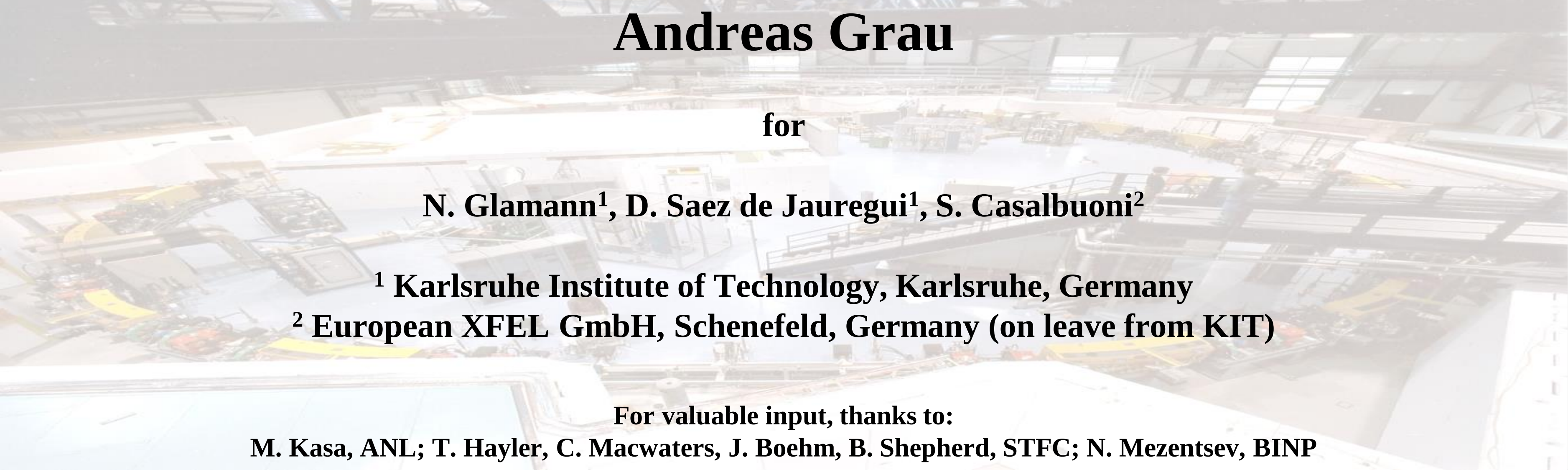
Magnetic Measurement Systems for Superconducting Undulators

IBPT – Institute for Beam Physics and Technology



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for

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M. Kasa, ANL; T. Hayler, C. Macwaters, J. Boehm, B. Shepherd, STFC; N. Mezentsev, BINP

Outline

Overview of a selection of existing measurement setups to characterize superconducting undulators

- Introduction
- Magnetic measurement techniques suitable for SCUs
- Characterization setups for short coils
- Existing setups for long coils (~2m, vertical, horizontal)
- Testsetups for devices in the final cryostat
- Summary, measurement techniques pros and cons

Motivation

Superconducting insertion devices, undulators, gain more and more interest within the accelerator community worldwide especially at advanced light sources.

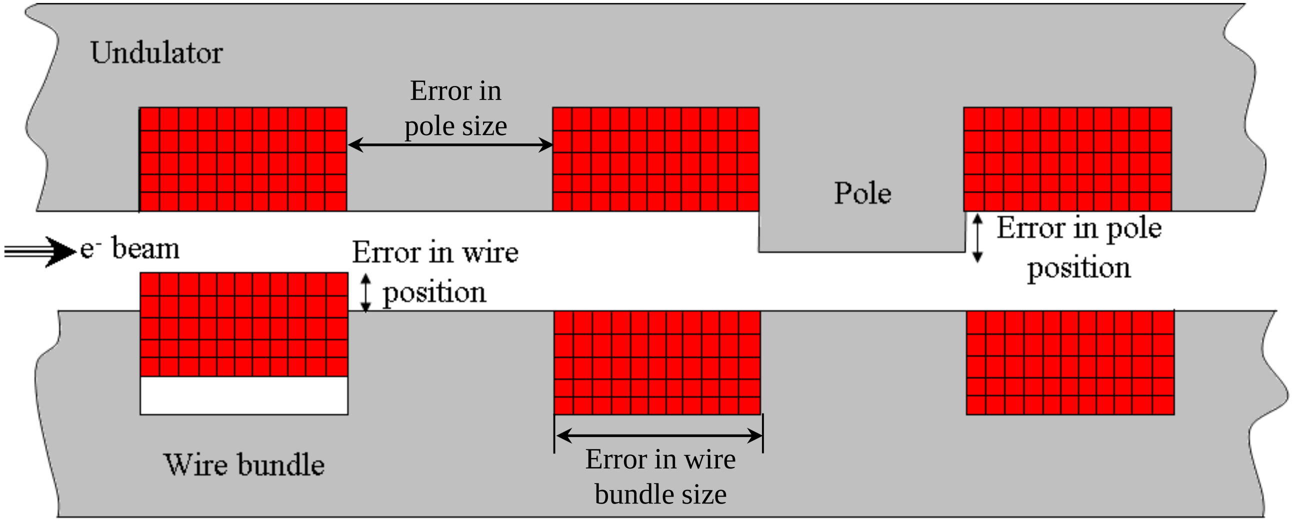
Main Tasks:

- Quality assessment of the devices before installation in an accelerator
- Precise local field measurements of individual devices
- Field integral measurements and minimization
- Improvement of magnetic field properties
- Alignment of several devices

Main errors in superconducting undulators

Field errors are mainly caused by:

- Mechanical deviations of the pole position e.g. the pole height
- Deviations in the period length
- Bending of the yoke
- The position of the superconducting wire bundles
- Pole and wire bundle size



Measurement techniques suitable for SCUs

Characteristic working environment:

- Low temperatures (≤ 4K)
- Narrow gap (≤ 8 mm)
- Evtl. in-vacuum, horizontal arrangement as in final devices

Measurement of field integrals, integral minimization and coil alignment (wire measurements):

- Rotating coil
- Moving stretched wire
- Stretched wire with constant current
- Stretched wire (vibrating)

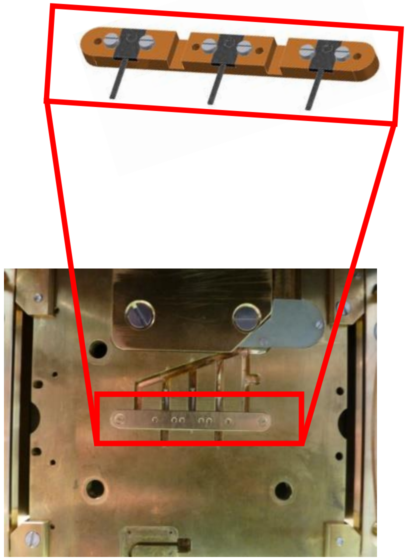
Local field measurements:

- Longitudinal field measurements stepwise by Hall samples
- Pulsed wire, vibrating wire

Characterization setups for short coils (I)

KIT (CASPER I)

- Operating vertically, test of mock-up coils in LHe
- Maximum dimensions 35 cm magnetic length and 35 cm in diameter
- Perform magnet training and quench tests, inductance measurements, test new winding schemes, new superconducting materials and wires, new field correction schemes
- Magnetic field distribution measured by 3 Hall samples on a sledge, calibrated at 4 K
- One in the middle and two at ± 10mm perpendicular to the beam axis to measure roll off
- Sledge moved from outside between precisely machined stainless guiding rails by a linear stage with stepper motor, gear box and a low expansion coefficient non magnetic tube (system resolution 3 μm)



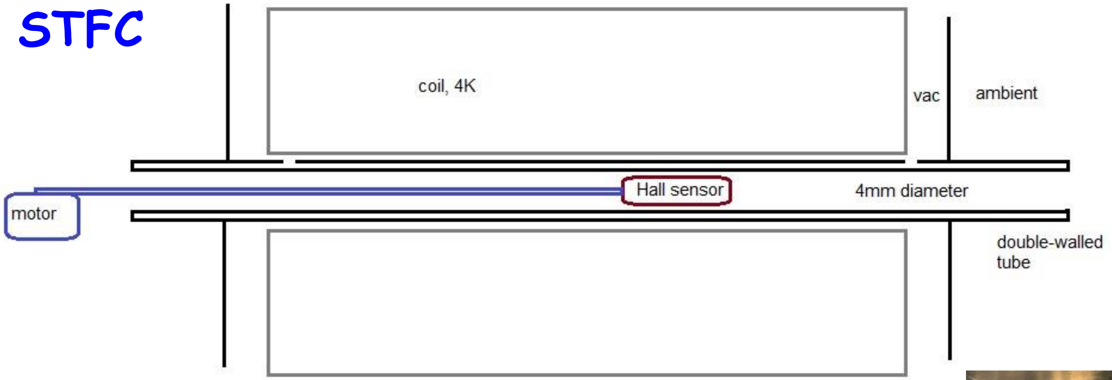
- Hall samples calibration in a Physical Properties Measurement System of the Institute for Technical Physics (ITEP) at the KIT

Further instrumentation

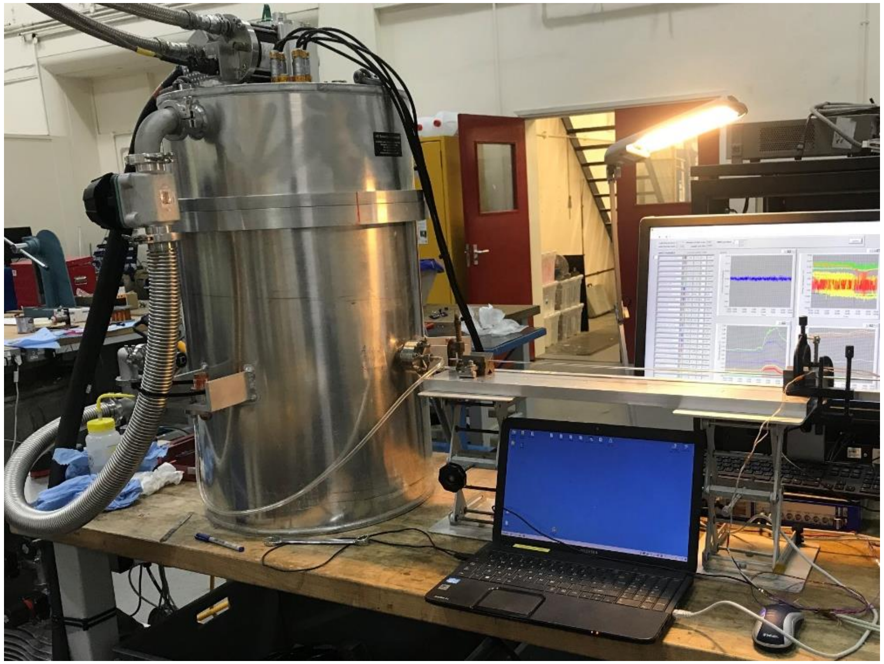
- Keithley constant current source and voltmeter (Hall samples)
- 1500 A power supplies
- Quench detector, quench diagnostics (100 kHz sampling rate)

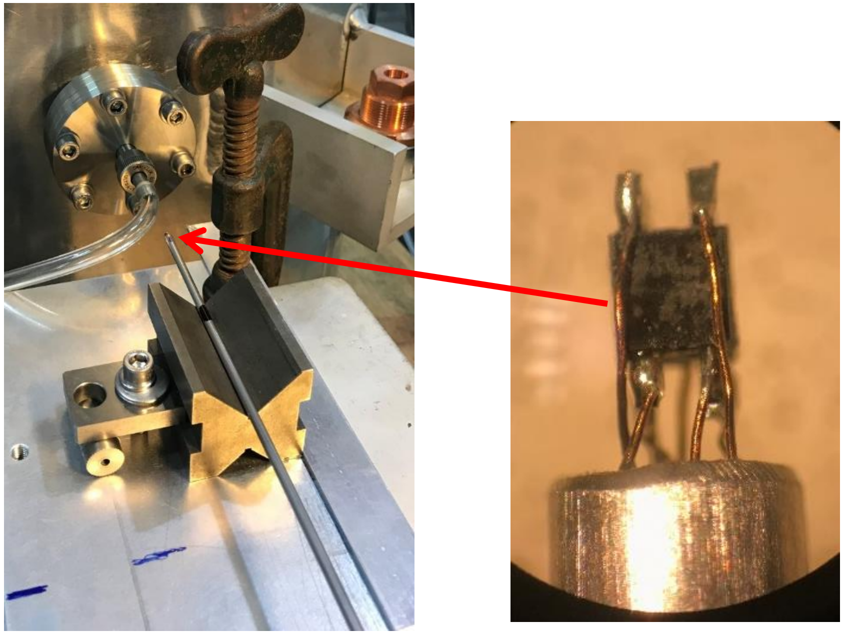
Characterization setups for short coils (II)

STFC



- Operating horizontally, coils cooled by cryocooler
- Measurement length ~50 cm
- Magnet training, quench tests, field measurements
- Warm bore (Ø 4 mm)
- 1 Hall sample on a stick

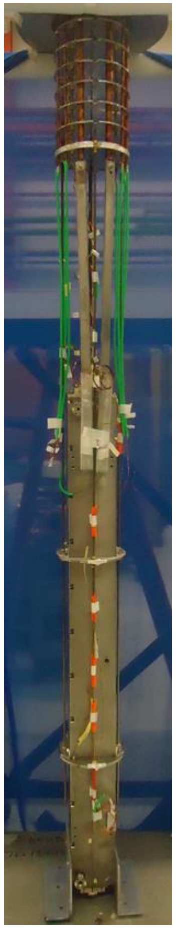




Courtesy of T. Hayler, C. Macwaters, J. Boehm, STFC

Characterization setups for long coils (LHe)

ANL



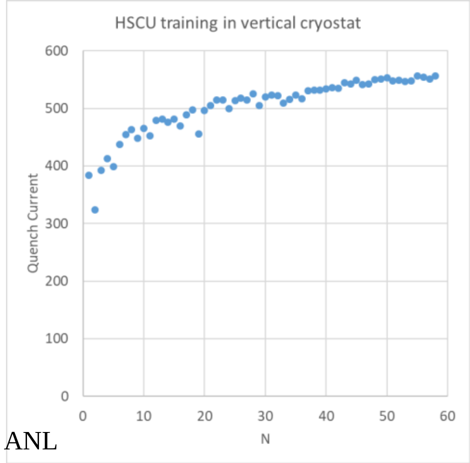
Setups

Two LHe bath cryostats, ~2 m and ~4 m deep, scanning system for magnetic measurements.

Bath cryostat LHe, height ~4.5 m
Diameter ~700 mm, magnet length up to 2.5 m magnetic field measurement system.

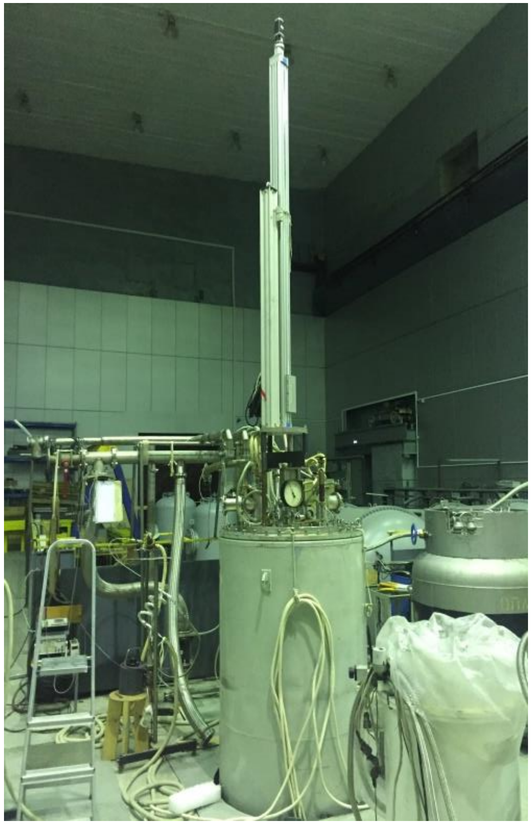
Tasks solved

- Coil training
- Preliminary magnetic measurements using a Hall probe calibrated at 4.2 K
- Inductance measurements



- Magnet training, check coil commutations and polarity and maximum field
- Quench analysis
- Quench protection testing
- Inductance measurements
- Magnetic field mapping with Hall sample array
- Examination of weak single poles of long coils (replacement)

BINP



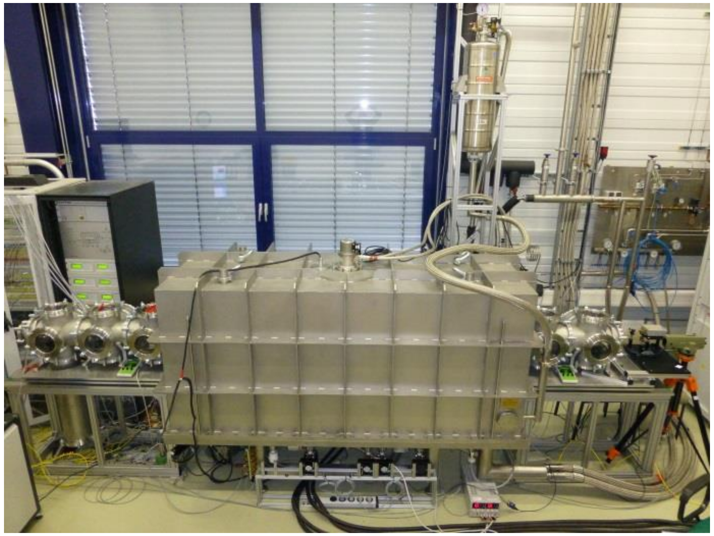
Courtesy of M. Kasa, ANL

Courtesy of N. Mezentsev, BINP

Characterization setup for long coils (conduction cooled)

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

KIT (CASPER II)



Magnet training:

- Quench detection
- Quench analysis (64 channels, max. sampling rate 200 kHz)
- Inductance measurements

Field integral measurements:

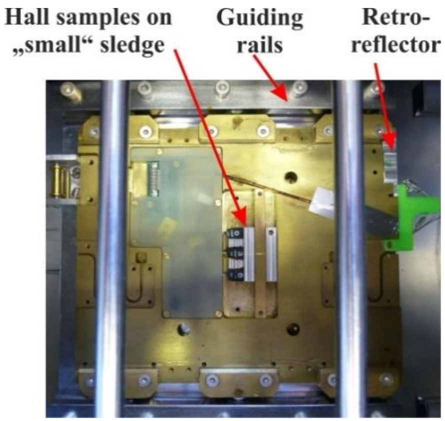
- Moving stretched wire

Local field measurements:

- Hall probes, calibrated at 4.2 K

A. Grau et al., IEEE Trans. on Appl. Supercond. 9001504 22-3 (2012)

CASPER II (Local field)

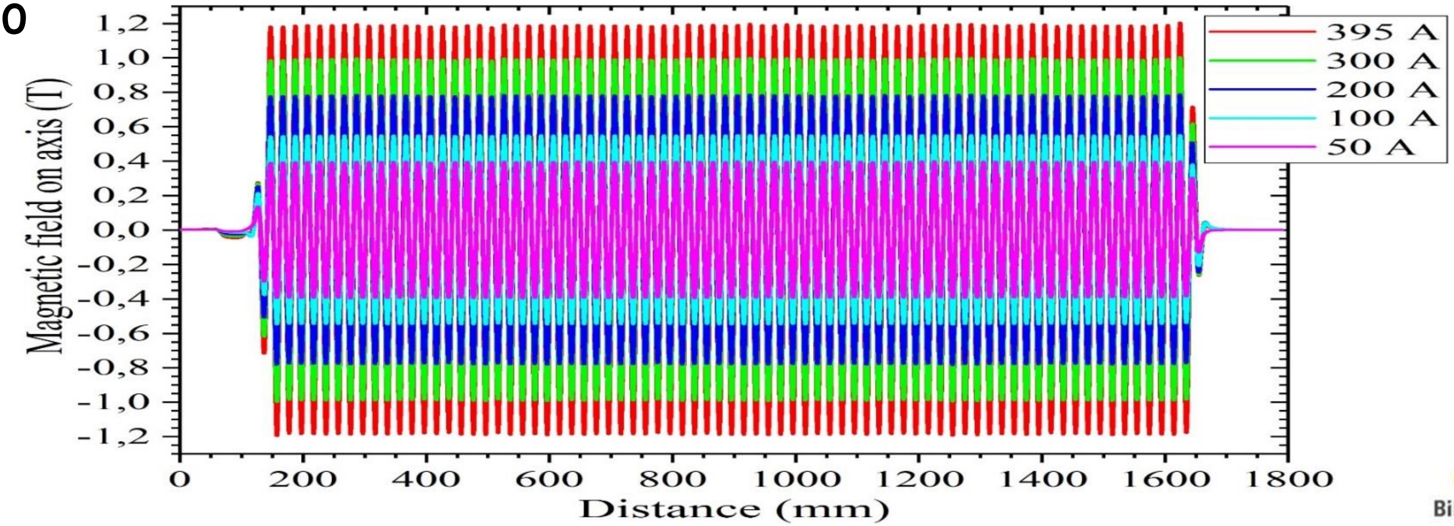


Characterization of „full scale“ SCU coils (conduction cooled)

- Measurement length 1800 mm, step wise (50 µm – 500 µm)
- Hall probe mounted on a sledge moving along the undulator length (pulled), between precisely machined guiding rails
- 3 Hall probes calibrated to ± 90 µT (PPMS System at Institute for Technical Physics)
- „Small sledge“ on measurement sledge allows shifting of middle Hall probe ± 10mm
  (Peak field comparison of all Hall samples possible, reduces errors
- Independent longitudinal position determination by laser interferometer (sub-µm accuracy/resolution) pointing on retroreflector
- Current feedthroughs for ~2000 A (main coils) and 6 correction coils (20 A, field integral optimization)

Local and integral field measurements can be performed during the same thermal cycle !

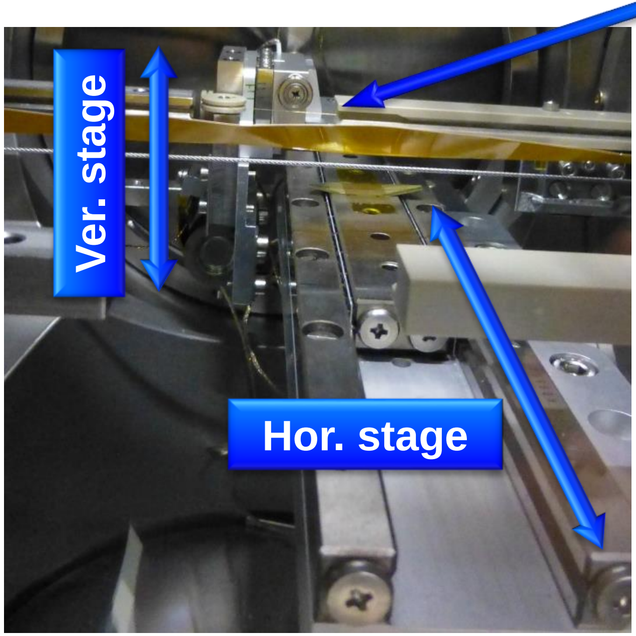
SCU20



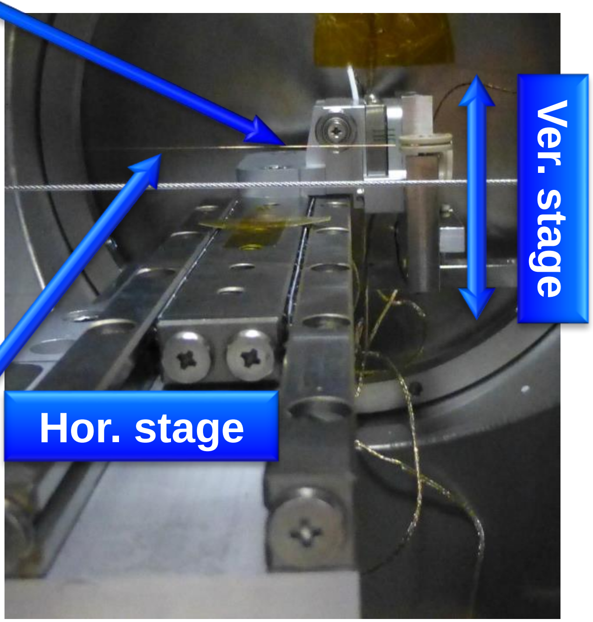
A. Grau et al.,
IMMW21, Grenoble,
France (2019)

CASPER II (Field integrals)

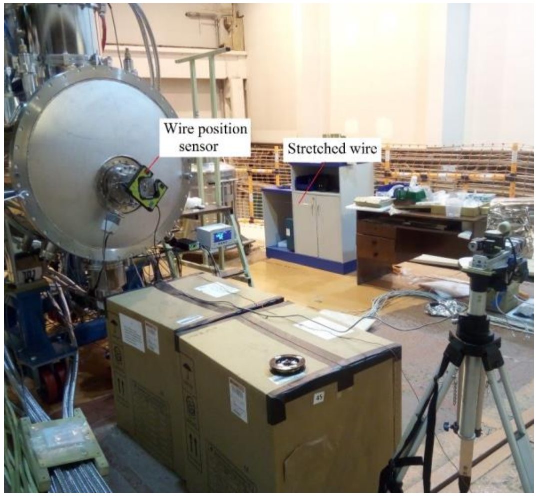
Stretched wire



- Movement by piezo stages
- Wire tension applied via constant force spring (6 N)
- Induced voltage amplified by a FEMTO DLPVA and measured by a Keithley Nanovoltmeter.



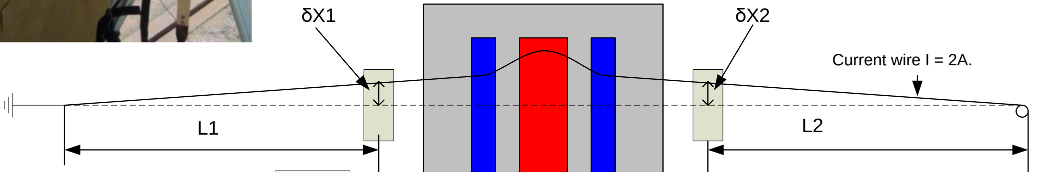
Measurement systems for devices in final cryostats (I)



Stretched wire with direct current (field integrals I1 and I2)

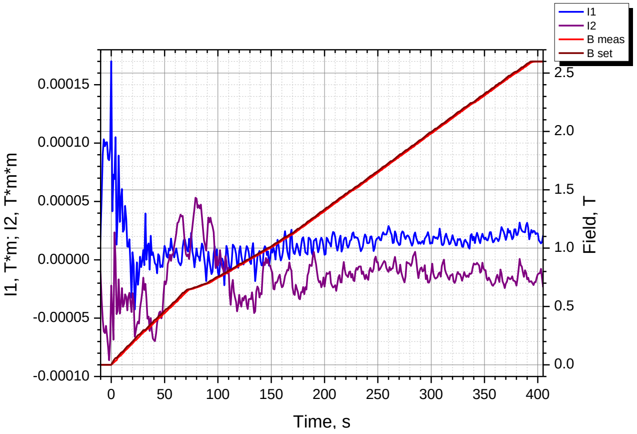
Measurement method based on the interaction of a wire with a direct current I with magnetic field, is similar to the interaction of an electron beam with magnetic field.

- Measure field integrals at any field level (static, minimization, multipole determination)
- Measure field integrals while ramping (dynamic)
- Current table for main coils and correction coils



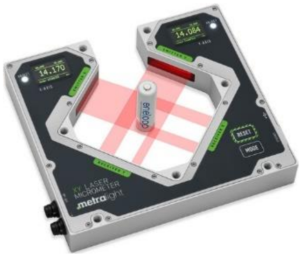
Instrumentation:

- Translational stages
- Current source
- Two-axis laser micrometer



$$I_{first} = I_1\left(\frac{L}{2}\right) = \delta\alpha^* \frac{T}{I} = \frac{T}{I}\left(\frac{\delta x1}{L1} + \frac{\delta x2}{L2}\right)$$

$$I_{second} = I_2\left(\frac{L}{2}\right) = \delta x \cdot \frac{T}{I} = \frac{T}{I}(\delta x2 - \delta x1)$$



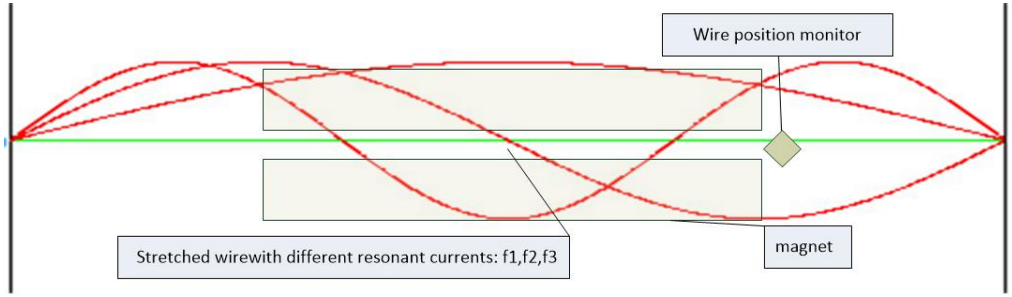
Courtesy of N. Mezentsev, BINP

Measurement systems for devices in final cryostats (II)

Stretched vibrating wire, resonant method (field integrals I1 and I2)

Measurement method based on powering tensioned wire at resonant frequencies of the wires natural vibrations (1st and 2nd harmonics) and its interaction with the magnetic field.

- Method very effective for minimizing field integrals
- Measure field integrals at any field level (static, minimization, multipole determination)
- Complementing stretched wire measurement with direct current technique
- Instrumentation: Translational stages, frequency generator, two-axis laser micrometer



Maximal wire amplitude

$$x_{0n} \approx \frac{J_0 * b_n}{2\,\omega_{nres}\,\delta\,\rho}$$

Resonance frequency

$$\omega_n = \sqrt{\frac{T}{\rho}\cdot k_n^2\cdot\left(1+\frac{E\,I_w}{T}k_n^2\right)-\delta^2}$$

k_n=nπ/L Wave vector n-harmonic

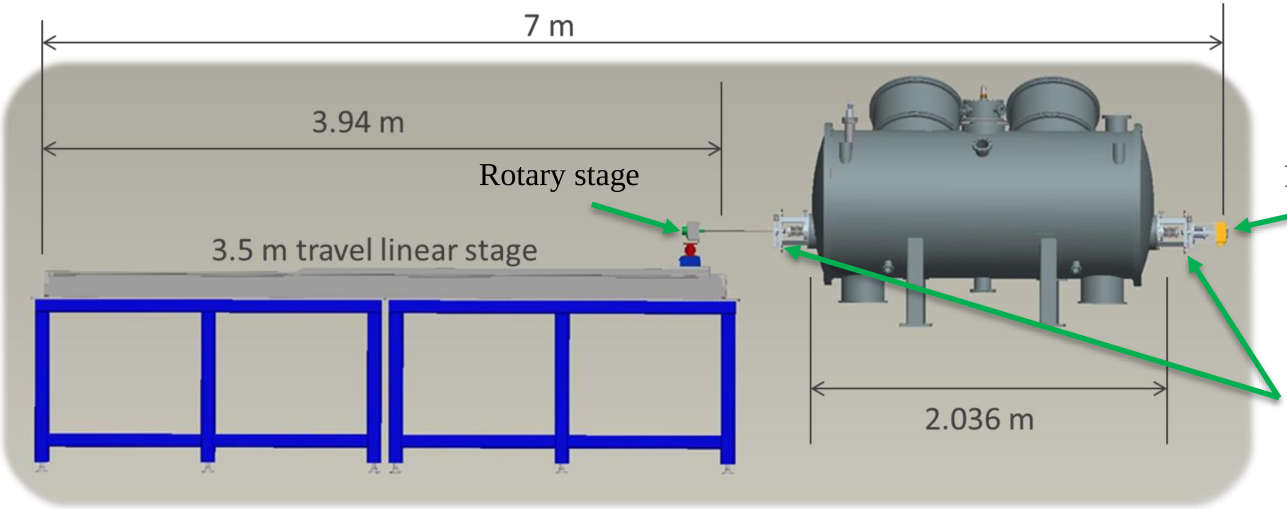
ρ – linear density of the wire
E - wire E-module
J_0 - current amplitude in the wire
B(s) – magnetic field
x_{0n} – wire amplitude of oscillations
I_w = πd^4/64 (d-wire diameter)
δ- damping decrement

Magnet field Fourier component

$$b_n = \sqrt{\frac{2}{L}}\int_0^L B(s)\sin(k_n\,s)\,ds$$

Courtesy of N. Mezentsev, BINP

Measurement systems for devices in final cryostats (III)



Rotary stage

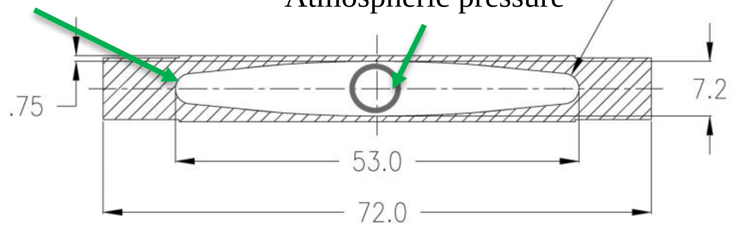
Linear stage
assemblies
mounted on each
end of the
cryostat

Local magnetic field measurements

- Warm bore guide tube adapted from BINP by C. Doose
- Titanium guide tube is tensioned to reduce sag
- Atmospheric pressure
- Heated to room temperature with current
- Translated horizontally using stages on the cryostat
- SENIS integrated 3-axis Hall probe mounted inside a carbon fiber tube and scanned through the device using the 3.5 m linear stage
- Instrumentation: Translational stages, current sources (heating and Hall samples) voltage DAQ system

Al beam chamber ~15 K,
under vacuum

6.4 mm OD Titanium
guide tube ~300 K
Atmospheric pressure

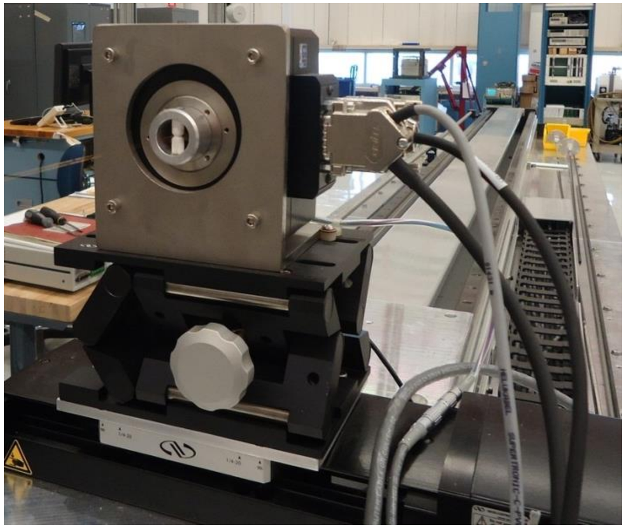


Courtesy of M. Kasa, ANL

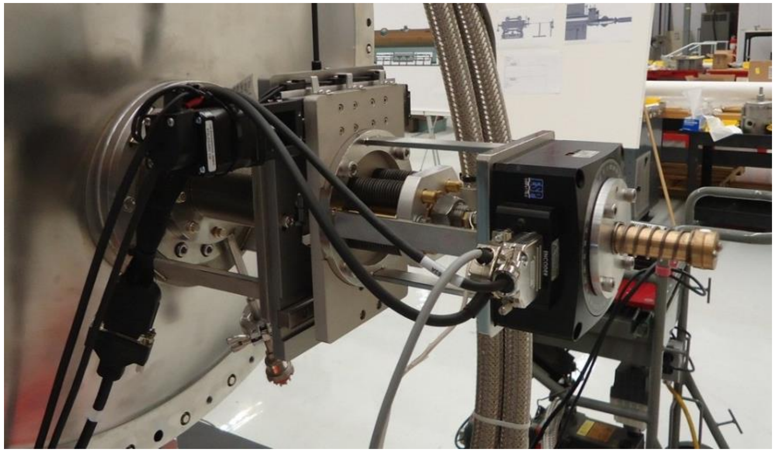
Measurement systems for devices in final cryostats (IV)

Rotating coil (field integrals I1 and I2)

- One turn integral coil
- Coil width 4 mm
- Mounting via ceramic pins (Ø4 mm)
- Different coil configurations possible
- Supported and tensioned at each undulator end



Upstream end rotating stage with ceramic pin to define coil width and position



Down-stream end rotating stage with ceramic pin and brass tensioning fixture

Instrumentation:

- Translational stages
- Rotational stages
- Encoders
- DAQ device (Volts, Nanovolts)
- Ampilifier (evtl.)

Courtesy of M. Kasa, ANL

Measurement systems for devices in final cryostats (V)

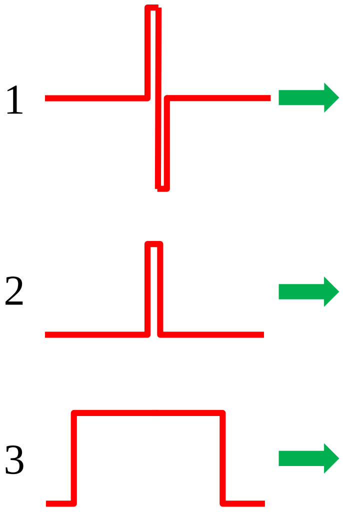
Pulsed wire (field integrals I1, I2 and local field distribution)

Interaction of pulses through a tensioned wire with the magnetic field distribution due to Lorenz force (R. Warren, Nucl. Instr. and Meth., 1988)

- Wire CuBe, AlSi or W (~100 µm)
- Pulse current ~1 A
- Pulse length (10µs – 20ms) and shape leads to I1(x), I2(x) or B(x)
- Wire vibrations are proportional to magnetic field integrals
- Signal of travelling wave (speed ~200 – 300m/s) measured by laser/photo diode and recorded with oscilloscope
- Characterization of small bore magnets (field integrals, magnetic center, alignment)

Instrumentation:

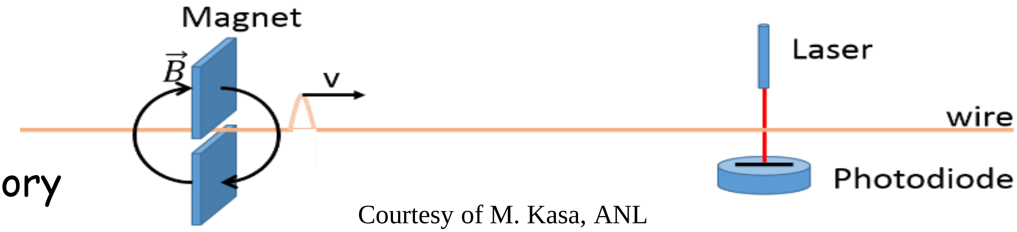
- Translational stages (wire alignment)
- Pulse generator, power supply, amplifier (pulse)
- Laser
- Photo diode
- Current - voltage converter (measurement signal), amplifier
- Digital storage oscilloscope



1 → B(x): magnetic field

2 → $\int B(x)\,dx$: angle

3 → $\int\int B(x)\,dx\,dx'$: trajectory



Courtesy of M. Kasa, ANL

Measurement techniques pros & cons

Hall probe measurements	Established, direct access to magnetic field, calculation of field integrals, direct position determination with laser interferometer, Zero-Gauss chamber (offset reduction), in-vacuum	• Calibration error <0,1 mT (offset), LT • Scanning length affects integral calc. • Positioning • Sensor dimensions (for small bore, PCB?)
Moving stretched wire	Established, direct access to values for I1 and I2, $\sim 10^{-6}$ Tm/Tm^2, small bore, low/room temperature, in-vacuum	• Small signal (nV) • Signal to noise ratio (Lock-in technique ?)
Stretched wire, constant current	Established, access to I1 and I2, dynamic measurements during ramping, fast measurement method, low/room temperature, vacuum, small bore	• I1, I2 $\sim 10^{-4}$ Tm/Tm^2 • Depends on accuracy of two-axis micrometer • Signal to noise ratio
Vibrating stretched wire	Effective for zeroing for field integrals, more sensitive than constant current method	• Receive field integrals from Fourier analysis measurement signal • Good calibration not easy
Rotating coil	Established, direct access to I1 and I2, static and dynamic measurements, low/room temperature, in-vacuum	• Minimum dimension (≥ 4 mm) • Low temperature with antechamber • In-vacuum • Tensioning & sag, spatial resolution
Pulsed wire	Access to I1 and I2 and B, fast measurement method, feedback during tuning, alignment, magnetic centering, measure multiple magnetic structures along the wire, in-vacuum, small bore	• Data processing needed, eliminate dispersion and pulse effects • Short pulse length, poor signal • Artefacts due to Eigenmodes, vibrations


Thank you!

Steps per move: 138

Time between steps (s): 0.5

Time for move: 0.0138

Move size [mm]: 0.0997111

wait after move [ms]: 200

Encoder readback

	Steps	Travel distance calculated [mm]
Axis 1	692901	500.651
Axis 2	692897	500.649

Absolute Position [mm]: 500.6514

Target distance [mm]: 500

Position rel. to Measurment start [mm]: 500.053

OFFSET: 0.59800

Linear stage readback

Position PI stage 1: 17.084359

Position PI stage 3: -37.612399

☑ Voltage1 [V]
☑ Voltage2 [V]
☐ Voltage3 [V]
☑ Hall1 [T]
☑ Hall2 [T]
☐ Hall3 [T]

Autoscale
X: OFF
Y: ON