Bi-periodic Undulator: Innovative Insertion Device for SOLEIL II

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(TH1D4)

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Outline

1/ Introduction

Synchrotron SOLEIL

Storage ring:

Electrons 2.75 GeV

Current 500 mA

Circumference 354 m

Horizontal emittance 3.9 nm.rad

29 beamlines:

Photon sources: Bending Magnet, Wiggler, Undulator

From infrared to hard x-rays

Scientific context

Synchrotron SOLEIL

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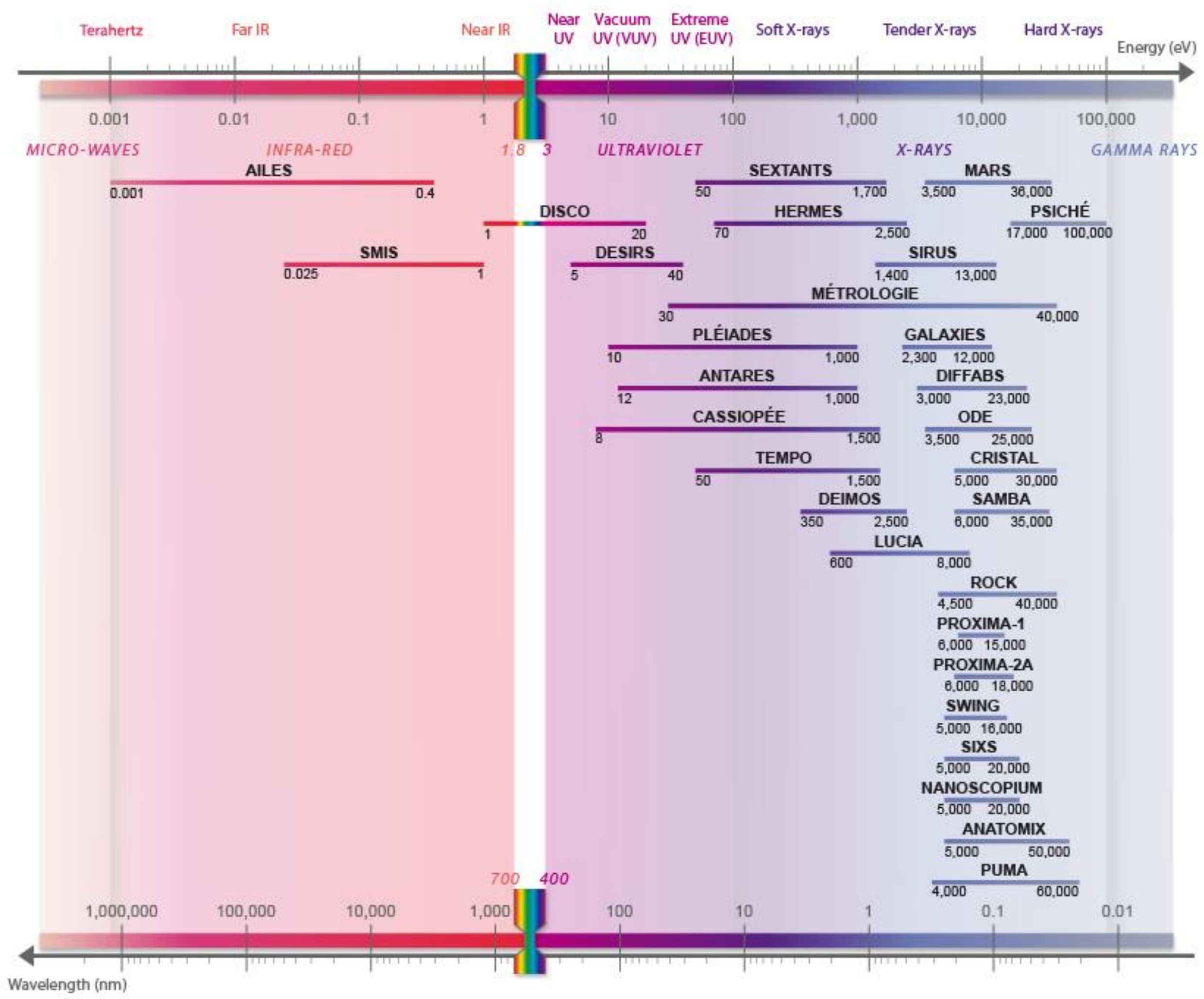

Synchrotron SOLEIL

Storage ring:

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29 beamlines:

Photon sources: Bending Magnet, Wiggler, Undulator

From infrared to hard x-rays

Upgrade Project*: SOLEIL II

Optimise production of photons:
Increase photon beam brightness

Reduction of electron beam emittance

From 3.9 nm.rad to **<100 pm.rad**

Increase number of magnetic elements for focusing and guiding electron beam

Reduce space reserved for insertion devices (30%)

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

Consequences

For medium straight sections

Currently:

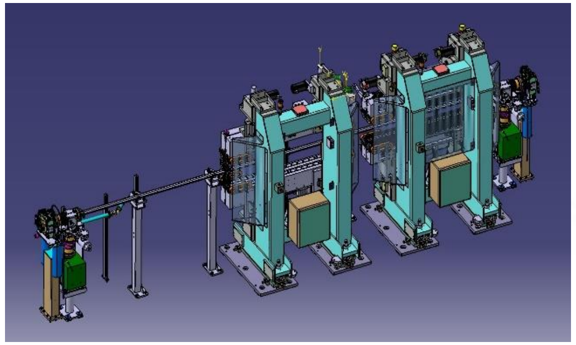
Medium straight sections of 7 meters

Juxtaposition of two undulators to cover the wide spectral range

Future ring:

Straight section passing down to 4.2 or 3.7 meters

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



HERMES beamline

Issues and suggested solution

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

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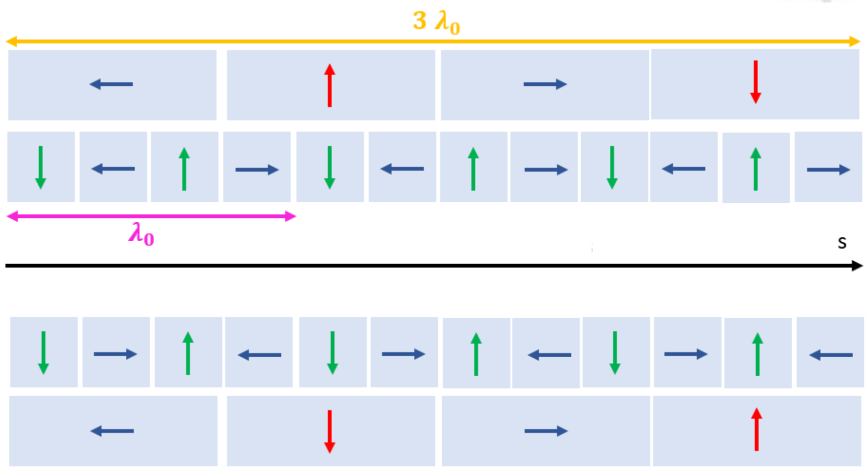
Suggested solutions:

→ ***DUAL*** *(alternate between 2 undulators by lateral movement)*

→ ***APPLE X*** *(composed of 4 magnet arrays tilted 45° and 135°)*



→Bi-Periodic

Compact device developed by SOLEIL (Concept patented*)

Use of two selectable magnetic periodicities by superimposition of magnets

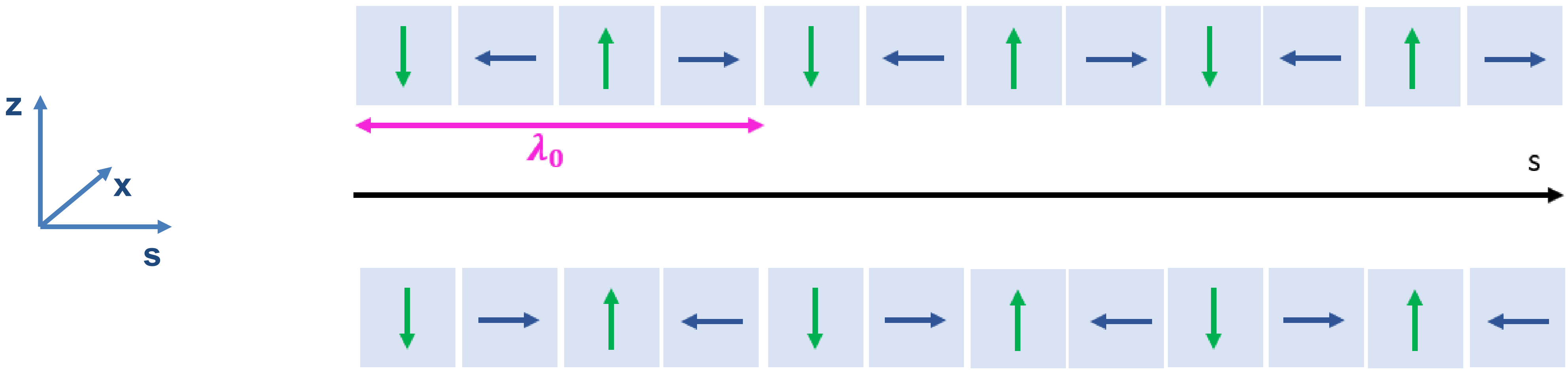
Soft X-rays beamlines, in particular CASSIOPEE and HERMES

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

2/ Principle of operation

Principle of operation

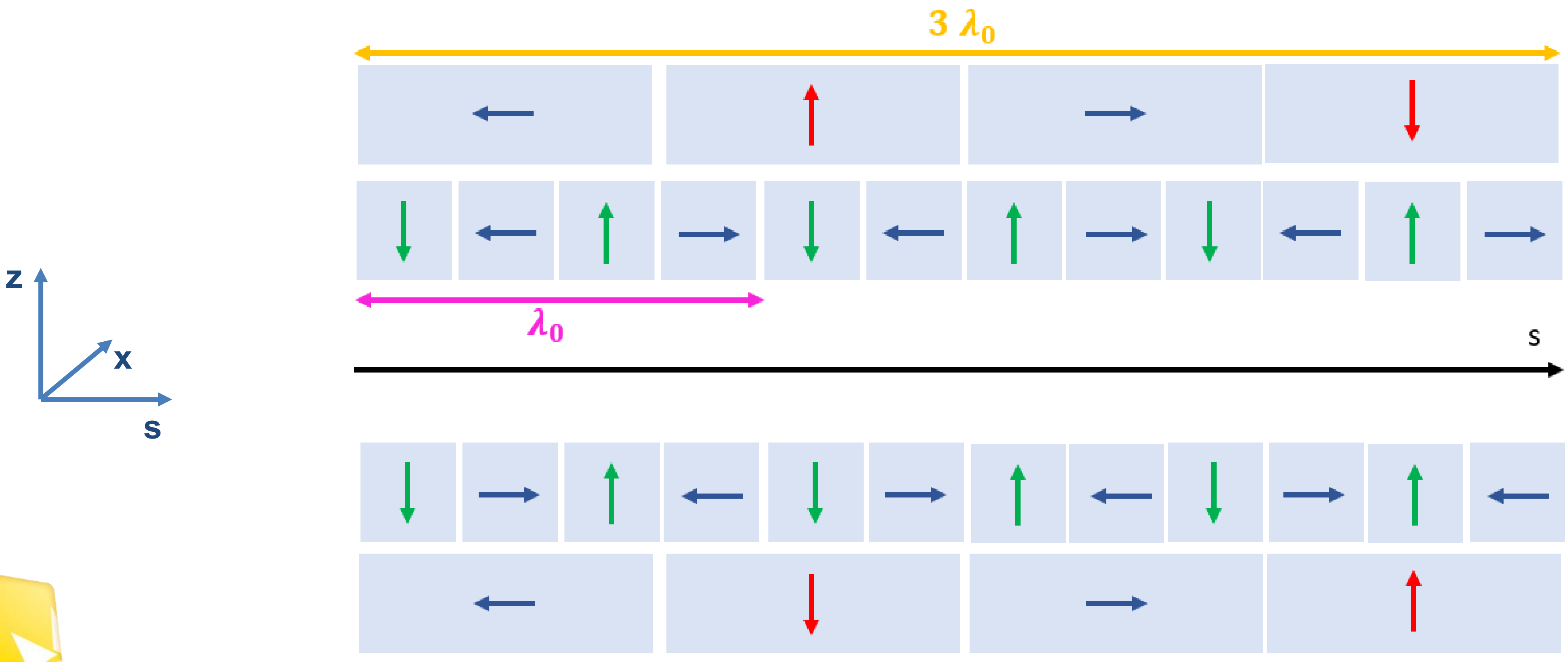
- System of magnets in Halbach* configuration with one periodicity



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

Principle of operation

- Another array of magnets with triple periodicity

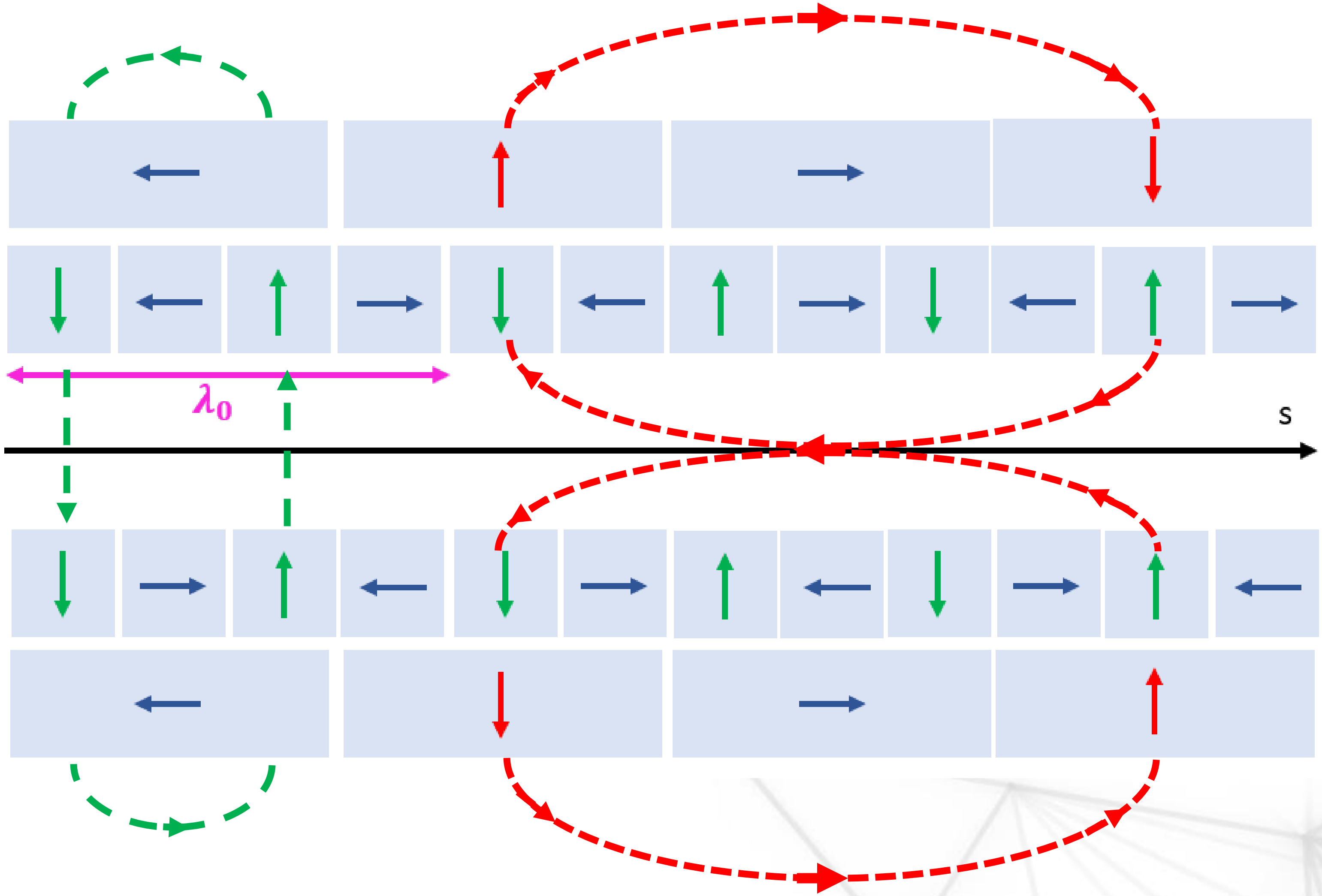


→ *Special arrangement of magnets enables two operating modes*

Principle of operation

- λ_0 mode:

Field line generated by the magnets of the λ_0 **period**: Addition of the B_z field on the axis

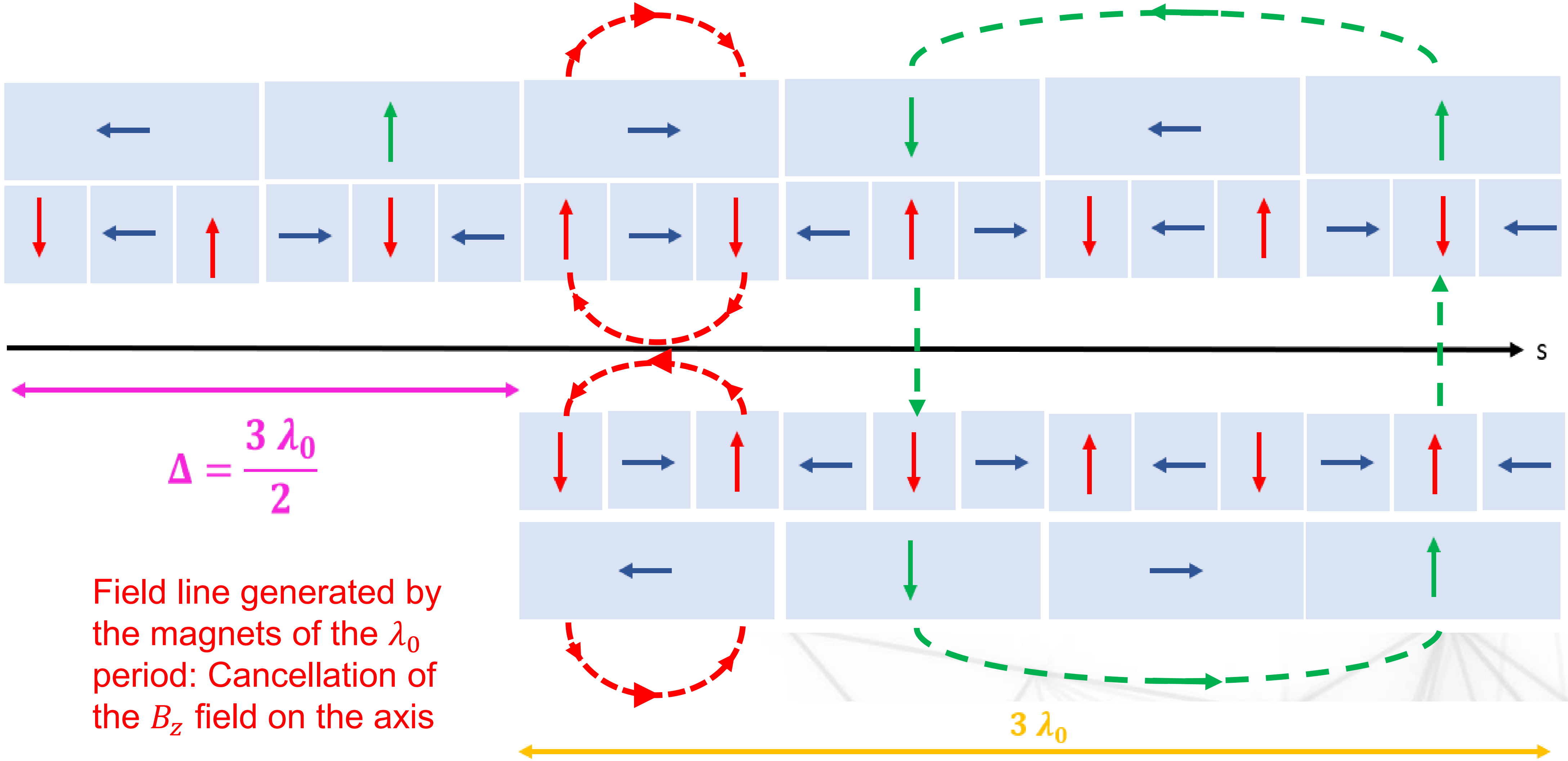


Field line generated by the magnets of the $3\lambda_0$ **period**: Cancellation of the B_z field on the axis

Principle of operation

- $3\lambda_0$ mode:

Field line generated by the magnets of the $3\lambda_0$ period: Addition of the B_z field on the axis



Field line generated by the magnets of the λ_0 period: Cancellation of the B_z field on the axis

3/ Bi-periodic undulator prototype design

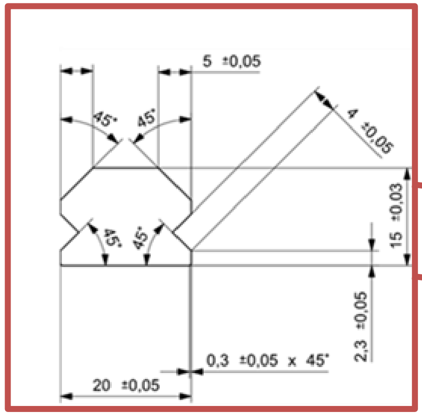
Motivation of this study

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

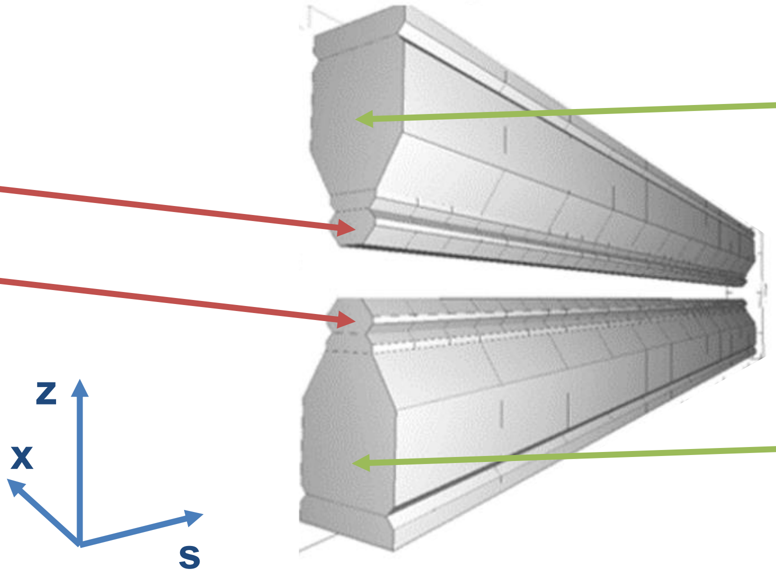
- Test on SOLEIL I
  - Characterize beam dynamics
  - Validate spectral performance

→ Produce large range of X-rays for SOLEIL II

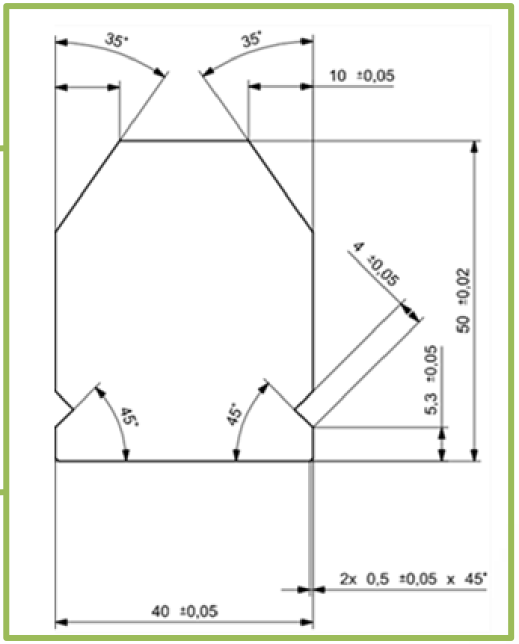
Magnetic design



50 mm period magnets



Simulations with Radia program*

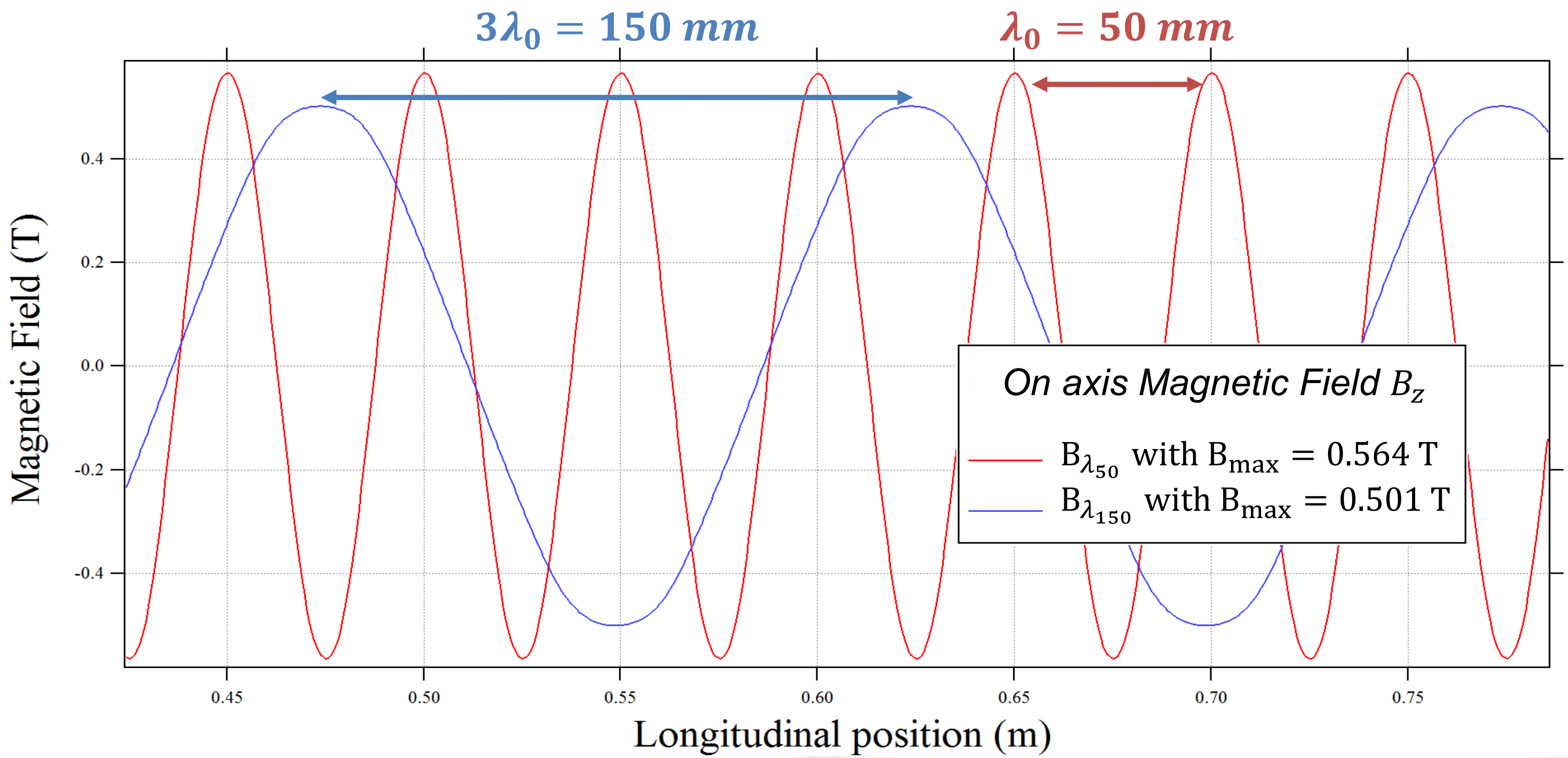


150 mm period magnets

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
Gap	▪ SOLEIL II: 14 mm ▪ Present facility SOLEIL I: 15.5 mm ▪ Other gaps studied: 17 mm et 20 mm

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

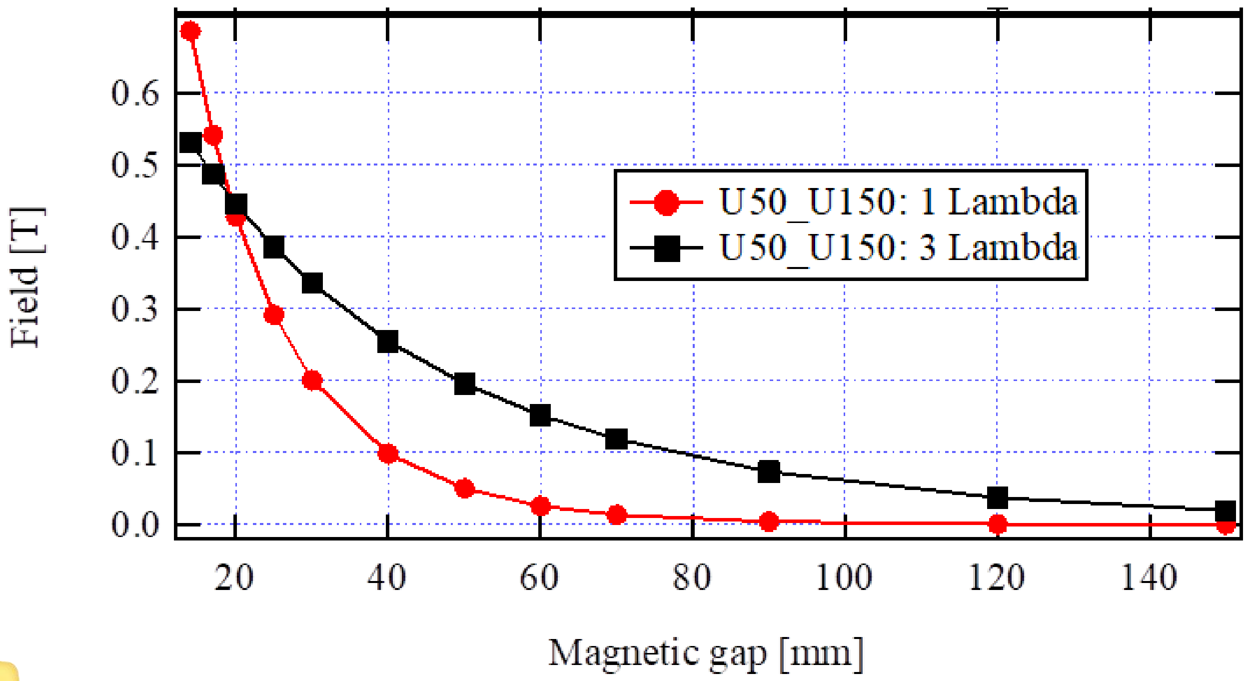
Magnetic field B_z on axis for two operating modes at gap 15.5 mm



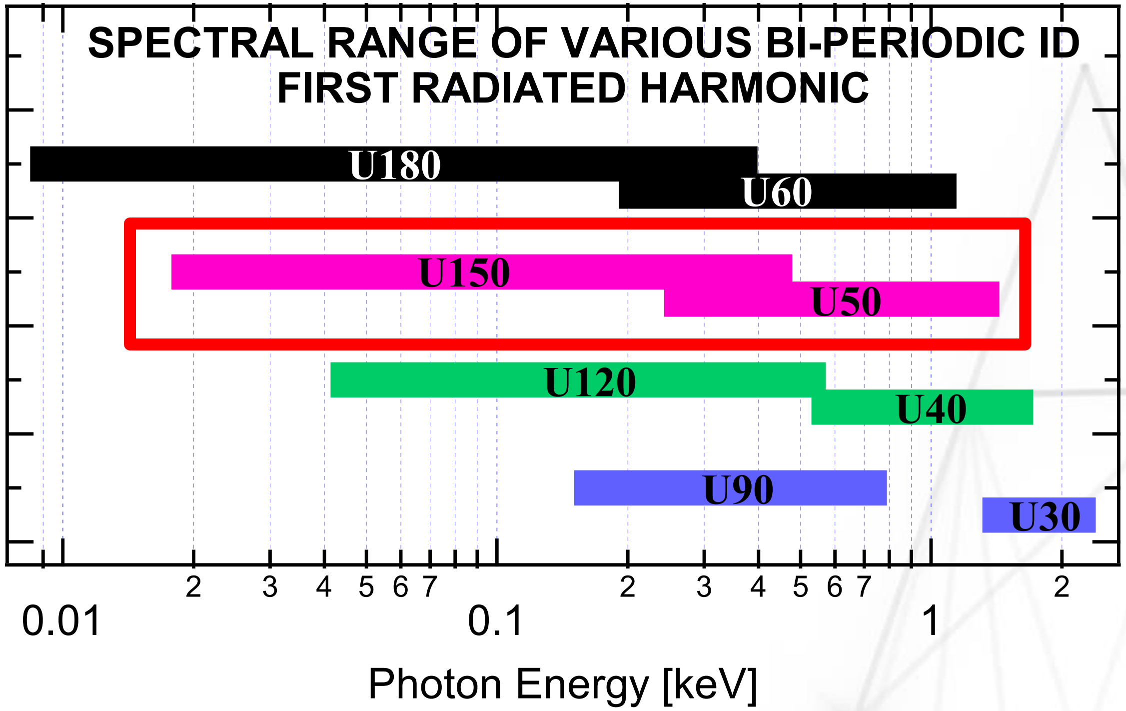
→ *On axis: can select one or the other period only*

Magnetic study

Magnetic field B_z as a function of gap:



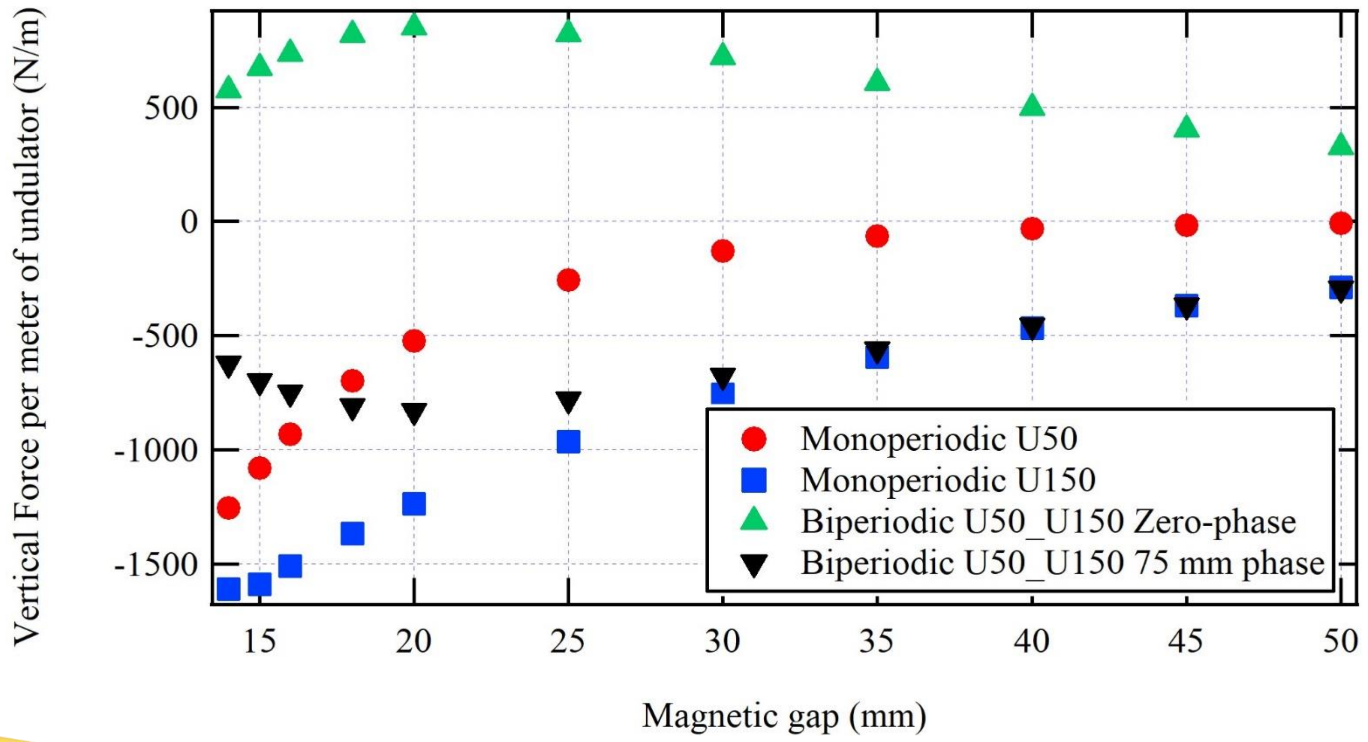
Spectral range (first radiated harmonic):

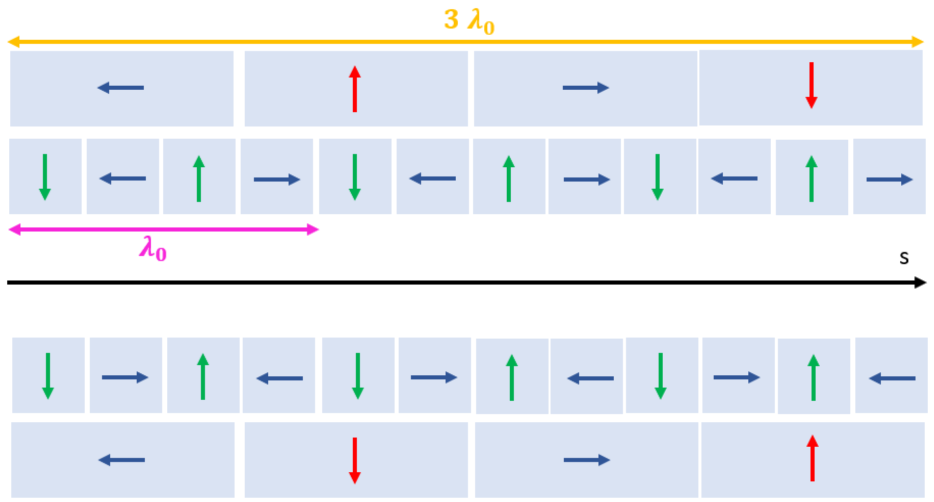


(Extented the concept to other periods)

Compensation of magnetic vertical forces

Vertical force as a function of gap:

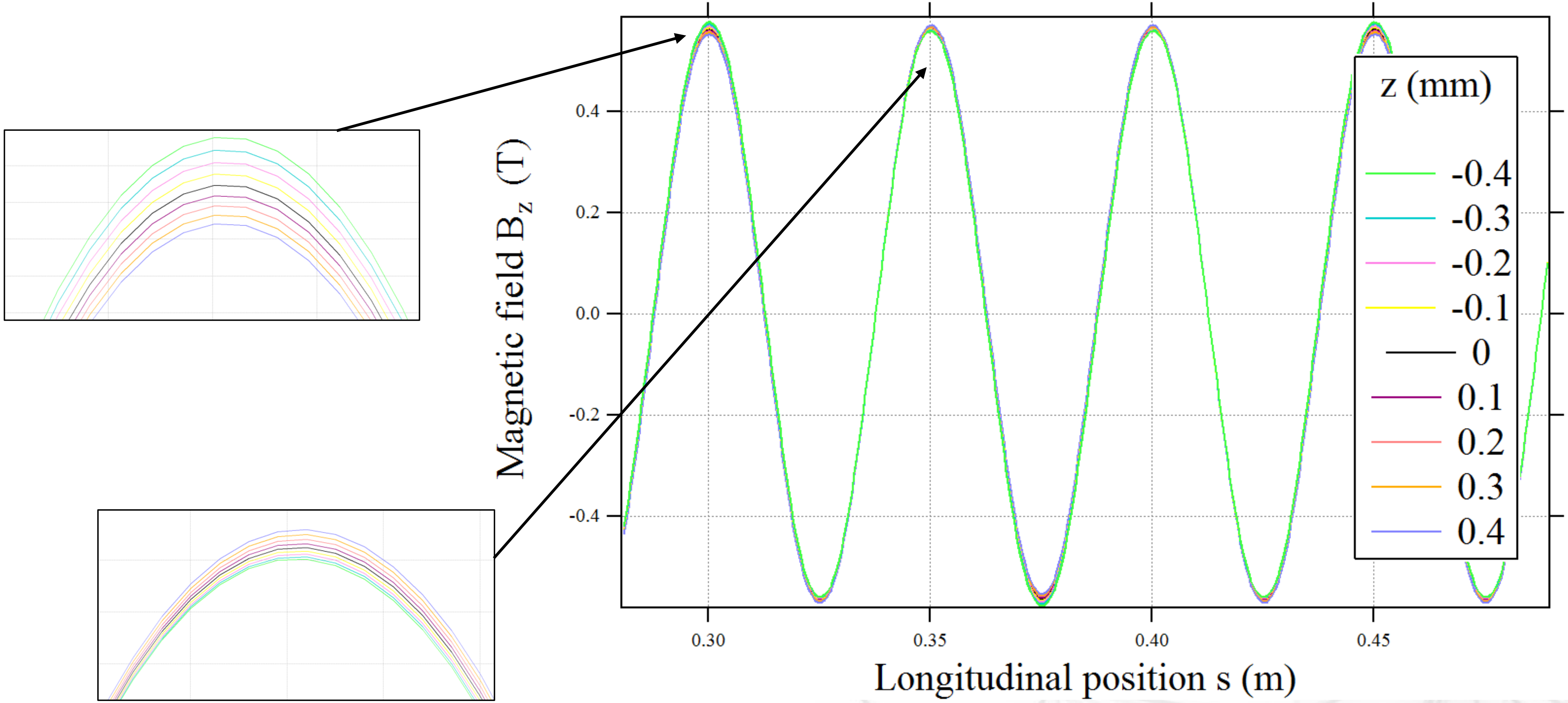




For small gaps corresponding to operating gaps
Bi-Periodic: 2 times less forces than monoperiodic
→ **Special arrangement of magnets permits a natural partial compensation of the magnetic forces**

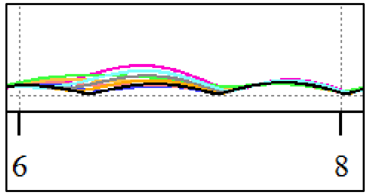
Evolution of the off-axis magnetic field

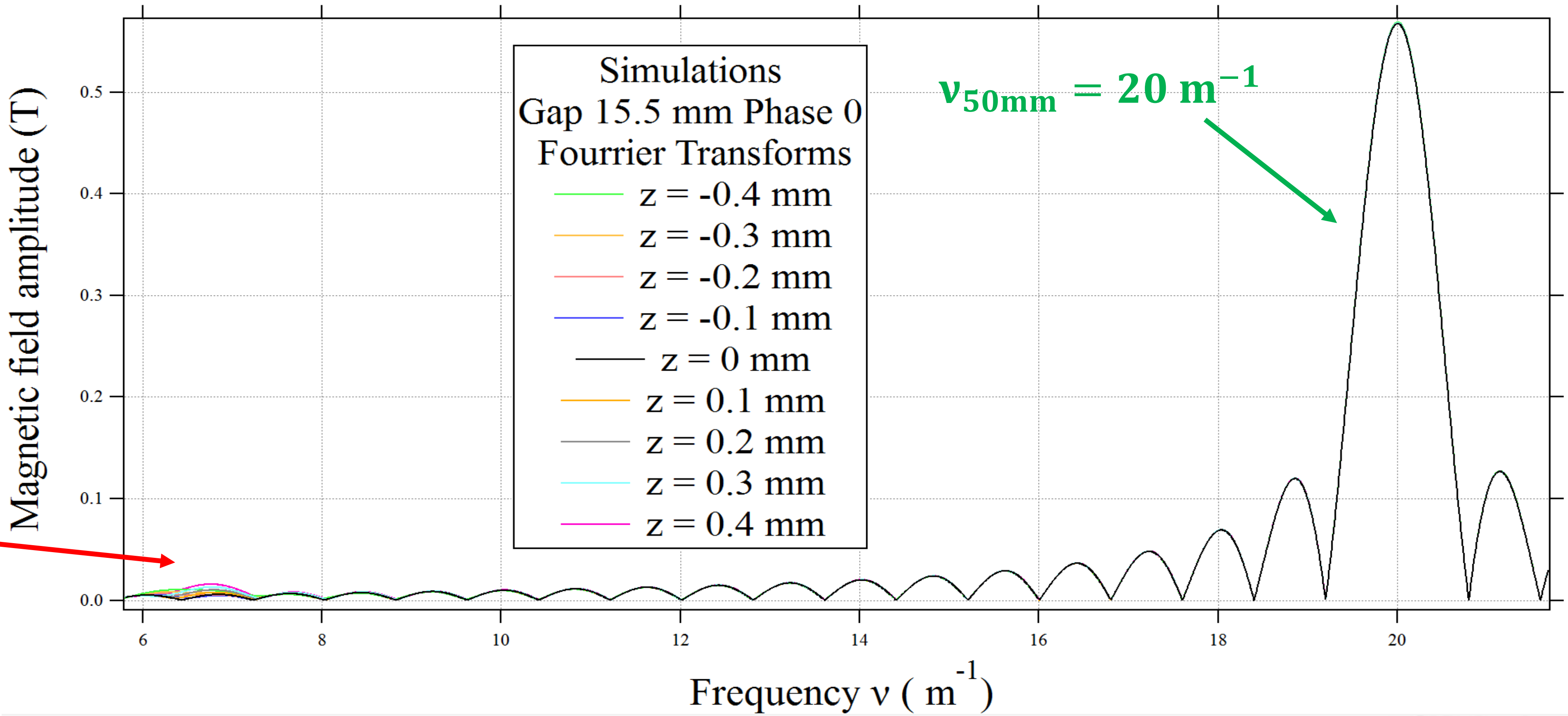
Impact on vertical magnetic field B_z when varying vertical position z at gap 15.5 mm for 50 mm mode



Frequency harmonic content of magnetic field B_z

Harmonic field content versus vertical position z for 50 mm mode

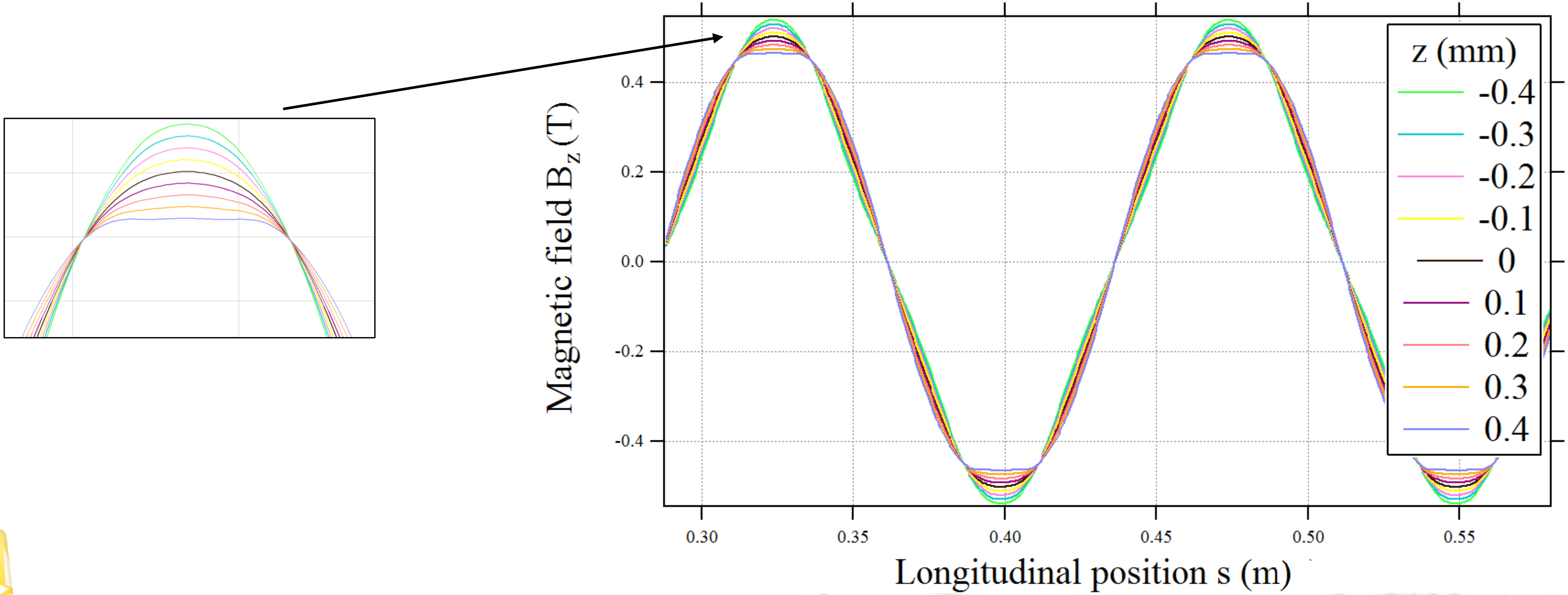




→ *Varying z would induce the appearance of 150 mm period initially absent in this mode*

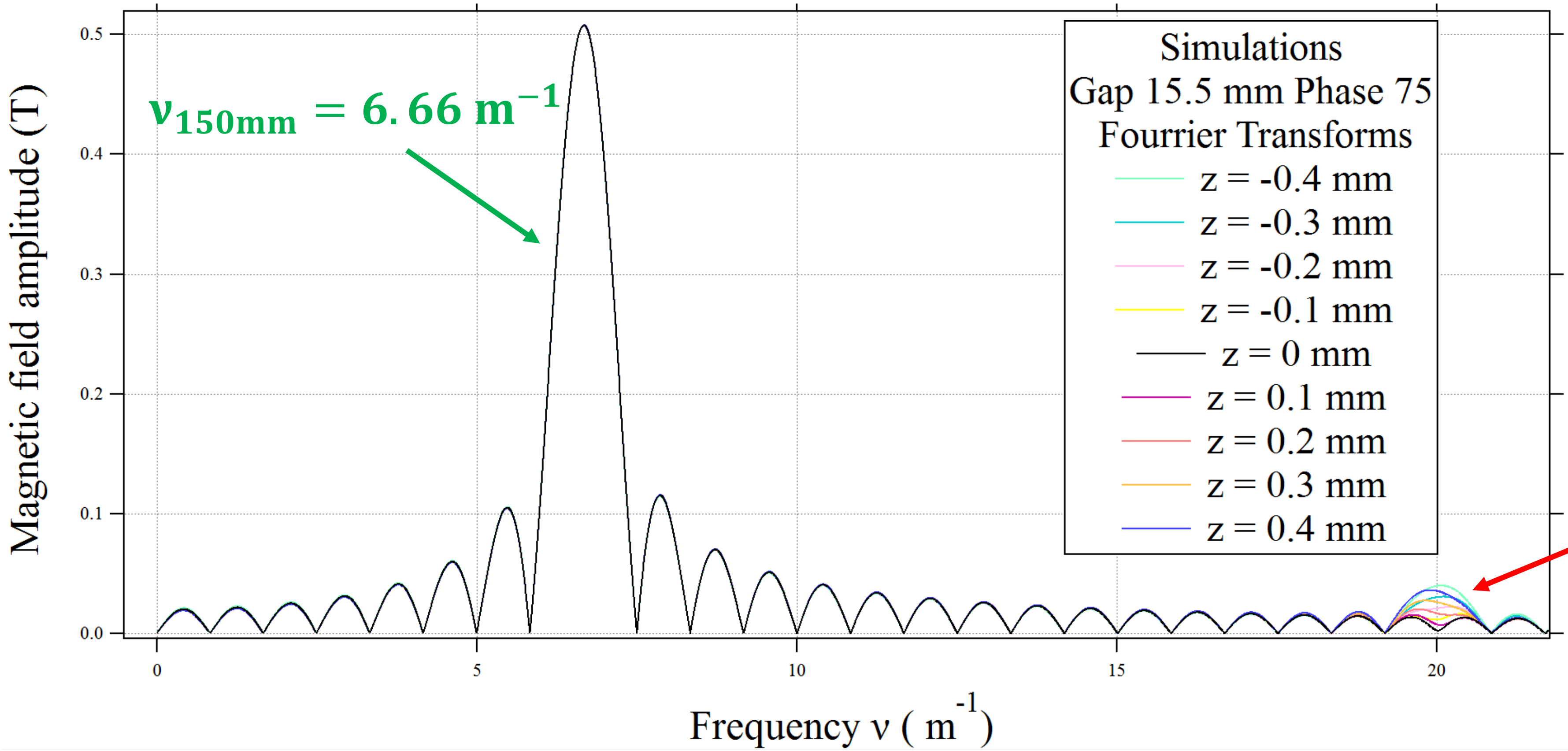
Evolution of the off-axis magnetic field

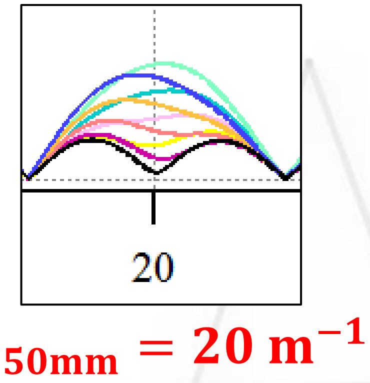
Impact on vertical magnetic field B_z when varying vertical position z at gap 15.5 mm for 150 mm mode



Frequency harmonic content of B_z magnetic field

Harmonic field content versus vertical position z for 150 mm mode





→ *Varying z would induce the appearance of 50 mm period initially absent in this mode*

Off-axis magnetic field and harmonic composition

A variation of z position could induce the appearance of the frequency related to the non-selected period of the mode.

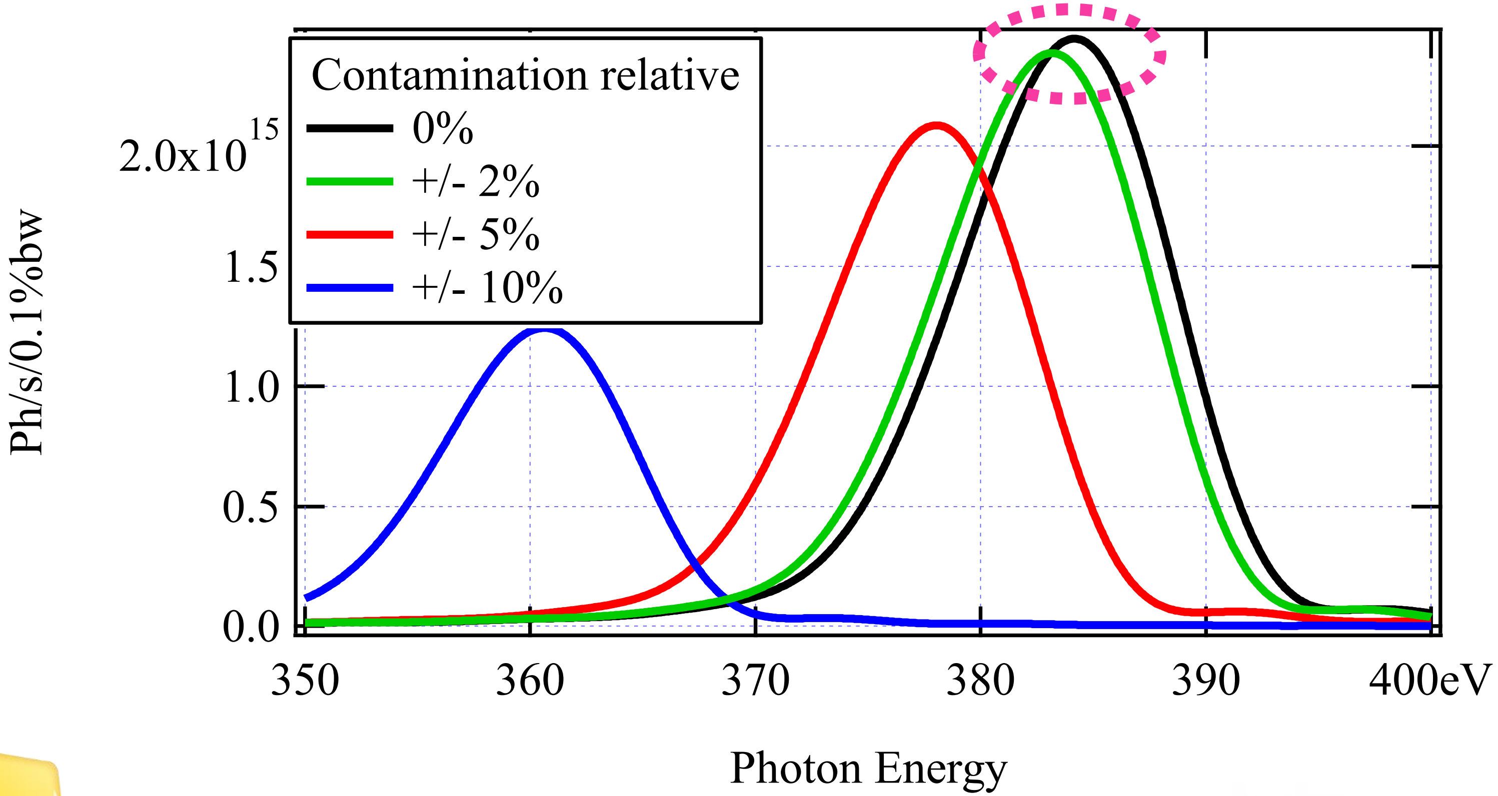
→ Harmonic content could have an impact on the synchrotron radiation.

Study variation of vertical position for $z = +/- 300\ \mu m$ *
corresponding to Security Interlock
(a higher variation of the position cuts the beam)

**Vertical alignment during installation on storage ring is better than* $\pm 100\ \mu m$

On-axis and off-axis emission spectrum

Example for 50 mm mode at gap 17 mm (SRW* Software)



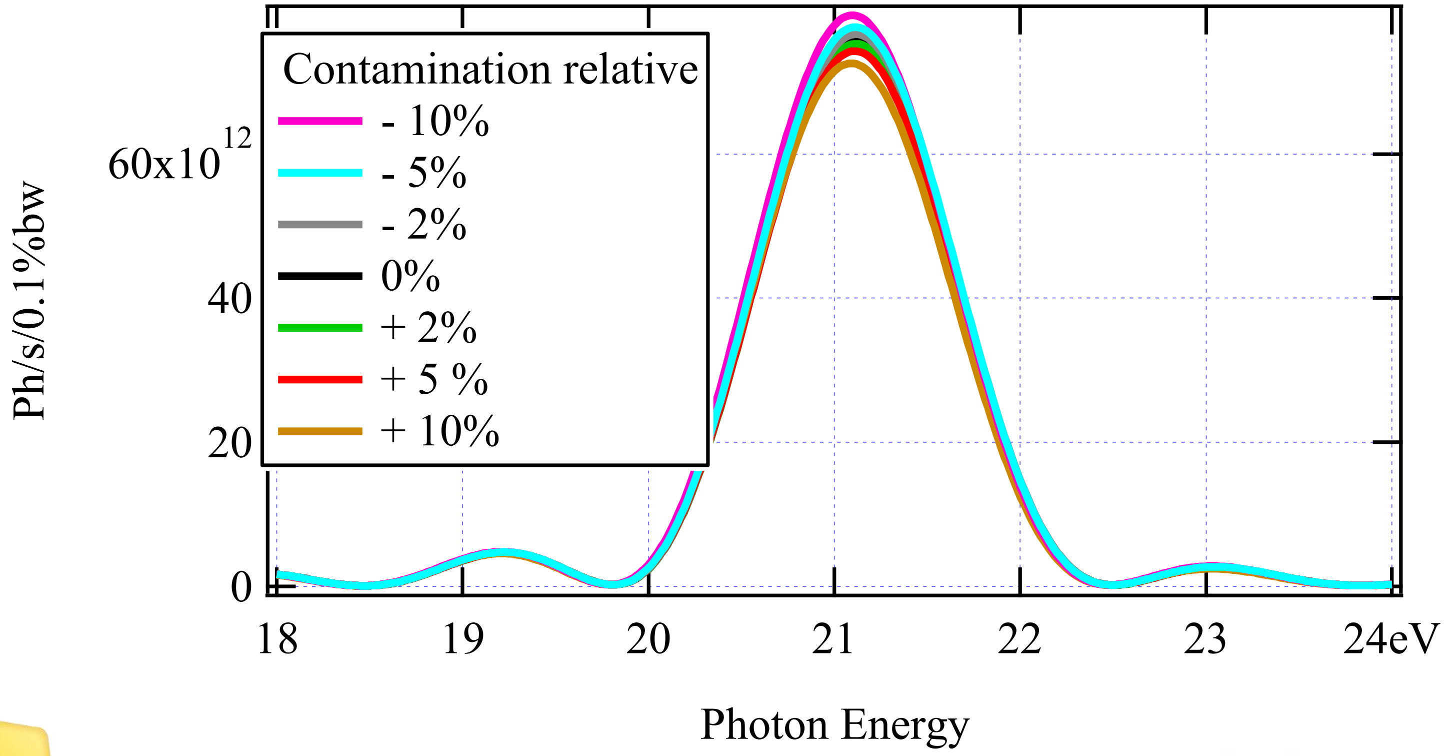
Vertical position z (mm)	Contamination (%)	Flux ratio
- 0.3	-0.8	**0.98**
+ 0.3	0.9	**0.98**

Modification of the magnetic peak magnitude
Shift from higher energy to lower energy

* *O. Chubar, P. Elleaume, “Accurate And Efficient Computation of Synchrotron Radiation In The Near Field Region”, Proceedings of the EPAC Conference, Stockholm, 1998, pp.1177-1179.*

On-axis and off-axis emission spectrum

Example for 150 mm mode at gap 17 mm (SRW Software)



Vertical position z (mm)	Contamination (%)	Flux ratio
- 0.3	5.5	**0.94**
+ 0.3	-4.9	**0.95**

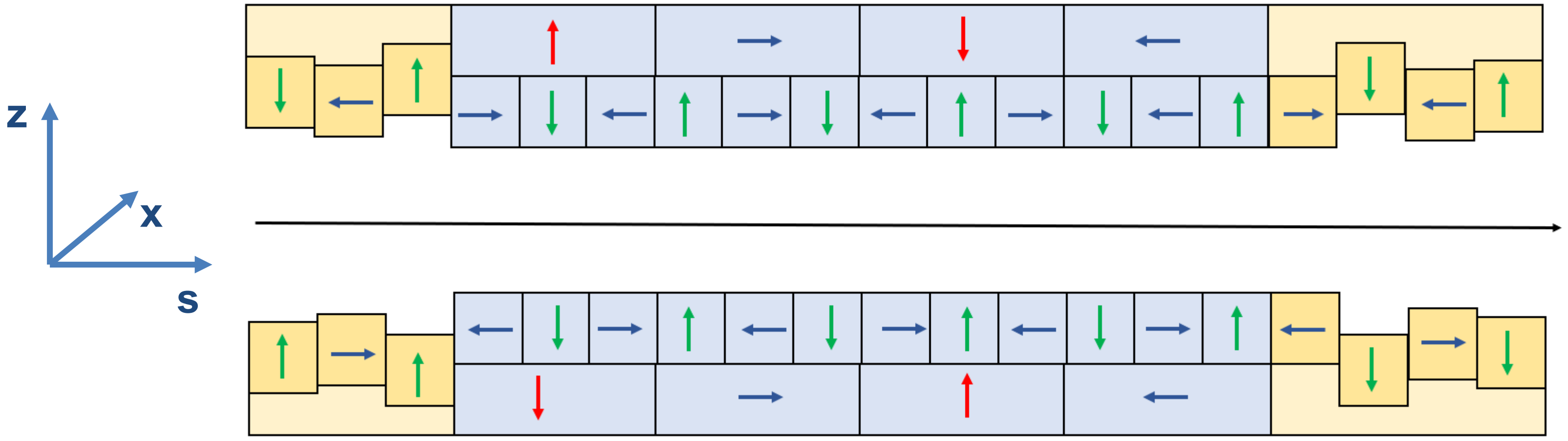
Modification of the magnetic peak magnitude

→ *Alignment is a critical point for this undulator*
→ *Harmonic composition has an impact on the synchrotron radiation*

First order effect: Field terminaison

- Termination elements: to reduce vertical and horizontal field integrals
- Trajectory of the electrons passing through the undulator
- Constraint of using the same geometry magnets: delivery delay reason

Special configuration at the entrance and the exit to correct 50 mm mode



After correcting the perfect 1.5 m undulator on axis at gap 15.5 mm:

$$\Delta x\,, \Delta z\ < 1\ \mu m$$

$$\Delta x', \Delta z' \approx\ \pm 0.019\ G.m$$

Tolerances:
$\pm 0.2\ G.m$
$\pm 10.9\ \mu m$

Second mode will be corrected by correctors of the storage ring orbit correction system

Second order effect: Beam dynamics for SOLEIL I

Modelisation of undulator with angle kick maps*:

impact of magnetic field on electron angles steps by steps along undulator

$$\Delta x'(x,z) = -\frac{1}{2n}\left(\frac{e}{\gamma mc}\right)^2 \frac{\partial}{\partial x}\Phi(x,z) \qquad \Delta z'(x,z) = -\frac{1}{2n}\left(\frac{e}{\gamma mc}\right)^2 \frac{\partial}{\partial z}\Phi(x,z)$$

$$\text{with} \quad \Phi(x,z) = \int_0^L \left(\left(\int_0^s B_x(x,z,s')ds' \right)^2 + \left(\int_0^s B_z(x,z,s')ds' \right)^2 \right) ds$$

Tune variation: focusing phenomema

Period (mm)	$\Delta\nu_x$	$\Delta\nu_z$
$\lambda_0 = 50$	-0.0005	0.0020
$3\lambda_0 = 150$	-0.0010	0.0021

No effect on Touschek lifetime (TRACY3**)

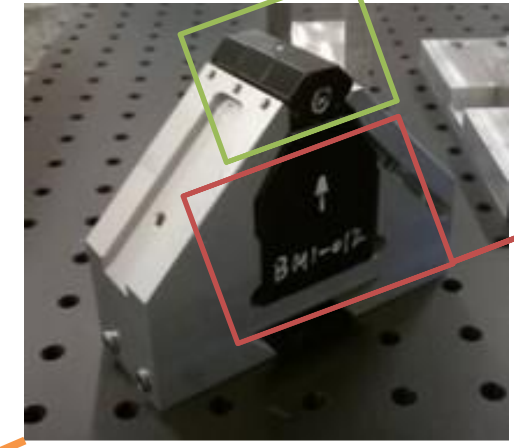
→ Perfect undulator induces no degradation of the beam dynamics

** P. Elleaume, "A New Approach to Electron Beam Dynamics in Undulators and Wigglers," Proceeding of EPAC 1992, Berlin, Germany, pp. 661-663*
*** A 6D true symplectic tracking code, SOLEIL version*

4/ Bi-periodic undulator prototype construction

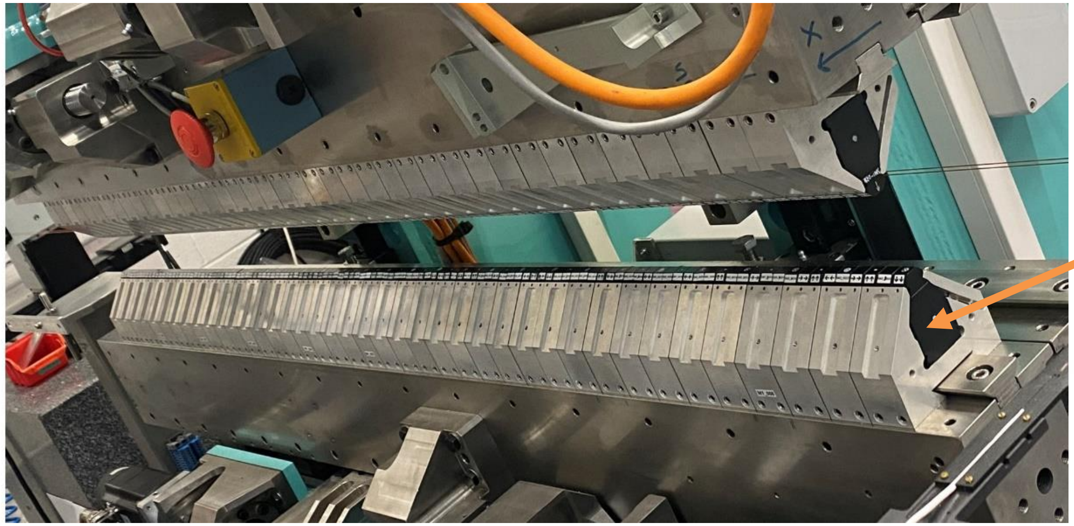
Characteristics of prototype

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

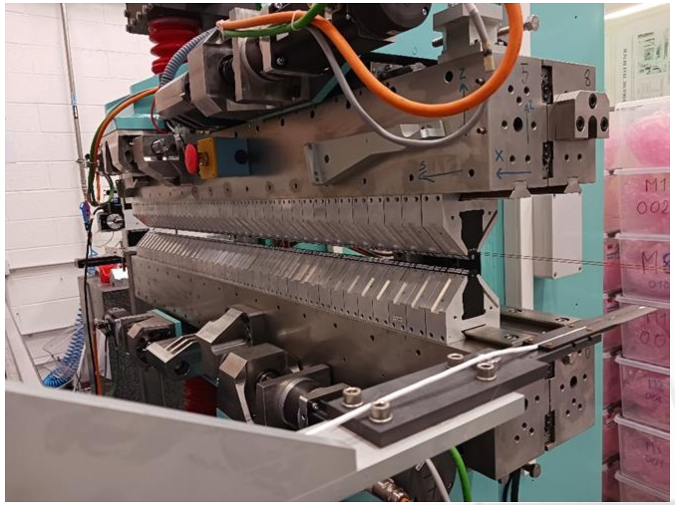


3 magnets
(50 mm period)

1 magnet
(150 mm period)



- Instrumentation of the measuring bench and calibration:



Hall probe: Senis probe (C type)

Offset voltage	$Hs = -0.0036\,V$ $Hx = -0.0225\,V$ $Hz = +0.0025\,V$
Orthogonality	Angles $< +/- 1°$
Sensibility	$Ss = 3.3015$ $Serr = 0.045\%$ $Sz = 3.2979$ $Serr = -0.064\%$ $Sx = 3.3040$ $Serr = 0.121\%$
Sensitive element	$100 * 100\ \mu m^2$

Flipping coils:

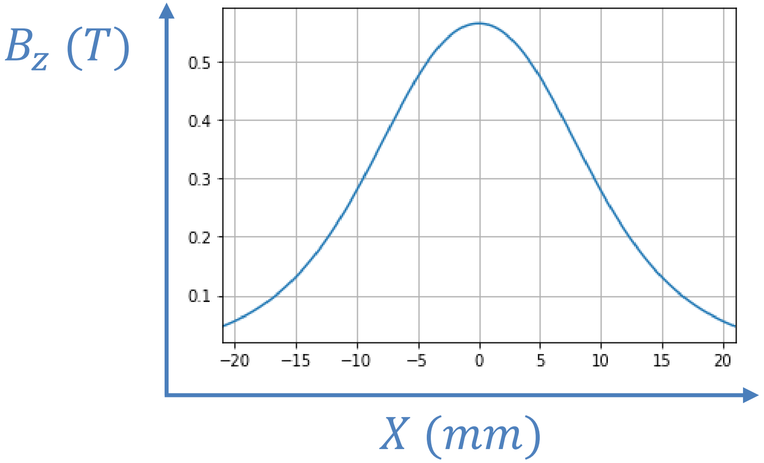
Material	20 insulated copper wires
Diameter	100 µm
Length	3.5 m

Alignment of magnetic axis: critical point

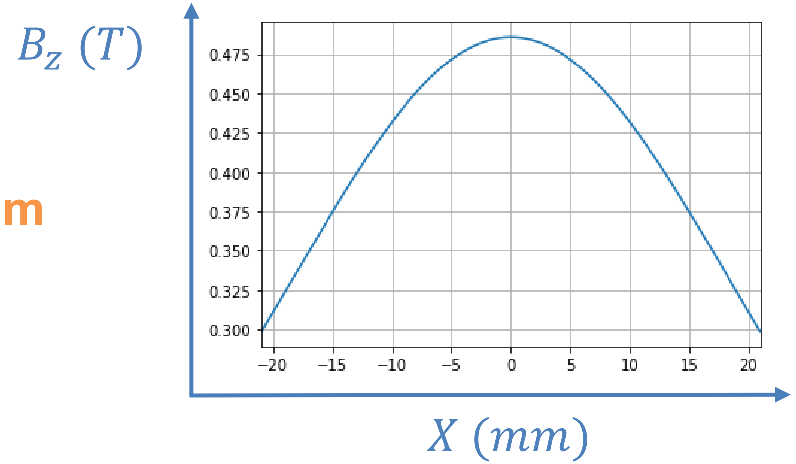
- Usual methods (evolution of the off-axis magnetic fields)

$B_s = 0$ on the magnetic axis

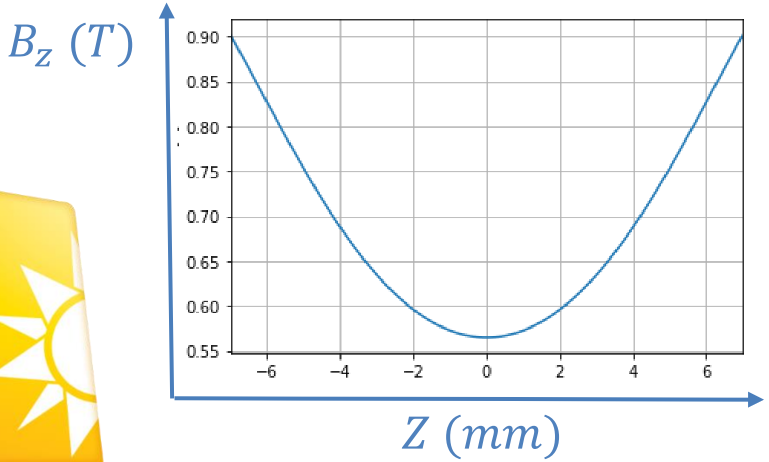
Mono-periodic vertical magnetic field (50 mm period)

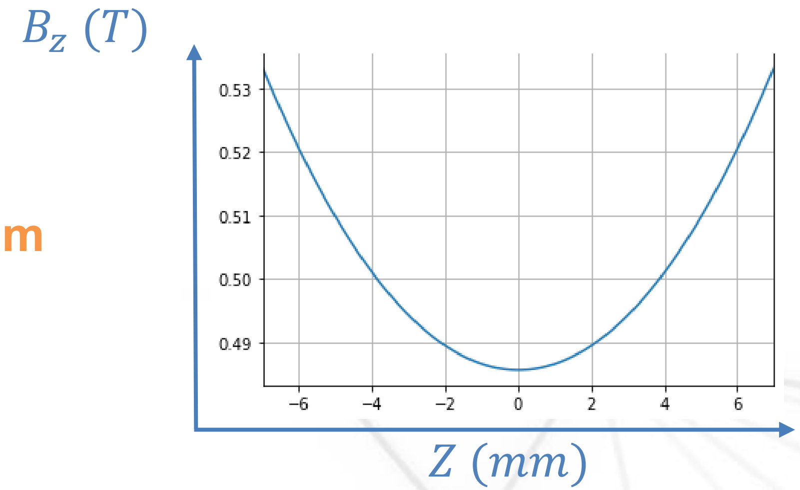


Mono-periodic vertical magnetic field (150 mm period)



Maximum $B_z(x)$

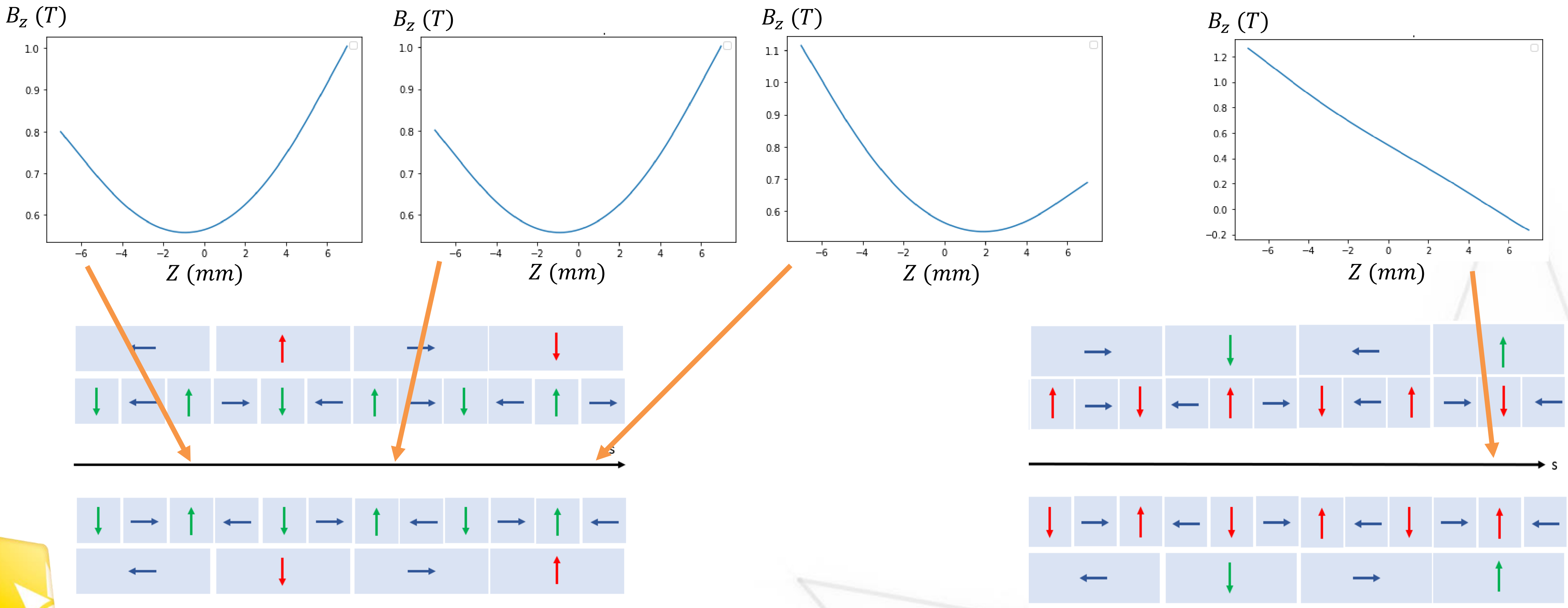




Minimum $B_z(z)$

Alignment of magnetic axis: critical point

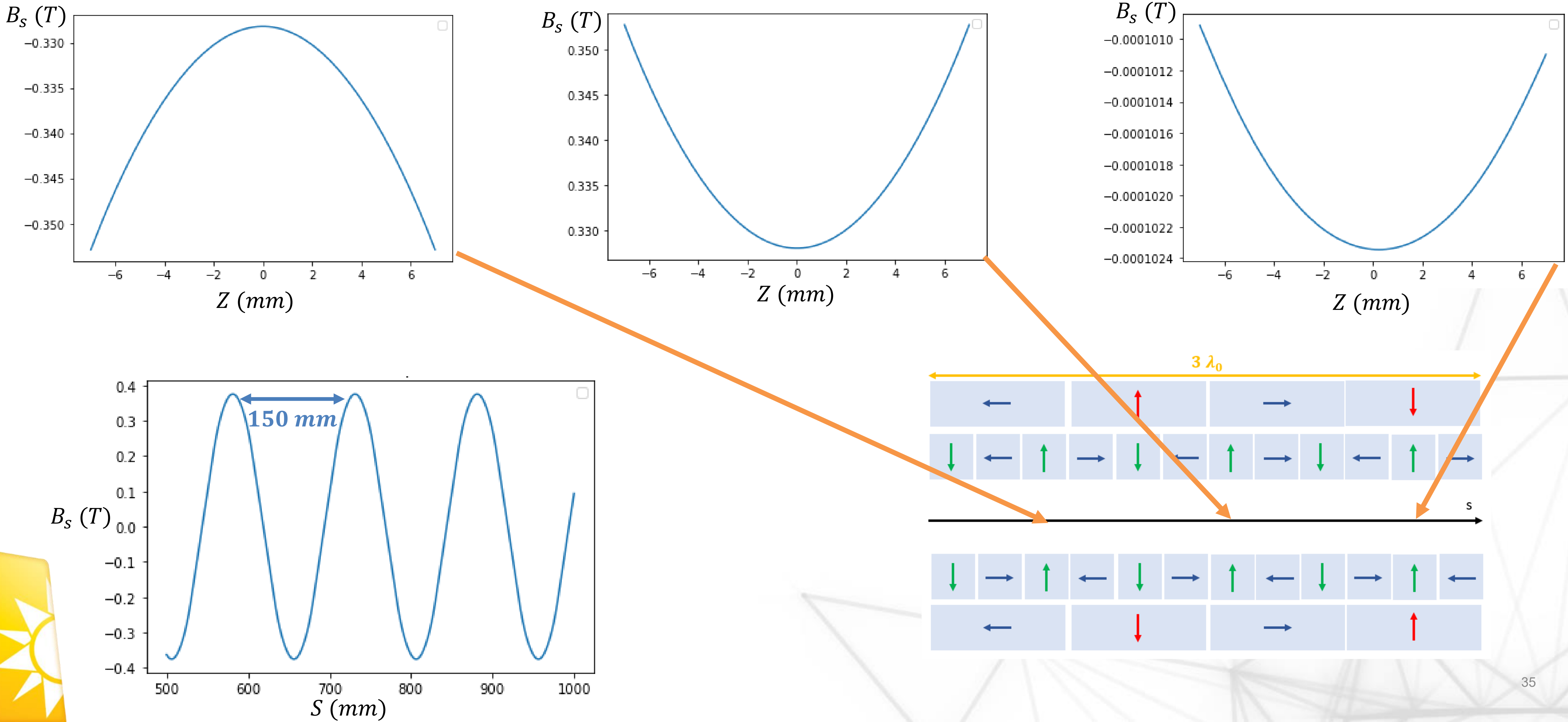
Bi-periodic magnetic field B_z along z axis (50 mm mode) **(150 mm mode)**



→ *Bi periodic magnetic field doesn't have a classic behavior*

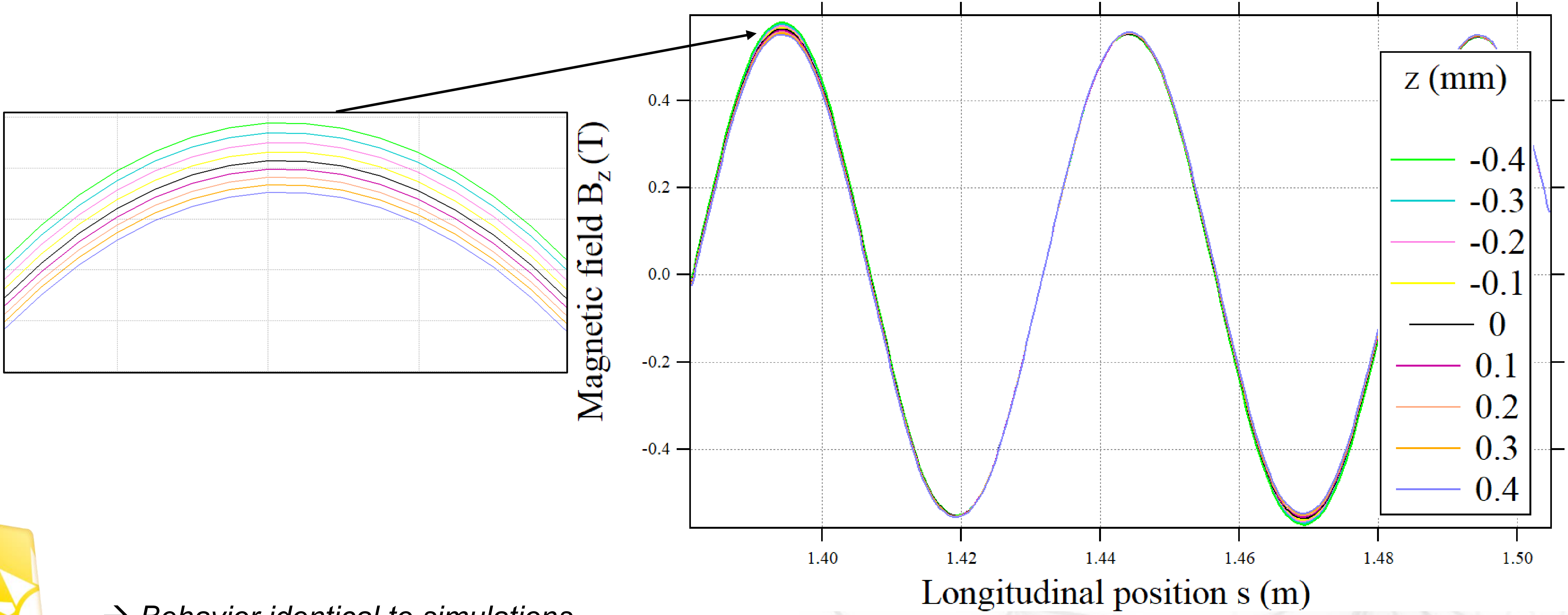
Alignment of magnetic axis: critical point

Bi-periodic magnetic field B_s along z axis (50 mm mode)



Preliminary magnetic measurements

Impact of z position variation for 50 mm mode at gap 15.5 mm:

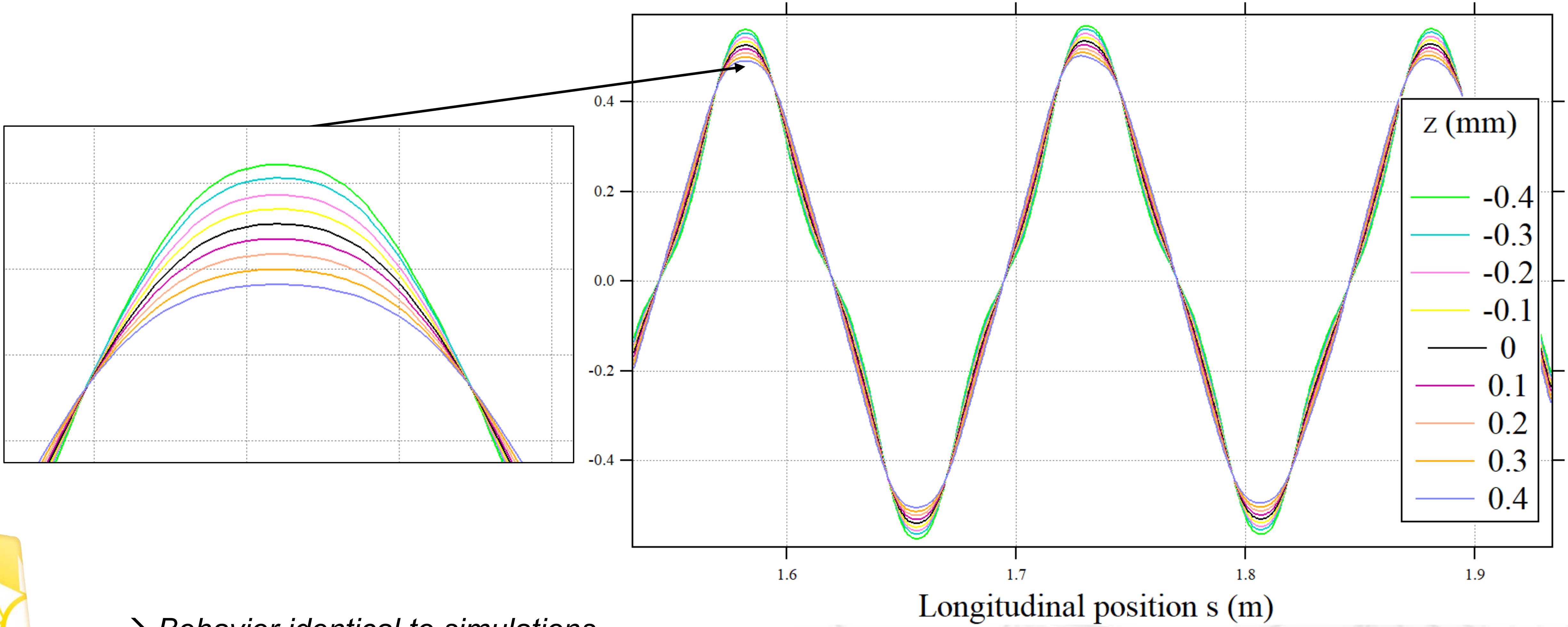


→ *Behavior identical to simulations*

→ *Difference of less 2.44% with simulations*

Preliminary magnetic measurements

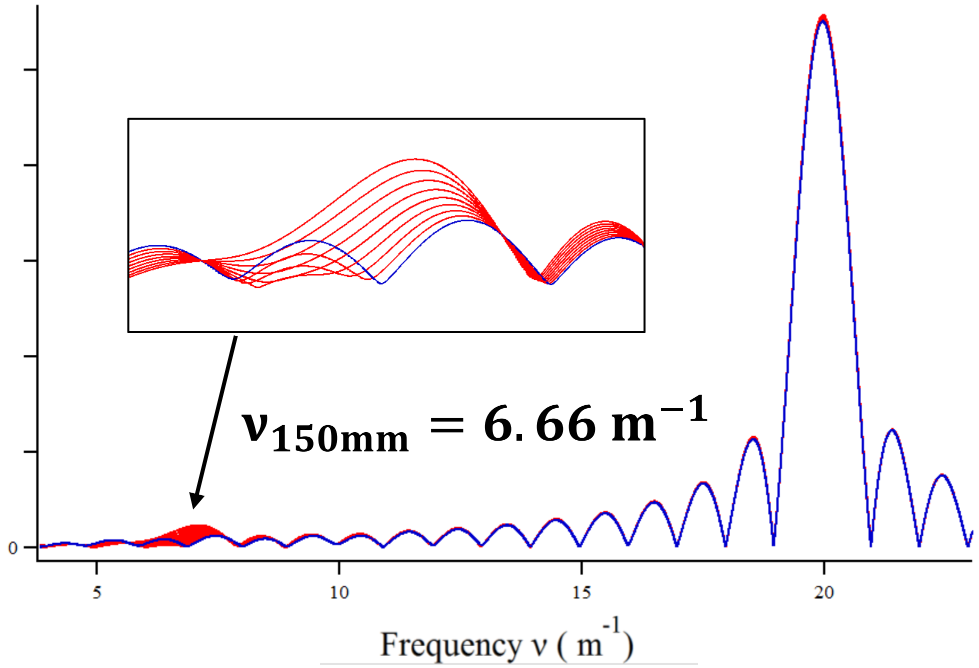
Impact of z position variation for 150 mm mode at gap 15.5 mm:



→ *Behavior identical to simulations*
→ *Difference of 2.58% with simulations*

Determination of z_0

Harmonic field content versus vertical position for 50 mm mode at gap 15.5 mm:

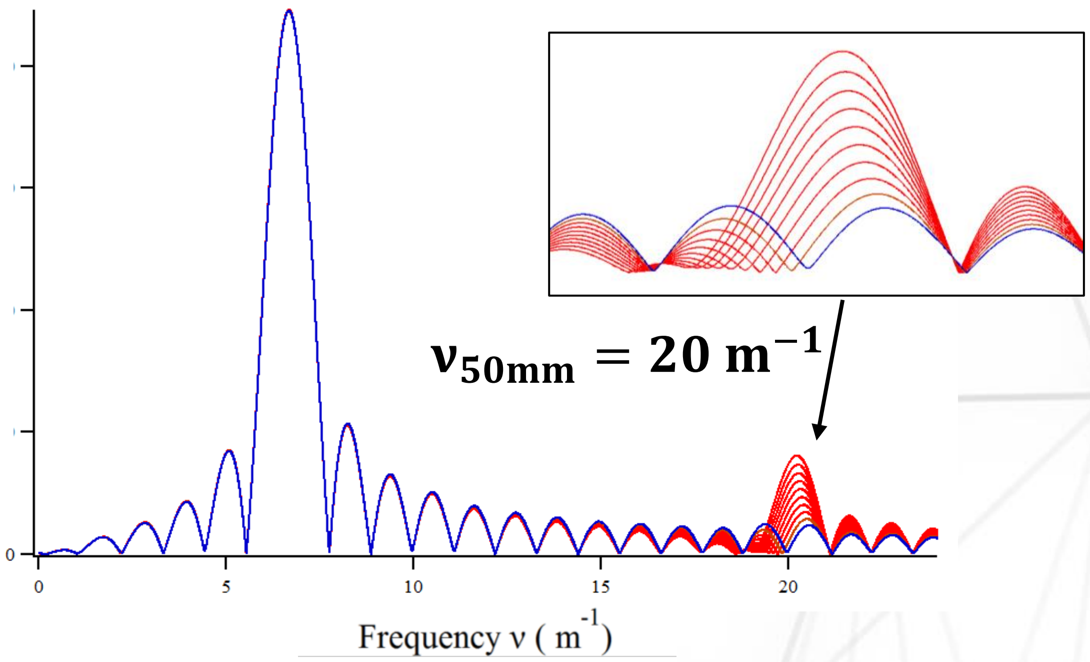


Blue curve:

$\Delta z = 400\ \mu m$

Offset relative to z reference position of hall probe

Harmonic field content versus vertical position for 150 mm mode at gap 15.5 mm:



Cancellation of the unselected period correspond to magnetic axis z_0

Preliminary magnetic measurements

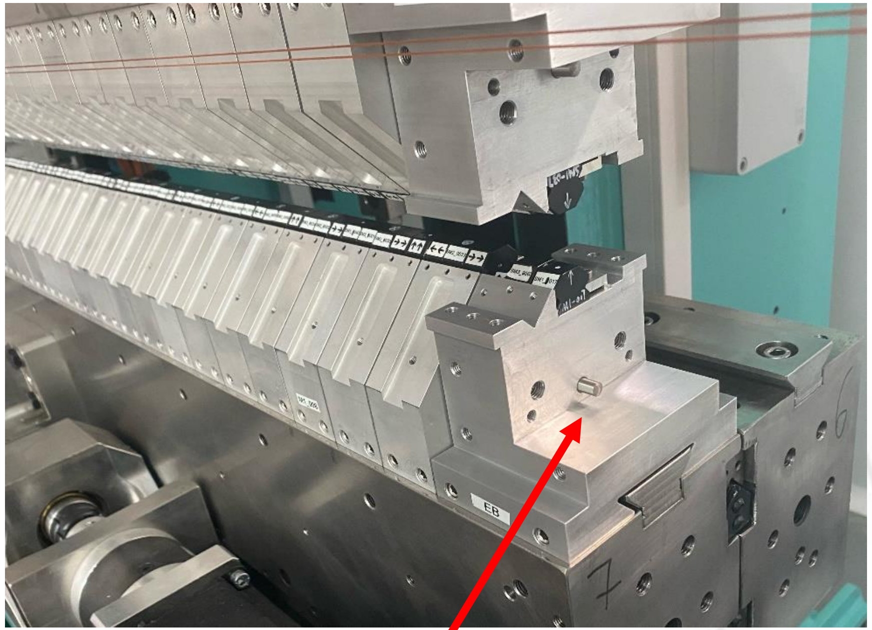
- Magnetic measurement behavior is in accordance with simulations
- Simulation fields are higher than the measured fields by less than 3%

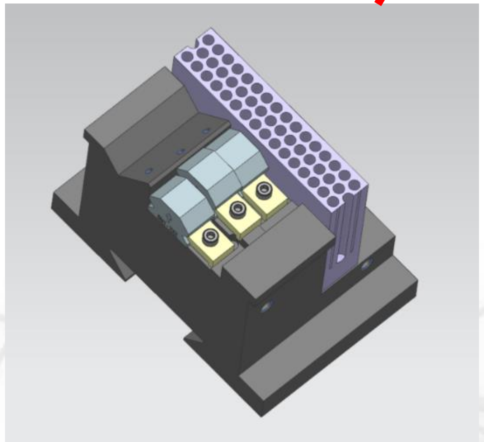
- Comparaison between behavior of simulations and measurements to define magnetic axis of this system (cancellation of unselected period)

→ Magnetic measurements are underway to determine if magnetic axis remains constant versus gaps and modes of operation

Prototype field terminaison

- Before to install prototype on storage ring
- Support design of field terminaison modules
- An additionnal correction using magic fingers
- Measurements with terminaisons are still in progress



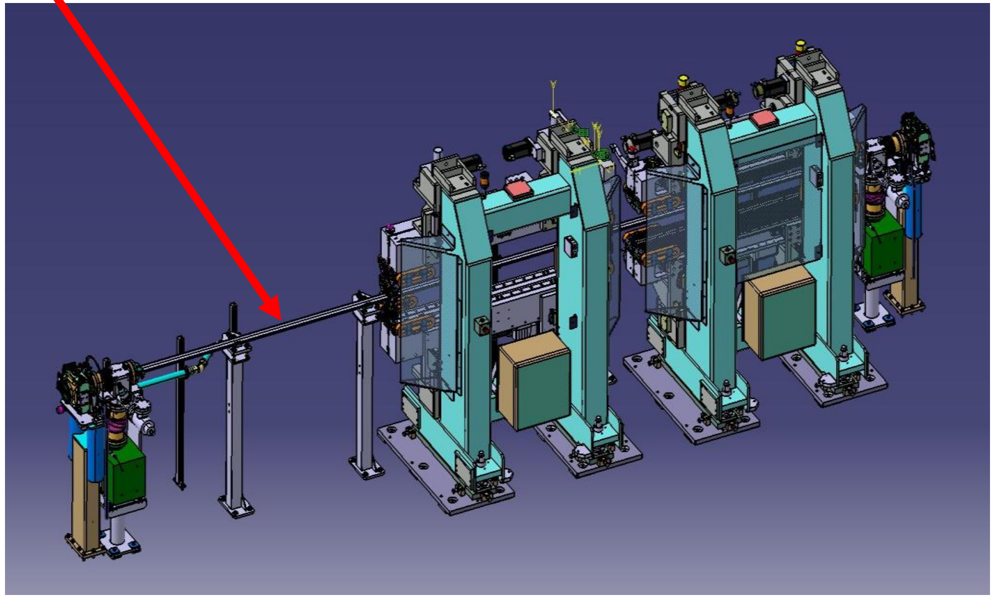


Installation on present storage ring

HERMES beamline:

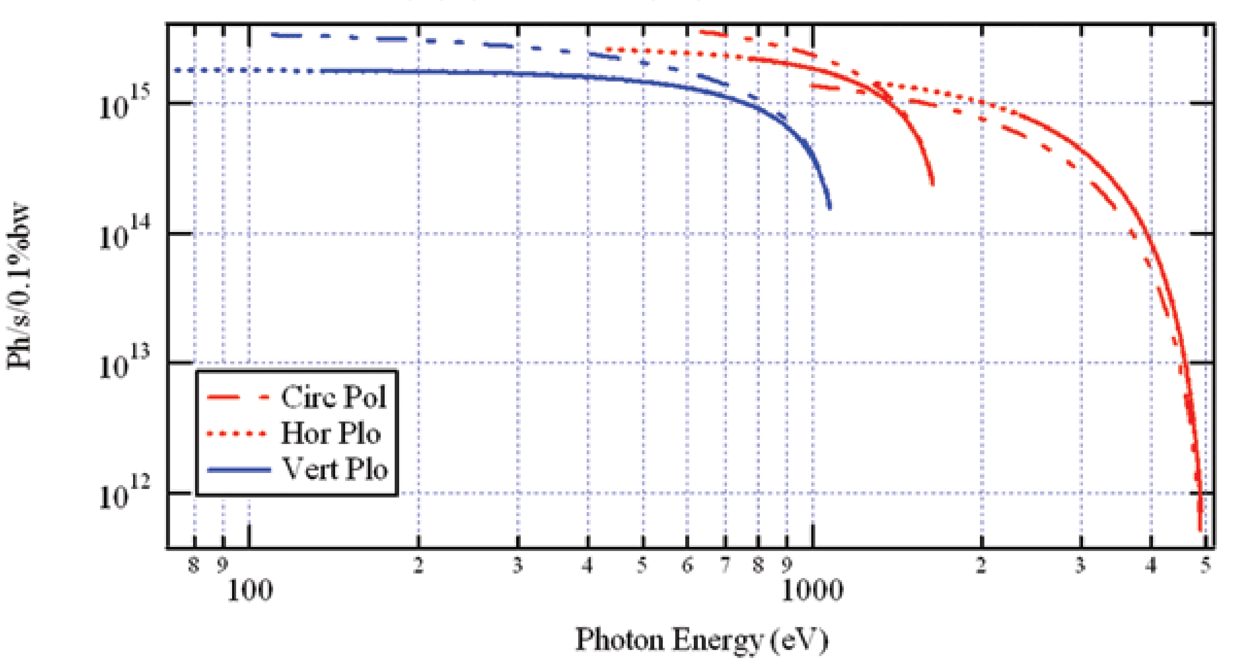
Undulators (technology)	Energy range (eV)	Length (m)	Numbers of period
HU64 (APPLE II)	70-600	1.7	25
HU42 (APPLE II)	500-2500	1.8	42
U50-U150 (BiPer)	18-1500	1.5	10 - 30

Bi-Periodic prototype



HERMES beamline
(DENNETIERE David, BELKHOU Rachid, optic SOLEIL group)

Calculated flux for HU64 (blue) and HU42 (red) undulators



Planning

Experimental study is planned in collaboration with accelerator staff and the HERMES beamline:

December 2023

Prototype installation on storage ring SOLEIL I

March 2024

Start of beam dynamics study (use during machine shift)

May 2024

Start of synchrotron radiation study on the beamline (possible adaptation of the beamline optics)

5/ Conclusion and outlook

Conclusion

- Replace two undulators by one which have the same spectral domain
- Prototype: 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
- Finish the magnetic correction and install prototype on the storage ring
- Study the beam dynamics to validate the use
- Study synchrotron radiation to validate performance of this light source