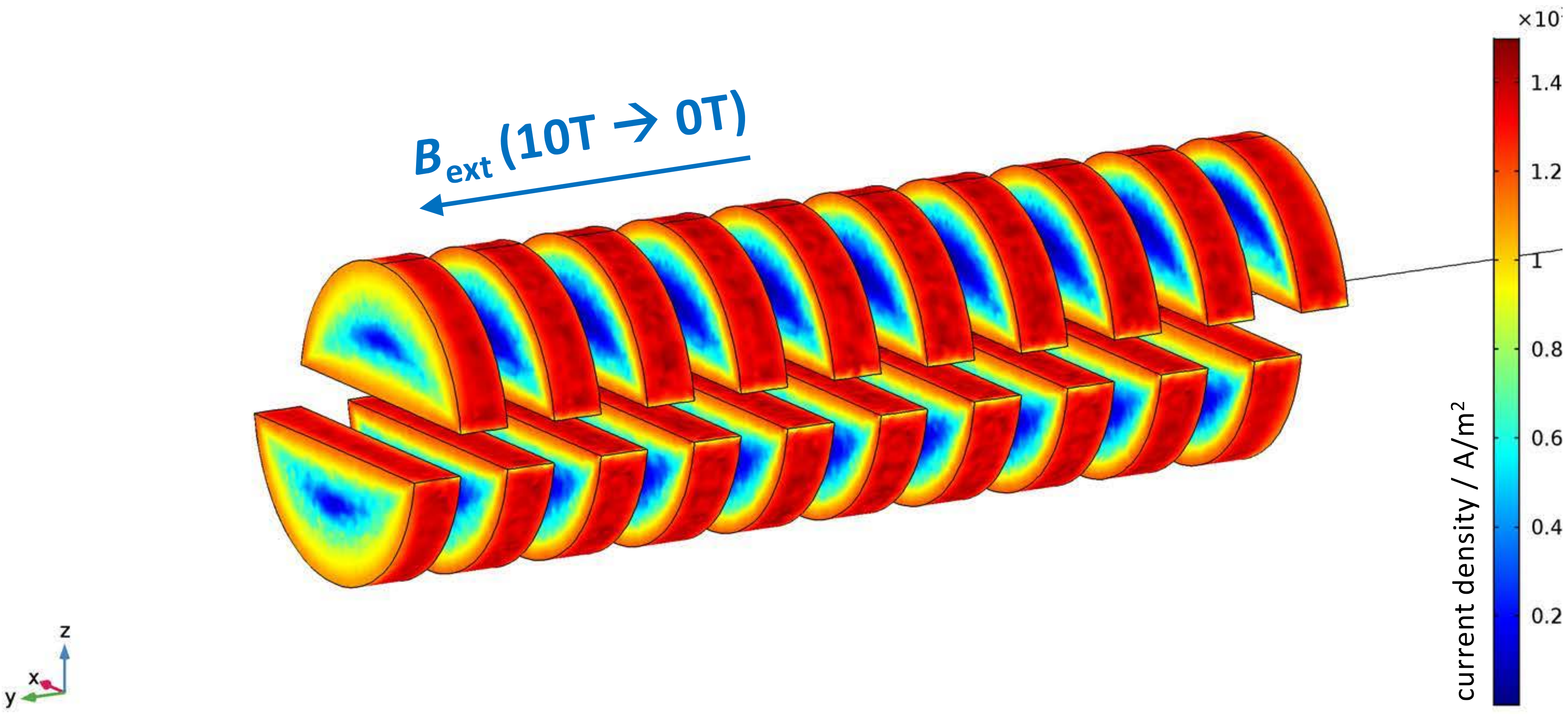
Superconducting Staggered Array

- Superconducting solenoid providing external field B_{ext} = +/- 10 T



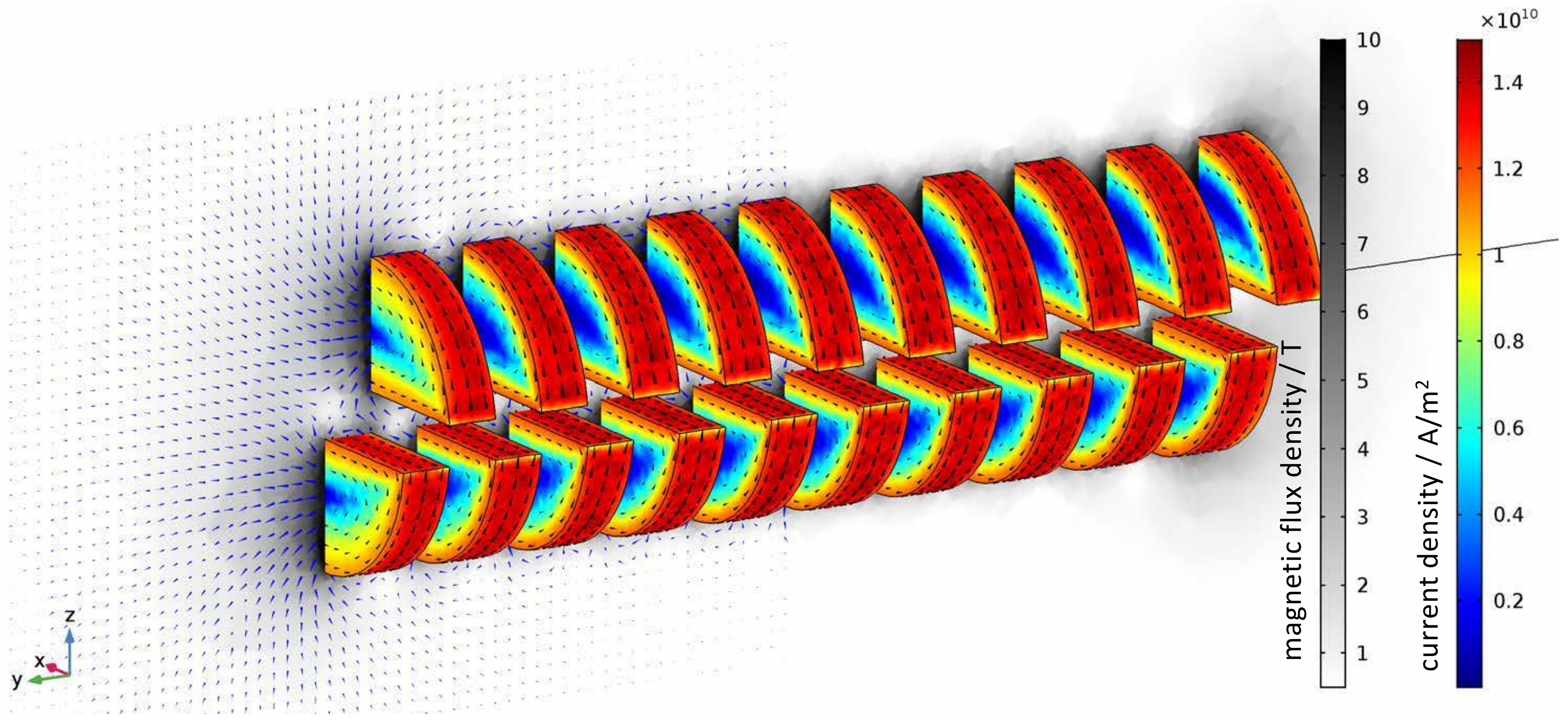
Superconducting Staggered Array

- Surface current density after magnetization with field 10T → 0T:



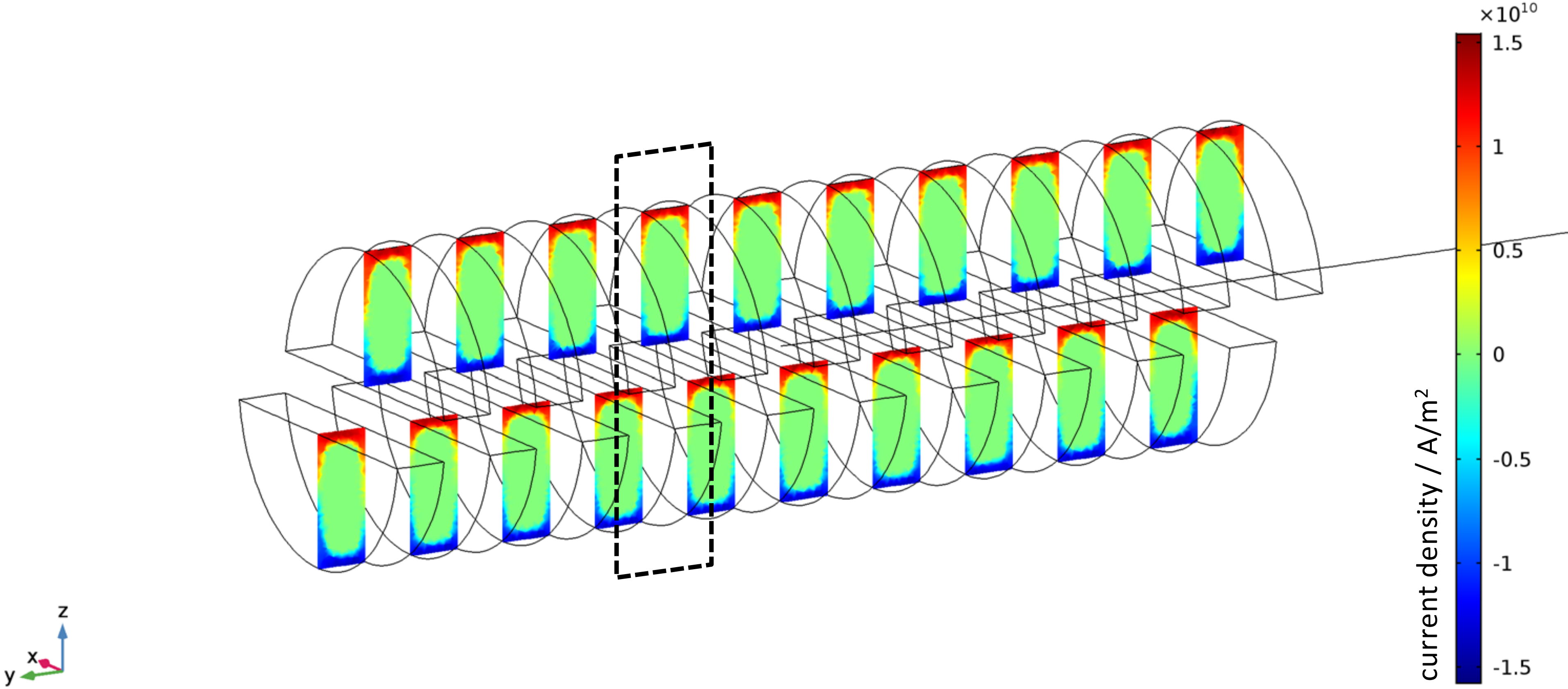
Superconducting Staggered Array

- Surface current density and trapped magnetic field after magnetization with field 10T → 0T:

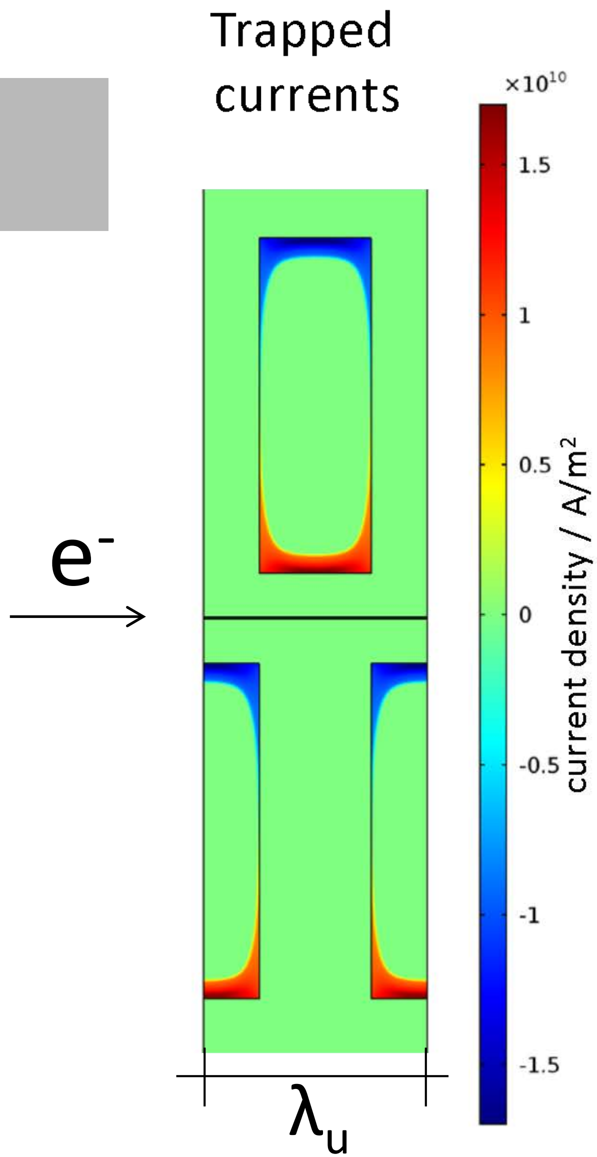


Superconducting Staggered Array

- Internal current density after magnetization with field 10T → 0T:



Superconducting Staggered Array



Example of operation: K tuning

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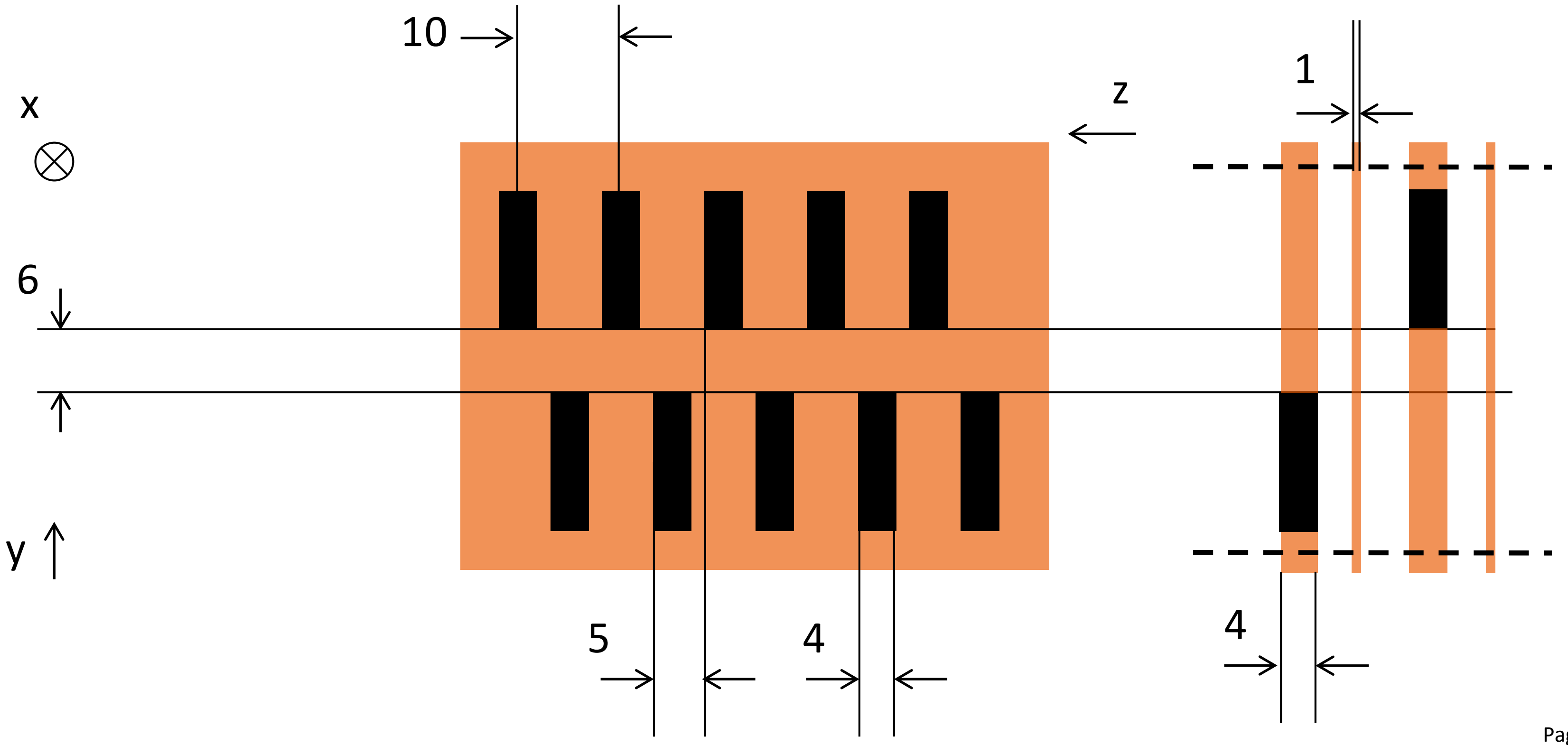
Our First sample

- 5 periods
- period length 10.0 mm
- gap 6.0 mm
- bulk diameter 30.0 mm
- NO end field shaping



The sample with its instrumentation

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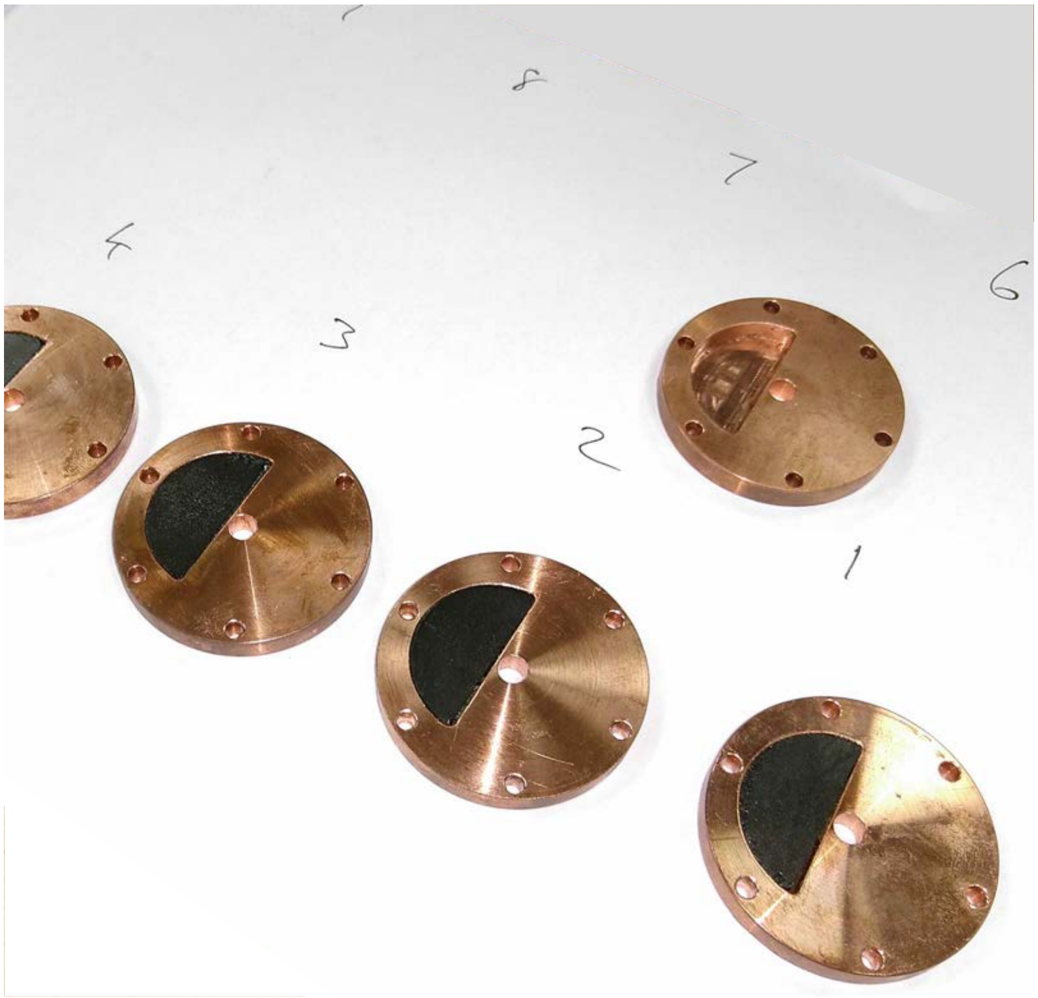
The sample with its instrumentation



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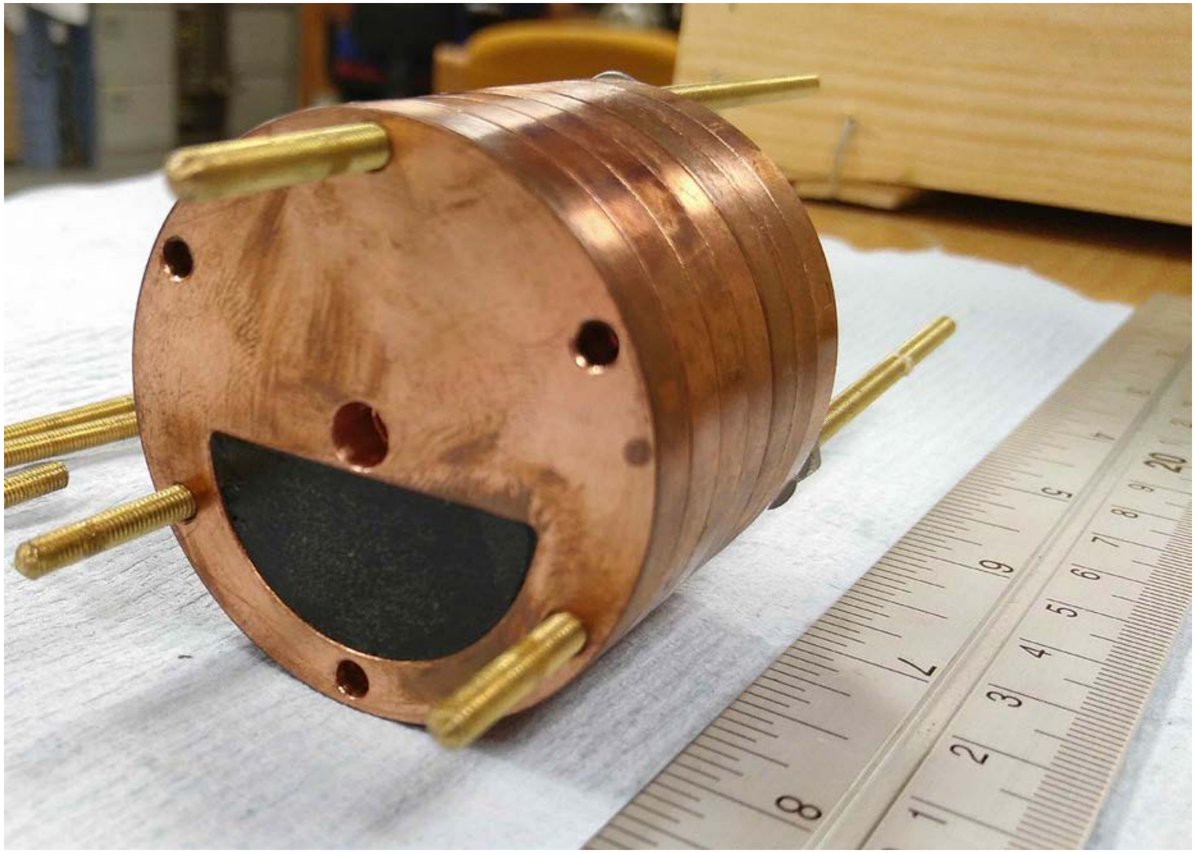

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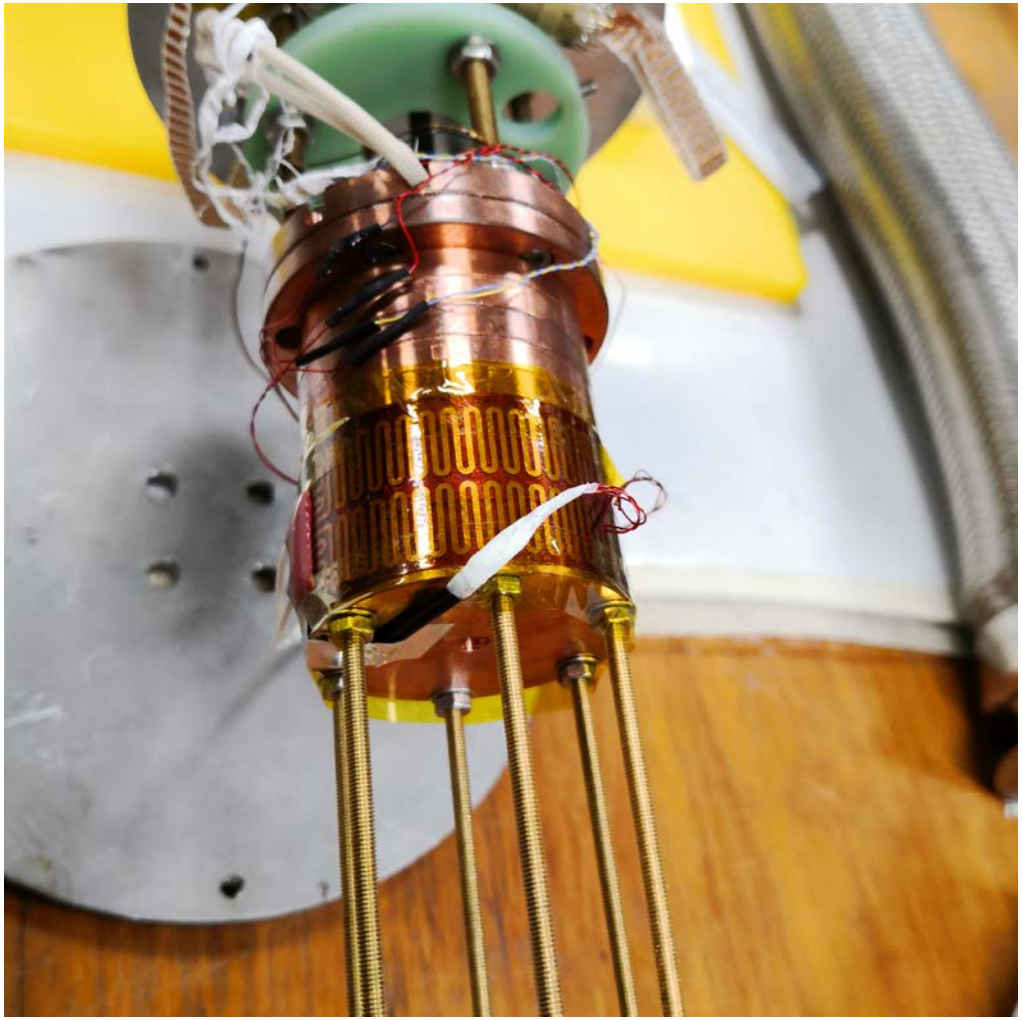
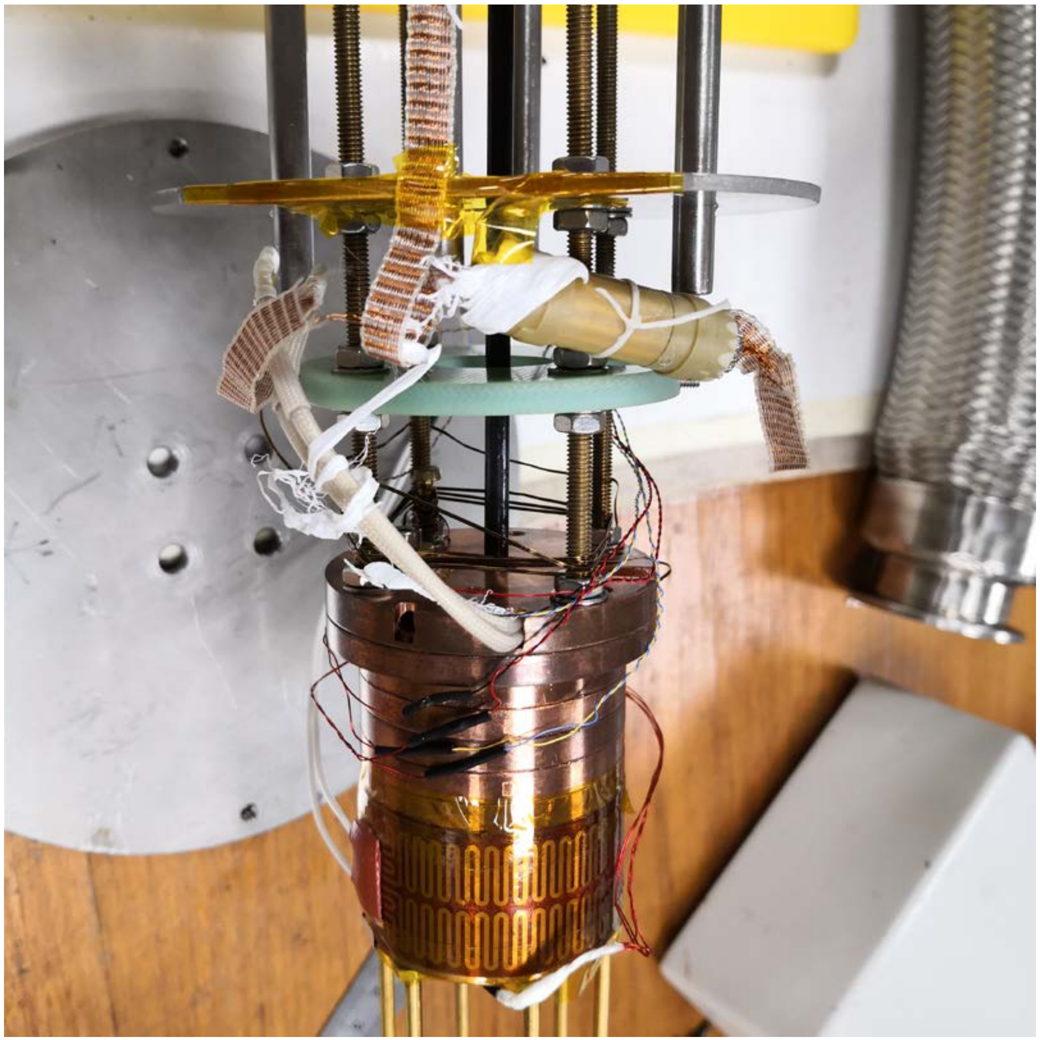
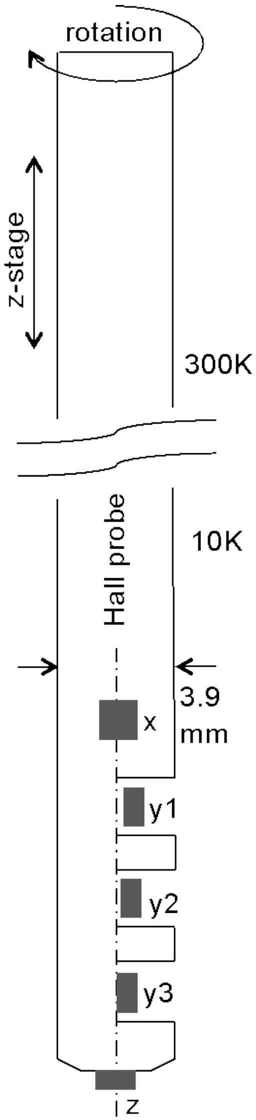


The sample with its instrumentation





Calibration up to 1.0T

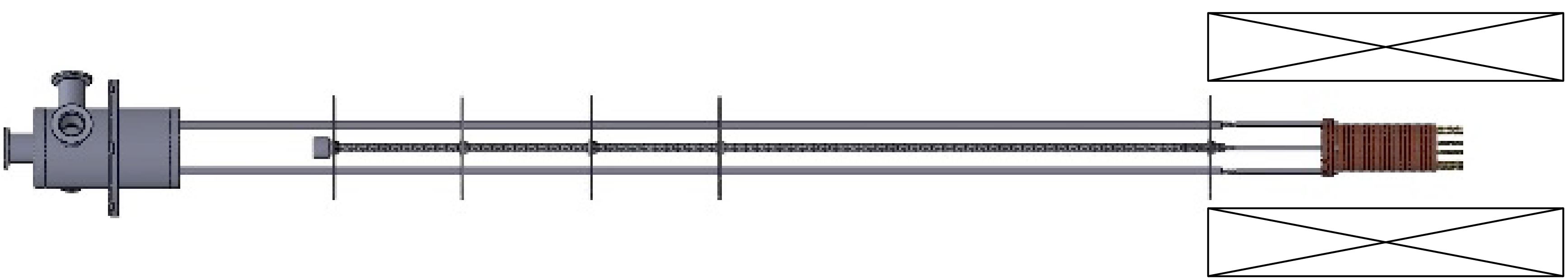
Temperature	TFx	TFy1	TFy2	TFy3	TFz
K	T/V	T/V	T/V	T/V	T/V
40.0	48.6	-	48.2	47.1	-
10.0	49.4	-	49.0	47.8	-

The sample with its instrumentation

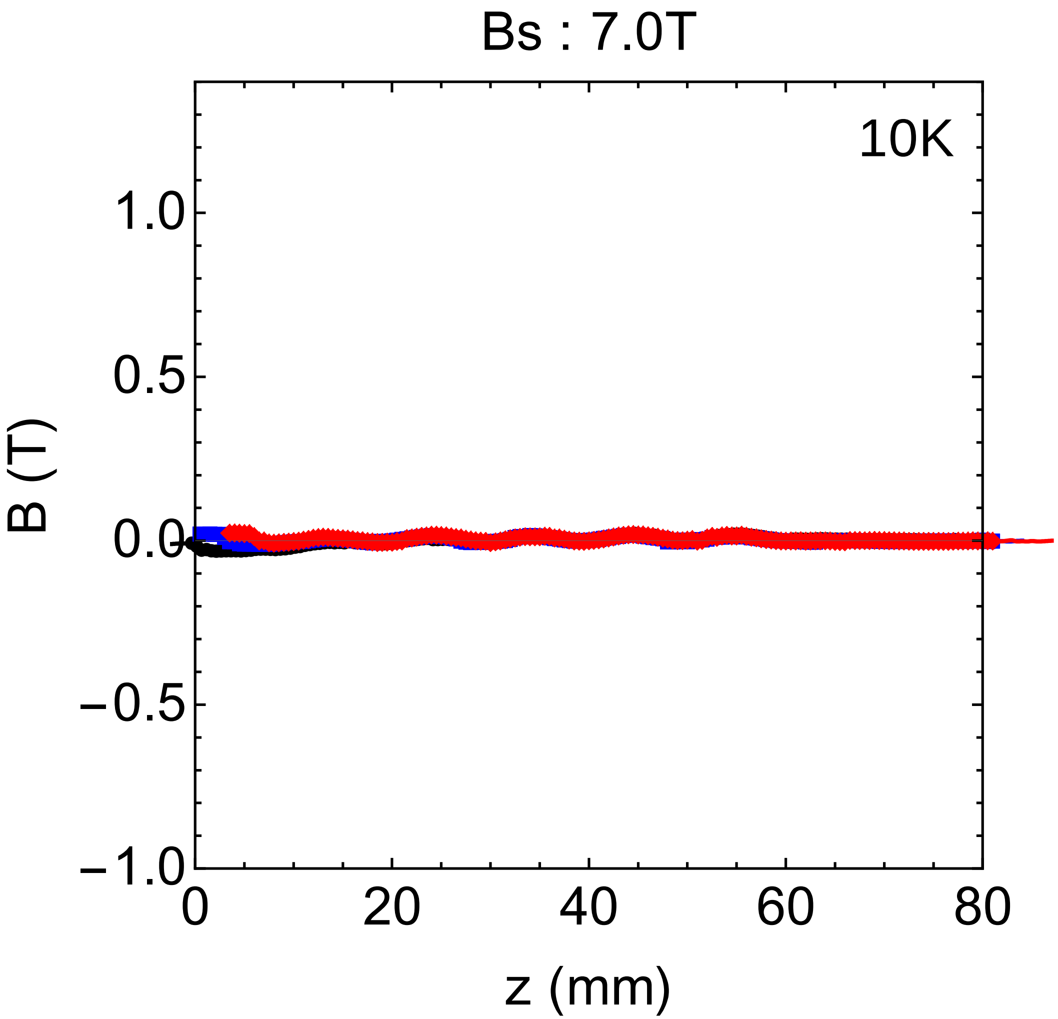
The sample with its instrumentation

First run – 23.08.2019

- The sample is cooled in a 7.0T solenoid
- its temperature is stabilised at 10K
- and the solenoid is ramped down in steps of 1T
- and the field profile (Bx,By1,By2,By3,Bz) is recorded during the field plateau



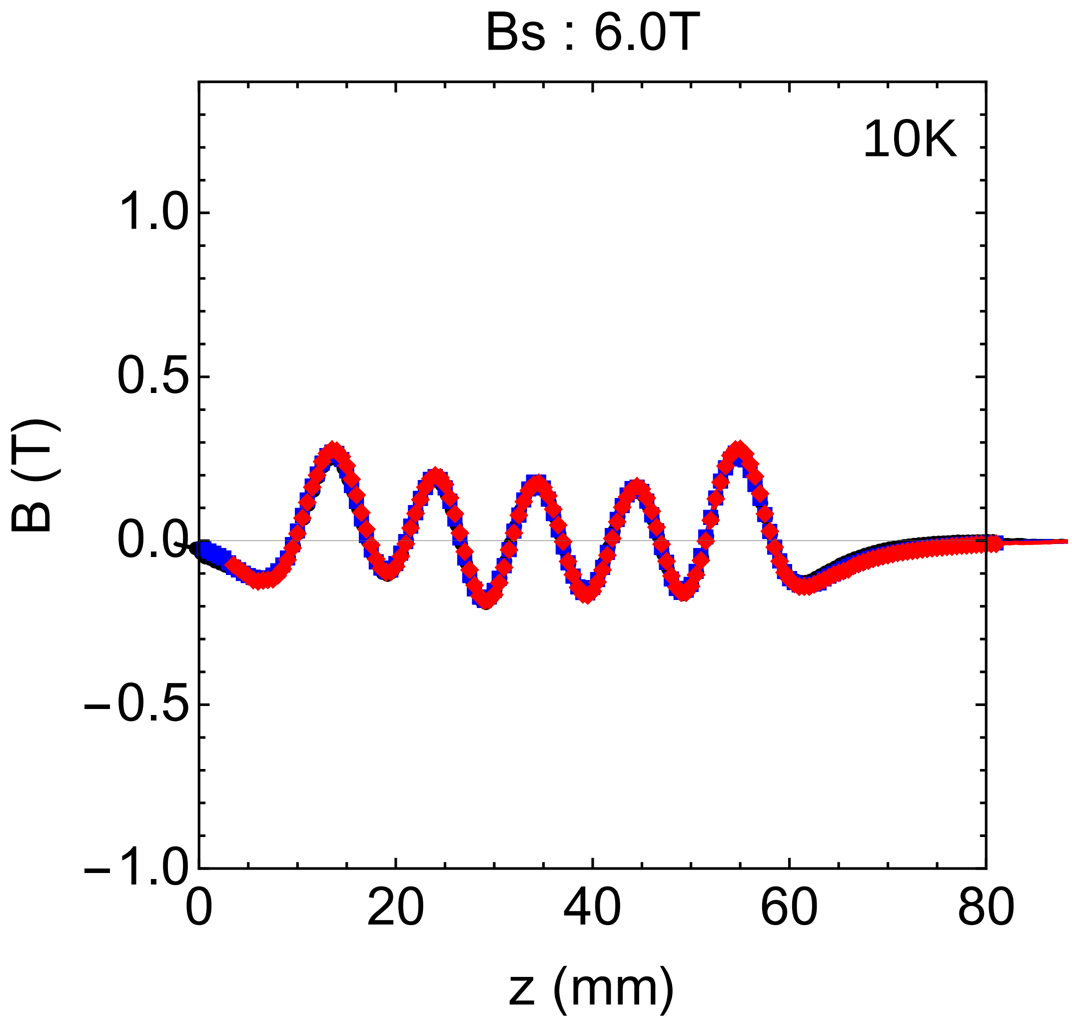
First run – 23.08.2019



ferromagnetic properties of Gd?

*B: By1, By2, By3

First run – 23.08.2019



*B: By1, By2, By3

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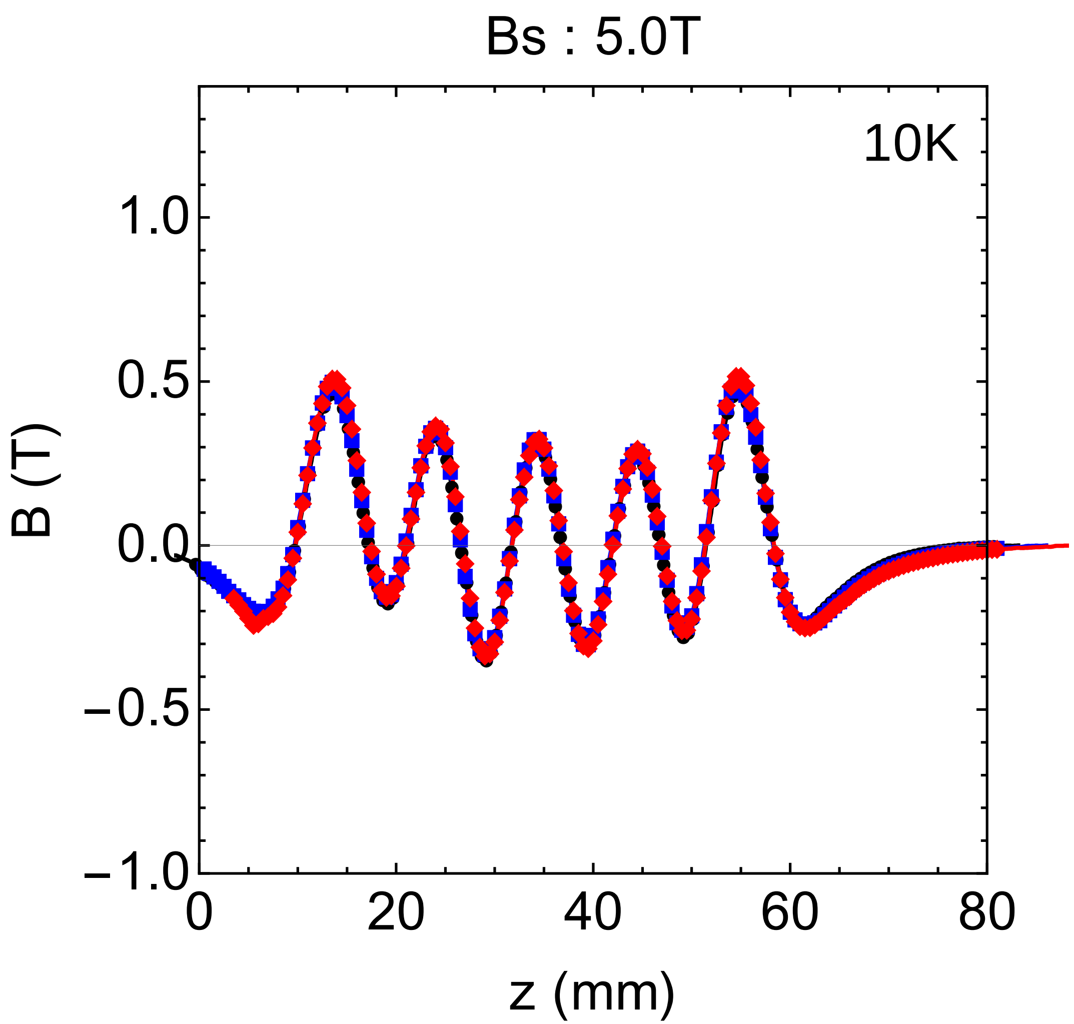

*B: By1, By2, By3

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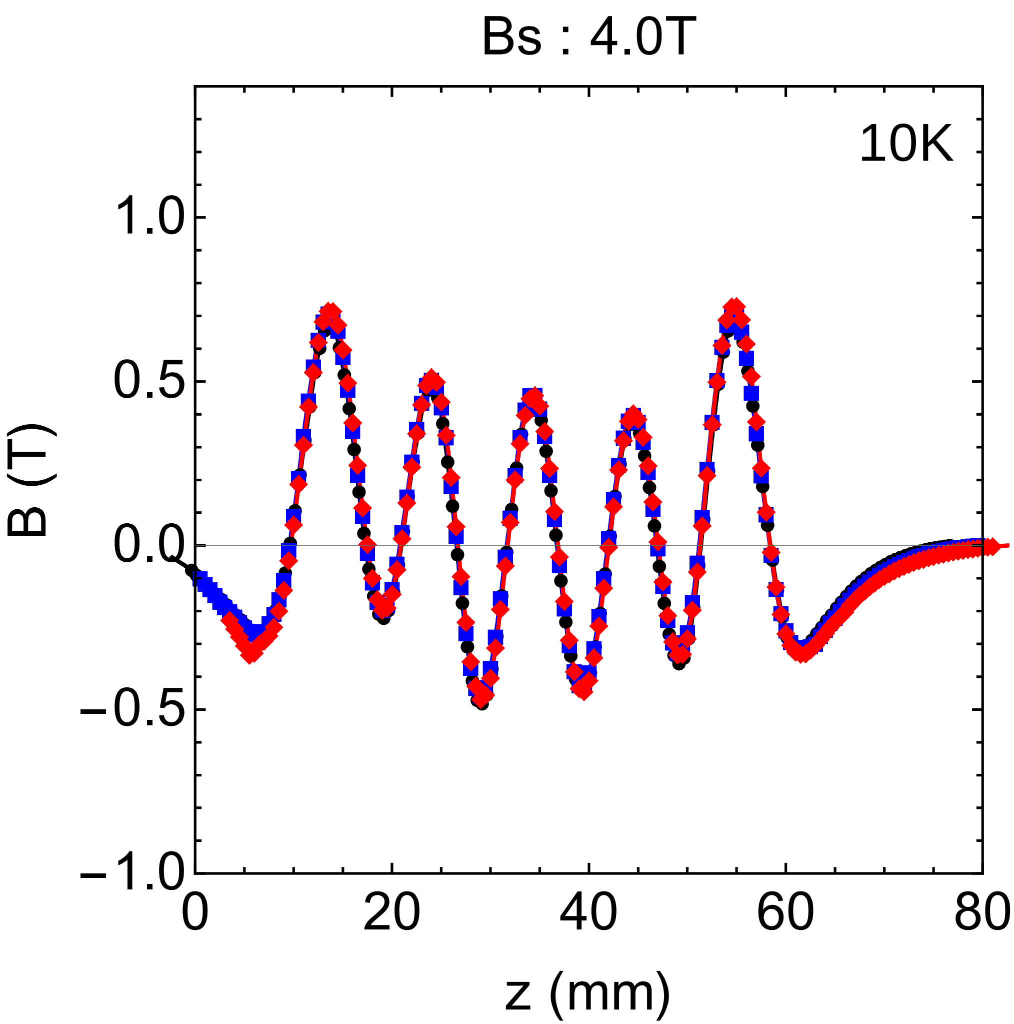
First run – 23.08.2019



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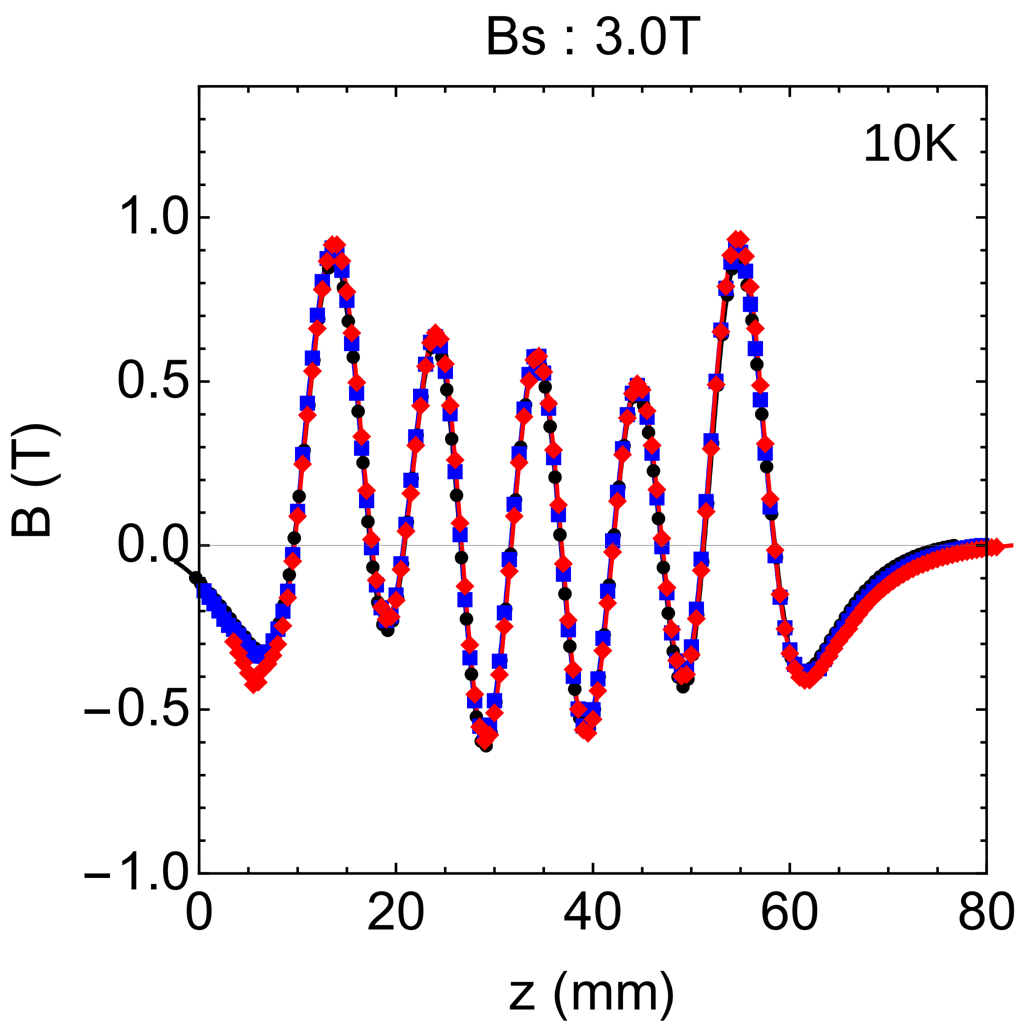
First run – 23.08.2019



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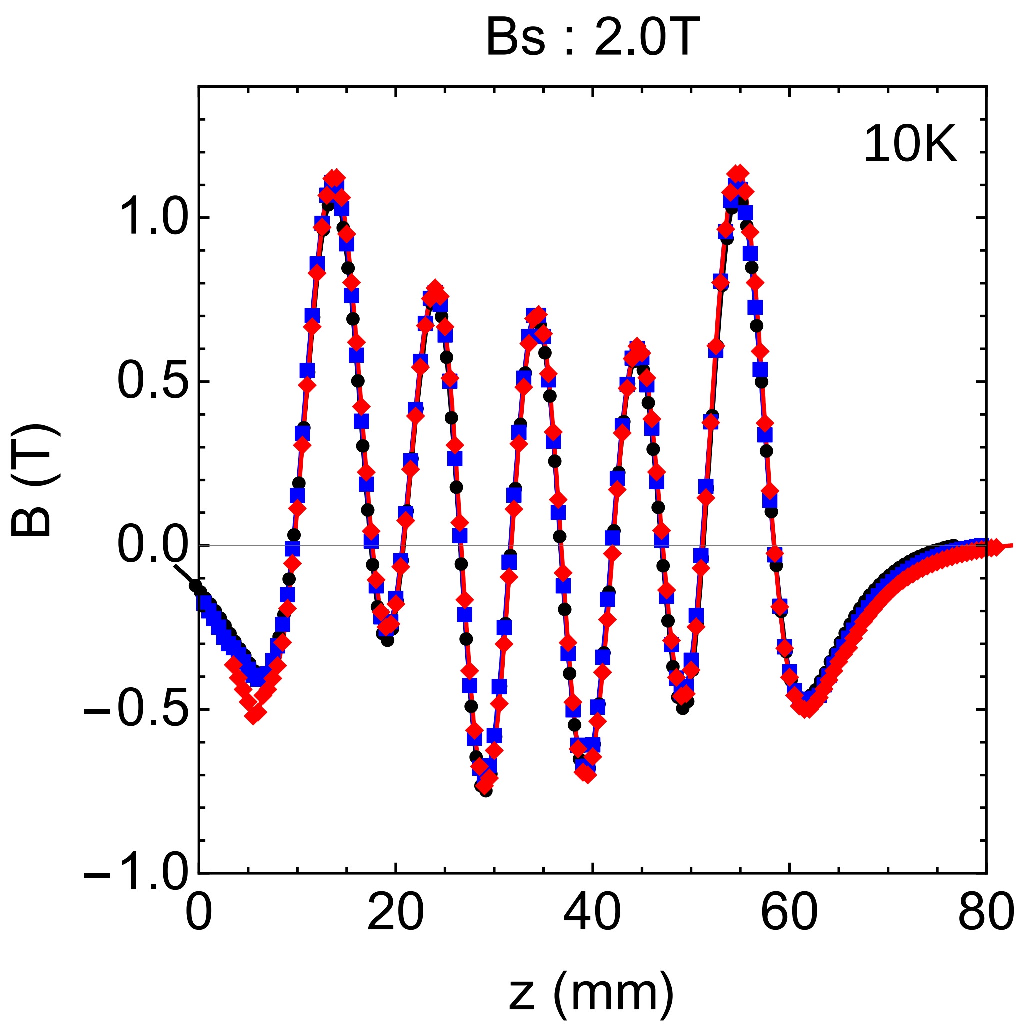

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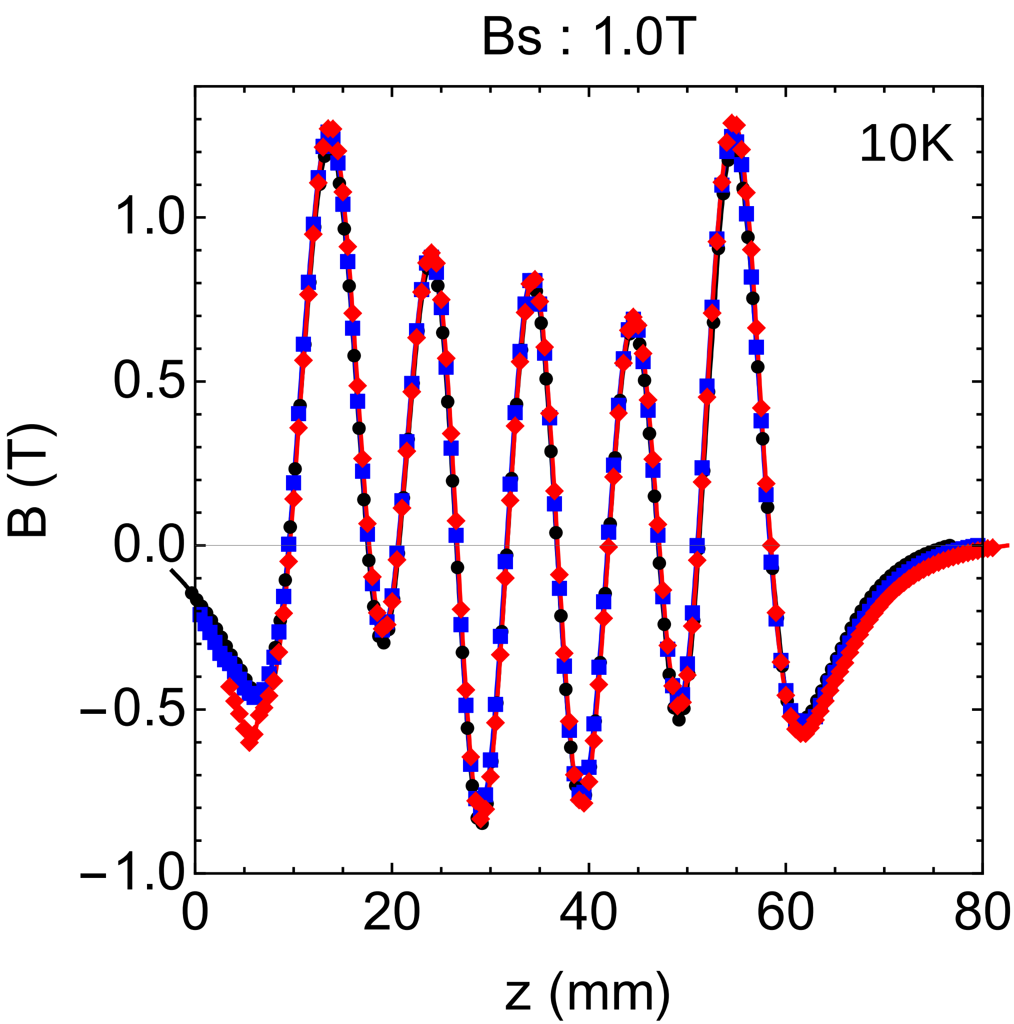

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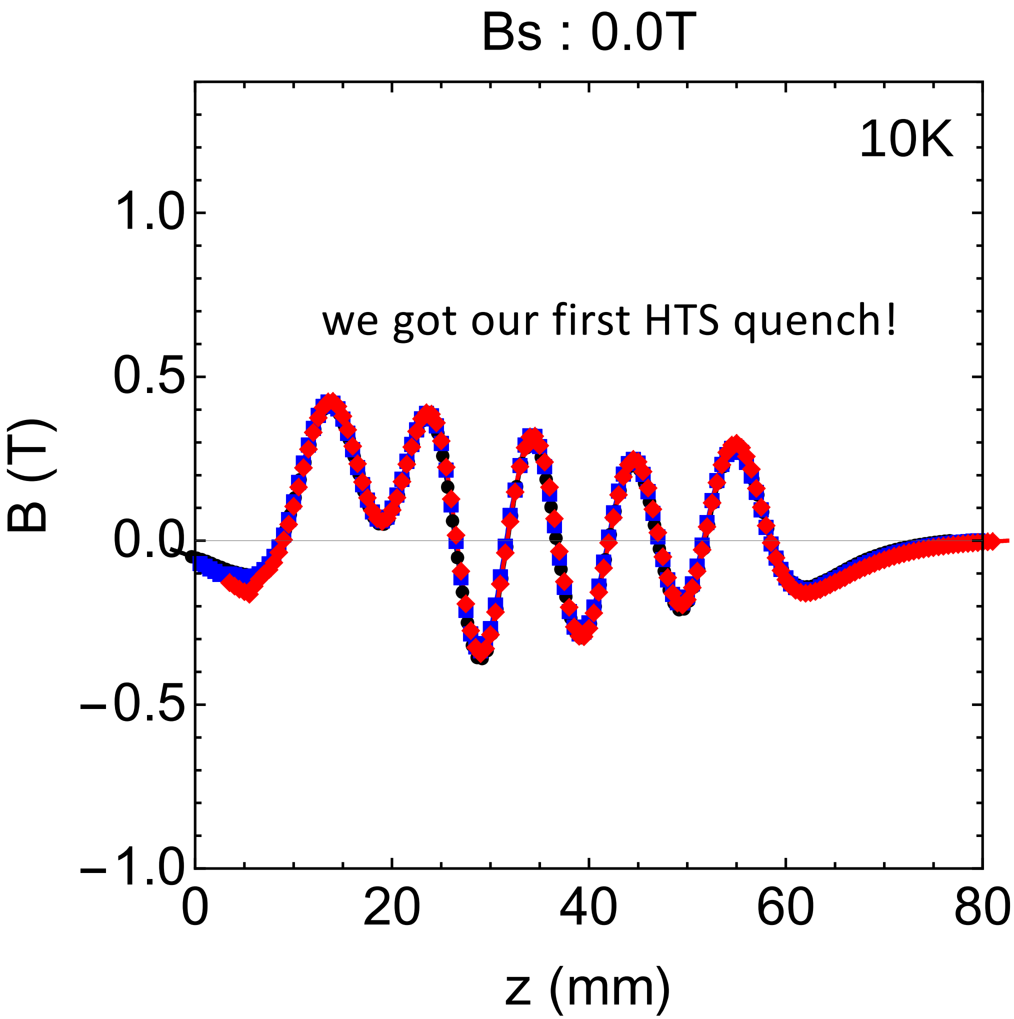

we got our first HTS quench!

*B: By1, By2, By3

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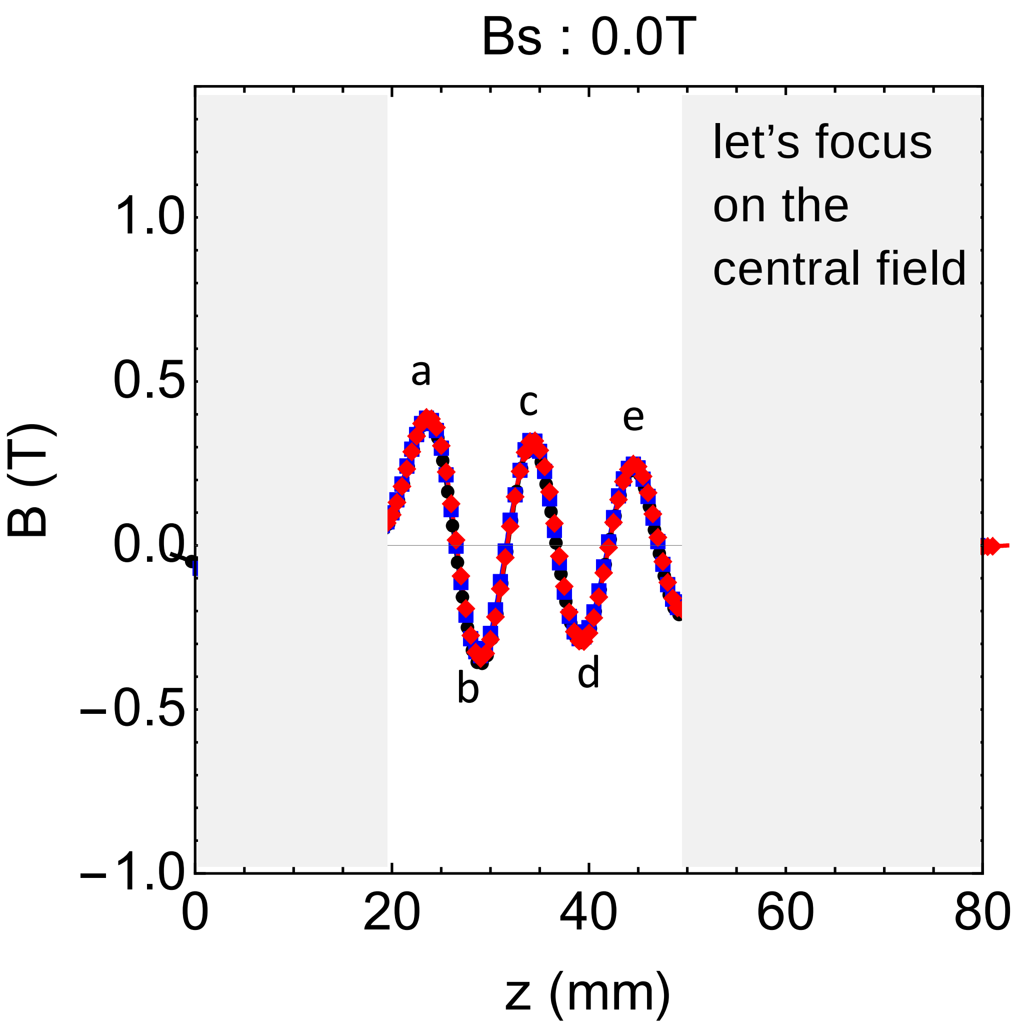

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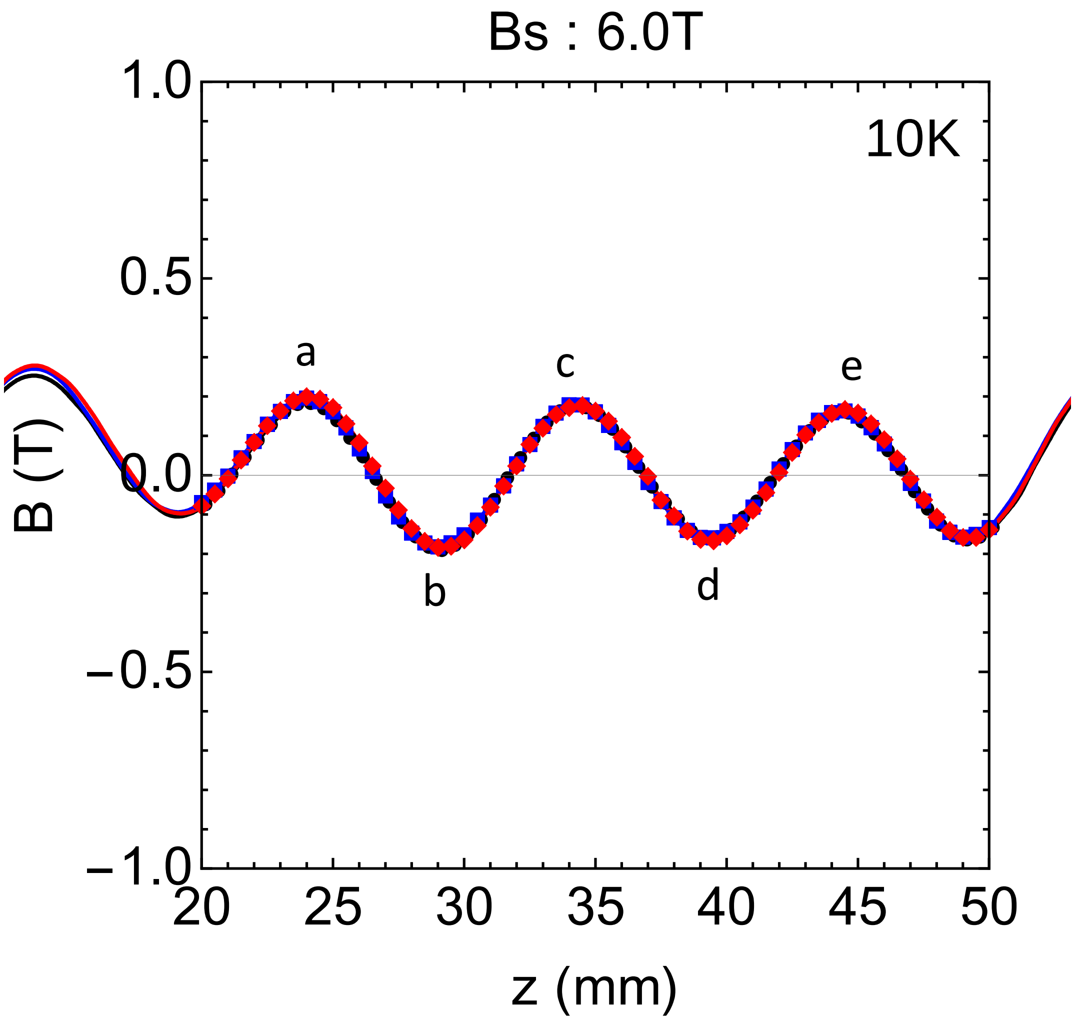

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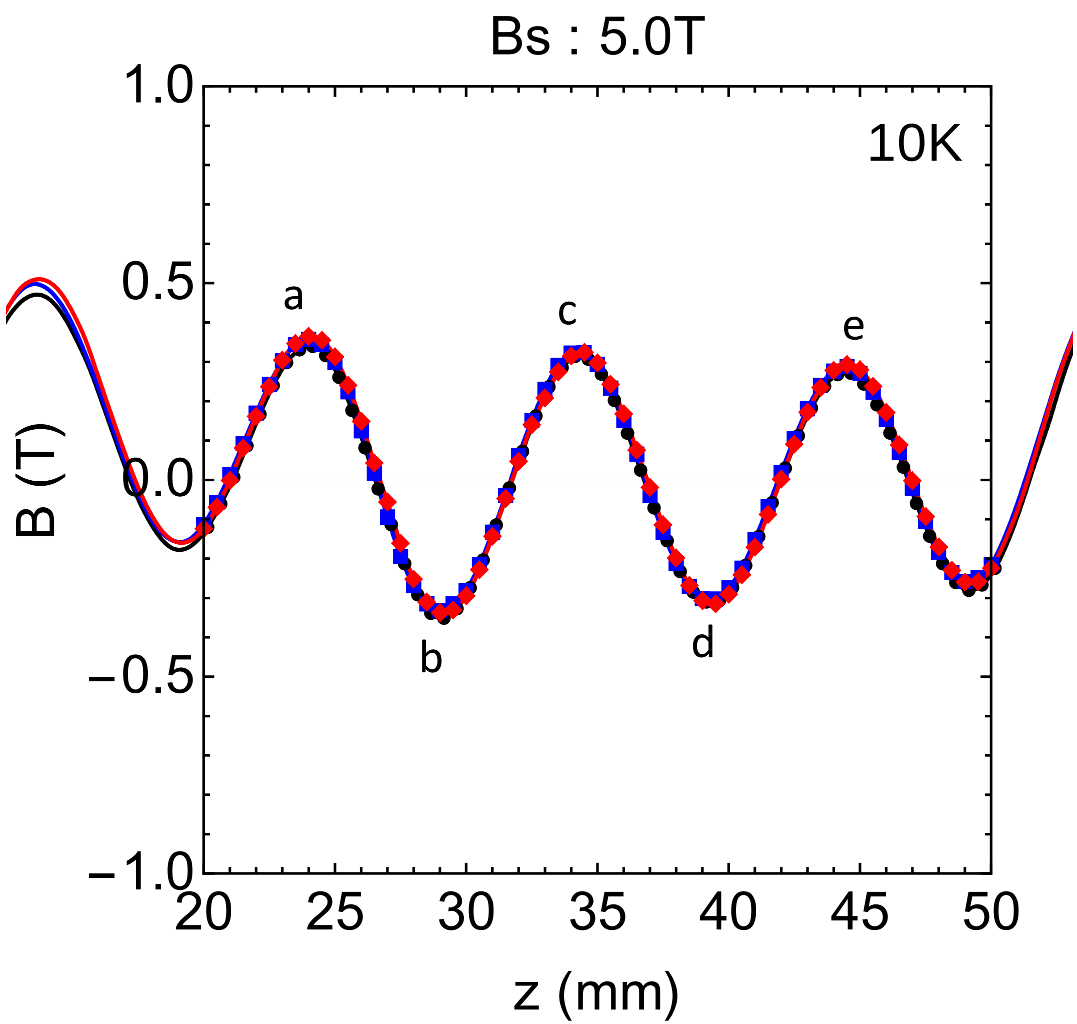

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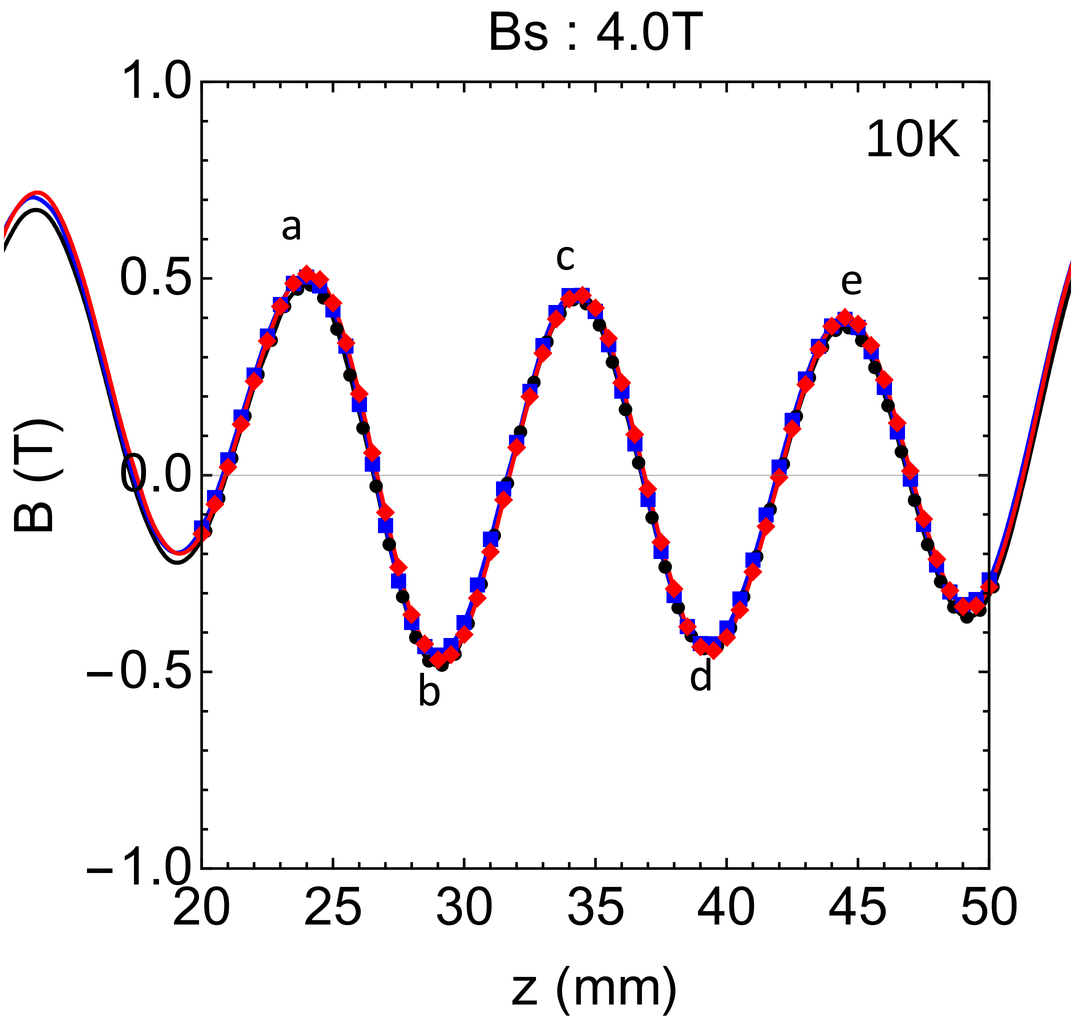

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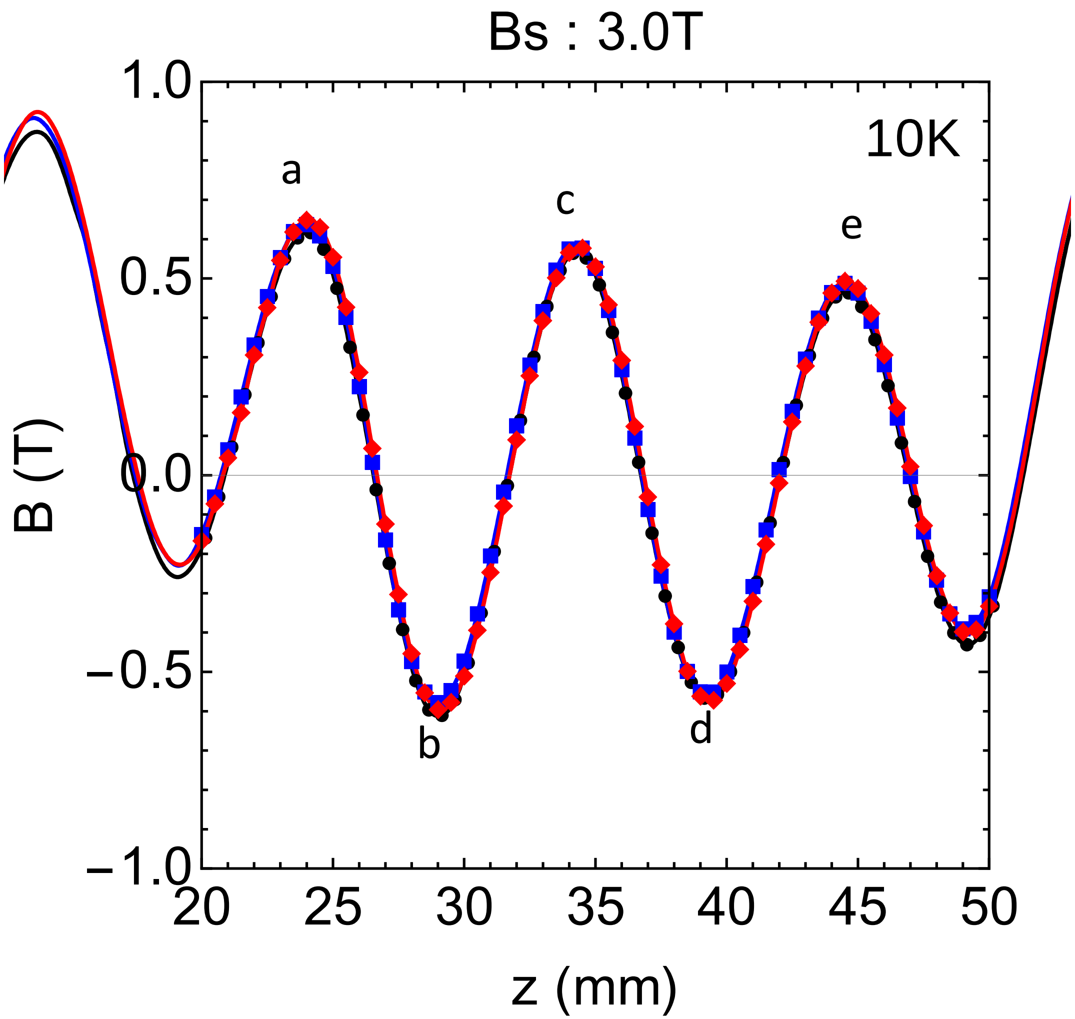

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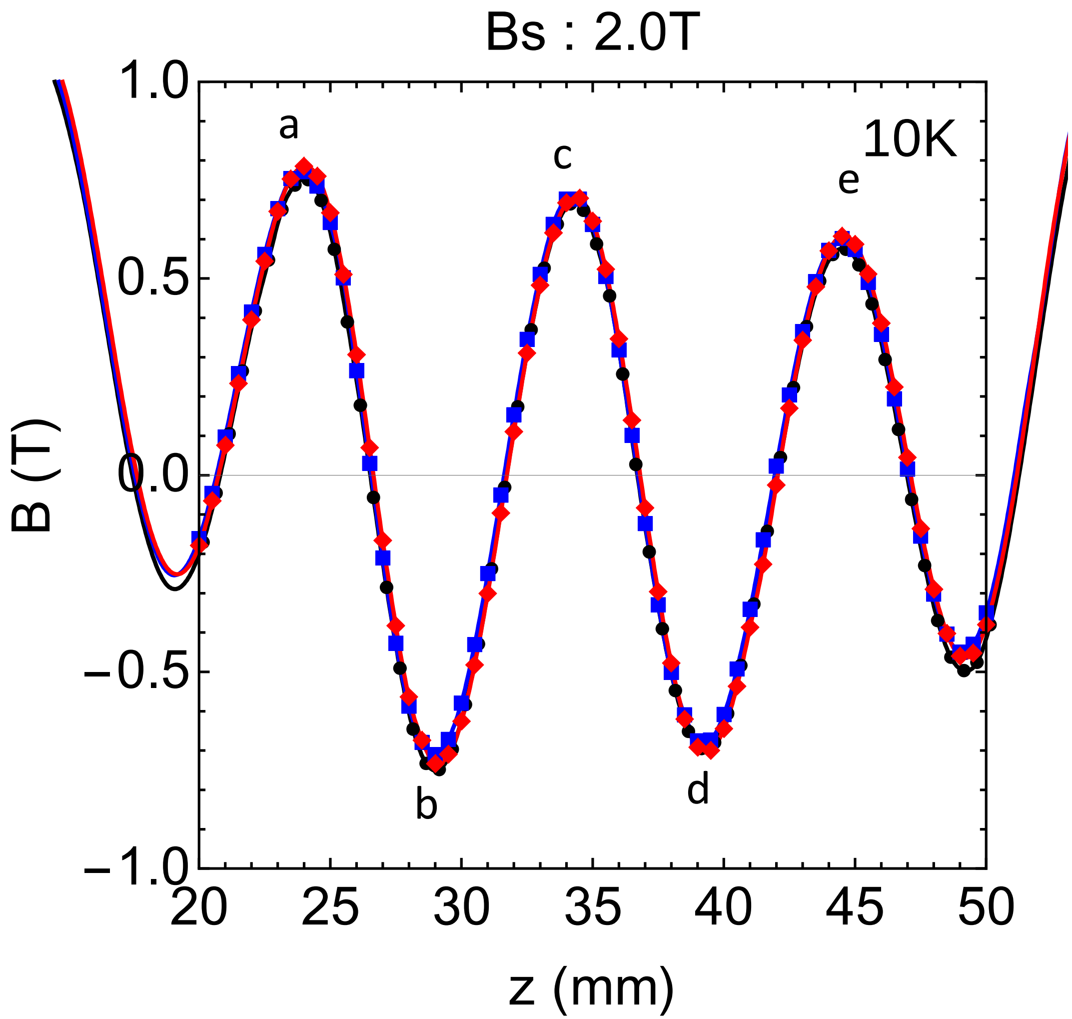

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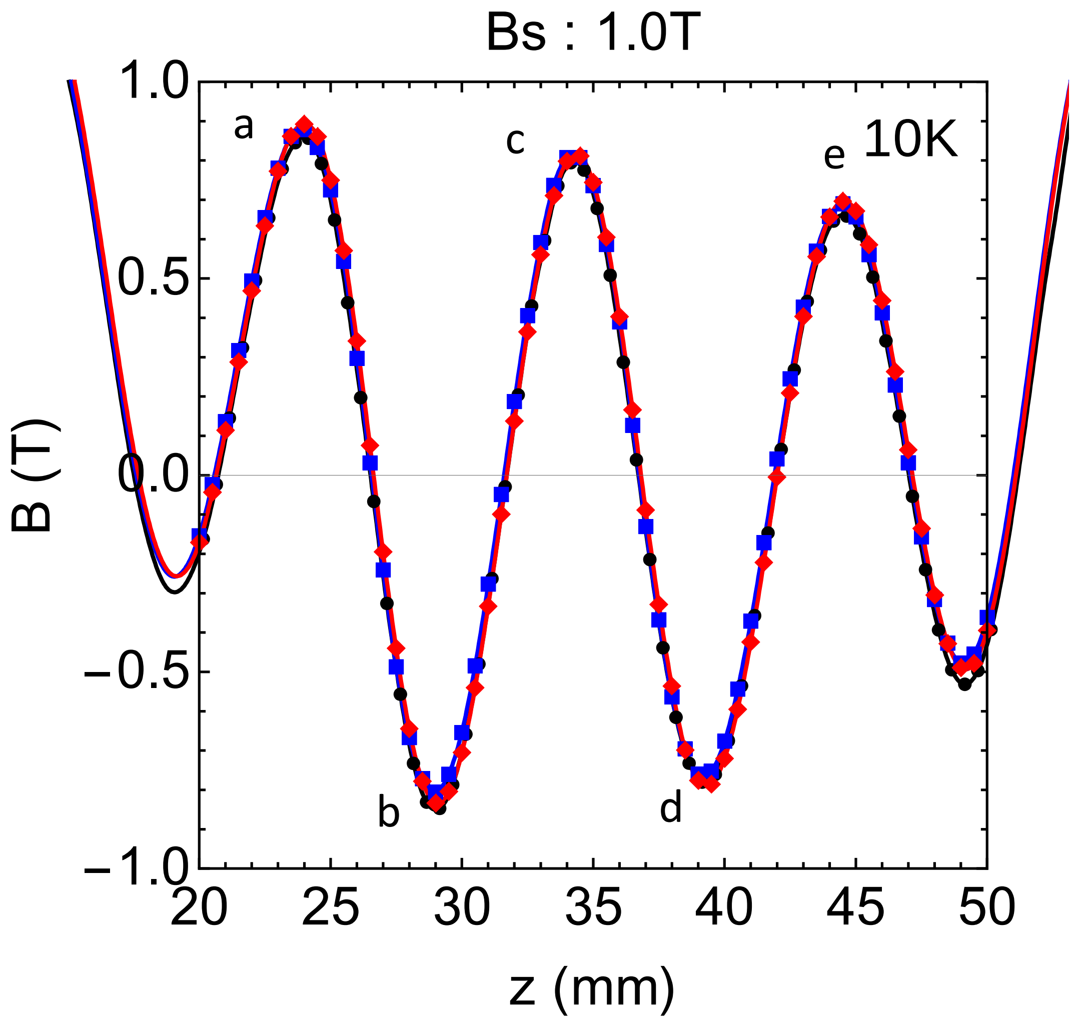

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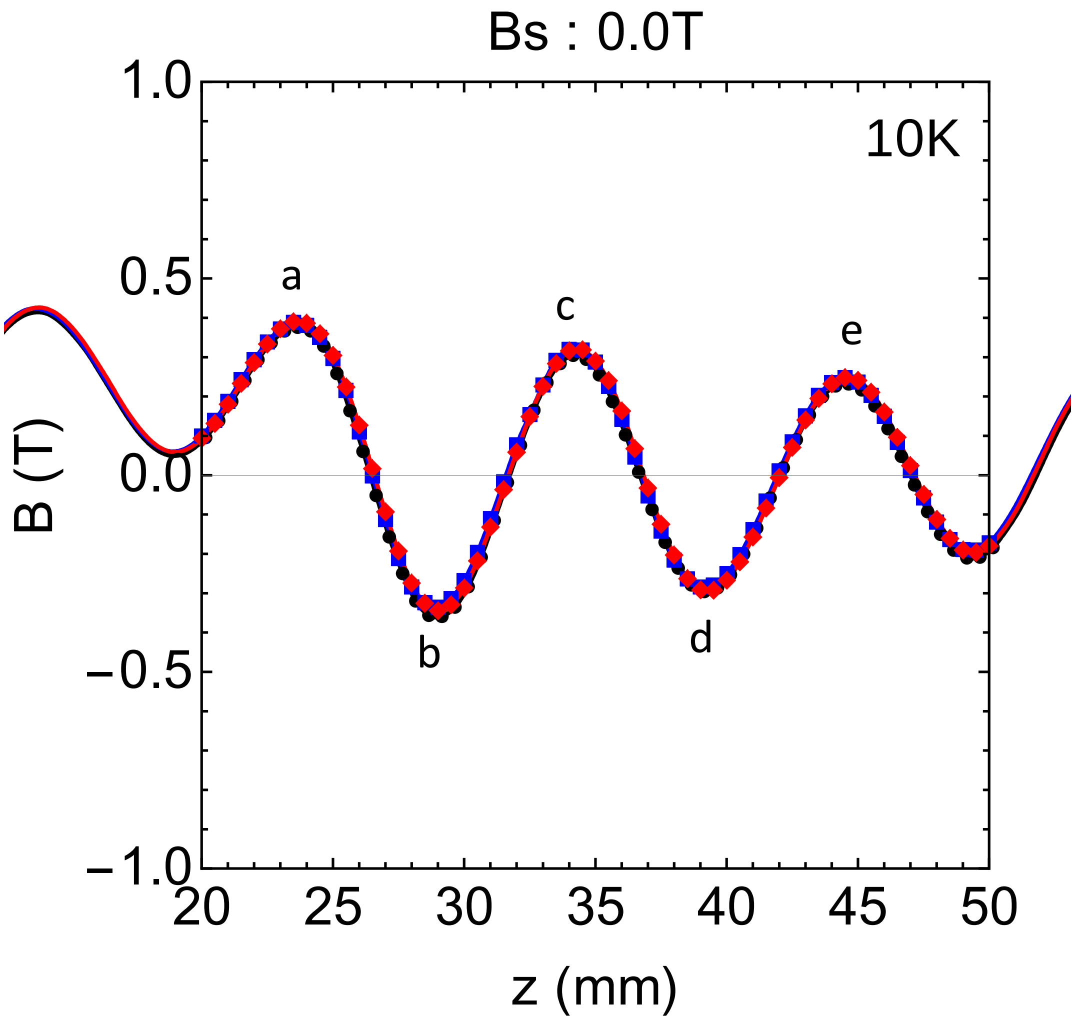

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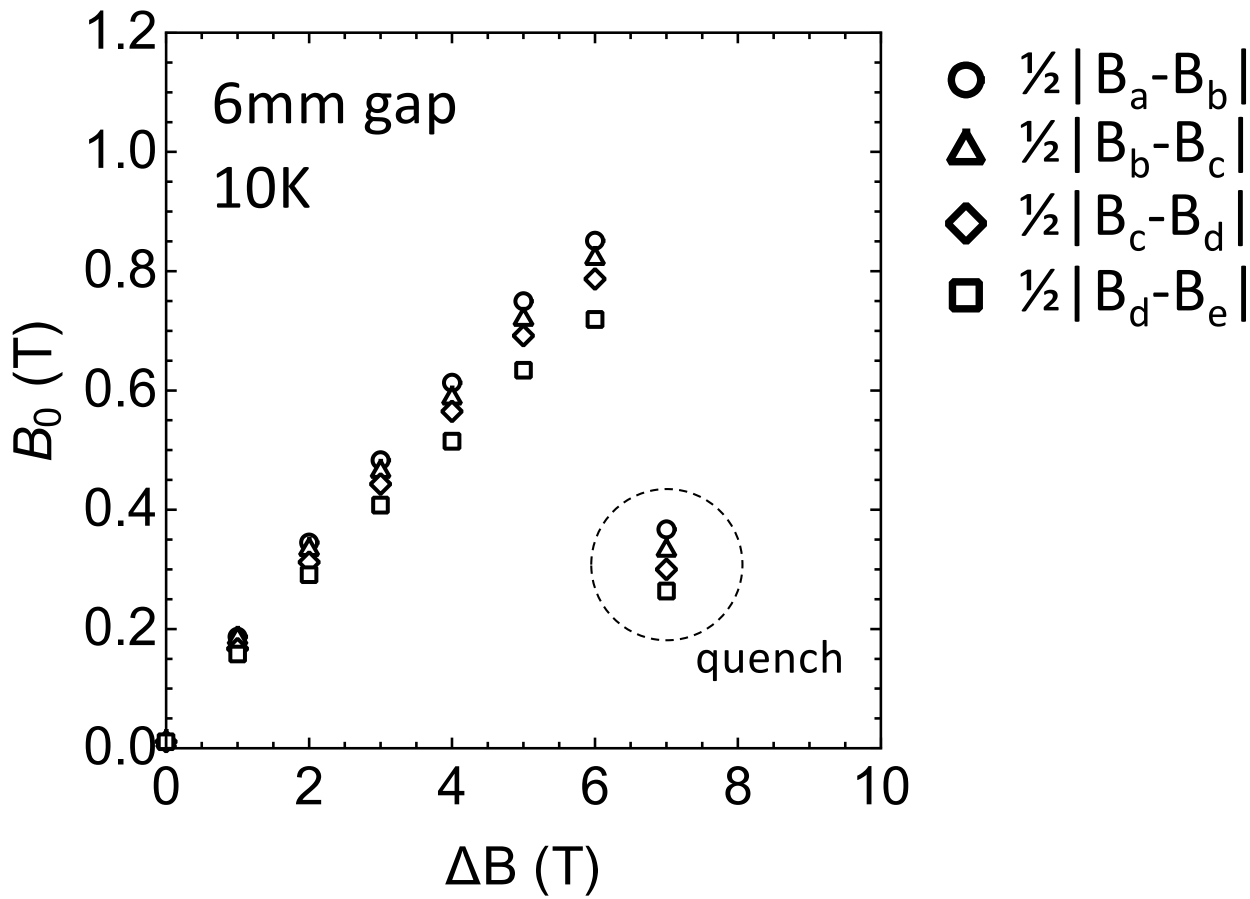
Summary first run



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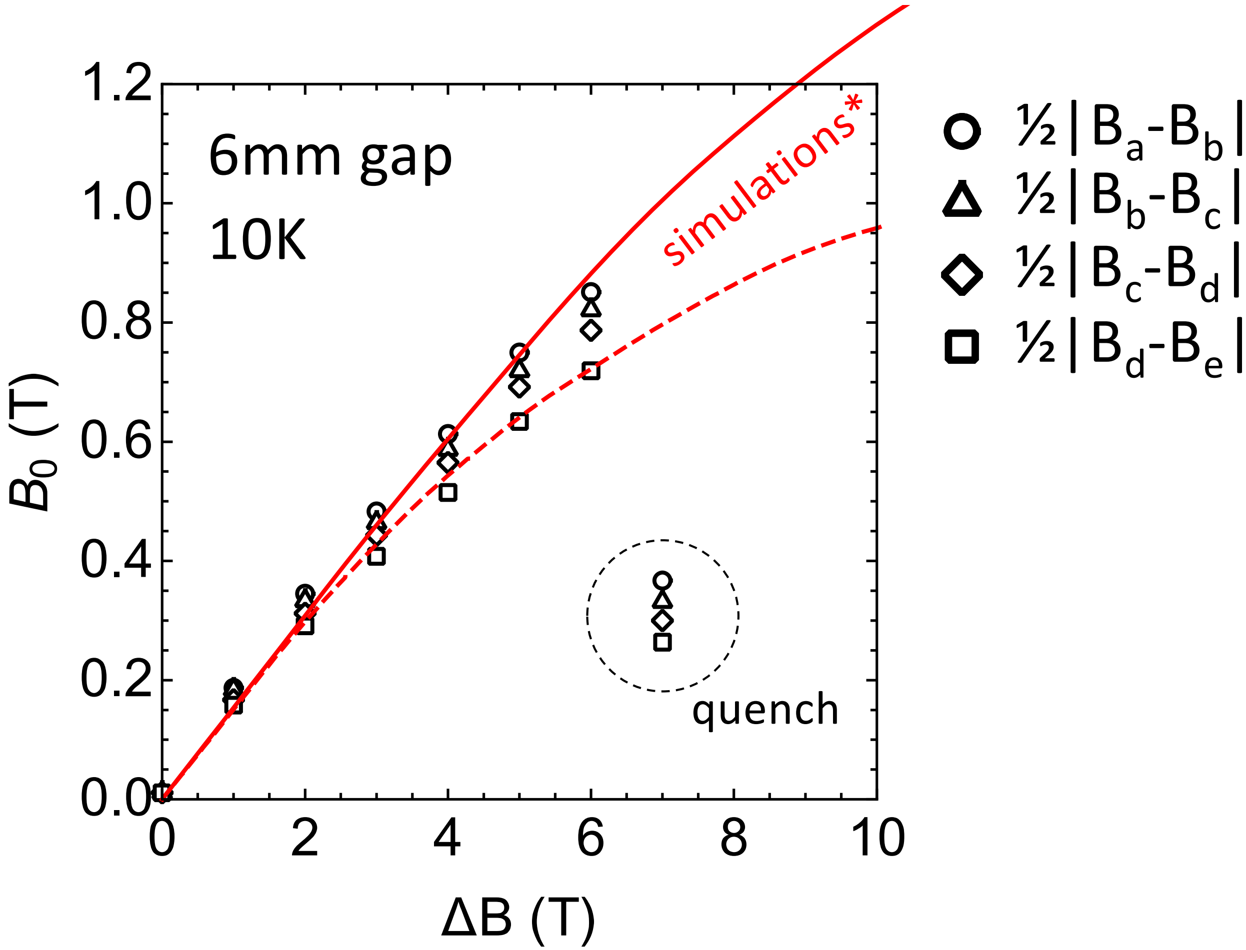
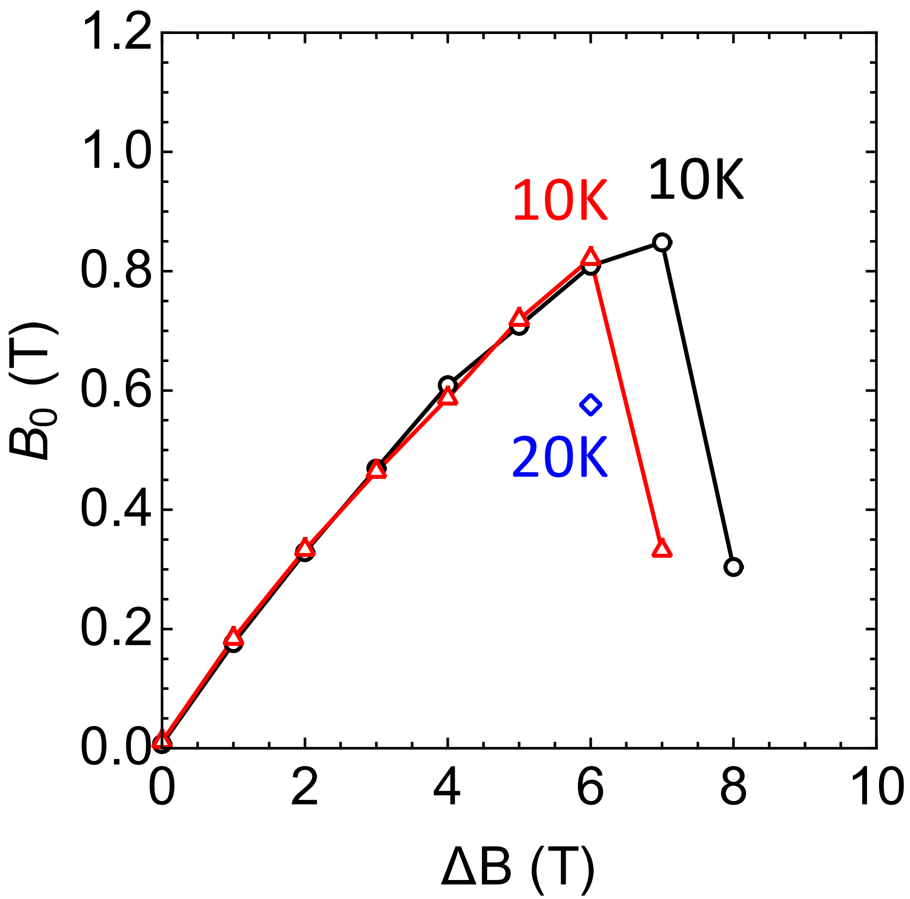
Summary first run



*simulations: the solid redline results from the scaling laws provided by the company ATZ, the dashed line is from measurements done in Cambridge @ 40K and scaled to 10K (x2.5)

Summary of the First Campaign – Aug 2019

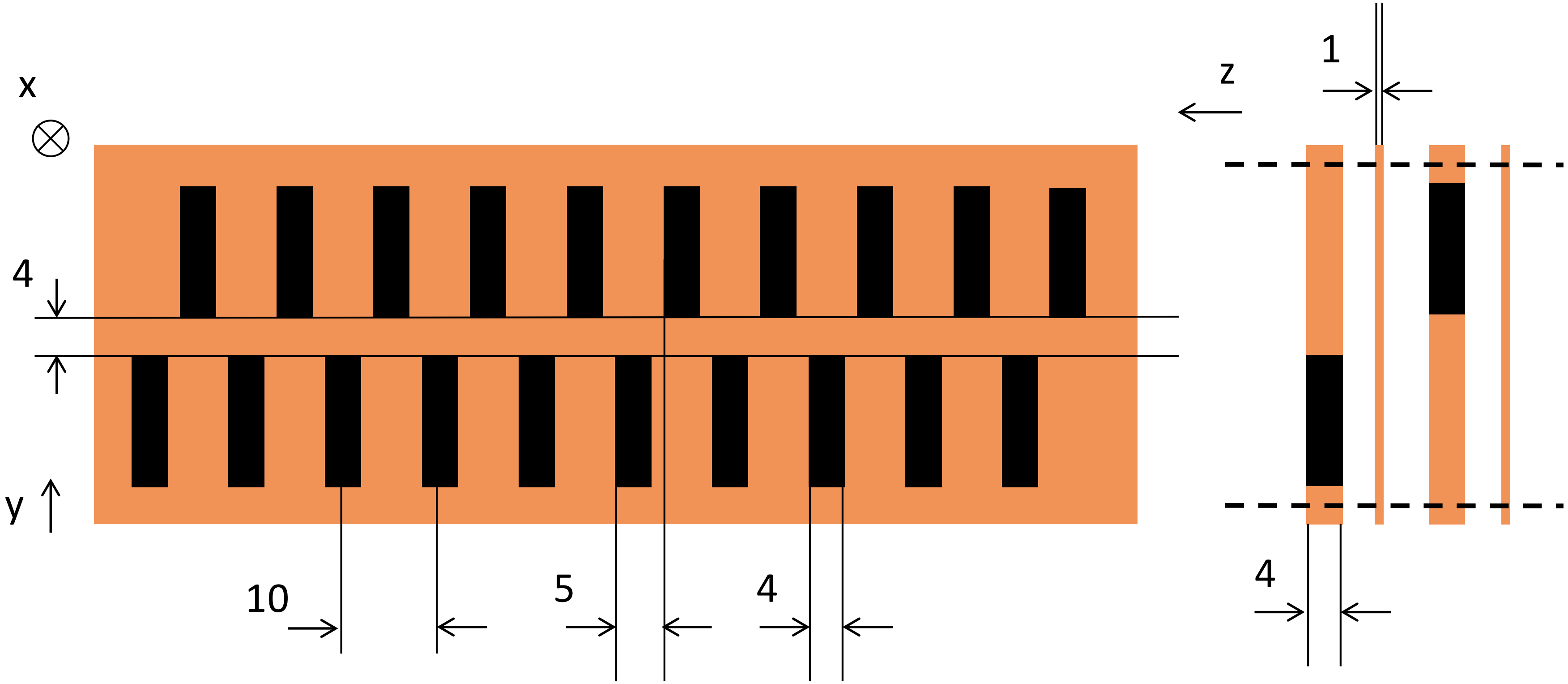
First run
Second run
Third run



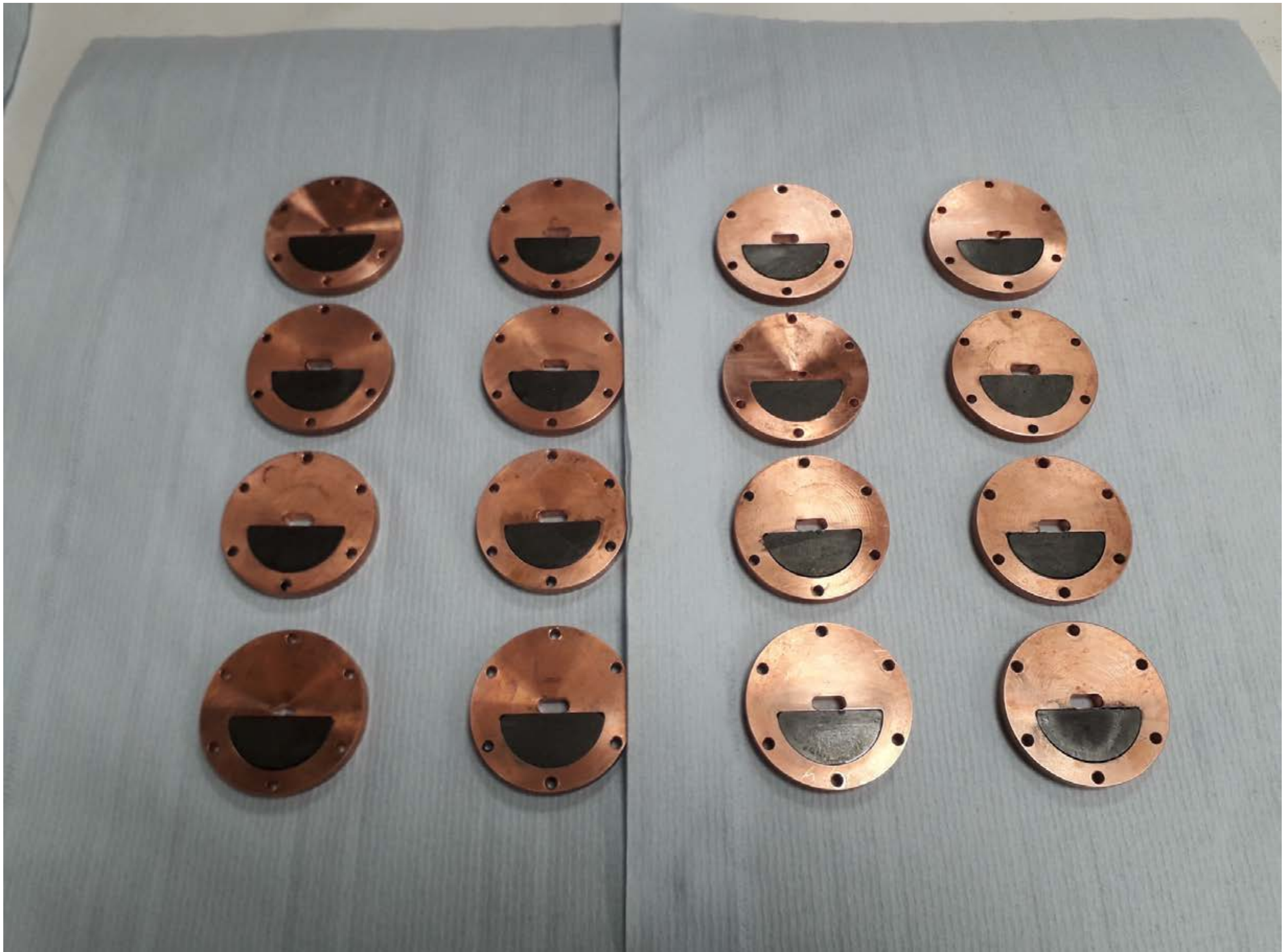
½|B_b-B_c|

Our Second short sample

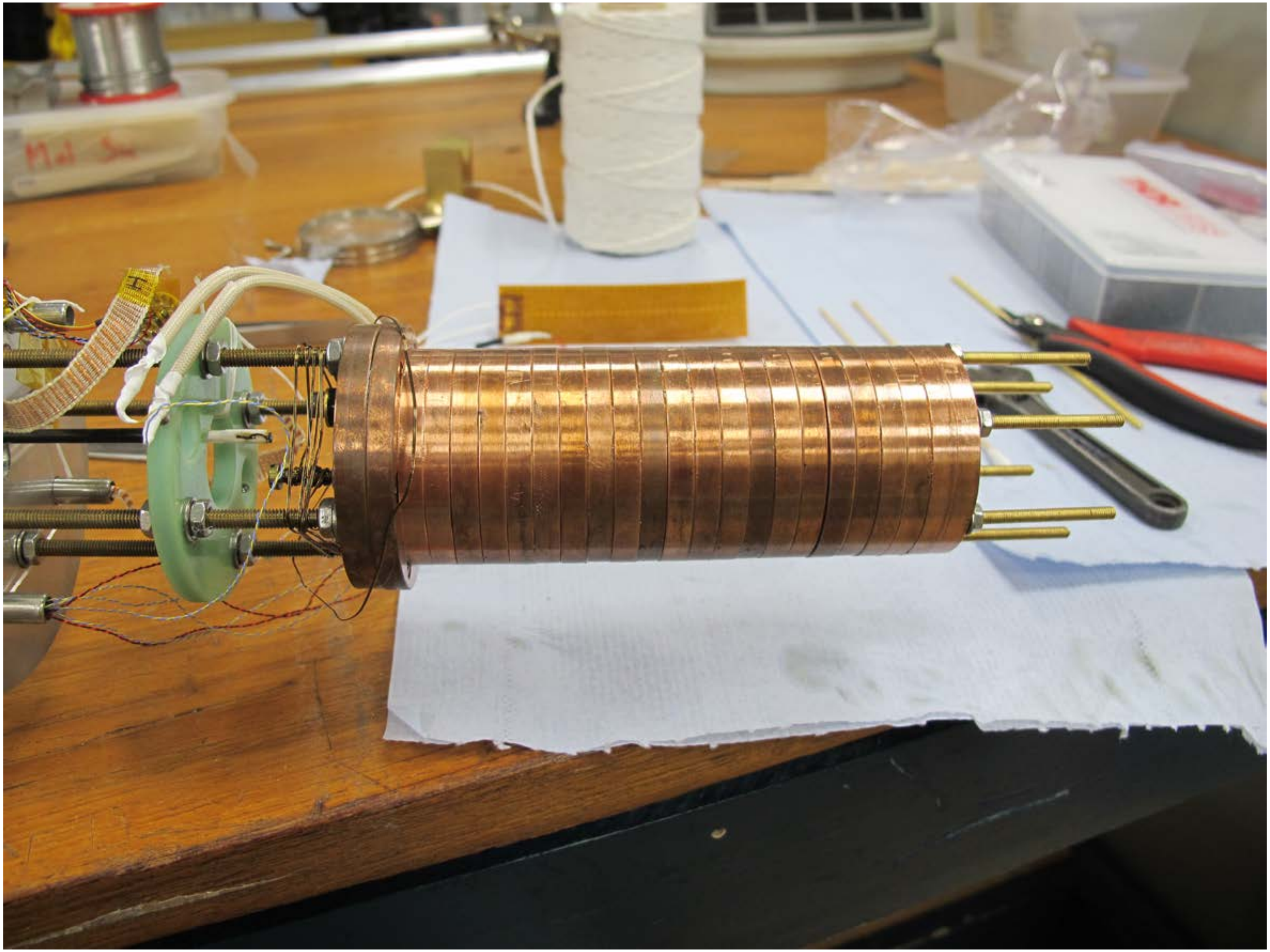
- 10 periods
- period length 10.0 mm
- gap 4.0 mm
- bulk diameter 30.0 mm
- No end field shaping



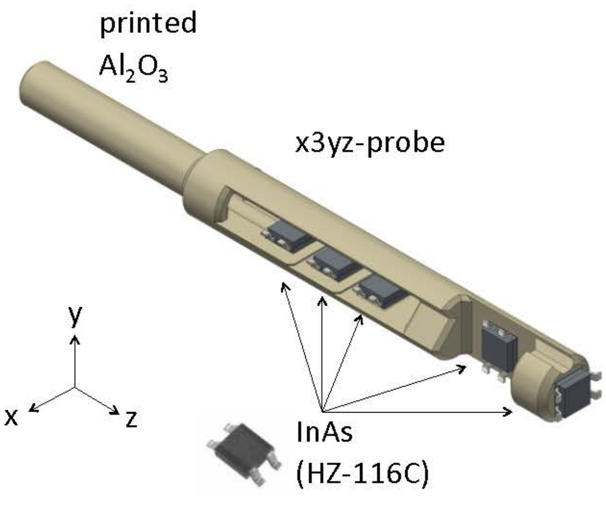
Second Campaign – Oct 2020



Second Campaign – Oct 2020



3D Cryogenic Hall Probe Development



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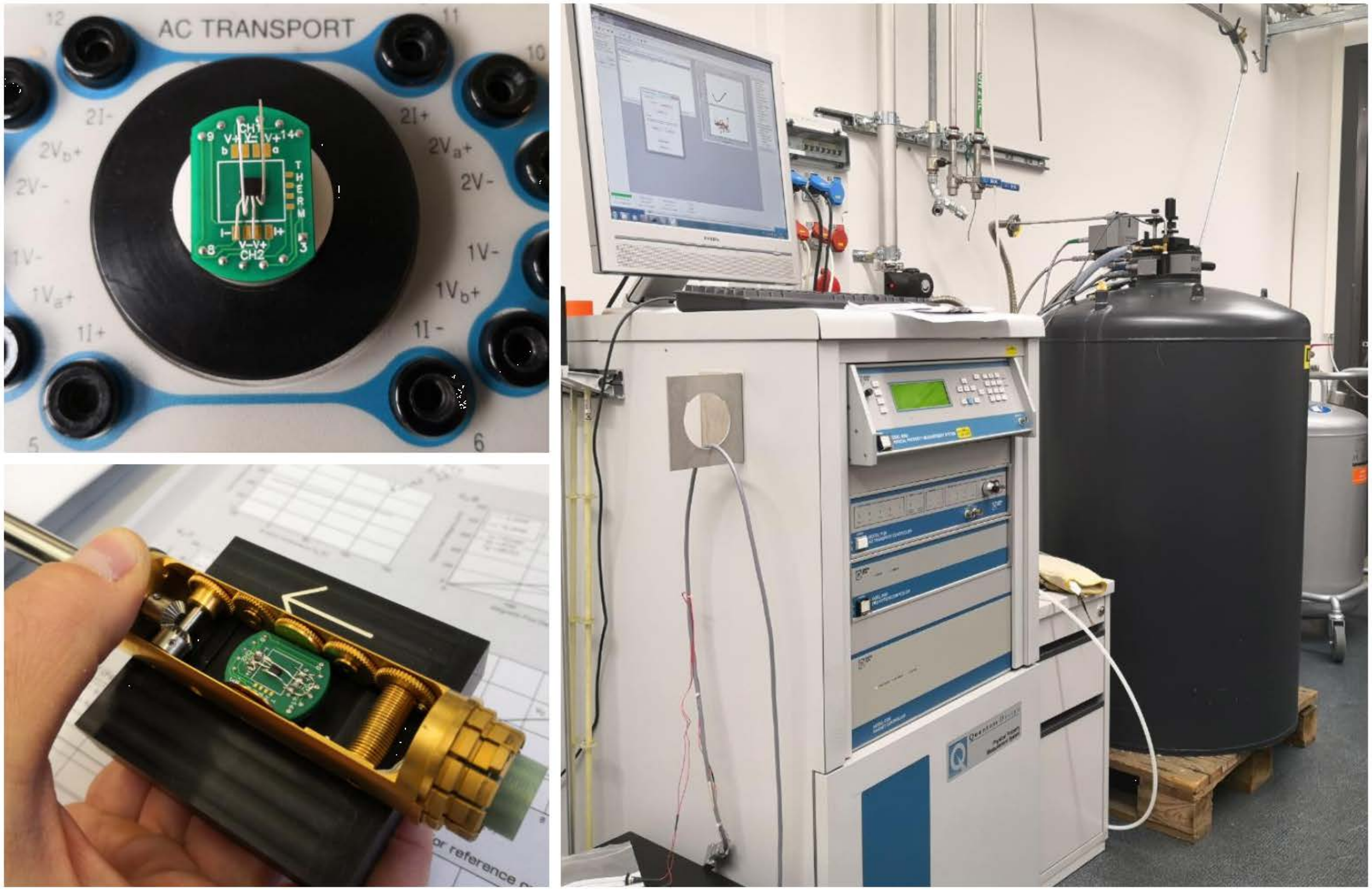

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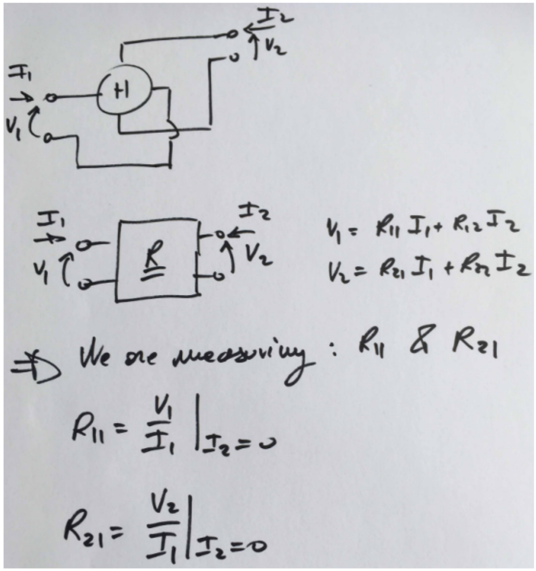
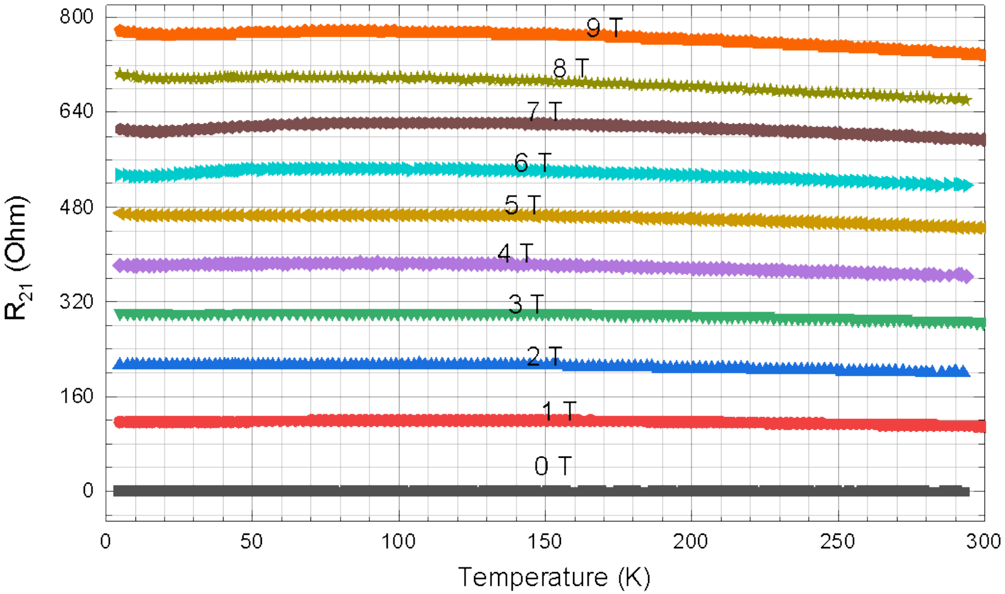
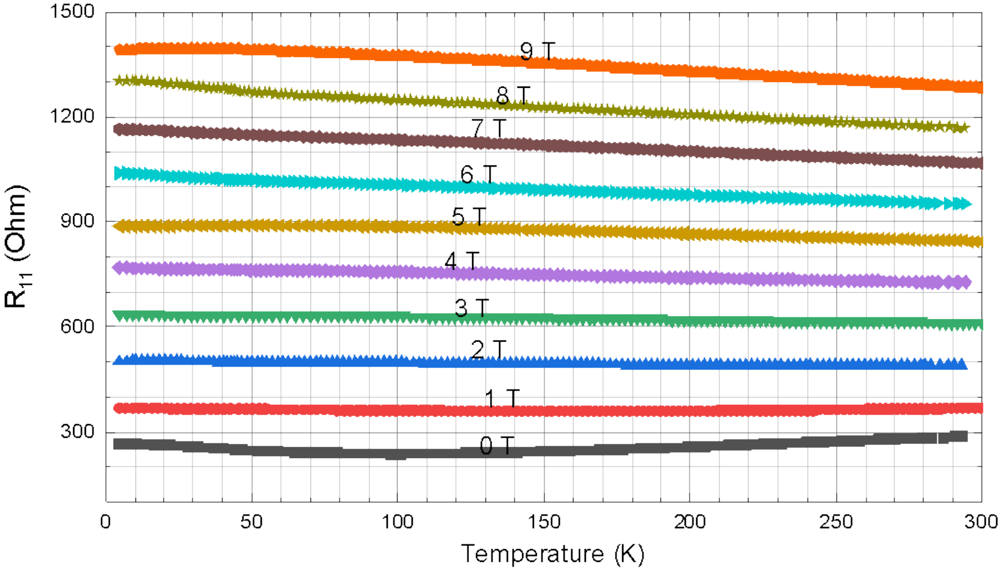




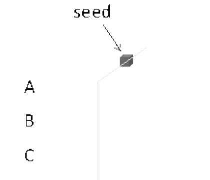
This run was done at constant current I_1= 200uA, unfortunately at high magnetic field the resistance R_{11} is so high that the current dropped.

For the Hall voltage just multiply:

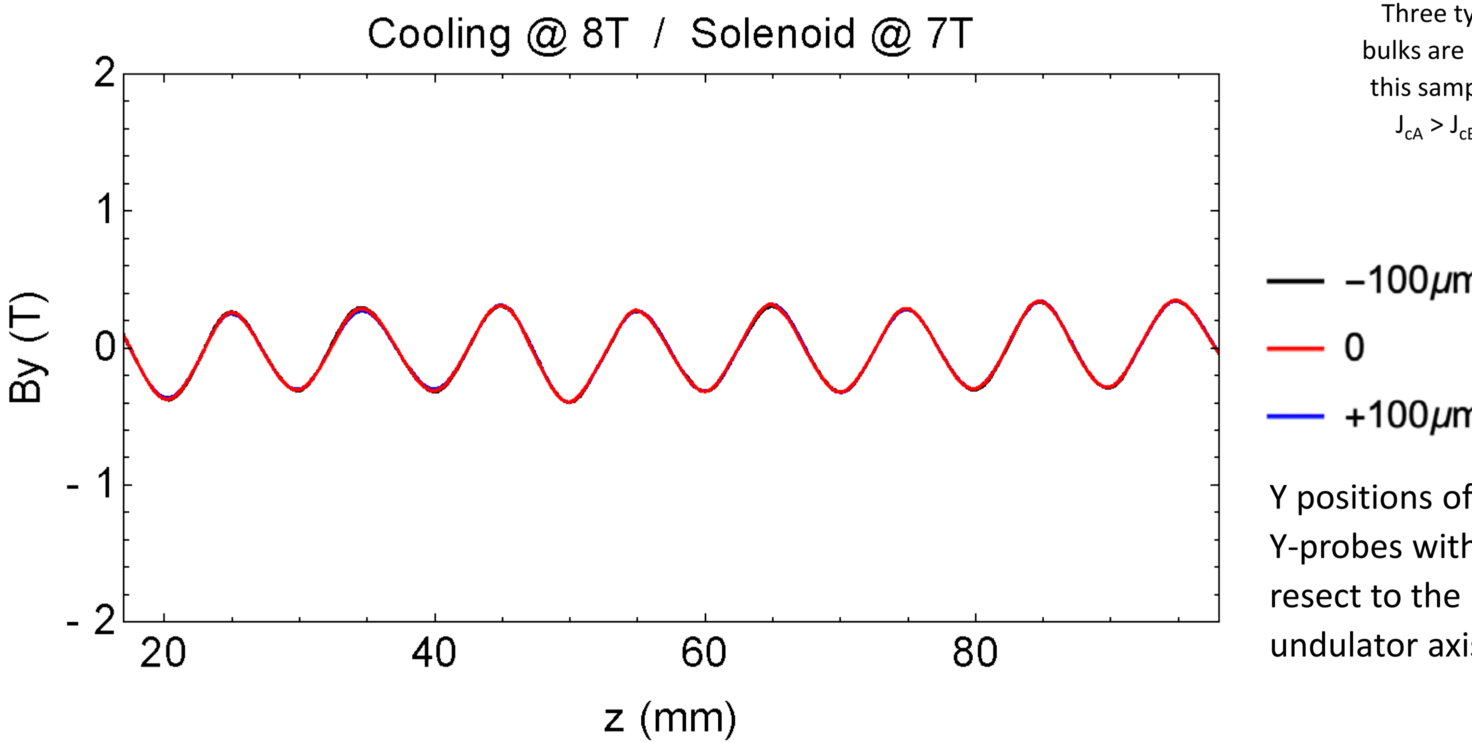
$$V_H = R_{21}\ I_1$$



First Run – 13/14 October 2020



Three types of bulks are used for this sample with $J_{cA} > J_{cB} > J_{cC}$

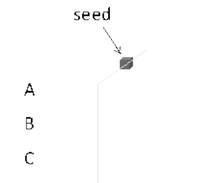


Y positions of the Y-probes with resect to the undulator axis

A B A B B B A A B A A A A B B B A A B B

└→ *visible damage*

First Run – 13/14 October 2020



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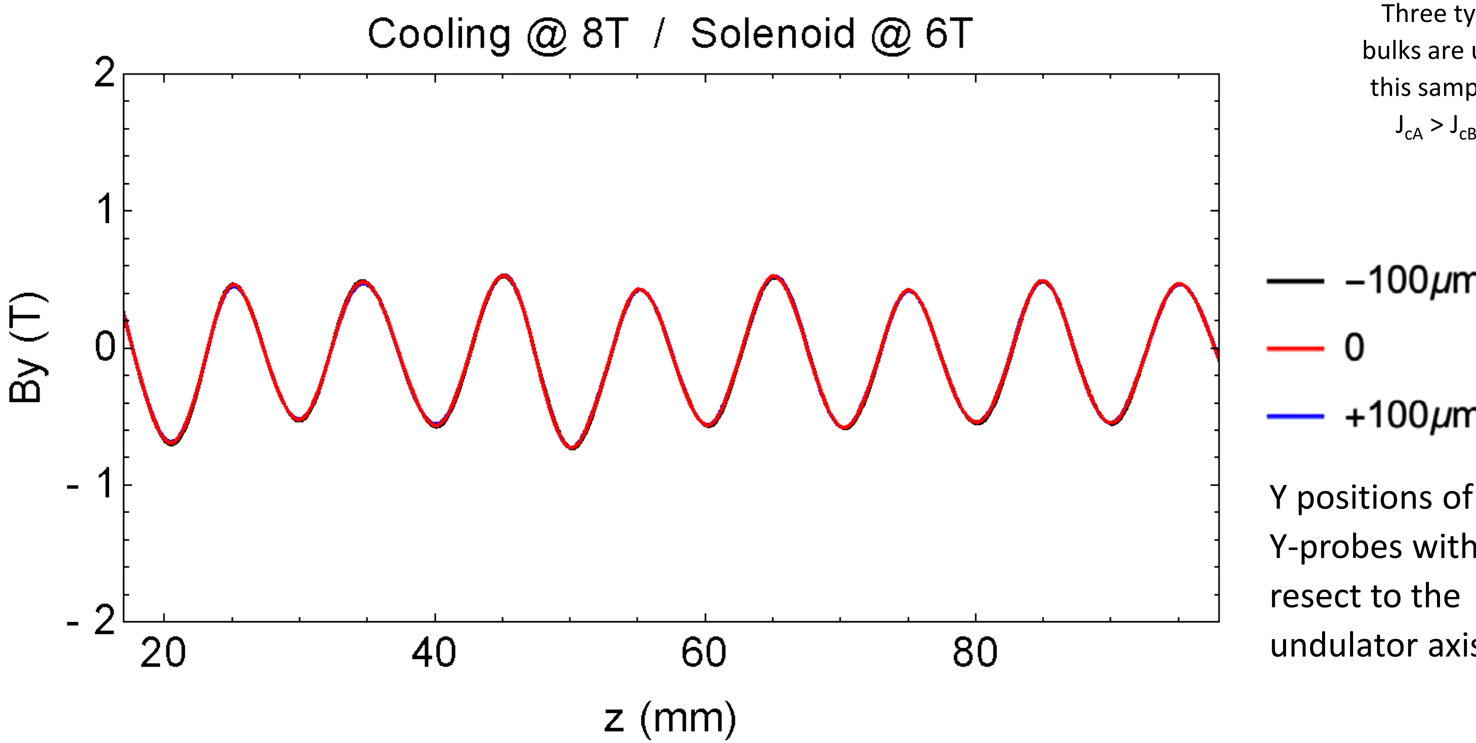

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A B A B B B A A B A A A A B B B A A B B

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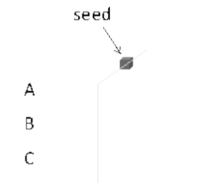
First Run – 13/14 October 2020



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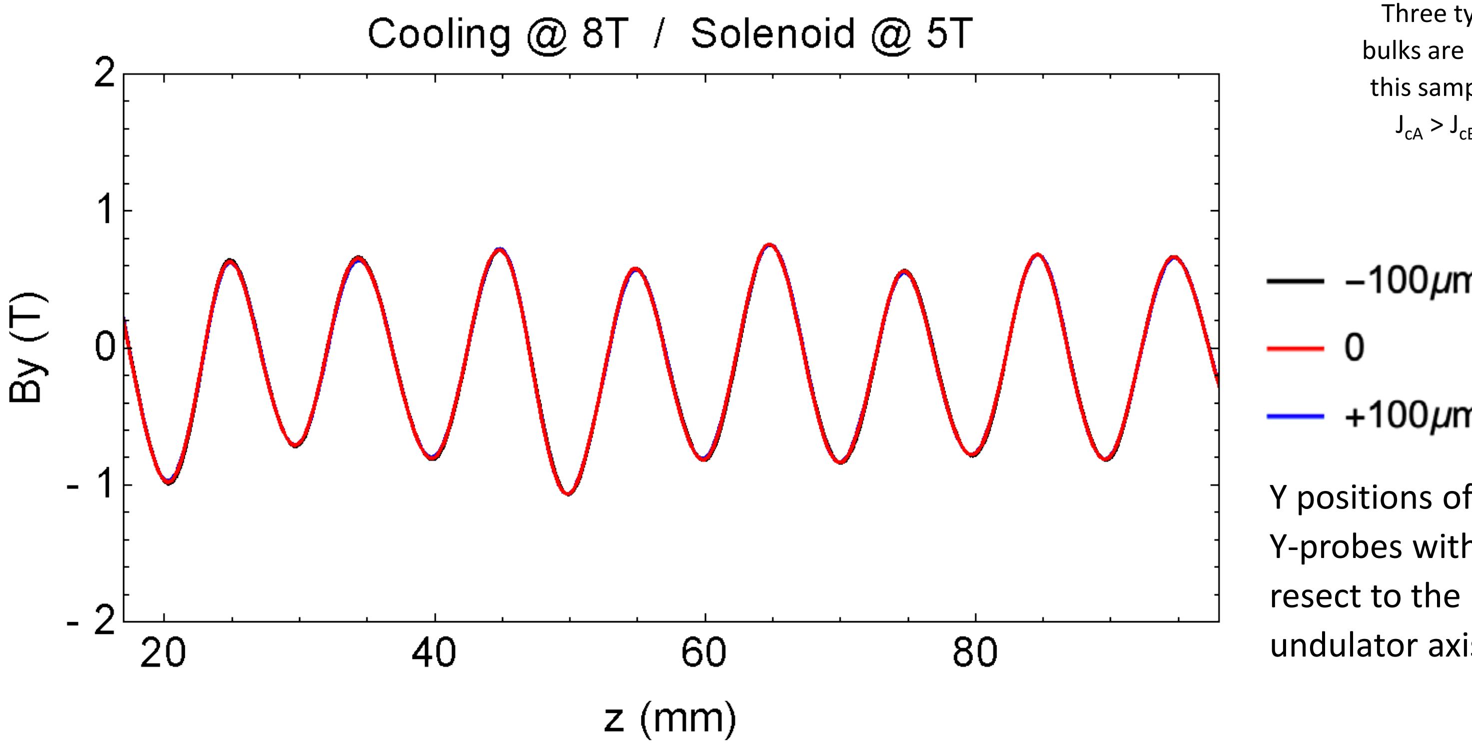

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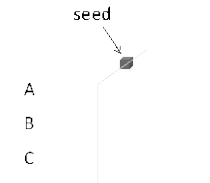
└→ *visible damage*

First Run – 13/14 October 2020



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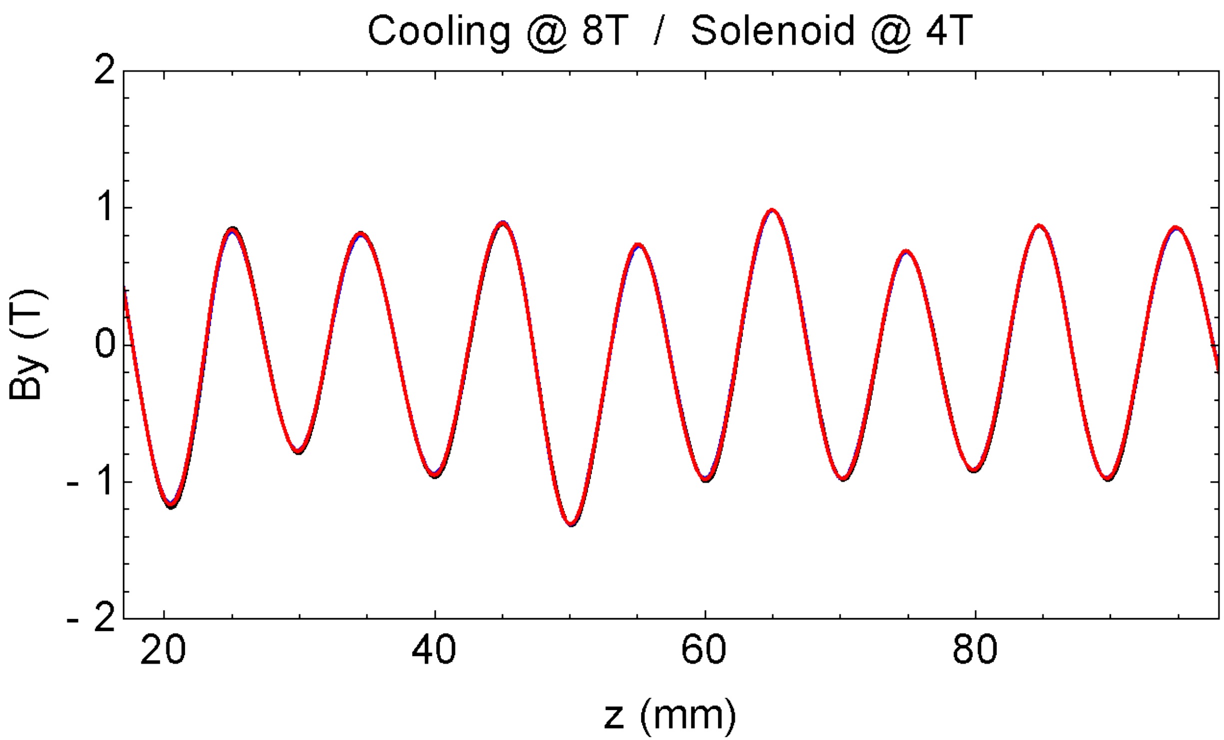
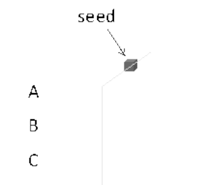


Y positions of the Y-probes with resect to the undulator axis

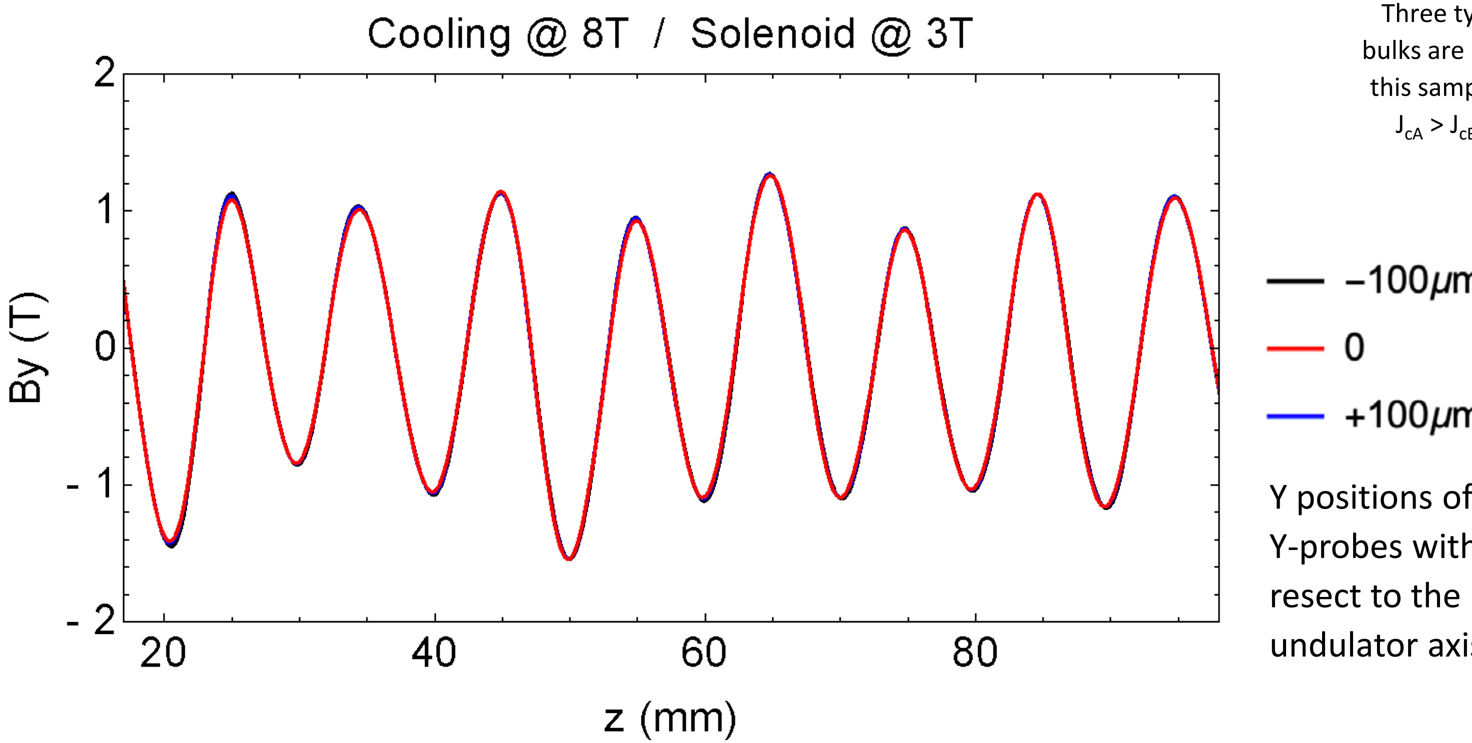
A B A B B B A A B A A A A B B B A A B B

└→ *visible damage*

First Run – 13/14 October 2020



Three types of bulks are used for this sample with $J_{cA} > J_{cB} > J_{cC}$

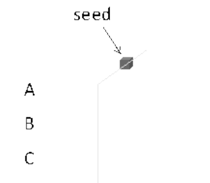


Y positions of the Y-probes with resect to the undulator axis

A B A B B B A A B A A A A B B B A A B B

└→ *visible damage*

First Run – 13/14 October 2020



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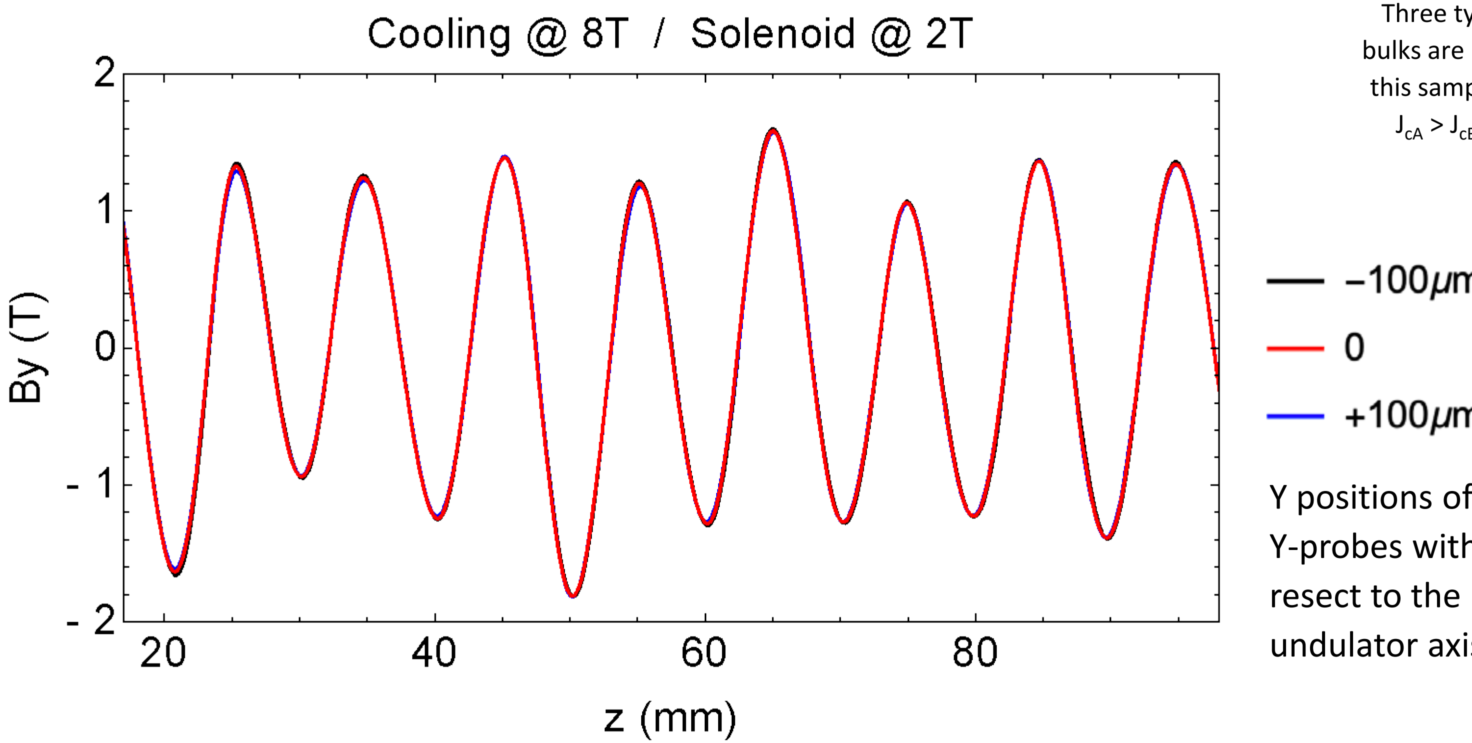
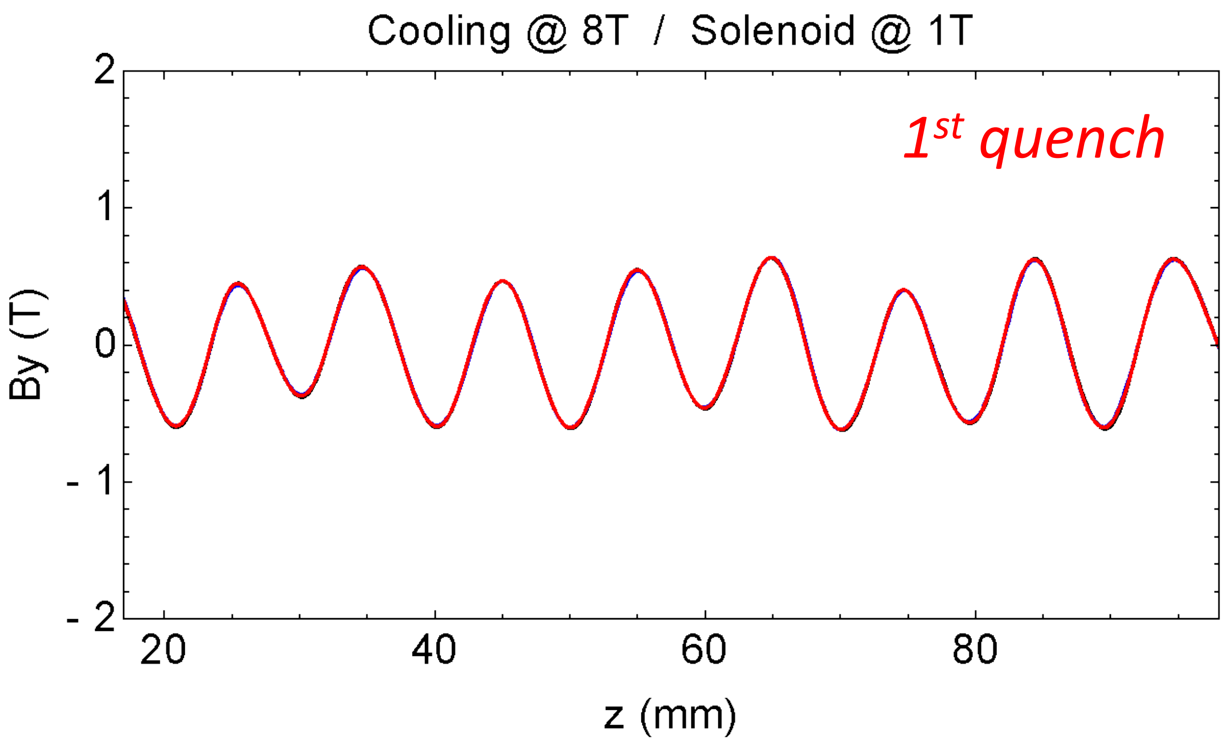


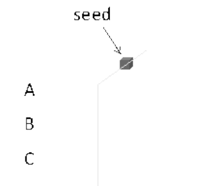
Y positions of the Y-probes with resect to the undulator axis

A B A B B B A A B A A A A B B B A A B B

└→ *visible damage*

First Run – 13/14 October 2020





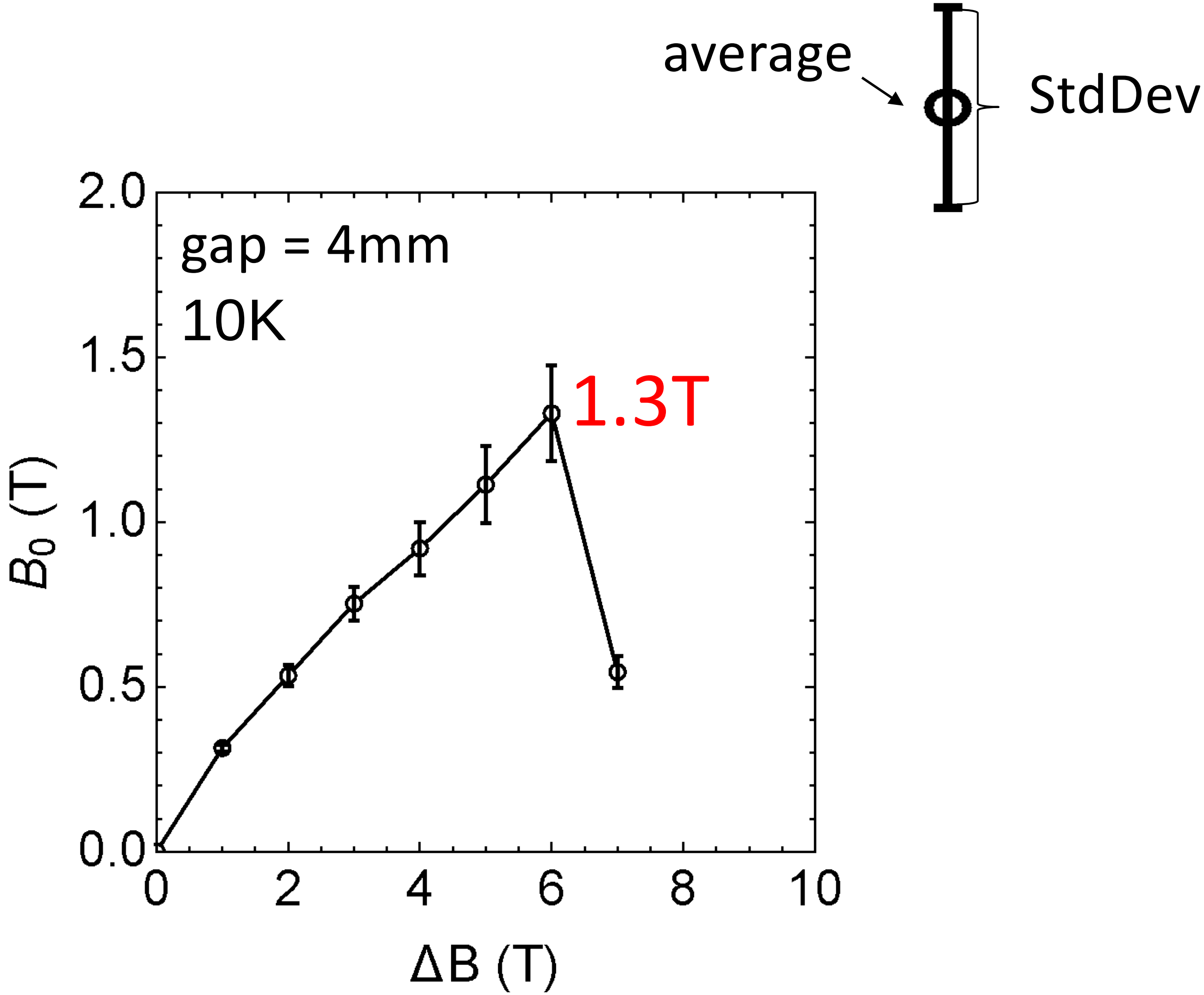
Three types of bulks are used for this sample with $J_{cA} > J_{cB} > J_{cC}$

Y positions of the Y-probes with resect to the undulator axis

A B A B B B A A B A A A A B B B A A B B

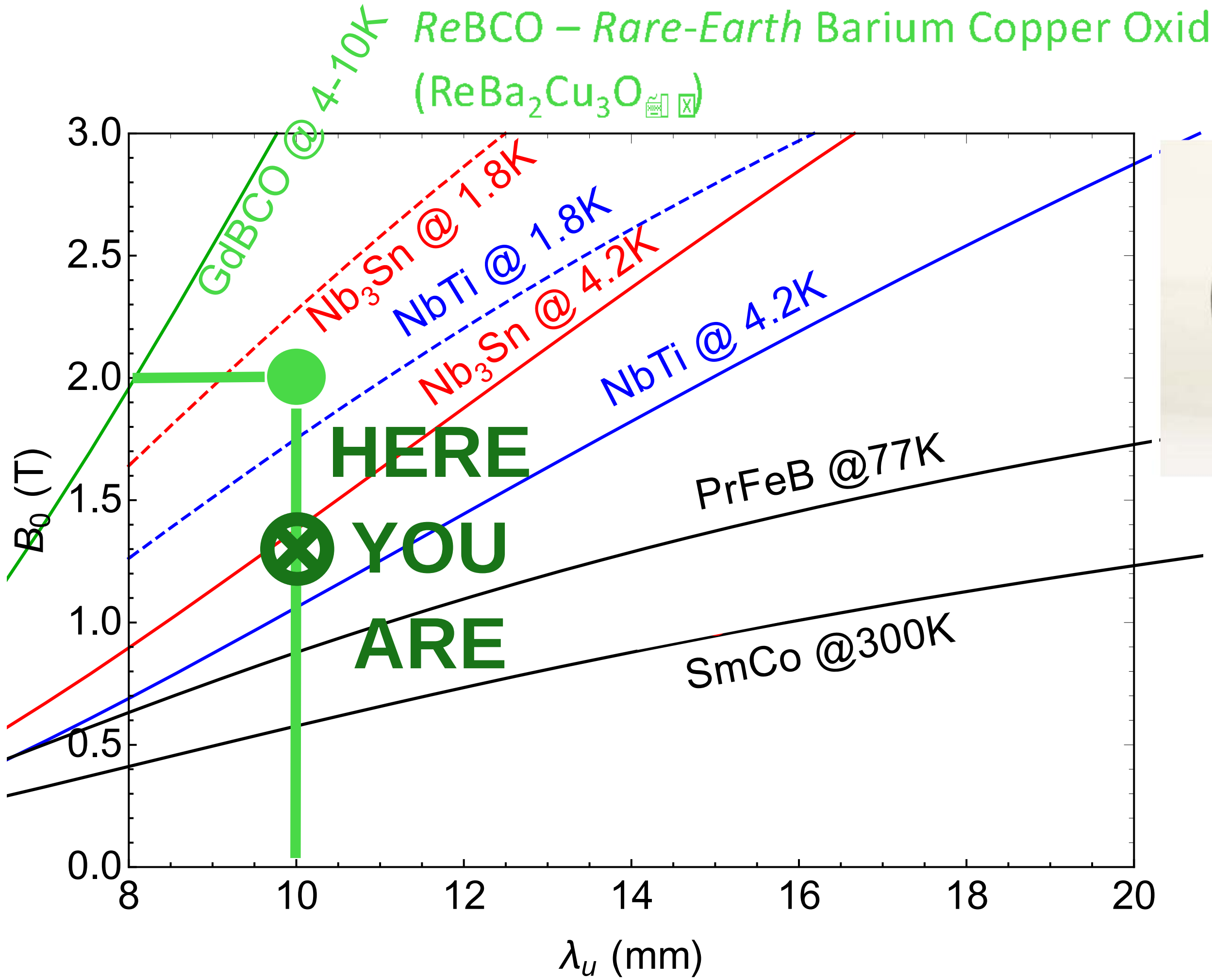
↳ *visible damage*

Summary of the Second Campaign – Oct 2020



Comparison among different technologies

ReBCO – Rare-Earth Barium Copper Oxide
($ReBa_2Cu_3O$)



[Scaling laws: E.R. Moog, R.J. Dejus, and S. Sasaki , Light Source Note: ANL/APS/LS-348
James Clarke, FLS 2012, March 2012, Ryota Kinjo Physical Review Special Topics, Accelerator and Beams 17, 022401 (2014)]

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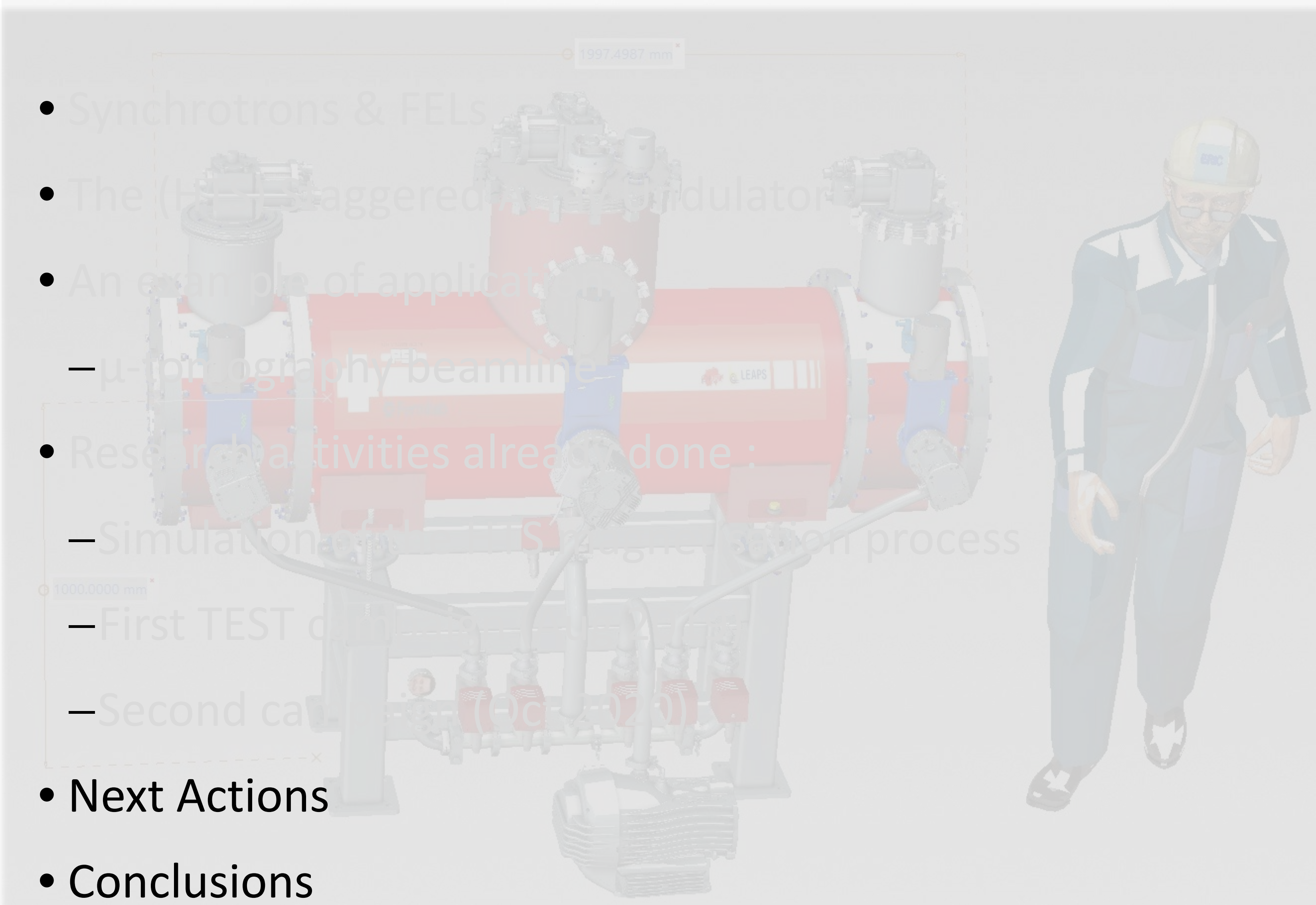
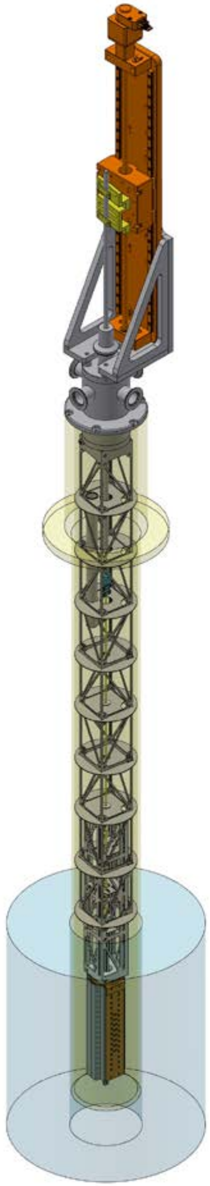
Overview

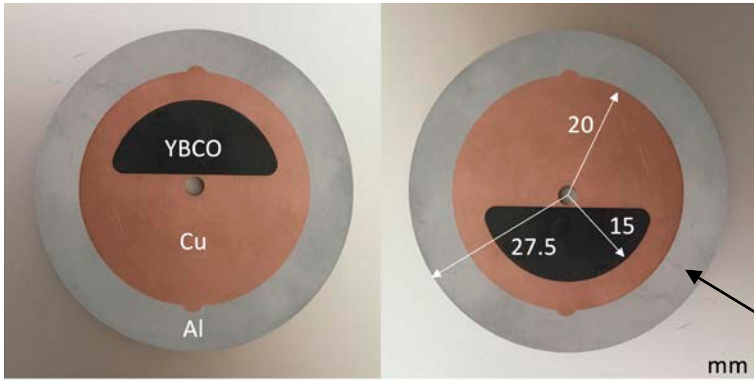


- Synchrotrons & FELs
- The (H[illegible]) staggered[illegible] undulator
- An example of application
  - µ-tomography beamline
- Research activities already done :
  - Simulation of [illegible] HTS magnetization process
  - First TEST [illegible]
  - Second ca[illegible] (Oct 2020)
- Next Actions
- Conclusions

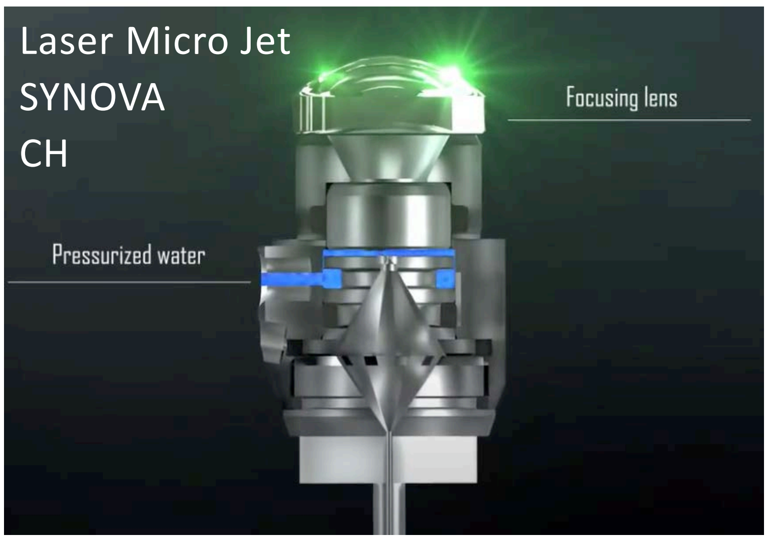
New Cryogenic Measuring System



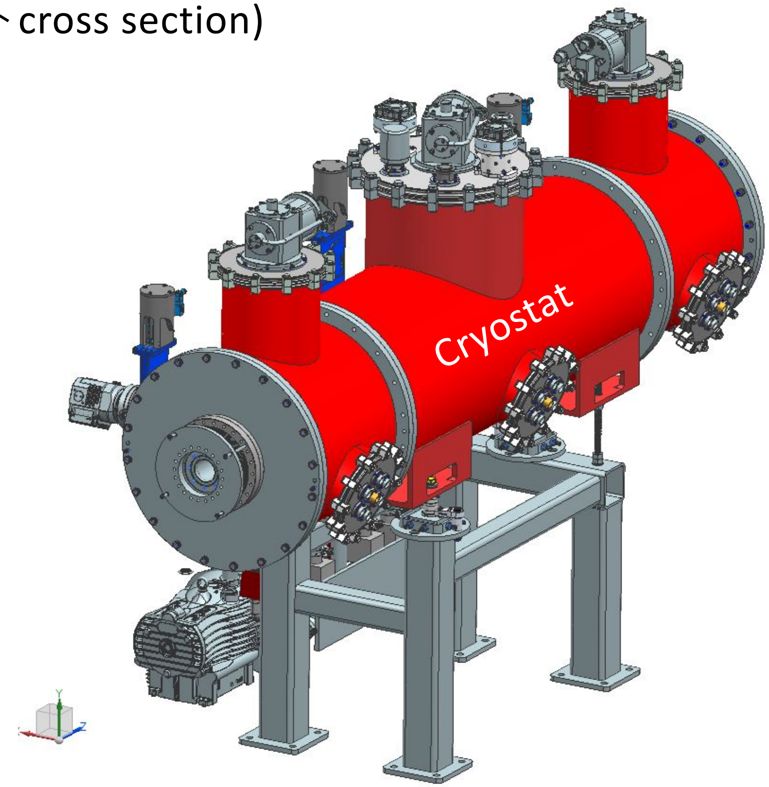
HTS Undulator – Engineering work



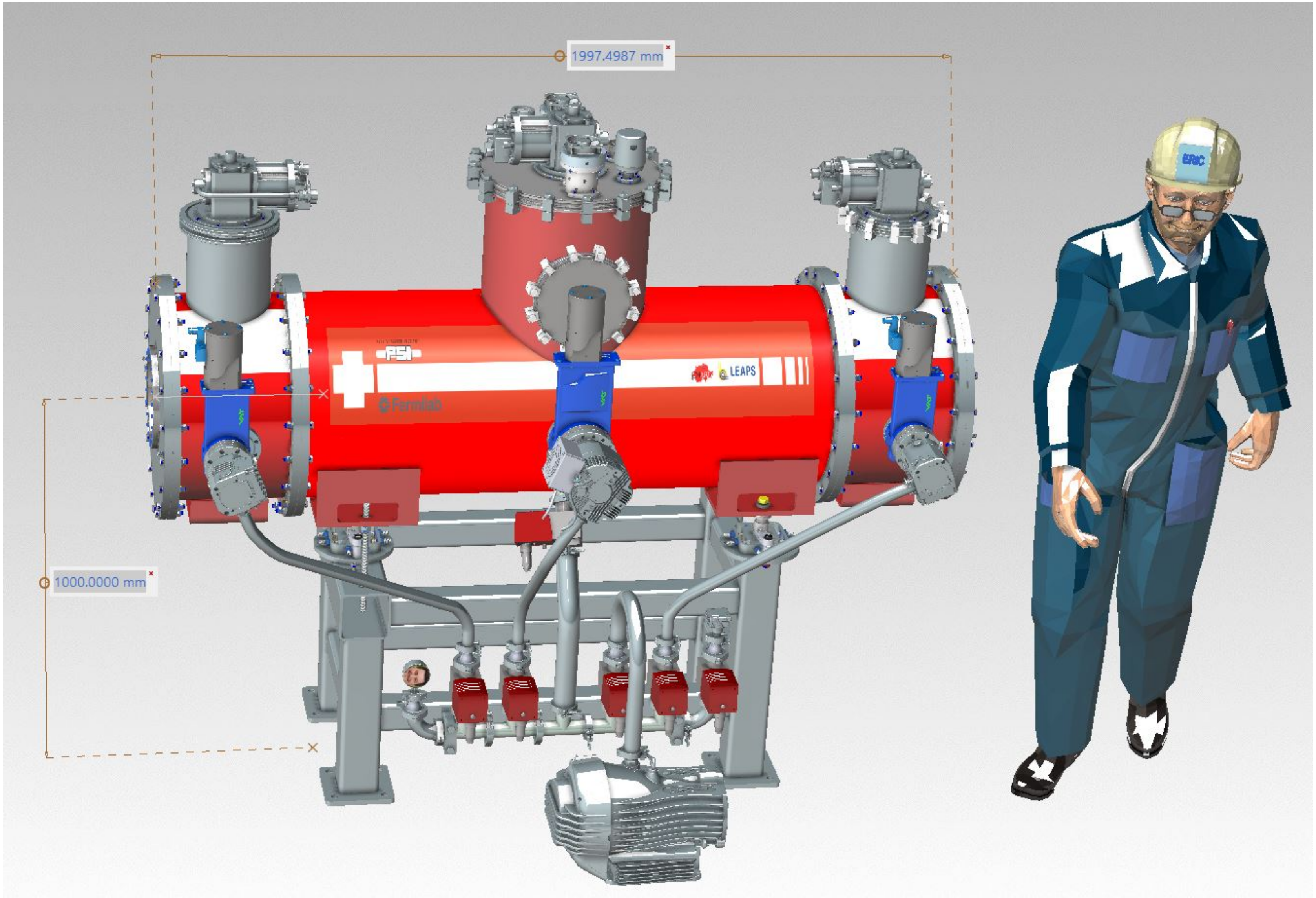
The HTS cristals are embedded into a copper matrix with micrometer accuracy, to be mechanical and themally stabilised. An additioanl Alluminum shrinking cylinder is used to precisly assemble the undulator array (in the picture only a cross section)



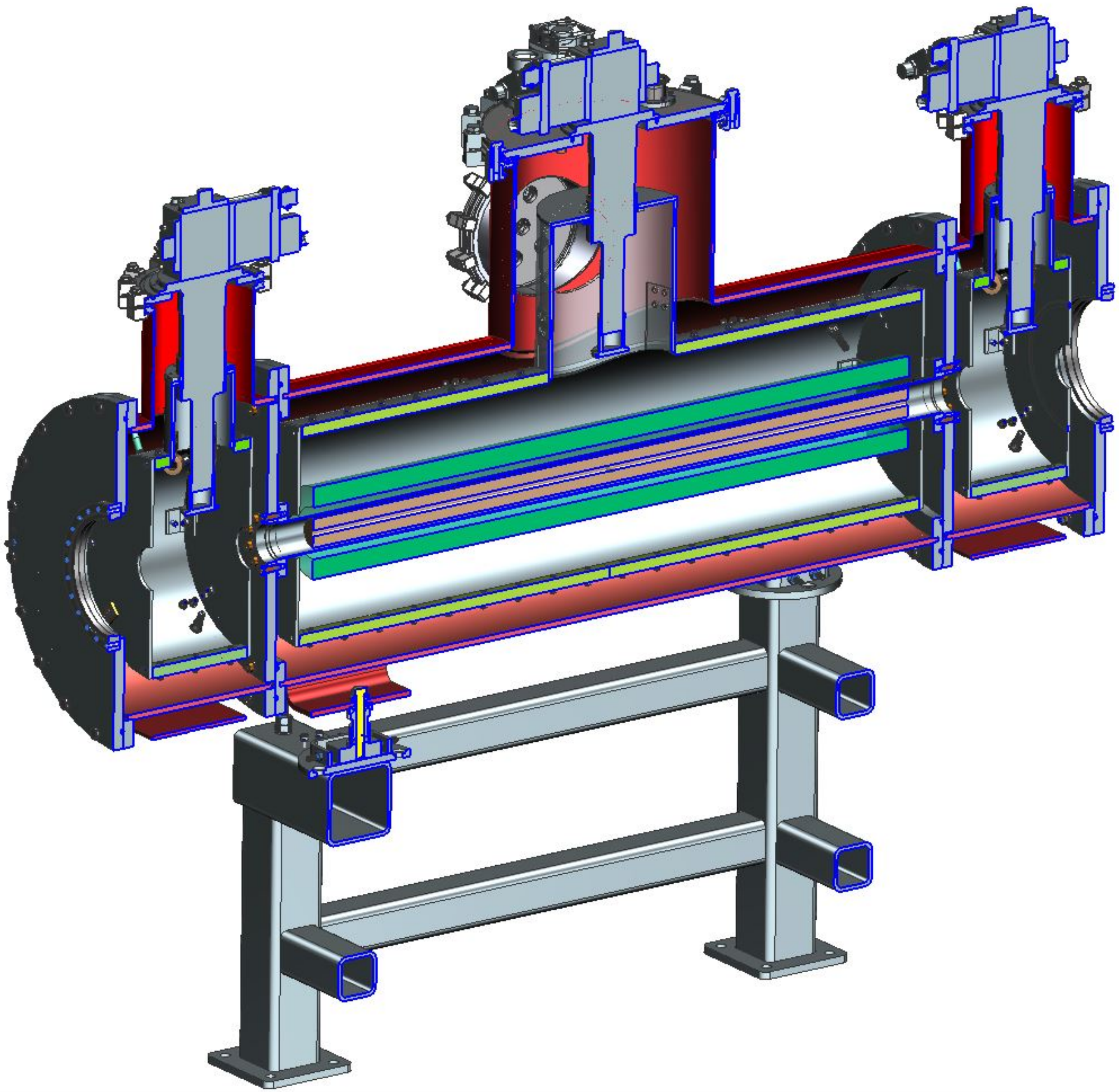
To precisly cut the HTS crystals at the optimum shape for our application



HTS Undulator – Engineering work



HTS Undulator – Engineering work



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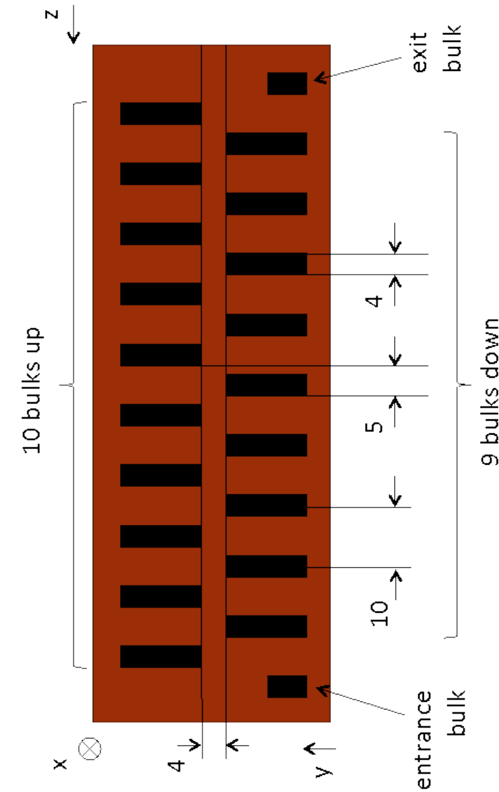
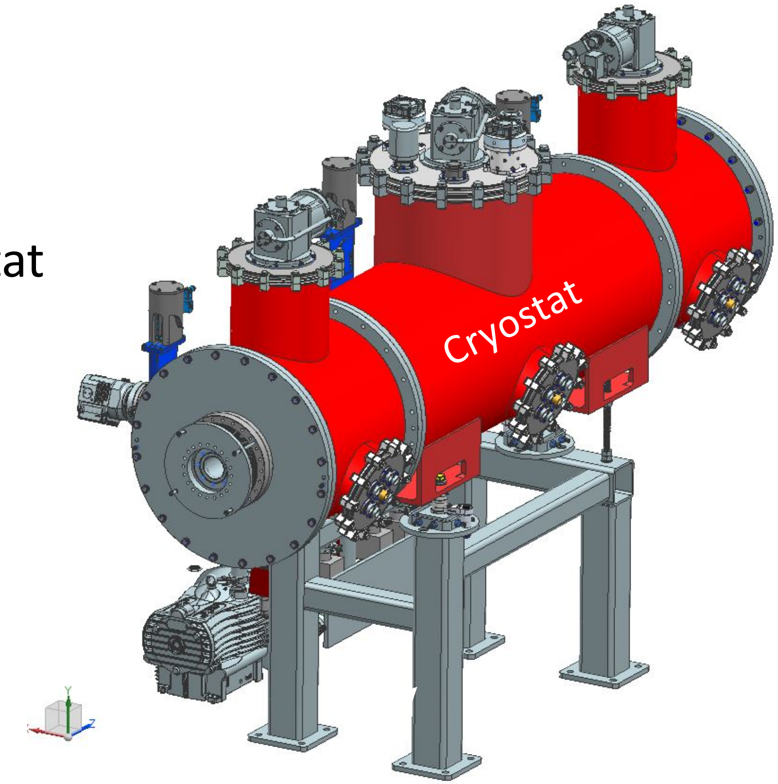
Short Sample Test Program



- Measure the undulator field versus solenoid field
- Study the quench behavior
- Study the pre-stress : shrink fitting techniques (bulks)
- Test different bulks : YBCO, GdBCO, EuBCO
- Bulk versus tapes : high field versus homogeneity
- Different geometries : planar, hybrid, circular
- Estimate the peak to peak field variation
- Try different shimming approach: period/pole height
- Reproducibility of the magnetization process
- End optimization study
- Test the flux freezing technique, 20-10K magnetization → 18-8K operation :
  - to reduce the decay
  - *<u>to introduce a temperature margin for operation</u>*

The first Prototype

- From a vertical to an horizontal cryostat
- to scale up to regular hard X-ray size (100 periods)
- Design & build a solenoid of 1m :
  - maximize its good magnetic length
  - reduced stray field on axis
  - shielding (<1mT @ 1m off-axis - radially)
- to demonstrate its operation :
  In SLS2.0 tomography microscopy beamline, I-TOMCAT



Conclusions

- We are still at the very beginning:
  - The ”high field” performance are NOT demonstrated yet: premature quenches to be understood asap
  - The phase error is HORRIBLE
- Next phase should focus on
  - Industrial samples with high degree of reproducibility and assemble accuracy
  - Finalize the design and the procurement of the 12T solenoid with Fermilab: at PSI Q1 2022

Acknowledgements

- *PSI* : K.Zhang, S.Hellmann, Th.Schmidt, L.Huber, S.Reiche, M.Bartkowiak, C.Calzolaio, Prof. M. Stampanoni
- *CHART* : Prof. H.R.Ott & Prof. L.Rivkin
- *Uni Cambridge* : J.Durrell, A.Dennis, M. Ainslie, Y. Shi
- *Spring8* : R.Kinjo, T.Takashi
- *Uni Malta* : N.Sammut, A.Sammut, J.Cassar
- *SENIS* : Prof.R.Popovic, S.Spasic, S.Dimitrijevic
- *KIT* : Prof. M.Noe

Reserved Slides

New Geometries

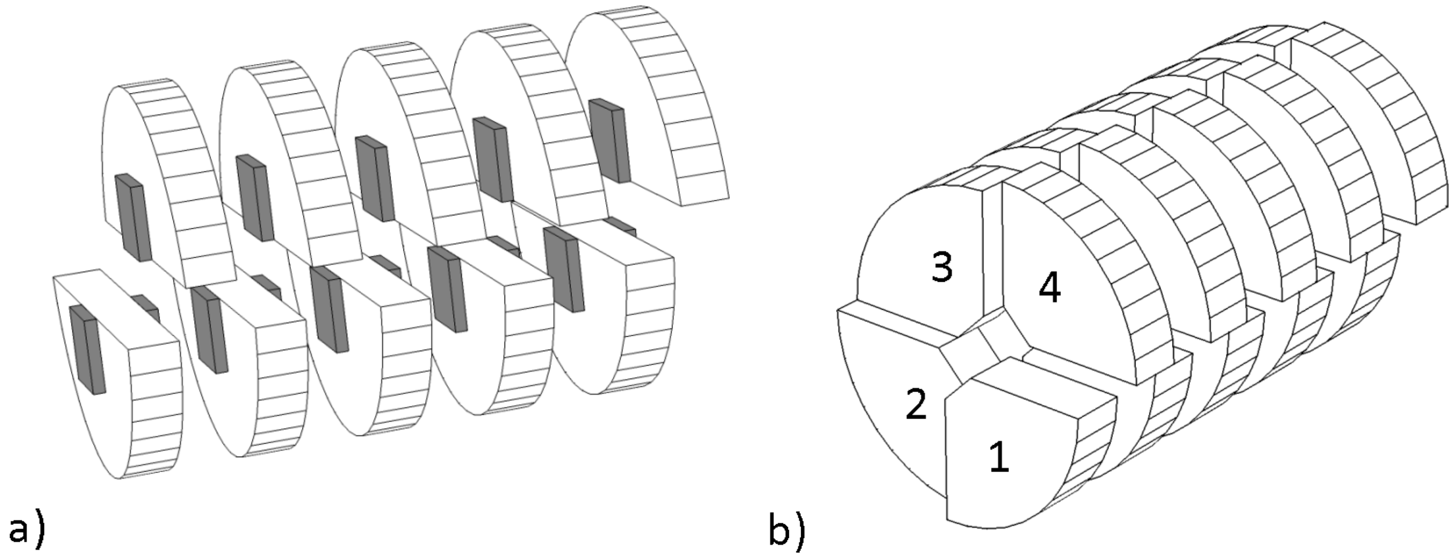


Figure 2. a) The optimised staggered array undulator (4 mm thick bulks) with additional ferromagnetic poles (dark-grey) positioned in the mm space left available. b) A new circular geometry which extends the staggered array to two dimensions. The round bulks are now cut in four pieces (1, 2, 3 & 4) and relatively shifted of $\lambda_u/4$ along the z-axis.

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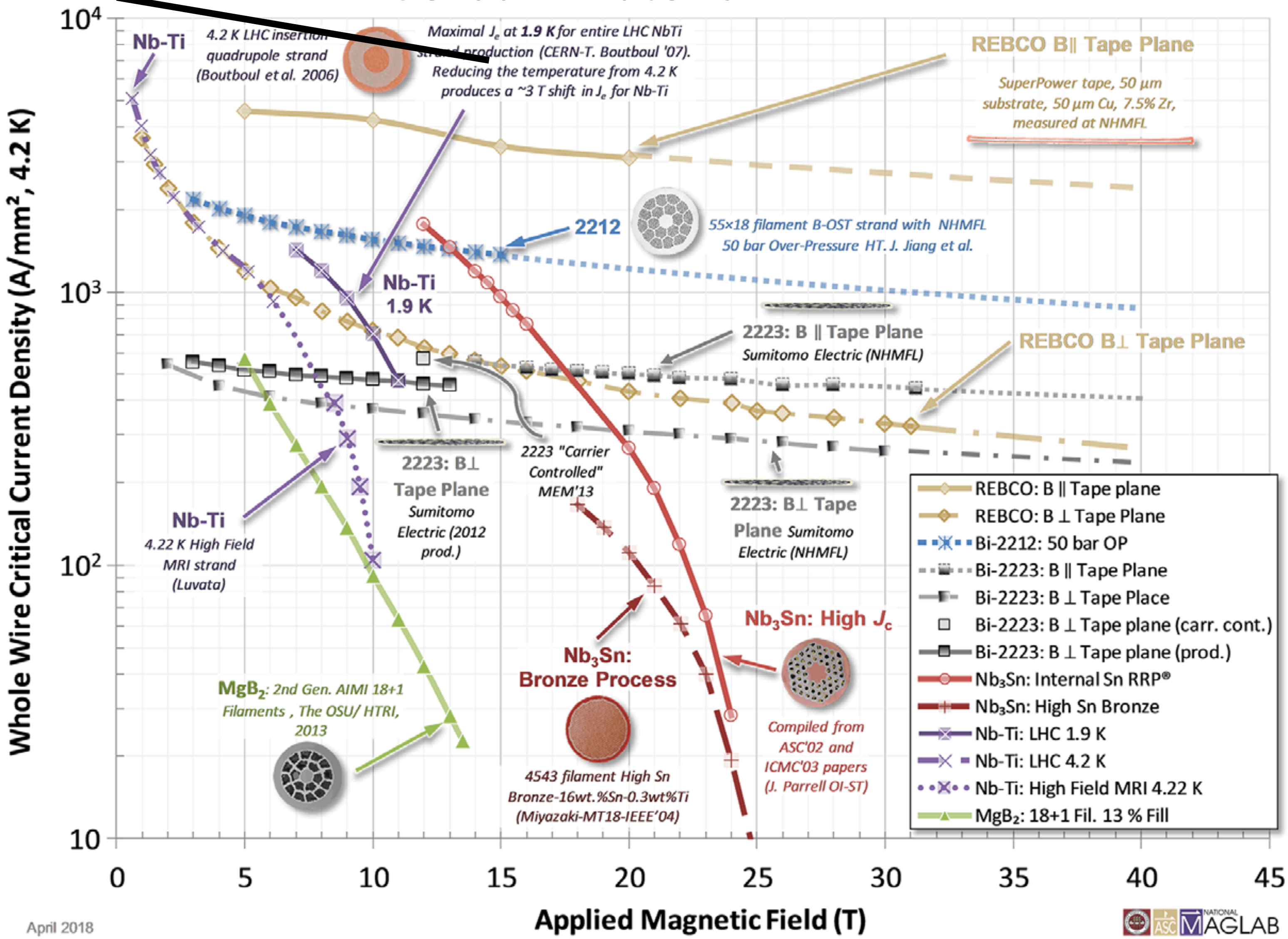
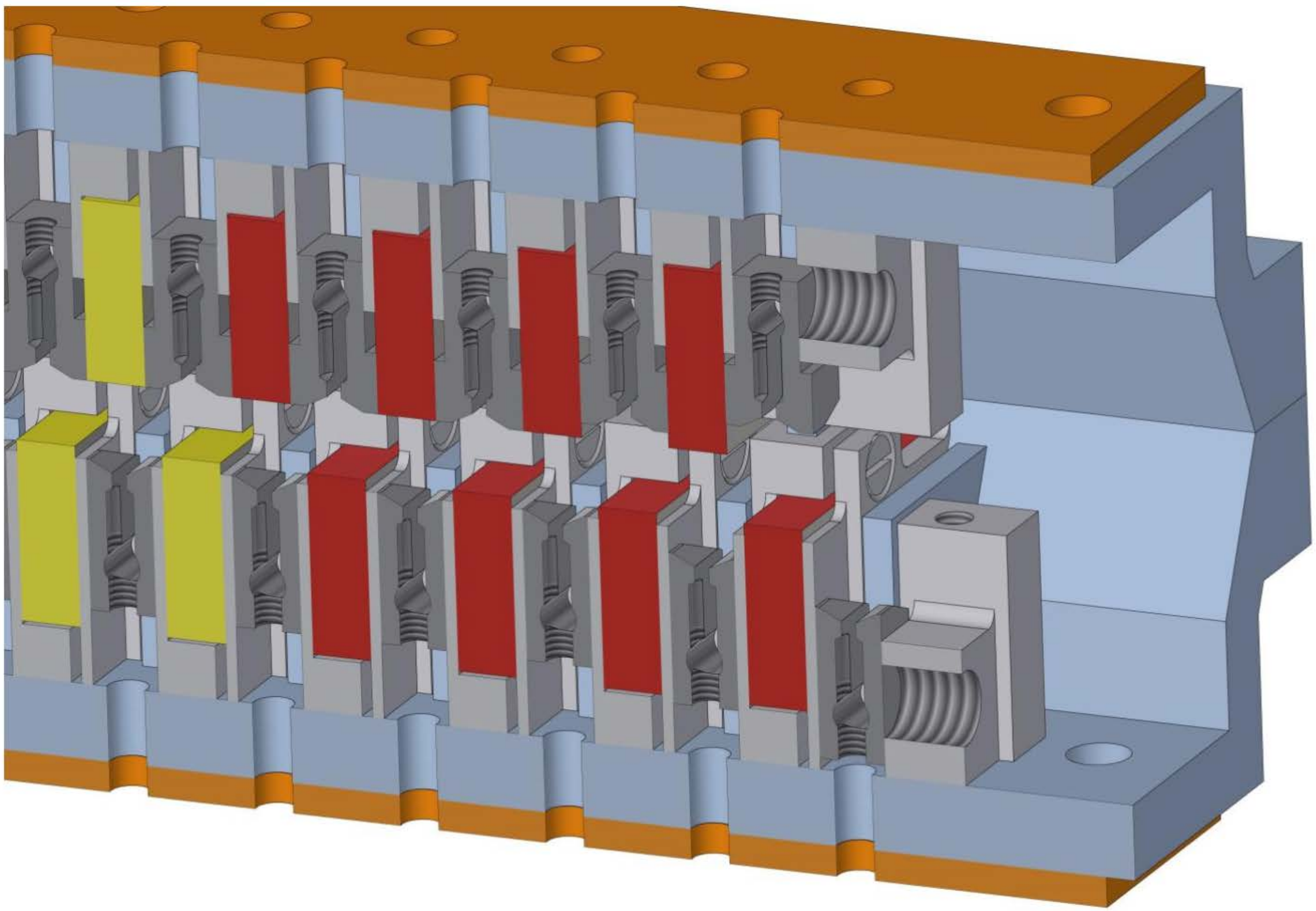
Comparison among superconducting materials

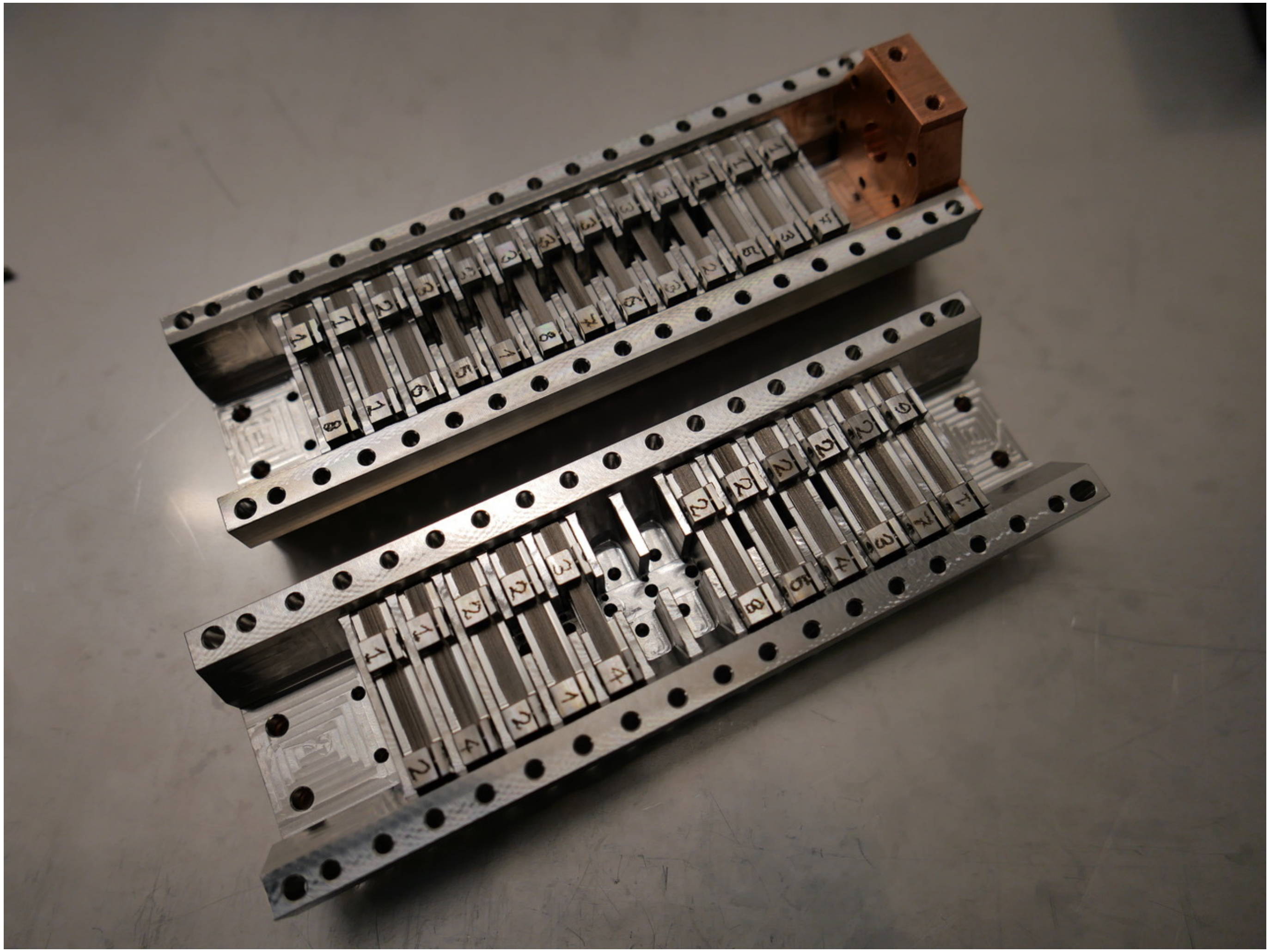
REBCO bulk material



SC-Tape Option



HTS Tape Option



HTS Tape Option