Operation of phase shifters at ESRF

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INTRODUCTION

ESRF Insertion Devices sources

- **27** IDs beamlines
- All IDs **built in-house**
- Large photon energy range

  $\mathbf{0.3 < energy < 100}$ **keV**

- Large variety of undulators

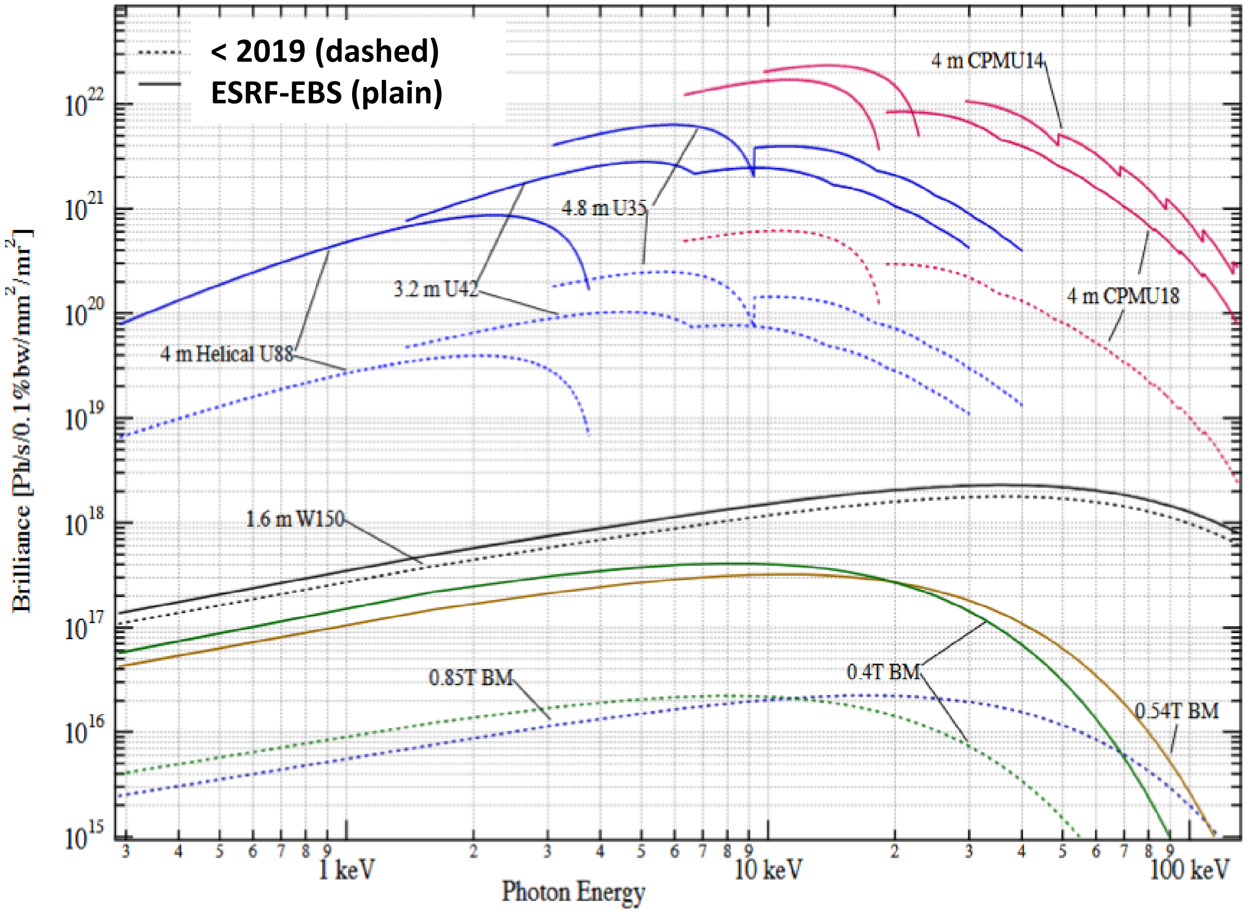
  $\mathbf{13 < period < 70}$ **mm** (today)

Segmented sections

- **5m-long** ID sections
- **Up to 3 segments** $0.8 < \text{length} < 2.3$ m

  Modularity for energy range
  Easier to **manipulate and align**
  Easier magnetic **measurements**
  Easier magnetic **error corrections**

- BUT impacts on **photon flux**



U = undulator
W = wiggler
BM = Bending Magnet

OUTLINE

I. Phasing undulators
   - Radiation phase and energy spectrum
   - Phasing methods

II. Phase shifter device
   - Design
   - Magnetic measurements
   - Control

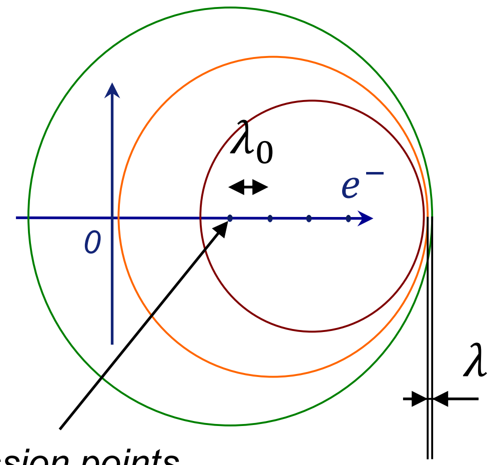
III. Feedback from users
   - ID14 – Nuclear Resonance Beamline
   - ID32 – Soft X-Ray Spectroscopy

Phase delay between two emission points of radiation with **wavelength λ** generated by a **moving charge e^-**

$$\Delta\varphi(L) = \frac{2\pi}{\lambda}\left(\underbrace{\frac{L}{2\gamma^2}}_{\text{Free drift}} + \underbrace{\frac{1}{2}\int_{-\infty}^{L}\theta^2 ds}_{\text{Trajectory deviation}}\right)$$

where θ is the deviation angle

Periodic emission of radiation, period λ_0
No transverse deviation, constant speed β_{rel}:



$$\lambda = \frac{\lambda_0}{\beta_{rel}} - \lambda_0 \simeq \frac{\lambda_0}{2\gamma^2}$$

Emissions are phased at a distance L if

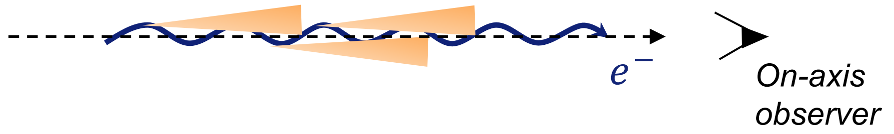
$$\Delta\varphi(L) = 2\pi k$$

ie $L = k\lambda_0 = 2k\gamma^2\lambda$

Emission in a periodic **transverse magnetic field** of deflection parameter $K = 0.00934\, B\lambda_0$

$$\Delta\varphi(L) = 2\pi k \Leftrightarrow k\,\lambda = \frac{L}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

$$\Leftrightarrow \boxed{L = k\,\lambda_0} \;\&\; \boxed{\lambda = \frac{\lambda_0}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)}$$

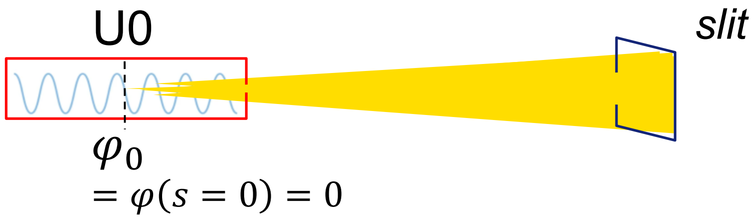


⇒ **Optimized emission phasing guarantees coherent interferences**

→ perfect sinusoidal field
→ matched phasing between segments

I. PHASING UNDULATORS – UNDULATOR SPECTRUM INTERFERENCES

- **Angular spectral flux** of harmonic n generated in an undulator



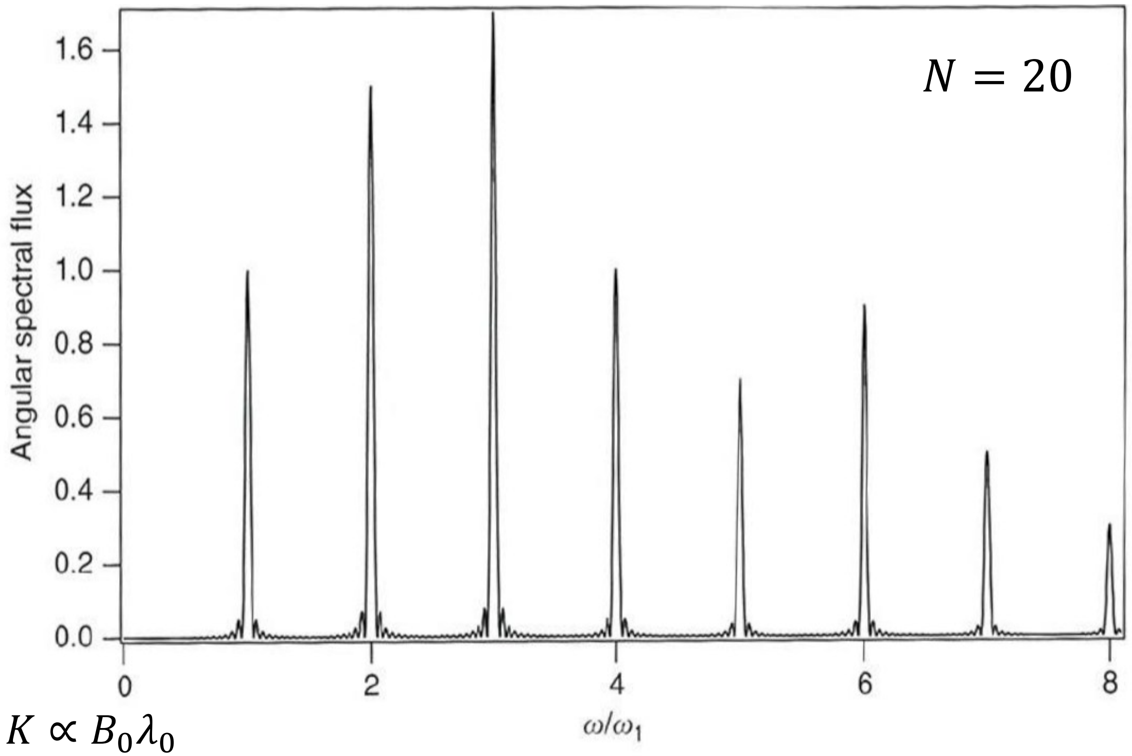
$$\frac{d\Phi_n}{d\theta_x d\theta_z d\omega} \propto N^2 \times |h_n(\theta_x, \theta_z)|^2 \times \left(\frac{\sin(\pi\, n\, N((\omega/\omega_1)-1))}{\pi\, n\, N((\omega/\omega_1)-1)}\right)^2$$

N^2: Number of periods

$|h_n(\theta_x, \theta_z)|^2$: "lobe" function, θ_x, θ_z observation angles

Interference function

ω_1 = Resonance frequency



- **Radiation wavelength**

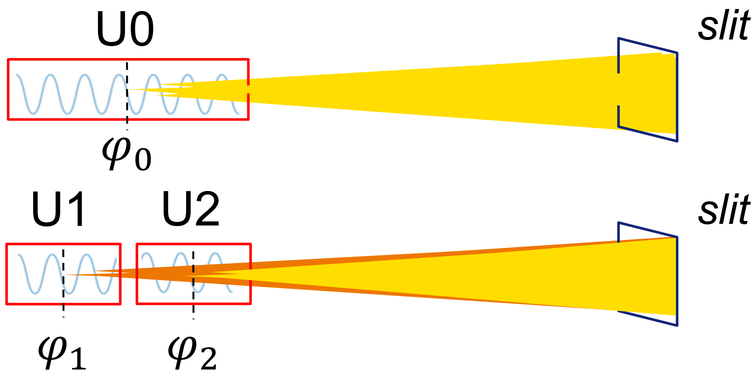
$$\lambda_1 = \frac{2\pi c}{\omega_1} = \frac{1}{2\gamma^2}\lambda_0\left(1 + \frac{1}{2}K^2 + \gamma^2{\theta_x}^2 + \gamma^2{\theta_z}^2\right)$$

λ_0: Undulator period

K: Deflection parameter, $K \propto B_0\lambda_0$
B_0 undulator peak field

I. PHASING UNDULATORS – SPECTRUM THROUGH A SLIT

U1 and U2 are phased if $\frac{d\Phi_n}{d\omega}(U1, U2)_{slit} = \frac{d\Phi_n}{d\omega}(U0)$



- **Case 1: maximum number of photons on sample**

  $\Longrightarrow$ operate off-resonance with large slits

  $\Longrightarrow$ maximize the angle integrated flux

  $$\frac{d\Phi_n}{d\omega} \propto \frac{1}{\gamma^2}\frac{N}{n} \times \left(1 + \frac{K^2}{2}\right) \times |h_n(0,0)|^2$$

  $\Longrightarrow$ **off-axis** radiation dominates

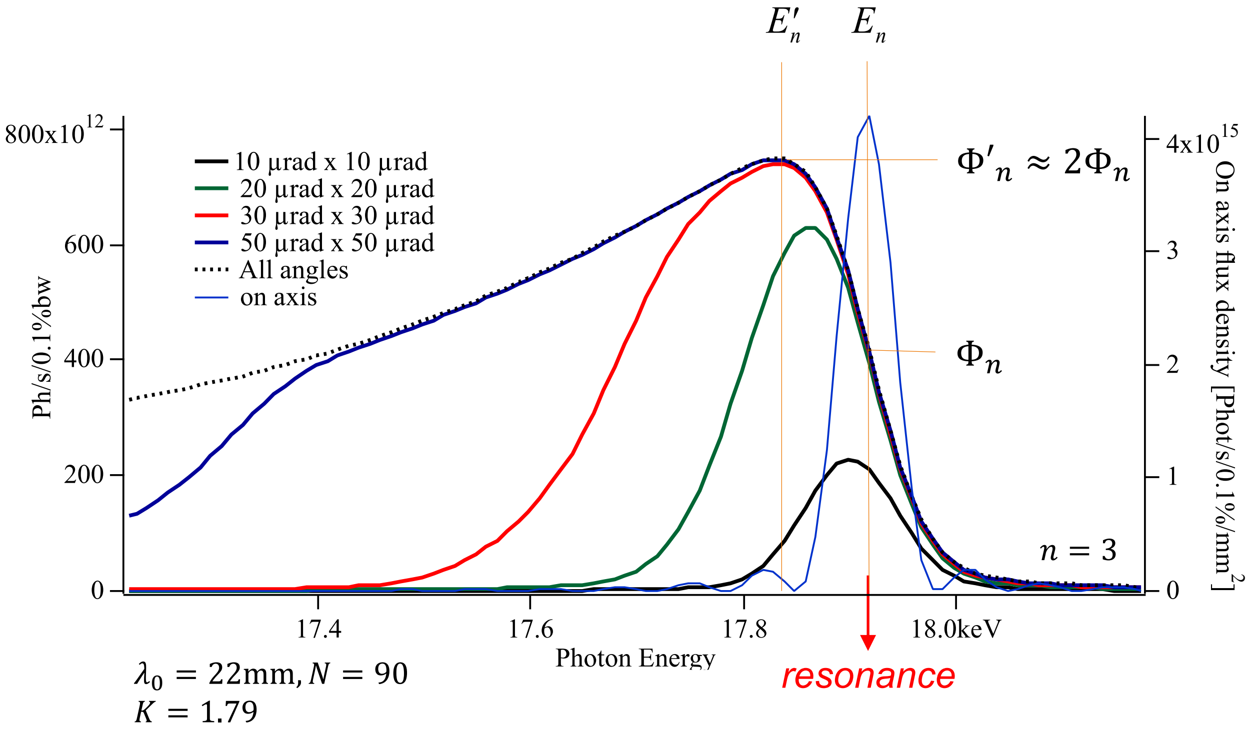
- **Case 2: coherent beams**

  $\Longrightarrow$ operate on resonance with small slits

  $\Longrightarrow$ maximize the on-axis flux density

  $$\left.\frac{d\Phi_n}{d\theta_x d\theta_z d\omega}\right)_{\min} \longrightarrow 0 \quad ; \quad \left.\frac{d\Phi_n}{d\theta_x d\theta_z d\omega}\right)_{\max} \propto N^2$$

  $\Longrightarrow$ **interference** regime, phasing is essential



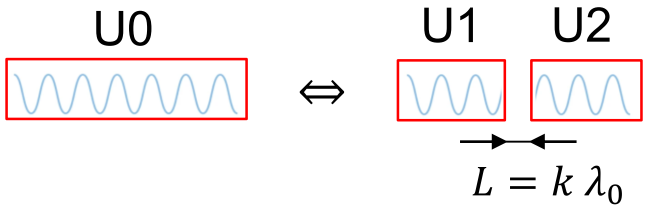
I. PHASING UNDULATORS – METHODS

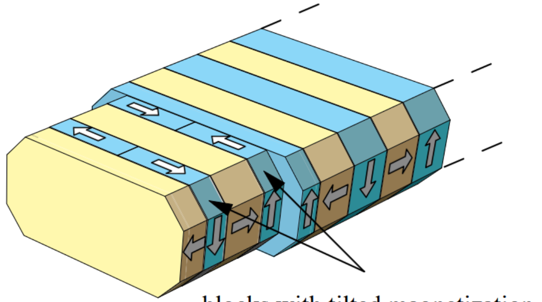
$$\Delta\varphi(L) = \frac{2\pi}{\lambda}\left(\underbrace{\frac{L}{2\gamma^2}}_{\text{Free drift}} + \underbrace{\frac{1}{2}\int_0^L \theta^2 ds}_{\text{Trajectory deviation}}\right)$$

- **Passive phasing** : phase the periodic field by design
  - Adapt the distance between segments with $\frac{1}{2}\int_0^L \theta^2 ds = 0$

    $L = 2k\lambda\gamma^2 = k\,\lambda_0$ → Depends on **available space**
  - Build phasing endings of IDs to satisfy $\Delta\varphi(L) = 2\pi k$

    $L + \gamma^2 \int_0^L \theta^2 ds = k\,\lambda_0$
    → Only valid for **same ID periods**
    → Valid for **one working point**
    → Not possible with **in-vacuum IDs**

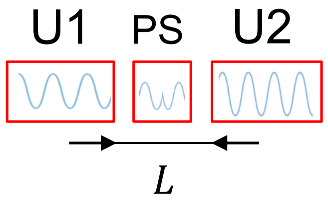




- **Active phasing** : phase the radiation, not the undulators

  Tune the electron trajectory introducing a **tunable phase shifter** device (PS)

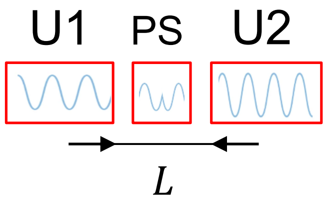
  $\gamma^2 \int_0^L \theta^2 ds = 2k\lambda\gamma^2 - L$
  → Valid for **any working point**
  → Valid for **any devices** U1(K_1, λ_1), U2 (K_2, λ_2)



I. PHASING UNDULATORS – ACTIVE PHASING

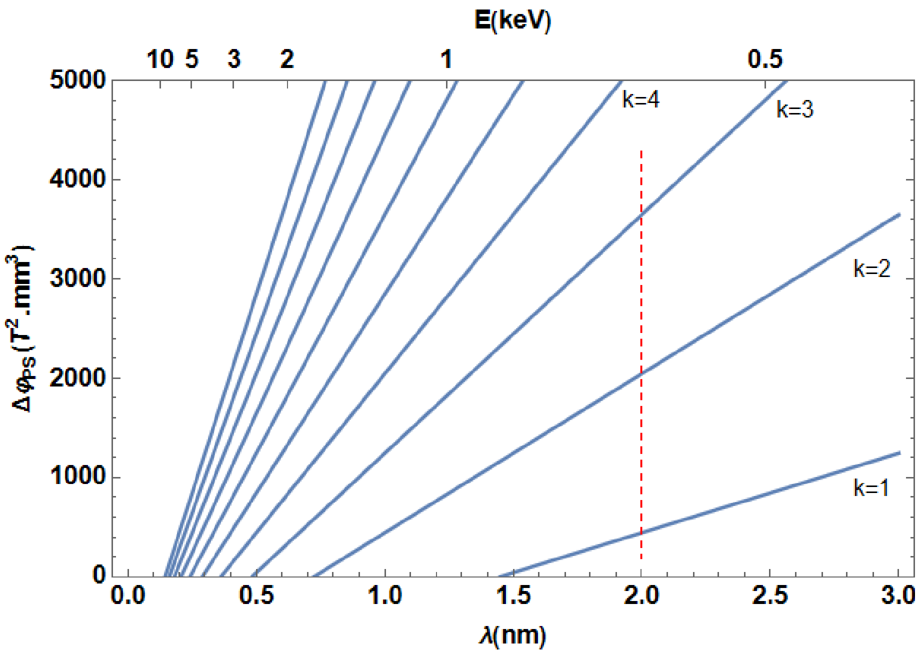
Beam rigidity at 6GeV:
$B\rho$ = *20.01 T.m*

$$\Delta\varphi(L) = \frac{2\pi}{\lambda}\left(\frac{L}{2\gamma^2} + \frac{1}{2}\int_0^L \theta^2 ds\right) \iff \Delta\varphi(L) = \frac{2\pi}{2\gamma^2\lambda}\left(L + \frac{\gamma^2}{(B\rho)^2}\Delta\varphi_{PS}\right)$$



$$\Delta\varphi(L) = 2\pi k \iff \Delta\varphi_{PS} = \frac{(B\rho)^2}{\gamma^2}\left(2\gamma^2\lambda k - L\right)$$

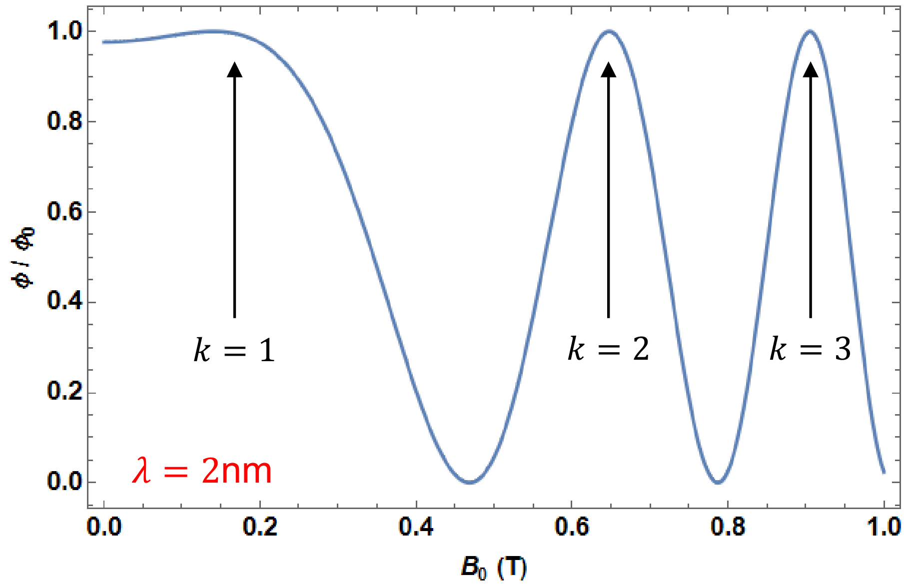
$\Delta\varphi_{PS} = B_0^2 \cdot \int_0^L \left(\int_0^s B_{PS}/B_0 d\sigma\right)^2 ds$ is the **phase integral** generated by the magnetic field B_{PS}



Required phase integral versus energy working point at 6GeV, L=0.4m

The solution is not unique.

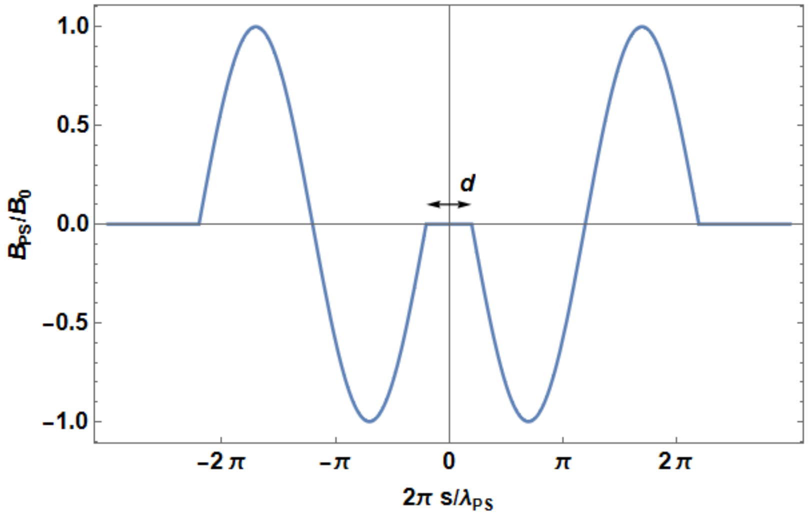
Normalized photon flux at
$\lambda = 2nm$
versus field amplitude B_0
$\int_0^L \left(\int_0^s \frac{B_{PS}}{B_0} d\sigma\right)^2 ds = 5000\ mm^3$

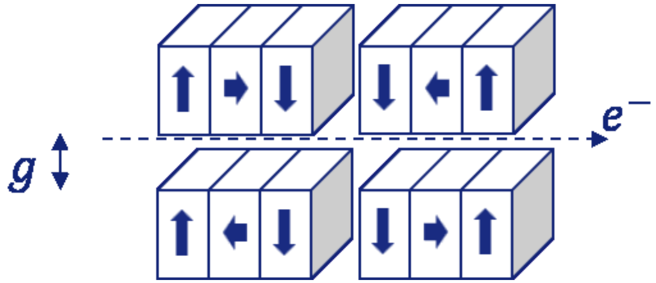


G. Le Bec

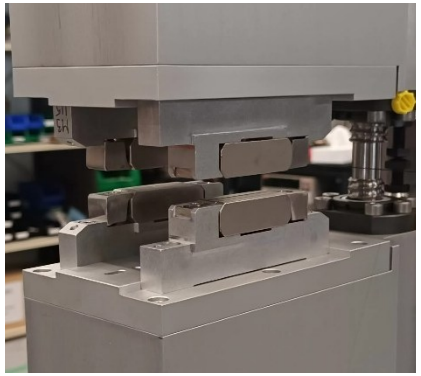
$$\Delta\varphi_{PS}(B_0,\lambda_{PS}) = B_0^2 \cdot \int_0^L \left(\int_0^s B_{PS}(\lambda_{PS})/B_0 d\sigma\right)^2 ds$$

Constraints	Solutions
Minimum 1st, 2nd field integrals	Double **mirror sine waves** with $d \geq 0$
Fit in 0.37m drift space	Use **permanent magnets** blocks
Tunable phase integral	Adapt the period λ_{PS} to target an energy range, **Movable vertical aperture g**



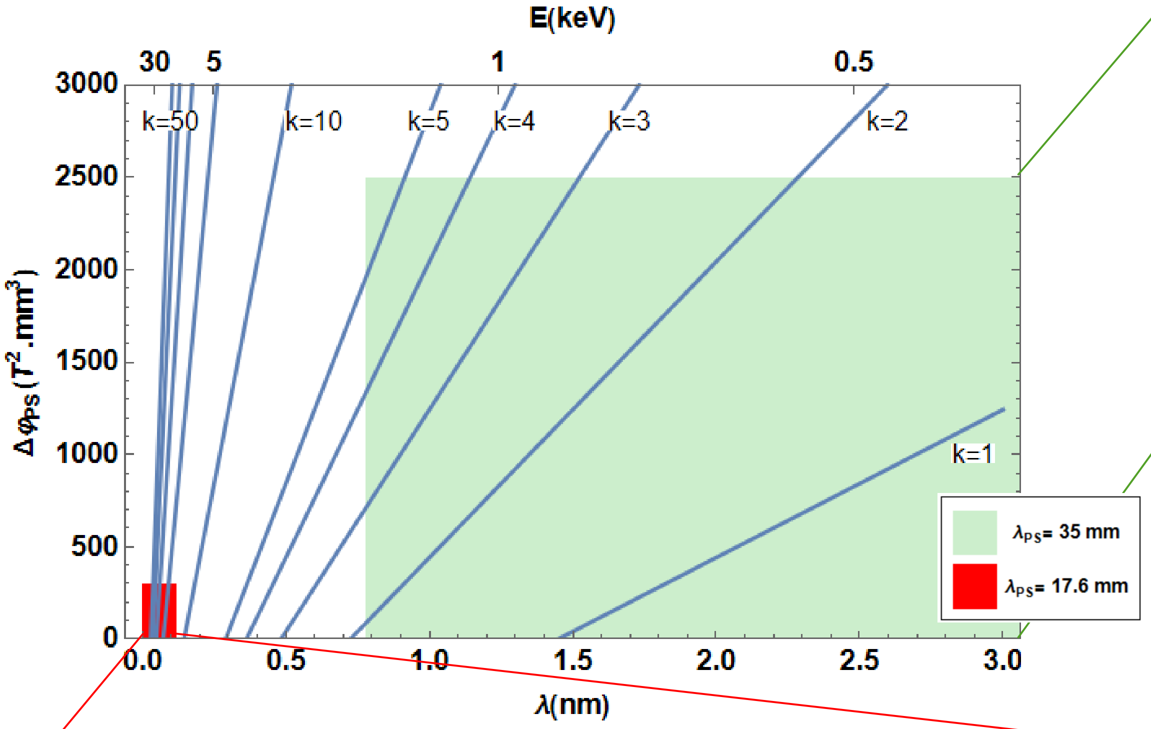


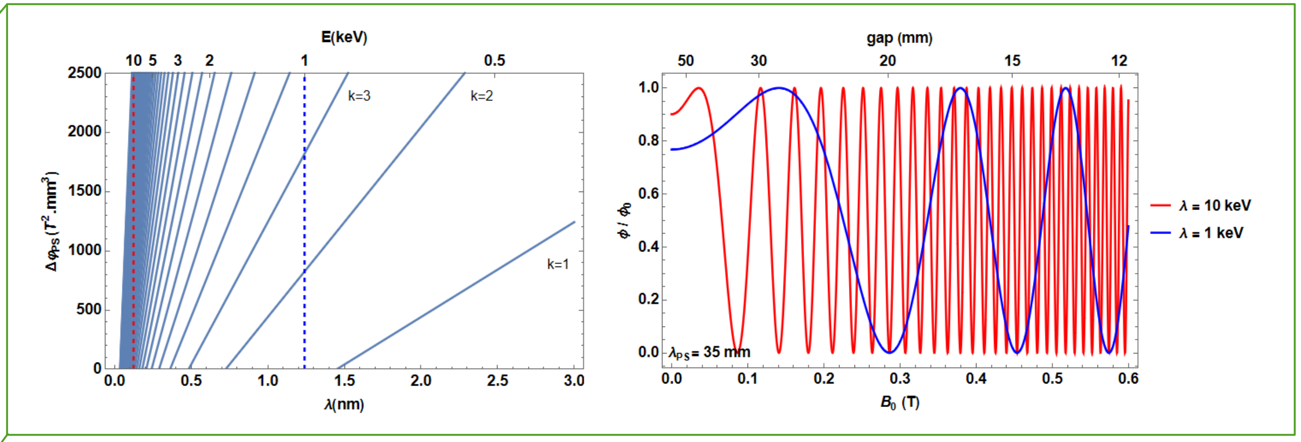
Built with 4 undulator magnet modules



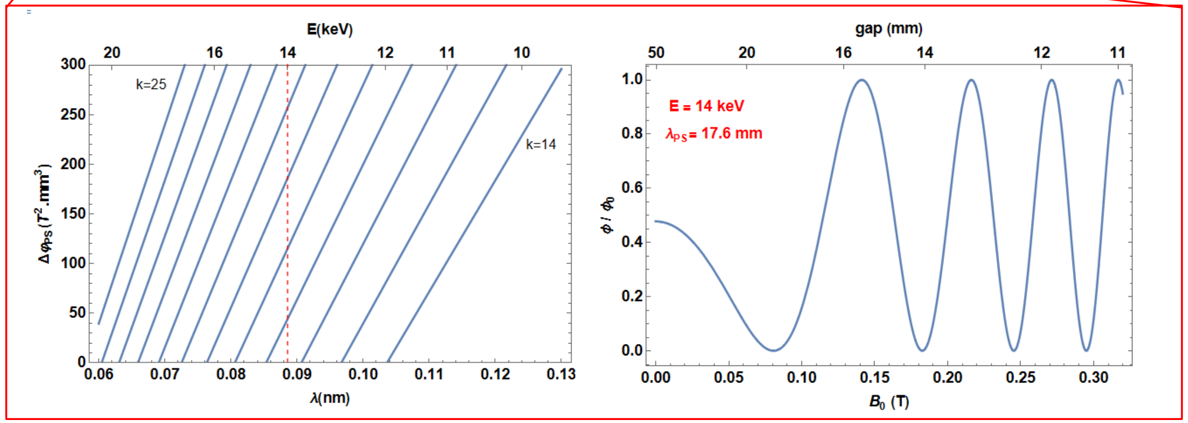
Refs: H. H. Lu, et al, NIMA, Vol. 650 (3), pp. 399-408, 2009
T. Chung, et al, IEEE Trans. Applied Supercond., Vol. 26 (4), 2016.

II. PHASE SHIFTER DEVICE – CHOICE OF PARAMETERS





$\lambda_{PS} = 35\text{mm}$



$\lambda_{PS} = 17.6\text{mm}$

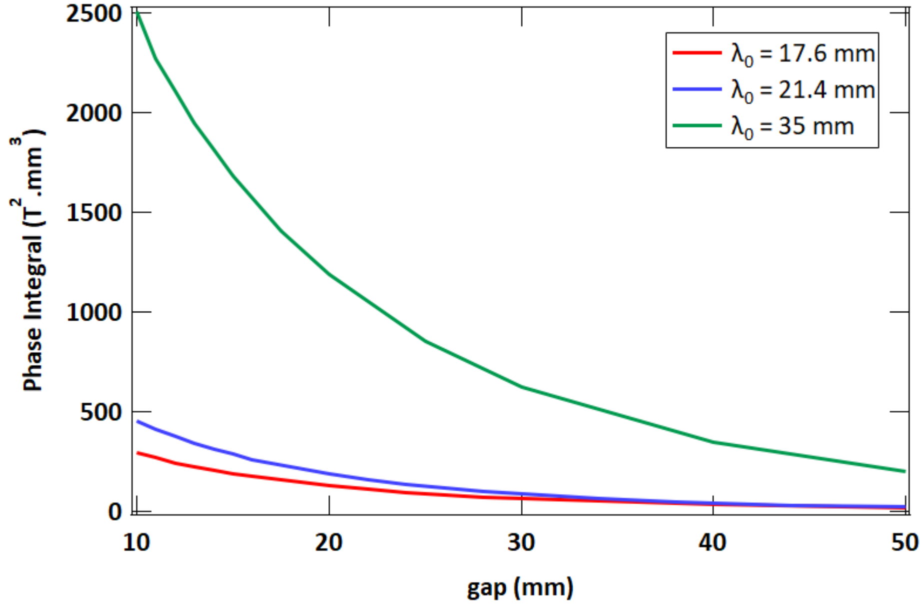
- λ_{PS} is chosen to optimize the **gap tuning capability** in the energy range of interest
- For a given λ_{PS}, the **higher** the working energy the more **sensitive to the gap** tuning
  - → **small period** is preferred for high energy
  - → but it **reduces** the maximum **phase integral** and hence the energy range

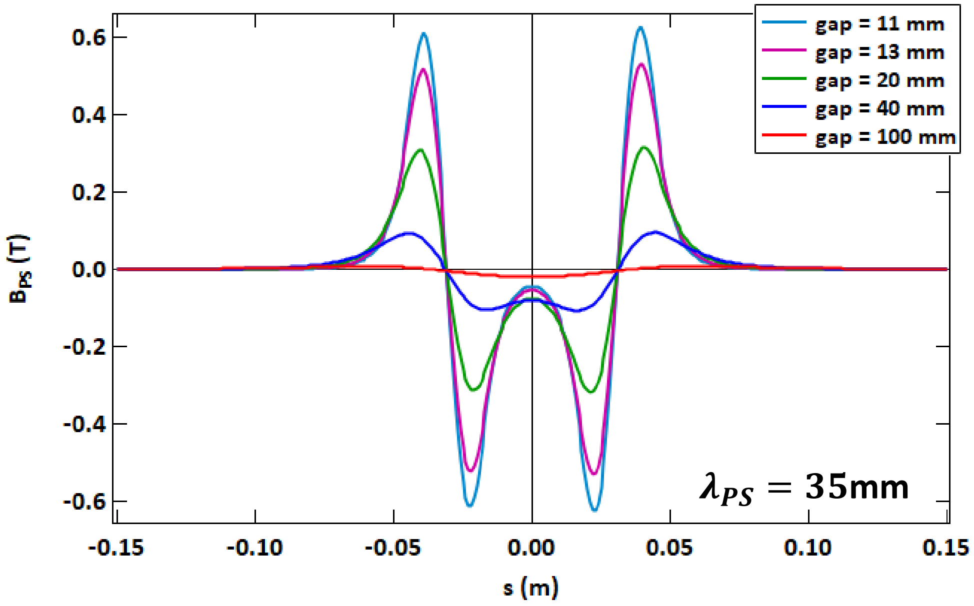
II. PHASE SHIFTER DEVICE – MAGNETIC MEASUREMENTS

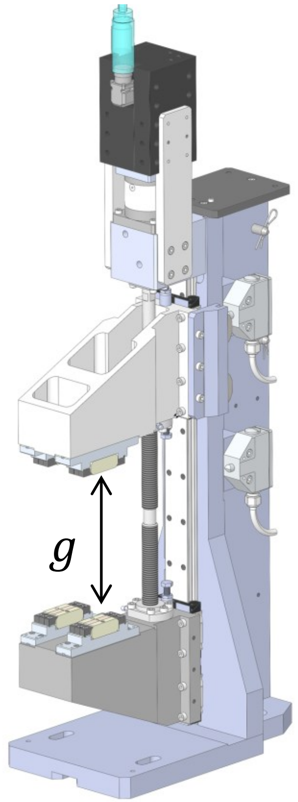
- Minimization of the **field integral** $I(\text{gap})$ for electron beam deviation with magnetic corrections

$$\mathbf{I(gap)} \lesssim \mathbf{0.05\ T.mm} \quad \text{for} \quad 10 < \text{gap} < 200\ \text{mm}$$

- Measurement of the **field profile** and **phase integral** vs gap g







- **Fringe fields and shape variation** of the profile are included in the **calibration to be done with beam**

II. PHASE SHIFTER DEVICE – CONTROL

- **Single axis** controlled by an IcePAP motor controller
- **No encoder** (radiation environment)
- **Seen as a standard ID from the beamline** point of view: the gap is the tuning knob

* Example of ID14 *

$U1 = \textit{Cryo. In-vacuum device}\ \lambda = 18.6mm$

$U2 = \textit{Revolving carriage},\ \lambda = 20 - 27mm$

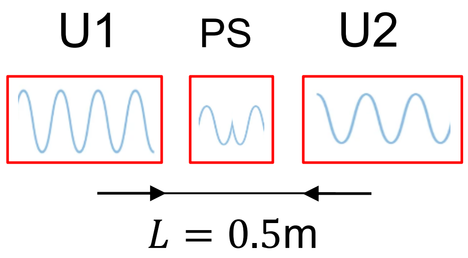
$\lambda_{PS} = 17.6mm$

ID14 control panel

- **Tuning procedure – by the user** :
  - ✓ Scan gap(U1) to maximize the photon flux
  - ✓ Scan gap(U2) to maximize the photon flux
    } ⟶ **Standard energy calibration of undulators**
  - ✓ Scan gap(PS) to observe the interference effect ⟶ **Phase integral calibration**
  - ✓ Select the solution with the lower k value (ie higher gap) to maximize the stability

- Electron beam parameters

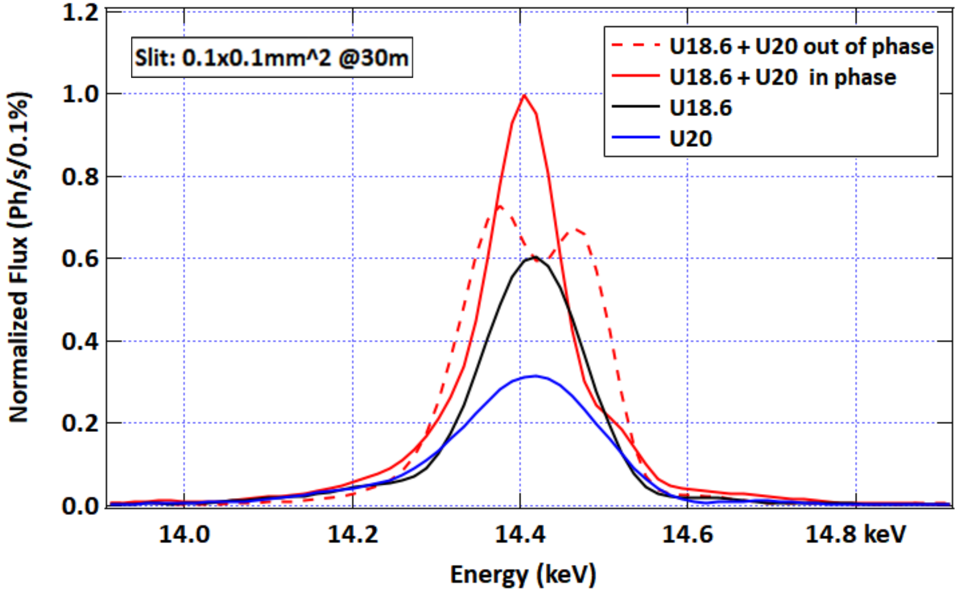
E_{beam} (GeV)	I_{beam} (mA)	(σ_x, σ_z) (µm)	(σ'_x, σ'_z) (µrad)	σ_δ
6	200	(30.6, 5.2)	(4.5, 1.9)	0.095%



- Beamline photon sources and studied working points:

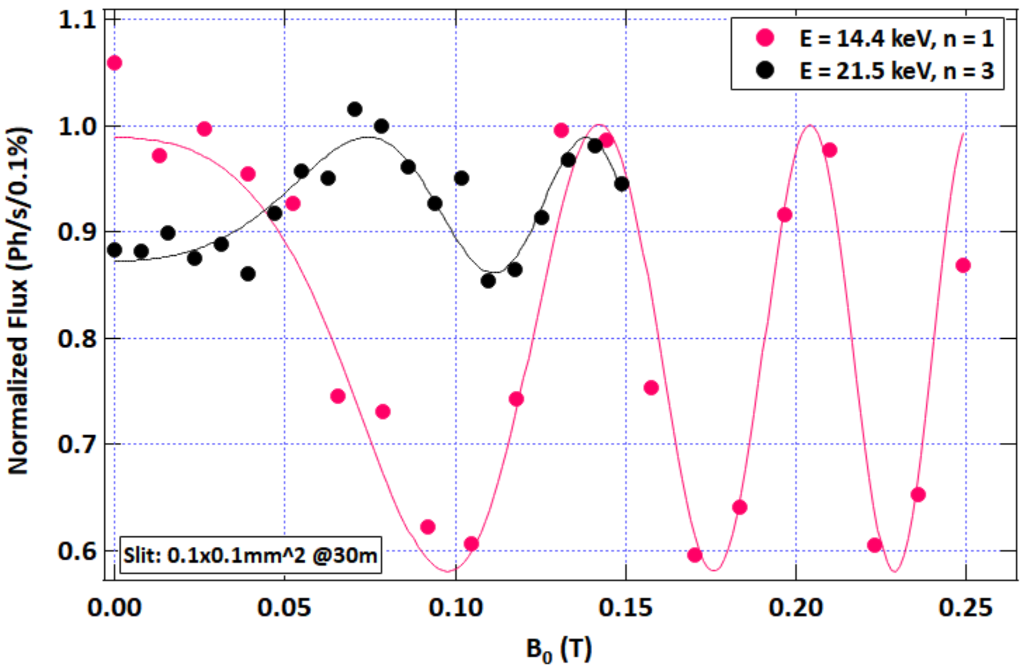
		U1	U2	
Undulator type		2m , In-vac. 6mm min.gap	1.6m , revolving ex-vacuum 11mm min. gap	
Period (mm)		18.6	20	27
$N_{periods}$		107	80	59
B_{max} (T)	E = 14.4 keV $(n = 1)$	**0.425**	**0.324**	-
	E = 21.5 keV $(n = 3)$	**1.012**	-	**0.490**

SRW multiparticle simulation at 14.4 keV

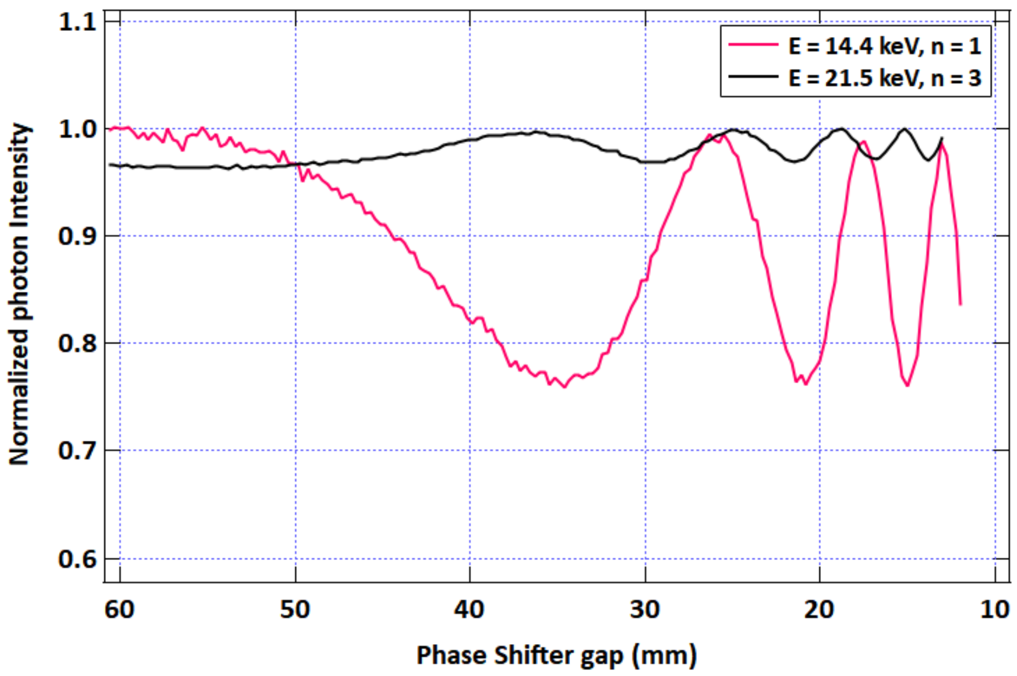


- **Expected and measured performances** – phasing harmonics 1 and 3 on U1, U2

SRW multiparticle simulation vs B_0



Intensity measurement vs gap at ID14



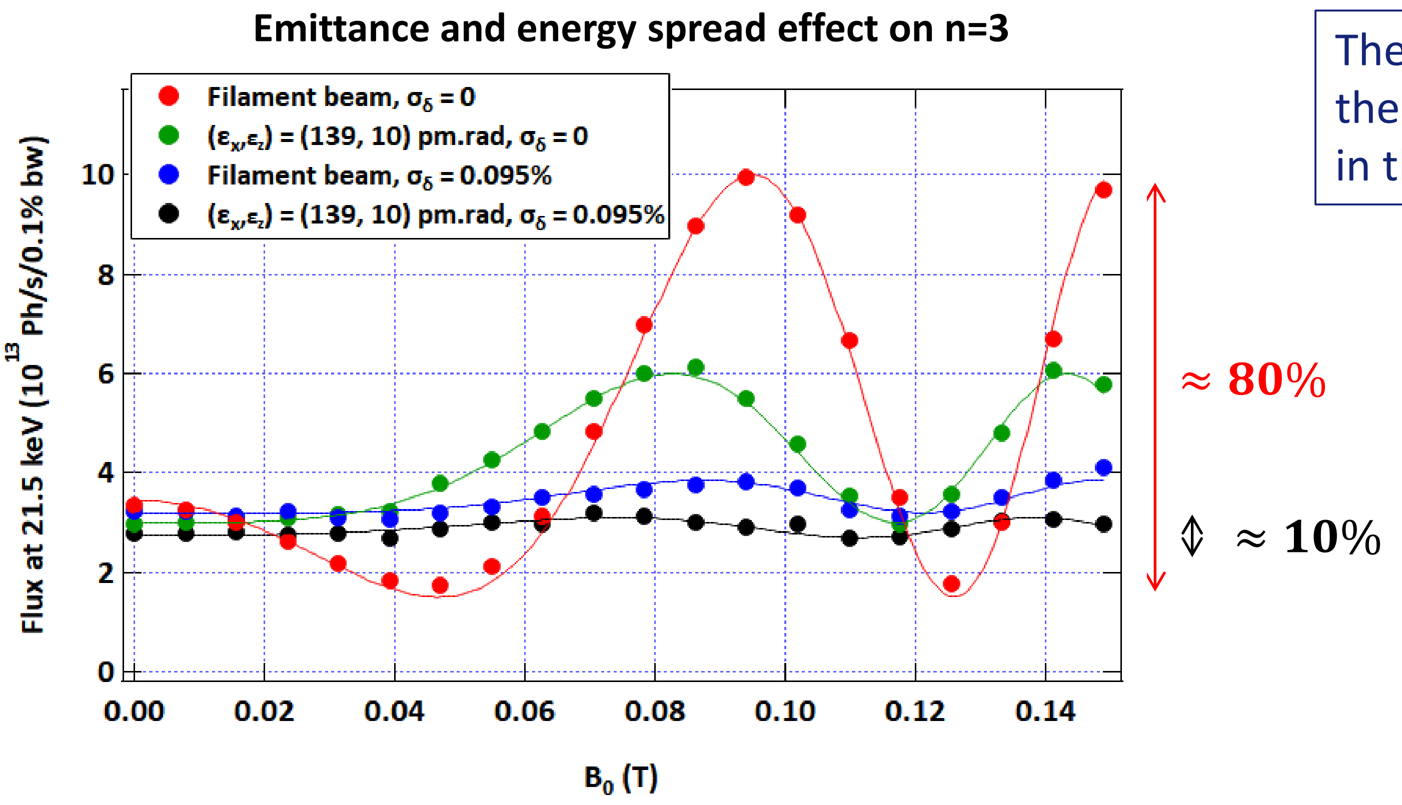
Courtesy A. Chumakov, ID14

- Simulation predictions are **compatible with measurements** (simulation assume perfect sinusoidal fields)
- The **phasing contrast** is smaller on harmonic **3**, only 3% visible on the beam

- The relative **amplitude** of interferences should **not depend** on the **harmonic** number for a filament beam,

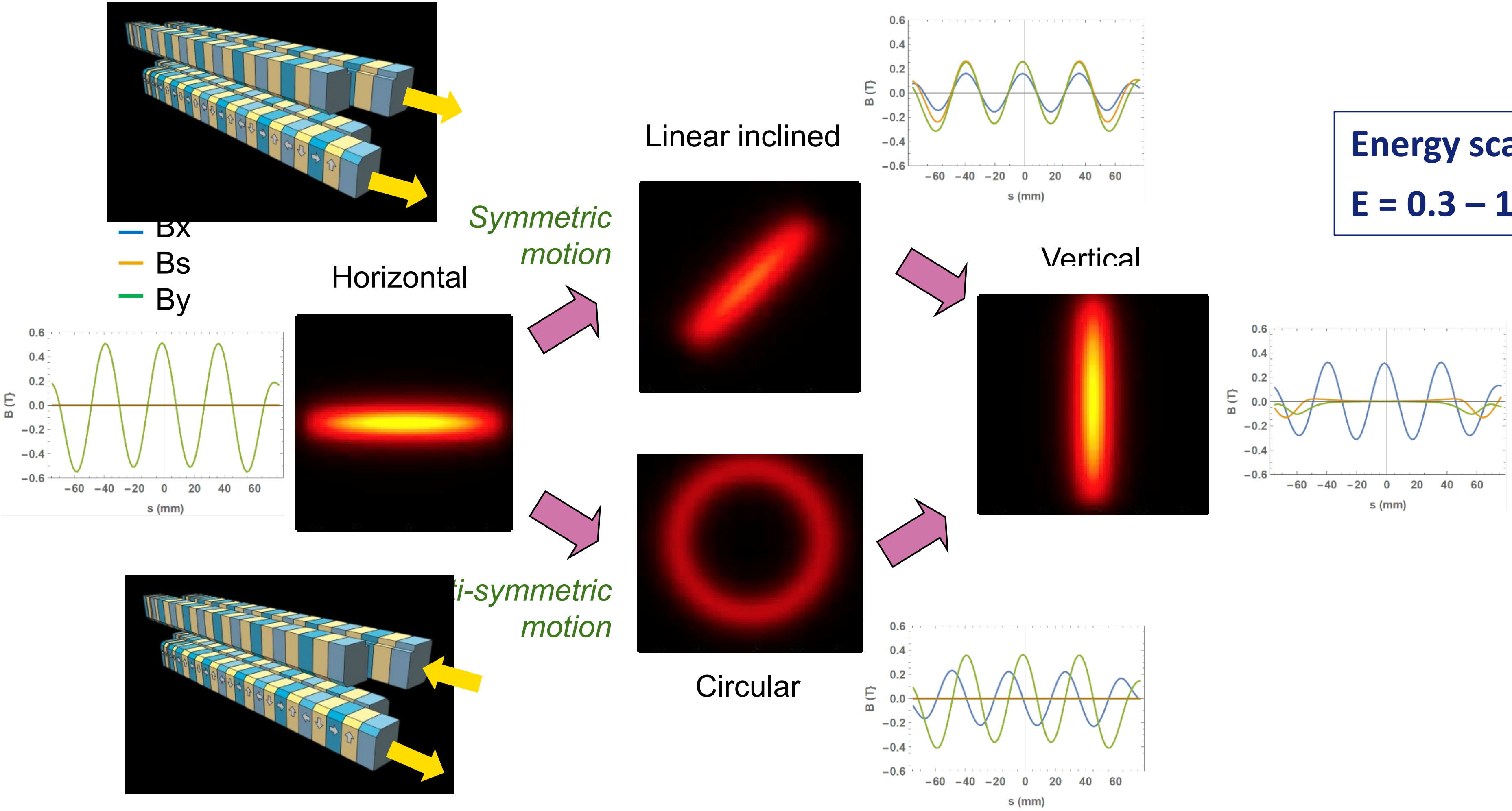
  BUT the simulations predict fluctuations of ~**40% for n = 1 and ~10% for n = 3**

- The effect of **beam emittance** and even more the **energy spread** on the spectrum reduces strongly the contrast as n increases (off-energy and off-axis radiation)



The PS is only used on the fundamental energy in this case.

- 2 x 2.3m APPLE2 undulators ($\lambda_{U1} = \lambda_{U2} = 70$mm) for linear / circular polarization control

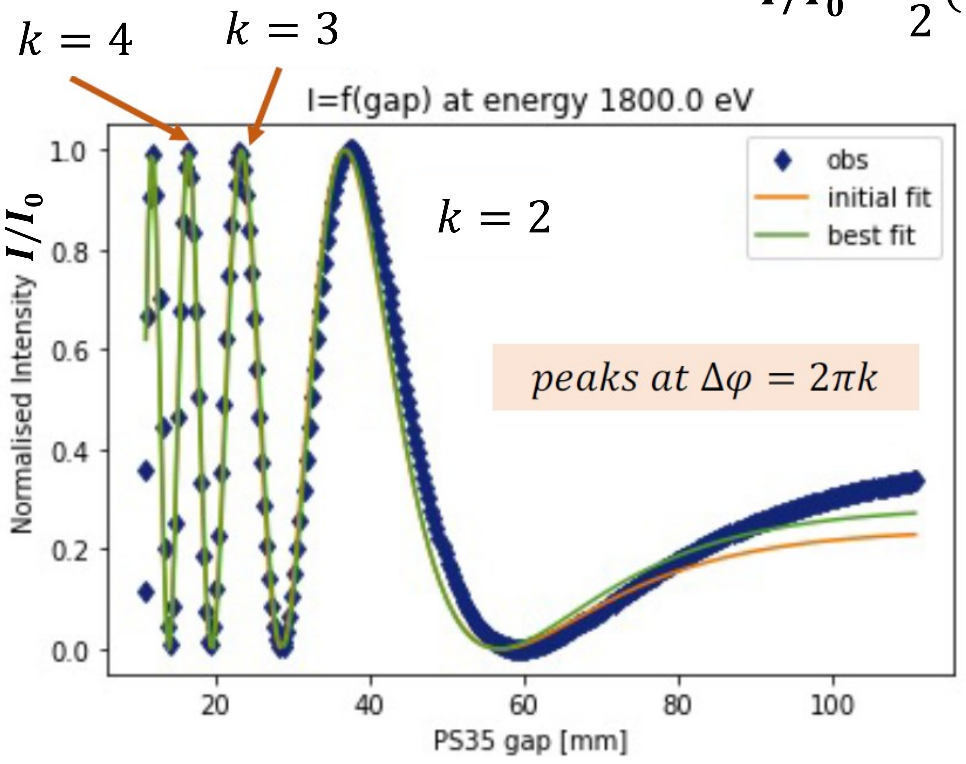


Energy scans

E = 0.3 – 1.6 keV

- **First PS prototype, strong phasing contrast – essential for operation with twin APPLE2 devices**
- **Calibration of E(gap) for all 3 gaps of U1, U2, PS** needed for spectroscopy applications

$$\boldsymbol{I/I_0} = \frac{1}{2}(1+\cos[\Delta\varphi(L)]) \quad \text{and} \quad \Delta\varphi(L) = E\,\frac{\pi}{hc}\left(\frac{L}{\gamma^2} + \frac{1}{(B\rho)^2}\Delta\varphi_{PS}\right)$$



Courtesy F. Yakhou, ID32

Tentative fit:

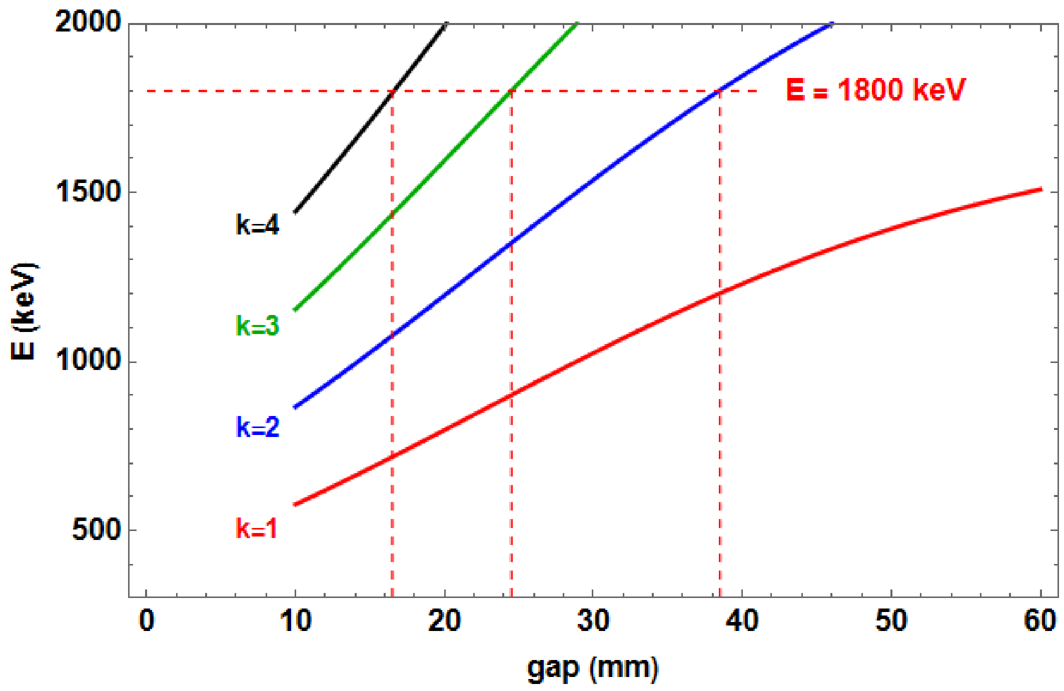
- Assuming $\Delta\varphi_{PS} \propto \exp[-\pi b.\,\mathrm{gap}/\lambda_{PS}]$
- Fit (a, b) so that :

$$I = \frac{1}{2}(1+\cos[\Delta\varphi(L)])$$

i.e. $$I = \frac{1}{2}\left(1+\cos\left[\boldsymbol{E}\frac{\pi}{hc}\left(\frac{L}{\gamma^2} + a.\exp[-2\pi b.\,\mathbf{gap}/\lambda_{PS}]\right)\right]\right)$$

III. FEEDBACK FROM USERS – ID32. SOFT X-RAY SPECTROSCOPY

- Solving $\boldsymbol{\Delta\varphi}(\mathrm{E}, \mathrm{gap}) = \boldsymbol{E}\frac{\pi}{hc}\left(\frac{L}{\gamma^2} + a.\exp[-2\pi b.\,\mathbf{gap}/\lambda_{PS}]\right) = \boldsymbol{2\pi k}, k \geq 1$ provides the PS gap at any energy



Observations:

- Works well to approach the maximum intensity, but **requires a final adjustment** of the PS gap
- The working point **depends** on the requested **polarization**

⇒ the calibration $\Delta\varphi_{PS}(\mathrm{gap})$ depends on the gap and phase settings of APPLE2 undulators i.e. fringe fields and residual magnetic errors of the undulators

- **Next step: continuous energy scans**
  - Require to remain on the **same $\boldsymbol{k}$-value** – may be a constraint at higher energy (lower period devices)
  - Need to **refine the calibration model** to derive the PS gap tuning curve for any settings of the undulators
  - Need to measure the **reproducibility**

CONCLUSION AND PERSPECTIVES

- Phasing undulators is essential for beamlines using **coherent beam** at ESRF-EBS

- Passive phasing is well adapted for **single energy beamlines**

But not feasible for a combination of **ex-vacuum & in-vacuum IDs**

New straight section layouts and ID types require **tunable phasing sections**

First phase shifter installed and tested successfully in 2021
2 more in operation, 3 foreseen

- The phase delay between undulators depends on the **energy working point**

The phase integral tuning of a PS device using its gap is made of **several curves** (given by **k-values)**

Using the photon intensity takes **the effect of fringe field** into account, it can only be done **on the beamline**

$$\Delta\varphi(L) = \frac{2\pi}{2\gamma^2\lambda}\left(L + \frac{\gamma^2}{(B\rho)^2}\Delta\varphi_{PS}\right) = 2\pi k$$

CONCLUSION AND PERSPECTIVES

- The **efficiency** of phasing undulators depends on the **harmonic number due to the electron beam properties**
- **The phasing of two twin APPLE2-70mm has proven to be very successful at fixed gaps**

  but tentative energy scans have shown the limitation of the current model to fit an accurate calibration

- **Continuous energy scans**
  - The phase shifter control needs to be integrated into the **ID-monochromater synchronization set up**
  - The scans should be performed along a **single k-value tuning** curve to avoid jumps in position

- **Next installation – 4^{th} Phase shifter device**:
  - Between 2.3m identical segments of planar undulators
  - Systematic scans for a full calibration over the beamline working energy range
  - Reproducibility tests for scans in energy without feedback (no encoder)

Thanks to :

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Accelerator Control Unit
Beamline Control Unit
Electronic Unit
Drafting Office

ESRF
The European Synchrotron

THANKS FOR YOUR ATTENTION