Future measurement systems

Johann E. Baader
European XFEL

Virtual Superconducting Undulators for Advanced Light Sources Workshop
Hamburg, April, 20^{th} 2021

Special thanks to Matthew Kasa (Argonne), Maximilian Trunk (UUH, LUX), Toshiya Tanabe (BNL), Andreas Grau (KIT), Nikolay Mezentsev (BINP), Zhou Qiaogen (SHINE), and Sara Casalbuoni (European XFEL), who provided valuable input for this talk.

Outline

- Introduction
- Hall probes
- Pulsed wire method
- European XFEL
- Summary

Introduction

Tendency towards the future

Future measuring systems for Superconducting Undulators (SCUs) will focus on:

1. having instruments capable of characterizing small-gap long devices;
2. measuring the field in the final cryostat;
3. improving local field measurements (accuracy and precision).

Hall probes & Pulsed wire

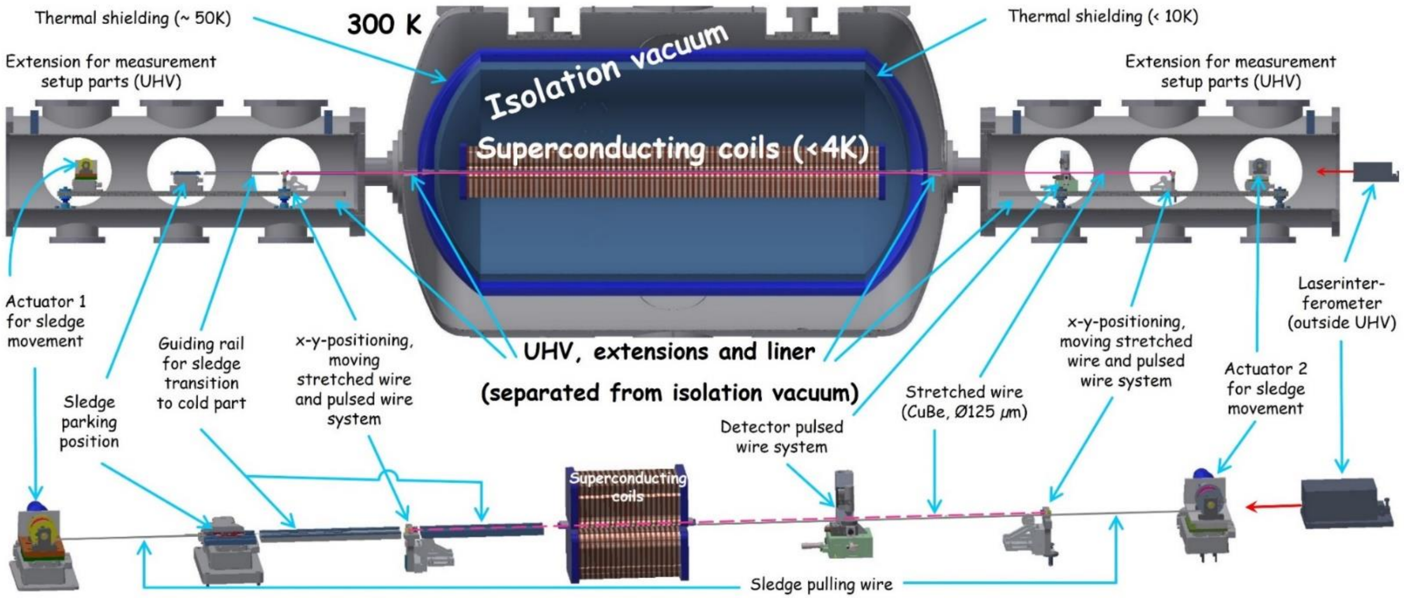
Pulsed wire technique is still not competitive with Hall probes.

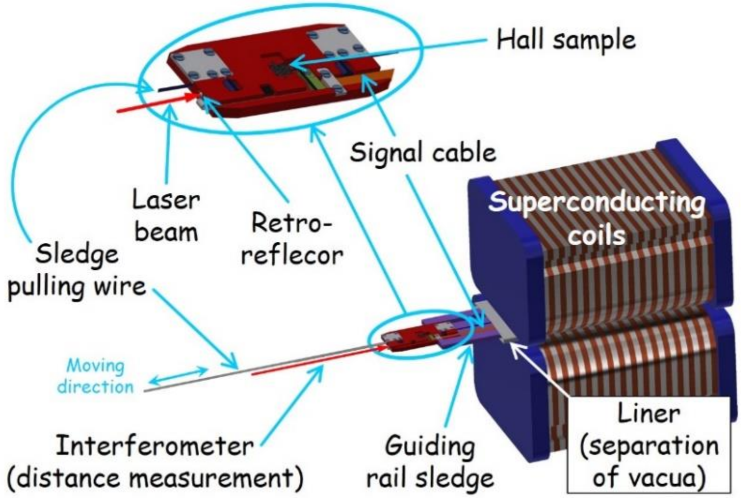
The advance of the pulsed wire technique will be important for SCUs.

Hall probes

KIT: Hall probes local field measurements

- **Vacuum gaps > 5 mm**.
- Hall sensor (**calibrated at low temperatures**) is mounted on a **sledge (70 mm x 30 mm x 3.5 mm).**
- Hall sensor is guided along the whole length of the magnetic structure by a 2-meters long accurately machined guiding rail (Phytron UHV stepper motors).
- **Calibration accuracy** (4K – 77K and ± 2T): **± 90 µT**.
- **Dislocation of the Hall sensor** in the height of the gap: <**100 µm**.
- **Laser interferometer** to measure **sledge's position at a resolution of 1 µm**.





Design drawing of the measurement setup for superconducting undulators attached to a SCU-dummy-cryostat (top) and the superconducting coils with local field measurement components (left).

Images and content courtesy of ***Andreas Grau***

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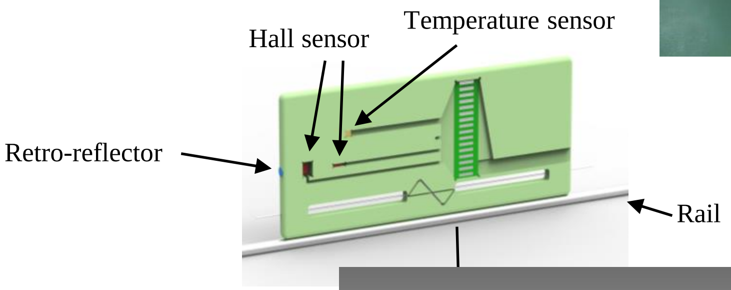
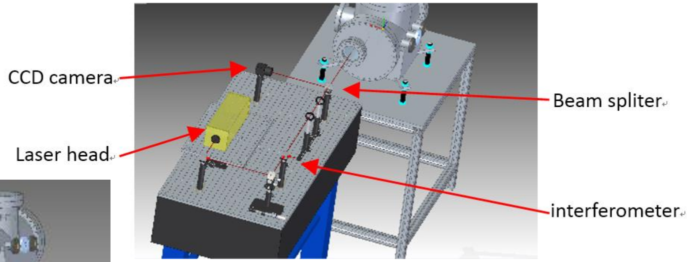
Karlsruher Institut für Technologie

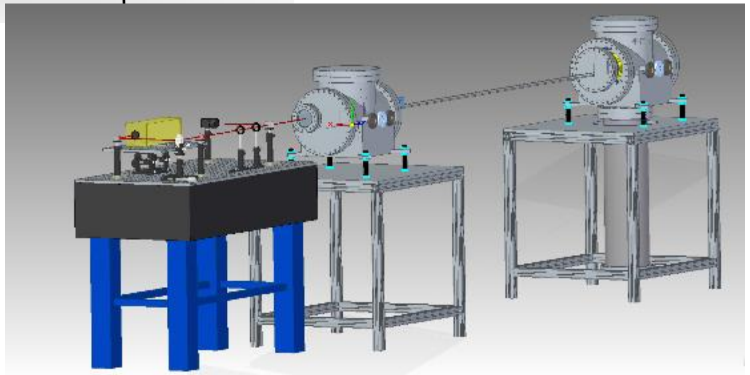
A. W. Grau et al., IPAC2019, Melbourne, Australia, TUPRB015, 2019

SHINE SC Undulator

- SHINE will use **40 SCUs** of **16mm period length** and **4m long** to produce 10-25KeV X-ray FEL with vertical polarization. The beam gap is **4mm**.
- For the magnetic field measurement, a carriage with thickness of **3.8mm** is designed on which **three Arepoc HHP-VU Hall sensors** and one Lakeshore CX-1030-SD-HT-1 .4L temperature sensor are mounted.
- The drive system of the carriage is enclosed in **two vacuum vessels attached to the two ends of the SCU vacuum chamber**. A long thin rod is placed at the bottom of the gap, which provides a continuous surface on which the carriage slides.
- The **Hall sensors** are **calibrated at the temperature from 3.8K to 300K** and the magnetic field from **-1.8T to 1.8T**.
- A laser interferometer (Keysight) is used to locate the carriage on which a retro-reflector is mounted.
- In order to get the transverse position of the carriage, the reflected laser beam is split and the smaller one shines at a CCD camera.



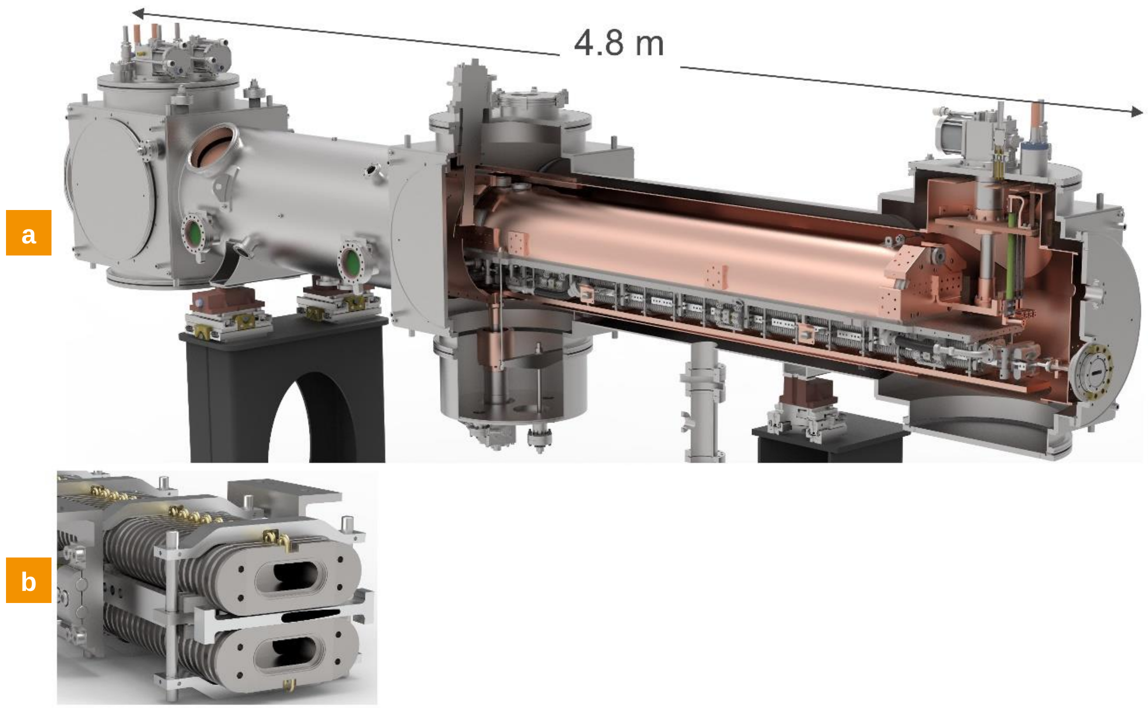




Images and content courtesy of ***Zhou Qiaogen***

APS Upgrade (APSU): the new cryostat

APSU cryostat layout



(a) Rendering of the APSU cryostat showing the thermal shield, end turret current leads, LHe tank, beam chamber, and magnets supported from below the LHe tank. (b) Model of the planar SCU magnetic assembly and beam vacuum chamber.

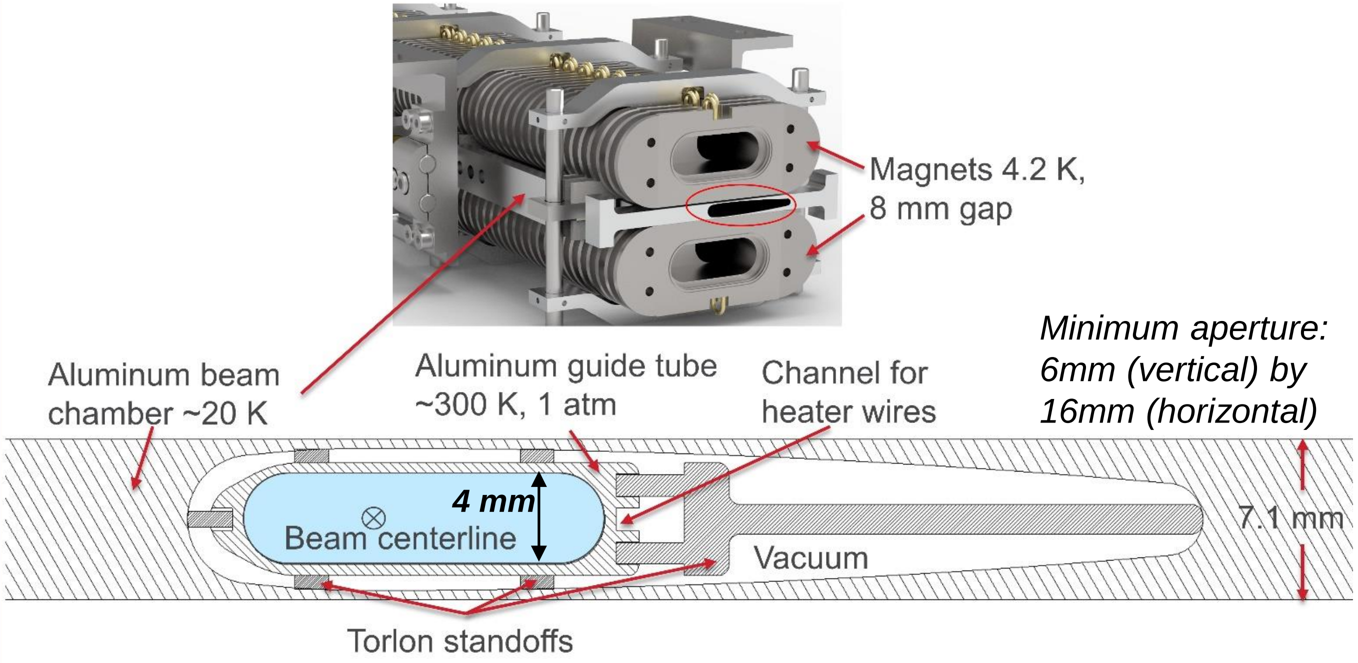
- APS is in the midst of preparing to upgrade the storage ring (APSU).
- Existing magnetic measuring system adapted from **Budker Institute of Nuclear Physics** (Russia).

Images and content courtesy of
Matthew Kasa

M. Kasa et al., IPAC2019, Melbourne, Australia, TUPRB095, 2019

APS Upgrade: required improvements

Extrude and machined guided tube



Cross section of the guide tube placement inside the beam vacuum chamber.

- Retain from previous system:
  - capability to measure the SCUs in the production cryostat under normal operating conditions.
  - ambient temperature and pressure aperture through the SCU magnetic gap.
- Upcoming challenges:
  - Scale the system to 4.8-meters long cryostat.
  - Maintain uniform temperature along the guide tube (aluminum).
  - Upgrade the drive system to accommodate Hall probe scan length ~4.8 m.

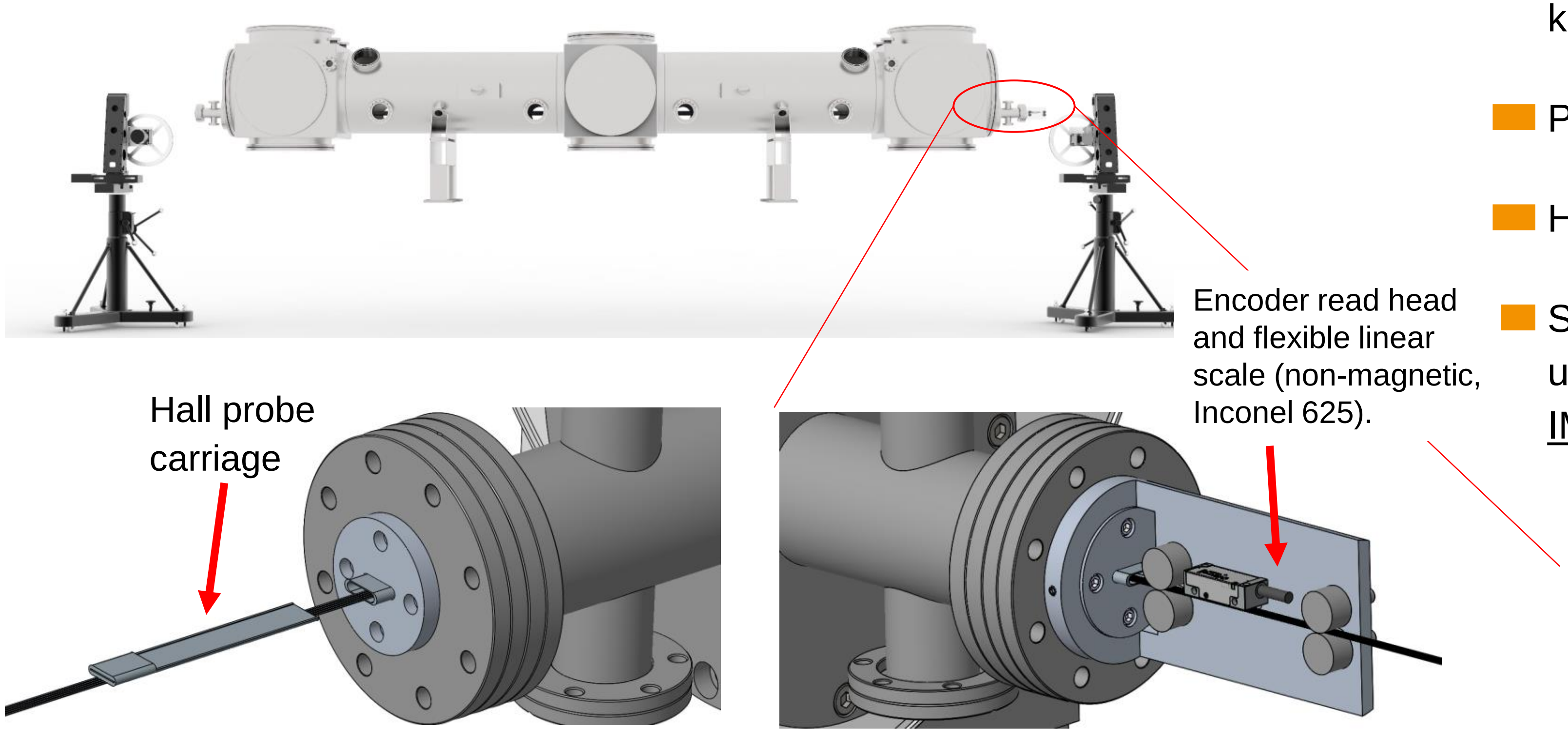
Images and content courtesy of
Matthew Kasa

M. Kasa and Yury Ivanyushenkov, IMMW21, Grenoble, France, 2019

M. Kasa et al., IPAC2019, Melbourne, Australia, TUPRB094, 2019

APS Upgrade: Hall probes for magnetic characterization

Hall probe drive system



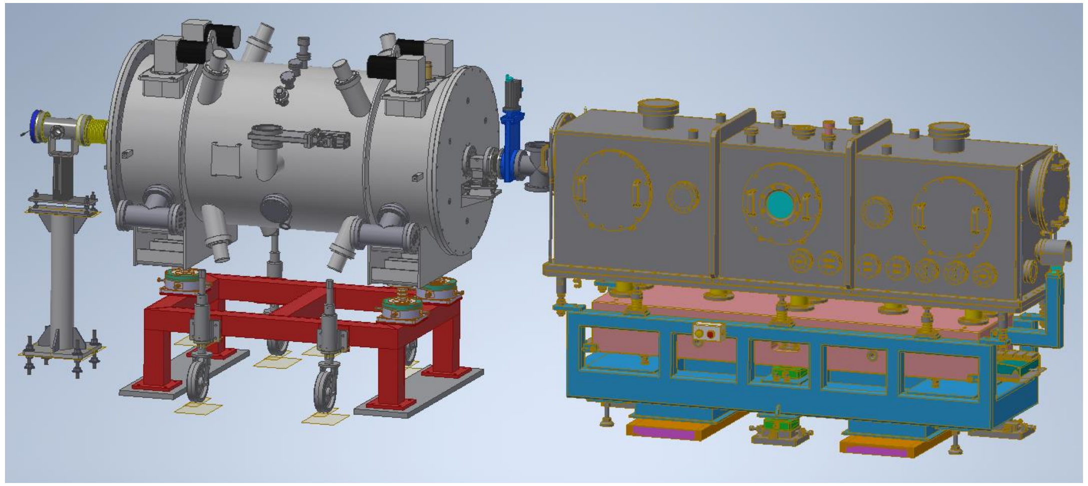
Measurement system installed at the ends of the SCU production cryostat and the concept of the Hall sensor carriage that slides within the guide tube.

- Servo + torque motors to move the scale and keep the tension.
- Pos. Resolution: 1 µm (accuracy of +/- 3 µm).
- Hall probes accuracy: 0.1 %.
- System has been tested with a hybrid undulator (M. Kasa and Yury Ivanyushenkov, IMMW21, Grenoble, France, 2019).

Images and content courtesy of
Matthew Kasa

M. Kasa et al., NAPAC2019, Lansing, USA, TUPLH01, 2019

In-Vacuum Hall Probe Bench at NSLS-II (SCW)



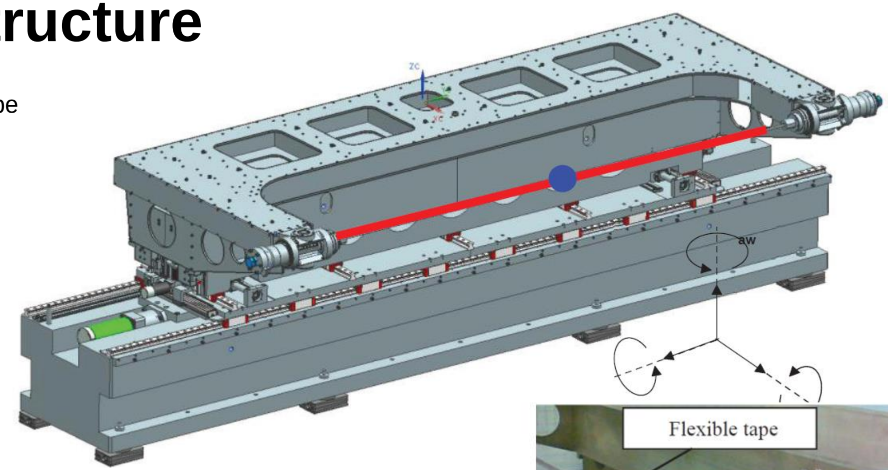
In-Vacuum Magnetic Measurement System (IVMMS)

- In-vacuum linear motor stage of 1.75m stroke.
- 3 Lakeshore Hall probe elements attached to alumina rod.
- Hall probes have been calibrated by KIT at 4K (beam chamber is set to 20K.

Images and content courtesy of ***Toshiya Tanabe***

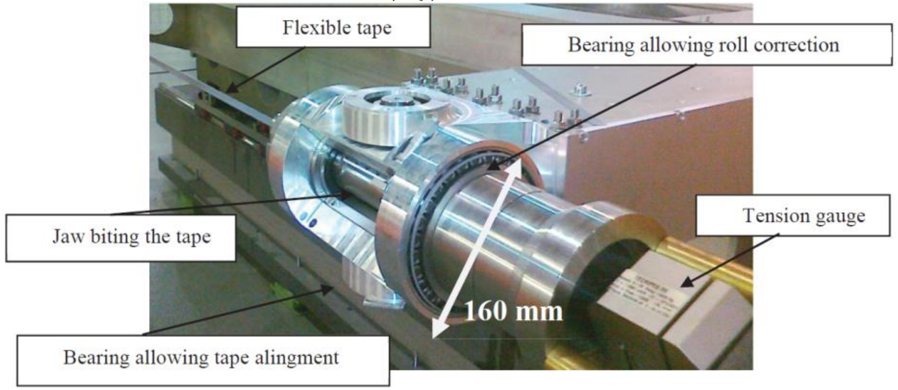
ALBA and a new bench for big closed structure

Picture of the prototype bench built at CELL.



General layout of the Hall probe bench prototype and reference system. Stretched tape is painted red, and Hall probe position is marked with a blue dot.

- Measurements taken with the device open (out of vacuum).
- Future upgrade (2021-2023):
  - 1st (2021-22): Adapt the bench to measure in-vacuum.
  - 2nd (2022-23): Adapt the bench to measure in cryo-environment.
- For SCUs applications, special attention must be given to the materials used for the tape, Hall probe housing, and cables.



Mechanism used to attach the carbon fiber to the "C" shaped structure.

Possibility to be adapted to 5-meters long devices.

J. Campmany et al., Physics Procedia, Vol. 75, pp. 1222-1229, 2015

Pulsed wire method

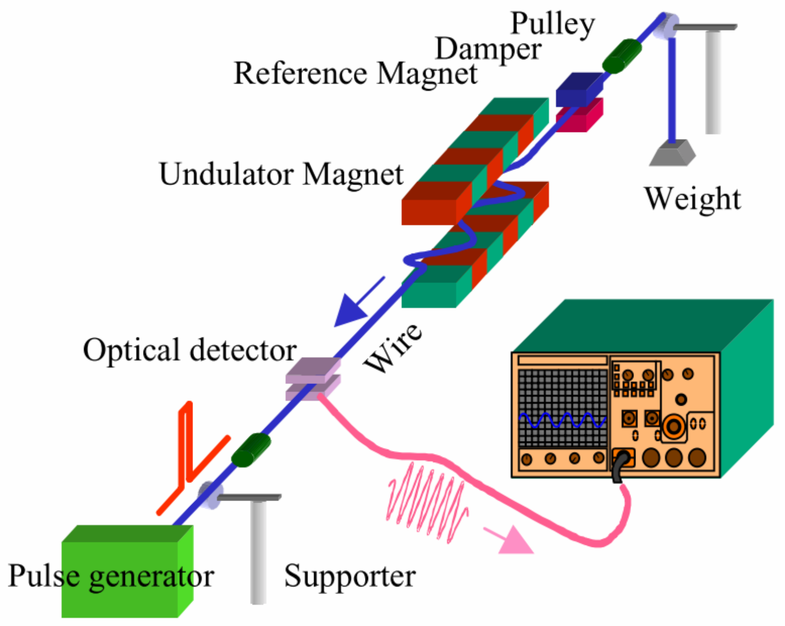
Pulsed wire method

Advantages

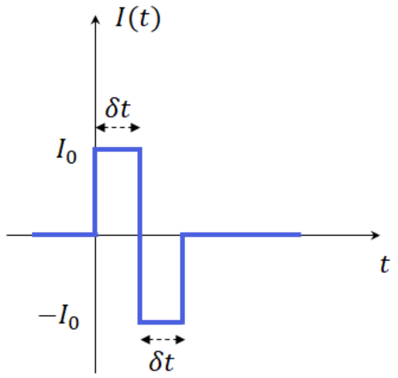
- Suitable for devices with small aperture.
- Fast.
- Easily measures both transversal field components.

Disadvantages

- Sensitive to external vibrations.
- Signal's reflection.
- Sag.
- Dispersion.



Simplified diagram of the pulsed-wire system (T.C. Fan et al., PAC2001, pp. 2775-2777).



- *Short pulses* ($\delta t < \lambda_u / c_0$): displacement of the wire is proportional to the **first field integral**.
- *Long pulses* ($\delta t > L / c_0$): displacement of the wire is proportional to the **second field integral**.
- *Positive-negative short pulses*: displacement of the wire is proportional to the **magnetic field.**

R. W. Warren, NIMA, Vol. 272, Issues 1-2, pp.257-263, 1988

Dispersion

$$u(t,z) = Ae^{(\omega t - \kappa z)}$$

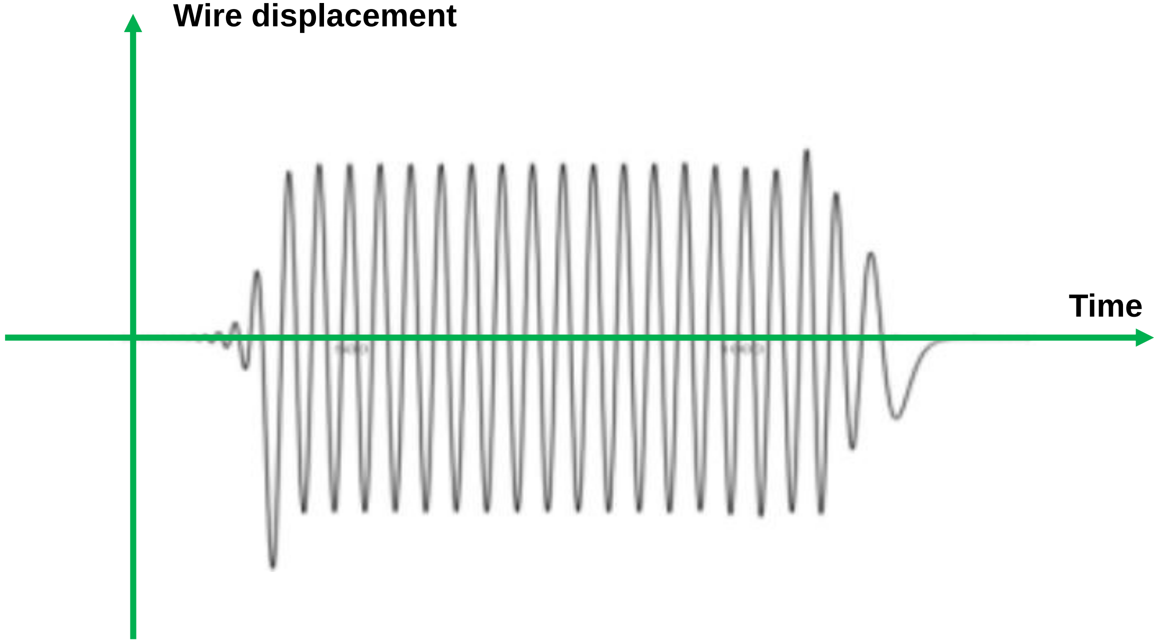
Angular frequency, in rad/s

Wavenumber, in rad/m

- Due to the finite flexural rigidity of the wire, $\omega = c(\kappa)\kappa$.

$$c(\kappa) = c_0\sqrt{1 + \frac{EI_w}{T}\kappa^2}$$

- Ideally, the wave speed propagation would be independent of the wavenumber ($\omega = c_0\kappa$).



Limitation caused by dispersion:

$$L \ll \frac{32T\lambda_u^3}{\pi^3 d^4 E}$$

Numerical example:
BeCu wire
$E = 124\ GPa$
$d = 75\ \mu m$
$T = 2\ N$

For $\lambda_u = 10\ mm,\ L \ll 0.53\ m$
For $\lambda_u = 15\ mm,\ L \ll 1.78\ m$
For $\lambda_u = 20\ mm,\ L \ll 4.21\ m$

V. Kumar and G. Mishra, Pramana, Vol 74, pp. 743–753, 2010
R. W. Warren, NIMA, Vol. 272, Issues 1-2, pp.257-263, 1988

Algorithms to correct dispersion in the pulsed wire technique

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

A dispersion and pulse width correction algorithm for the pulsed wire method

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[a] Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
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<u>Short pulse</u> $(\delta t < \lambda_u / c_0)$

$$I_1(z) = \frac{2c_0 m_L}{I\delta t}\, u_0\left(t = \frac{z}{c_0}\right)$$

<u>Long pulse</u> $(\delta t > L / c_0)$

$$I_2(z) = \frac{2T}{I}\, u_0\left(t = \frac{z}{c_0}\right)$$

1. Measure the displacement of the wire as a function of time $u(t)$.

   Fourier transform

2. Obtain $U(\omega)$ (frequency domain)

   Multiply by a proper scaling function $F(\kappa)$.

3. Obtain the non-dispersive solution $U_0(\omega)$, i.e., $U_0(\omega) = F(\kappa)U(\omega)$.

   Inverse Fourier transform

4. Back to the time domain $u_0(t)$.

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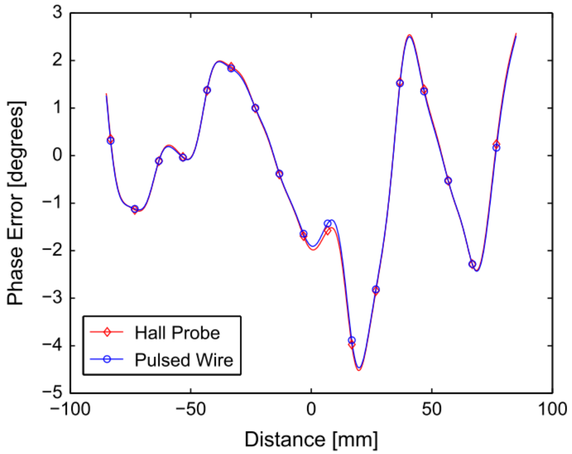
<u>*D. Arbelaez et al., NIMA, Vol. 716, pp. 62-70, 2013*</u>

Some results from the pulsed wire technique and correction algorithms



Berkeley: (D. Arbelaez et al., NIMA, Vol. 716, pp. 62-70, 2013)

- Undulator period: 20 mm.
- Length: ~20 cm (10 ½ periods).
- Tension: 2 N.
- Wire diameter: 75 µm (BeCu).
- EI_w: 2.14x10^{-7} Nm².
- **Max. length due to dispersion limit: L<<3.8 m.**

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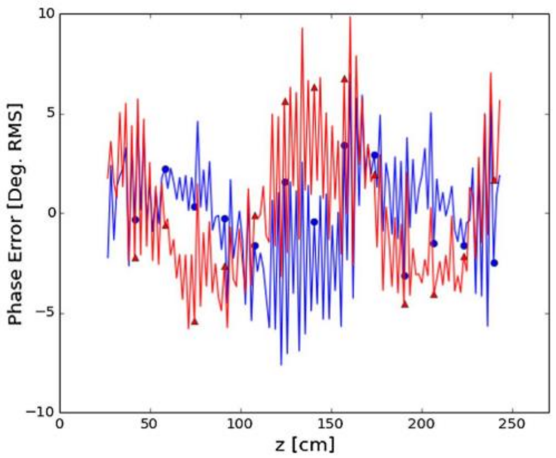


Argonne: (M. Kasa, Measurement, Vol. 122, pp. 224-231, 2018)

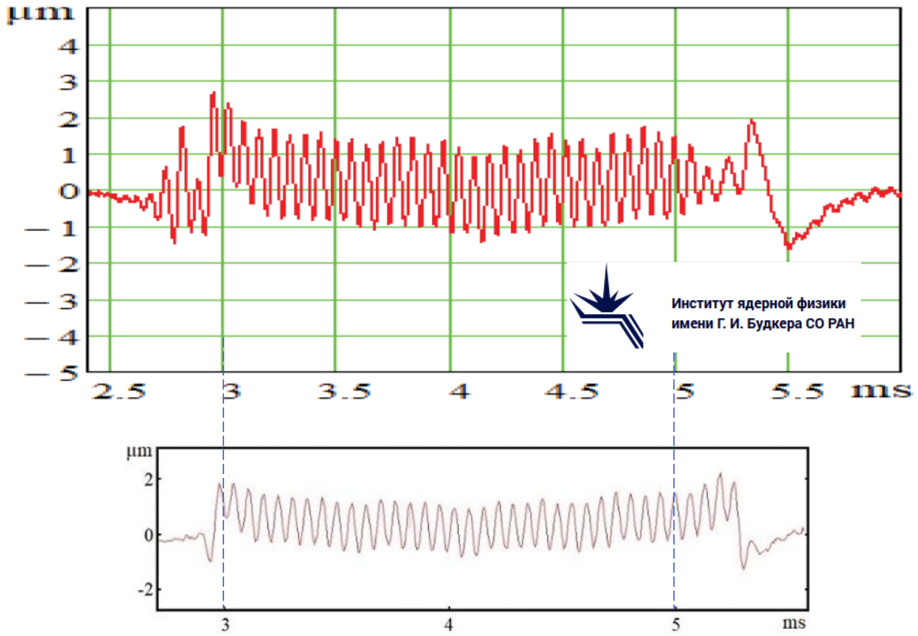
- Undulator period: 33 mm.
- Length: 2.4 m.
- Tension: 2 N.
- Wire diameter: 75 µm (BeCu).
- EI_w: 2.08x10^{-7} Nm².
- **Max. length due to dispersion limit: L<<17.5 m.**

Argonne NATIONAL LABORATORY

Limitation caused by dispersion

$$L \ll \frac{\lambda_u^3 T}{2\pi^2 EI_w}$$

Raw and reconstructed displacement of the wire.



BINP: (F. Kazantsev and P. Kanonik, AIP Conference Proceedings, Vol. 2299, p. 020015, 2020)

- Undulator period: 15.6 mm.
- Length: ~60 cm (38 periods).
- Wire diameter: 140 µm (Brass).
- EI_w: 2.45x10^{-6} Nm².

The system is currently in the process of being upgraded.

*Images and content courtesy of **Nikolay Mezentsev***

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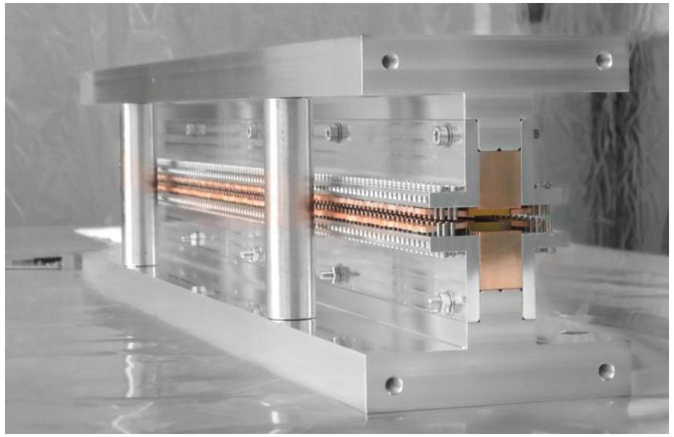
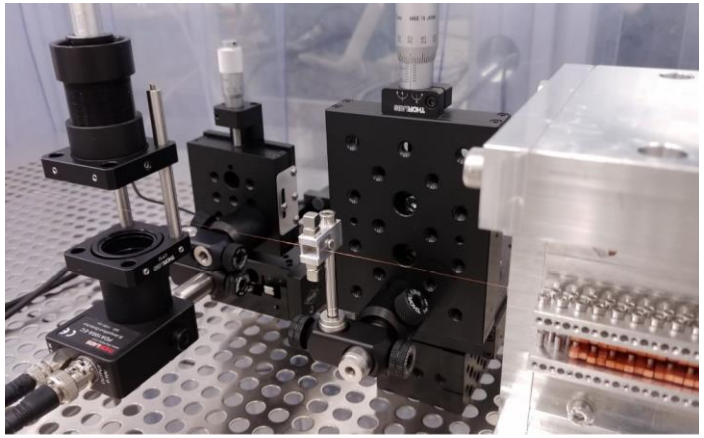
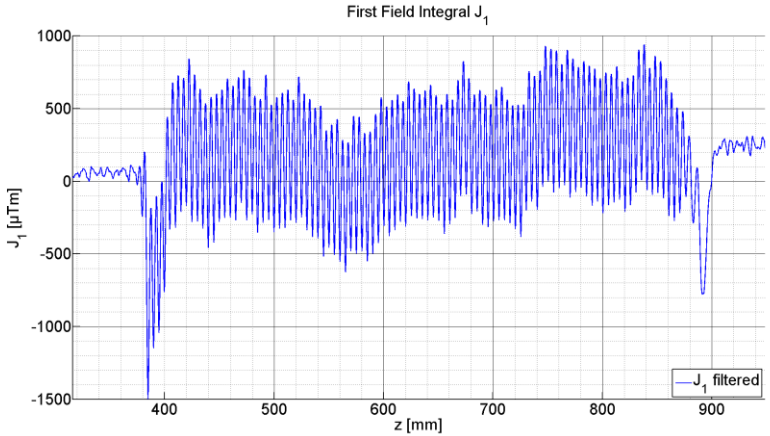
Pulsed wire system (UHH, LUX)







<u>Design considerations:</u>

In-vacuum

Periods: 100

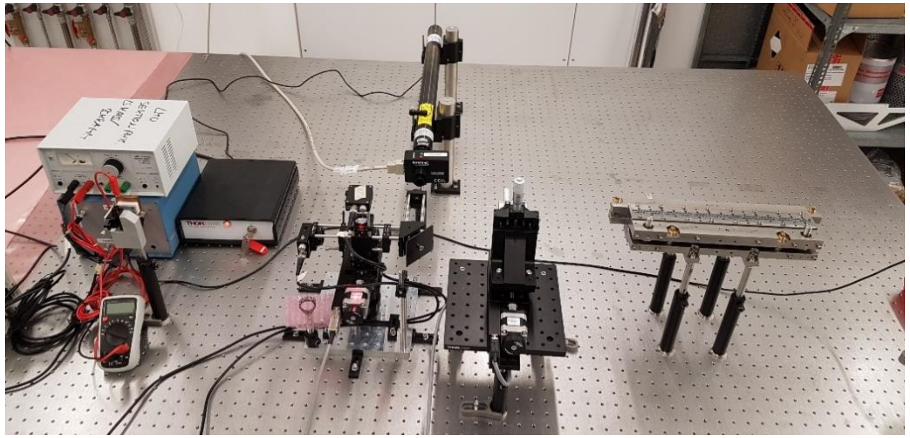
λ_u: 5 mm

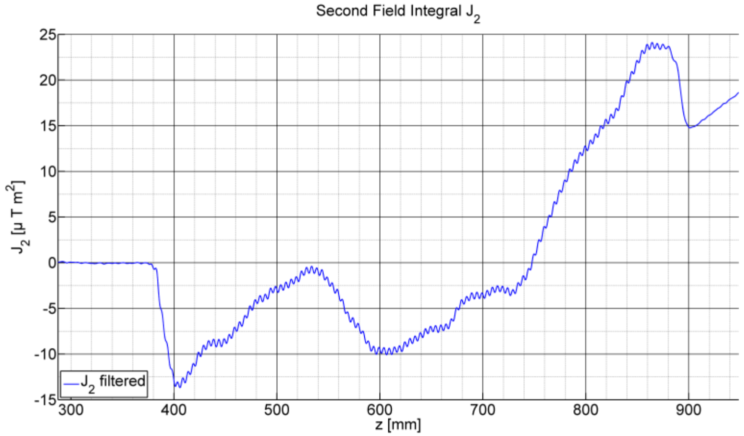
Fixed gap: 2 mm

Total length: 0.5 m

B_0 = 0.67 T

K = 0.3





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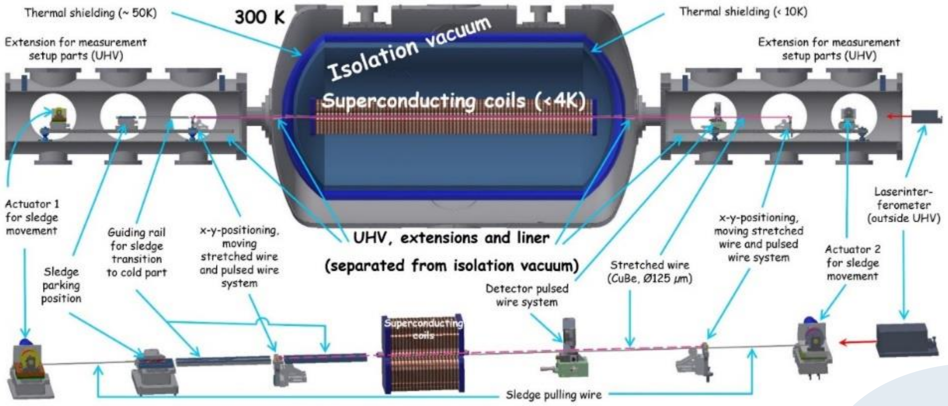
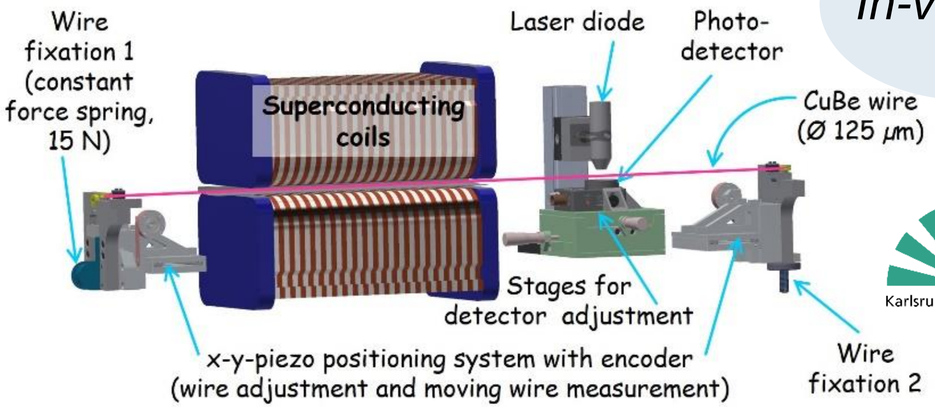
http://lux.cfel.de/

Images and content courtesy of
***Maximilian Trunk** (UHH, LUX)*

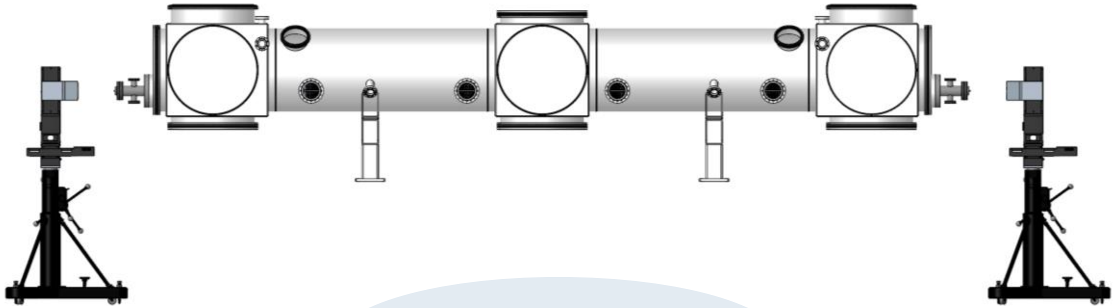
Pulsed Wire System at KIT & APS



In-vacuum



Measurement components for field integral measurements with a stretched wire.



Out-of-vacuum

- **<u>Pulsed wire measurements</u>** could be implemented by moving one stage assembly further from the cryostat.
- Photodiodes and optical detectors would be room temperature and at atmospheric pressure.

Images and content courtesy of ***Andreas Grau*** *and* ***Matthew Kasa***

<u>M. Kasa and Yury Ivanyushenkov, IMMW21, Grenoble, France, 2019</u>

<u>A. W. Grau et al., IPAC2019, Melbourne, Australia, TUPRB015, 2019</u>

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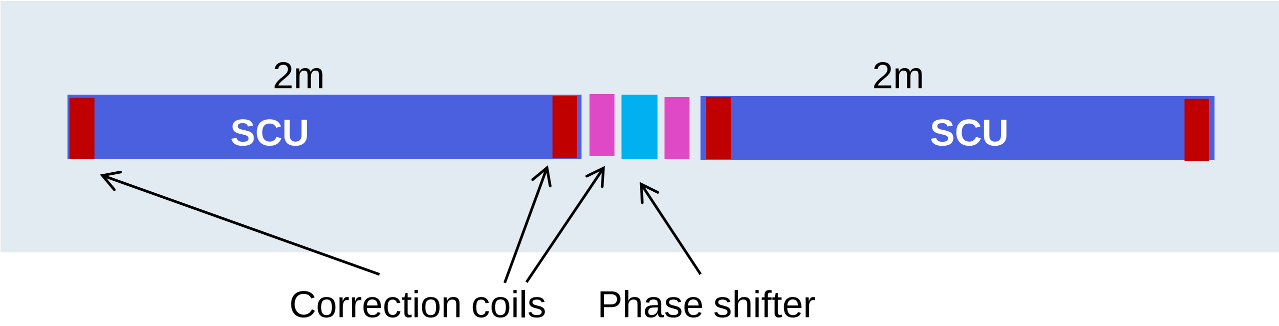
Plans at the European XFEL: SCU afterburner for SASE2

- SCU afterburner to be installed at the end of SASE2: 5 modules with about the same length as the installed permanent magnet undulators (5 m).



First test yoke
Courtesy of Massimiliano Di Felice

- Use of same intersections as for existing undulators.
- Pulsed wire system must be capable of measuring for
  - **5 mm** vacuum gap;
  - **15 mm** period length;
  - **~5 m** long cryostat.

Summary

Summary

- New small gap long devices require improvements of the current techniques to map the local magnetic field.
- The pulsed wire method becomes a promising solution, although it is still difficult to abandon Hall probe-based tests completely.
- The pulsed wire method has to be demonstrated to reconstruct the magnetic field for long undulators with a short period, particularly when dispersion effects dominate.

References

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M. Kasa, Measurement, Vol. 122, pp. 224-231, 2018

F. Kazantsev and P. Kanonik, AIP Conference Proceedings, Vol. 2299, p. 020015, 2020

http://lux.cfel.de/

Sara Casalbuoni Supercond. Sci. Technol. 32 023001, 2019

Thank you!

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