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Particle Accelerators and Beams Conference

Phase Shifters in Free-Electron Lasers

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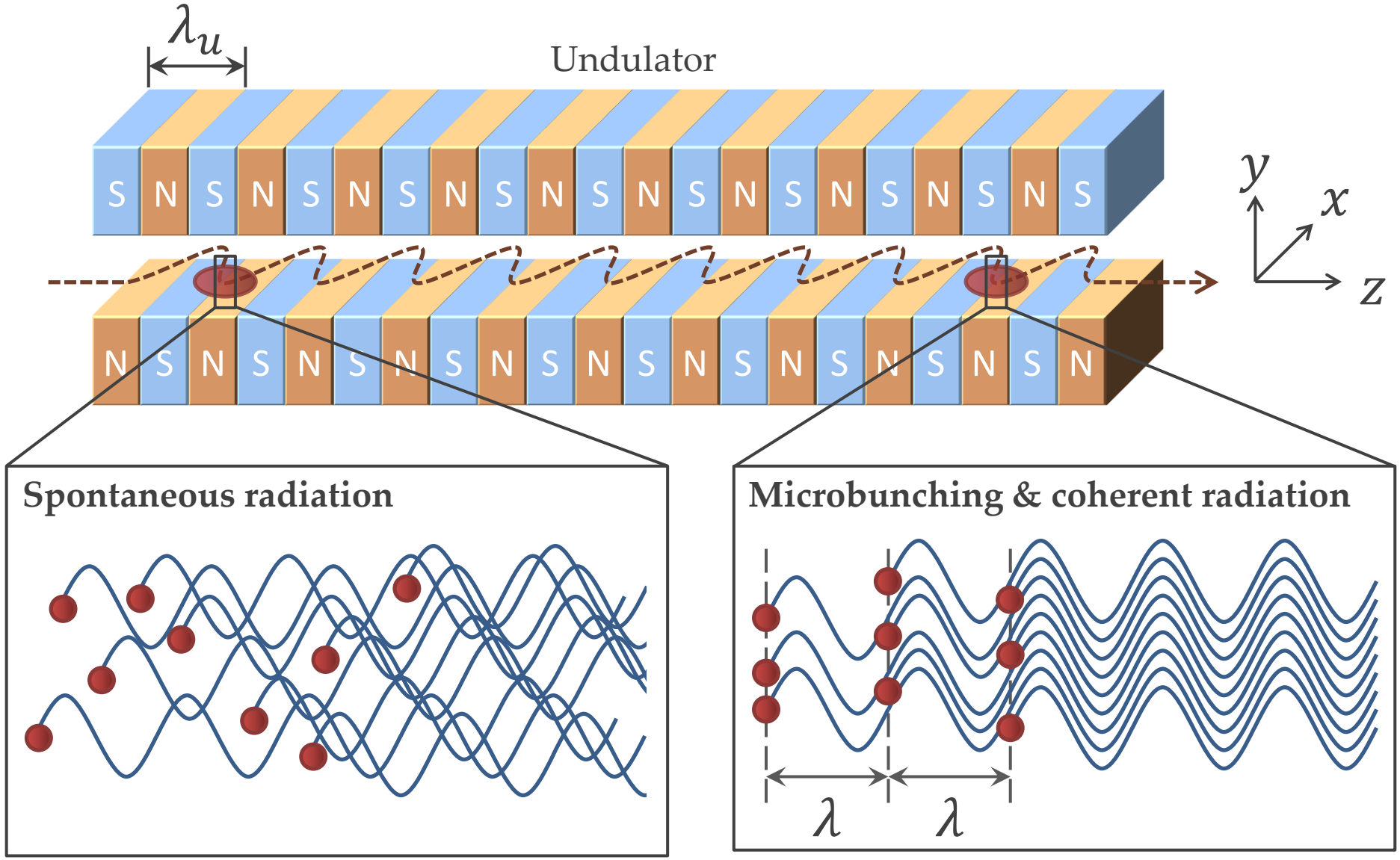
UKXFEL

Science and Technology Facilities Council

The Cockcroft Institute of Accelerator Science and Technology

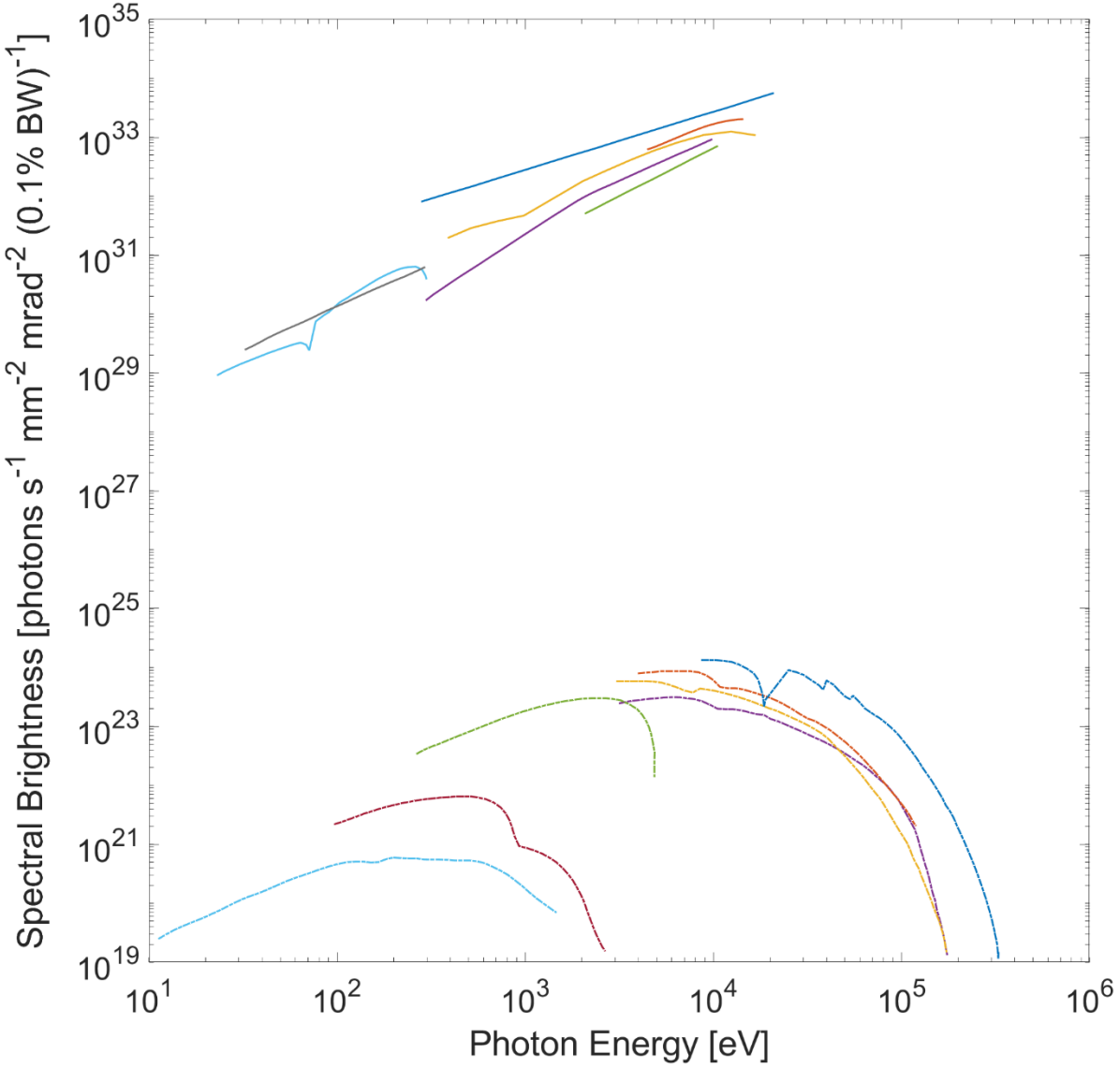
Free-Electron Laser (FEL)



Distinctive properties

- Good spatial and temporal coherence
- High power (> GW, potentially TW)
- Short pulse duration (< ps, potentially zs)
- Narrow bandwidth ($\Delta\lambda/\lambda \approx 0.1\%$)
- Tuneable wavelength
- *Brightest* laboratory x-ray source to date

Free-Electron Laser (FEL)



European XFEL *(Germany)*
SACLA *(Japan)*
PAL XFEL *(South Korea)*
LCLS *(USA)*
Swiss FEL *(Switzerland)*
FERMI *(Italy)*
FLASH *(Germany)*
SPring-8 *(Japan)*
PETRA III *(Germany)*
ESRF *(France)*
APS *(USA)*
NSLS II *(USA)*
SLS *(Switzerland)*
BESSY *(Germany)*

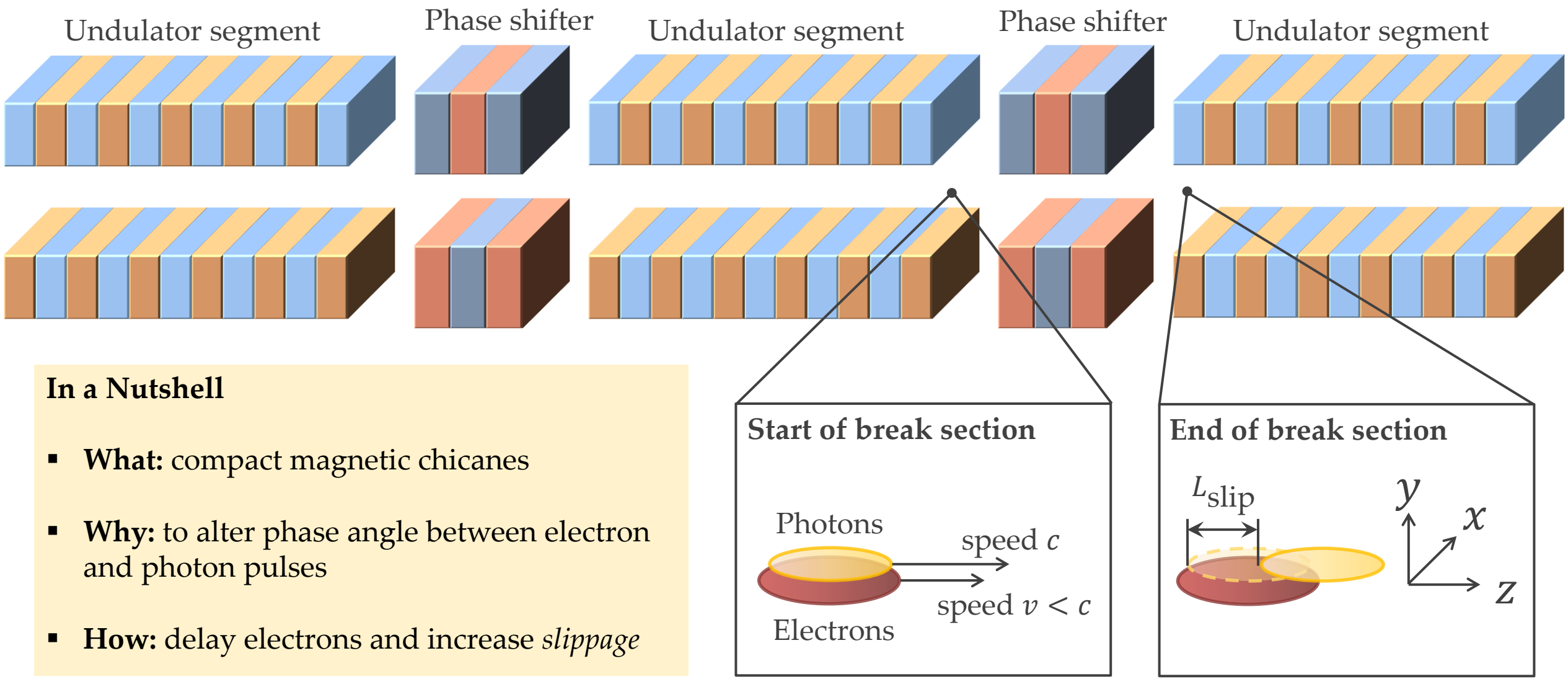
Free-Electron Lasers (solid lines)

Electron Synchrotrons (dash lines)

Spectral brightness = number of photons emitted

- per unit time
- per unit cross-sectional area
- per unit solid angle
- per 0.1% of the relative bandwidth

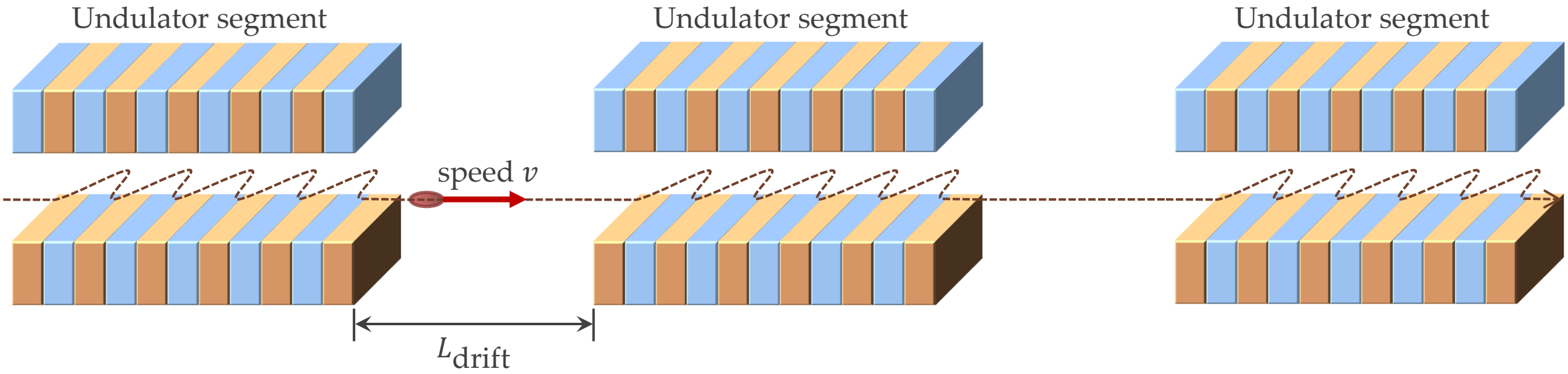
Phase Shifters



In a Nutshell

- **What:** compact magnetic chicanes
- **Why:** to alter phase angle between electron and photon pulses
- **How:** delay electrons and increase *slippage*

Without Phase Shifters



- Electron pulse traversing the break section

$$L_{\mathrm{drift}} = v\,\Delta t$$

- Photon pulse within the same time interval

$$L'_{\mathrm{drift}} = c\,\Delta t = \frac{c}{v} L_{\mathrm{drift}}$$

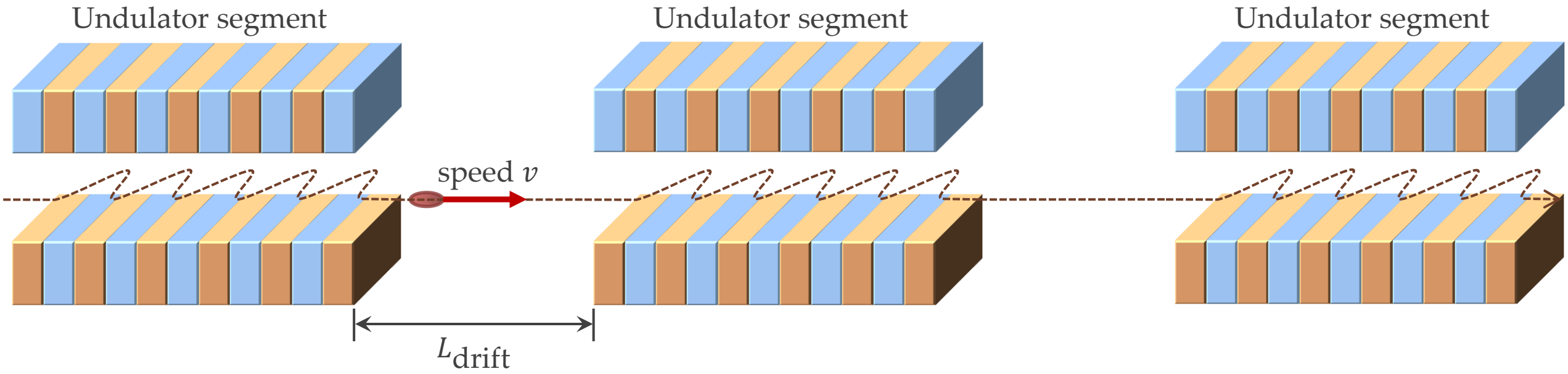
- Slippage across the break section

$$L_{\mathrm{slip}} = L'_{\mathrm{drift}} - L_{\mathrm{drift}} = \left(\frac{c}{v} - 1\right) L_{\mathrm{drift}}$$

- In terms of electron energy

$$\gamma = 1/\sqrt{1 - v^2/c^2}$$

Without Phase Shifters



- Taylor expansion

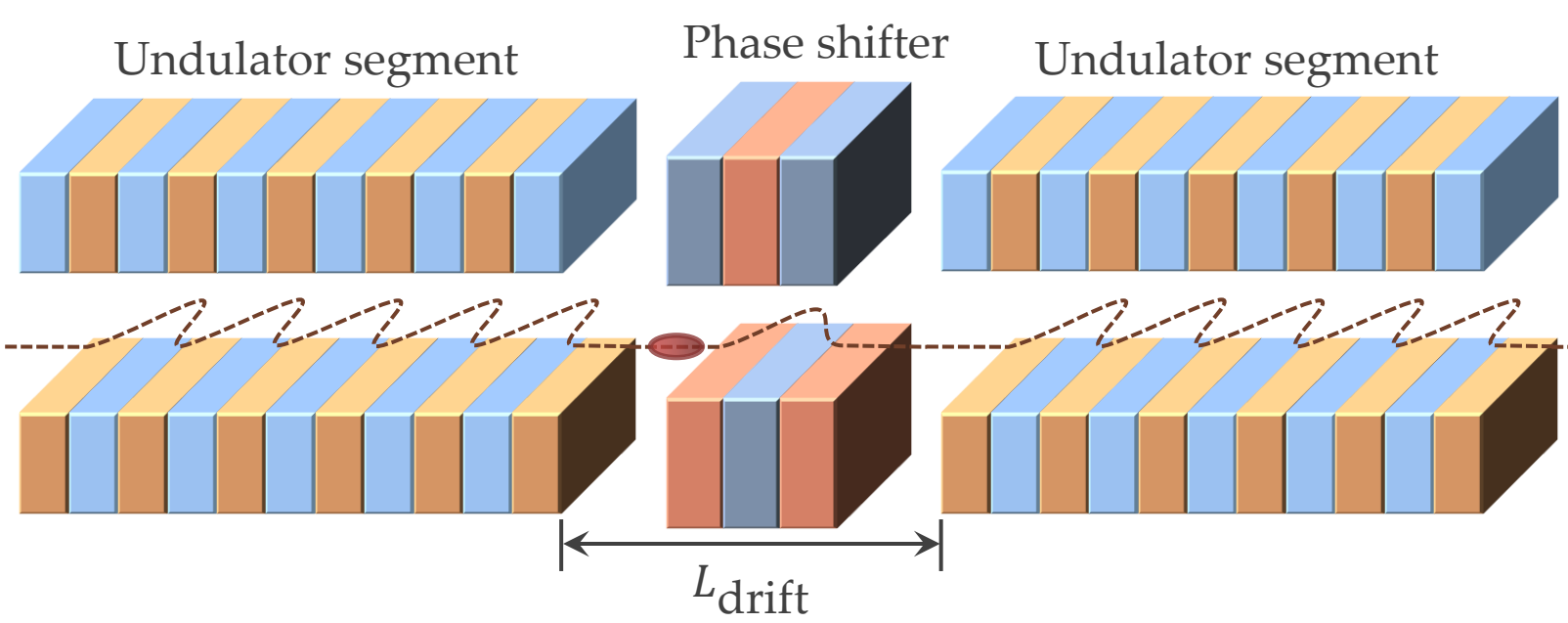
$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}} \Rightarrow \frac{c}{v} = \left(1 - \frac{1}{\gamma^2}\right)^{-\frac{1}{2}} \approx 1 + \frac{1}{2\gamma^2}$$

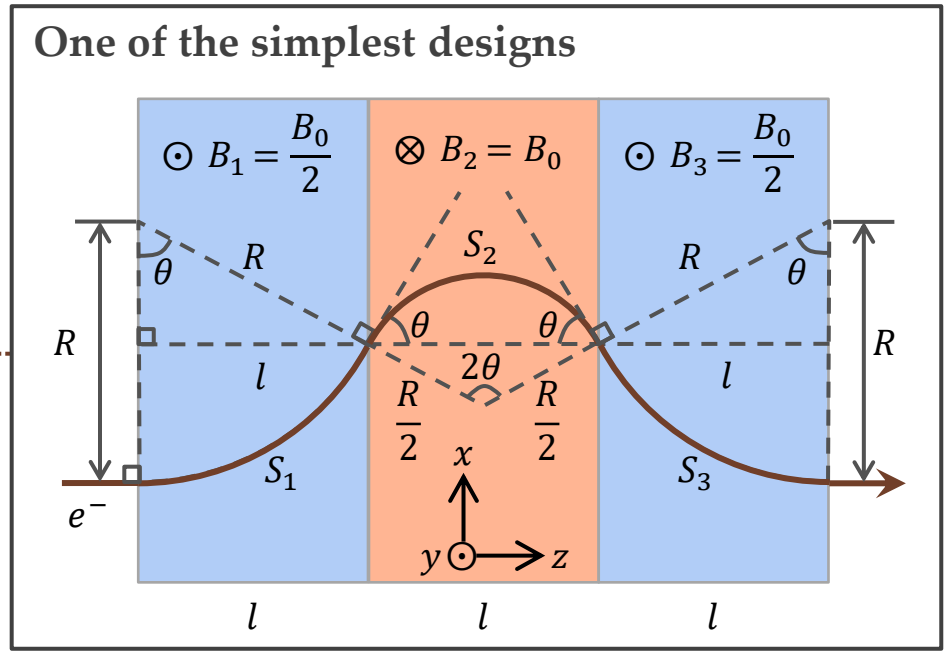
- Result

$$L_{\text{slip}} = \left(\frac{c}{v} - 1\right) L_{\text{drift}} \approx \frac{L_{\text{drift}}}{2\gamma^2}$$

- For **effective** energy transfer from electrons to photons, we want $L_{\text{slip}} = n\lambda$ (for some $n \in \mathbb{Z}$).
- However, L_{drift} and γ are generally **fixed**.
- A **knob** for L_{slip} in each break section is desirable.

With Phase Shifters





- Without a phase shifter

$$L_{\text{slip}} = \frac{L_{\text{drift}}}{2\gamma^2}$$

- With a phase shifter

$$L_{\text{slip}} = \frac{L_{\text{drift}}}{2\gamma^2} + \Delta L$$

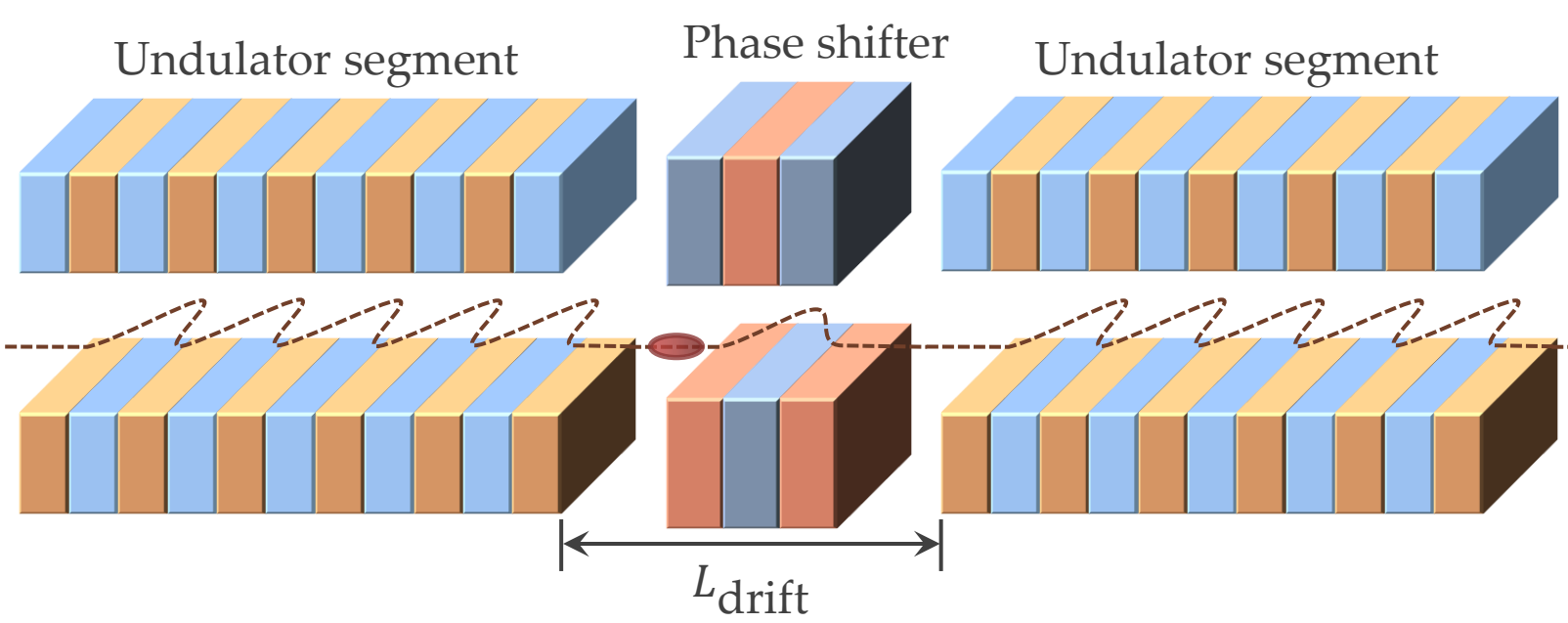
- Electron-photon path difference

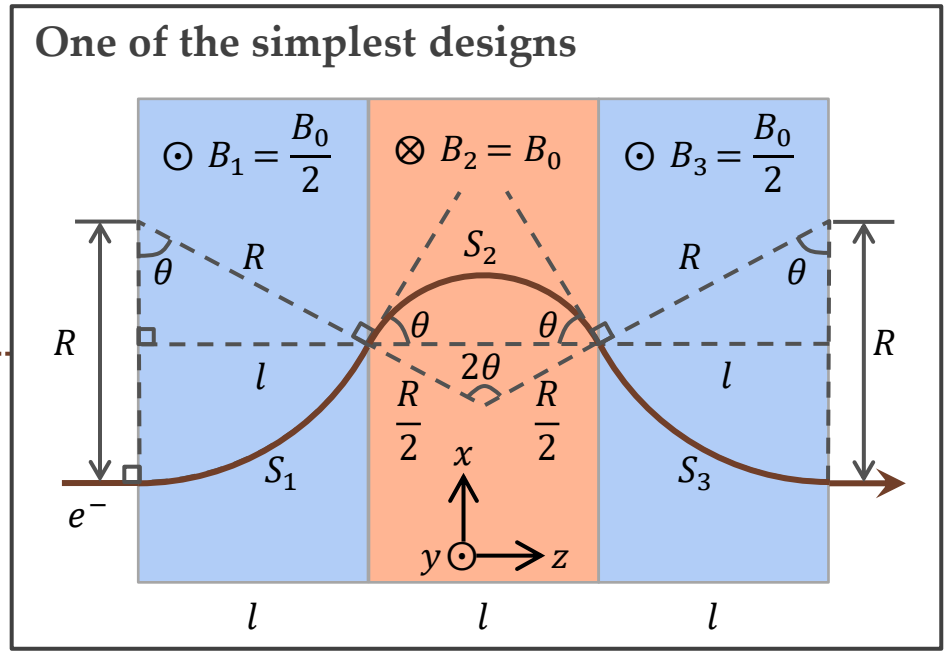
$$\Delta L = S_1 + S_2 + S_3 - 3l$$

$$= R\theta + \frac{R}{2} \times 2\theta + R\theta - 3l$$

$$= 3R\theta - 3l = 3R \sin^{-1}\left(\frac{l}{R}\right) - 3l$$

With Phase Shifters





- Taylor expansion

$$\Delta L = 3R\sin^{-1}\left(\frac{l}{R}\right) - 3l \approx 3R\left(\frac{l}{R} + \frac{l^3}{6R^3}\right) - 3l = \frac{l^3}{2R^2}$$

- Recall

$$\frac{1}{R} = \frac{eB_0}{p}, \qquad p = m_e c\sqrt{\gamma^2 - 1}$$

- Result

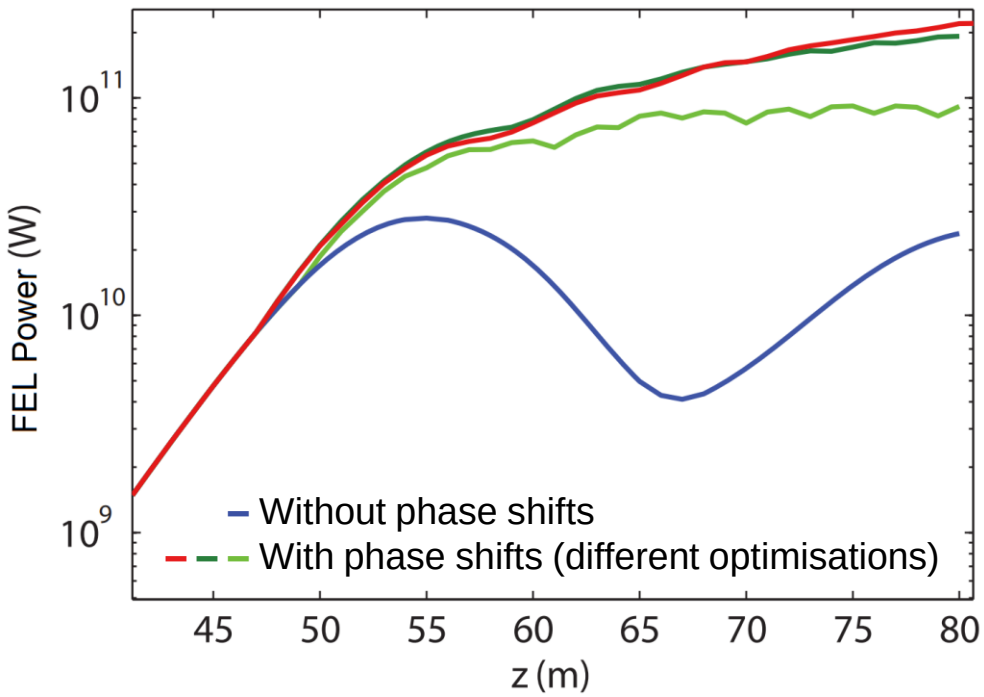
$$L_{\text{slip}}(B_0) = \frac{L_{\text{drift}}}{2\gamma^2} + \Delta L \approx \frac{L_{\text{drift}}}{2\gamma^2} + \frac{e^2 l^3 B_0^2}{8m_e c^2(\gamma^2 - 1)}$$

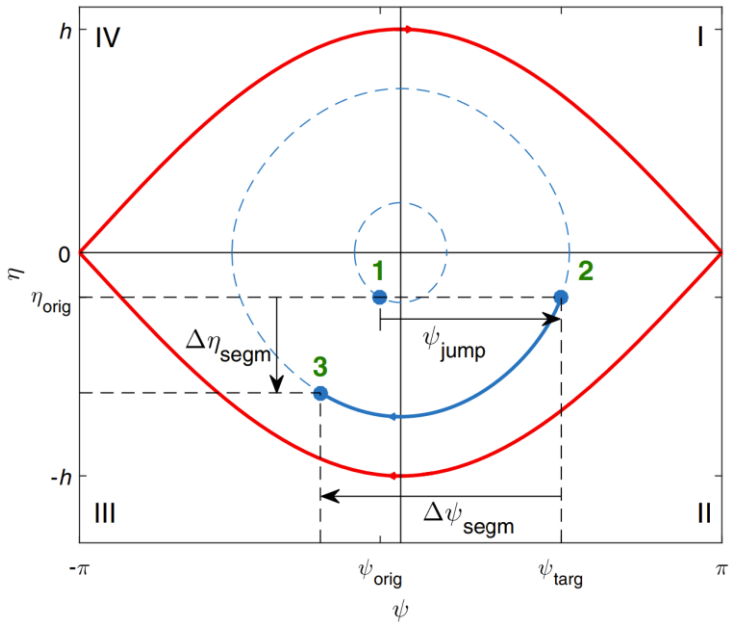
- B_0 serves as an **independent knob** for L_{slip}.
- **Phase correction:** $L_{\text{slip}} = n\lambda$ (for some $n \in \mathbb{Z}$).

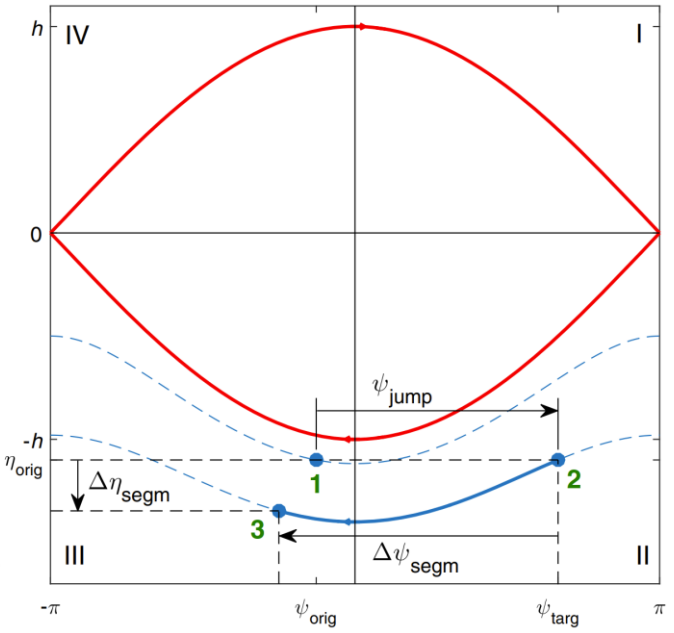
Advanced Operation Modes

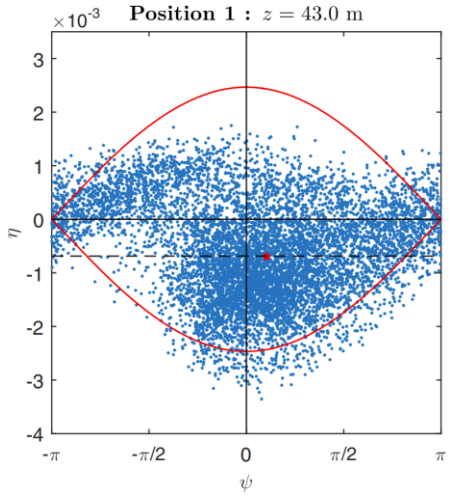
Selected Applications of Phase Shifters

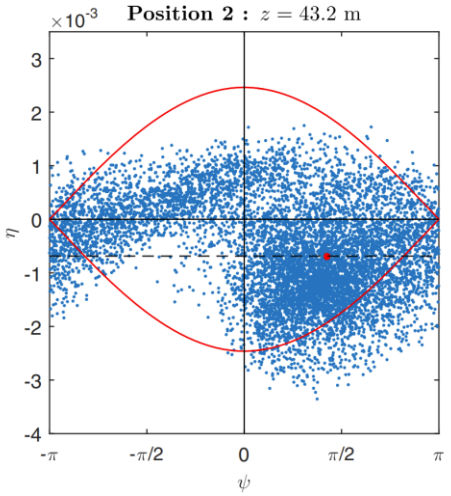
Power Enhancement

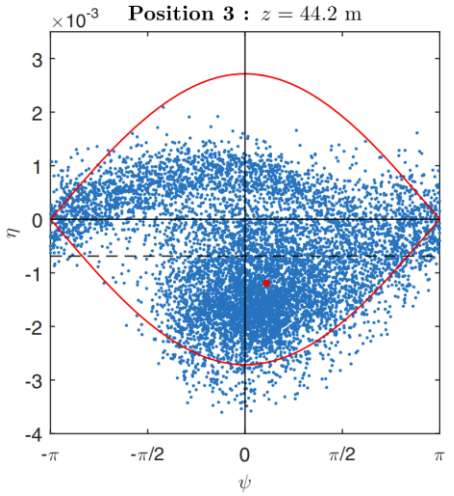








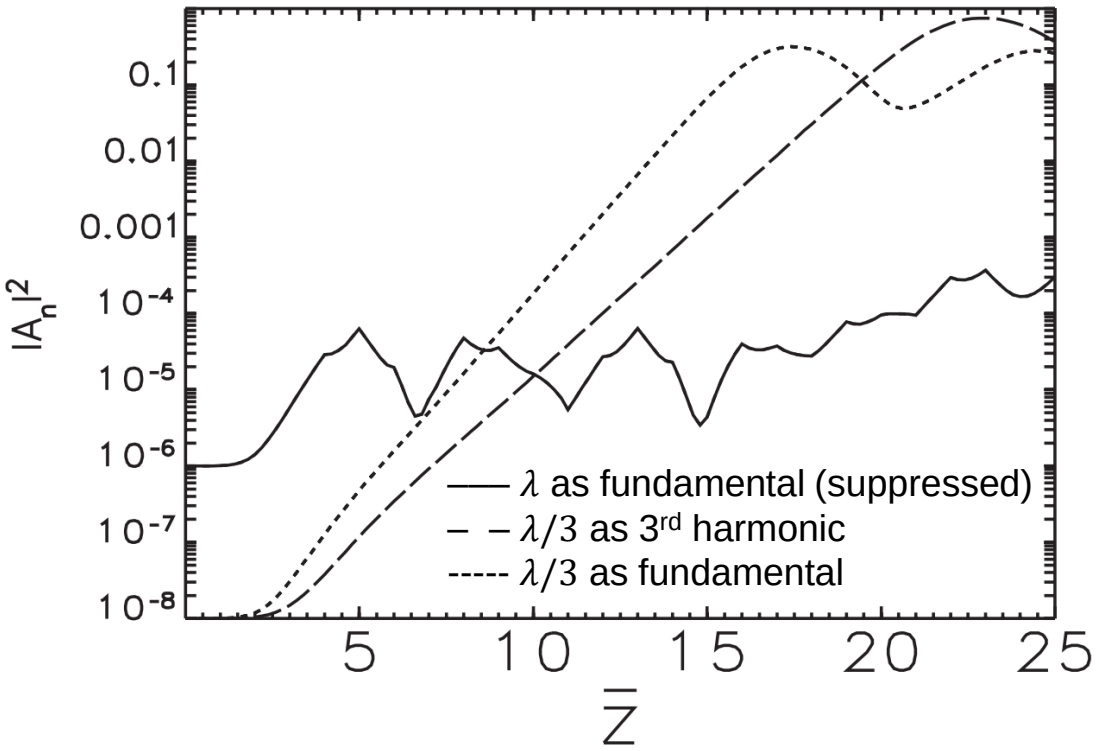


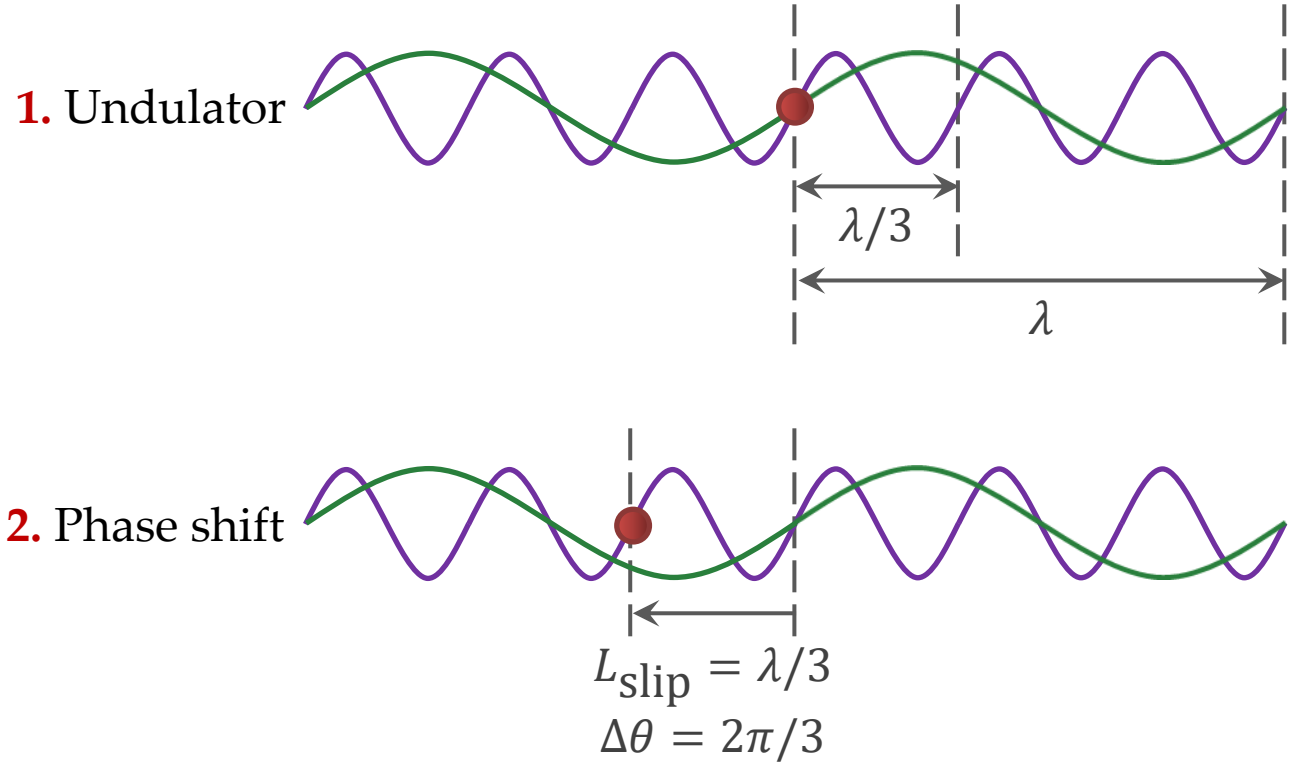


References

- Daniel Ratner *et al.*, *Proceedings of FEL 2007, Novosibirsk, Russia*, 69–72 (2007).
- Alan Mak *et al.*, *Physical Review Accelerator and Beams* **20**, 060703 (2017).

Harmonic Lasing

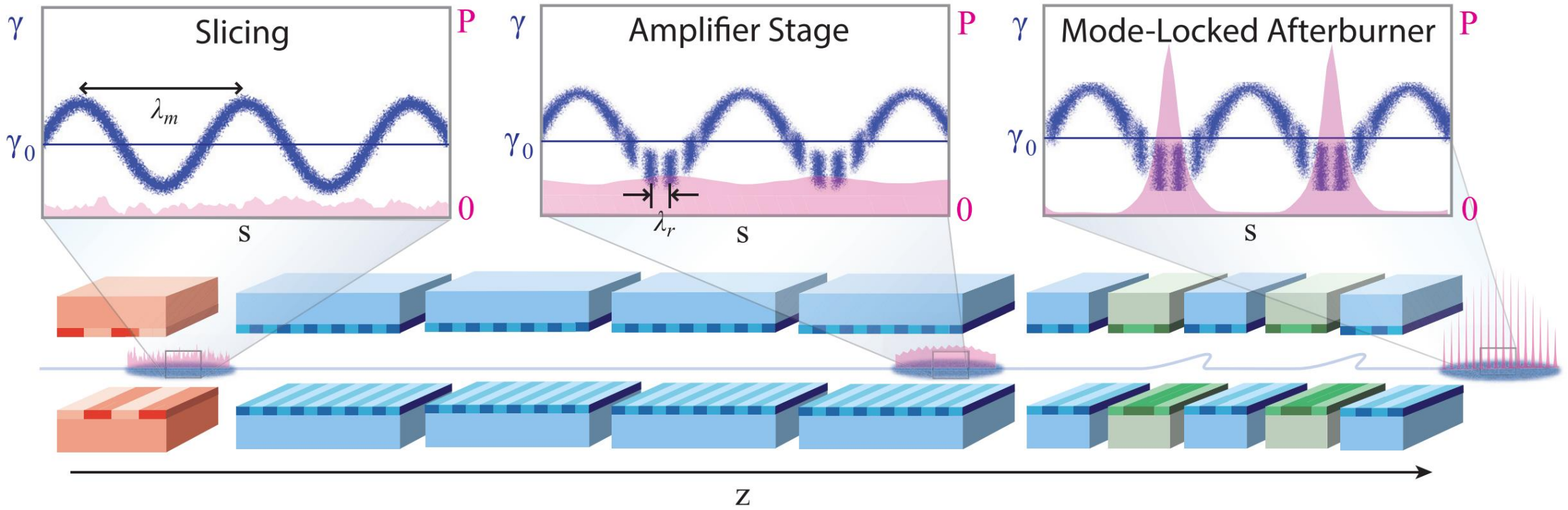




References

- Brian W. J. McNeil *et al.*, *Physical Review Letters* **96**, 084801 (2006).
- Evgeny A. Schneidmiller *et al.*, *Physical Review Accelerator and Beams* **24,** 030701 (2021).

Zeptosecond Light ($1\ \mathrm{zs} = 10^{-21}\ \mathrm{s}$)



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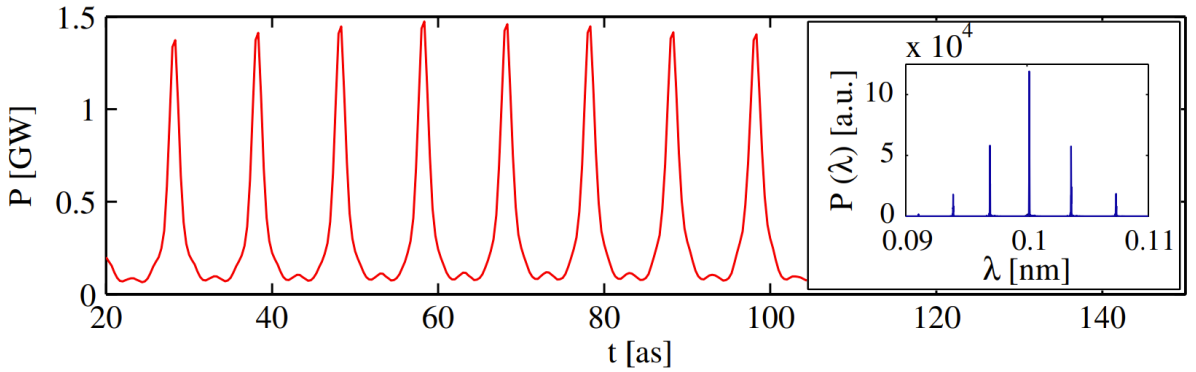
- David Dunning *et al.*, *Physical Review Letters* **110**, 104801 (2013).
- Alan Mak *et al.*, *Reports on Progress in Physics* **82**, 025901 (2019).



Summary

Science and Technology Facilities Council

Phase shifters in FELs

- **Purpose:** to control phase angle between electron and photon pulses
- **Principle:** delaying electrons with respect to photons, thus increasing slippage

Examples of applications

- Enhancing FEL power beyond saturation
- Lasing at harmonic whilst suppressing fundamental
- Generating trains of zeptosecond FEL pulses
- ⇒ Under consideration for the proposed UKXFEL

Not covered in this talk

- Harmonic-lasing self-seeding (HLSS)
- High-brightness self-amplified spontaneous emission (HB SASE)
- Recent experiments at PAL on two-colour lasing using phase shifters

Thank You