PAUL SCHERRER INSTITUT

PSI

UNIVERSITY OF CAMBRIDGE

Fermilab

SPring-8

ESRF The European Synchrotron

Xiaoyang Liang :: Insertion Device Group :: Paul Scherrer Institut

High-Temperature Superconducting Undulator Development at PSI/CHART

Joint Annual Meeting of ÖPG and SPS, 1st September 2021

CHART
Swiss Accelerator Research and Technology

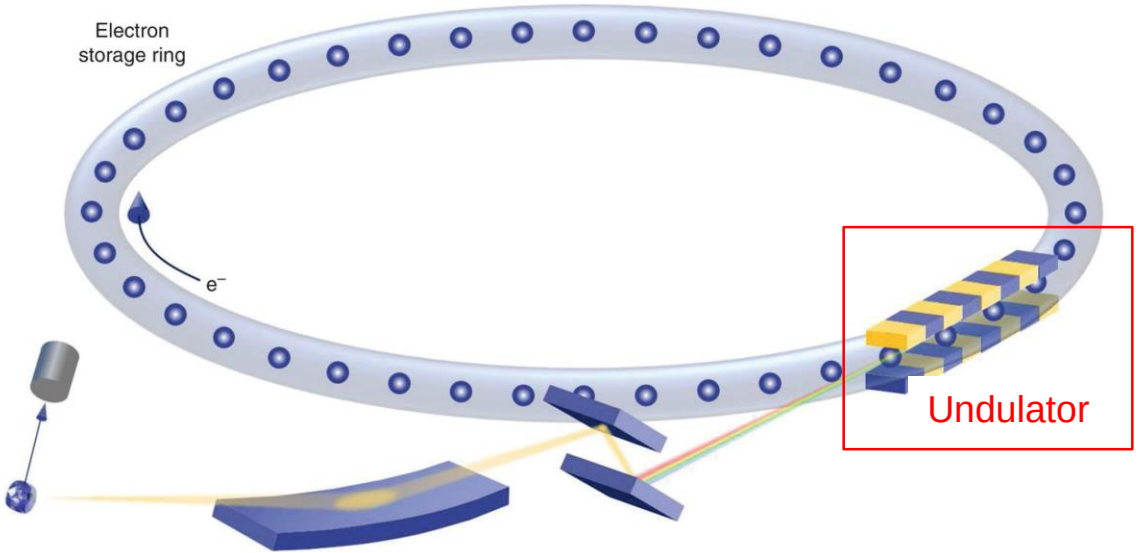
LEAPS INNOVATION

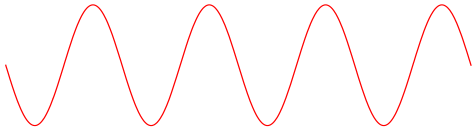
SLS 2.0

Overview

- Introduction:
  - Synchrotron Radiation Source
  - The (HTS) Staggered Array Undulator
  - Tomography Microscopy beamline for SLS 2.0
- Status of the Project:
  - Simulations & Design
  - Experimental achievements (03.2021 campaign)
  - Industrial samples towards <u>first meter-long prototype</u> for SLS 2.0
- Conclusions and outlook

Synchrotron Radiation Source





Effective magnetic field strength

Radiation wavelength

Undulator period length

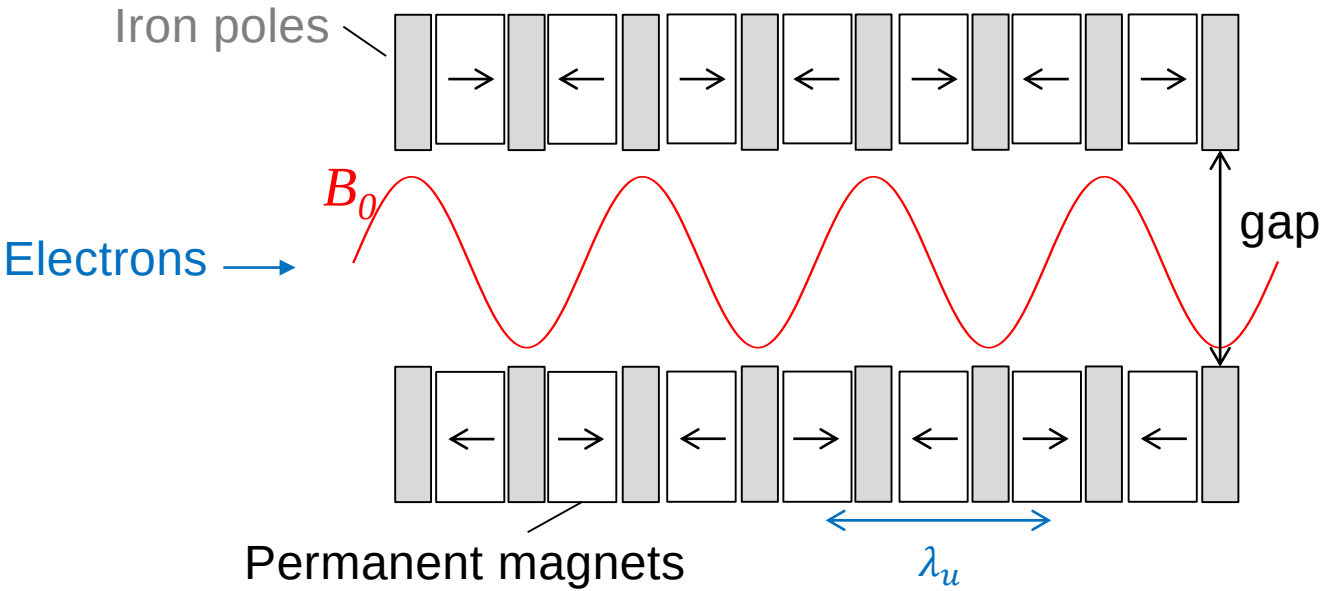
$$\lambda_r = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{1}{2}K^2\right)$$

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

γ : Lorentz factor of e⁻ ~ GeV

Undulator deflection parameter

Permanent Magnet Undulator with iron poles



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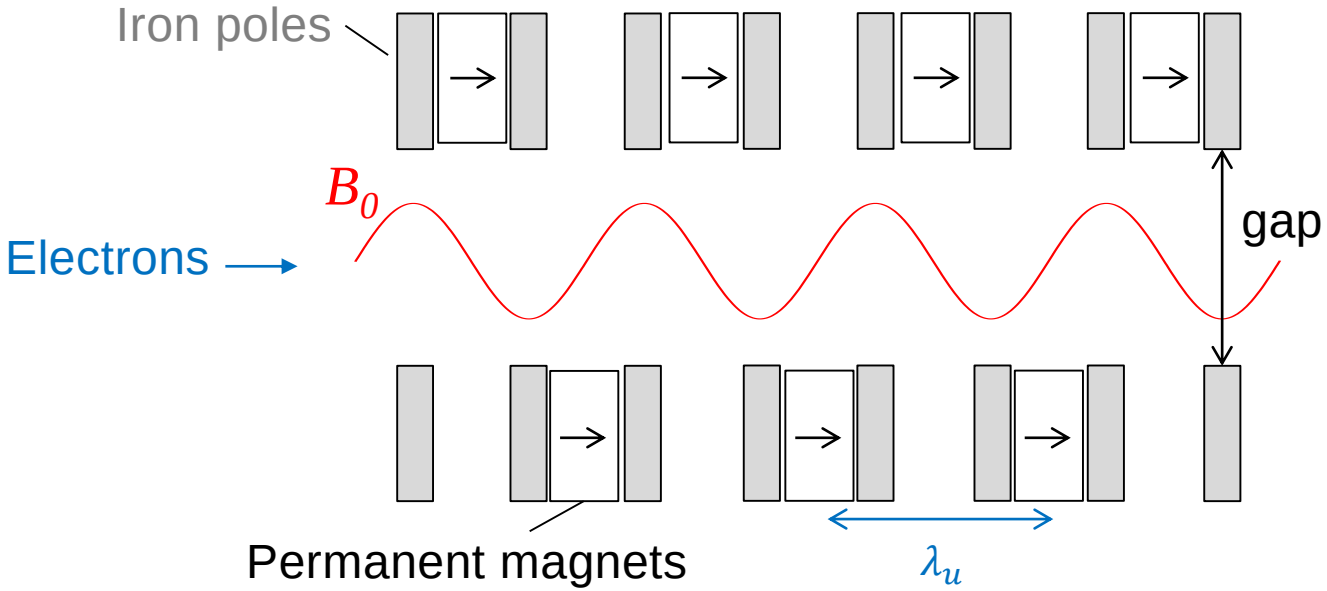
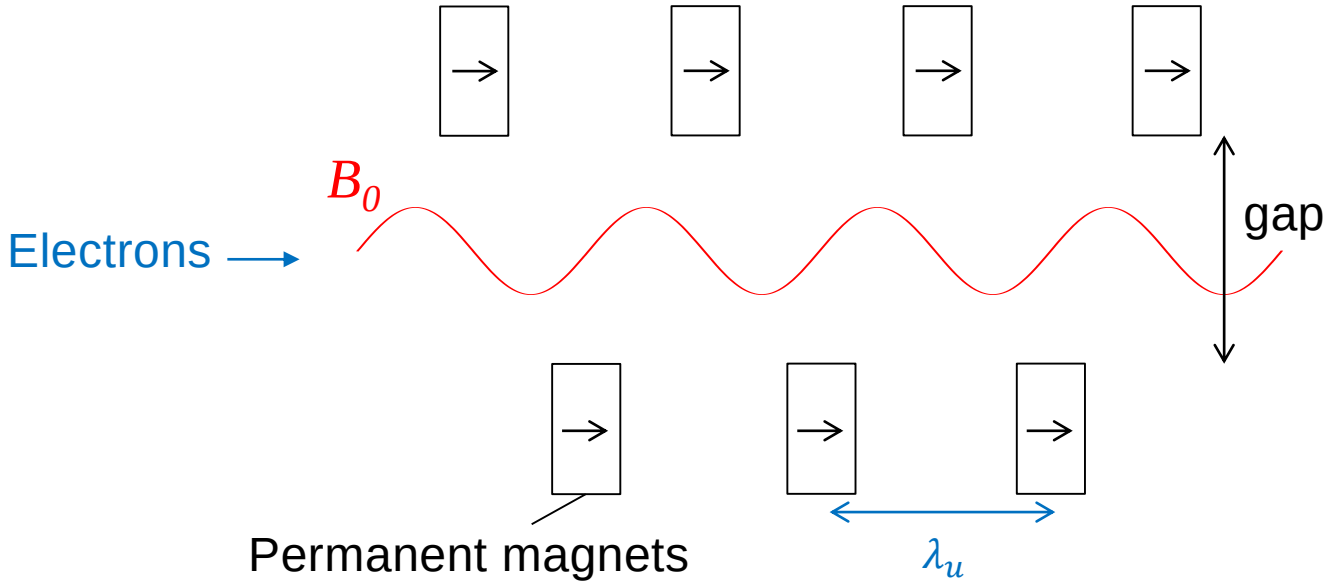
Staggered Array Undulator with iron poles

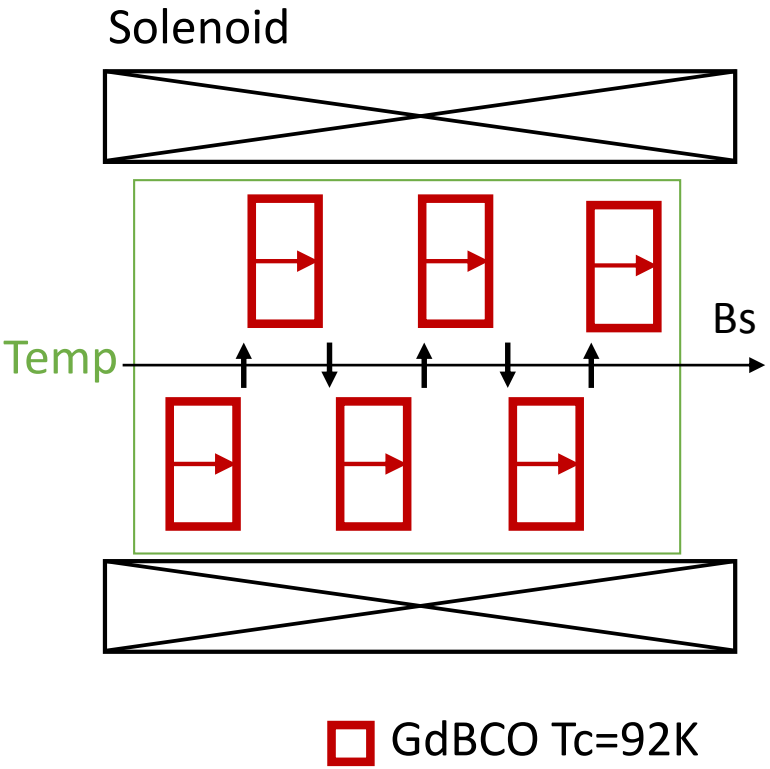


Staggered Array Undulator

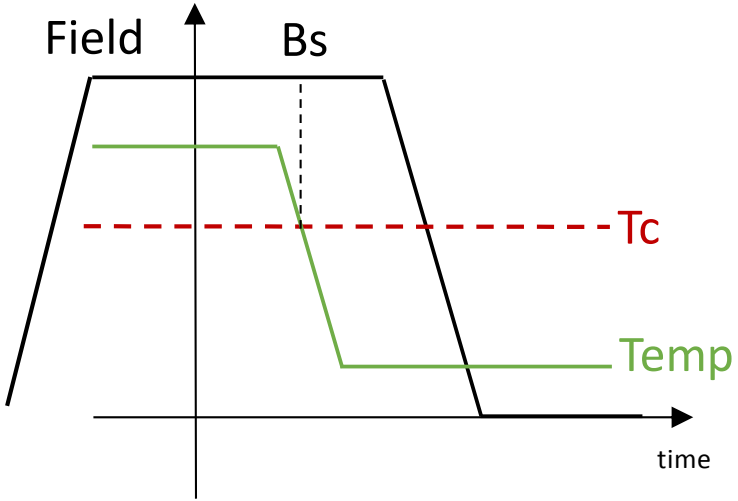


- Br(PM) ~ 1.3 T (1.7 T at 77 K)
- HTS material: “Br” ~ 17 T in-situ magnetization
- Without iron poles: simplification for preliminary design

Superconducting Staggered Array Undulator



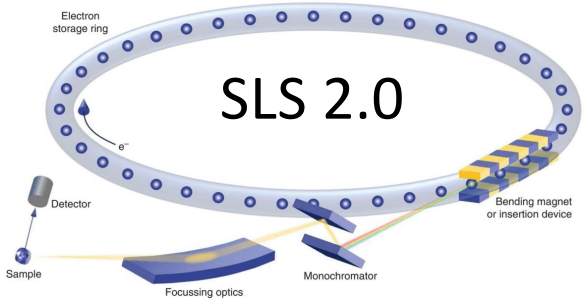
Example of *field cooling (FC)* magnetisation



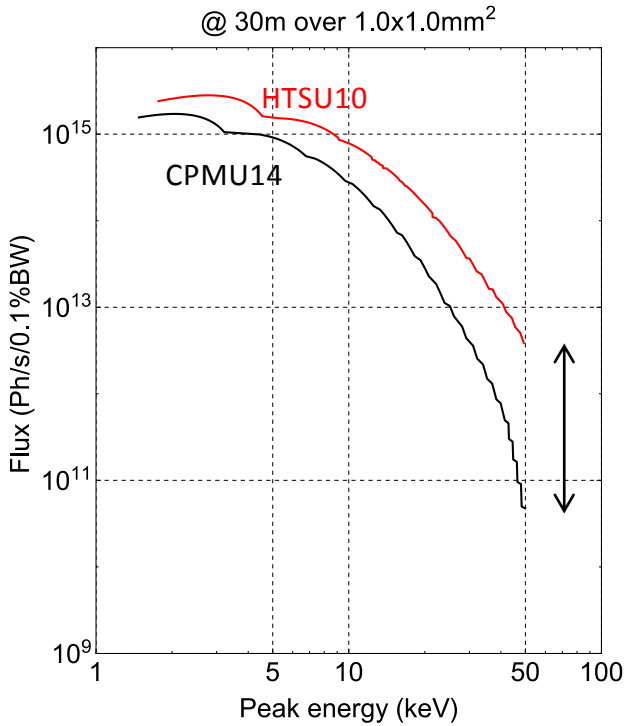
R.Kinjo et al. Appl.Phys. Express 6 (2013)

R. Kinjo et al. Proceedings of FEL. Vol. 473. 2008.

Undulator for I-TOMCAT beamline @ SLS 2.0



Dedicated to tomographic microscopy with photon energy up to 80 keV



100x more flux @50 keV

CPMU, $\lambda_u = 14$ mm with $B_0 = 1.3$ T

HTSU, $\lambda_u = 10$ mm with $B_0 = 2.0$ T

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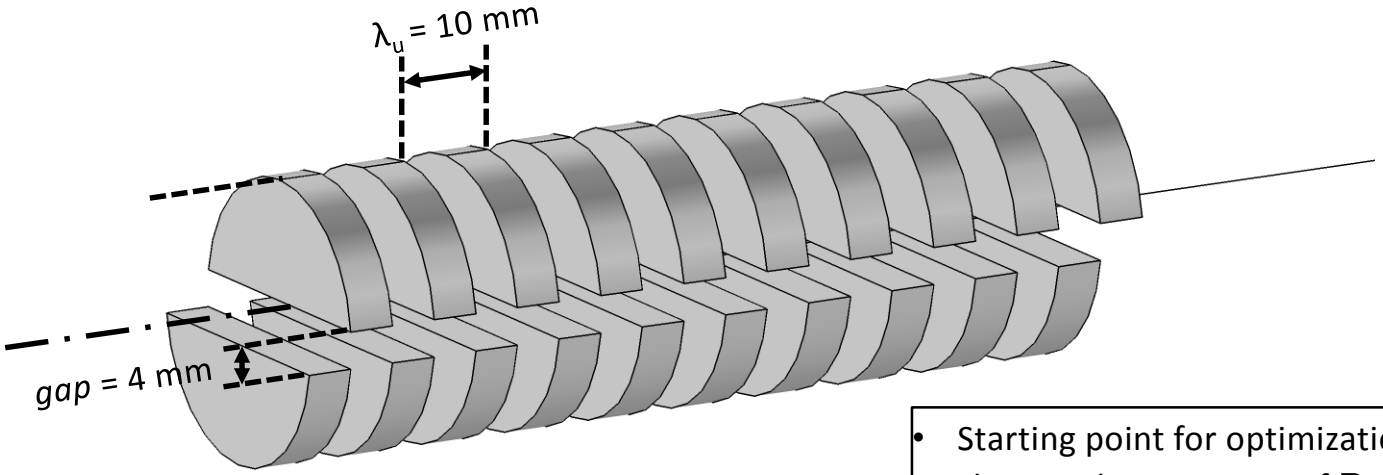
Bulk HTS Staggered Array Undulator

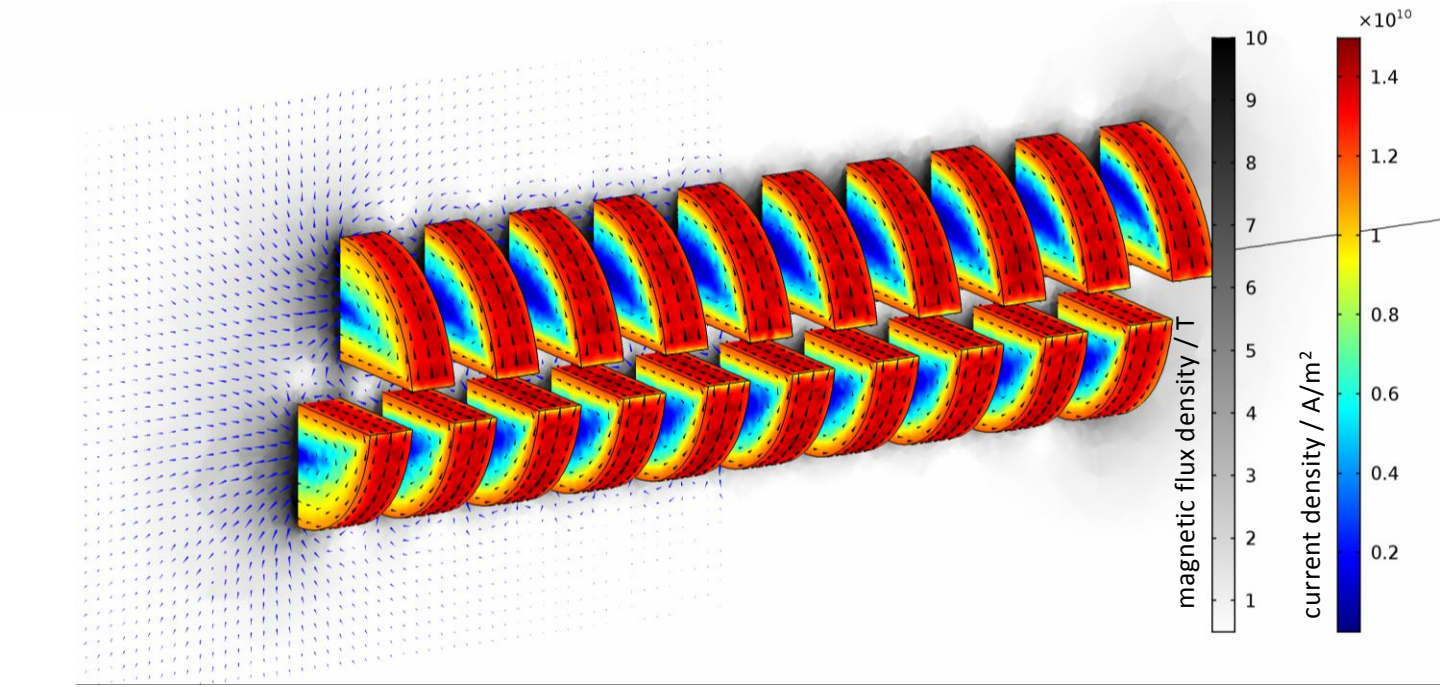
10 period geometry for simulation and optimization:



- Starting point for optimization is close to the geometry of R. Kinjo
- *Re*BCO bulks
- J_c(0 T, 4.2 K) = 1.5e10 A/m^2

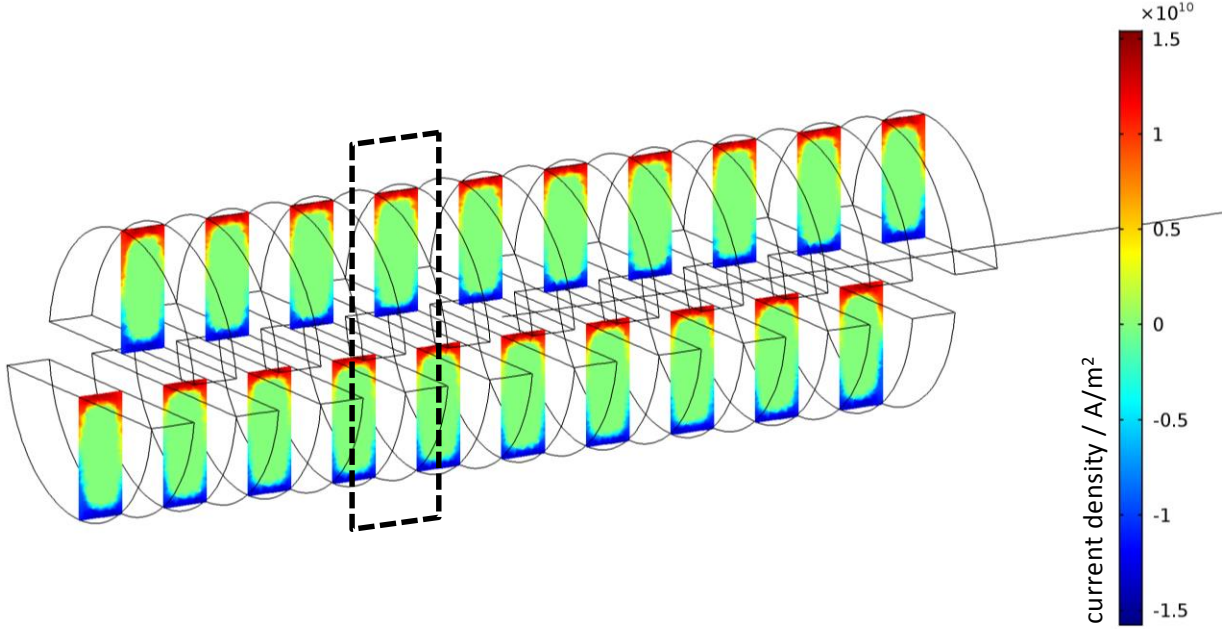
Bulk HTS Staggered Array Undulator

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

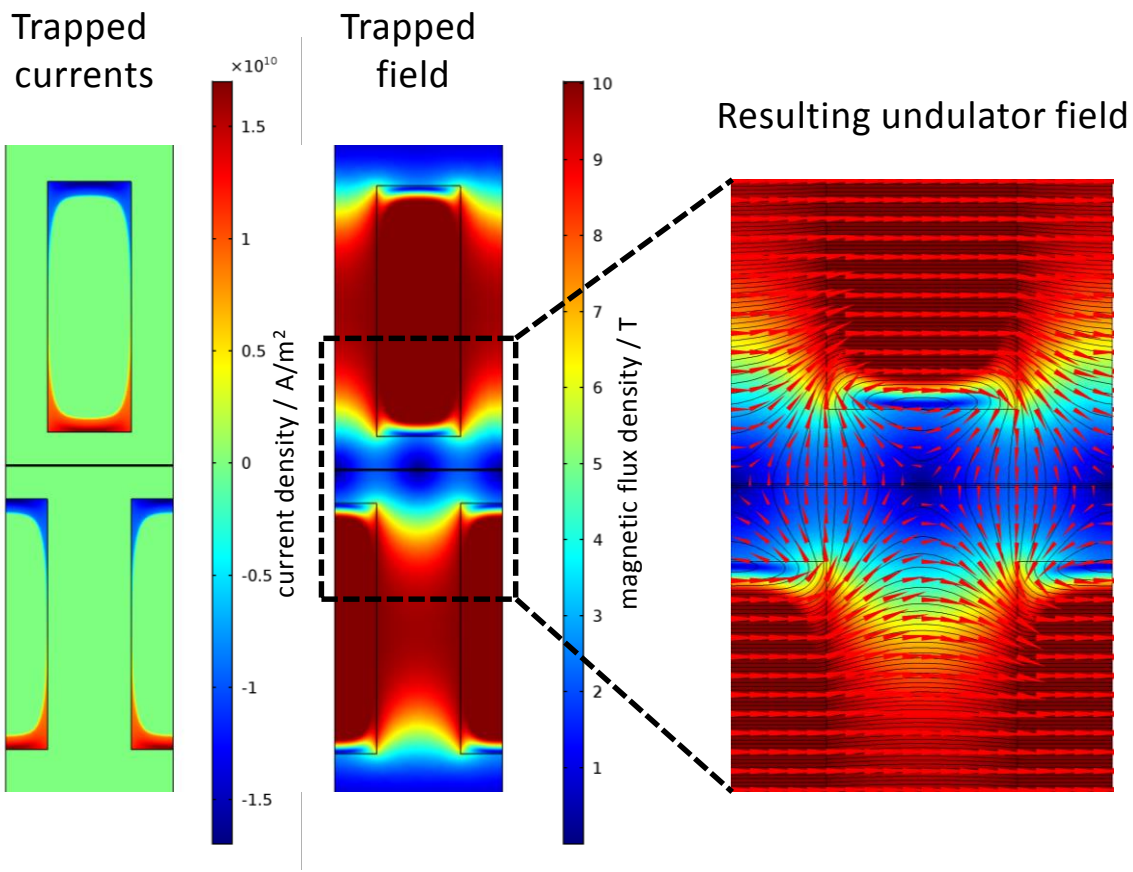


Bulk HTS Staggered Array Undulator

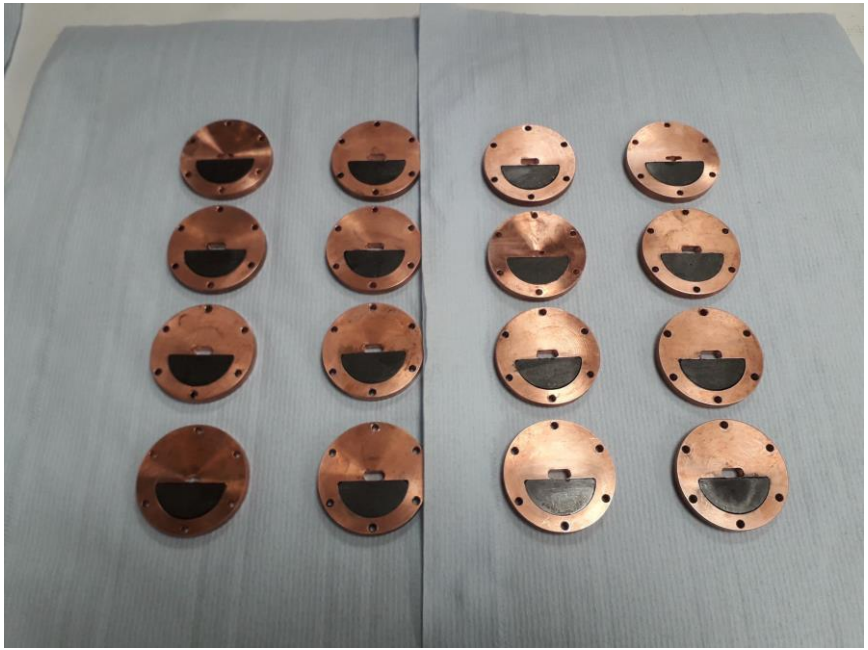
Internal current density



Bulk HTS Staggered Array Undulator



Short Sample



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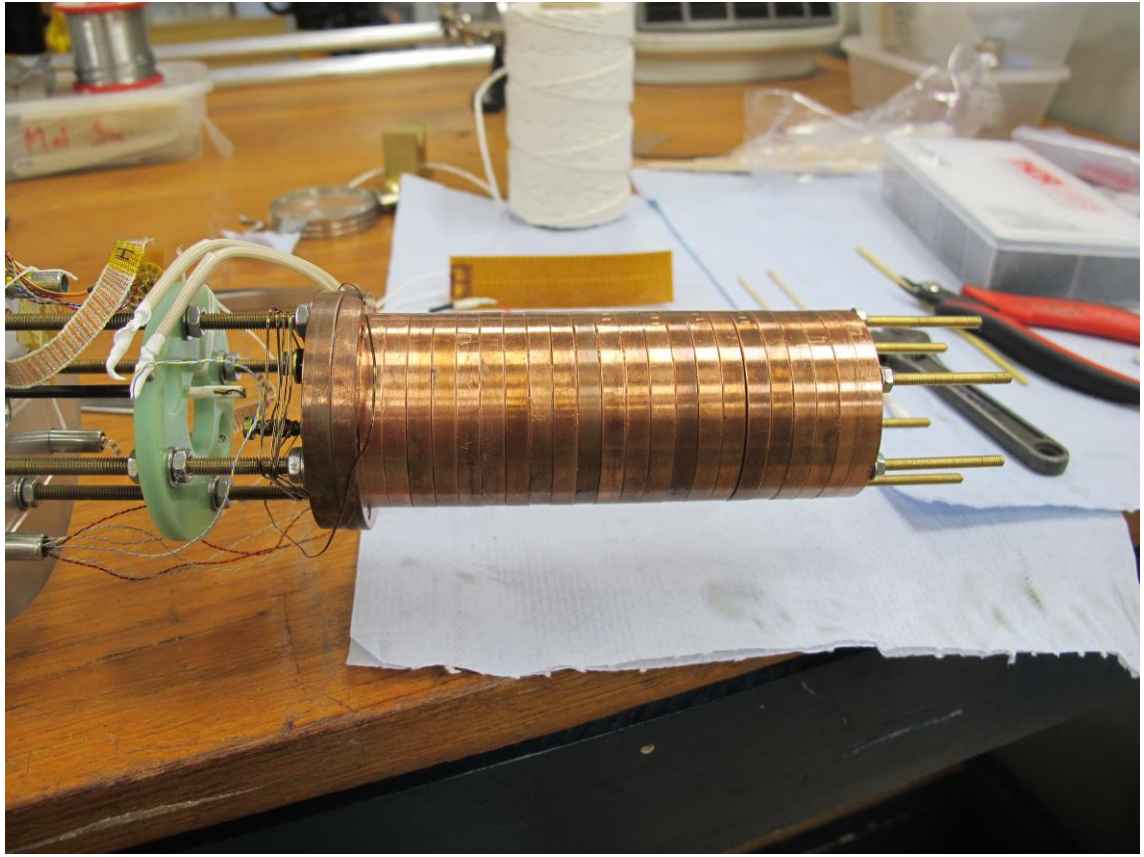
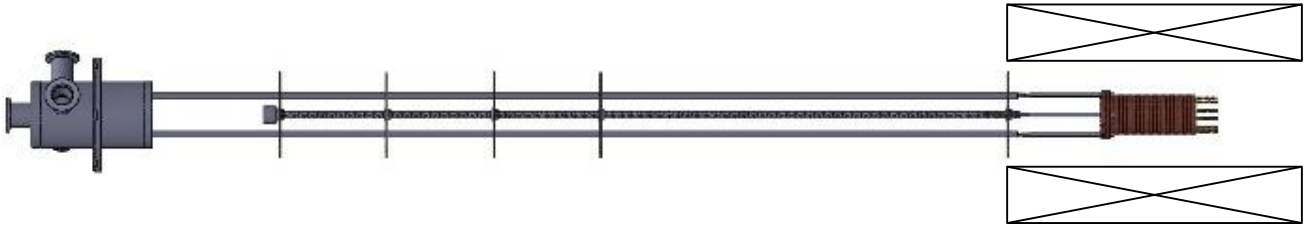


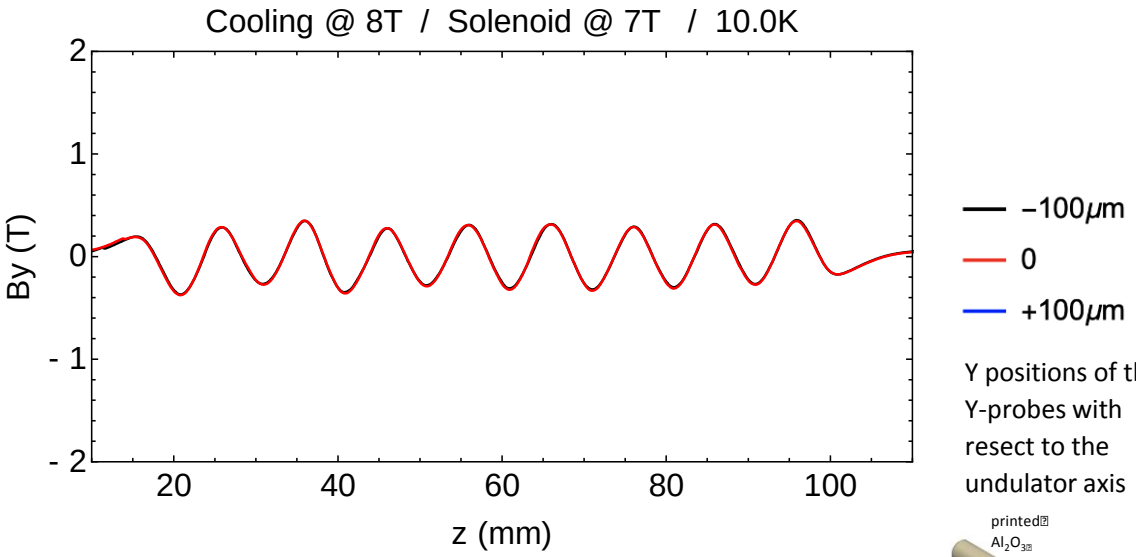
Test Campaign – 03.2021

Test Campaign – 03.2021

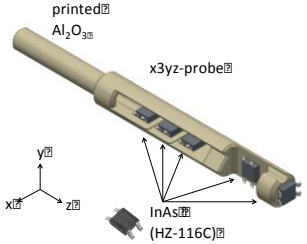
- The sample is cooled in a 8.0 T solenoid
- Temperature is stabilised at 10 K
- Solenoid is ramped down (1 T/h) in steps of 1 T
- Field profile (Bx,By1,By2,By3,Bz) was recorded during the plateau



Test Campaign – 03.2021



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



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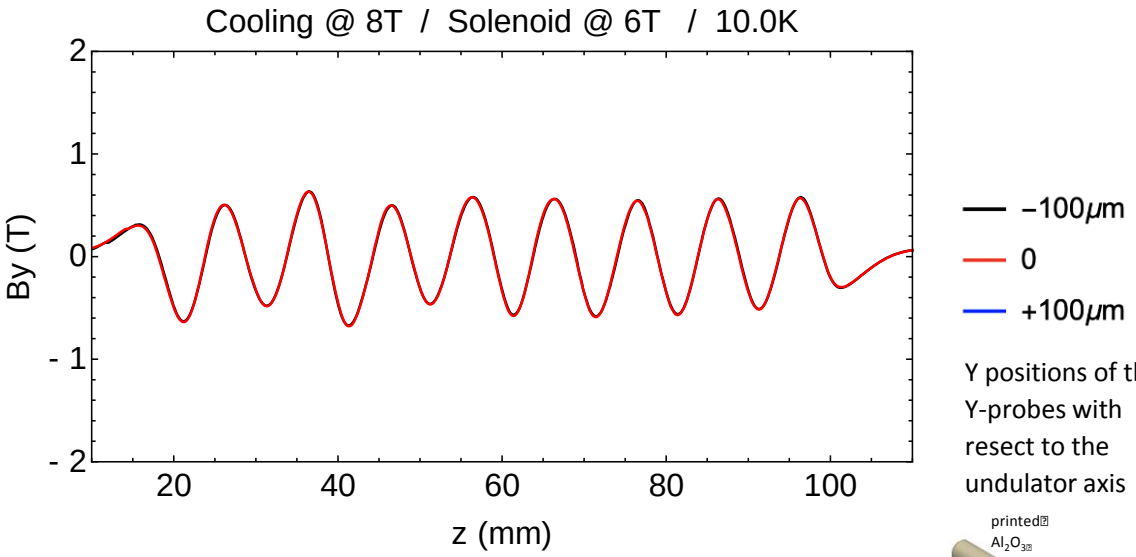

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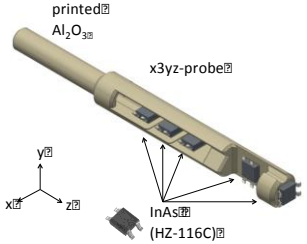

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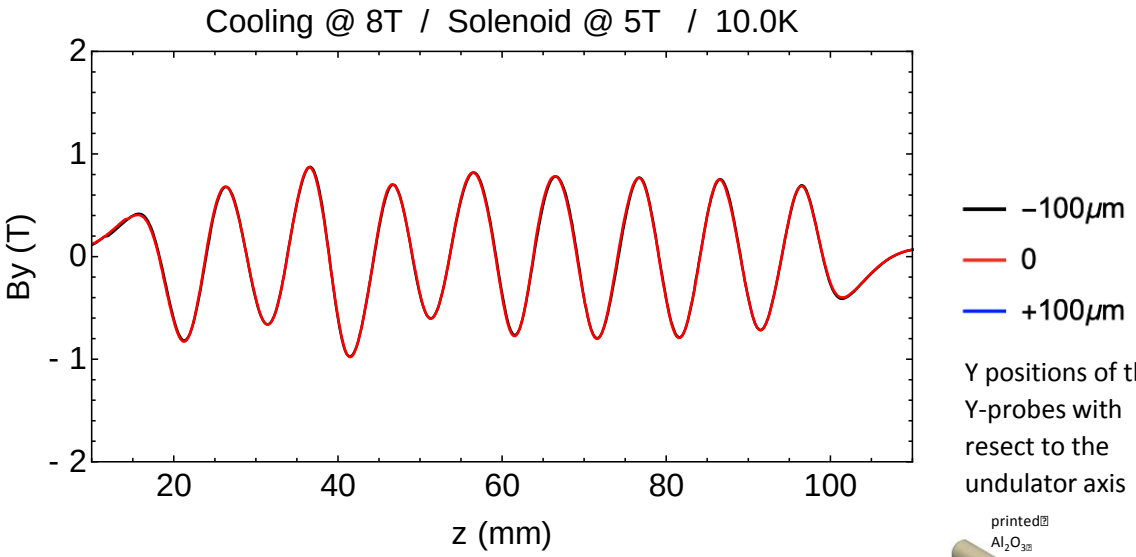

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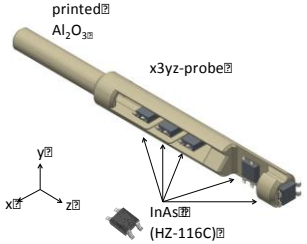

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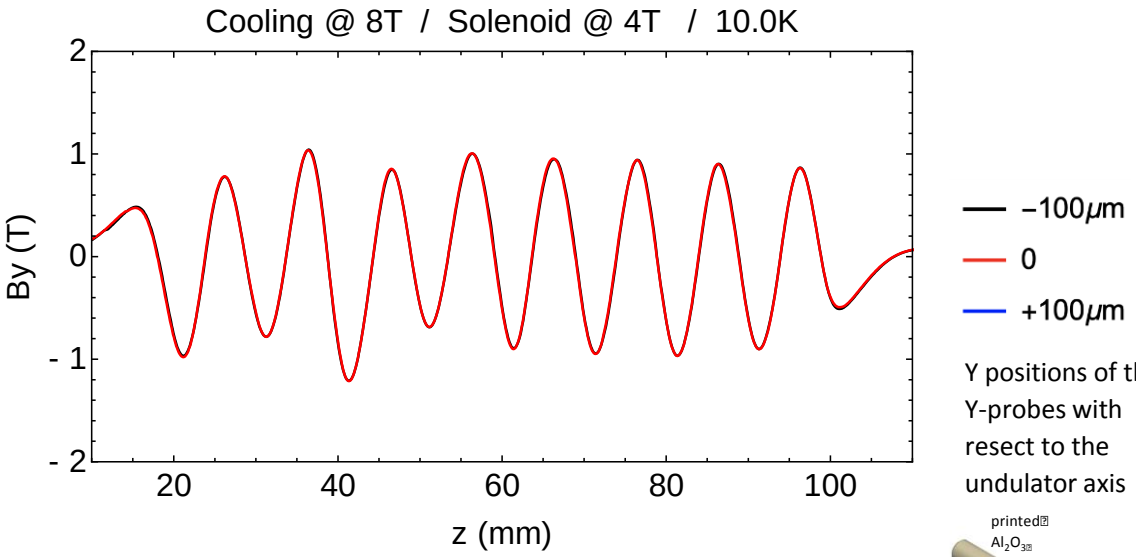

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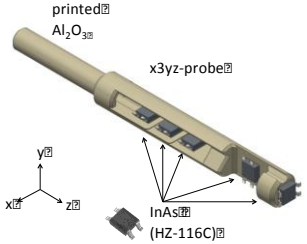

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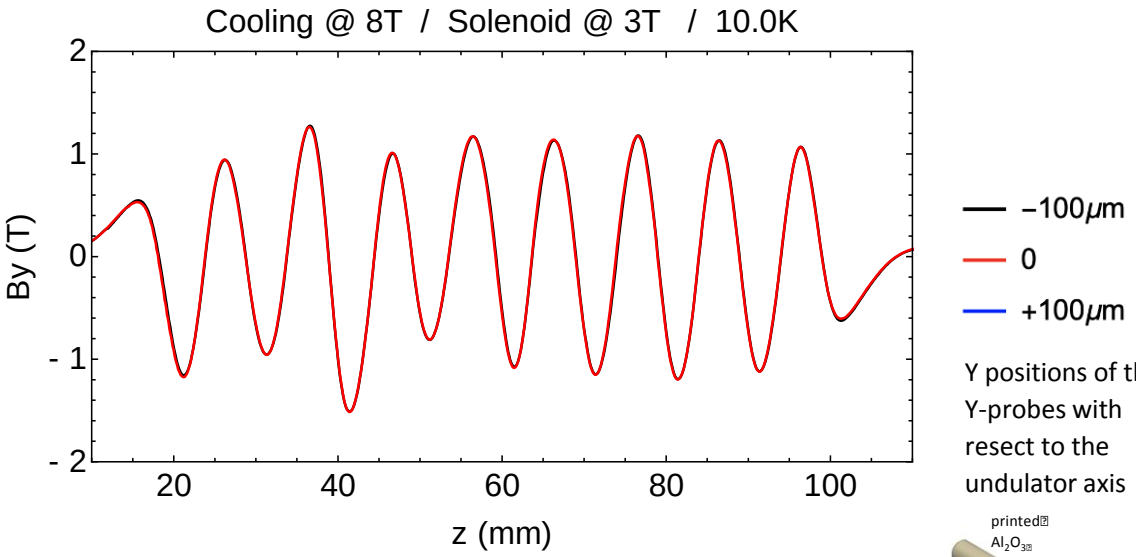

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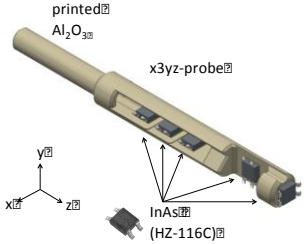

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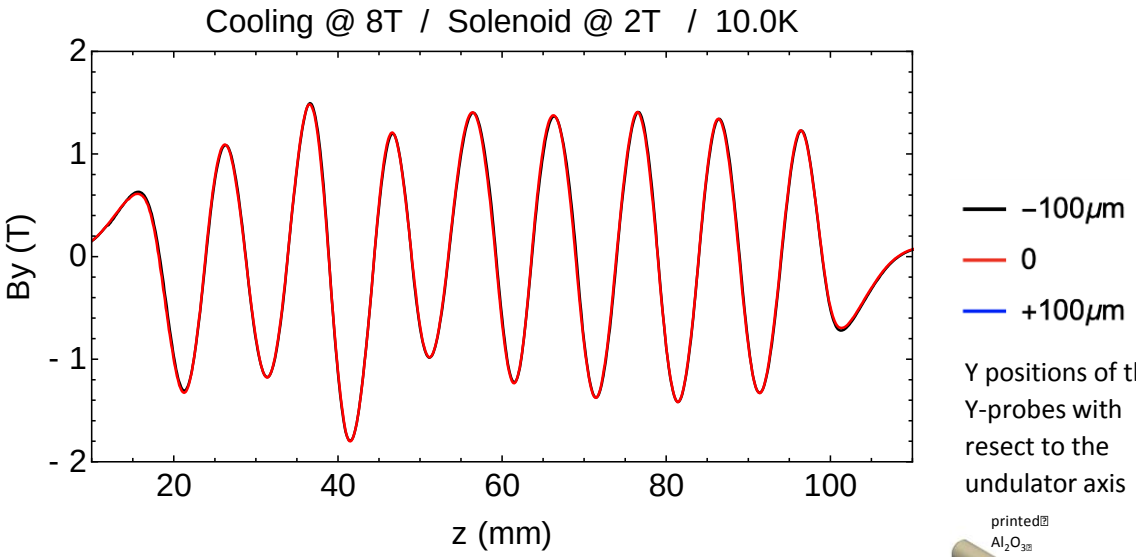

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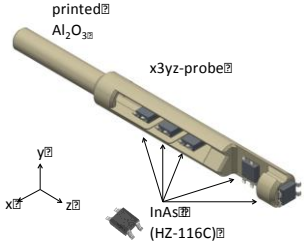

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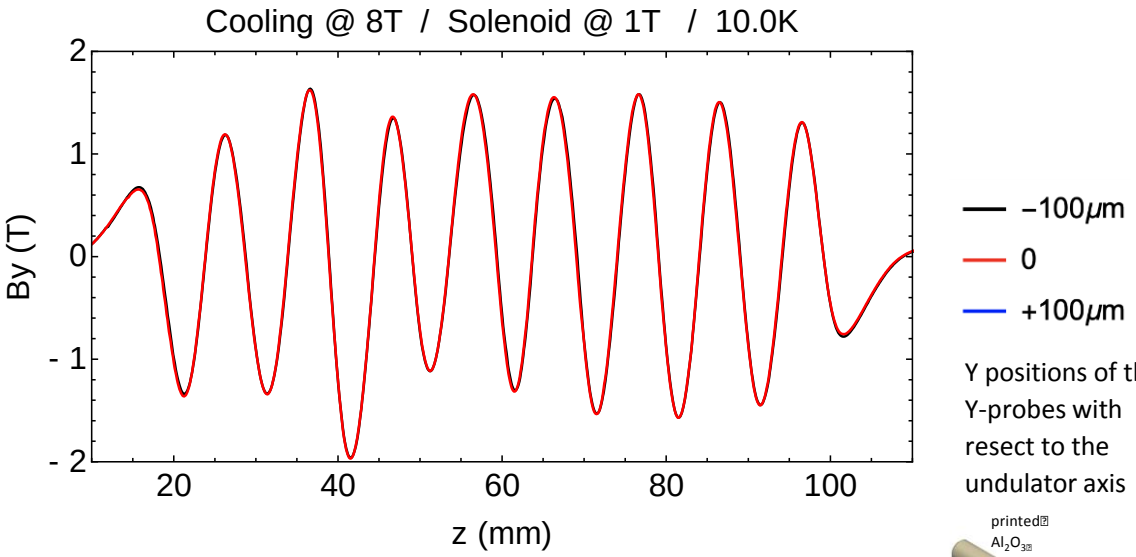

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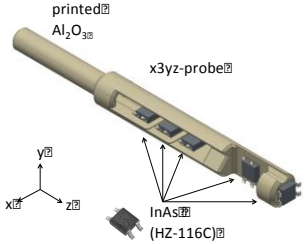

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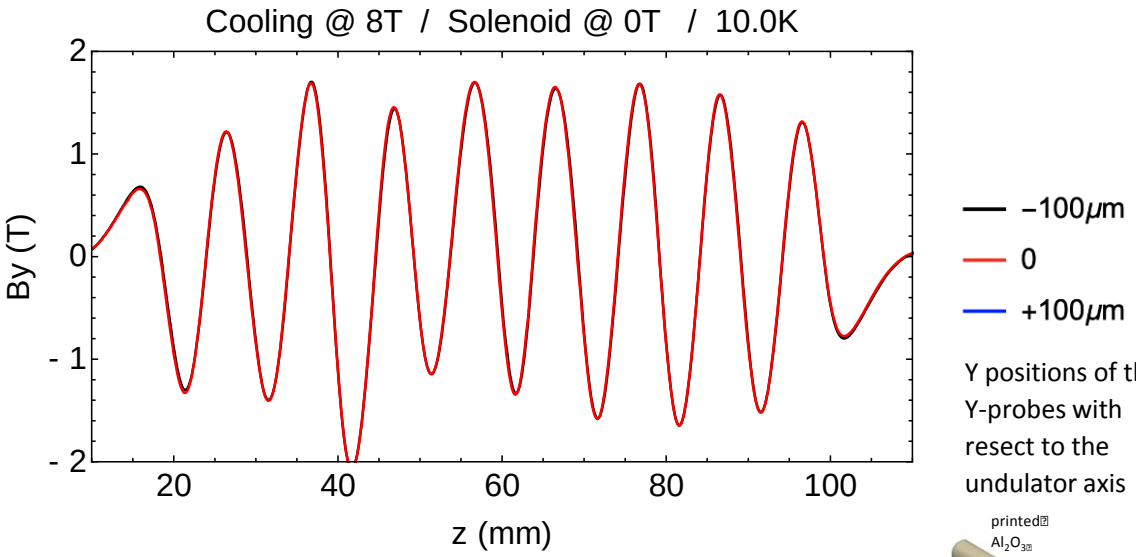

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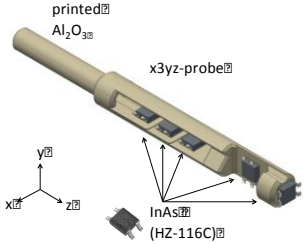

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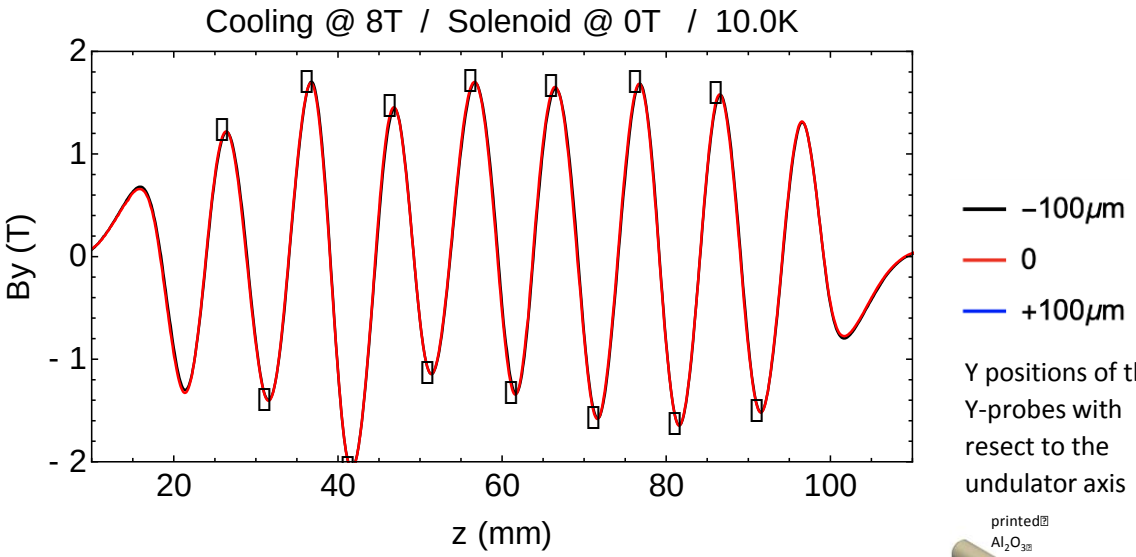

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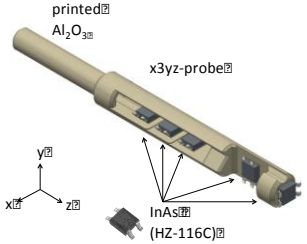
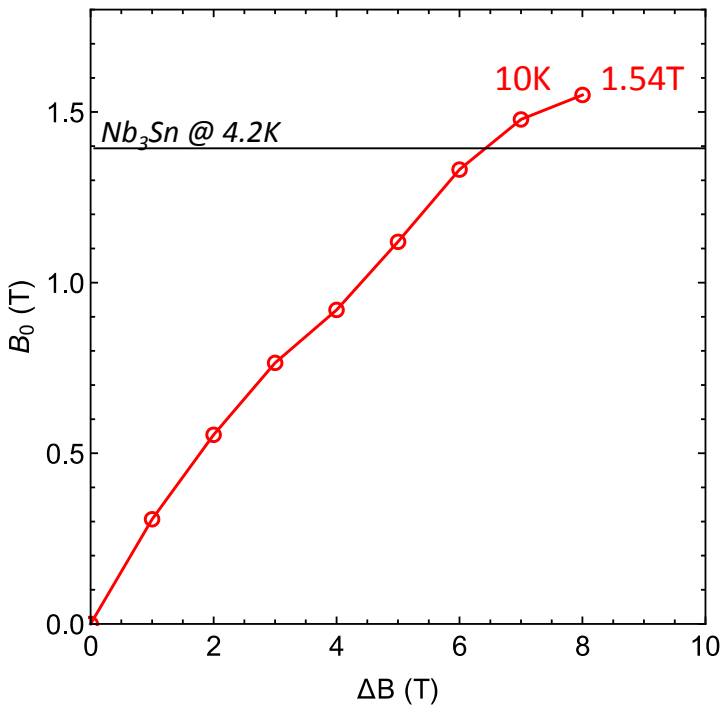
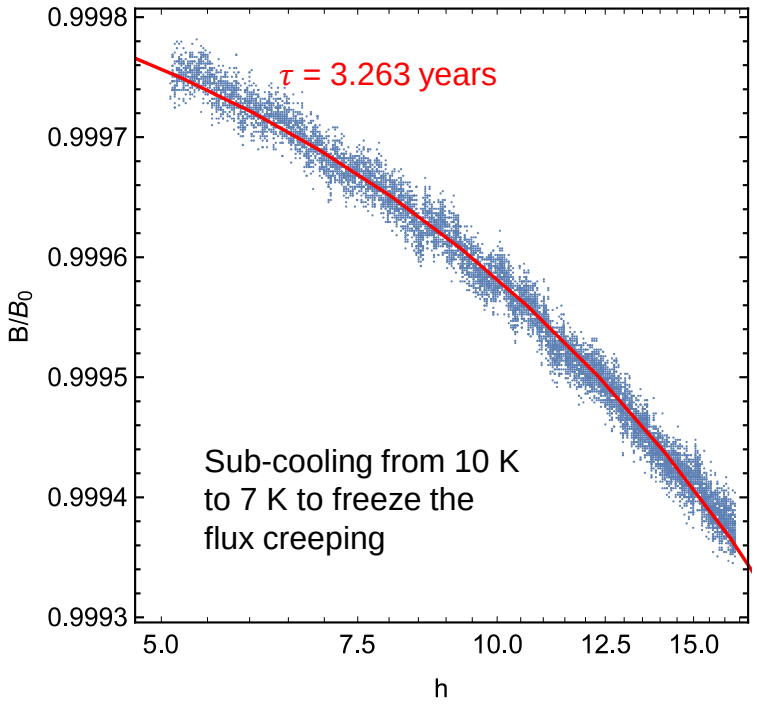


Summary of the results





B_s: 8 T -> 0 T, $\Delta B = 8 - B_s$

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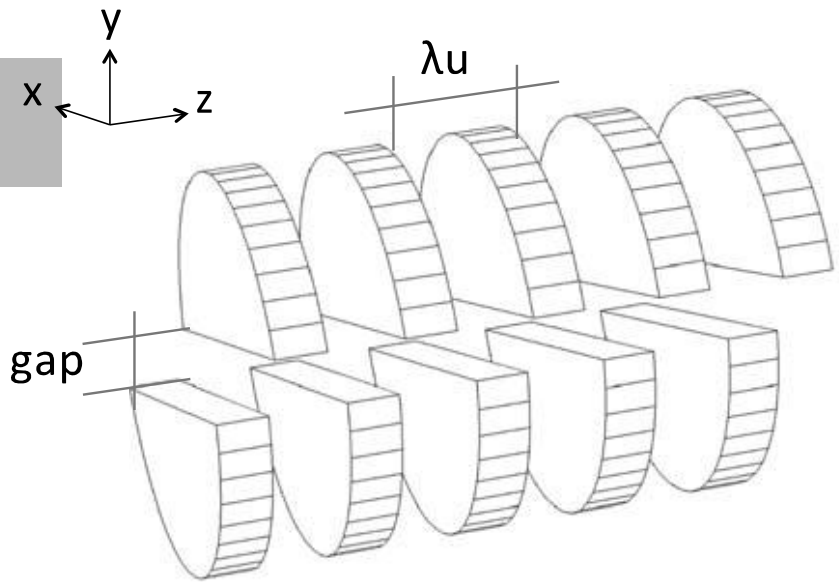
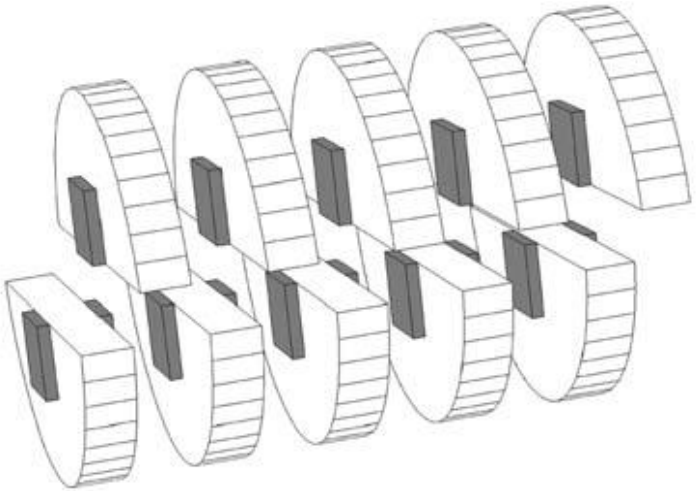
Ideas to enhance the field





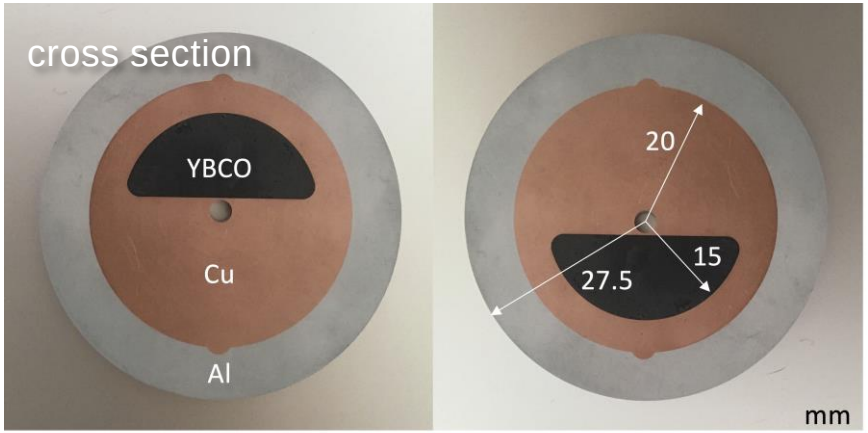
At the time being the record undulator field demonstrated is :

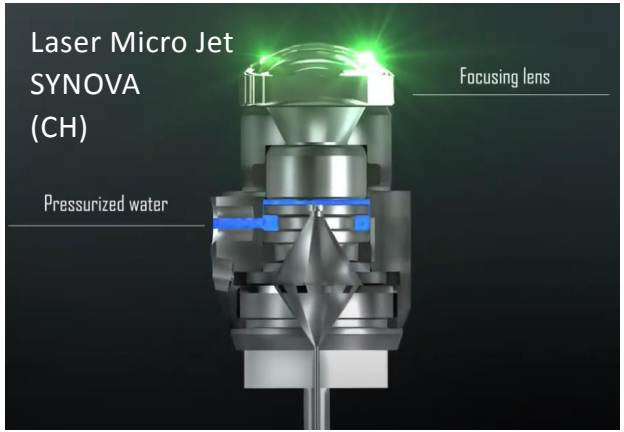
B_0 = 1.54 T

Extrapolation with ferromagnetic poles :

Fe	B_0 = 1.70 T
CoFe	B_0 = 1.75 T
Ho	B_0 = 1.85 T

Test Program with Industrial Short Samples



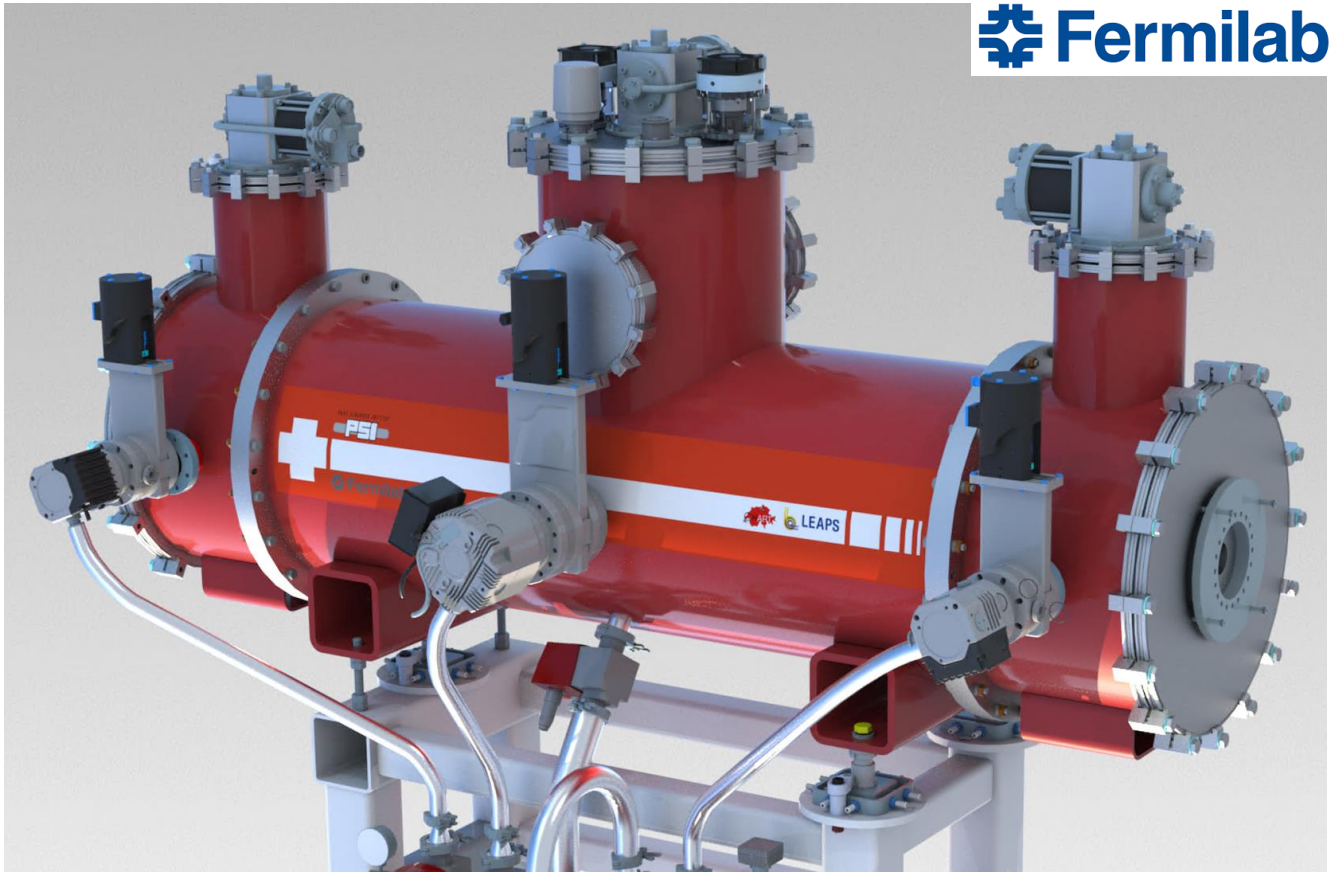


The HTS crystals are embedded (shrink-fit) into a copper matrix with micro-meter accuracy, to be mechanical and thermally stabilised. An additional Aluminium shrinking cylinder is used to precisely assemble the undulator array

Test Program with Industrial Short Samples

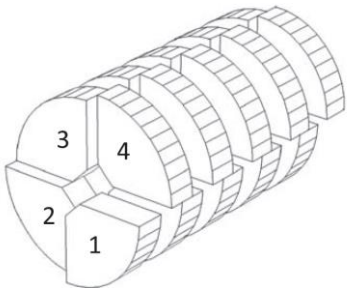
Next test campaign is expected in this month. Series of samples are on the way to test the performance of the iron poles and different HTS material.

2 meter-long full scale prototype for SLS 2.0



Conclusions and outlook

- The first experimental results are encouraging
- Higher fields (>1.54 T) should be possible with ferromagnetic poles
- Quality control (pre-sorting) at the production site is a key element
- Field quality, i.e. peak to peak variation < 5% shall be achieved to allow a fine magnetic field optimization below 0.1% (phase error <2°)
- Further possible applications:
  - Compact FELs, like 2nd hard X-ray beamline for SwissFEL
  - ILC positron source requiring **short-period, high-field** helical



Acknowledgements

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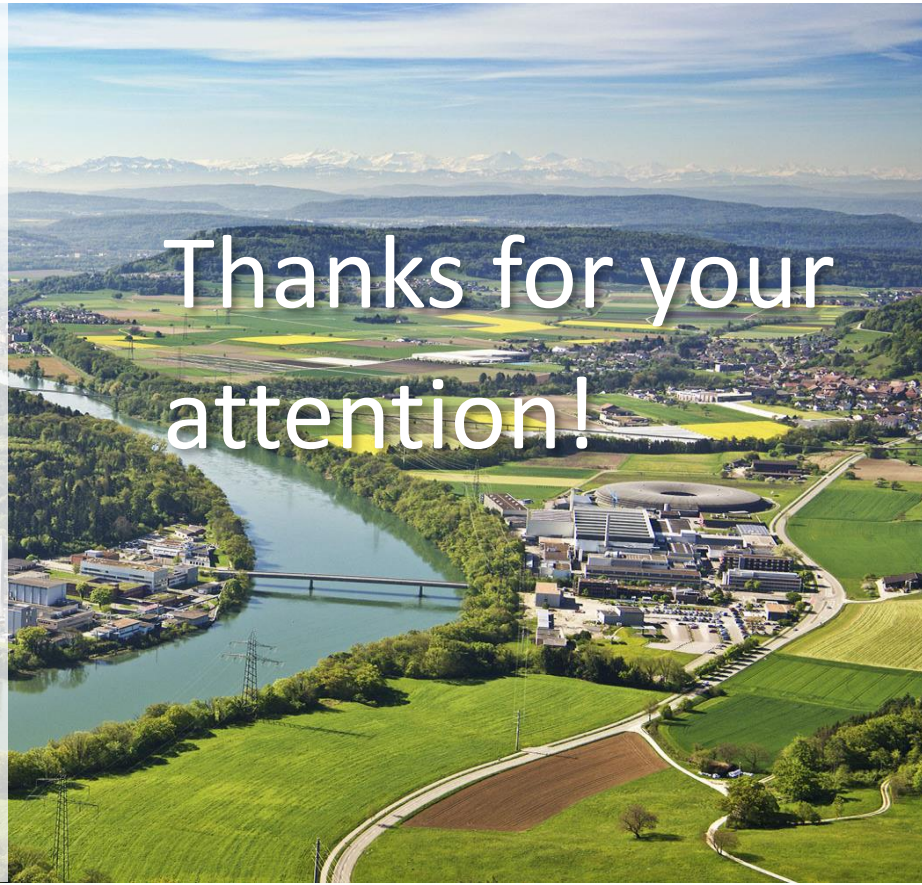
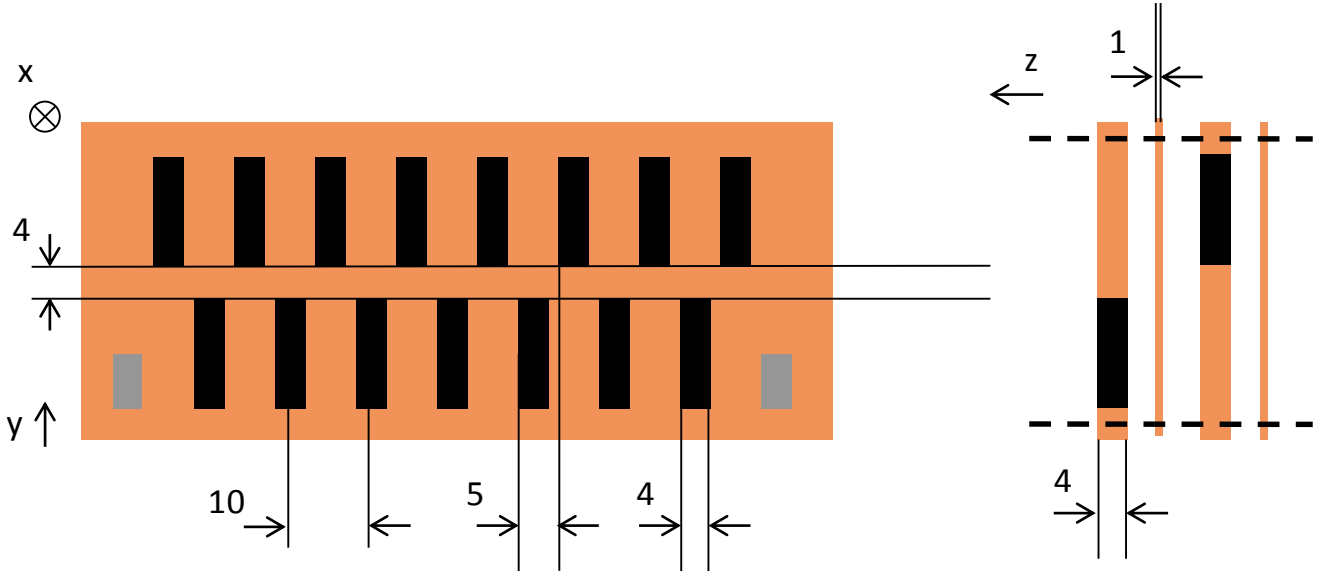
- *CHART* : Prof. H.R. Ott & Prof. L. Rivkin
- *Uni Cambridge* : J. Durrell, A. Dennis, M. Ainslie, Y. Shi, D. Moseley
- *Spring8* : R. Kinjo, T. Takashi
- *Uni Malta* : N. Sammut, A. Sammut, J. Cassar
- *SENIS* : Prof. R. Popovic, S. Spasic, S.Dimitrijevic
- *KIT* : Prof. M. Noe
- *Fermilab*: C. Boffo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



Short Sample

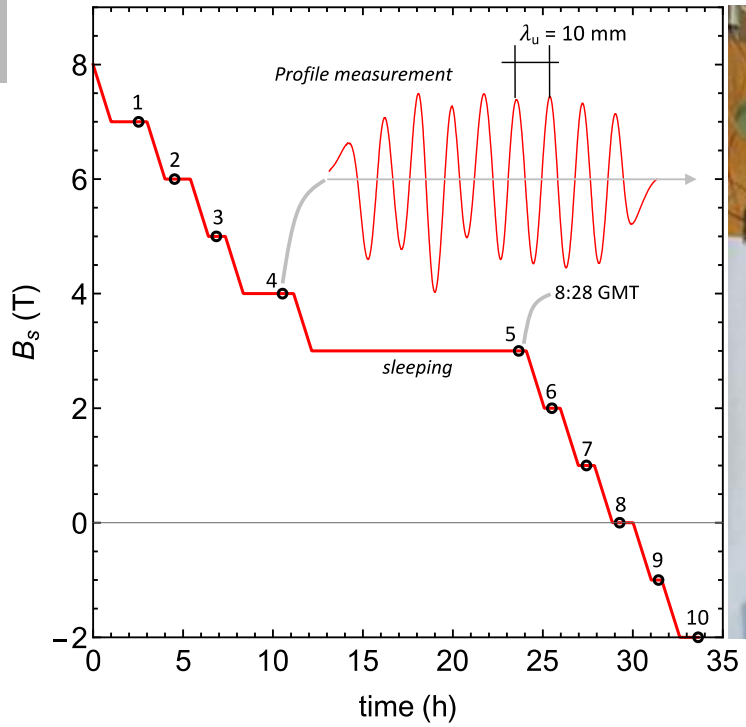
- Magnetic gap 4.0 mm
- Period length 10.0 mm
- Bulk diameter 30.0 mm
- Bulk thinness 4.0 mm
- End field shaping → to match the electron orbit

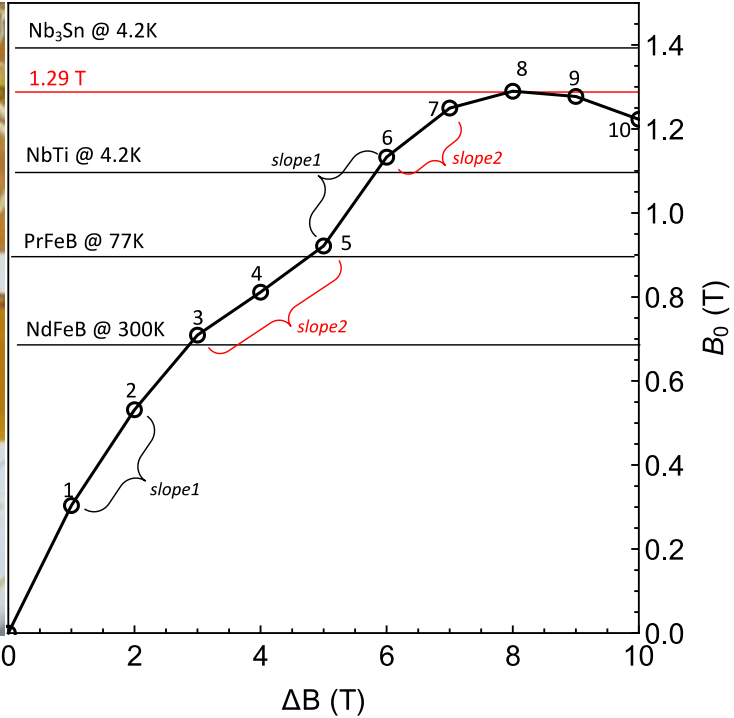


Summary of the results

B_0 is the undulator field
B_s is the solenoidal field
$\Delta B = 8 - B_s$ (T)

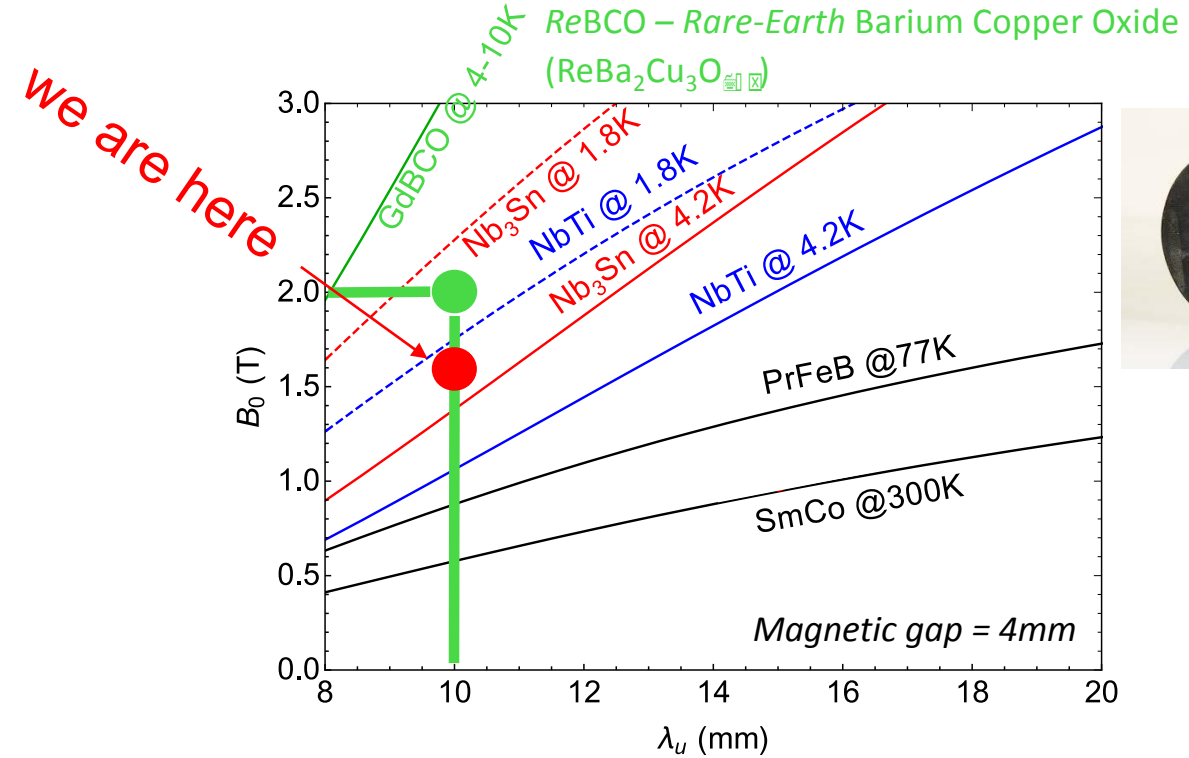
15K & 4mm gap





Summary of the results

*Re*BCO – *Rare-Earth* Barium Copper Oxide
($ReBa_2Cu_3O_{7-x}$)



[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)]

Test Program with Industrial Short Samples

- 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 (phase error)
- Try different shimming approach: swapping/period/pole height
- Reproducibility of the magnetization process
- End optimization study
- Flux freezing