Magnetic studies of a new insertion device: Bi-periodic undulator

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Outline

1/ Scientific context

2/ Bi-periodic undulator concept

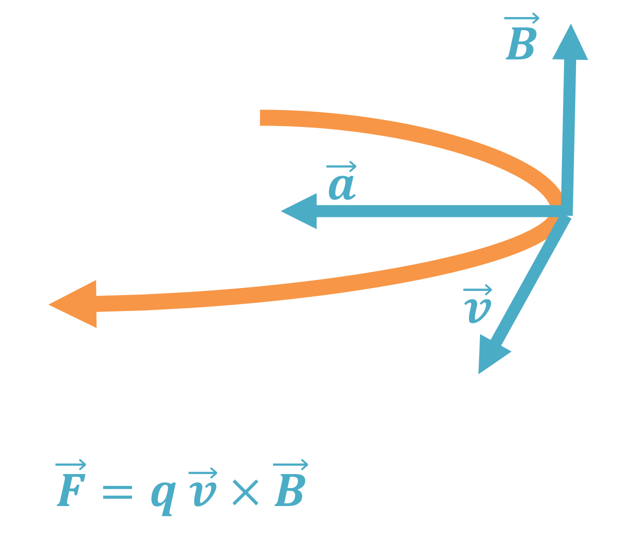
3/ Magnetic studies of a prototype

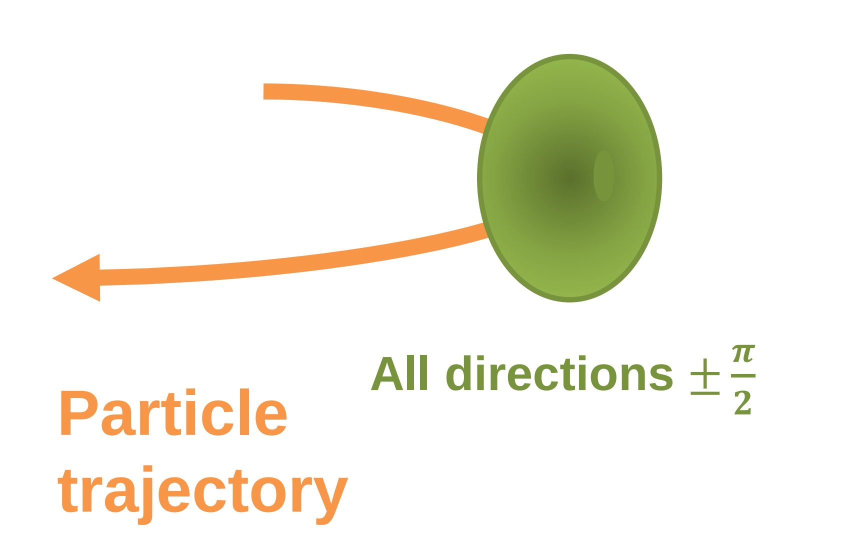
4/ Conclusion and outlook

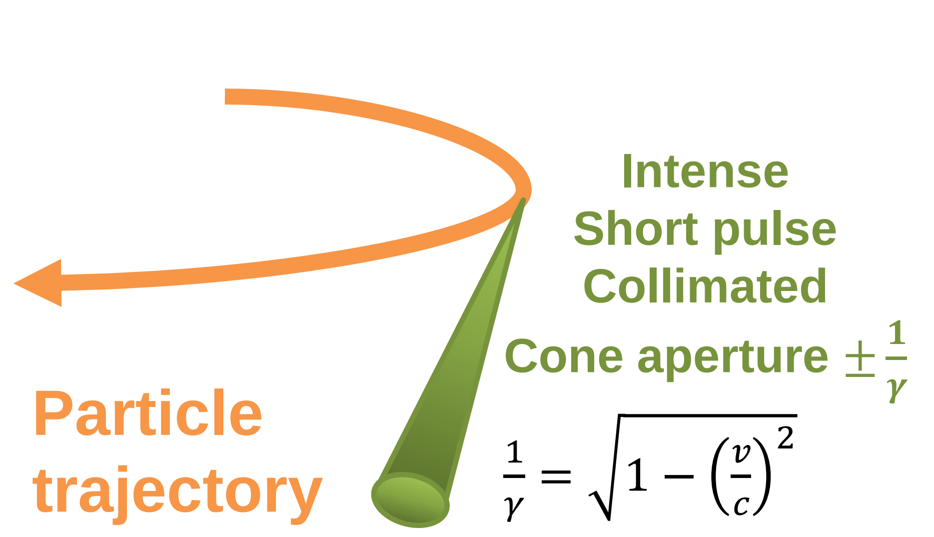
1/ Scientific context

Purpose of a synchrotron

- Synchrotron: Particle accelerator designed to accelerate charged particles to obtain a beam of ultra-relativistic charged particles **to produce light**.



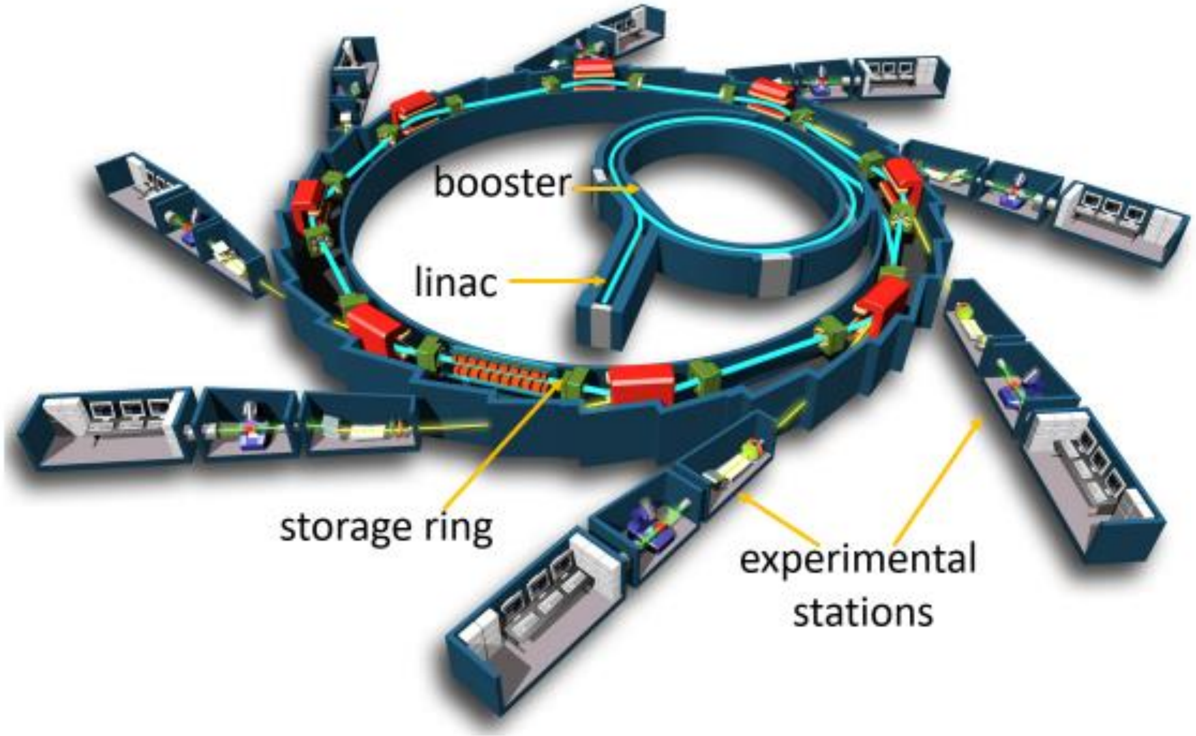




Magnetic field: trajectory deviation + synchrotron radiation	Particles with a speed much lower than speed of light	Particles with a speed close to speed of light (ultra-relativistic)

Synchrotron SOLEIL

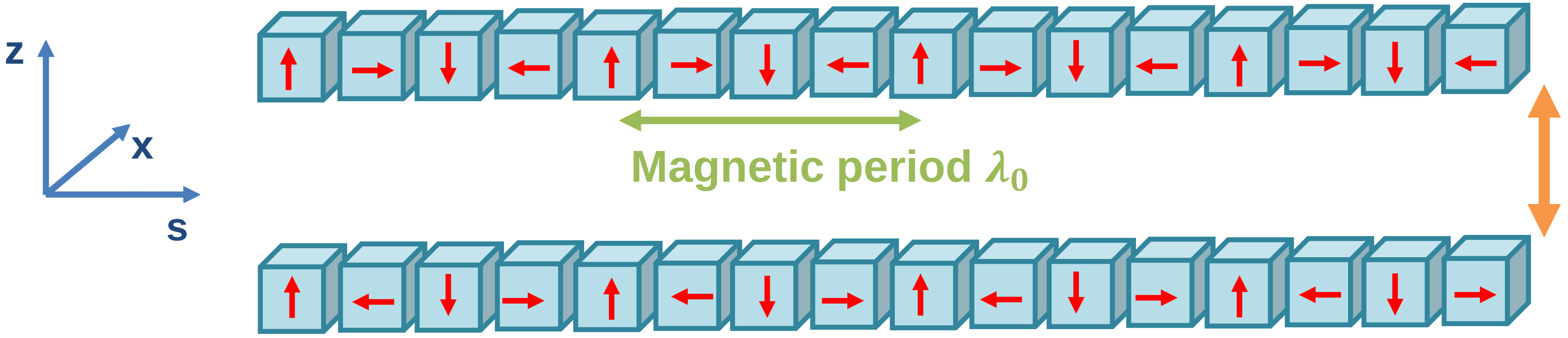
Synchrotron SOLEIL
Since 2006 Beam of electrons **Linac:** first acceleration, 27 m **Booster:** Brings electrons energy to 2.75 GeV **Storage ring:** Circumference 354 m Small bunches, total stored current 500mA Horizontal emittance 3.9 nm.rad Photon sources like bending magnets, wigglers, **undulators** **Experimental stations:** 29 beamlines Laboratory, cover all field of science



Undulators

- Strong periodic magnetic field uniformly over a large distance
- Permanent magnets or electromagnets

- Example: Planar undulators

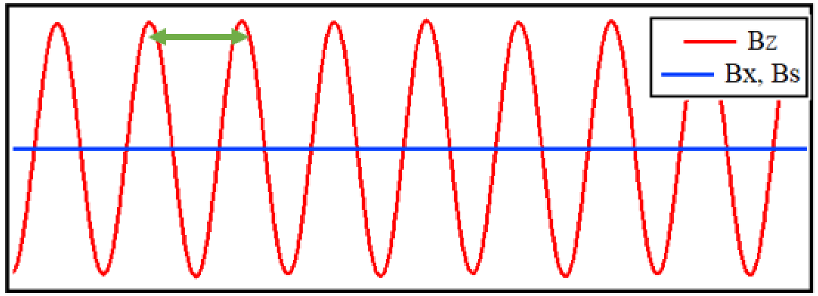


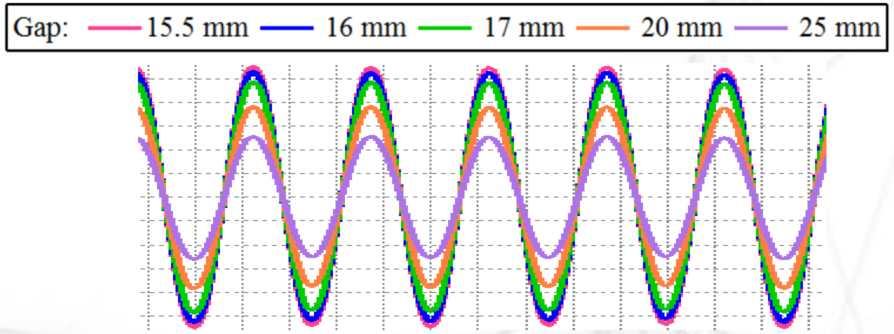
Change magnetic field amplitude
Parameter « Gap »

Magnets

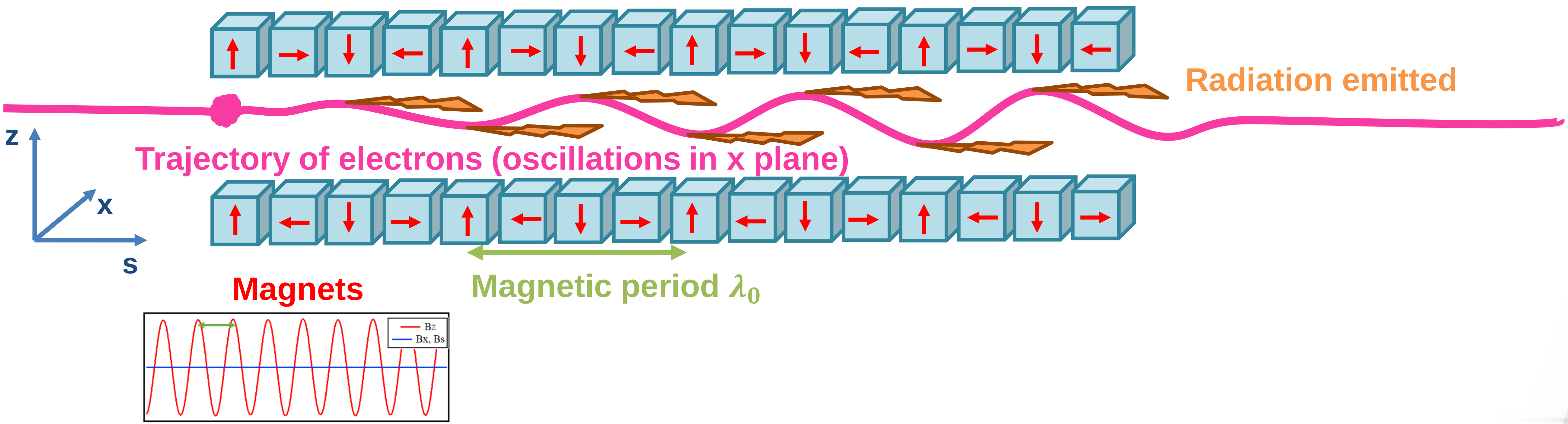
Periodic vertical magnetic fields

Magnetic period λ_0

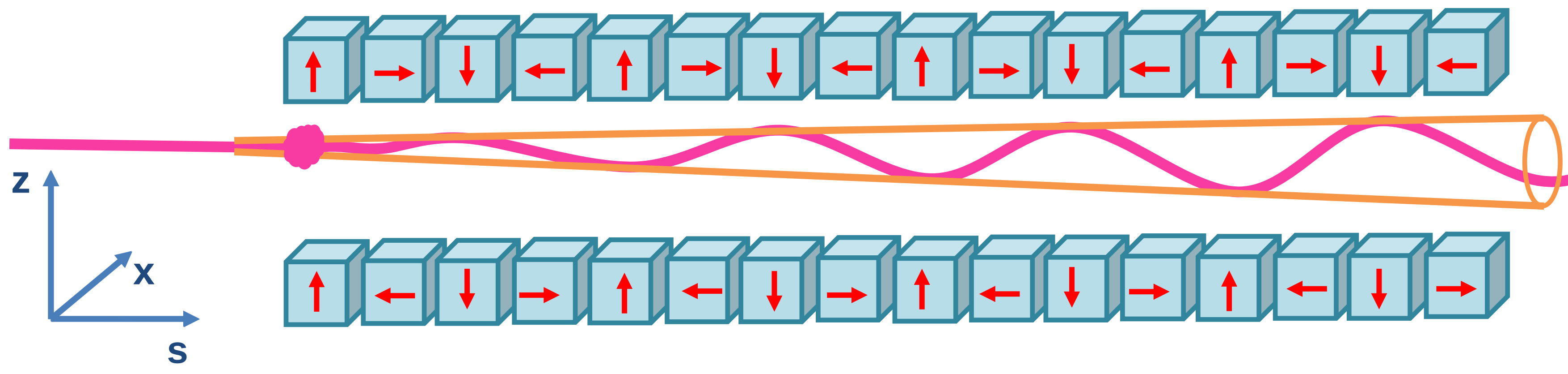




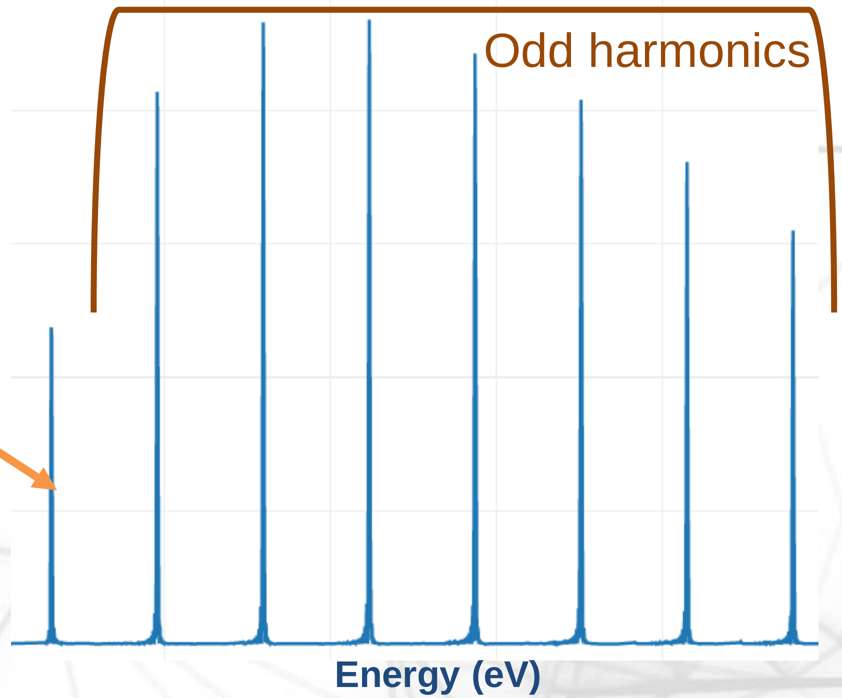
Synchrotron radiation with planar undulators



Synchrotron radiation with planar undulators



Radiation emitted periodically
Succession of sources which interfere with each other
Spectrum: fundamental energy and its higher order harmonics

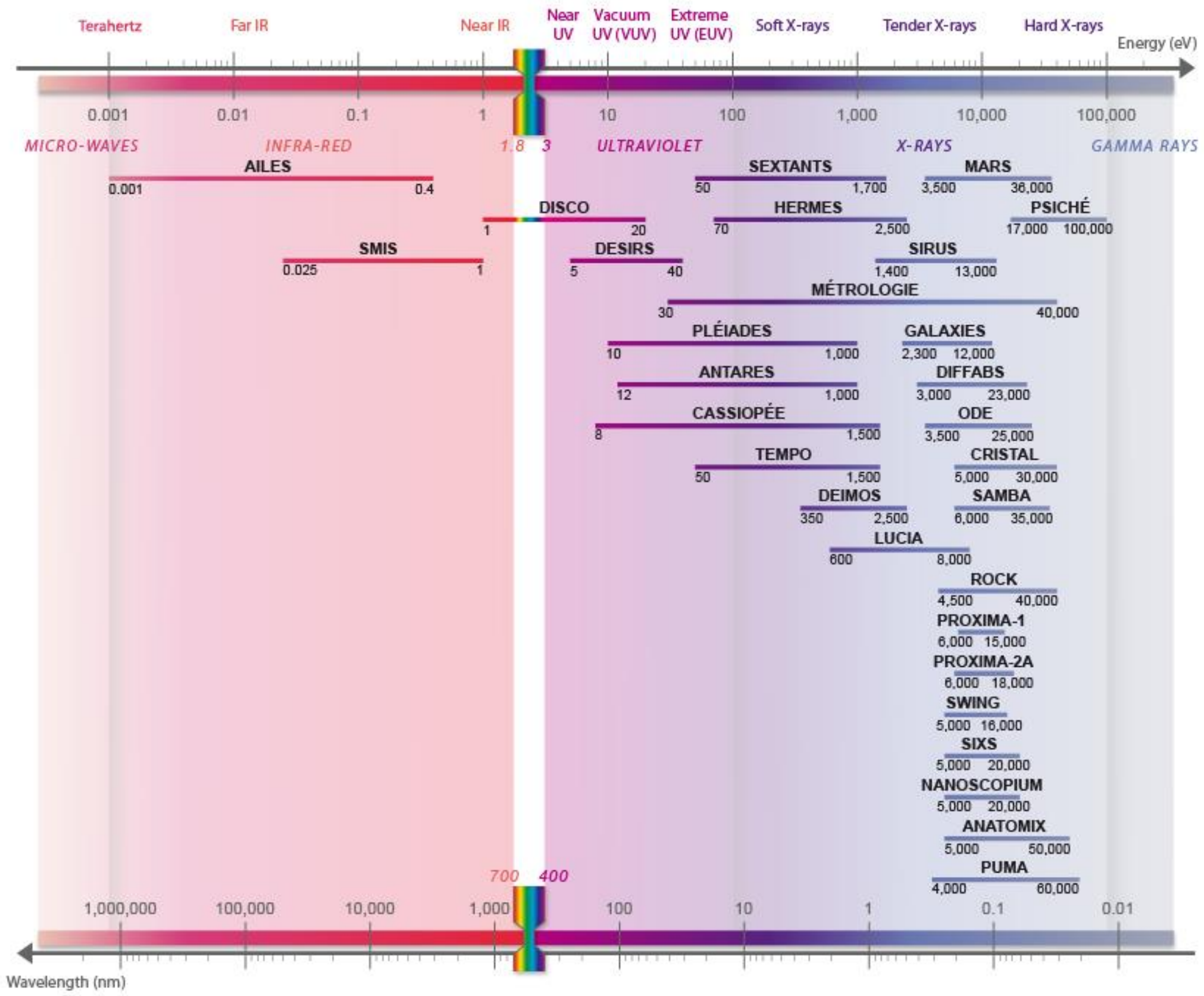


Fundamental energy

$$E_{photons}[keV] = 0.950 \times \frac{E^2[GeV]}{\lambda_0[cm] \times \left\{1+\frac{1}{2}\left(\sum_i 0.934 \times B_i[T] \times \frac{\lambda_0[cm]}{i}\right)^2\right\}}$$

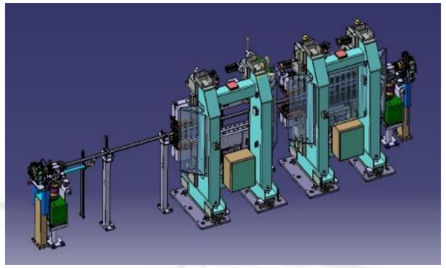
Synchrotron SOLEIL spectral range

Wide range of energy thanks to the complementarity and diversity of light sources

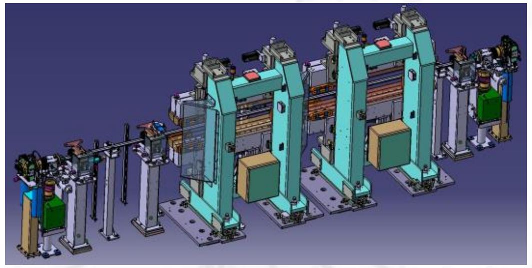


from infrared to hard x-rays

Medium straight sections:
Juxtaposition of two undulators with different magnetic periods to cover the wide spectral range



HERMES Beamline



TEMPO Beamline

Objective: Increase photon beam flux density and brightness

Reduce electron beam emittance from 3.9 nm.rad to **<100 pm.rad** to obtain smaller and less divergence source

Increase number of magnetic elements for focusing and guiding beam.

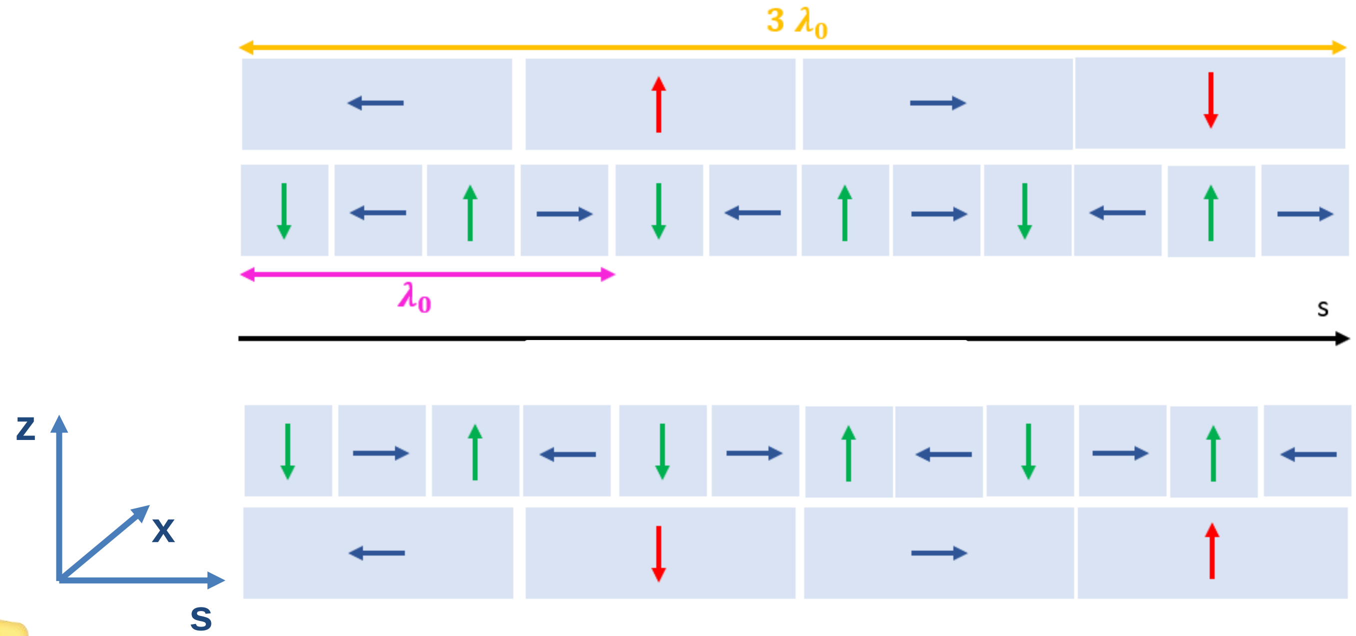
Reduce space reserved for insertion devices (30%).

No space to juxtapose two undulators to maintain present spectral range for users

Find technical solutions to the problem of limited space and search for compact radiation sources to maintain present spectral range for beamlines

** TDR baseline lattice for the upgrade of SOLEIL, A. Loulergue et al., Proceeding of IPAC2022, Bangkok, Thailand, 2022, pp. 1393-1396.*

Bi-Periodic undulator (Concept patented*):

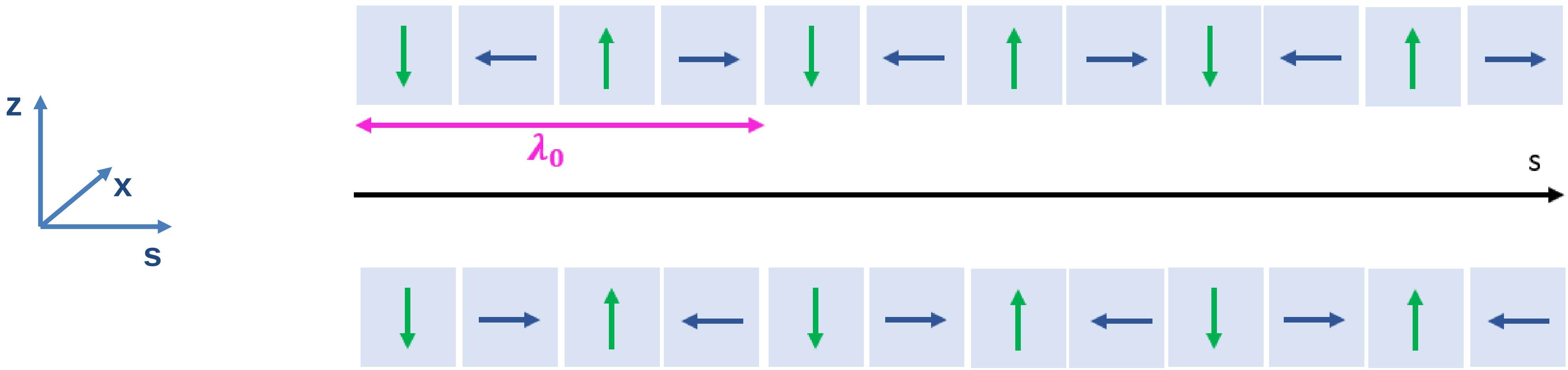


Innovative and compact device
Two selectable magnetic periodicities by superimposition of magnets
Select a magnetic period or its triple value by longitudinal mechanical shift of magnetic arrays

** Brevet: Onduleur bi-périodique, dispositif, installation et procédé associé n° FR3125670*

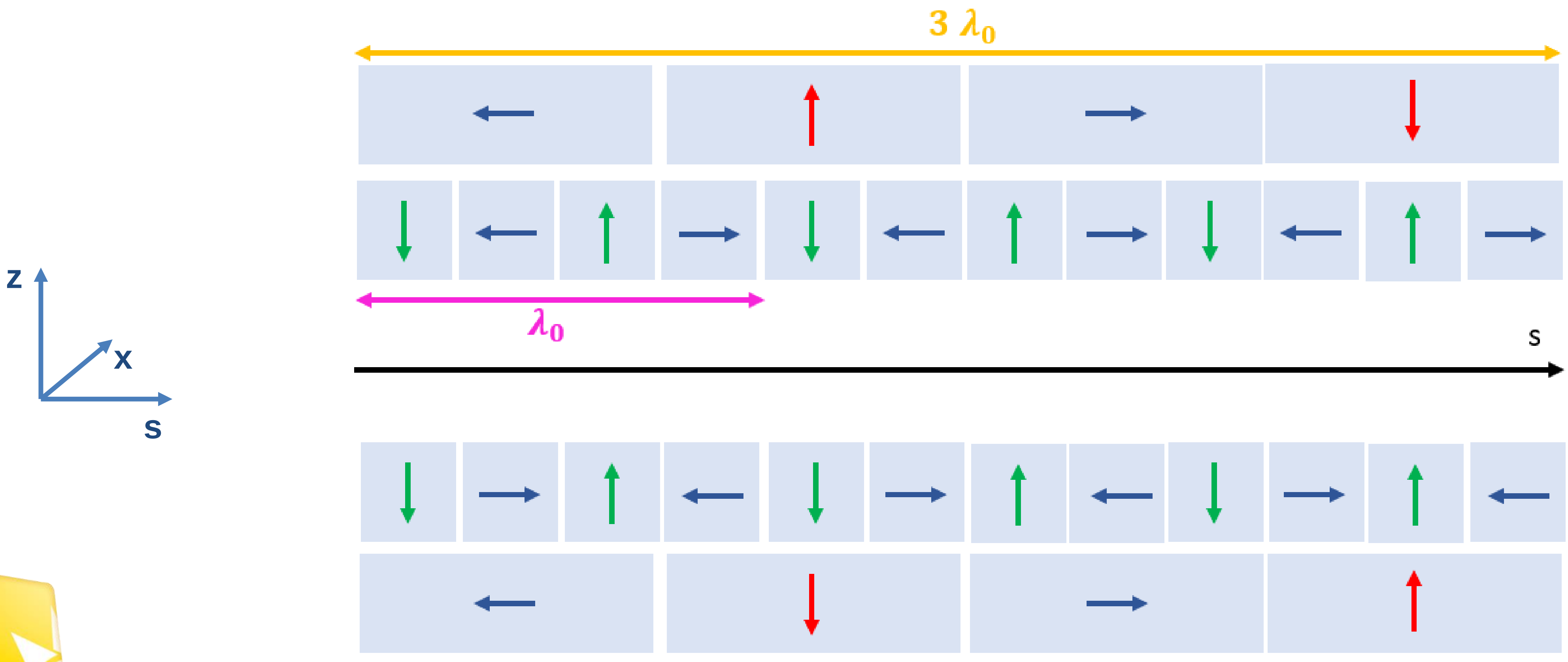
2/ Bi-periodic undulator concept

- System of magnets in Halbach* configuration with one periodicity



* *Halbach Configuration : K.Halbach, Nucl. Instrum. Methods, 169 (1980) 1–10*

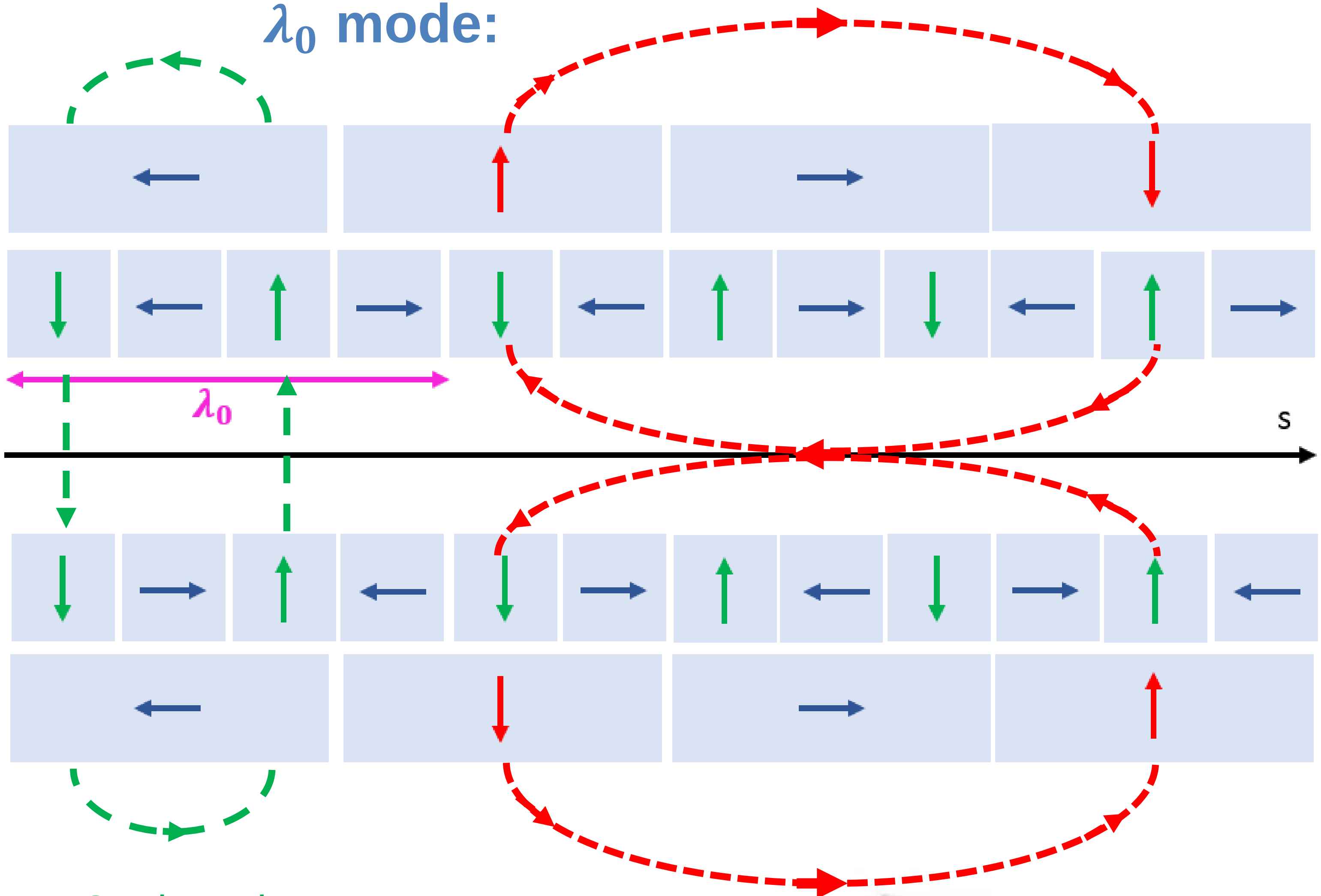
- Another array of magnets with triple periodicity



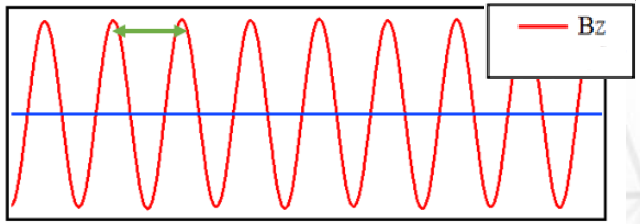
→ *Special arrangement of magnets enables two operating modes*

Principle of operation

λ_0 mode:



Magnetic field with a period λ_0

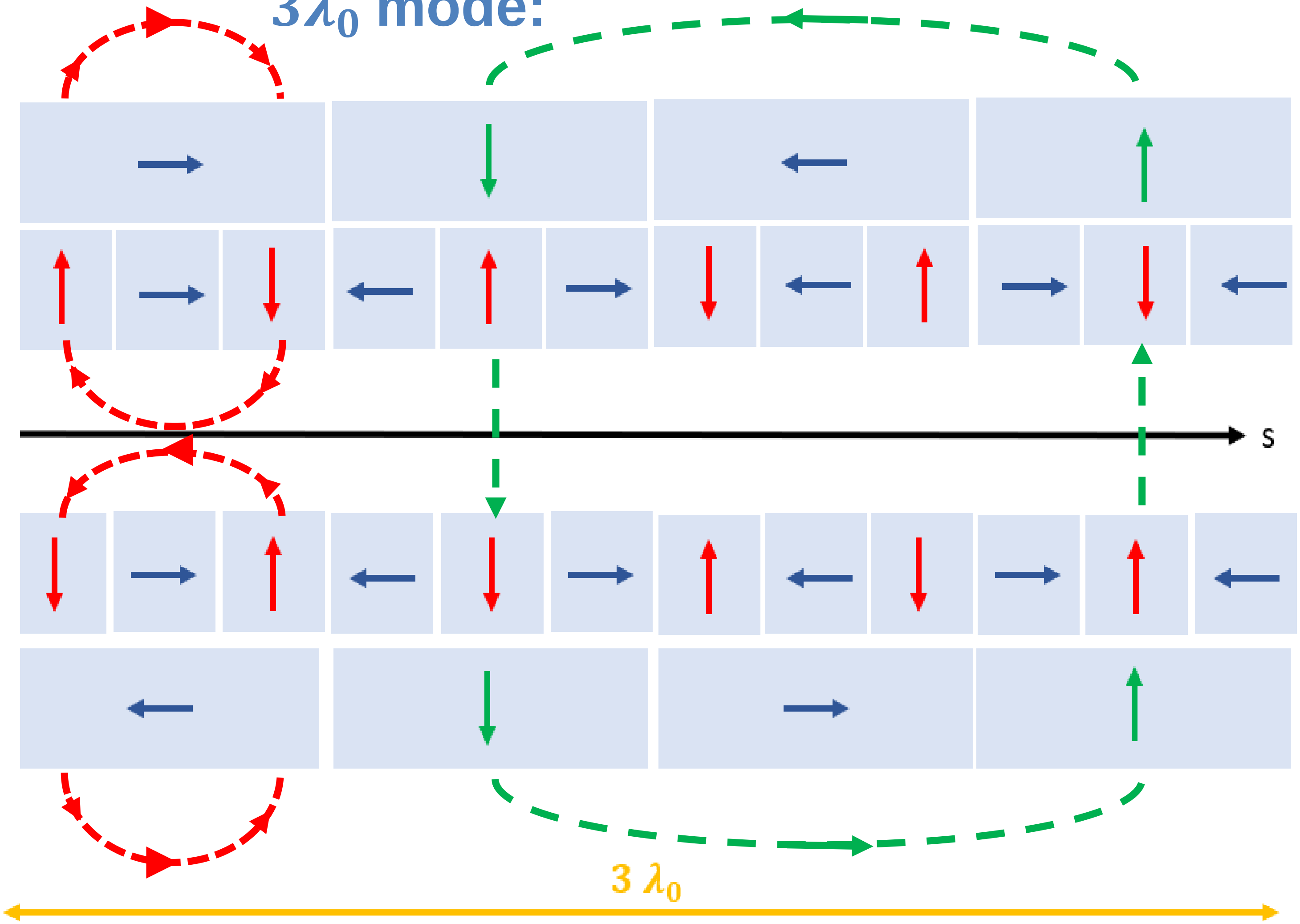


On the axis:
Vertical magnetic field contribution with a periodicity of λ_0

On the axis:
Cancellation of vertical magnetic field contribution with a periodicity $3\lambda_0$

Principle of operation

$3\lambda_0$ mode:



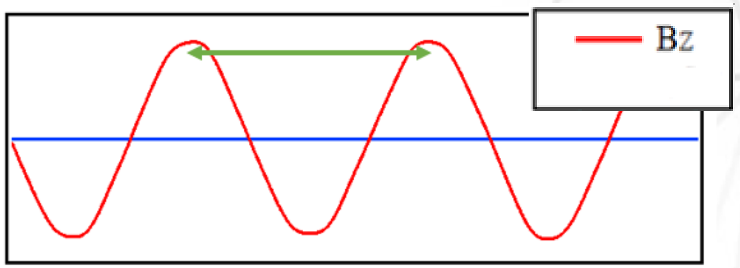
On the axis:
Cancellation of vertical magnetic field contribution with a periodicity of λ_0

On the axis:
Vertical magnetic field contribution with a periodicity $3\lambda_0$

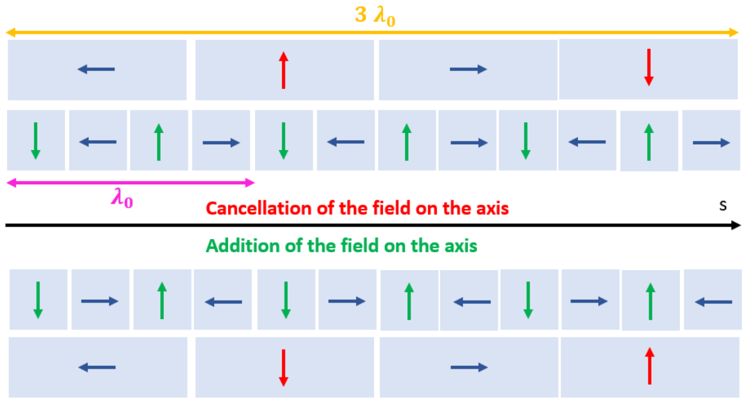
Moving longitudinally the magnetic arrays

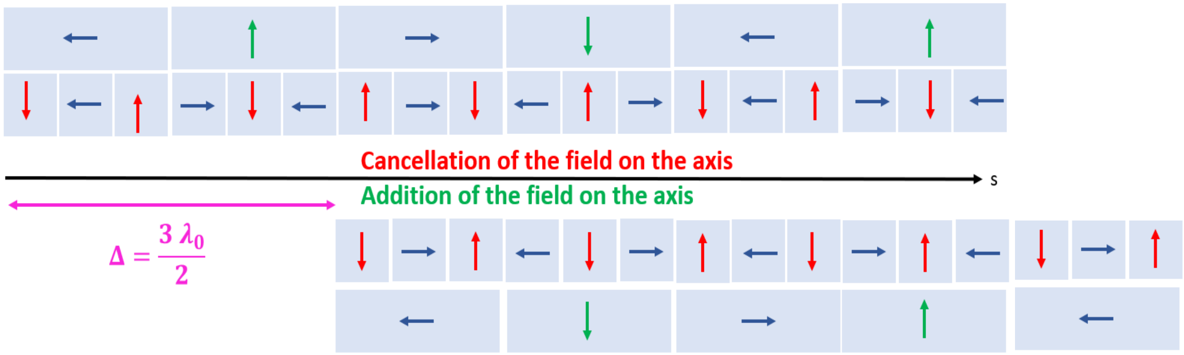
$$\Delta = \frac{3\ \lambda_0}{2}$$

Magnetic field with a period $3\lambda_0$



Principle of operation

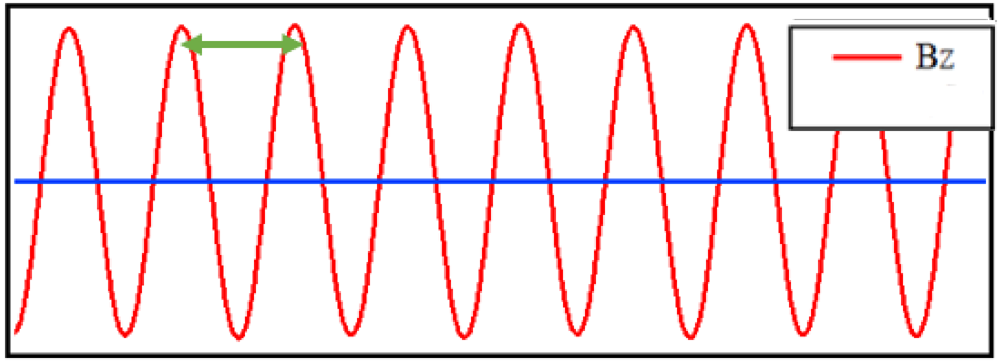




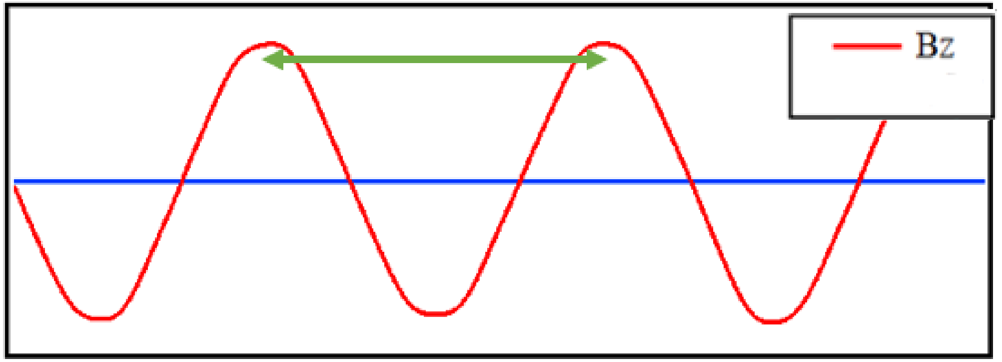
λ_0 mode:

$3\lambda_0$ mode:

Magnetic period λ_0



Magnetic period $3\lambda_0$



→ *On axis: can select one or the other period only by changing operating mode*

→ *Change magnetic period and energy range*

→ ***Performances of two undulators for one insertion device***

3/ Magnetic studies of a prototype

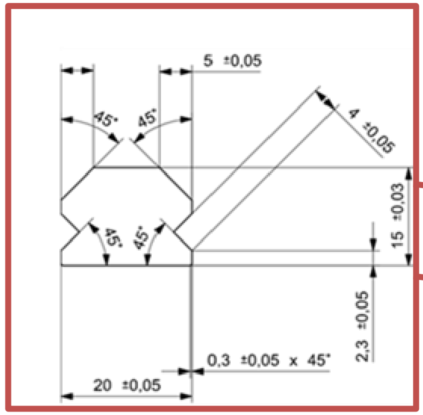
Motivation of this study

In this presentation

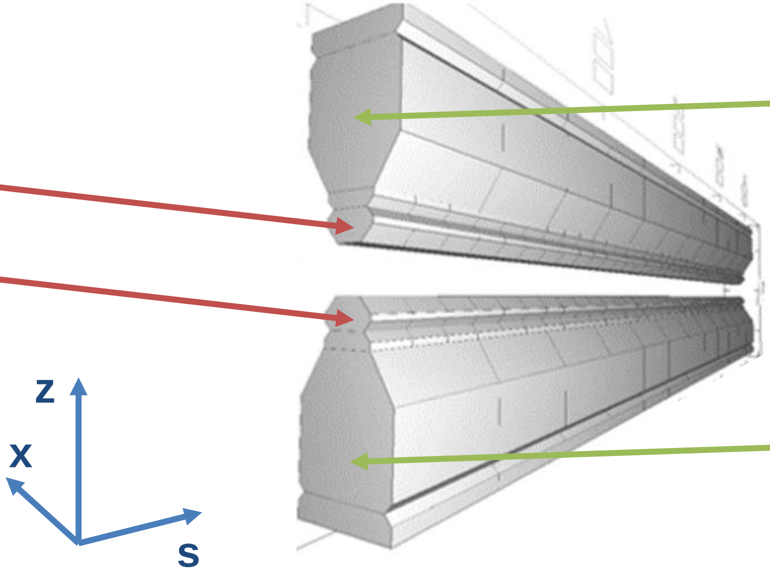
- Design for SOLEIL II + Construction of prototype
  - Verify possibility to select only one period
  - Verify magnetic performance
  - Validate mechanical design

- Test on SOLEIL I
  - Characterize beam dynamics
  - Validate spectral performance

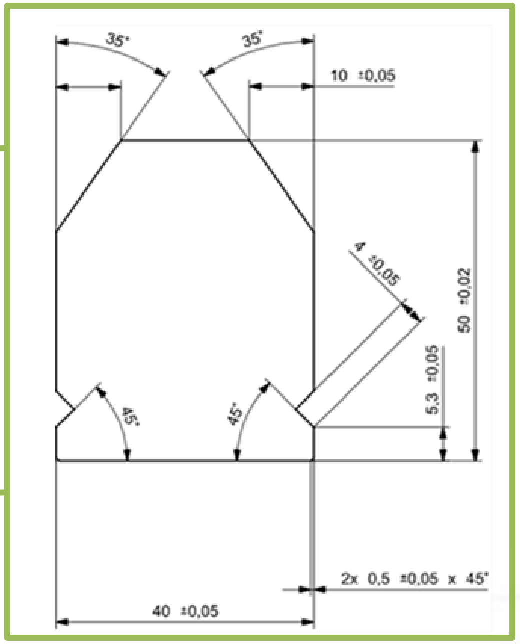
Magnetic design



50 mm period magnets



Simulations with Radia program*



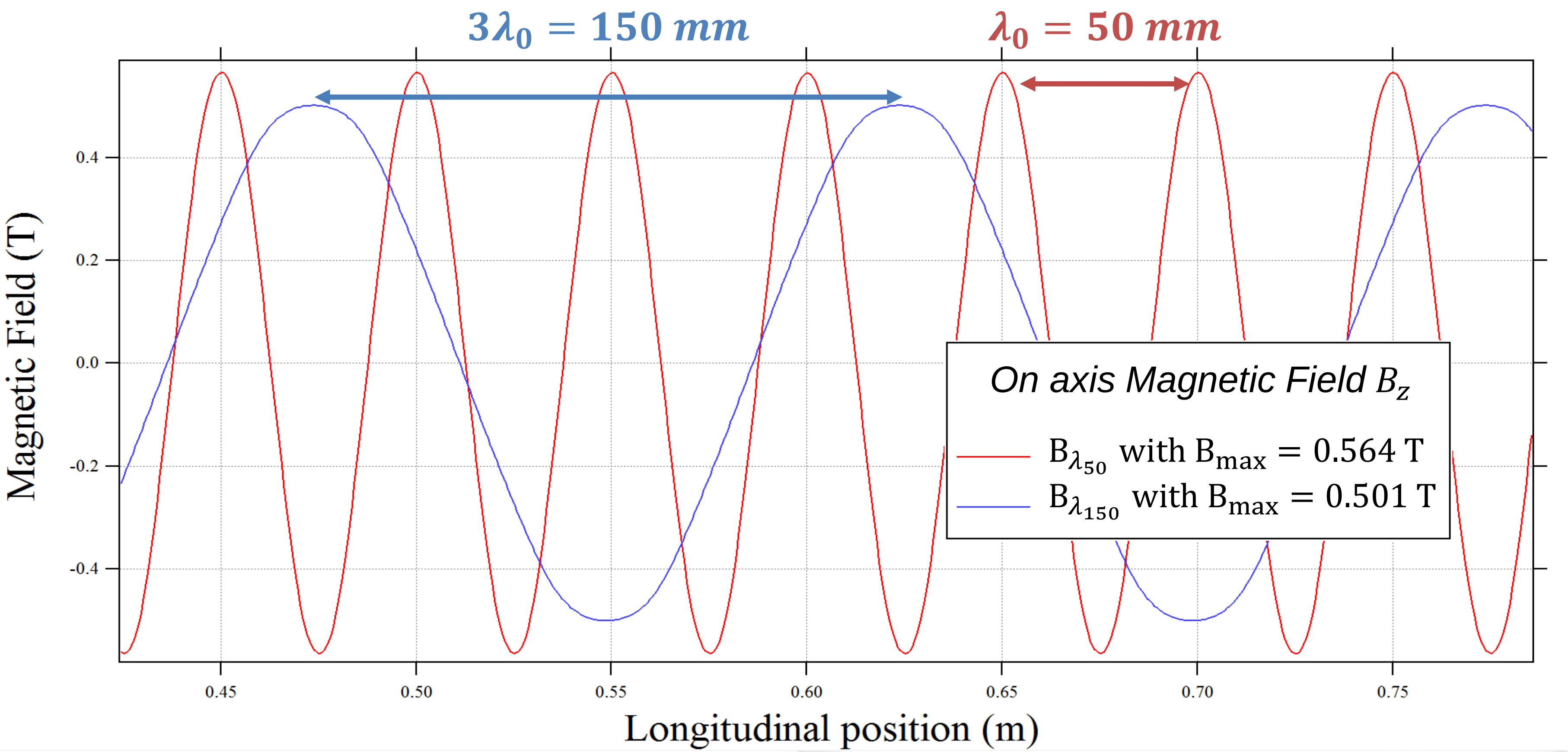
150 mm period magnets

Periodicity	$\lambda_0 = 50$ mm and $3\,\lambda_0 = 150$ mm
Magnets	Permanent magnets NdFeB: Trapezoidal geometry
Magnetization	$\lambda_0 = 50$ mm → $M_{avg} = 1.38$ T $3\,\lambda_0 = 150$ mm → $M_{avg} = 1.42$ T

** Computing 3D. Magnetic Field from Insertion Devices, P. Elleaume, O. Chubar, J. Chavanne, Proceedings of PAC97, Vancouver, 1997*

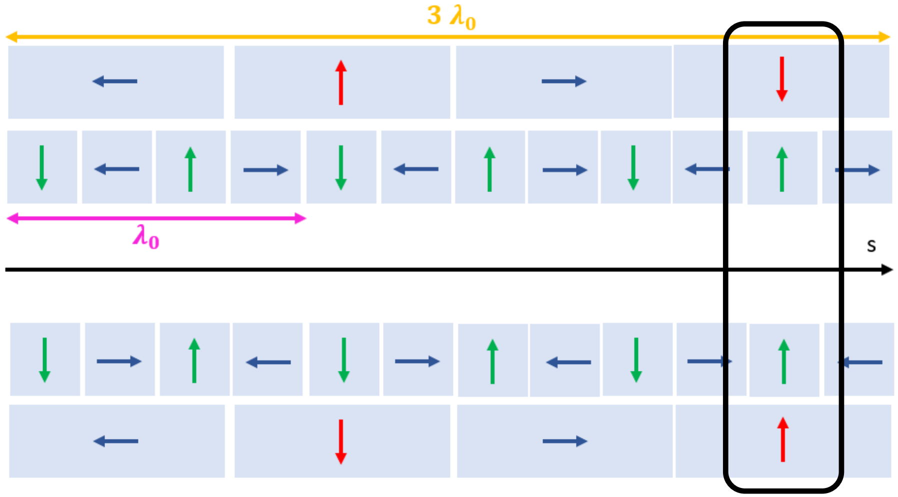
Magnetic study on the axis

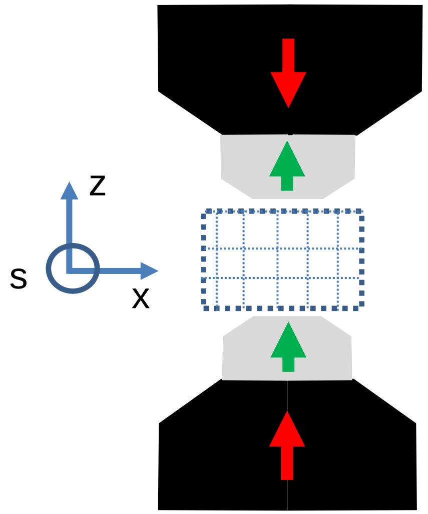
Vertical magnetic field on axis for two operating modes at gap 15.5 mm (minimal gap)



→ ***On axis:*** *can select one or the other period only*

Magnetic stydy: off-axis magnetic field





Consider the system as two independent planar undulators operating at $\lambda_0 = 50$ mm and $3\lambda_0 = 150$ mm

Express magnetic field as a periodic signal defined by a sum of Fourier coefficients:

$$A1_{x,z,s}(x,z) = \frac{2}{L_u}\int_{-L_u/2}^{+L_u/2} B_{x,z,s}(s)\sin(\frac{k_0}{3}s)ds$$

$$A3_{x,z,s}(x,z) = \frac{2}{L_u}\int_{-L_u/2}^{+L_u/2} B_{x,z,s}(s)\sin(k_0 s)ds$$

$$B1_{x,z,s}(x,z) = \frac{2}{L_u}\int_{-L_u/2}^{+L_u/2} B_{x,z,s}(s)\cos(\frac{k_0}{3}s)ds$$

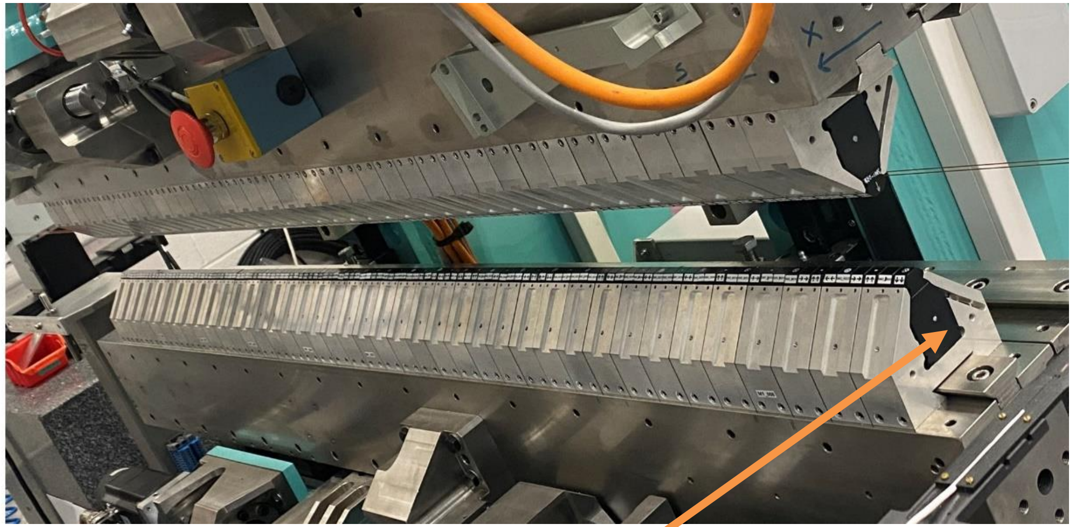
$$B3_{x,z,s}(x,z) = \frac{2}{L_u}\int_{-L_u/2}^{+L_u/2} B_{x,z,s}(s)\cos(k_0 s)ds$$

Magnetic axis:

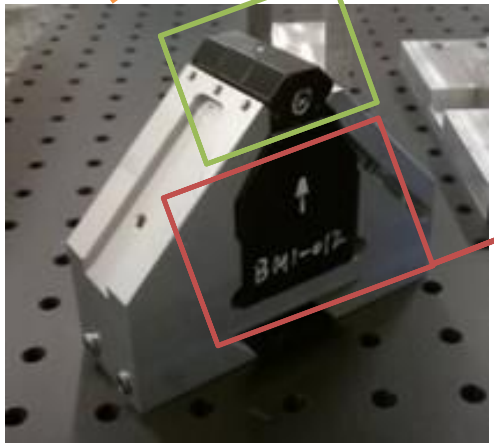
50 mm mode: Coefficient $A1_z$ is canceled

150 mm mode: Coefficient $A3_z$ is canceled

Construction of prototype

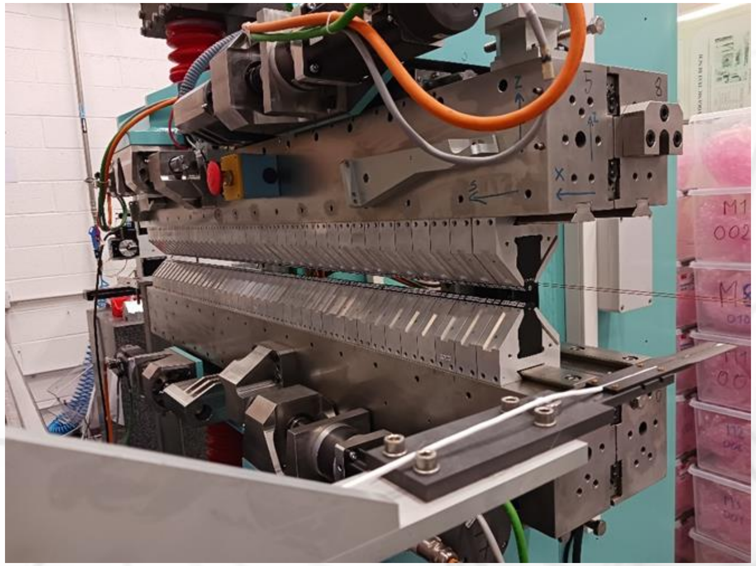


Periodicity	$\lambda_0 = 50$ mm and $3\,\lambda_0 = 150$ mm
Magnets	Permanent magnets NdFeB Trapezoidal geometry
Magnetization	$\lambda_0 = 50$ mm → $M_{avg} = 1.38$ T $3\,\lambda_0 = 150$ mm → $M_{avg} = 1.42$ T
Length	$l = 1.5$ m
Instrumentation of measuring bench	Hall probe and Flipping coils



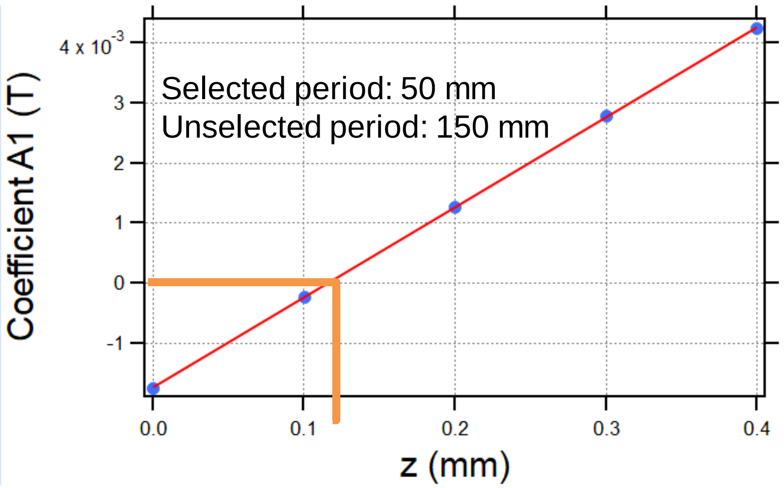
3 magnets
(50 mm period)

1 magnet
(150 mm period)

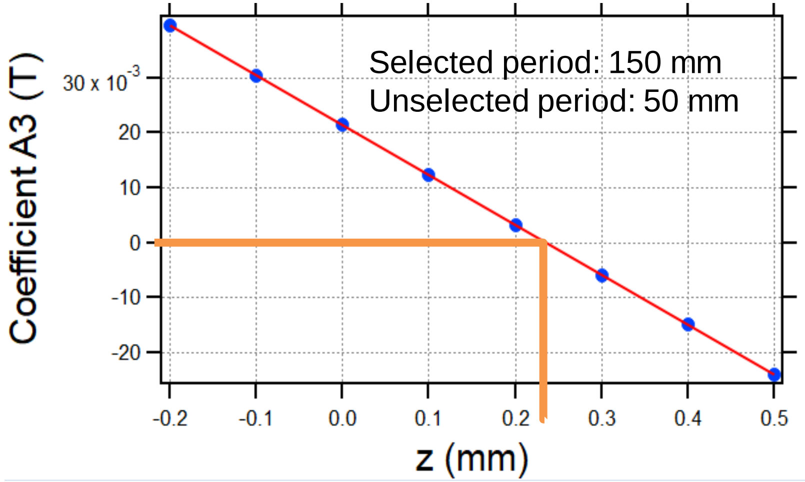


- Hall probe alignment on magnetic axis: study of Fourier coefficients

50 mm mode:



150 mm mode:



Each mode had its own magnetic axis because of magnetic and mechanical defects (the two are separated by less than 100 µm)
→ Determine average axis

Gap 15,5 mm	50 mm mode	150 mm mode
% unselected period	$0,25\ \%$	$1,6\ \%$

➢ Prototype: Be able to cancel almost the unselect period on the axis for the two operating modes

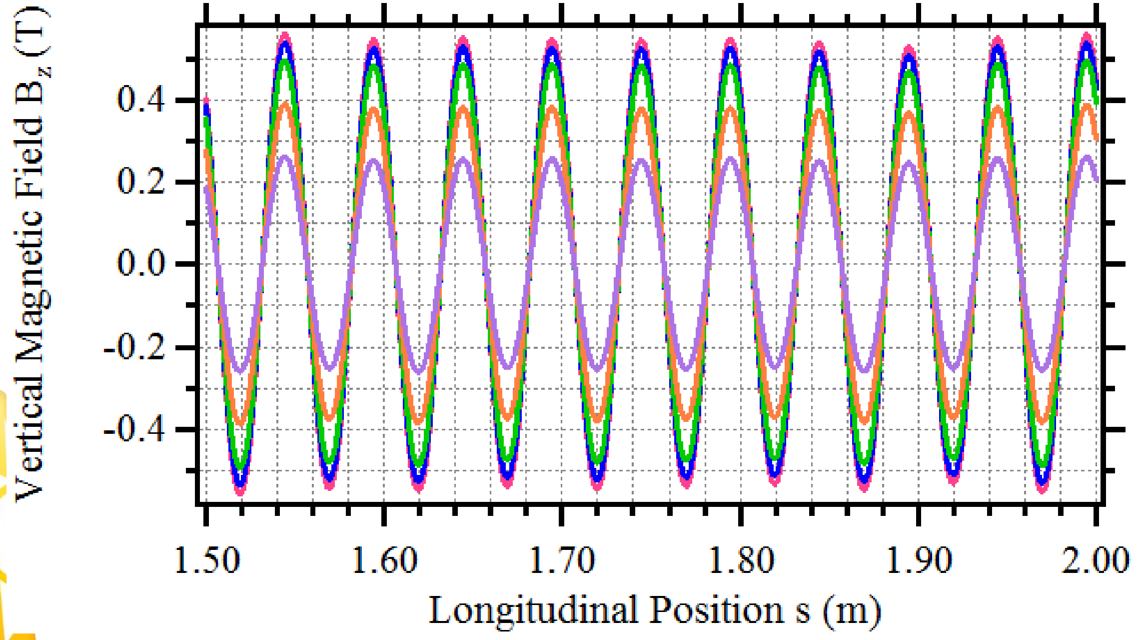
Prototype magnetic field

- Measurements for differents gaps:

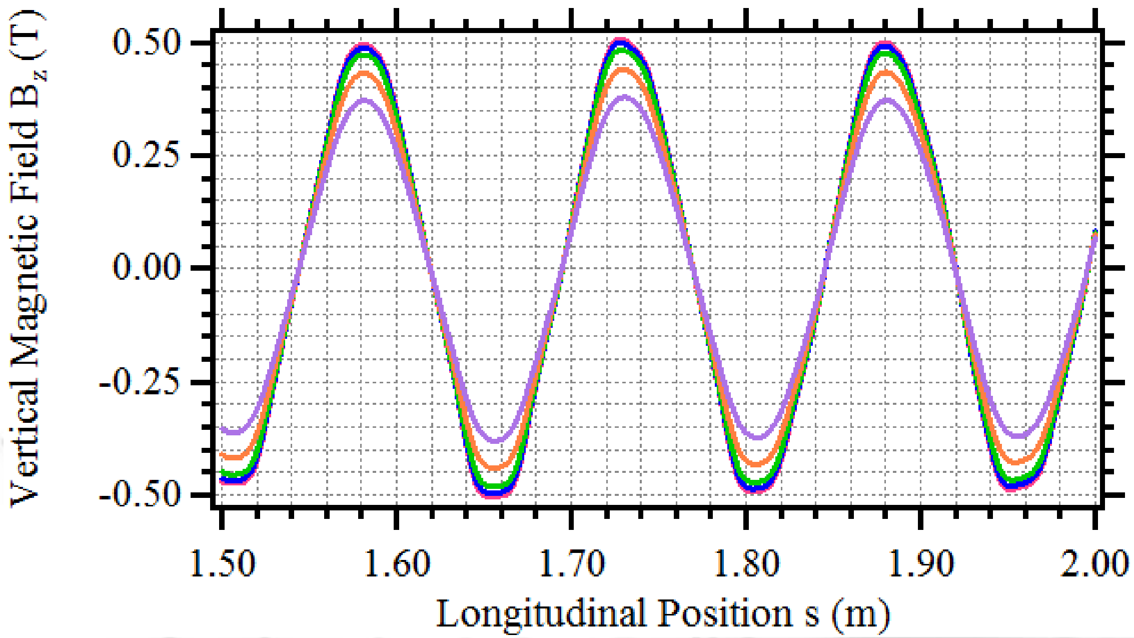
Gap	Period: 50 mm		Period: 150 mm	
15.5 mm	0.55 T	330 eV	0.50 T	19 eV
16 mm	0.52 T	350 eV	0.49 T	19.5 eV
17 mm	0.48 T	395 eV	0.47 T	20.6 eV
20 mm	0.38 T	546 eV	0.43 T	24.6 eV
25 mm	0.25 T	823 eV	0.37 T	32.5 eV

Gap: 15.5 mm, 16 mm, 17 mm, 20 mm, 25 mm

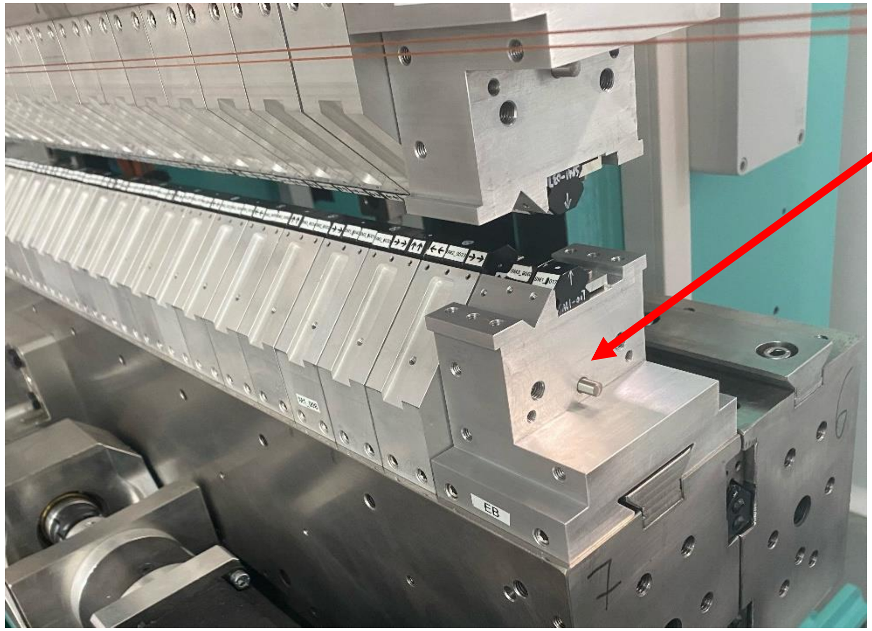
50 mm of period



150 mm of period

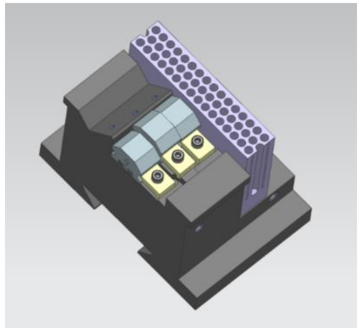


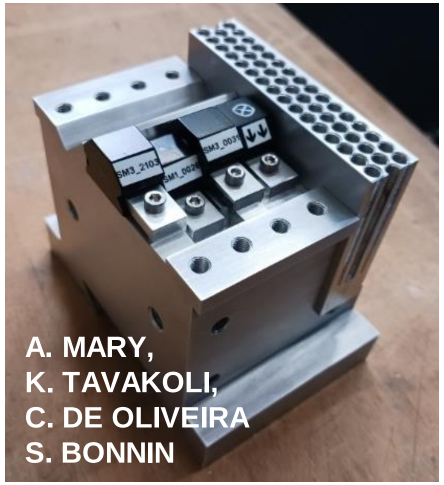
Magnetic corrections



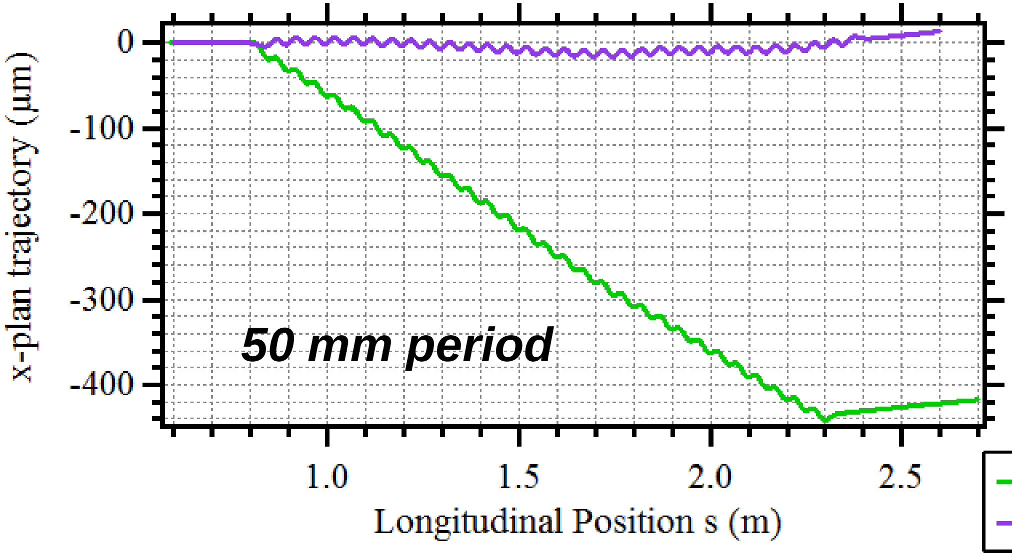
End terminaisons:

At the ends of the undulator (at the input and output) magnetic environment disrupts electron trajectory and generates angular deviations. Impacts on the electron trajectory and on emission axis of the radiation.

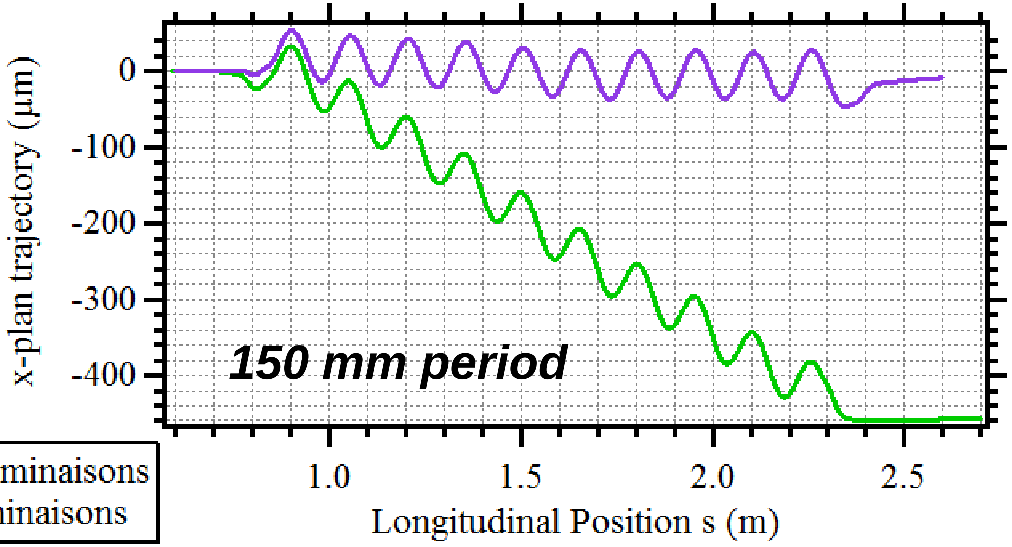




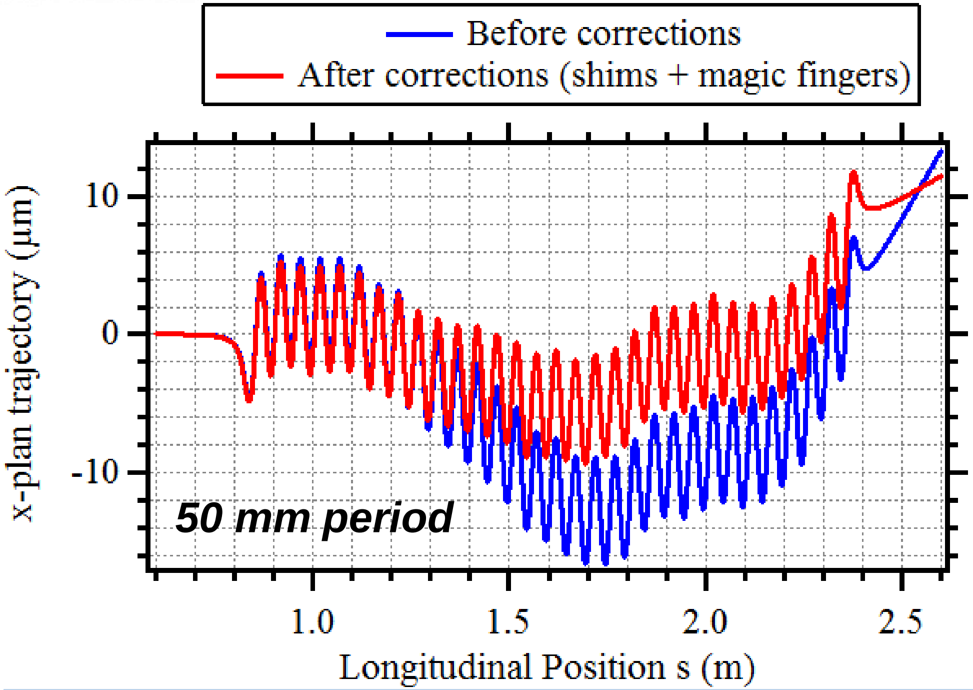
A. MARY,
K. TAVAKOLI,
C. DE OLIVEIRA
S. BONNIN

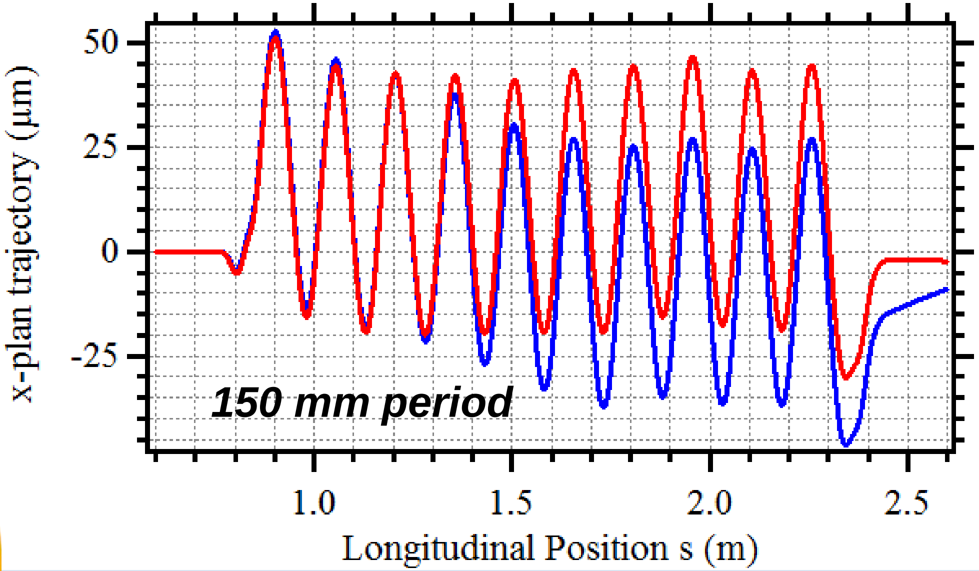


Before end terminaisons
After end terminaisons



Magnetic corrections



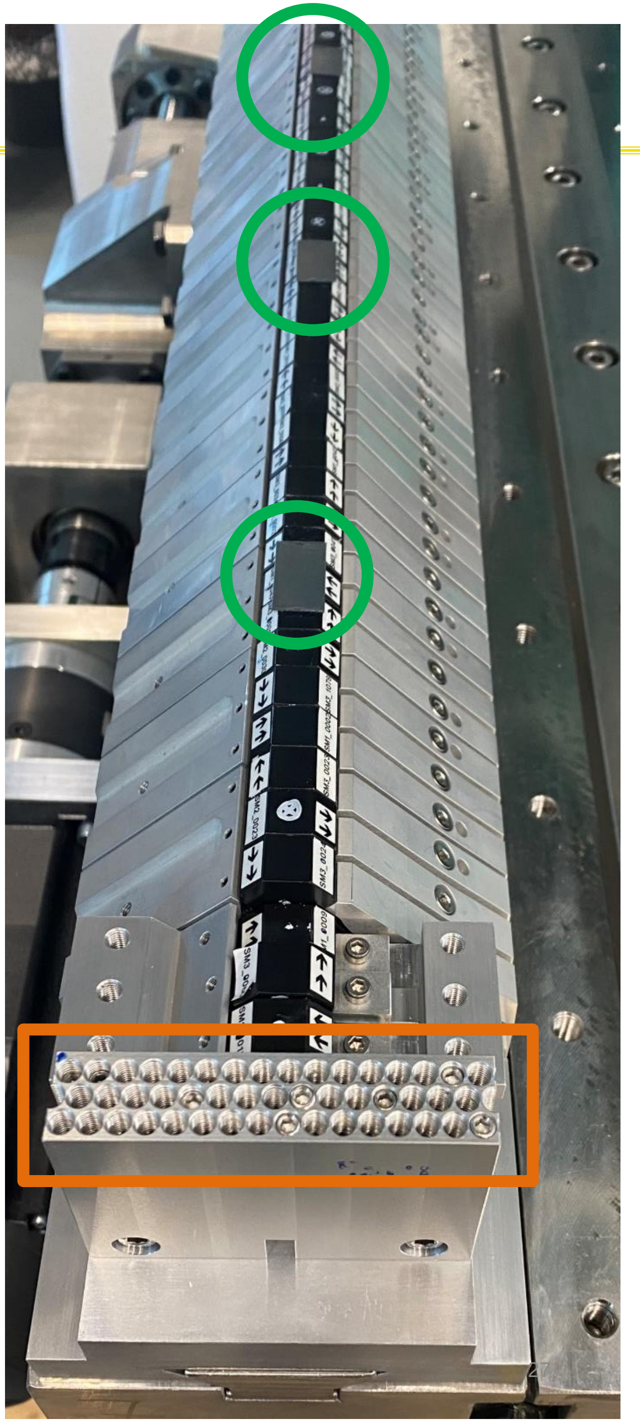


Shims:

250 µm thick iron shims. Installed on magnets at precise positions along the prototype to reduce the field locally where there is an excess of magnetic field.

Magic Fingers:

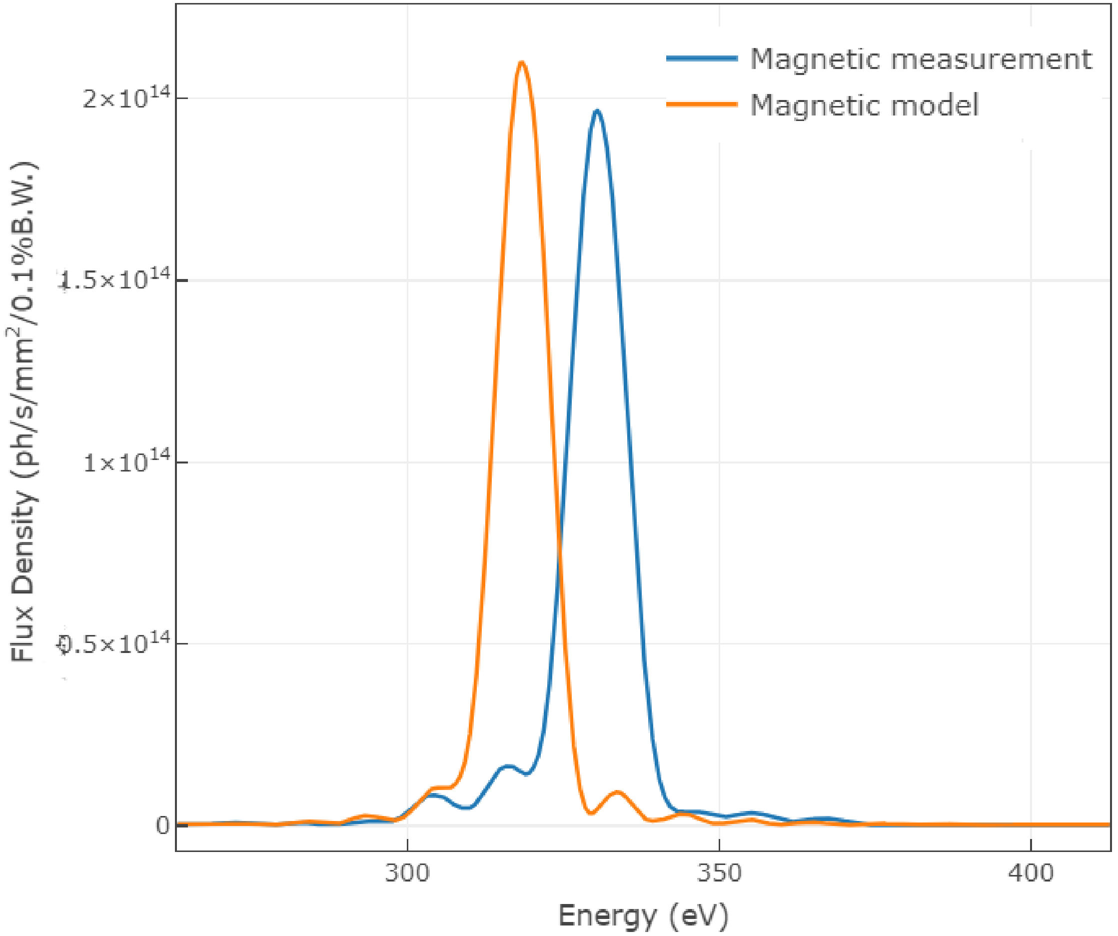
**Small cylindrical magnets in small boxes
Installed at the ends of the undulator to locally correct off-axis impacts and trajectory at the ends by imposing new transverse distribution of the field**



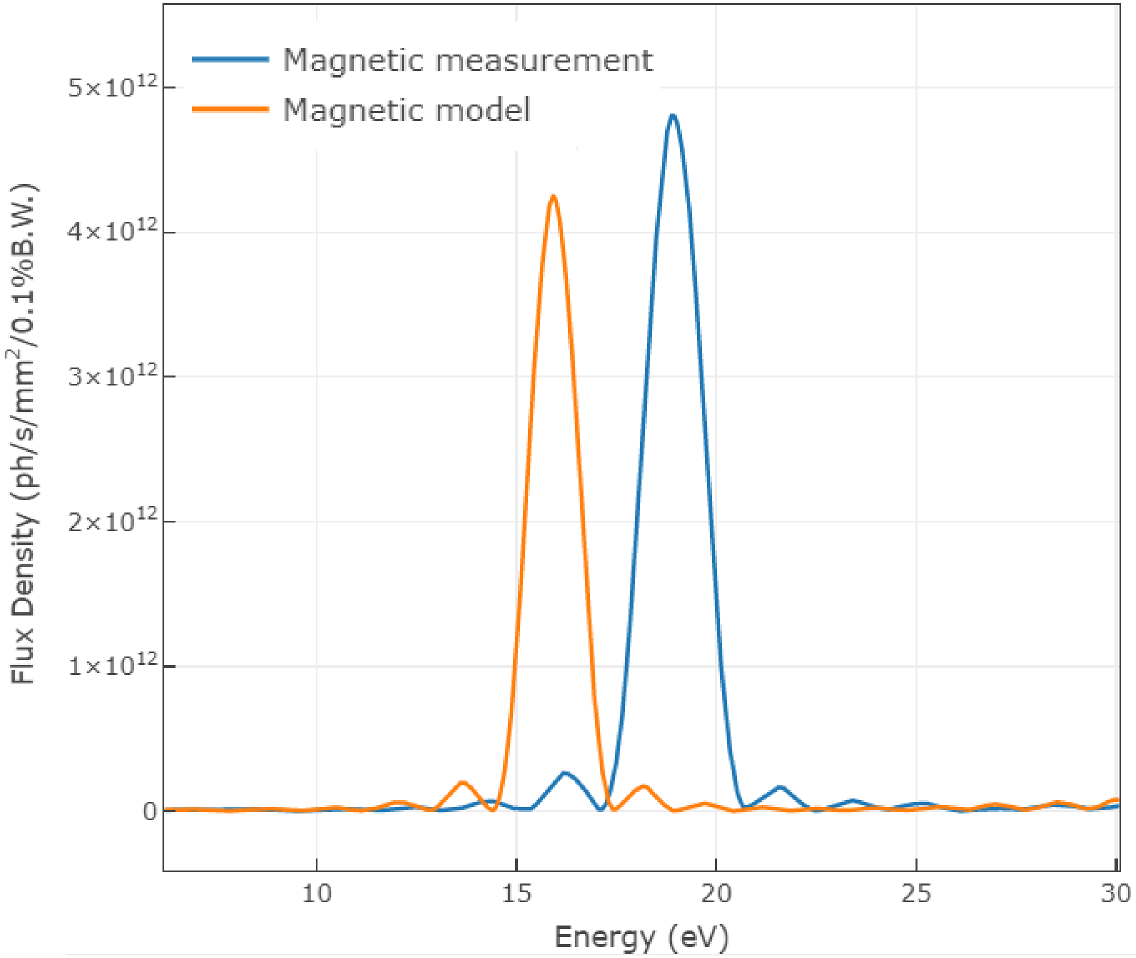
Simulated spectrum with Spectra software*

15,5 mm gap

50 mm period



150 mm period



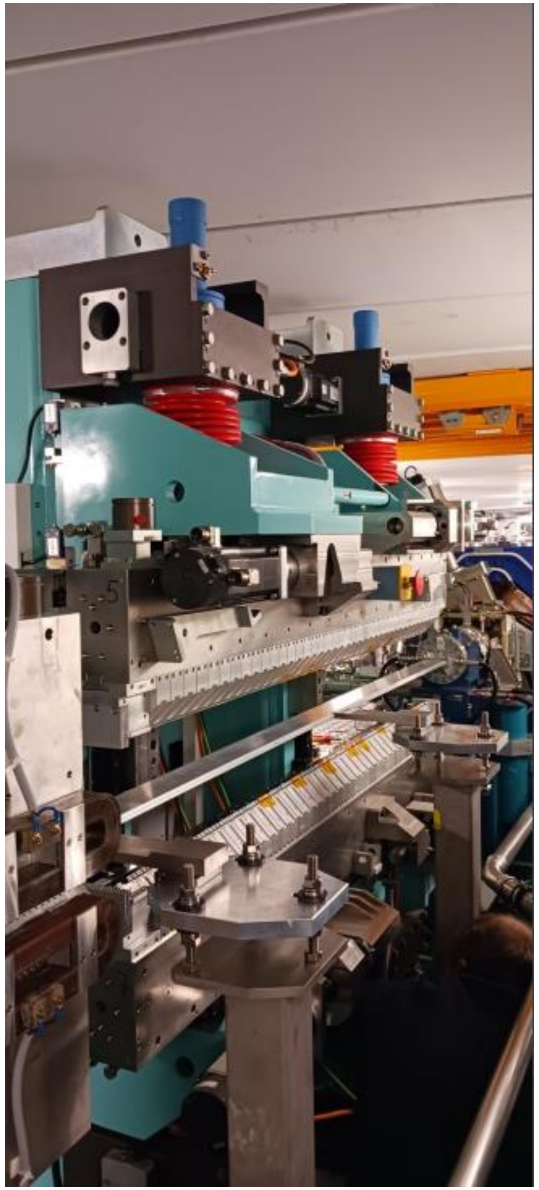
** SPECTRA - a synchrotron radiation calculation code, T. Tanaka and H. Kitamura, J. Synchrotron Radiation 8, 1221 (2001)*

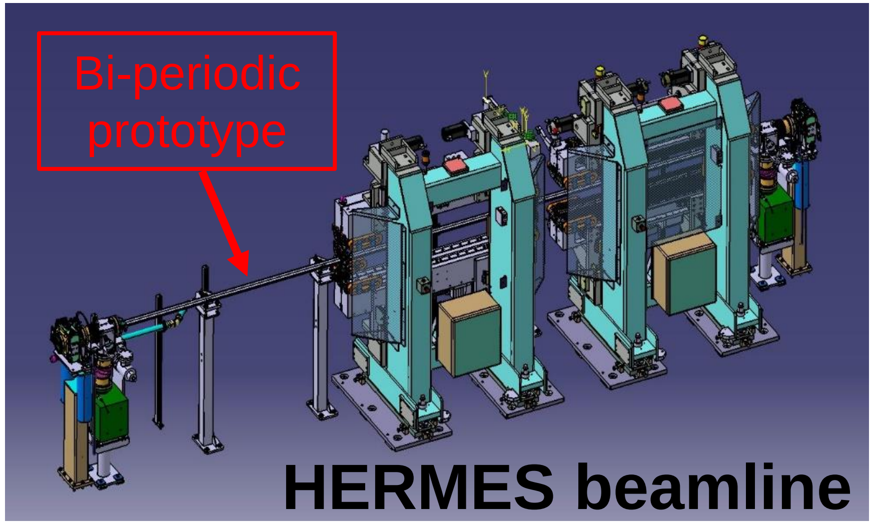
4/ Conclusion and outlook

Conclusion

- Replace two undulators by one which have the same spectral domain
- Prototype: to validate the concept of the bi-periodic undulator and to identify the potential constraints
- Encouraging results: possibility to select one of the two periods only

Outlook: Experimental study on storage ring





(DENNETIERE David, BELKHOU Rachid, optic group)

January 2024

Prototype installation on present storage ring

February 2024

We began the study of the impact on the beam dynamics

March 2024

We began the study of the radiation obtained on the beamline

Thank you for your attention!

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