
WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

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Input slides from V. Vrankovic, C. Wouters and M. Calvi

Magnetic measurement techniques & systems at the Paul Scherrer Institut

2nd PACMAN workshop

June 2016, Debrecen, Hungary

Outline

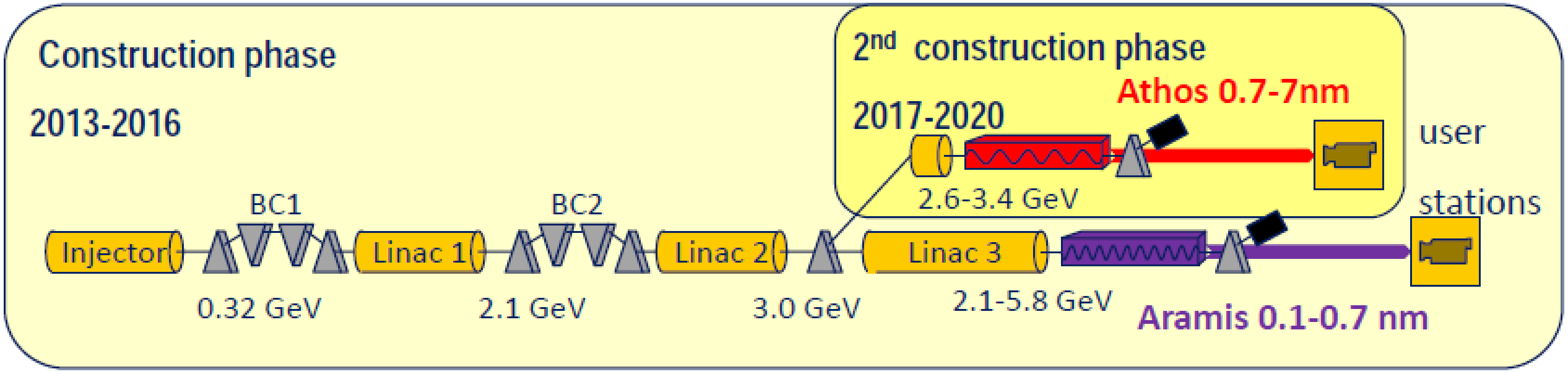
- ○ *Context : The magnetic elements of the Swiss Free Electron laser*
- ○ *System development since 2009*
- *Rotating coils for small aperture quadrupoles (CERN-PSI collaboration)*
- *Hall probes: from single axis to three - axis ones*
- *A vibrating wire system for magnetic axis measurements*
- ○ *Specific results*
- ○ *Future challenges*

"Demain importe plus qu'hier" , P. Mendes France, Député de Grenoble
Colloque Recherche & Enseignement, Caen,1er Novembre 1956

Tomorrow is more important than yesterday

The Swiss-FEL: Facility in construction at PSI

Swiss Free Electron laser: Linear Particle accelerator at PSI
to produce ultrashort X-ray laser radiation pulses



Two FEL Beamlines:
Hard X-ray Beamline Aramis: SASE FEL (1 – 7 Å), tuning mostly by energy (2016)
Soft X-ray Beamline Athos: SASE FEL (7 – 70 Å), seeded FEL (10 – 70 Å), tuning by gap and energy (2020)

Aramis line : 273 magnets in total+12 in-vacuum undulators (15 mm period, 4 m long)

Guide, focus e- (low-emittance beam)

Photon production and signal amplification

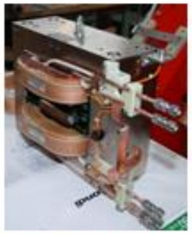
Responsibility of the Magnet and Insertion Device groups (2012-2016)

Design, engineering, production follow-up, assembly and **magnetic measurements**

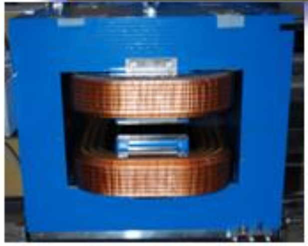
The Swiss-FEL magnets (air or water cooled)

- Strengths range from 10 mT up to 1.34 T
- Lengths range up to 2 m !
- Various apertures (12 mm→220 mm) and gaps (20 mm, 30 mm, 101 mm)
- Air cooled quadrupoles and sextupoles working at I_{max}~10 A

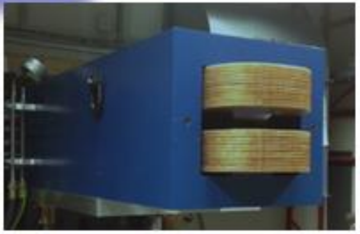
Dipoles



(0.3 T, G=30 mm, L=0.1 m)



(0.5 T, G=30 mm, L=0.5 m)

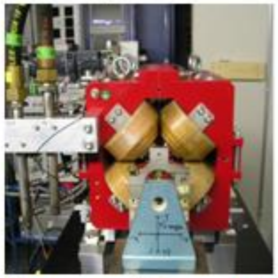


(1.34 T, G=20 mm, L=2 m)

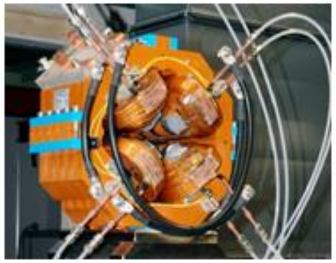
Quadrupoles

(50T/m Φ=12 mm, L=80 mm)

(20T/m Φ=22 mm, L=150 mm)



(50T/m Φ=22 mm, L=300 mm)



(30 T/m Φ=45 mm, L=170 mm)

Steerers

(0.01 T, G=12 mm, L=10 mm)

(20 mT, G=80mm, L=150 mm)

Sextupoles

(145 mT, Φ=20 mm, L=120 mm)

Solenoids

(0.1 T, Φ=220 mm, L=750 mm)

An amount of 220 magnets for the three linacs and the 5.8 GeV line

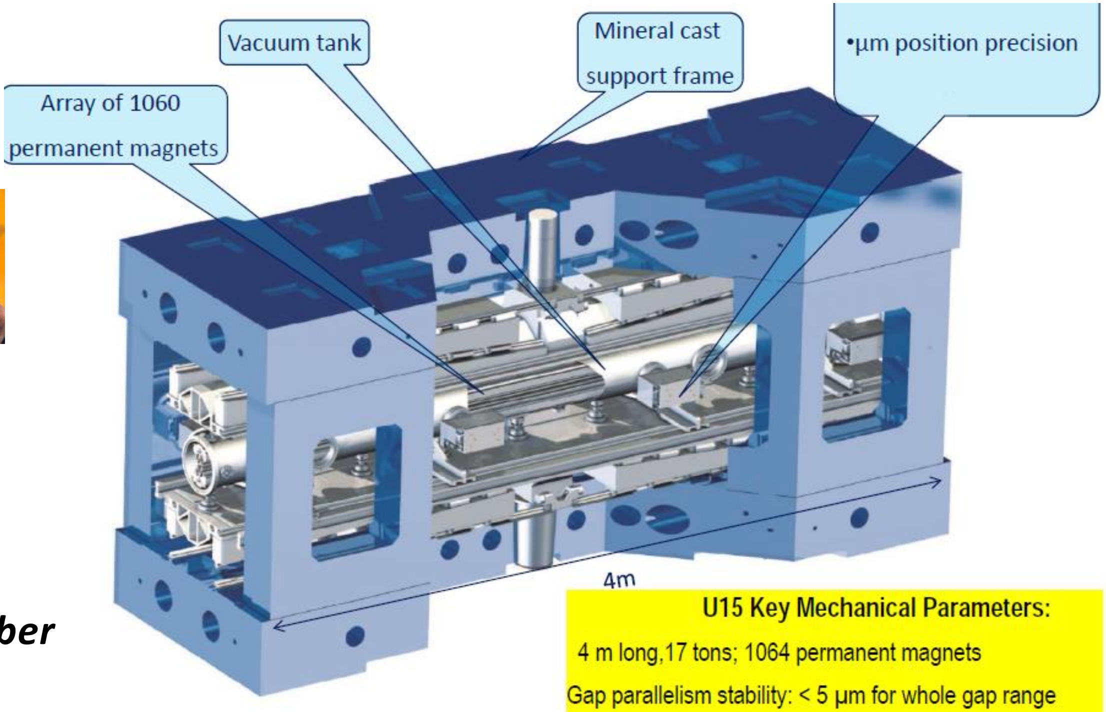
The Swiss-FEL undulators for Aramis line

Undulator:

Magnetic system designed in a way that the electrons oscillate or "wiggle" along a straight line

In-Vacuum undulator :

Magnet array <u>inside</u> the vacuum chamber



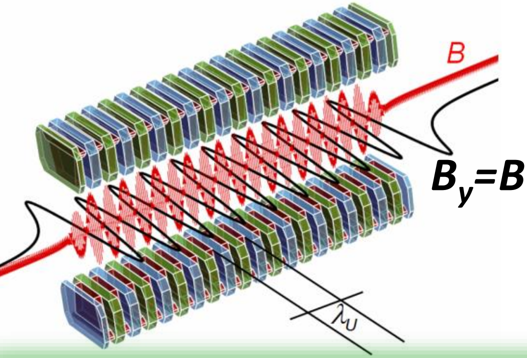
U15 Key Mechanical Parameters:

4 m long,17 tons; 1064 permanent magnets

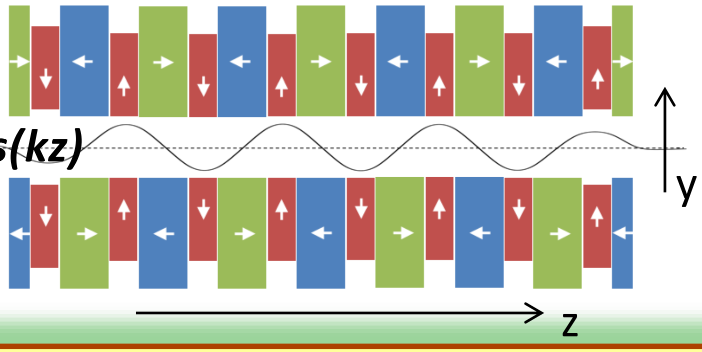
Gap parallelism stability: < 5 µm for whole gap range

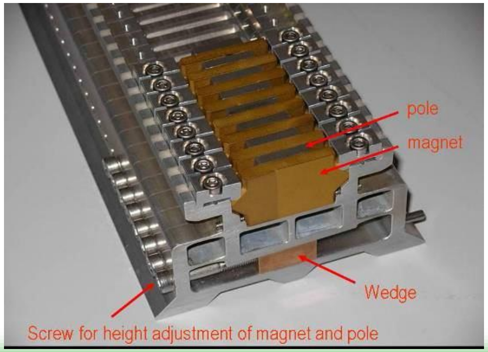
Magnet / Pole position height: sub-micrometer shimming

Magnetic design : **<u>Periodic</u>** array of **NdFeB magnets** (1.25 T)+ CO-FE poles



$B_y = B_0 \cos(kz)$





12 modules to be magnetically characterized for the end of 2016

Testing objectives-three families of systems

Hall Probes

- Field integrals and local fields

(B vs. I curves)-effective length

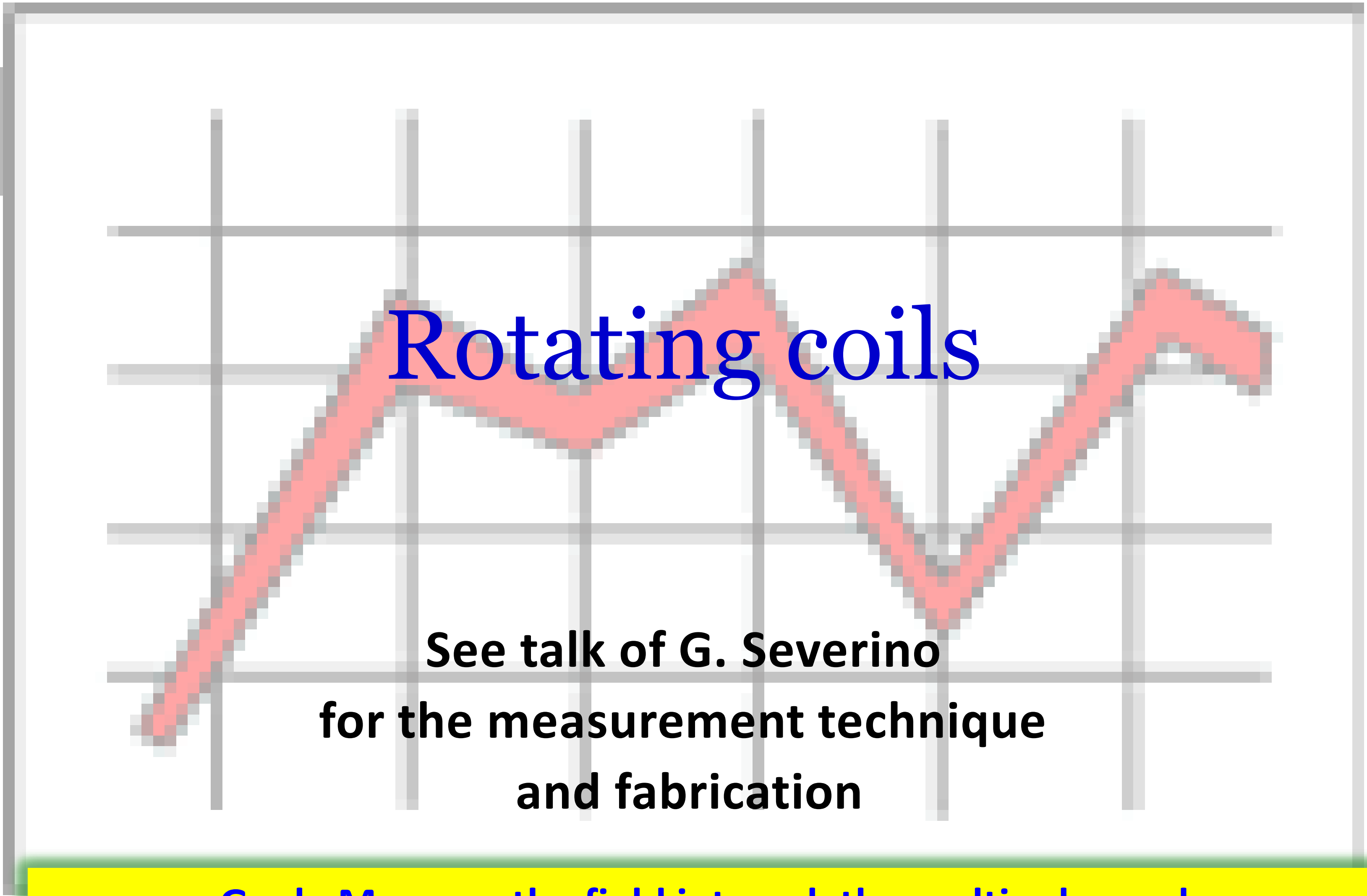
- 3D Field map
- Fringe field
- Magnetic axis (solenoids)
- Field profile in undulators
- Phase errors in undulators

Rotating coils (quadrupoles)

- Field integral vs. I curves
- Harmonics
- Alignment : Roll angle & magnetic axis stability

Vibrating/moving wire systems

- Magnetic axis position + fiducialisation
- Thermal stability in time
- First and second field integral (undulators)



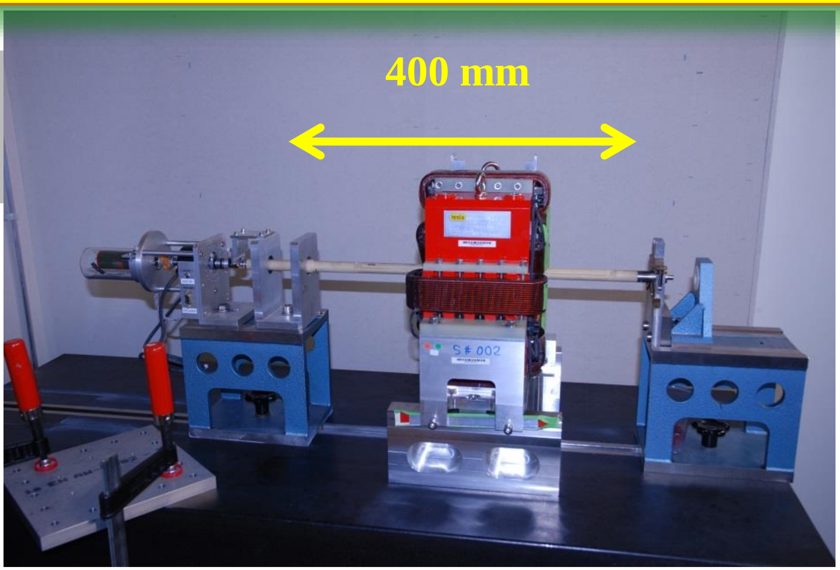
Rotating coils

See talk of G. Severino
for the measurement technique
and fabrication

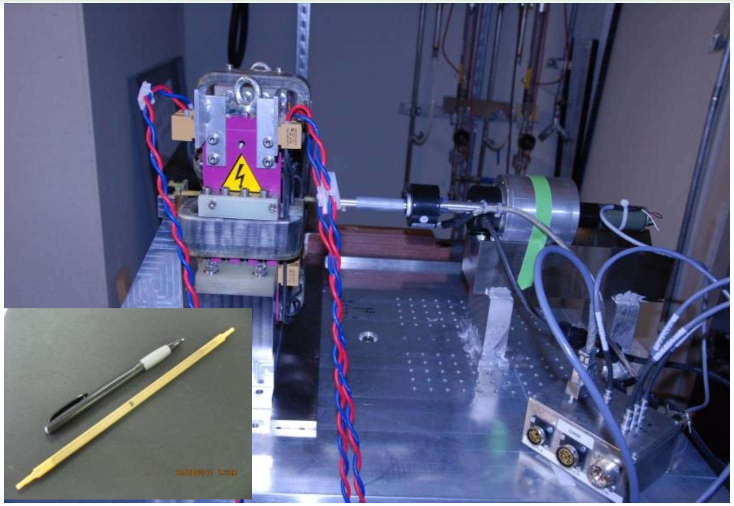
Goal : Measure the field integral, the multipoles and the roll angles of the small aperture quadrupoles (Ø=12mm, Ø=22 mm)

Rotating coils for Swiss-FEL Quadrupoles

CERN“linac 4” coil (Ø=19 mm)



CERN PCB coils (Ø=8 mm)



3 tangential coils to reject dipole and quadrupole components ((b1 and b2 bucking))

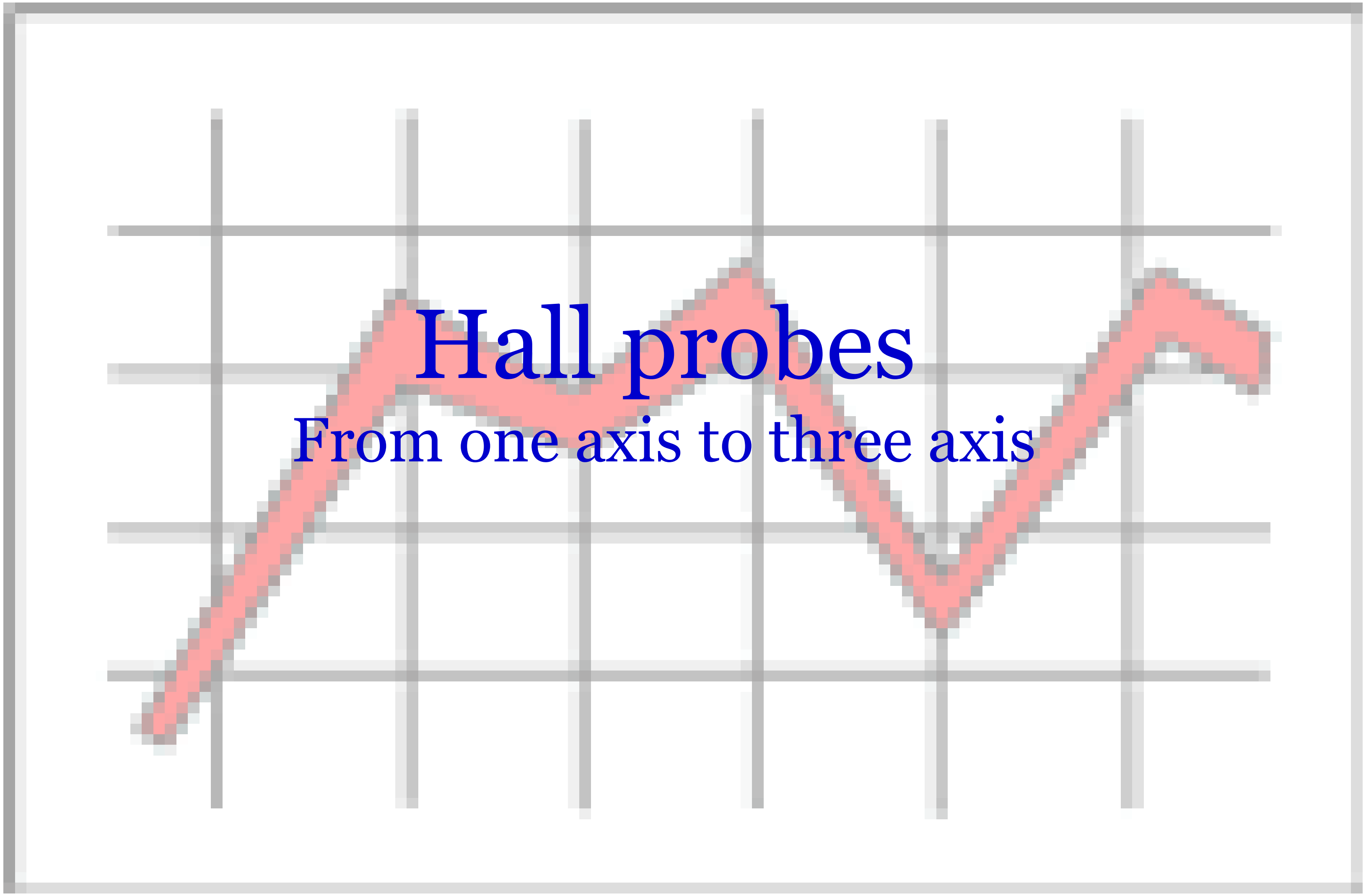
- ø19 mm x **400 mm** coil head
- “On body” winding technique: windings directly on a precisely machined rotating support
- Measurement radius: 8 mm
- 100 and 64 turns/coil
- **In situ calibration**

- Ø7.8 mm x **150 mm** coil head
- Coils :Monobloc PCB technology
- Measurement radius: 3 mm
- 3 coils: 200, 100 and 200 turns
- **In-situ calibration (ref-Hall probe)**

	Field gradient (+/ -10 A)	Multipoles (10 A)
Accuracy (ref : Hall probe)	0.15 %	
Reproducibility	<0.05 %	0.02 %

OK for our magnets

(PSI-CERN- collaboration, at the PSI since march 2012)



Hall probes

From one axis to three axis

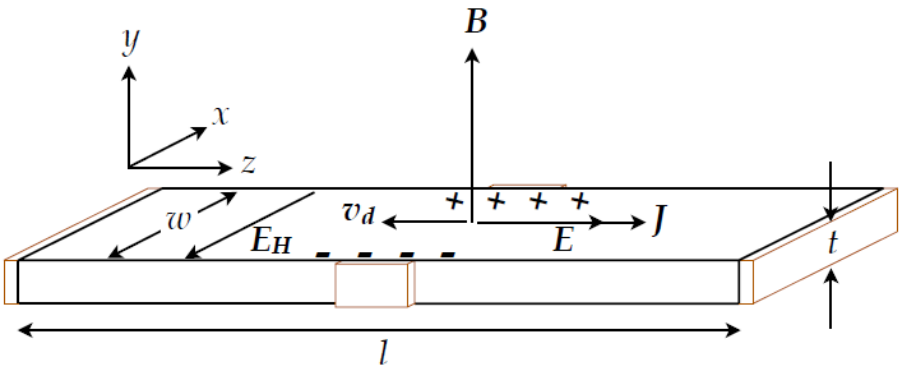
The hall effect in a nutshell

Electron and hole conduction:

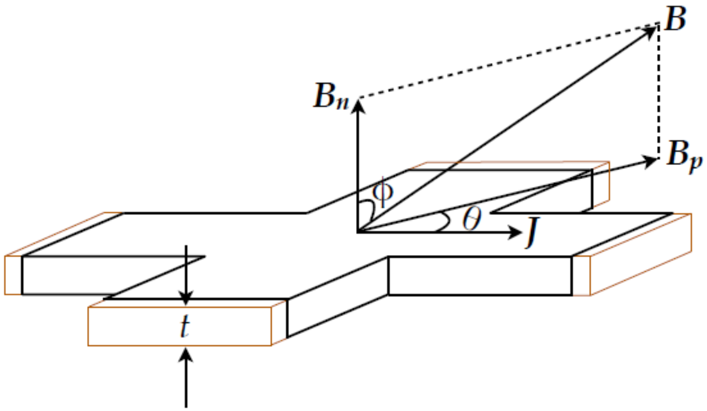
$$\left.\begin{matrix}\mu_n \neq \mu_p\\ \text{or}\\ n_n \neq n_p\end{matrix}\right\} V_H = G\frac{R_H}{t}IB$$

$$R_H(B,T), G\left(\frac{l}{w}, B\right)$$

$l >> w$, cruciform: $G \approx 1$



Hall effect in an n-type semiconductor



Planar Hall effect

$$\boxed{V_{out} = V_H + V_{PH} = \frac{R_H}{t}IB_n + \frac{R_{PH}}{t}IB_p^2\sin 2\theta}$$

PHE, Hall Planar effect
Double angular dependence

$$V_{PH} = \frac{R_{PH}}{2t}IB_p^2\sin 2\theta$$

if $R_{PH1} = R_{PH2}, B_{p1} = B_{p2}, |\theta_2 - \theta_1| = 90^\circ$:

$$\boxed{\frac{1}{2}(V_{PH1} + V_{PH2}) = 0}$$

- Sensitivity depends on carrier concentration & sensor geometry
- Temperature dependence of the Hall coefficient
- Periodic calibration V=f(B) needed
- B sensing accuracy depends on the field orientation vs. active area

Courtesy Ch. Wouters
(Ph.D defense 2016)

Hall probe measurements

Pro

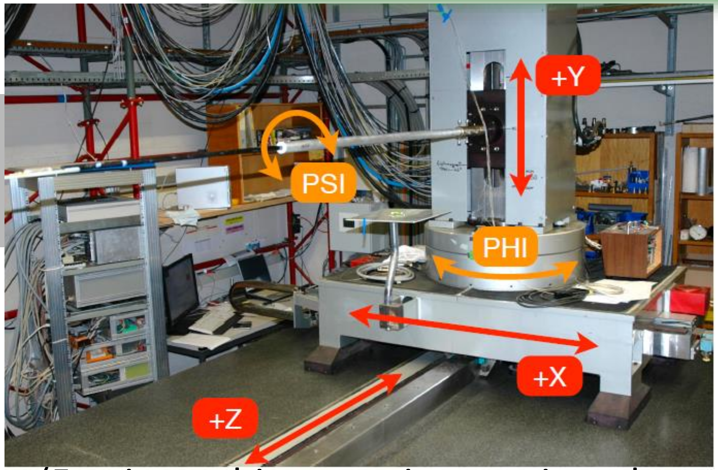
- Field mapper for the main field component;
- high accuracy field measurement for computing K, trajectory, phase error (undulators)
- Broad magnetic field range (mT to few T),
- Field integrals by numerical integrations
- Can be inserted in narrow apertures (magnets, undulators) ;
- Work in non-homogeneous field
- Can be used for low temperature measurements;
- Medium accuracy for single component measurement (~0.01%), resolution ~0.3 G;
- Easy to use, easily portable/moved;
- Inexpensive, big market;
- Easy element to integrate in a electronic circuit;

Cons

- Temperature sensitivity
- Non linearity V=f(B) to be corrected
- Offset to be compensated
- Drift of offset, Non Linearity and temperature sensitivity with time;
- Planar hall effect; To be compensated for accurate (below 0.1%) three axis measurements
- Calibration (delicate for multi axes sensors)
- Do not deliver harmonics
- Not ideal for magnetic axis measurements
- Time consuming for integral measurements

Hall probe magnetic lab at PSI

Hall probe lab. of the Magnet Section exists for over 30 years



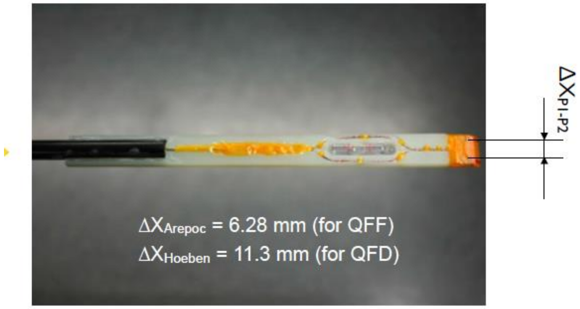
(5-axis machine, moving on air pads, flying mode measurement)

Transverse Hall Probe	Siemens SVB 601S1
Semicond. material	InAs
Active area	2.6 mm^2
Sensitivity	60 mV/T
Hall Probe absolute accuracy	10 µT
Hall probe resolution	1 µT
Maximum calibrated Field	3.1 T
Non linearity (0-1T)	<0.2 %
Temperature sensibility	70 ppm/°C

- Accurate measurement in the main direction (**1 D probe**)
- System dedicated to dipole measurements

1st Major upgrade for the SwissFEL magnets: Multi-probes for quadrupole field mapping

- multiple Hall sensors (1D) on one arm
- water levels integrated in measurement arms



ΔX_{Arepoc} = 6.28 mm (for QFF)
ΔX_{Hoeben} = 11.3 mm (for QFD)

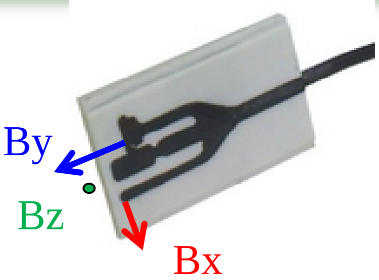
Compact system for the small aperture quads

- ○ Direct measurement of the field gradient
- ○ Constant ΔX →corrects for position errors:
  - due to arm vibrations
  - magnet misalignment

Hall probe for Insertion Devices at PSI

Hall probe system for the U15 Swiss-FEL undulators measurements

Three components of magnetic field needed
→Use of a three-axis Hall probes



Epitaxial grown
ceramic support

Hall Probe “S”
from SENIS

Step 1: Magnetic optimization (ex vacuum)

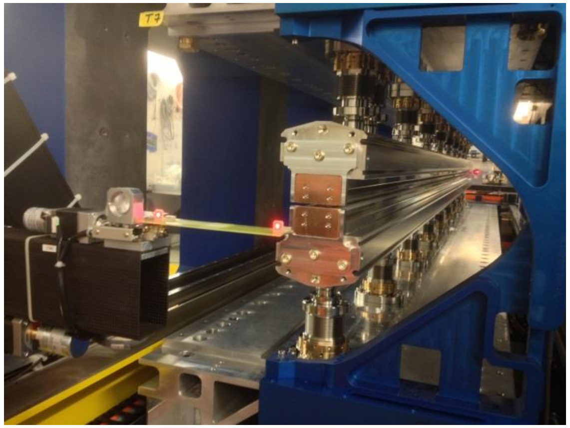
- Measurement **w/o the vacuum chamber**
- **Automatic screw driver for corrections**
- Shimming based on Hall probe trajectory and phase error measurements.

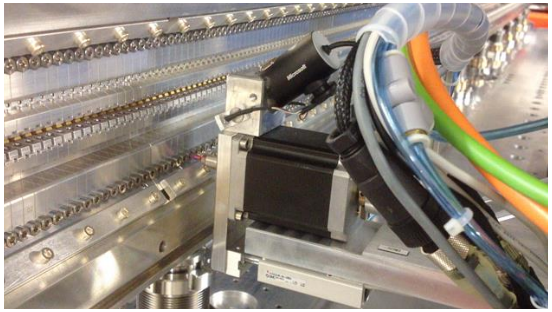
Step 2: In- vacuum optimization

- Dismounting of the out-vacuum beam-out vacuum shafts-PM array;
- Insert the vacuum chamber/ PM array;
- Hall Probe measurements & adjustments

PSI : Integrated systems using a 3D Hall Probe
for out and in-vacuum measurements and corrections
Inspired from SAFALI (Tanaka-Spring 8)

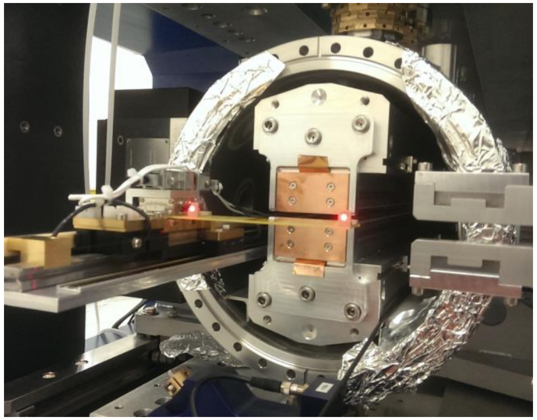
Ex-vacuum





Optimization with an automatic controlled screw driver

In-vacuum



U15 measurement process

Measurement w/o vacuum chamber

- Measure the magnetic field along the undulator with the hall probe bench:
- Bz(s), Bx(s) and By(s)
- Measure the first and second field integral with the moving wire in z and x direction:
- I1z,I2x & I1z,I2x
- **Calibration**

$$\int B(s)ds = I1$$

$$\int\int B(s)dsds = I2$$

- **Shimming** : Calculate the Trajectory and Phase
  - ✓ Estimate the correction both in z and y:
  - ✓ Apply and repeat the correction with the **columns** and **robot screw-driver (height adjustment)** till
    - ○ I1~0; I2~0
    - ○ Phase error <10°

Measurement with the vacuum chamber

- Measure the magnetic field along the undulator with the hall probe bench:

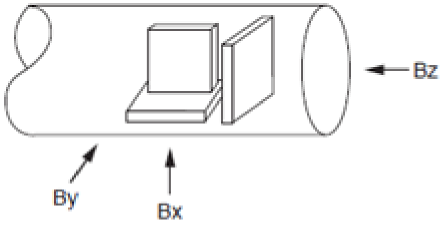
  Bz(s), Bx(s) and By(s)
- Check the Trajectory and Phase
- Correction by moving up/down the 20 out-vacuum shaft to compensate the errors from the I-beam movement

Three axis Hall sensor- brief reminder

Type I

Combine three orthogonally arranged uniaxial Hall sensors

- Poor spatial resolution (>250 µm)
- Planar Hall effect to be compensated
- Angular errors (up to few deg.)

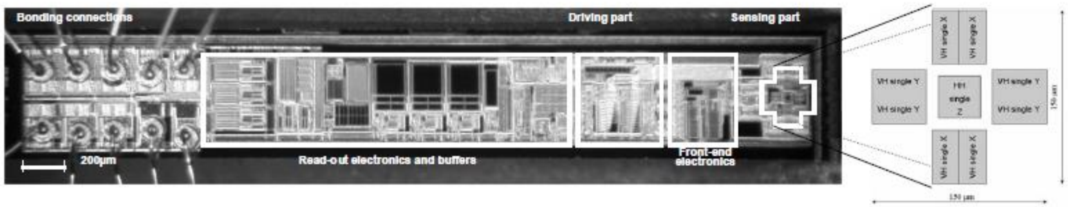


Association of three single axis planar devices

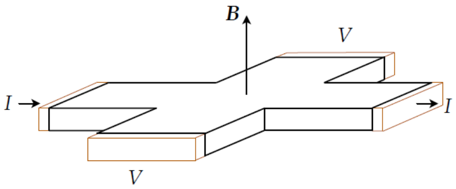
Type II

Integrated Hall Sensor in CMOS technology (three sensors in one chip)

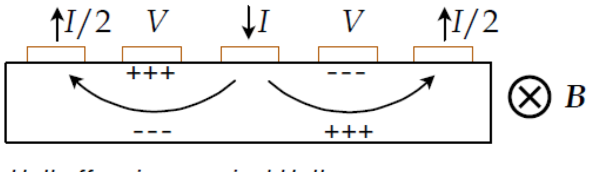
- Performance of vertical Hall devices (-)
- Noise coming from electronic to amplify the output signals and compensate the parasitic effects
- Angular errors (up to 0.5 °)



Association of vertical and planar Hall probe devices (example of SENIS)



Planar devices

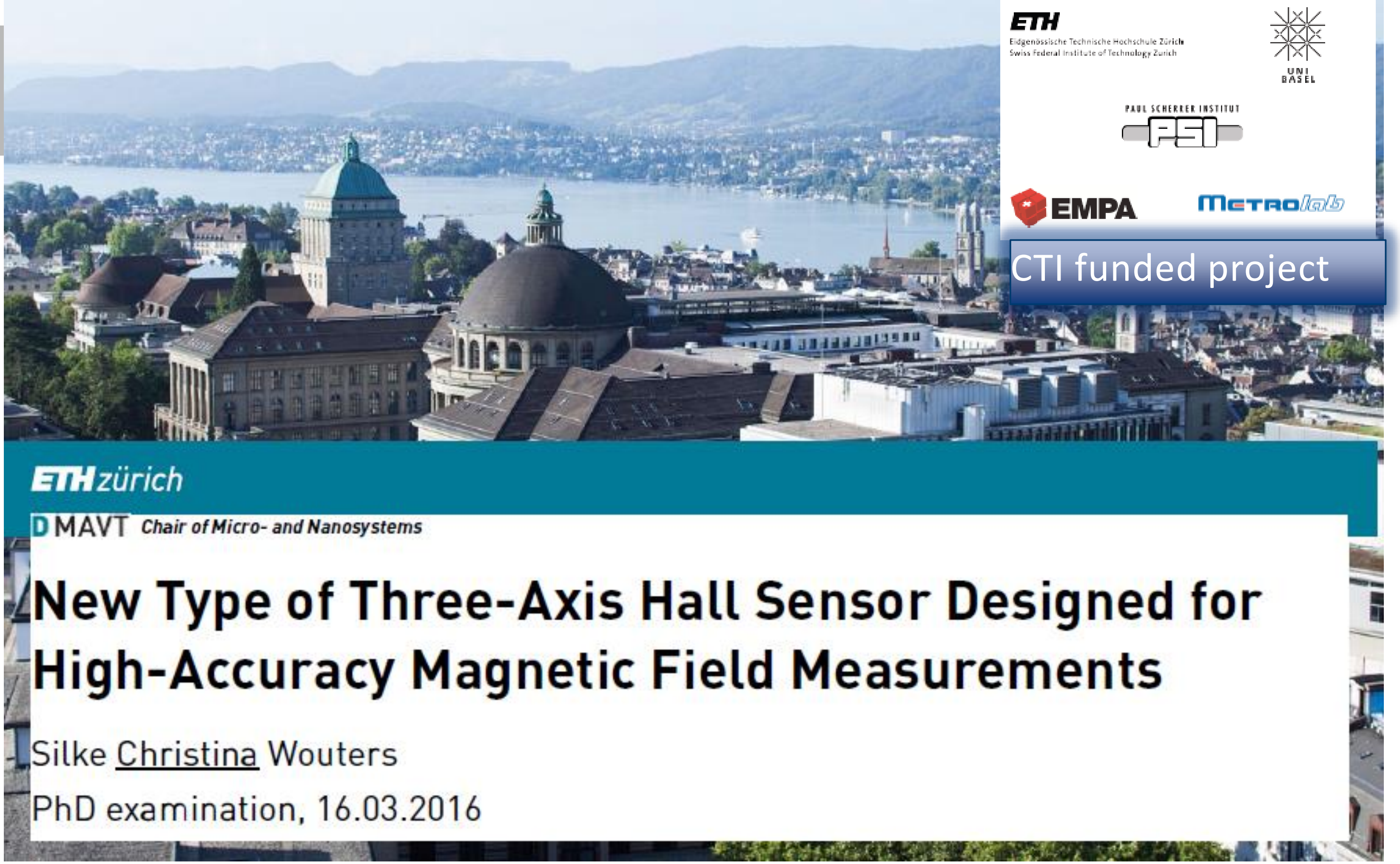


Vertical devices

Can we combine :high sensitivity, small volume, measure at the same spot, HPE cancelled?

Compact and accurate three-axis sensor at PSI

2nd Major upgrade : for next Swiss-FEL undulators and inhomogeneous magnets



CTI funded project

ETH zürich

D MAVT Chair of Micro- and Nanosystems

New Type of Three-Axis Hall Sensor Designed for High-Accuracy Magnetic Field Measurements

Silke Christina Wouters

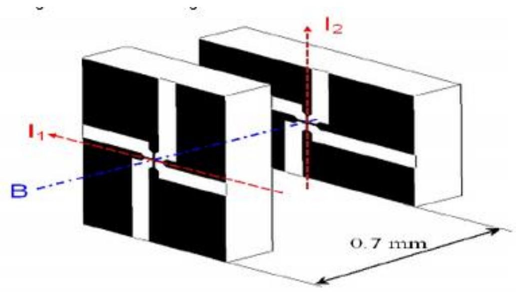
PhD examination, 16.03.2016

Motivation : novel Hall sensor for highly accurate (< 0.1 %) 3D magnetic field measurements

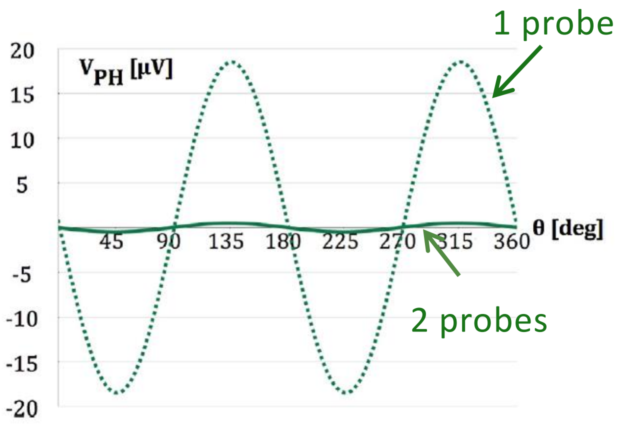
Compact and accurate three-axis sensor : The Hall cube

Hallmarks

- Hall sensor prototype with 3D measurement precision (10^{-4} at 1 T in the three directions)
- Miniaturized sensors made of six high-precision 1D planar Hall sensors without compensation electronics : High sensitivity and precision of uniaxial Hall sensors is exploited
- Geometry : 6 probes (Double readings per field component) at the edge of a cube to measure at single point in space and time
- PHE compensation thank to pairs of probes per field direction positioned orthogonally



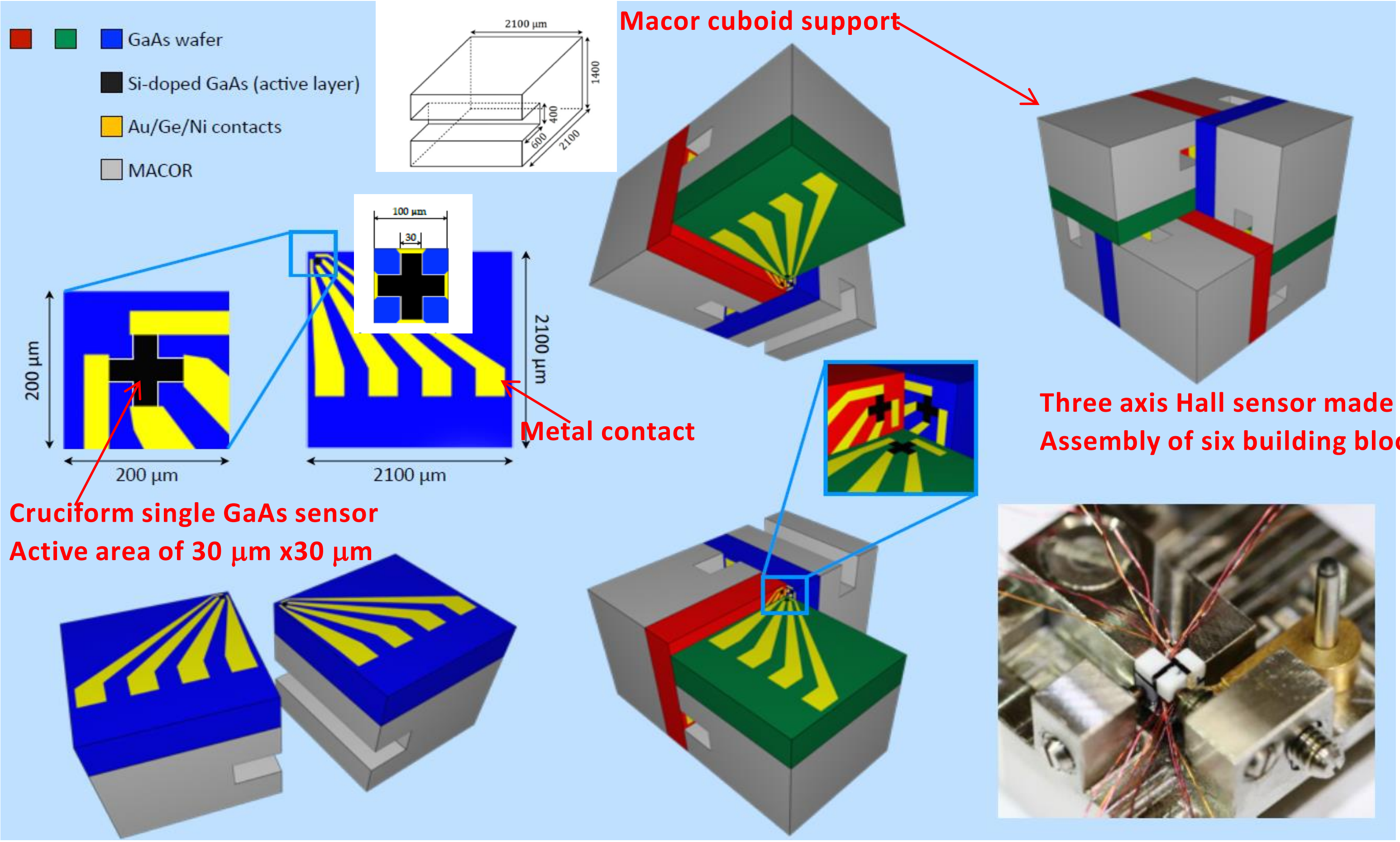
I. Vasserman, B. Berkes, J. Xu, J. Kvitkovic (PAC2009)



Compensation of the Hall planar component with a pair of parallel Hall plates rotated in plane $\sim 90^\circ$ to each other

25 times reduced !

Hall Cube design



Macor cuboid support

Metal contact

Cruciform single GaAs sensor
Active area of 30 µm x30 µm

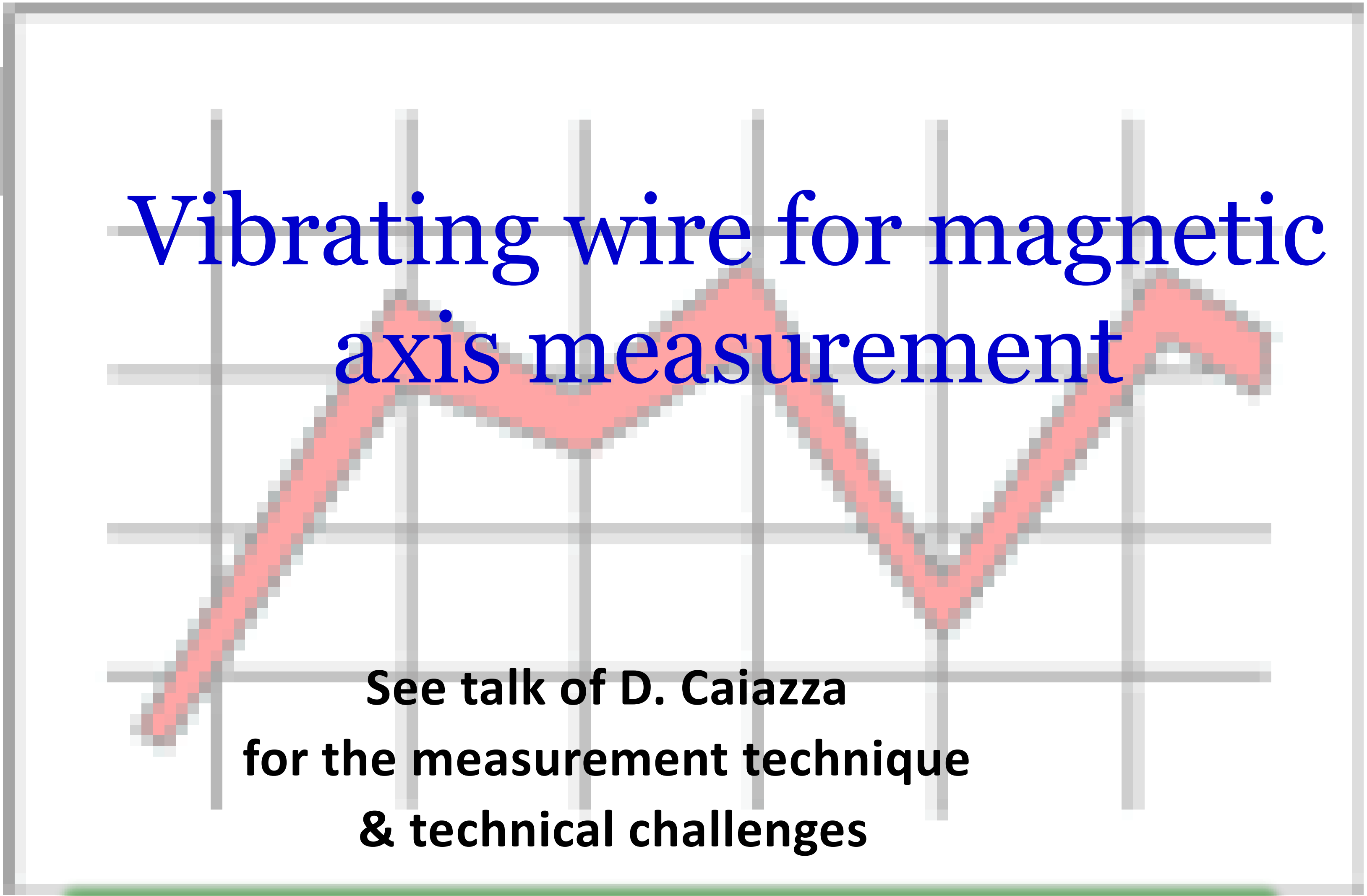
Three axis Hall sensor made of
Assembly of six building blocks

Geometry : sub-mm active volume (150x150x150 µm^3) and outer sensor dimension in mm-range (<4x4x4*mm^3)

“Design and fabrication of an innovative three-axis Hall sensor”, C. Wouters et al., Sensors and Actuators A 237 (2016) 62–71

Prototype calibrated and tested in a magnet and an undulator in Fall 2015

Vibrating wire for magnetic axis measurement



See talk of D. Caiazza
for the measurement technique
& technical challenges

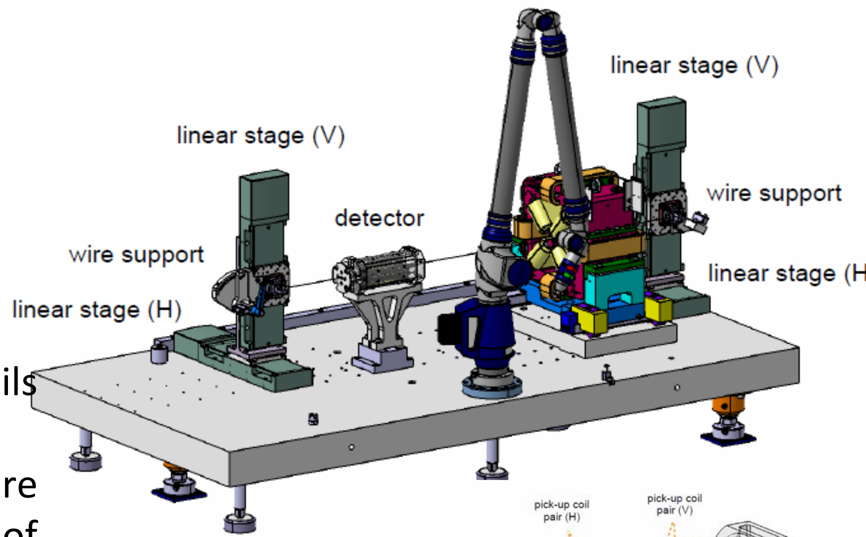
Goal : Measure the magnetic axis position of the Quadrupoles
Tolerance (fiducialisation included)< 50 µm rms

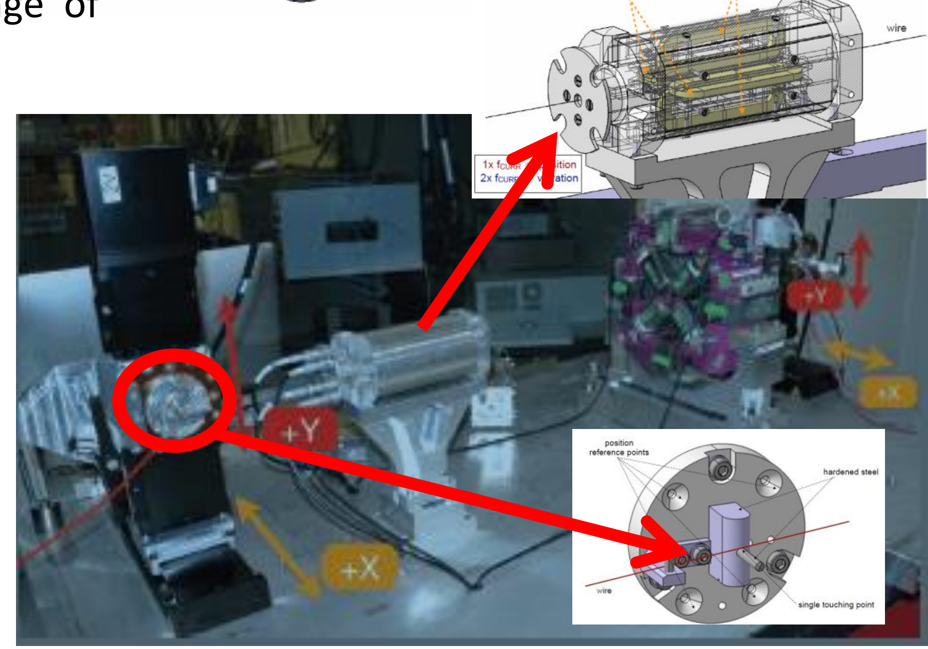
PSI vibrating wire system

PAUL SCHERRER INSTITUT

Key points

- Developed at PSI in 2011; Improvements up to 2014.
- Small/medium size magnets (few hundreds of kg, ~0.5 m)
- Tensioned wire (CuBe, ø ~100 μm) between two stages
- Magnet **is fixed; Wire is moved**; L_{wire} ~1.2 m
- Vibration detection : inductive method with 2 pairs of coils working in the 1st and 2nd harmonic;
- Lock-in amplifier to detect the voltage drops and measure the change of phase + PLL to compensate the change of resonance frequency during the movement.
- Fiducialisation : 12 points measured with a FARO arm (4 fiducials+ 8 points related to the wire holders)





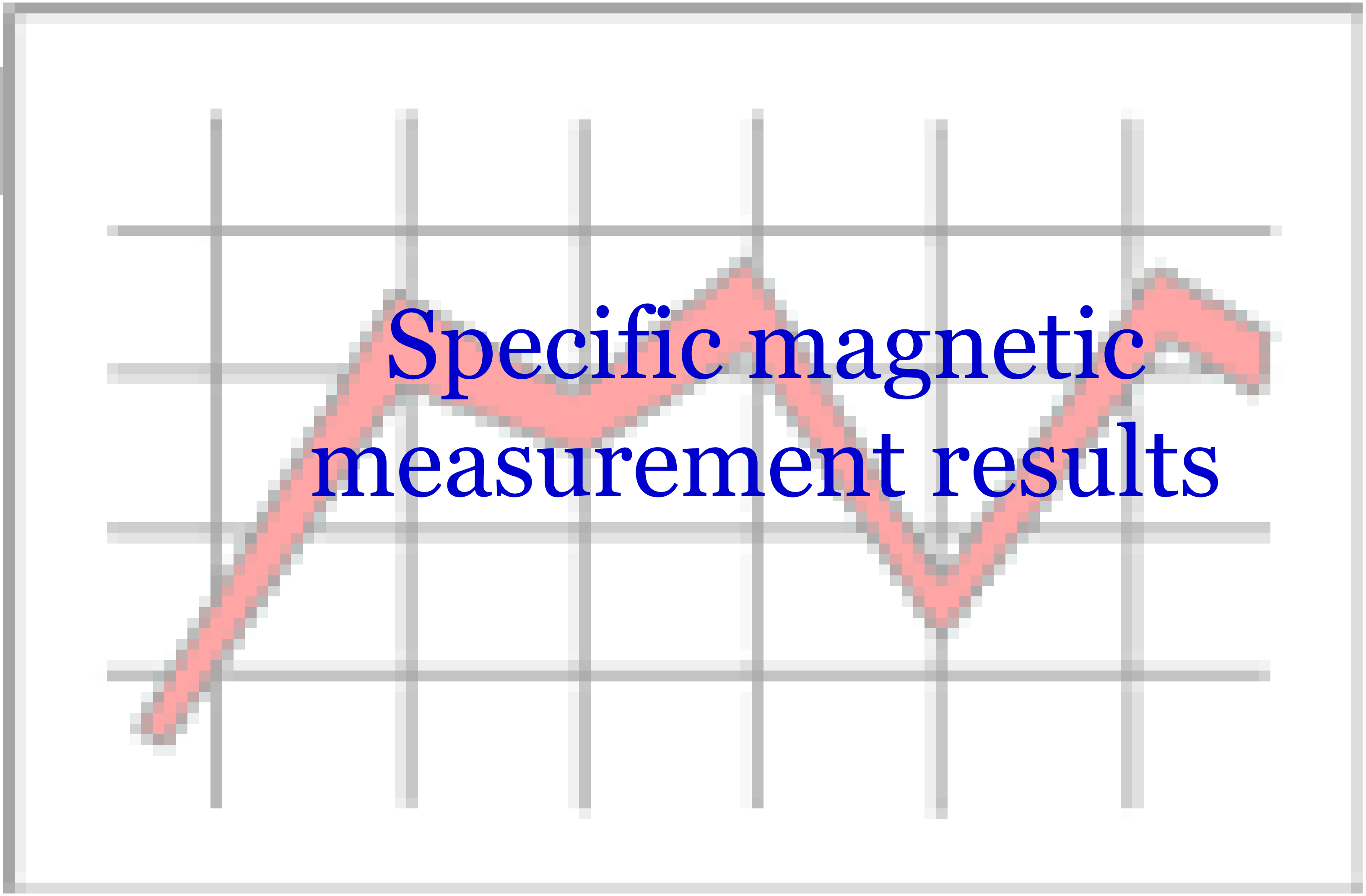
Uncertainty

- Coming from the **fiducialisation method**
  (reference points, home position)

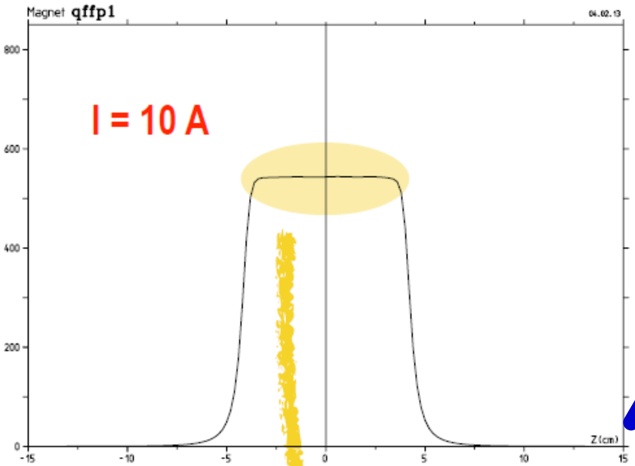
  σ~25 μm

- Relative accuracy (mag. Method) σ~1 μm

Specific magnetic measurement results

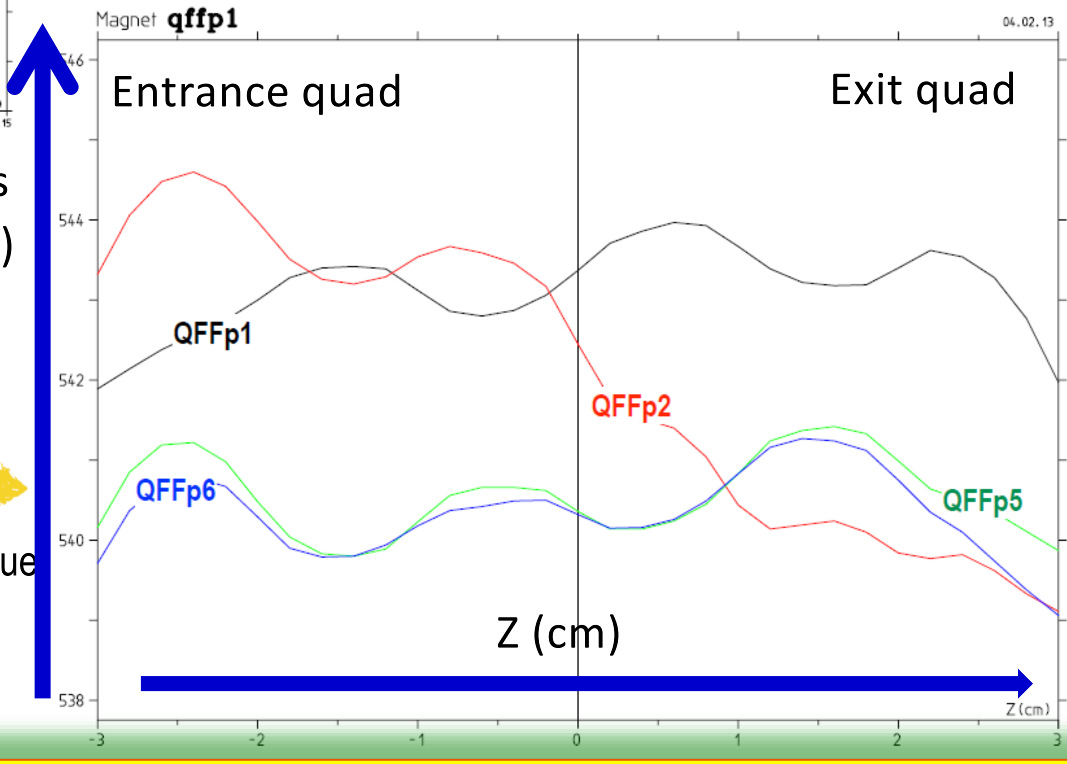


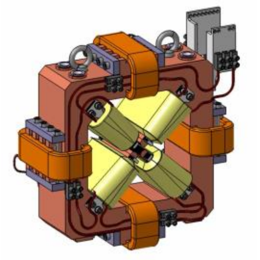
Multi-probes: Field scan SwissFEL quadrupole



Hall probe : Field profiles (magnet homogeneity)

QFF	p1	p2	p5	p6
G_0 Gauss/mm	543.4	542.5	540.4	540.3



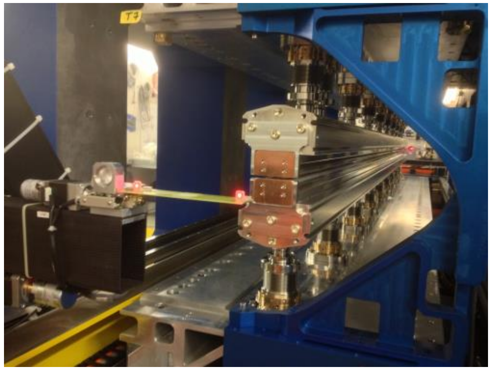


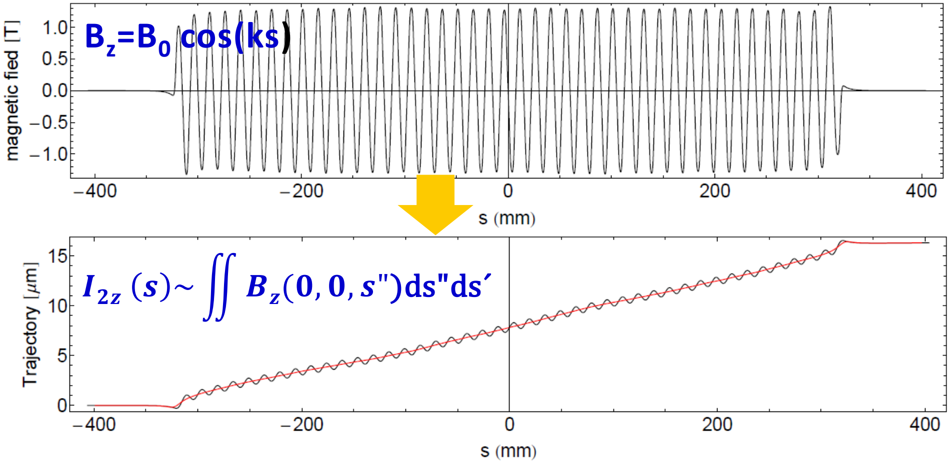
QFFP2: OK for the field integral value but 0.7 % variation of the field gradient value along the axis

Hall probe measurements are essential to complement Rot. Coils measurements which measured only field integrals

U15 undulator: trajectory optimization (Senis probe)

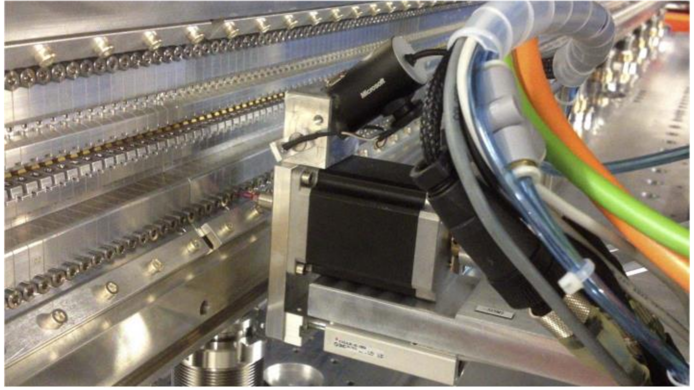
Hall probe measurements

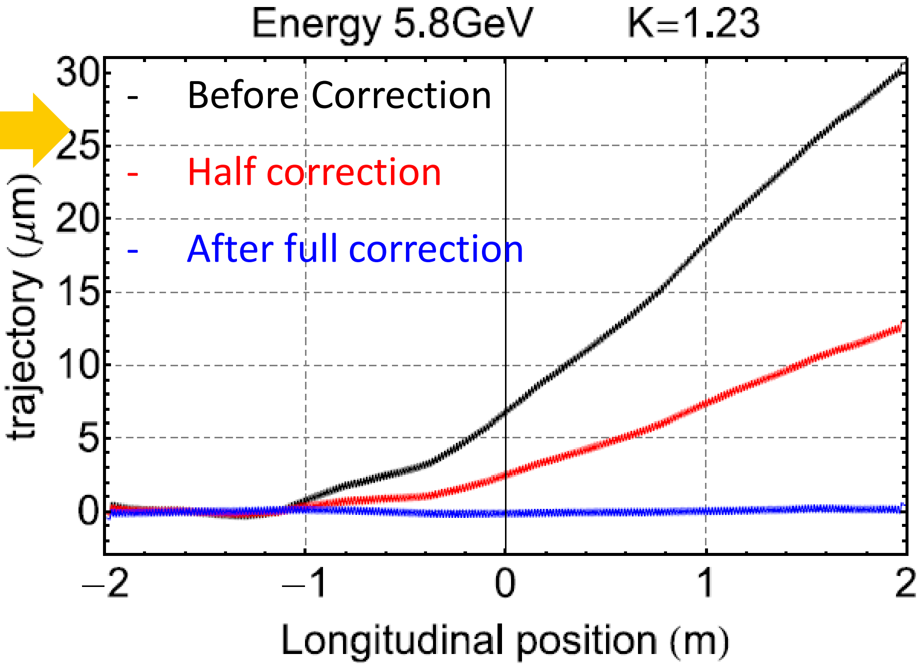




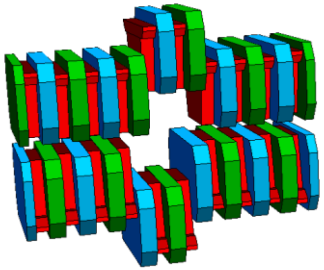
Local correction

of the PM position



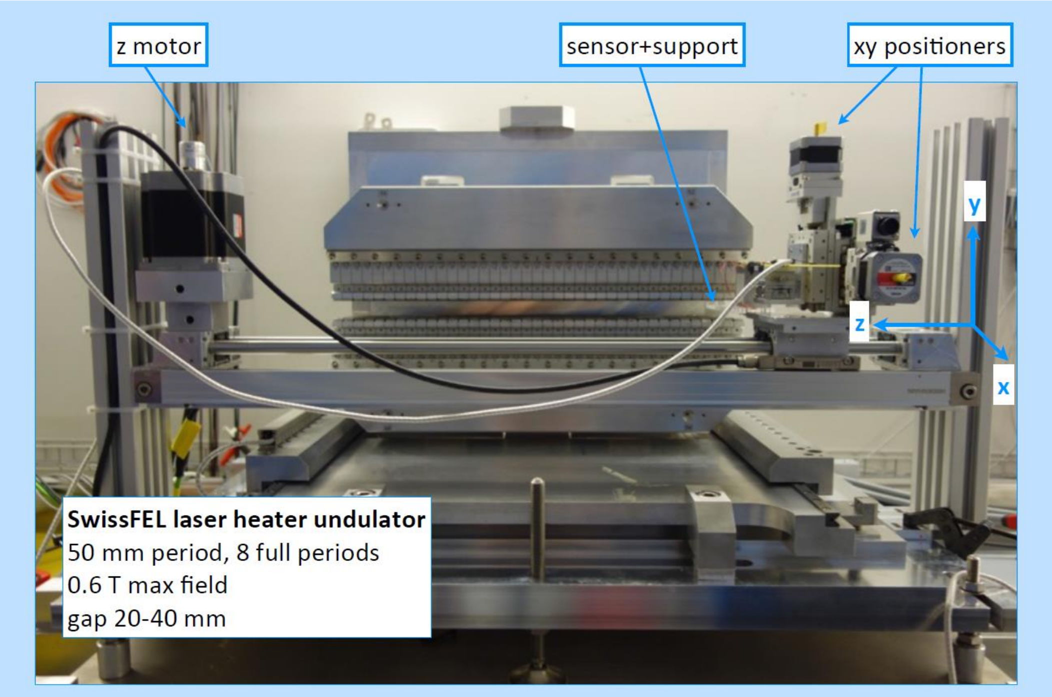


Few μm ↑

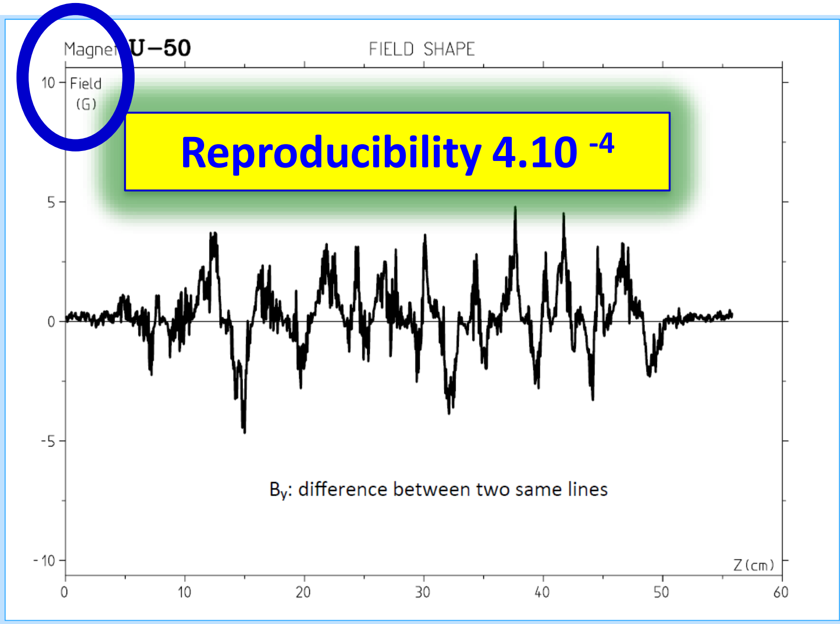


Courtesy M. Calvi

Hall-Cube : Undulator U50 measurement

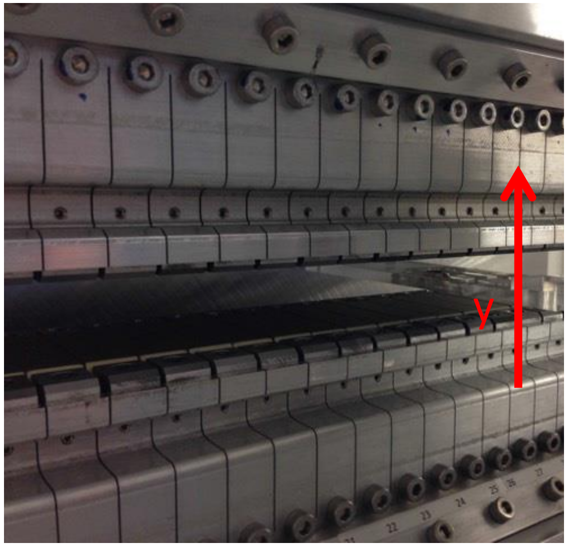


SwissFEL laser heater undulator
50 mm period, 8 full periods
0.6 T max field
gap 20-40 mm



Reproducibility 4.10 $^{-4}$

B_y: difference between two same lines



$$B_y = B_{\max} \sin\left(\frac{2\pi z}{\lambda}\right)$$

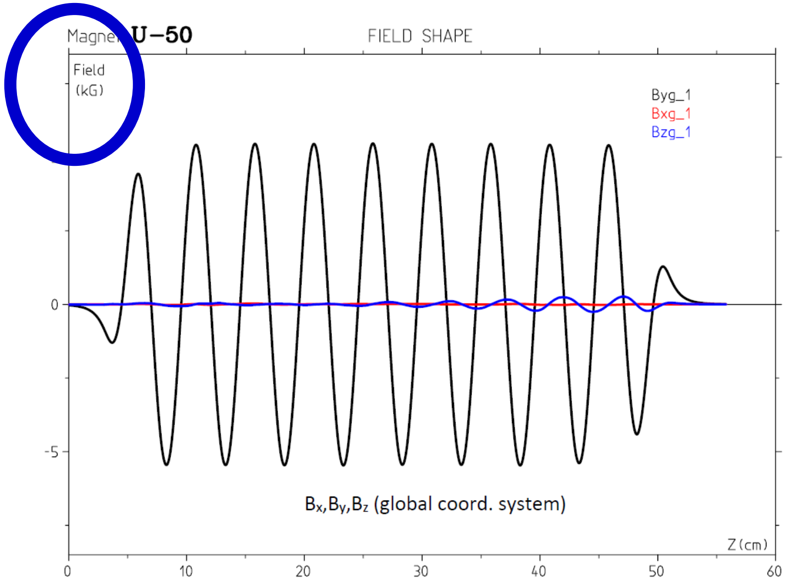
0.6 T

50 mm

at any position *s* along *z*:

Main component B_y

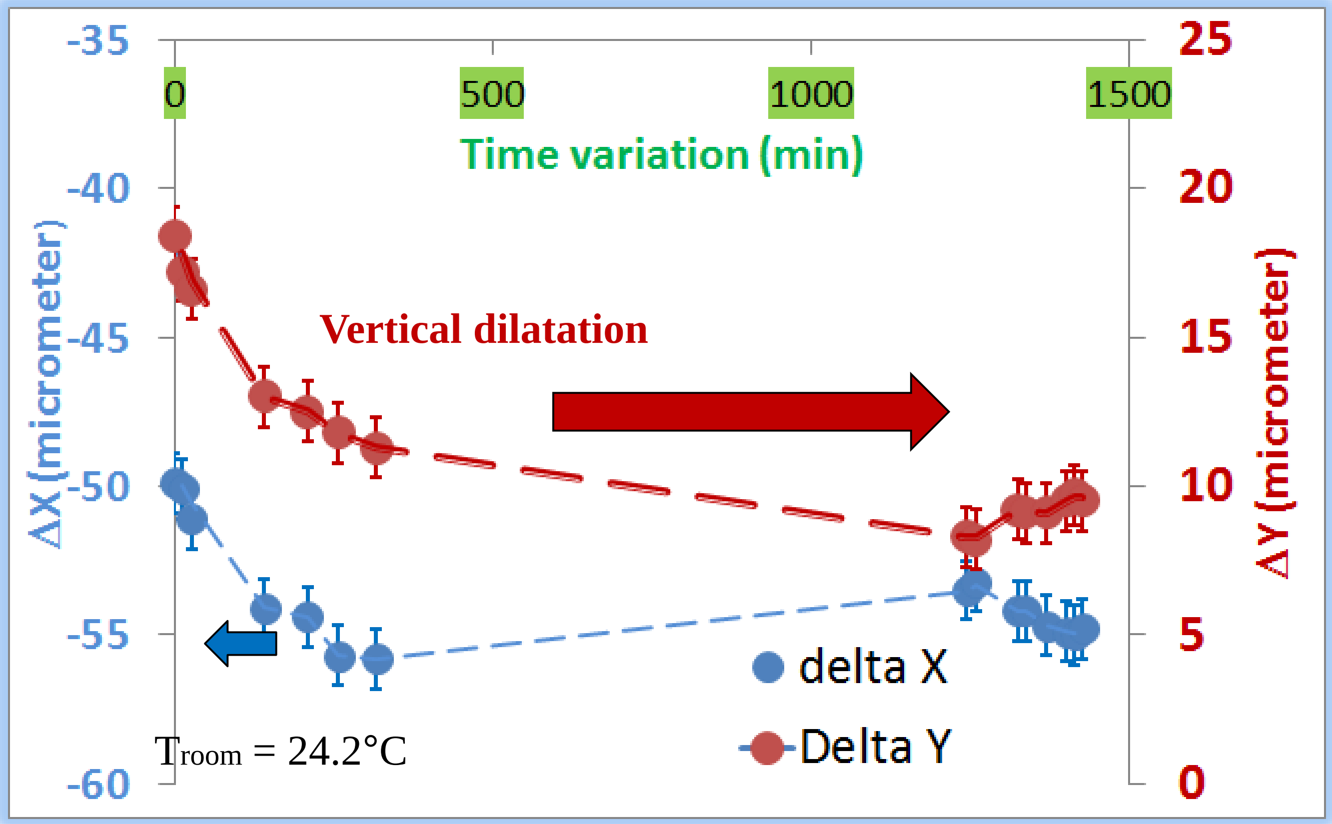
Side components, B_x, B_z

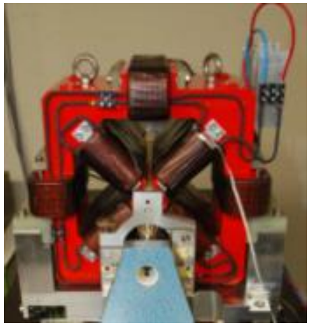


B_x, B_y, B_z (global coord. system)

Magnetic field components along the undulator

Vibrating wire : magnetic axis vs. time (air-cooled quadrupole at I=6 A)





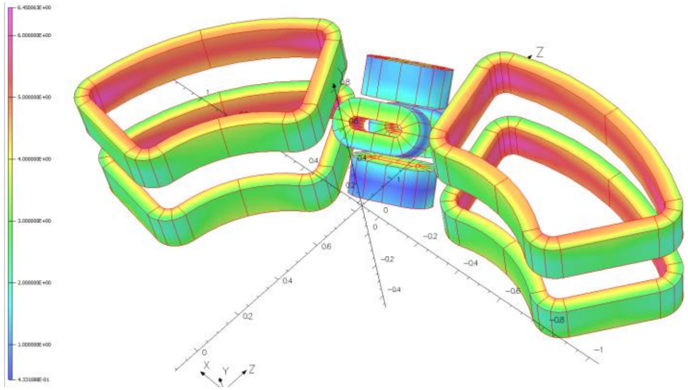
Steady state after 6 hours (T_{end} =28.5 ºC)

Vertical dilatation (at 6 A): 9 µm

Summary and future directions

- For the Swiss-FEL, various complementary magnetic measurement systems were developed and used to measure 273 magnets and 12 undulators. Measurements will be completed for September 2016
- Future measurement system developments are linked with the next PSI projects and collaborations

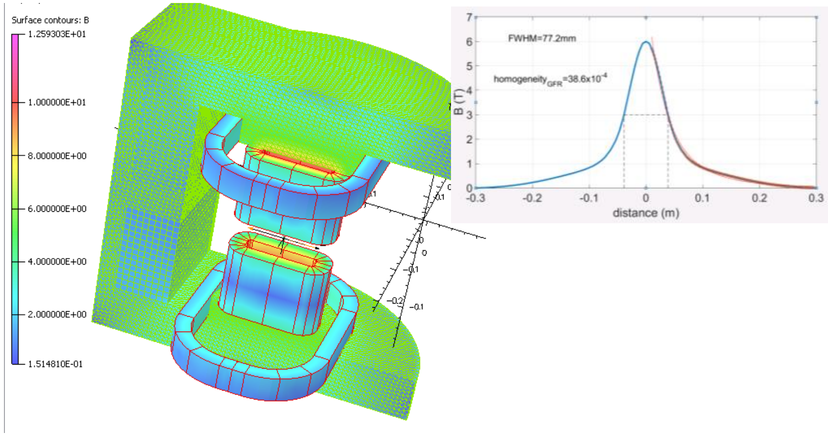
Superconducting dipole /quadrupoles
for a Gantry (2015-2018) -Racetrack geometry



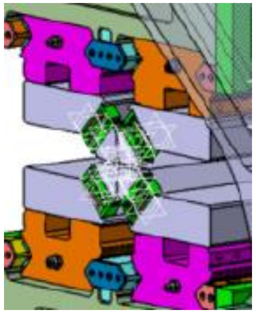
Bending angle: 60°;
Bending R=0.8 m

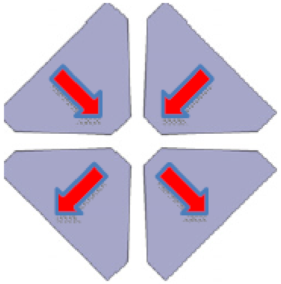
C.Calzolaio

Super-bend for the SLS upgrade
6 T peak in the middle (2016-2018)

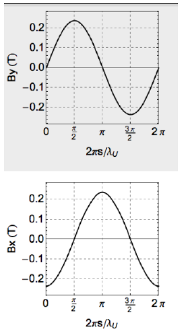


Undulators with
a circular mode (Athos line-2018)





Th.Schmidt



Challenges are measurement systems for
- Large aperture and strongly curved dipoles
- Small aperture and inhomogeneous field
- Undulators with circular polarization
- Small gap –in vacuum (supercon.) undulators

Some useful references

SwissFEL- Magnets/undulators

- Design and magnetic performance of small aperture prototype quadrupoles for the SwissFEL at the Paul Scherrer Institut ; S. Sanfilippo et al.; IEEE Transaction on Applied Superconductivity VOL. 24, 3, (2014)
- "In-situ undulator field measurement with the SAFALI system," T. Tanaka et al., in Proc. FEL Conf., Novosibirsk, Russia, 2007, pp. 468–471
- "SwissFEL U15 Magnet Assembly : First experimental Results"; M. Calvi et al., Proceedings of FEL2012, Nara, Japan;

Hall probes

- Hall effect Devices-2nd Edition; R.S. Popovic; IOP (2004)
- "Design and fabrication of an innovative three-axis Hall sensor", C. Wouters et al., Sensors and Actuators A 237 (2016) 62–71

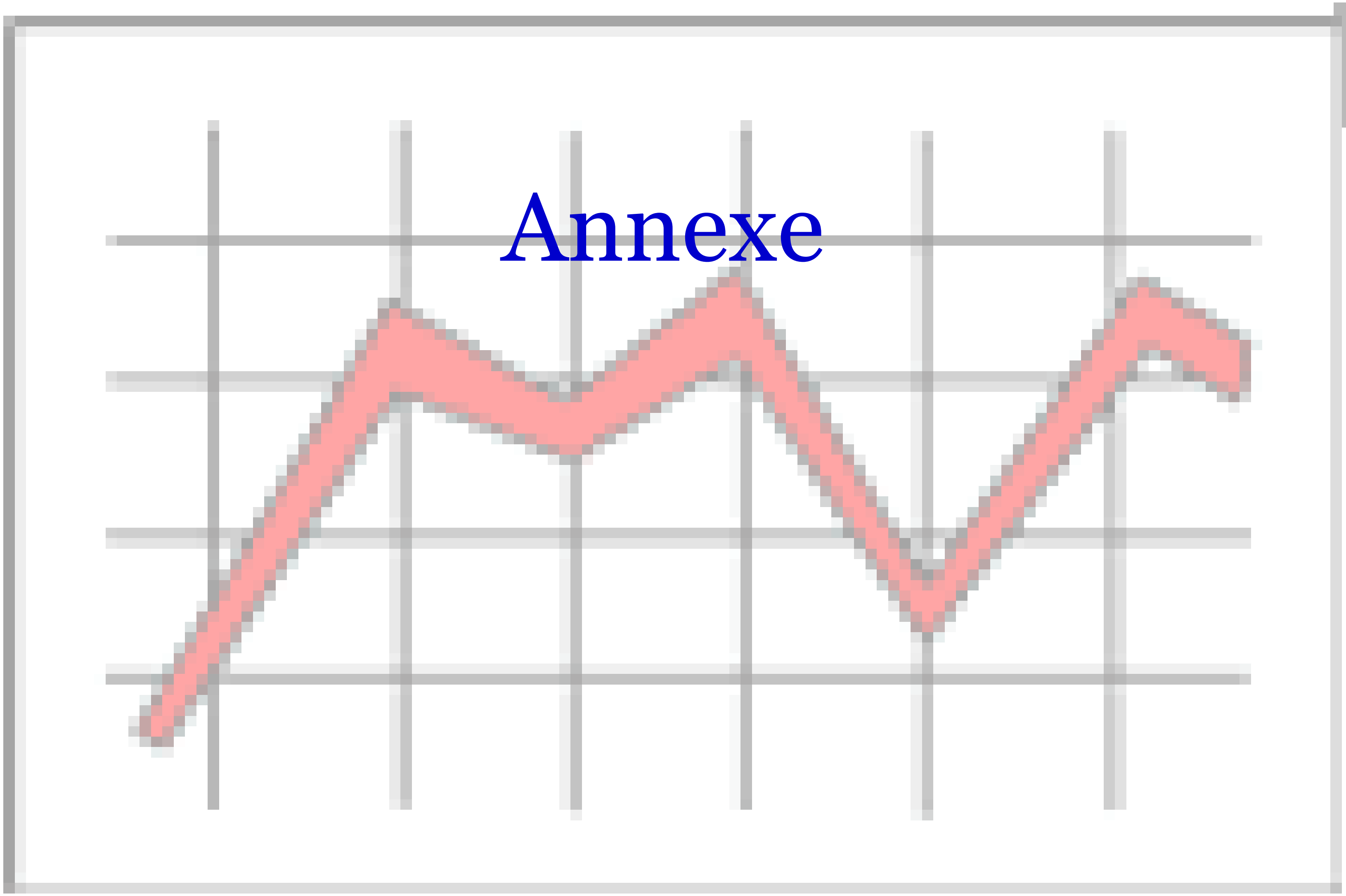
Vibrating Wire

- "Vibrating wire field-measuring technique," A. Temnykh, Nucl. Instr. And Meth. A, vol. 399, pp. 185–194, 1997.
- "Vibrating Wire Technique and Phase Lock Loop for Finding the Magnetic Axis of Quadrupoles", C. Wouters et al., IEEE Transaction on Applied Superconductivity VOL. 22, 3, (2012)

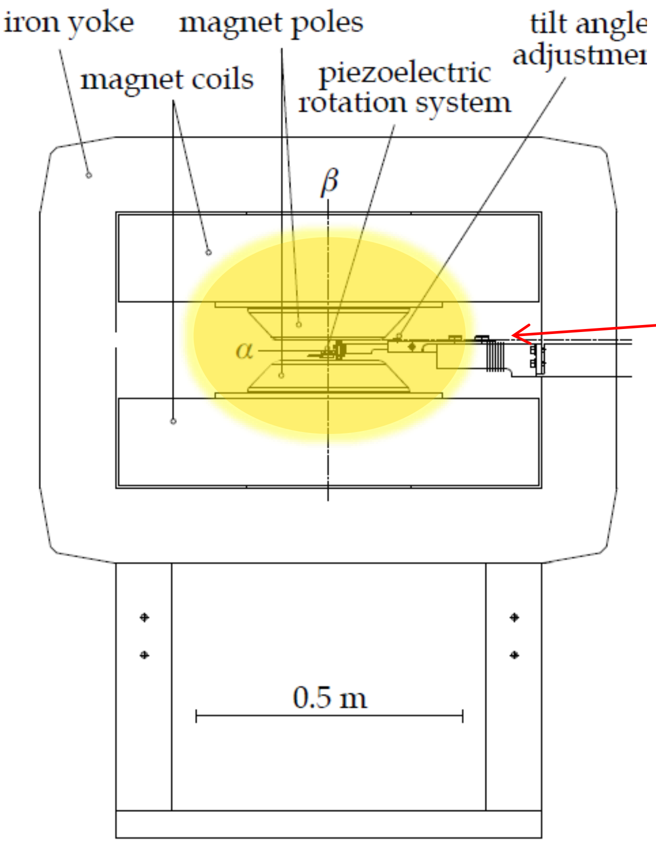
Thank you for your attention

Questions?

Annexe



Hall Cube calibration



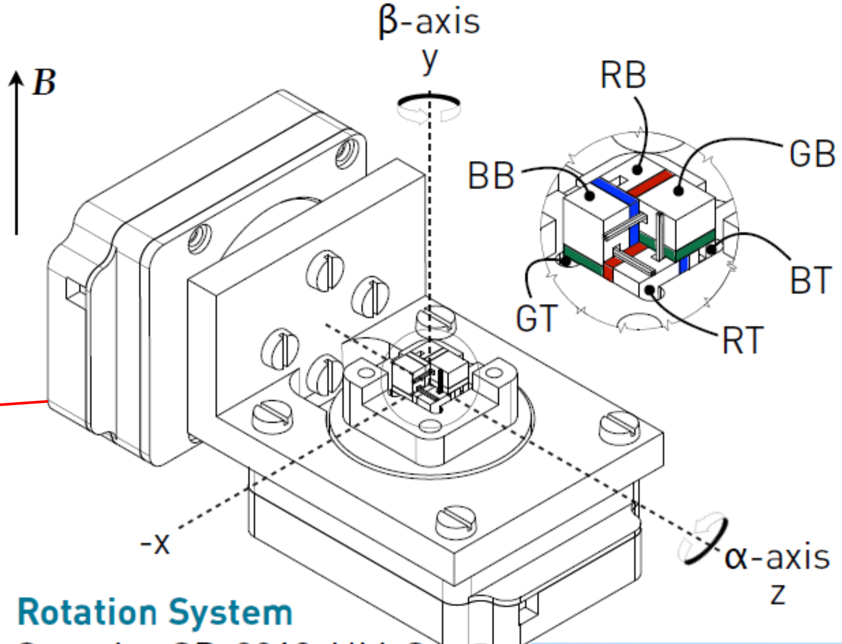
Calibration Magnet

-96 A ←→ 96A or -2 T ←→ 2T

gap = 38 mm

homogeneity at 2 T: 100 ppm

in area of 10 mm radius



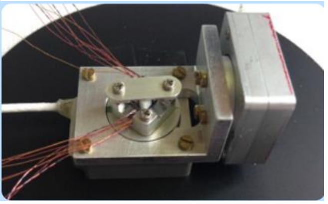
Rotation System

SmarAct SR-2013-NM-S

movement resolution: <3 μrad

sensor resolution: 25 μrad

rot. ⌀: 33.12 mm



Calibration of each individual sensor

Sensor assembly (angular errors ~ 0.1 mrad)

Calibration of the Hall-cube per pairs:

- Orthogonality error among sensors
- Planar Hall effect compensation

"Design and fabrication of an innovative three-axis Hall sensor", C. Wouters et al., Sensors and Actuators A 237 (2016) 62–71

Vibrating wire development

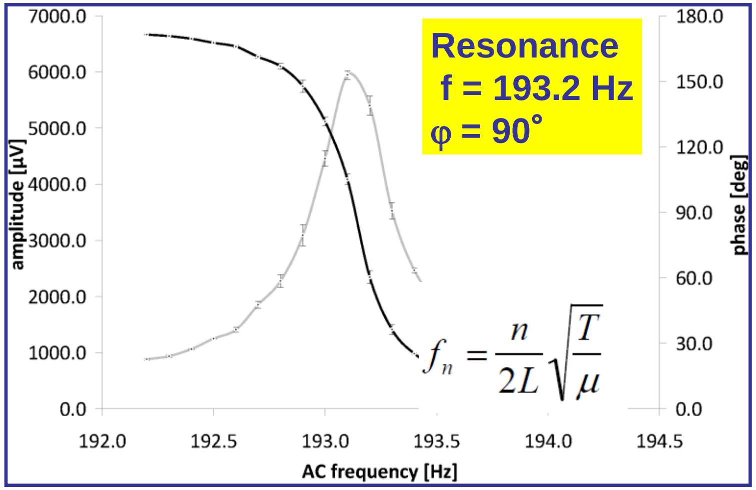
(A. Temnykh, Nucl. Instr. and Meth.. A399 (1999) 185)

Principle

Stretched conducting wire driven with an AC current I= $\mathbf{I_0 \cos \omega t}$ at one of its natural frequencies ω_n in the presence of a magnetic field:

- Off axis: strong vibration (resonance) → Voltage can be detected by a lock-in amplifier
- Wire along the magnetic axis: no vibration because no magnetic field
- Vibration detector and fiducialisation system → position of the magnetic axis w.r.t fiducials

At resonance (off magnetic axis)

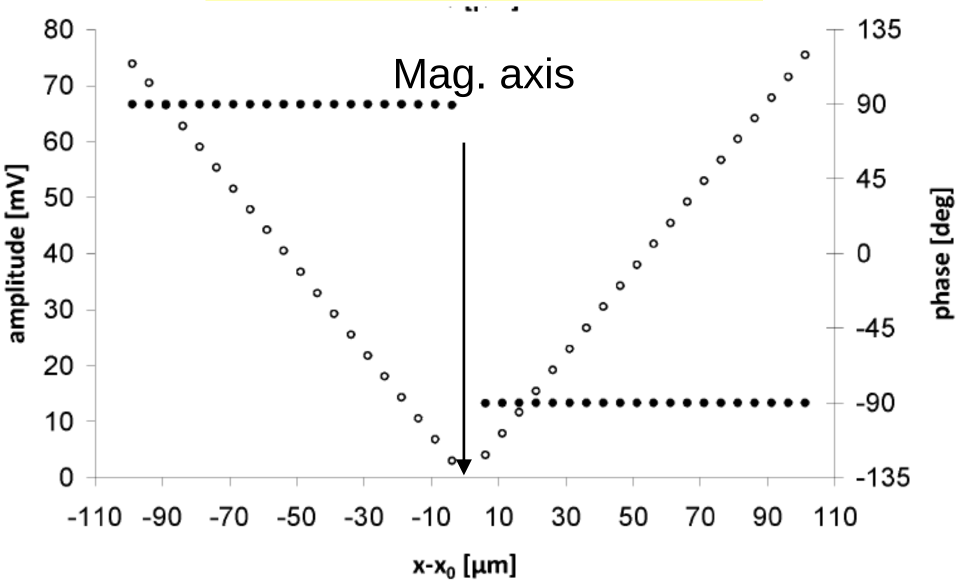


Resonance
f = 193.2 Hz
φ = 90˚

$$f_n = \frac{n}{2L}\sqrt{\frac{T}{\mu}}$$

voltage detected (vibration) and $\phi=\pi/2$

Crossing the magnetic axis

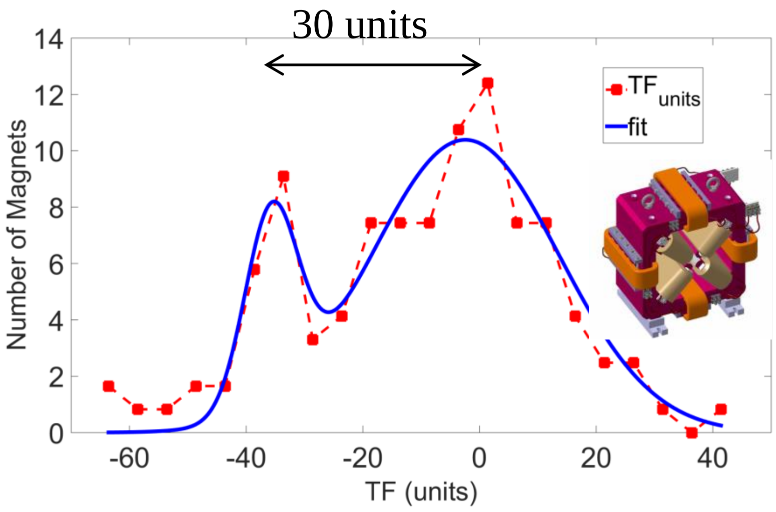


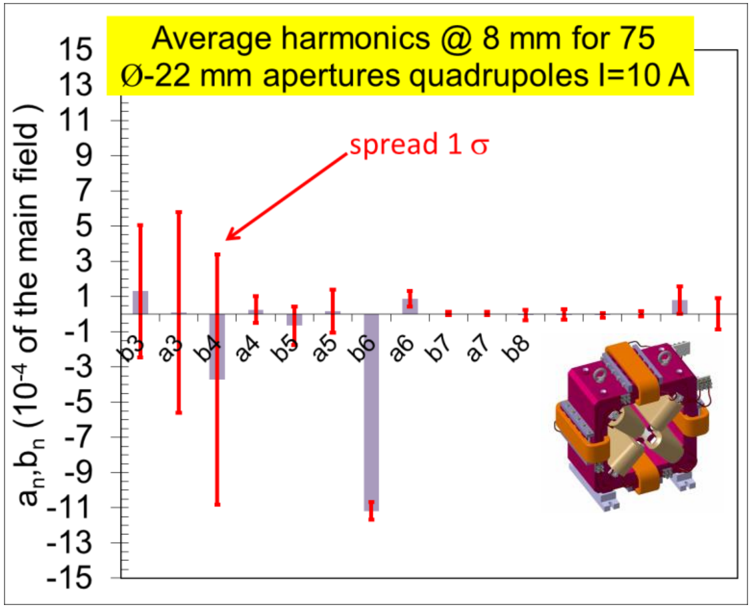
- “V” shape for the amplitude
- Jump from $\pi/2$ to $-\pi/2$ for the phase

Difficulties:

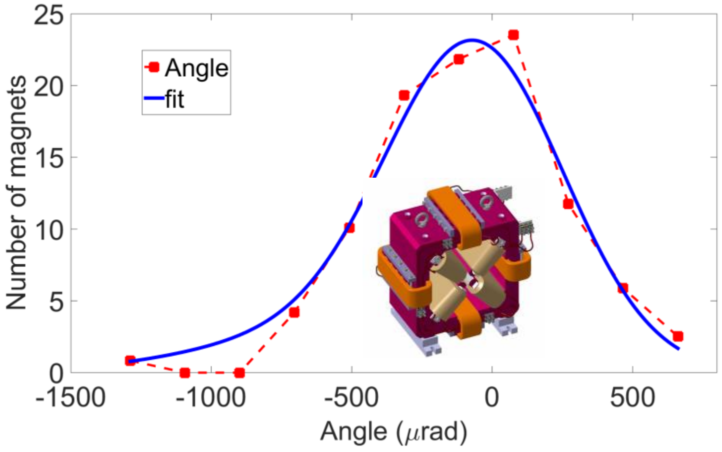
- Sensibility of the vibration detectors
- Fiducialisation

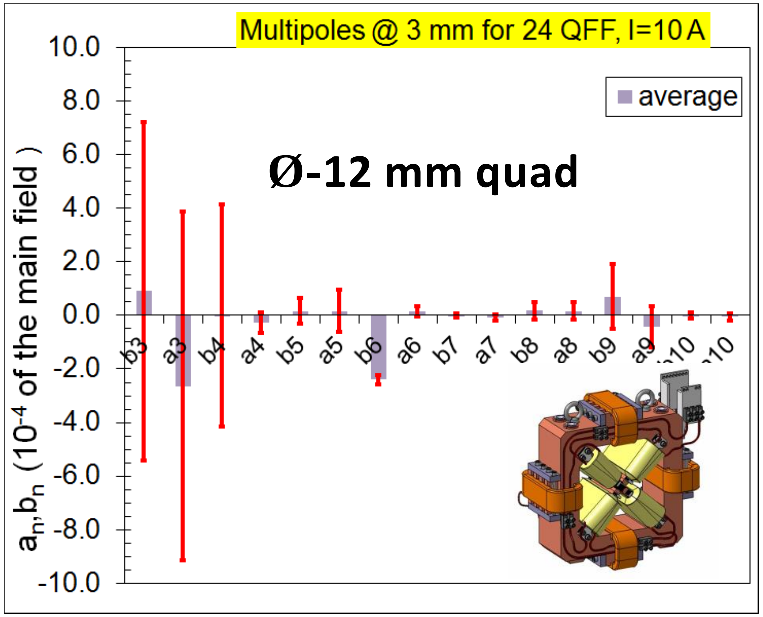
Rotating coil: SwissFEL quadrupole measurements





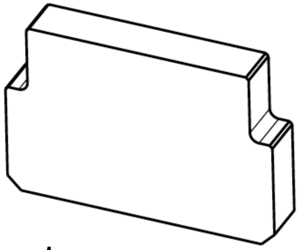
Statistics on 120 quads



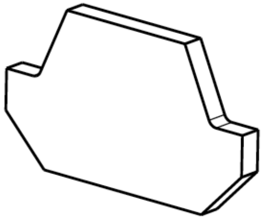


U15 flexor block keeper design

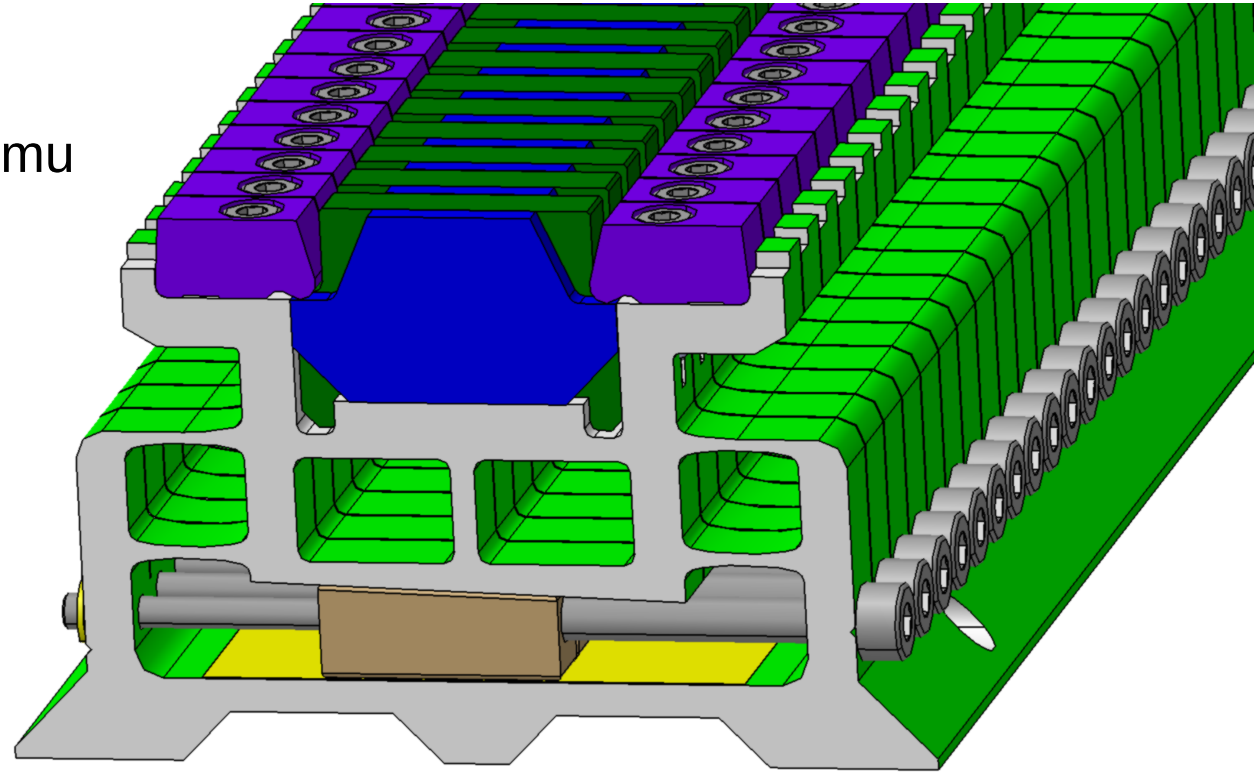
- Block keeper extruded Al
- Common clamp with
  a 50mu nose for plastic
  deformation to
  match tolerances
- Preload 60mu
  Adjustment +- 30mu



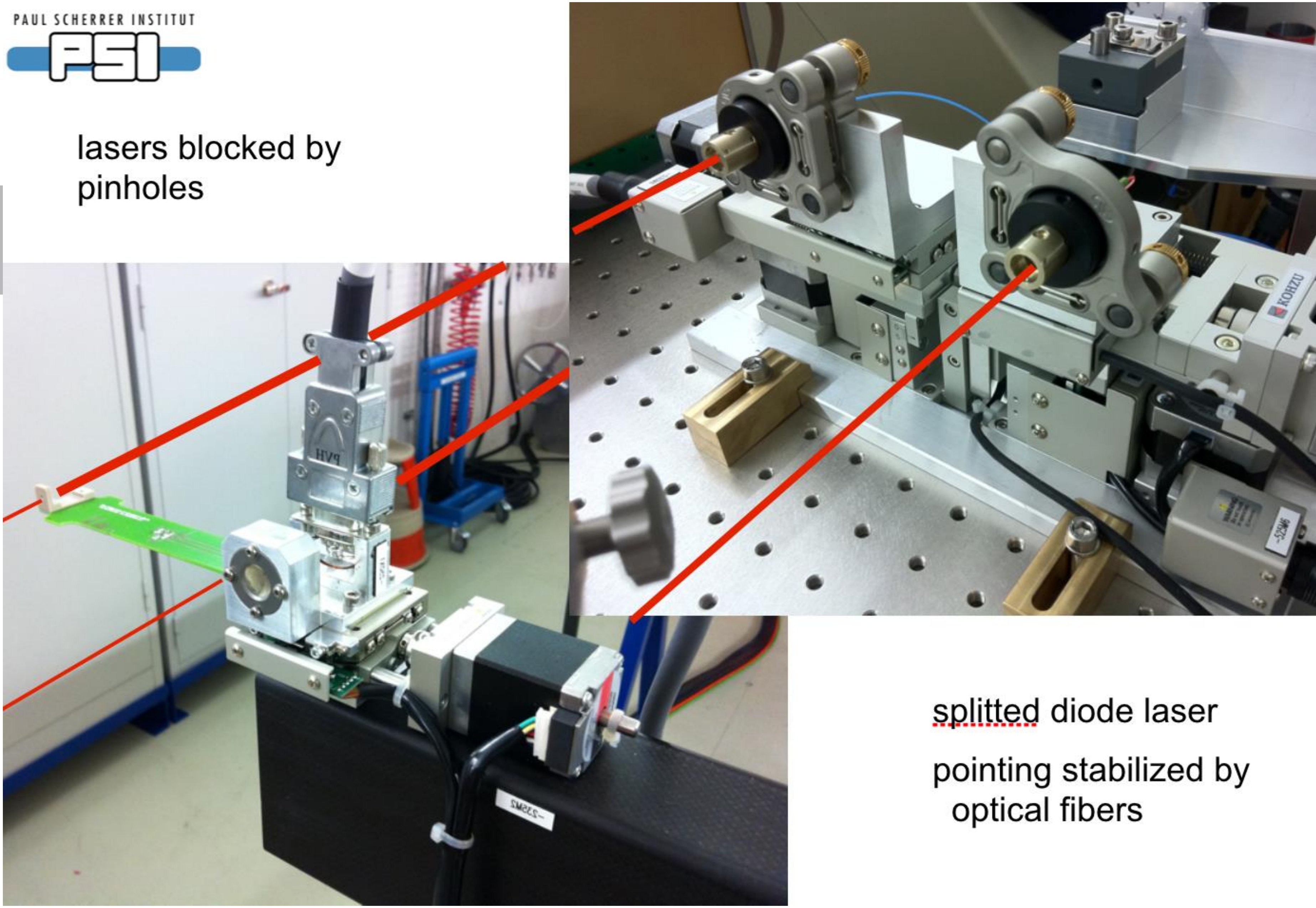
magnet
Dy diffused NdFeB



pole
with 15mm pole tip

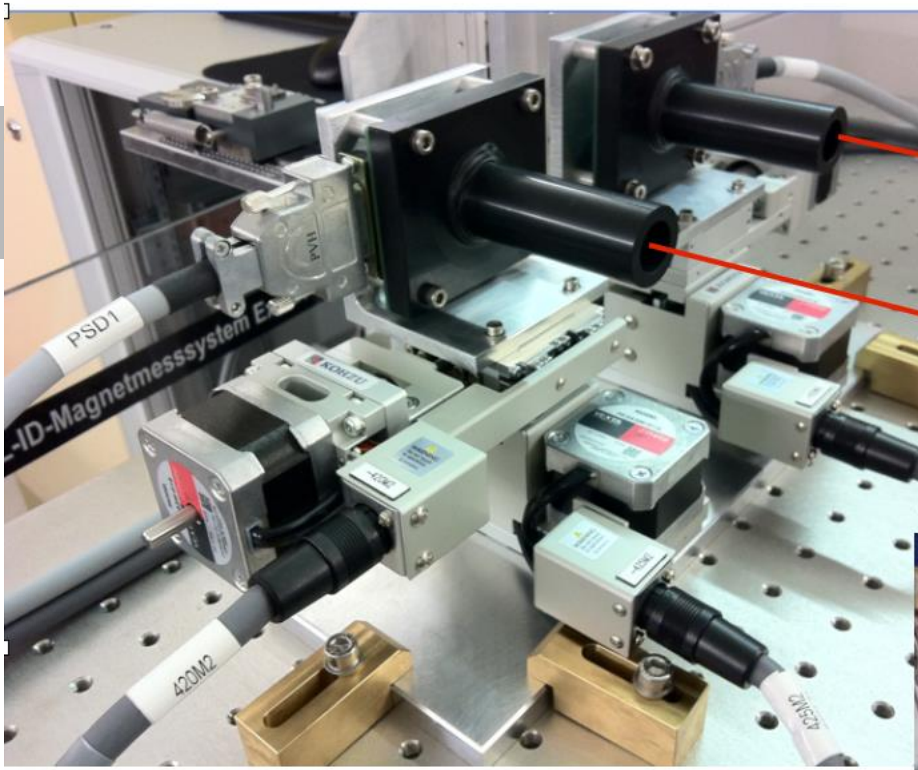


lasers blocked by pinholes



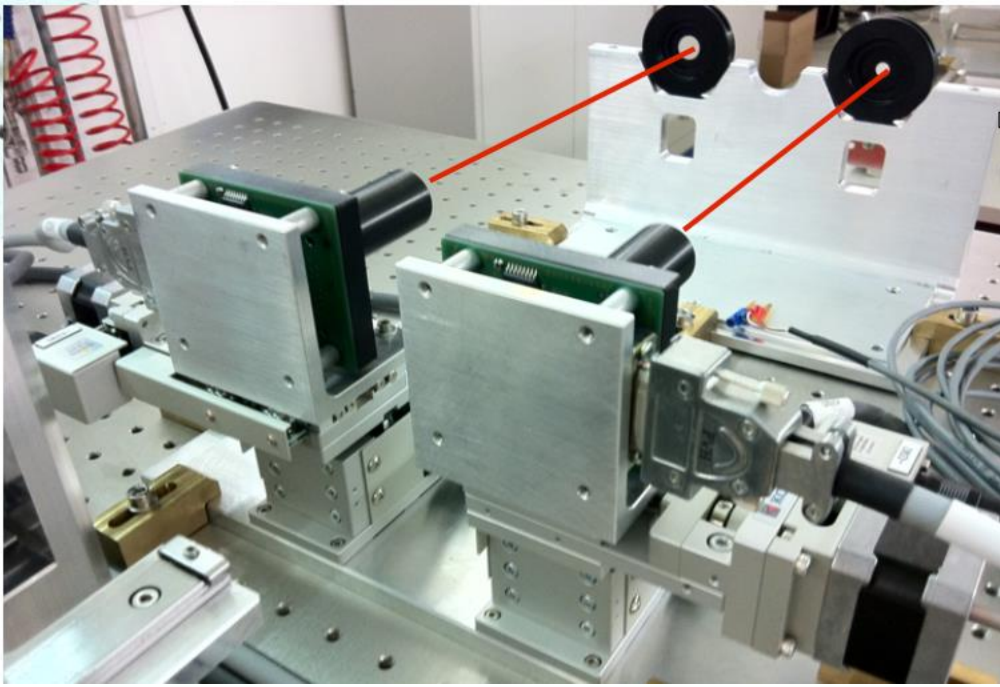
splitted diode laser

pointing stabilized by optical fibers



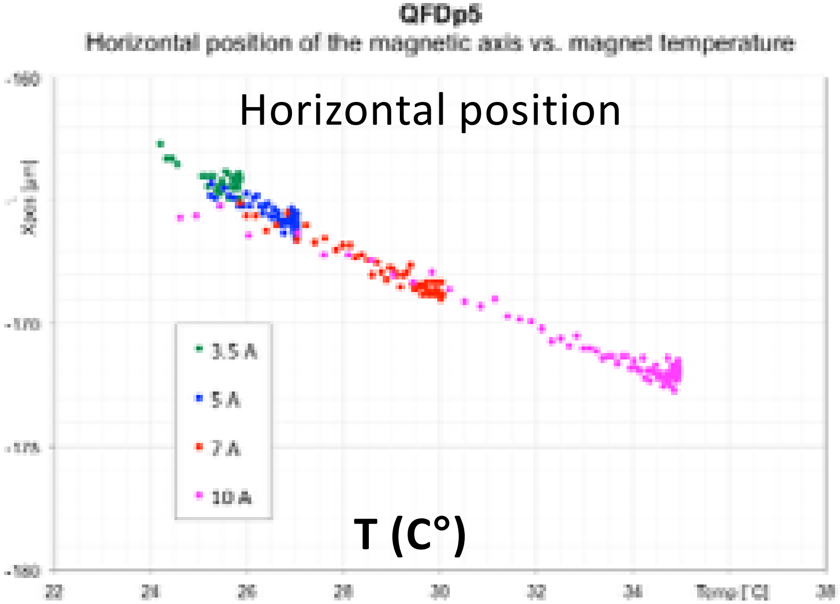
PSD
position sensitive diode
for position control

closed loop for Hall probe



Vibrating wire : magnetic axis vs. temperature (air-cooled quadrupole)

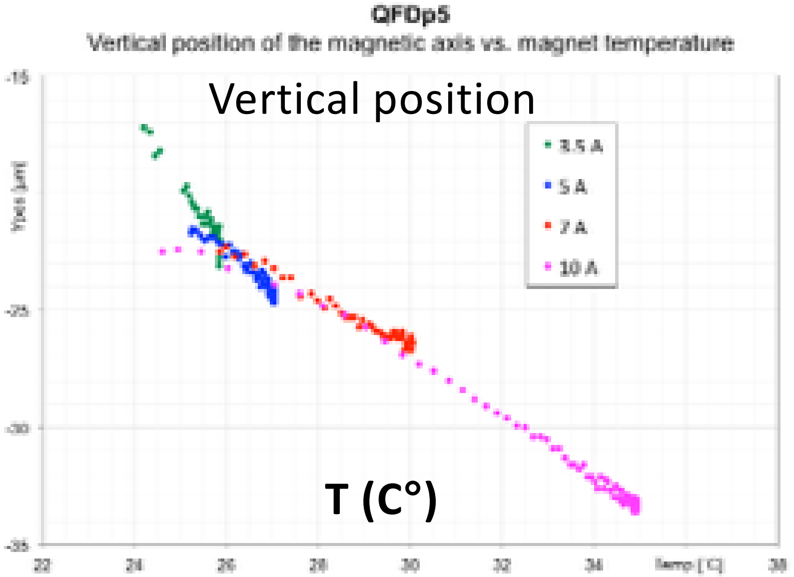
Xpos (µm)



Horizontal position

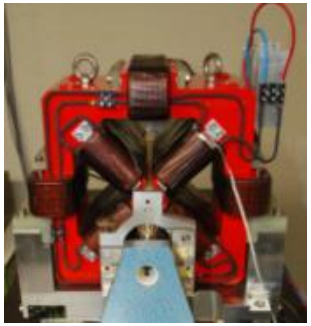
T (C°)

Ypos (µm)



Vertical position

T (C°)



Courtesy V. Vrankovic