# Undulator technologies for future FEL facilities / Storage rings

Marie-Emmanuelle Couprie (Synchrotron SOLEIL)

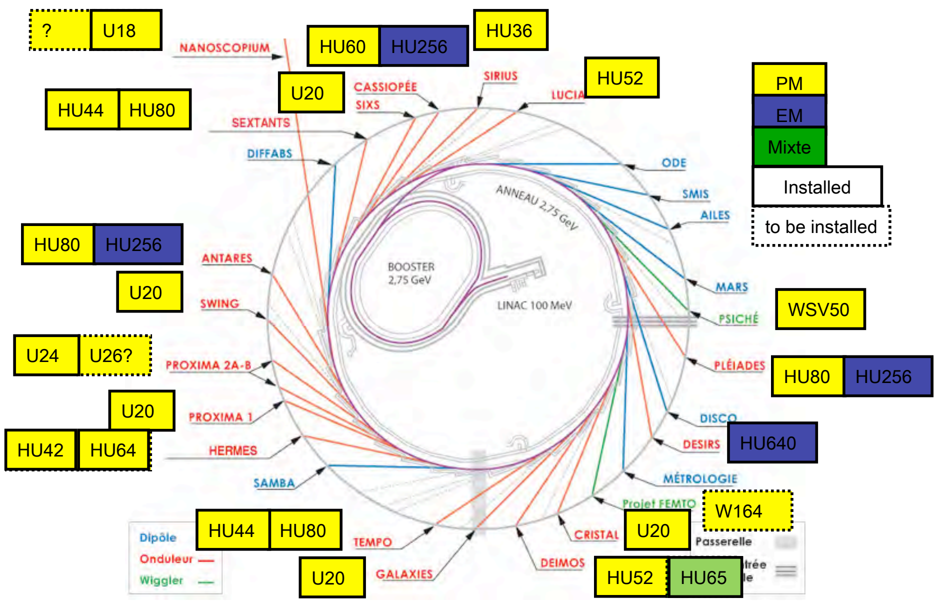
Acknowledgments : J. Chavanne (ESRF), Y. Ivanyushenkov (APS), S. Casualbuini (KIT, ANKA), O. Chubar (BNL), F. Ciocci (SPARC), my group

Tribute to P. Elleaume († 2011, March 19)

# Synchrotron Radiation Light source

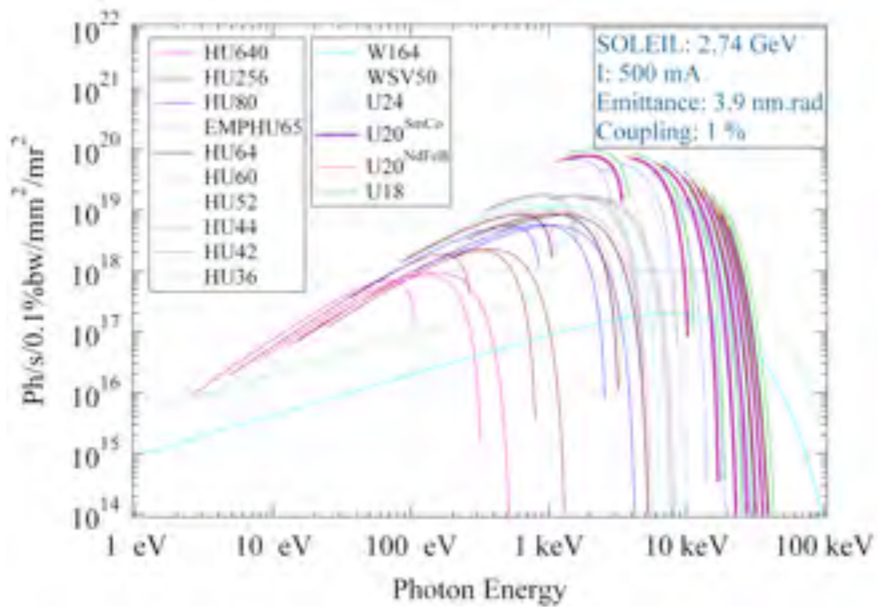
Medium energy storage rings : SOLEIL, DIAMOND, CLS, ALBA, TPS, Australian Synchrotron, NSLS II, MAX IV....
High energy storage rings : SPring-8, ESRF, APS, PETRA III, PEP-X
Towards USR

the SOLEIL example




2.75 GeV, emittance 3.7 nmrad, 500 mA
20-3 ps + femto-slicing project under way

*A. Nadji et al., IPAC 2011, San Sebastian, Spain, 3002-3004*




Brilliance calculated with SRW

*O. Chubar, P. Elleaume, Proc. EPAC-98, 1177.*
*O. Chubar et. al., Proc. SPIE 4143 (2000) 48; SPIE 4769 (2002) 145.*

# Free Electron Lasers

Medium energy linacs for soft X-ray FELs : FLASH, FERMI@ELETTRA ...
High energy linacs for hard X-ray FELs : LCLS, SACLA@SPring-8, E XFAL, Swiss FEL, Pohang FEL

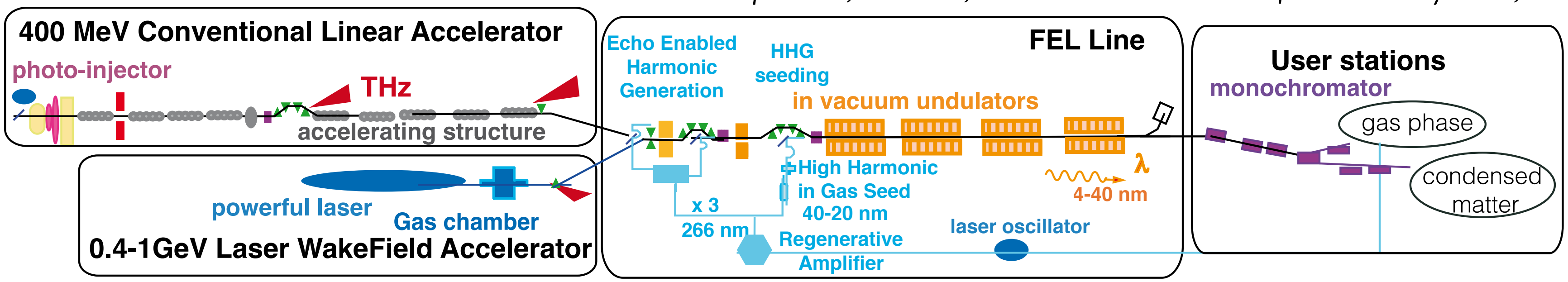
*project* operating FEL *VUV- soft X ray* *hard X ray*

# I- Introduction

## Towards the use of Laser Wakefield Accelerator

free electron Laser Using a New accelerator for the Exploitation of X-ray radiation of 5th generation

*M.E. Couprie et al., IPAC 2011, Proced. 13th International Conference on X-ray Lasers, Paris, June 11-15, 2012*

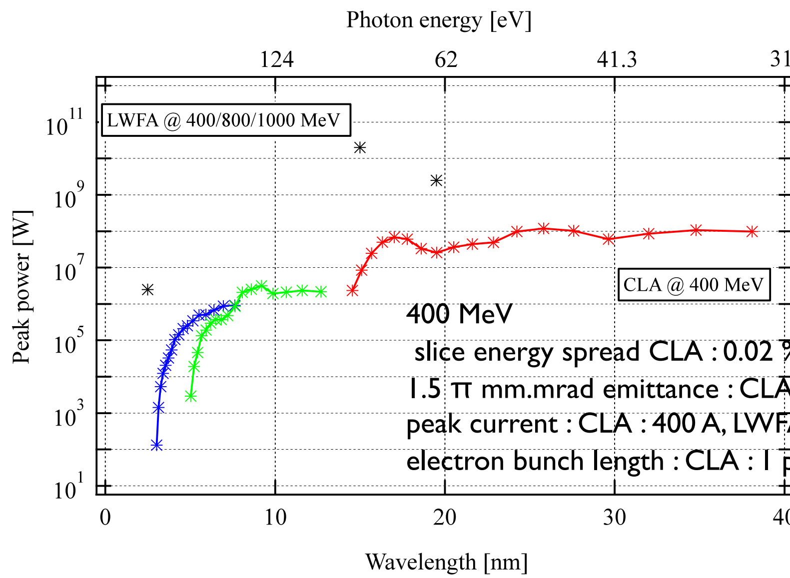



40-4 nm, 20 fs and shorter

0.4-1 GeV, emittance 1 π nmrad, 1 ps - 10 fs

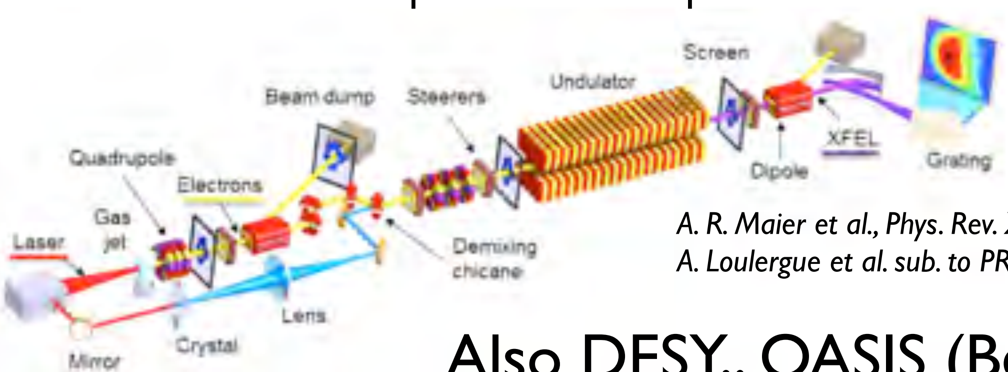
4G+ : towards full temporal and transverse, short pulses, multi-FEL lines to be validated by, 5G: (Conventional Linac replaced by a LWFA), FEL being viewed as an qualifying LWFA application

pilot user experiments




400 MeV
slice energy spread CLA : 0.02 %, LWFA : 0.1 %
1.5 π mm.mrad emittance : CLA : 1.5, LWFA 1
peak current : CLA : 400 A, LWFA : 10 kA, 50 pC
electron bunch length : CLA : 1 ps, LWFA : 2 fs

electron beam transport for FEL amplification




*A. R. Maier et al., Phys. Rev. X 2, 031019 (2012)*
*A. Loulergue et al. sub. to PRL*

*T. Togashi et al., Optics Express, 1, 2011, 317-324*
*G. Lambert et al., Nature Physics Highlight, (2008) 296-300*
*G. Stupakov., PRL 102, 074801 (2009)*

Also DESY,, OASIS (Berkeley), Stratclyde et al.

# Accelerator type issues for insertion devices

| | storage ring | linac / ERL | LWFA |
|---|---|---|---|
| Emittance | $E^2$ | 1/E | |
| Beamsize (µm) | 100 (H)-10 (V) | 50-10 | 10-3 |
| vacuum chamber H /V aperture | flat<br>min gap: 5 mm | round (ex : bore 5 mm), min gap : 3 mm | round |
| charge | high | 1 nC | 10 pC |
| Pulse duration | 10 ps | 100 fs | 10 fs |
| impedance | very critical | critical | critical |
| field integrals | very critical | very critical | very critical |
| double field integrals | very critical | very critical | very critical |
| phase error | very critical for high harmonics operation | critical | critical |
| multipoles | for beam lifetime and injection efficiency | less critical | not critical |

# Multipolar terms for storage rings

P. Brunelle, SOLEIL

Dipolar terms: field integral
FFWD tables
Fast/slow orbit feedback to keep to source position and divergence in 10% of the beam size
Dynamic field integral compensation

*J. Safranek et al, Phys. Rev. Special Topics (2002), Vol. 5, 010701*
*O. Marcoullé et al, IPAC 2011, 3236*

Sextupolar terms=> chromaticity

Quadrupolar terms:
normal quadrupoles => tune shift => feedback on the tunes, or FFWD tables
Skew quadrupoles => coupling
Compensation : current sheet for APPLE-II devices

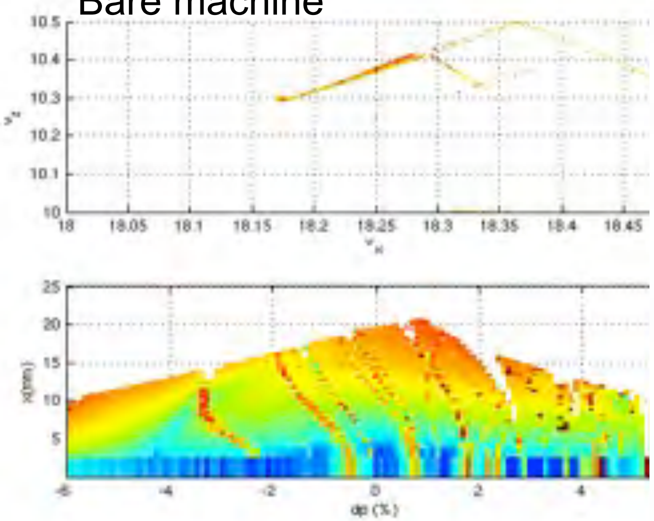
*J. Bahrdt, et. al., "Active shimming of the dynamic multipoles of the BESSY UE112 Apple Undulator", Proceedings of EPAC'08, p. 2222 (2008).*

Magnetic field maps (RADIA; measurements)
TRACY electron beam simulation (on and off momentum) for injection efficiency and lifetime study

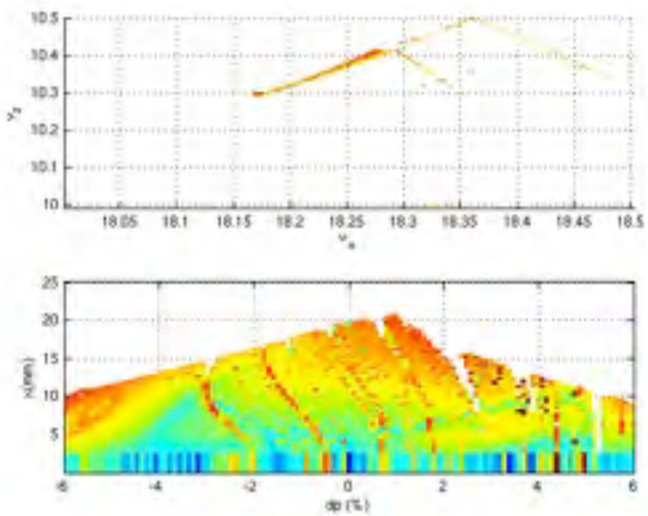
*SOLEIL HU36 undulator located in a short straight section (betax = 17.8 m)*

Measured lifetime : bare machine, 19.4 h@400 mA => 14.3 h, RP configuration 7.8 h => 6.6 h

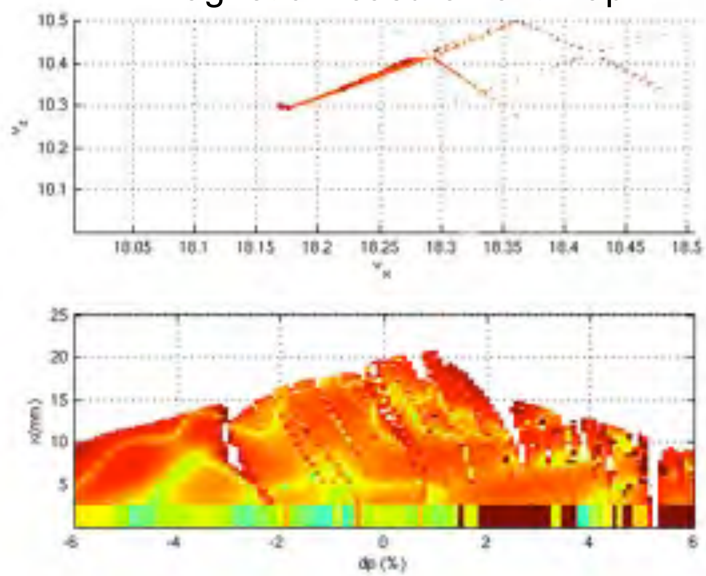
Bare machine



2nd order kick map from RADIA

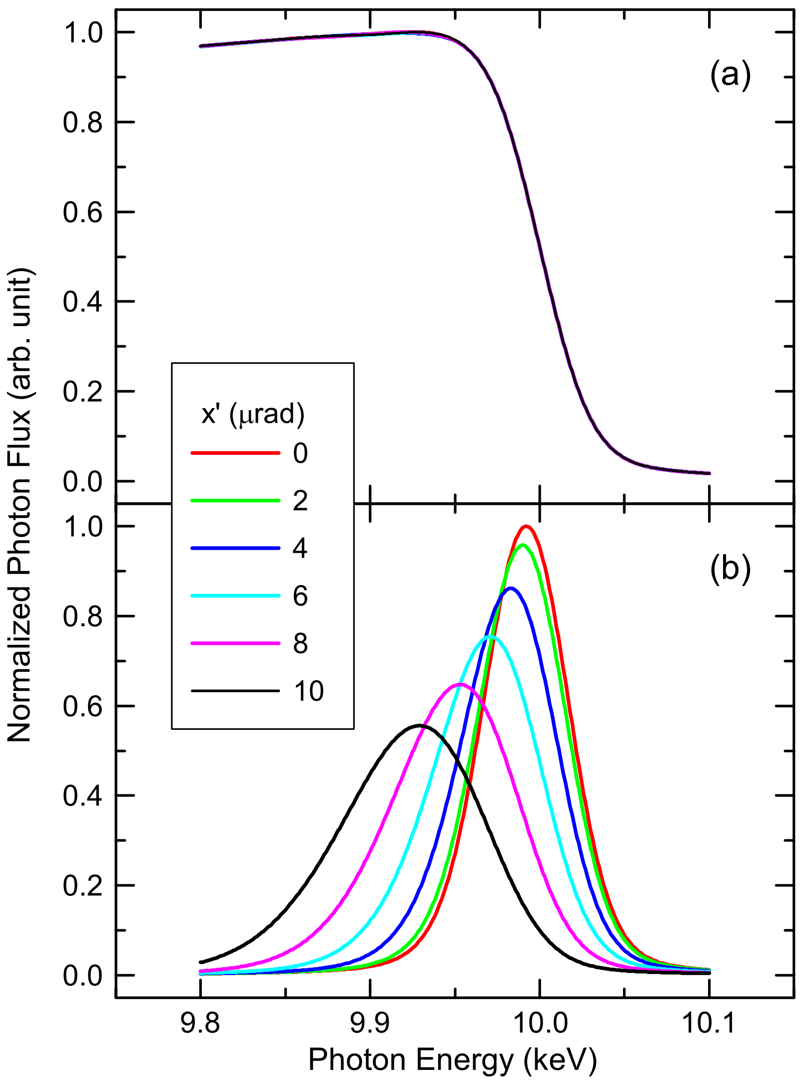


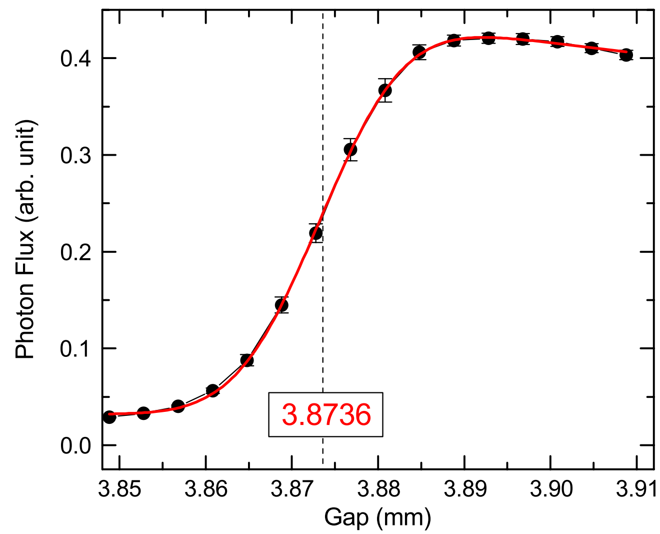
2nd order kick map from RADIA + magnetic measurement map



# Undulator adjustment for FEL

Example of gap tuning of the different segments

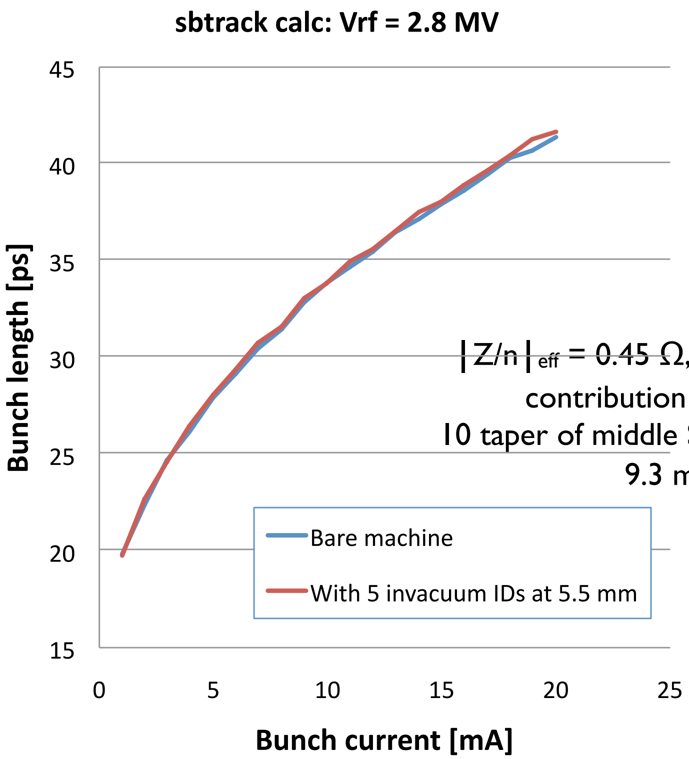


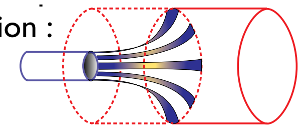

*T. Tanaka et al., Undualtor commissioning by characterizaiton of radiation in x-ray free electron lasers, Phys. Rev. Spe. Topics AB 15, 110701 (2012)*

# Impedance issue & e-beam induced heat load

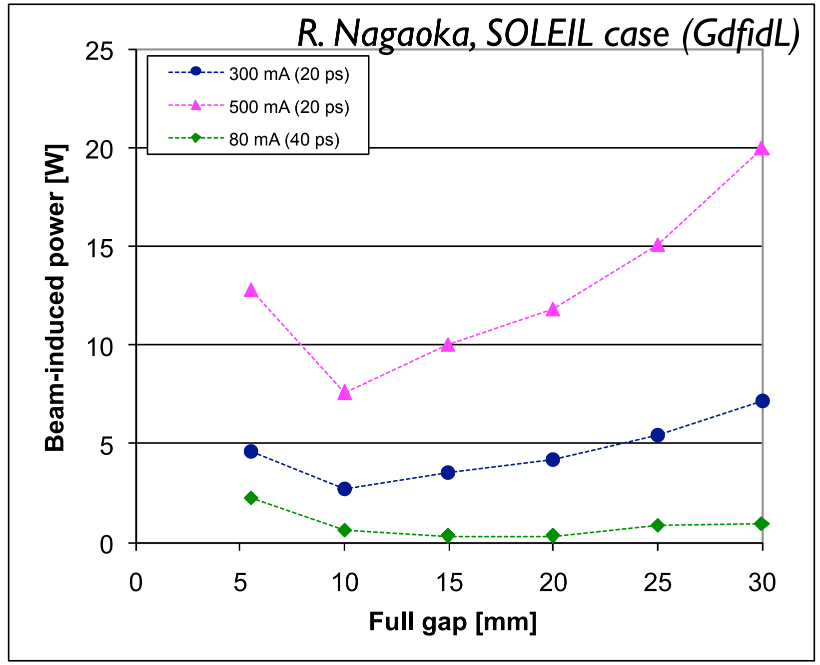
Need to avoid discontinuity in vacuum chamber
=> transition for in-vacuum system



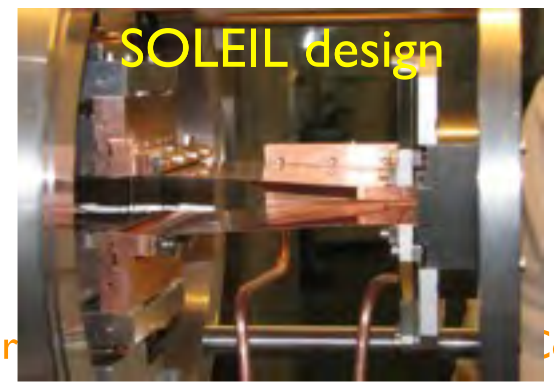

|Z/n|$_{eff}$ = 0.45 Ω, 5 in vacuum ID
contribution : 11.6 mΩ
10 taper of middle SS contribution :
9.3 mΩ

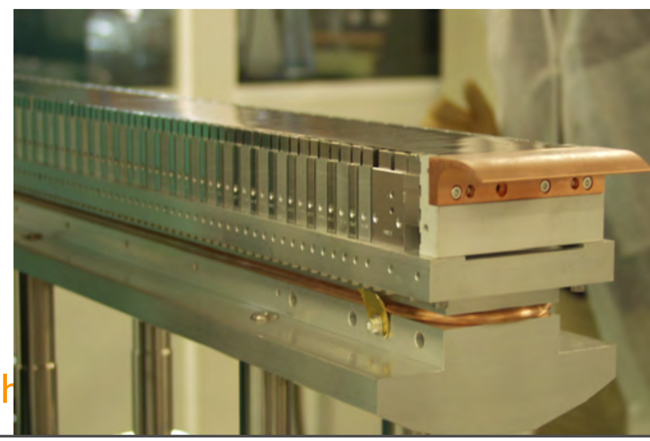


*T. Nakamura et al. PAC 2001, 1969*




e-beam heat load
=> conductive foil to prevent
from image current

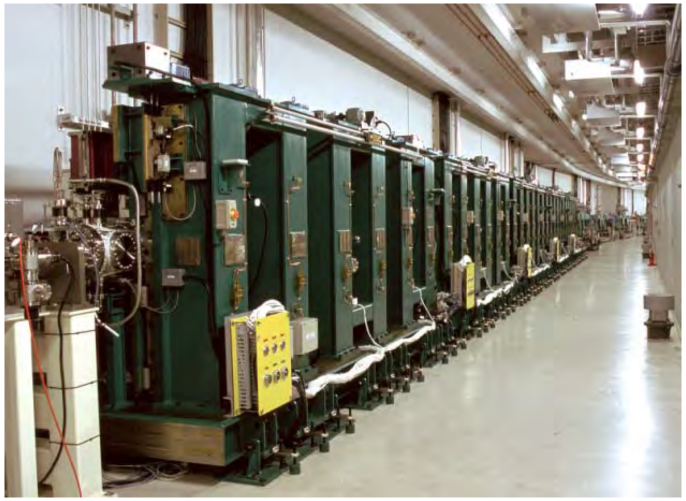
# In-vacuum undulators

Motivation : reach a higher field by placing directly the magnets inside the vacuum chamber

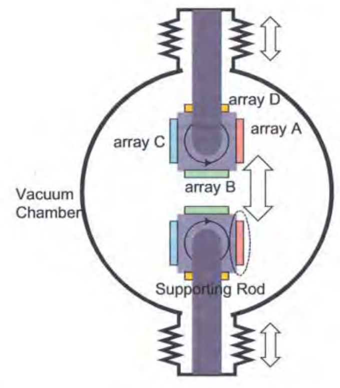
Historical steps :

• First prototype at BESSY
*W. Gudat et al. NIMA 246, 1986 50*

• First In vac. undulator Installed on TRISTAN AR, Period : 40 mmX90, NdFeB (Br=1.2 T, iHc=21kOe), min gap 10 mm, B=0.82-0.36 T, NEG and sputter ion pumps, magnet stabilization at 125°C and vacuum commissioning at 115°C, *S. Yamamoto et al. Rev. Sci. Instr 63, 400 (1992)*



• 30 m long in-vacuum undulator at SPring-8 (SLUS-1) :
32 mm x 780, min gap = 12 mm (betaV = 15 m) B=0.59 T
5 segments without gaps, very fine adjustments of the gap segments for phase error (11°=> 3.6°)
*H. Kitamura et al., NIMA 467 (2001) 110; T.Tanaka et al. NIMA 467, (2001) 149*




• Revolver in-vacuum undulator (INVRUM) :
6 mm x 133, 10 mmx100, 15 mmX66, 20mmx50; min gap = 3.2 mm, B=0.74, 1.07, 1.32, 1.44 T
*T. Bizen et al. AIP 705, (2004), 175, 18th International Conference on Synchrotron Radiation Instrumentation, San Franscisco, 2003 417, H.S. Kang et al., EPAC 2006, 2771*

Pure Permanent magnet configuration to Hybrid technology *K. Halbach, Jour. Physics, 44 (1983) 211*

# Magnet choices

• high remanence magnets

$Sm_2Co_{17}$ : $B_r \leq 1.05$T; $\mu H_{cj} = 2.8$ T;
$Nd_2Fe_{14}B$ : $B_r \leq 1.4$T (1.26T); $\mu_o H_c = 1.4$-$1.6$ (resp. 2.4 T)

$B_r$<1.26T to maintain sufficient coercivity to avoid demagnetisation (baking, irradiation (GeV electrons, high energy photons and gamma-rays, neutrons))

+ Machine protection for the IVU to avoid magnet degradation, cases ESRF, APS

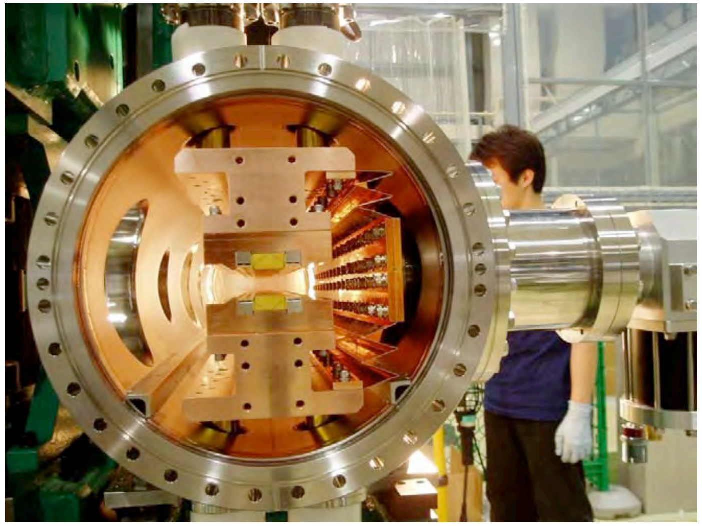
Possible use of Dysprosium poles instead of Vanadium Permendur poles

• cryogenic undulator

- increase of remanent field and coercivity at low temperature
- operation at liquid nitrogen temperature => manageable heat budget
- easy operation on synchrotron light sources

Cryogenic undulator with high Tc superconductors

*T. Tanaka et al. PRSTAB 7, 090794 (2004)*



*T. Hara, T. Tanaka, H. Kitamura, T. Bizen, X. Maréchal, T. Seike, T. Kohda, Y. Matsuura, Phys. Rev. Spc. Topics 7, 050702 (2004)*

# Magnet choices

Temperature coefficients :

$\Delta B_r$= 0.11-0.13 % /°C

$\Delta H_{cj}$ = 0.58-0.7%/°C

Spin Transition Reorientation

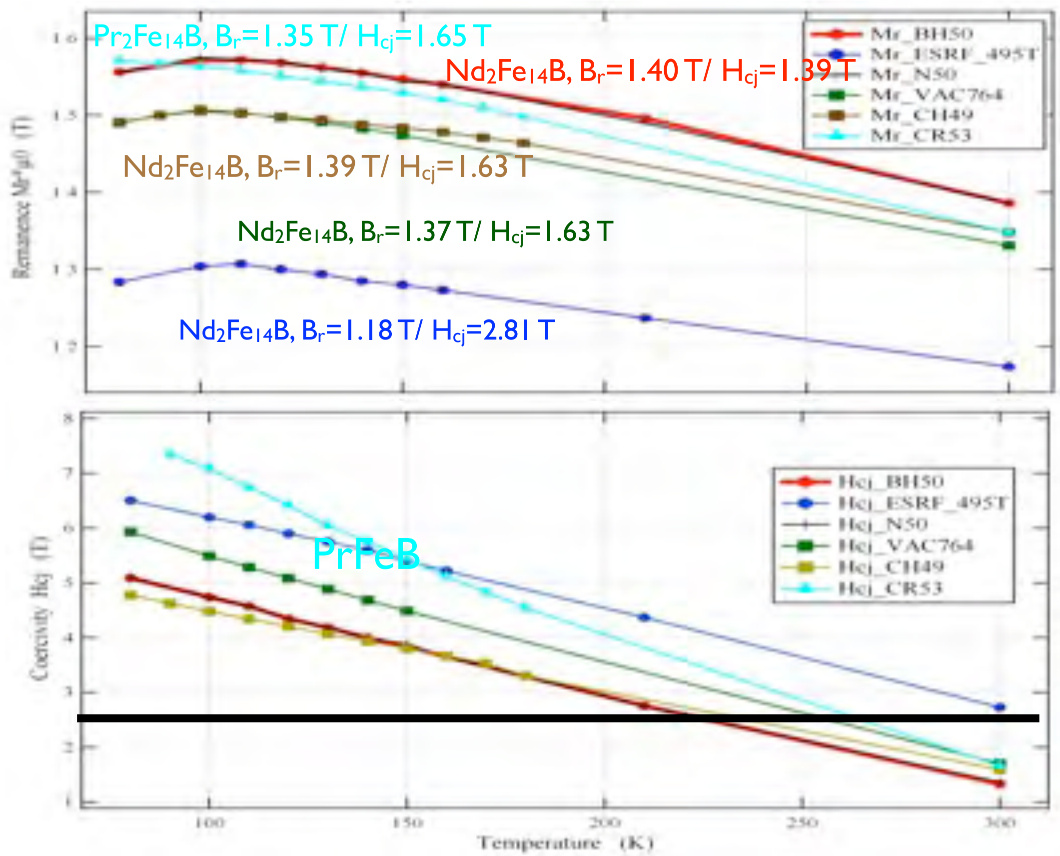
NdFeB strong Magneto-Crystalline Anisotropy (MCA) => orientation along [001]

Magneto-cristalline orientation given by the energy : $E(T) = K_1\sin^2(\theta) + K_2\sin^4(\theta)$ , $\theta$ angle between the magnetisation and [001]

at room temperature : magnetisation // c

Fe MCA independant of T, Nd : $K_1$ // [001] dominant at room T and $K_2$//[110] at low T

=> Variation of the susceptibility vs T




*M. Sagawa et al. J. Magn. Magn. Mater. 70, 316 (1987)*

*T. Hara et al. APAC2004, Gyeongju, Korea, 216*

*D. Givord et al. Solid State Comm. 51 (1984) 857*

*L. M. Garcia et al. Phys. Rev. Lett. 85 (2) 429*

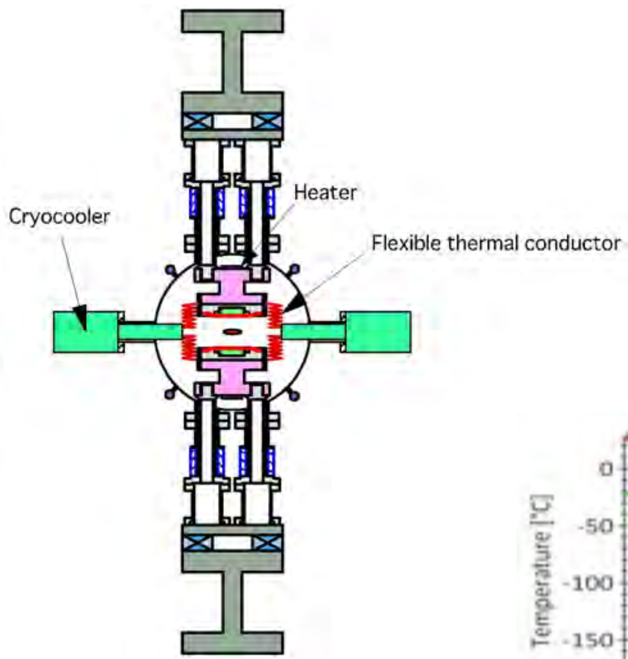
*F. Bartolomé et al. Jour. Appl. Phys. 87, 9, 2000, 4762-4764*

*C. Benabderrahmane et al, NIM A 669 (2012) 1-6*

*K. Uestuener et al., Sintered (Pt,Nd)FEB permanent magnets with $(BH)_{max}$ of 520 kJ/m³ at 85 K for cryogenic applications, 20th Workshop on Rare Earth Permanent Magnets 2008, Crete*

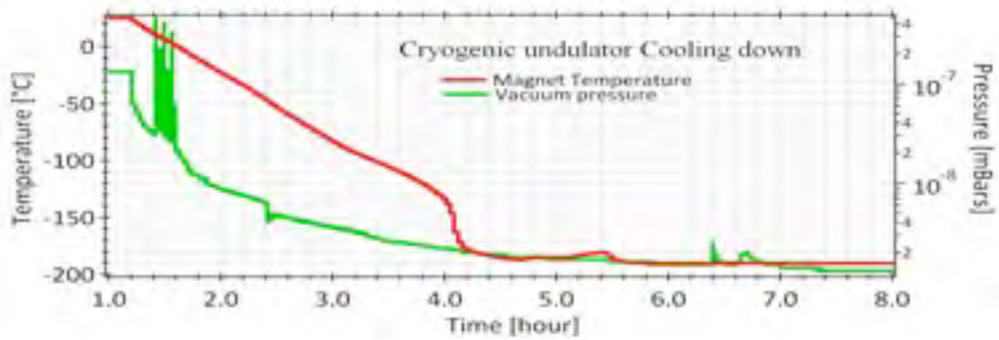
# Cryogenic undulator : cooling

Cryocoolers



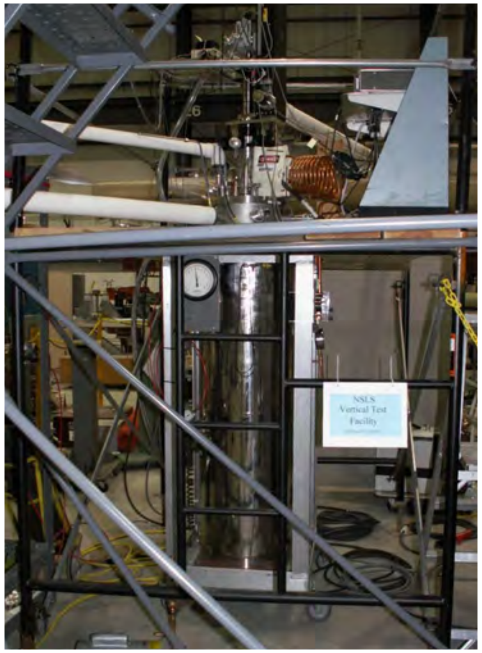

*SPring-8*
*T. Hara et al. Phys. Rev. Spc. Topics 7, 050702 (2004)*

Cryo Cooler: Power 2000 W (<300 W), Liquid LN2, Pump : 30 to 90 Hz (40 Hz), Flow : 1 to 30 l/mn (5 l/mn)



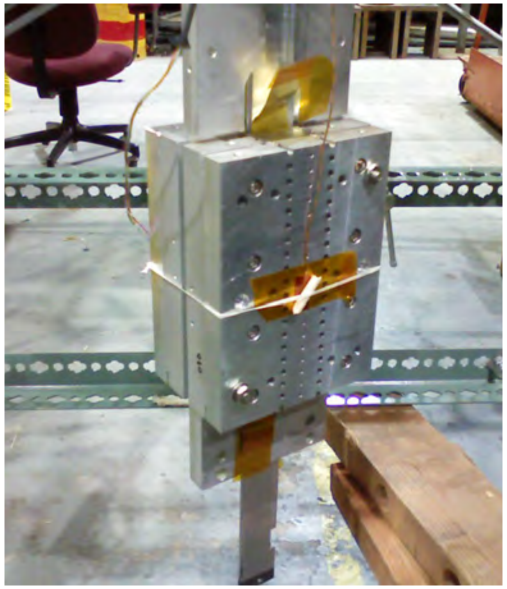

*SOLEIL*
*C. Benabderrahmane et al 7, 050702 (2004)*

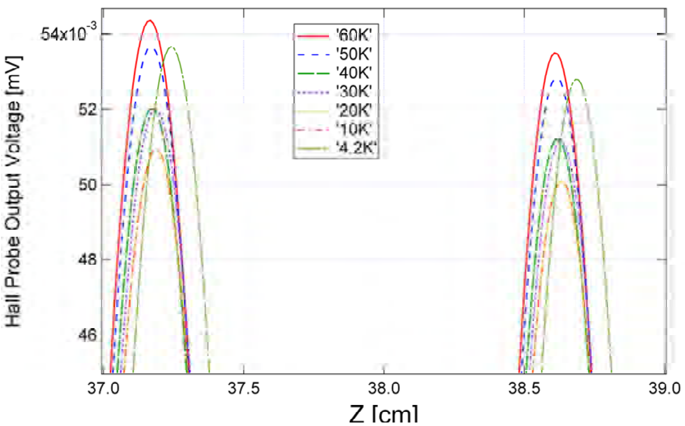
Cooling to He temperature at BNL



# Mini Cryogenic undulators

at NSLS-II

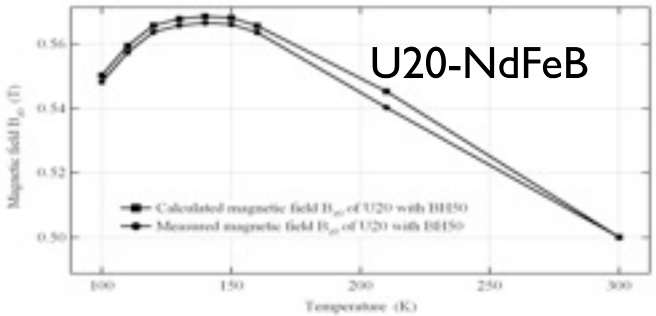


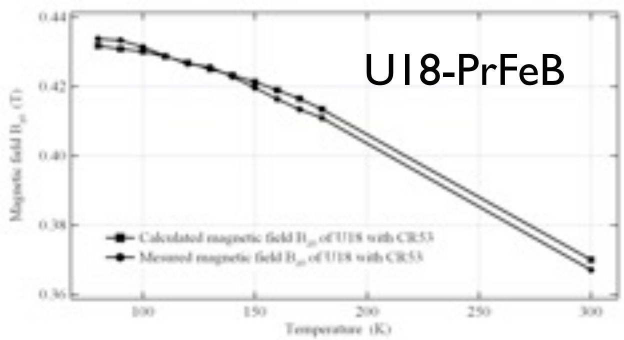


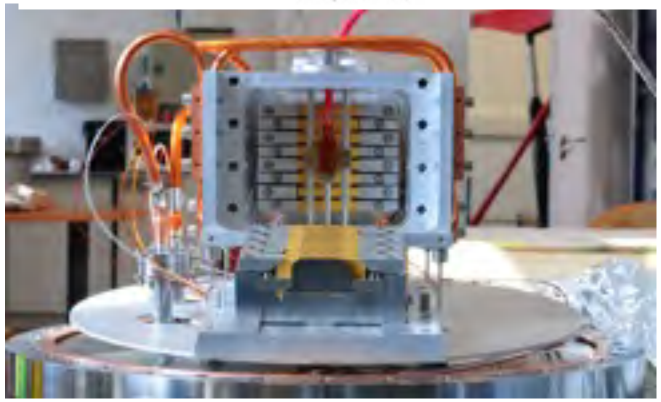

T.Tanabe, et. al., AIP Conference Proceedings, Vol. 1234, p.29 (2010). 4.85 mm gap

at SOLEIL

Validation of magnetic model at low temperature

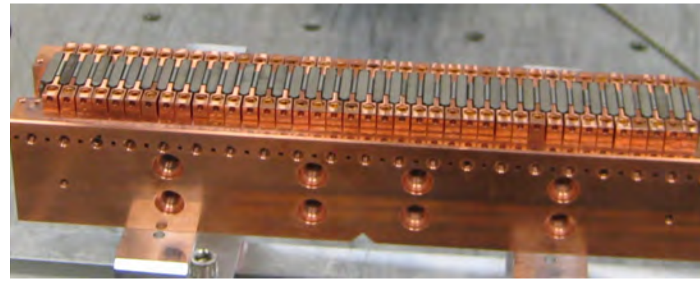


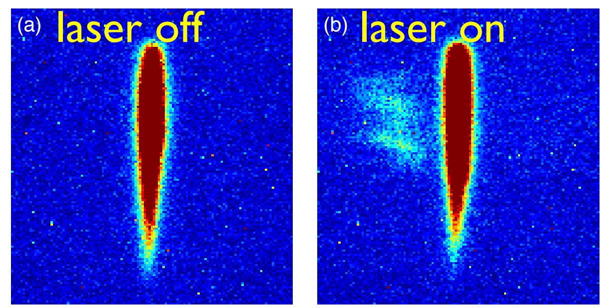
C. Benabderrahmane, P. Berteaud, M. Valléau, C. Kitegi, K. tavakoli, N. Béchu, A. Mary, J. M. Filhol, M. E. Couprie, Nucl. Instrum. Methods A 669 (2012) 1-6

at BESSY/ UCLA



U9-PrFeB, fixed gap : 2.5 mm
20 periods, 11 K, 1.15 T

test on NLCTA (43 K)
bunching observation



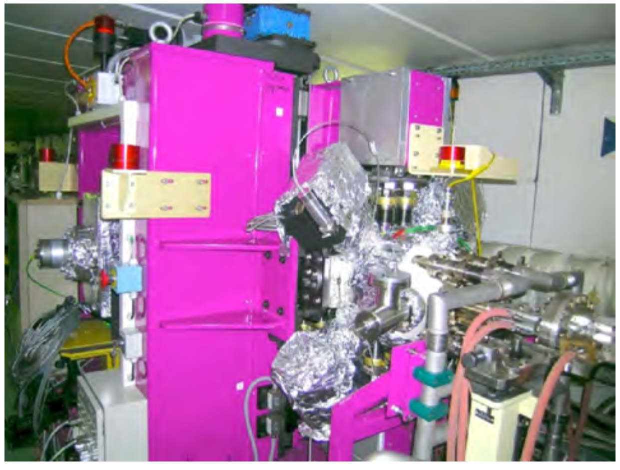

*J. Bahrdt et al. IPAC10, 3111*

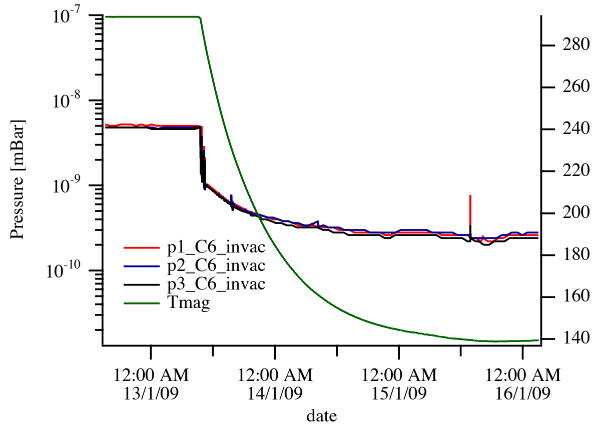
*F. O'Shea et al. PRSTAB 13, 070702 (2010)*

*F. O'Shea, HBEB workshop, Puerto Rico, 2013*

# Cryogenic undulators in operation (3G)

## ESRF (X2)





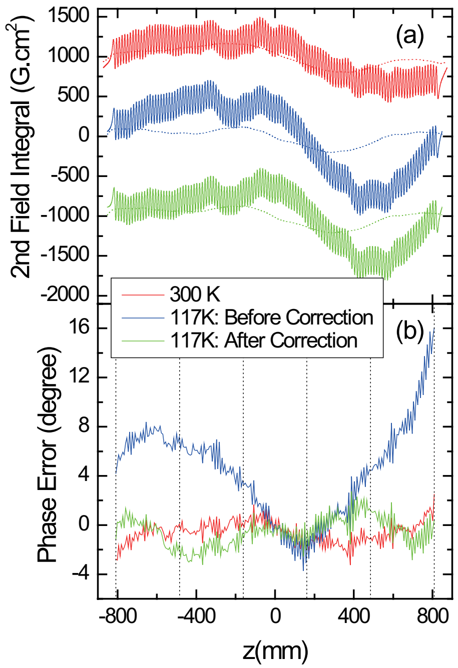

n°1 : U18, $B_r$ = 1.16 T

n°2 : U18, $B_r$ = 1.383 T

*J. Chavanne et al., First operational experience with a cryogenic permanent magnet undualtor at the ESRF, PAC09, 2414*

*J. Chavanne, G. Le Bec, C. Penel, F. Revol, recent progress on insertion devices at the ESRF, IPAC2011, San Sebastian, 3245-3247; Proceeding SRI 2012*

## SLS




U14, $B_r$ = 1.33 T

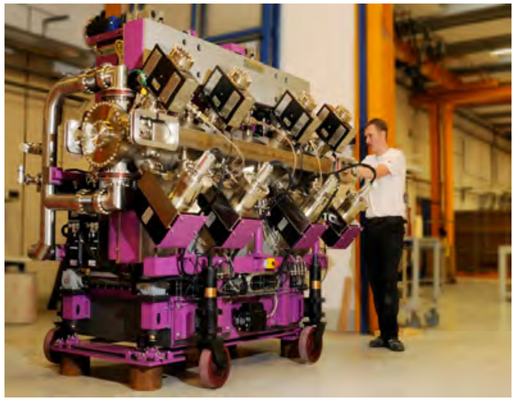
*T. Tanaka et al., IPAC 2010, 3147*

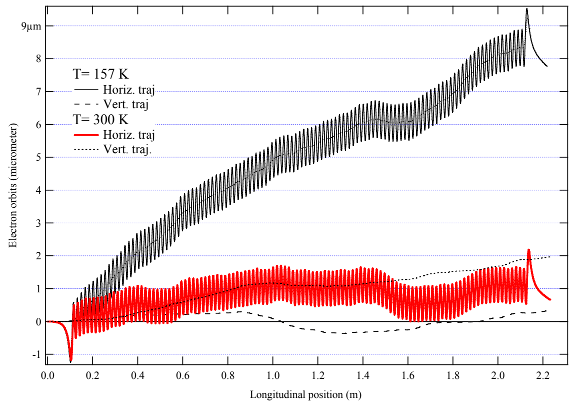
*Tanaka, et al., . Phys. Rev. Spec. Topics 12, 120702 (2009)*

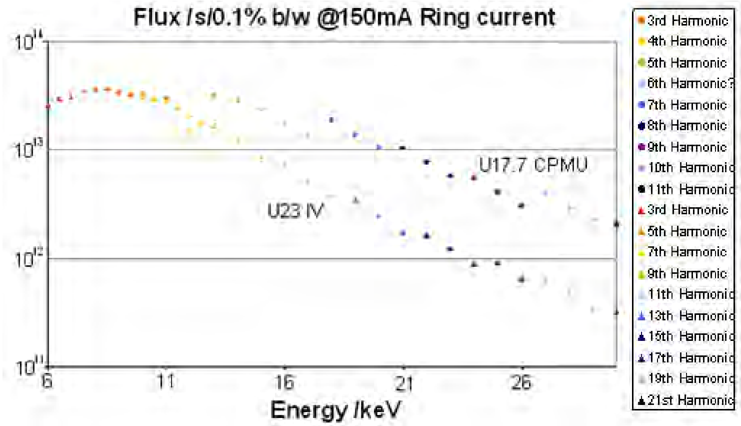
# Cryogenic undulators in operation (3G)

## DIAMOND

NdFeB, operation at 157 K, Non baked, B= 1.04 T@ 4 mm gap $B_r$ = 1.31 T





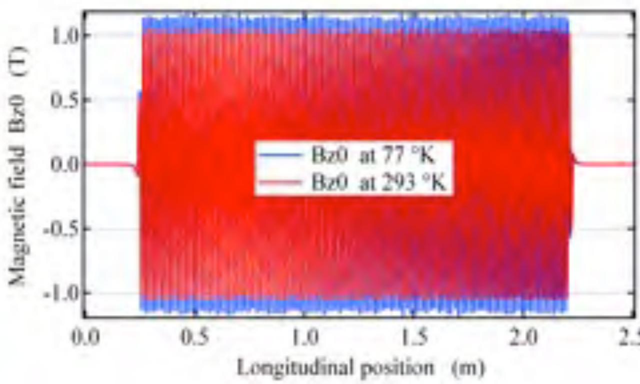



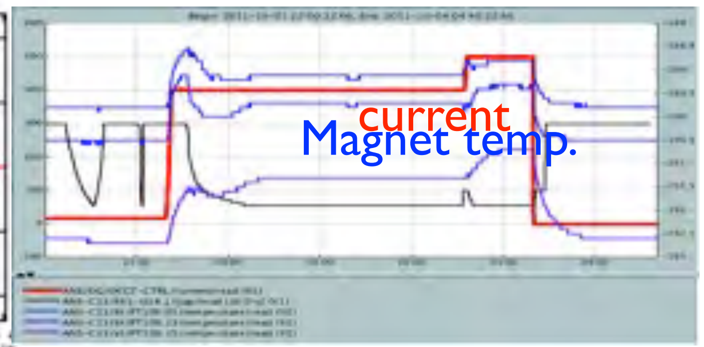

## SOLEIL Cryo U18 PrFeB

operation at 77 K, Non baked, B= 1.16 T @5.5 mm gap

*C. Benabderrahmane et al. IPAC 2011*

U18, $B_r$ = 1.35 T



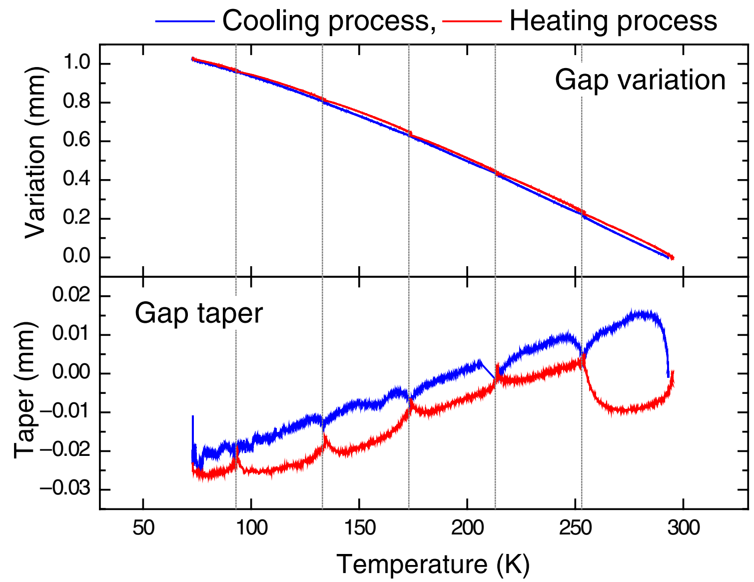

Thermal gradient on the magnetic system **< 1.2 K/m**

Total temperature variation due to electron beam (500 mA) and gap variation **< 2.5 K**

*C.W. Ostenfeld et al., Cryoegnic in vacuum unduator at Danfysik, IPAC2010, 3093*

*J. Schouten et al, Electron beam heating and operation of the cryogenic undulator and superconducting wigglers at DIAMOND, IPAC 2011, 3323*

# Cryogenic undulators : Mechanical changes at low temperature

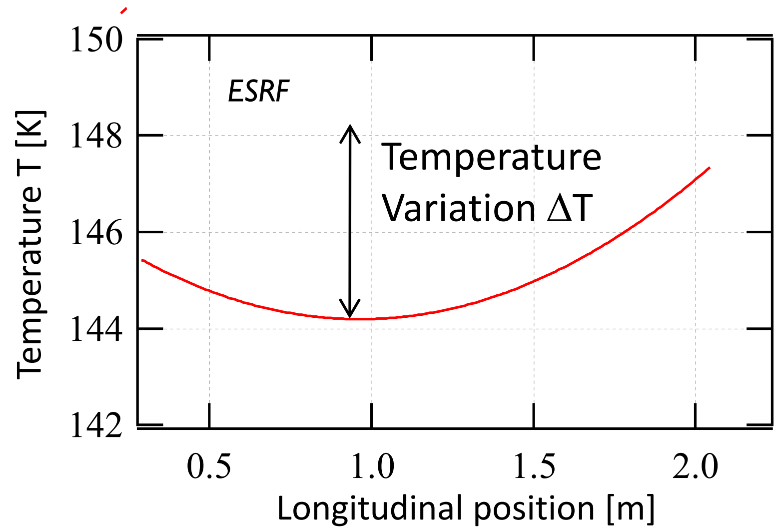



*T.Tanaka et al., New Journal of Physics, Development of cryogenic permanent magnet undulaotrs operating around liquid nitrogen temberature. New Jour. Phvsics 6. 2011. 287*

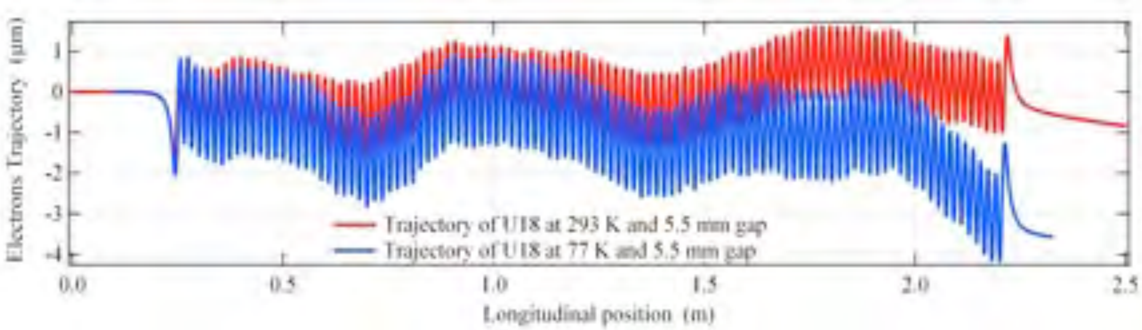
- Gap opening due to thermal contraction of the supporting rods to be compensated
  Measurement :
  Capacitance type displacement monitors (Nantex Corp.) SPring-8
  Wire resistivity : ESRF, SOLEIL

- Period reduction due to girder contraction, ex at SOLEIL 9 mm over 2 m, i.E. 38 µm / period)

- Phase error correction via rod shimming



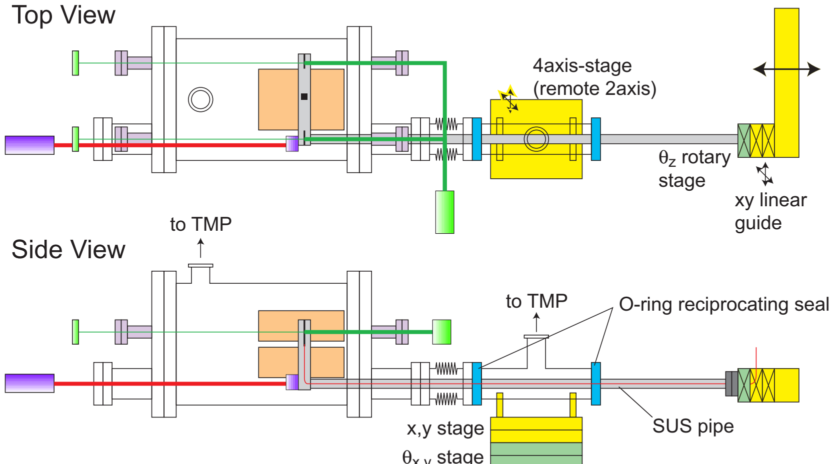

*SOLEIL*

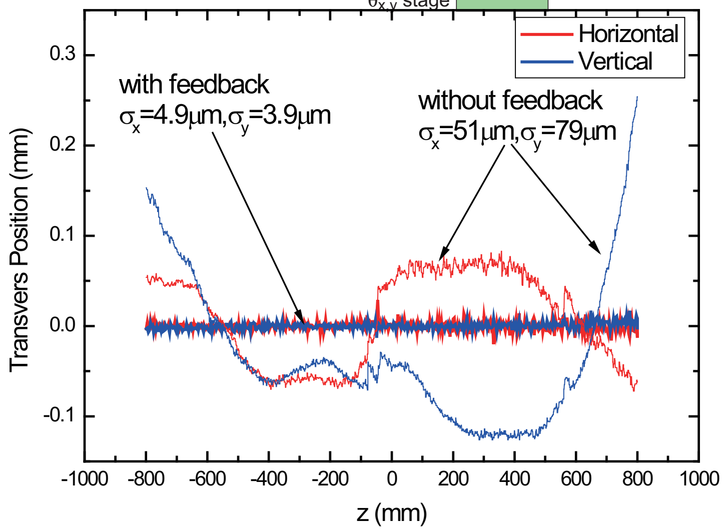


# Cryogenic undulators : Magnetic measurements

## - in situ magnetic measurements

ex : SAFALI (Self aligned field analyzer with laser instrumentation)



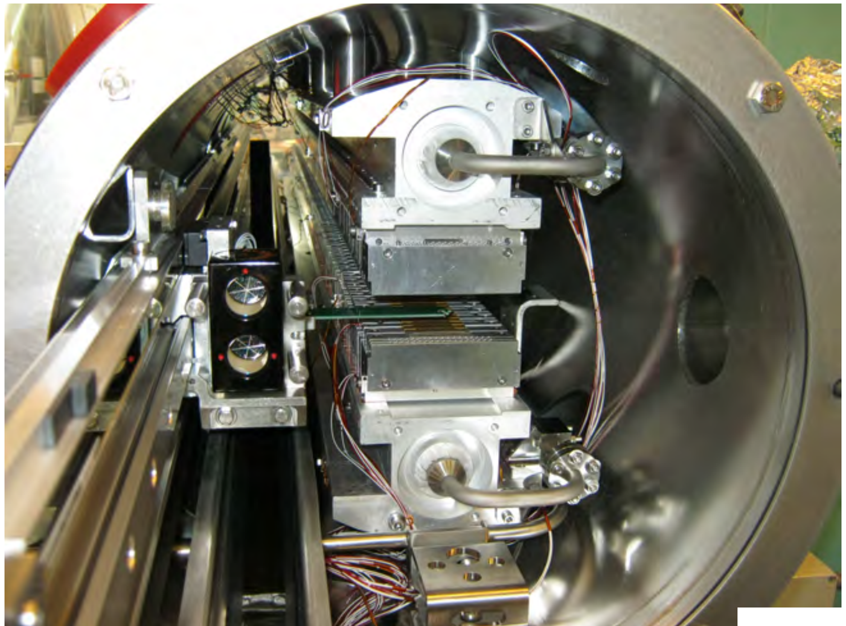




SACLA undulators

*T. Tanaka et al, FEL 2007, Novosibirsk, 468;*
*T.Tanaka et al. FEL 2008, Gyeonju, 371;*
*T. Tanaka, et al., . Phys. Rev. Spec.Topics 12, 120702 (2009)*

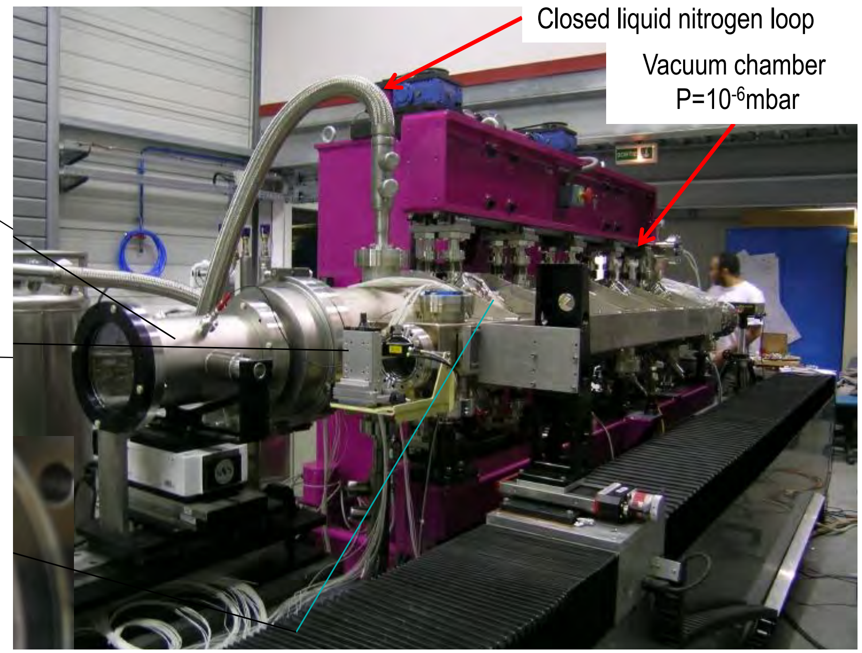
*T. Tanabe, et al., . Design concept for a modular in vacuum probe mapper for use with CPMU convertible in vacuum undulators of varying magnetic length, PAC 2011, 2534*

# Cryogenic undulators : Magnetic measurements



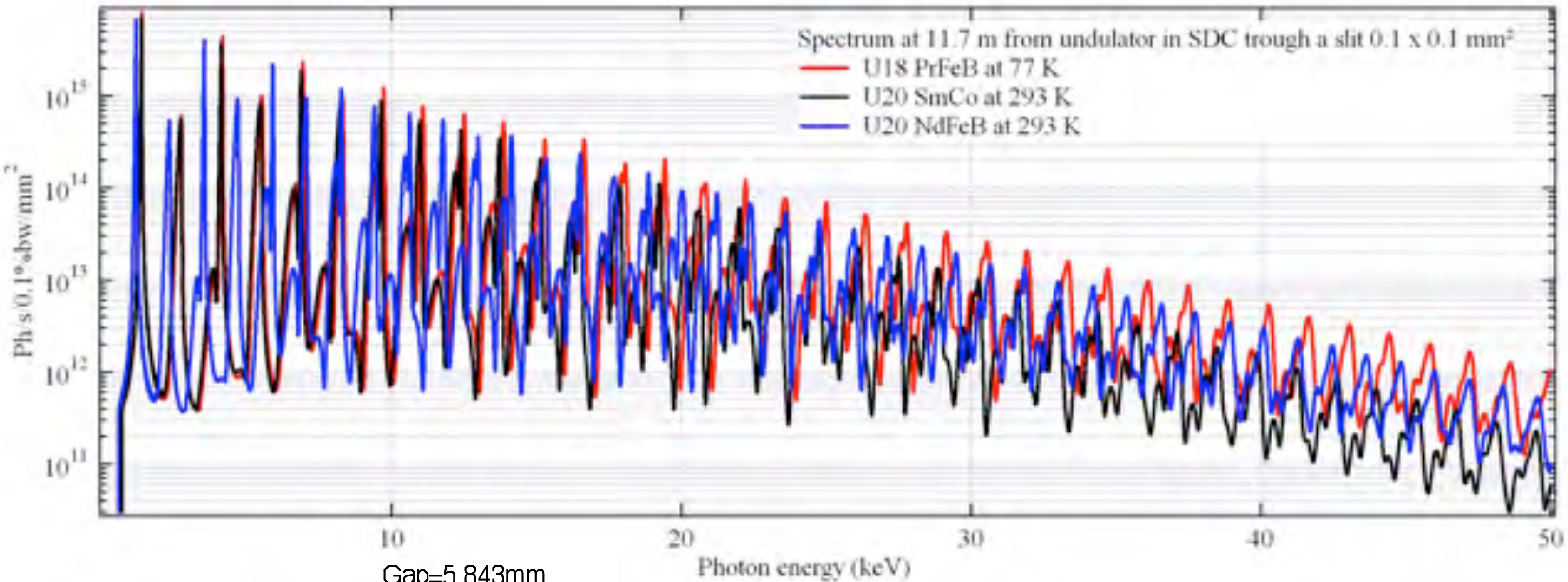
SOLEIL

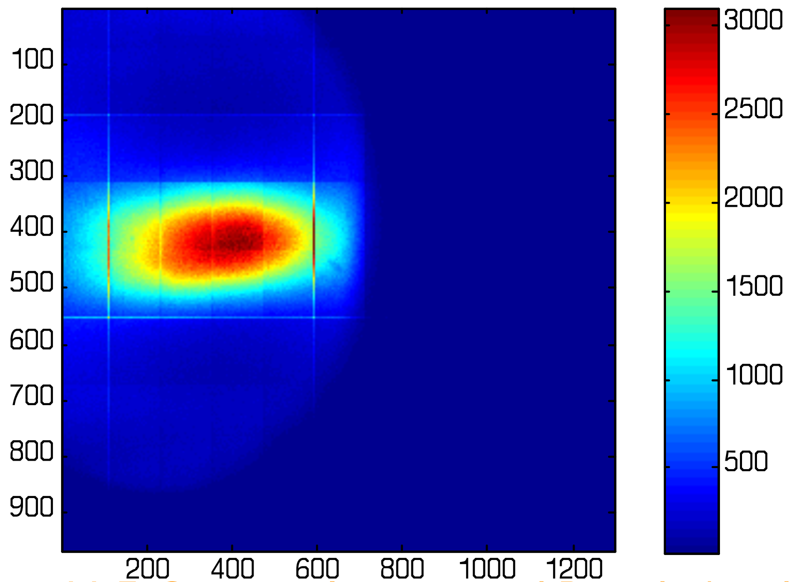
ESRF

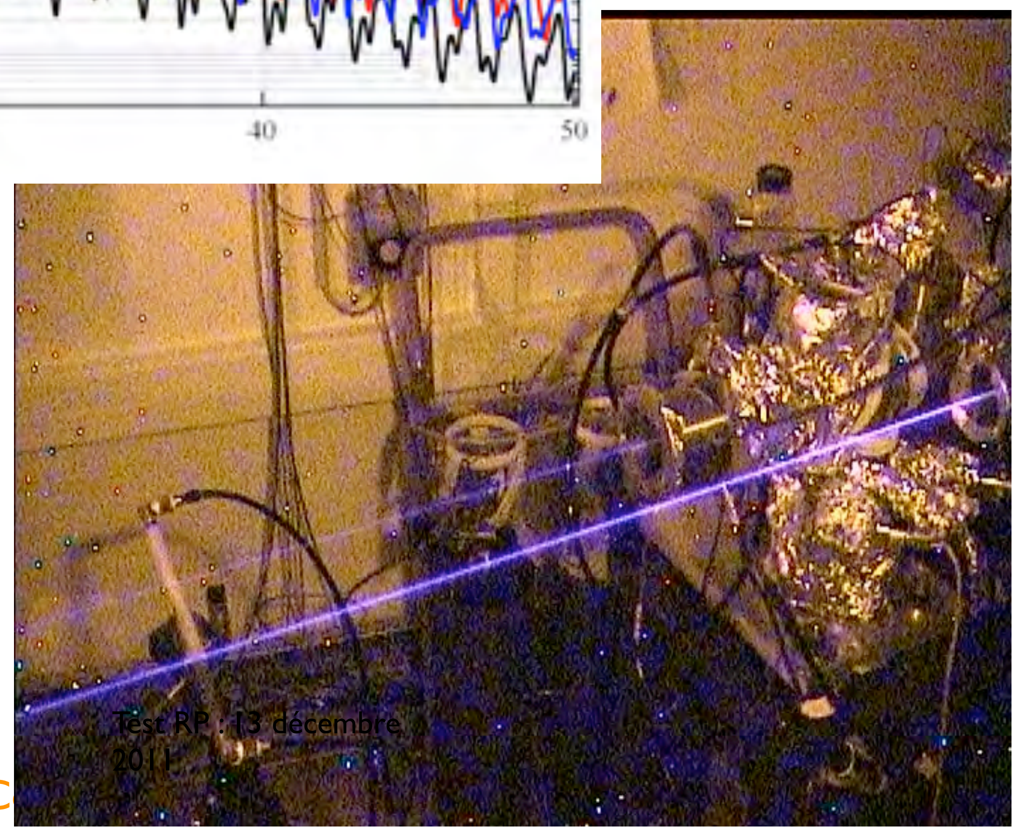


# Cryogenic undulators Radiation : radiation

SOLEIL



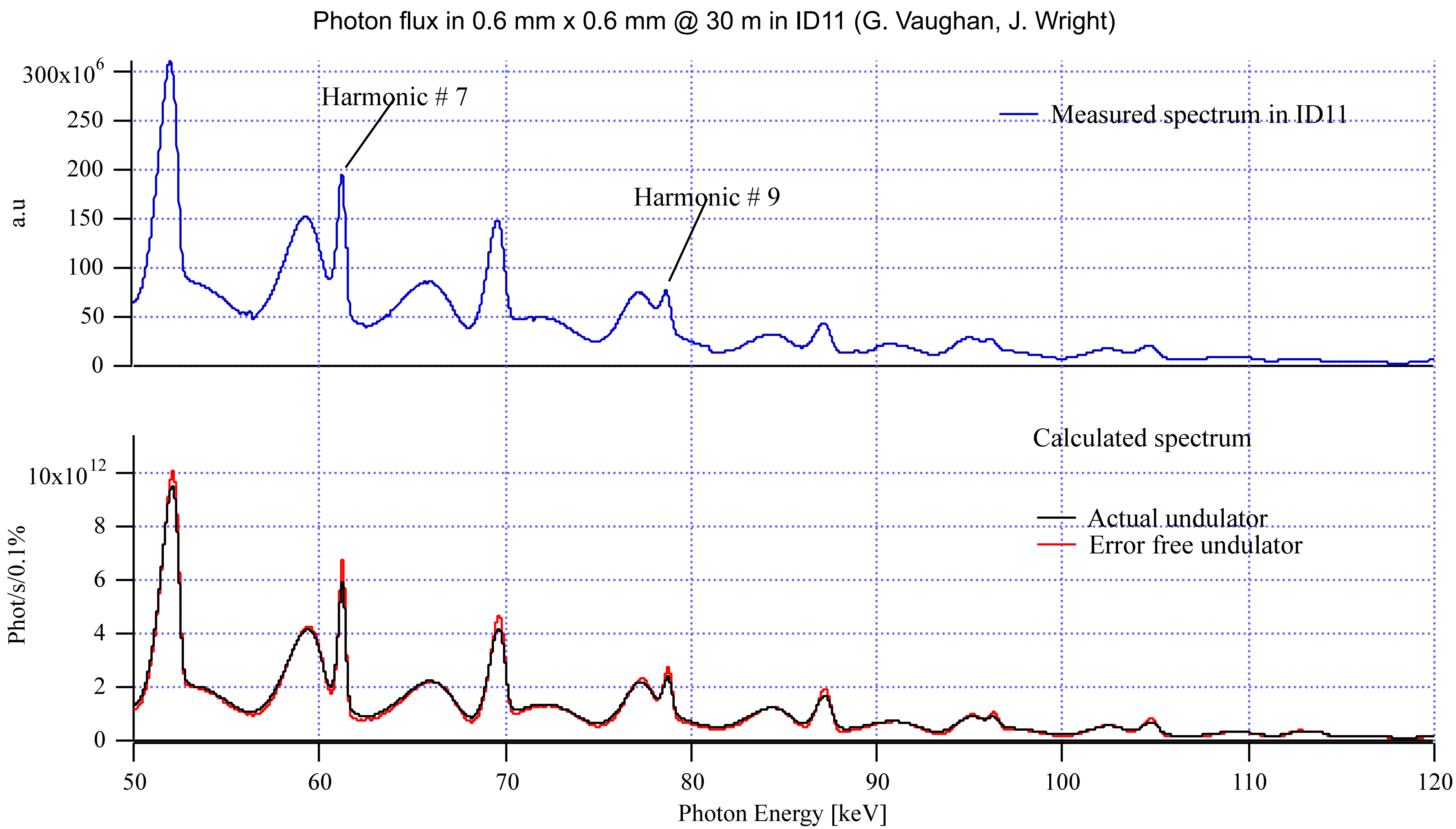



# Cryogenic undulators Radiation : measured spectra

Example of measured spectra at ESRF

Courtesy J. Chavanne

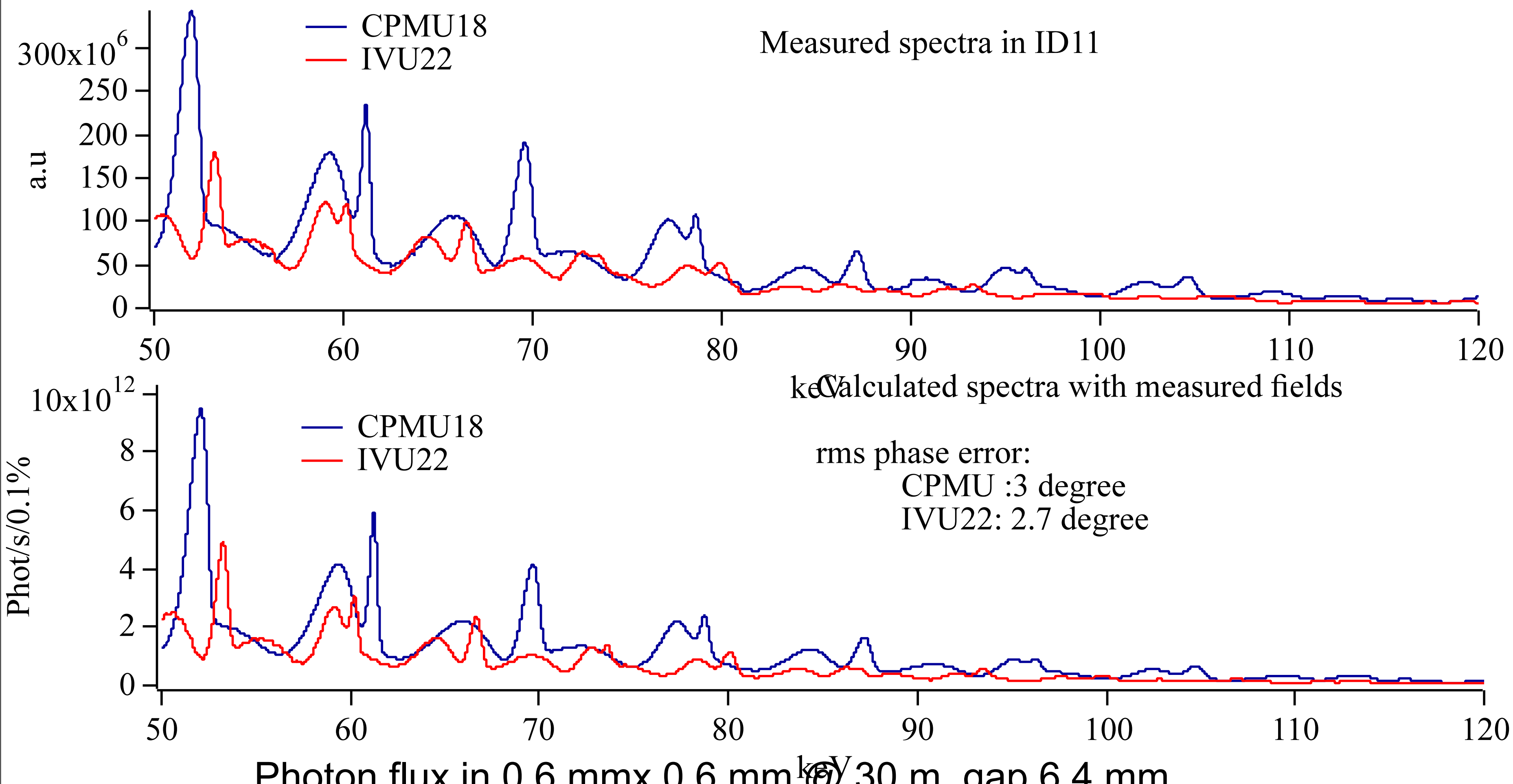



Robust consistency between magnetic design - field measurements - observation in beamline

# Cryogenic undulators Radiation : comparison with in-vacuum undulator

Courtesy J. Chavanne

Check CPMU performance wrt conventional $Sm_2Co_{17}$ hybrid IVU22 in ID11




Photon flux in 0.6 mmx 0.6 mm @ 30 m, gap 6.4 mm

Gain in photon flux ~ 2 @ 60 keV, ~3 above 90 keV as expected

ID11 CPMU expected to be operated with minimum gap 5 mm in 2014

# Cryogenic undulators Radiation : measured spectra

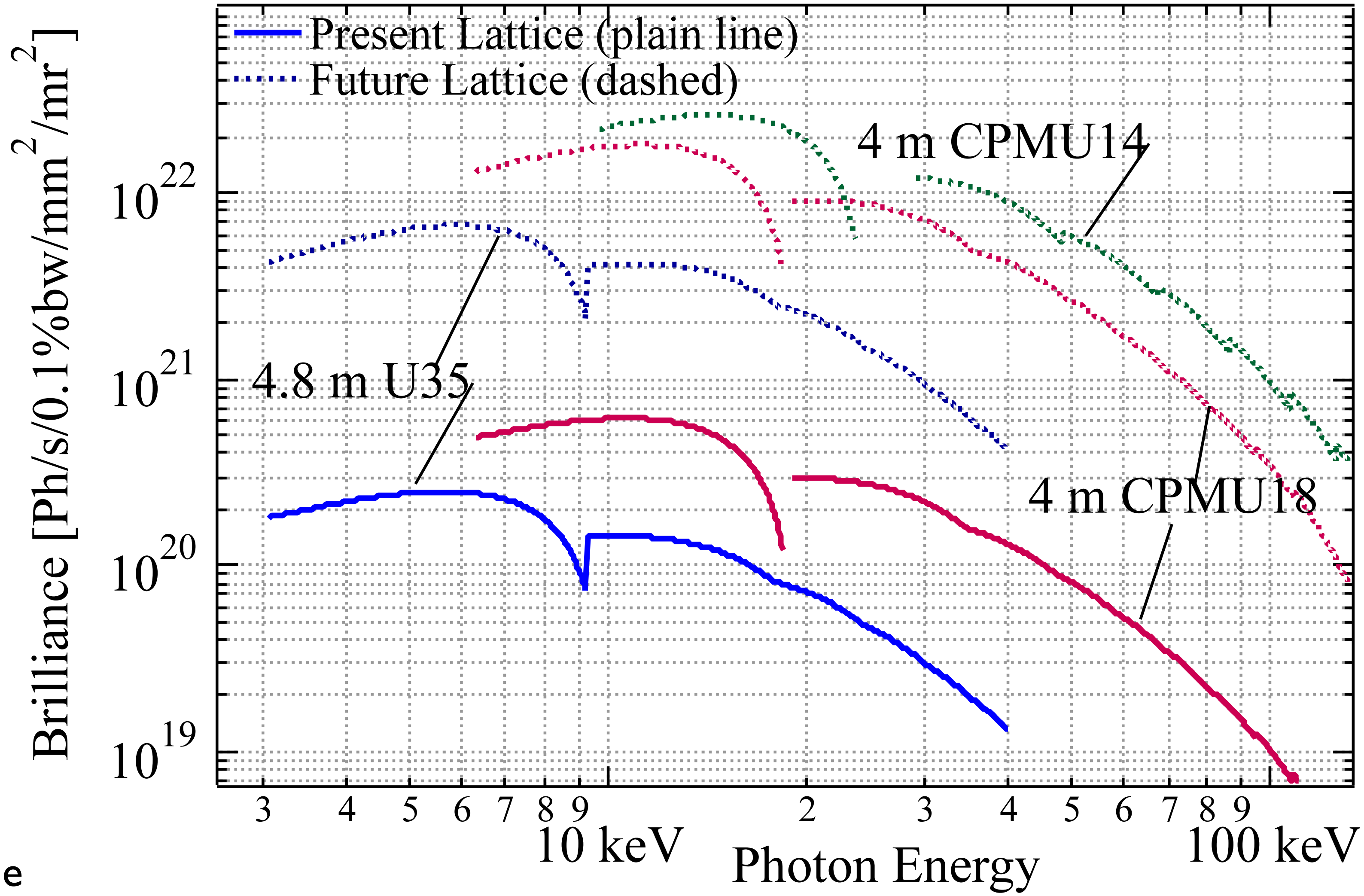
CPMUs for new Ultra Low Emittance (150 pm) Storage Ring

gap ~ 4 mm

period ~ 14

Peak field ~ 1.3 T

K ≥ 1.7



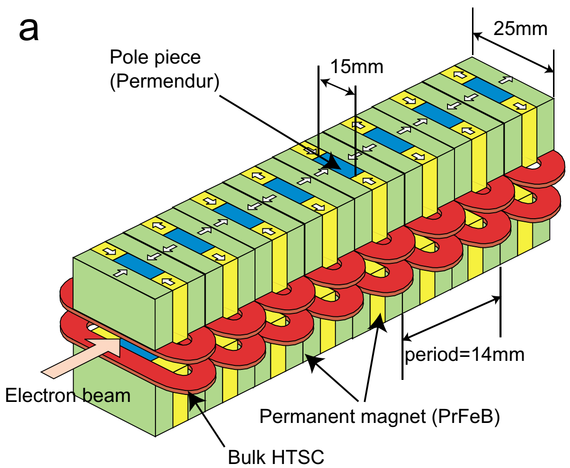

Courtesy J. Chavanne

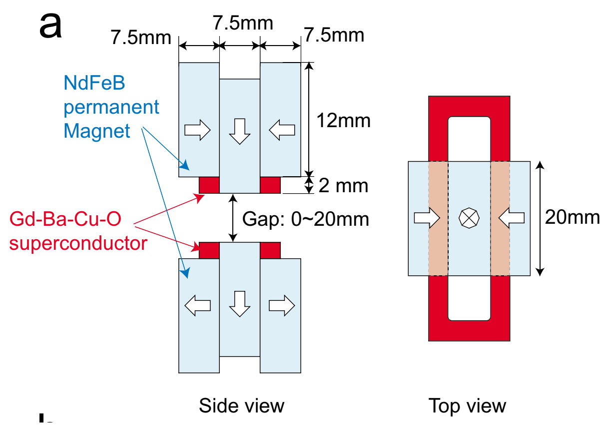
1 very short period CPMU to be constructed in 2014

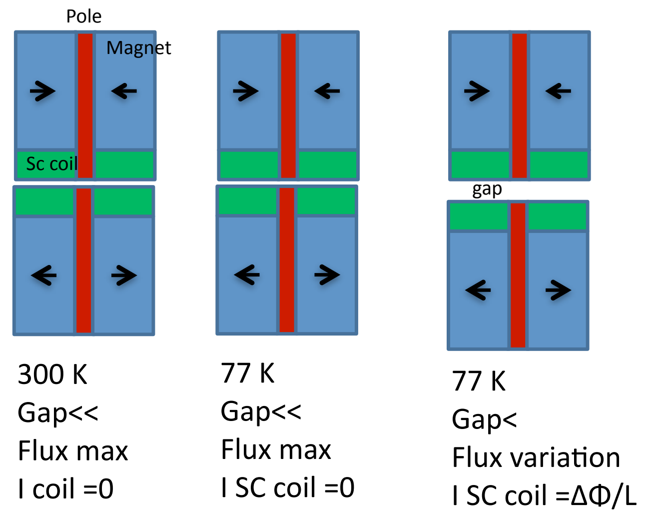
# Cryogenic undulators with high Tc superconductors

Add a high Tc coil for field enhancement
Preliminary test of the high Tc coil on the 4 period assembly

*T. Tanaka et al. PRSTAB 7, 090794 (2004)*



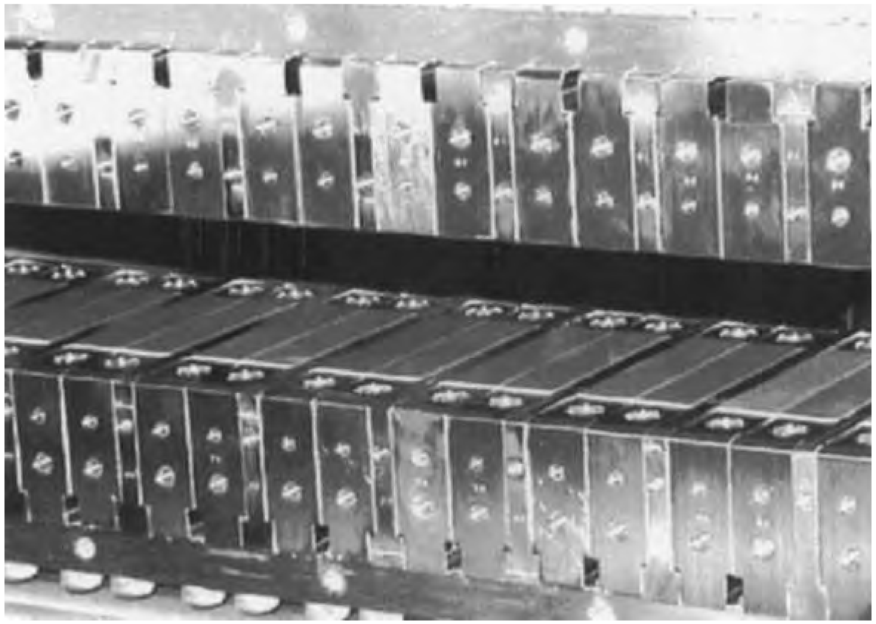




Operate at T<77 K, i.e. at 40 K for Jc= 1.8 kA/mm2 (200 A/mm2 @77K)

| U15 | U15 cryo@77K | U15 cryo+@77K | U15 cryo+@40K |
|---|---|---|---|
| 3 mm | 1.64 | 1.77 | 2.05 |
| 5.5 mm | 0.9 | 0.97 | 1.13 |

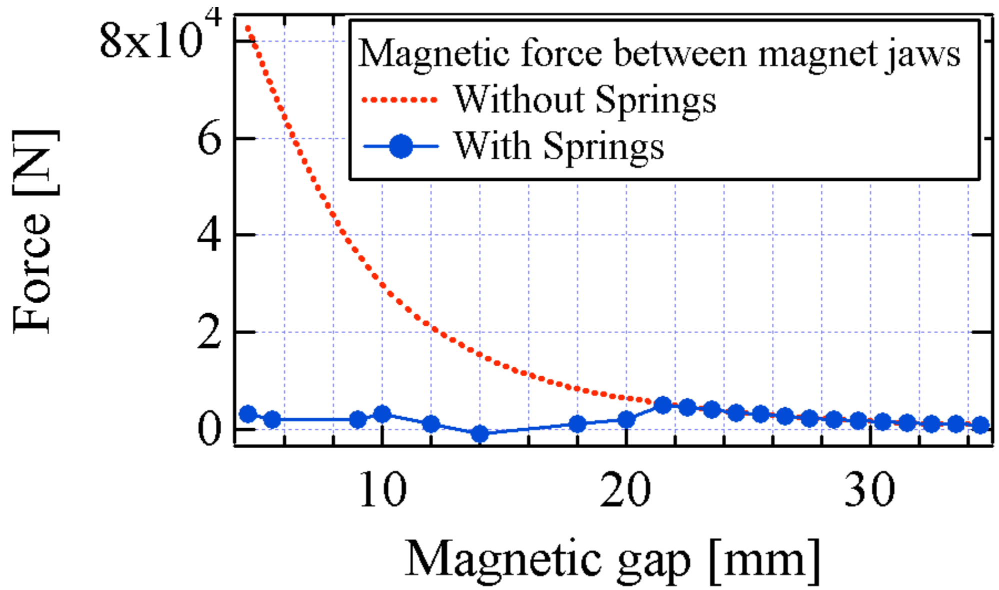
# In vacuum wiggler

## Choice of an in vacuum wiggler rather than a superconducting wiggler



SPring-8 : 1.95T, gap=7 mm, 10x90 mm

*X.M. Marechal et al, NIMA 4676-468 (2001) 138-140*

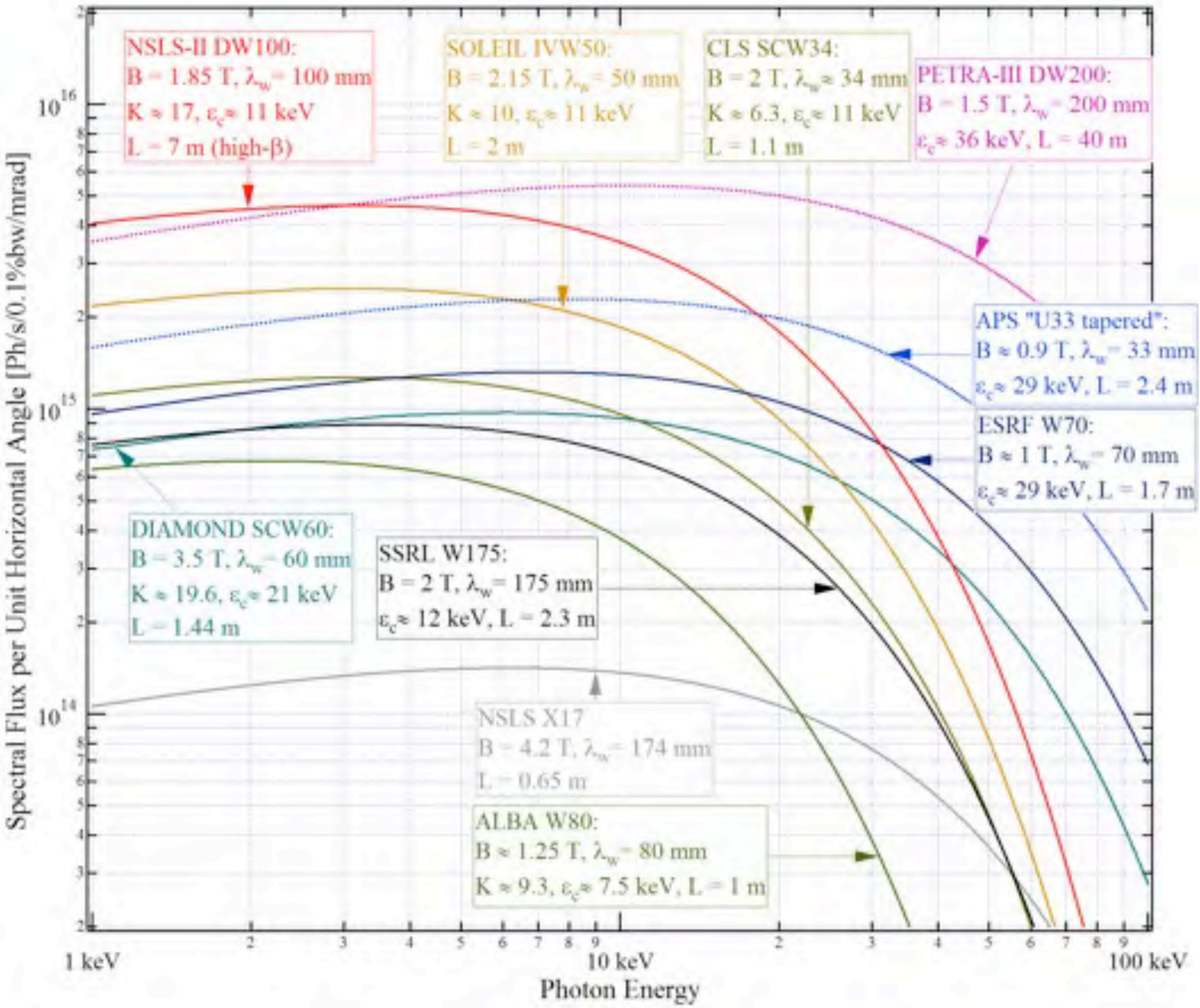



SOLEIL : 2.1T, gap=5.5 mm, 10x150 mm

*O. Marcouillé et al., SRI 09*
*O. Marcouillé et al., to appear in PRSTAB 2013*

# In vacuum wiggler

## Spectral Flux per Unit Horizontal Angle (Far-Field Estimation)




O. Chubar

# III- Superconducting undulator

## Historical steps

### MARK III

B=0.5 T
Period : 3,2 cm
length : 5.2 m
superconducting double helix

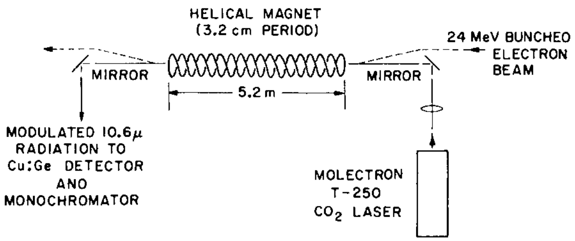


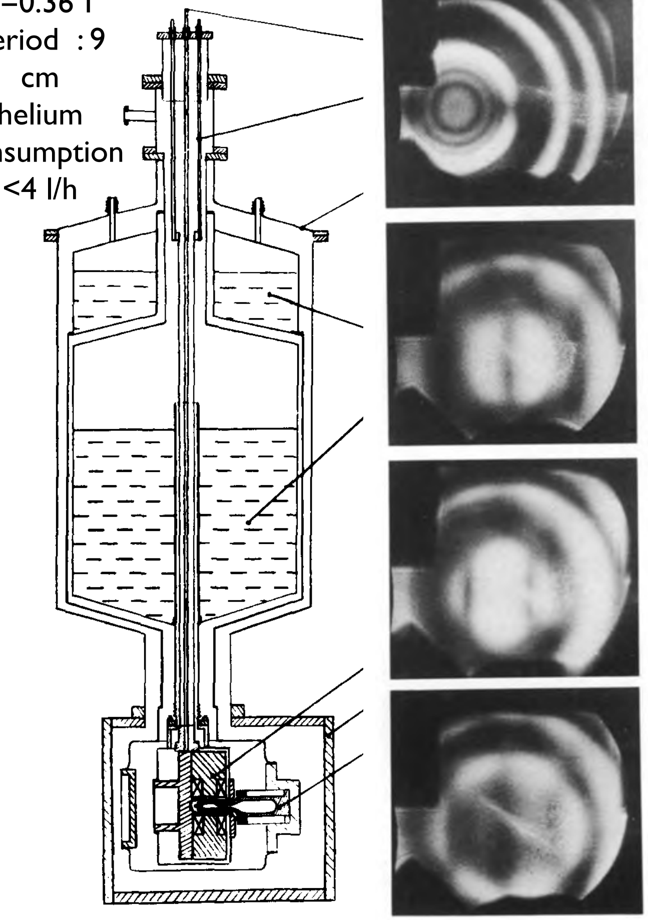

FIG. 1. Experimental setup. The electron beam was magnetically deflected around the optical components on the axis of the helical magnet.

*L. Elias et al. Observation of stimulated emission of radiation by relativistc electrons in spatially periodic transverse magnetic field, PRL 36 (5) 1976, 717- 720*

*D.A.G. Deacon et al. First Operation of a FEL, PRL 38 (16) (1977) 892-894*

### VEPP3

B=0.36 T
Period : 9 cm
helium consumption <4 l/h

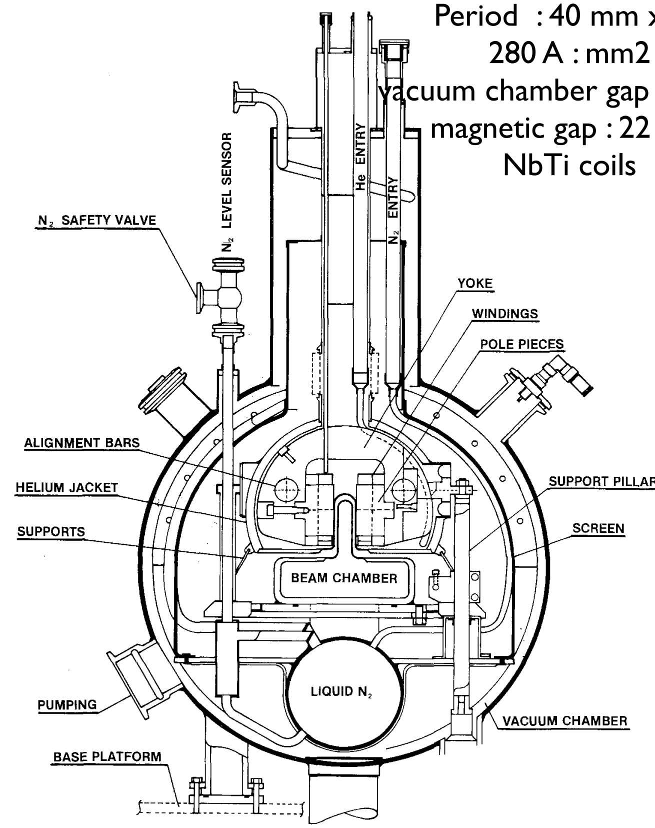


*L. M. Barkov, V. B. Baryshev, G. N. Kulipanov, N.A. Mezentsev, V. E. Pindyurin, A. N. Skrinsky, V. M. Khorev, A proposal to install a superconducting wiggler magnet on the storage ring VEPP3 for generation of the synchrotron radiation, NIM 152 (1978) 23-29*

*A. S. Artamonov et al., First reuslts of the work with a superconducting «snake» at the VEPP-3 storage ring, NIM 177 (1980) 239-246*

### ACO

B=0.5 T
Period : 40 mm x 23
280 A : mm2
Vacuum chamber gap : 12 mm
magnetic gap : 22 mm
NbTi coils




*C. Bazin, Y. Farge, M. Lemonnier, J. Perot, Y. Petroff Design of an undulator for ACO and its possible use as FEL, NIM 172 (1980) 61-65*

*C. Bazin, M. Billardon, D. Deacon, Y. Farge, J. M. Ortéga, J. Pérot, Y. Petroff, Y. Farge, M. Velghe, First results of a superconcting undualtor on the ACO storage ring, J Physique-LETTERS 41 (1980) L-547-L-550*

# III- Superconducting undulator

## Present achievements with NbTi coils

ANKA / Babcok Nolle :

• **SCU15Demo** (NbTi) :
period 15 mm, operating magnetic gap : 8 mm, beam gap : 7 mm, 0.69 T, design beam heat load : 4 W, acheived phase error 7.4 ° rms
- Tests at 4K have shown bending of the coils by ~0.25 mm per side, Achieved 7.6 deg phase error on 0.8 m - Adjustable-gap beam vacuum chamber: manufactured and successfully passed the vacuum test reaching P < 3 x $10^{-10}$ mbar in cold conditions

•**Short prototypes with 15 mm and 20 mm period length**
manufactured and tested in the test facility CASPER I
to qualify the wire and different winding schemes for new SCIDs.

*C. Boffo et al., to be presented at MT23*
*S. Casalbuoni et al., to be presented at MT23*

Courtesy S. Casalbuoni

Daresbury :

Undulator based source polarized electrons,
short model period 14 mm, 0.81 T, free beam aperture : 4 mm
1.74 m devices, period 11.5 mm, vessel aperture : 5.85 mm, winding bore : 6.35 mm, field : 1.15 T

*D. J. Scott et al. Phys. Rev. Lett. 107, 174803, 2011*

# III- Superconducting undulator

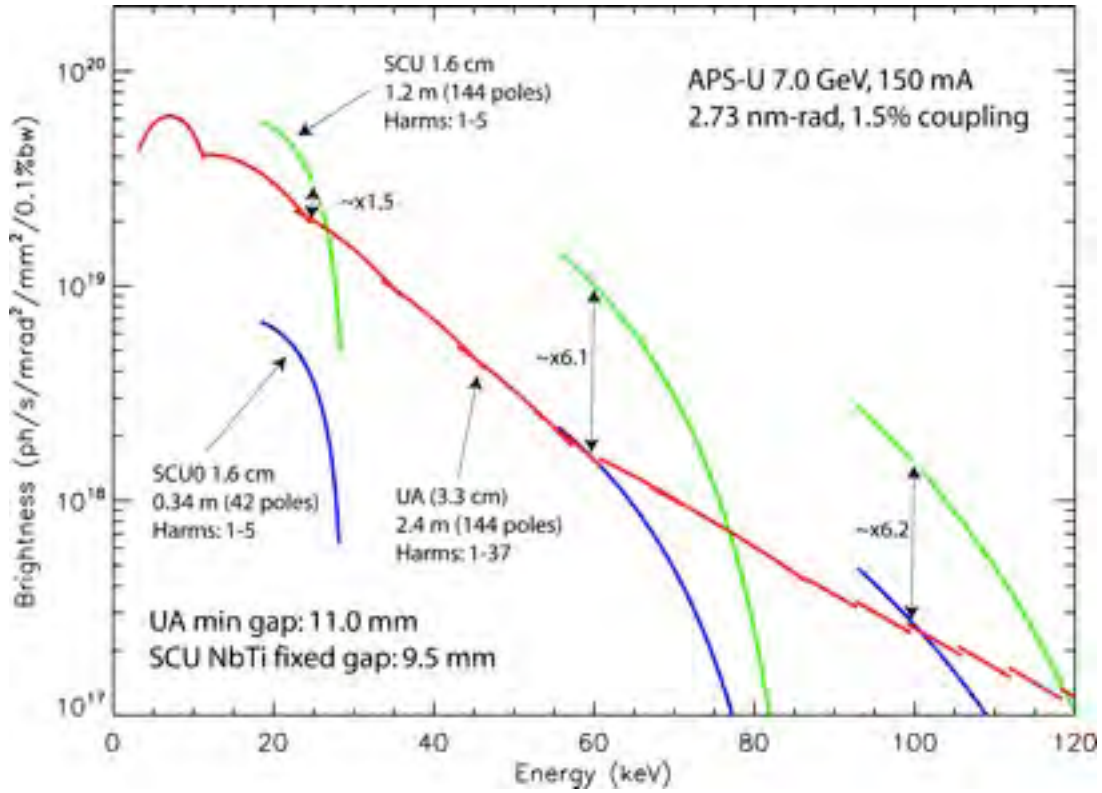
## Present achievements with NbTi coils

### First superconducting undulators at the Advanced Photon Source (APS)

Courtesy Yury Ivanyushenkov (APS)

APS superconducting undulator specifications

| | Test Undulator SCU0 | Test Undulator SCU1' |
|---|---|---|
| Photon energy at 1st harmonic | 20-25 keV | 12-25 keV |
| Undulator period | 16 mm | 18 mm |
| Magnetic gap | 9.5 mm | 9.5 mm |
| Magnetic length | 0.330 m | 1.140 m |
| Cryostat length | 2.063 m | 2.063 m |
| Beam stay-clear dimensions | 7.0 mm vertical × 36 mm horizontal | 7.0 mm vertical × 36 mm horizontal |
| Superconductor | NbTi | NbTi |




Tuning curves for odd harmonics for two planar 1.6-cm-period NbTi superconducting undulators (42 poles, 0.34 m long and 144 poles, 1.2 m long) versus the planar NdFeB permanent magnet hybrid undulator A (144 poles, 3.3 cm period and 2.4 m long). Reductions due to magnetic field error were applied the same to all undulators (estimated from one measured undulator A at the APS). The tuning curve ranges were conservatively estimated for the SCUs.

# Present achievements with NbTi coils

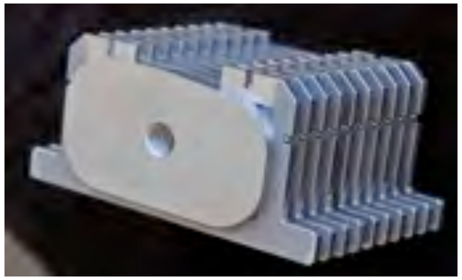
Courtesy Yury Ivanyushenkov (APS)

## First short superconducting undulator SCU0

SCU0:

- Designed by APS and Budker Institute, Russia
- Built and commissioned by APS
- Installed at the Sector 6 of the APS ring in December 2012
- In operation by APS user since January 2013

A model of test coil

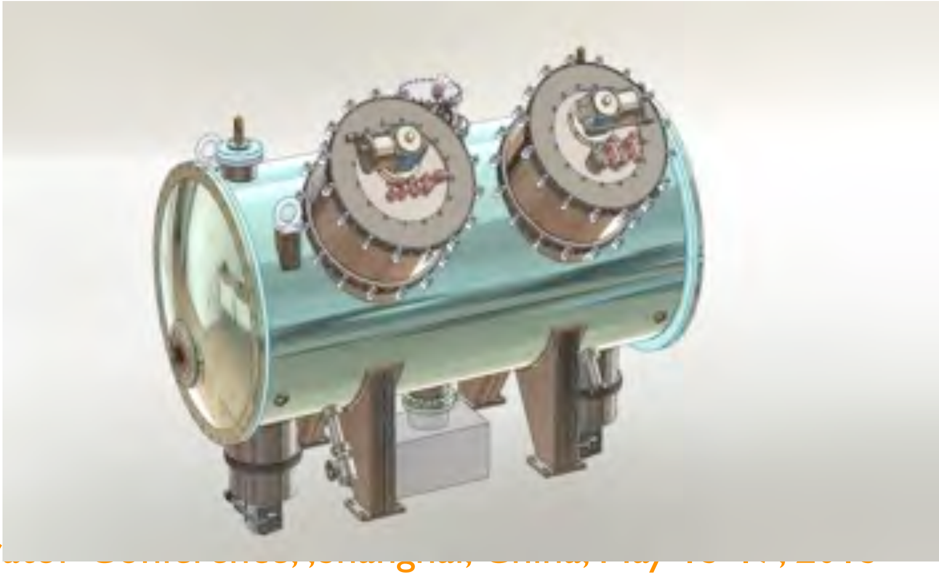


First wound 42-pole test coil

SCU0 Design Conceptual Points:

- Cooling power is provided by four cryocoolers
- Beam chamber is thermally insulated from superconducting coils and is kept at 15-20 K
- Superconducting coils are indirectly cooled by LHe flowing through the channels inside the coil cores
- LHe is contained in a 100-liter buffer tank which with the LHe piping and the cores makes a closed circuit cooled by two cryocoolers
- Two other cryocoolers are used to cool the beam chamber that is heated by the electron beam

SCU0 3d design model



# III- Superconducting undulator

## Present achievements with NbTi coils

Courtesy Yury Ivanyushenkov (APS)

### SCU0 performance at APS

SCU0 in the APS storage ring

SCU0 Performance:

- Designed for operation at 500 A, operates reliably at 650 A
- E-beam is not affected by quenches. Didn't quench except of when the e- beam was intentionally dumped
- No loss of He is observed in about 3-month run period

SCU0 Measured Photon Flux:

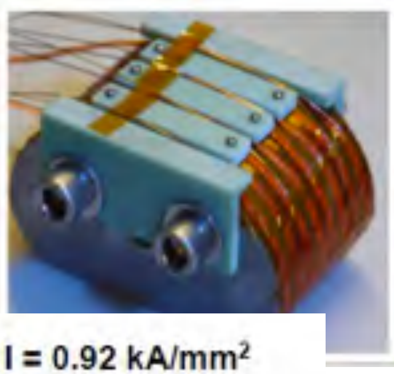
- SCU0 ( 0.3-m magnetic length ) flux at 85 keV is 1.4 times higher than the one of Undulator A ( 2.4-m magnetic length)

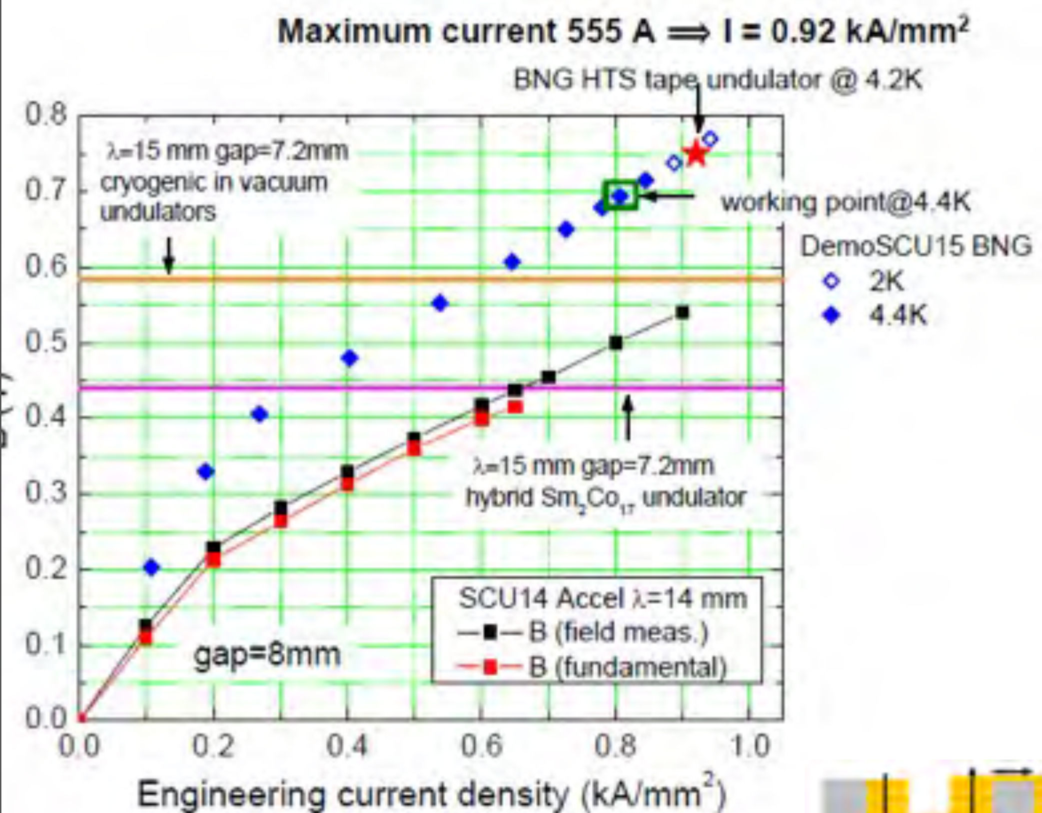
# HTS tape undulator

## HTS tape undulator

ANKA :

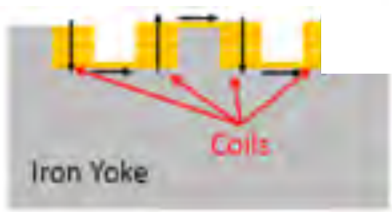
**HTS tape planar undulator mockup: results of test at CASPERI (ANKA, KIT**






*C. Boffo, http://www.maxlab.lu.se/usermeeting/2010/sessions/*

Courtesy Sara Casalbuoni, KIT

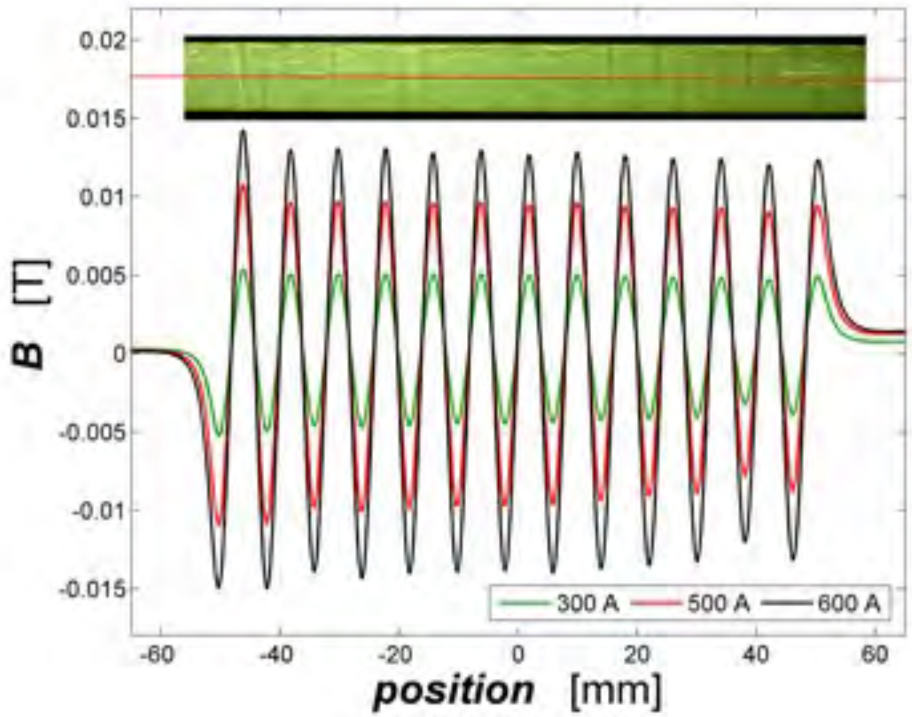



## HTS tape stacked undulator

LBNL :

*S. Prestemon et al. IEEETrans. on Appl. Supercond. 21-3, 2011, 1880-1883*

ANKA : First tests on laser structured wire




*T. Holubek et al., accepted for publication in IEEE Trans. on Appl. Supercond.*

# III- Superconducting undulator

## Instrumentation and diagnostics

### COLDDIAG

**More details in poster session on Wednesday**
**S. Gerstl et al., WEPWA006**

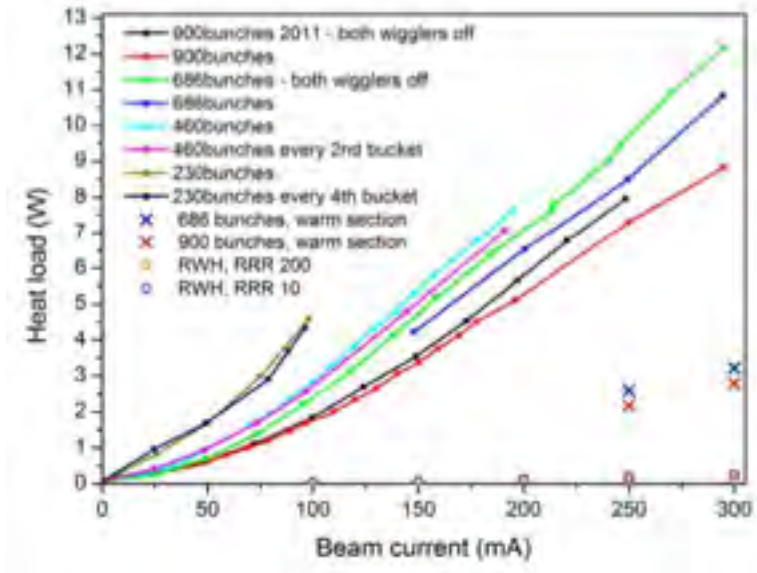
Cold vacuum chamber for diagnostics to measure the beam heat load to a cold bore in different synchrotron light sources

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

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




**Significant difference compared to theoretical expectations …**
**S. Casalbuoni et al., 2012 JINST 7 P11008**

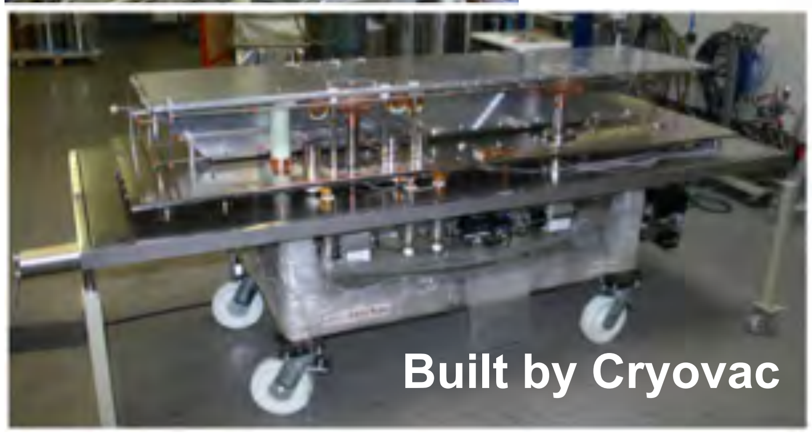

Courtesy Sara Casalbuoni, Karlsruhe Institute of Technology

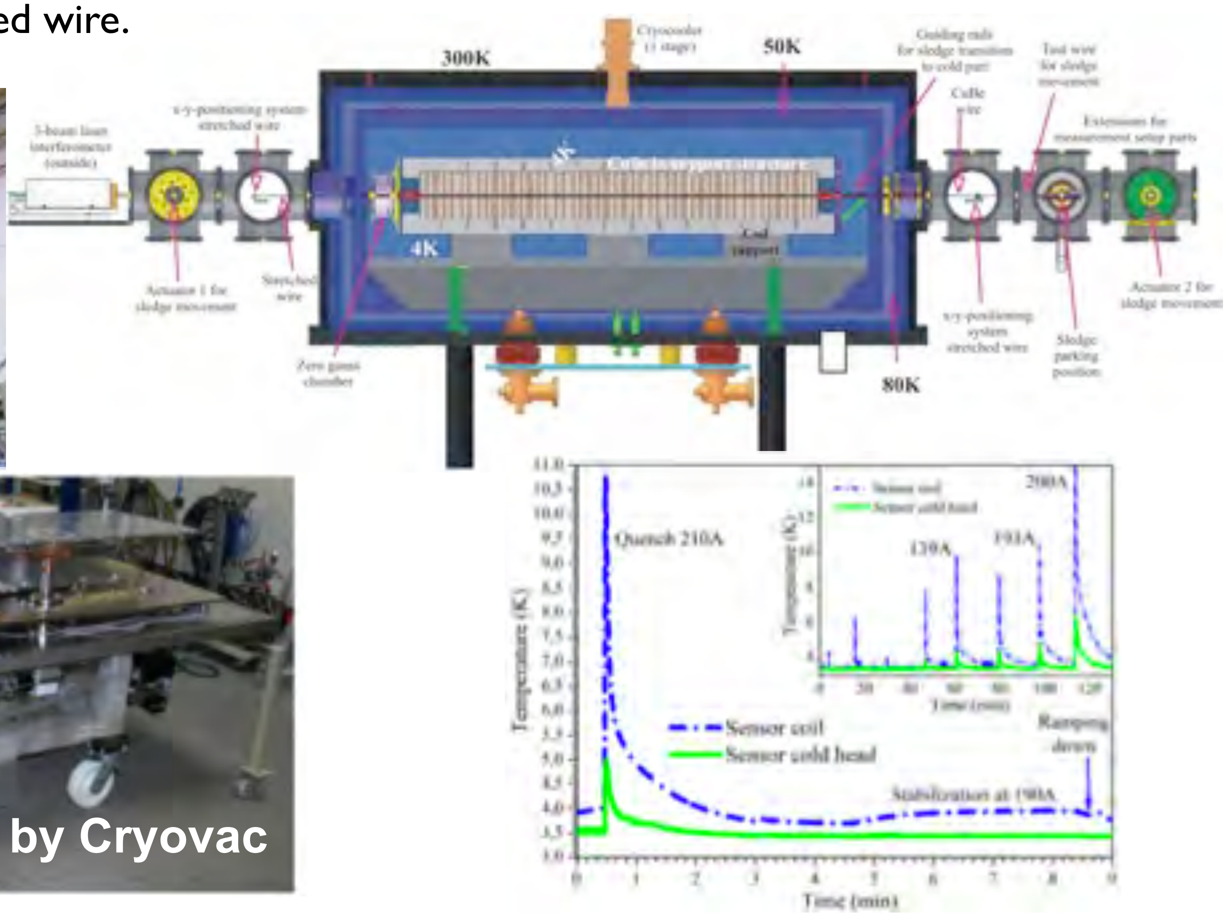
# Instrumentation and diagnostics

## CASPER II
## (ChAracterisation Setup for Phase Error Reduction)

•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.

Progress with first tests presented in poster session on Wednesday
A. Grau et al., WEPWA007



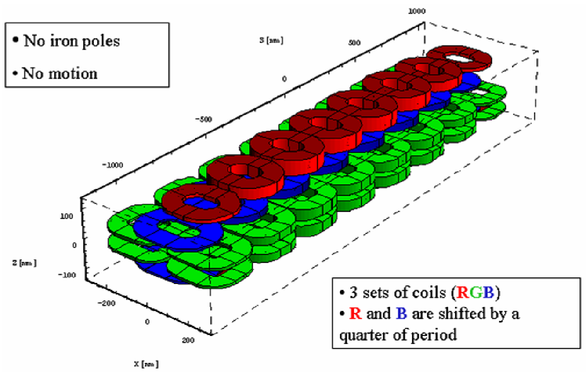
Courtesy Sara Casalbuoni, Karlsruhe Institute of Technology

# IV- EPU and fast polarisation switching

## Electromagnetic undulators

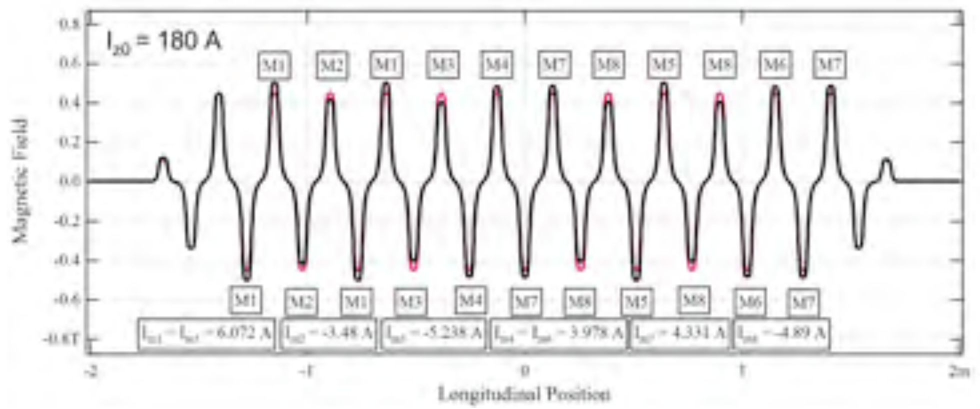
### Ex of the SOLEIL 10 m HU640

z : 270 ms for switching -±600 A on PS1, 300 ms flat top for data acquisition




$B_z(s)=B_B.\cos[2\pi s/\lambda_o]+B_R.\sin[2\pi s/\lambda_o]+B_{zo}.\cos[2\pi s/\lambda_o+f]$

### Ex of the SOLEIL HU256

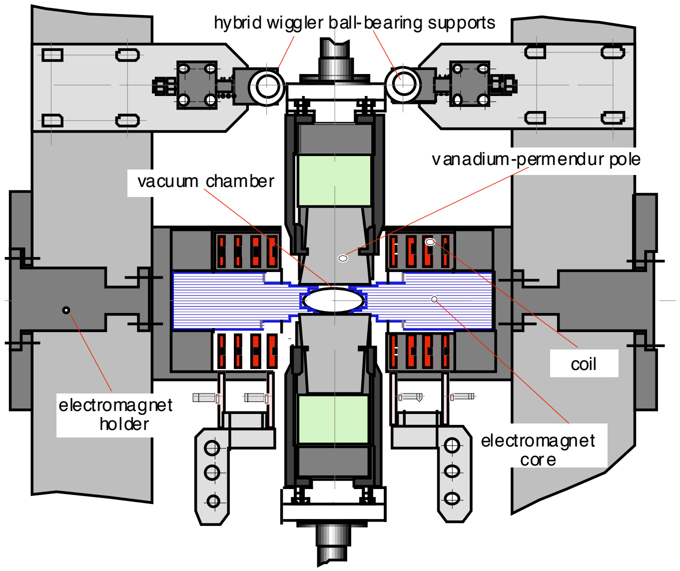



*O. Marcouillé et al., International Conference on Synchrotron Radiation Instrumentation Daegu (KO) 2006, AIP Conference Proceedings 2007, 879, 396-399*

# IV- EPU and fast polarisation switching

## Fast switching (100 ms) ElectroMagnetic Permanent magnet Helical Undulator Wiggler

### NSLS/APS/Budker Institute

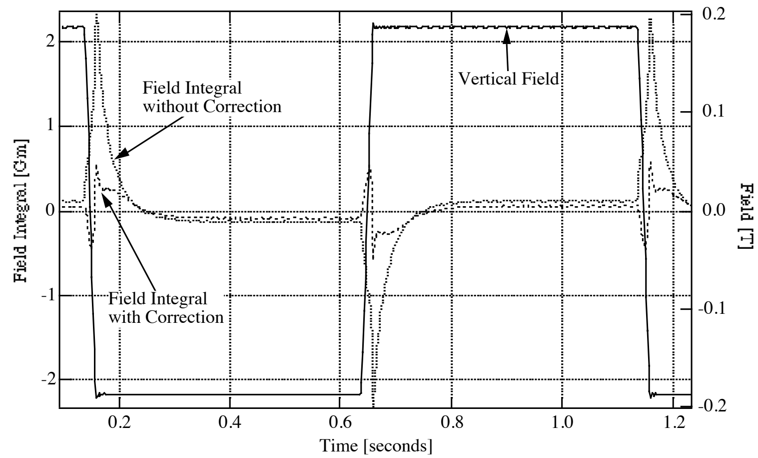



0.1 - 10 keV (2.6 keV)

$B_h$ = 0.22 T
$B_v$ = 0.8 T
$\lambda_0$ = 16 cm

*O. Singh O., S. Krinsky, Proceedings PAC 1997, 2161-2163*

### ESRF




*J. Chavanne, P. Elleaume, P. Van Vaerenbergh, Proceedings of EPAC 98, 317 (1998).*

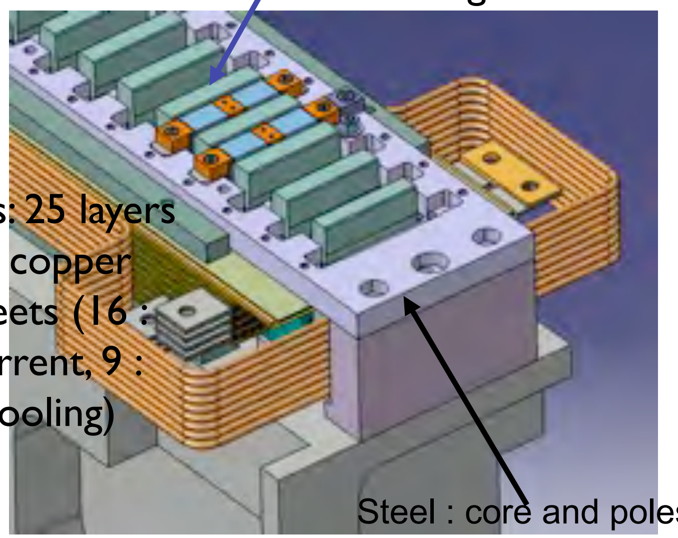
### Jefferson Lab

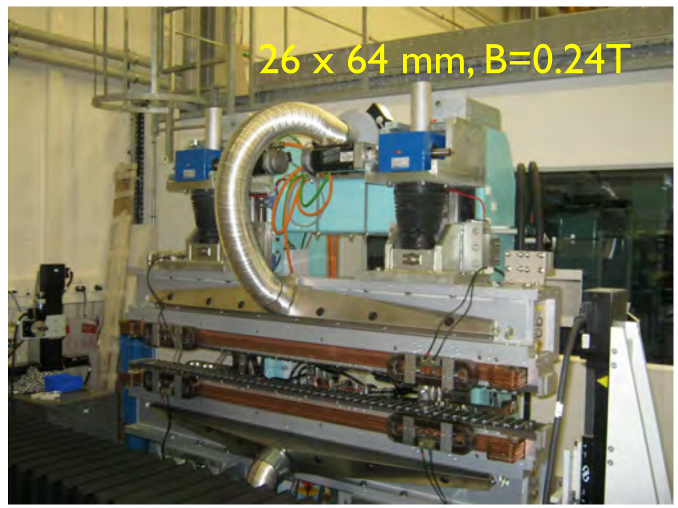
28 x 80 mm, B=0.134T

*G. Biallas et al. an 8 cm period electromagnetic wiggler magnet with coils made from sheet copper", Proceedings of PAC 2005, Knoxville, 4093 ; FEL04, 554-557*

### SOLEIL

NdFeB magnets



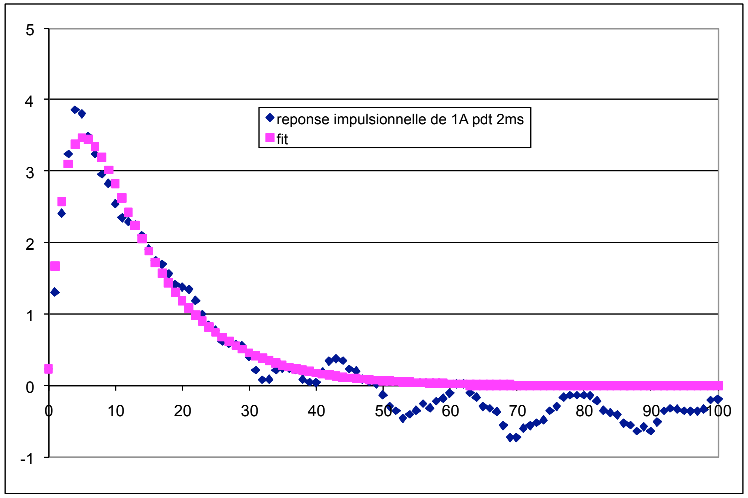




*F. Marteau et al., Description of a Electromagnet Permanent Magnet Helical Undulatorfor fast polarisation switching, F. Marteau, et al, Proced. Magnet technology 22, Sept. 2011, IEEE Transactions on Applied Superconductivity, 2012,*

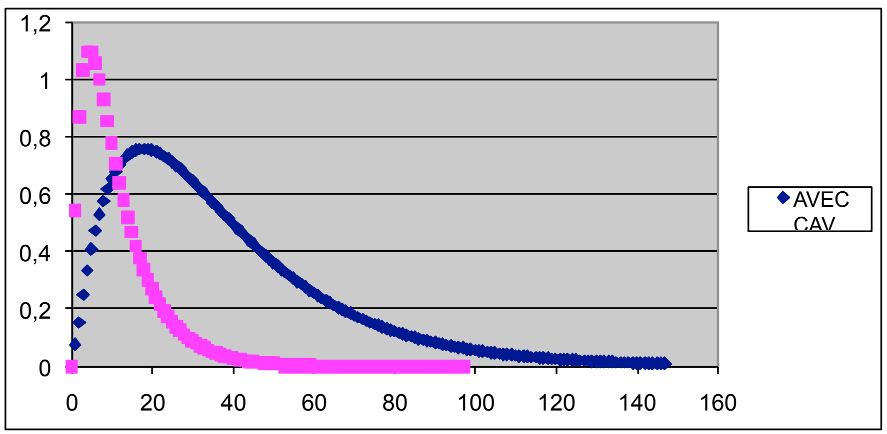
# ElectroMagnetic Permanent magnet Helical Undulator

## Dynamical measurements

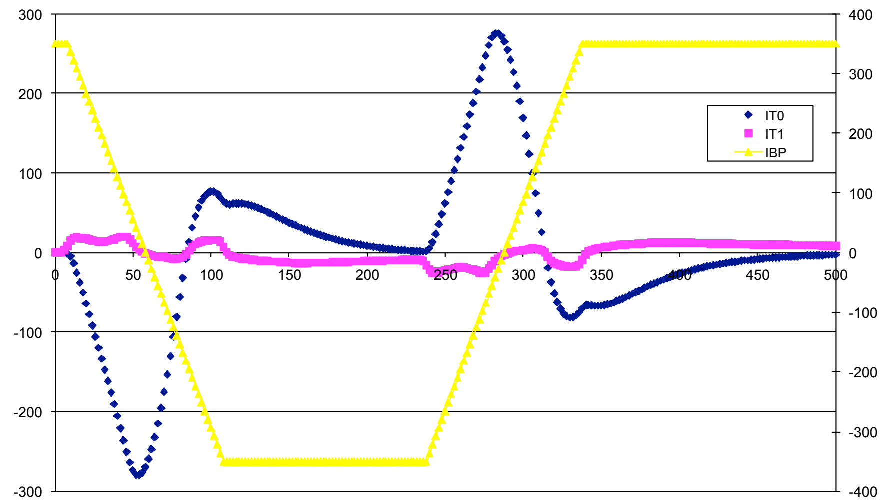
### Pulse response without vacuum chamber



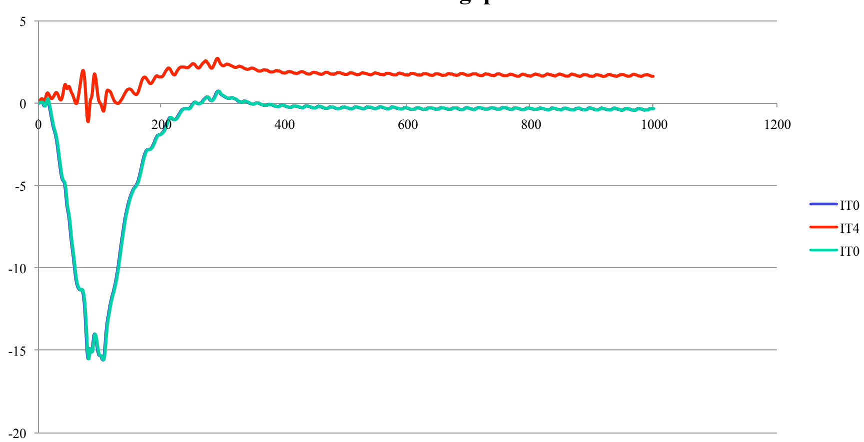

### Pulse response with vacuum chamber




### Matlab iterative correction

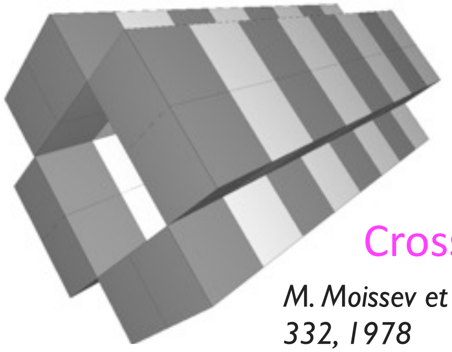



Correction à gap 14.7



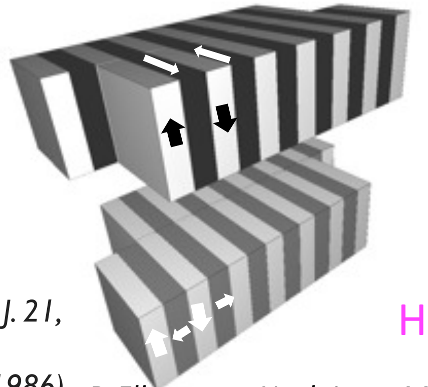
# IV- EPU and fast polarisation switching

## Permanent magnets EPU



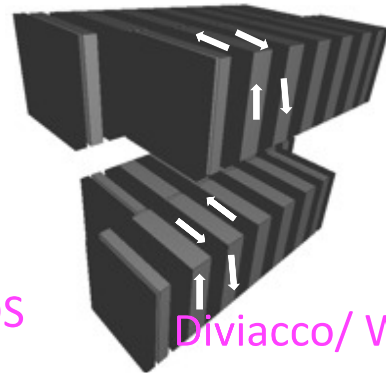
Crossed EPU

*M. Moissev et al. Sov. Phys. J. 21, 332, 1978*
*K. J. Kim NIMA219, 426 (1986)*
*H. Onuki, Nucl. Instr. Meth., A246, 94, (1986)*
*H. Onuki et al, Appl. Phys. Lett., 52, 173, (1988)*



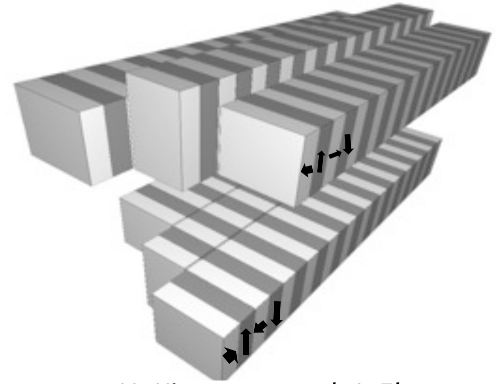
HELIOS

*P. Elleaume, Nucl. Instr. Meth., A291, 371 (1990)*
*P. Elleaume, J. Synch. Rad.,1, 19 (1994)*

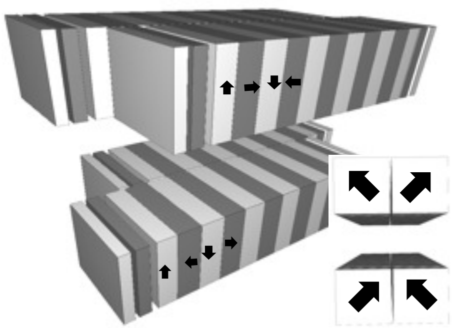


Diviacco/ W

*B. Diviacco and R. P. Walker, Nucl. Instrum. Meth., A292, 517 (1990)*

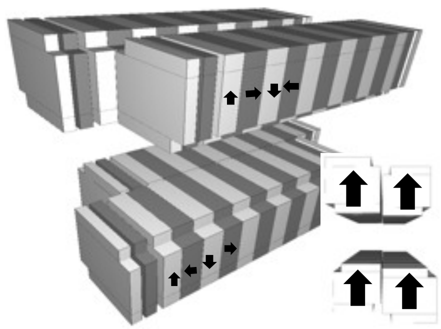


*H. Kitamura et al, J. Electron Spectr. Relate Phenom., 80 , 437, (1996)*
*A. Hiraya et al, J. Synchr. Rad., 5, 445, (1998)*



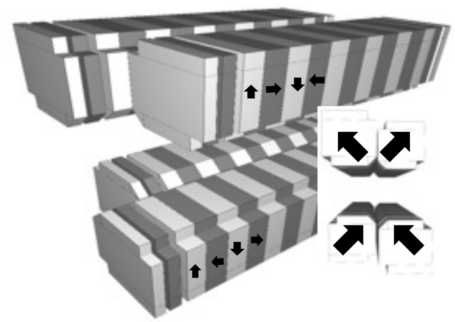
APPLE-I

*S. Sasaki et al,, Jpn. J. Appl. Phys., 31, L194 (1992)*
*S. Sasaki et al, Nucl.* Instr. Meth., A331, 763 (1993)
*S. Sasaki et al, Nucl.* Instr. Meth., A347,87 (1994)



APPLE-II

*R. Carr , Nucl.* Instr. Meth., A306, 391 (1991)
*R. Carr et al , Rev*. Sci. Instrum., 63, 3564 (1992)
*R. Carr, Proceedings of 1992 EPAC, p489* (1992)



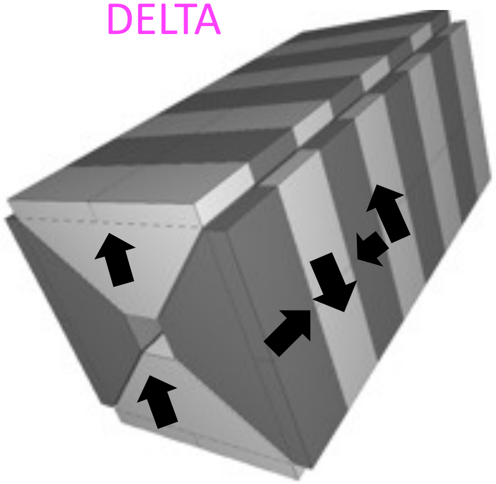
APPLE-III

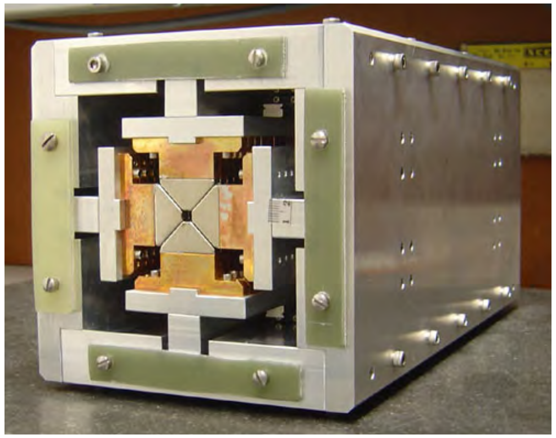
*Bahrdt et al, Proceedings of the 2004 FEL Conference, Triestre, ITALY*, p610 (2004)

# IV- EPU and fast polarisation switching

## Permanent magnets EPU

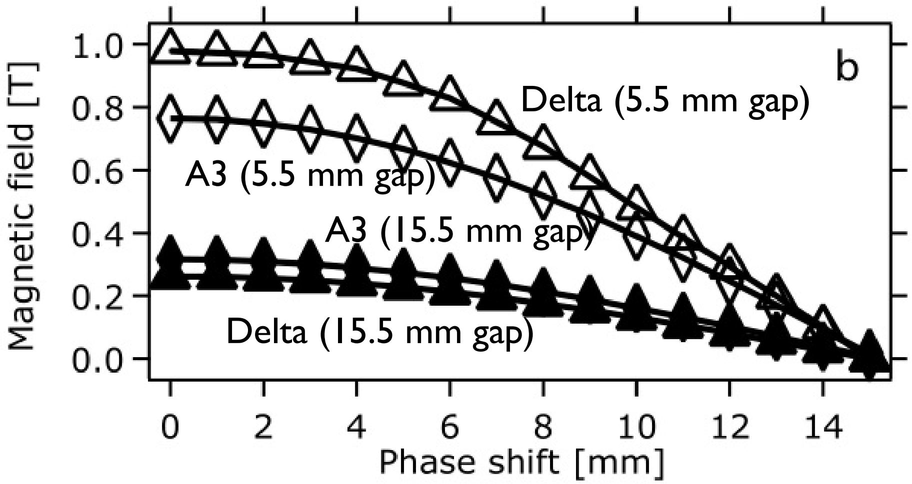
DELTA

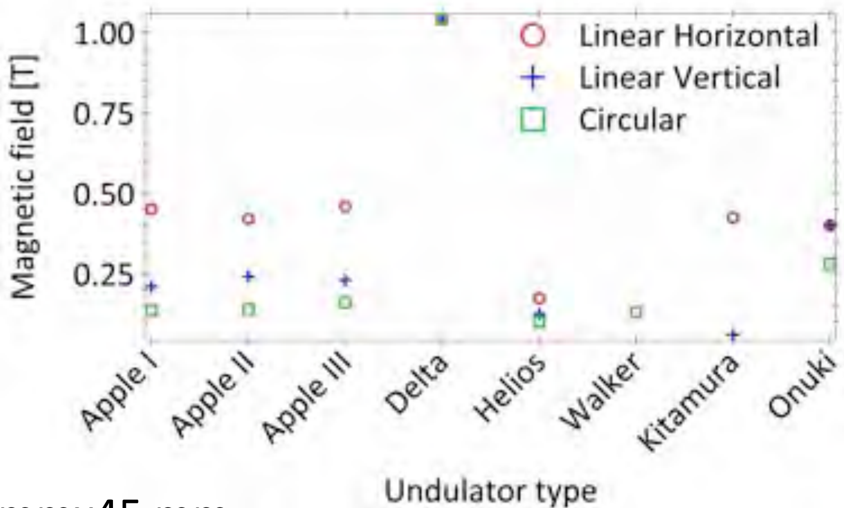




A. B. Temnykh, Phys. Res. Spec. Topics AB, 11,120702 (2008)

| Polarisation modes | LH | LV | C | Remarks |
|---|---|---|---|---|
| Apple I | 0,45 | 0,21 | 0,135 | |
| Apple II | 0,42 | 0,24 | 0,14 | |
| Apple III | 0,46 | 0,23 | 0,16 | |
| Delta (Apple IV?) | 1,04 | 1,04 | 1,04 | 5mm round gap |
| Helios | 0,173 | 0,125 | 0,1 | |
| Diviacco-Walker | - | - | 0,13 | Circular only |
| Kitamura | 0,424 | 0,06 | - | Low field strength in circular |
| Onuki | 0,4 | 0,4 | 0,28 | |

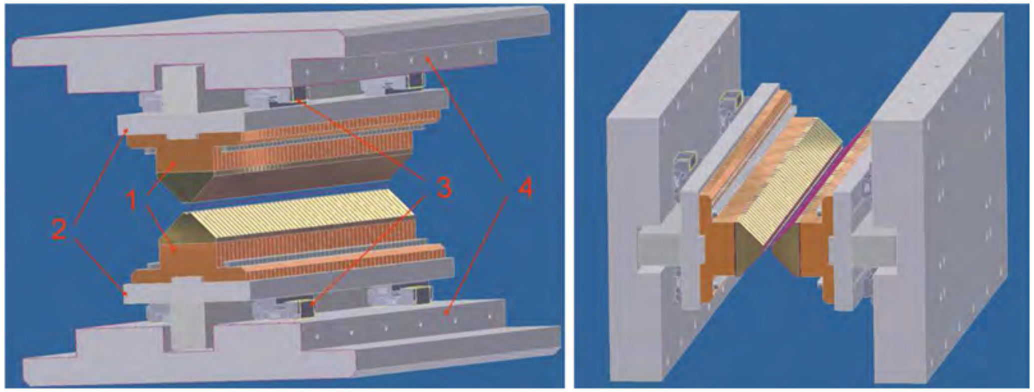


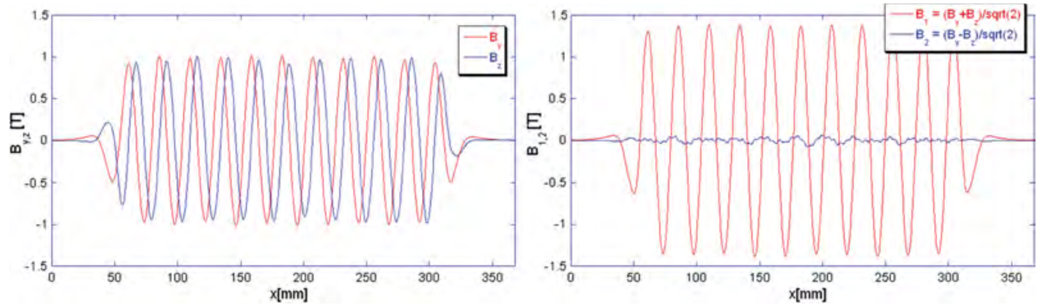




Period : 30 mm, gap 15,5mm/5 mm, Br = 1.26 T, 45 mmx45 mm

# DELTA undulator prototype

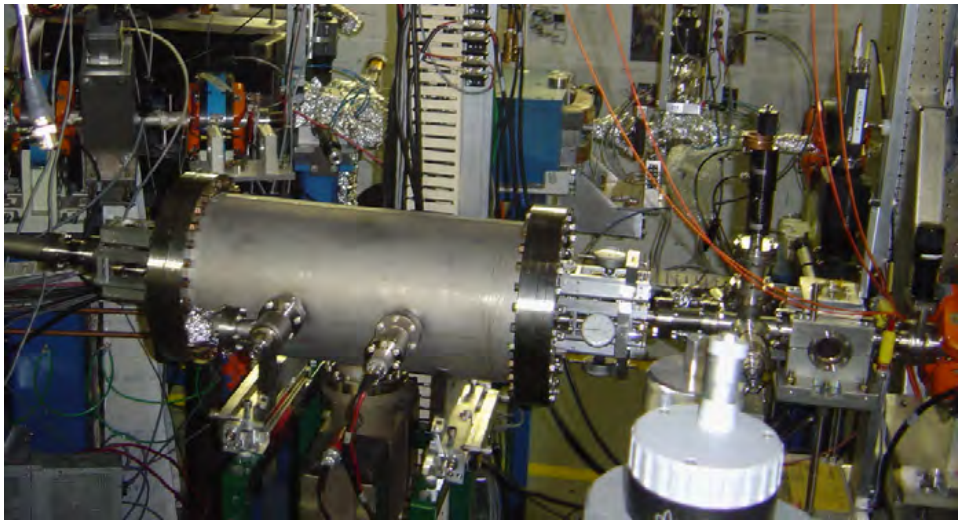
## First prototype @ Cornell (0.3 m)



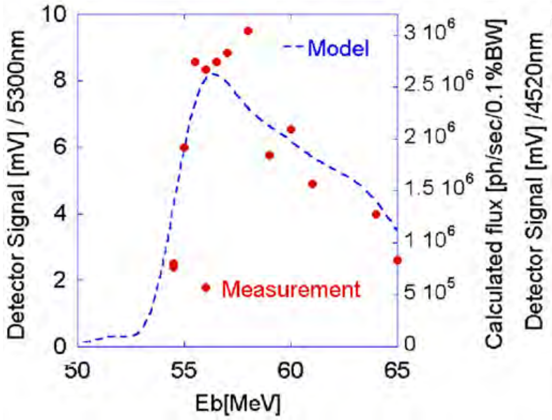




*A. B. Temnykh, DELTA undulator for Cornell Energy Recovery Linac, Phys. Res. Spec. Topics AB, 11,120702 (2008)*

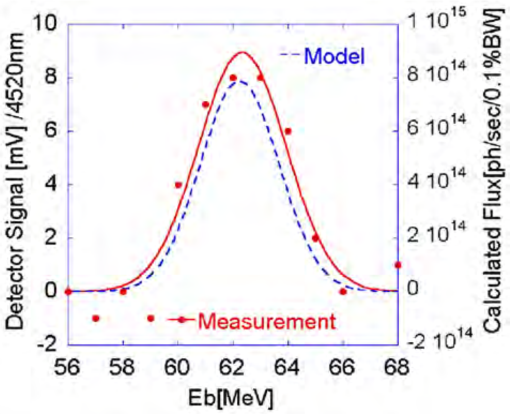
## electron beam test @ ATF



planar




helical

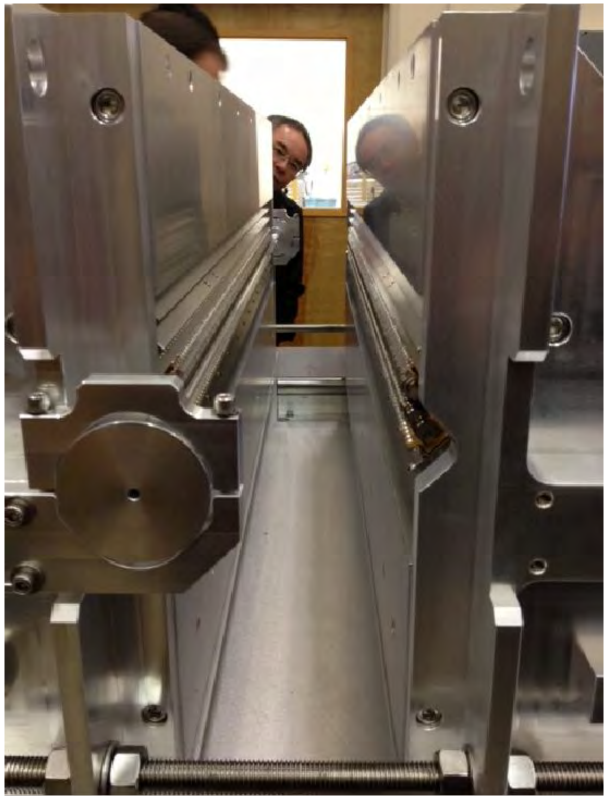



*A. B. Temnykh, DELTA undulator model : Magnetic field and beam test results, Nucl. Instr. Meth. A 649 (2011) 42-45*

# IV- EPU and fast polarisation switching

## DELTA undulators

LCLS-II

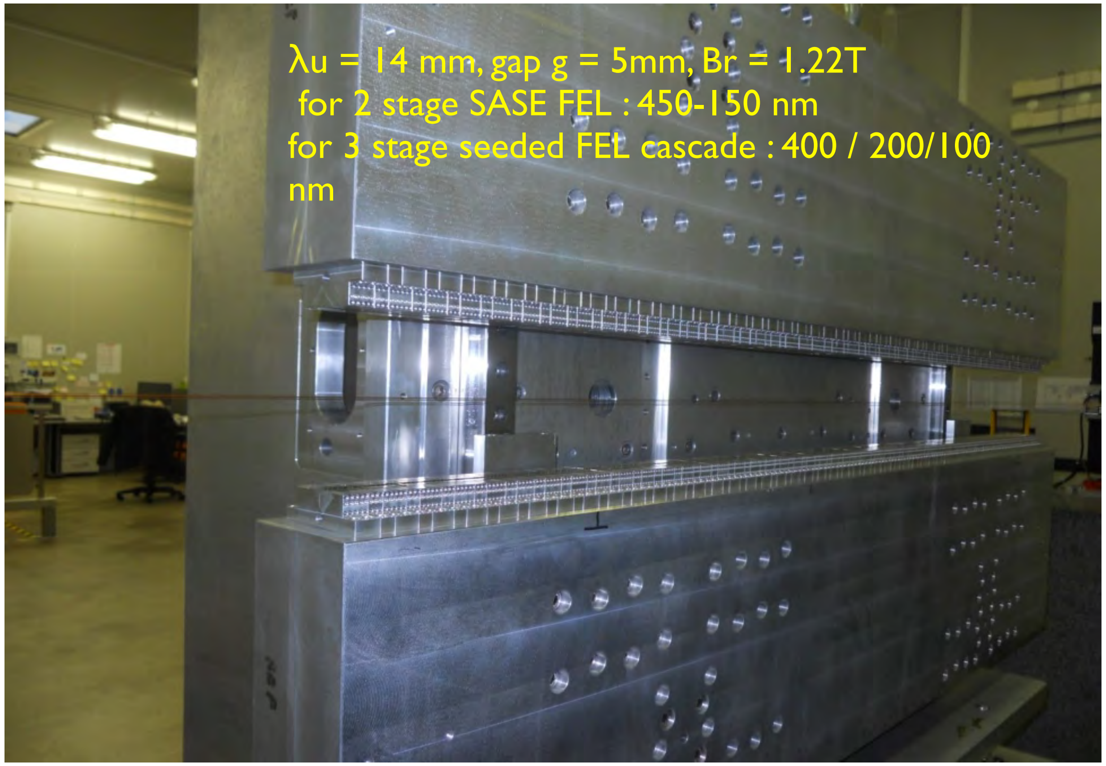


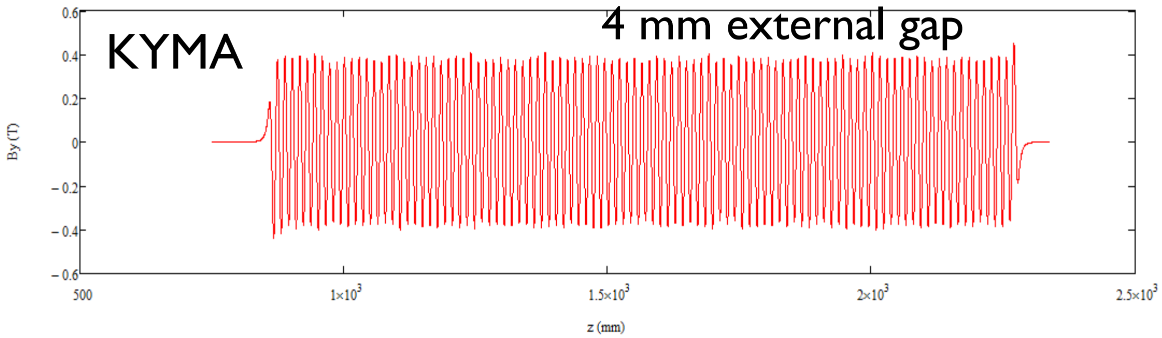
***LCLS 1-m prototype***
***H.-D. Nuhn, E. Kraft***

*T. Raubenheimer HBEBP workshop, 2013, Puerto Rico*

SPARC

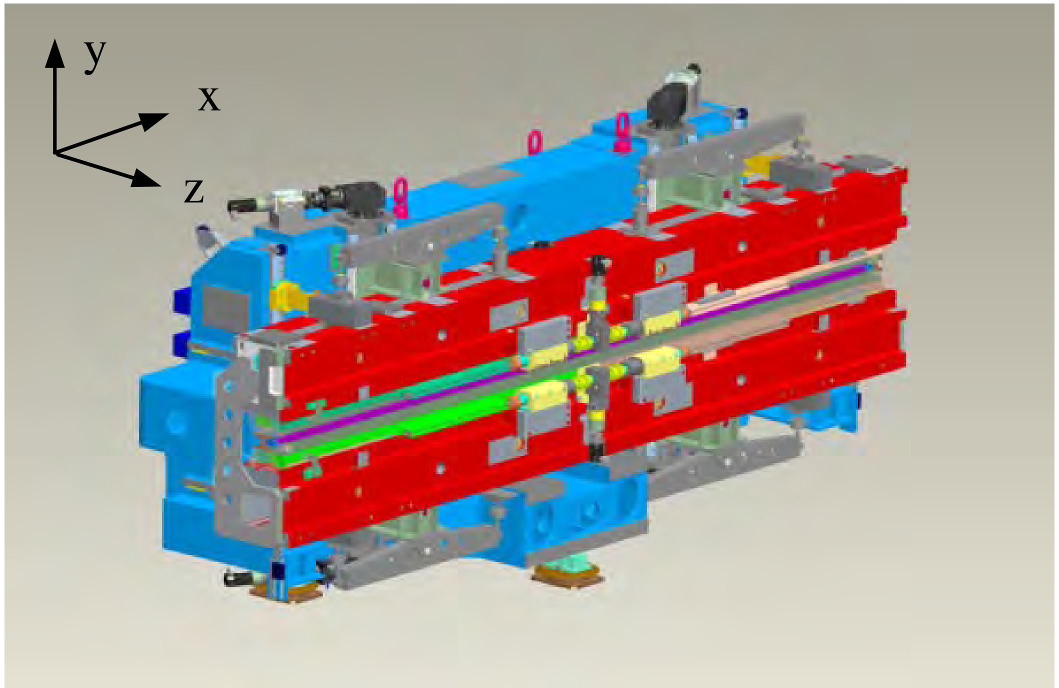
Courtesy F. Ciocci

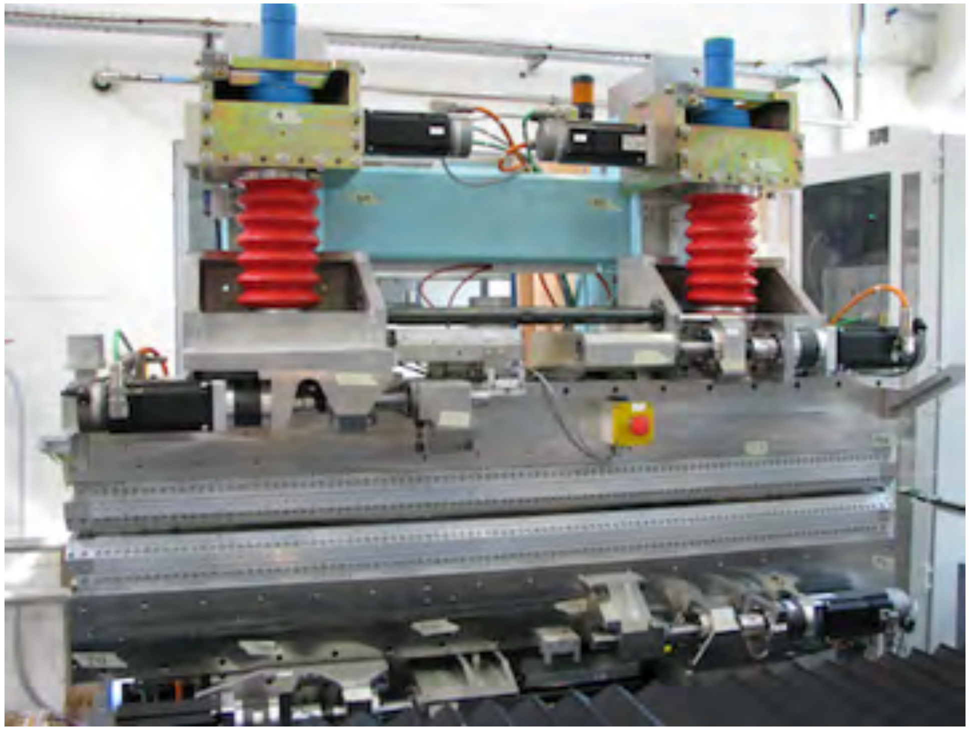


# IV- EPU and fast polarisation switching

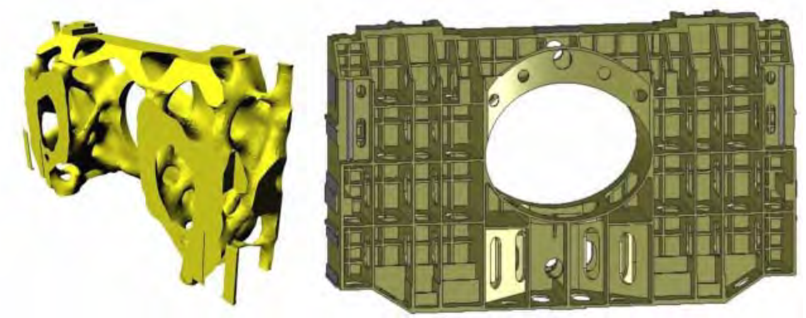
## Permanent magnets EPU carriages



HU64 at SOLEIL : 4 arrays and gap movement

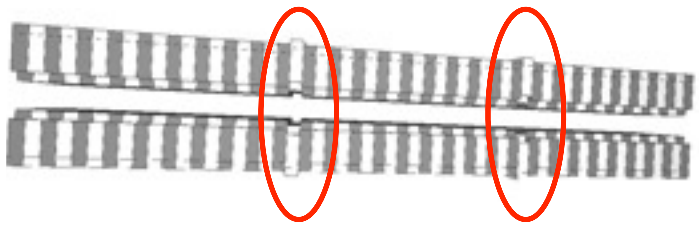
phase and gap variation
aperiodicity
taper
correction coils

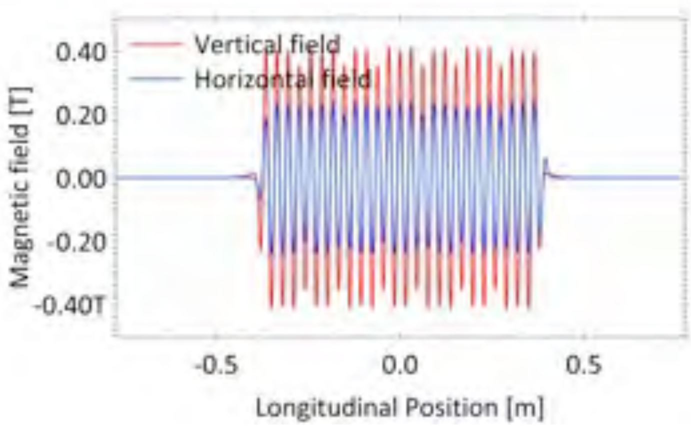


*J. Bahrdt et al., "APPLE Undulator for PETRA III", Proc. EPAC08, 2219 (2008)*

# Quasi periodic PM

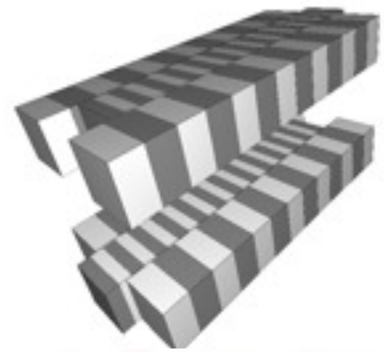
APPLE-II

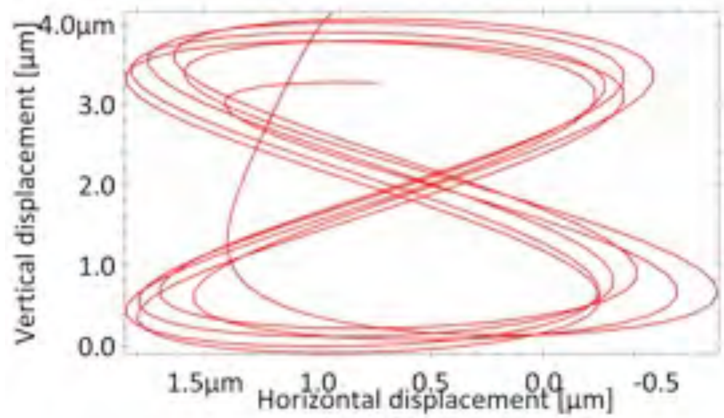





*Sasaki et al. Review of Scientific Instrum. 66 (2), 1995*
*J. Chavanne et al, Proceedings of the European Particle Accelerator Conference, Sweden (1998)*
*B. Diviacco et al, Proceedings of the European Particle Accelerator Conference, Sweden (1998)*

Figure-8

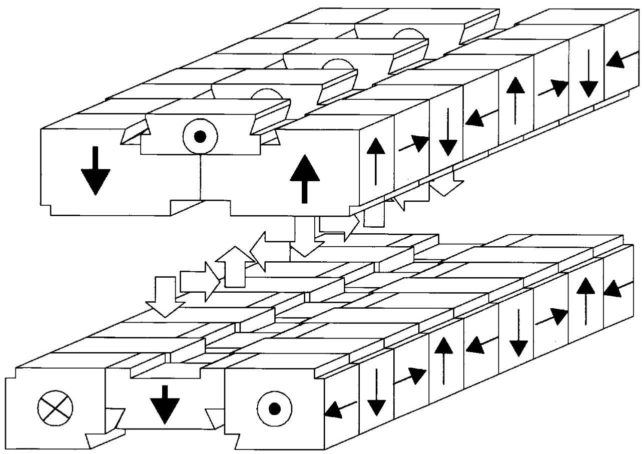


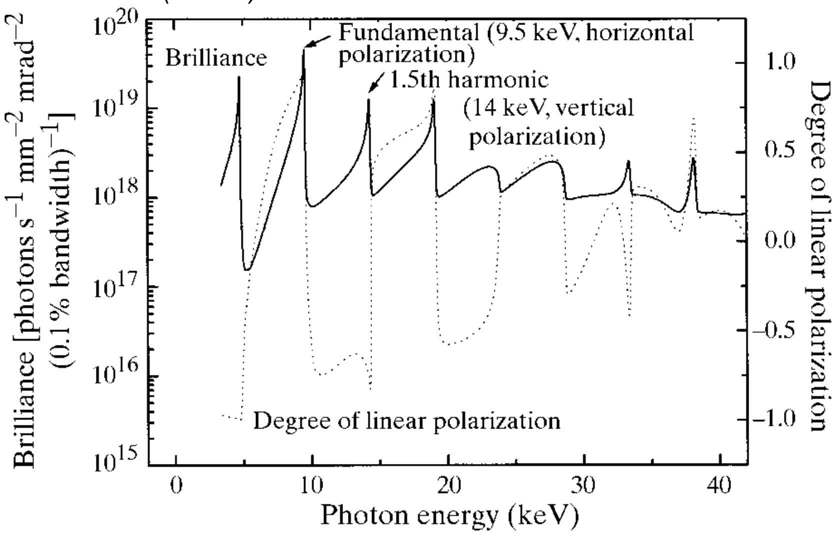



*T. Tanaka, H. Kitamura, J. Synchrotron Radiation (1998), 5, 412-413*
*T. Hara et al. Nucl. Instrum. Methods A 467-468 (2001) 165-168*

# In-vacuum Figure 8

*T. Tanaka, H. Kitamura, J. Synchrotron Radiation (1998), 5, 412-413*
*T. Hara et al. Nucl. Instrum. Methods A 467-468 (2001) 165-168*

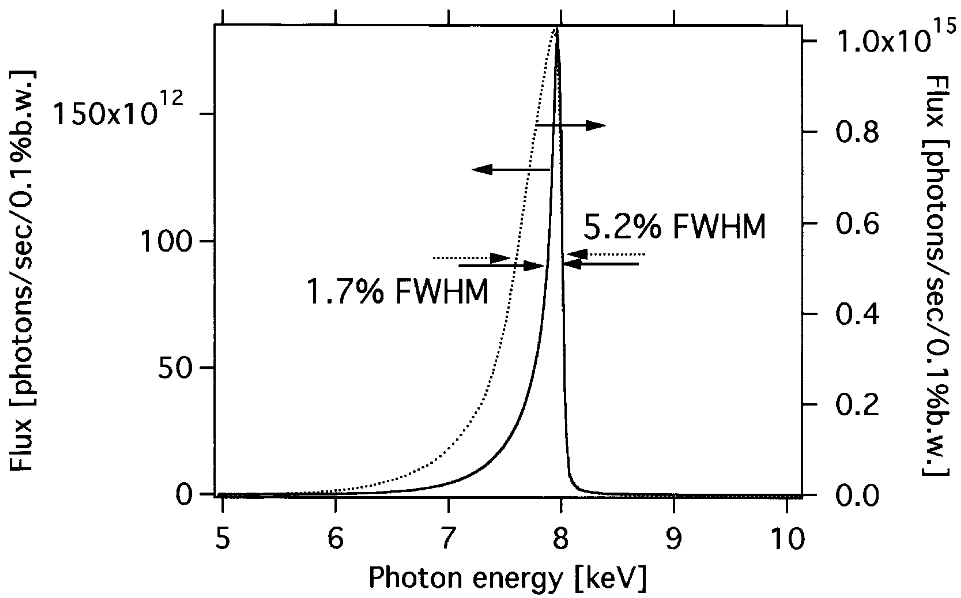





Central arrays : vertical field
side arrays : horizontal field

TiN coating on the magnets
Cu Ni foil, baking 145 °C
no phasing mechanics

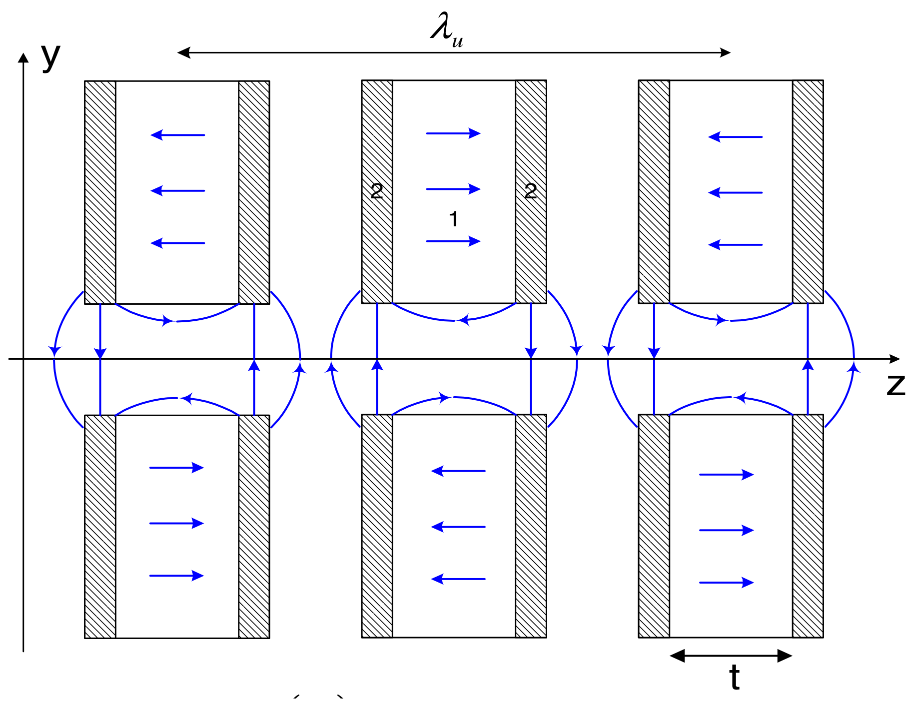
Gap : 11.6 mm (min . 8 mm)
Period : 26 mm
Length : 4.5 m
Bz=0.728 T @ 8 mm
Bx= 0.31 T @ 8 mm
22k W



# V- Exotic concepts

## Period change : variable period with split-pole undulator

Concept

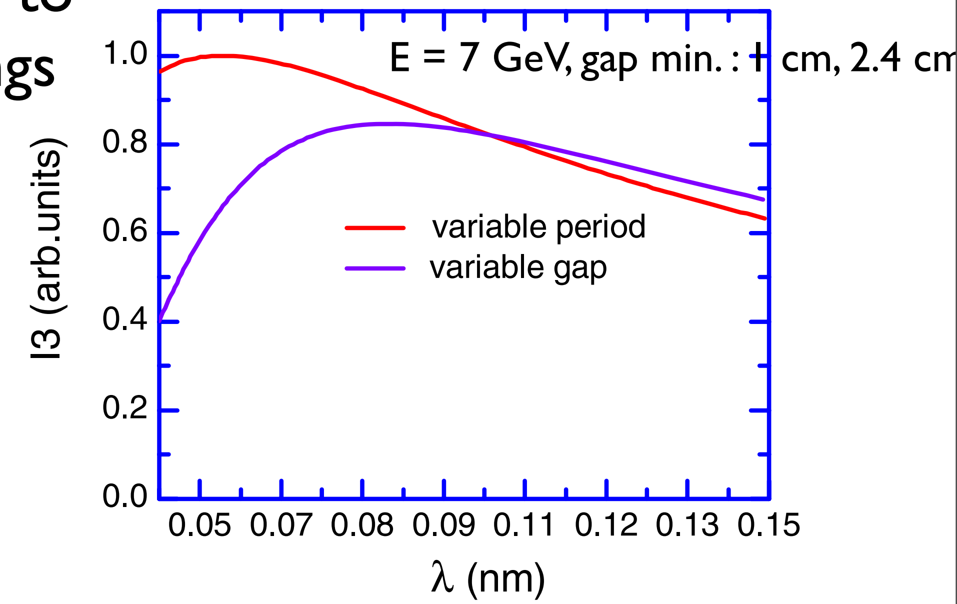



*N. Vinokurov, O.A. Shevchenko, V. G. Tcheskidov Variable-period permanent magnet undulator, Phys. Rev. Spe. Topics AB 14, 040701 (2011)*

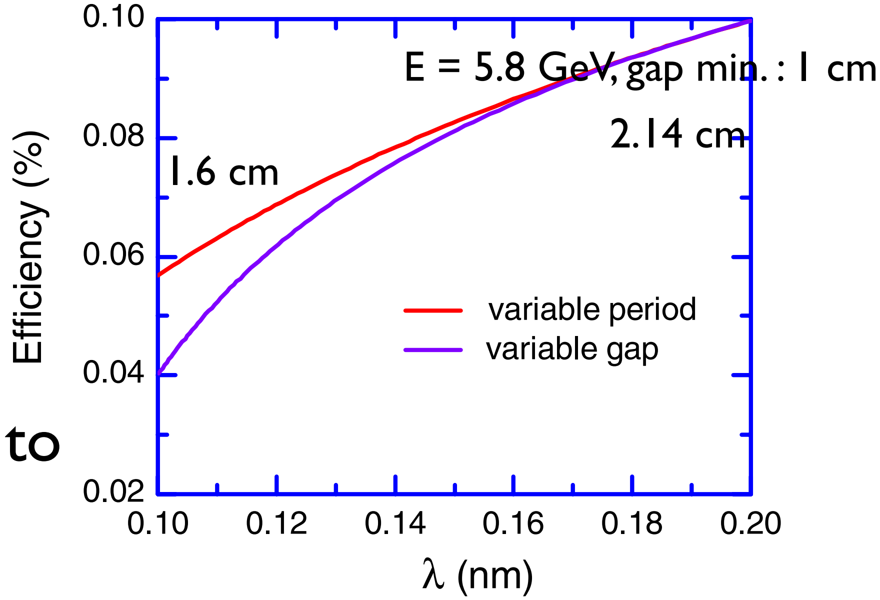
Built for THz FEL Korea

*J. Jeong et al., Proceed FEL conf, Nara, 2012*

Application to storage rings




Application to FELs



# V- Exotic concepts

## Period change

### Composite period undulator

$$K_c^2(g,\Delta z) = K_{c1}^2(g)\cos^2\left(\frac{\pi\Delta z}{\lambda_u}\right) + K_{c2}^2(g)\cos^2\left(\frac{\pi\Delta z}{2\lambda_u}\right),$$

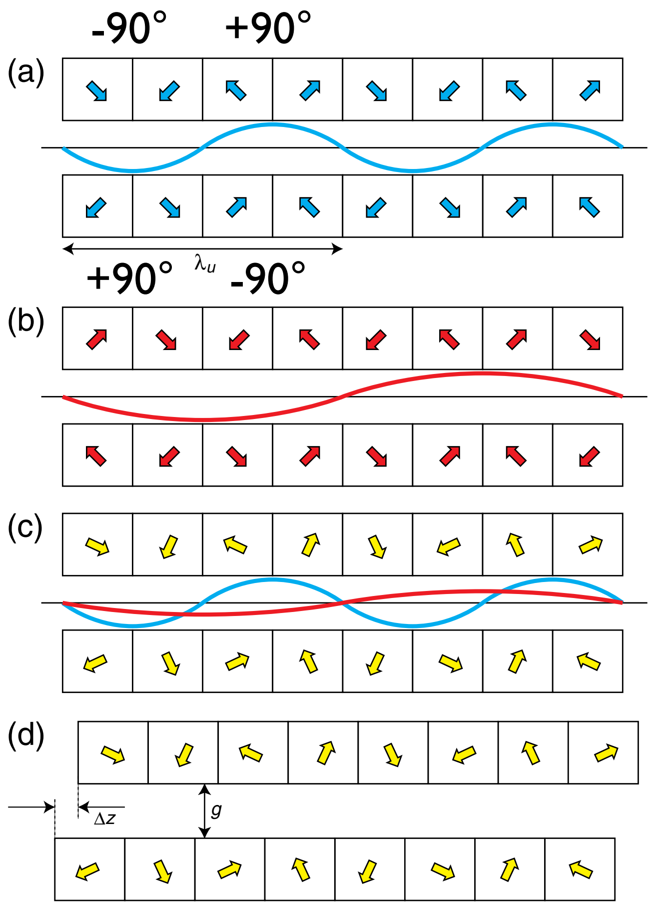
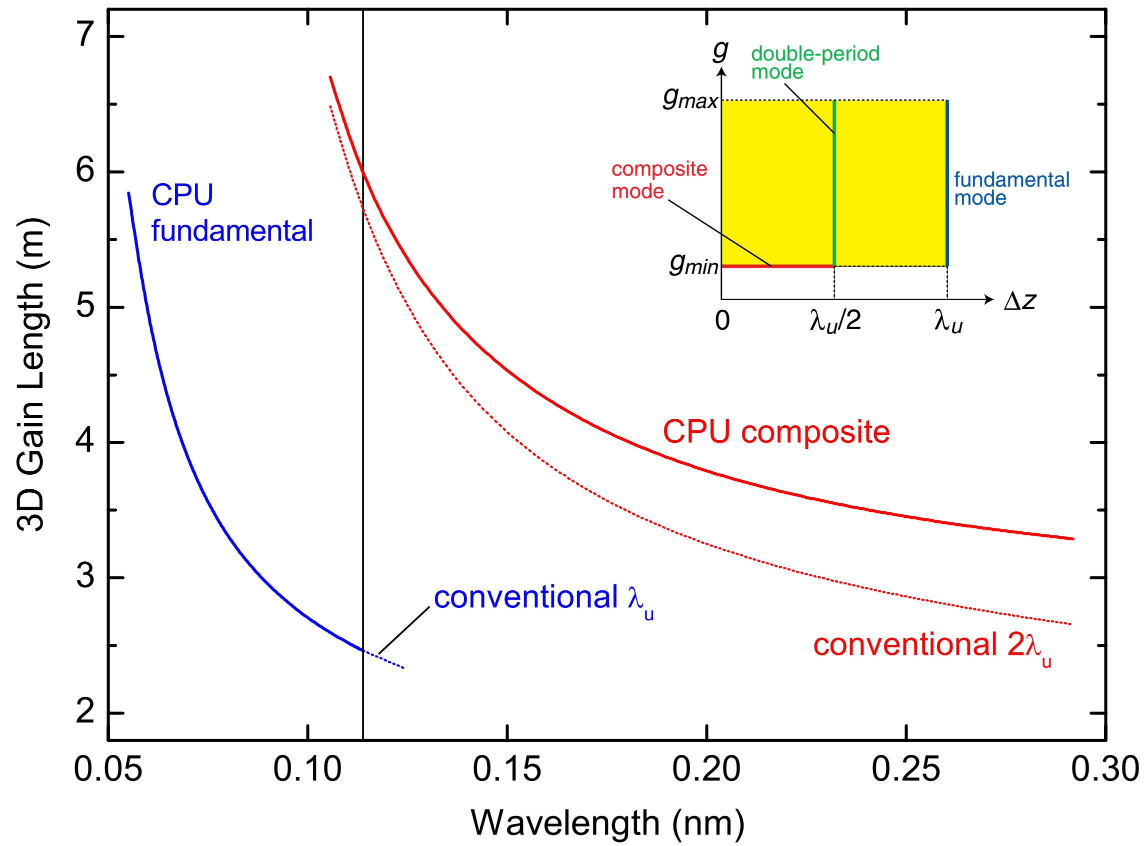



FIG. 1. Halbach-type undulator magnet circuits with four blocks per period (a) for the fundamental period and (b) for the double period. (c) Composite configuration of (a) and (b). (d) Two parameters to tune the photon energy: magnet gap $g$ and magnet shift $\Delta z$.

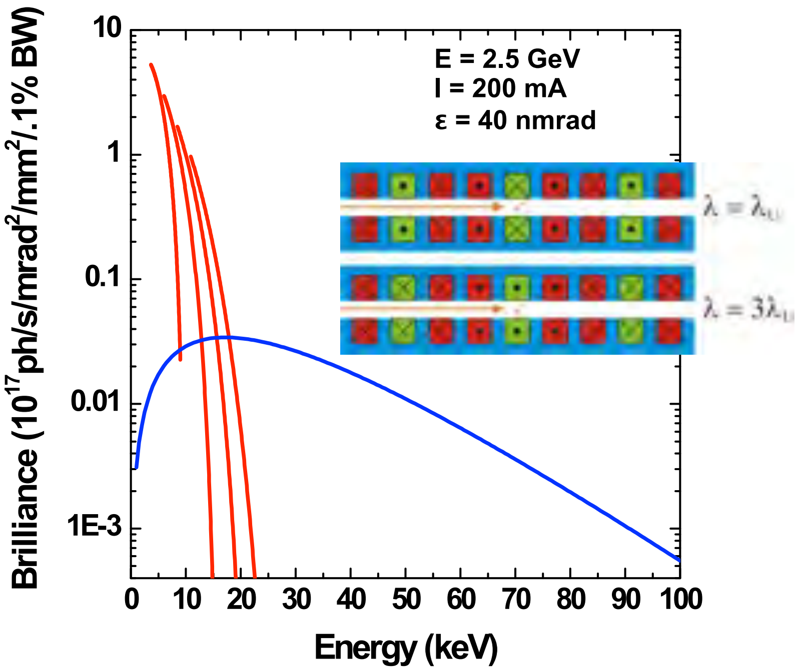



*T. Tanaka, H. Kitamura, Composite period undulator to improve the wavelength tuneability of free electron lasers , Phys. Rev. Spe. Topics AB 14, 050701 (2011)*

# Bi-period superconducting 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*
*A. Bernhard et al., EPAC06*
*A. Bernhard et al., EPAC08*
*T. Holubek et al., IPAC11*




Foreseen for the planned IMAGE beamline at ANKA.

Applications:

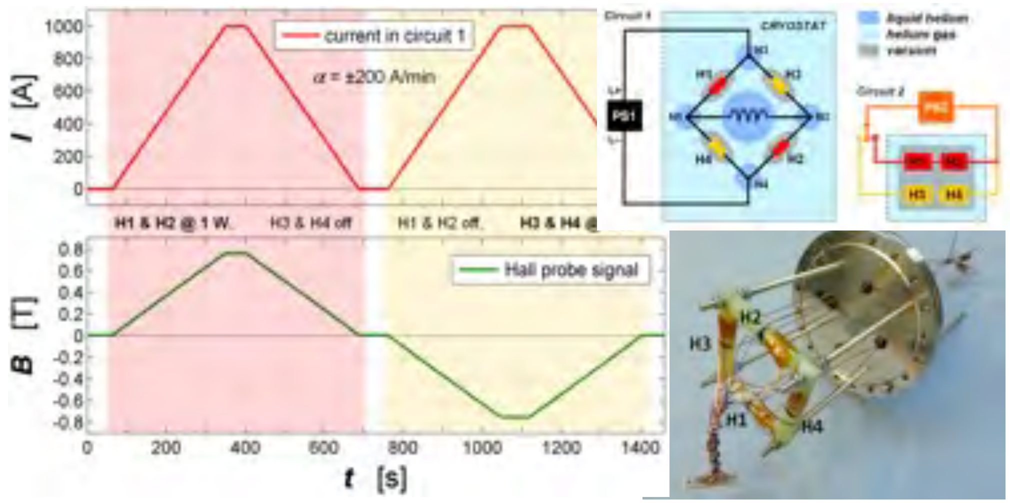
- High brilliance of the undulator from 6 to 15 keV for imaging,
- wiggler mode for higher photon energies to perform phase contrast tomography.

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)*

Successful test of the conduction cooled superconducting switch

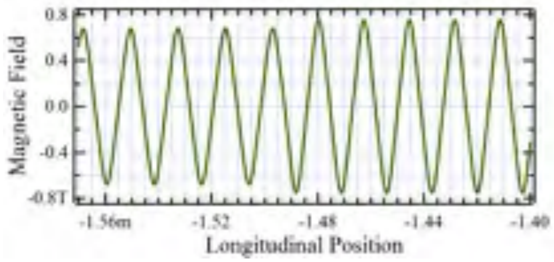



*T. Holubek et al., accepted for publication in IEEE Trans. on Appl. Supercond.*

# Adaptative gap undulator

*Courtesy O. Chubar*

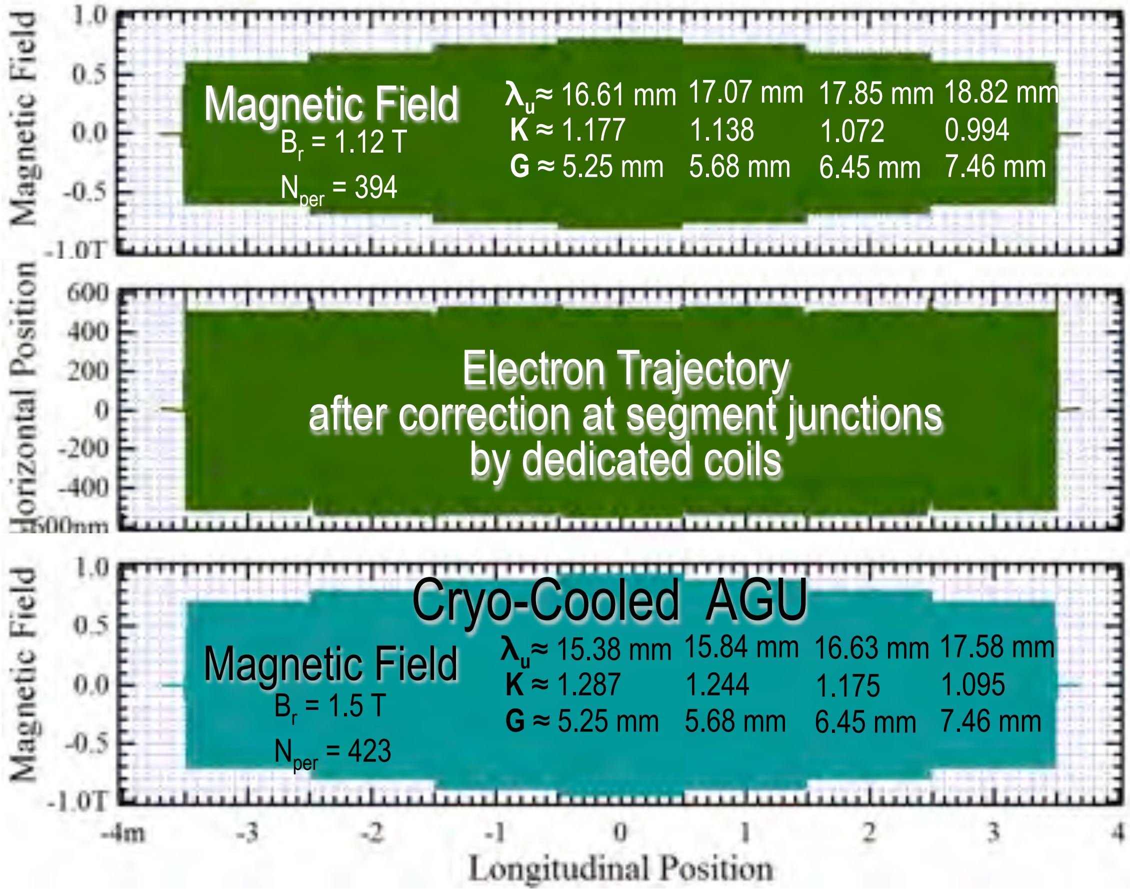
- Adaptation of the gap to the betatron function




- Segments are independent, yet tuned to the same Resonant Photon Energy
- Vertical Gaps in the segments satisfy "Stay-Clear" and Impedance Constraints
- Undulator Period may vary from segment to segment (however it is constant within each segment)

$$g_i \approx N_\sigma \sqrt{(s_i^2 + \beta_{y0}^2)\varepsilon_y / \beta_{y0}}$$

$$\lambda_1 = \frac{(1 + K_i^2/2)\lambda_{ui}}{2\gamma^2} = const$$

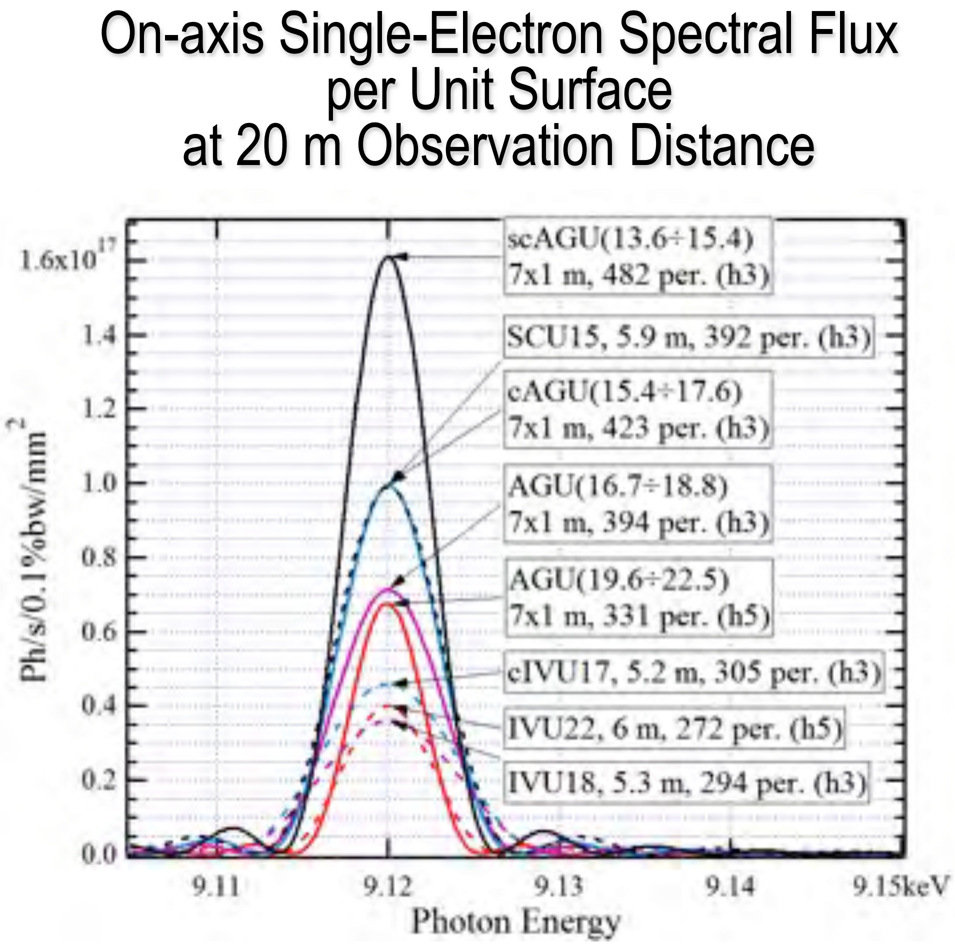


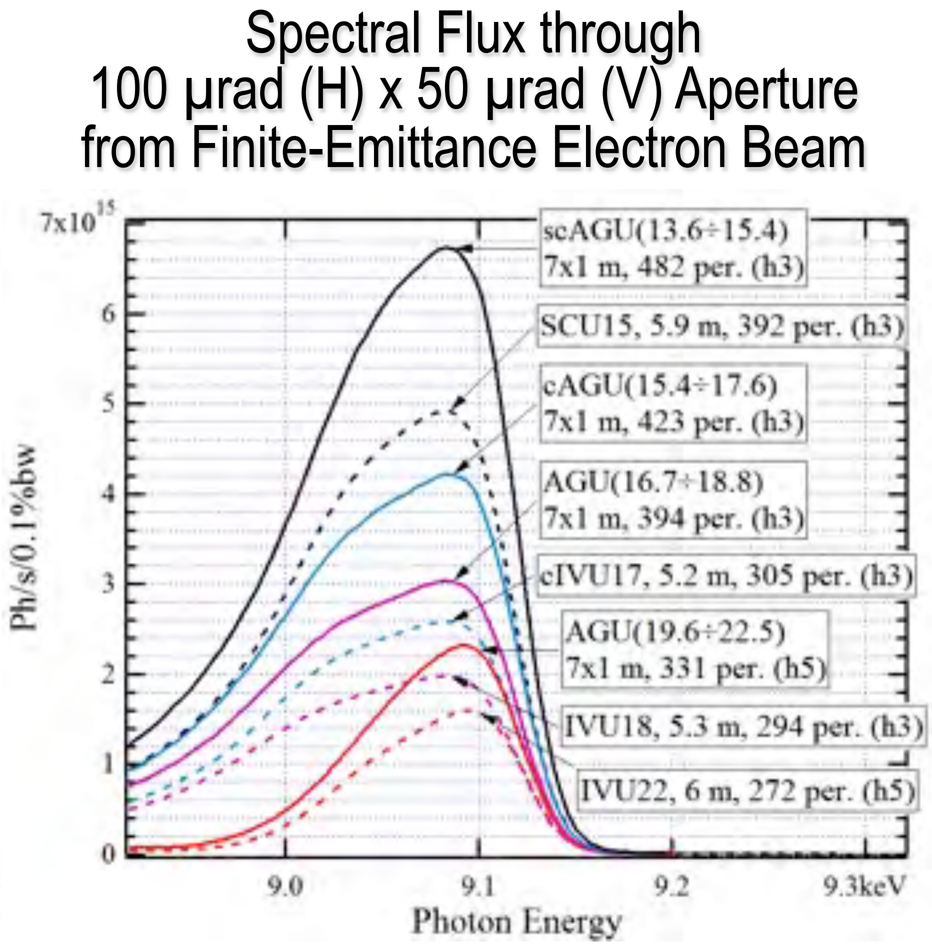

*O.Chubar, J.Bengtsson, A.Blednykh, C.Kitegi, G.Rakowsky, T.Tanabe, J.Clarke, "Spectral Performance of Segmented Adaptive-Gap In-Vacuum Undulators for Storage Rings", Proc. of IPAC2012, MOPPP090, pp.765-767.*

*O.Chubar, J.Bengtsson, A.Blednykh, C.Kitegi, G.Rakowsky, T.Tanabe, J.Clarke, "Segmented Adaptive-Gap Undulators - Potential Solution for Beamlines Requiring High Hard X-Ray Flux and Brightness in Medium-Energy Synchrotron Sources?", 2013 J. Phys.: Conf. Ser. 425 032005.*

# Adaptative gap undulator

Comparison for the Inelastic X-ray Scattering NSLS-II beamline




$E_e$ = 3 GeV, $I_e$ = 0.5 A; NSLS-II High-β (Long) Straight

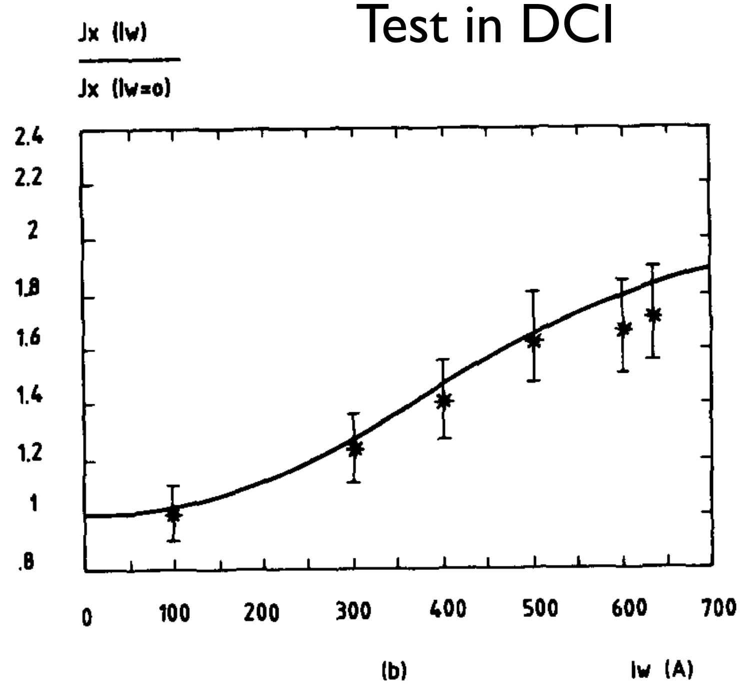
*Courtesy O. Chubar*

*See O. Chubar et al, Poster Wednesday*

# V- Exotic concepts

## Transverse gradient undulator / wiggler

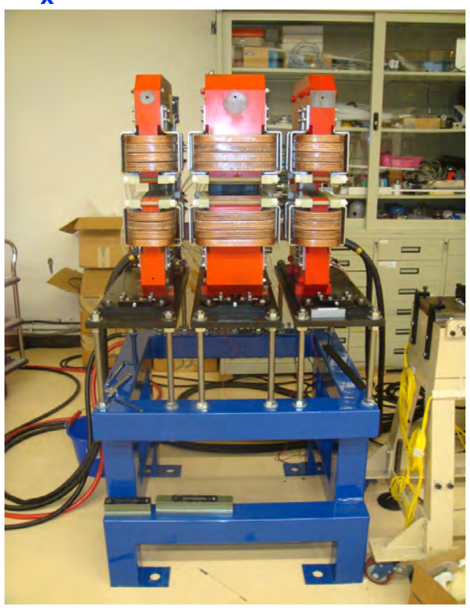
Test in DCI




CERN PS (1983)

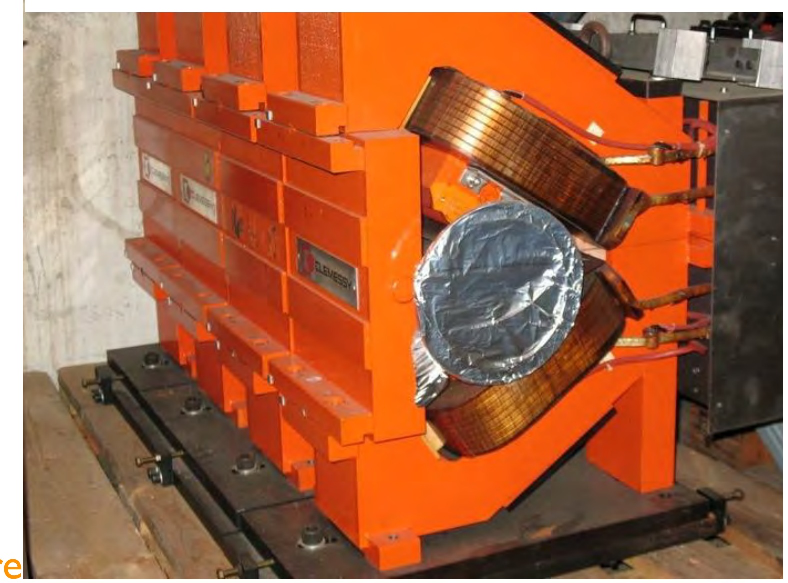
damping of horizontal betatron oscillations

$J_x$=3 et D = -2



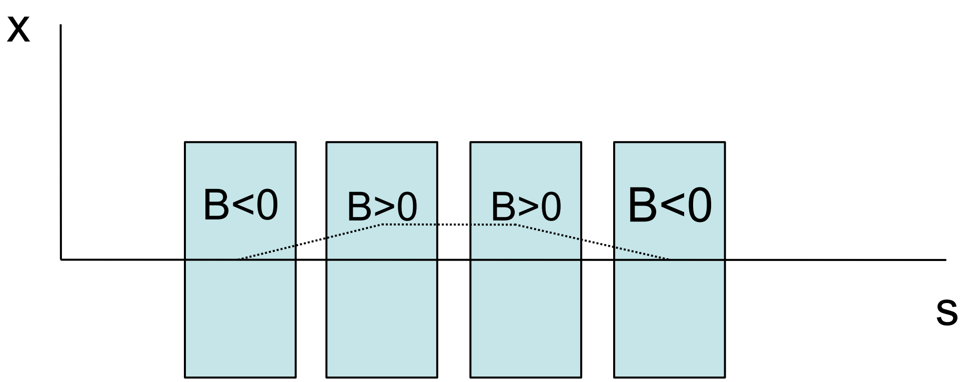
*Y. Baconnier et al, Emittance control of the PSe± beam as using A Robinson wiggler, Nucl. Instr. Meth. A 234 (1985) 244-252 Nucl. Instr. Meth. A266 (1988) 24-31.*

*Lee SY Kolski J Review of Scientific Instruments 78, 075107 (2007)*
*C.W Huang et al. IPAC 2010, 3186, PAC 2011, 1265*



# V- Exotic concepts

## Transverse gradient undulator / wiggler

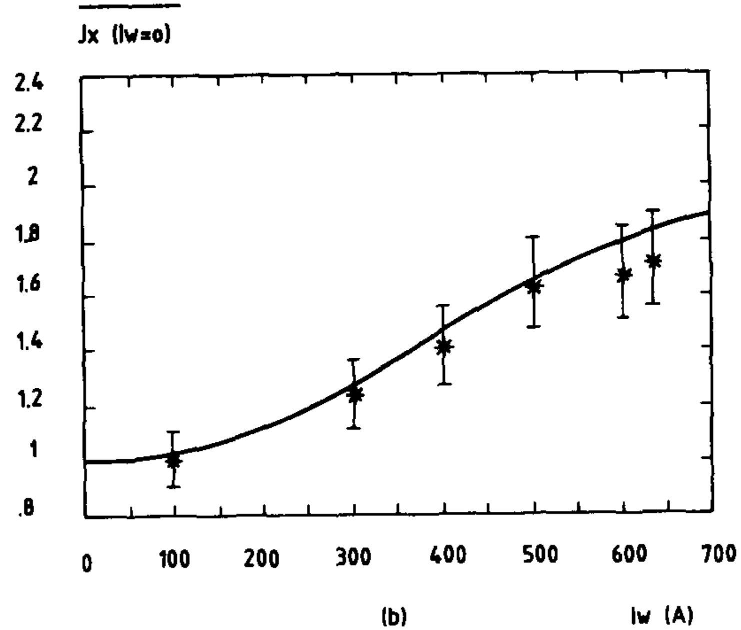


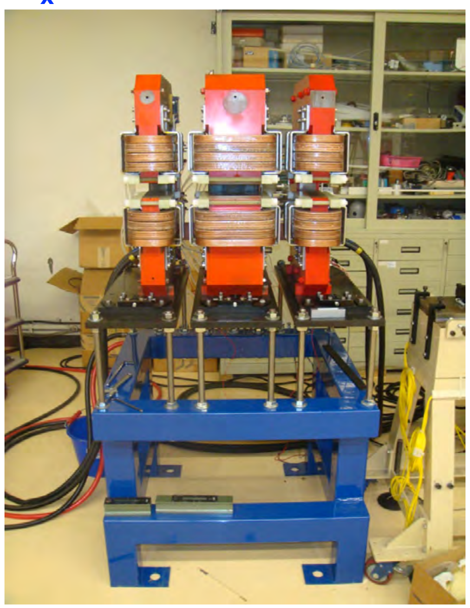

CERN PS (1983)

damping of horizontal betatron oscillations

$J_x$=3 et D = -2

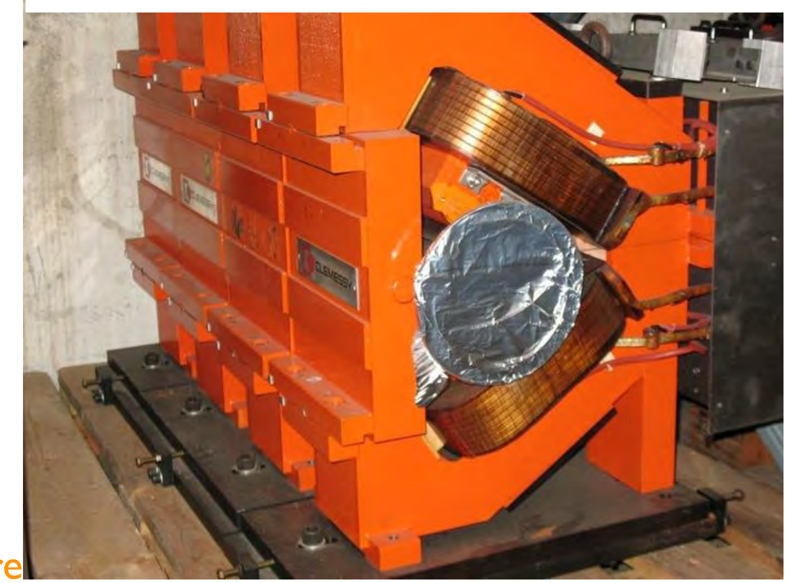
Test in DCI



*Y. Baconnier et al, Emittance control of the PSe± beam as using A Robinson wiggler, Nucl. Instr. Meth. A 234 (1985) 244-252 Nucl. Instr. Meth. A266 (1988) 24-31.*

*Lee SY Kolski J Review of Scientific Instruments 78, 075107 (2007)*
*C.W Huang et al. IPAC 2010, 3186, PAC 2011, 1265*

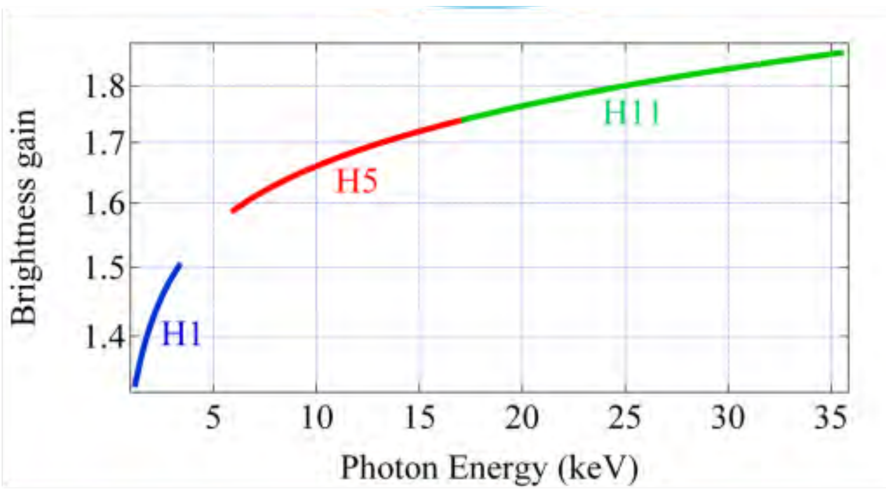


# Transverse gradient undulator / wiggler for Storage rings

Purpose : emittance reduction

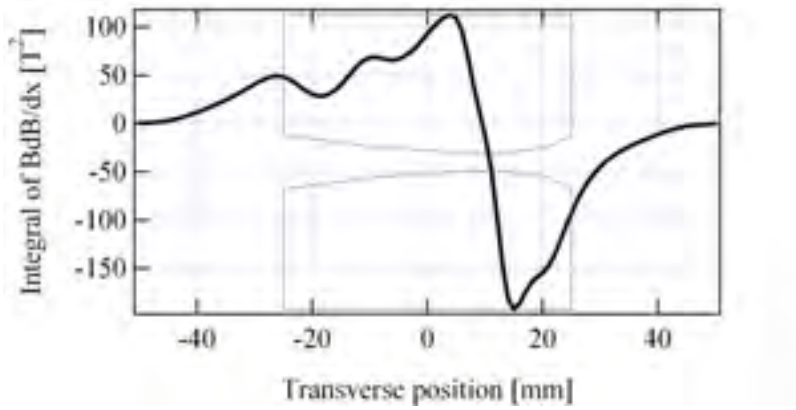
$$\varepsilon_x = \varepsilon_{x0}\frac{1}{1-D} \qquad \left(\frac{\sigma_E}{E}\right)^2 = \frac{2}{2+D}\left(\frac{\sigma_{E0}}{E_0}\right)^2$$

$$D=-1 \quad \varepsilon_x = \frac{\varepsilon_{x0}}{2} \quad \left(\frac{\sigma_E}{E}\right) = \sqrt{2}\left(\frac{\sigma_{E0}}{E_0}\right)$$




H. Abualrob, P. Brunelle, M-E. Couprie, O. Marcouillé, A. Nadji, L. Nadolski, R. Nagaoka, SOLEIL emittance reduction using a Robinson wiggler, IPAC12, Louisiana, La Nouvelle Orleans 20-25 Mai 2012

Preliminary design for a Robinson wiggler at SOLEIL




| | |
|---|---|
| Gap | 6 mm |
| $B_{max}$ | -2.5 T |
| Int[BdB/dX] | 193 $T^2$ |
| Period length | 164 mm |
| No. of periods | 12 |

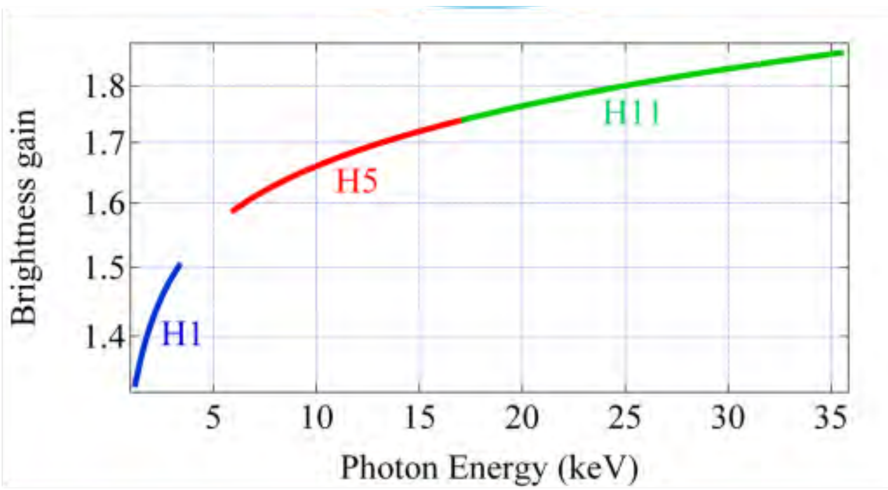
# Transverse gradient undulator / wiggler for Storage rings

Purpose : emittance reduction

$$\varepsilon_x = \varepsilon_{x0}\frac{1}{1-D} \qquad \left(\frac{\sigma_E}{E}\right)^2 = \frac{2}{2+D}\left(\frac{\sigma_{E0}}{E_0}\right)^2$$

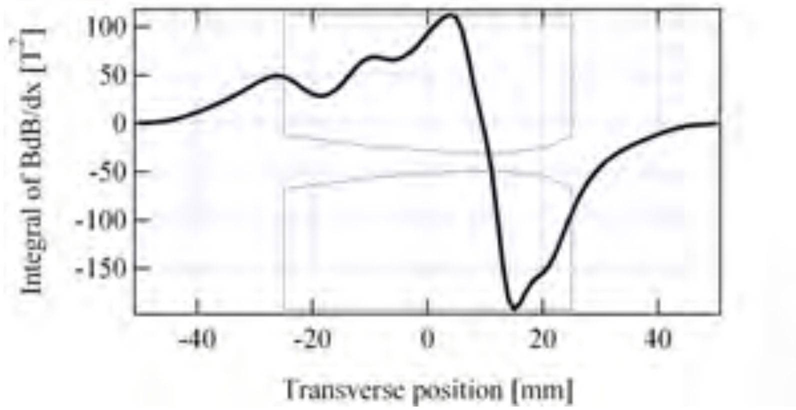
$$D = \frac{\rho_0 \eta_x}{\pi(\rho_0 B_0)^2}\int_0^{L_w} B_w \frac{dB_{w,z}}{dx}\, ds$$

$$D = -1 \qquad \varepsilon_x = \frac{\varepsilon_{x0}}{2} \qquad \left(\frac{\sigma_E}{E}\right) = \sqrt{2}\left(\frac{\sigma_{E0}}{E_0}\right)$$




H. Abualrob, P. Brunelle, M-E. Couprie, O. Marcouillé, A. Nadji, L. Nadolski, R. Nagaoka, SOLEIL emittance reduction using a Robinson wiggler, IPAC12, Louisiana, La Nouvelle Orleans 20-25 Mai 2012

Preliminary design for a Robinson wiggler at SOLEIL

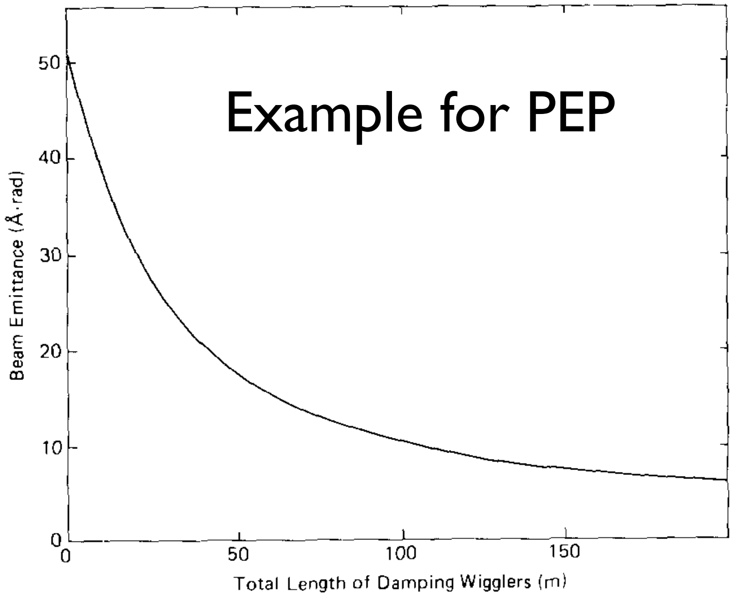



| | |
|---|---|
| Gap | 6 mm |
| $B_{max}$ | -2.5 T |
| Int[BdB/dX] | 193 $T^2$ |
| Period length | 164 mm |
| No. of periods | 12 |

# V- Exotic concepts

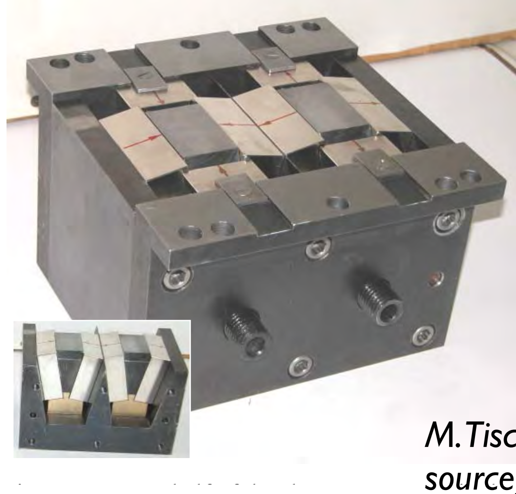
## Transverse gradient undulator / wiggler for Storage rings as an alternative to damping wigglers

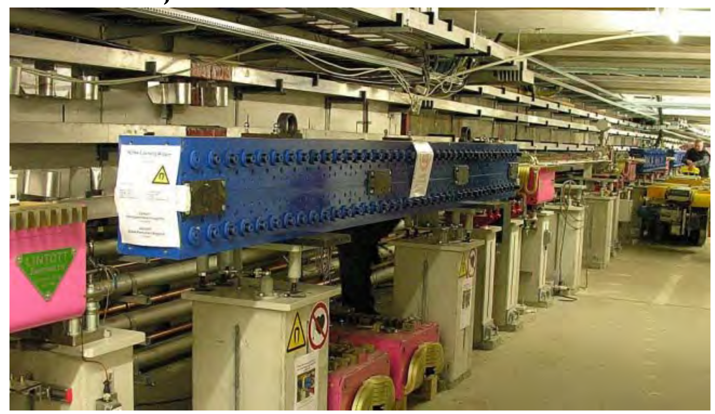
More damping with additional synchrotron radiation through installation of strong wiggler magnets placed in a dispersion free location (for the equilibrium orbit to be independant of the particle energy) => emittance reduction




*H.Wiedemann, An ultra-low emittance mode for PEP using damping wigglers, Nucl. Instr. Meth. A266 (1988) 24-31.*
*T. Raubenheimer et al. SLAC PUB 4808, 1988*

PETRAIII: Horizontal emittance : 1 nm.rad, Vertical emittance : 0.01 nmrad

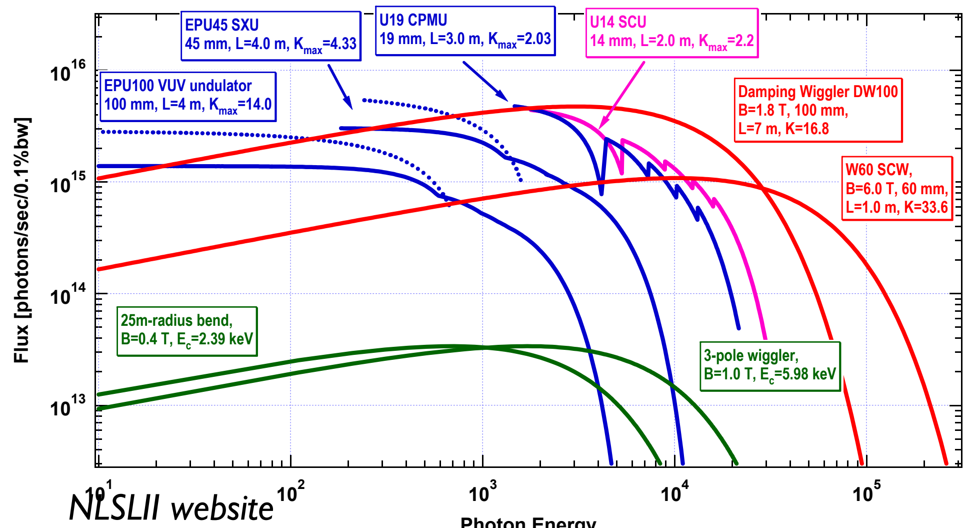




*M.Tischer et al. Damping wigglers for the PETRA III light source, PAC 2005, Knoxville, 2446; EPAC08, 2317*

NSLSII (3 GeV):
Horizontal emittance : 0.55 nm.rad
Vertical emittance : 0.008 nmrad
2x3.4 mperiod 9 cm, gap 12.5 mm, K=15.2

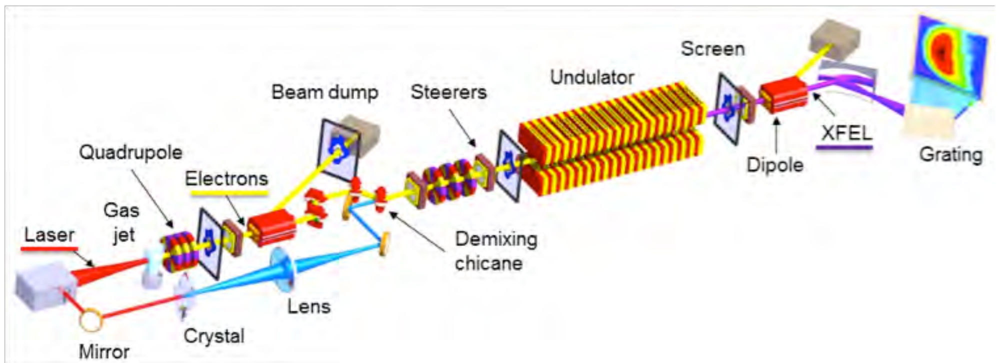
MAX-IV (3 GeV):
Horizontal emittance : 0.24 nm.rad



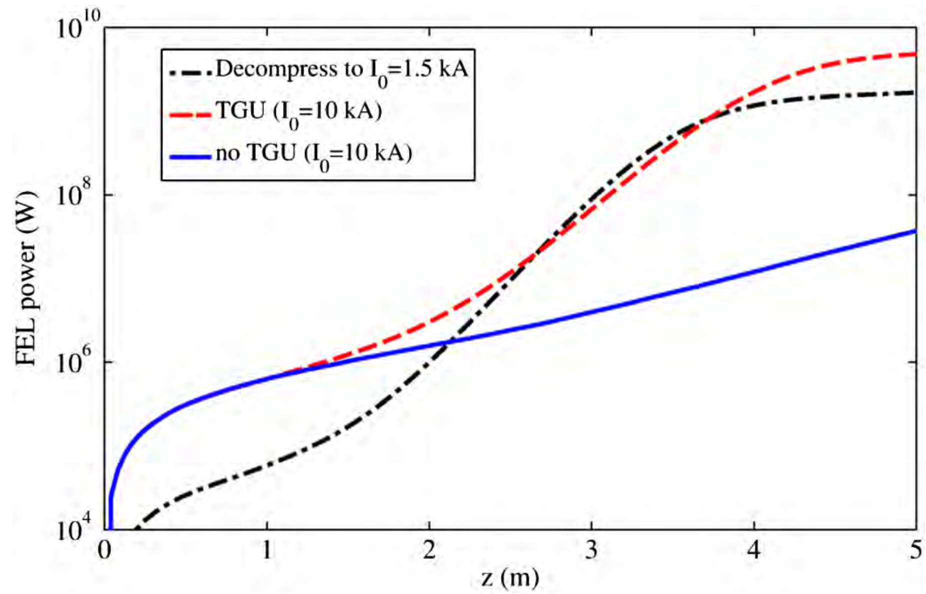

*NLSLII website*

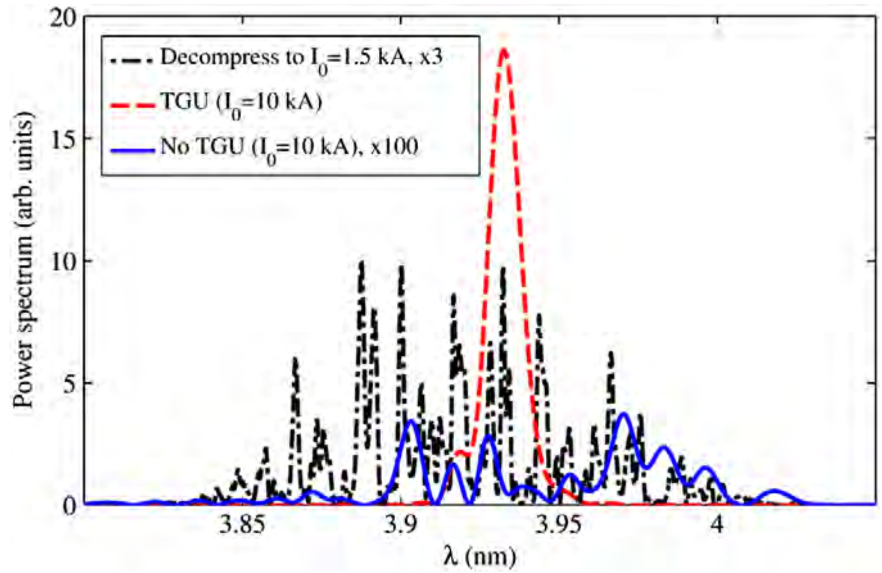
# Transverse gradient undulator / wiggler for LWFA FEL

Purpose : handle the large energy spread (1 %) and divergence ( 1 mrad) of LWFA beams :
- decompression
- transverse gradient




$$\frac{\Delta K}{K_0} = \alpha x. \qquad \eta = \frac{2 + K_0^2}{\alpha K_0^2}$$

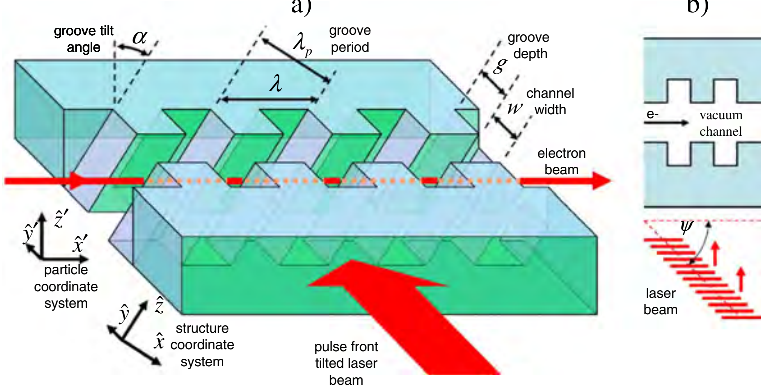



*Z. Huang et al., Phys. Rev. Lett. 109, 204801 (2012)*
*T. Smith, J. M. J. Madey, L. R. Elias, and D. A. G. Deacon, J. Appl. Phys. 50, 4580 (1979)*

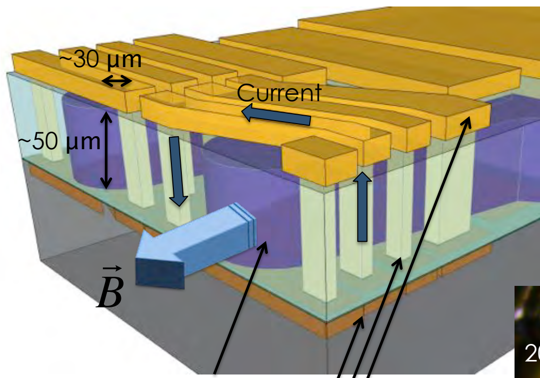
# Towards dramatic reduction of the period

## Microstructure laser driven undulator



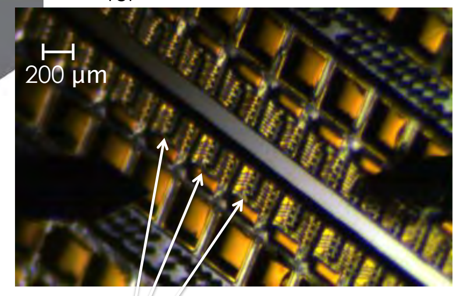

*T. Plettner, R. L. Byer, Proposed dielectric micrstructure laser-driven undulator PRSTAB 11, 030704 (2008)*

## Surface Micromachined undulator




L ~ 10s nH – 10s $\mu$H
C ~1 pF
R~ 10 m$\Omega$

NiFe core
-$B_{sat}$ ~1T
- $\mu_{rel}$ ~8000




Batch-fabricated Electromagnets

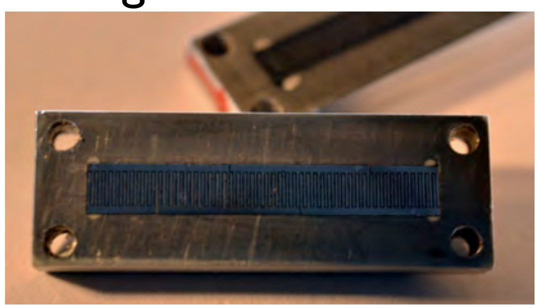
*J. Harrison et al. PRSTAB 15, 070703 (2012)*
*R. Candler, HBEB workshoip, Puerto-Rico 2013*

## RF undulator

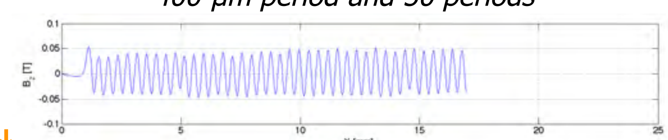
*S. Tantawi, HBEB workshop, Puerto-Rico, 2013*

## Micromachined magnet undulator

*G. Ramian et al., NIM A 250, 125 (1986)*
*K. Paulson, NIMA 296, 624 (1990)*
*R. Tachyn et al. Rev. Sci. Instrum. 60, 1796 (1989)*
*D. Arnold et N. Wang, J. Microelectromech. Syst. 18, 1255 (2009)*
*D. Arnold, HBHEB Workshop, Puerto-Rico, 2013*



*Laser-machined SmCo undulator array with 200-µm thick, 2-mm long poles, 400-µm period and 50 periods*




## Optical undulator

*A. Bacci et al. PRSTAB 9, 0607704 (2006)*
*R. Lehé, Proced. FEL cong, 2012*

# Conclusion

Clear advances for :
- permanent magnet based systems
- superconducting undulators
-EPU
and combinations of the technolgies

+ New concepts

Quest for more flexibility for the radiation properties
Besides compensation of the induced effect, manipulation of the beam via the undulator

New technological develpments towards ultra-short period high fields (but low deflection parameter, wakefield and heat issues...)

towards future light source, search for :
coherence
compactness
law size on the sample....
more flexibility for the photon users