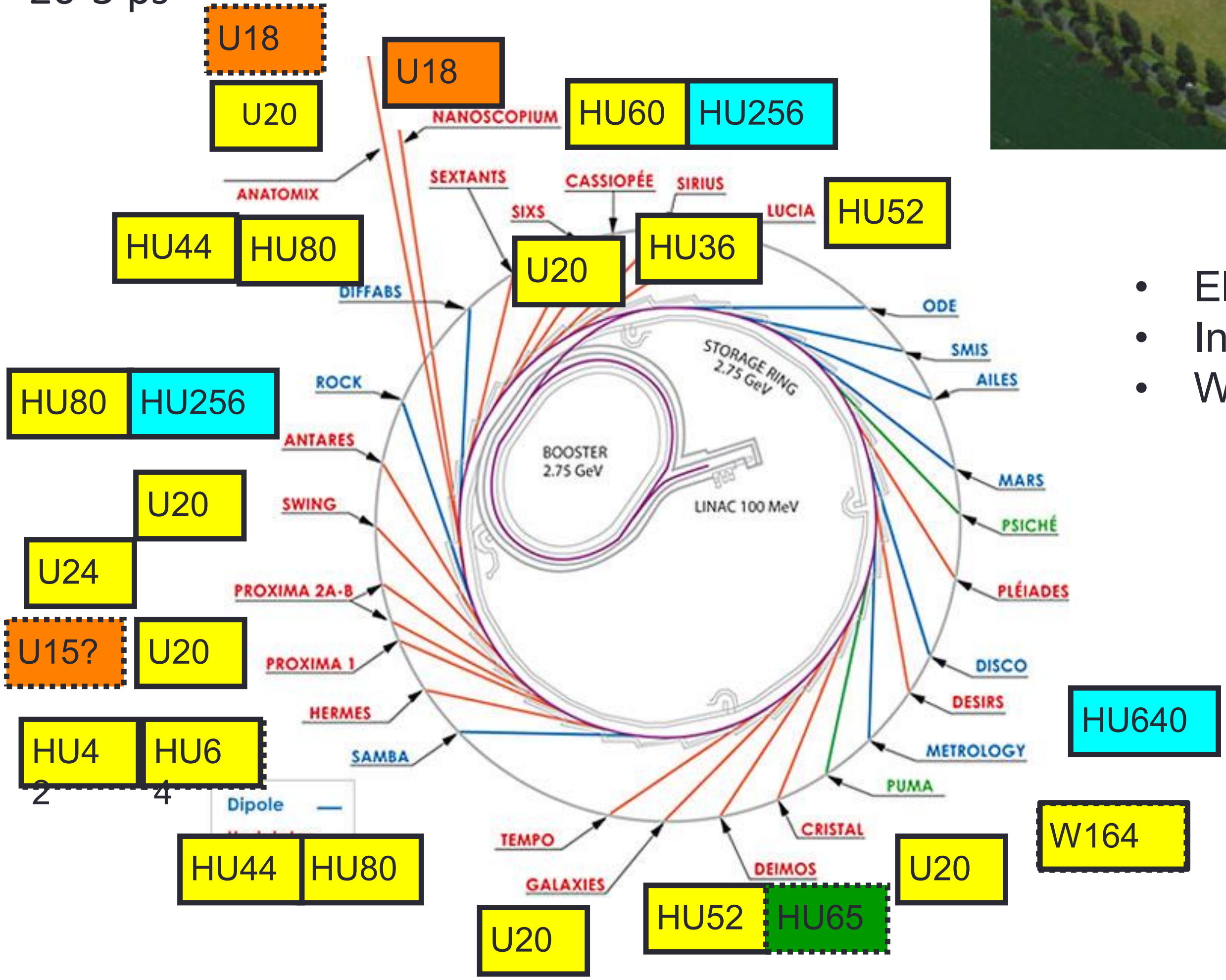
Progress of PrFeB Based Hybrid Cryogenic Undulators at SOLEIL

A. Ghaith, M. Valléau, F. Briquez, G. Sharma, F. Marteau, M. E. Couprie, P. Berteaud, C. Kitegi, M. Tilmont, J. Da Silva Castro, K. Tavakoli, J. M. Dubuisson, D. Zerbib, N. Béchu, C. Herbeaux, M. Sebdaoui, C. Benabderrahmane, O. Marcouill´e, A. Lestrade, A. Somogyi

Motivation

SOLEIL beamlines:

2.75 GeV,
emittance 3.9 nmrad,
500 mA
20-3 ps



- Elliptical Polarized Undulators
- In-vacuum planar Undulators
- Wigglers

Cryo
PM
EM
Mixed

Installed
to be installed

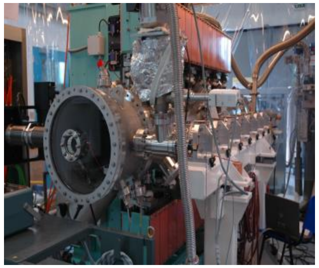
Intermediate energy

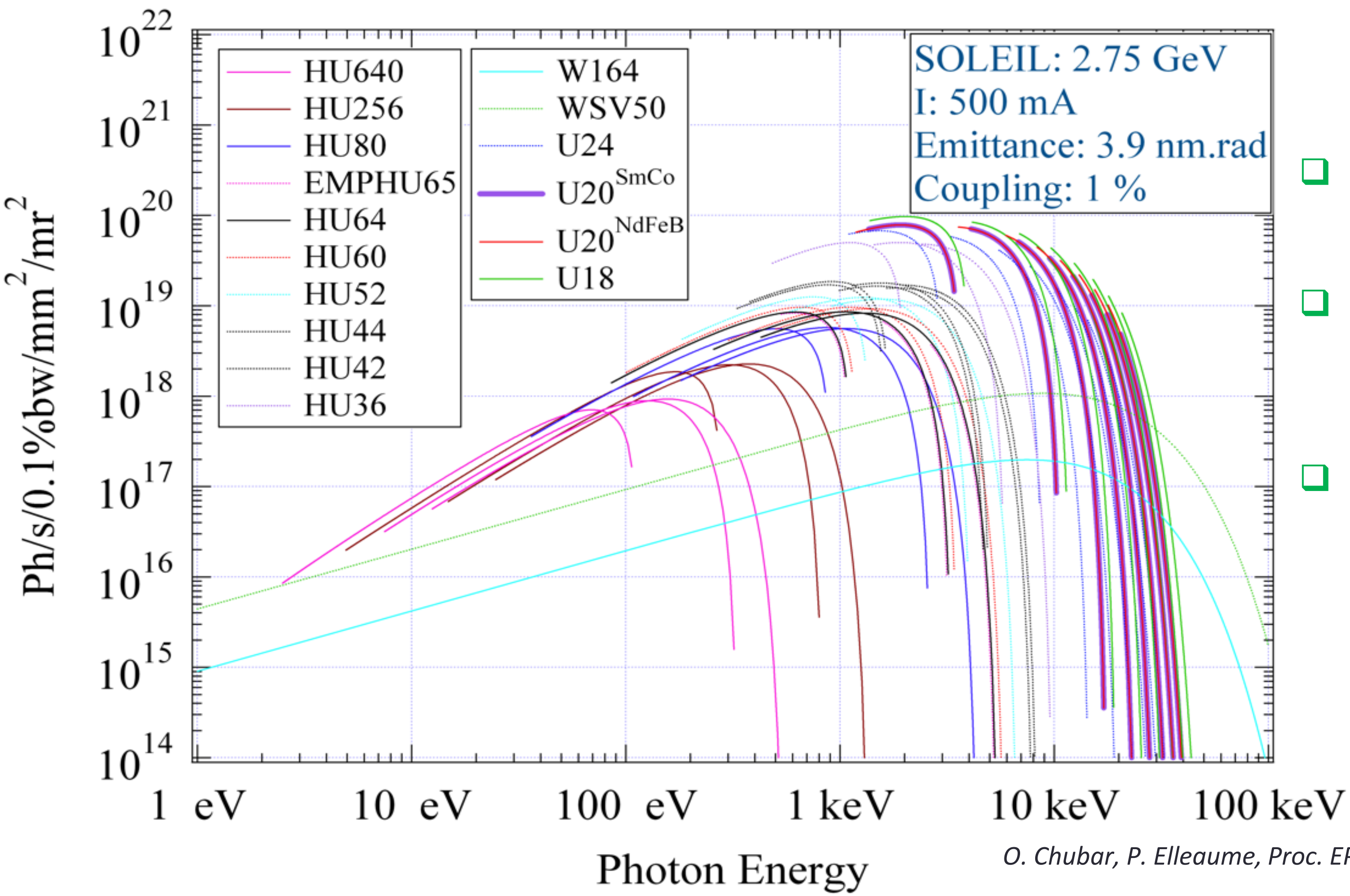
Need of short period in-vacuum undulators to produce intense xrays

Brilliance:







- Ranging from Infrared to x-rays
- High energy photons are produced by the in-vacuum undulators
- Cryogenic permanent magnet undulators (CPMUs) are of interest to achieve higher brilliance at higher energies. How???

O. Chubar, P. Elleaume, Proc. EPAC-98, 1177.

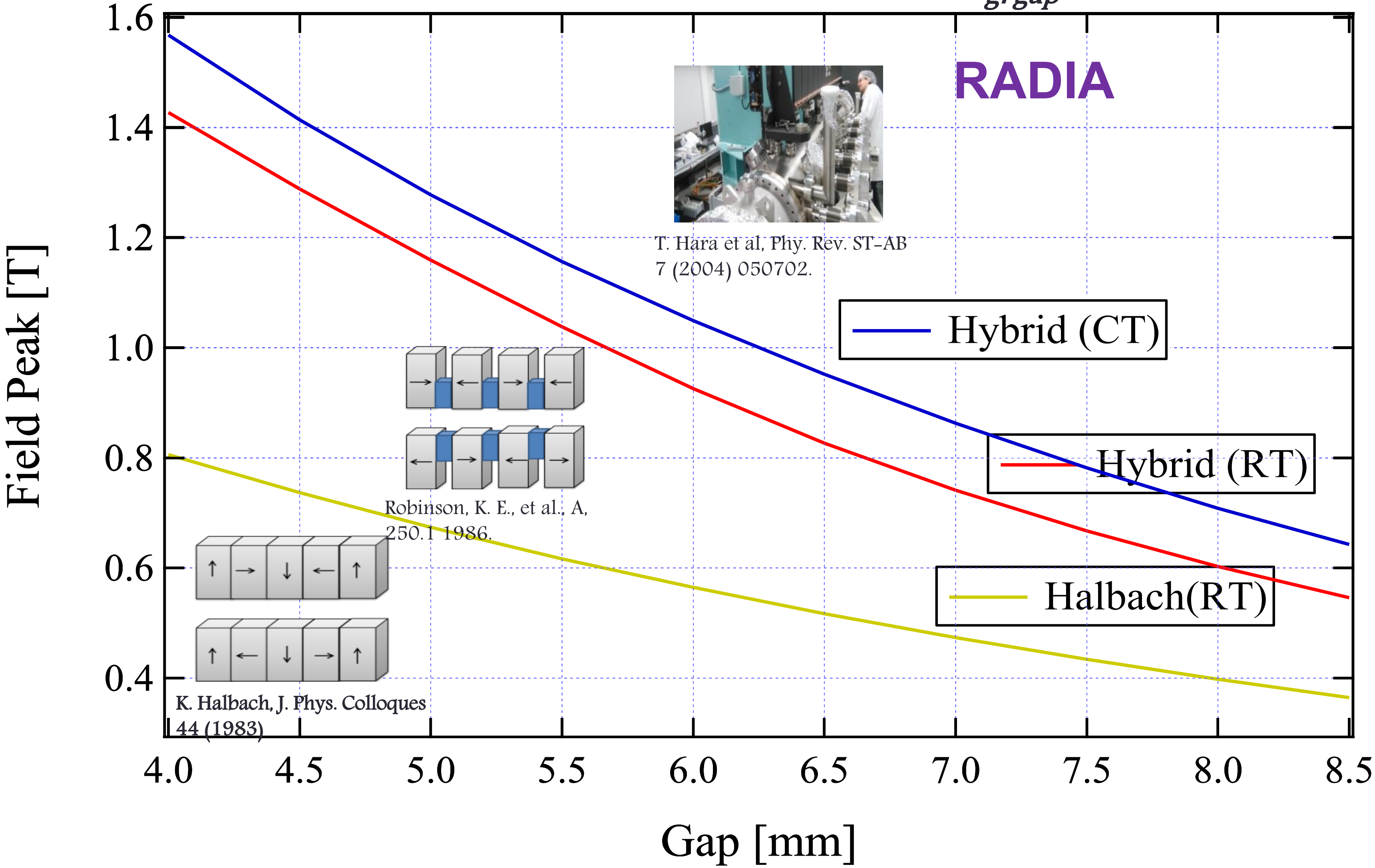
O. Chubar et. al., Proc. SPIE 4143 (2000) 48; SPIE 4769 (2002) 145.

Motivation

Period=18 mm

- $B \propto e^{-\frac{\pi g}{\lambda_u}}$

B: Peak Field
λ_u: Magnetic period
g: gap

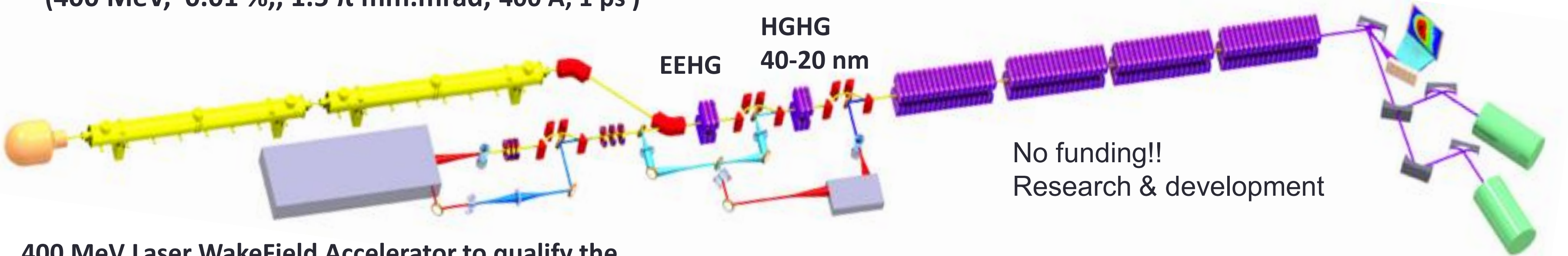


Higher field → Shorten period → More periods within a given length → Higher Brilliance

LUNEX5 : An advanced and compact FEL project

free electron **L**aser **U**sing a **N**ew accelerator for the **E**xploitation of **X**-ray radiation of **5**th generation

400 MeV Superconducting Linear Accelerator
(400 MeV, 0.01 %,, 1.5 π mm.mrad, 400 A, 1 ps)

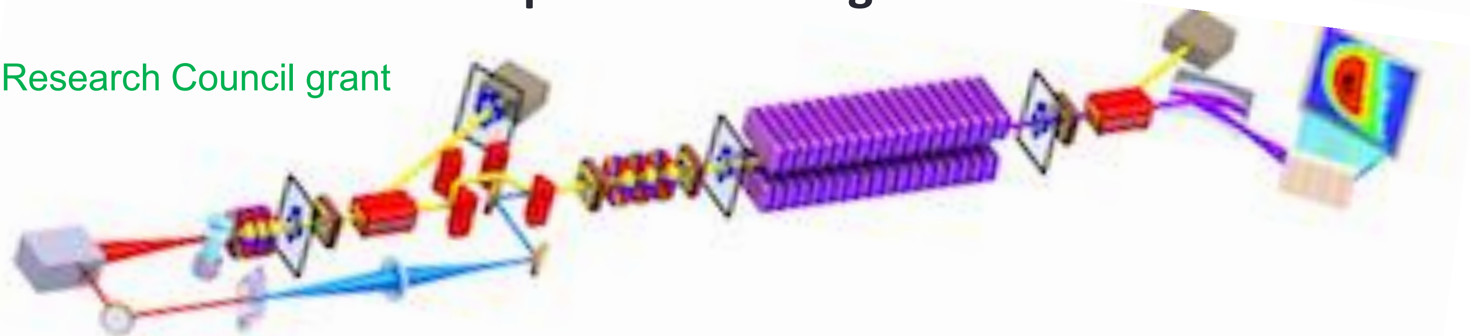


400 MeV Laser WakeField Accelerator to qualify the electron beam for an FEL application

- Reference undulator: CPMU15, 5 m long

COXINEL : FEL amplification using Laser Plasma Acceleration

European Research Council grant



Objectives :

- **demonstrate an appropriate transport to the undulator**
- **demonstrate FEL amplification at 200 nm and later at 40 nm using undulators from SOLEIL**
- **investigate and control (theory/experiments) FEL performance**

- CPMU18 (200 nm)
- CPMU15 (40 nm)

M. E. Couprie et al. J. Physics B : At., Mol. Opt. Phys. (2014) 234001
A. Loulergue et al.., New J. Phys. 17 (2015) 023028 (2015)
M. E. Couprie et al., Plasma Physics and Controlled Fusion, Volume 58, Number 3 (2016)

Cryogenic Undulators

- **CPMU18n°1 has been installed at NANOSCOPIUM long BL for the past 5 years**
- **CPMU18n°2 currently used for COXINEL project to demonstrate FEL at 200 nm with laser plasma acceleration**
- **CPMU18n°3 under progress and to be installed for the ANATOMIX long BL**
- **CPMU15 under construction for COXINEL and possibly for PROXIMA II BL**

Choice of Magnets:

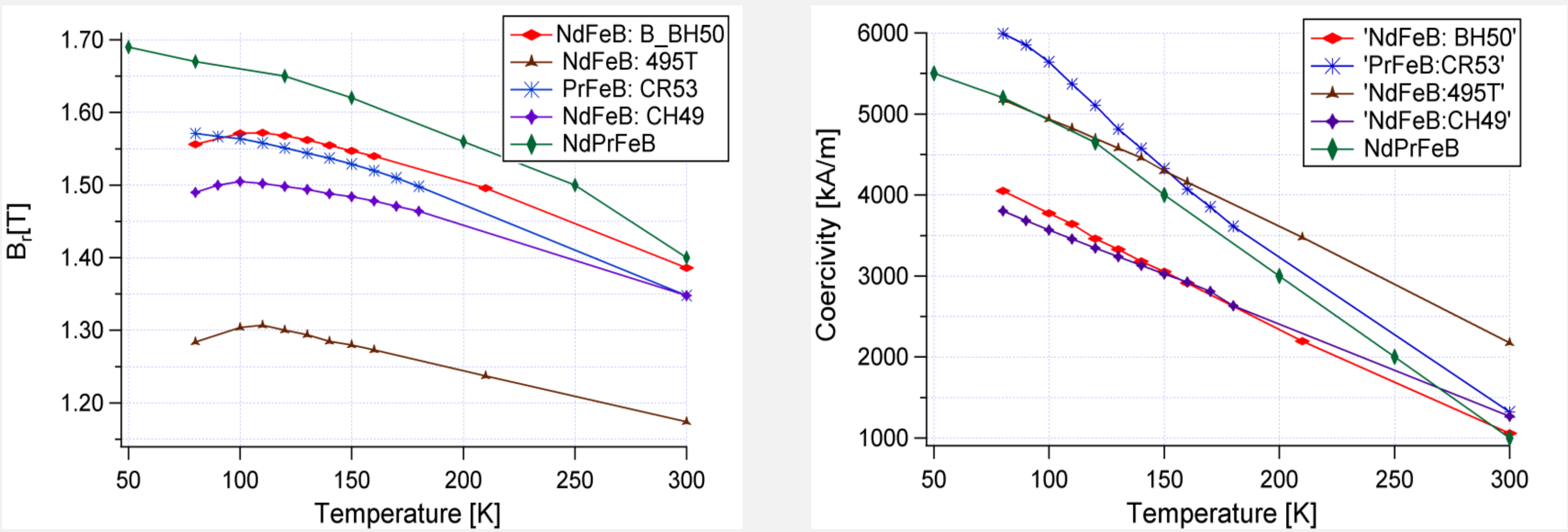
Room Temperature: RT
Cryogenic Temperature: CT

- **First cryogenic undulators used Neodymium Iron Boron magnets ($B_r \sim 1.2\ T\ and\ H_c > 2000$ kA/m @ RT)**

At Cryogenic temperature:

- Spin Re-orientation Transition (SRT) occurs
- Exhibit a negative dependence of the field against temperature

SRT: Change in the preferred magnetization axis



M. E. Couprie et al., SPIE

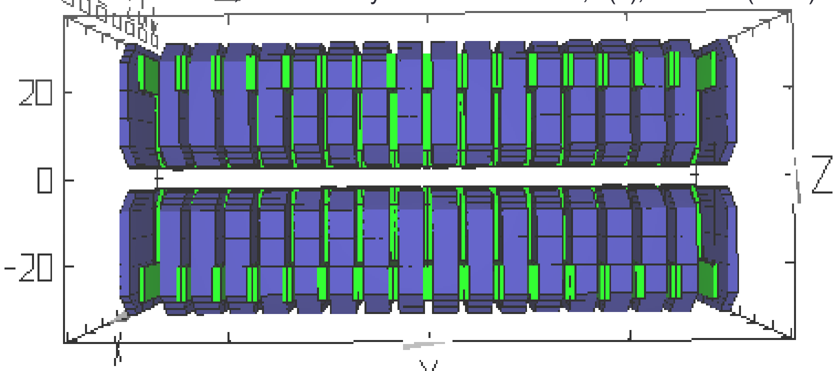
- **$Nd_2Fe_{14}B$: undergoes SRT effect at T=120 K**
- **$Pr_2Fe_{14}B$: does not undergo SRT**
- **Coercivity maintain increasing**

- For Neodymium Iron Boron (150 K), heaters have to be installed along the undulator.
- Praseodymium can be cooled down directly to 77 K (liquid Nitrogen) and achieve a higher field.

CPMU18 cryogenic undulator

Radia 3D magnetostatic software

Chubar, O., Elleaume, P., Chavanne, J., “A three-dimensional magnetostatics computer code for insertion devices”, Journal of synchrotron radiation, 5(3), 481-484 (1998)



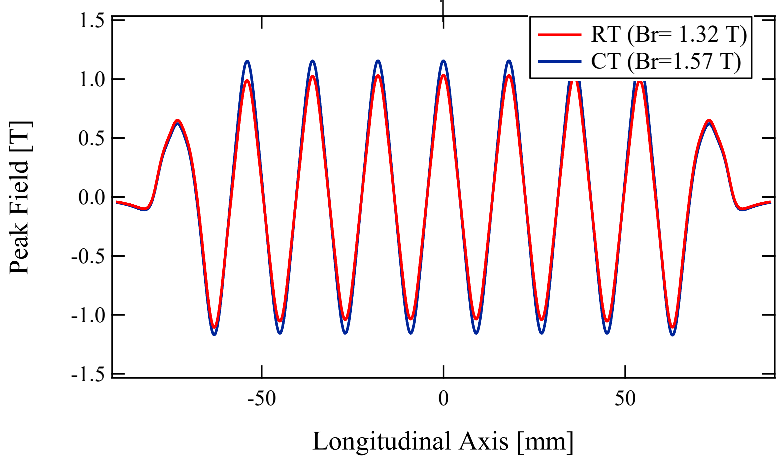
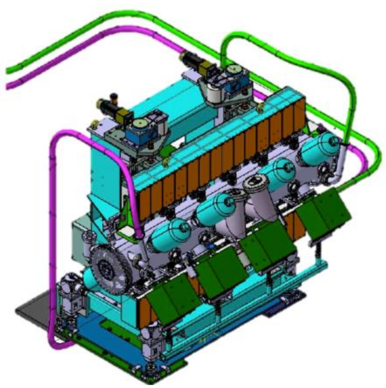


TABLE I. SOLEIL Cryogenic undulator main characteristics.

Item	Unit	Value
Technology		Hybrid
Magnet Material CR53 (Hitachi)		$Pr_2Fe_{14}B$
Remanence B_r	T	1.35 at 293 K 1.57 at 77 K
Coercivity H_{cj}	T	1.63 at 293 K 7.6 at 77 K
Magnet size (x, z, s)	mm^3	$50 \times 30 \times 6.5$
Pole material		Vanadium Permandur
Pole size(x, z, s)	mm^3	$33 \times 22 \times 2.5$
Period	mm	18
Minimum magnetic gap	mm	5.5
Maximum magnetic gap	mm	30
Magnetic peak field at minimum gap	T	1.152
Deflection parameter		1.936
Number of periods		107

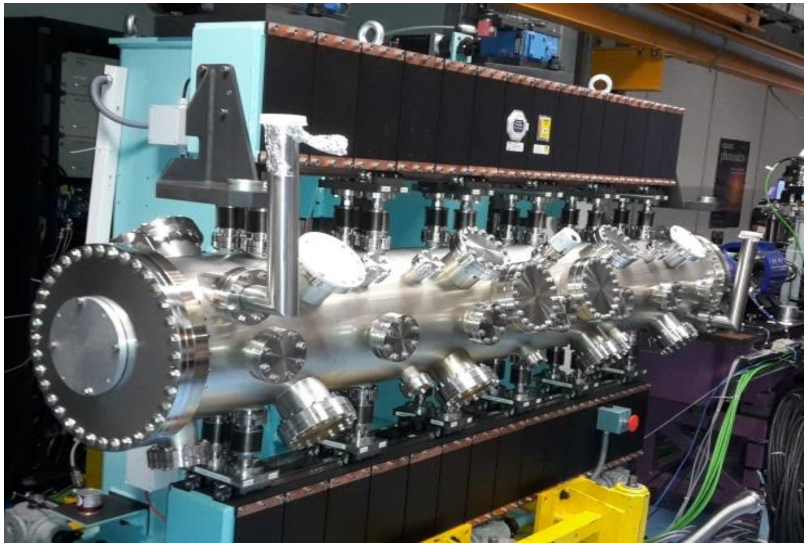


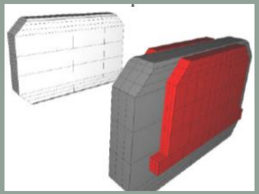
- **The peak field at RT is 1.005T, and increases to 1.155 T at CT (at a gap= 5.5 mm)**

- Out/In-vacuum girders are connected by 24 rods; gap range : 5.5-30 mm
- Cooling: injecting LN through a hole in the girder
- No baking, magnets at CT act as cryo-pumps

Development and operation of a Pr2Fe14B based cryogenic permanent magnet undulator for a high spatial resolution x-ray beam line, C. Benabderrahmane, M. Valléau, A. Ghaith, P. Berteaud, L. Chapuis, F. Marteau, F. Briquez, O. Marcouillé, J.-L. Marlats, K. Tavakoli, A. Mary, D. Zerbib, A. Lestrade, M. Louvet, P. Brunelle, K. Medjoubi, C. Herbeaux, N. Béchu, P. Rommeluere, A. Somogyi, O. Chubar, C. Kitegi, and M. E. Couprie, Phys. Rev. Accel. Beams 20, 033201(2017)

CPMU18 cryo-ready undulator





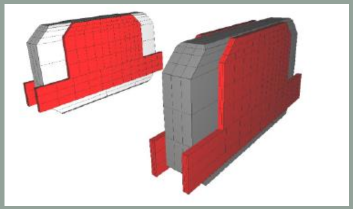
U18n°1

2 types of modules

$H_c = 1355\ kA/m$ @ RT

Can not operate at room temperature

dysprosium



U18n°2,3

1 type of modules

- Enables magnets swapping for field optimization

$H_c = 1912\ kA/m$ @ RT

Can operate at room temperature and cryogenic temperature

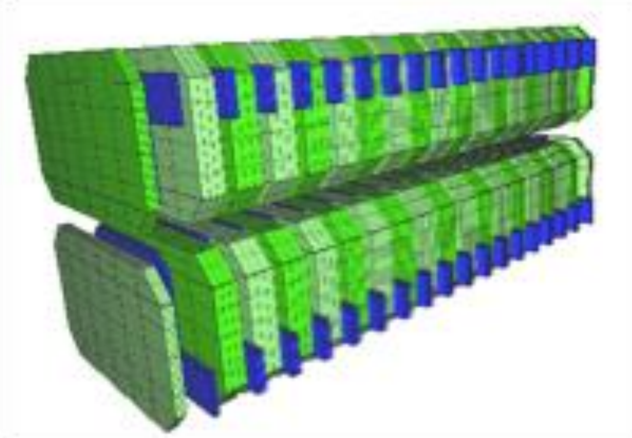
Couprie, M. E., et al. "Advances on the LUNEX5 and COXINEL Projects." *Proc. 37th International Free Electron Laser Conference (FEL2015)*. 2015.

- Separate baking of magnet holders, girders and vacuum chamber to improve the vacuum at RT

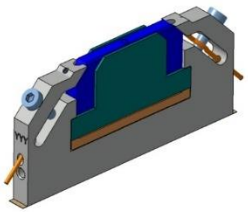
CPMU15 cryogenic undulator

Length L (m)	3
Period length λ_u (mm)	15.16
Number of periods N	200
Type (Hybrid/PPM)	In-vacuum hybrid
Minimum gap (mm)	3
Magnet material	$Pr_2Fe_{14}B$ (CR53Hitachi-Neomax)
Pole material	Vanadium Permendur
Remanent field B_r @293K (T)	1.32
Remanent field B_r @77K (T)	1.55
H_{cB} @300K (kA/m)	1016
H_{cJ} @300K (kA/m)	1906
Cooling	LN_2 (77K)
Dimensions of magnets (mm)	50×30×5.5
Dimensions of poles (mm)	33×26×2

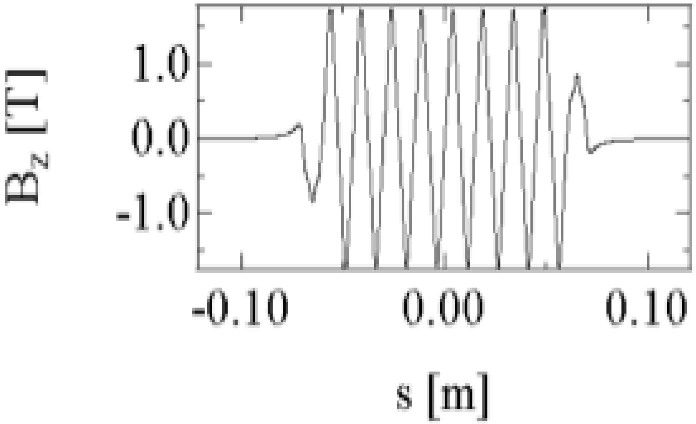
LUNEX5 prototype, interest for PX2 BL

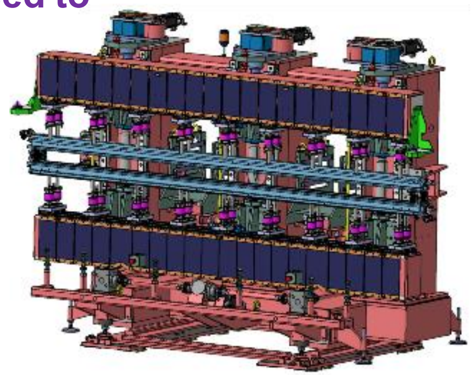


1 type of module



- **The peak field at RT is 1.589 T, and increased to 1.735 T at CT (at a gap= 3 mm)**



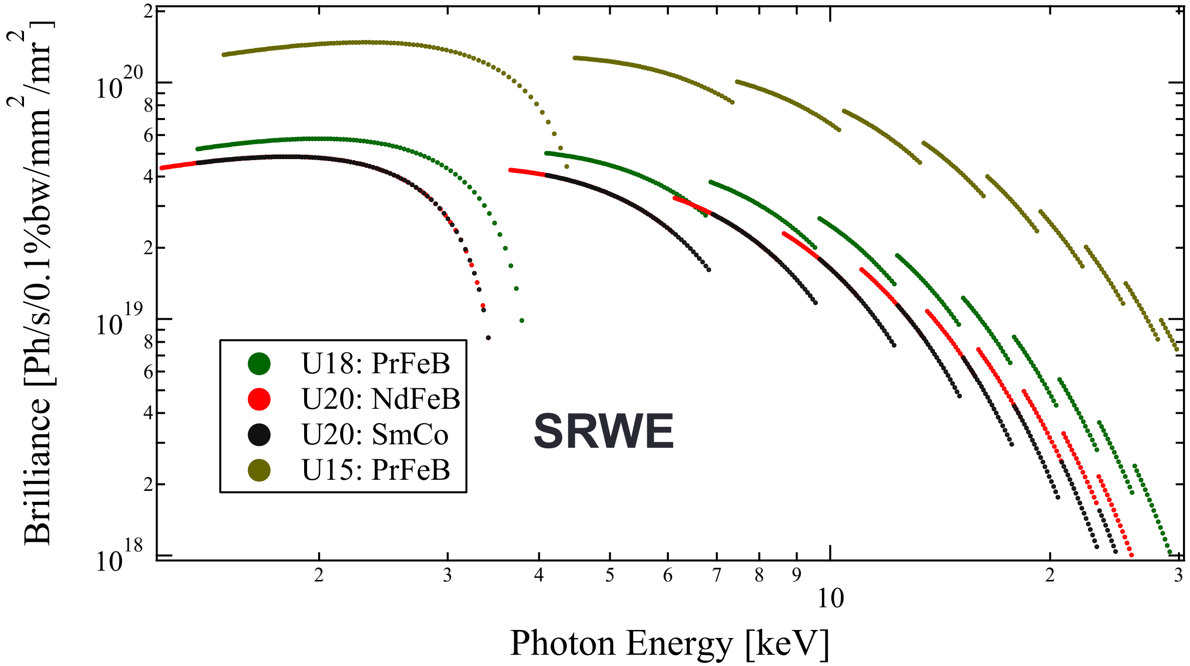


3 m long

- Inner/outer girders are connected by 36 rods
- Separate baking of magnet holders, girders and vacuum chamber

G. Sharma, F. Briquez et al., U15 cryogenic undulator progress report, LUNEX5-RA-099_U15Report-COXINEL (2016)

Brilliance of the cryogenic undulators:



Energy = 2.75 GeV with rms energy spread of 0.1%, Current 0.5 A, Emittance(H,V)= (3.9 nm, 0.039 nm), Beta(H,V)=(5.577 m, 8.034 m), Alpha(H,V)= (0,0.1 mrad)

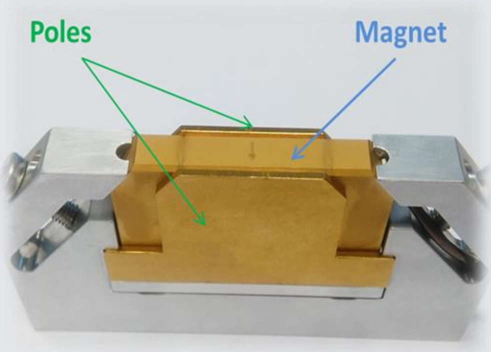
Radiation wavelength:

$$\lambda_R = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K_u^{\,2}}{2}\right)$$

	Magnets	Period [mm]	N° of periods	Length [m]	Gap [mm]	Temperature [K]	Peak Field [T]
U20	SmCo	20	96	2	5.5	293	0.96
U20	NdFeB	20	96	2	5.5	293	1.06
U18	PrFeB	18	107	2	5.5	77	1.15
U15	PrFeB	15	200	3	3	77	1.735

Construction and assembly:

❑ Building modules



- Composed of magnet and two poles
- Aluminum support

❑ Module Shimming

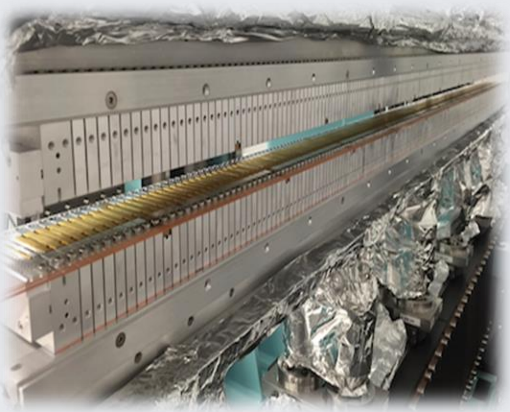
- Altitude measurement using a comparator
- Shim the poles to decrease height difference

❑ Field measurement

- Rotating coil: measures field integral
- Hall Probe: measures local field

❑ Mounting modules

- ❑ Mount 4 modules (1 period) on the girders
- ❑ Measure the field integral
- ❑ Run an algorithm (ID builder home-made software based on a genetic algorithm), which choses the 4 convenient consecutive modules

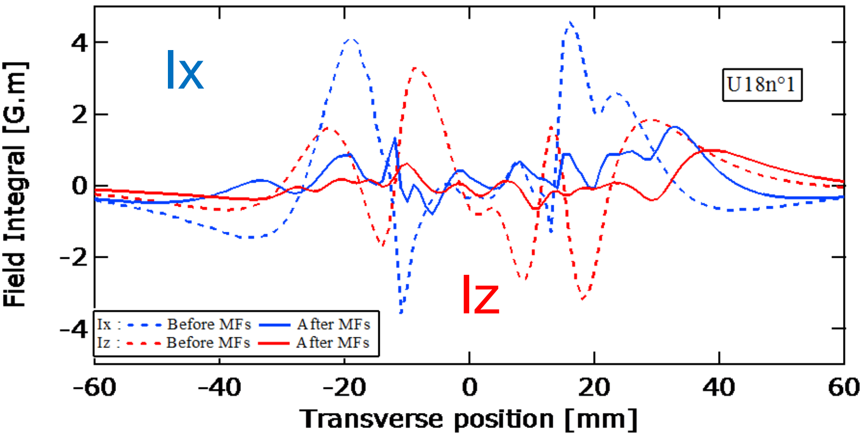


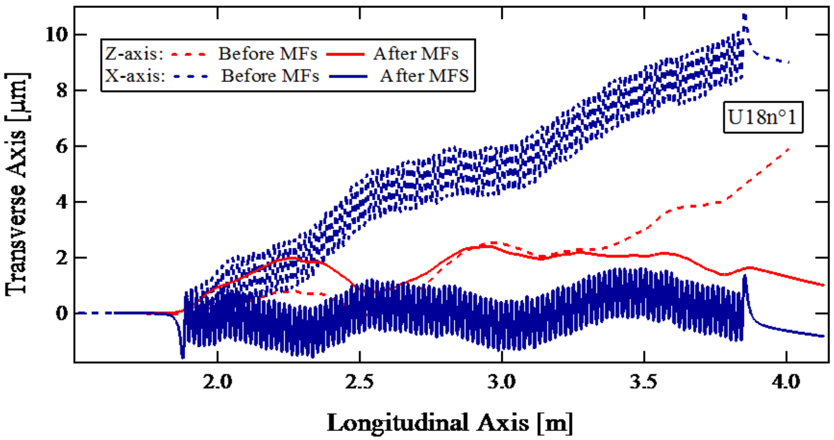
- Period by period the modules are sorted and mounted on the girders

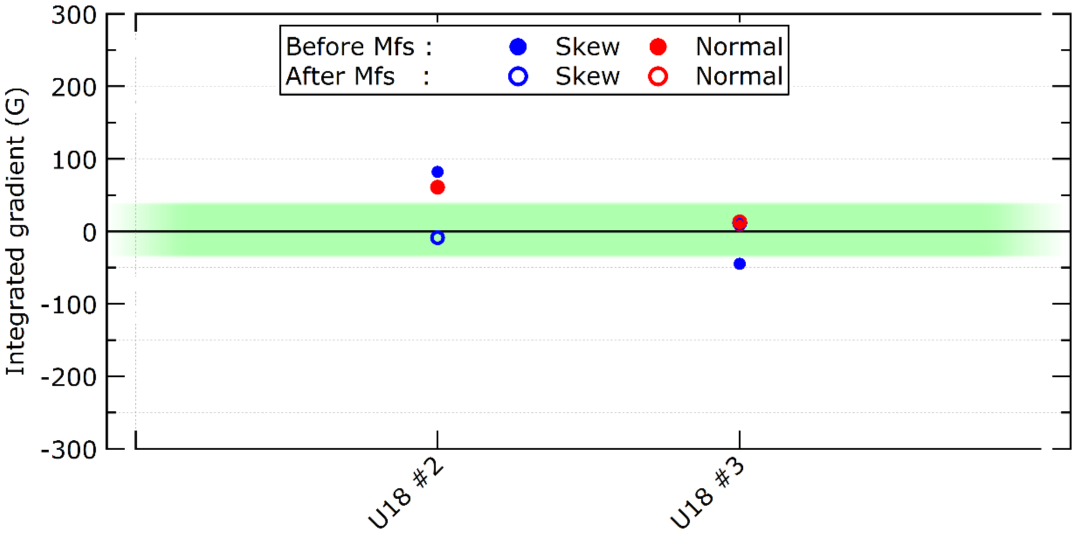
O. Chubar, O. Rudenko, C. Benabderrahmane, O. Marcouille, J. Filhol, and M. Couprie, Application of genetic algorithms to sorting, swapping and shimming of the SOLEIL undulator magnets, AIP Conference Proceedings 879, 359 (2007).

Measurements and Optimization @ RT

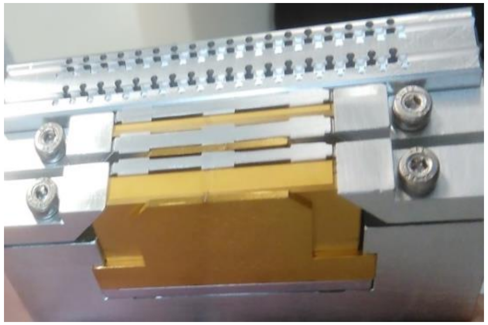
Field Integral and multipolar terms adjustment using magic fingers:







MFs: Placed at the extremities of the undulator



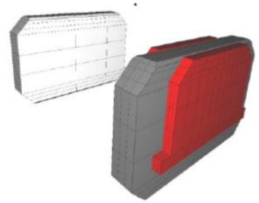
Add small cylindrical magnets in the holes to null down the field integrals

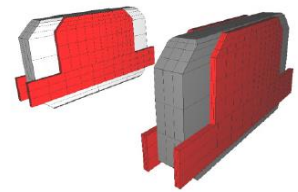
- Mechanical shimming of poles and magnets

Measurements and Optimization @ RT

Phase error adjustment :

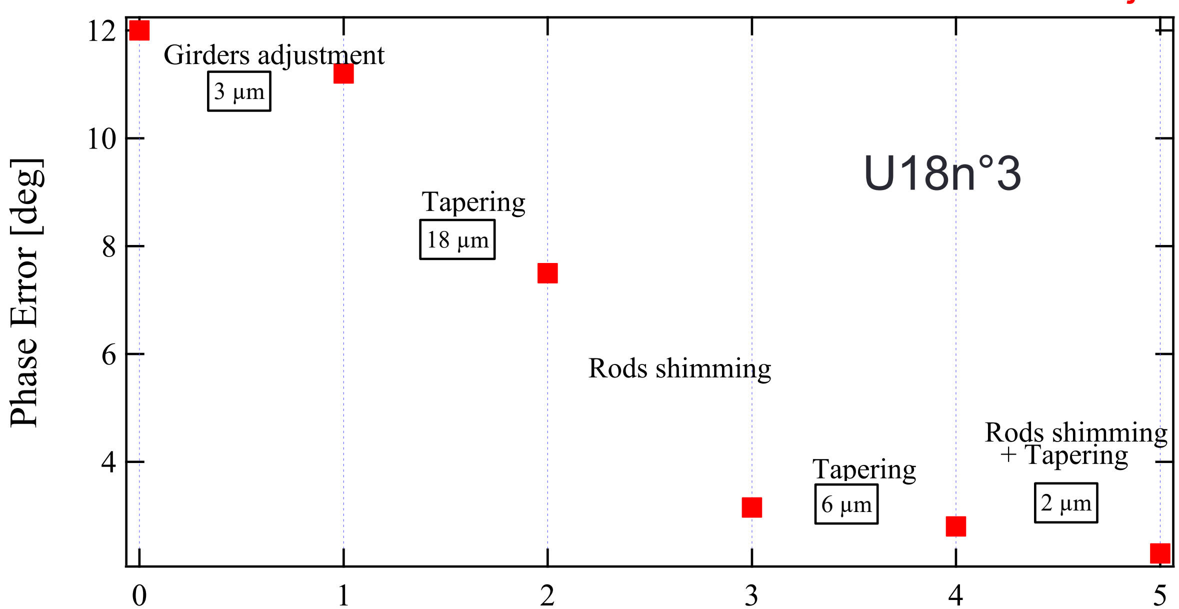
B2E: A software to compute Synchrotron Radiation from Magnetic field data



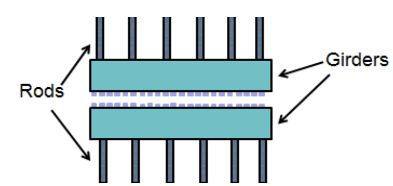


	U18n°1	U18n°2	U18n°3
After Assembly	14.5°	12.5°	12°
Taper + Rod Shimming (10 – 200 µm)	9°	2.3°	2.3°
Modules Shimming	2.8°		

Individual modules were shimmed for U18n°1 to reduce the phase error. As for U18n°2,3 it was not necessary due to the new mechanical adjustments of the modules

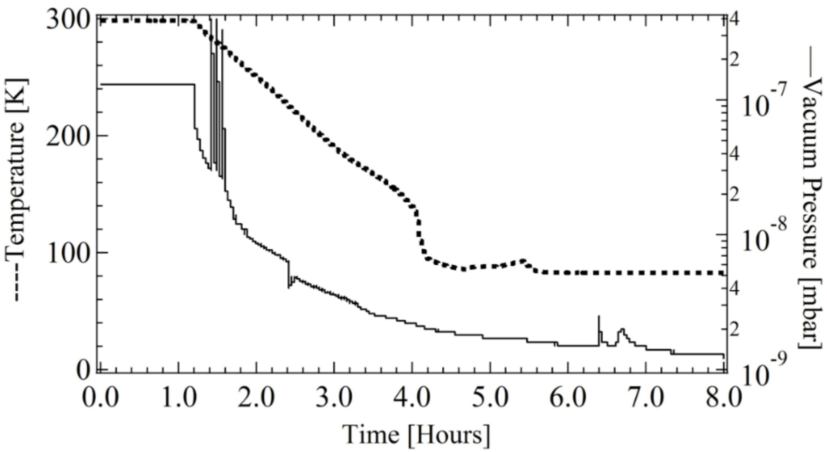


- **Adjustments**
  - Rod shimming
  - Girder optimization
  - Tapering



Cooling down

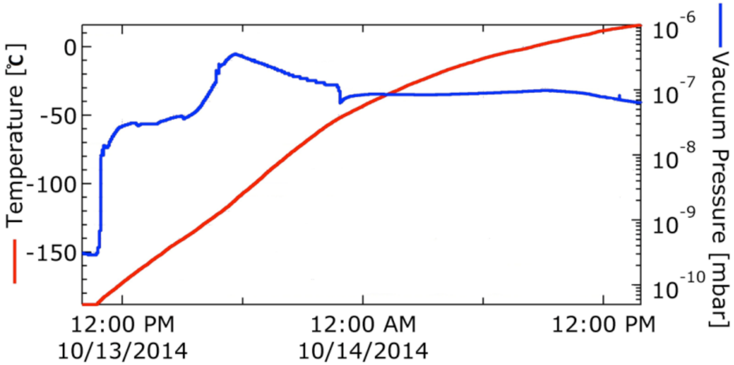
Cryo Cooler(Cryotherm Bruker)
: Power 2000 W (<300 W), Liquid LN2, Pump : 30 to 90 Hz (40 Hz), Flow : 1 to 30 l/mn (5 l/mn)



- Magnet temperature and vacuum pressure variation of the cryogenic undulator using a cryocooler system
- Magnets reach liquid nitrogen temperature of 77 K after 6 hours

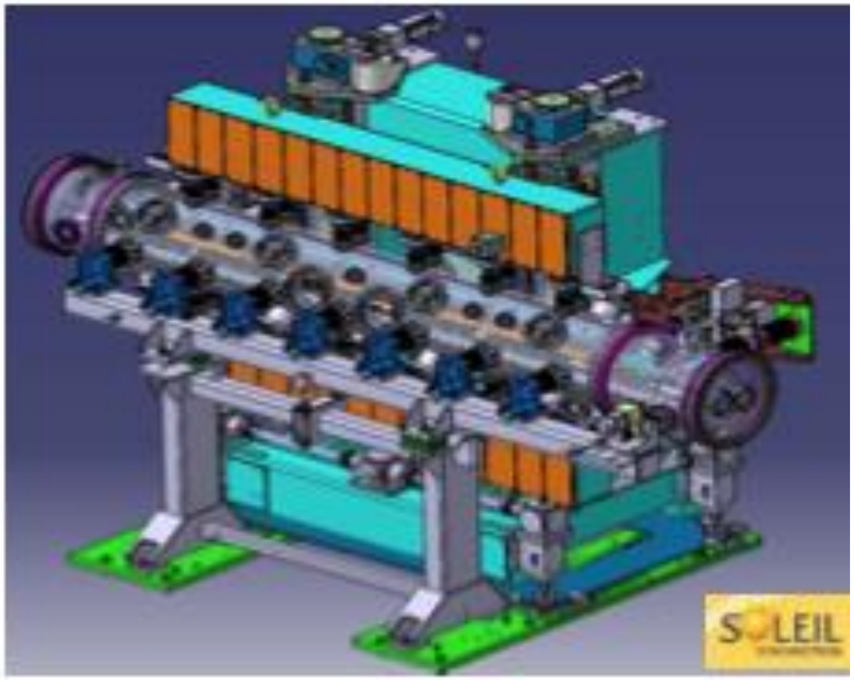
C. Benabderrahmane et al 7, 050702 (2004)

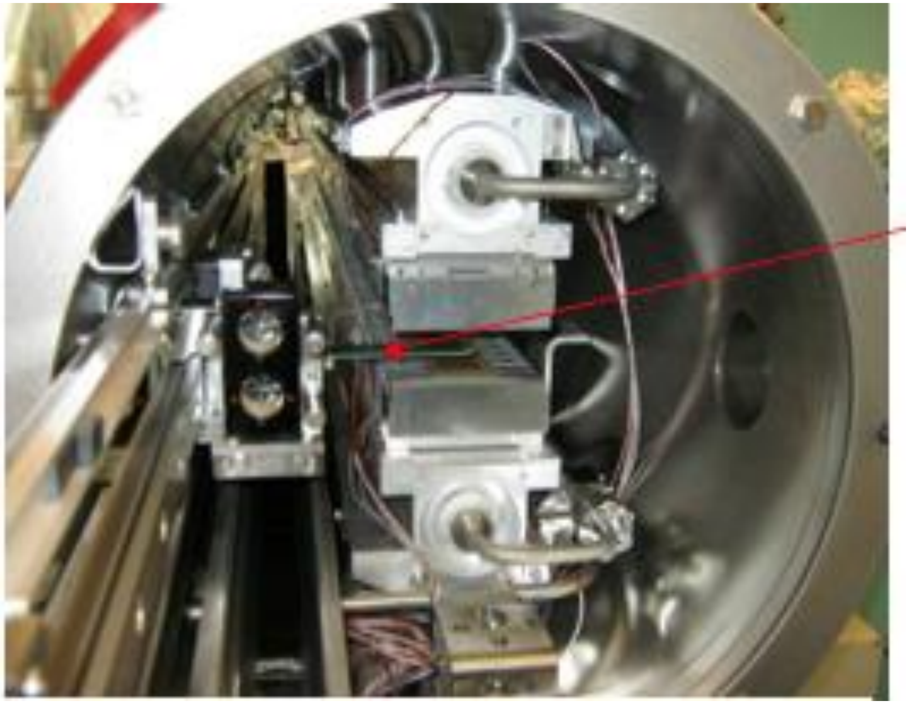
Warming up



- The warming of the undulator is relatively long, about 72 hours, but it could be accelerated to 24 hours by injecting nitrogen gas at 60°C (333 K) in the cooling circuit.

Cryogenic bench

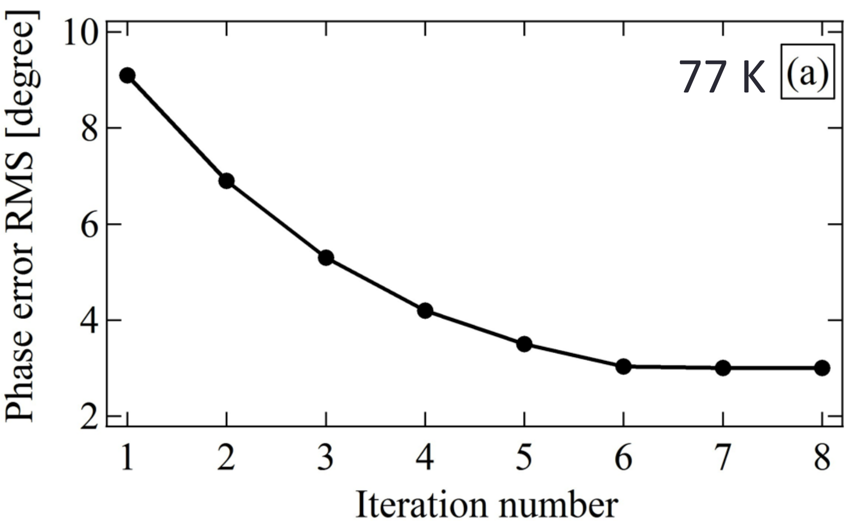


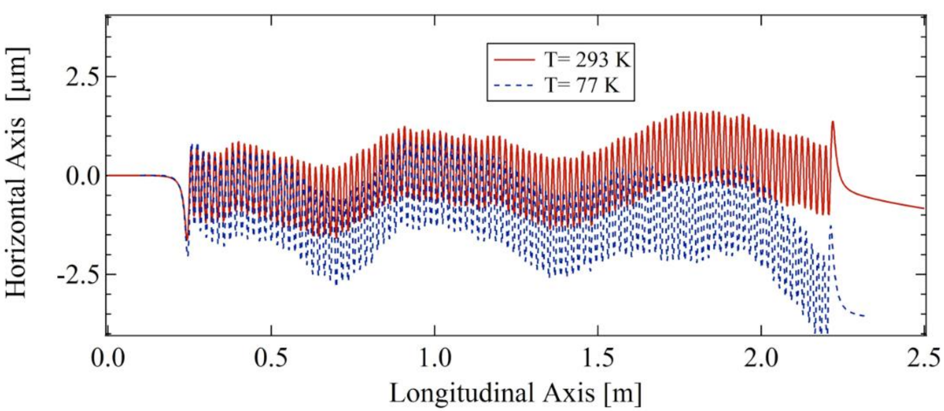


Bench mounted in the final vacuum chamber

- Hall probe (longitudinal displacement by motors, optical rule)
- laser interferometer (measure the exact position of the Hall probe)
- stretched wire (field integral measurement)

PrFeB CPMU18 n°1: 77 K magnetic measurement





Contraction at CT

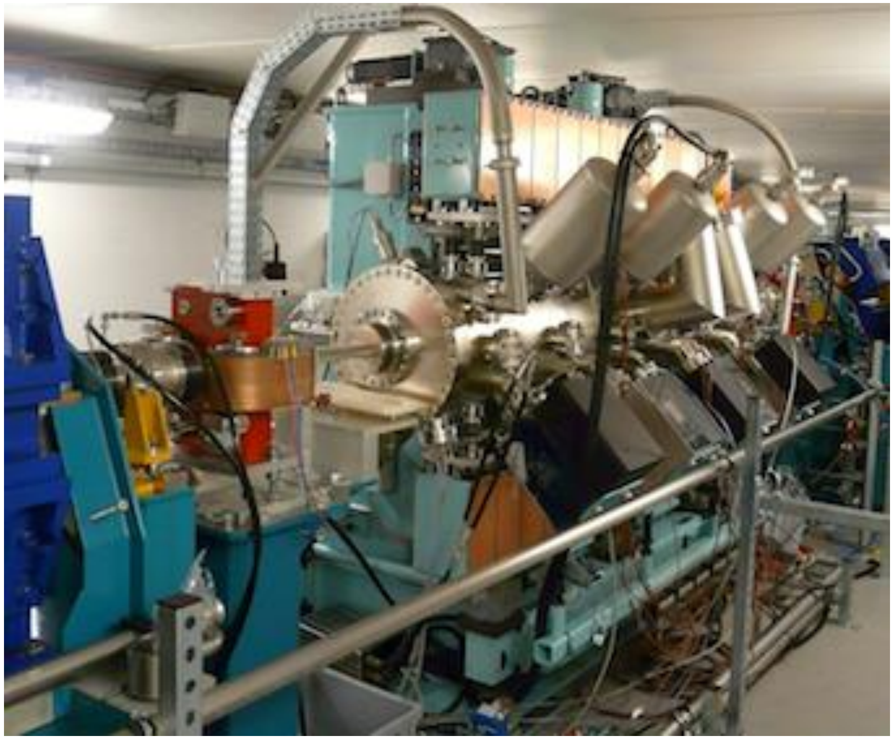
Due to the heat gradient, the phase error increased to 9° at CT

Rod shimming

3.2° phase error

Straightness degraded at CT and is corrected by steerers when the undulator is installed

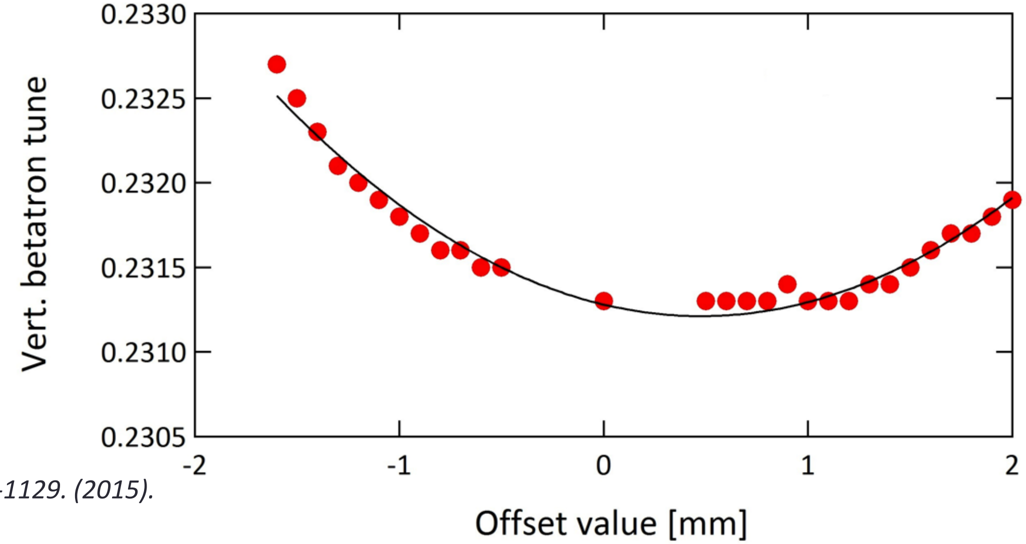
Electron Beam alignment



- Alignment : reference taken on the measurement bench
- <u>Electron beam alignment :</u>
• Electron beam decay
• Electron beam tunes

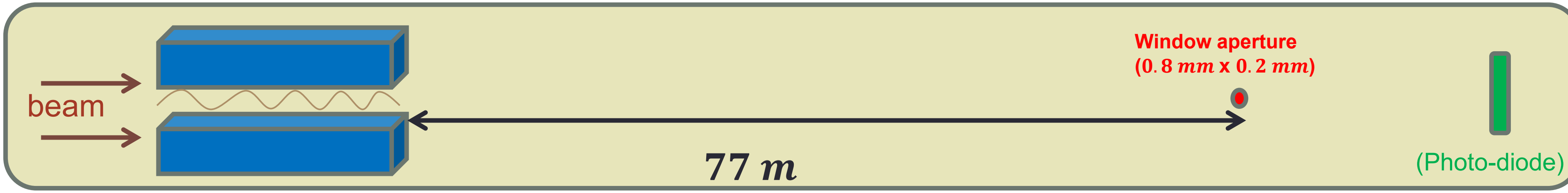
U18n°1 installed on the long straight section

MOPVA004



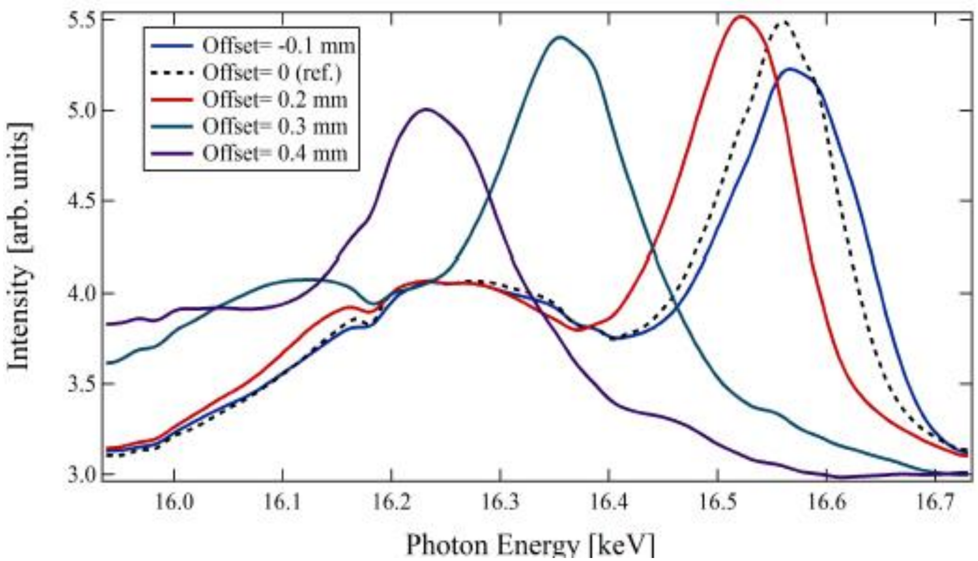
Somogyi, A et al. Journal of Synchrotron Radiation., 22(4): 1118-1129. (2015).

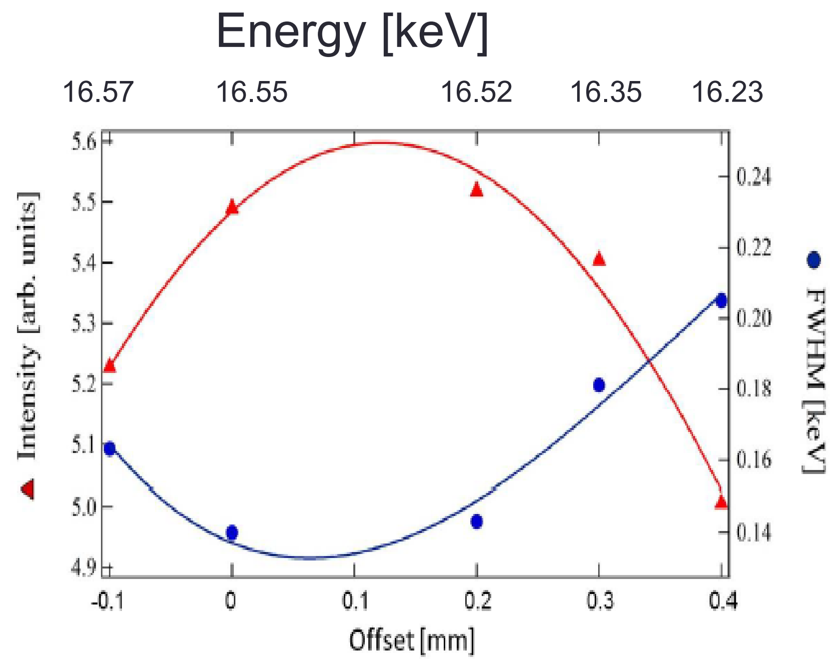
❖ Photon beam based alignment: Align electron beam with the magnetic axis



- Move the girders up or down while keeping magnetic gap constant

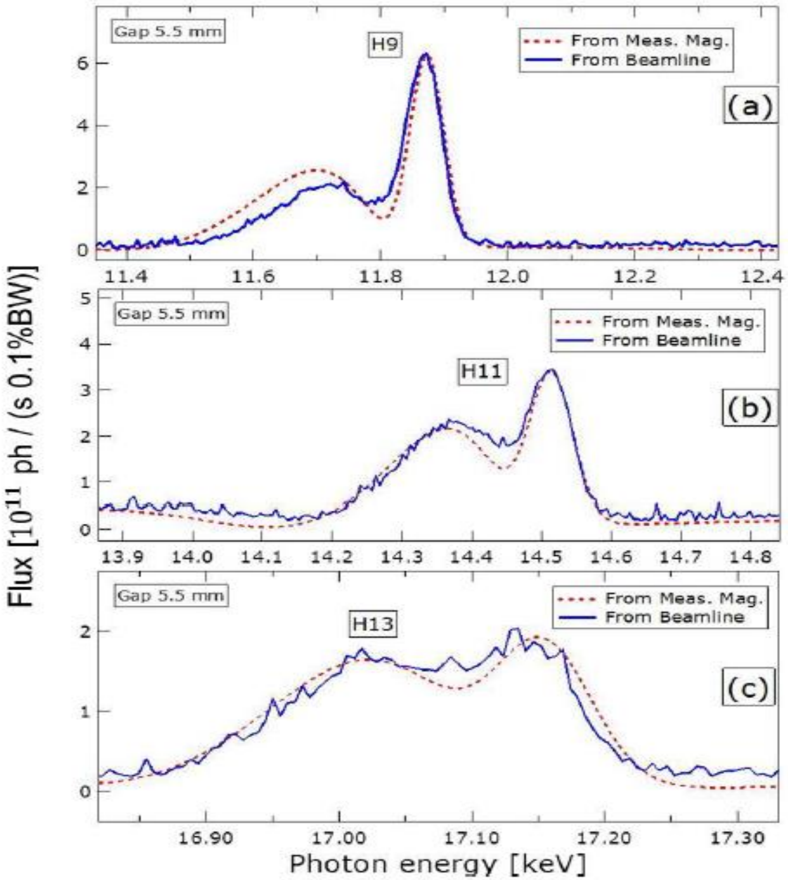
- 11th harmonic spectra





❖ New offset : $100\ \mu m$

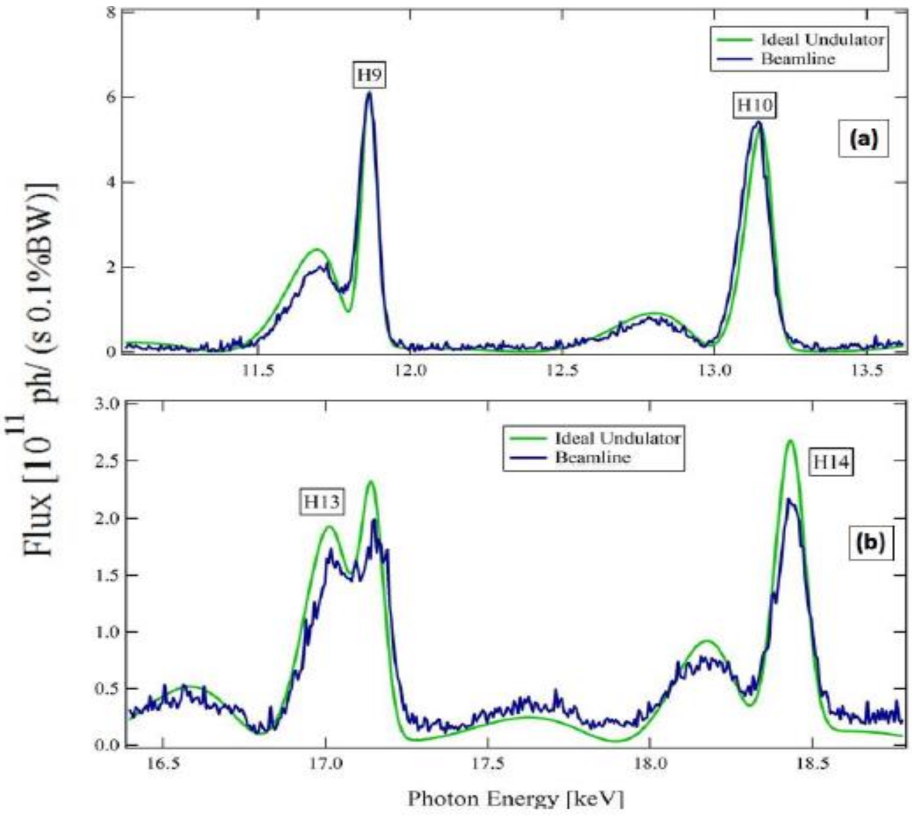
Spectra measured on the beamline and compared to the one calculated from the magnetic measurements



- Good agreement (equal bandwidth)

→ **Measurements at CT are indeed precise**

Measured spectra compared with simulations of an ideal undulator



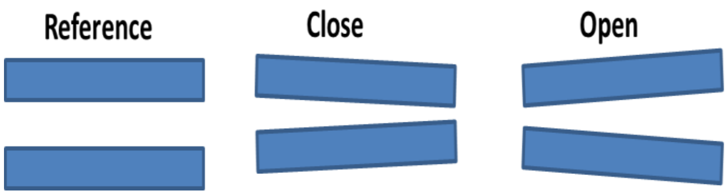
- **Good agreement, residual phase error is quite low**

→ **CPMU has good field quality**

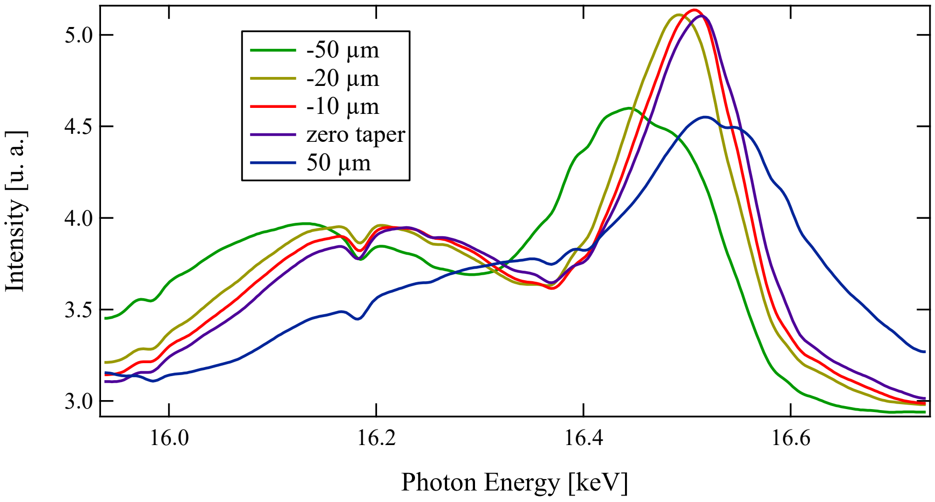
Benabderrahmane, C., Valléau, M., Ghaith, A., Berteaud, P., Chapuis, L., Marteau, F., ... & Mary, A. (2017). Development and operation of a Pr2Fe14B based cryogenic permanent magnet undulator for a high spatial resolution x-ray beam line. *Physical Review Accelerators and Beams*, *20*(3), 033201.

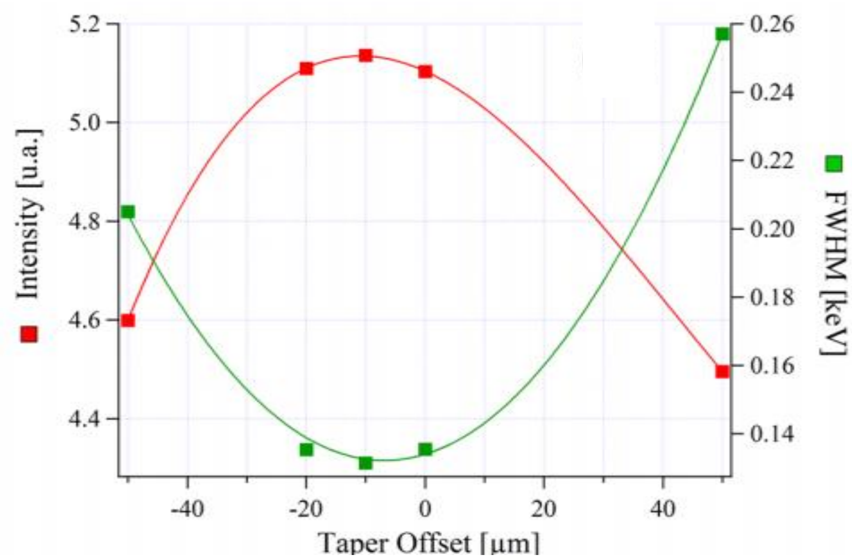
Taper Optimization

❖ Achieve best radiation performance



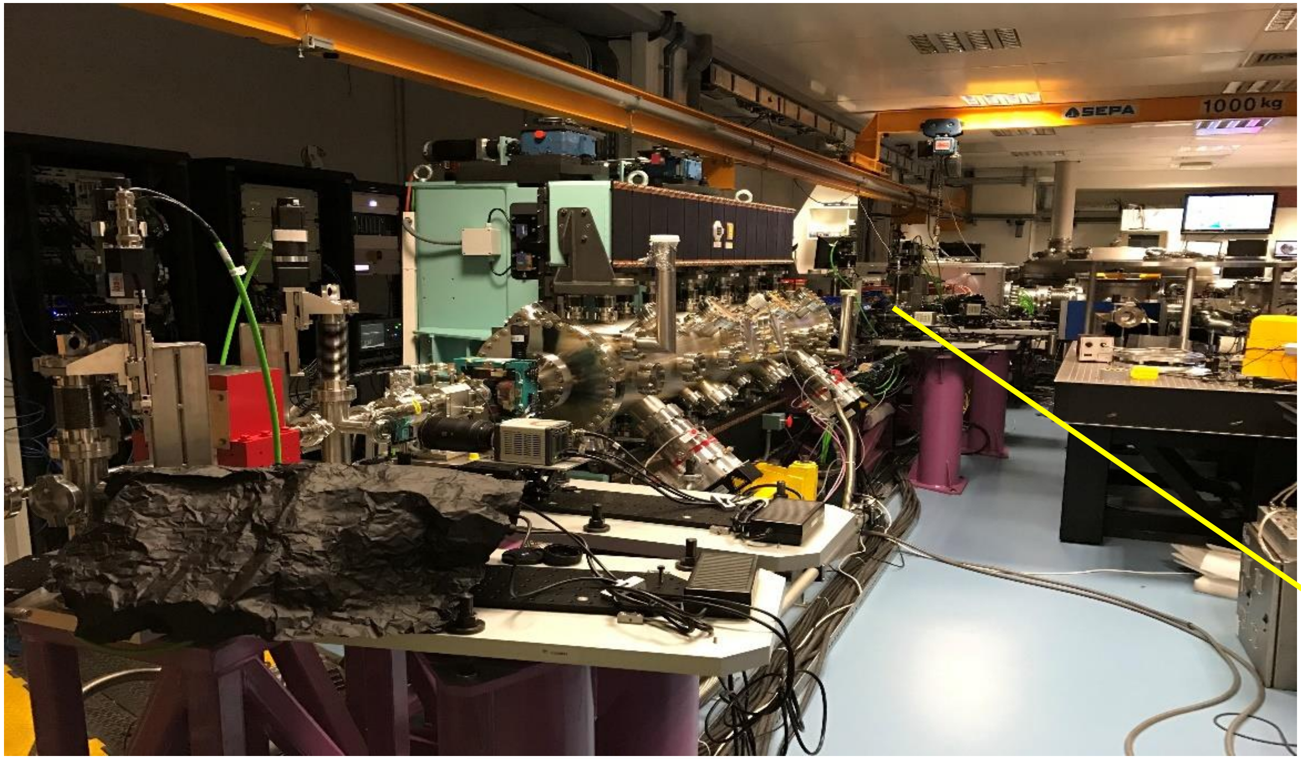
- Change the peak field along the longitudinal axis





❖ Ref. : Supposedly “no taper”
New : $-10\ \mu m$

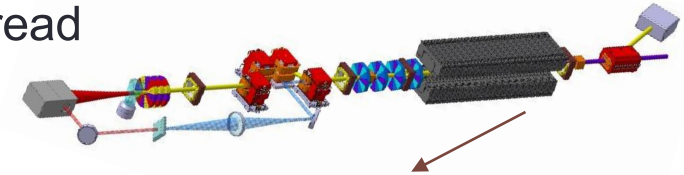
First photons from the PrFeB CPMU18 n°2 installed at LOA on the COXINEL test line



Tunable high gradient permanent magnet based quadrupoles

T. Andre (TUPIK003)

Broad energy spread



Operation at room temperature (infrastructure reasons)

P. N'gotta (THPIK006)

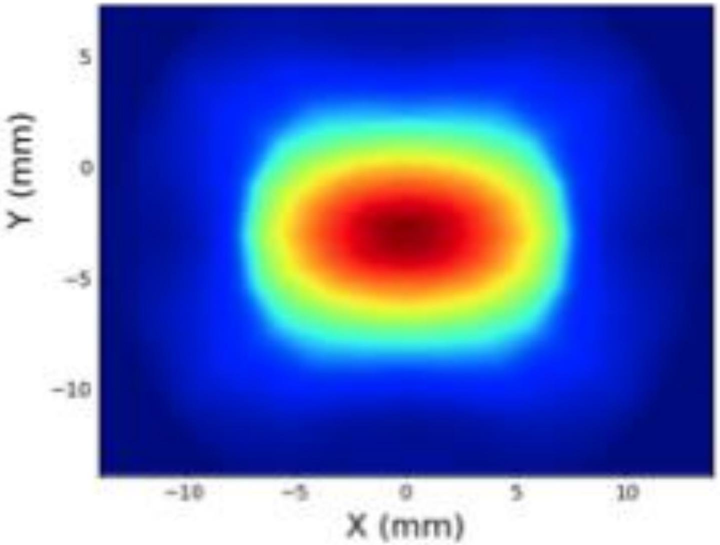
Undulator Radiation U18n°2 (COXINEL)

Transverse beam shape

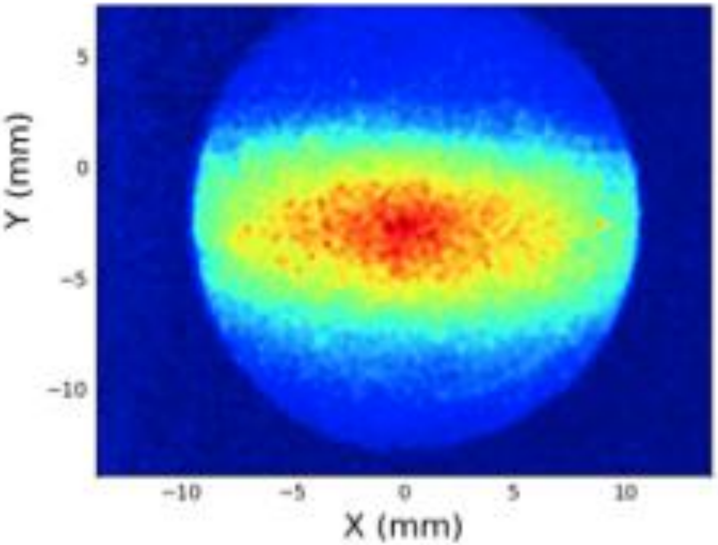
LPA source
Large energy spread

CCD camera

Slit width = 2 mm (placed inside the chicane)



simulation



experiment

Conclusion:

- **CPMU18n°1**: First full scale PrFeB based operating on SOLEIL NANOSCOPIUM beamline
- Photon beam alignment with a pinhole placed 77 m away from the undulator
- Taper optimization has been adjusted by 5 µrad (10 µm)
- **CPMU 2,3**: Low phase error without further shimming after assembly
- Photon from U18°2 were observed (COXINEL) with a LPA beam after 8 m of controlled electron beam transport

- **CPMU15**: Construction under progress

Prospects:

- Possible replacement of in-vacuum undulators with CMPUs
- Use of more efficient PrFeB magnet grades
- Combine CMPUs with SCU (T. Tanaka et al. PRSTAB 7,090794 (2004)

Thank you for your attention