# Work Package 5: Undulators and light production

## Variable polarisation and design choices

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# Overview



Constraints on design and undulator technologies

Scenarios of variable polarisation

Study of feasibility of an after-burner(AB) for polarisation control
- Comparison with saturation length of SCU
- FEL performance and compactness
- Degree of polarisation

Concluding remarks

# Constraints on design and undulator technologies

# Constraints on undulator choice



- **Photon energy** $\Rightarrow$ Resonance condition, $\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + {a_{w_0}}^2\right)$.
- **Tuning across photon energies** $\Rightarrow$ *undulator scanning* (2 $\lambda$).
- **Two-colour operation** $\Rightarrow$ *independent of undulator technology*.
  - *Single undulator line* $\Rightarrow$ Multiple bunches
  - *Separate undulator lines* $\Rightarrow$ $\lambda$ tuning of 10-20%
- **Pulse duration down to 100 as**
  - *Independent of undulator technology*
  - Larger $\lambda$ in SXR $\Rightarrow$ Few cycle FEL pulses
    - Very short undulator modules.
    - Mode-locking afterburner.
    - Undulators with a strongly chirped undulator period
- **Repetition rate ($\approx$ 1 kHz) and $<$10 fs synchronization** $\Rightarrow$ *independent of undulator technology*
- **Variable polarisation**

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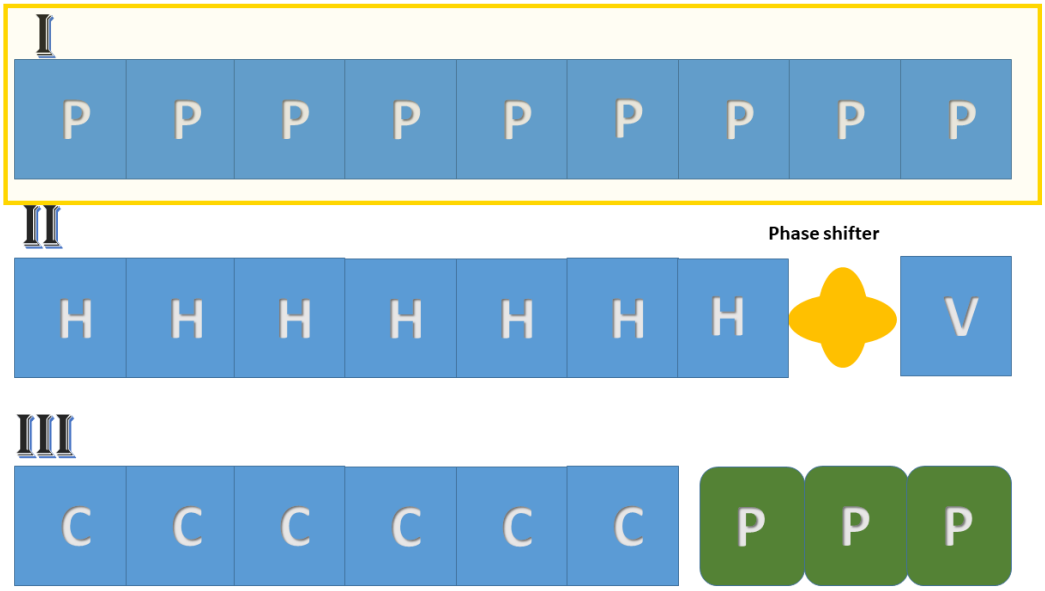
I. Variable polarization undulator for the full undulator line
   - Straight-forward
   - Not achievable for some technologies (e.g. CPMU and SCU).

II. Crossed undulator technique

III. Undulator plus after-burner(AB)

**Variable polarisation via beamline (not investigated)**



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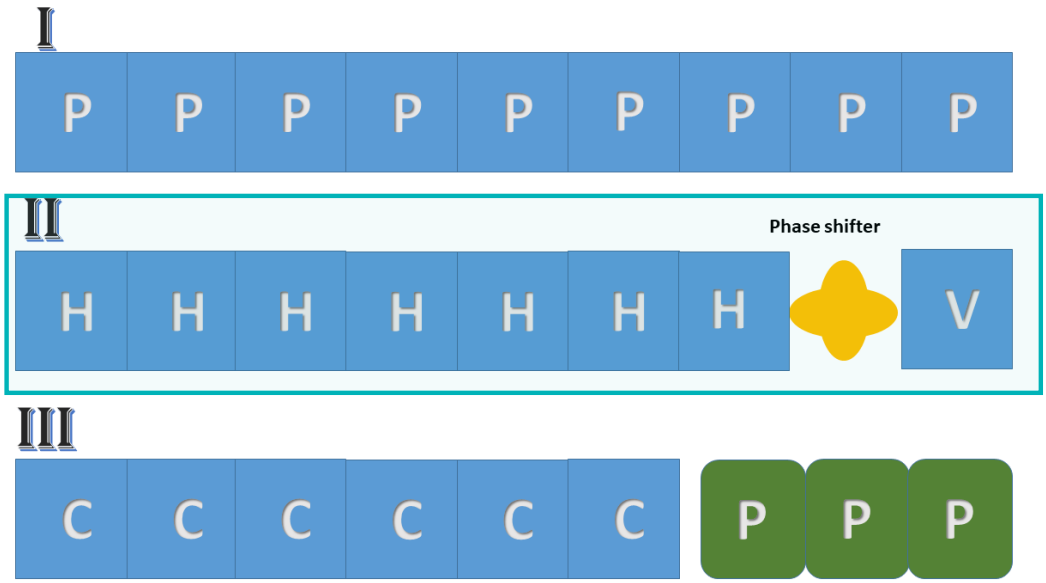

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III. Undulator plus after-burner(AB)
   - Any undulator can be used.
   - The afterburner then sets the shortest wavelength achievable.

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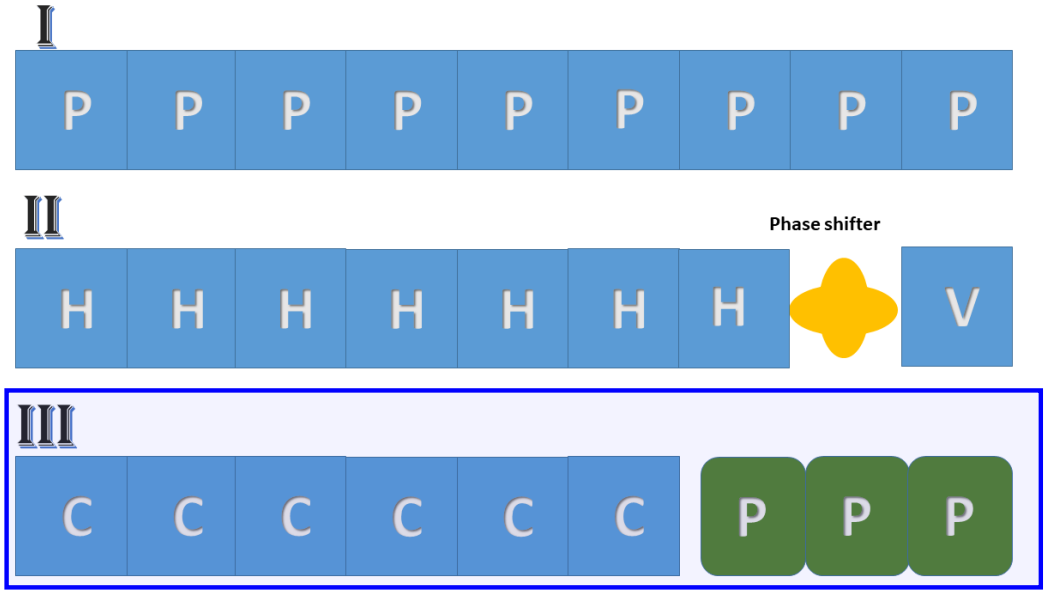


# Study of feasibility of an after-burner(AB) for polarisation control

# Afterburner option



Comparison between options (**I.**) and (**III.**) (helical SCU plus a delta planar AB) was done.

## Beam parameters

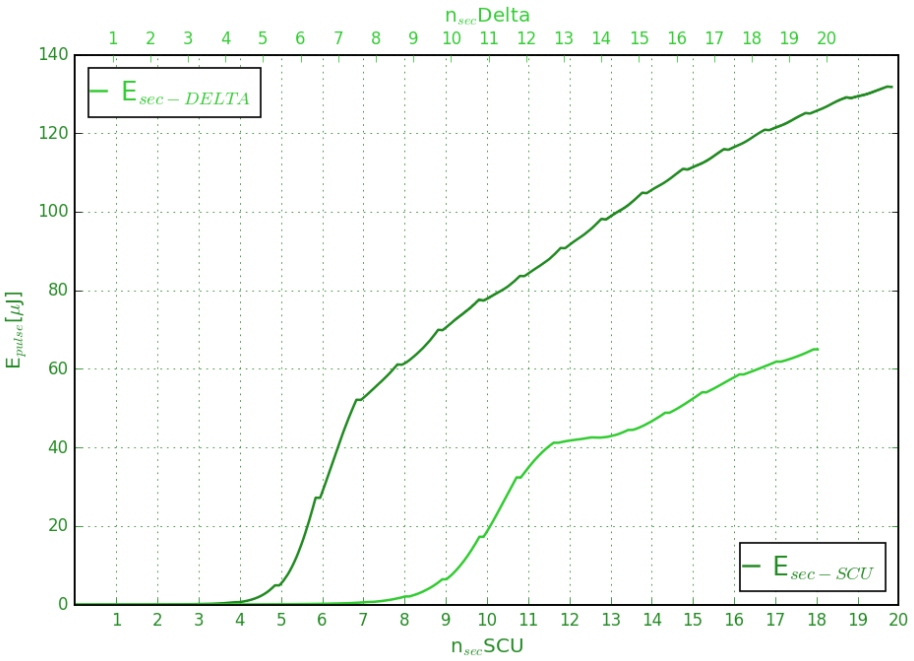
| **Electron beam parameter** | **Value** |
|---|---|
| **Beam Energy** | 5.5 GeV |
| **Peak Current** | 5 kA |
| **Normalised $\varepsilon_{x,y}$** | 0.2 mm-mrad |
| **RMS slice energy spread** | 0.01% |
| **Maximum Photon Energy** | 16 keV |
| **Average $\beta$ function** | 9 meters |

## Undulators parameters

| **Undulator type** | **$a_w$** | **$\lambda_u$ (mm)** | **$L_{section}$(m)** |
|---|---|---|---|
| **SCU** | 0.907 | 9.85 | 2.27 |
| **Delta planar(AB)** | 0.546 | 13.83 | 2.28 |

# $L_{AB}$ and $L_{sat\text{-}SCU}$ (Compactness)






## Length of AB

- GENESIS simulation of the scenario (**I.**), SCU and delta planar undulator.
- $L_{AB} < L_{\text{Delta-sat}} - L_{\text{SCU-sat}}$ .
- Scenario (**III.**) is more compact as long as the length of the afterburner is less than **13m**.

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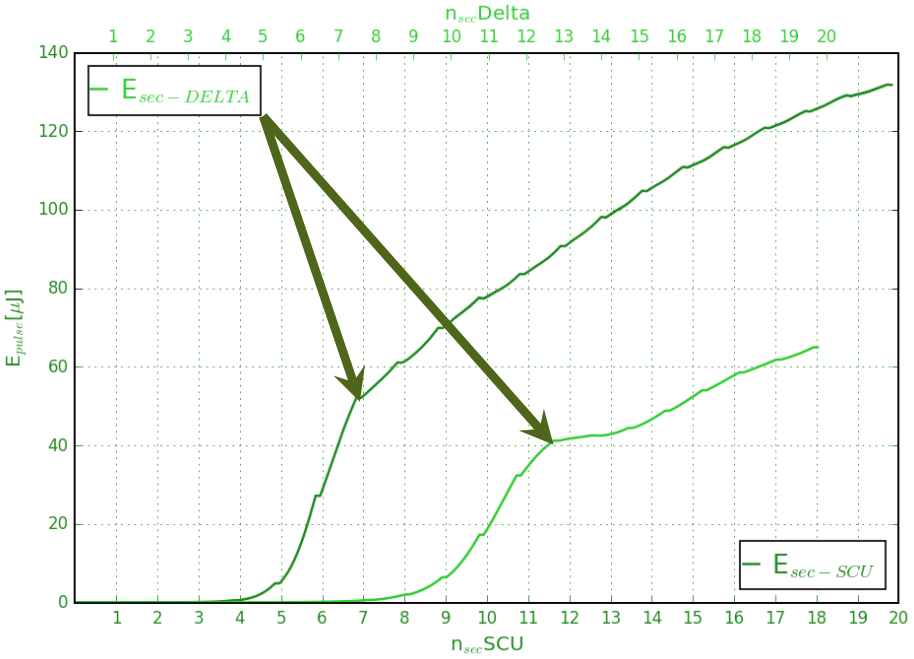


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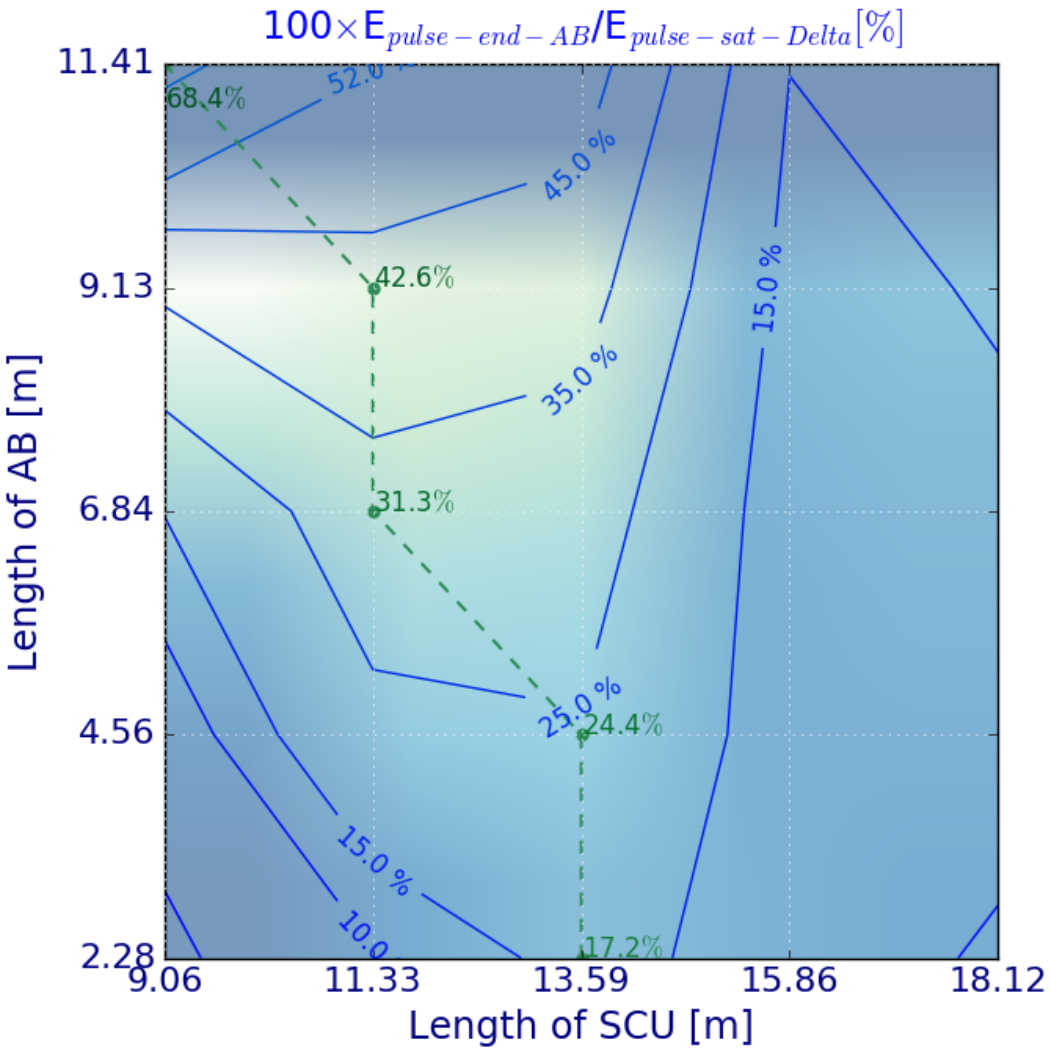
## GENESIS FEL figures of merits

| **Undulator type** | $L_{sat.}$ (m) | | $P_{saturation}$ (GW) | | $E_{pulse\text{-}sat.}(\mu J)$ | |
|---|---|---|---|---|---|---|
| | **SS** | **TD** | **SS** | **TD** | **SS** | **TD** |
| **SCU** | 21.85 | 15.61 | 15.37 | 9.53 | N/A | 52.11 |
| **Delta planar** | 36.24 | 29.13 | 3.52 | 7.53 | N/A | 41.19 |

# $L_{AB}$ and $E_{pulse\text{-}AB}$ (FEL performance)






## FEL performance

- $\Delta L = L_{\text{undulator-line}} - L_{\text{sat-Delta}}$
- $\eta_{\text{delta}} = 100 \times \max\left(E_{\text{pulse-end-AB}} / E_{\text{pulse-sat-Delta}}\right)$
- $E_{\text{pulse}}$ at the end of AB(- - ) $\rightarrow$ $17\% - 68.4\% \times E_{\text{sat-delta}}$ (41.19 $\mu$J).

| $L_{AB}$ (m) | $\Delta L$ (m) | $\eta_{\text{Delta}}$ |
|---|---|---|
| 2.28 | 10.9 | 17.2% |
| 4.56 | 8.7 | 24.4% |
| 6.84 | 6.4 | 31.3% |
| 9.13 | 4.1 | 42.6% |
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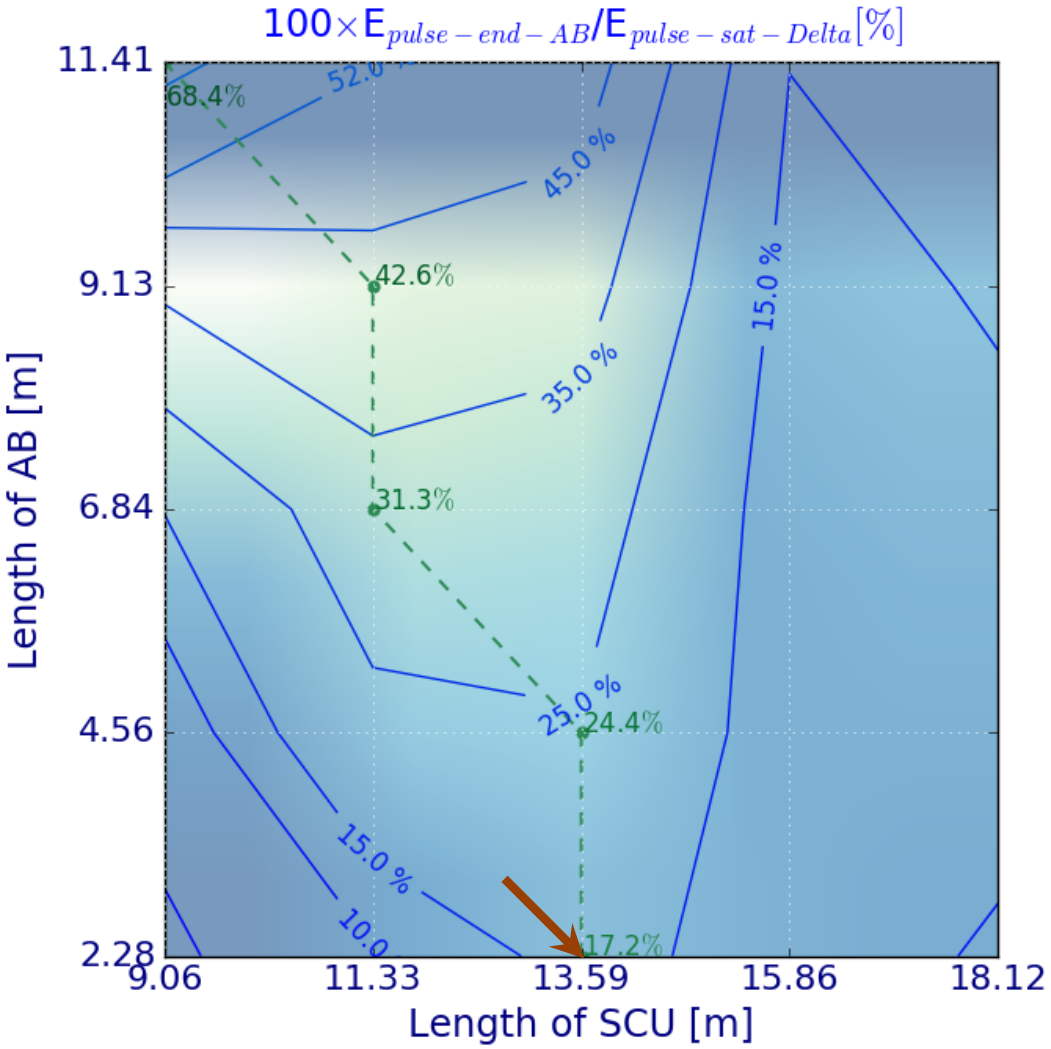


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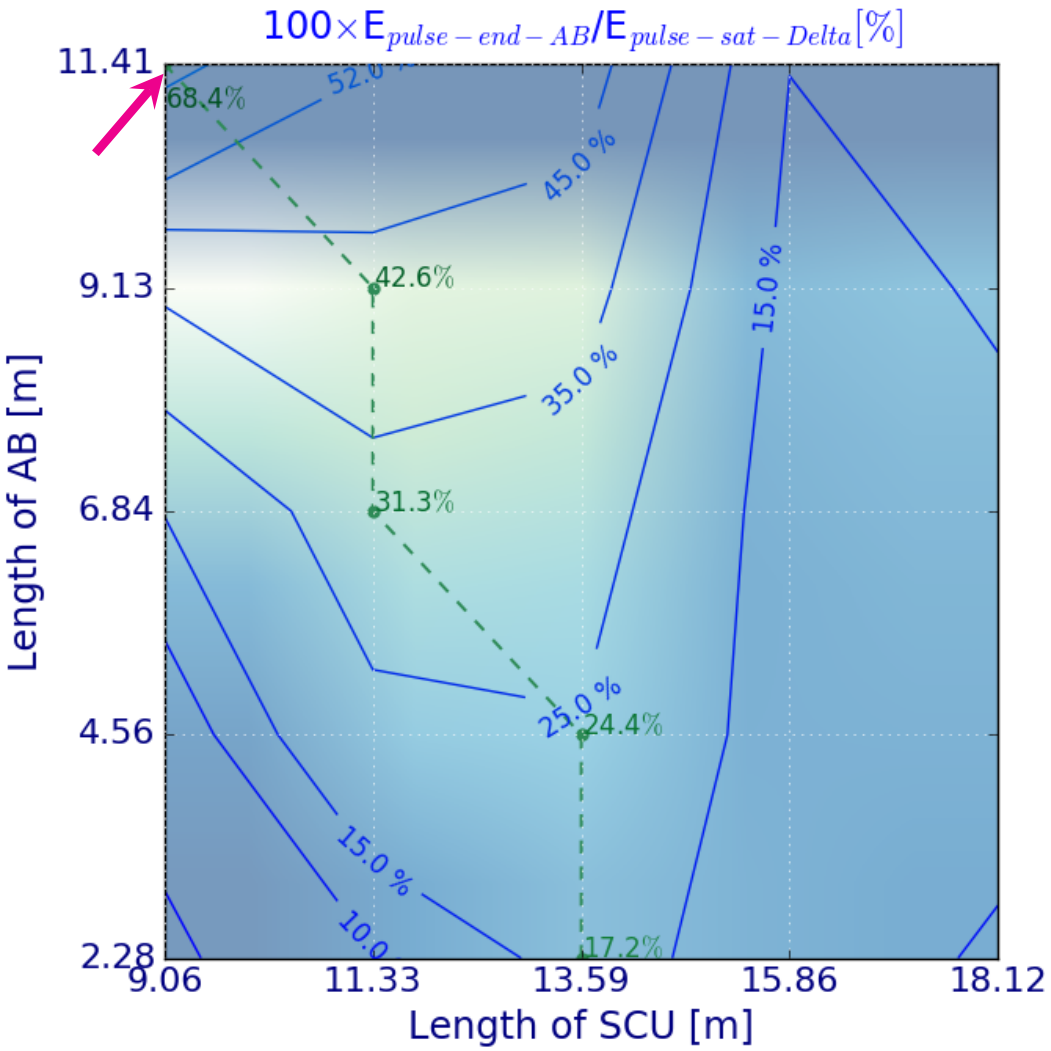


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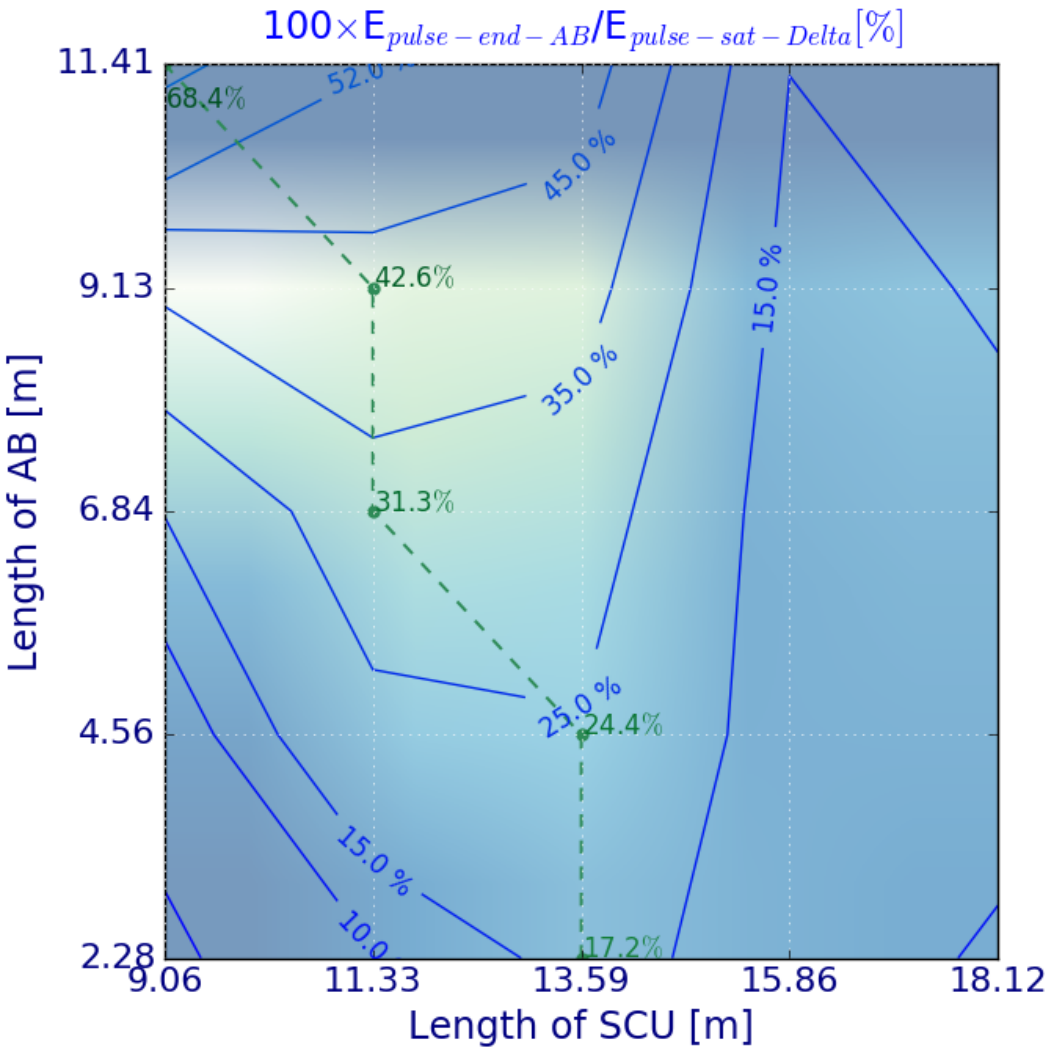


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# Degree of polarisation



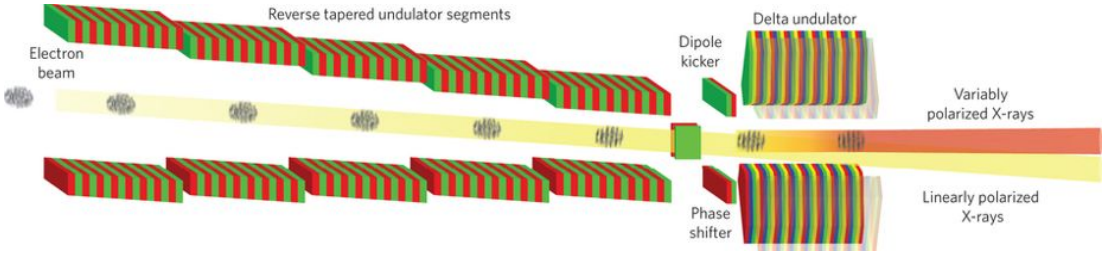


Figure: Reverse taper and beam diverting scheme to achieve variable polarisation[1, 2]

## Degree of polarisation

- Assumption: Radiation of the SCU is **blocked** $\Rightarrow$ AB Radiation 100% **linear**.

- Scheme using reverse taper and beam diverting technique demonstrated experimentally [1] (planar undulator and helical AB)
  - Bunching at the level at saturation at the end of the undulator.
  - Peak Power suppressed.

# Concluding remarks

## Constraints of undulator choice

- Constraint on photon energy given the resonance condition.
- Tuning across photon energies via undulator scanning ($2\lambda$)
- Two-colour operation (independent of undulator technology) ($\lambda$ tuning between 10 and 20 %)
- Pulse duration down to 100 as (few cycle FEL schemes for larger $\lambda$ in SXR. Otherwise, independent of undulator technology)
- Repetition rate and synchronisation independent of undulator choice

## Variable polarisation

- Variable polarisation undulator for the whole undulator line (not achievable for some technologies).
- Crossed undulator technique (low degree of polarisation)
- Undulator + AB (AB dictates $\lambda$ and maximum $E_{beam}$ of the facility)

## Helical SCU+Delta planar AB

- Experimentally demonstrated for planar undulator and helical AB [1].
- $L_{AB} < L_{\text{Delta-sat}} - L_{\text{SCU-sat}} \approx 13\text{m}$.
- FEL performance between 17% and 68.4 % $\times$ $E_{\text{pulse-Delta-sat}}$.
- Reduction in length of undulator line up to 10.9 meters.
- **A compromise between compactness and FEL performance shall be done.**

# References



A. Lutman et al.

"Polarization control in an X-ray free-electron laser"

*Nature Photonics* 10(468).

E. A. Schneidmiller and M. V. Yurkov

"Obtaining high degree of circular polarization at x-ray free electron lasers via a reverse undulator taper"

*Phys. Rev. ST-AB* 16, 110702(2013).

# Thank you!

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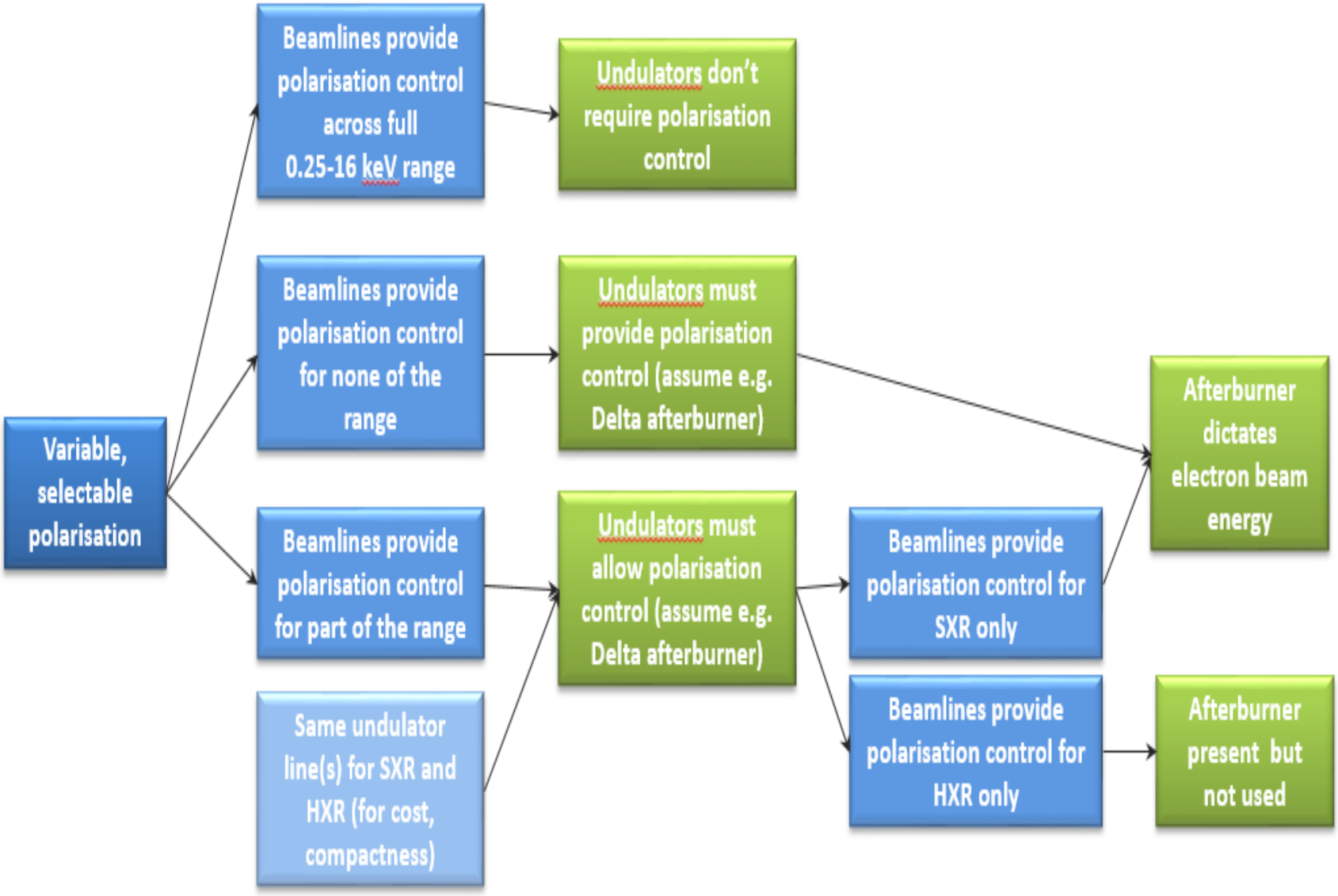
# Extra-slides

# Variable polarisations scenarios






Slide by David Dunning.