KIT Karlsruhe Institute of Technology

ANKA Synchrotron Radiation Facility

Superconducting undulators: experience from ANKA

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ANKA, KIT
C. Boffo, Th. Gerhard, M. Turenne, W. Walter
Babcock Noell GmbH

Babcock Noell GmbH

ANKA Synchrotron Radiation Facility

Outline

- Motivation R&D of SCIDs
- SCU14 demonstrator
- Ongoing collaboration with BNG:
  - SCU15DEMO
  - SCU20
  - SCUW18-54
- HTS SCUs
- Tools and instruments for R&D
- Summary

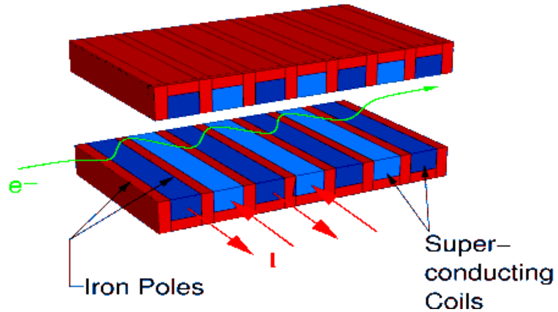
Motivation R&D of scIDs

Develop SCUs for ANKA and low emittance light sources

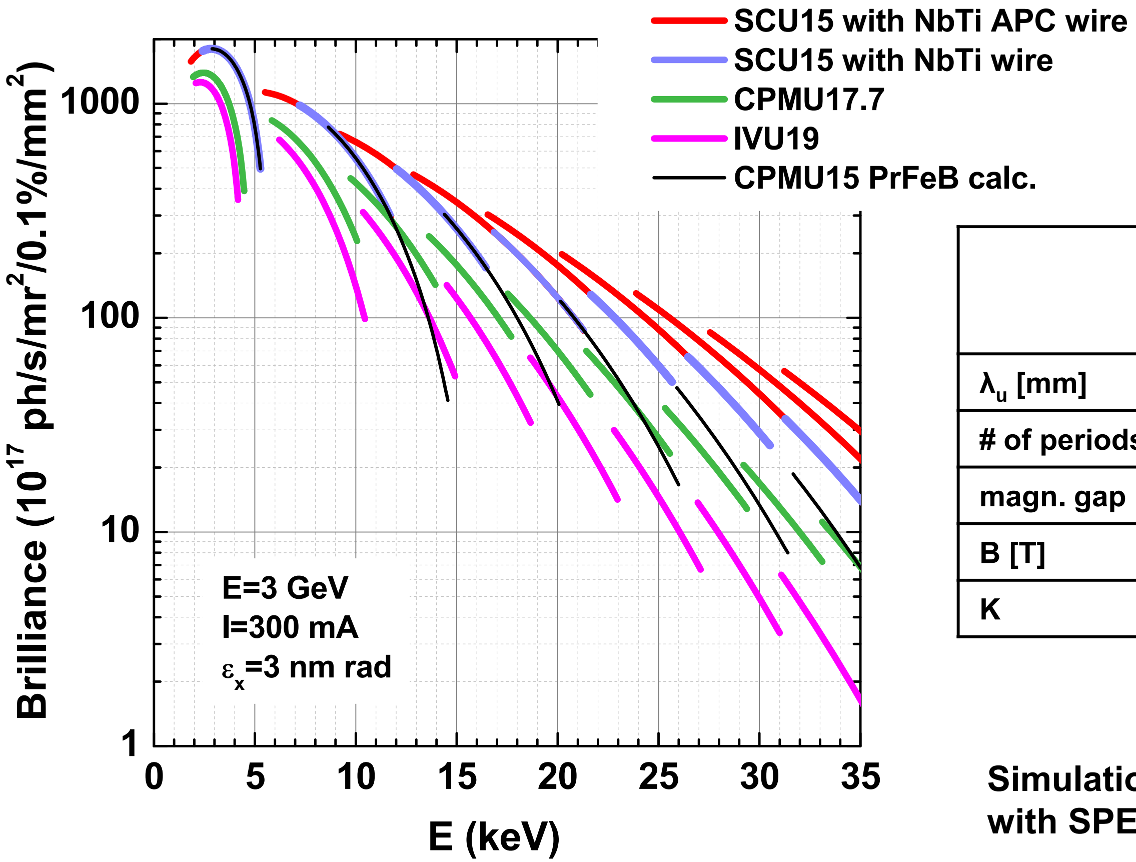
With respect to permanent magnet undulators SCUs can generate :

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

Why? Larger magnetic field strength for the same 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

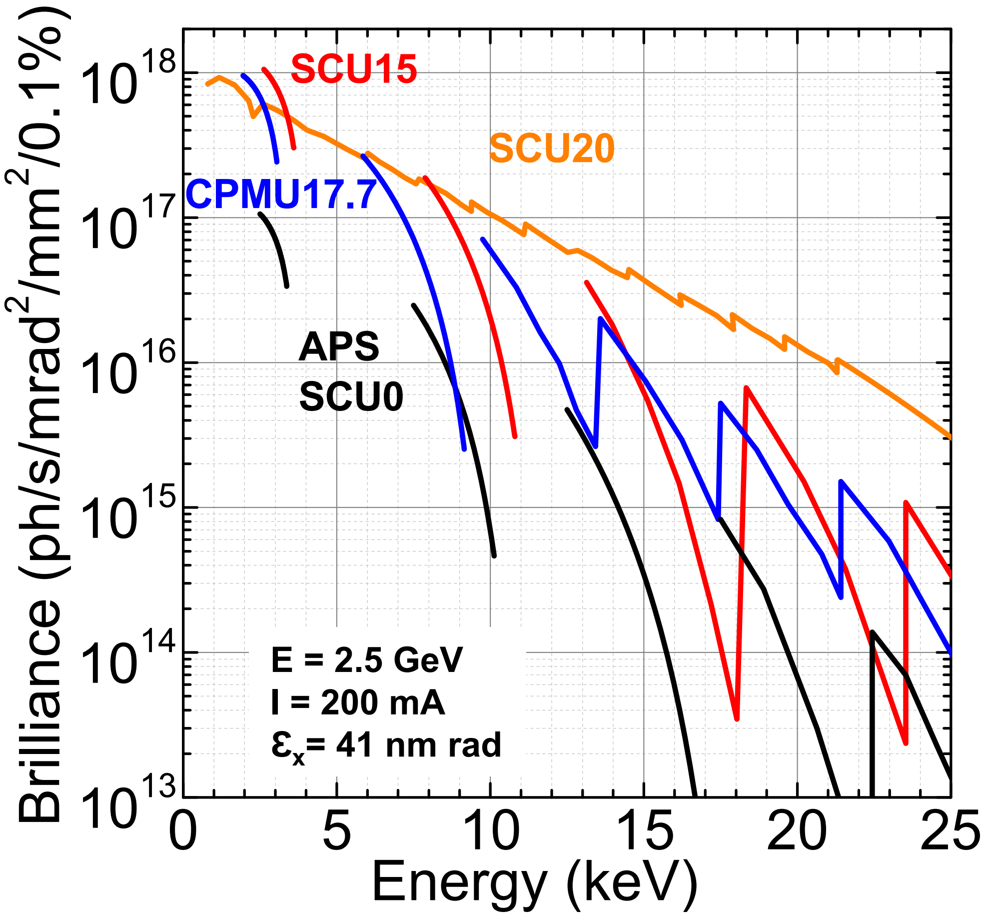
Simulations performed with SPECTRA§

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).

Motivation R&D of scIDs

At ANKA large vacuum gap 7 mm instead of 5 mm
→ longer period lengths



SCU20 has larger brilliance and flux than SCU15

vacuum gap = 7 mm

	CPMU† (DLS)	APS SCU0*	SCU15**	SCU20††
λ_u [mm]	17.7	16	15	20
# of periods	87	20	102	77
B [T]	0.71	0.64	0.70	1.46
K	1.17	0.96	0.98	2.20

†C.W. Ostenfeld & M. Pedersen, IPAC10
*Y. Ivanyushenkov et al., IEEE Trans. on Appl. Supercon. 4102004, Vol. 24-3 (2014)
**D. Saez de Jauregui et al., IPAC11
†† S. C. et al., IEEE Trans. on Appl. Supercon. 4101305, Vol. 24-3 (2014)

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

SCU14 demonstrator

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

- Period length: 14 mm
- Periods: 100
- Conduction cooling
- NbTi - coils

Main issues:

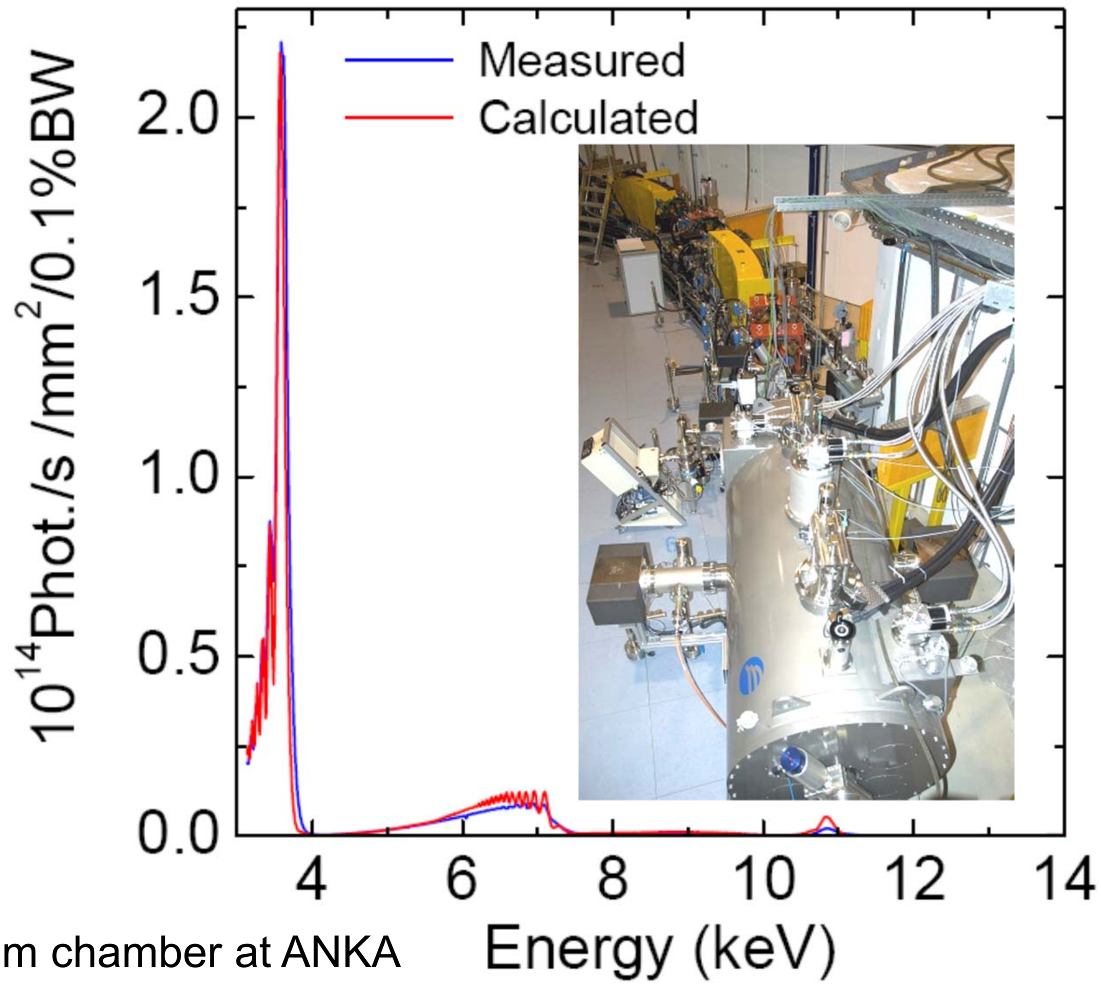
- Reduction of peak field on axis B of ~30% from LHe 0.55 T to conduction cooling 0.4 T

- Performance in ANKA limited by too high beam heat load: in user operation B = 0.3 T

Outcome used:

•to measure beam heat load to a cold vacuum chamber at ANKA

•to improve the design of next generation sc undulators

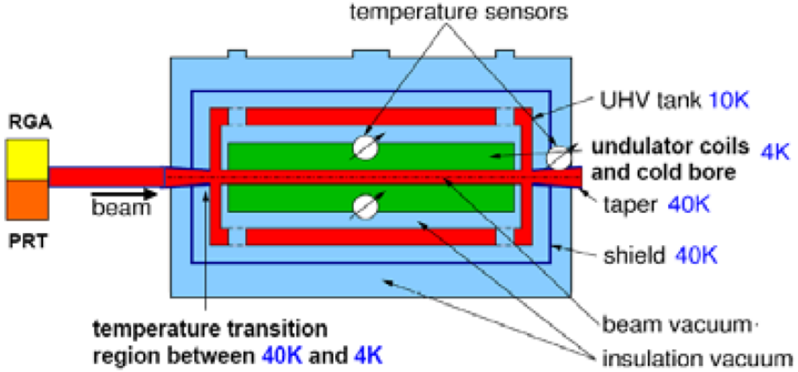


R. Rossmanith et al., SRI 2006, AIP-Conf. Proc. 301-304 Vol. 879 (2007).

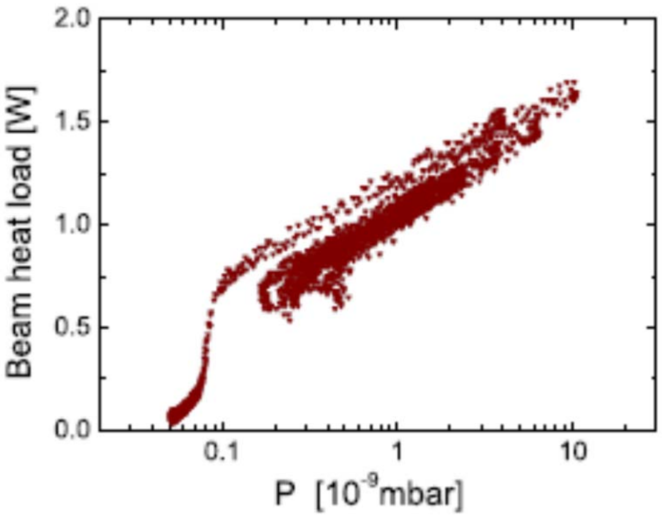
SCU14 demonstrator

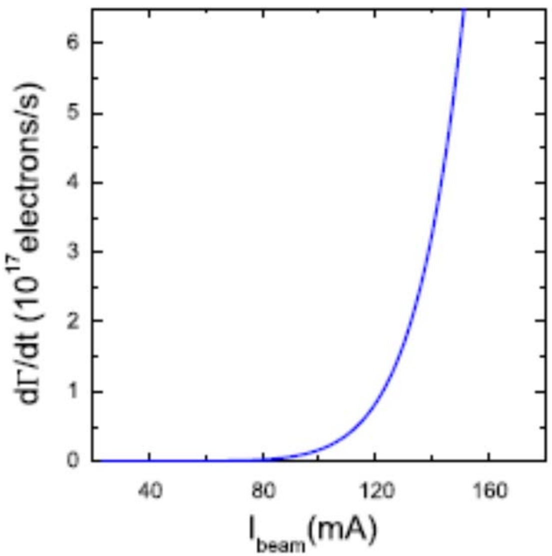
Beam heat load studies

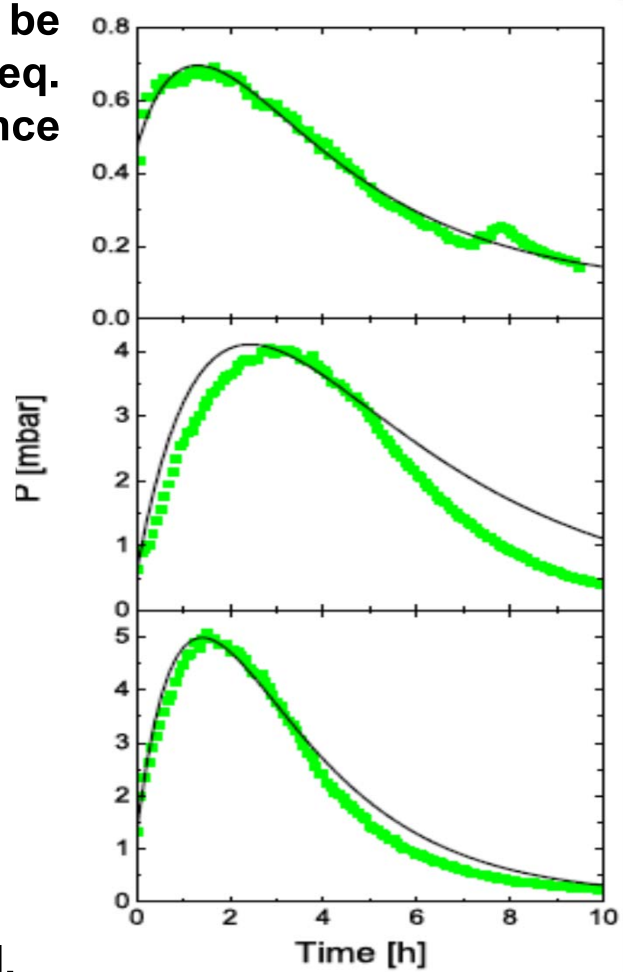
Beam heat load observed cannot be explained by synchrotron radiation from upstream bending and resistive wall heating. S. C. et al., PRSTAB2007



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







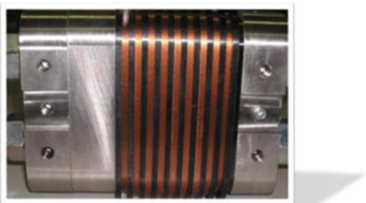
Possible beam heat load source: electron bombardment of the wall, beam dynamics to be studied

Ongoing collaboration of ANKA and BNG to develop SCUs for ANKA and low emittance light sources

- NbTi wire
- Conduction cooling
- Movable vacuum chamber

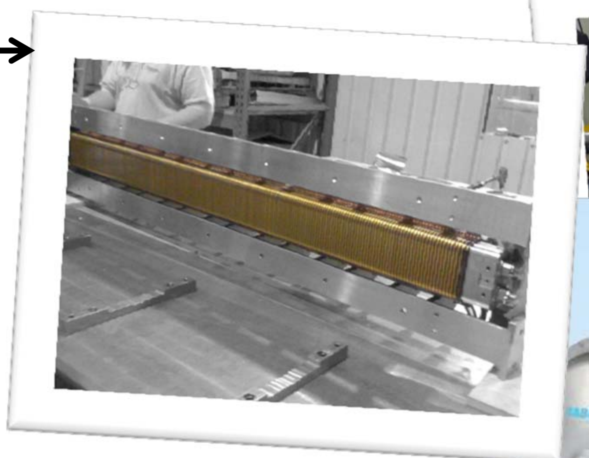
Common design ANKA and BNG
Manufacturing: BNG
Testing: ANKA

SCU15DEMO



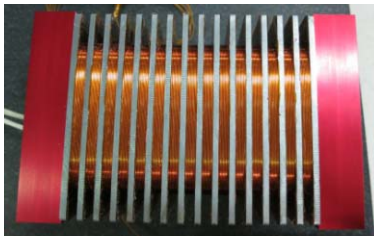
Mockup1

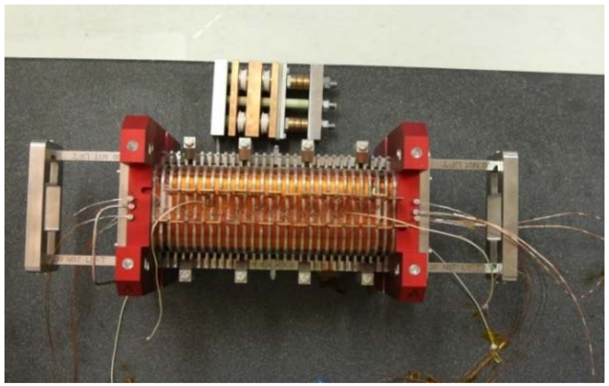
Mockup2



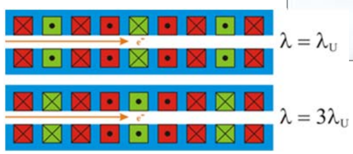
Long coils

time





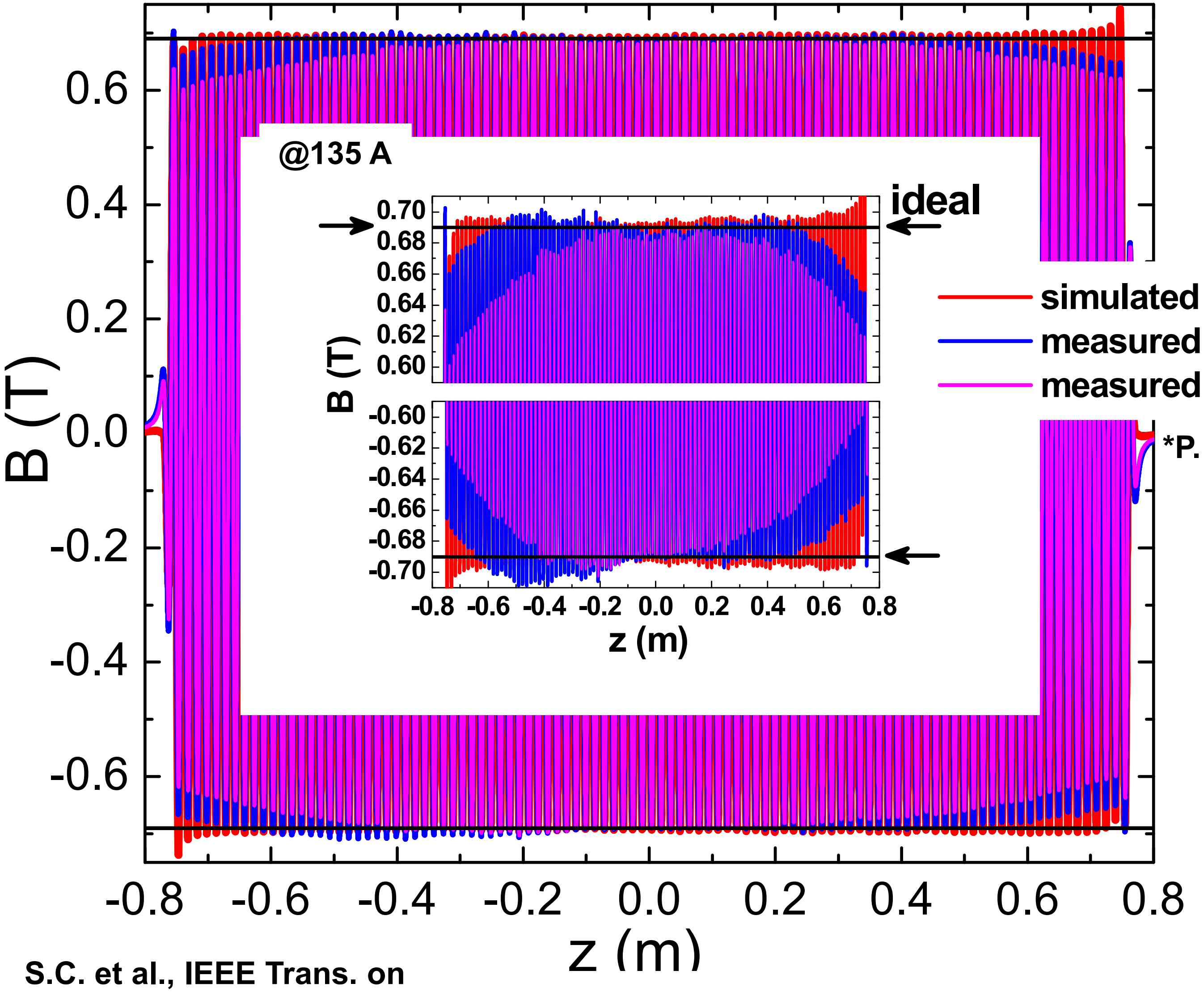
SCU20



SCUW18-54

Babcock Noell GmbH

SCU15DEMO: magnetic field measurements



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

λ_U= 15 mm
100.5 full periods
B = 0.69 T
v. gap = 7 mm

Measurements performed at CERN in a LHe bath

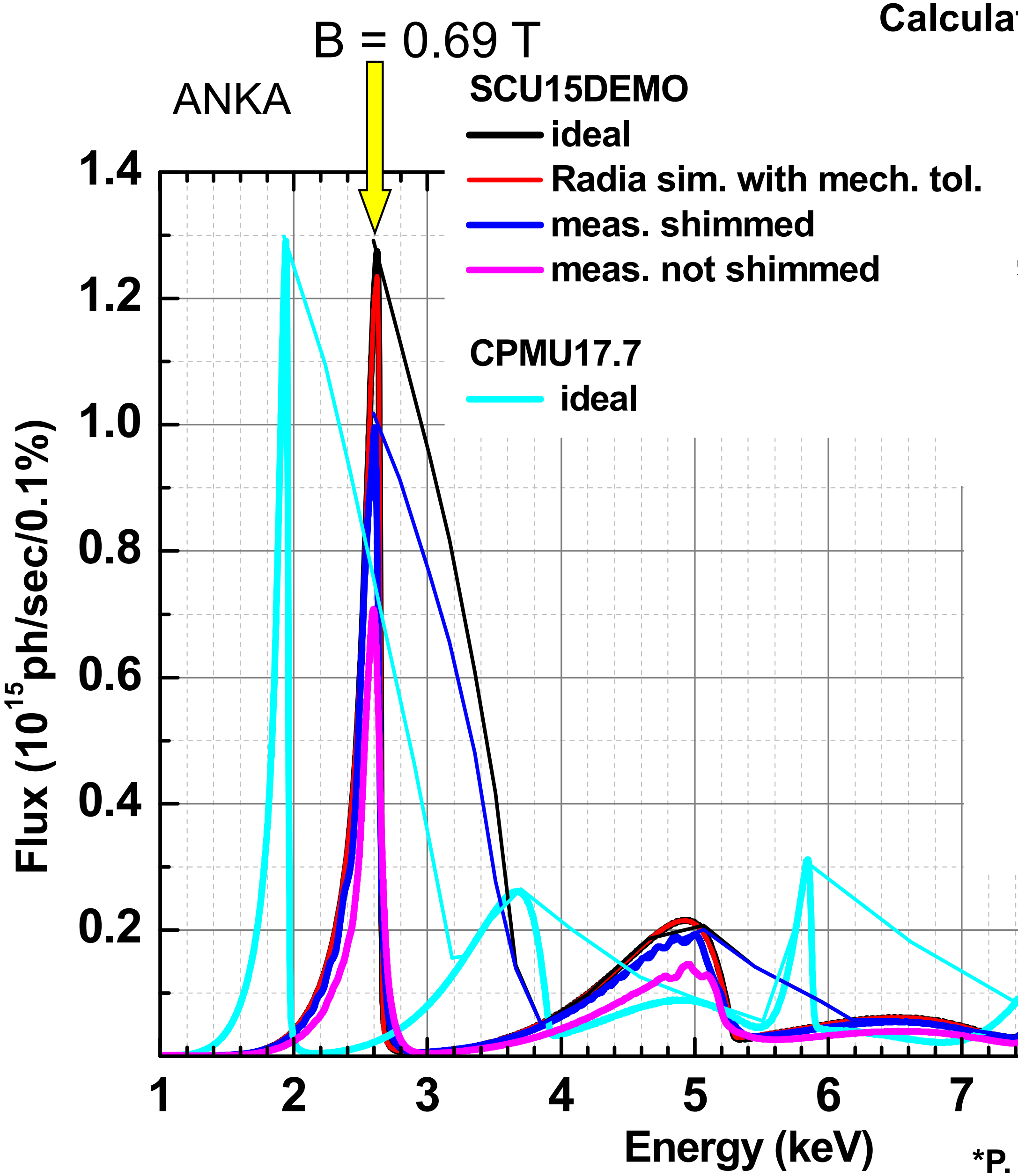
Stainless steel support structure, which fixes the magnetic gap at room temperature to 8.00 ± 0.01 mm

Mechanical shimming applicable to fixed gap undulators

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

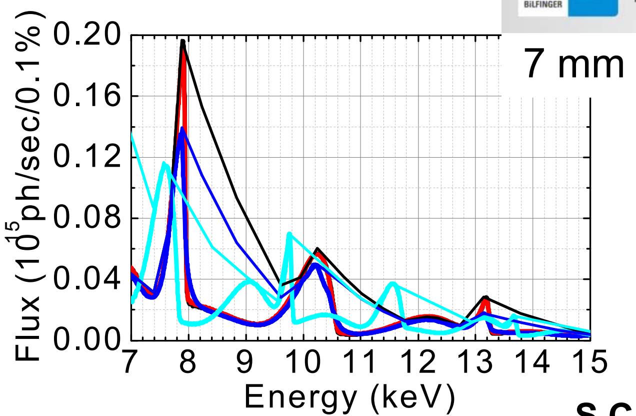
Coils have been pre-bent at room temperature to try to compensate the bending measured at 4 K

SCU15DEMO: spectral performance

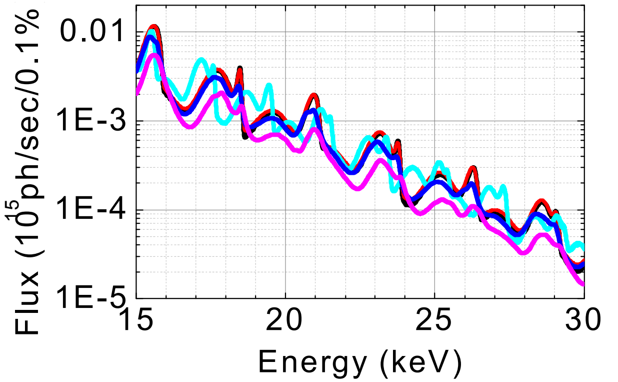


Calculated with B2E*

7 mm vacuum gap



S.C. et al., IPAC12



slit of 4 mm x 0.9 mm @ 10 m distance

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

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

SCU15DEMO: spectral performance

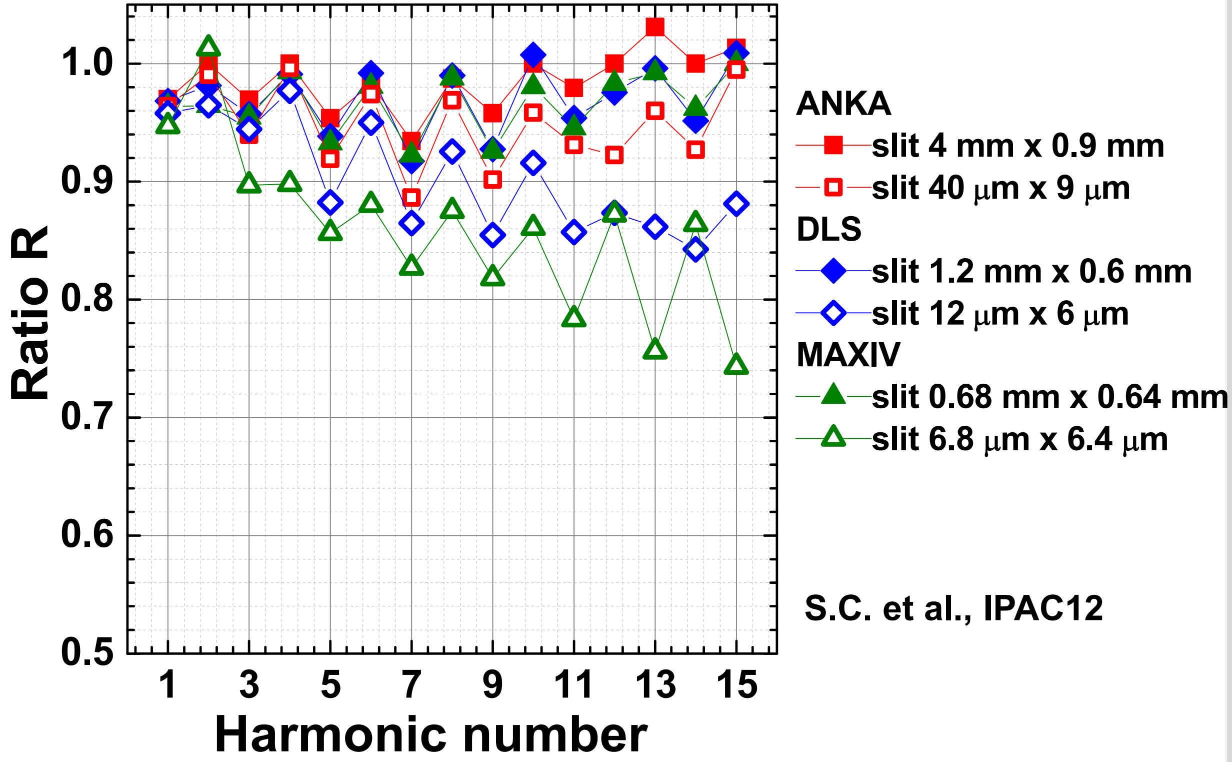
"ideal" = flux produced by the field from ideal device

"Radia" = flux produced by the field simulated with Radia[#] assuming mechanical tolerances measured at 300 K

$$\text{Ratio R} = \frac{\text{"Radia"}}{\text{"ideal"}}$$

Mechanical tolerances reached at 300 K
Half period length: 10 μm
Pole heights deviation: 50 μm
C. Boffo et al.,
IEEE Trans. on Appl. Supercond.
1756-1759 Vol. 21-3 (2011)

	ANKA*	DLS †	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



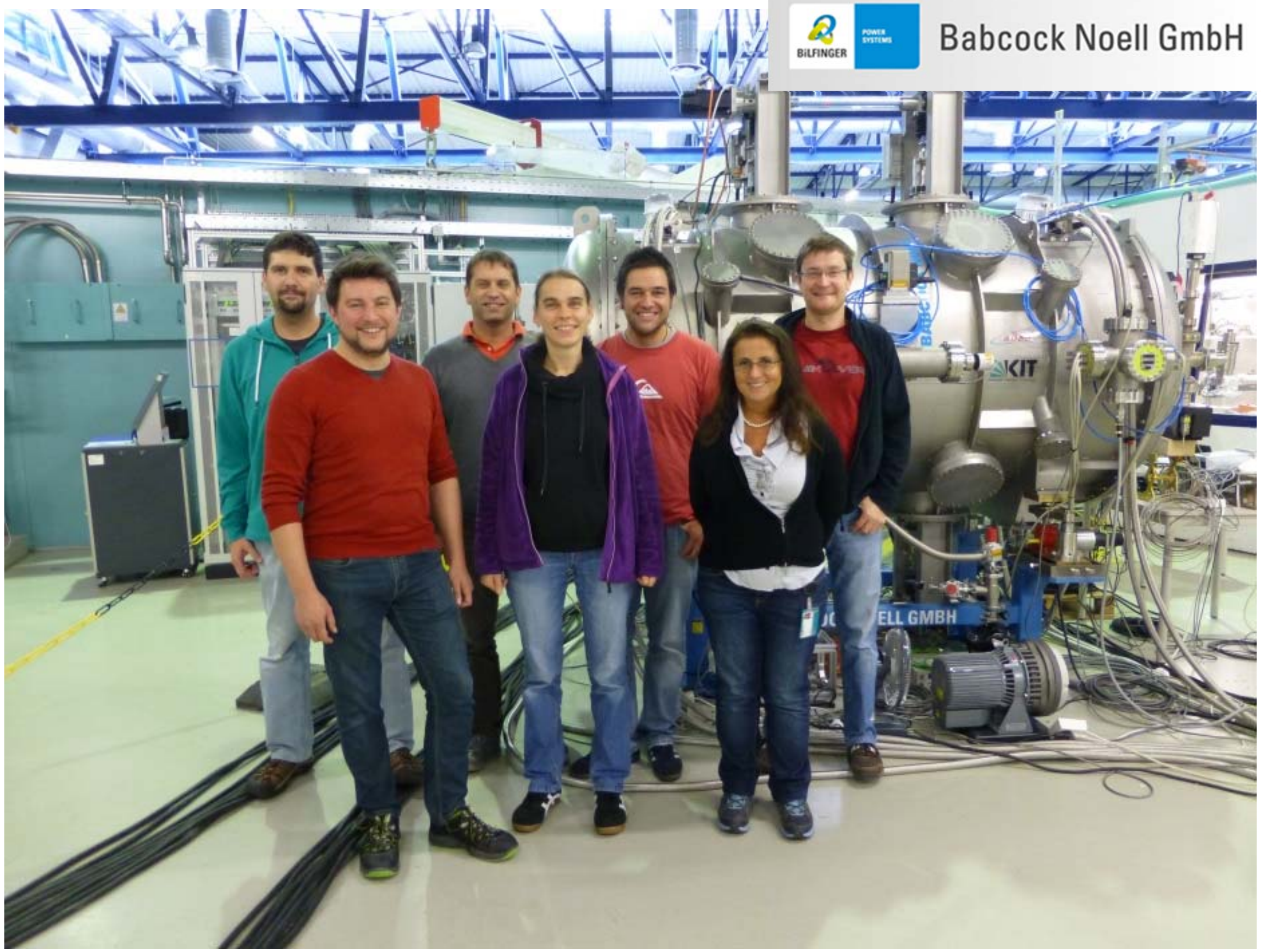
- **Ratio R > 75% for the existing and planned storage rings up to the 15th harmonic**

#O. Chubar, P. Elleaume, J. Chavanne, J. Synchrotron Rad. 5, 481 (1998)
*** A. S. Müller, priv. comm.**
† I. P. S. Martin et al, PAC07
**** S. C. Leemann et al., Phys. Rev. ST Accel. Beams 120701 12 (2009)**

SCU15DEMO: tests in conduction cooling

Babcock Noell GmbH

- FAT completed
- Cooling time 7 days
- Warming up 4 days
- Ramping time < 600 s
- Current stability of main coils at max. current 150 A and correction coils successfully tested for 6 days
- Movable vacuum chamber 7 mm – 15 mm: successful vacuum test < 3 x 10^{-10} mbar in cold conditions

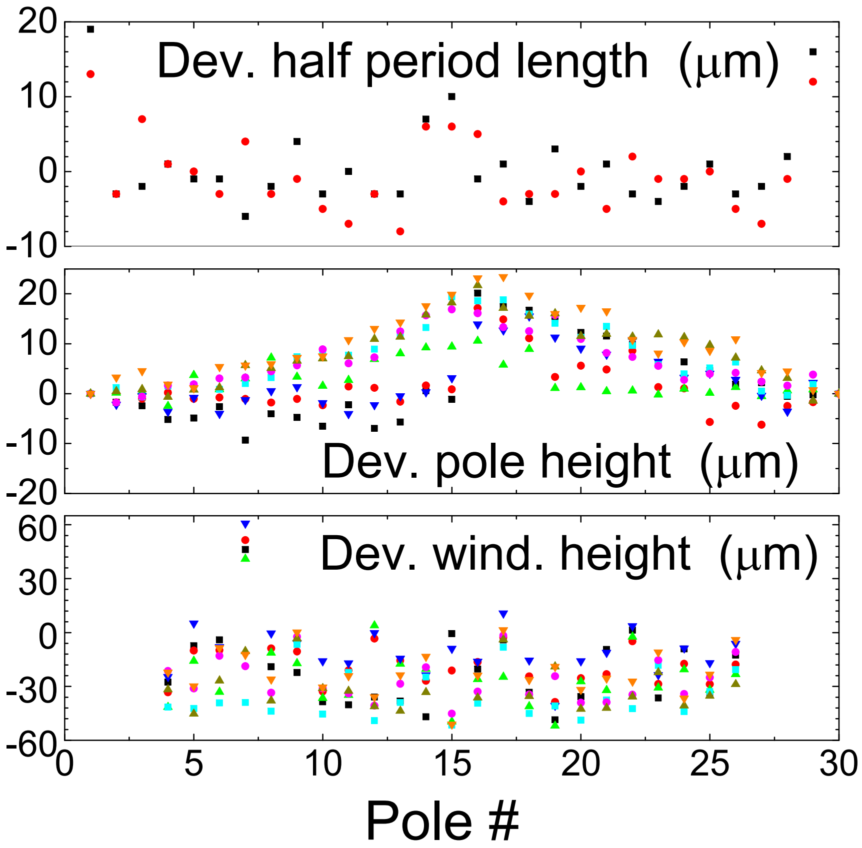


- **Next steps :**
  - Installation in ANKA 12.2014-1.2015
  - Tests with beam in 2015

SCU20

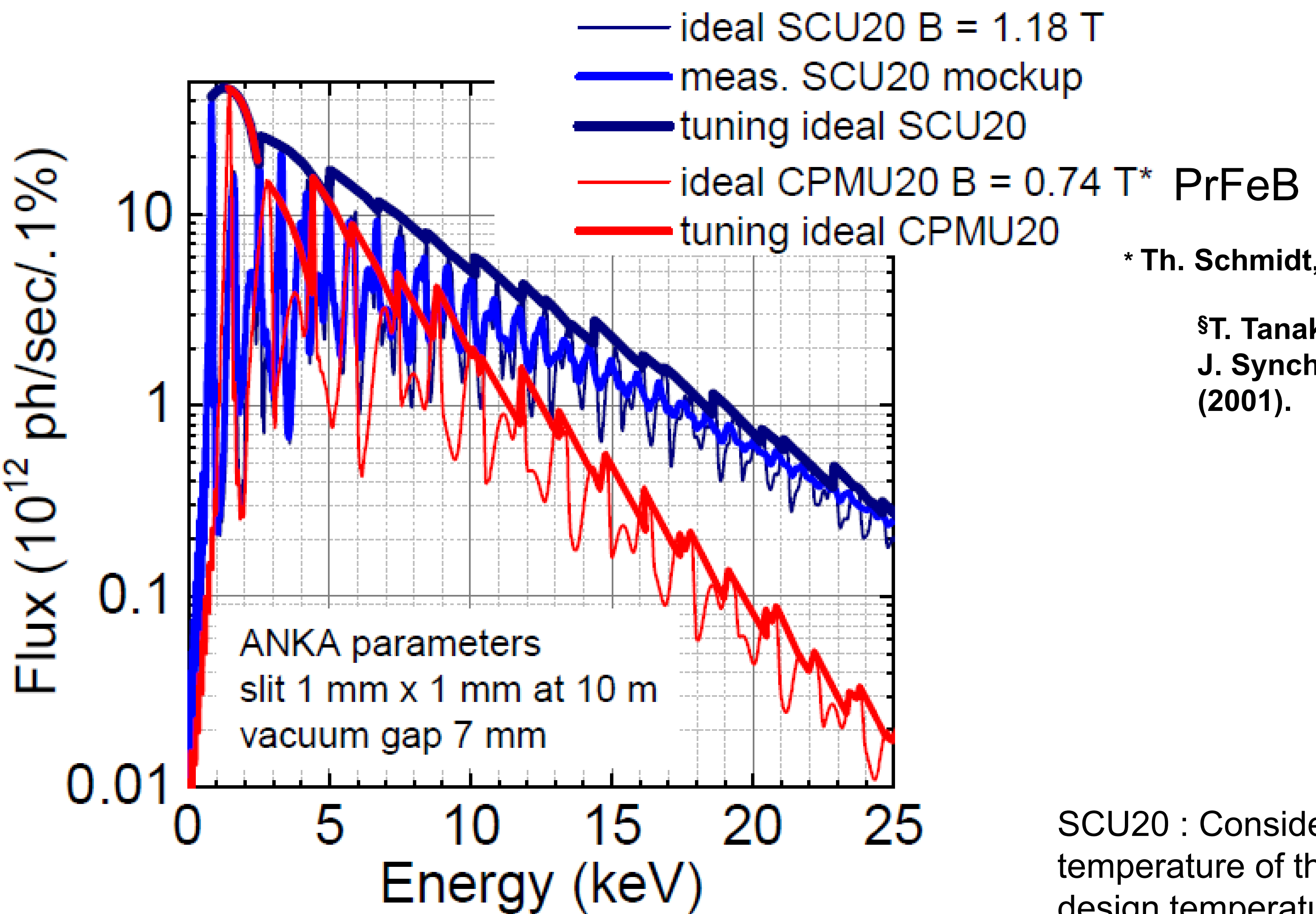
- Lessons learned from previous development of 1.5 m long undulator coils:
  round wire, low carbon stainless steel, blocks ~0.15 m, racetrack,
  new winding scheme: from one groove to the next changing winding direction

- Achievements of Mockup 2 (~ 30 cm long)
  - Mechanical accuracies at 300 K
  - Test in LHe and in conduction cooling 400 A reached without quench (nominal current 380 A)
  - In conduction cooling at ~ 3.5 K 680 A reached at the end of training



SCU20: Achievements of Mockup 2

Calculated spectral performance with SPECTRA§



*** Th. Schmidt, private communication.**

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

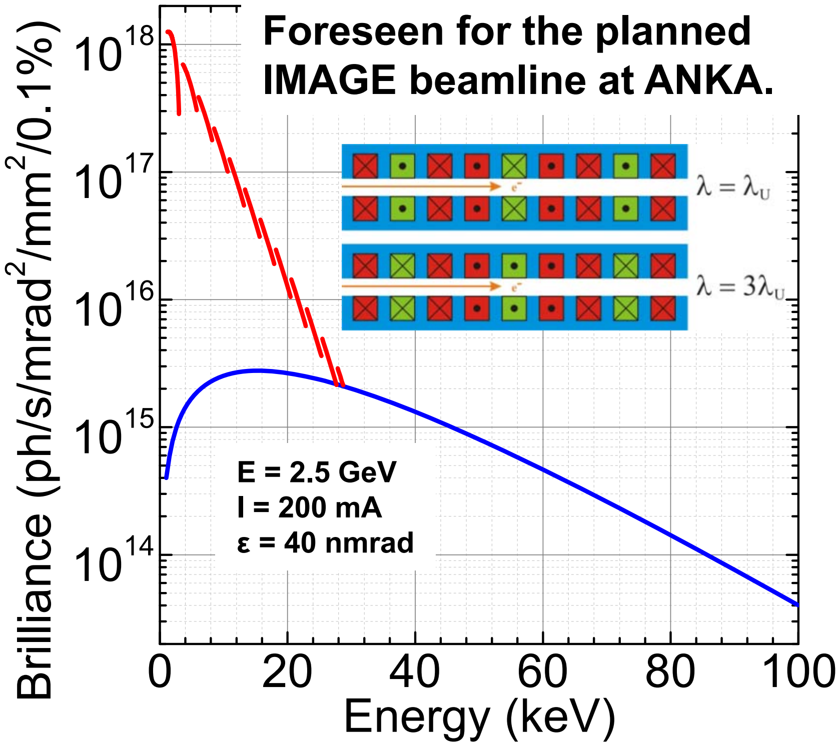
SCU20 : Considering an operating temperature of the magnet of 4.2 K, design temperature margin of about 2 K.

SCUW18-54

A device to switch between a 18 mm period length undulator and a 54 mm wiggler.

T. Holubek et al., IPAC11

Foreseen for the planned IMAGE beamline at ANKA.

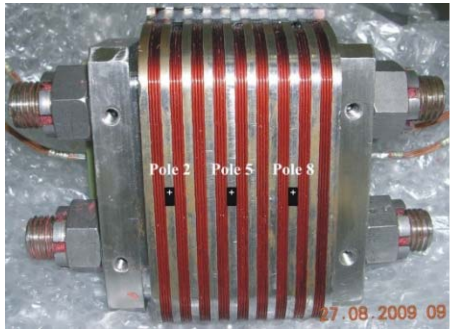


Applications:

- High brilliance of the undulator from 6 to 15 keV for imaging,
- wiggler mode for higher photon energies to perform phase contrast tomography.

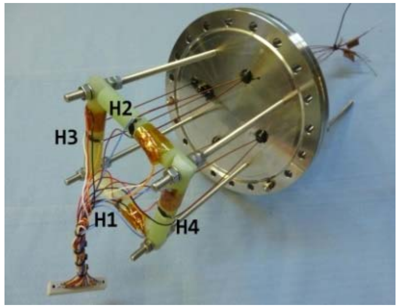
First experimental demonstration of period length switching for scIDs

Built by BNG



A. Grau et al., IEEE Trans. on Appl. Supercond. 1596-1599 Vol. 21-3 (2011)

Conduction cooled superconducting switch



T. Holubek et al., IEEE Trans. on Appl. Supercond. 3800104 Vol. 23-3 (2013)

Aim:
use only one power supply instead of several for the different circuits, reducing the thermal input to the device

Applications:

- period length switch (i.e., SCUW)
- active shimming

Minimum power dissipation of 200 mW per heater, demonstrated in an ad hoc conduction cooling setup in CASPER I
Minimum power dissipation can be further reduced: Ongoing additional tests in CASPERII

Bundesministerium für Bildung und Forschung

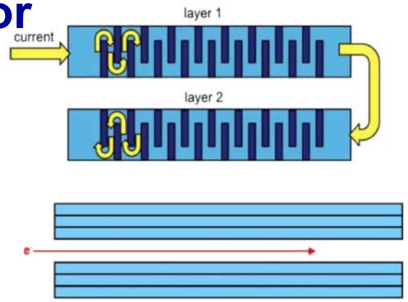
Babcock Noell GmbH

KIT Karlsruhe Institute of Technology

Application of other materials: HTS tape

HTS tape stacked undulator

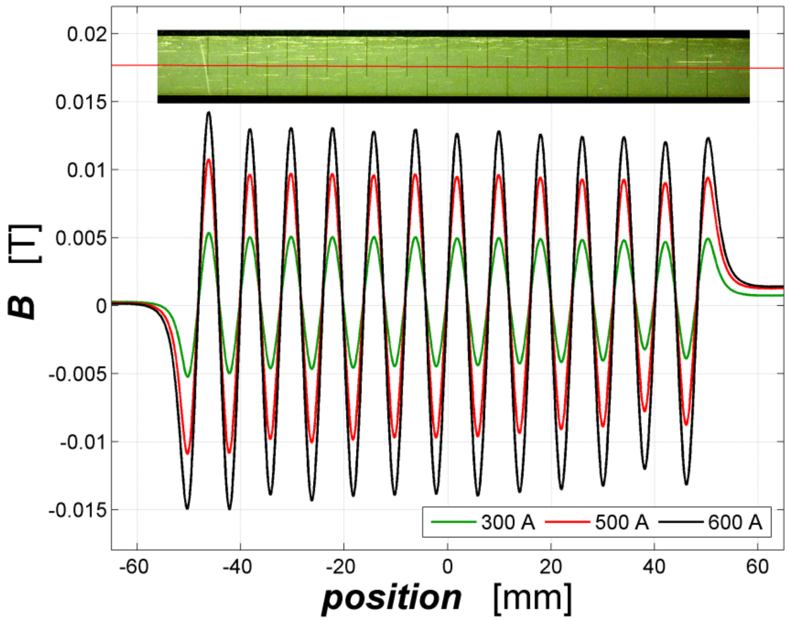
S. Prestemon et al., IEEE Trans. on /
Supercond. 1880-1883 Vol. 21-3 (201



KIT internal collaboration:
ANKA with ITEP

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

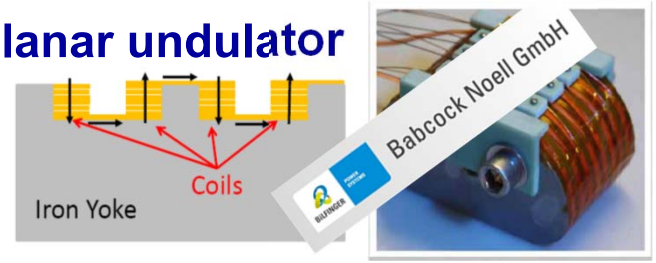
Groove formation very reliable applying laser
No contamination of groove detected (SEM)



T. Holubek et al., IEEE Trans. on Appl. Supercond. 4602204 Vol. 23-3 (2013)

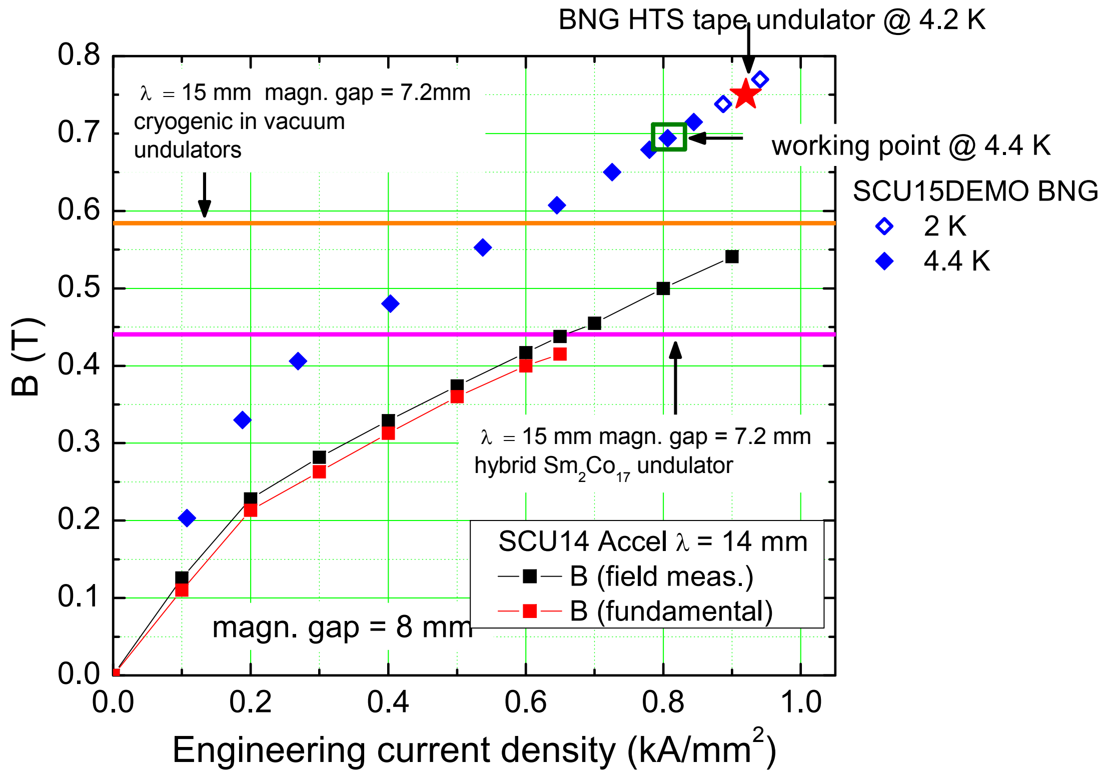
HTS tape planar undulator

C. Boffo,
IDMAX10



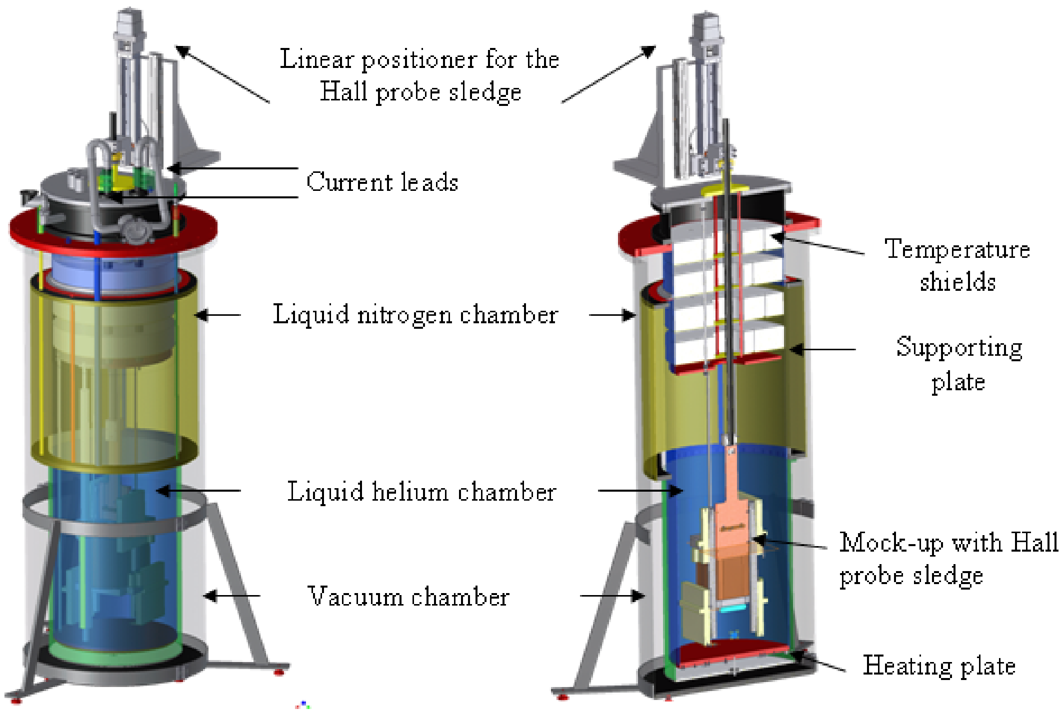
BNG HTS tape planar undulator mockup: results of test at CASPERI (KIT)

Maximum current 555 A ⟹ I = 0.92 kA/mm²



Tools and instruments for R&D: CASPERI

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



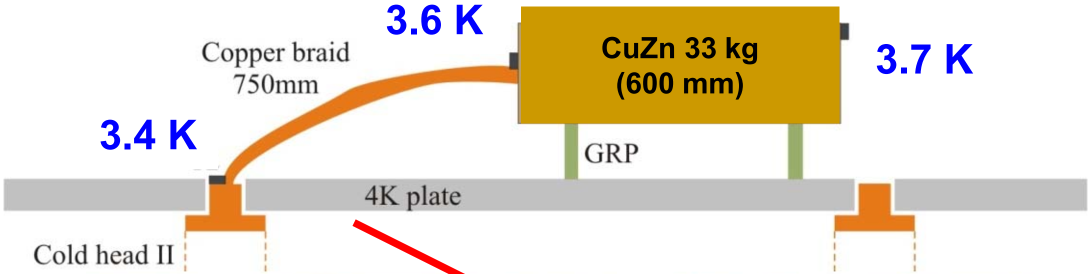
•**Operating vertical test in LHe of mock-up coils** with maximum dimensions 35 cm in length and 30 cm in diameter

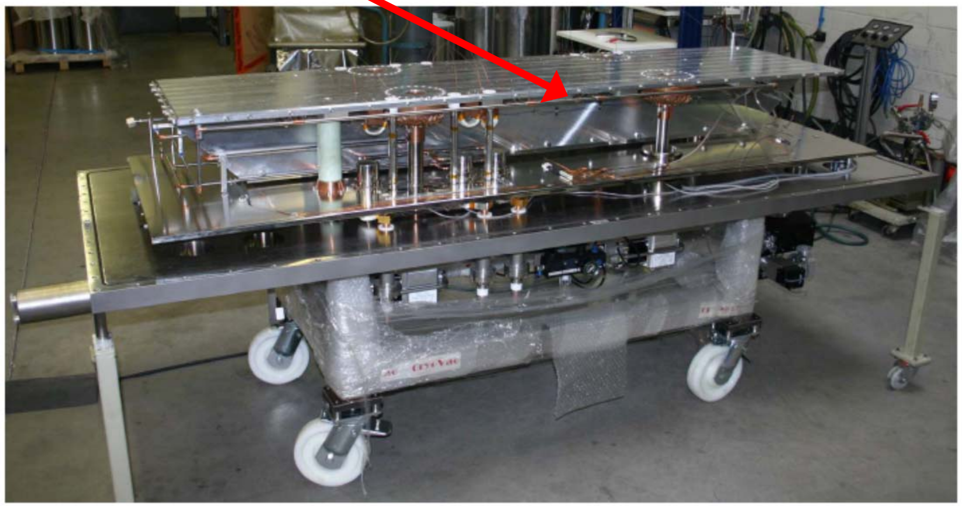
•The magnetic field along the beam axis is measured by Hall probes fixed to a sledge moved by a linear stage with the following precision ΔB < 1mT and Δz < 3 μm

E. Mashkina et al., EPAC08

Tools and instruments for R&D: CASPERII

Successful factory acceptance test

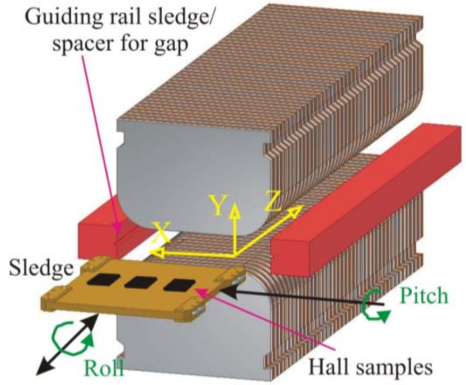




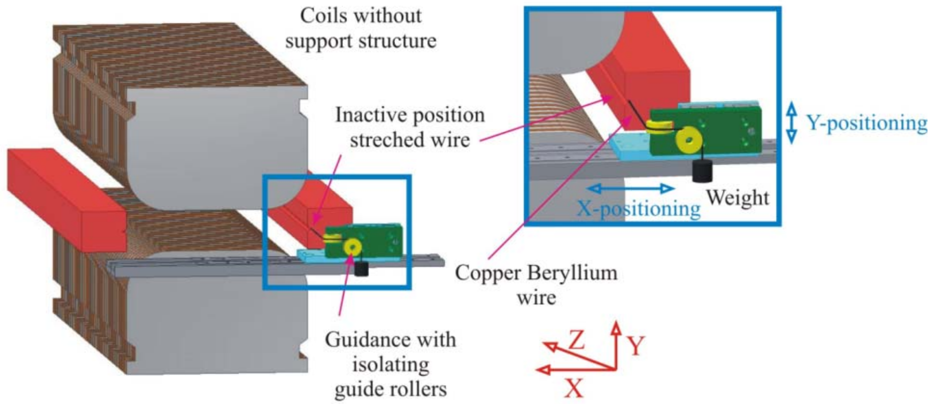
A. Grau et al., IEEE Trans. on Appl. Supercond. 9001504 Vol. 22-3 (2012)

Ongoing commissioning of :

•Local field measurements with Hall probes



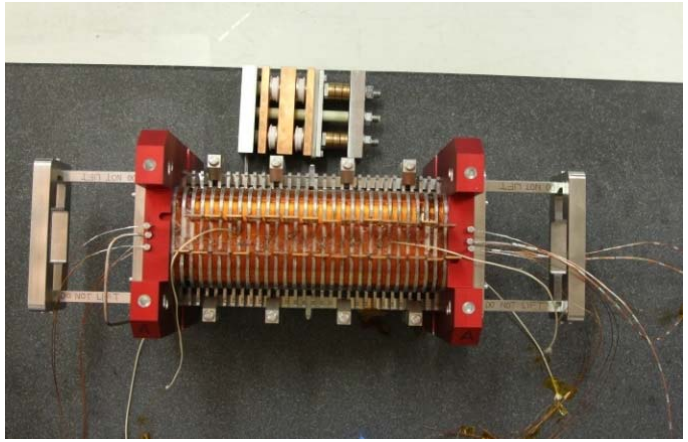
•Field integral measurements with stretched wire

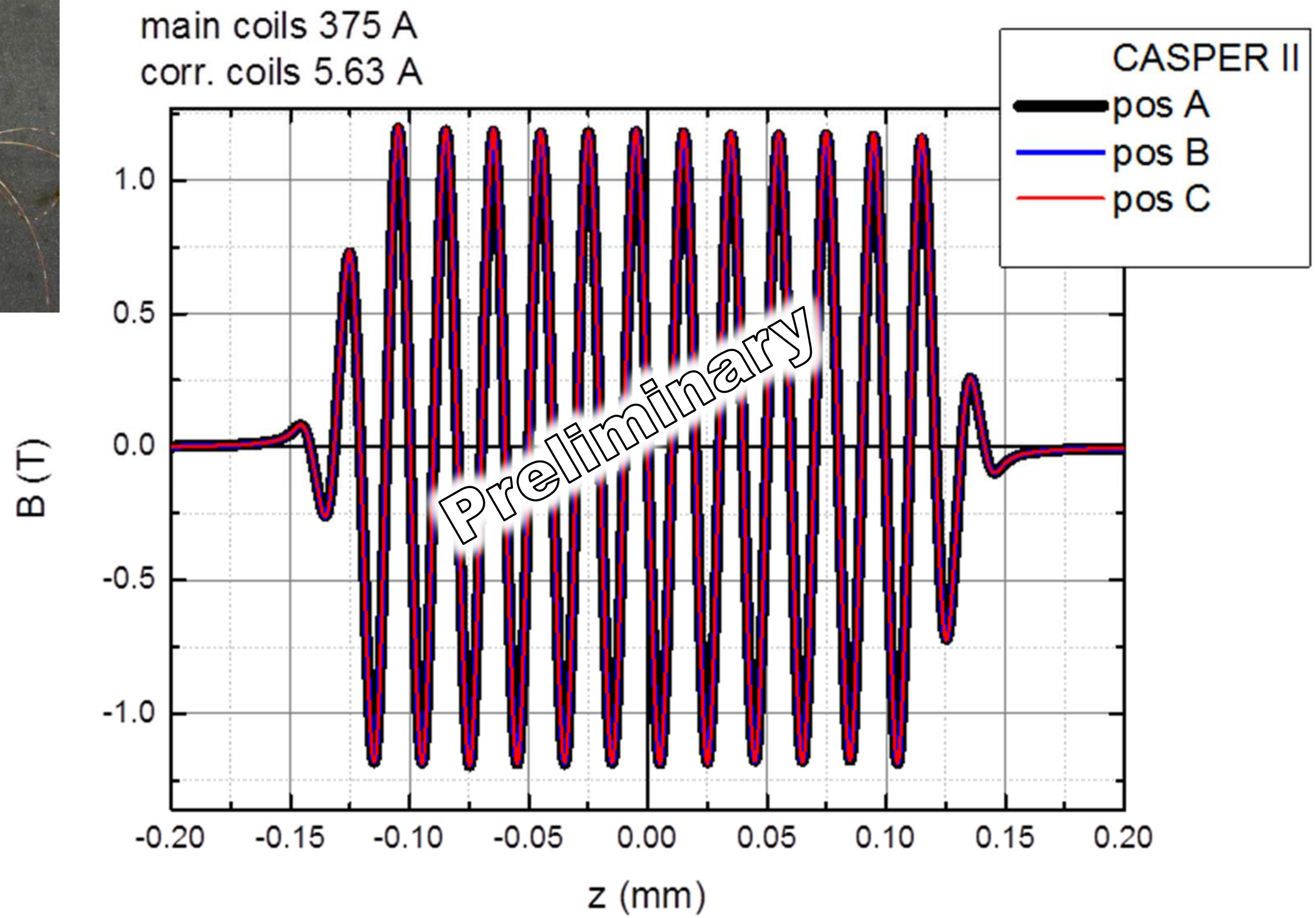


A. Grau et al., IEEE Trans. on Appl. Supercond. 2312-2315 Vol. 21-3 (2011)

Tools and instruments for R&D: CASPERII

SCU20 Mockup 2





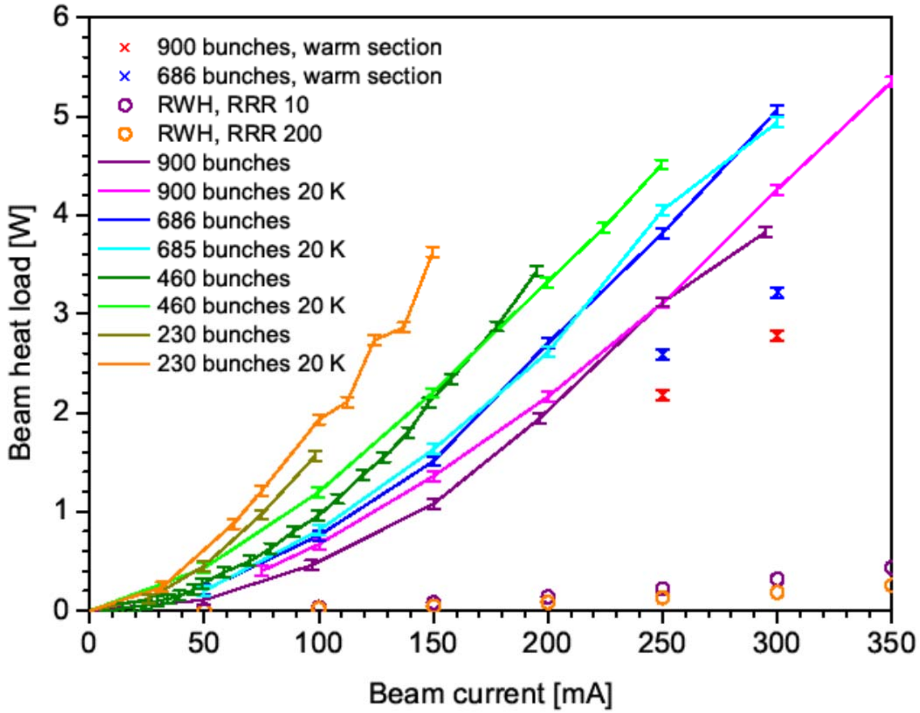
Tools and instruments for R&D: COLDDIAG

Cold vacuum chamber for diagnostics to **measure the beam heat load** to a cold bore in different synchrotron light sources

The beam heat load is needed to specify the cooling power for the cryodesign of superconducting insertion devices

The **diagnostics** includes measurements of the:

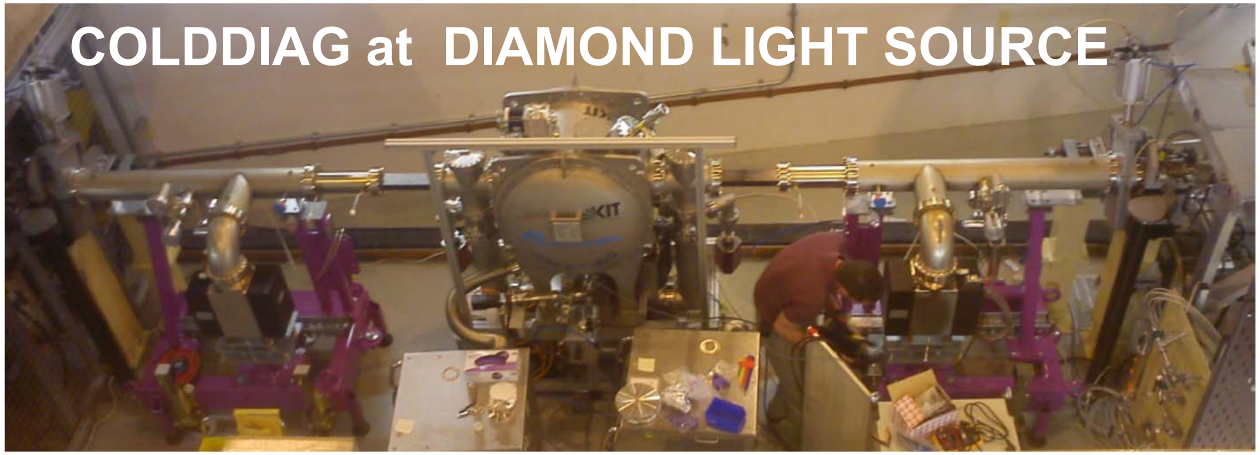
- **heat load**
- **pressure**
- **gas composition**
- **electron flux of the electrons bombarding the wall**



Significant discrepancy compared to theoretical expectations …

S. C. et al., JINST 7 P11008 (2012)

In collaboration with
CERN: V. Baglin
LNF: R. Cimino, B. Spataro
University of Rome ‚La sapienza': M. Migliorati
DLS: R. Bartolini, M. Cox, E. Longhi,
G. Rehm, J. Schouten, R. Walker
MAXLAB : Erik Wallèn
STFC/DL/ASTeC: J. Clarke
STFC/RAL: T. Bradshaw



S. Gerstl et al., PRSTAB, 17, 103201 (2014)

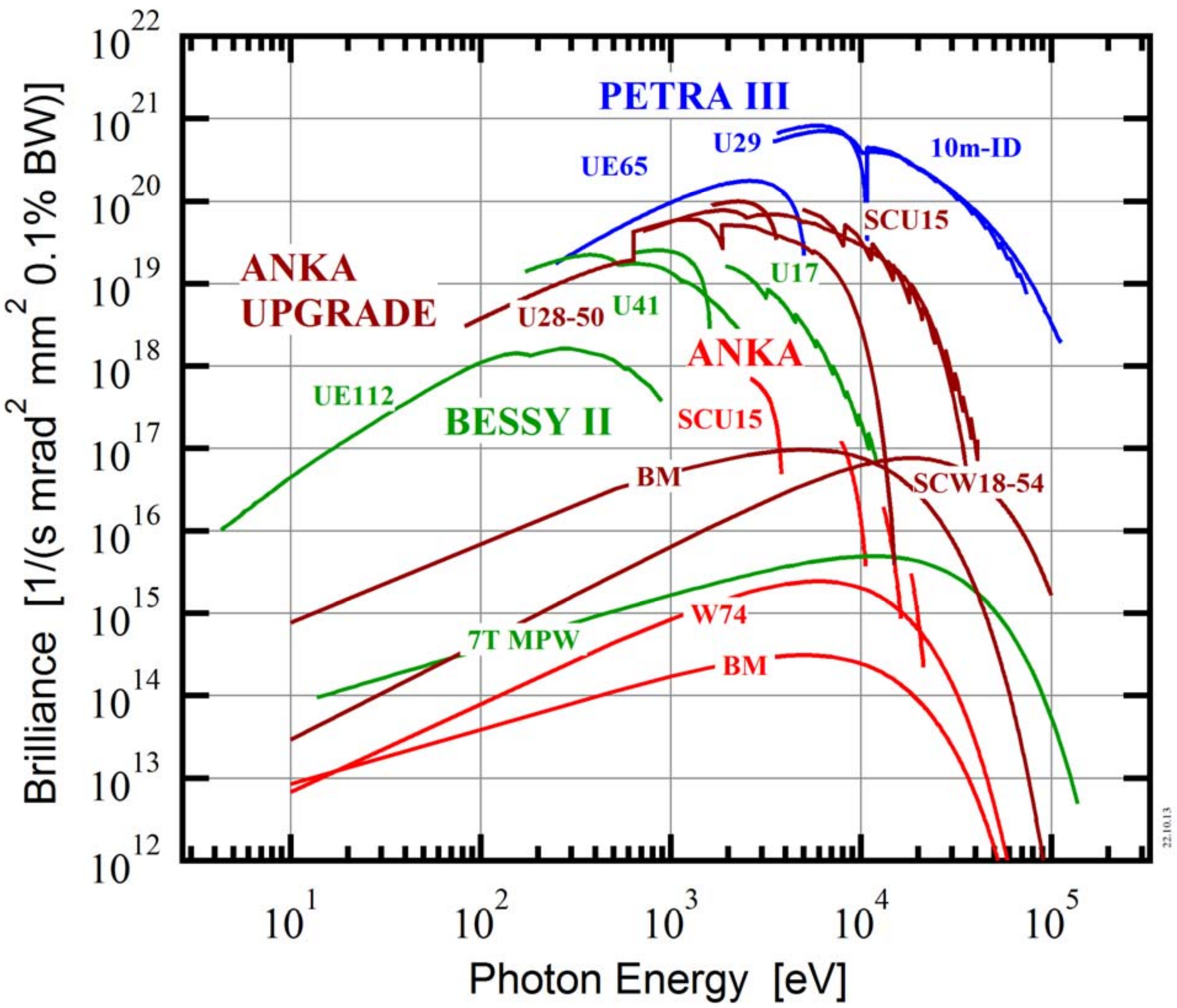
Summary

Karlsruhe Institute of Technology

- Advantages of SCIDs on permanent magnet IDs
- Experience with SCU14 demonstrator
- SCU15DEMO achievements:
  - Mechanical tolerances at RT < 50 μm
  - 1.5 m long coils successful test in LHe and in conduction cooling
  - Unique movable UHV vacuum chamber at 4 K: gap 7-15 mm
  - Potential spectral performance advantages on CPMU and on APS-SCU0 to be demonstrated with test in the ring
- SCU20 Mockup 2 achievements:
  - Mechanical tolerances at RT < 60 μm
  - Test in LHe and in conduction cooling 400 A reached without quench (nominal current 380 A)
  - Spectral performance advantages on CPMU
- SCUW18-54:
  - Demonstrated feasibility of period length switching
  - Successful studies on conduction cooled switch
- Development of our own tools for R&D on SCIDs:
  - CASPER II: cryostat succesful factory acceptance test, preliminary results of magnetic field measurements
  - COLDDIAG measured beam heat load to a cold bore installed in the Diamond Light Source

Backup slides

Outlook

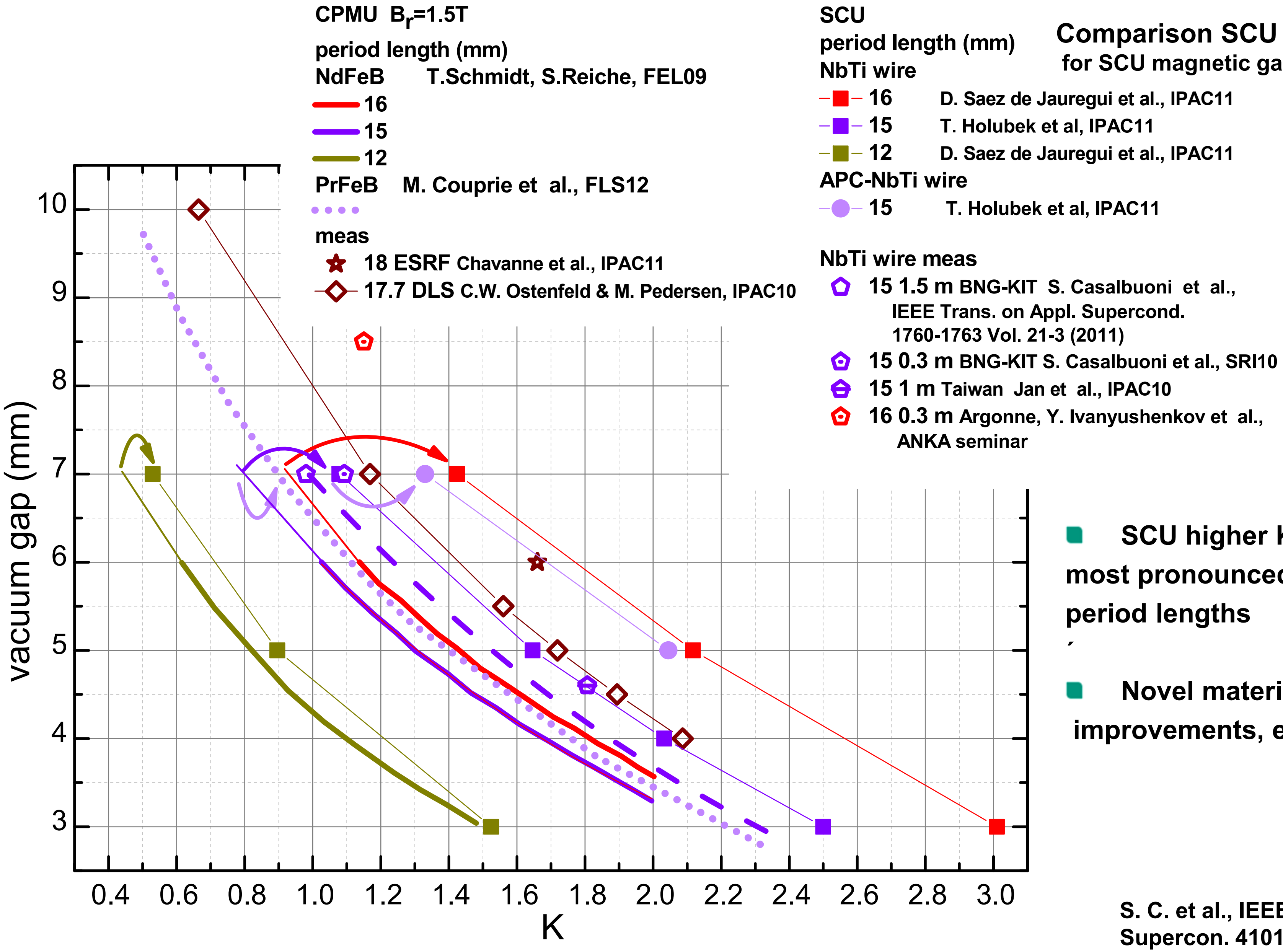


PETRA III
U29
10m-ID
UE65
SCU15
ANKA
UPGRADE
U28-50
U41
U17
ANKA
UE112
BESSY II
SCU15
BM
SCW18-54
7T MPW
W74
BM
Brilliance [1/(s mrad^2 mm^2 0.1% BW)]
Photon Energy [eV]

Motivation R&D of scIDs

Comparison SCU - CPMU

for SCU magnetic gap = vacuum gap + 1 mm



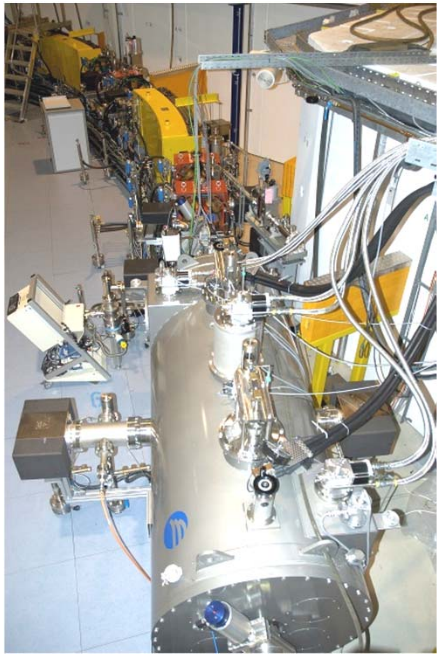
- SCU higher K CPMU, most pronounced for longer period lengths
- Novel materials give further improvements, especially for SCUs

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

Experience at ANKA: SCU14 demonstrator

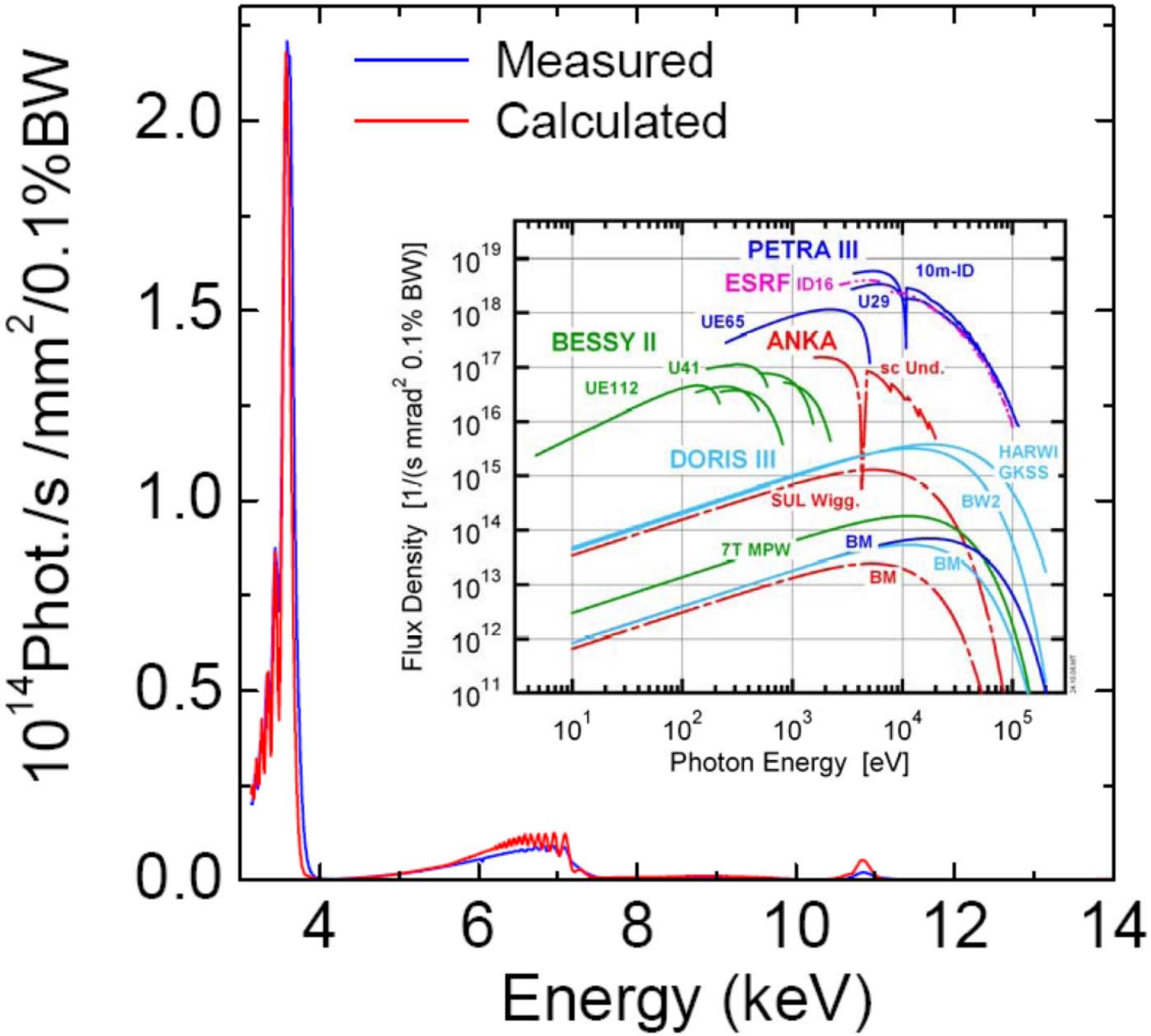
Proof of principle of scu technology first time worldwide demonstrated at ANKA (2005)

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

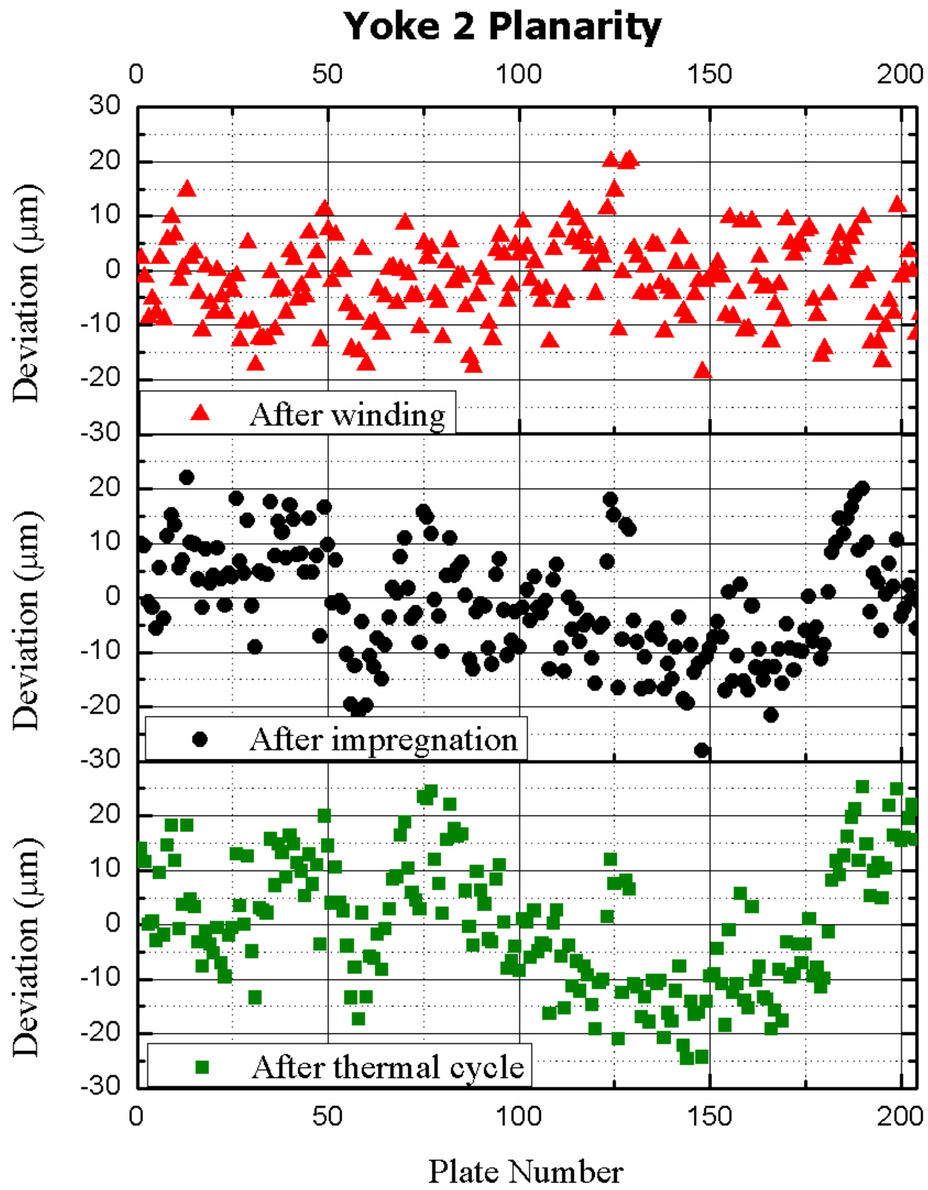


Outcome used:

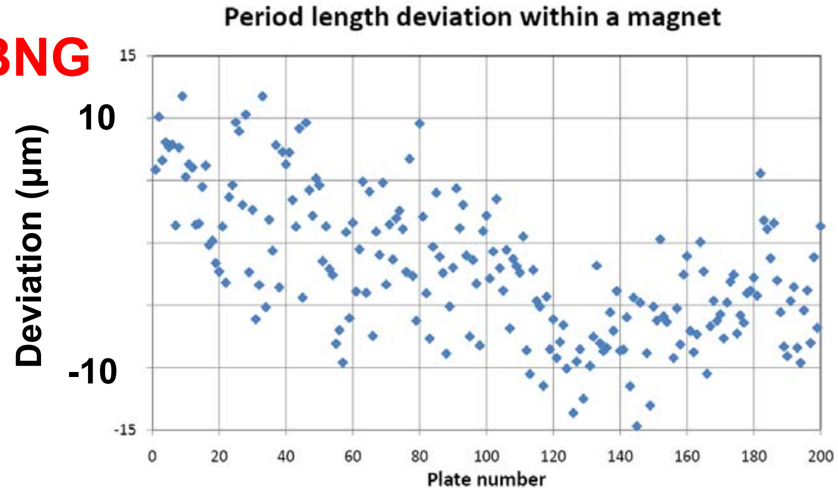
•to measure beam heat load to a cold vacuum chamber at ANKA
•to **improve the design of next generation sc undulators**

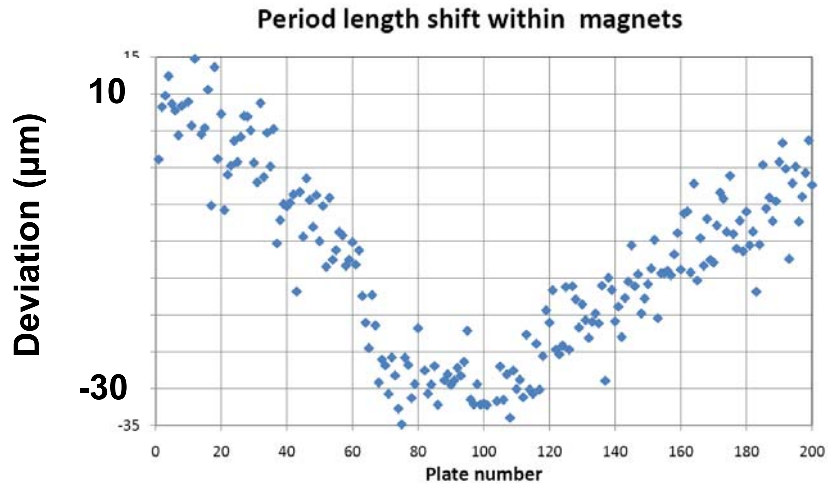


Accuracies measured @300K



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

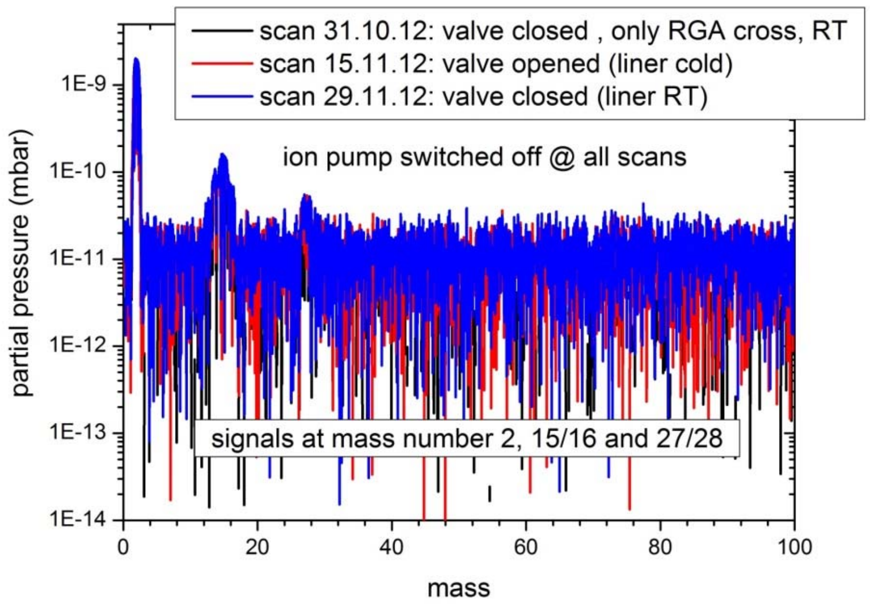
C. Boffo et al., IEEE Trans. on Appl. Supercond. 1756-1759 Vol. 21-3 (2011)

SCU15DEMO: beam vacuum chamber

Challenges:

- Must withstand UHV radiation hard environment
- Resistive losses must be kept as low as possible
- Must move: it needs to open to 15 mm during electron beam injection and energy ramping in the ANKA storage ring

The chamber has been manufactured and successfully withstood the vacuum test reaching < 3 x 10^{-10} mbar in cold conditions



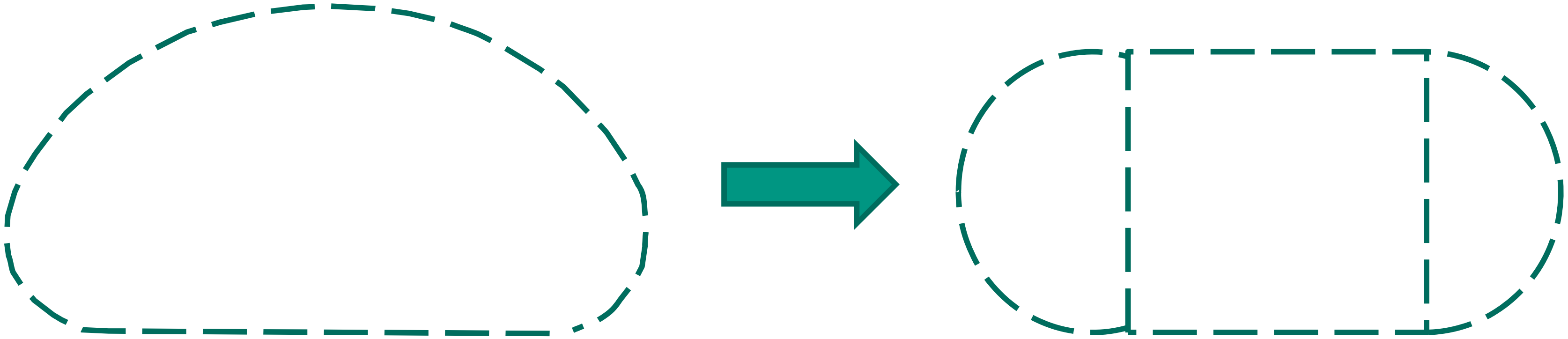
SCU20

- Lessons learned from previous development of 1.5 m long undulator coils:
  - rectangular wire 0.54 mm x 0.34 mm — round wire diameter 0.76 mm
  - cobalt-iron yoke — low carbon stainless steel
  - plates made of one pole and one groove — blocks $\simeq$ 0.15 m

- Optimization of coils performance by varying winding pack geometry to minimize:
  - required wire current to achieve specified peak B on axis
  - magnetic field on the conductor at maximum required wire current

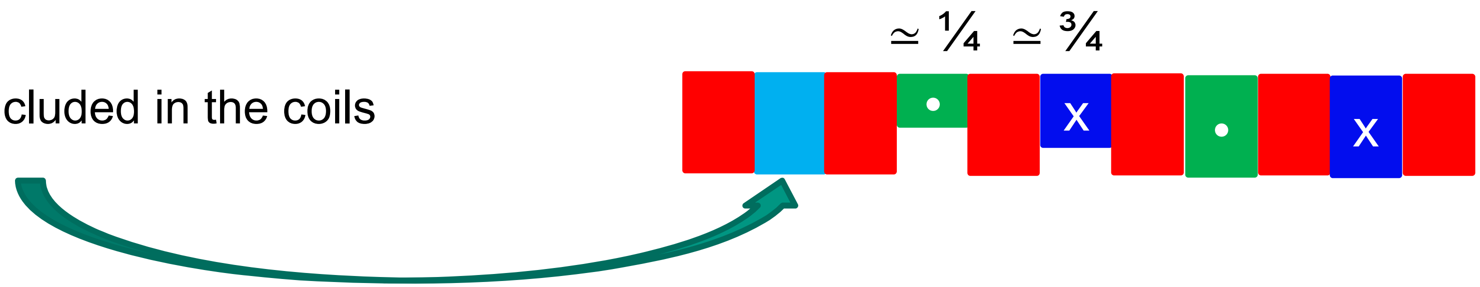
SCU20

- Racetrack shape to reduce multipoles

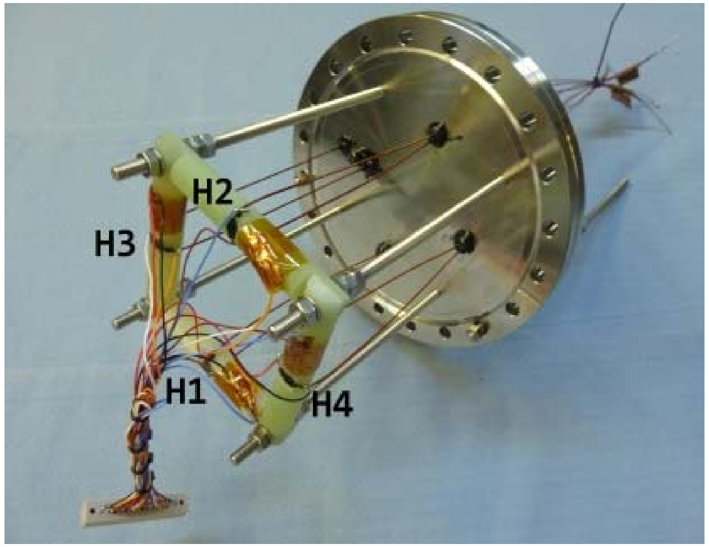


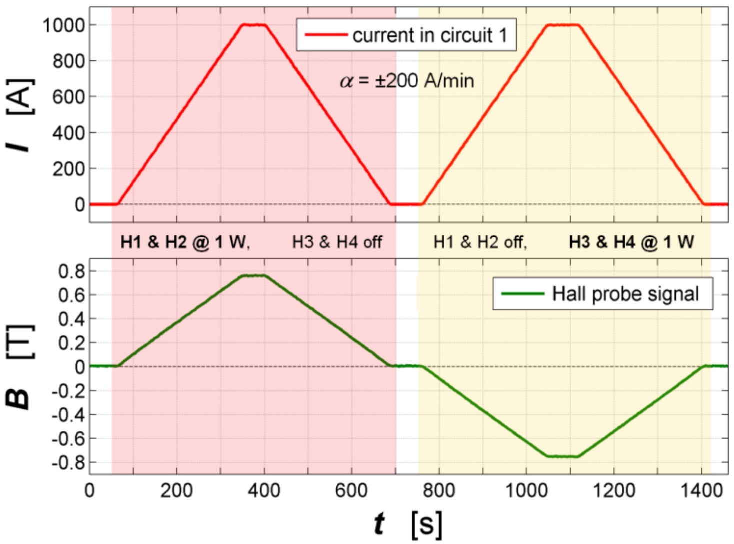
- New winding scheme: from one groove to the next changing winding direction. Staggering removed to avoid possible unwanted increase of field integrals and a reduction of on axis B quality

- Correctors included in the coils



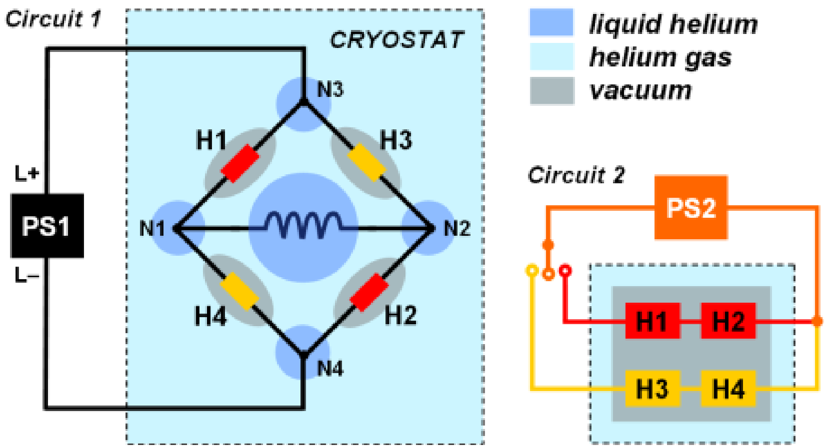
Superconducting switch





Aim:
use only one power supply instead of several for the different circuits, reducing the thermal input to the device

Applications:
- **period length switch (i.e., SCUW)**
- **active shimming**



Minimum power dissipation of 200 mW per heater, demonstrated in an ad hoc conduction cooling setup in CASPER I

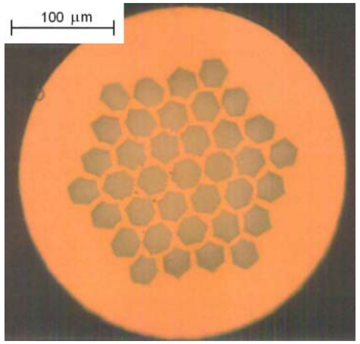
T. Holubek et al., IEEE Trans. on Appl. Supercond. 3800104 Vol. 23-3 (2013)

Minimum power dissipation can be further reduced: Ongoing additional tests in CASPERII

Bundesministerium für Bildung und Forschung

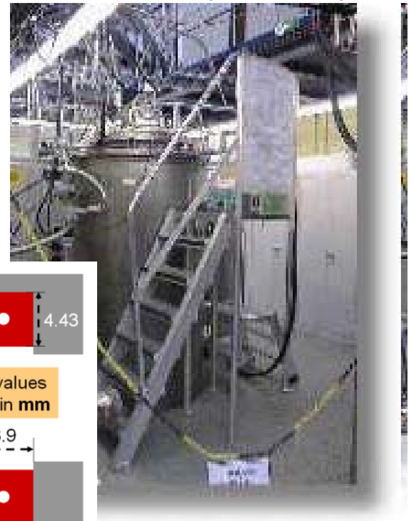
Application of other materials: NbTi wire with artificial pinning centers

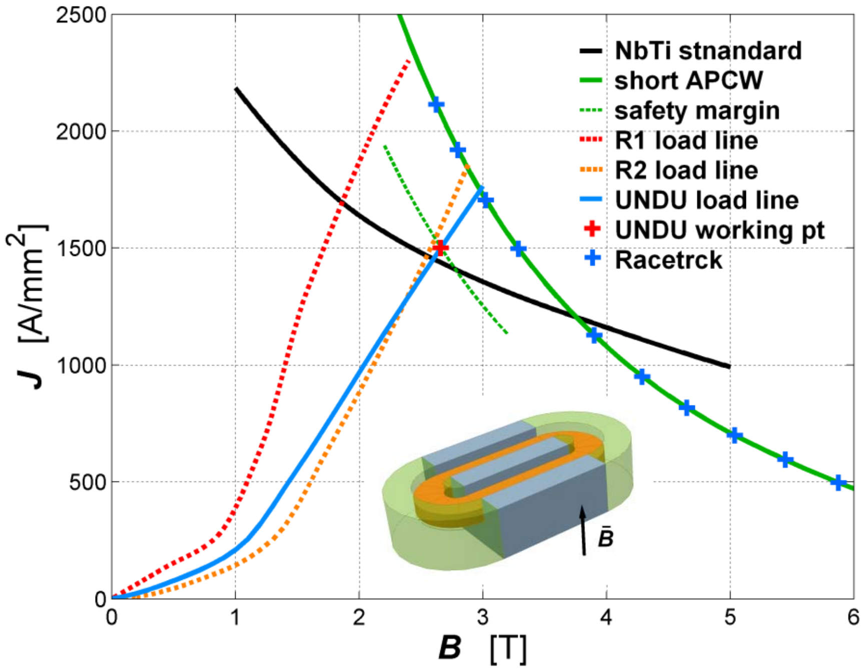
ANKA collaboration with ITeP (Th. Schneider and M. Kläser, KIT) and SupraMagnetics, Inc., USA

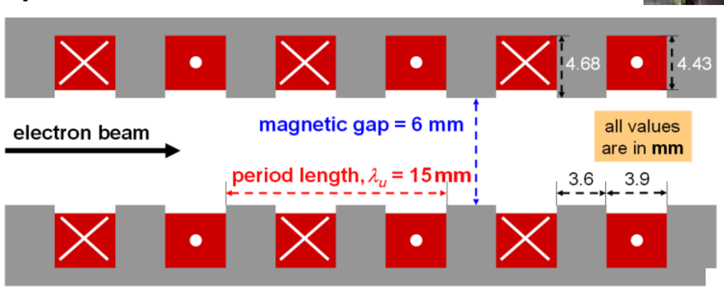


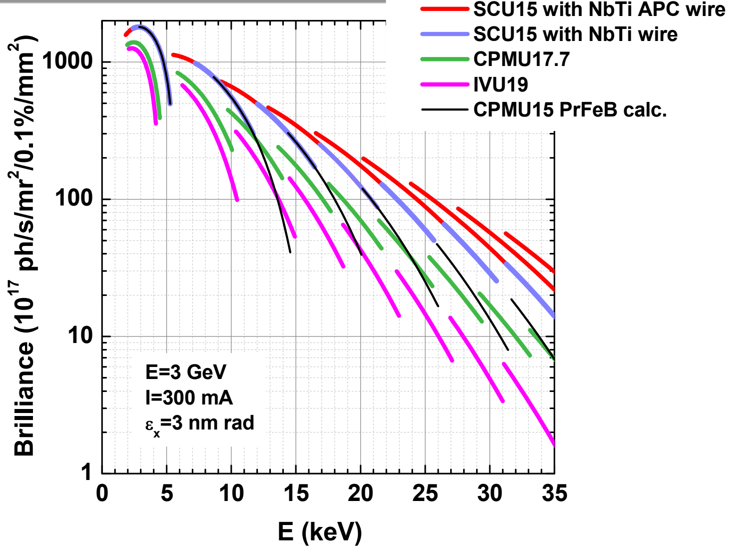
NbTi with artificial pinning centers wire developed by SupraMagnetics, Inc., USA:
outer diameter = 0.31 mm
Including insulation = 30 µm,
Cu/SC= 2.125
37 filaments with diameter = 21 µm

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









T. Holubek et al.,
Physics Procedia 36 1098 – 1102 (2012)