Karlsruhe Institute of Technology

ANKA Synchrotron Radiation Facility

Magnetic field measurements of full scale conduction cooled superconducting undulator coils

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Babcock Noell GmbH

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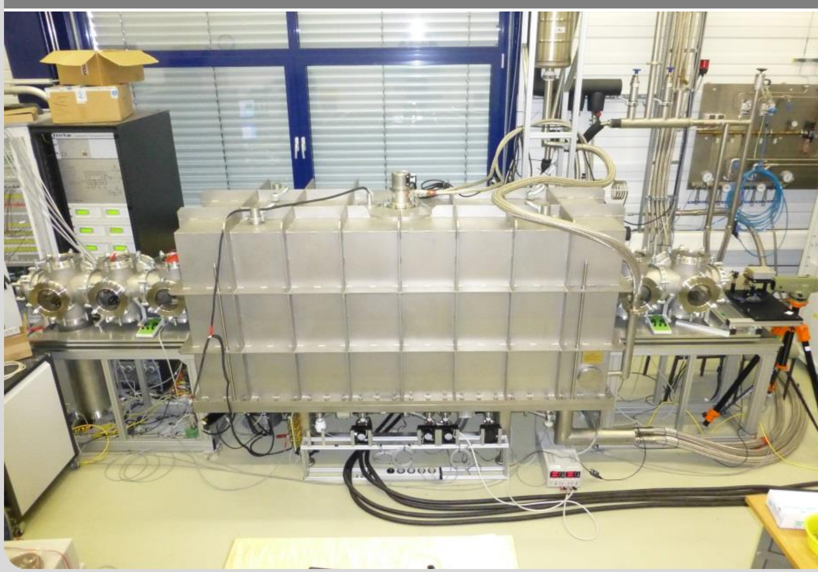
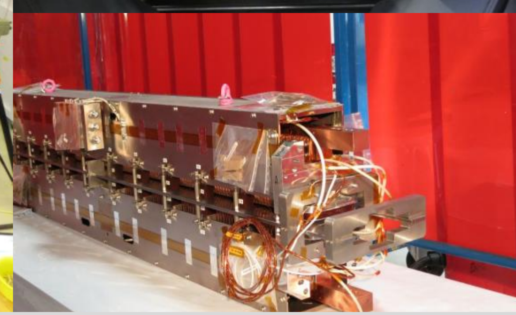
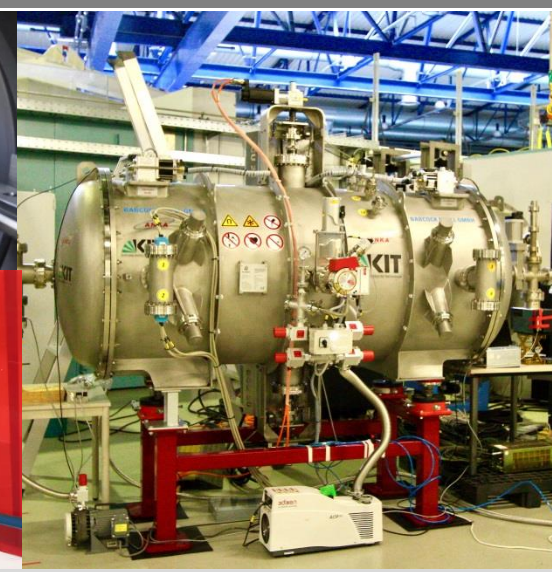
Institute for Beam Physics and Technology



Outline

- Introduction
- KIT and BNG SCUs development
- CASPER II
- SCU20 coils
- Local magnetic field
- Magnetic field integrals and multipoles
- Calculated spectrum
- Conclusions

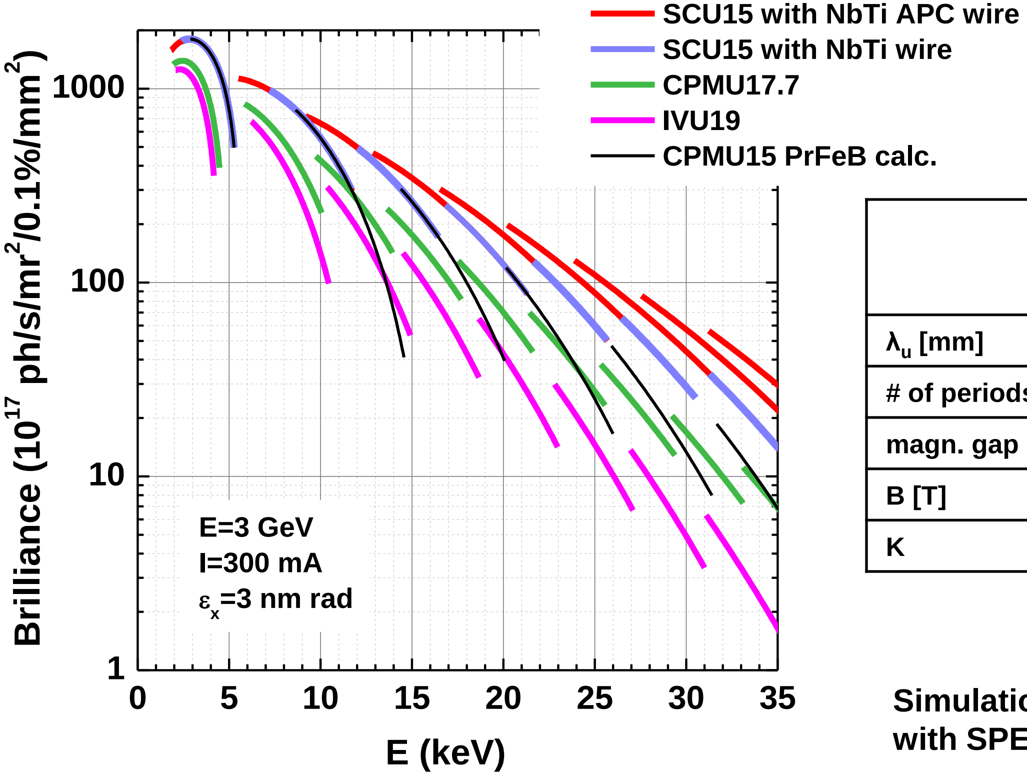
Introduction

With respect to permanent magnet undulators SCUs can generate :

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

Why? Larger magnetic field strength for the same vacuum gap and period length

Same magnetic length = 2 m and vacuum gap = 5 mm



IVU= in-vacuum undulator
CPMU= cryogenic permanent magnet undulator
SCU=superconducting undulator

	IVU* (SLS)	CPMU† (DLS)	CPMU PrFeB#	SCU NbTi wire**	SCU NbTi APC††
λ_u [mm]	19	17.7	15	15	15
# of periods	105	112	133	133	133
magn. gap [mm]	5	5.2	5.2	6	6
B [T]	0.86	1.04	1.00	1.18	1.46
K	1.53	1.72	1.4	1.65	2.05

*F. Bødker et al., EPAC06
†C.W. Ostenfeld & M. Pedersen, IPAC10
#M.E. Couprie et al., FLS2012
**D. Saez de Jauregui et al., IPAC11
††T. Holubek et al, IPAC11

Simulations performed with SPECTRA§

S. C. et al., IEEE Trans. on Appl. Supercon. 4101305, Vol. 24-3 (2014)

§T. Tanaka and H. Kitamura, J. Synchrotron Rad. 8, 1221 (2001).

KIT and BNG development of SCUs for ANKA and low emittance light sources

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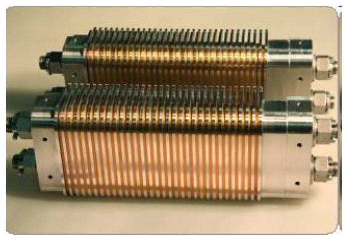
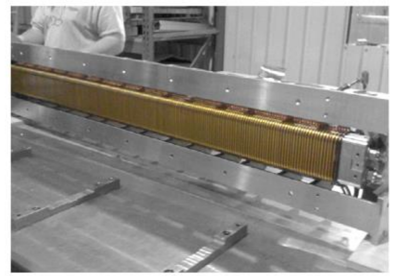
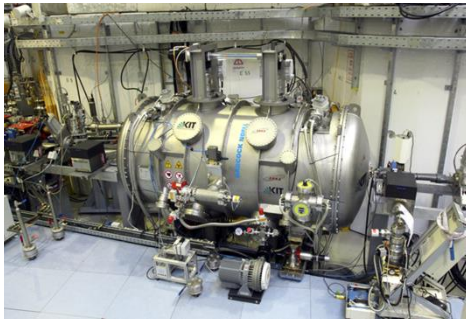
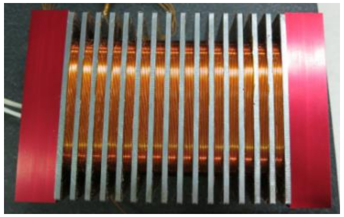
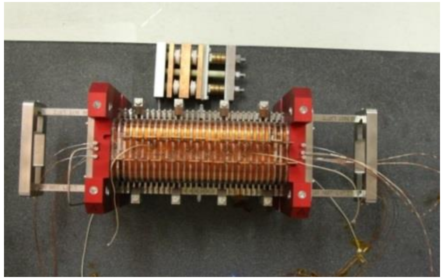
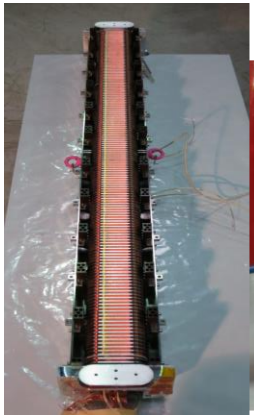
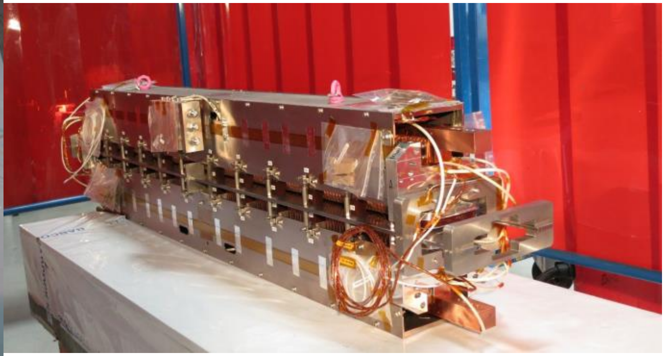
- NbTi wire
- Conduction cooling => no need of cryogenic fluids
- Movable vacuum chamber: highly desirable during commissioning and "nice to have" during operation

Mockup1 SCU15 Mockup2 Long coils

0.15 m 0.30 m 1.5 m time

SCU20

CASPER II

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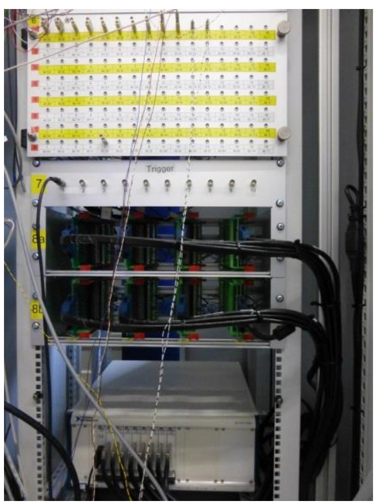
Unique horizontal cryogen free test stand to characterize conduction cooled undulator coils up to ~ 2 m long.

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

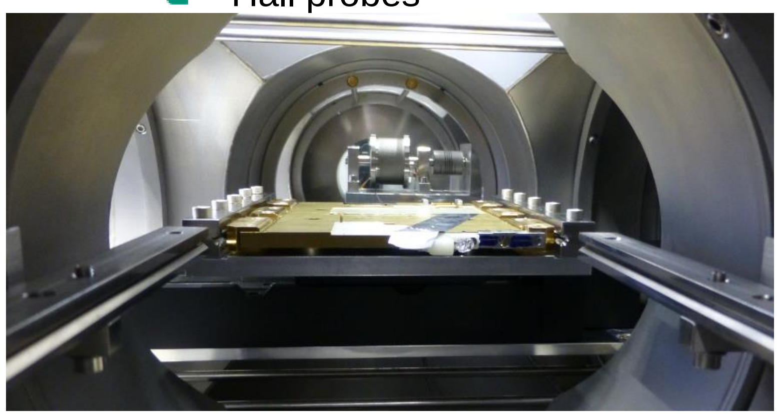
Training:

- Quench detection
- Quench analysis



Local field measurement:

- Hall probes



Integral field measurement:

- Stretched wire

CASPER II

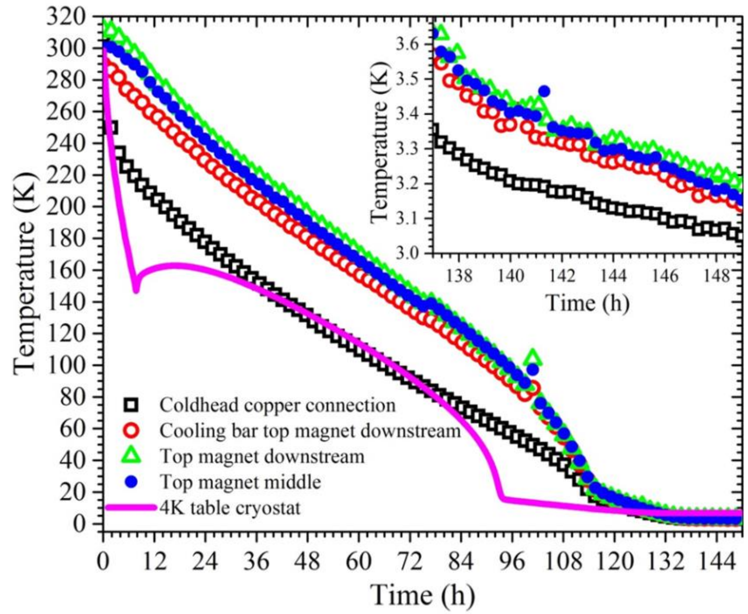
- **Local field measurements**
  - **Hall probe mounted on a sledge moving along the undulator length sliding on precisely machined guiding rails**
  - **Hall probe calibrated to ± 90 µT**
  - **Longitudinal position measured with a laser interferometer with sub µm resolution**

- **Integral field measurements**
  - **CuBe wire with a diameter of 125 µm is stretched between two stages placed at a distance of 2.7 m (strain force 6 N)**
  - **Alignment coils magnetic plane to stretched wire movements measured only at room temperature with a precision of 50 µm**
  - **Reproducibility of I_1 is ± 3.5×10^{-6} T mm and of I_2 is ± 1×10^{-5} T mm^2**

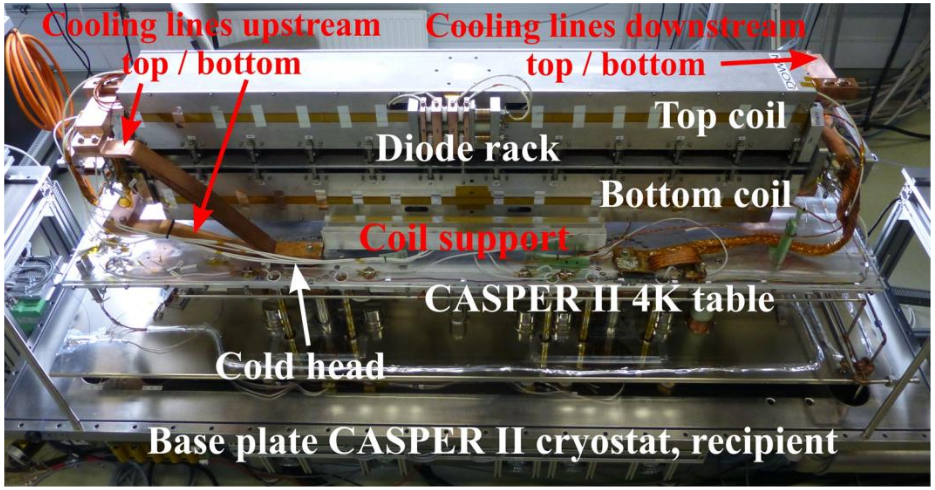
- **Local and integral field measurements can be performed during the same thermal cycle**

SCU20 coils in CASPER II

- **Cooldown time ~ 6 days**
- **Coils minimum temperature 3.1- 3.2 K**
- **Temperature gradient along cooling line ~ 0.1 K**
- **Coils connected to 2 cryocoolers 1.5 W@ 4.2 K**



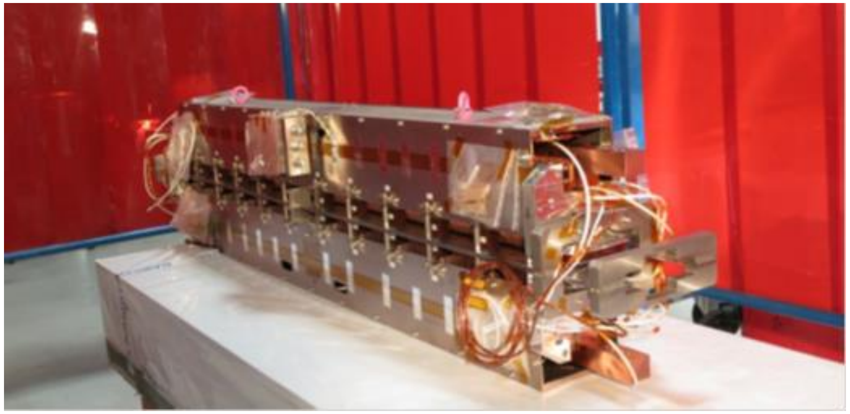
A. Grau et al., IPAC17 (2017)



See poster THU-AF-PO 4-03 presented by A. Grau on Thursday for more details on training, stability and thermal behaviour

SCU20 coils

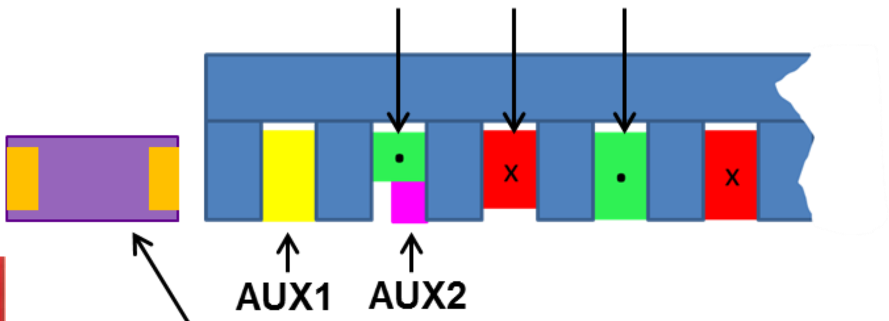
- Period length : 20 mm
- Number of full periods: 74.5
- Peak field on axis = 1.187 T
- Magnetic gap = 8 mm



Each coil is made by 11 blocks

Diameter NbTi wire:
0.76 mm (including insulation)

End fields upstream and downstream:



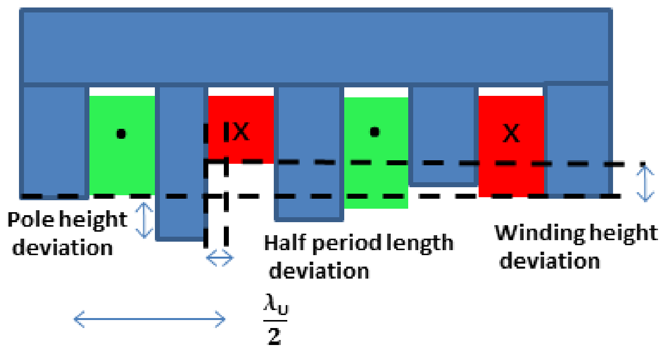
Helmholtz coils upstream and downstream
NbTi wire with diameter 0.254 mm (including insulation)

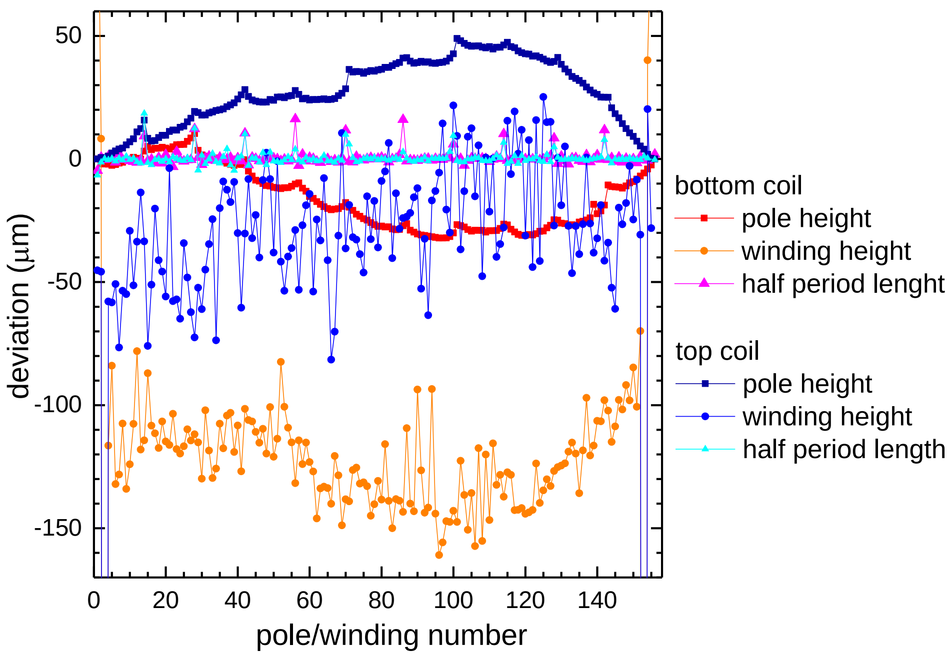
AUX1 and the HH DS have been used to keep $|I_{1v}| < 3\ 10^{-5}$ T m, and $|I_{2v}| < 4\ 10^{-4}$ T m^2

SCU20 coils

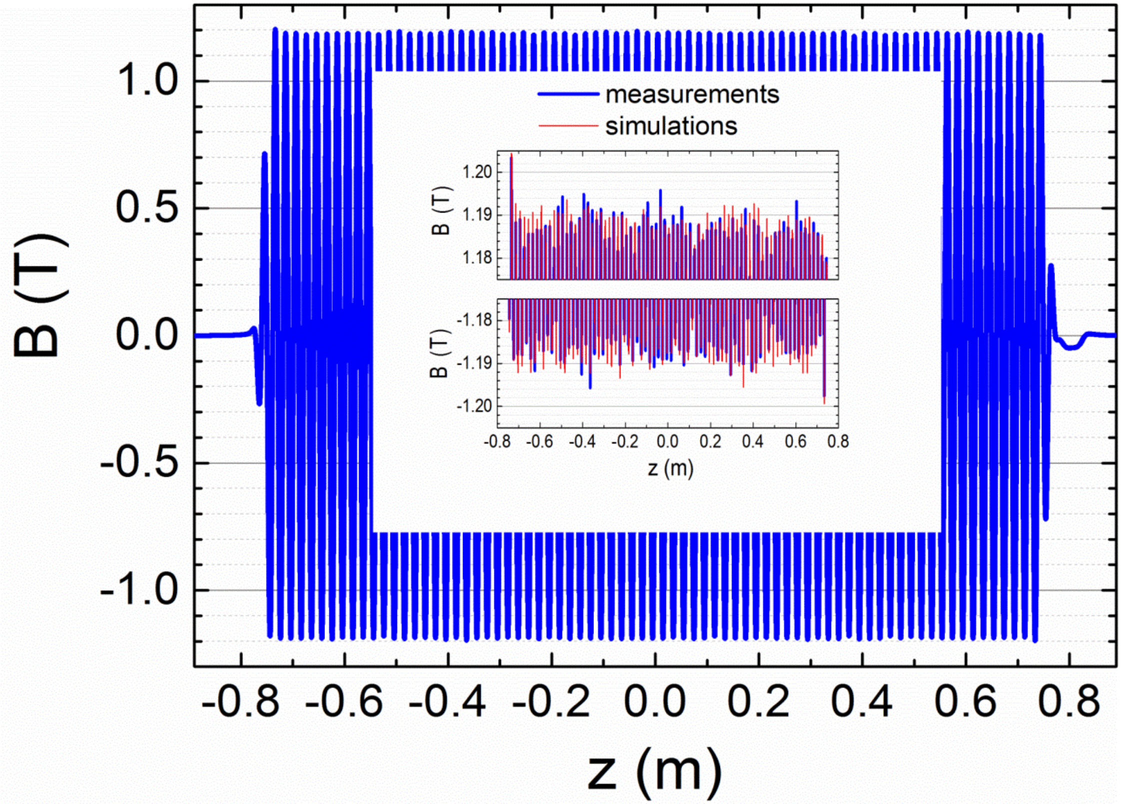
- To reach good field quality in cold conditions, required to maximize the spectral response, it is necessary to precisely manufacture the yoke and wind the coils

Measurements with CMM at room temperature: deviation from nominal/ideal values
Pole and winding heights after impregnation
Half period length before winding





Local field measurements



$I_{main\ coil}$ = 395 A

Simulations performed with Radia* considering the mechanical accuracies measured at room temperature

What happens after cooling ?

- The observed changes are consistent with random changes in the winding packages height of ~ ± 50 µm

*P. Elleaume, O. Chubar, J. Chavanne, PAC97

Integral field measurements

First and second vertical field integrals minimized below

$|I_{1v}| < 3\ 10^{-5}$ T m, and $|I_{2v}| < 4\ 10^{-4}$ T m^2

by powering the AUX1 and HH DS coils to values up to 5.6 A and 0.82 A.

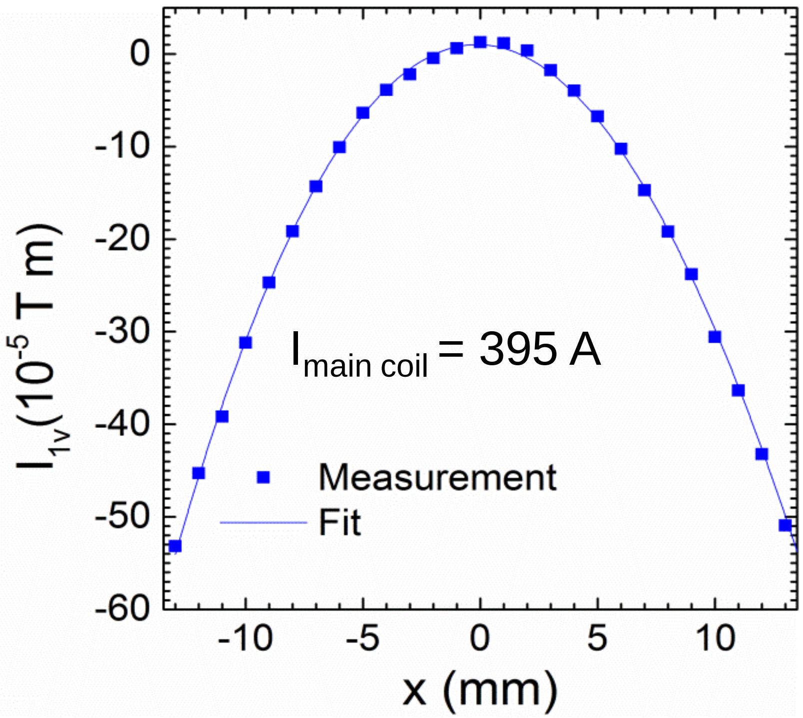
To reach

$|I_{1h}| < 3\ 10^{-6}$ T m, and $|I_{2h}| < 10^{-5}$ T m^2

correctors will be added outside the cryostat.

Multipoles

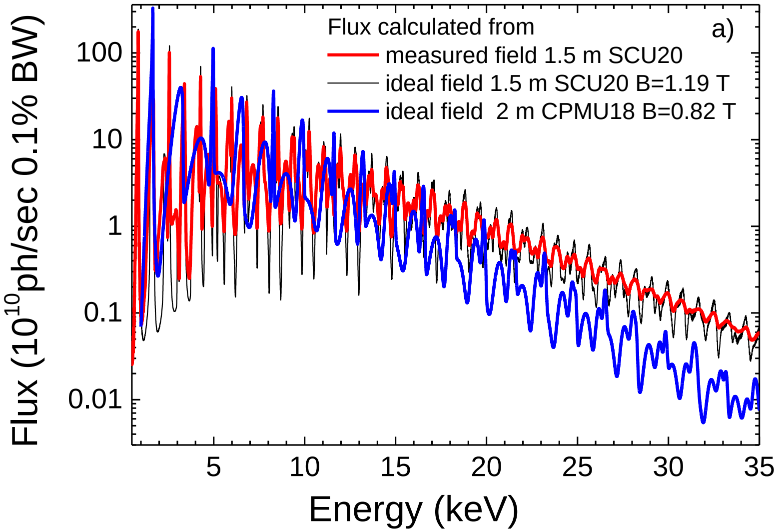
$|Q|<0.005$ T, $|S|<5$ T/m and $|O|<15$ T/m^2

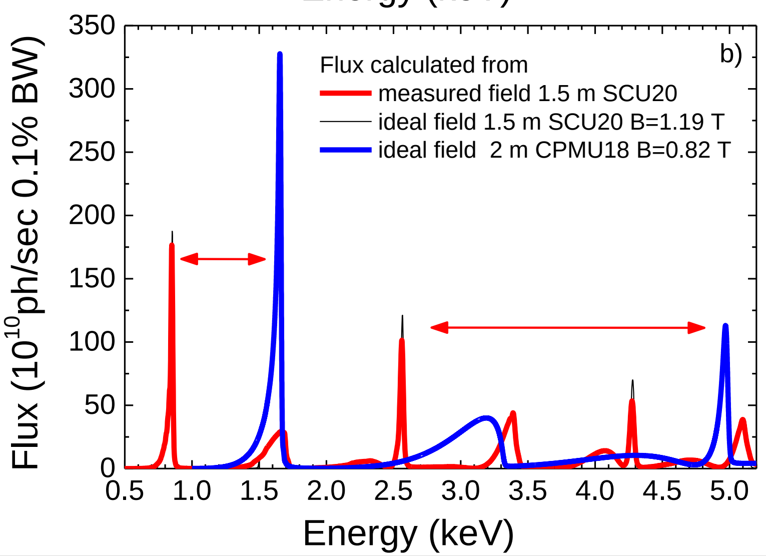


For all currents the values of the integrated multipoles are small enough not to change the dynamic aperture of the beam for the 2.5 GeV operation of ANKA.

Calculated spectrum

Flux at 10 m from the source through a slit 50 µm × 50 µm at ANKA





1.5 m SCU20 versus an ideal (without mechanical errors and perfect end fields) 2 m PrFeB CPMU18 with the same parameters as the one built at SOLEIL. The vacuum gap is for both 7 mm.**

**** C. Benabderrahmane et al., Phys. Rev. Accel. Beams 20, 033201 (2017)**

- Larger flux of the SCU20 with respect to the CPMU18 at high energies up to a factor of 5.

- At low photon energies the energy regions allowed with the SCU20, are not reachable with the CPMU18, due to its lower peak field on axis.

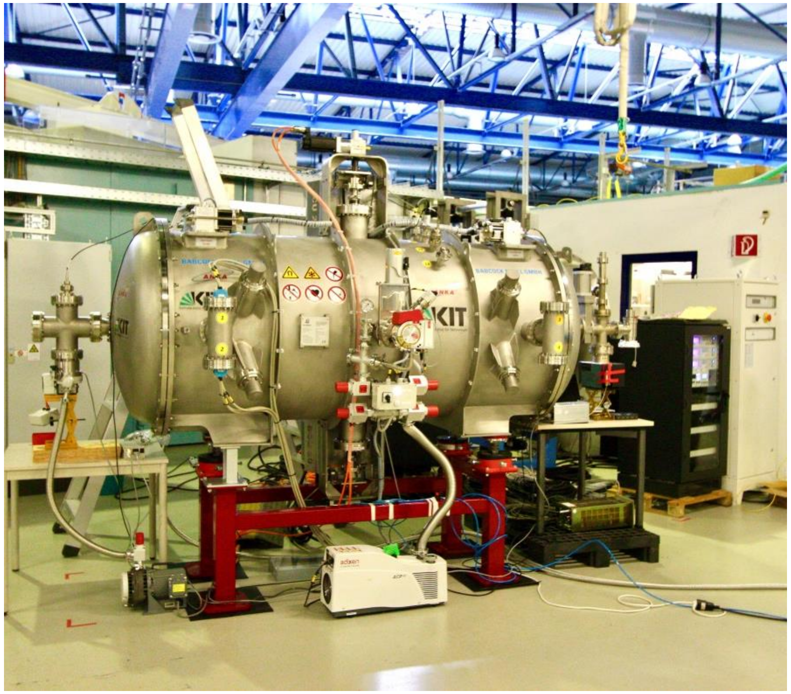
S. C. et al, IOP Conf. Series: Journal of Physics: Conf. Series 874 (2017) 012015

Conclusions

- The 1.5 m long coils of the SCU20 have been successfully measured in the test facility CASPER II.

- The advantages of the spectrum produced by the measured field profile of the SCU20 with respect to an ideal CPMU18 (without mechanical errors and perfect end fields) with the same parameters as the one built at SOLEIL and same beam stay clear have been demonstrated.

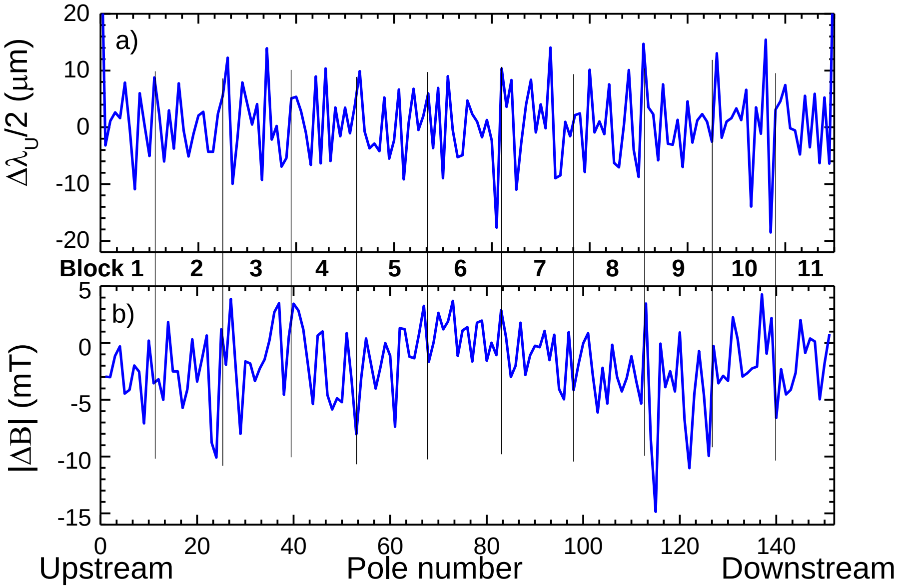
- The 1.5 m long coils of the SCU20 are now installed and tested in the final cryostat at ANKA



Thank you for your attention

Backup slides

Local field measurements



$\Delta\lambda_U/2$ = difference between $\lambda_U/2$ calculated from the measured and simulated field profiles

$|\Delta B|$ = difference between the absolute value of the peak magnetic field calculated from the measured and simulated field profiles

- During winding, impregnation and/or cooldown some of the connections between the blocks get looser increasing $\Delta\lambda_U/2$ up to about 15 µm
- The observed random changes in $\Delta\lambda_U/2$ (~ ± 7 µm) and in $|\Delta B|$ (~ ± 4 mT) are consistent with random changes in the winding packages of ~ ± 50 µm

Local field measurement

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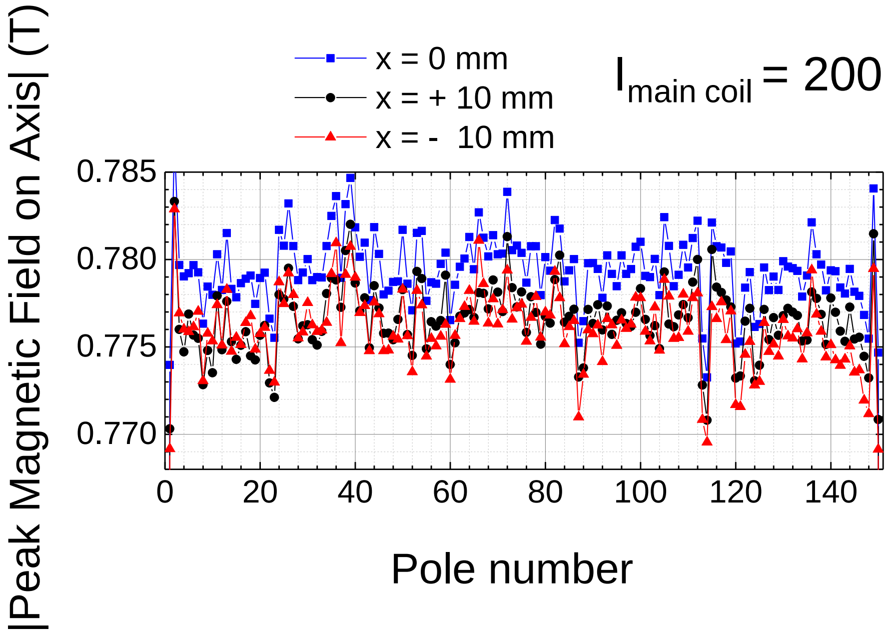
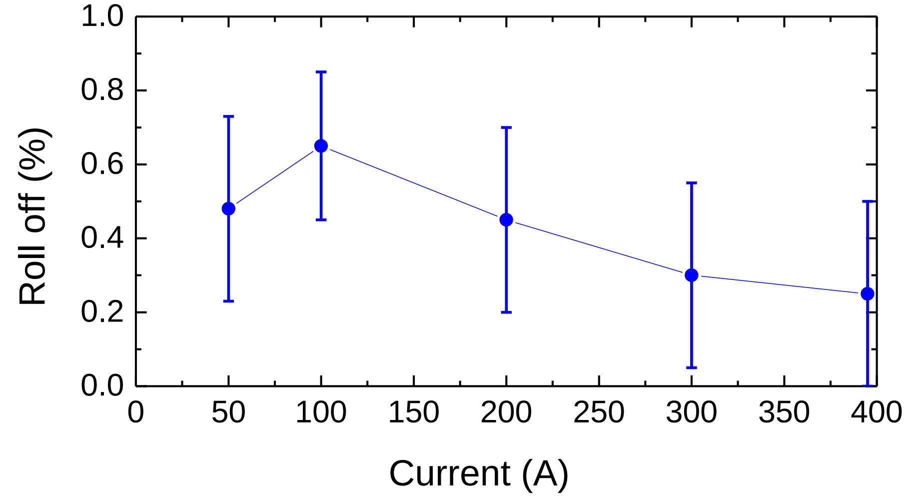
$I_{main\ coil} = 200$ A



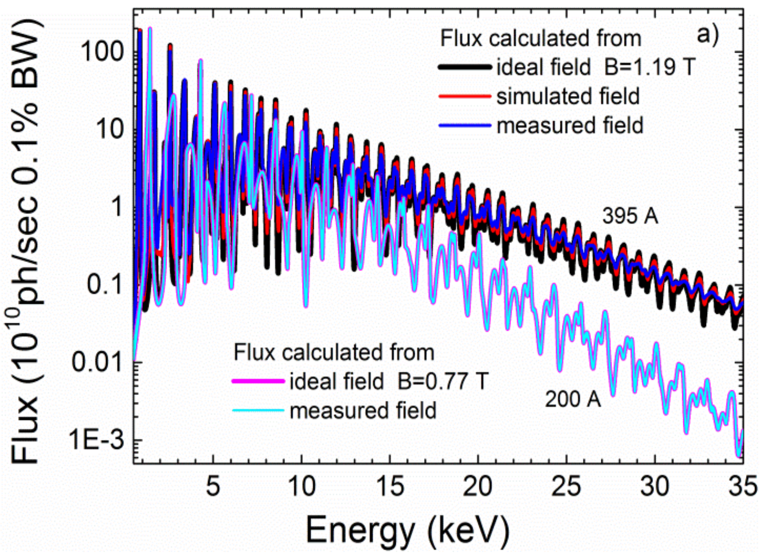
$$\text{Roll off} = \frac{|B(x = \pm 10\ \text{mm}) - B(x = 0\ \text{mm})|}{|B\ (x = 0\ \text{mm})|}$$



The roll off measured induces a negligible dynamic kick.

Calculated spectrum

Flux at 10 m from the source through a slit 50 µm × 50 µm at ANKA

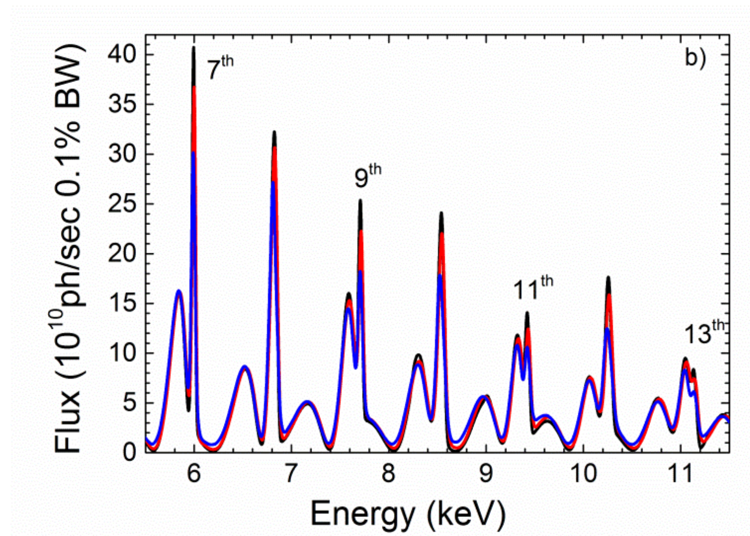


A slight reduction (less than 28% up to 35 keV) in flux of the spectrum from the measured field with respect to the ideal case, for the odd harmonics, due to the mechanical errors and to the non-ideal end field configuration, is observed.

The reduction in flux of the spectrum from the measured field to the ideal one at the odd harmonics is much smaller at lower currents in the main coils.

The reduction in flux is maximal at the 9th harmonic, and it decreases for the higher odd harmonics.

The spectrum from the simulated field at the odd harmonics is very close to the ideal case: a maximal reduction of 10% is observed.



An improvement in the spectral performance could be obtained by using a rectangular wire.