Recent progress with superconducting undulators at ANKA

Sara Casalbuoni

for

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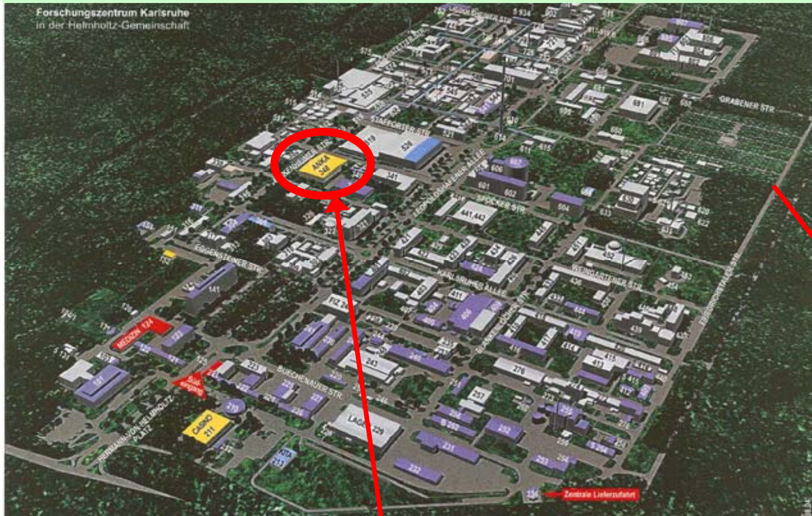
ISS/ANKA

Outline

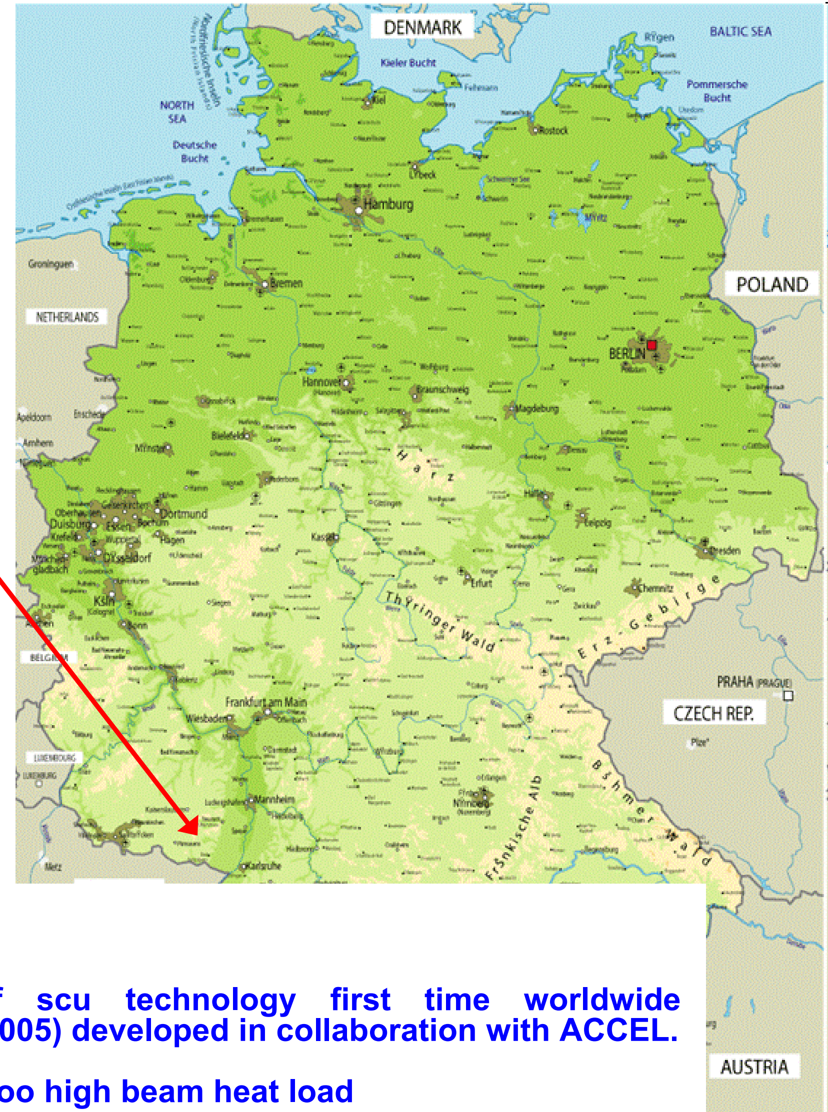
- Introduction
  - ANKA
  - Motivation R&D of SCIDs
- Superconducting undulator
- Period length switching
  - Experimental demonstration of feasibility
  - Supeconducting switch
- New materials
- Tools and instruments for R&D
  - CASPERI
  - CASPERII
  - COLDDIAG

ANKA

Karlsruhe Institute of Technology Campus North



Energy: 2.5 GeV
Current: 200 mA
Circumference: 110.4 m

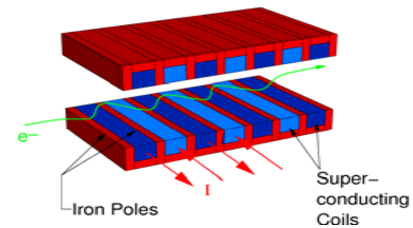


SCU14

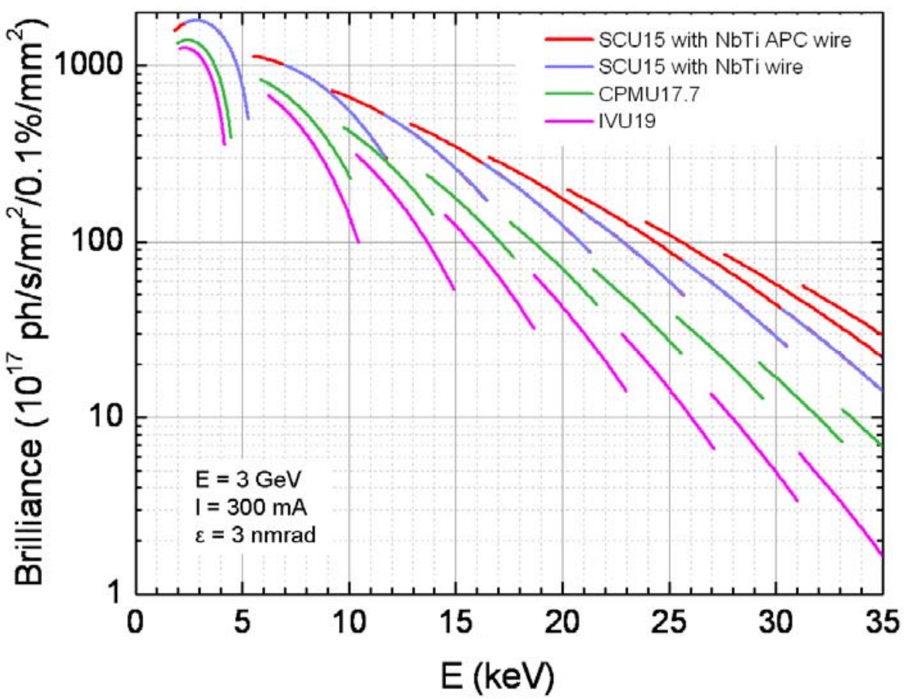
- **Proof of principle of scu technology first time worldwide demonstrated at ANKA (2005) developed in collaboration with ACCEL.**
- **Performance limited by too high beam heat load**

Motivation R&D of scIDs

Aim is to develop, manufacture, and test superconducting undulators 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.



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

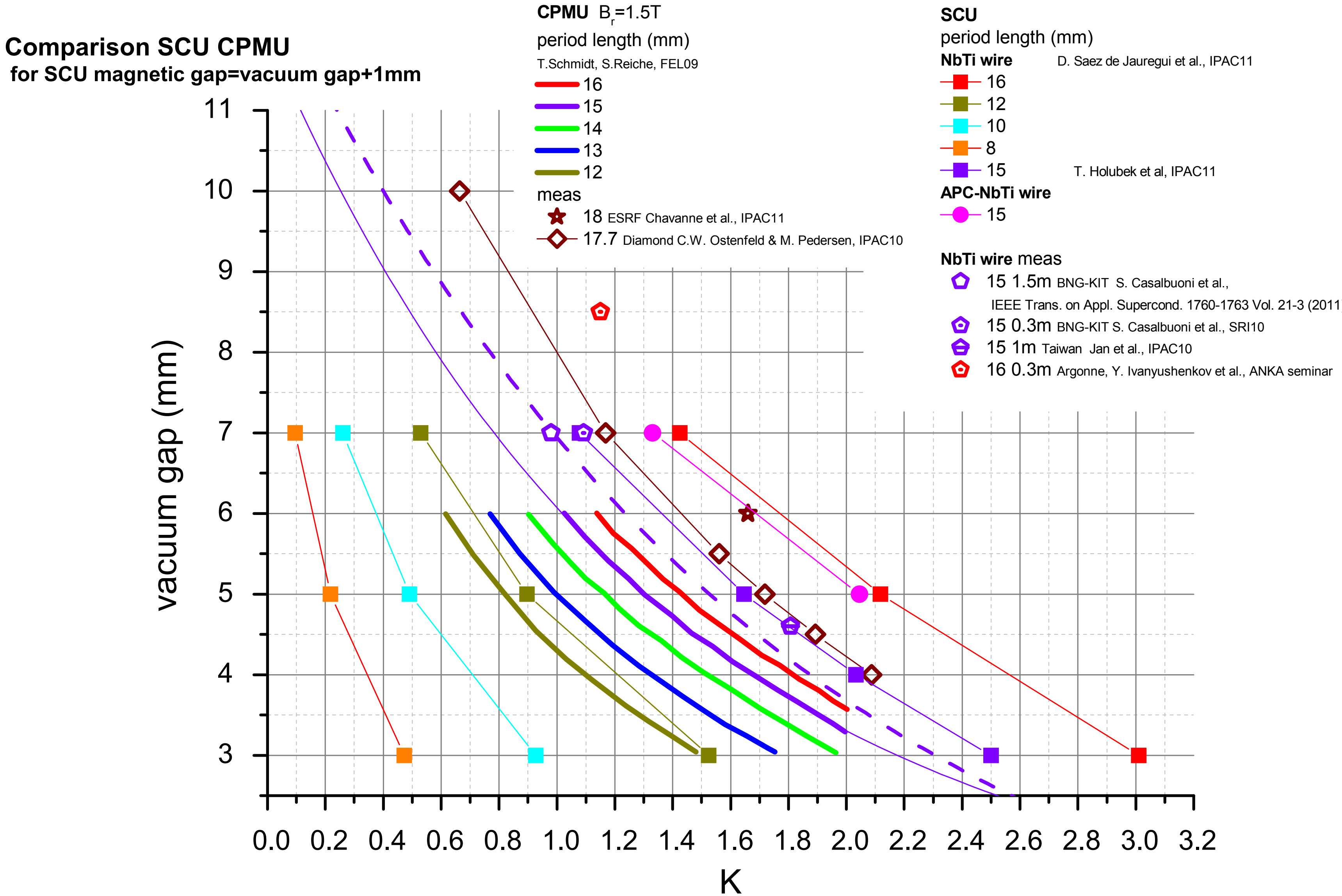


	IVU*	CPMU†	SCU NbTi wire**	SCU NbTi APC††
λ_u [mm]	19	17.7	15	15
N	105	112	133	133
m. gap [mm]	5	5.2	6	6
B [T]	0.86	1.04	1.2	1.46
K	1.53	1.72	1.7	2.05

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

A given photon energy can be reached by the SCU with lower order harmonic:
20 keV reached with the 7th harm. of SCU, with the 9th harm. of CPMU and of IVU

Motivation R&D of scIDs

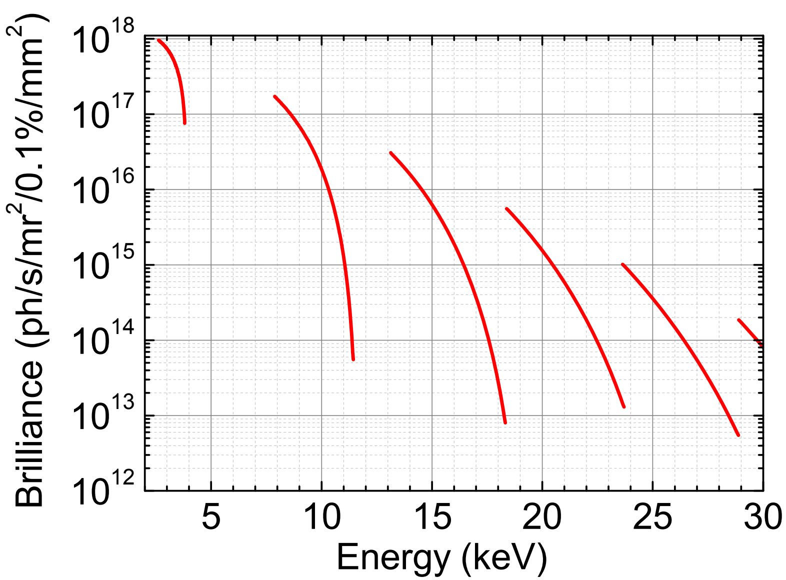


New superconducting undulator demonstrator to be tested at ANKA

Under development in collaboration with BNG

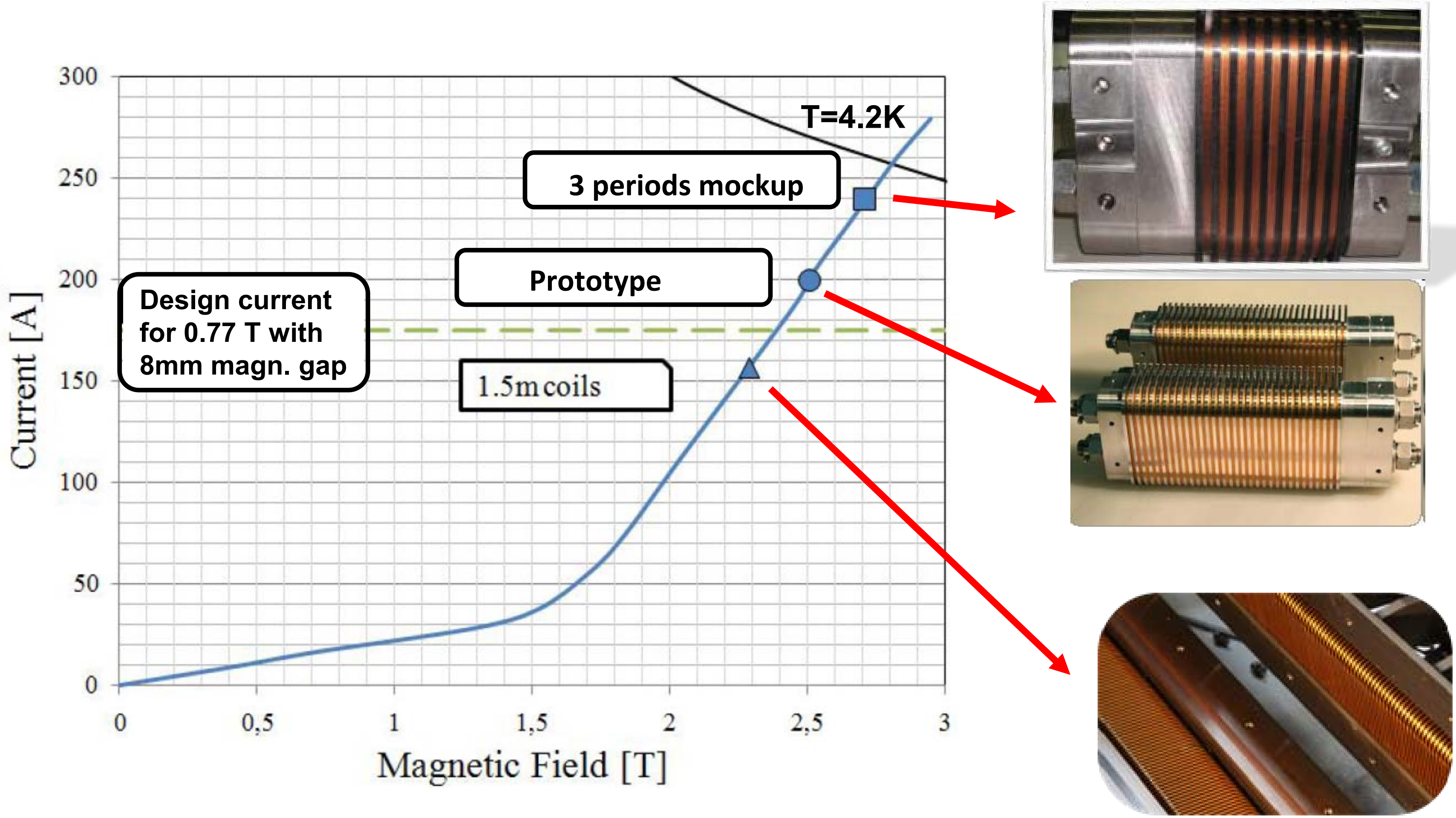
Period length	15 mm
Number of full periods	100.5
Max field on axis with 8 mm magnetic gap	0.69 T
Max field in the coils	2.4 T
Operating magnetic gap	8 mm
Operating beam gap	7 mm
Gap at beam injection	16 mm
Design beam heat load	4W

- Cryogen free magnet
- NbTi superconductor
- Integral field compensation
- Passive quench protection



SCU15 demonstrator: magnet loadline

Measured @KIT

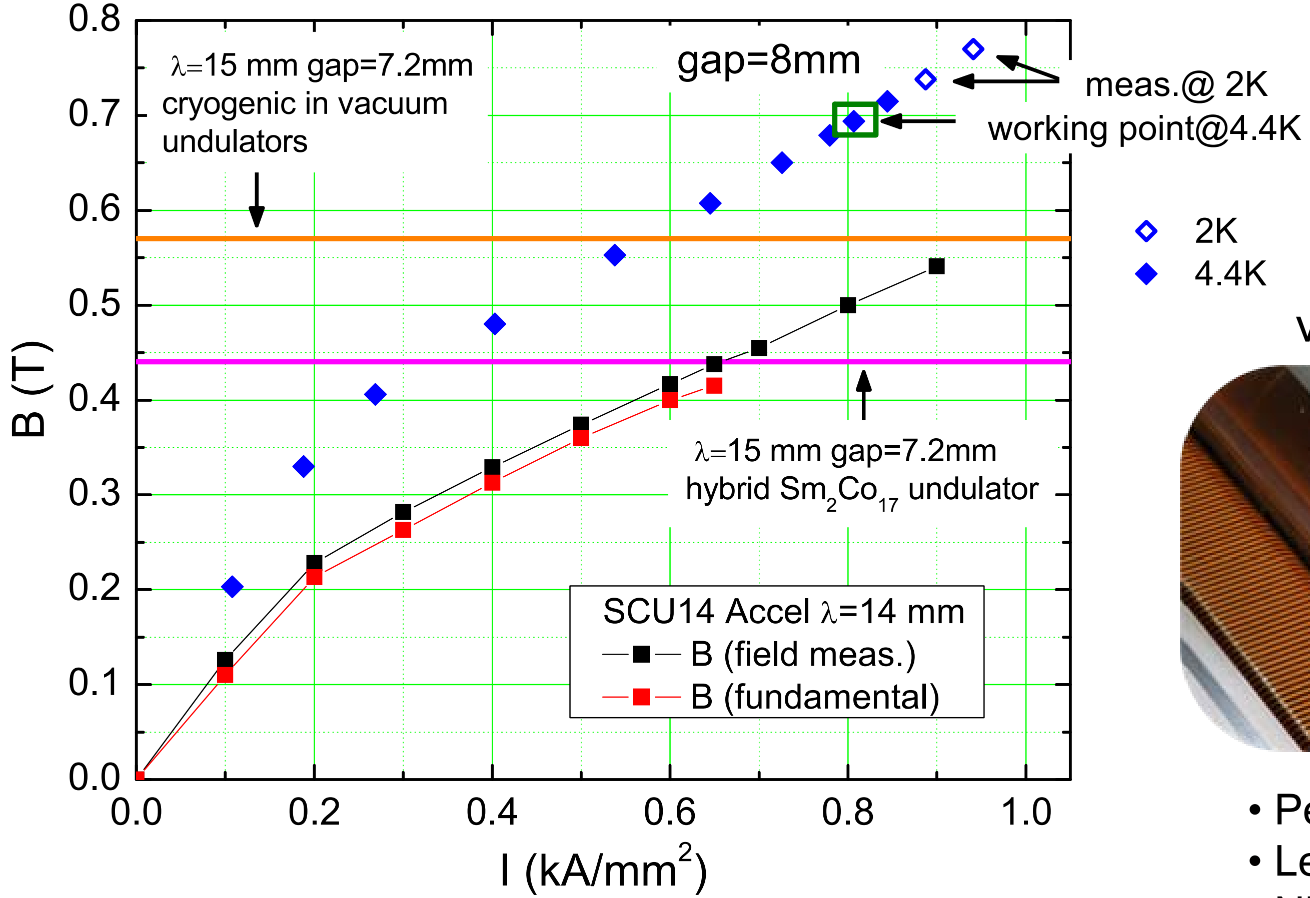


Measured @CERN

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

SCU15 demostrator

Comparison with competing technologies and with SCU14 demonstrator



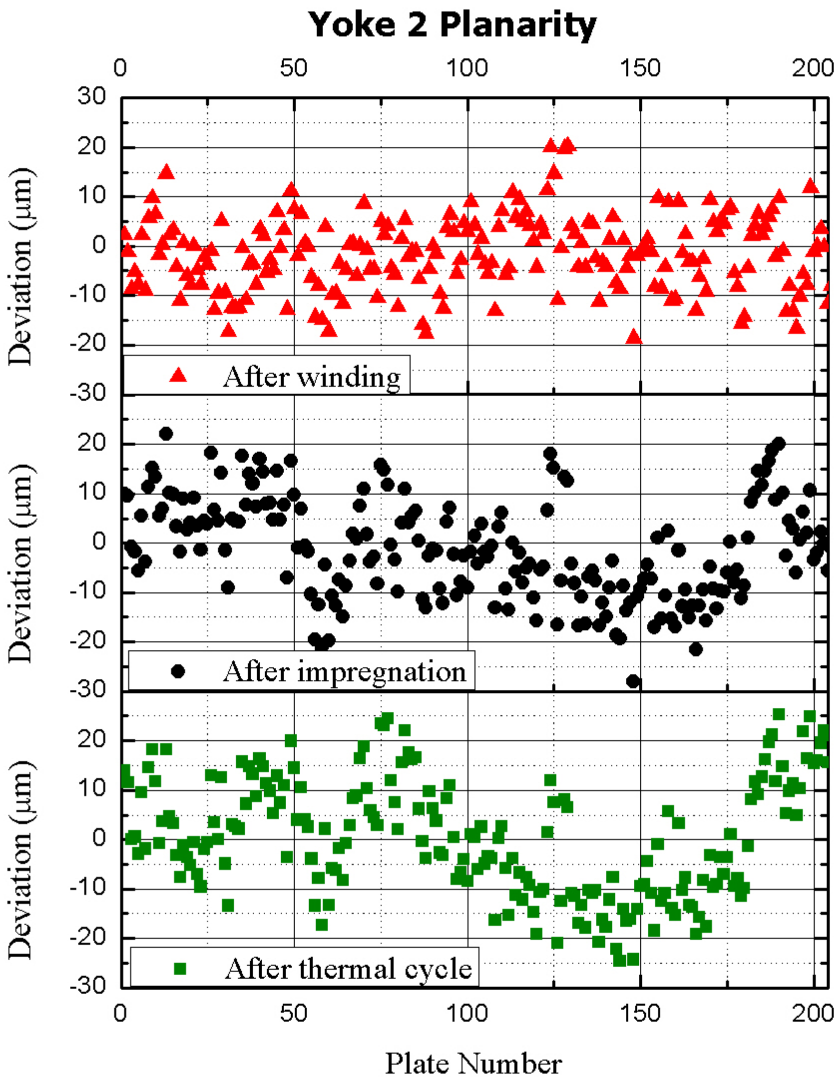
vacuum gap=7 mm

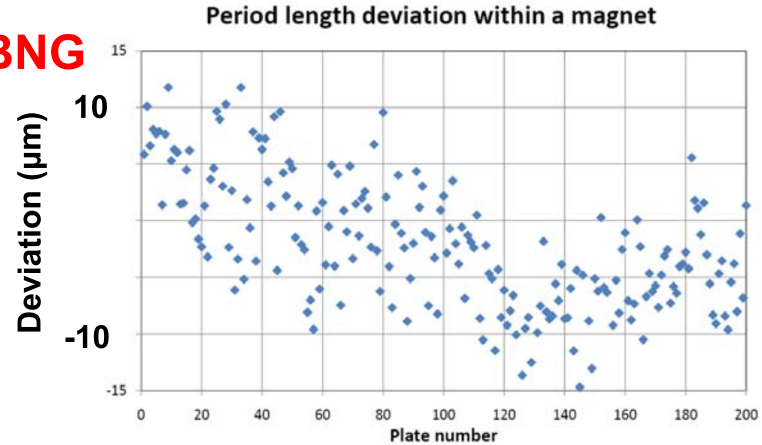
- Period length: 15 mm
- Length: 100 periods
- NbTi - coils

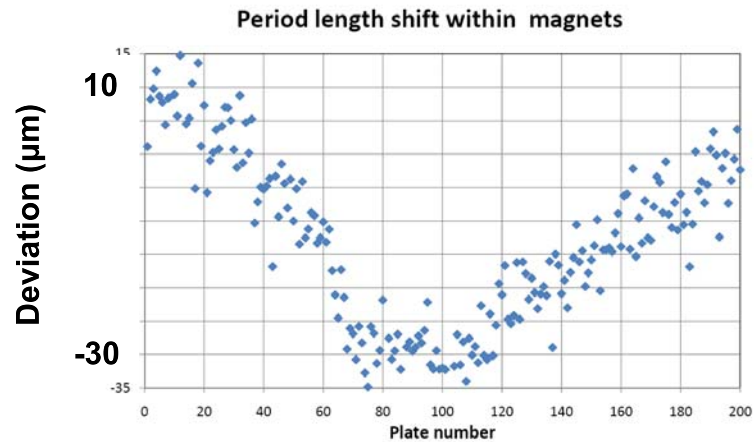
S.C. et al., IEEE Trans. on Appl. Supercond. 1760-1763 Vol. 21-3 (2011)

Accuracies measured @300K

by BNG



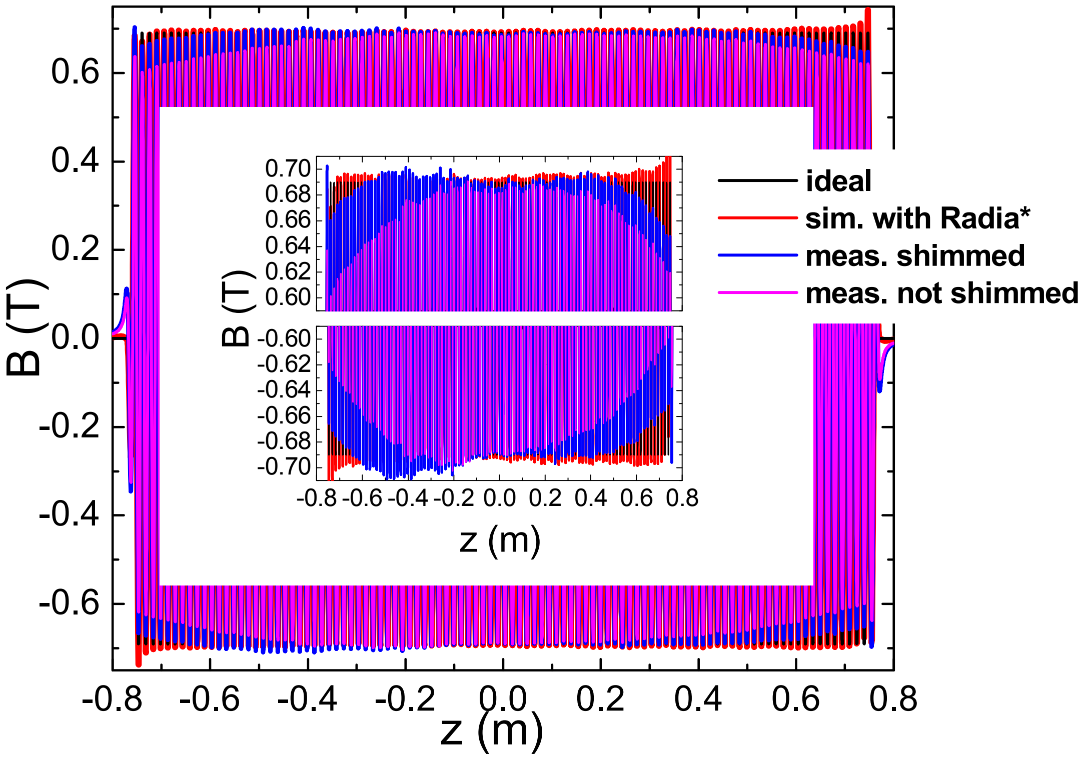




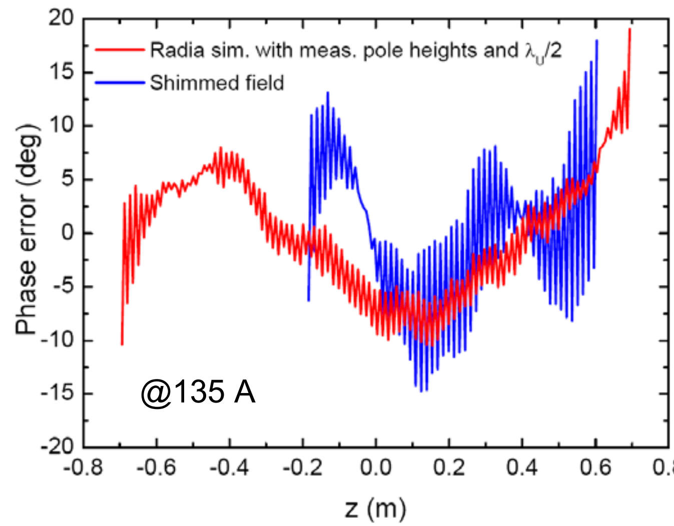
WINDING POSITIONING ACCURACY:	40 μm
POLE LONGITUDINAL POSITION:	30 μm
LENGTH DIFFERENCE BETWEEN COILS:	20 μm
COIL PLANARITY ALONG 1.5 M :	50 μm
GAP DIMENSION AT ENDS DEVIATION:	10 μm

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

SCU15 demostrator: phase error



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



Shimmed field:

Phase error of 7.4 degrees over a length of ~0.8 m

Radia* simulations with meas. pole heights and half period lenghts at 300K (~50μm):

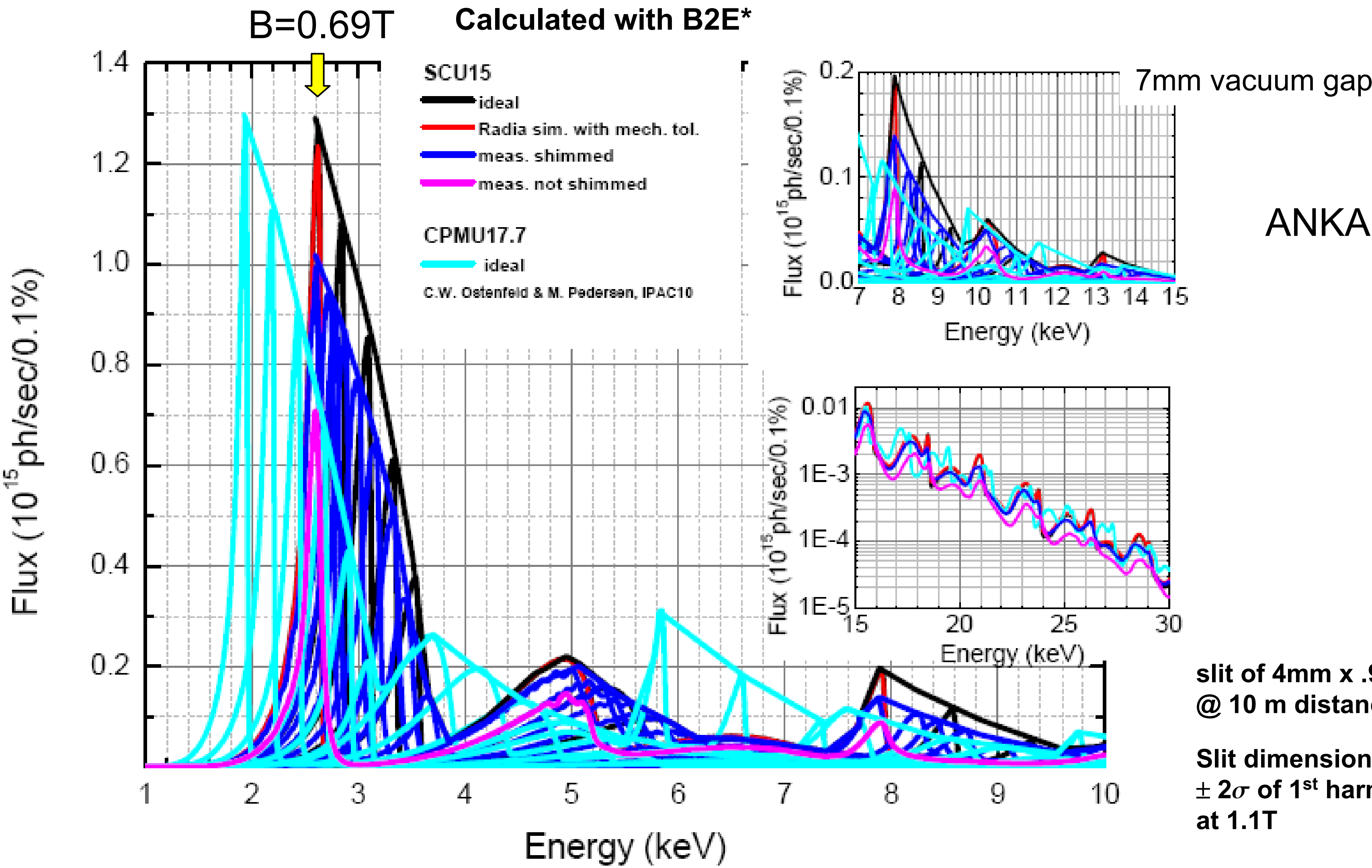
Phase error of 5.6 degrees over a length of ~1.4 m

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

The use of mechanical shims to reduce the bimetallic effect, applicable to fixed gap undulators, together with a planarity further reduced to 40 μm would make it possible to reach 3.5 degrees phase error without additional correction coils.

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

SCU15 demonstrator: spectral performance



ANKA

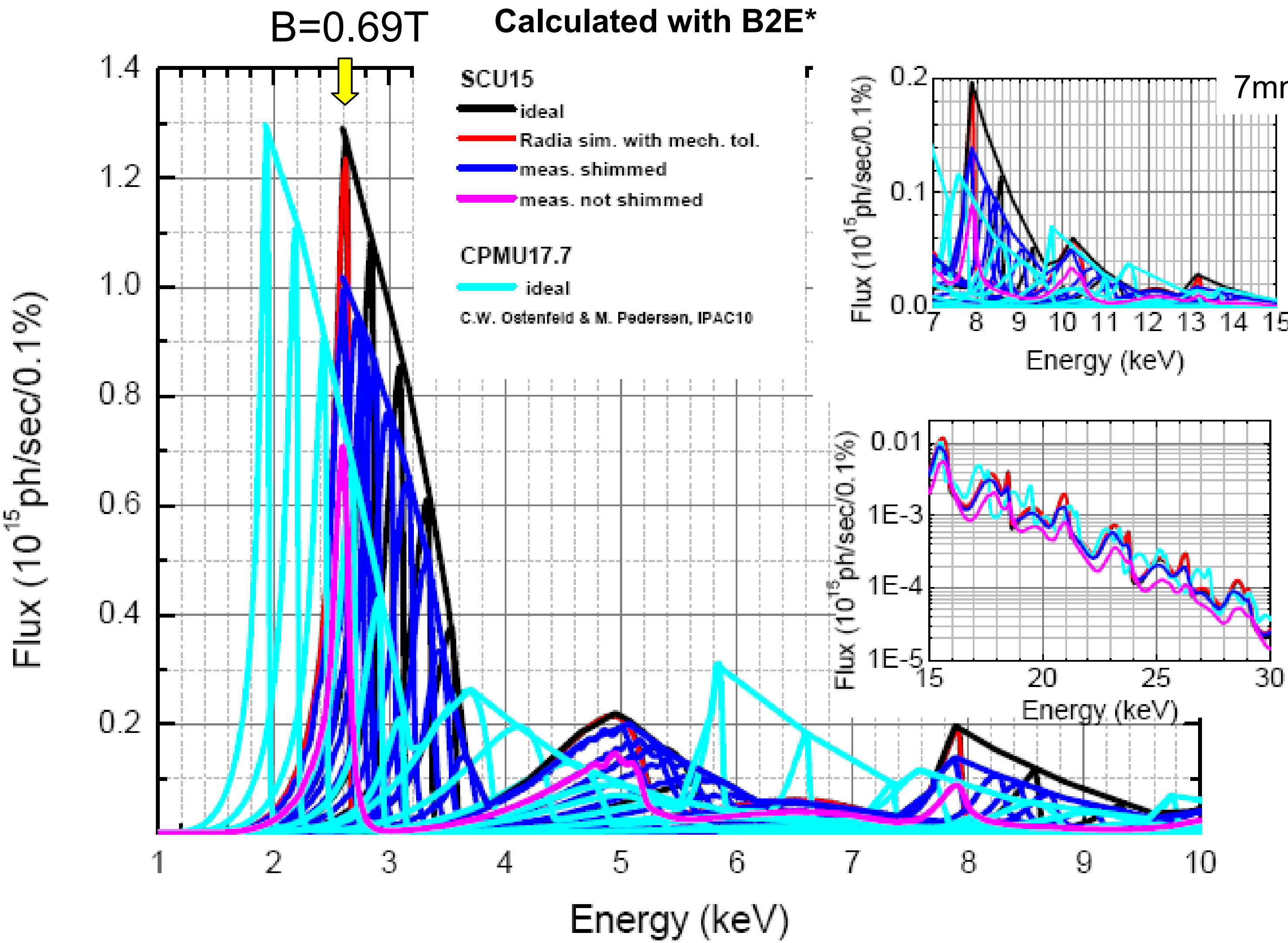
slit of 4mm x .9mm @ 10 m distance

Slit dimensions: $\pm 2\sigma$ of 1st harmonic at 1.1T

***P. Elleaume, X. Marechal, Report ESRF-R/ID-9154 (1991)**

S.C. et al., to appear in IPAC12

SCU15 demonstrator: spectral performance



7mm vacuum gap

ANKA

slit of 4mm x .9mm @ 10 m distance

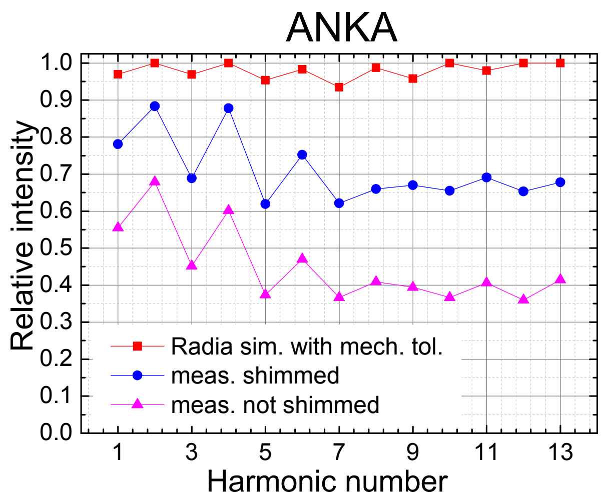
Slit dimensions: ± 2σ of 1st harmonic at 1.1T

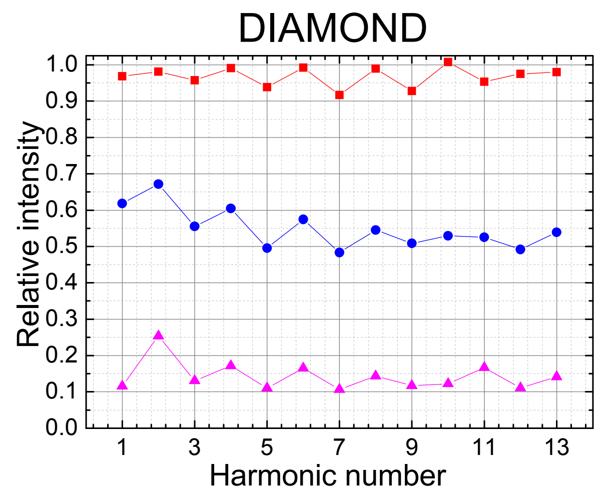
***P. Elleaume, X. Marechal, Report ESRF-R/ID-9154 (1991)**

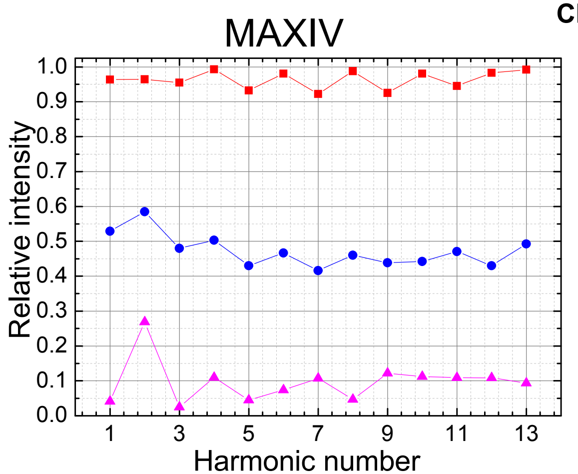
S.C. et al., to appear in IPAC12

SCU15 demonstrator: spectral performance

Ratio of flux of different harmonics to spectrum calculated used ideal field







SCU λu=15mm Nperiods =101
CPMU λu=17.7 mm Nperiods =87

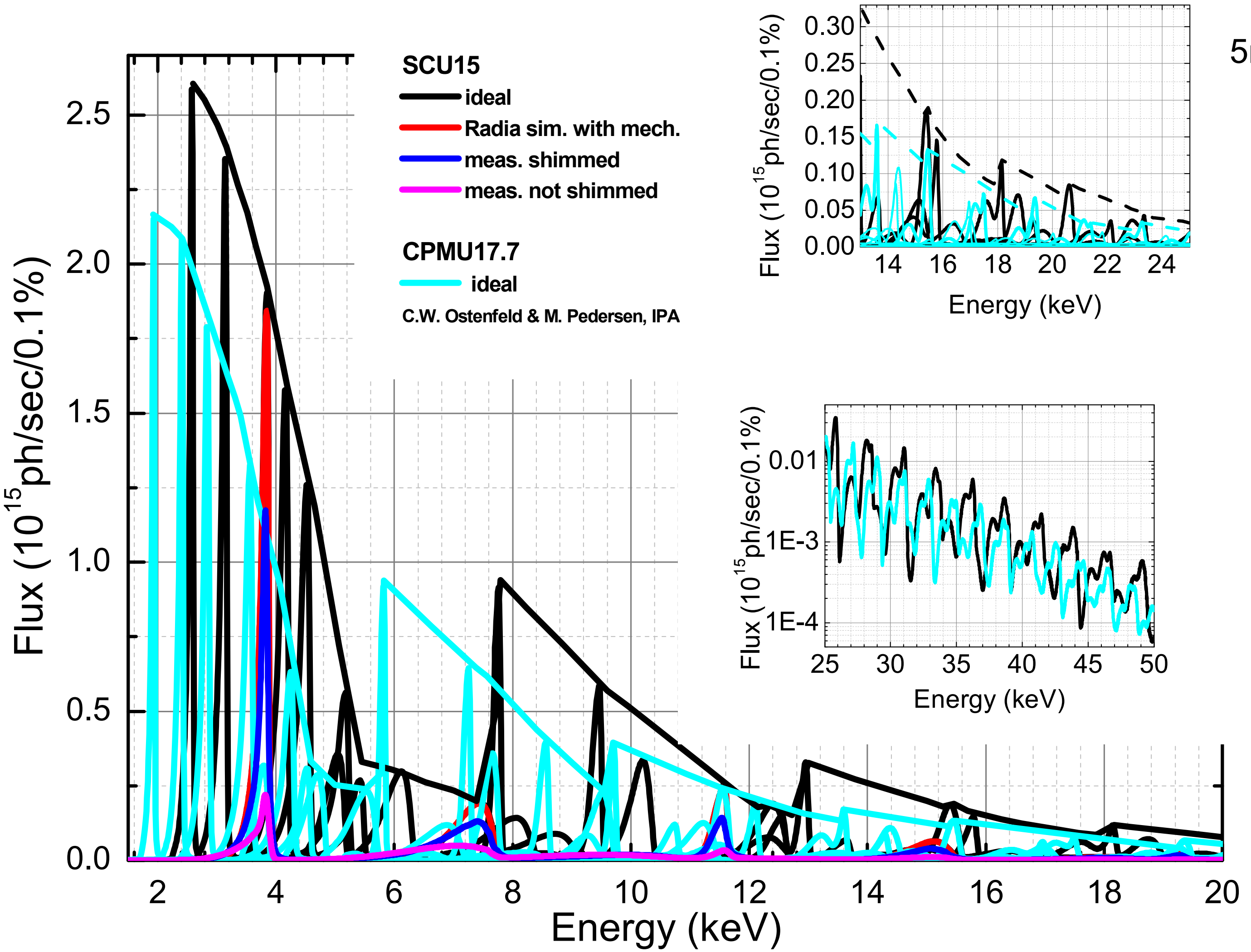
	ANKA*	DIAMOND †	MAXIV**
E (Gev)	2.5	3	3
I (A)	0.2	0.3	0.5
ΔE/E	0.001	0.001	0.001
ϵ_x (nm rad)	41	2.7	0.26
ϵ_y (nm rad)	0.3	0.27	0.008
β_x (m)	14.7	4.8	9
β_y (m)	1.93	1.43	4.8
η_x (m)	0.36	0.07	0
vac. Gap	7	5	4
$Bmax_{SCUideal}$	0.69	1.1	1.4
$Bmax_{CPMUideal}$	0.707	1.04	1.263

*** A. S. Müller, priv. comm.**
† I. P. S. Martin et al, PAC07
**** S. C. Leemann et al., Phys. Rev. ST Accel. Beams, 12:120701, 2009**

S.C. et al., to appear in IPAC12

SCU15 demonstrator: spectral performance

Calculated with B2E*



5mm vacuum gap

DIAMOND

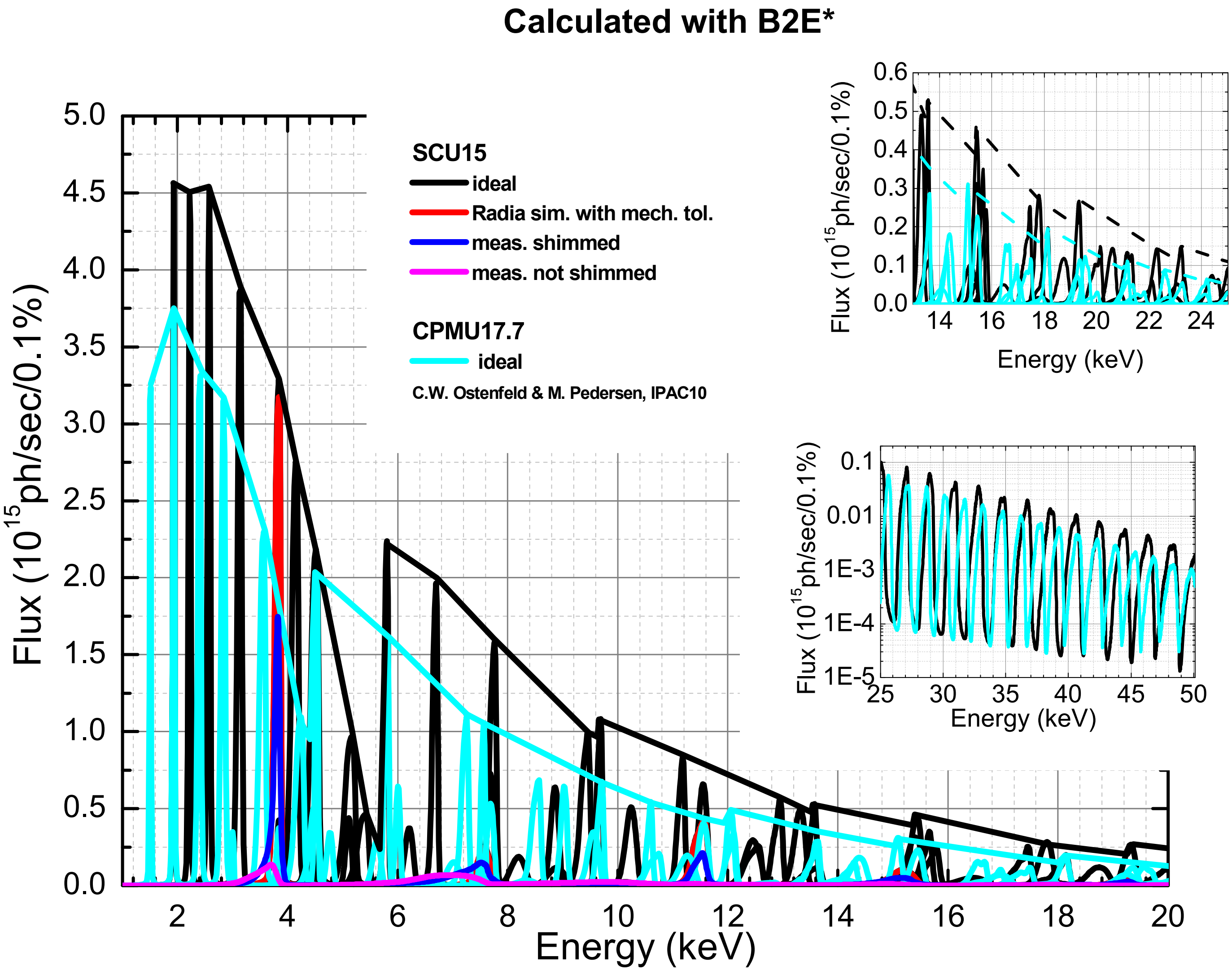
slit of 1.2mm x .6mm @ 10 m distance

Slit dimensions: ± 2σ of 1st harmonic at 1.1T

***P. Elleaume, X. Marechal, Report ESRF-R/ID-9154 (1991)**

S.C. et al., to appear in IPAC12

SCU15 demonstrator: spectral performance



4mm vacuum gap

MAXIV

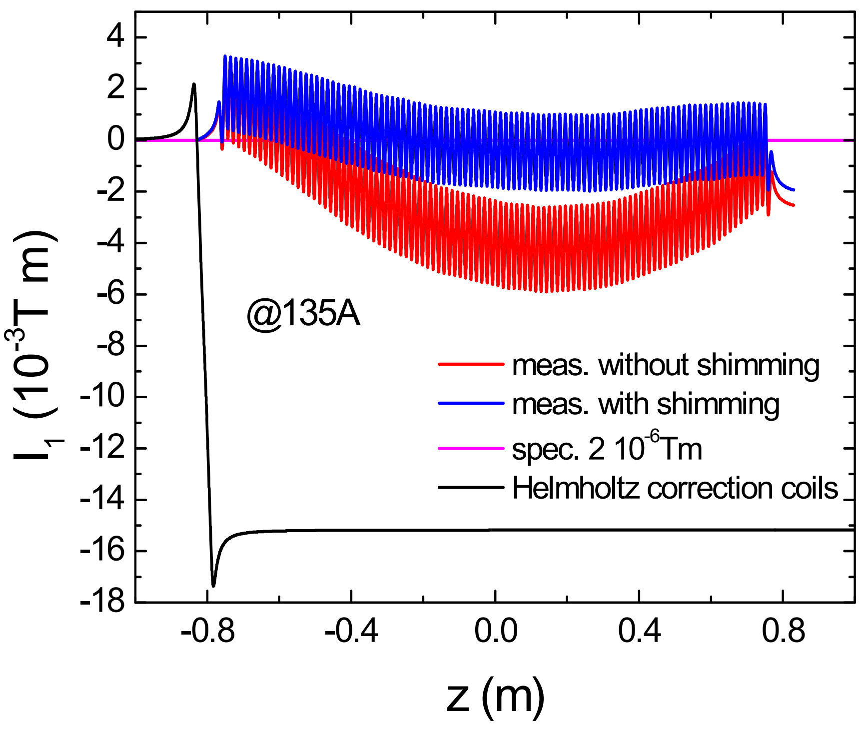
slit of .68 mm x .64 mm @ 10 m distance

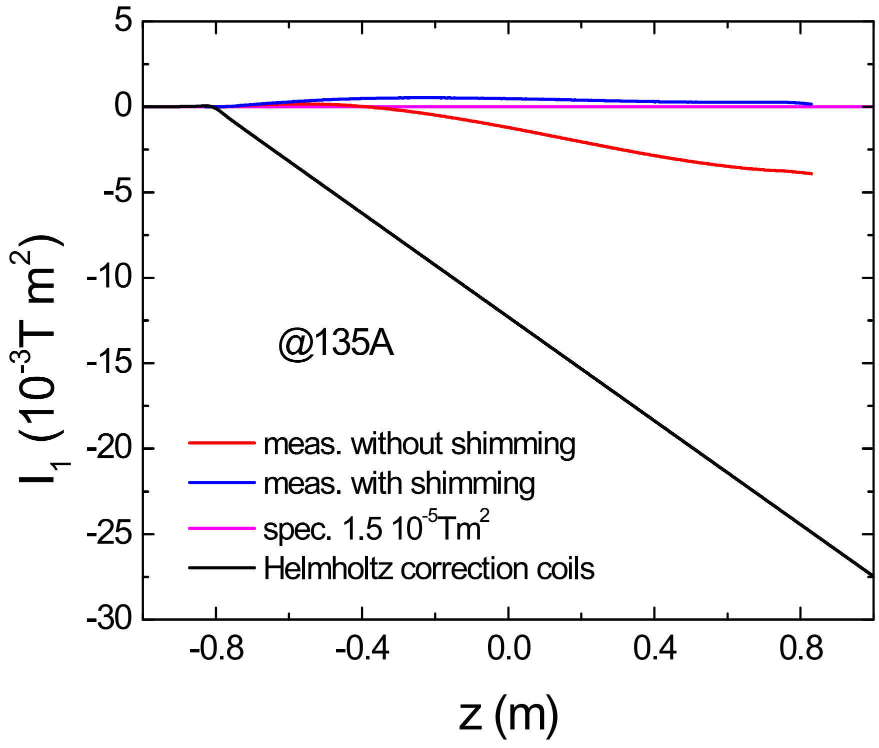
Slit dimensions: $\pm 2\sigma$ of 1st harmonic at 1.4T

***P. Elleaume, X. Marechal, Report ESRF-R/ID-9154 (1991)**

S.C. et al., to appear in IPAC12

SCU15 demostrator: field integrals





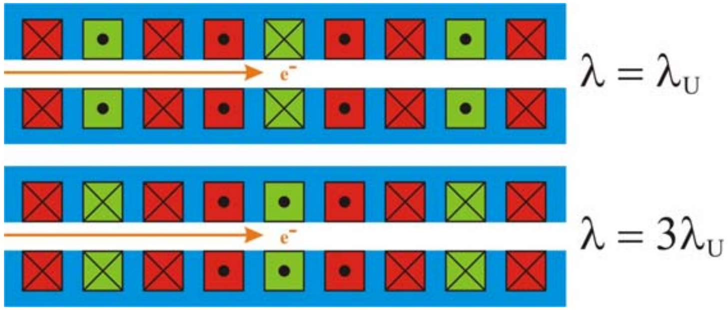
For all currents it is possible to correct the first and second field integrals by means of two pair of Helmholtz coils.

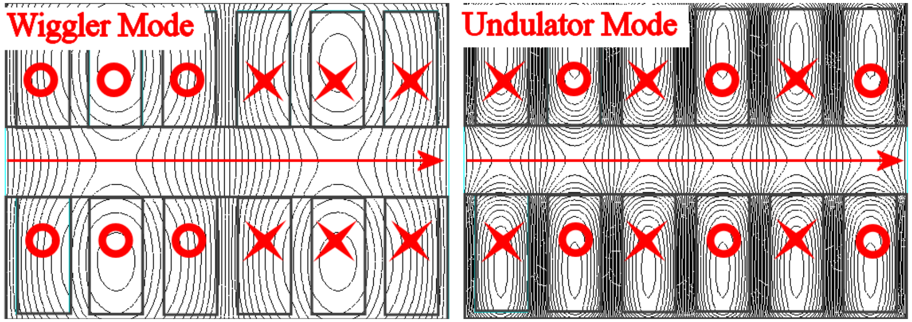
S.C. et al., IEEE Trans. on Appl. Supercond. 1760-1763 Vol. 21-3 (2011)

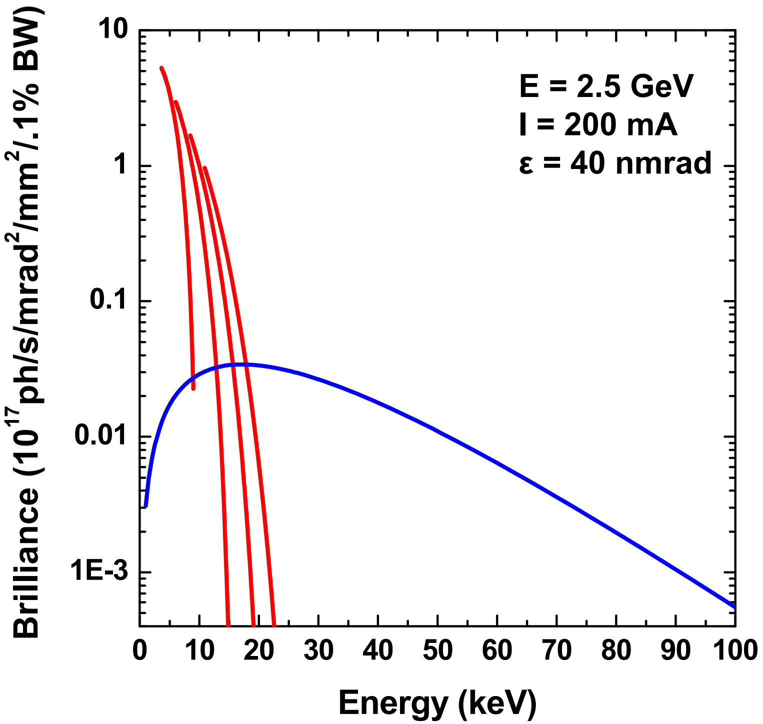
Sc Undulator Wiggler

A device which allows switching between a 18 mm period length undulator and a 54 mm wiggler.

R. Schlueter et al., Synch. Rad. News, 2004
B. Kostka et al., PAC05, 2005
A. Bernhard et al., EPAC06, 2006
A. Bernhard et al., EPAC08, 2008
T. Holubek et al., IPAC11, 2011







Foreseen for the planned IMAGE beamline at ANKA.

Applications:

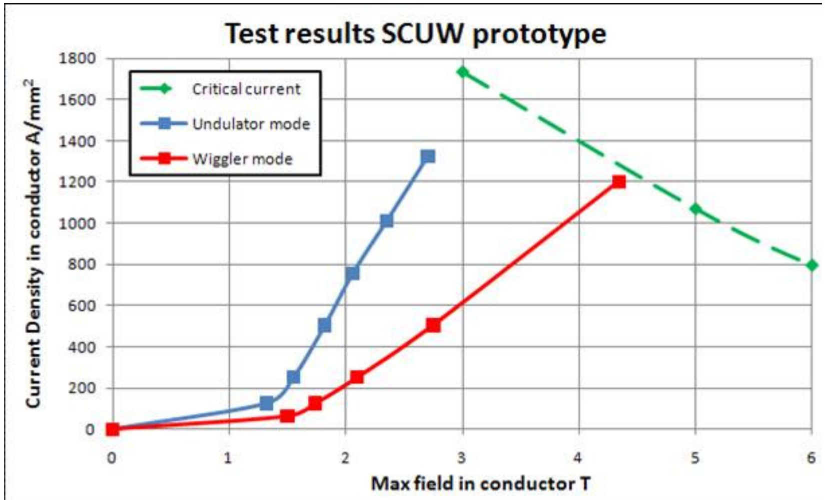
•High brilliance of the **undulator** from 6 to 15 keV for imaging,

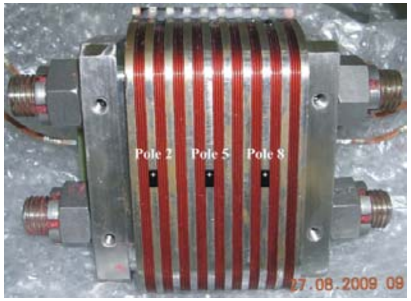
•**wiggler** mode for higher photon energies to perform phase contrast tomography.

Sc Undulator Wiggler

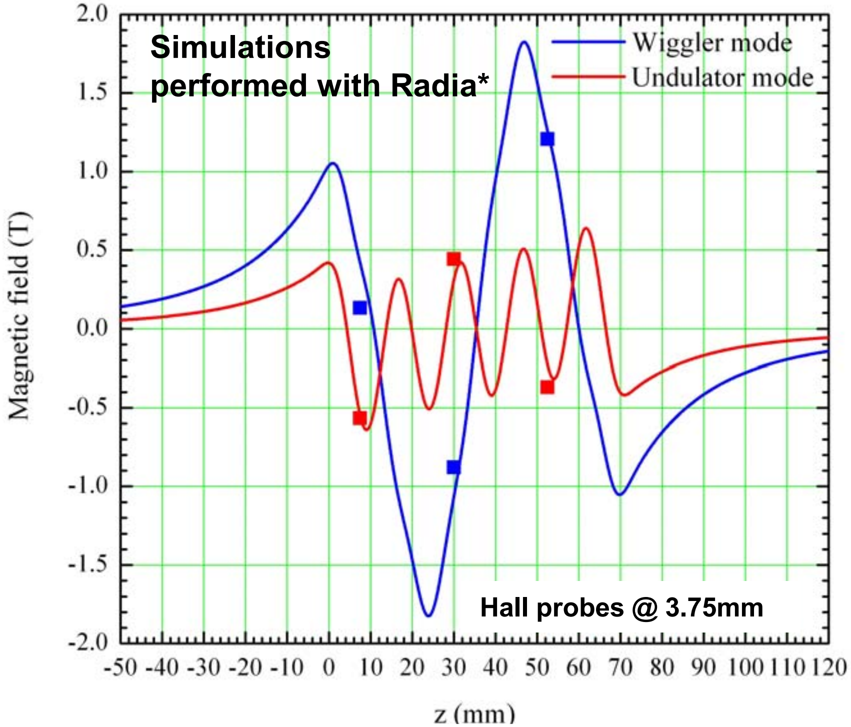
First experimental demonstration of period length switching for scIDs

Training





Built by BNG



	undulator		wiggler	
Mag. Gap	B (T)	K	B(T)	K
8 mm	0.77	1.08	3.00	12.6
5 mm	1.46	2.05	4.34	18.2

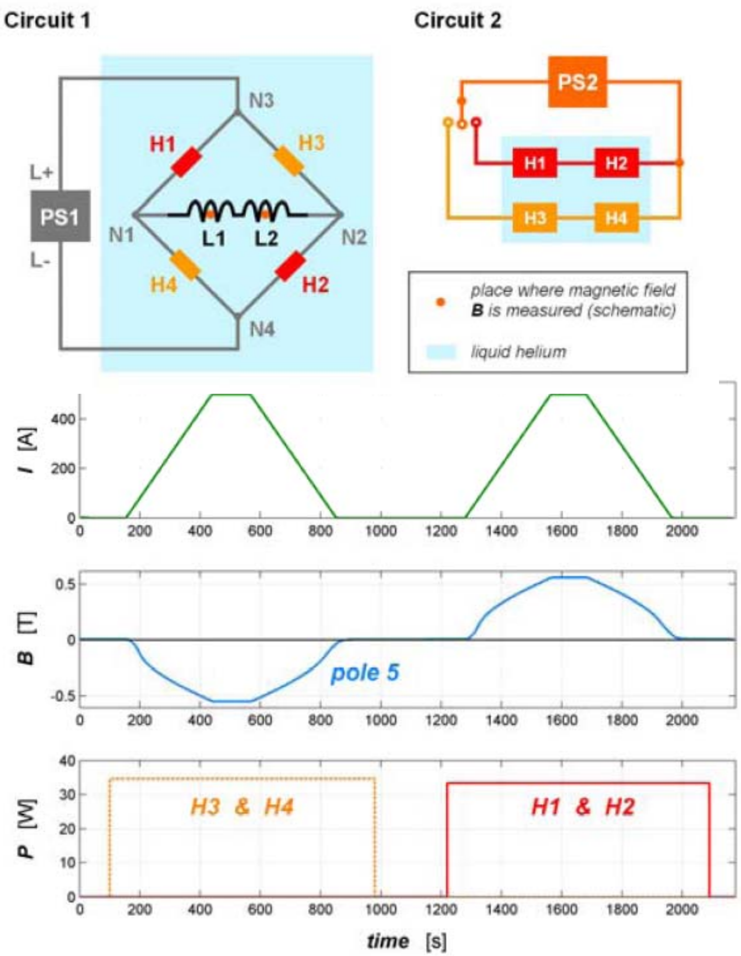
A. Grau et al., IEEE Trans. on Appl. Supercond. 1596-1599 Vol. 21-3 (2011)
*P. Elleaume, O. Chubar, J. Chavanne, PAC97

Sc Undulator Wiggler: Superconducting switch

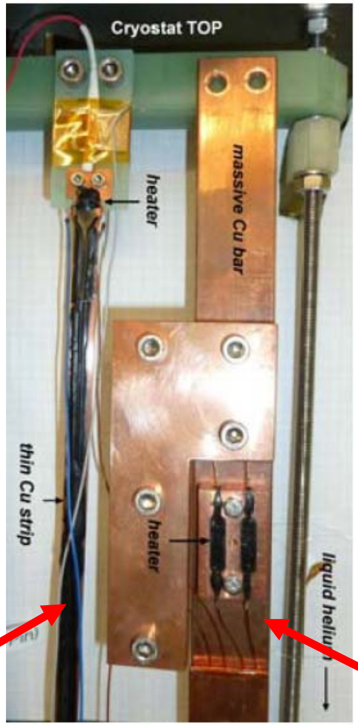
To use only one power supply instead of two for the two circuits, reducing the thermal input to the device

In liquid helium

Reproduced results of A. Madur et al., FEL2009



Conduction cooled



250 mW

11W

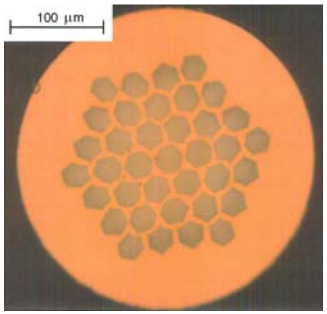
CASPERI

T. Holubek et al., IPAC11, 2011

Additional tests ongoing

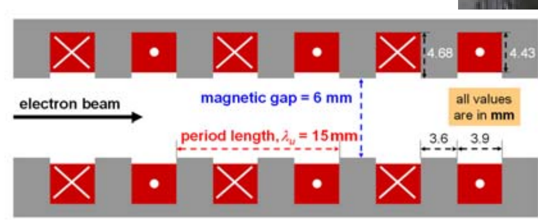
New materials: NbTi with artificial pinning centers wire

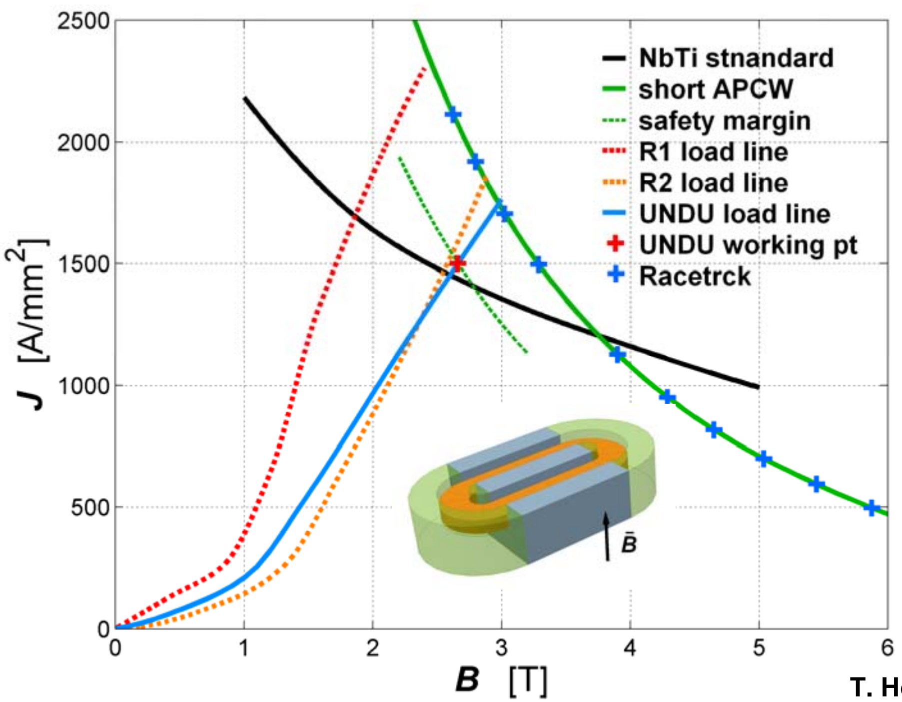
ANKA collaboration with ITeP (Th. Schneider and M. Kläser, KIT) and SupraMagnetics, Inc., USA

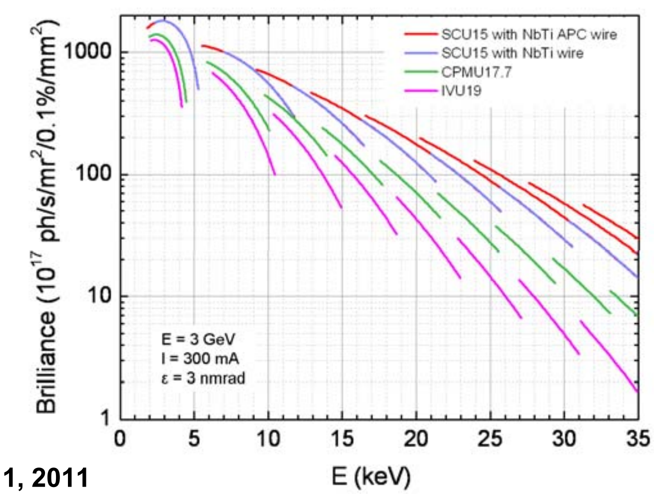


NbTi with artificial pinning centers wire developed by SupraMagnetics, Inc., USA:
outer diameter = 0.31 mm
Including insulation = 30 µm,
Cu/SC= 2.125
37 filaments with diameter = 21 µm

Racetrack loadline and wire critical current density measured at JUMBO (ITeP, KIT)





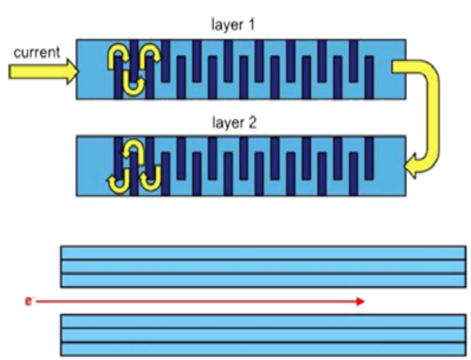


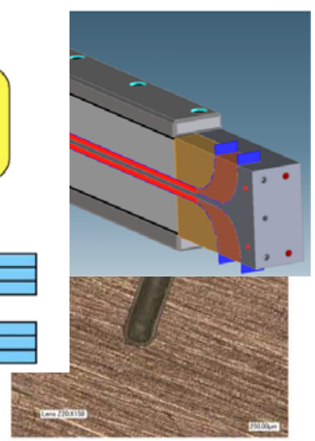
T. Holubek et al., IPAC11, 2011

New materials: HTS tape

- The engineering current density of commercial HTS materials is rapidly increasing in performance making them more and more attractive, so that they could be competitive with NbTi.
- HTS tapes can be operated at higher temperatures than NbTi allowing to sustain higher beam heat loads, and therefore simplifying the cryostat design for the final device.
- High mechanical accuracy required for SC undulators in light sources exclude application of Nb_3Sn coils with actual technology, that requires heat treatment after winding
- Two concepts of application of HTS tapes to produce a sinusoidal field have been so far proposed:

HTS tape stacked undulator

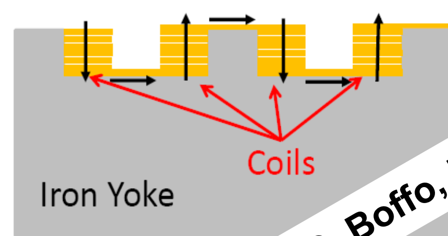


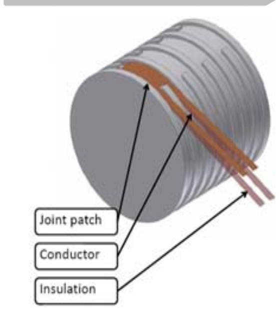


Etched using lithography techniques

S. Prestemon et al., IEEE Trans. on Appl. Supercond. 1880-1883 Vol. 21-3 (2011)

HTS tape planar undulator





with Superpower 2G HTS wire

http://www.maxlab.lu.se/usermeeting/2010/sessions/

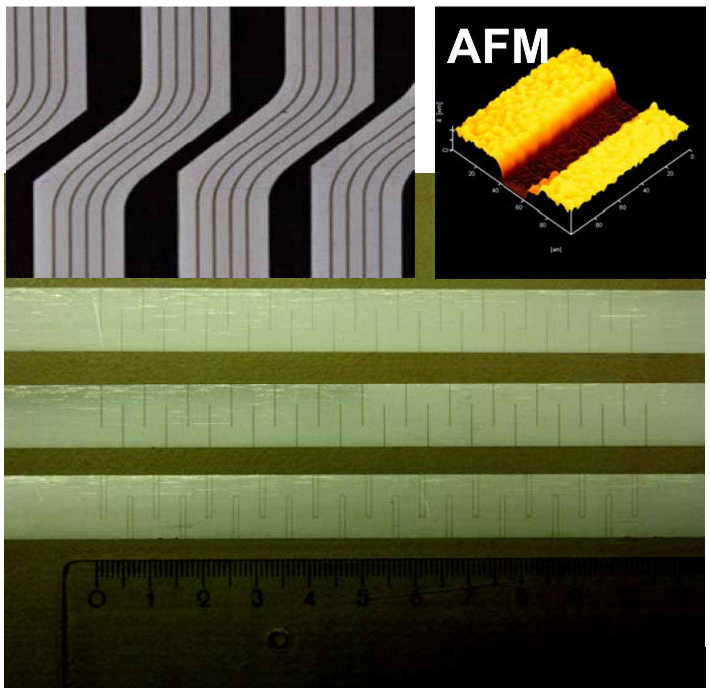
New materials: HTS tape

HTS tape stacked undulator

KIT internal collaboration:
ANKA with ITeP (W. Goldacker)

Etching using Trumpf picosec YAG - IR laser, programmable beam control used for Roebel cables

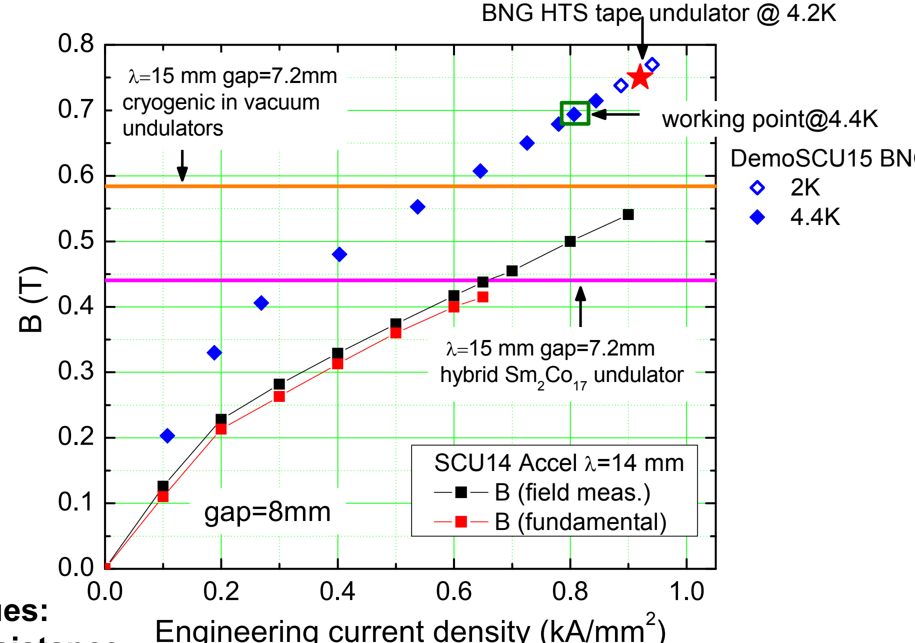
Groove formation very reliable applying laser grooving
No contamination of groove detected (SEM)



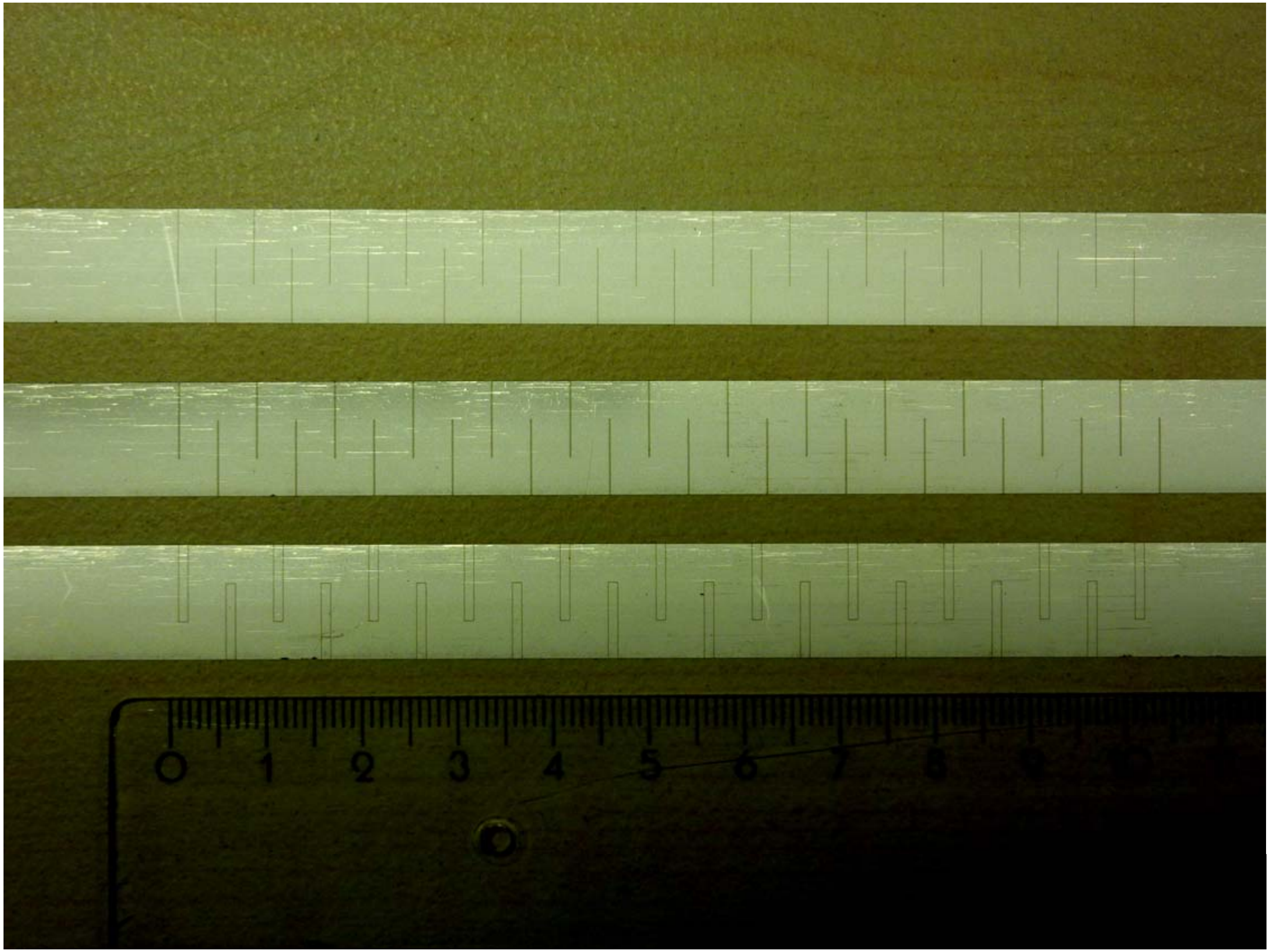
HTS tape planar undulator

Babcock Noell Gmbh (BNG)
HTS tape planar undulator mockup: results of test at CASPERI (KIT)

Maximum current 555 A ⟹ I = 0.92 kA/mm²



Open issues:
- **Joints resistance**
- **Quench detection and protection**
- **Test field accuracy**
- **Radiation damage**
- **Engineering current density as a function of the magnetic field, geometry, stress**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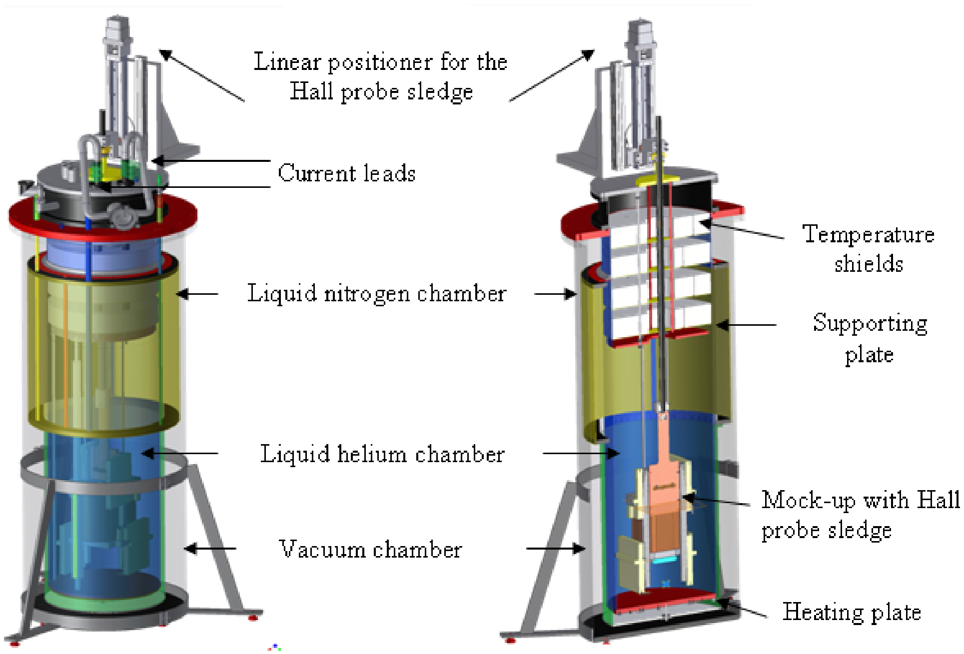
Tools and instruments for R&D: CASPERI

To test:
- **New winding schemes**
- **New superconducting materials and wires**
- **New field correction techniques**



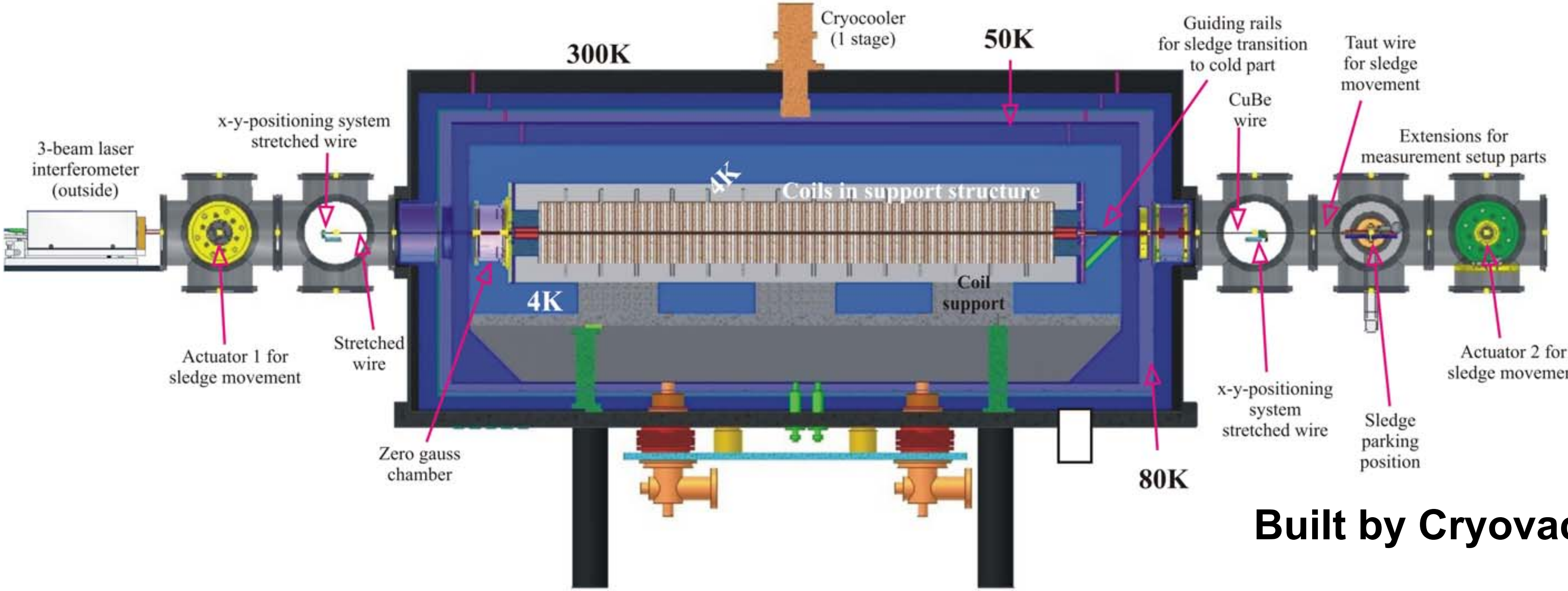
•**Operating vertical test in LHe of mock-up coils** with maximum dimensions 35 cm in length and 30 cm in diameter.

•The magnetic field along the beam axis is measured by Hall probes fixed to a sledge moved by a linear stage with the following precision ΔB< 1mT and Δz< 3 μm.

E. Mashkina et al., EPAC08

Tools and instruments for R&D: CASPERII

For **quality certification** of new sc insertion devices



Built by Cryovac

•**Under construction horizontal cryogen free test of long coils** with maximum dimensions 1.5 m in length and 50 cm in diameter.

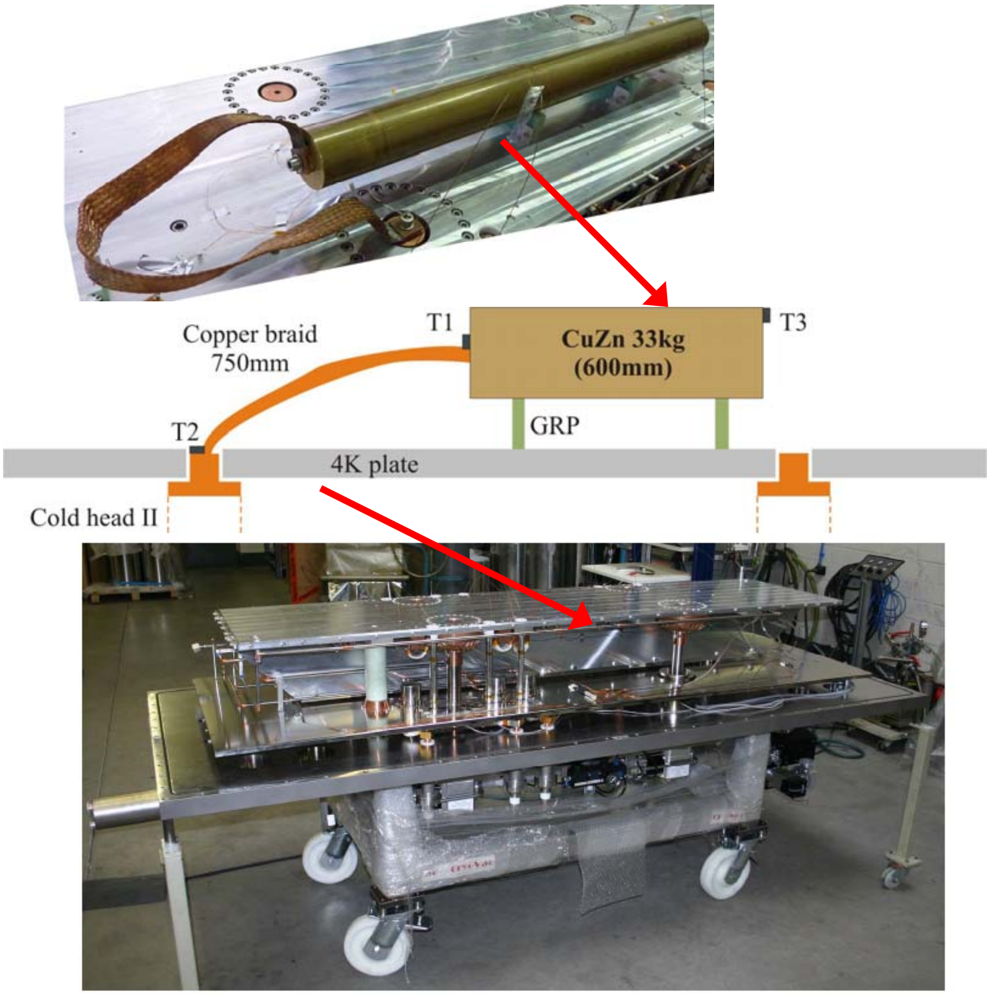
•Local field measurements with Hall probes. Field integral measurements with stretched wire.

The magnetic field along the beam axis is measured by Hall probes fixed to a sledge moved by a linear stage with the following precision $\Delta B < 1mT$ and $\Delta z = 1\ \mu m$.

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

Tools and instruments for R&D: CASPERII

Factory acceptance test

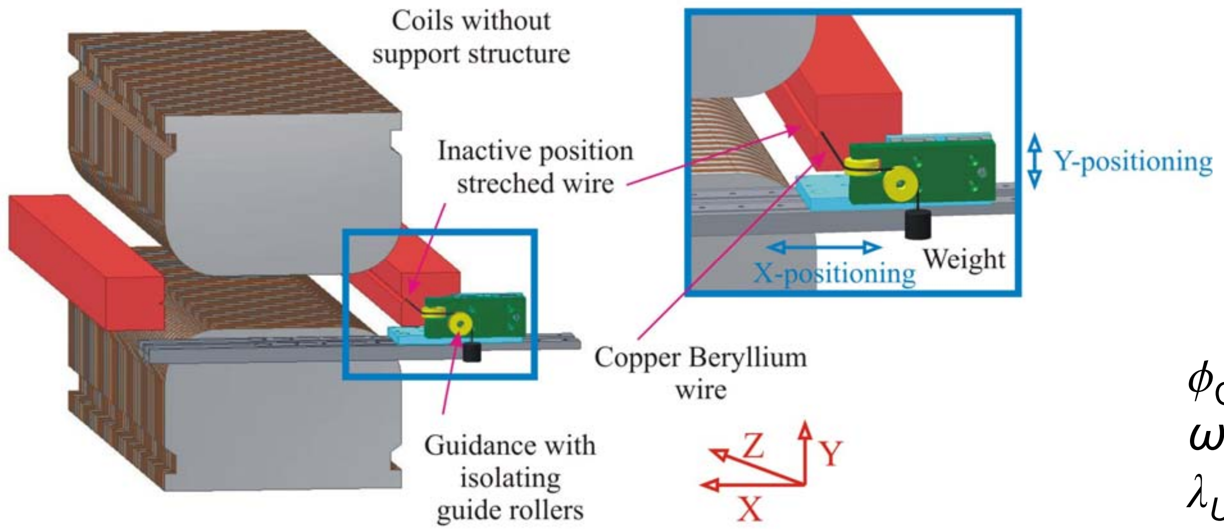


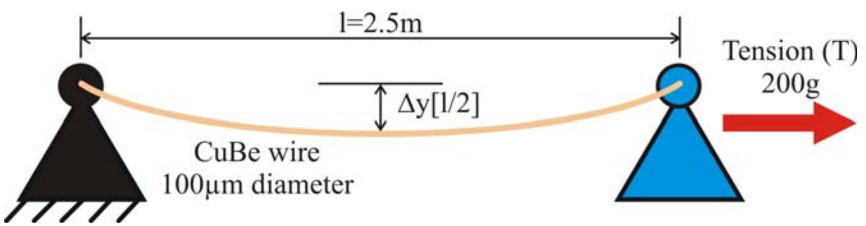
A. Grau et al., MT22, 2011

Component	Specified value	Reached value
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

Tools and instruments for R&D: CASPERII

Integral field measurements with stretched wire





ϕ_{CuBe}=100 µm
ω_{CuBe}=0.064g/m
λ_U=0.015m

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

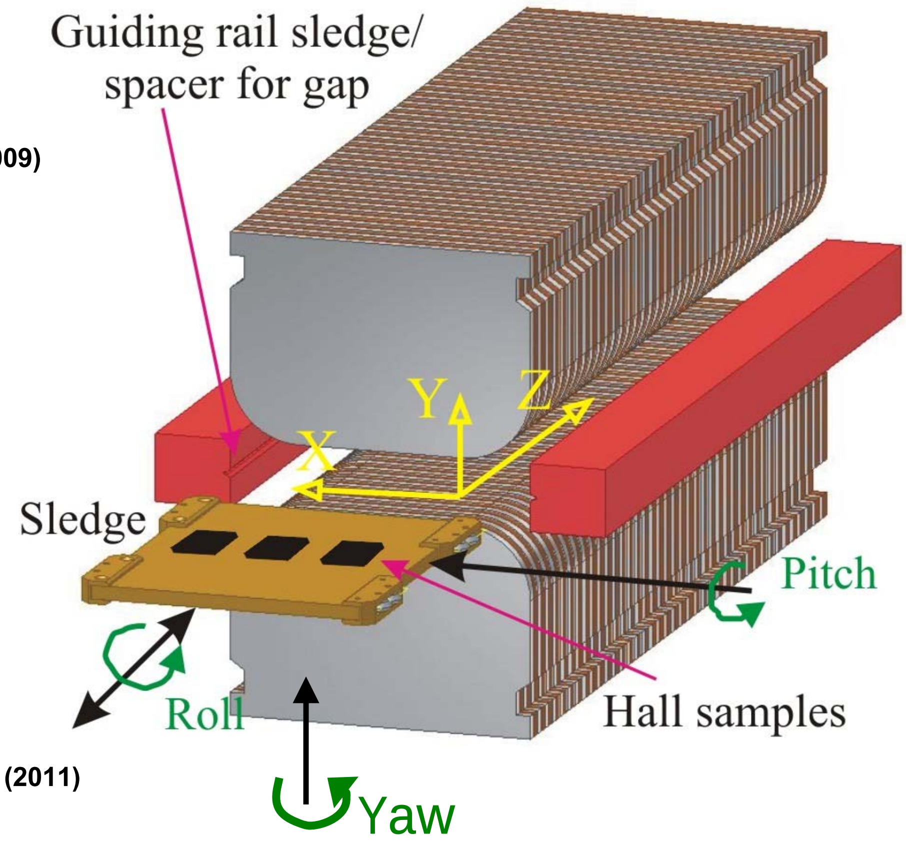
$$\frac{\Delta I_y}{I_y} \approx \frac{1}{2}\left(\frac{2\pi}{\lambda_U}\right)^2 \cosh\left(\frac{2\pi}{\lambda_U}\Delta y\right)(\Delta y)^2 \approx 5\times 10^{-3}.$$

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

Tools and instruments for R&D: CASPERII

Local field measurements with Hall probes

Mechanical requirements to reach measurement accuracy for phase error
A.Grau et al., IEEE Trans. App. Supercond. 2333- 2336 Vol. 19-3 (2009)
$\Delta\phi$ = 1° (λ_U=15mm, K=2):
Δx = 400 µm
Δ y = 50 µm
Δ z = 5 µm
roll = 1 mrad
yaw= 1 mrad
pitch = 30 mrad



Relative longitudinal position of Hall probes measured with laser interferometer with 1µm accuracy.

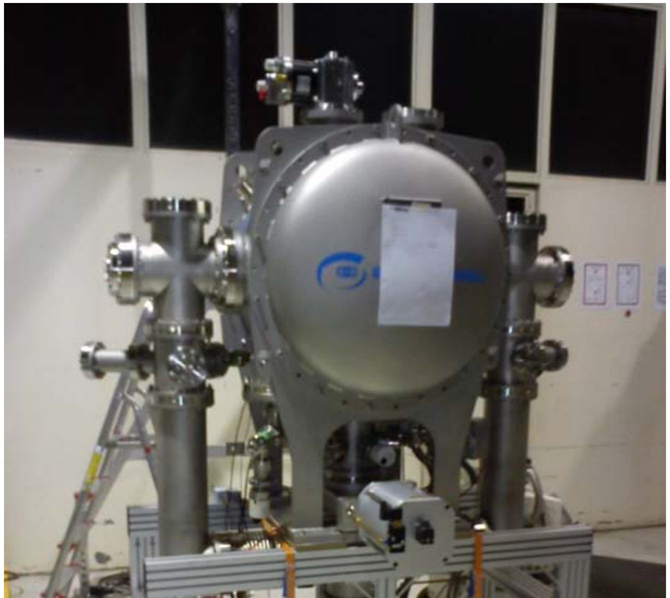
A. Grau et al., IEEE Trans. on Appl. Supercond. 2312-2315 Vol. 21-3 (2011)

For more details see
http://immw17.cells.es/presentations/Mon02-IMMW17-AGrau.pdf

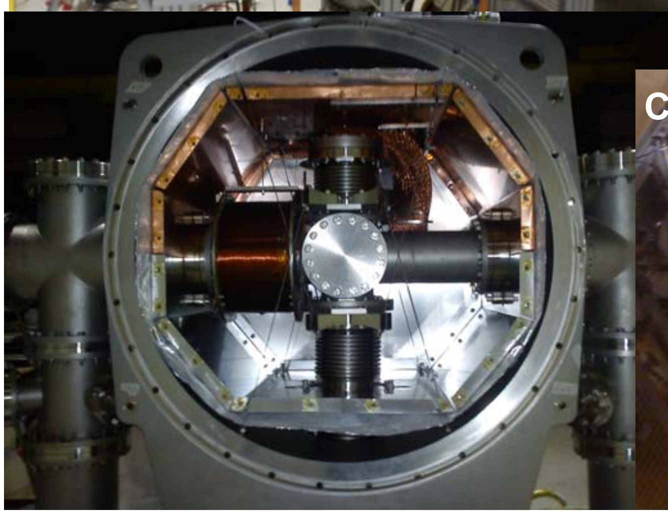
Tools and instruments for R&D: COLDDIAG

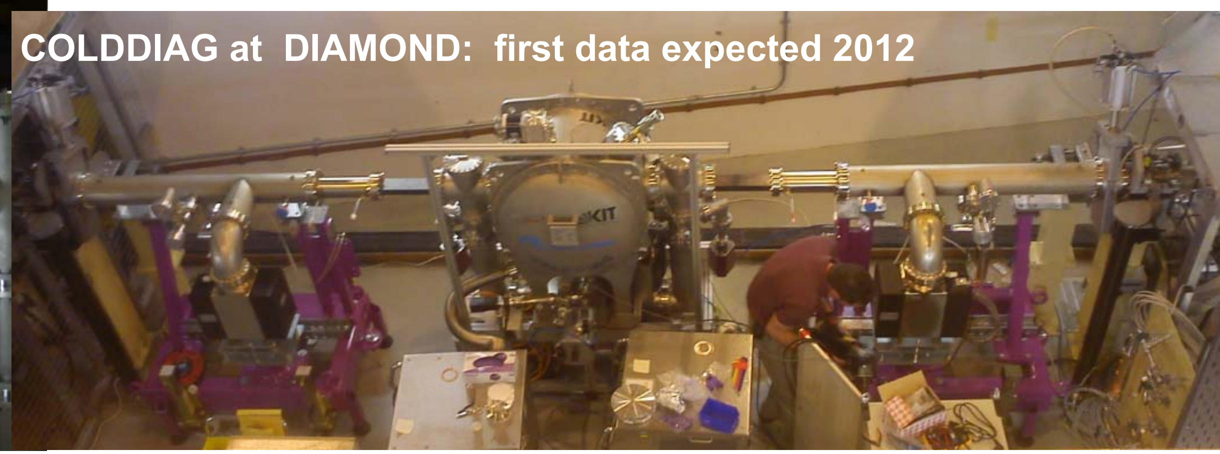
Karlsruhe Institute of Technology

Cold vacuum chamber for diagnostics to **measure the beam heat load** to a cold bore in a storage ring. The beam heat load is needed to specify the cooling power for the cryodesign of superconducting insertion devices.



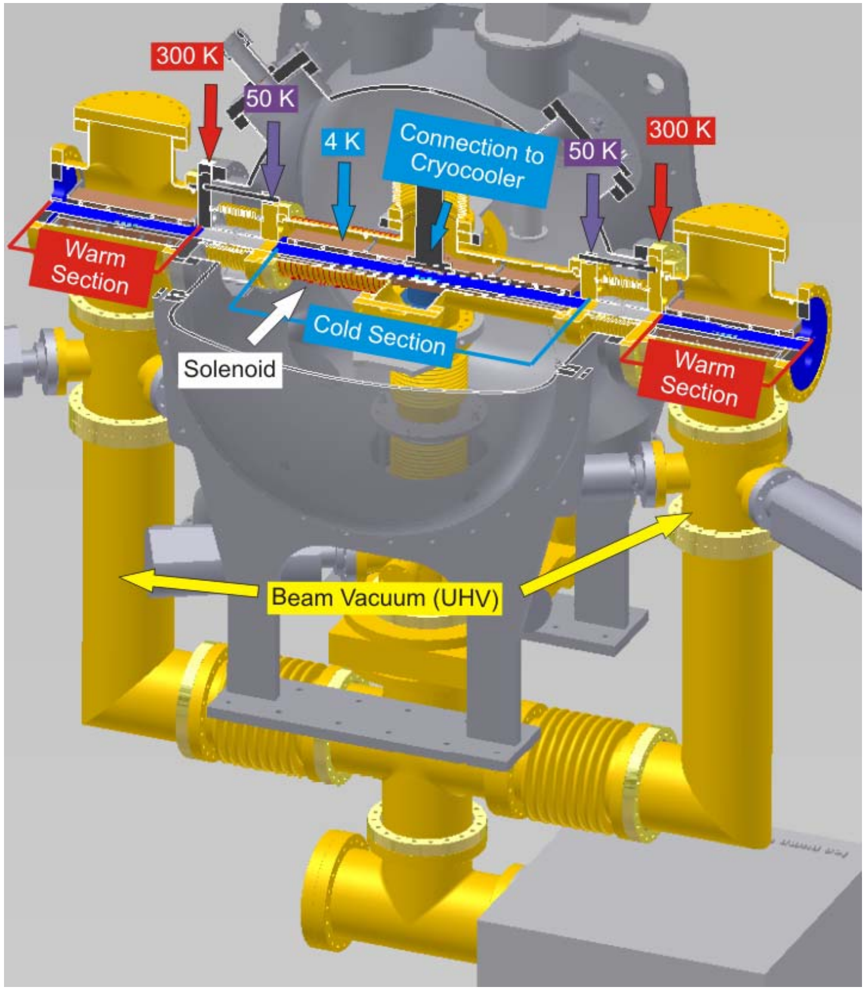
In collaboration with
CERN: V. Baglin
LNF: R. Cimino, B. Spataro
University of Rome ‚La sapienza‘: M. Migliorati
DIAMOND: R. Bartolini, M. Cox, G. Rehm, J. Schouten, R. Walker
MAXLAB : Erik Wallèn
STFC/DL/ASTeC: J. Clarke
STFC/RAL: T. Bradshaw
University of Manchester: I. Shinton





Tools and instruments for R&D: COLDDIAG

The vacuum chamber



- Cryogen free: cooling with Sumitomo RDK-415D cryocooler (1.5W@4.2K)
- Cold vacuum chamber located between two warm sections to compare beam heat load with and without cryosorbed gas layer
- 3 identically equipped diagnostic ports with room temperature connection to the beam vacuum
- Exchangeable liner to test different materials and geometries
- Copper bar copper plated (50µm)

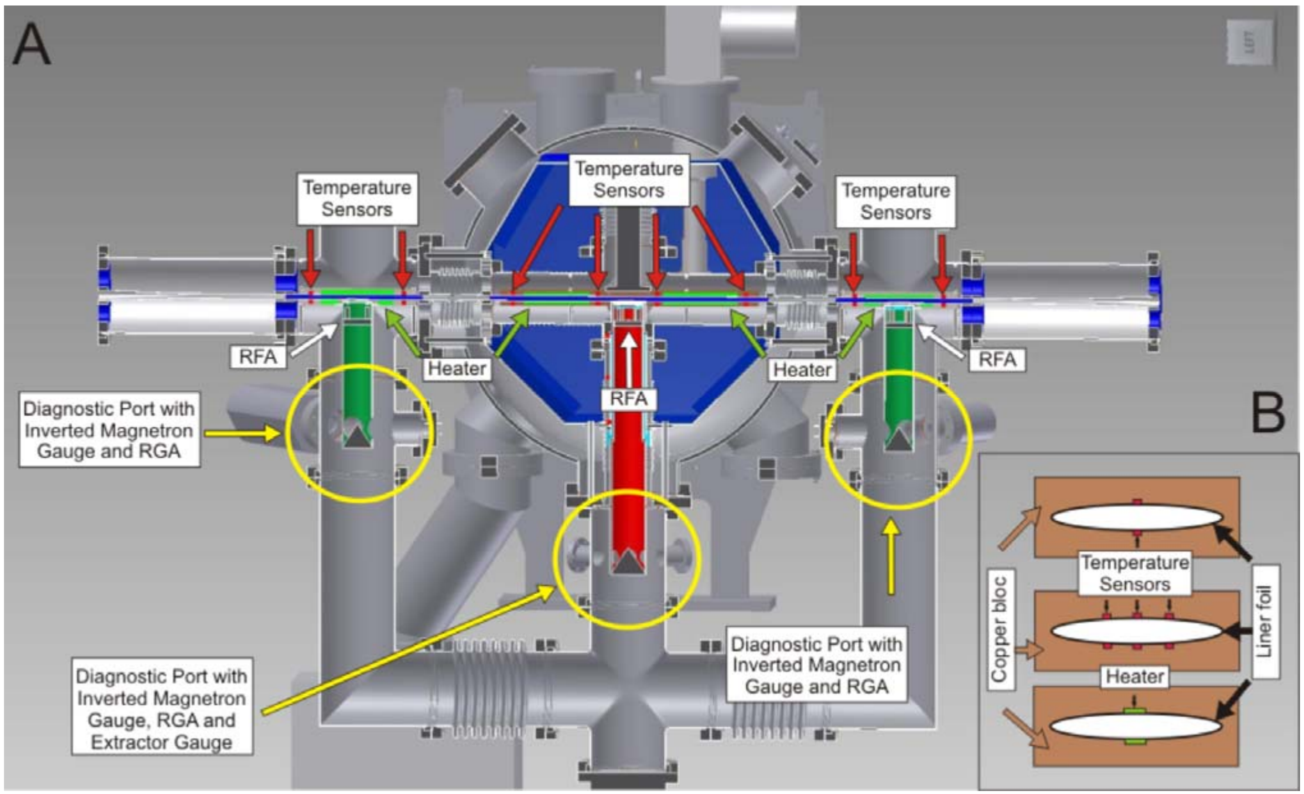
S.C. et al., IEEE Trans. on Appl. Supercond. 2300-2303 Vol. 21-3 (2011)

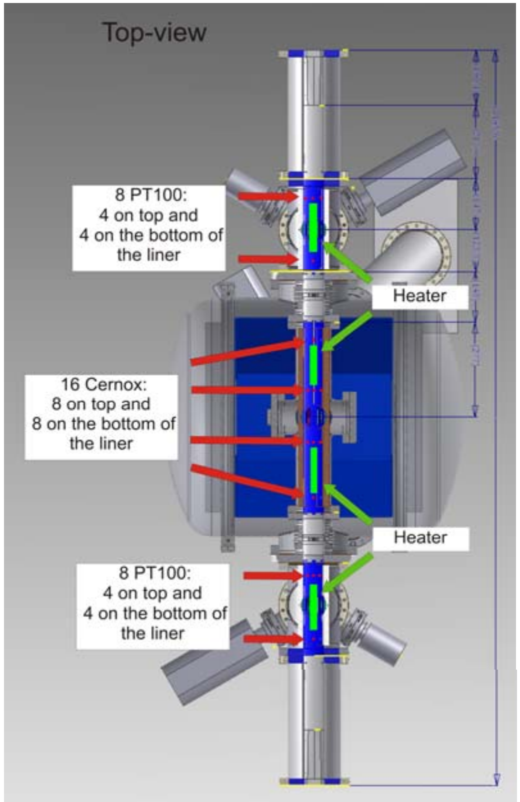
Tools and instruments for R&D: COLDDIAG

KIT Karlsruhe Institute of Technology

Diagnostics

Possible Beam Heat Load Sources: 1) Synchrotron radiation from upstream bending magnet, 2) Resistive wall heating, 3) RF effects, 4) Electron and/ or ion bombardment



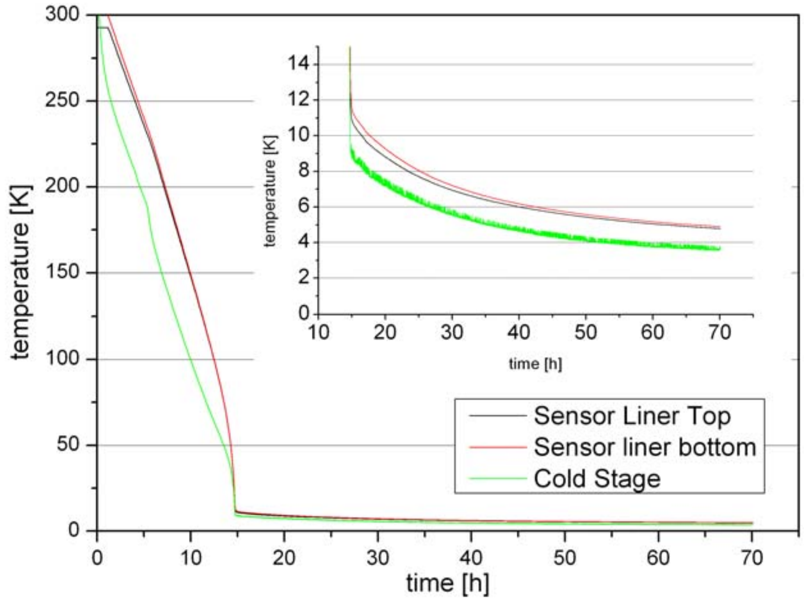


The diagnostics will include measurements of the heat load, the pressure, the gas composition, and the electron flux of the electrons bombarding the wall.

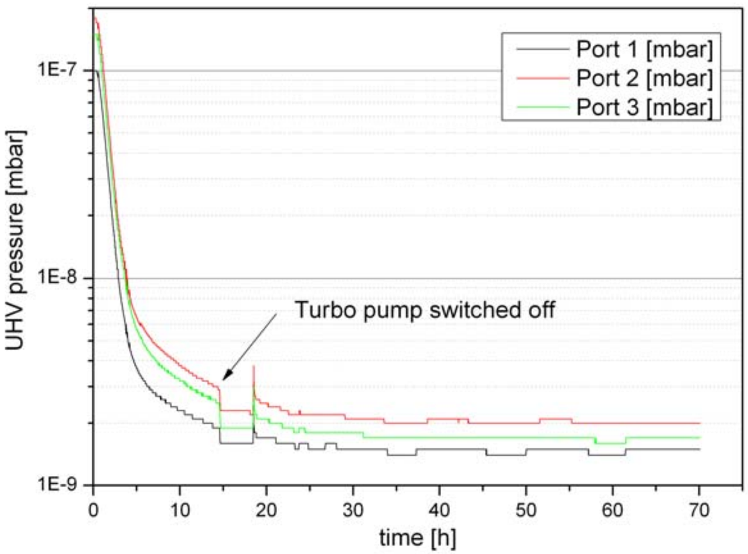
S.C. et al., IEEE Trans. on Appl. Supercond. 2300-2303 Vol. 21-3 (2011)

Tools and instruments for R&D: COLDDIAG

Factory acceptance test



- **Leakrate UHV:**
  <4.3e-10 mbar
- **Leakrate Insulation Vacuum:**
  <8.1e-9 mbar
- **Lowest Temperature:**
  4.8 K after 87h
- **Pressure at 300 K:**
  <2.0e-7mbar
- **Pressure at 4.8 K:**
  <3.0e-9mbar



S. Gerstl et al., IPAC11, 2011

Tools and instruments for R&D: COLDDIAG

Planned measurements

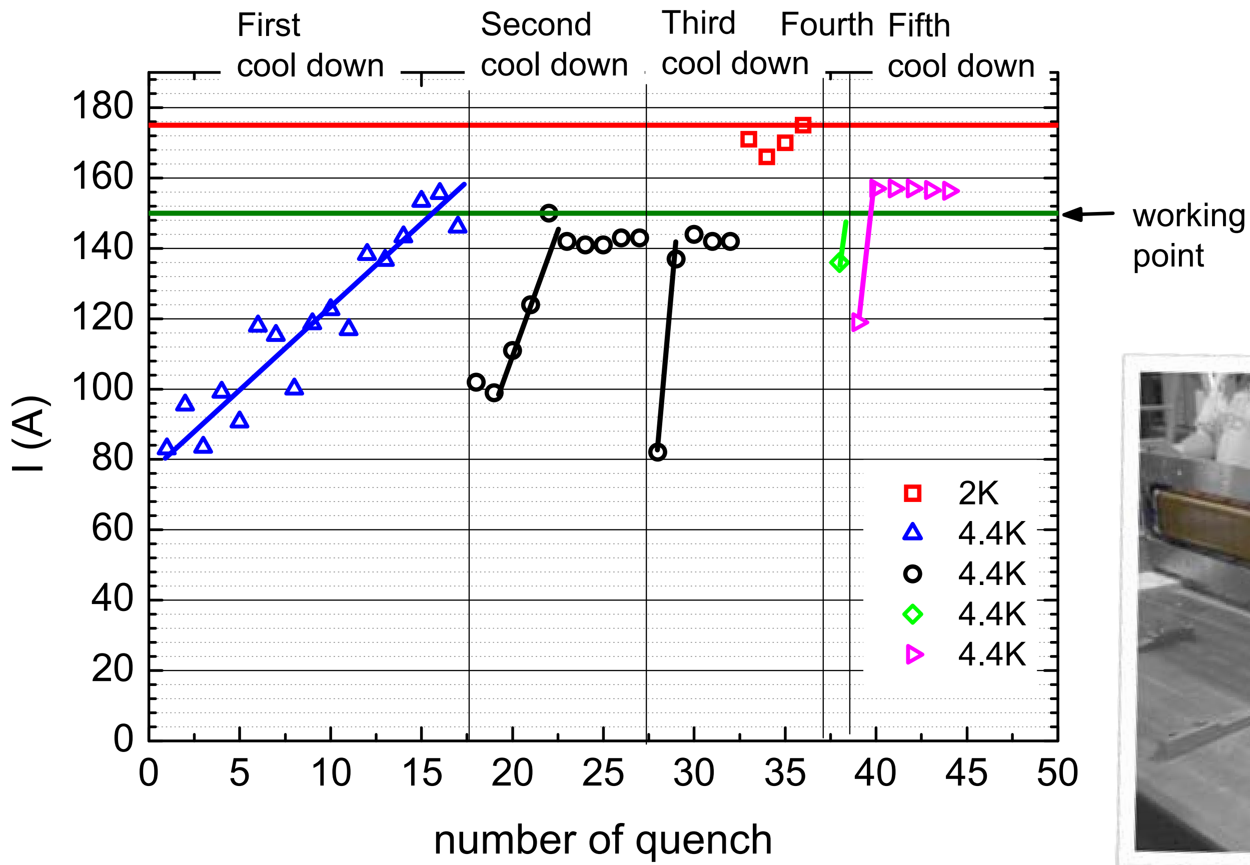
Monitoring the temperature, the electron flux, pressure and gas composition with different:

- **average beam current** to compare the beam heat load data with synchrotron radiation and resistive wall heating predictions
- **bunch length** to compare with resistive wall heating predictions
- **filling pattern** in particular the bunch spacing to test the relevance of the electron cloud as heating mechanism
- **beam position** to test the relevance of synchrotron radiation and the gap dependence of the beam heat load
- **injected gases** naturally present in the beam vacuum (H_2, CO, CO_2, CH_4) to understand the influence of the cryosorbed gas layer on the beam heat load

Backup slides

SCU15 demonstrator: training

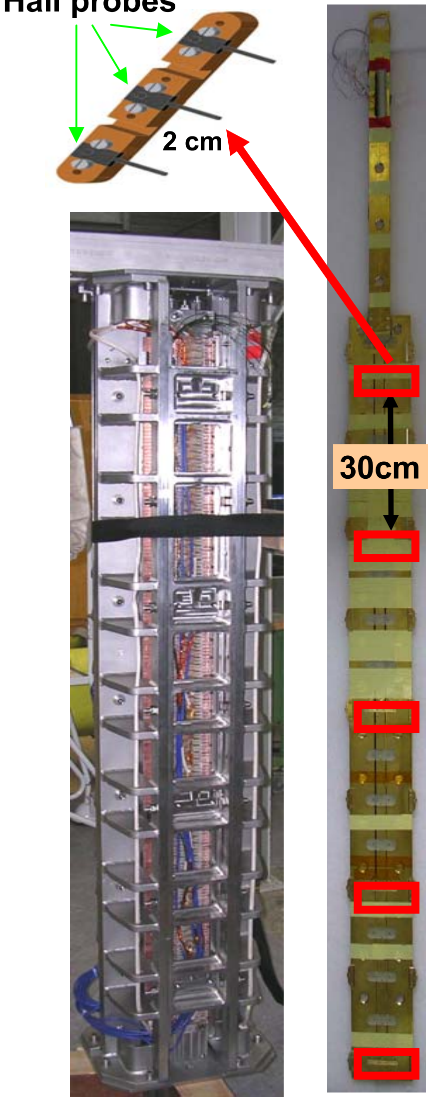
Measured @CERN

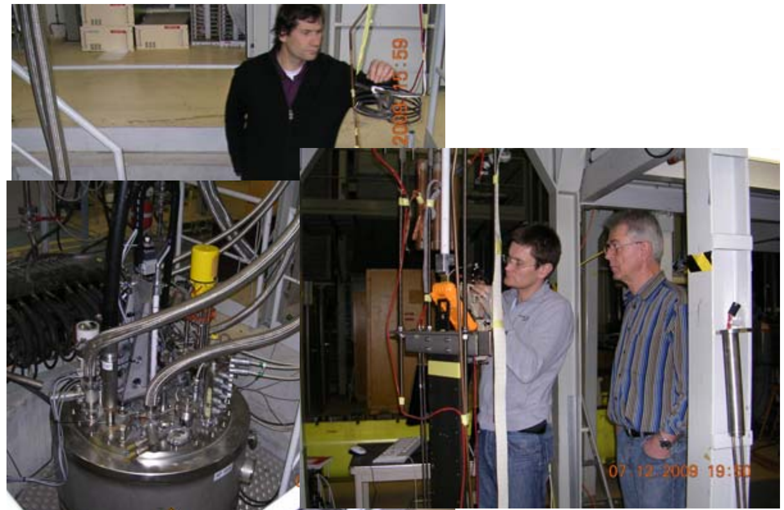


Next devices thicker wire and for the yoke C10E steel.

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

Experimental setup



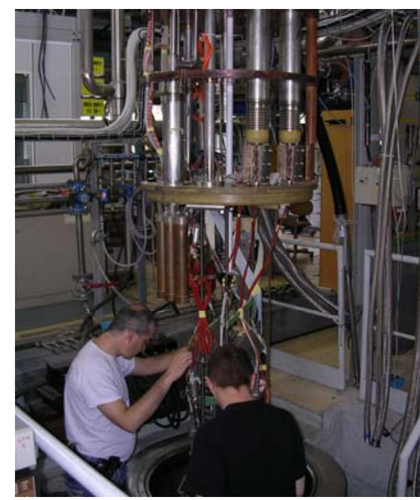


Test sledge 8.12.10

Installation 31.03.10

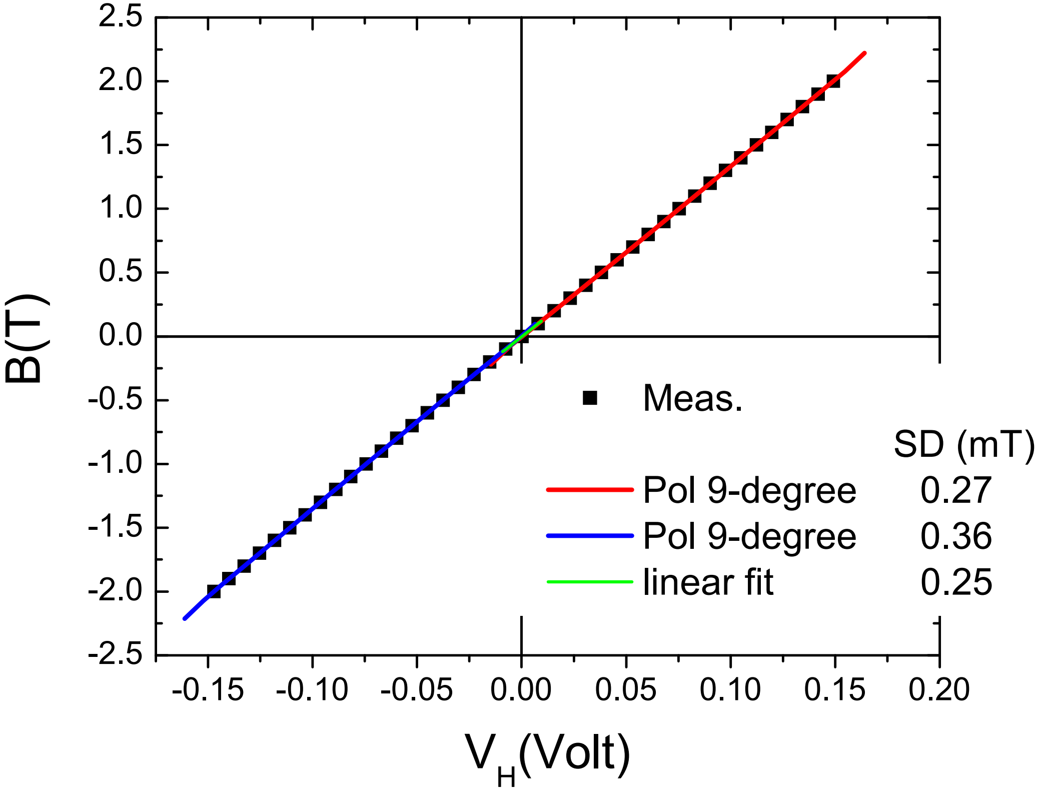
First magnet arrival 12.01.10

Deinstallation 03.05.10



Hall probes calibration

Hall probes calibrated at the Institute of Technical Physics (KIT) in a liquid helium bath in a field -3T<B<3T with homogeneity better then 10^{-4}.



Local phase error induced by calibration of the Hall probes ΔB<1mT:

$$\Delta\Phi = \frac{K^2}{1+K^2}\frac{\Delta B}{B}360^\circ < 0.35^\circ$$

$$K = 93.37\lambda_u B = 1.08$$

$$\lambda_u = 0.015\text{m} \qquad B = 0.77\text{T}$$

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

Design – Cryogenic circuit

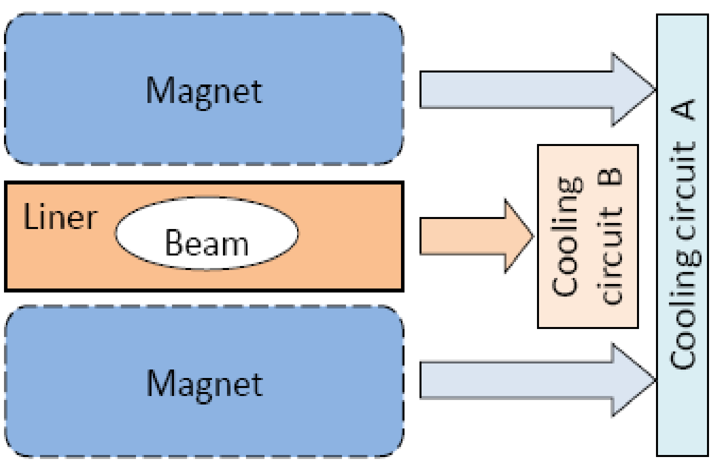
Main concepts:

○ Two separate circuits for magnet and beam liner.

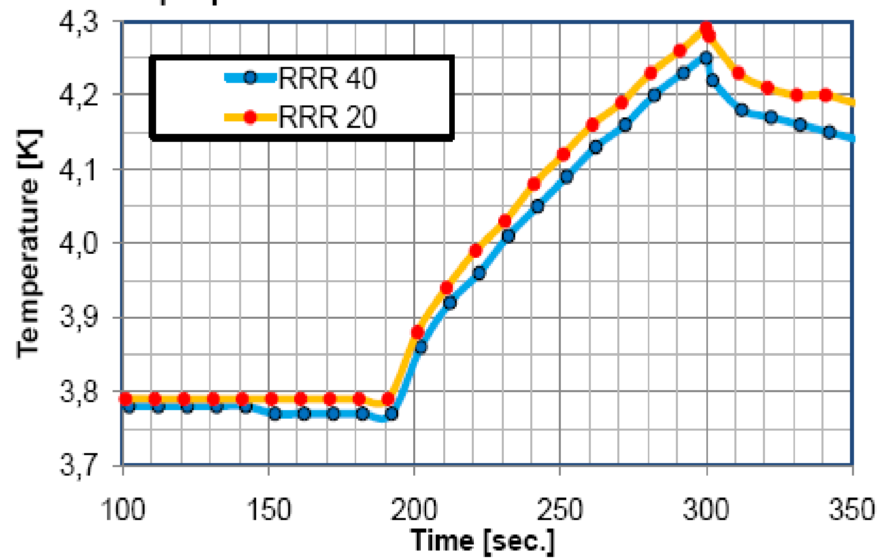
○ Two base temperatures: 4K for the magnet and 10K for the beam liner.

○ Minimization of gradients between cold head and most distant point in the magnet.

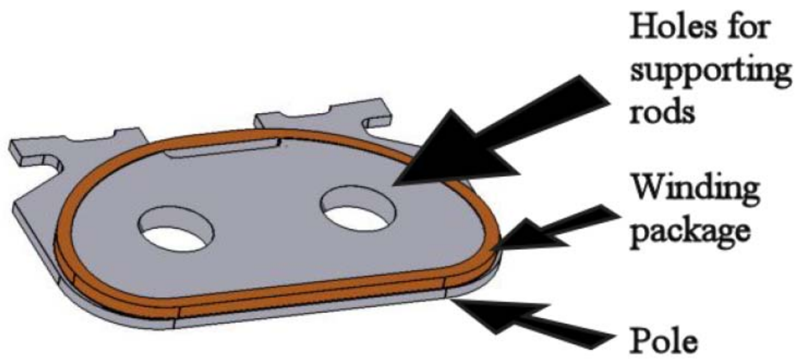
Heta Loads			
	Shield	Circuit B	Circuit A
Radiation	7.93	0.05	
Conduction	21.98	0.53	0.28
Current leads	18.80		0.13
Eddy currents			0.20
Hysteresis			0.14
Coupling SC			1.71
Beam Heat	16	4.00	
TOTAL (W)	64.71	4.58	2.46



Magnet Heating during Ramp -hot spot-
Input power 2.5 W for 100s Init. 0.5W Cu RRR 40/20

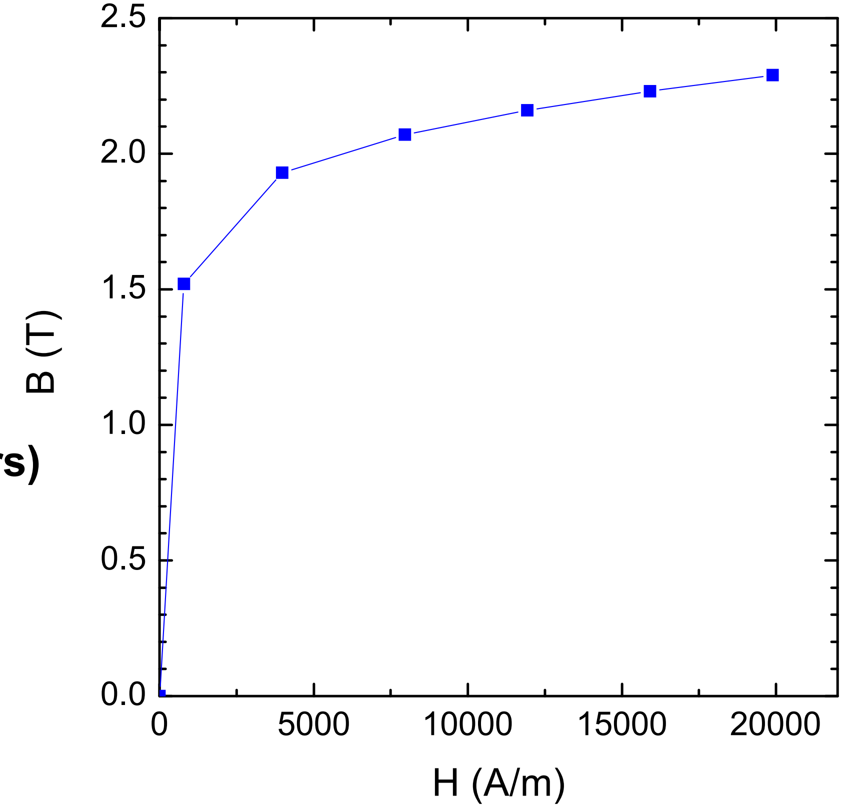


SCU15 demonstrator



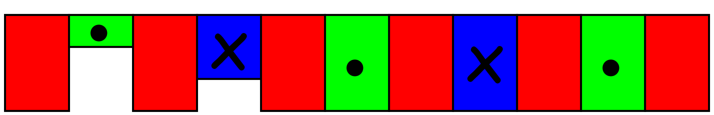
206 plates of high magnetic field saturation cobalt-iron alloy

Magnetization curve of cobalt-iron alloy from constructor @300K



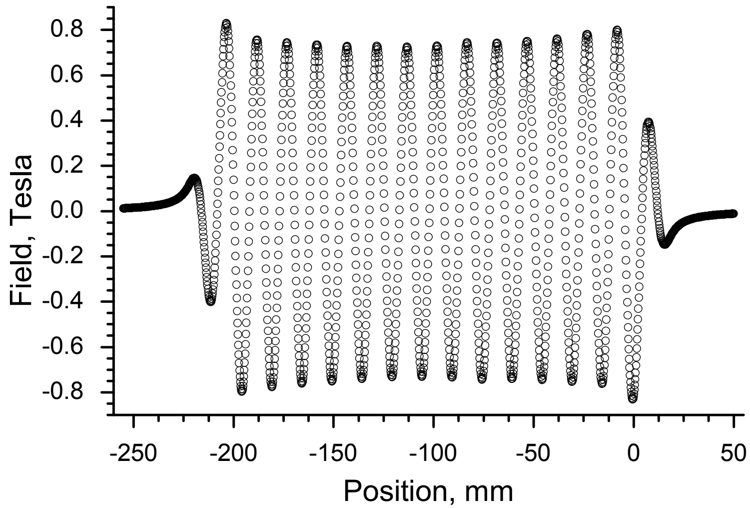
Cross section NbTi wire:
0.54mm x 0.34mm (including insulation)

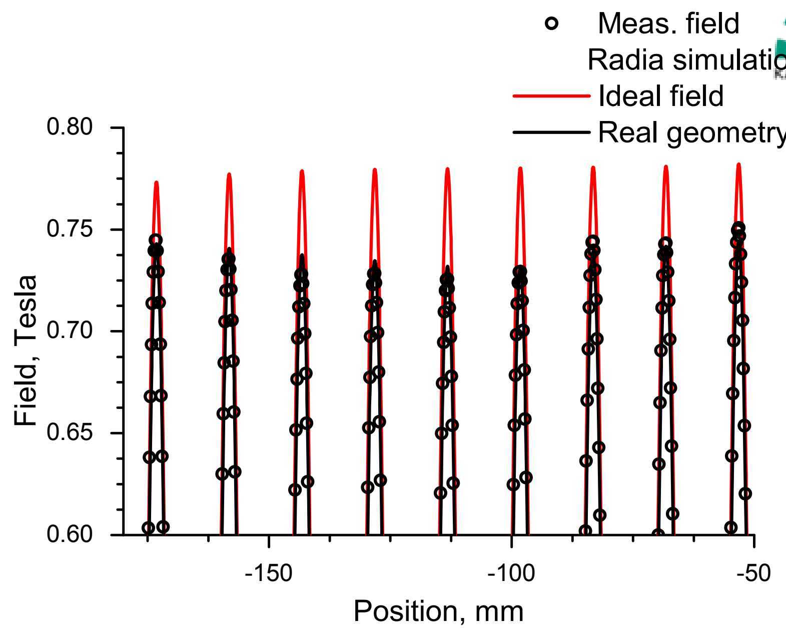
End fields:
first winding packages 21 turns (3 layers)
second winding packages 63 turns (9 layers)



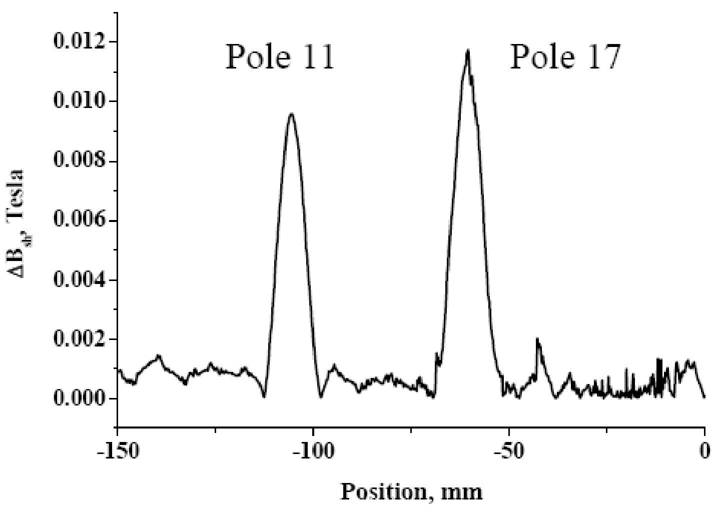
Sara Casalbuoni, Thomas Jefferson National Accelerator Facility Newport News, VA

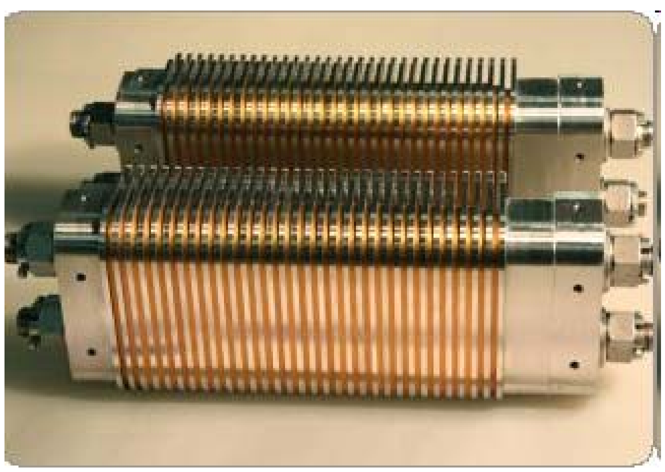
SCU15 prototype





Active shimming using racetrackcoils





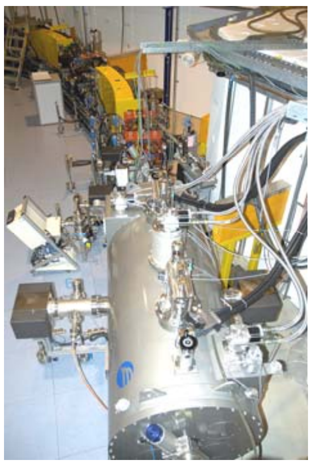
S. C. et al., SRI 2009, AIP-Conf. Proc. 33-36 Vol. 1234 (2010).

Experience at ANKA: SCU14 demonstrator

Karlsruhe Institute of Technology

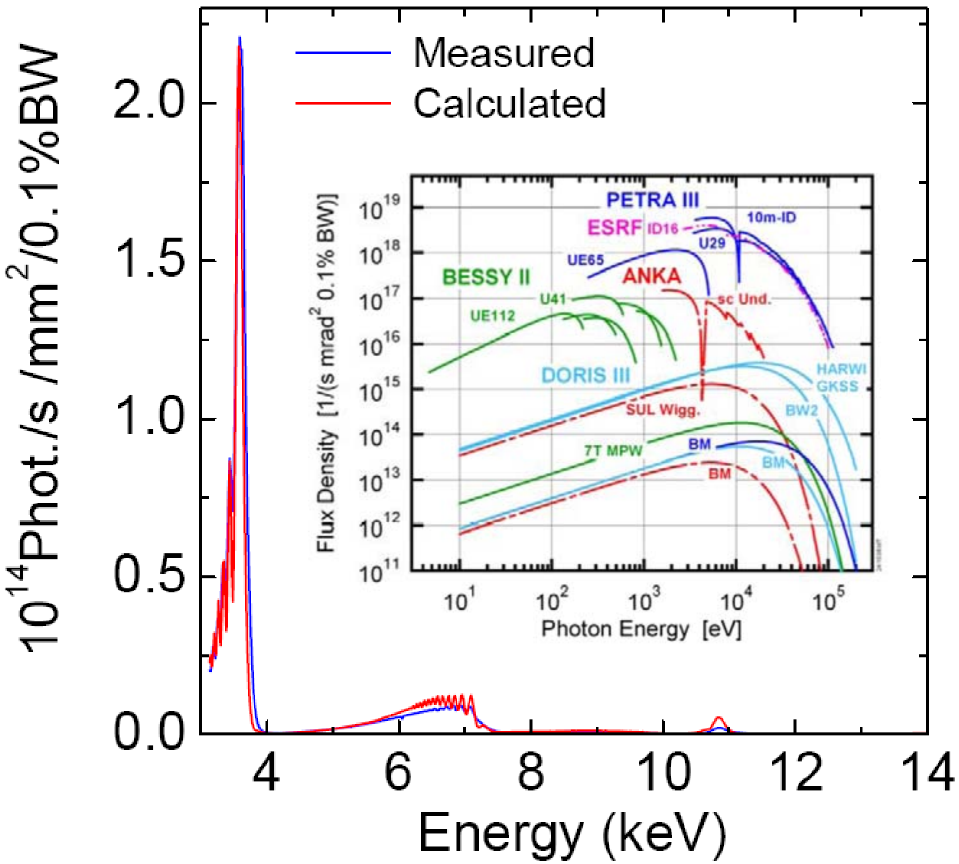
Proof of principle of scu technology first time worldwide demonstrated at ANKA (2005) developed in collaboration with ACCEL.

- Period length: 14 mm
- Length: 100 periods
- NbTi - coils



- Outcome used:

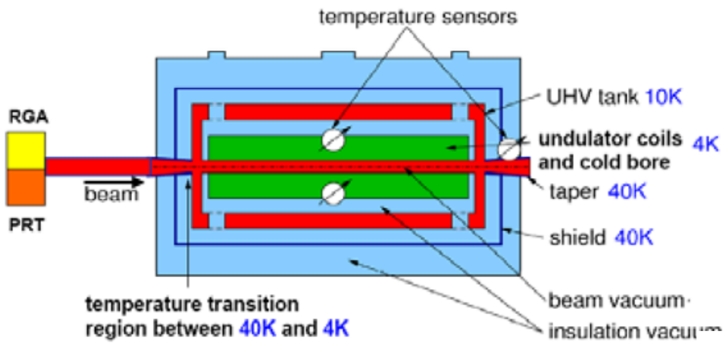
- to measure beam heat load to a cold vacuum chamber at ANKA
- to improve the design of next generation sc undulators



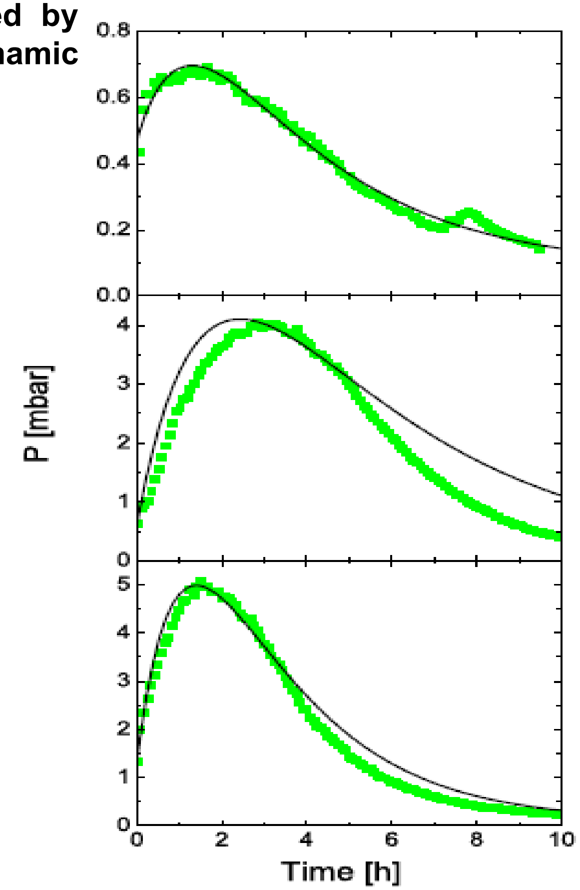
R. Rossmanith et al., SRI 2006, AIP-Conf. Proc. 301-304 Vol. 879 (2007).

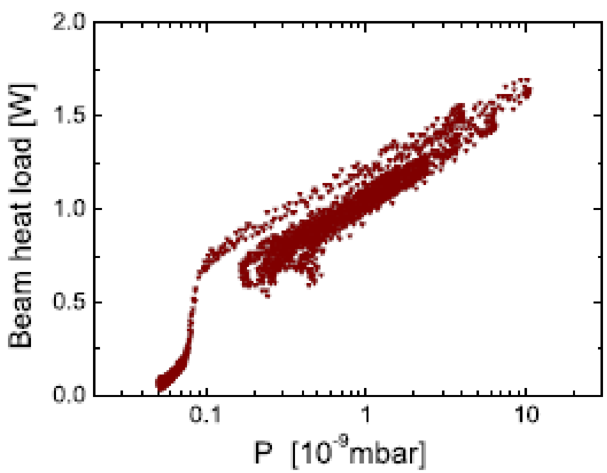
Experience at ANKA: SCU14 demonstrator

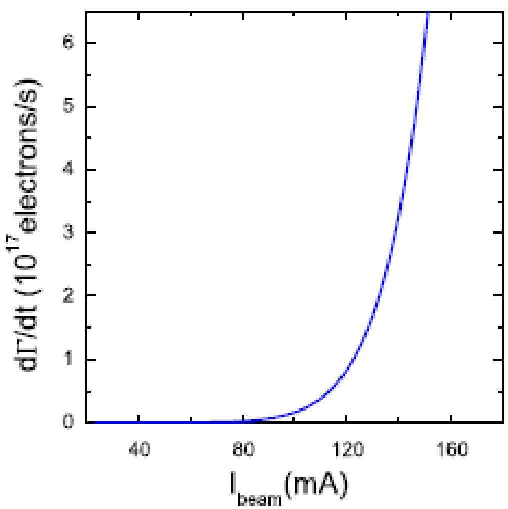
Performance limited by too high beam heat load: beam heat load observed cannot be explained by synchrotron radiation from upstream bending and resistive wall heating. S. C. et al., PRSTAB2007



Pressure rise can be explained by including in eq. of gas dynamic balance electron multipacting.
S. C. et al., PRSTAB2010







Possible beam heat load source: electron bombardment of the wall, beam dynamics under study