Karlsruhe Institute of Technology

Measurement Devices for Magnetic Fields of Superconducting Undulator Coils

INSTITUTE FOR SYNCHROTRON RADIATION (ISS) / ANKA

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for

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Karlsruhe Institute of Technology

Outline

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   - Motivation
   - Magnetic field errors
2. CASPER I
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   - Measurement accuracies
   - Some results
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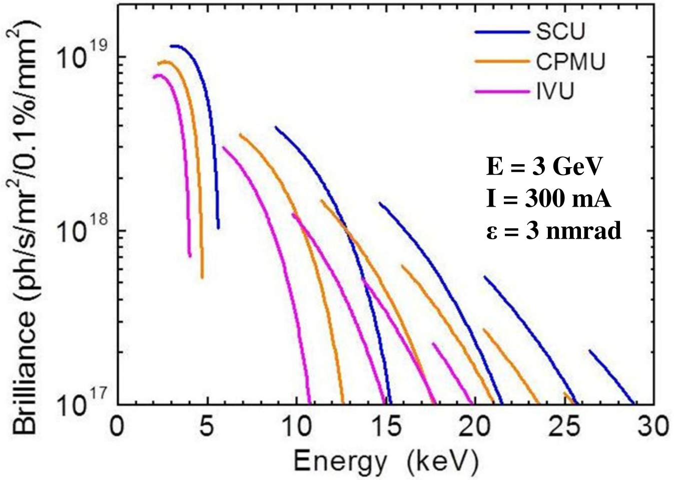
   - Factory acceptance test
   - Local field measurement setup
   - Accuracy requirements and setup limits
   - setup for field integral measurements
   - Additional components and quench diagnostics

R&D of superconducting undulators

Develop, manufacture, and test superconducting undulators (SCUs) to generate:

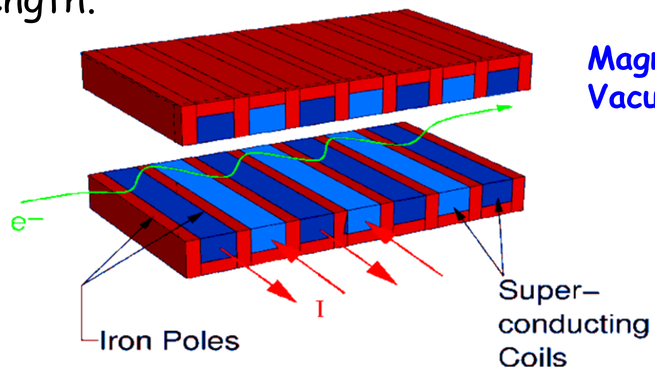
- Harder X-ray spectrum
- Higher brilliance X-ray beams

with respect to permanent magnet undulators.



Why?

Larger magnetic field strength for the same gap and period length.



Magnetic length = 2 m
Vacuum gap = 6 mm

	IVU	CPMU	SCU
λ_u (mm)	21	18	15
N	95	111	133
Magnetic gap (mm)	6	6	7
B (T)	.75	.88	.98
K	1.47	1.48	1.37

To realize:

- SCUs for high brilliance ID beamlines at ANKA
- Next generation SCUs for low emittance synchrotrons and FELs

A given photon energy can be reached by the SCU with lower order harmonic:

20 keV reached with the 5th harm. of SCU, with 7th harm. of CPMU and with the 9th harm. of IVU

Motivation

Task within our R&D program :

Improvement and quality assessment of **magnetic field properties**.

Magnetic errors can cause:

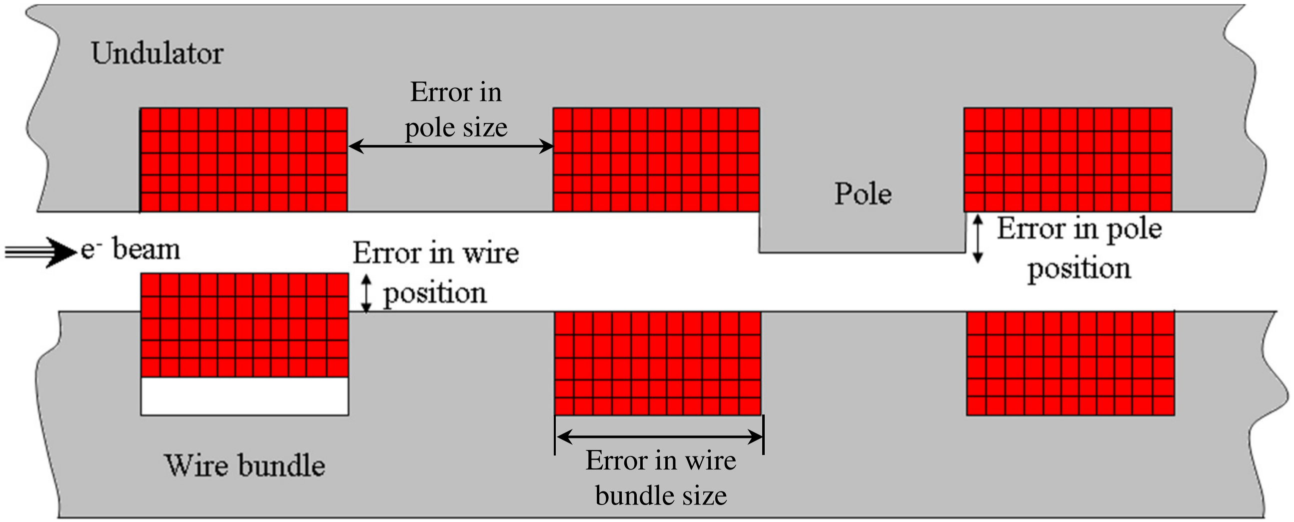
Perturbation of the closed orbit and the dynamics of the electron beam

- Measure field integrals

Reduction of the quality of the emitted radiation

- local field measurements to obtain phase error

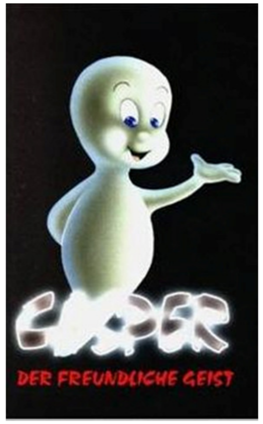
Main errors in superconducting undulators



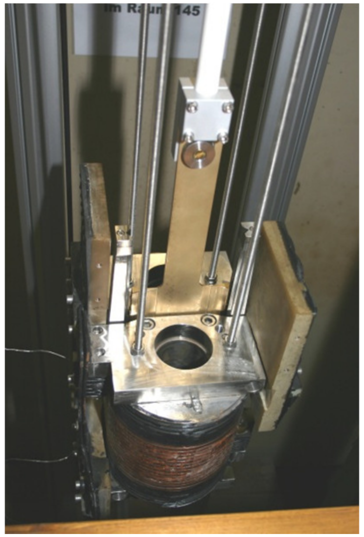
Field errors are mainly caused by:

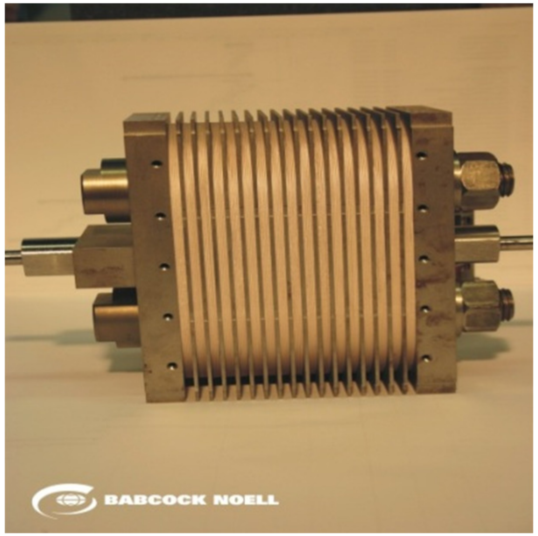
- mechanical deviations of the pole position e.g. the pole height
- bending of the yoke
- the position of the superconducting wire bundles
- pole and wire bundle size

CASPER – Characterization Setup for Field Error Reduction



CASPER I – Measurement facility for short undulator mock-up coils

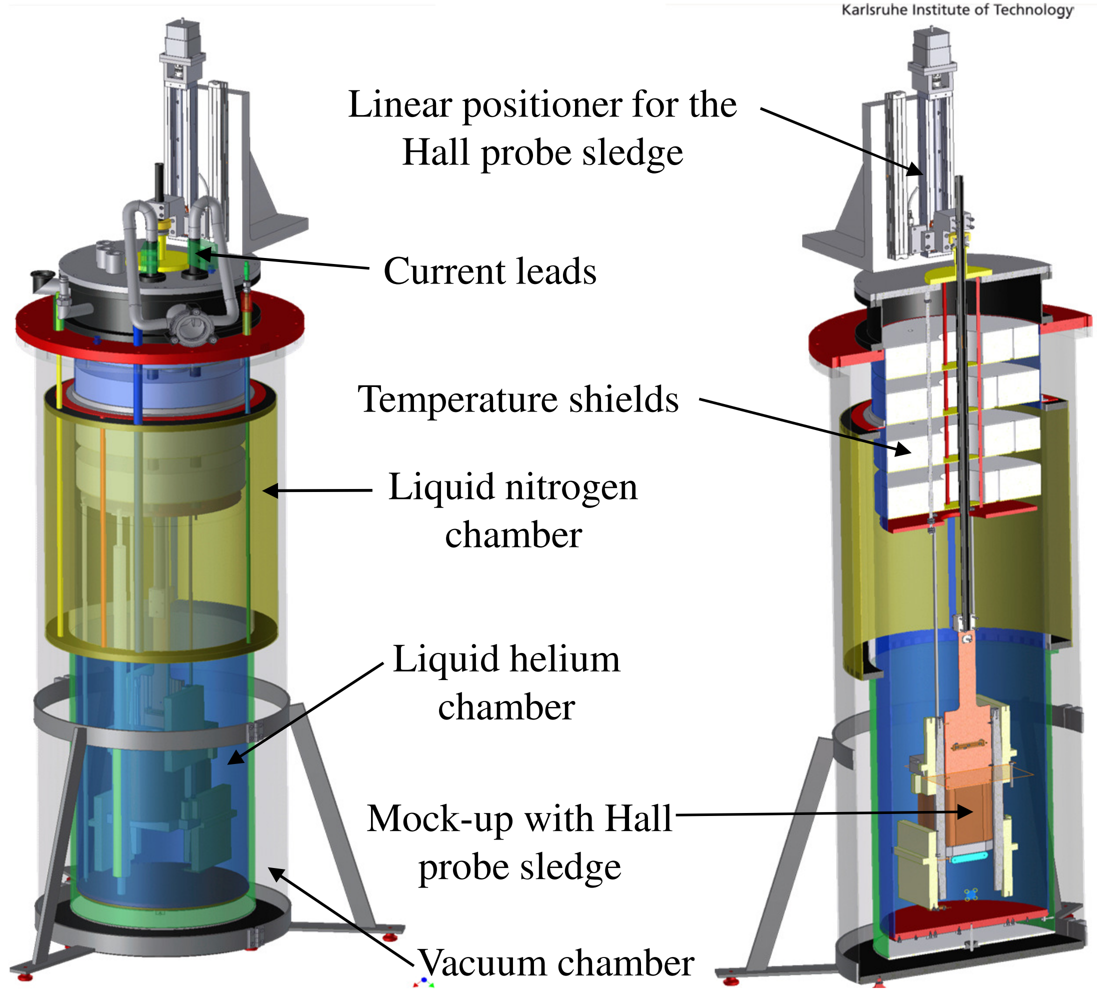




CASPER II – A measurement system for undulator coils up to 2m length

CASPER I

- Training and quench tests can be performed
- New winding schemes,
- New superconducting materials and wires
- and new field correction techniques can be tested

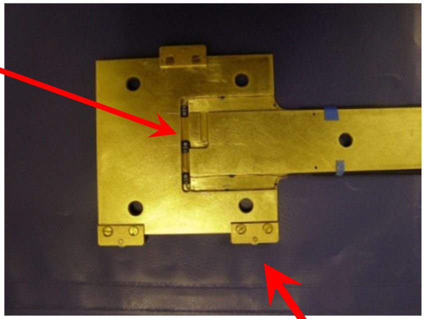


- Operating vertical
- Test of mock-up coils in LHe
- Maximum dimensions 35cm in length and 35 cm in diameter.
- The magnetic field along the beam axis is measured by Hall probes mounted on a sledge moved by a linear stage with the precision for $\Delta B < 1mT$ and $\Delta z < 3\ \mu m$.

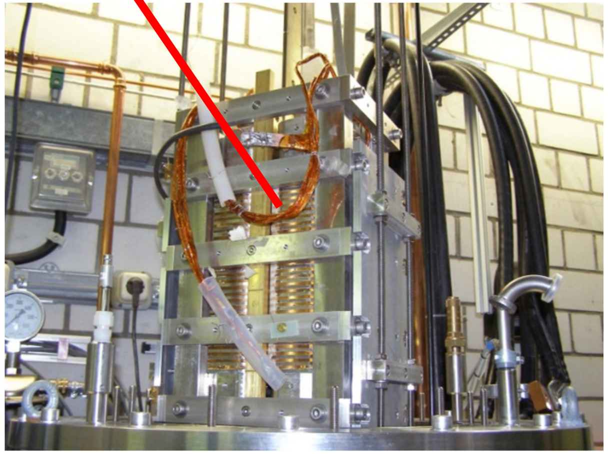
E. Mashkina et al., EPAC08

Measurement equipment

- Magnetic field distribution measured locally
- Field sensors: 3 calibrated Hall probes mounted on a sledge



- Hall current provided by a Keithley a precision current source
- Hall voltage measured with a Keithley multichannel voltmeter
- Sledge moved from outside by a low expansion coefficient non magnetic tube via a linear stage, a stepper motor and a gear box (resolution 3μm)
- Position measured with a linear encoder outside
- Operating currents provided by a 1500A/±5V and/or 500A/±5V power supply connected to a quench detectors

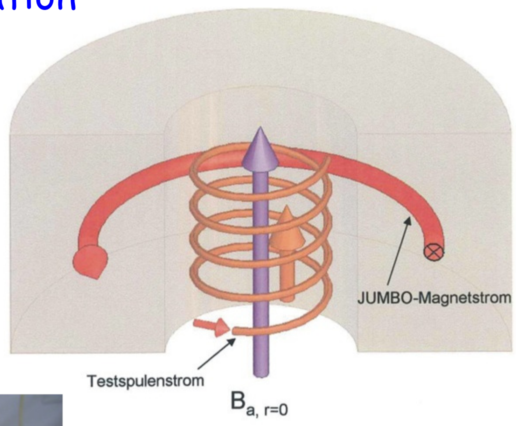


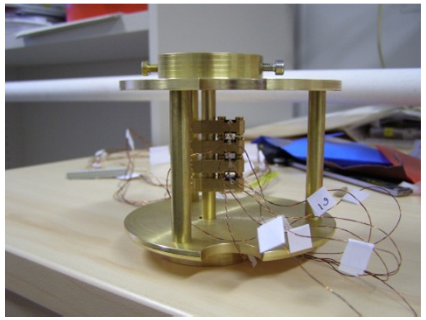
Measurement accuracy limits

Which main errors effect the local field measurements ?

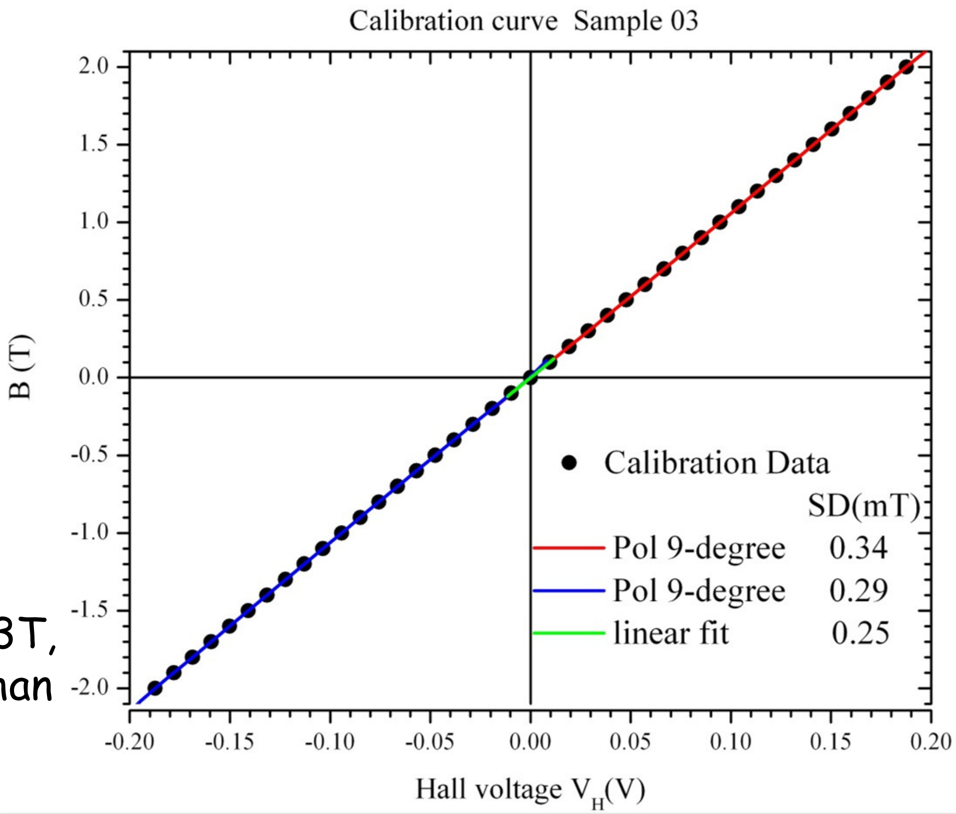
1. Errors caused by Hall sample calibration
2. Field errors mainly due to mechanical misalignment of the guiding rails or the field sensors

Hall sample calibration
(ITeP at the KIT)



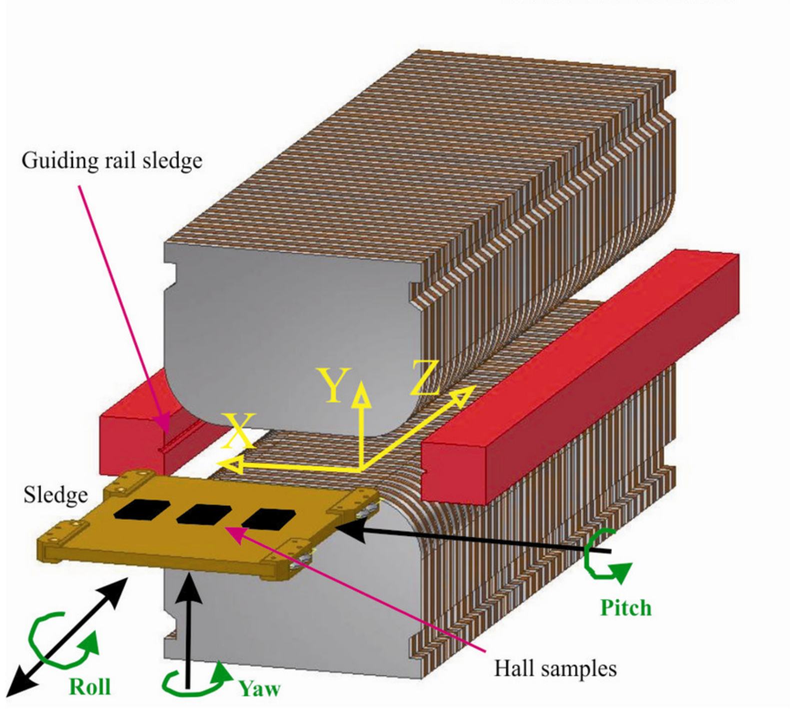


Liquid helium bath cryostat, field -3T<B<3T, homogeneity better than 10^{-4}.



Mechanical accuracy limits

Relative alignment precision of guiding rails 20μm.
For the Hall probe in the middle the distance to coils changes by 10μm.



In x-direction the field is fairly uniform
➧ error is negligible

In y-direction the 10μm yields according to [1] with λ_u=0.015 to:

$$\cosh\left(\frac{2\pi\Delta y}{\lambda_u}\right)=1+\frac{\Delta B}{B}$$

$\Delta B/B = 9 * 10^{-6}$

In longitudinal direction $\Delta z < 5\ \mu m$

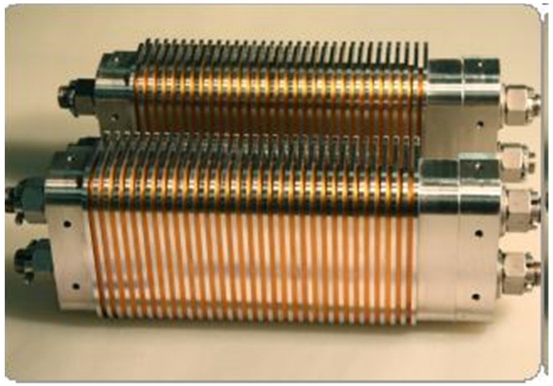
The angle errors cause a $\Delta B/B < 5 * 10^{-8}$

$\Rightarrow$ Limiting factor on B is the Hall probe accuracy

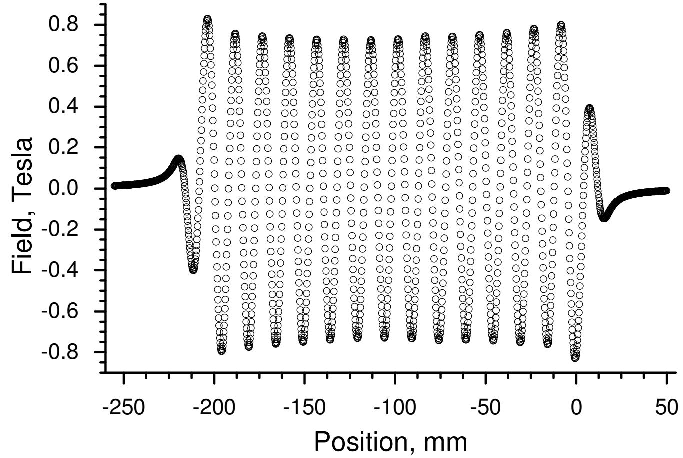
[1] Zachary Wolf, "Requirements for the LCLS Undulator magnetic measurement bench", Technical report # LCLS-TN-0, 4-8 http:/www-ssrl.slac.stanford.edu/lcls/technotes

Some results

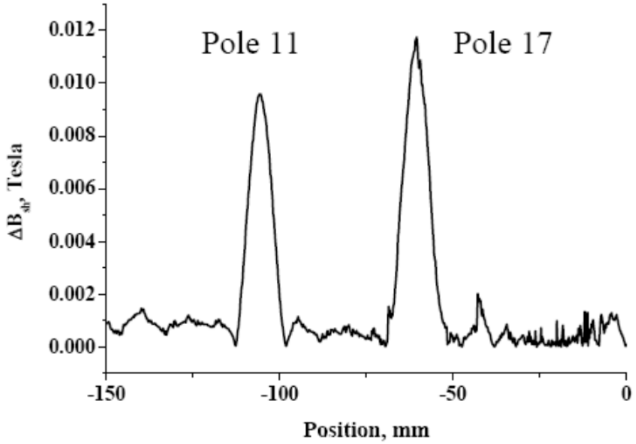
To qualify the production process, the magnetic field quality for the new superconducting undulator for ANKA had to be checked.



Short model coils were produced, the field was measured and possible local shimming methods were checked.



Active shimming using racetrack coils



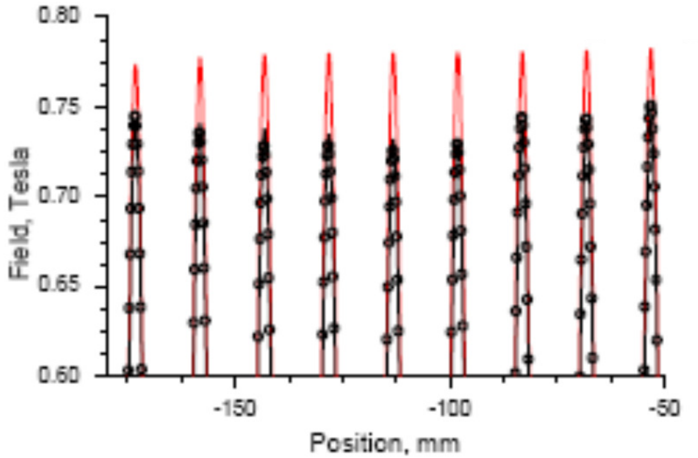
S. Casalbuoni et al. SRI2010

○ measured field

Radia simulations :

ideal field

real geometry



Bending appeared during impregnation process due to different materials and expansion coefficients.

Final Device

Light source Under development in collaboration with BNG for the beamline NANO at ANKA

Period length	15 mm
Number of full periods	100.5
Max field on axis with 5.4 mm magnetic gap	1.43 T
Max field on axis with 8 mm magnetic gap	0.77T
Max field in the coils	2.4 T
Minimum magnetic gap	5.4 mm
Operating magnetic gap	8 mm
Operating beam gap	7 mm
Gap at beam injection	16mm
K value at 5.4 mm magnetic gap	2
Design beam heat load	4W

Delivery beginning 2012

C. Boffo et al., IEEE Trans. on Appl. Supercond Vol. 21-3, 1756-1759 (2011)

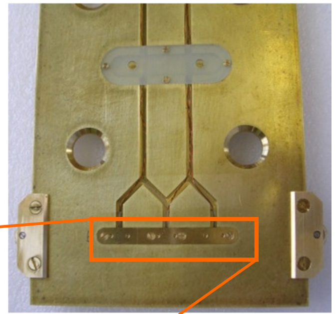
Field characterization SCU 15

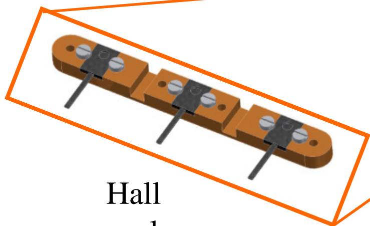
Training, Quench tests and field measurements of the SCU coils were performed in a vertical LHe bath cryostat at CERN (Thanks to L. Bottura, M. Bajko, C. Giloux)

Training and quench tests with CERN equipment

Field measurement equipment done by KIT

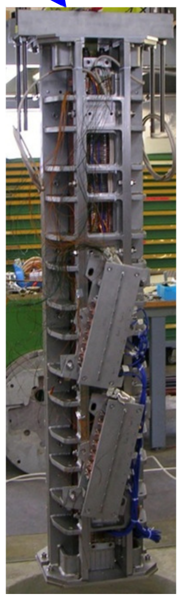
- Measurement like CASPER I Linear stage (45cm), encoder, moving tube
  - precise guided sledge with field sensors
- Array of Hall samples 5x3 (5 along the sledge to cover the whole coil length, 3 in a row)





Hall samples

Sledge with Hall samples

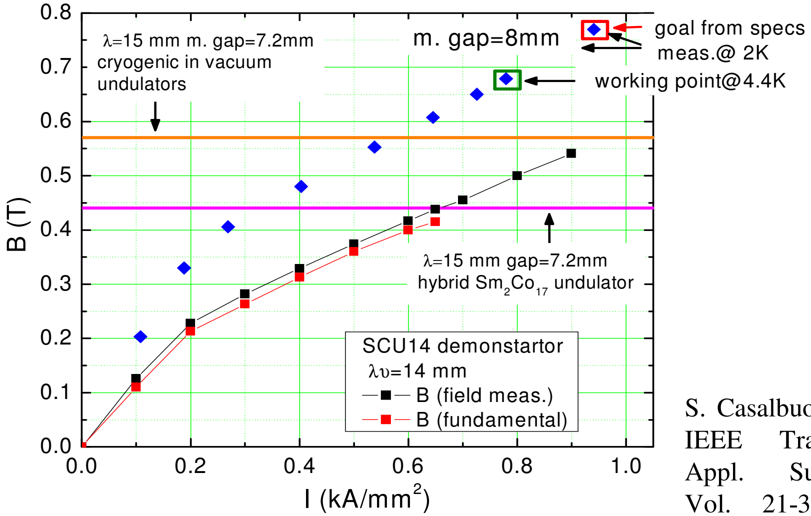


Coil support structure

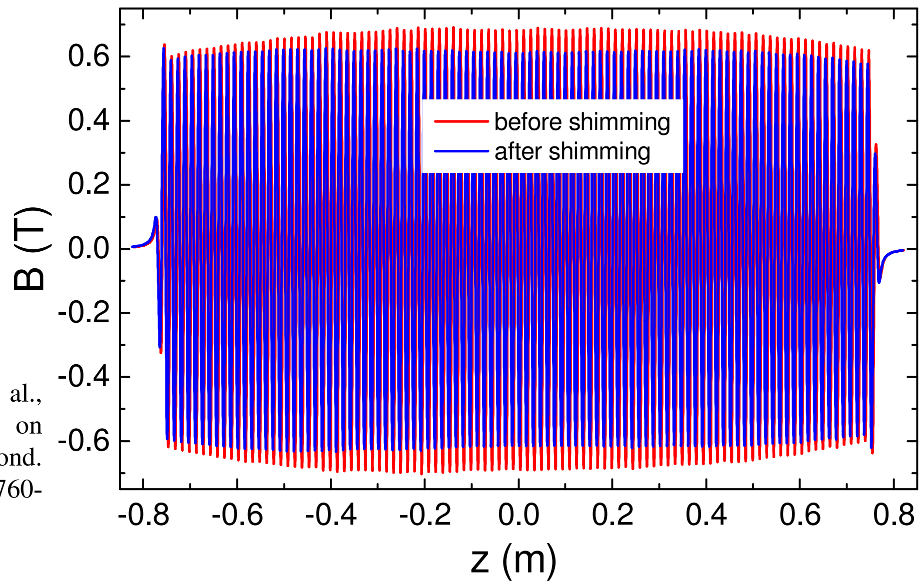
Moving equipment (cryostat top)

Cryostat inset (CERN)

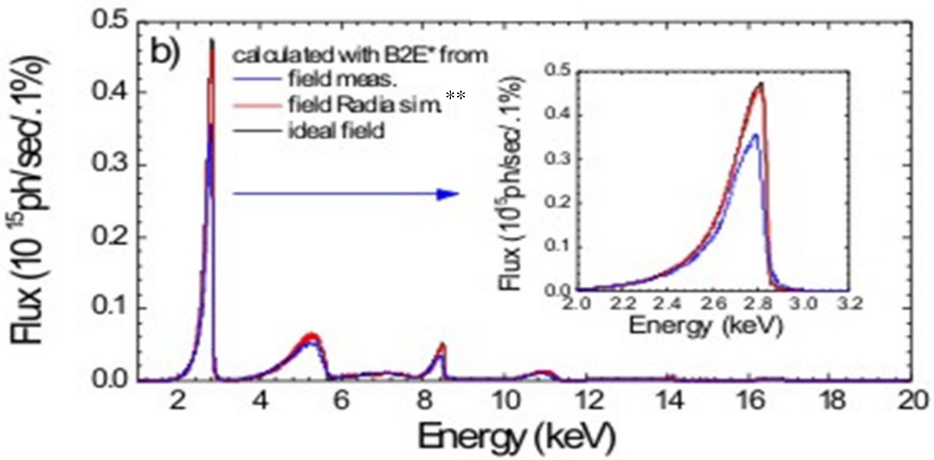
Results



S. Casalbuoni et al., IEEE Trans. on Appl. Supercond. Vol. 21-3, 1760-1763 (2011)



Stainless steel support structure fixes the magnetic gap at room temperature to 8 ± 0.01 mm.



Phase error of 7.4 degrees over a length of 0.795 m, obtained by a simple mechanical shim, which is easily applicable to fixed gap devices.

Next devices round thicker wire and for the yoke C10E steel.

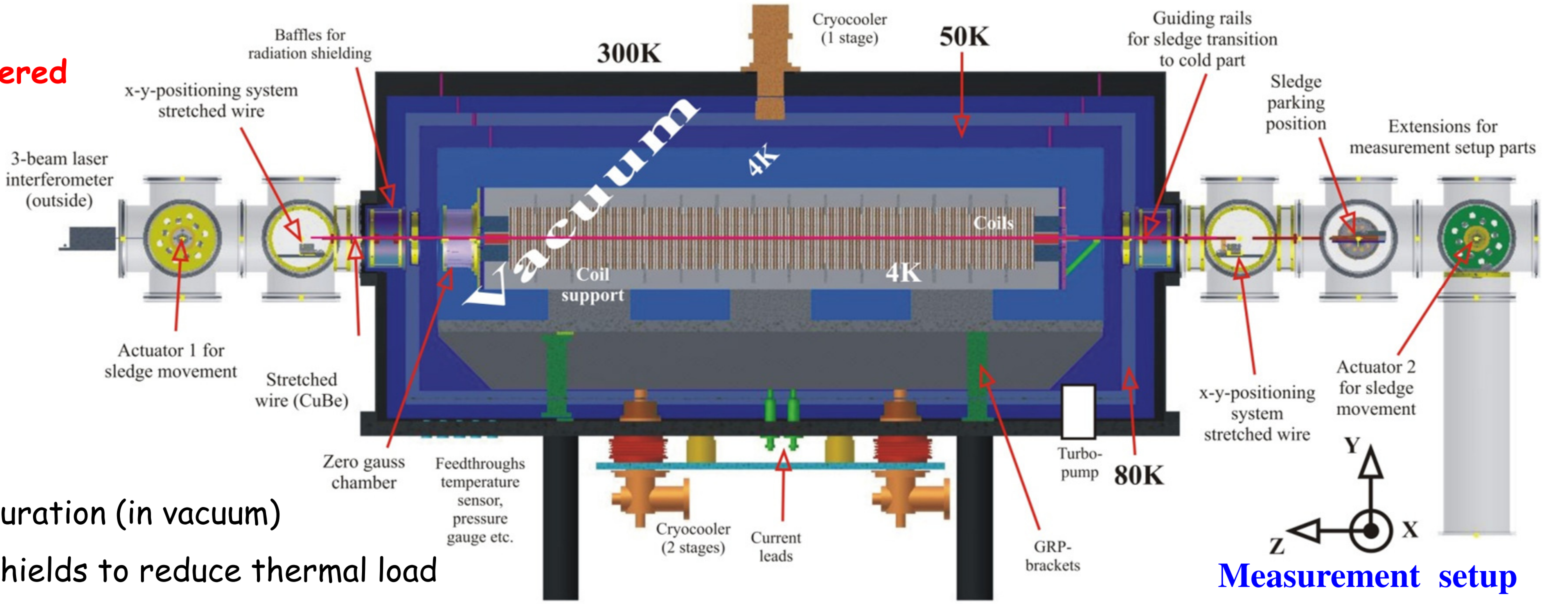
*P. Elleaume, X. Marechal, Report ESRF-R/ID-9154 (1991), **P. Elleaume, O. Chubar, J. Chavanne, PAC97

Cryostat CASPER II

The goal…

Measure magnetic field distributions of superconducting coils with dimensions like in „real“ IDs (e.g. up to ~2 m length, ~50cm diameter)

Cryostat delivered July 2011



Measurement setup parts under construction

A. Grau et al., MT-22, 2011

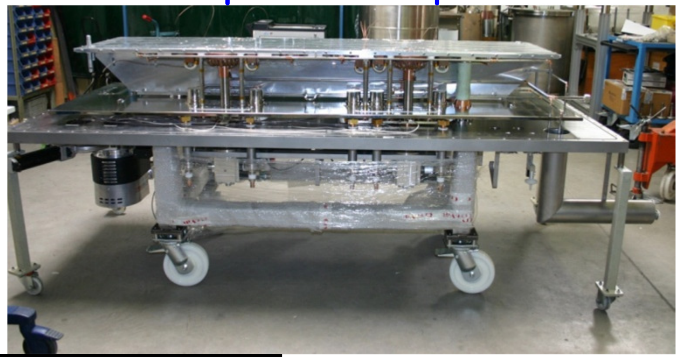
- Vertical configuration (in vacuum)
- Temperature shields to reduce thermal load
- Partially cryogen free :
  - To 4K via cryocooler
  - precooling 4K plate and thermal shields (80K) with liquid N_2
- Dimensions 4K region 2m x 0.5m x 0.5m
- Current leads 8 x 500A, can be variable connected
- Local and integral field measurements possible, access through the flanges

For **quality certification** of new sc-insertion devices developed together with the industrial partner Babcock Noell GmbH.

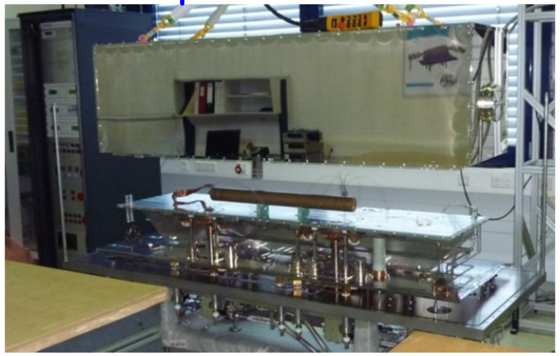
Cryostat

Complete

4K plate & base plate



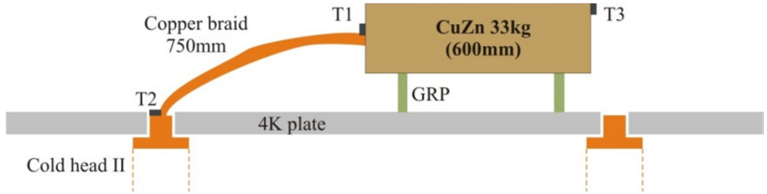
4K plate & 50K shield

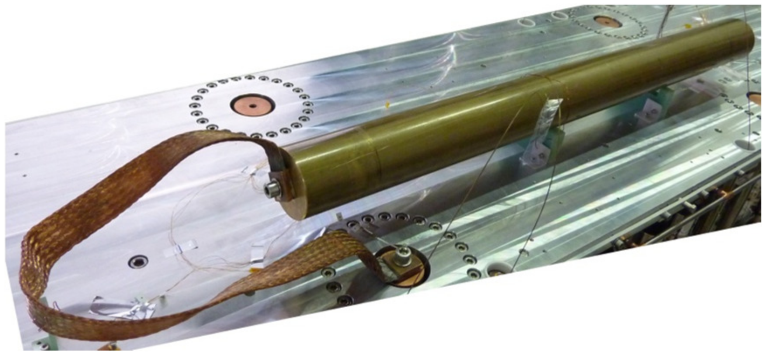


Component	Specified value	Reached value
Recipient pressure before starting turbo pump	p ~ 0.5 mbar	1 mbar
Time to reach this pressure	t < 1 h	35 min.
Base pressure before start cooling	p ~ 10^{-4} mbar	$5*10^{-4}$ mbar
Time to reach base pressure	t < 2 h	55 min.
Final pressure while operation	p < $5*10^{-6}$ mbar	< 10^{-6} mbar
Temperature 80K-plate	T < 85 K	∅ 83 K
Temperature 80K-shield	T < 100 K	∅ 85 K
Temperature 50K-shield	T < 60 K	∅ 50 K
Temperature 4K-shield	T < 10 K	∅ 6.2 K
Temperature 4K-plate	T < 4.5 K	∅ 4.5 K
T1	targeted < 4 K	3.6 K
T2	“	3.4 K
T3	“	3.7 K

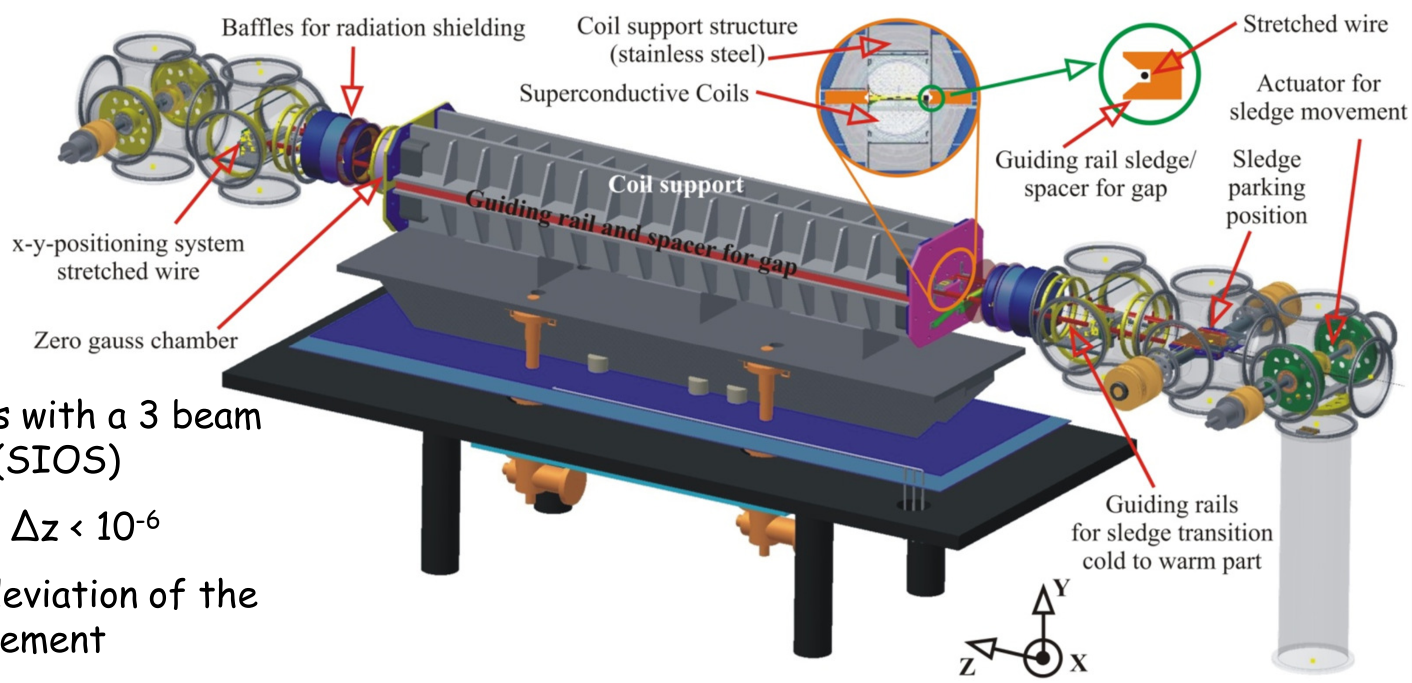
Factory acceptance test

Testsetup to simulate temperature in 4K region

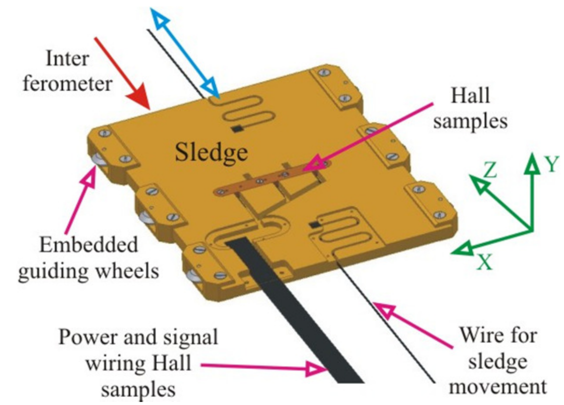




Measurement setups



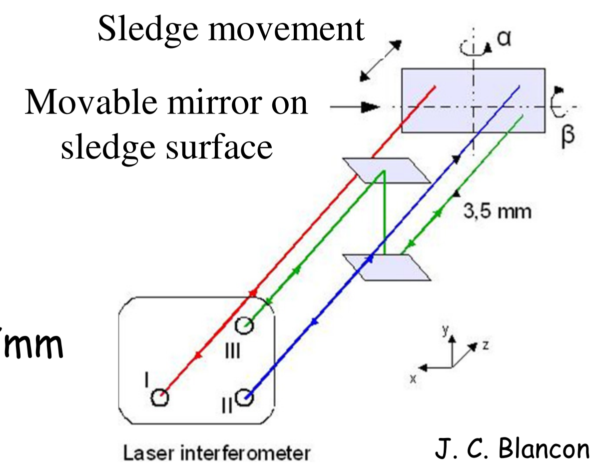
- Position measurements with a 3 beam laser interferometer (SIOS)
  - Precise z-position $\Delta z < 10^{-6}$
  - Values for angle deviation of the sledge during movement
- Field sensors: 3 calibrated Hall probes on a sledge
- Hall current provided by a Keithley precision current source
- Hall voltage measured with a Keithley multichannel voltmeter
- Field integral measurements with stretched wire technique (CuBe wire Ø125µm)
- Position adjustment for stretched wire in x-y-direction via linear stages with encoders (precision ~1µm)



Position measurement

Laser interferometer (3 beams)

- Z-positioning (1 beam)
- Angle deviation during moving (3 beams)

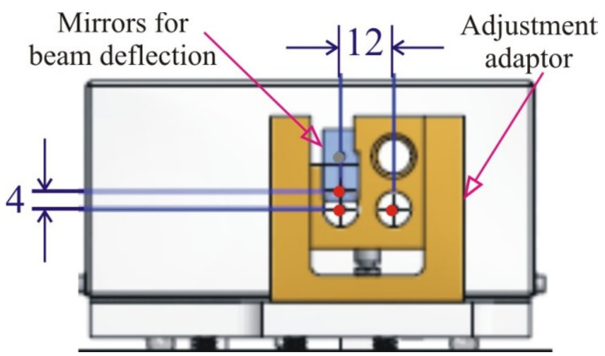


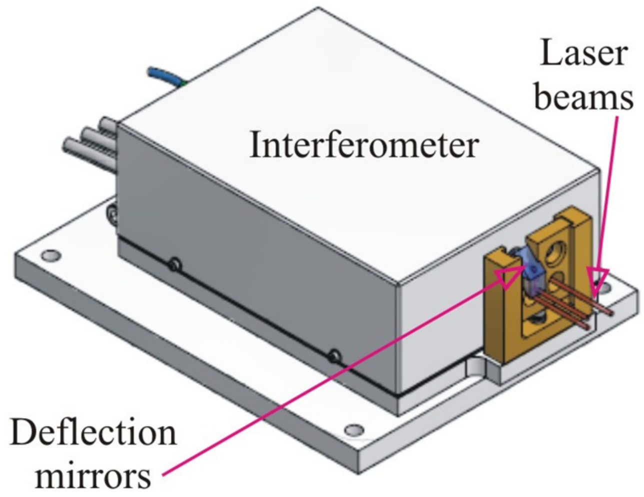
Problem: Beam distance 12mm, usable gap in the undulator max. 7mm

➡ preliminary test and setup to reduce vertical beam distance

Final Device :

Commercial interferometer with attachment of two mirrors for beam distance rescaling

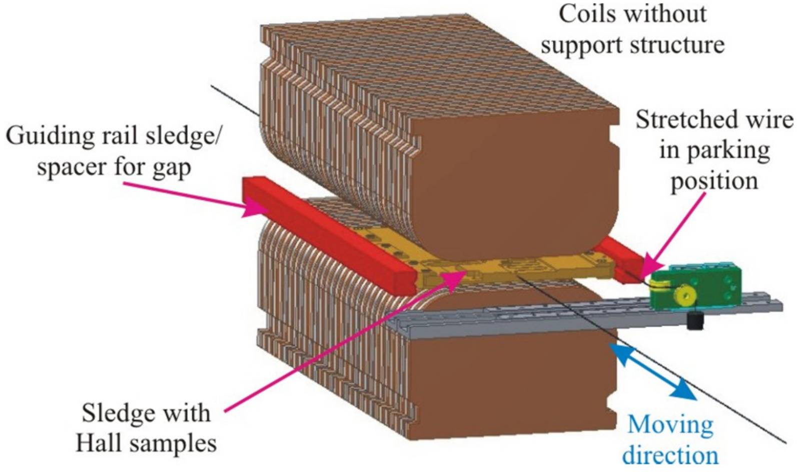




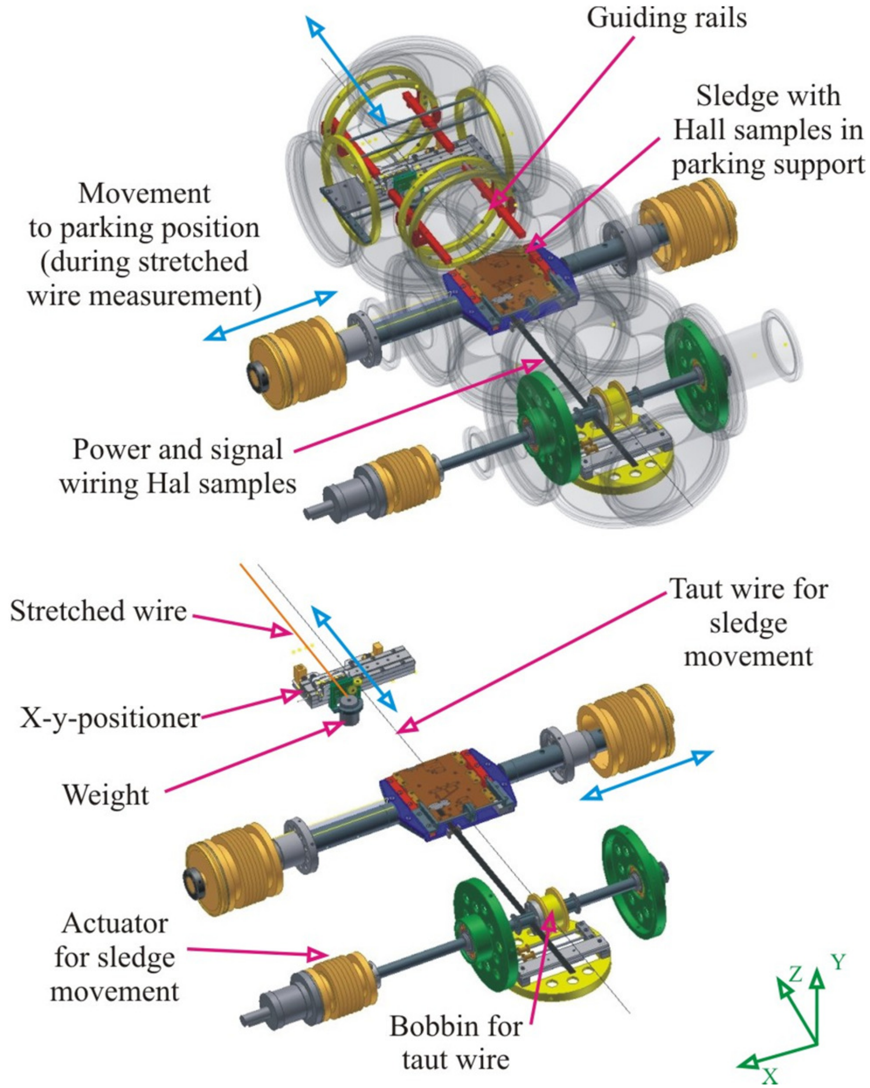
Company SIOS

Local field measurements

3 Hall probes in a row placed perpendicular to beam axis (20mm distance)



Sledge movement by a taut wire for each direction spooled on a bobbin at each side mounted in the extensions of the cryostat.

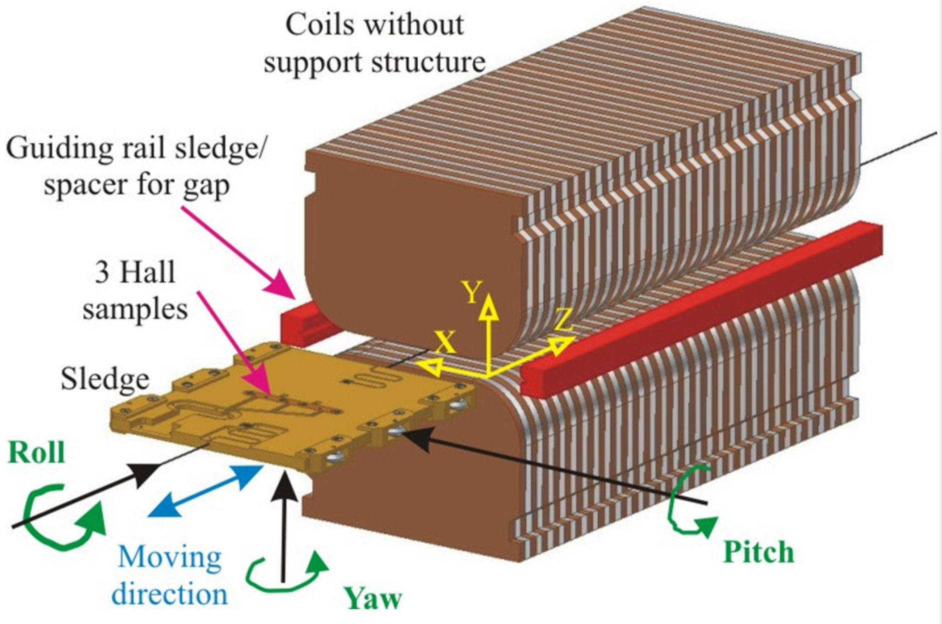


Accuracy requirements

Mechanical requirements to reach measurement accuracy for phase error $\Delta\phi$ = 1° (λ_U=15mm, K=1.1, ANKA SCU 15):

Parameter	Calculated value [1]	Set limit
Horizontal deviation (Δx)	500 µm	300 µm
Vertical deviation (Δy)	200 µm	50 µm
Horizontal deviation (Δz)	13 µm	3 µm
Roll angle error (α)	2.5 mrad	1 mrad
Pitch angle error (β)	83 mrad	30 mrad
Yaw angle error (χ)	500 µrad	300 µrad

A. Grau et al., IEEE Trans. on Appl. Supercond. Vol. 21-3, 2312-2315 (2011)



[1] Zachary Wolf, "Requirements for the LCLS Undulator magnetic measurement bench", Technical report # LCLS-TN-0, 4-8 http:/www-ssrl.slac.stanford.edu/lcls/technotes

Setup accuracy limits

Relative alignment precision of guiding rails $\Delta y_{Guiding\ rail}$=40μm. For the Hall probe in the middle the distance to coils changes by Δy=20μm.

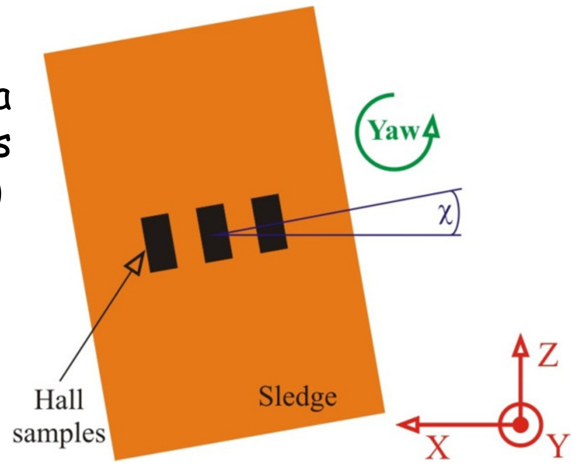
- In x-direction the field is fairly uniform $\Rightarrow$ error is negligible
- Δy=20μm in y-direction fulfills the requirements
- In longitdinal direction precision for Δz = 1μm

Roll

According to the drawing with x_{sledge}=0.15m the maximum roll angle α=266μrad

➧ below the limit

Yaw



The yaw angle χ=270μrad results from taking into account a maximum misalignment of the guiding rails with respect to the coils of 0.2mm along the whole support structure length of 1.8m (z-axis)

➧ set limit fulfilled

Pitch

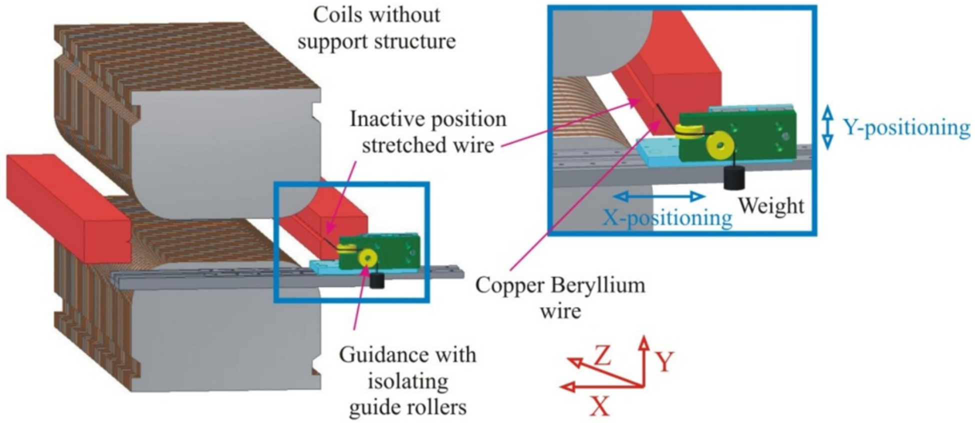
Due to guiding rail precision the limit for pitch angle β=30mrad (rotation around x-axis) is not a critical point

$\Rightarrow$ Limiting factor on measurement precision is the Hall probe accuracy

A. Grau et al., IEEE Trans. on Appl. Supercond. Vol. 21-3, 2312-2315 (2011)

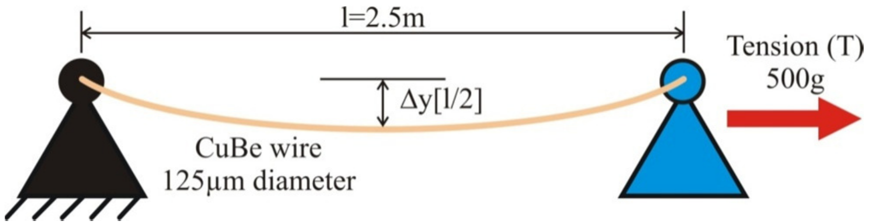
Stretched wire

- Copper Beryllium wire
- Diameter 125µm
- Length through the whole cryostat ~2.5m
- Movable along 2 axes (150mm x-axis, 20mm y-axis) synchroneous or opposite directions



Error consideration

Accuracy limit is set by the sag Δy in the middle (l/2) of the wire and depends on the tension and the self-weigth [1]



$$\Delta y\left(\frac{l}{2}\right) \cong -\frac{\omega_{CuBe}\, l^2}{8T} = -100\,\mu m$$

With $\varnothing_{CuBe}$ = 125 µm, ω_{CuBe} = 0.064g/m, λ_U = 0.015m

Resulting Error in the field integral [2]

$$\frac{\Delta I_y}{I_y} \approx \frac{1}{2}\left(\frac{2\pi}{\lambda_U}\right)^2 \cosh\left(\frac{2\pi}{\lambda_U}\Delta y\right)(\Delta y)^2 \approx 8.8\times 10^{-4}.$$

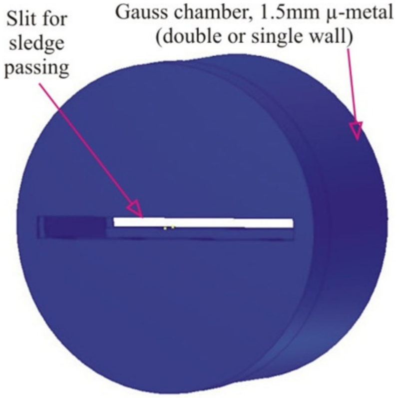
[1] G. Bowden "stretched wire mechanics," Technical report, #SLAC-Pub-11465, Stanford Linear Accelerator Center, 2004

[2] F. Ciocci et. Al. „some considerations on the SPARC undulator magnetic measurements," Technical report #SPARC-FEL-06/001, ENEA Frascati, 2006

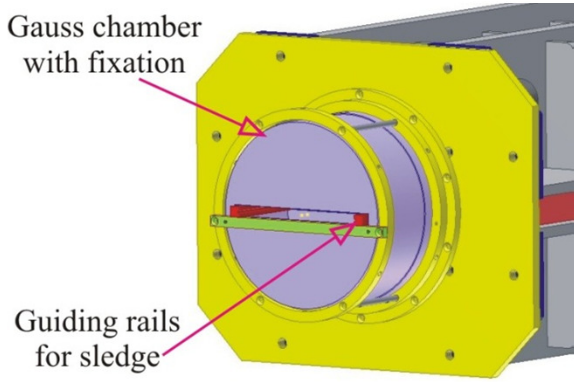
A. Grau et al., IEEE Trans. on Appl. Supercond. Vol. 21-3, 2312-2315 (2011)

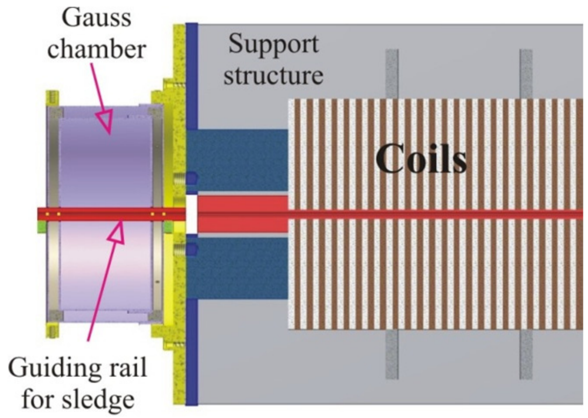
Supplementary

Field shielding chamber to adjust the zero-point of Hall samples when cold



Company Sekels



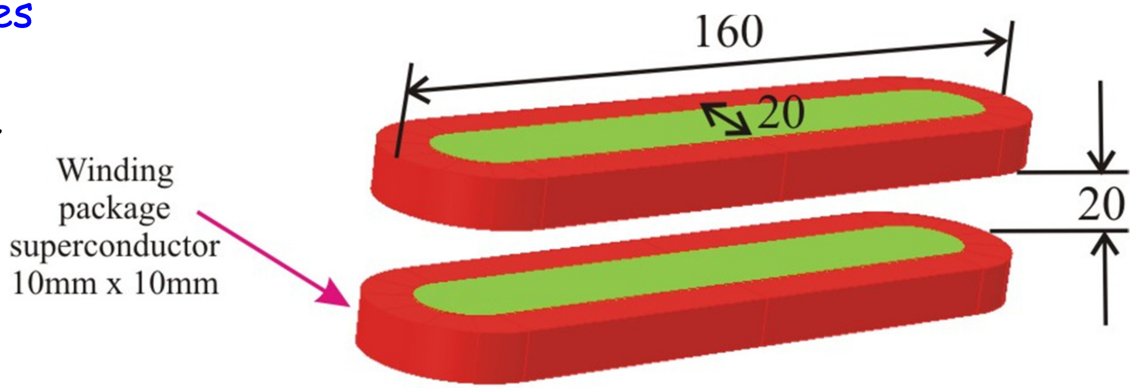


Racetrack coils mounted in Helmholtz configuration to check calibration curve of the Hall samples

Field homogeneity over 40mm in the center ~0.2mT

- Can be improved (in design stage)

Winding at ITeP at KIT



Quench diagnostics

Quench detection

- 6 quench detectors to protect superconducting wire during training an quench tests
- Sampling rate 100 kS/s
- Adjustable parameters : pre- and post-trigger time, quench limit voltage, quench time, voltage offset between compared coil parts, etc.
- Software controlled
- Suitable for individual connection to all coil parts
- Manufactured by IPE at KIT

Quench diagnostics

- Data acquisition system up to 64 channels
- 8 x 8 channel simultaneous sampling multifunction cards
- Sampling rate 250 kS/s
- Pre- and post-trigger time variable up to 5s
- Data processing for quench analysis via Labview (IPE)

Acknowledgements

Thanks to :

N. Glamann D. Erbe	Institute for Synchrotron Radiation (ANKA) Karlsruhe Institute of Technology
ITeP IPE	Karlsruhe Institute of Technology
C. Boffo W. Walter	Babcock Noell GmbH
E. Mashkina N. Vassiljev	University of Erlangen - Nürnberg
J. Feuvrier J. Hurte M. Ky P. Viret	Bloc 4 CERN
Fa. CryoVac Fa. SIOS National Instruments	

. . . and to you for your attention !

For sure we get nice results