Bending Magnet & Insertion Devices

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MAX IV

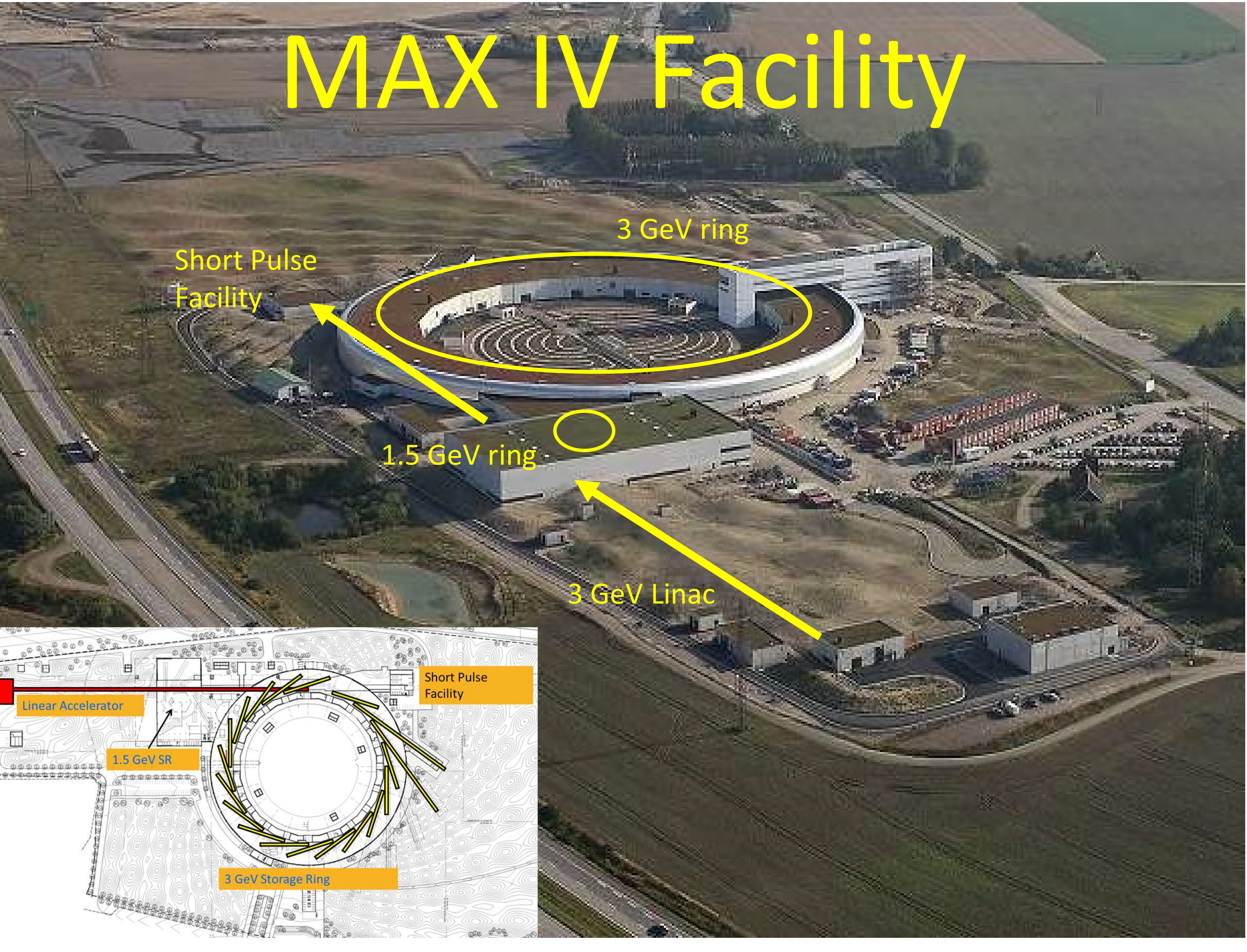
Bending Magnet & Insertion Devices

Outline:

- Synchrotron radiation (SR) sources.
- SR Characterstics
  - Photon Energy
  - Flux & Brilliance
  - Coherence
  - Polarization
- Insertion Devices (ID) Technologies.
- ID Performance.
- Magnetic Measurements Techniques.
- ID's Effect on Electron Beam.
- Summary.
- Bibliography.

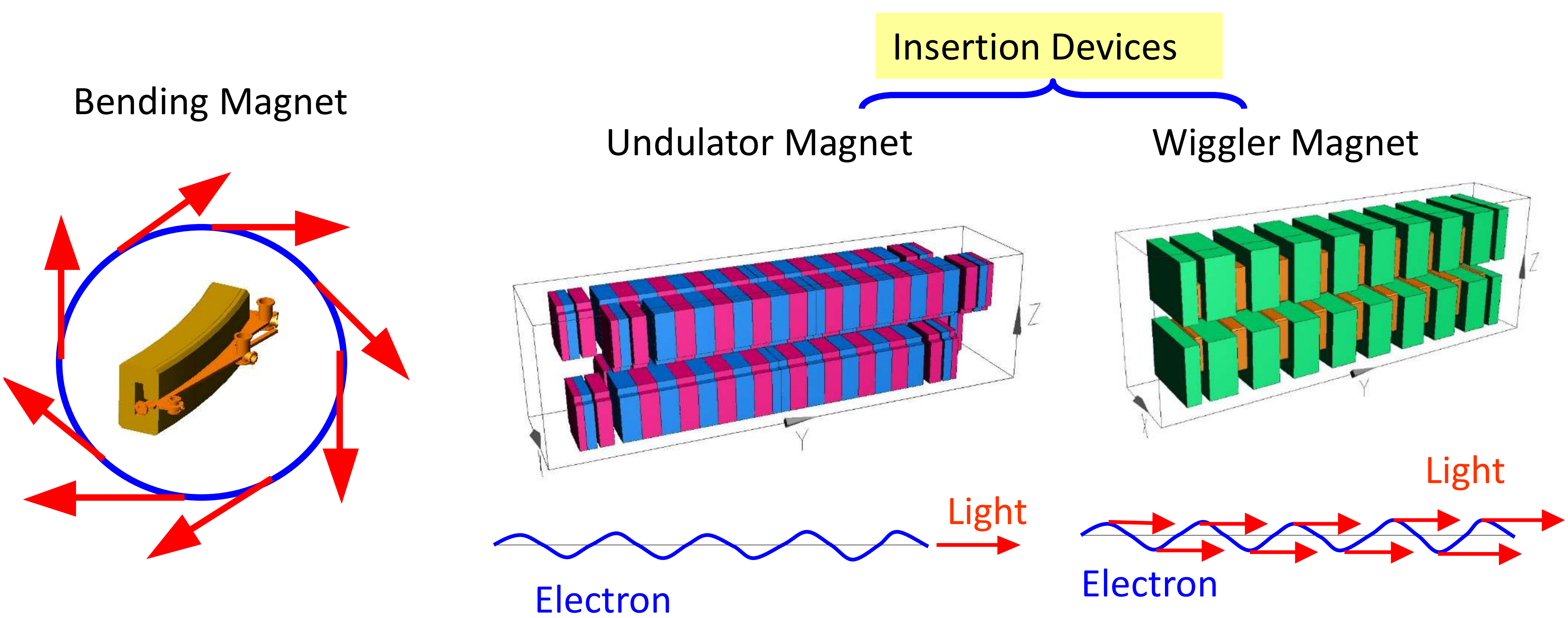
MAX IV

MAX IV Facility



Synchrotron Radiation Sources

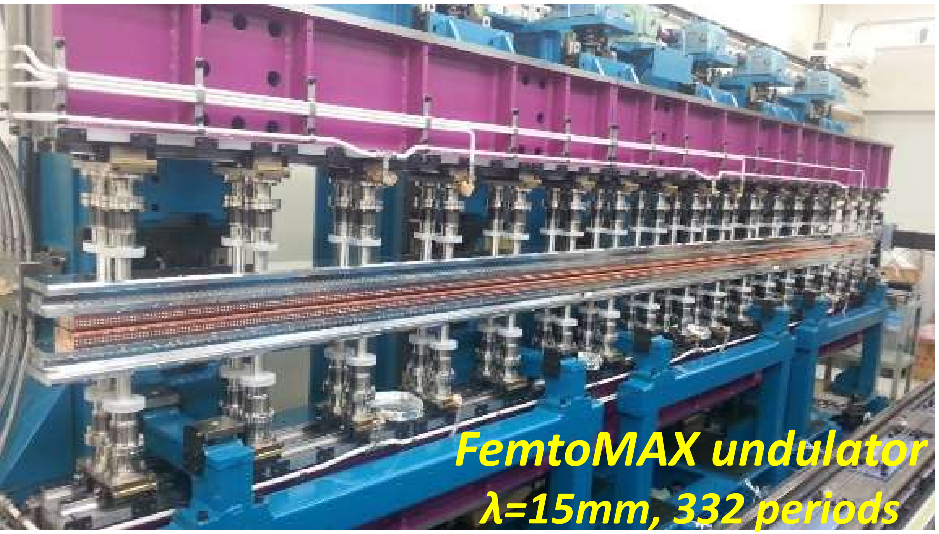
- Synchrotron Radiation is an electromagnetic radiation emitted when charged particles, Electrons, travel in a curved path. The electrons are moving under the influence of an electromagnetic force.
- Bending magnet and wiggler are producing continuous spectrum whereas undulator is producing quasi-monochromatic spectrum.

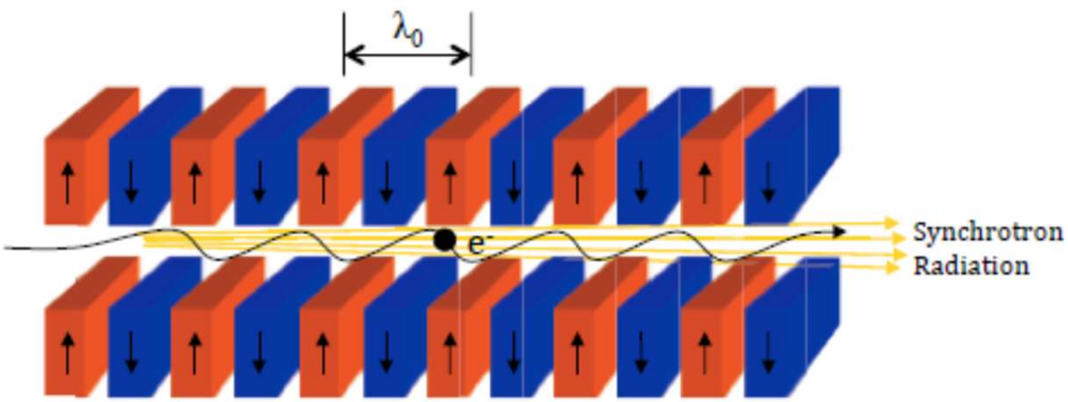


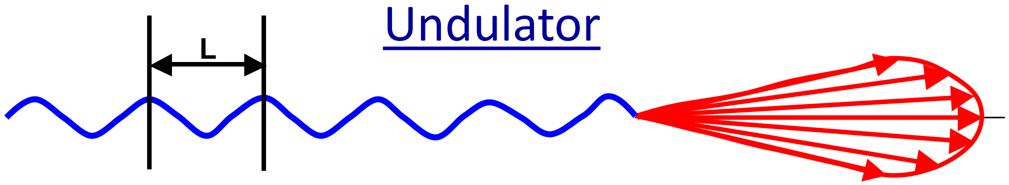
Undulator & Wiggler

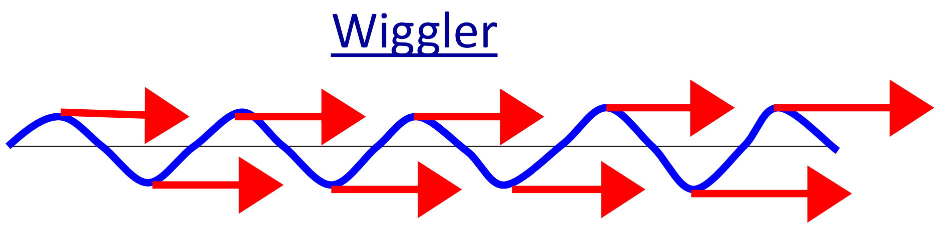
- Undulator and wiggler are periodic array of magnetic poles providing an alternating magnetic field on axis for the production of synchrotron radiation.
- The wiggler and undulator are characterized by period length and the deflection parameter K for the production of certain photon energy (wavelength) range.

$$K = 93.3737\lambda_0[\mathrm{m}]\mathrm{B}_0[\mathrm{T}] \qquad \lambda_n = \frac{\lambda_0}{2n\gamma^2}\left(1 + \frac{K^2}{2}\right)$$







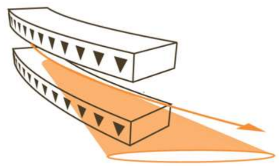


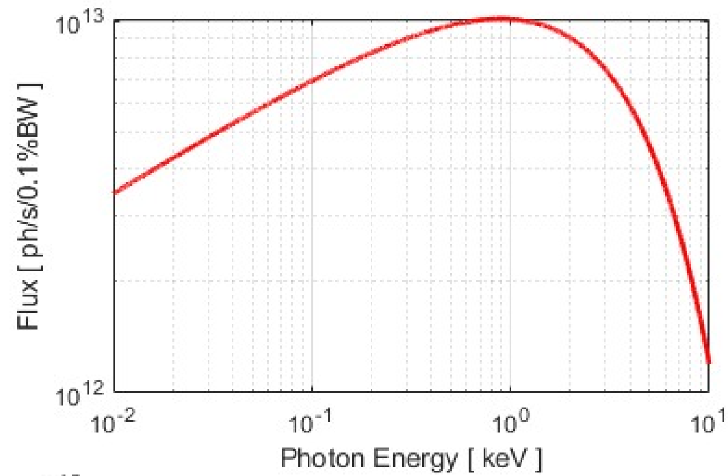
MAX IV

Example: MAX IV 3 GeV ring

Bending Magnet:

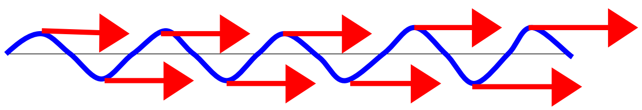
0.523 Tesla Bending Field

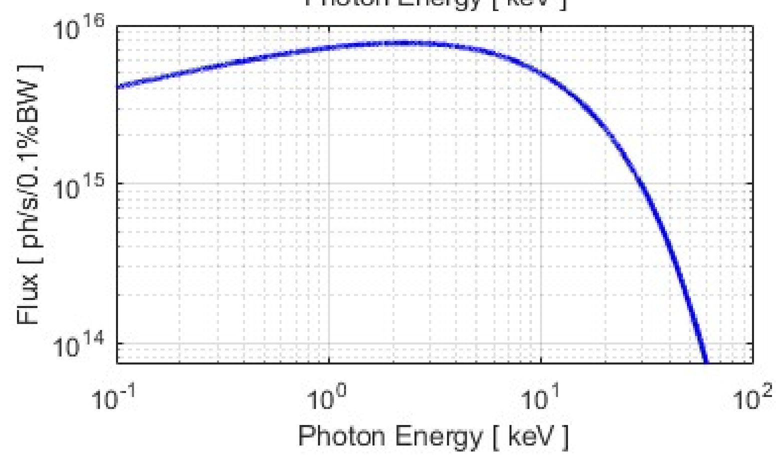




Wiggler:

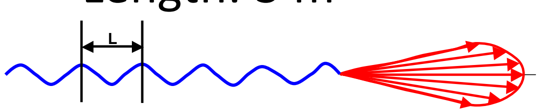
Period length: 50 mm
K-value: 9.0
Length: 2 m

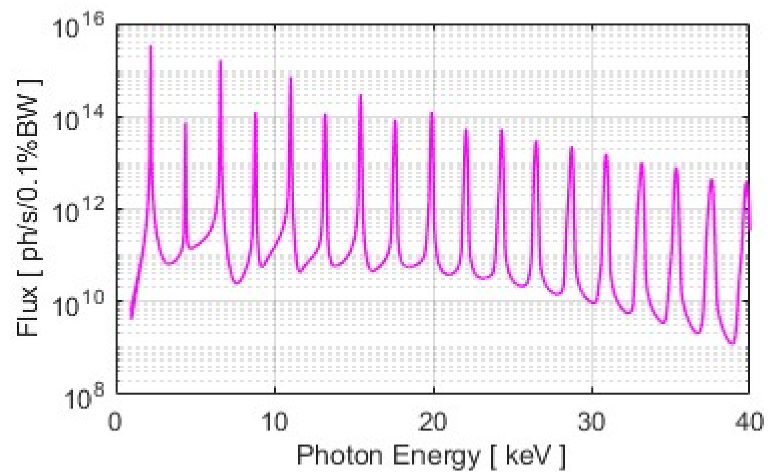




Undulator:

Period length: 16 mm
K-value: 1.7
Length: 3 m





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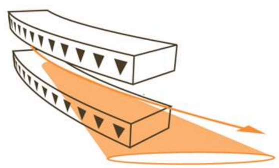

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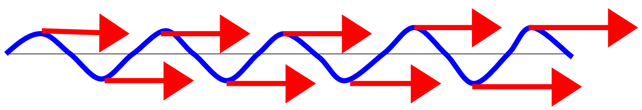

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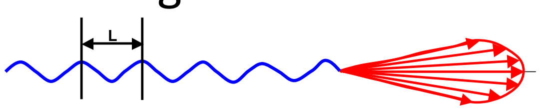

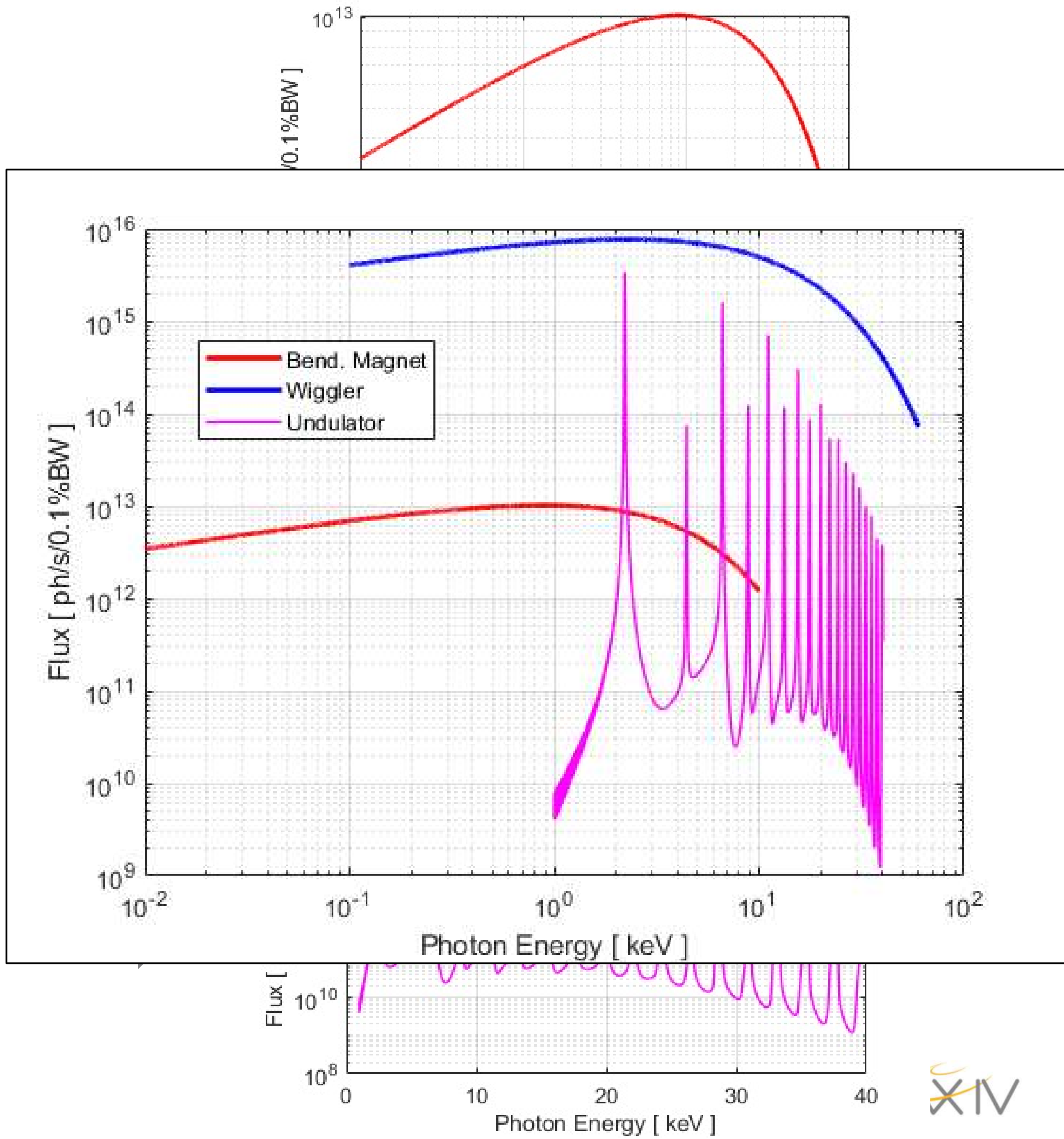

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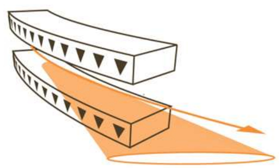

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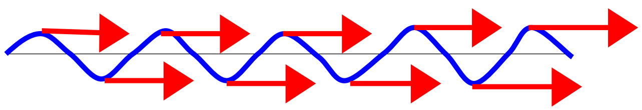
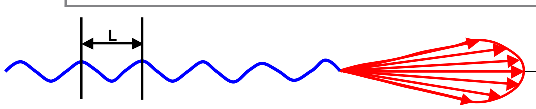
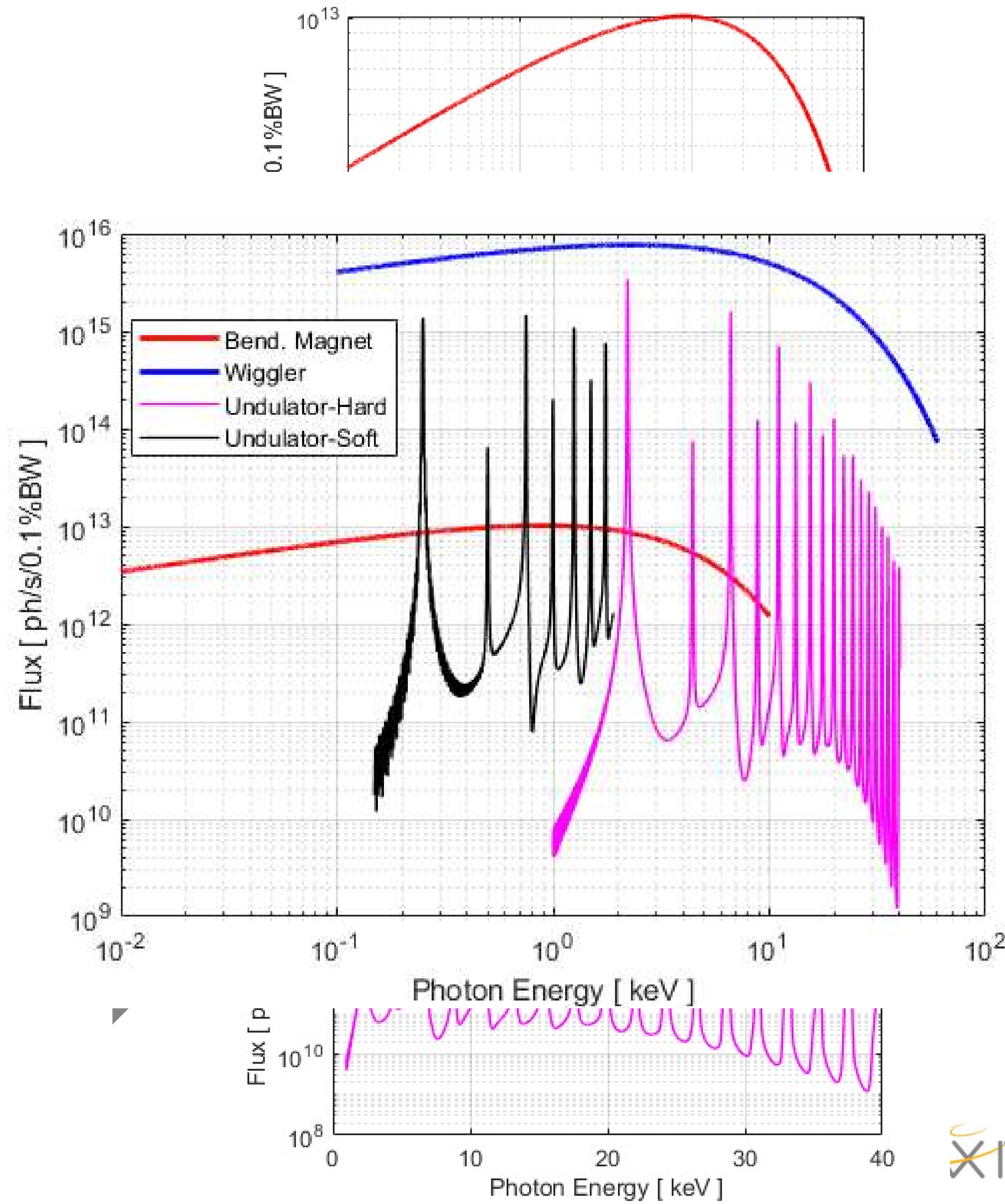


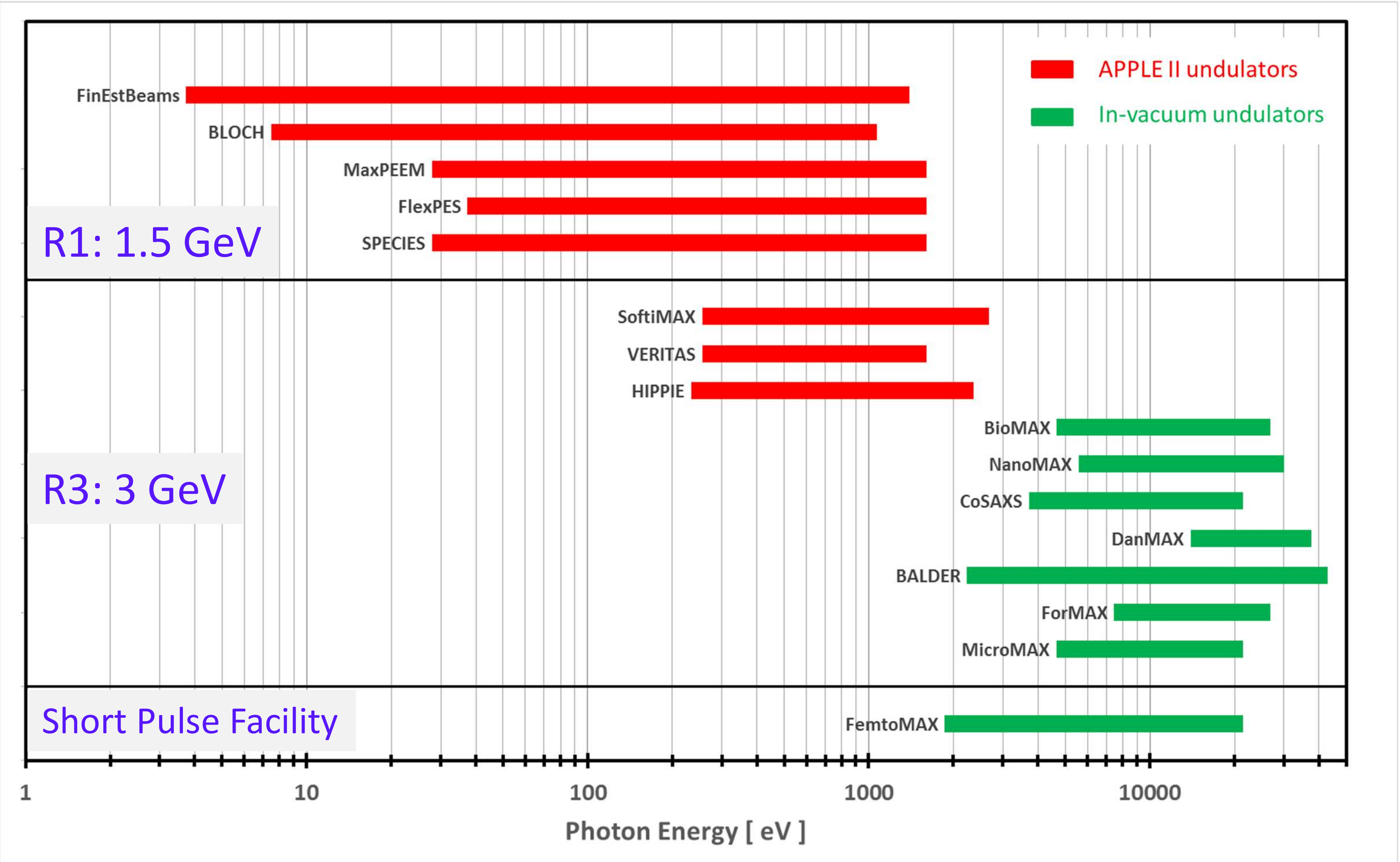
Undulator:

	'Hard'	'Soft'
λ, mm	16	53
K	1.7	3.3
L, m	3	4



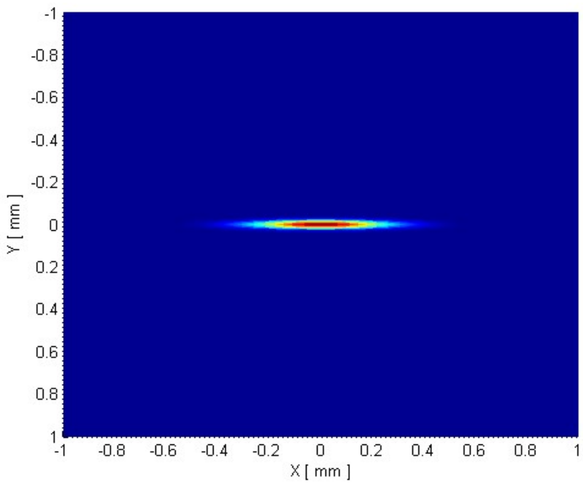


Beamlines @ MAX IV: A Portfolio

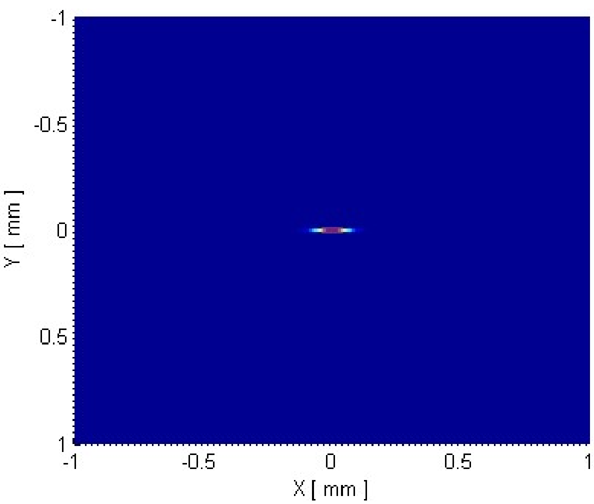


Flux, Brilliance & Coherence

Beam spot size at MAX IV 1.5 GeV ring at the center of undulator



Beam spot size at MAX IV 3 GeV ring at the center of undulator



$$\mathbf{Spectral\ Flux} = \frac{\mathbf{Number\ of\ Photons}}{(\mathbf{Time\ [sec]}).(\mathbf{0.1\%\ bandwidth})}$$

$$\boldsymbol{Brilliance} = \frac{\boldsymbol{Spectral\ Flux}}{(2\pi)^2 \sigma_{Tx} \sigma_{Tx'} \sigma_{Ty} \sigma_{Ty'}}$$

Total Horizontal Beamsize:

$$\sigma_{Tx} = \sqrt{\sigma_x^2 + \sigma_\gamma^2}$$

Electron beam Size

Photon beam Size

Total Horizontal Divergance:

$$\sigma_{Tx'} = \sqrt{\sigma_{x'}^2 + \sigma_{\gamma'}^2}$$

Electron beam Divergence

Photon beam Divergence

$$\boldsymbol{Coherence\ Fraction} = \frac{\lambda^2/(2\pi)^2}{\sigma_{Tx} \sigma_{Tx'} \sigma_{Ty} \sigma_{Ty'}}$$

List IDs @ MAX IV

Accelerator	*Beamline ID*	*ID Type*	*λ_U[mm]*	*Length [m]*	*K_{eff}-value*	*Magnetic Gap [mm]*	*ID Status (Jan. 2023)*
3 GeV Ring	BioMAX	IVU	18	2	2	4.2	Available for Users
	NanoMAX	IVU	18	2	2	4.2	Available for Users
	Hippie	APPLE II	53	4	3.3	11	Available for Users
	Veritas	APPLE II	48	4	3.3	11	Available for Users
	BALDER	IV Wiggler	50	2	9	4.5	Available for Users
	CoSAXS	IVU	19.3	2	2.2	4.2	Available for Users
	DanMAX	IVU	16	3	1.66	4	Available for Users
	SoftiMAX	APPLE II	48	4	3.3	11	Available for Users
	ForMAX	IVU	17	3	1.85	4	Available for Expert Users
	MicroMAX	IVU	18	3	2.0	4.2	Beamline Commissioning
1.5 GeV Ring							
	ARPES	Q-APPLE II	84	2.6	8.65	14	Available for Users
	FinEstBeam	APPLE II	95.2	2.6	10.4	14	Available for Users
	SPECIES	APPLE II	61	2.6	4.85	16	Available for Users
	MAXPEEM	APPLE II	58	2.6	4.95	14	Available for Users
	FlexPES	Planer	54.4	2.6	4.2	16	Available for Users
SPF 3 GeV Linac	FemtoMAX	IVU	15	5x2	2.2	2.2	Available for Users

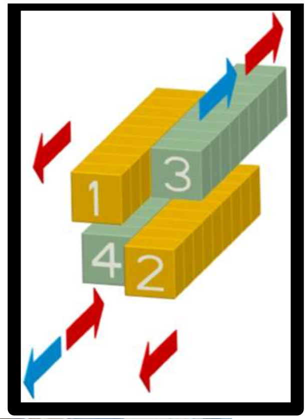
*) Built by collaboration with SOLEIL synchrotron

*) Built by industry (In-vacuum Undulators)

*) Built in-house (APPLE II)

*) Transfer from MAX-II ring (characterized at MAX IV ID magnet lab)

Permanent Magnet Technolgy



Pure Permanent Magnet Technologies (Out-of-vacuum) for VUV-Soft X-ray beamlines (4 – 2000 eV). Hybrid structure of magnet and iron pole is also utilized.

Period-lengths between 48 mm to 95 mm and minimum magnetic gap of 11 mm.

Examples:

Period Length	Ring	Min. gap	Max. K value	Length	Energy Range
95.2 mm	1.5 Gev	14 mm	10.2	2.6 m	4 – 200 eV
48 mm	3 GeV	11 mm	3.33	4 m	275 – 1600 eV

Features:

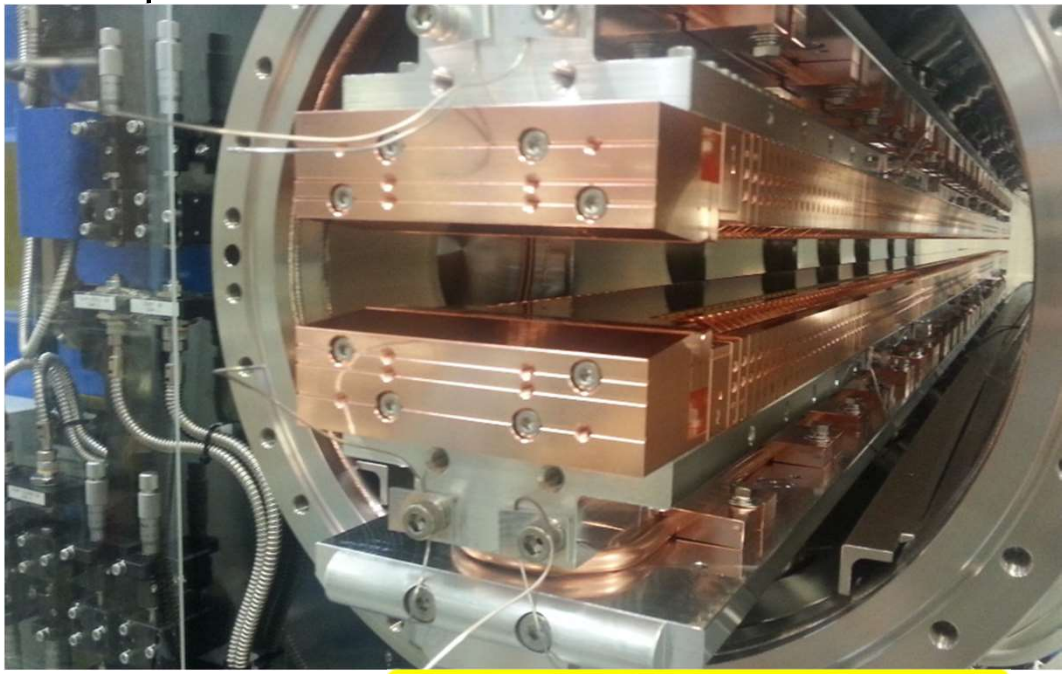
High flux & briliance, high degree of Coherence, variable polarization & quasi-periodic structure for heat-load management.

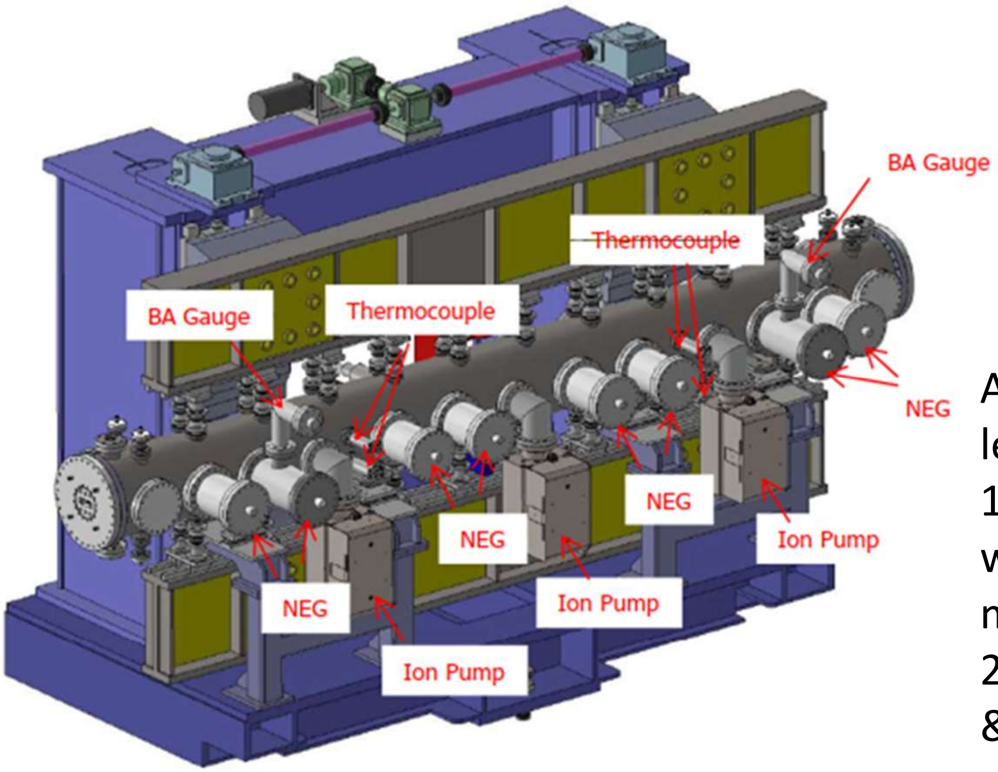
MAX IV

In-vacuum Technology

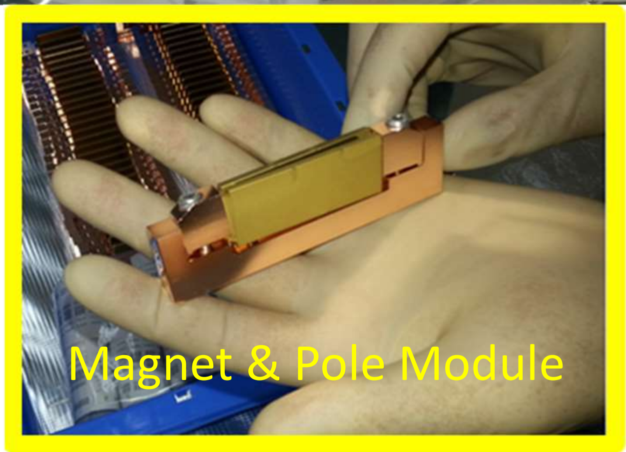
- Short magnet period of an undulator is desired for experimental stations using hard X-rays. The magnet arrays are installed inside the vacuum chamber.
- The 'In-vacuum Undulator' (IVU) magnetic circuit could be made out of pure permanent magnet or hybrid, i.e., Magnet & Iron pole.

- The operation of IVU could be at room temperature or at cryogenic temperature to gain more magnetic strength and stability.





At MAX IV, period lengths ranges from 15 mm to 19.3 mm with minimum magnetic gap around 2.2 mm at Linac's ID & 4 mm at ring's ID.



Magnet Technologies

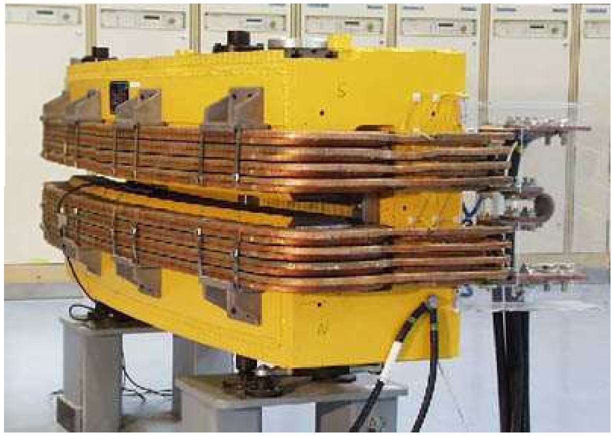
Compact APPLE X @ MAX IV

More radiation sources:

1. Electromagnets:
   - Bending magnet.
   - Undulator & Wiggler.

   More efficient for long period ID or fast polarization switching in helical undulators. Cooling limitation on magnetic field strength.
2. Bending Magnet based on permanent magnets.
3. Superconducting magnets.
   - Bending magnet (Superbends).
   - Wiggler for high flux.
   - Undulator for short period and high K value.
4. And more.
   - Revolver IV undulator
   - Delta Undulator
   - …

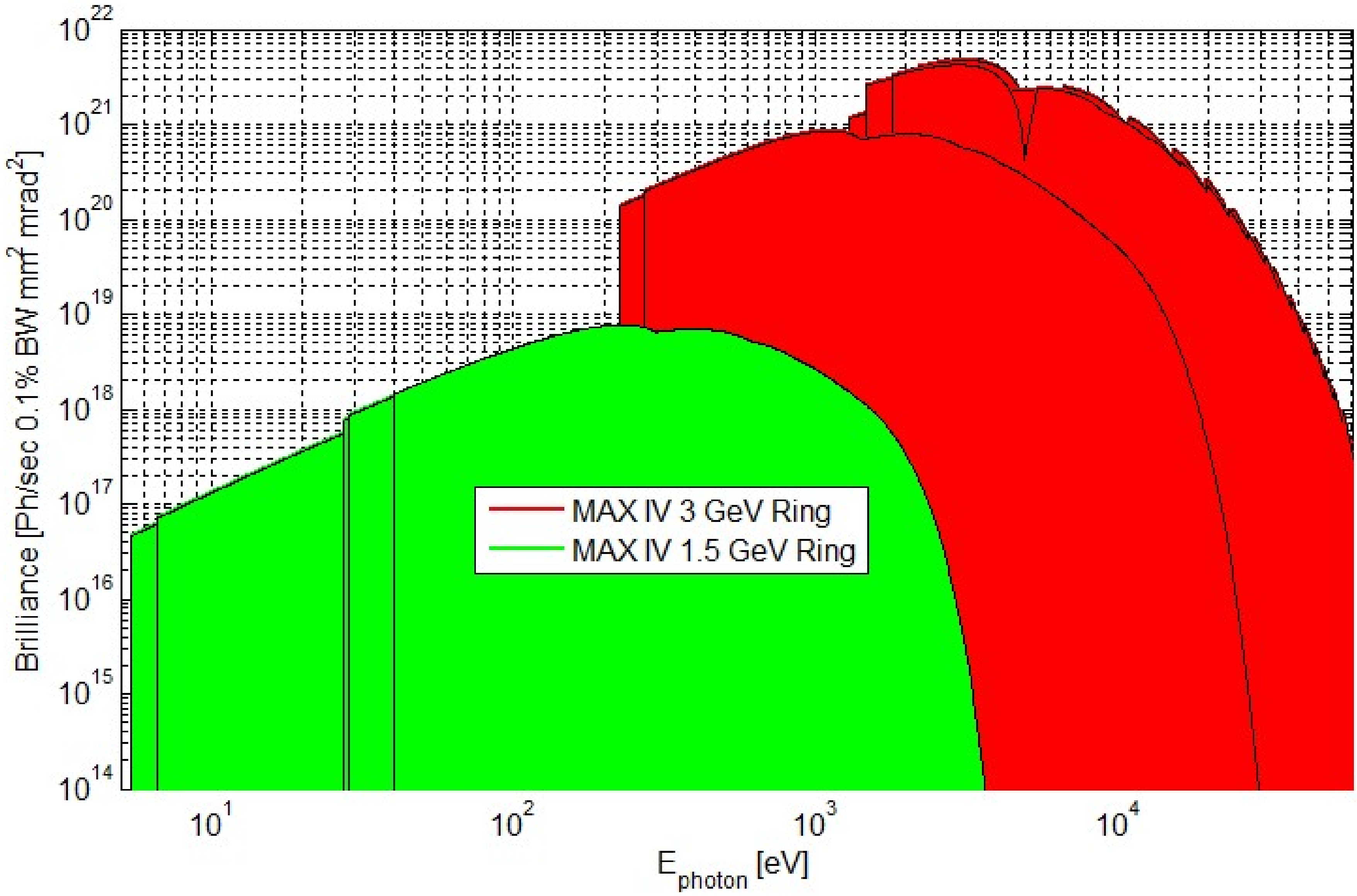
ALBA bending magnet



Helical Undulator at SOLEIL

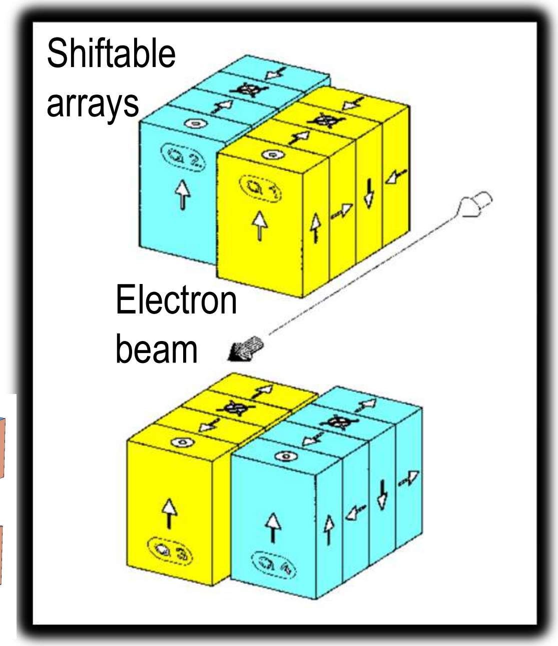
MAX IV

Brilliance @ MAX IV Rings

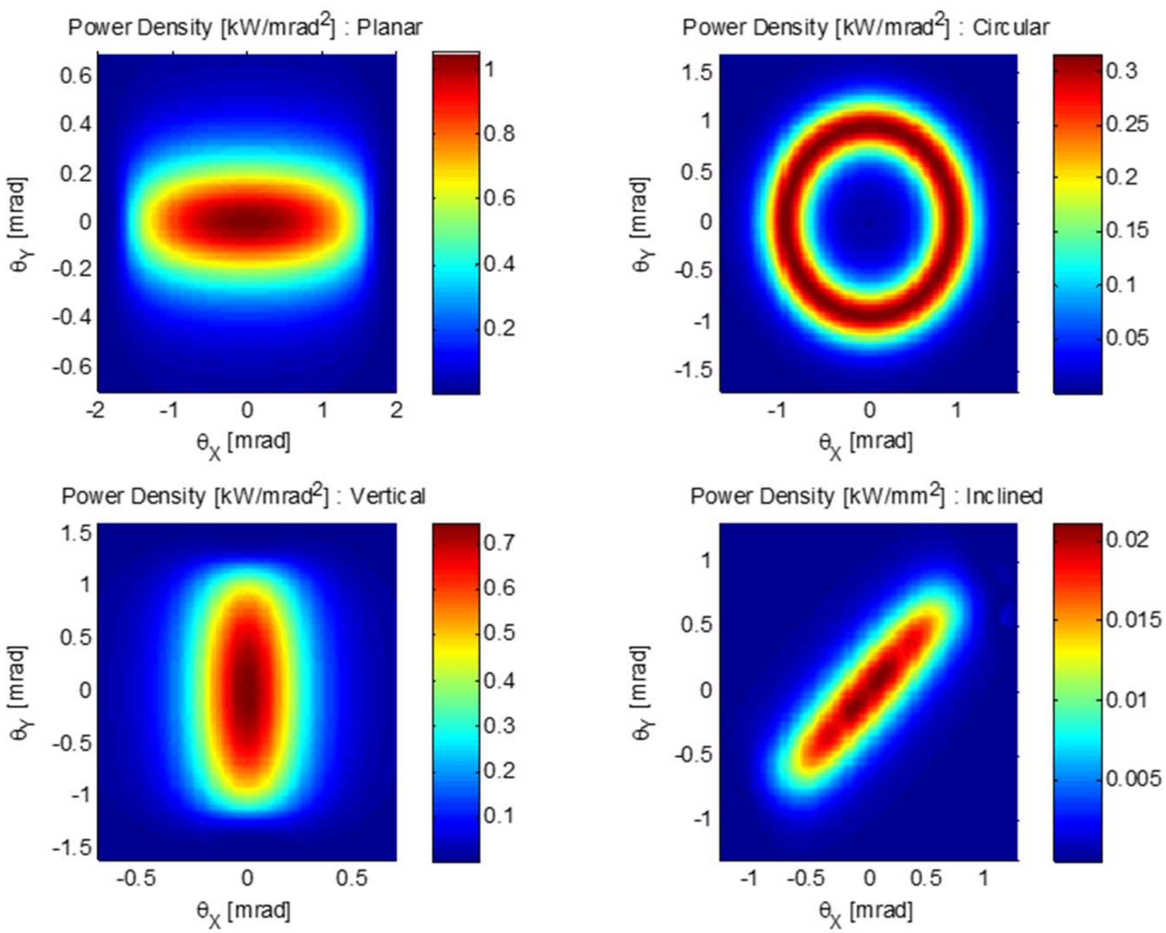


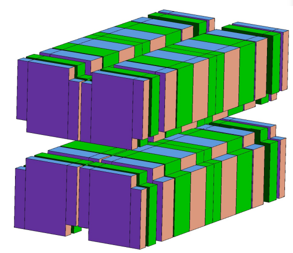
Polarization

- Beamline requirements for variable polarization, elliptical and/or linear, is achievable by many magnetic configurations, most commonly used the APPLE II configuration. It enables polarization switching too.



Radiation pattern from an APPLE II undulator





- Other configurations do exist:

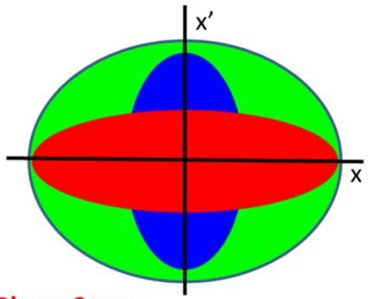
Crossed undulators, Bifilar Helix, APPLE-Knot and helical electromagnet.

Coherence

The small emittance of electron beam, the length of the undulator and the β function at ID location enable better matching of the electron and photon phase spaces to enhances significantly the transverse coherence of the photon beam from an ID.

Mis-matched

Apparent source size is not optimal



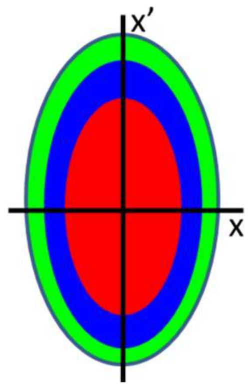
Electron Phase Space

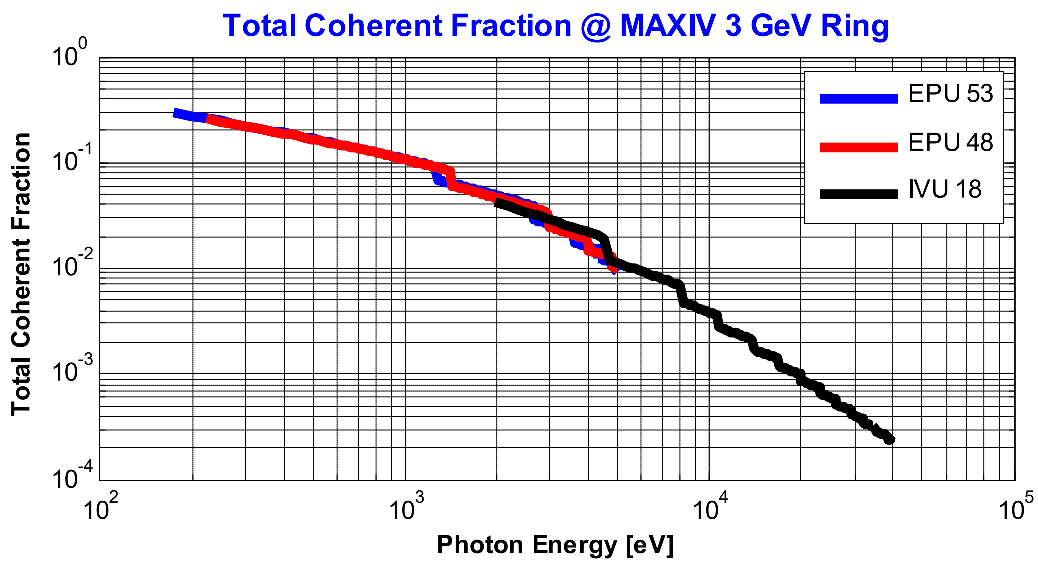
Photon Phase Space

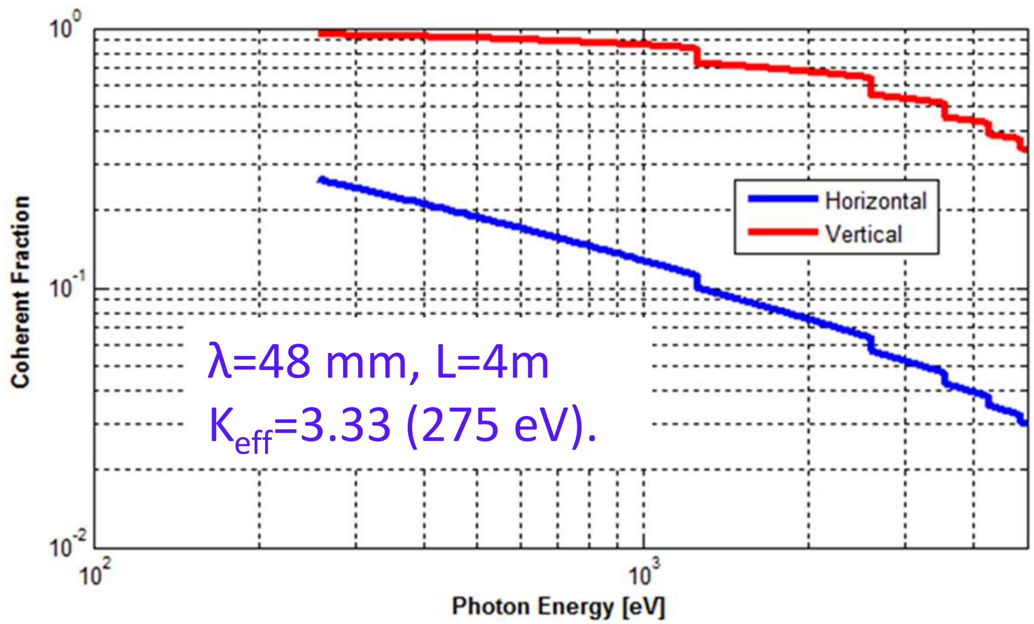
Combined Phase Space

Matched

Optimal source size, Max. brilliance







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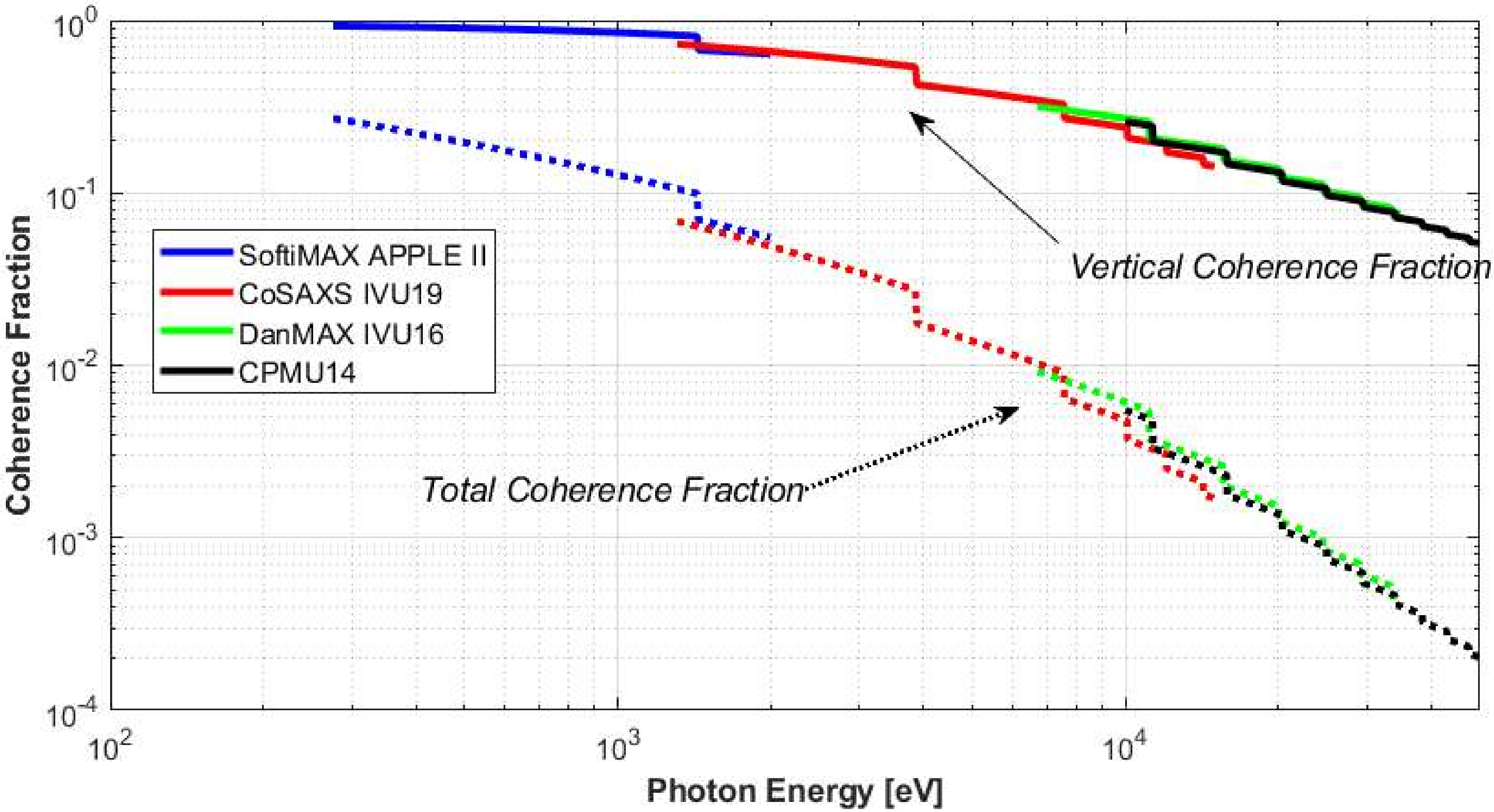
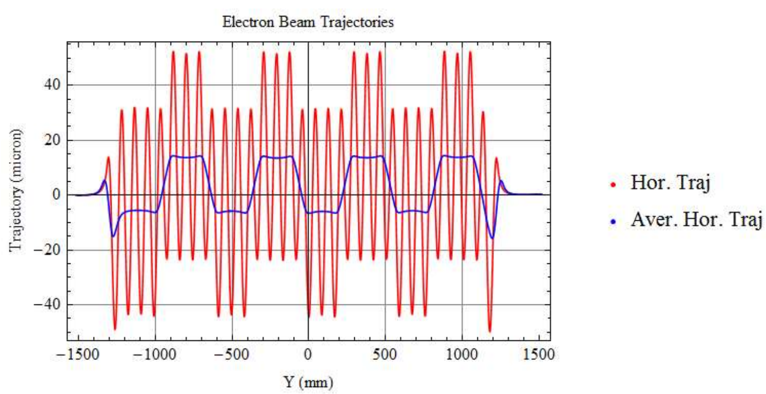
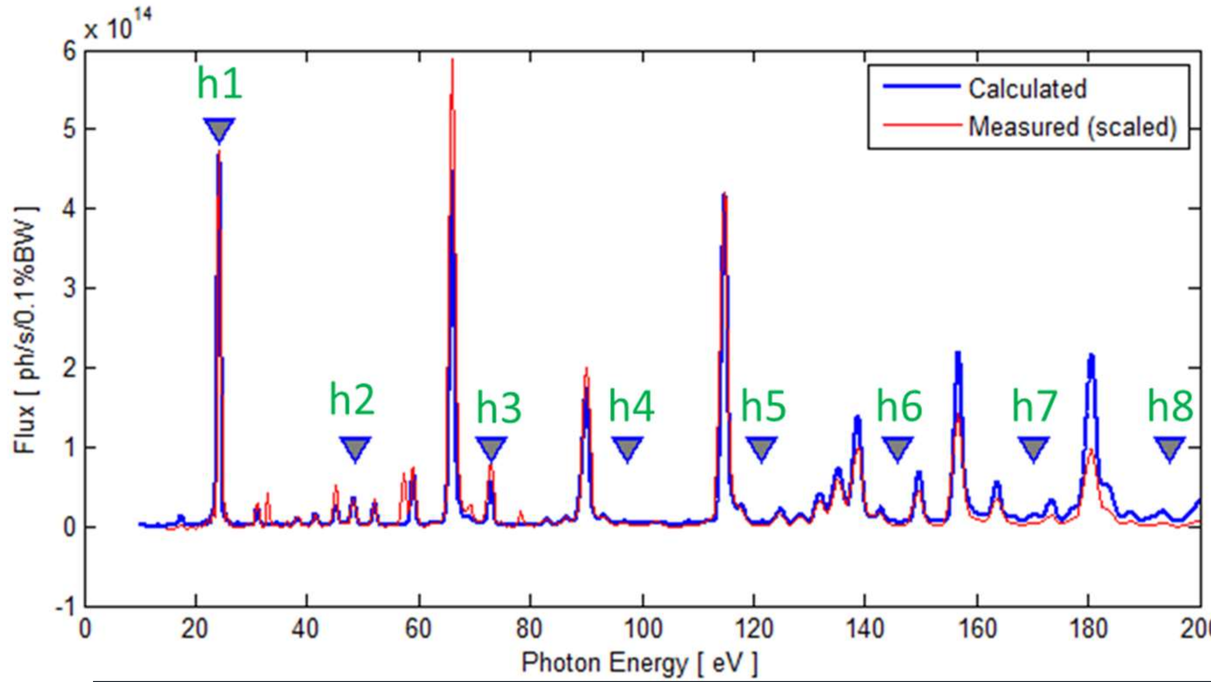
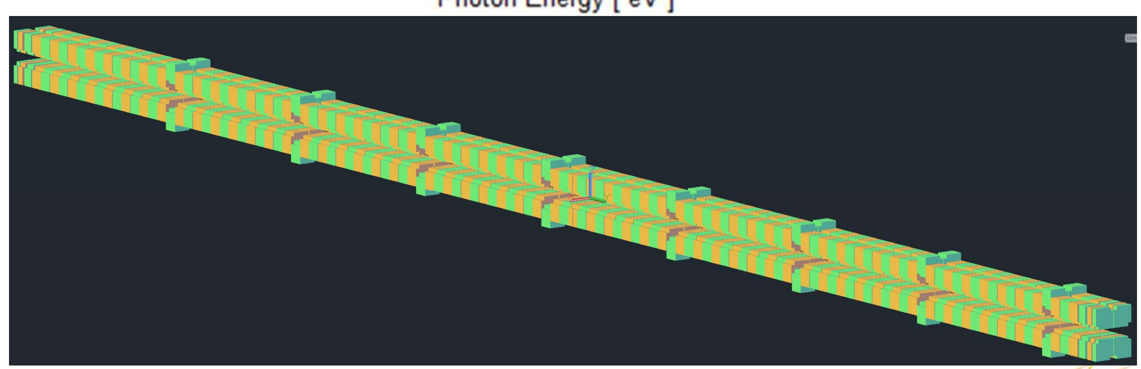


Quasi-periodic Undulator

- The on-axis radiation power for the low photon energy beamlines creates heating problems. The periodic magnetic field is modified by introducing quasi-periodicity.
- The qauasi-periodic motion of the electron beam leads to irrational higher harmonics, i.e., harmonic suppression.







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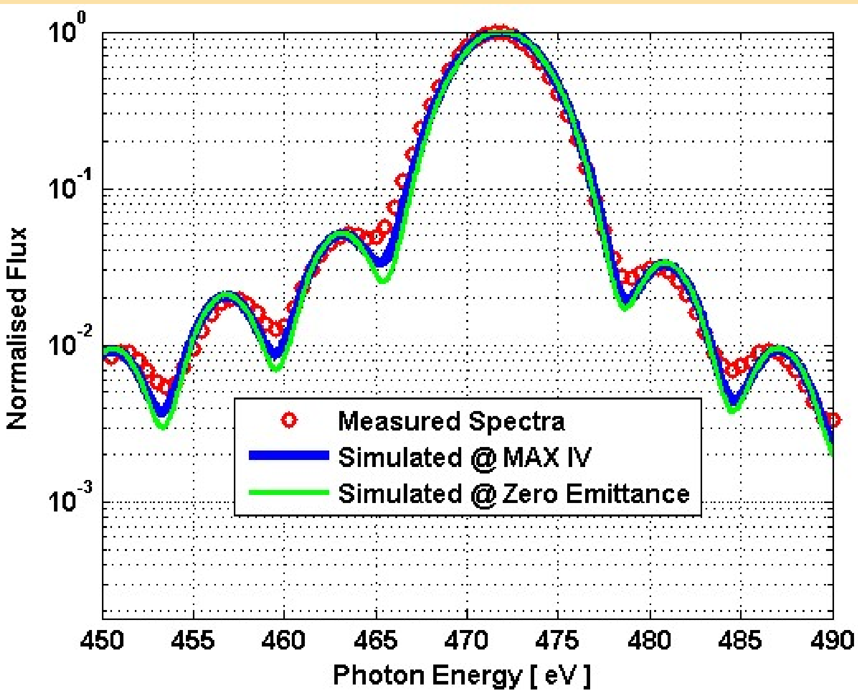
APPLE II Undulators - Spectra

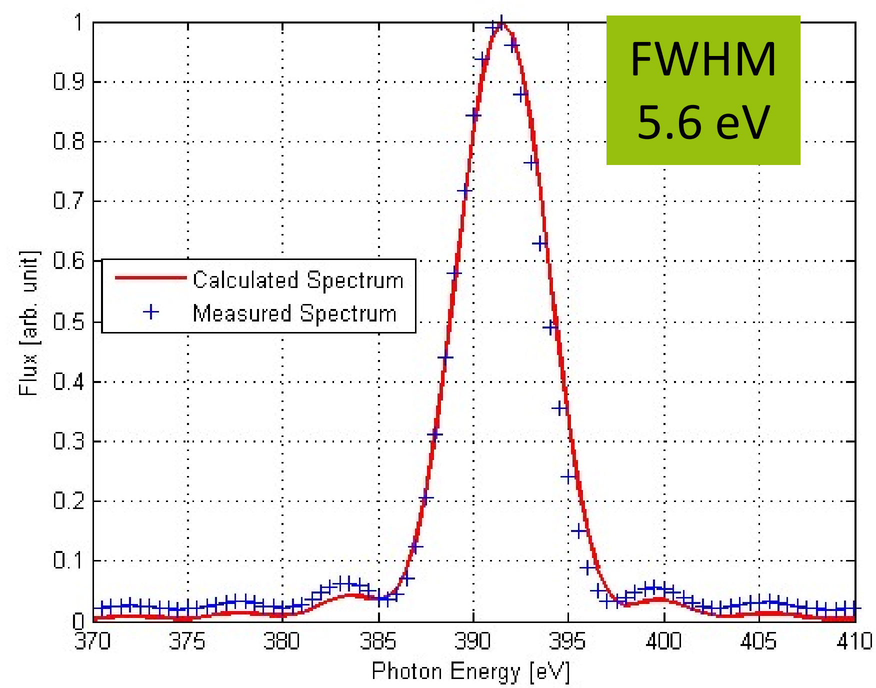
- The APPLE II undulators are the VUV-Soft X-ray sources at MAX IV with full polarization control.
- Step and continuous scanning is available in gap-phase (energy-polarization) space.

APPLE II λ_u=48 mm & L= 4 m

The measured peak and side lobes features of the VERITAS spectrum are indistinguishable from the zero-emittance case. This precision is impossible with the much larger emittance of 3rd generation machines



APPLE II λ_u=53 mm & L= 4 m



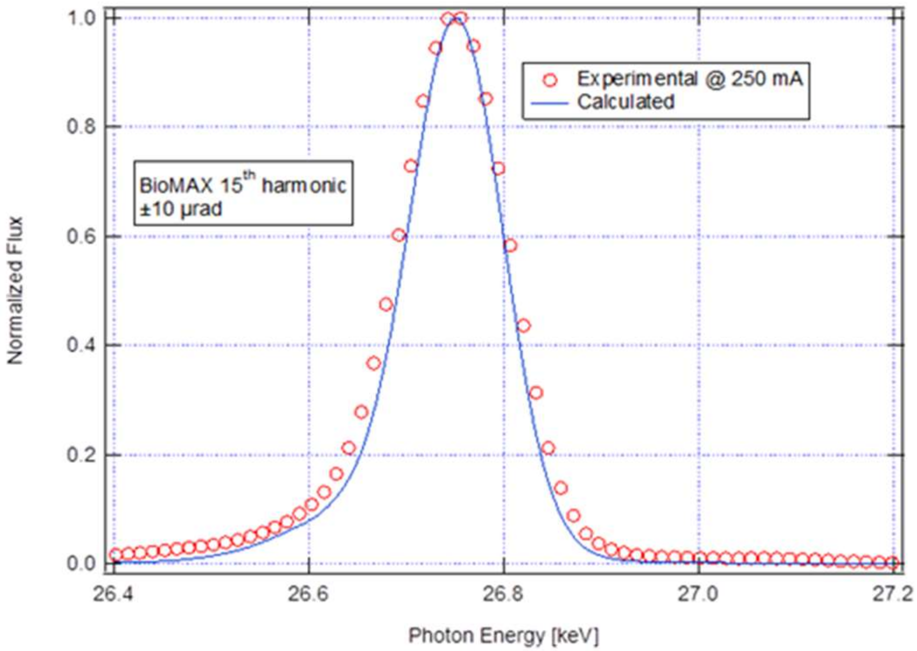
In-vacuum Undulators - Spectra

- High brilliance, hard x-rays sources are based on room temprature and short period In-vacuum undulators with hybrid magnetic structure.
- The definition of undulators' parameters (gap & λ) has capitalized on the delivered electron beam bunch length.

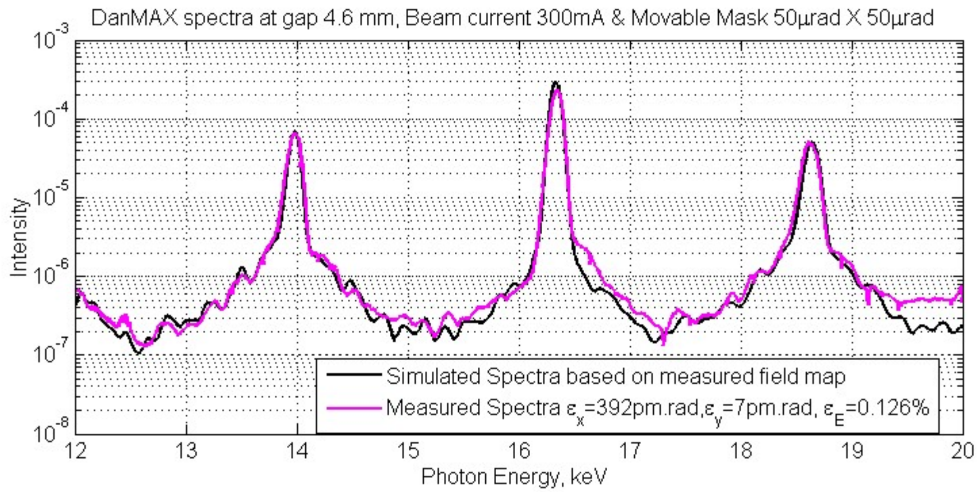
BioMAX undulator, λ=18 mm

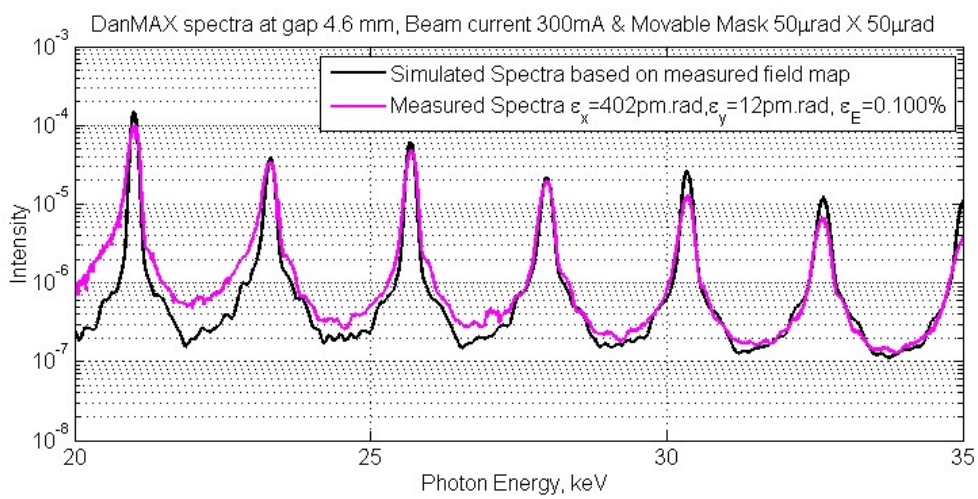
Length 2 meters, Min. gap 4.2 mm

- *Spectral width is negligibly broadened due to small emittance.*
- *Diagnostic tool for accelerator performance*



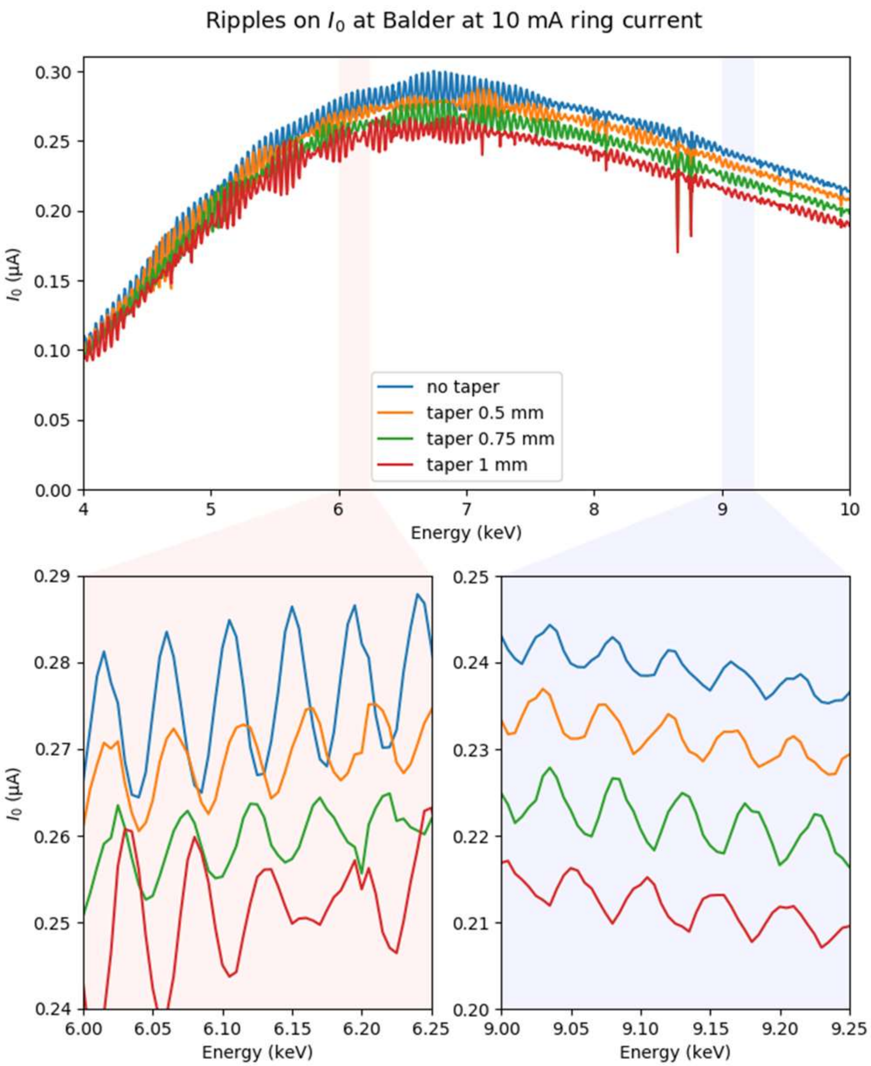
DanMAX undulator, λ=16 mm, L=3m.



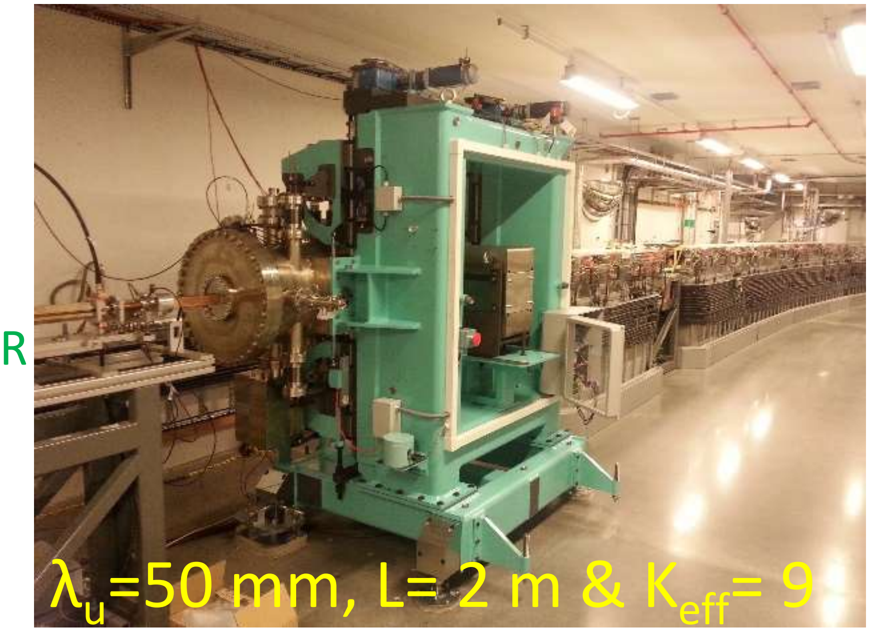


Wiggler @ MAX IV

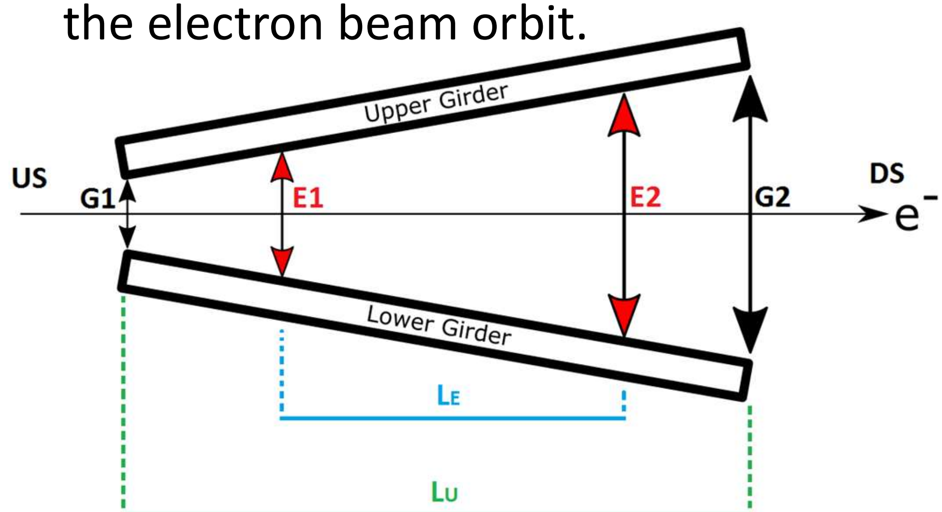
- High flux wiggler (21 kW @ 500 mA, 3 GeV) contributes to emittance damping by 5%.
- Undulator-like spectrum due to low emittance.



Undulator radiation structure from BALDER wiggler. (small emittance)



Tapering & beamline control over the electron beam orbit.



[(*)] K. Klementiev, H. Tarawneh. P. F. Tavares, J. Synchrotron Rad. 2021.

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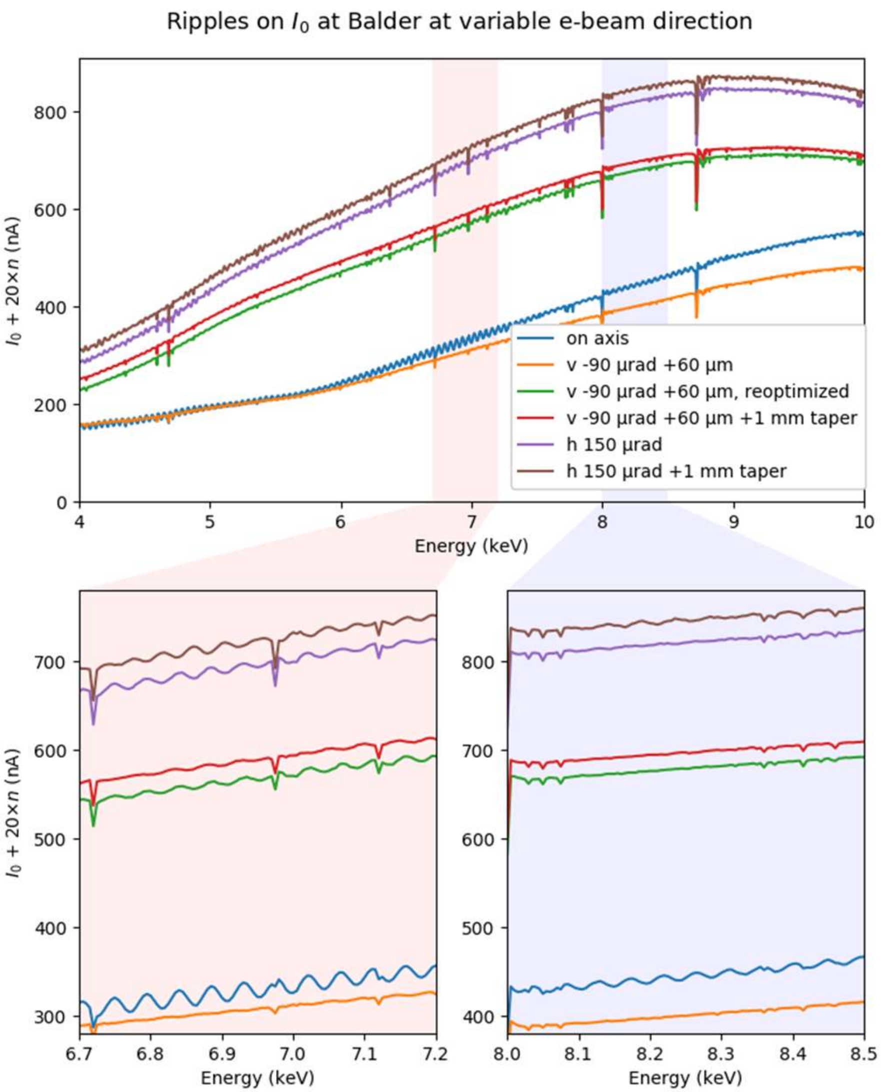

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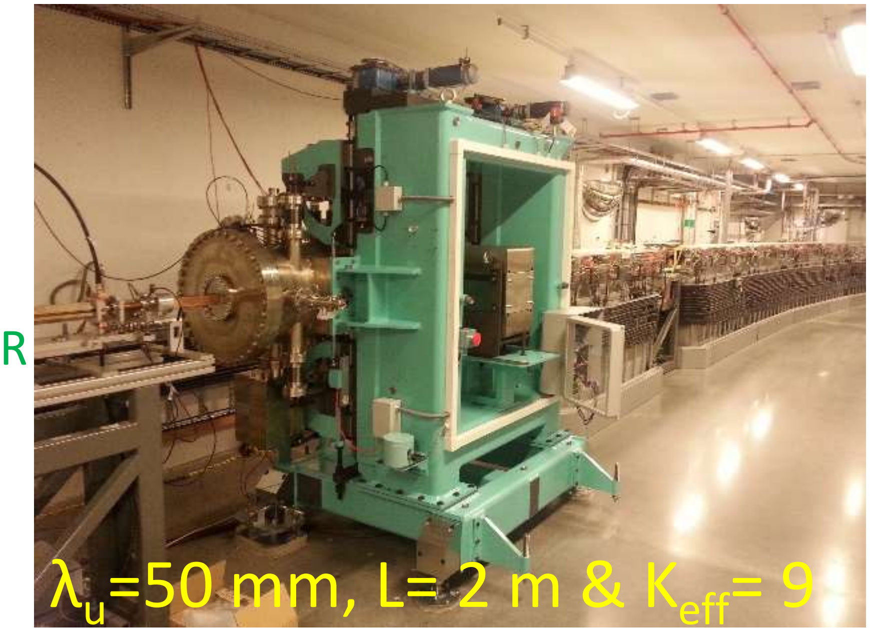

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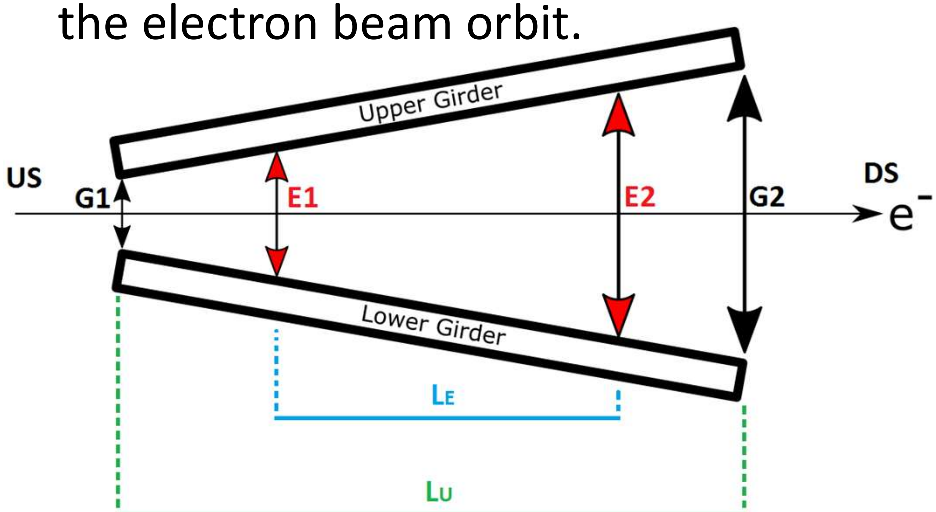
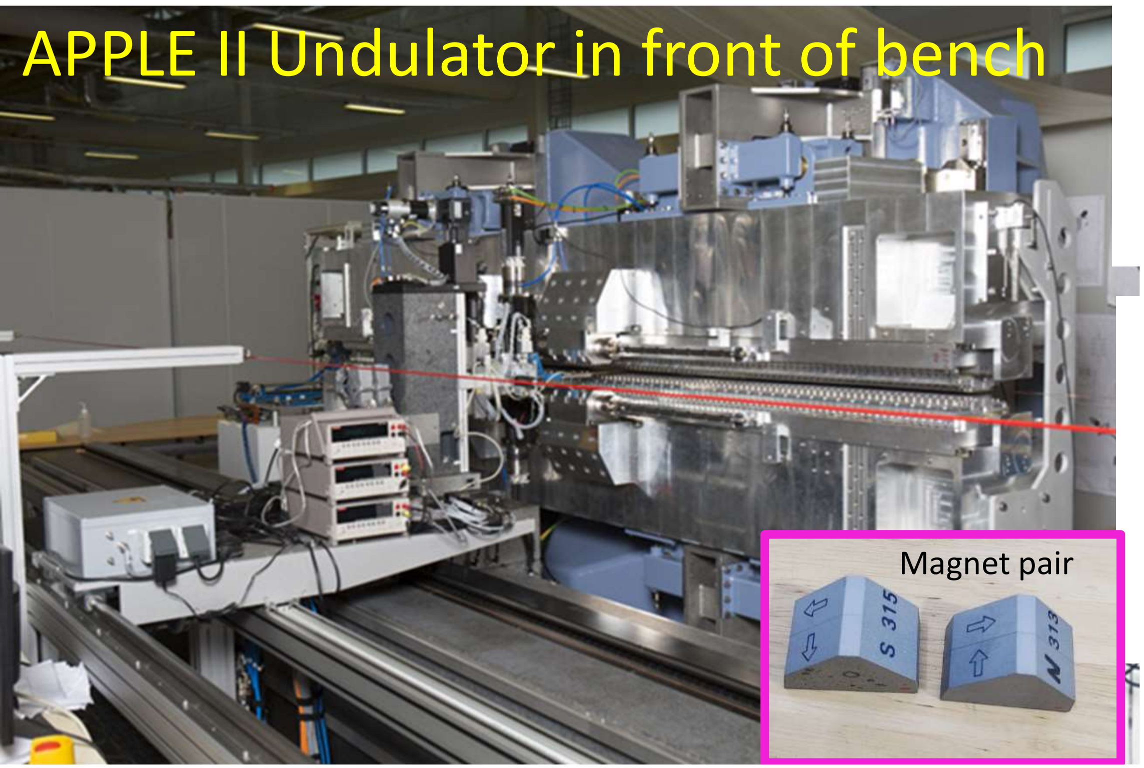
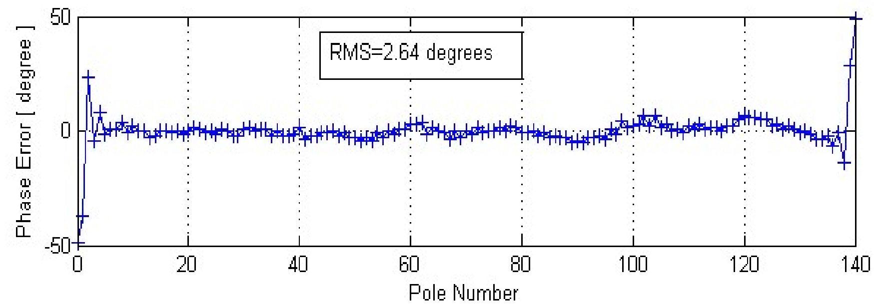


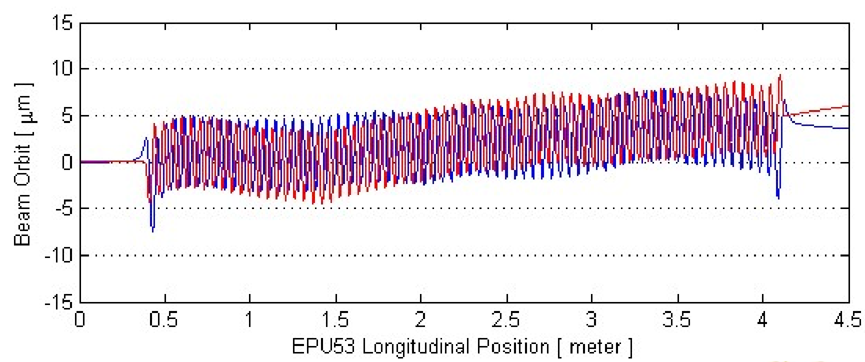
Magnetic Field Measurements

- An ID consists of many magnets that require measurement for tuning to achieve the required magnet field quality as defined by both the accelerator physics constraints and the undulator brilliance & line width.
- Magnetic measurement methods of point and integrated field of In/Out of vacuum, room temperature or cryogenic insertion devices.
- Hall probes and wire systems such as flip coil, stretched wire or pulsed wire techniques.

Hall Probe bench @ MAX IV







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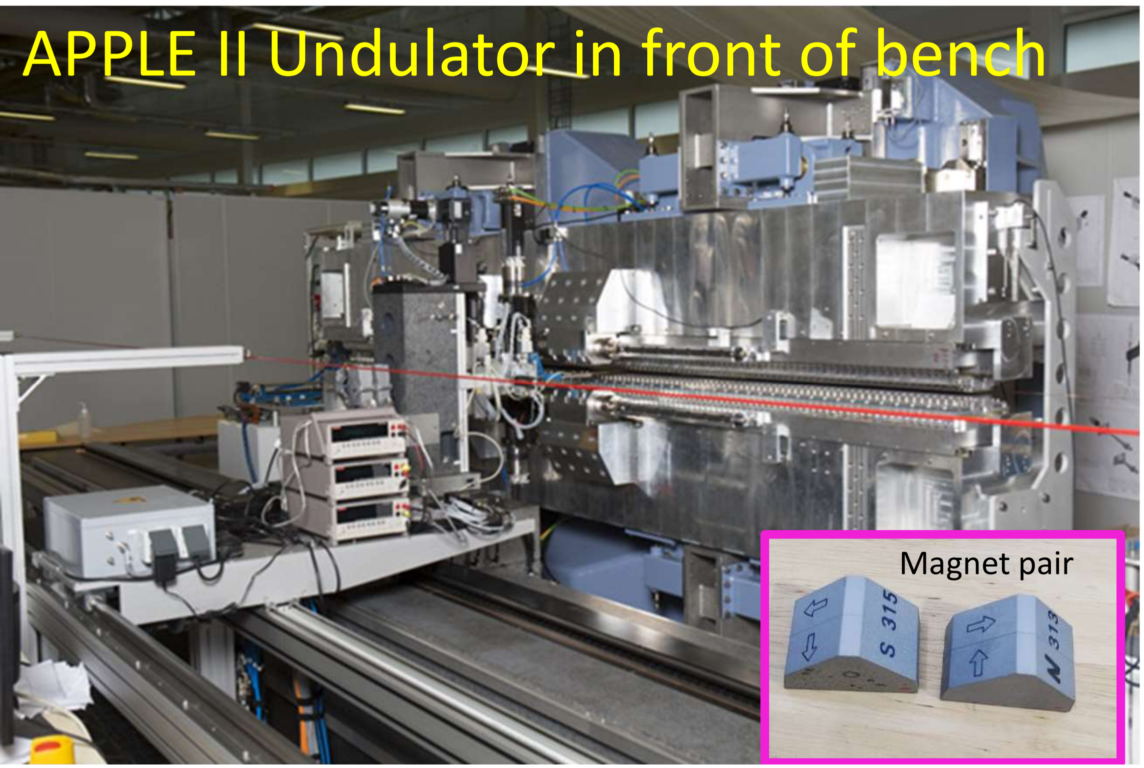

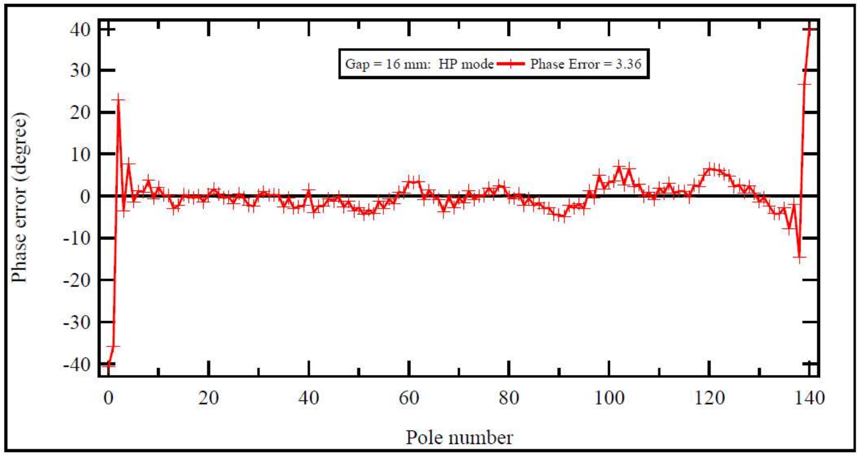

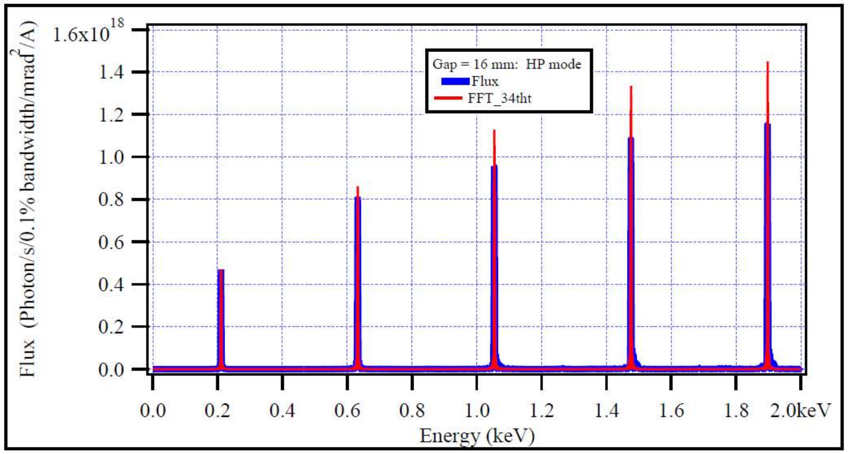

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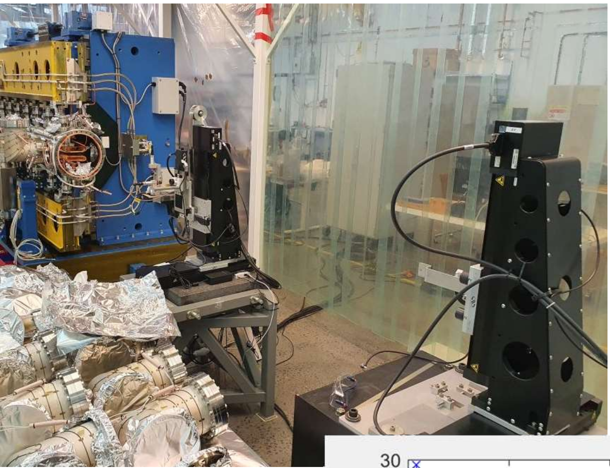
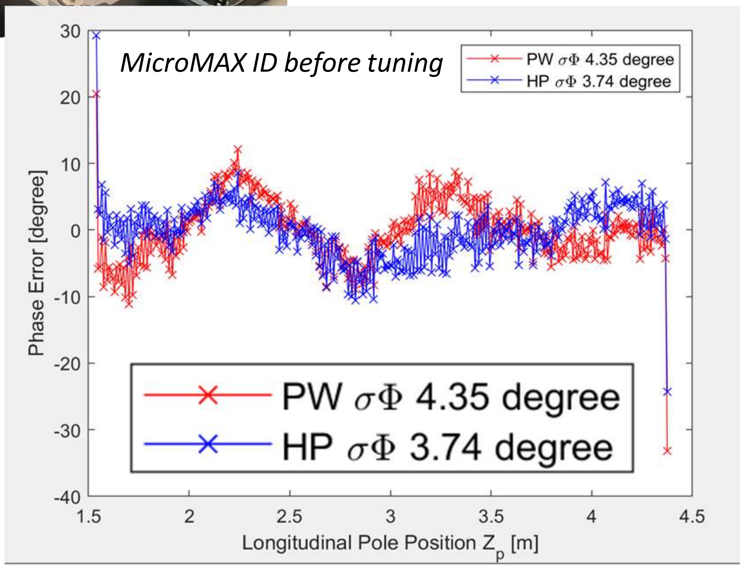
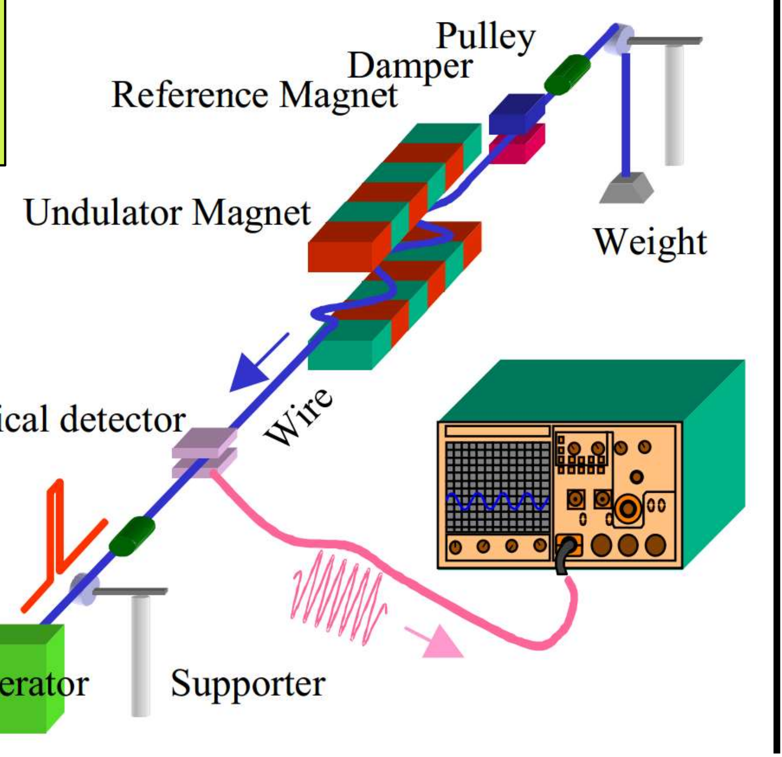


Pulsed Wire system @ MAX IV



Sending a pulse of current that forces the wire into oscillation, when analyzed the magnetic field can be reconstructed.

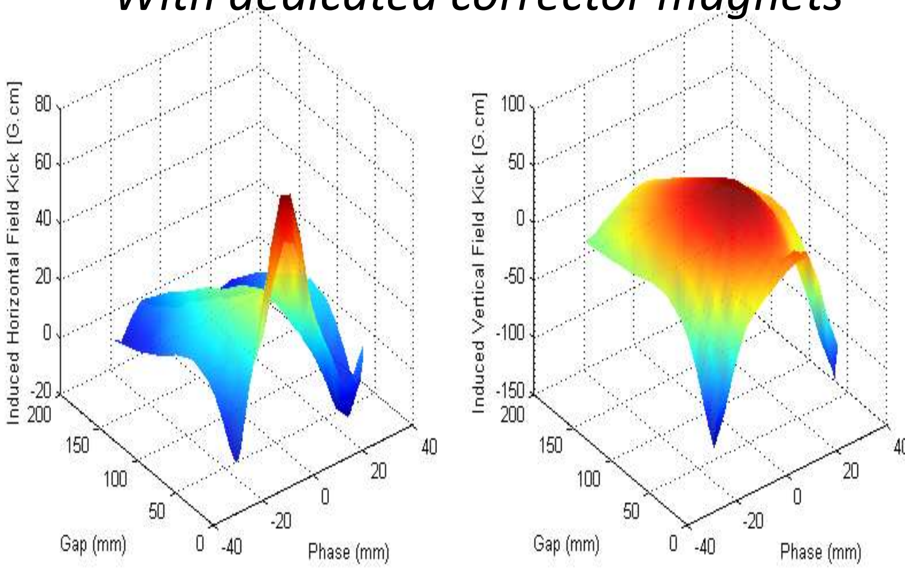
Pulsed Wire System

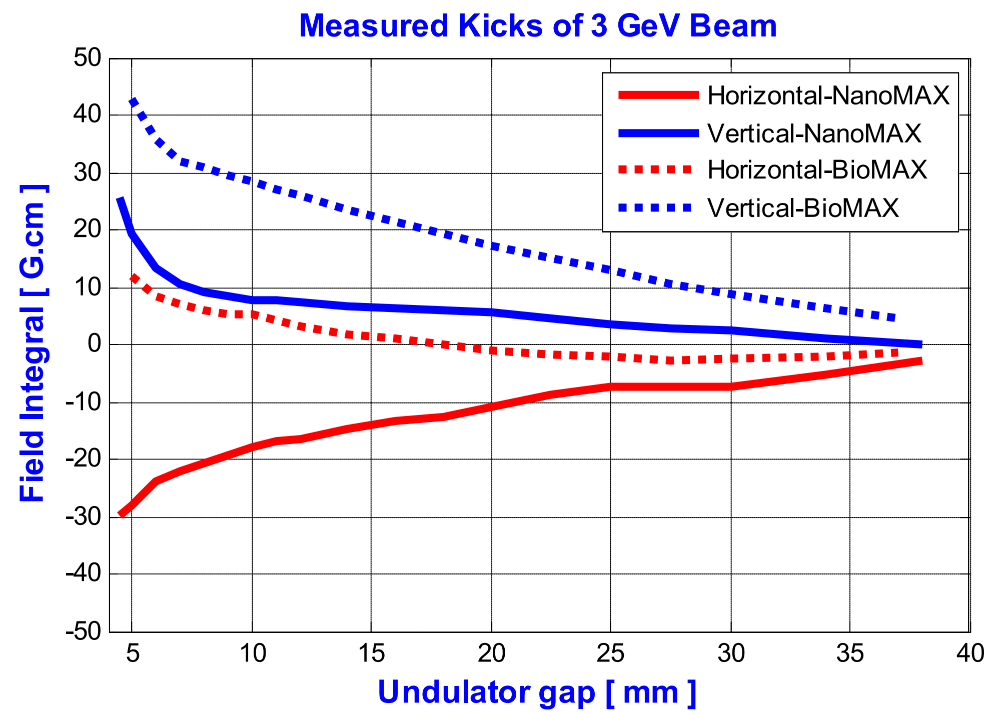


ID's Effect on Electron Beam

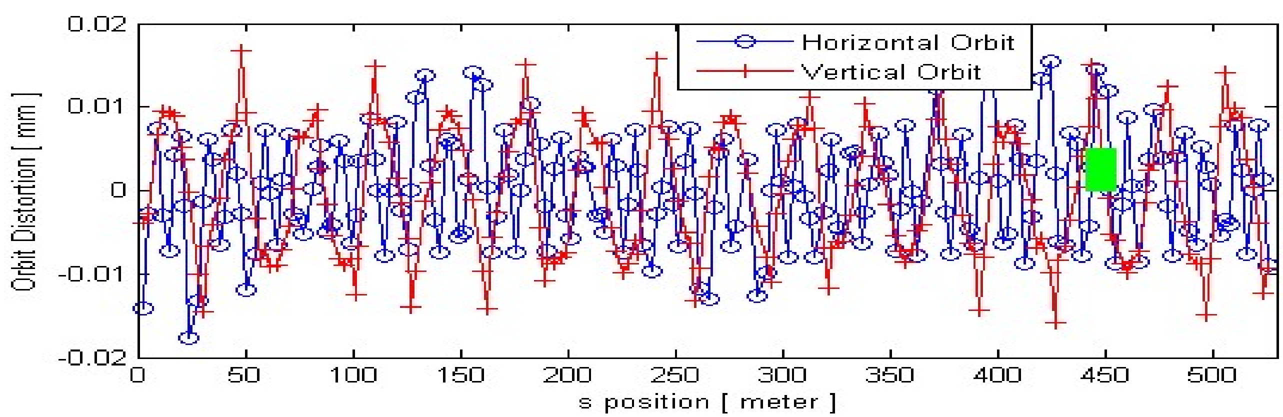
- The integrated magnetic field seen in the electron beam trajectory must be minimized, otherwise the residual field induces an angular kick, i.e., an orbit distortion.
- An ID introduces focusing on the electron beam optics that needs compensation. It does lead to reduction in dynamic aperture and affect the beam emittance and energy spread.

Compensation for APPLE II residual field
With dedicated corrector magnets





Orbit distortion w/o Correction from an APPLE II undulator



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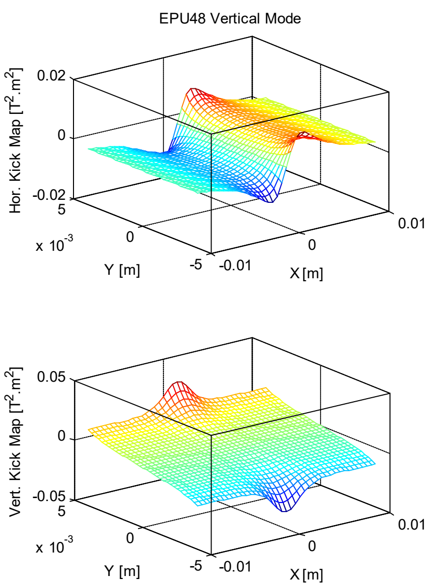
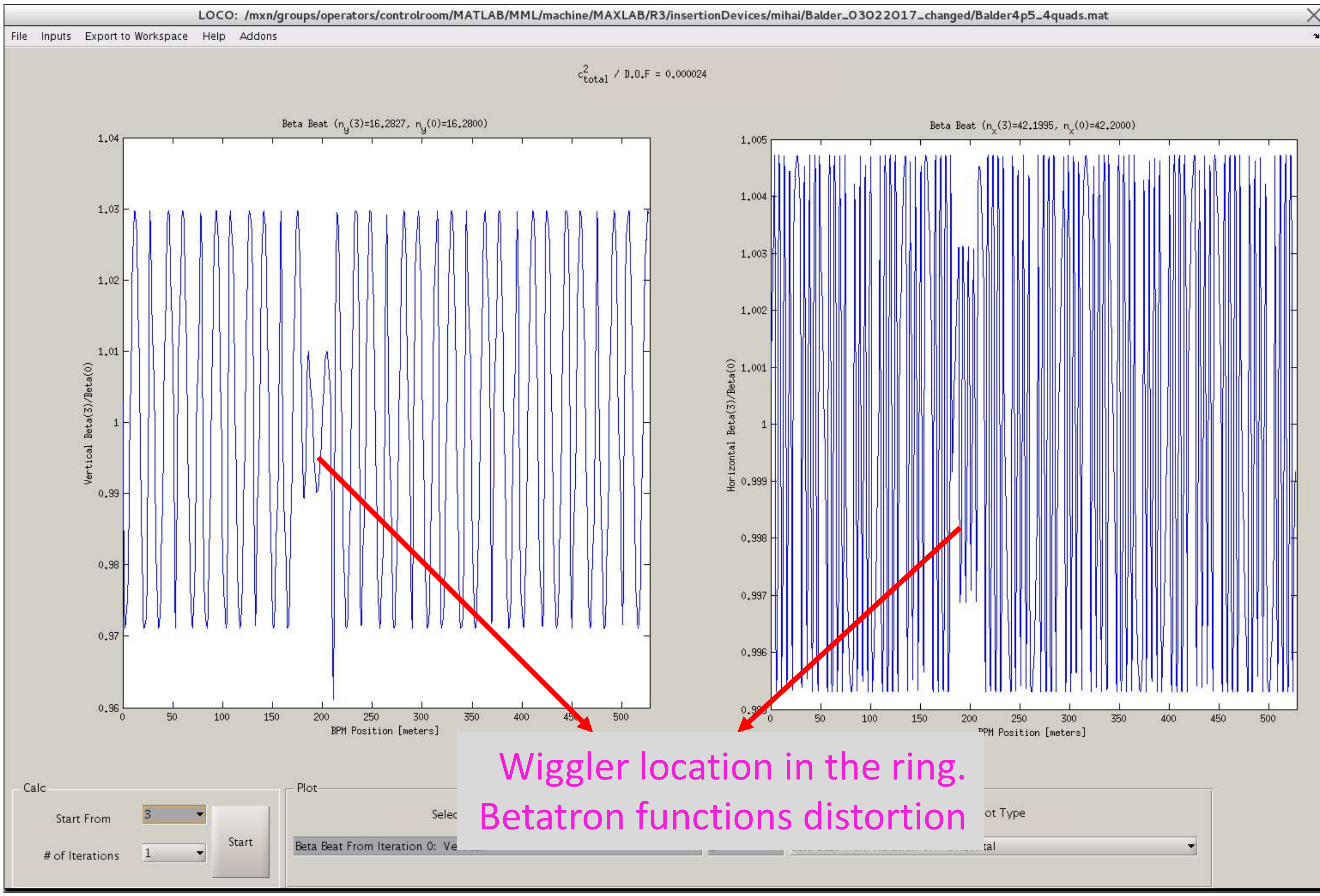
Linear Optics distortion due to wiggler’s focusing effect at the 3 GeV ring.

Kick Maps





Summary

- Bending magnet produces continuous spectrum of synchrotron radiation.
- Undulator and wiggler enhance the production of SR. The undulator produces narrow band series of harmonics whereas wiggler produces a broadband radiation.
- The beamlines requirements vary in terms of photon energy range, polarization, coherence, quasi-periodicity of harmonics, …etc.
- Permanent magnet and electromagnets are the main sources of magnetic field for the production of radiation.
- Insertion devices purturb the electron beam dynamics, orbit & linear/nonlinear optics. Effective correction scheme are available.
- Magnetic field measurement is essential in tuning insertion devices during assembly phase to meet the accelerator and beamline sets of requirements on field quality.

MAX IV

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