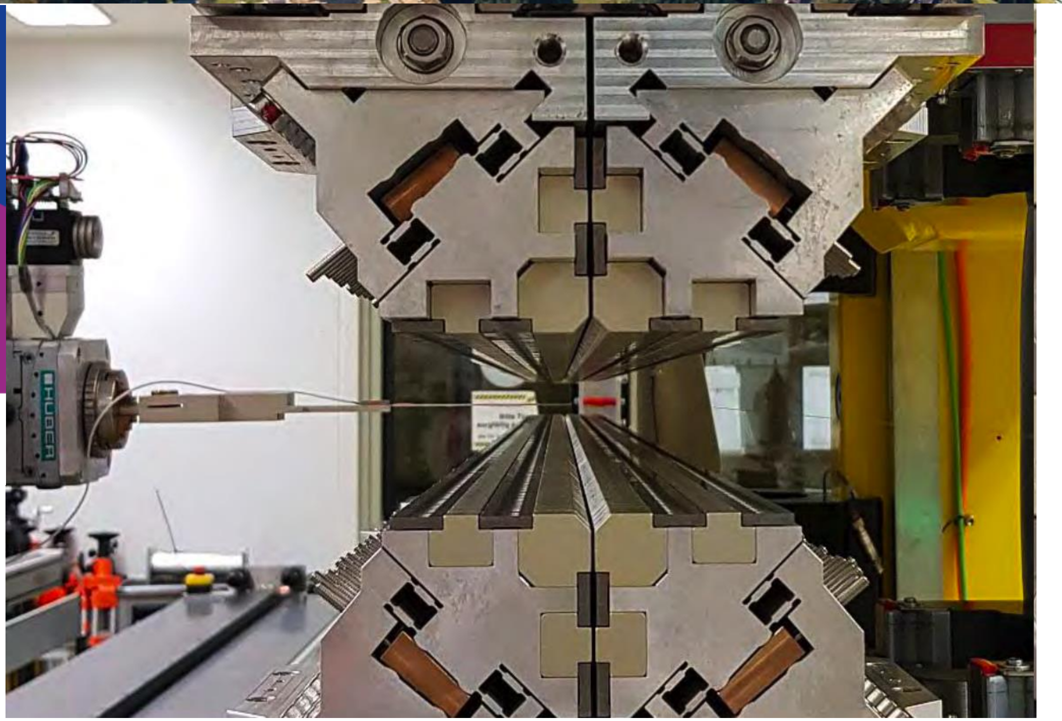
The new APPLE-III undulators for FLASH

FLASH: The High Repetition Rate Soft X-ray FEL Operating Two Undulator Beamlines Simultaneously

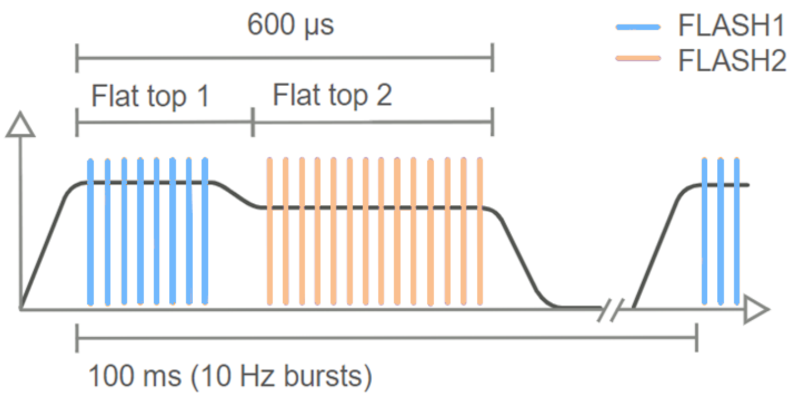
Juliane Rönsch-Schulenburg

for the FLASH Team



HELMHOLTZ

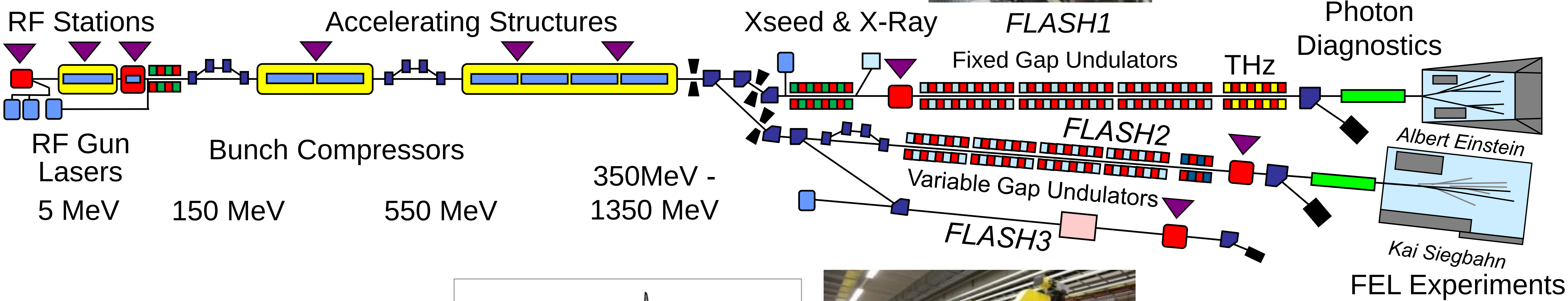
FLASH until 2024



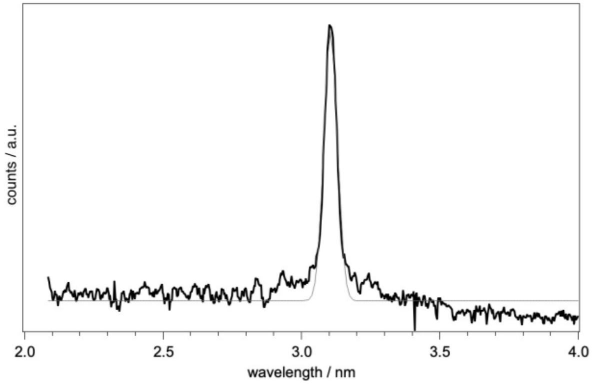
Xseed: planar, variable gap undulators

FLASH1: fixed gap undulators

THz: electro magnetic undulator



SASE FLASH2:
Photon energy range: 390 - 14 eV
Pulse duration: 1.3-200 fs
Min. spectral width: 0.5%



FLASH2: planar, variable gap undulators

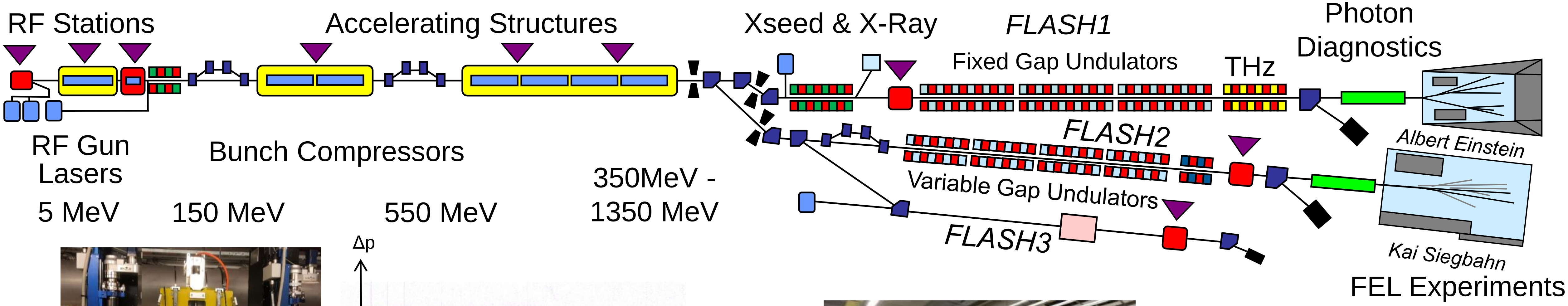
FLASH until 2024

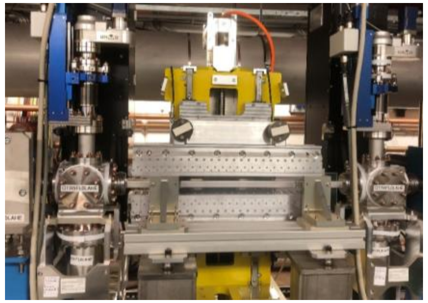
Laser heater 2022, Afterburner 2023

Xseed: planar, variable gap undulators

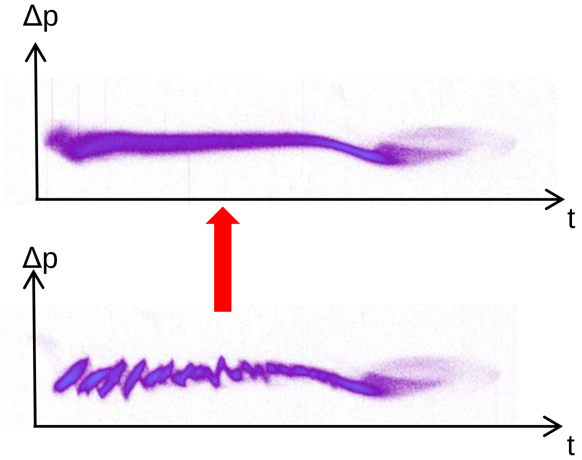
FLASH1: fixed gap undulators

THz: electro magnetic undulator





Laser heater undulator;
planar, variable gap undulator



FLASH2: planar, variable gap undulators

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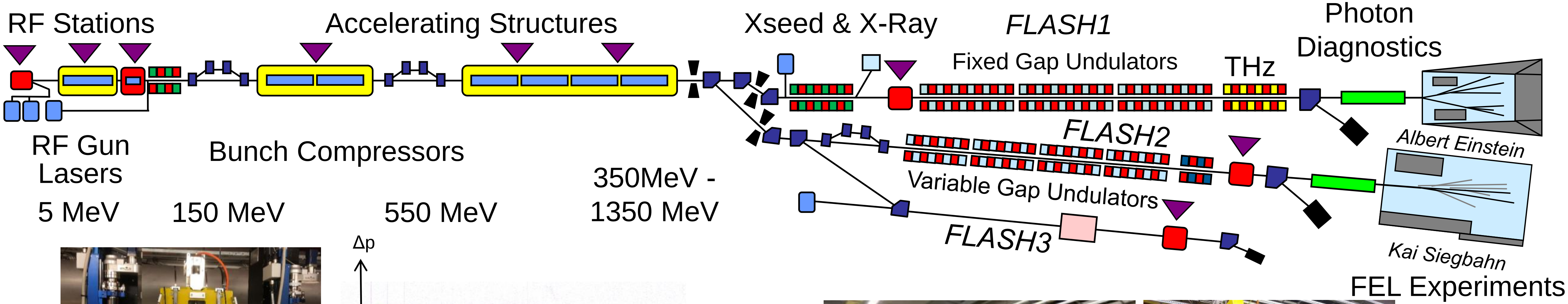
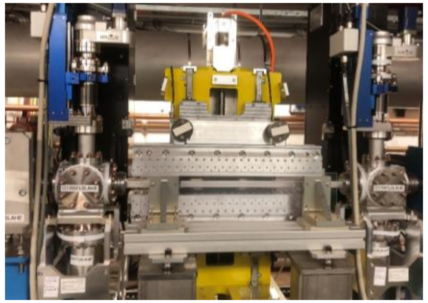
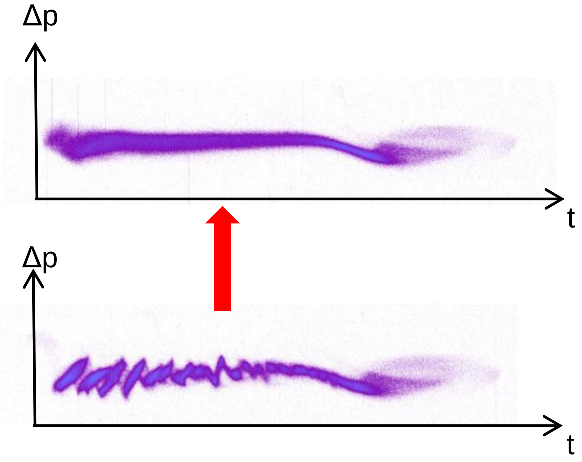




Laser heater undulator; planar, variable gap undulator

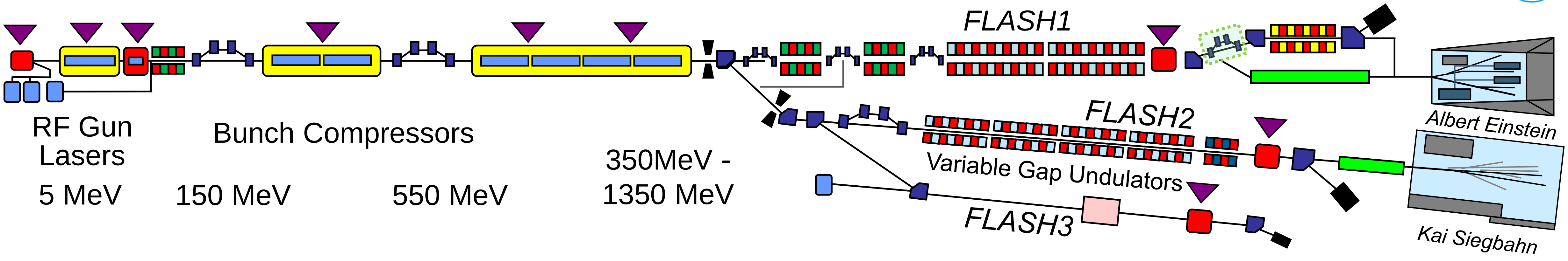


FLASH2: planar, variable gap undulators

FLASH2: afterburner; APPLE III undulator

Afterburner:
Polarisation: variable
Photon energy range: 890 - 80 eV

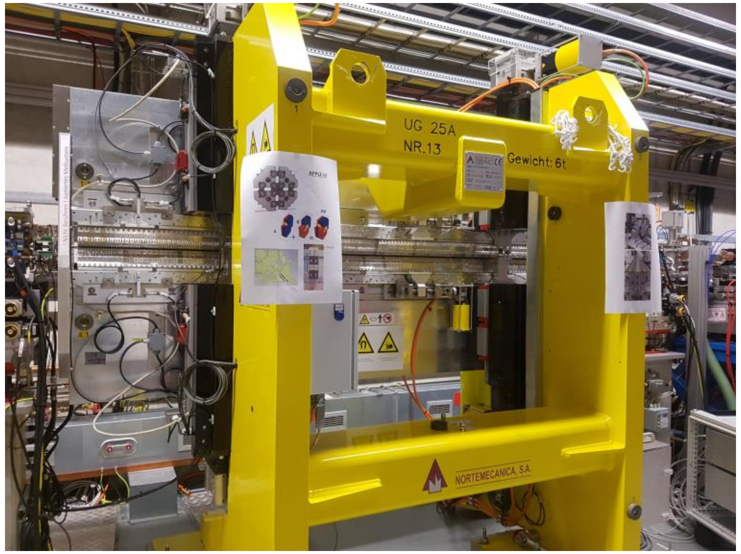
Afterburner at FLASH2



afterburner undulator

- installed in Sept. 2023
- 2.5 m long
- Downstream 30m planar main undulator
- third-harmonic optimized to provide wavelengths around the L-edges of Fe, Co, and Ni (upto 890eV)
- selectable polarization
- allows investigation of dynamic properties in nanomagnetism (e.g. ultrafast magnetization dynamics)

SASE FLASH2:
Photon energy range: 390 - 14 eV
Pulse duration: 1.3-200 fs
Min. spectral width: 0.5%

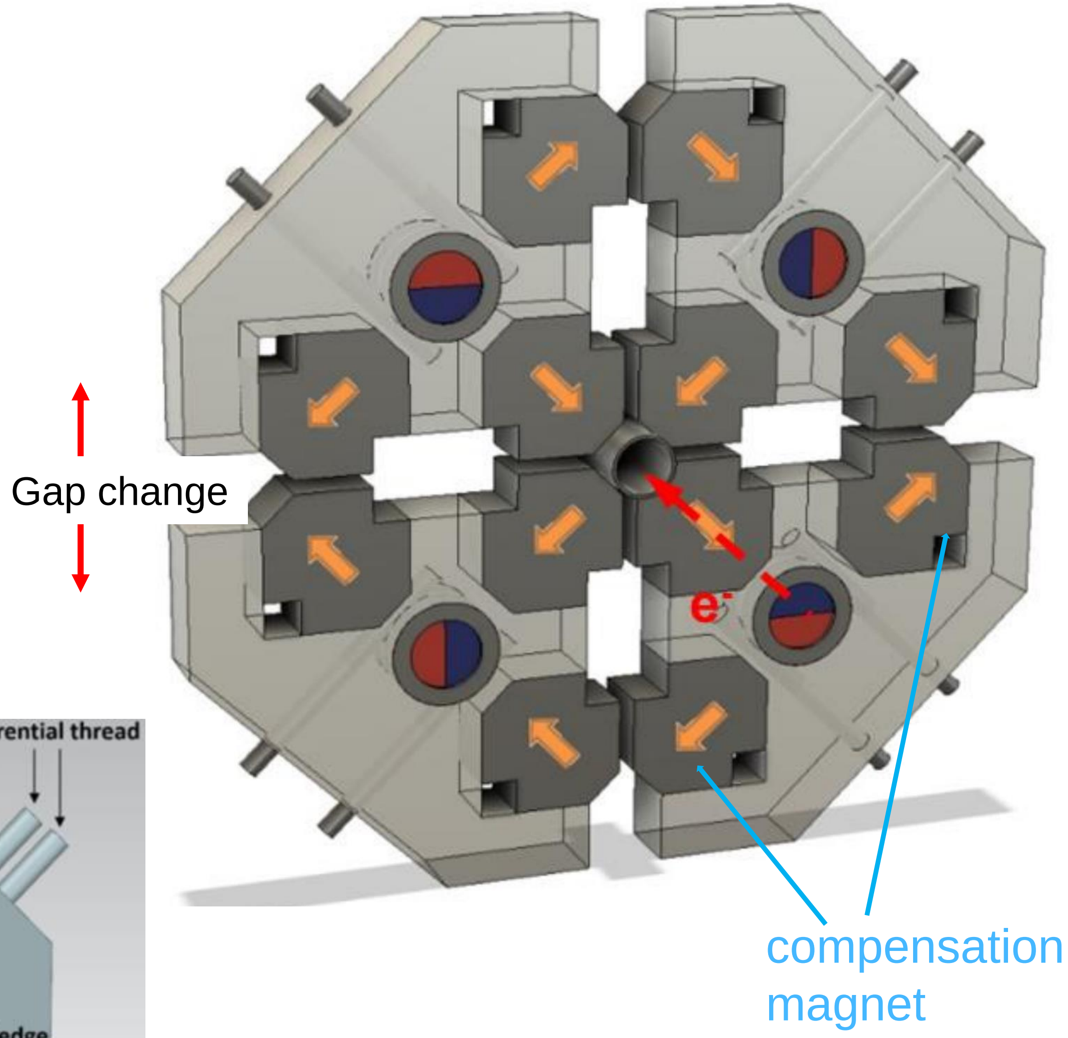


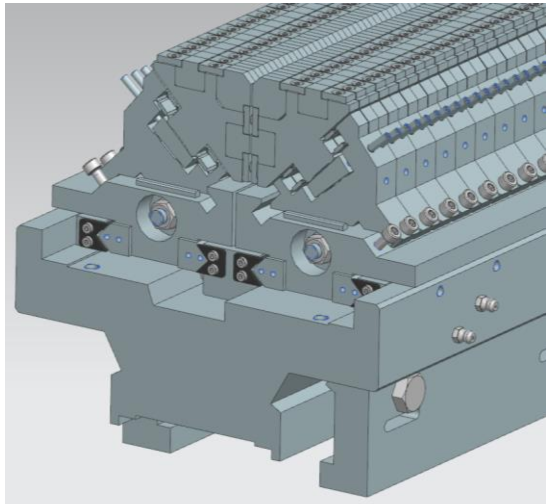
Afterburner:
Polarisation: variable
Photon energy range: 890 - 80 eV

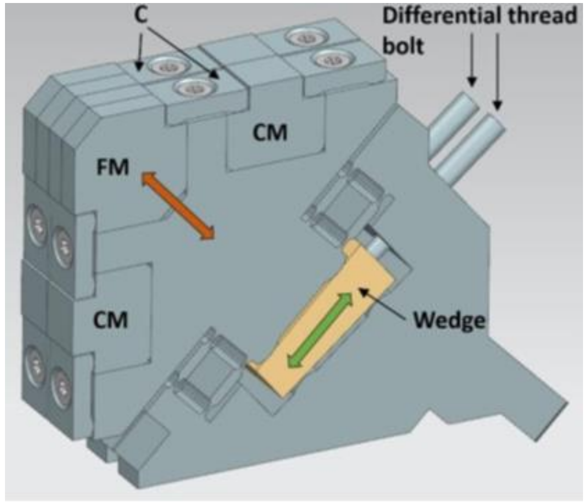
APPLE III undulator

Advanced Planar Polarized Light Emitting undulator

- APPLE-III undulators allow selectable polarization
- consists of four permanent magnet arrays in Halbach configuration
- compact magnet systems with an implemented force compensation scheme
- the force compensation scheme reduces the magnetic forces by about a factor of 8
- wedges are moved by turning the differential thread bolts and will move the function magnets towards or away from the beam axis.







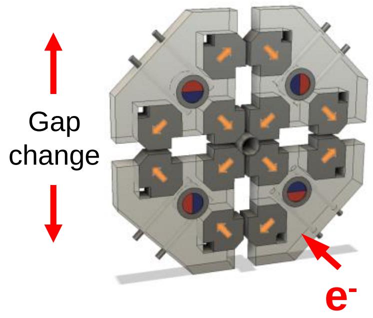
Development of an APPLE-III undulator for FLASH-2, Journal of physics / Conference Series 2380(1), 012017 (2023)

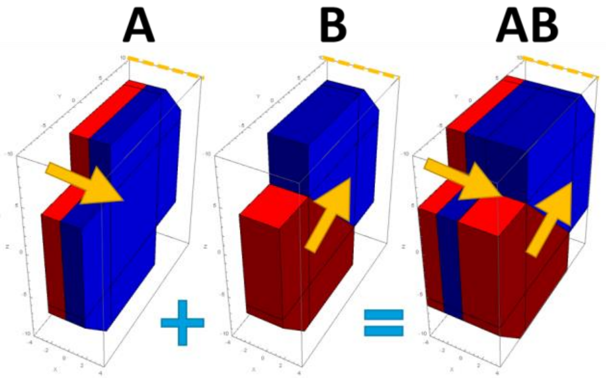
APPLE III undulator

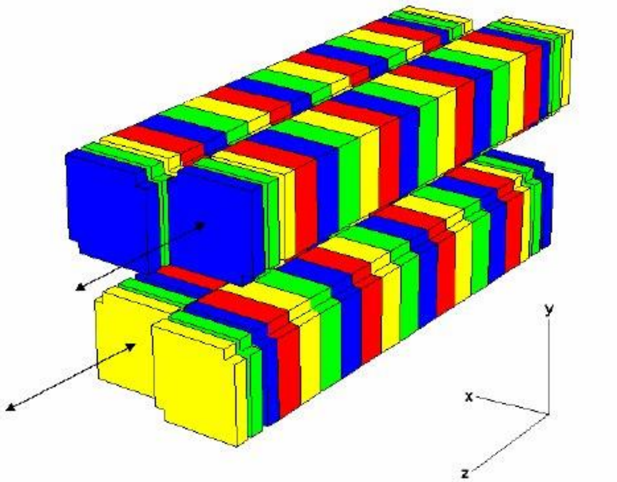
Advanced Planar Polarized Light Emitting undulator

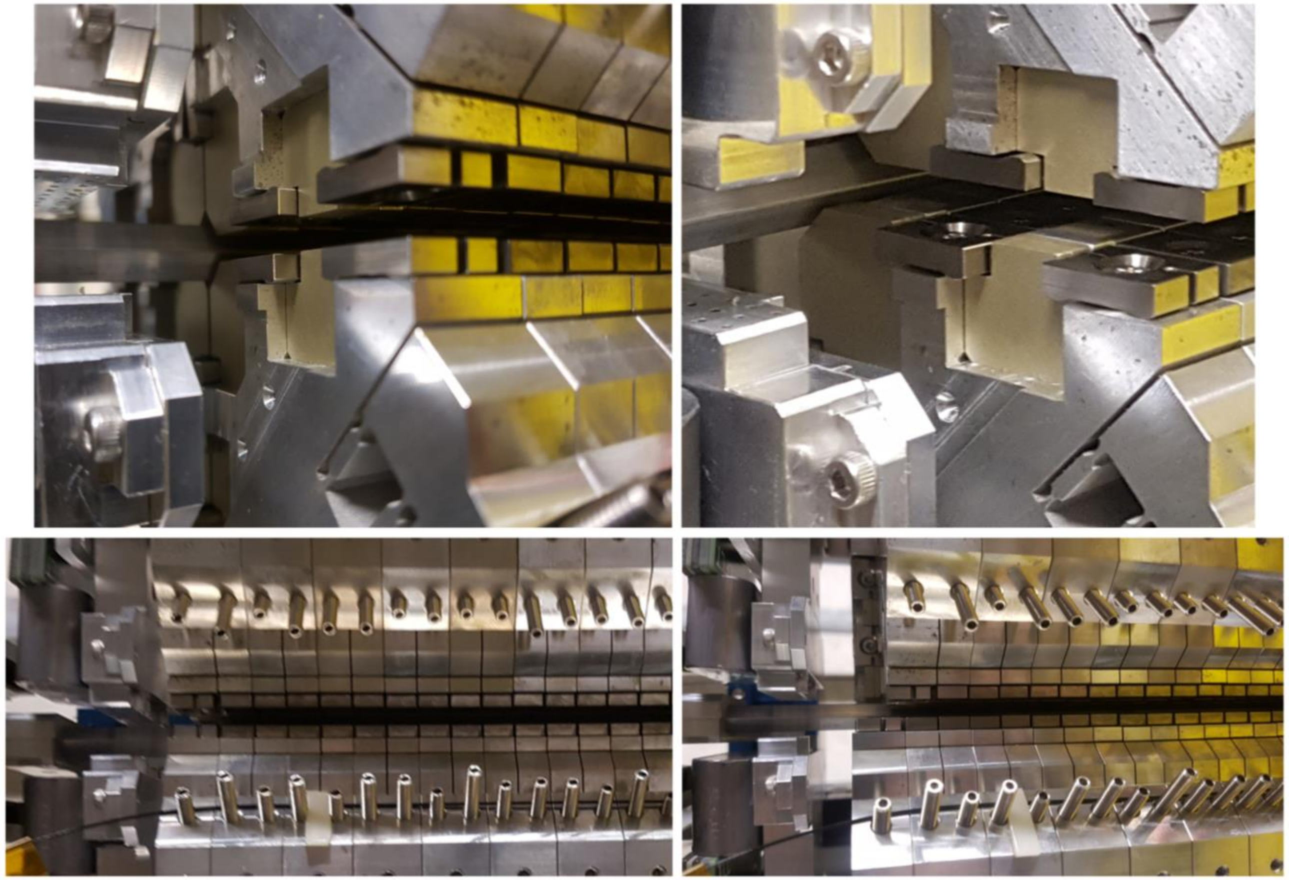
- Longitudinally (A) and transversally (B) magnetized blocks are glued to a pair as a smallest magnetic unit

- subgirders on which the magnets arrays are mounted can be moved
  - vertically away from the beam
    -> to adjust wavelength
  - along the beam axis with respect to each other
    -> to adjust polarization







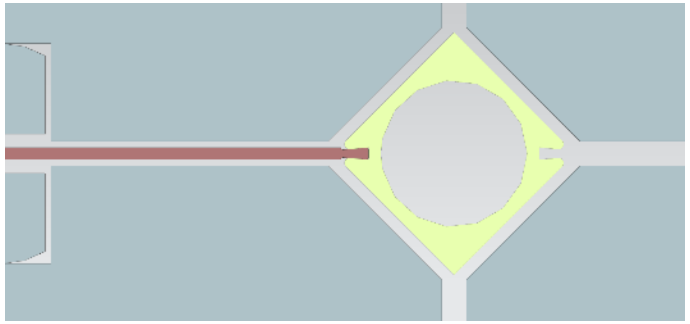


shift = 0
horizontal linear polarization

shift = 0.5
vertical linear polarization.

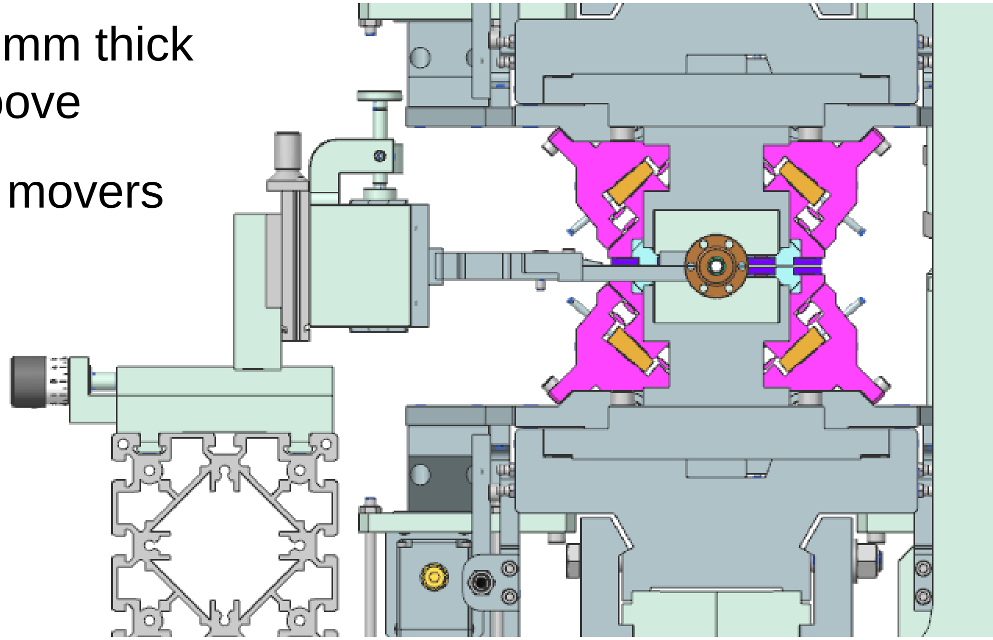
Vacuum Chamber and Support

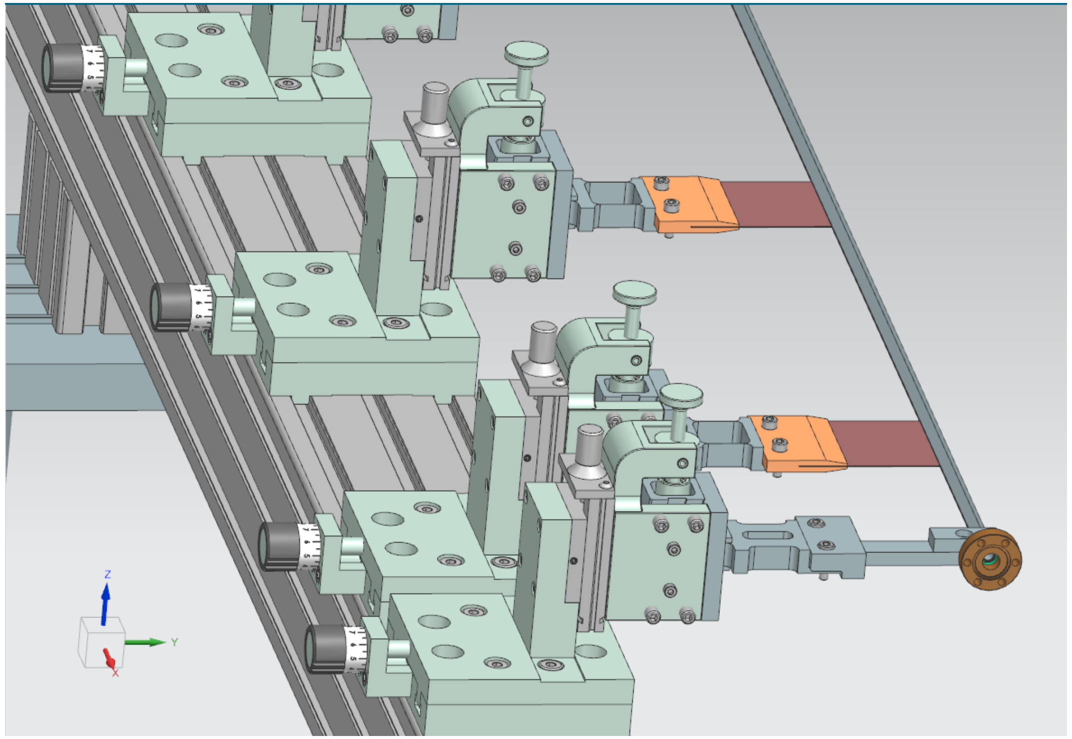
- Extruded aluminum chamber
- 7x7mm^2 cross-section
- Inner diameter: 6mm
- Length ~2.5m



Courtesy A. de Zubiaurre Wagner, S. Lederer

- Support by 0.5mm thick blades in a groove
- Adjustment by movers





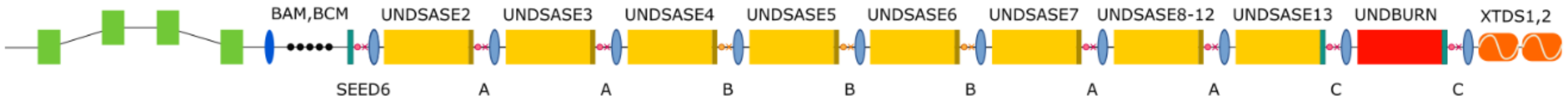
Reverse Taper Experiments

Supression of radiation of main undulators

- Main SASE undulator is planar
- helical afterburner
- Need to get rid of powerful linearly polarized radiation from the main undulator

planar undulator (saturation)
30 m

helical
afterburner
2.5 m



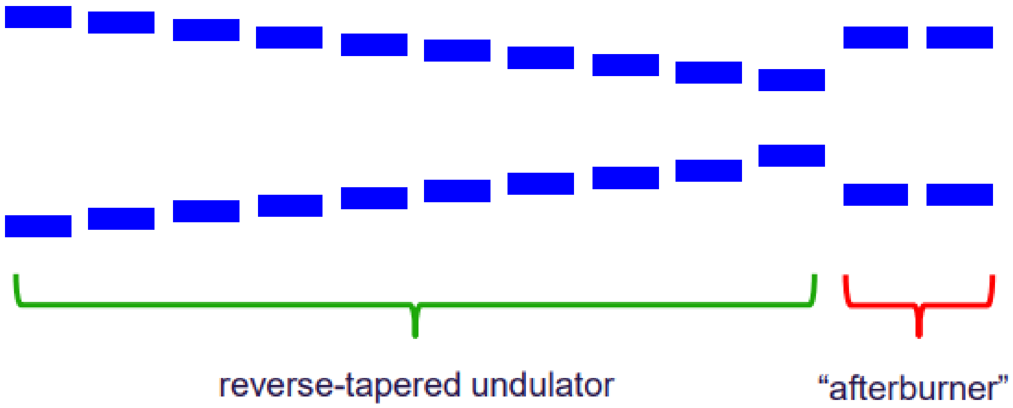
reverse-tapered planar undulator (K increases)

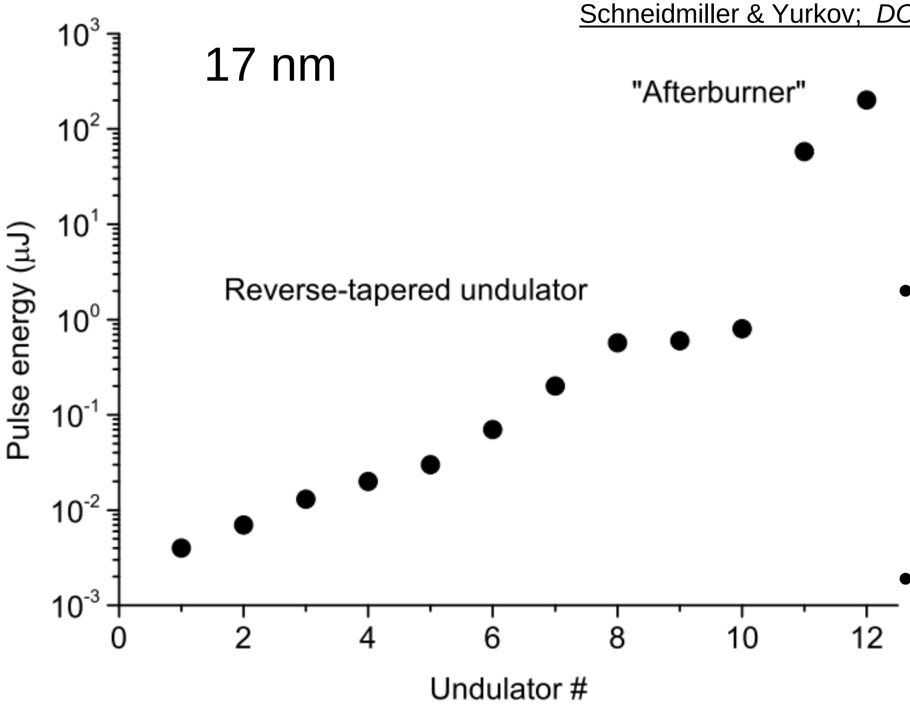
- Fully microbunched electron beam but strongly suppressed radiation power at the exit of reverse-tapered planar undulator
- The beam radiates at full power in the helical afterburner tuned to the resonance

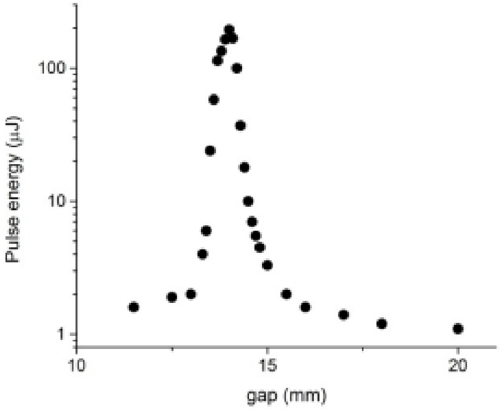
Reverse Taper Experiments

Test with FLASH2 main undulators

Reverse Undulator Tapering for Polarization Control and Background-Free Harmonic Production in XFELs: Results from FLASH,- Schneidmiller & Yurkov; *DOI: 10.18429/JACoW-FEL2017-MOP032*

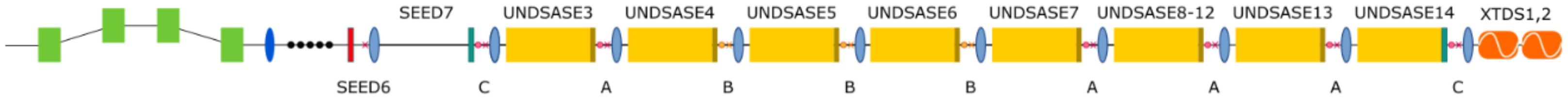






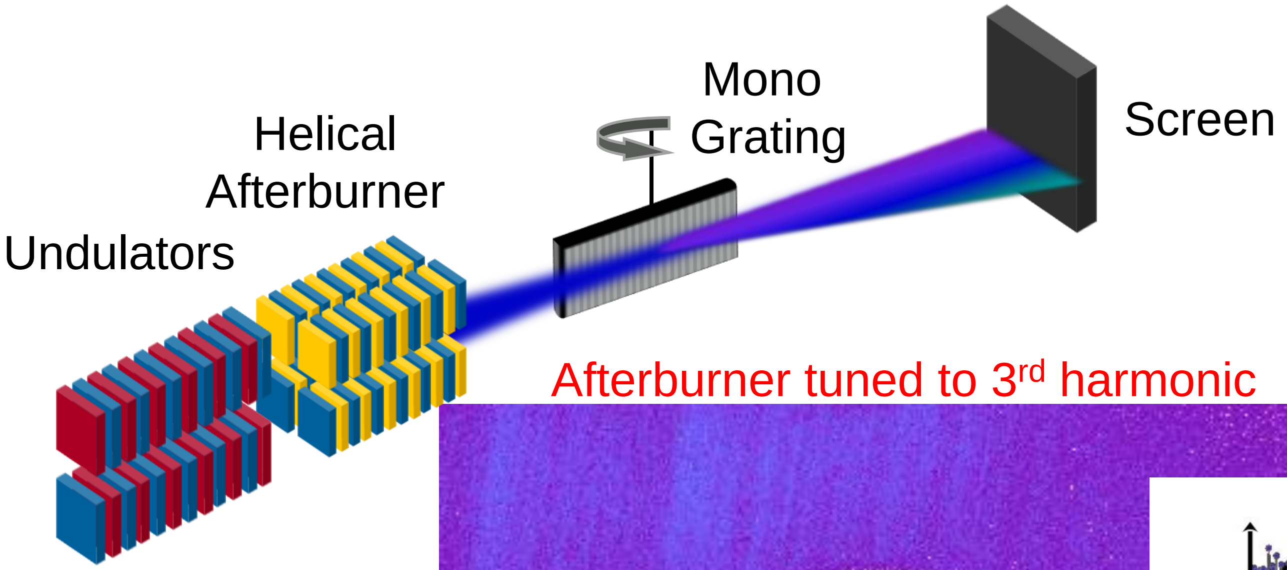
~ 200
(x 2)

- bunching factor at saturation can be the same as in the case of a non-tapered undulator,
- the saturation length increases moderately while the saturation power is suppressed by orders of magnitude



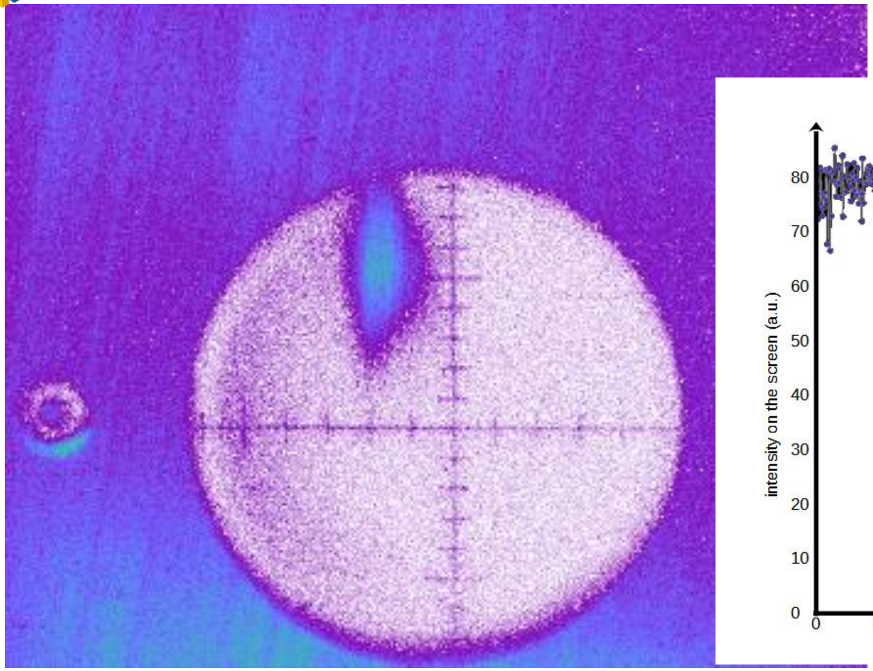
Successful Suppression of Linear Polarization

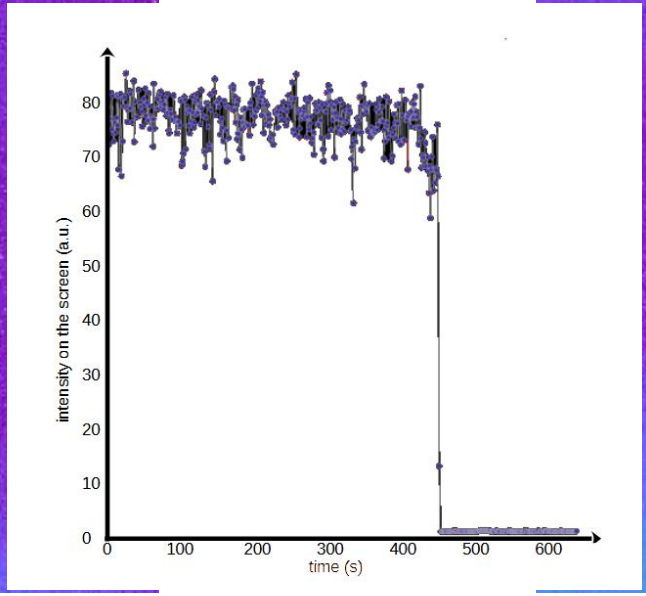
Supression of main undulator radiation while obtaining polarized afterburner radiation



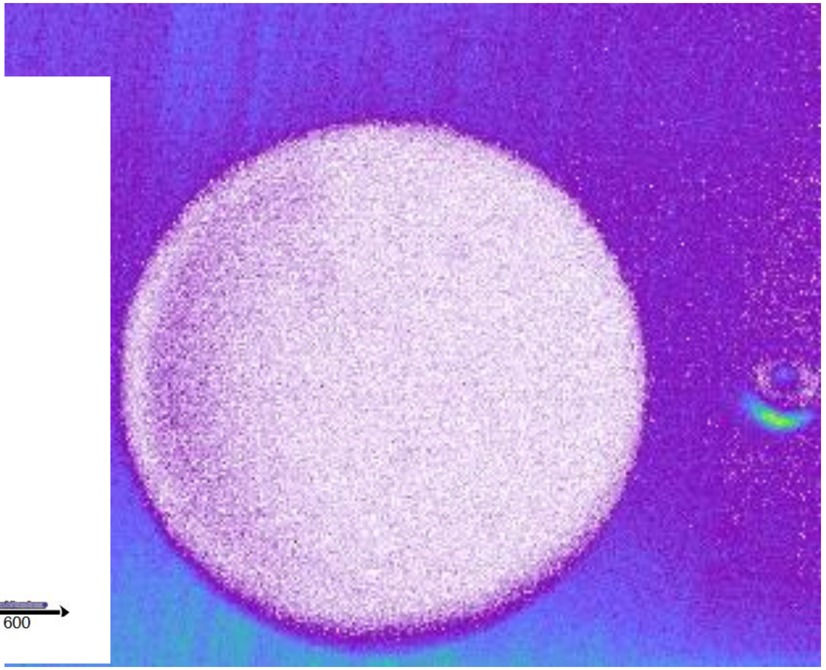
New double monochromator Beamline FL23 used setup to distinguish fundamental and 3rd harmonic

Afterburner tuned to 3rd harmonic



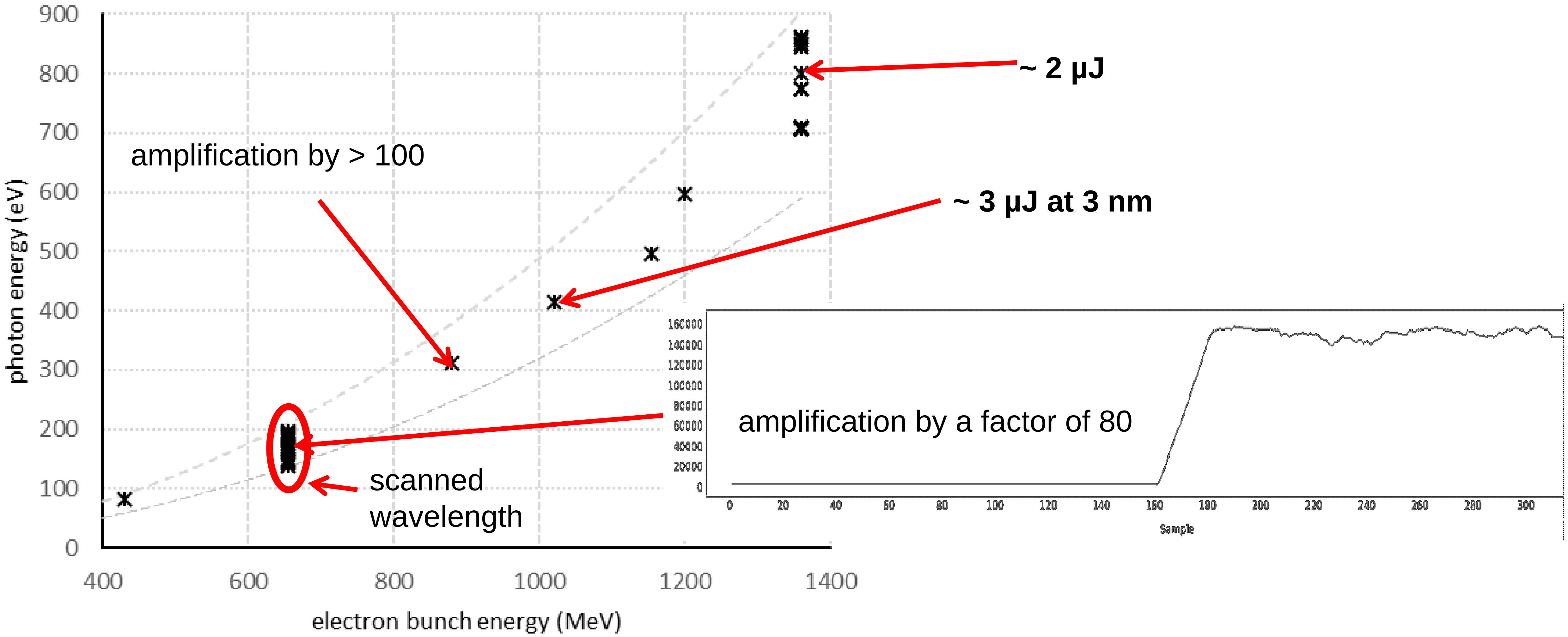


Afterburner detuned



Different working points

80 eV – 860 eV demonstrated

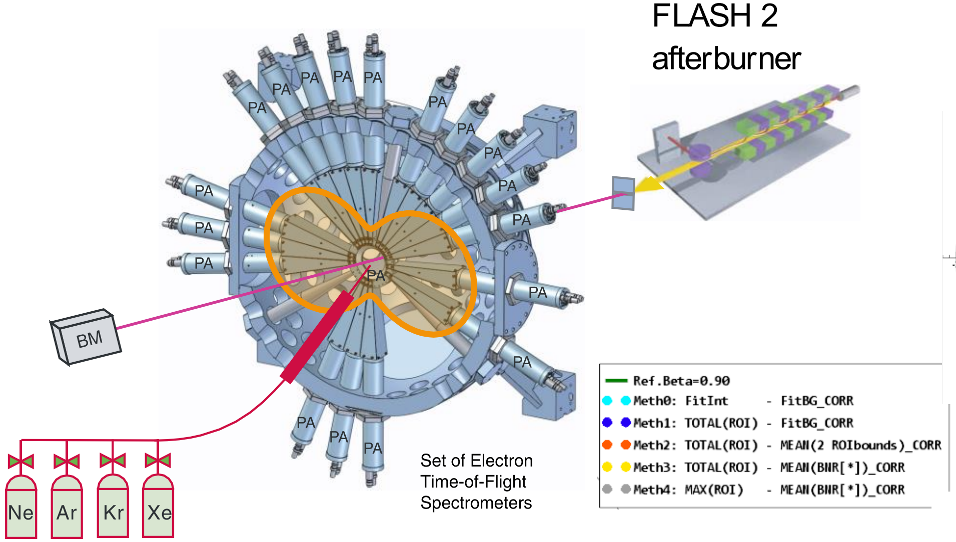


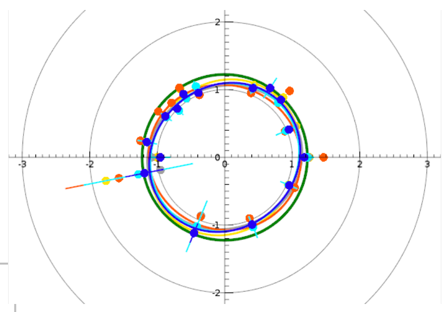
Afterburner

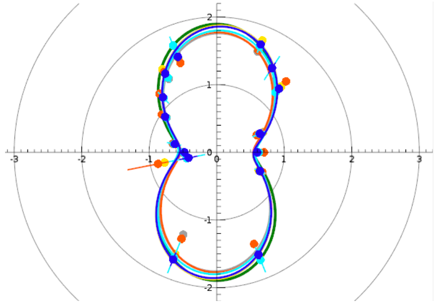
FLASH2 APPLE III afterburner in operation

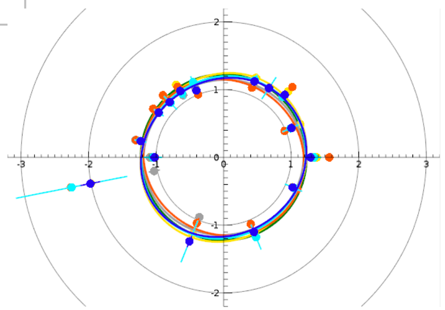
E_{ACC} = 880 MeV
hν = 104.6 eV / 313.8 eV

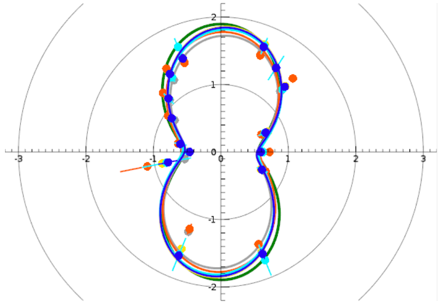
- Circularly polarized light down to 1.46 nm generated
- First successful user experiments



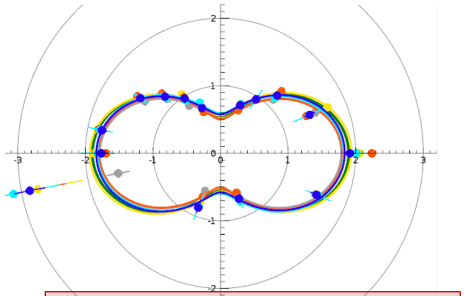








- Ball chamber instrument
- Measuring angular distribution of photoelectron emission
  of a certain photoelectron feature from 3rd harmonic



ABU shift = 0.0

ABU shift = +/- 0.25

ABU shift = +/- 0.5

Degree of circular polarization of the 3rd harmonic at 313.8 eV is:

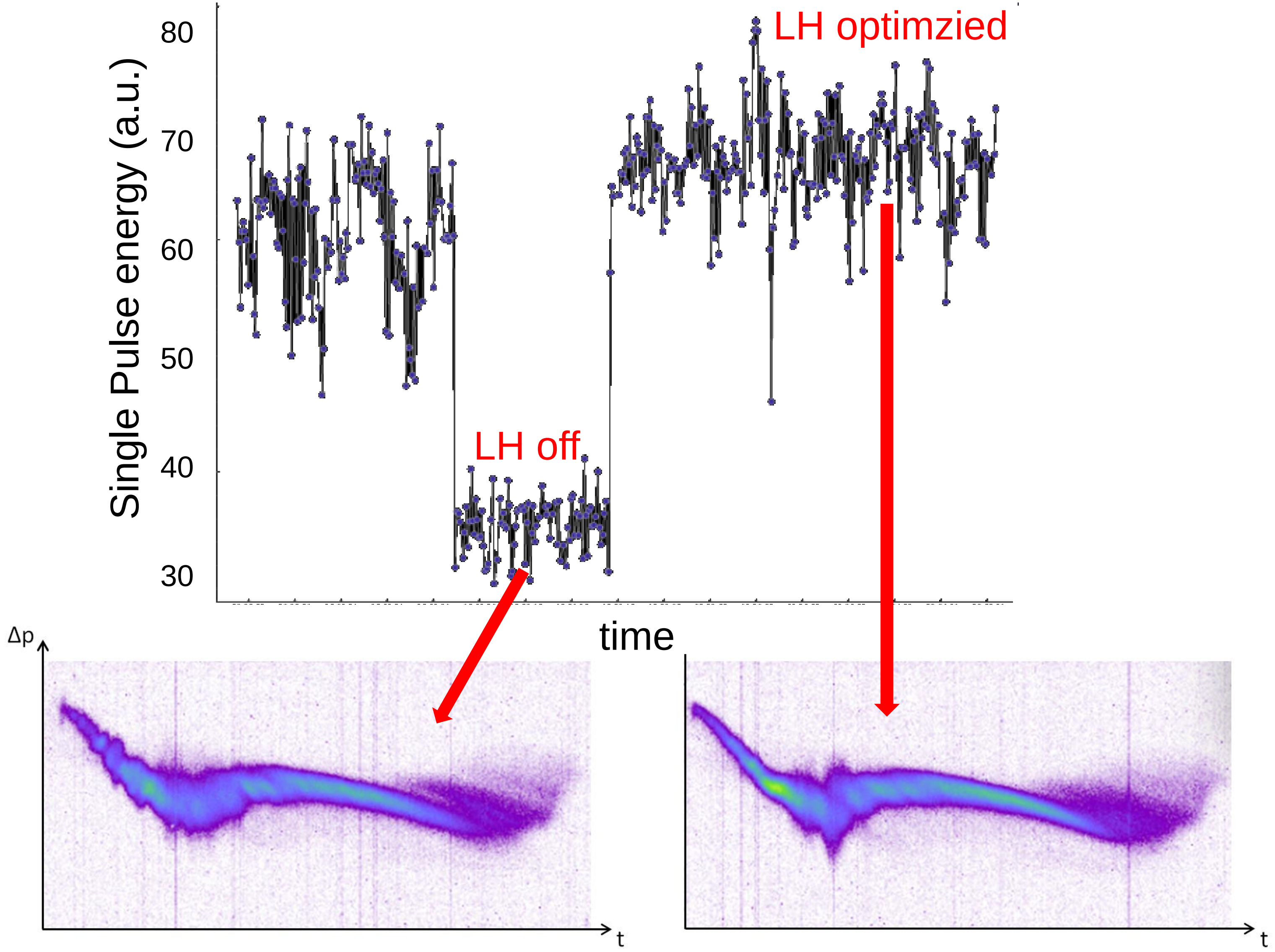
$$P_{Circ} = 99.7^{+0.3}_{-0.4}\%$$

Influemce of electron beam quality

Laser heater (LH)

The output power of the afterburner could be doubled by optimizing the longitudinal phase space distribution using the laser heater

Focusing into the afterburner helps to increase the output power especially for short wavelength with long gain length.



FLASH

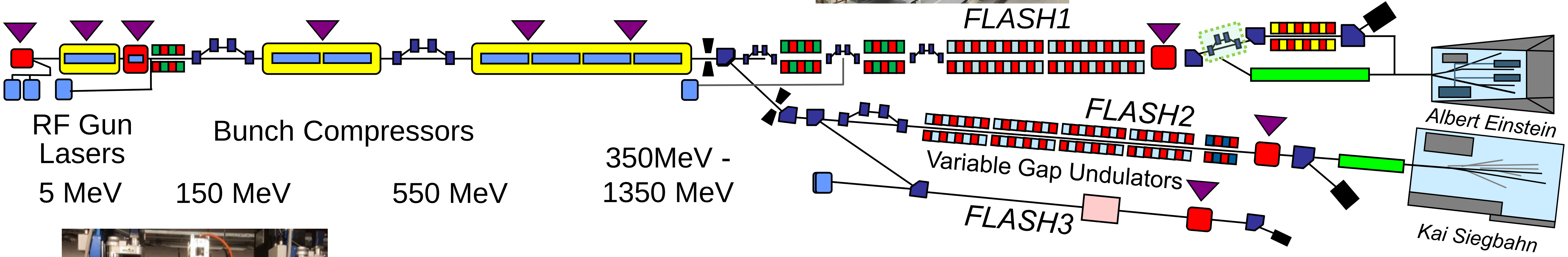
FLASH2020+ upgrade 2024/25

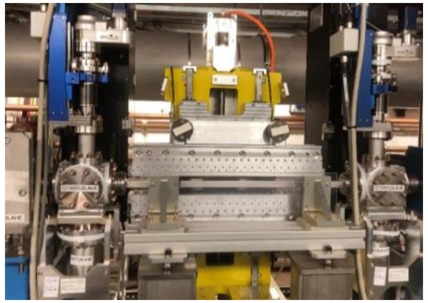
The afterburner served also as a full length prototype for six helical undulators for seeded FLASH1.

Seeded FLASH1:
Photon energy range:
310 – 20.6 eV
Pulse duration: 11- 40 fs
Min. spectral width: 0.05%

FLASH1: 2 planar, variable gap modulators, 3 planar, variable gap undulators, 6 APPLE III undulator

THz: electro magnetic undulator





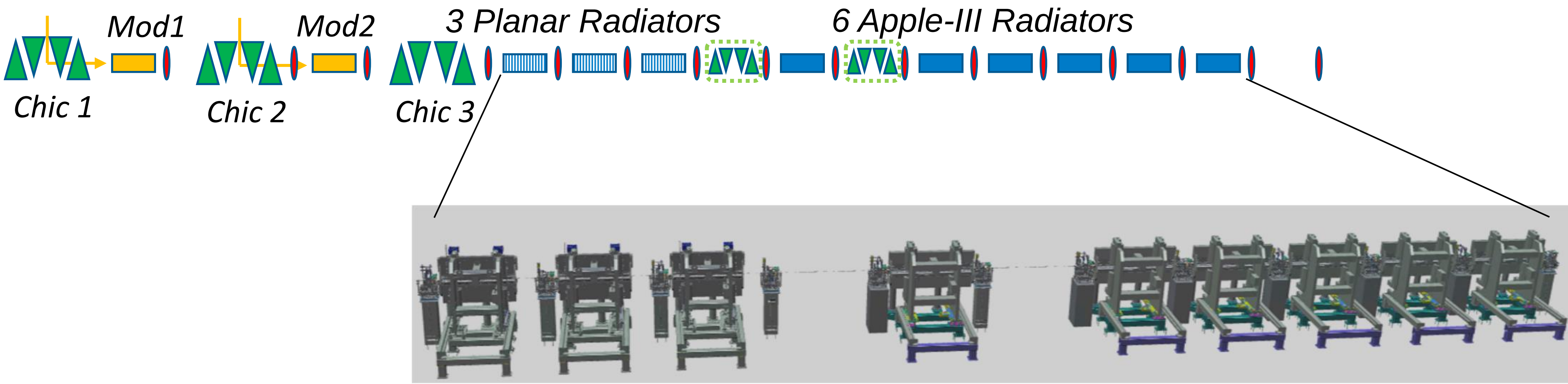
Laser heater undulator; planar, variable gap undulator

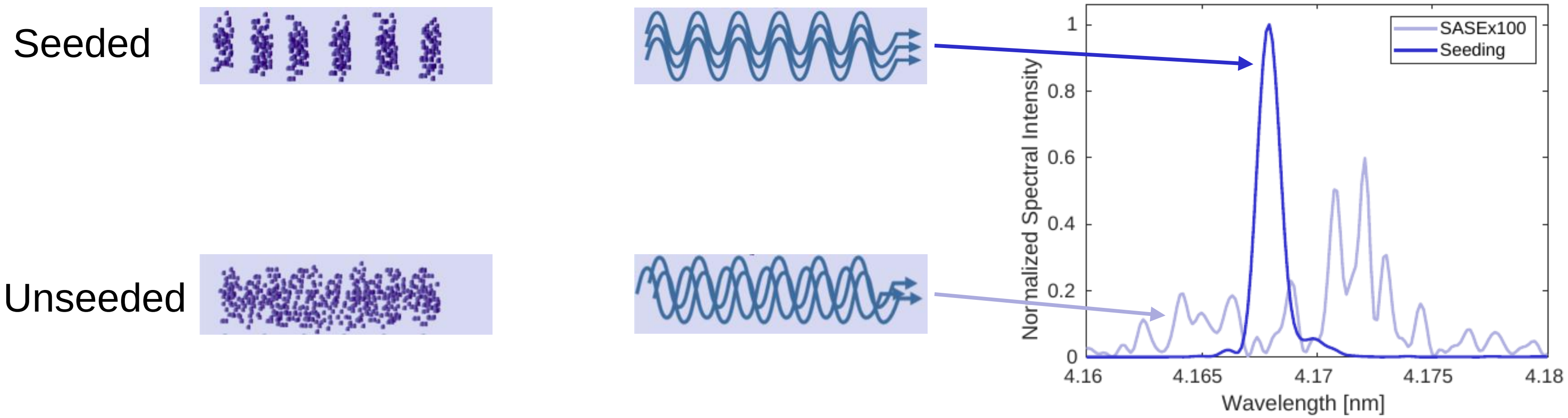
FLASH2: planar, variable gap undulators

FLASH2: afterburner; APPLE III undulator

The new FLASH1

Undulator configuration in the new FLASH1 beamline





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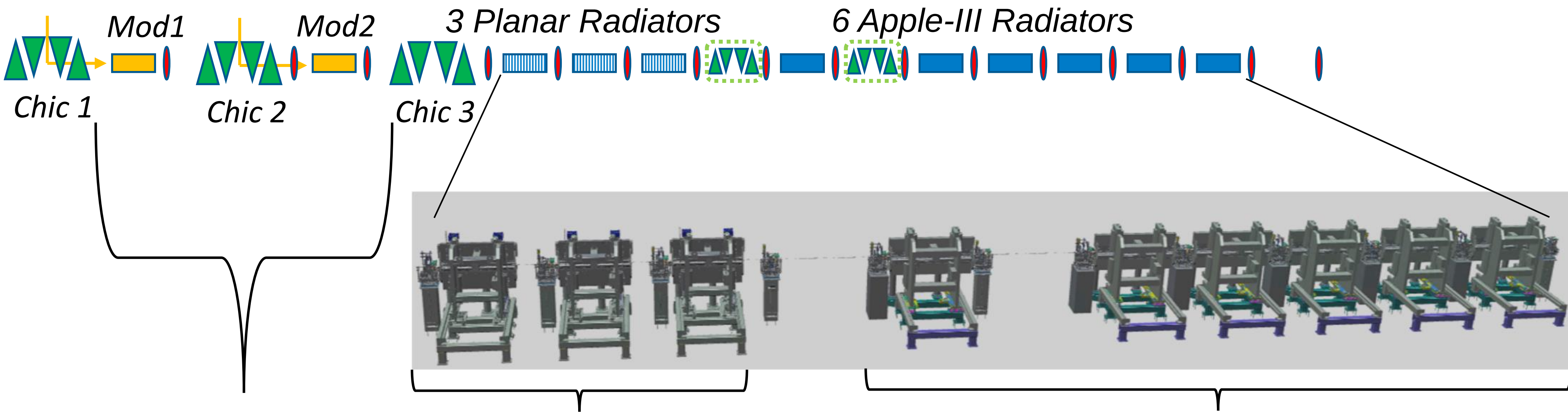
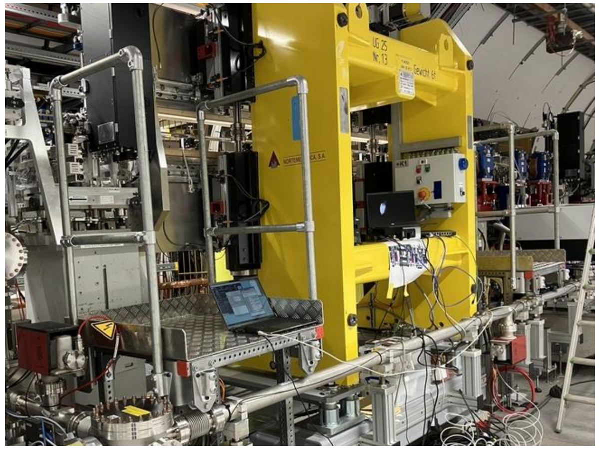


Modulators: U84 undulators

U32 undulators from Xseed

Radiator undulators (APPLE III)

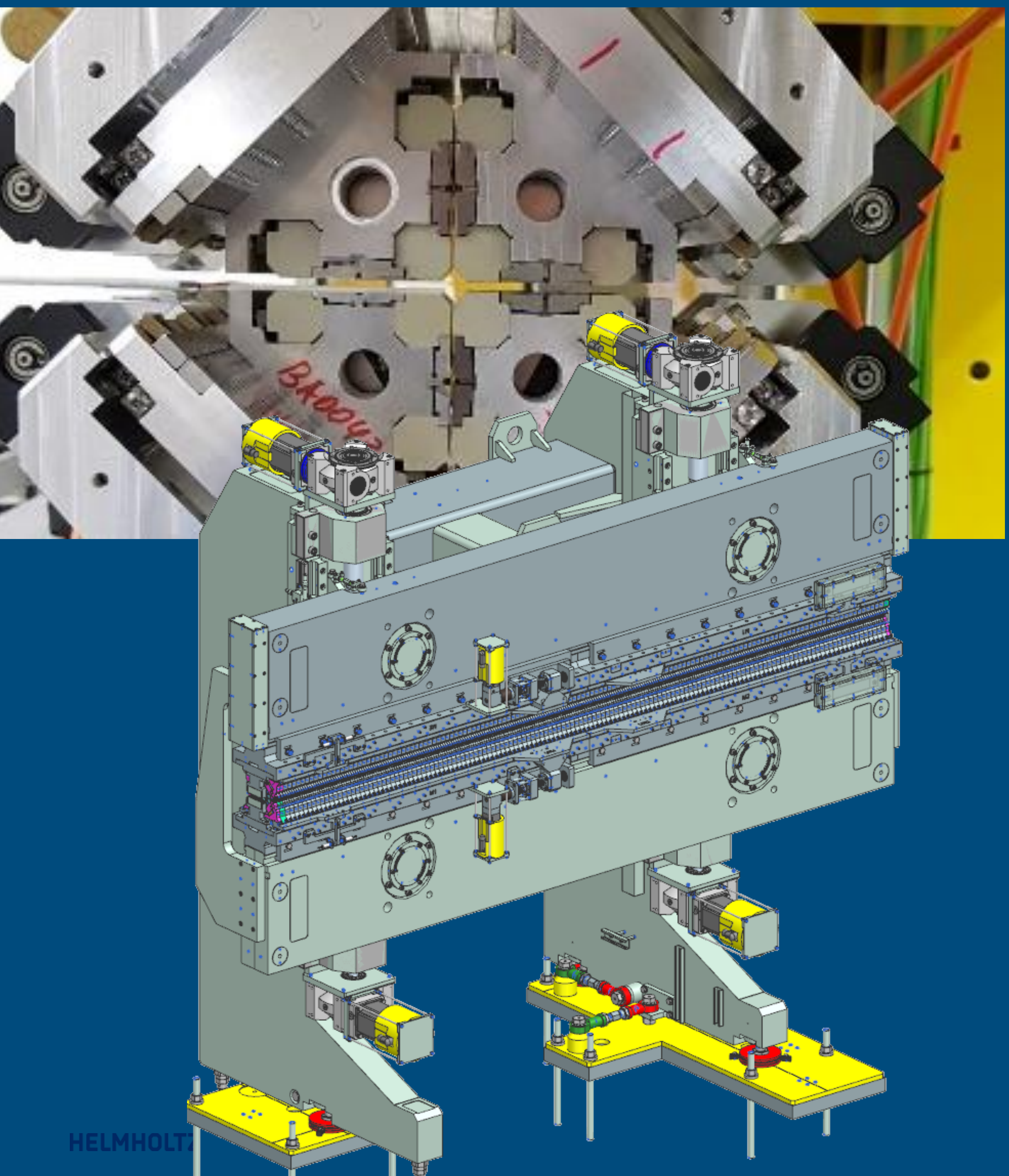


Undulators at FLASH

Parameters

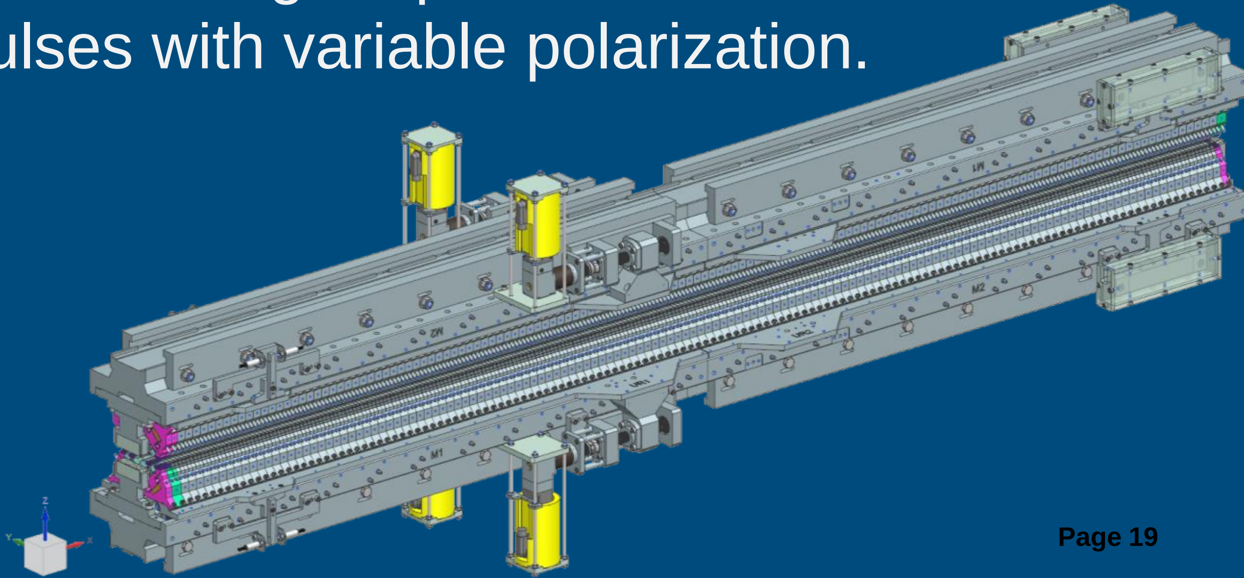
	FLASH1: Modulators	FLASH1: planar Radiators U32	FLASH1: APPLE-III Radiators U32	FLASH2: planar Radiators U32	FLASH1: APPLE-III Afterburner
minimum magnetic gap (mm)	9,00	9,00	8,00	9,00	8,00
period length λ_U (mm)	84,00	31,40	35,00	31,40	17,50
device length L (m)	2,50	2,00	2,50	2,50	2,50
number of full periods	27	61	70	77	
deflection parameter K_{max}	10,60	2,70	3,90	2,81	0,95
number of devices	2	3	6	12	1
peak field B_{max} (T)	1,40	1,00	1,20	0,98	0,56

Summary



FLASH2: APPLE-III afterburner allowed to extended the spectral range of the facility down to 1.4 nm and provided circularly polarized radiation.

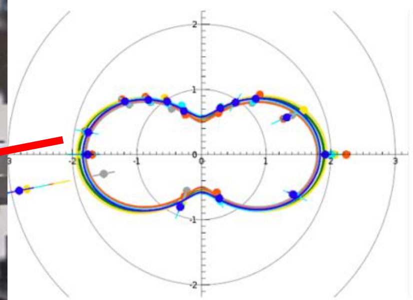
FLASH1: six APPLE-III radiators will generate high repletion rate, seed FEL pulses with variable polarization.



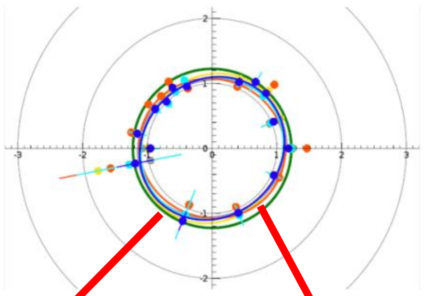
Thank you

Variable Polarization

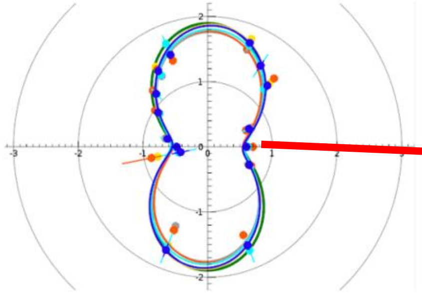
Linear horizontal polarization



Circular polarization



Linear vertical polarization



Degree of circular polarization of the 3rd harmonic at 313.8 eV is: $P_{Circ} = 99.7^{+0.3}_{-0.4}\%$

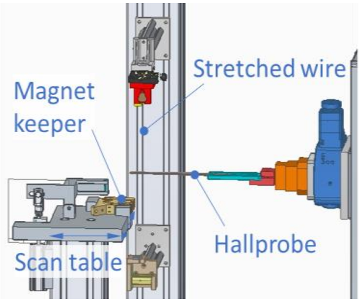
FLASH1 Radiators

6 APPLE III devices with 35mm period length

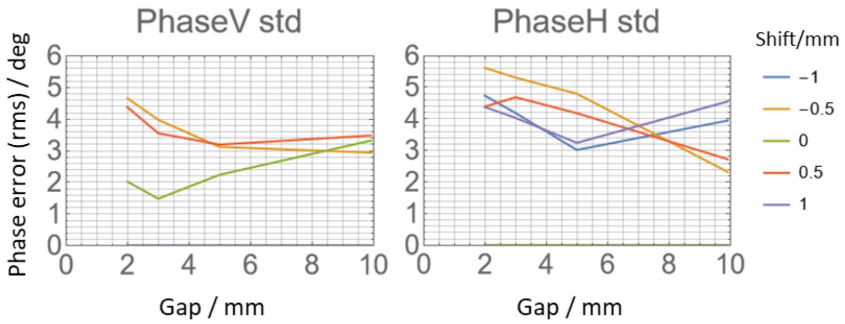
Once we received magnets assembled in keepers:

Stretched-wire measurements of all individual keepers → Sorting based on these data → Assembly onto girders/support structures → Measure and tune complete device with Hall probe and stretched-wire set-up

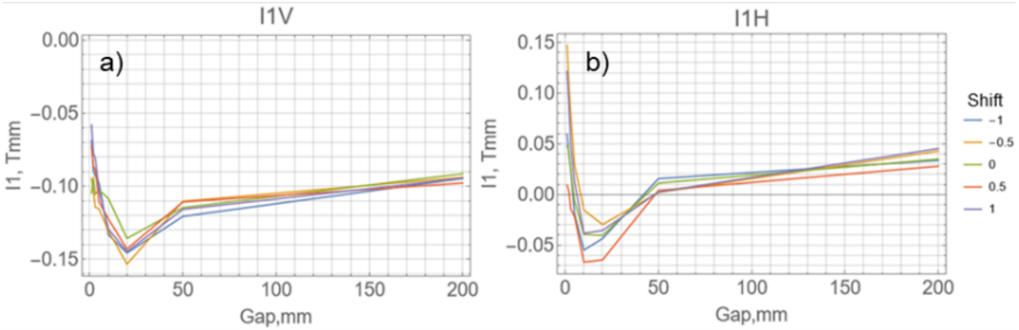
- Each step in a different lab – continuous work flow
- Experience from afterburner
- 2 labs for the final step of measuring and tuning



Final parameters afterburner



Phase error <6deg, little variation with shift mode

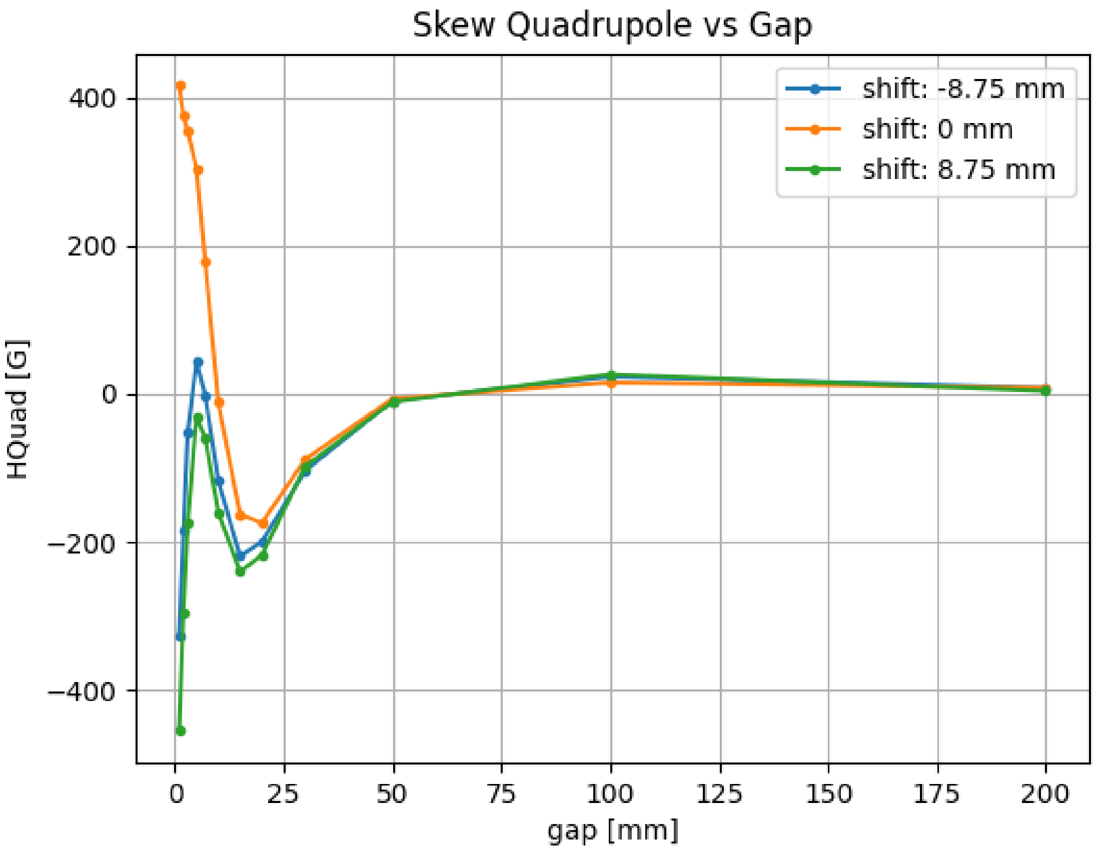


Remaining kick errors: ±50 Gcm +shift-dependent kick error of similar size. Corrected in a feed-forward by small air coils.

FLASH1 Radiators

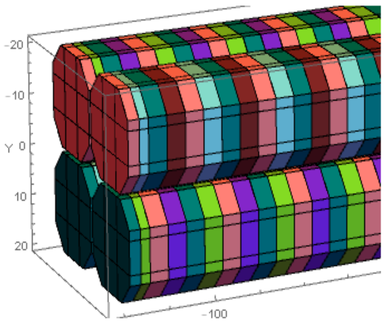
APPLE III

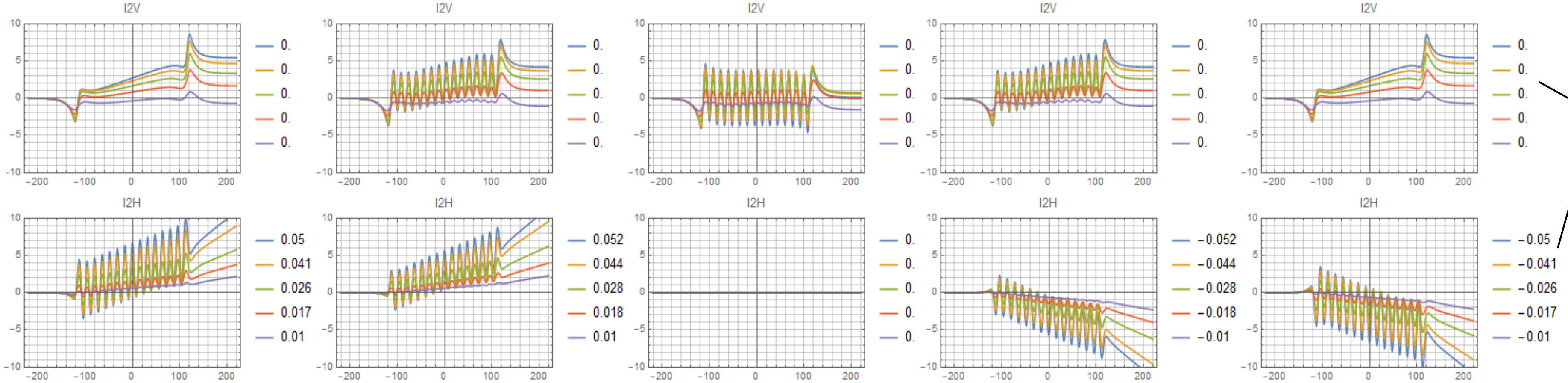
Final gap dependency of the skew quadrupole at horizontal and circular polarization for RAD02 for FLASH1.



APPLE-III Endstructure

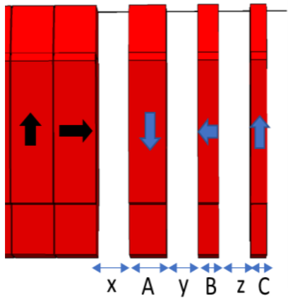
Simple (mechanically) endstructure with just reduced width magnets ~25Gs*cm residual kicks each side



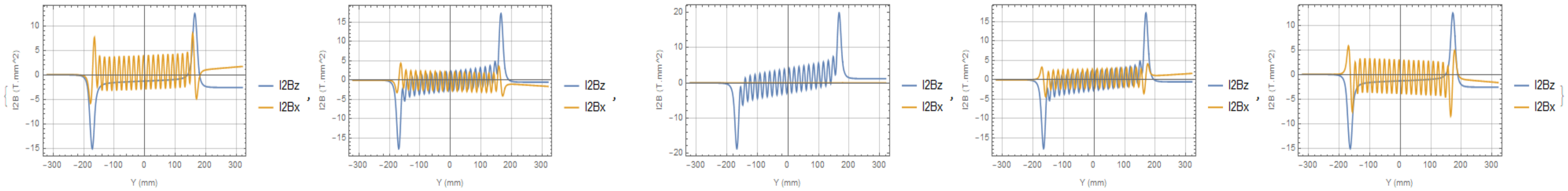


Residual kick [Tmm] for various gaps

Optimized for minimum kick

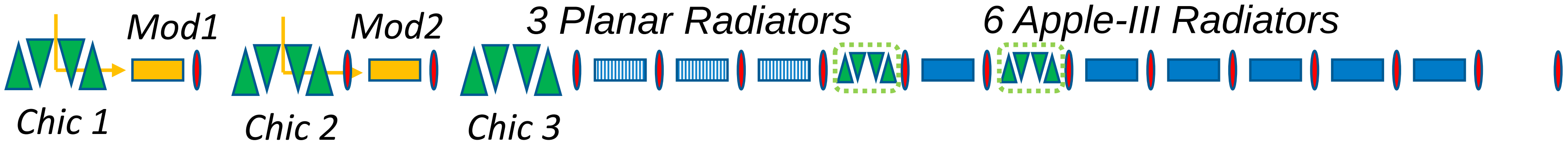


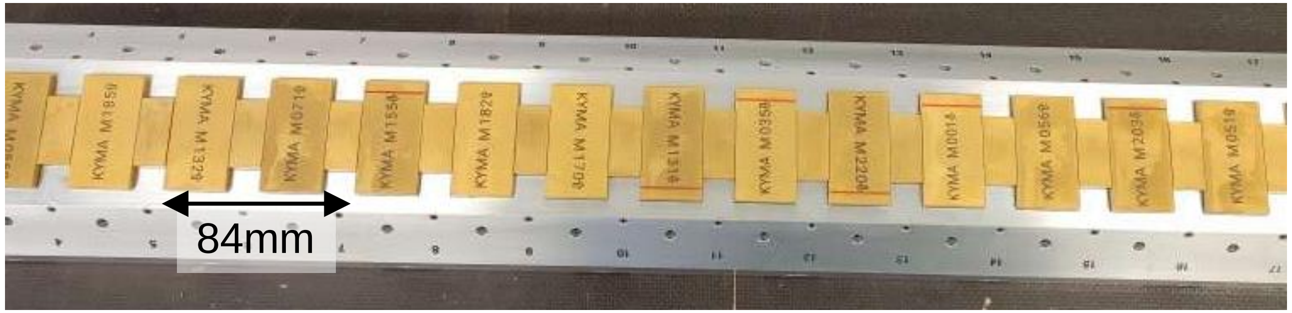
phi = -Pi/2 -Pi/4 0 Pi/4 Pi/2

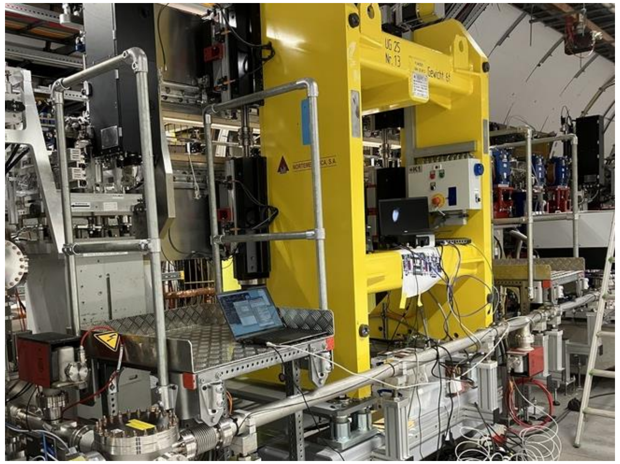


Modulators

Two U84 planar undulators with hybrid structure (magnet and poles)



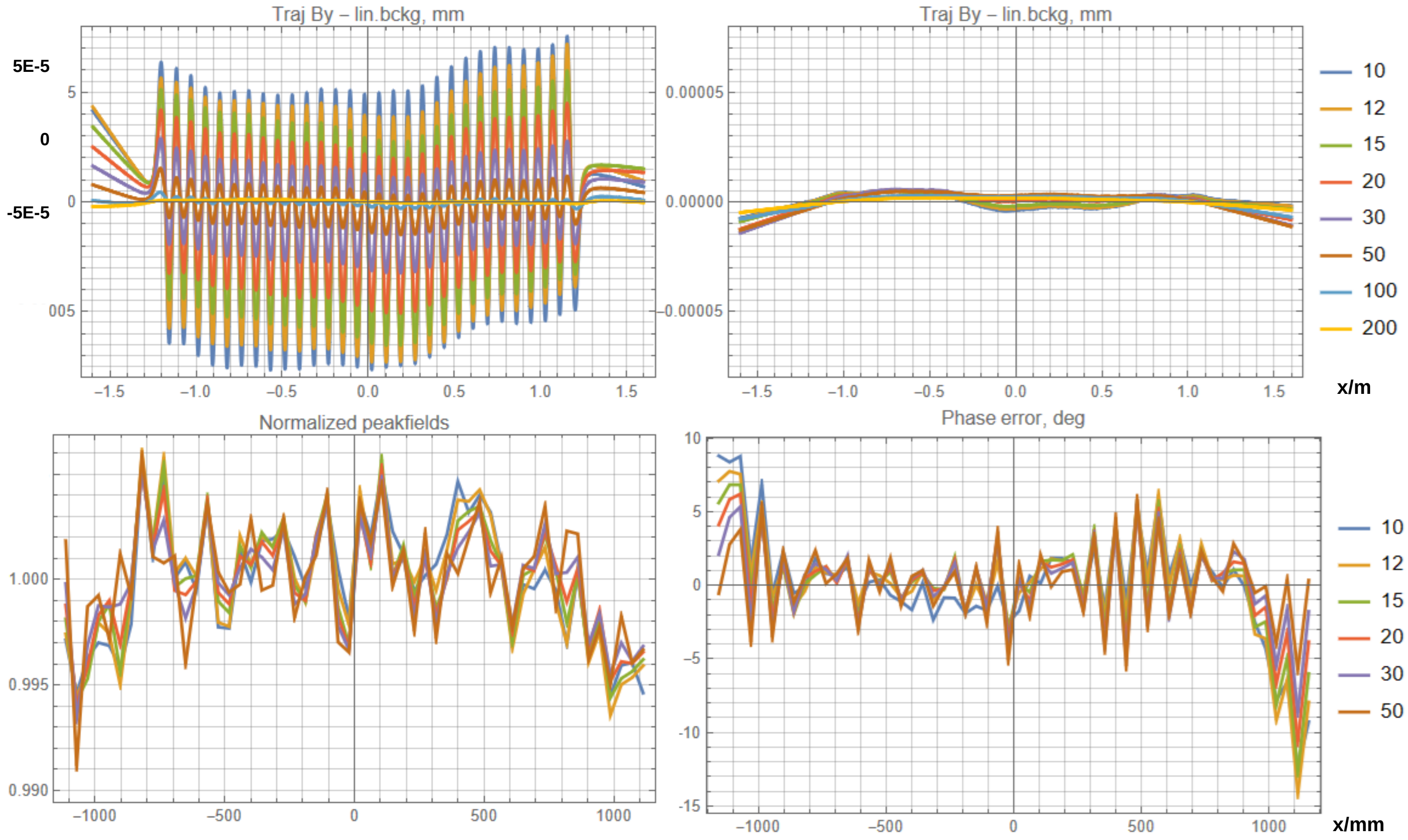




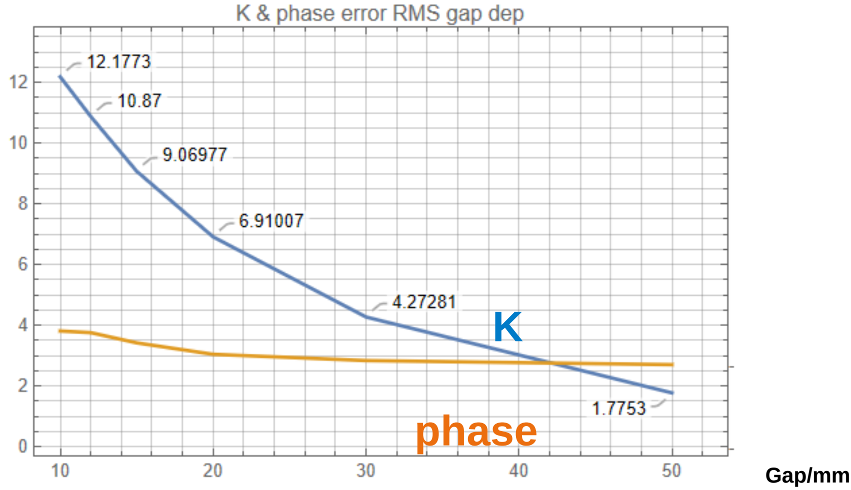
- Length = 2.5m
- Period = 84mm
- Min. gap = 9mm
- B_{max} = 1.8T
- Specs: K=11, achieved: K = 12.9

Modulators

Two U84 planar undulators with hybrid structure (magnet and poles)



- Sorting of magnets based on novel Hall mapper reduces amount of pole tuning
  - ➢ Parameters were within specs without any pole tuning (straight trajectory, phase error <4°).
- Additional girder curvature spoiled phase error
- Strong fields
  - ➢ Strong forces
  - ➢ Reaching limits of sensor calibration



Measurements and data analysis: P. Vagin

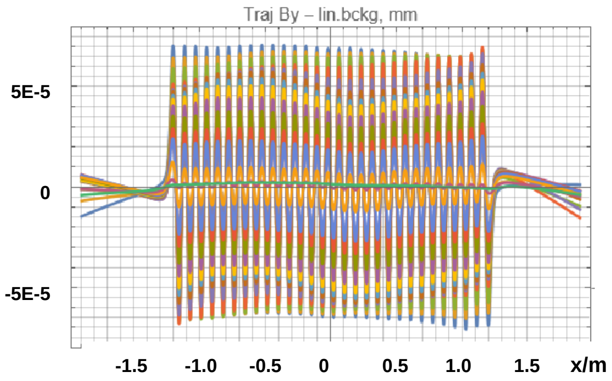
Modulators

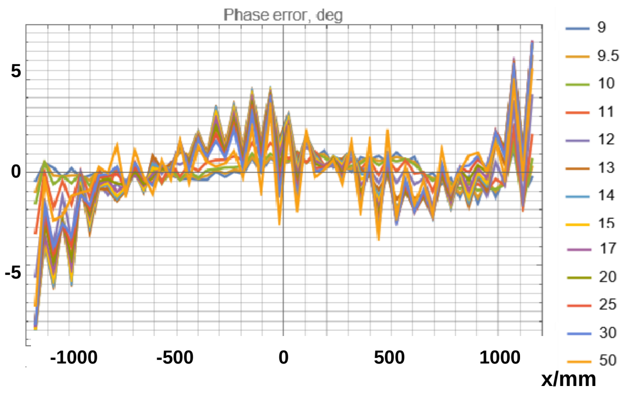
Two U84 planar undulators with hybrid structure (magnet and poles)

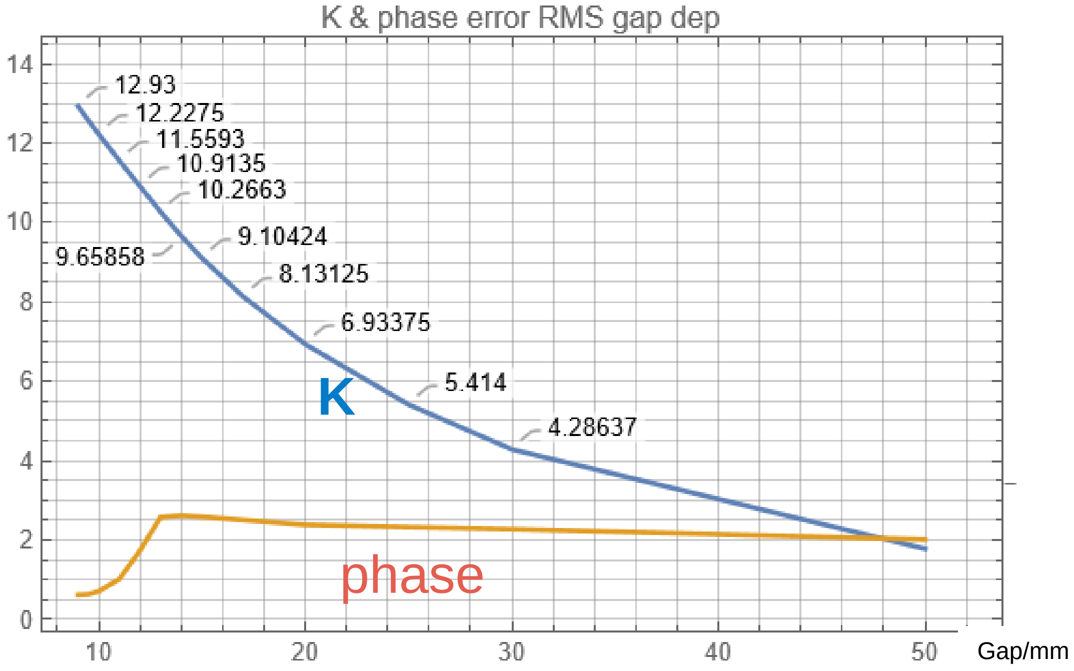
After tuning

- Trajectories further straightened
- 0.5deg RMS phase error at minimum gap
- Girder shape strikes back at intermediate gaps due to different gap dep.
- K = 12.9
- „Target" value was K_{target}=11 at 9.5mm gap, to reach 343nm at 1.4GeV
- Now at 1.35GeV: 343nm reached at K=10.6, or operating gap ~12.5mm

➢ Both Modulators tuned and close to ready.







Measurements and data analysis: P. Vagin

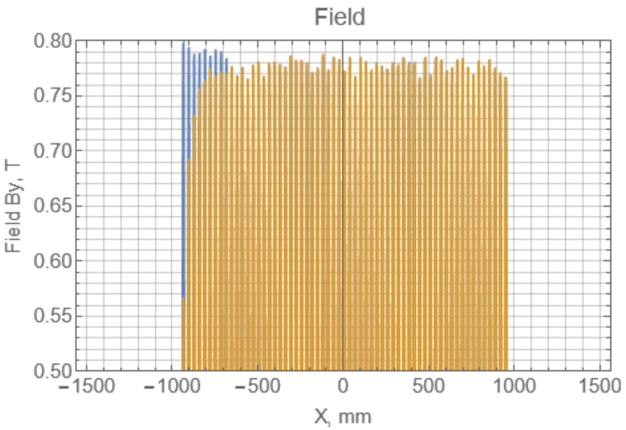
Refurbished U32s from XSeed

Three planar devices to increase pulse energy at short wavelengths.

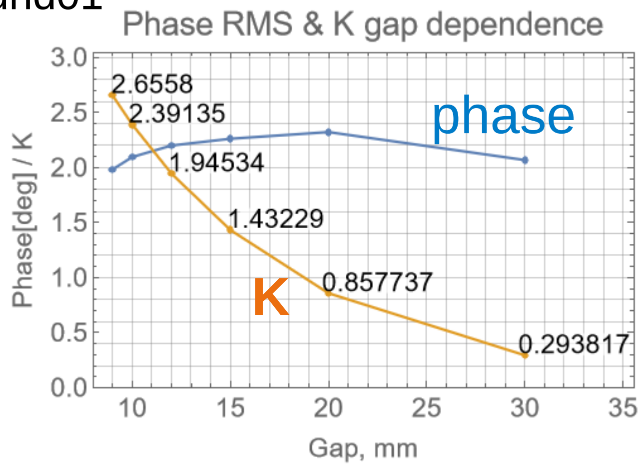
- sfund01, sfund02 and sfund03 retuned.
- sfund01: Severe radiation damage (>10%) – flipped 18 magnet pairs and replaced end magnets upstream.
- K between 2.65 and 2.70 at min gap of 9mm
- Phase errors <3°
- Remaining kick errors: ±50 Gcm. Corrected in a feed-forward by small air coils.

➢ All three devices tuned and ready.

sfund01

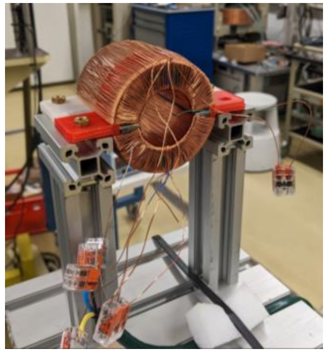


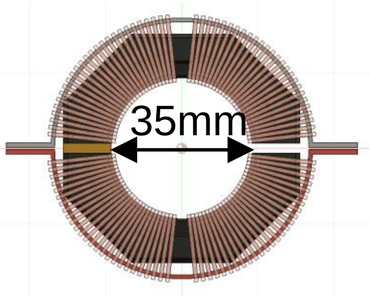
-- Field before
-- Field after flipping 18 magnets US

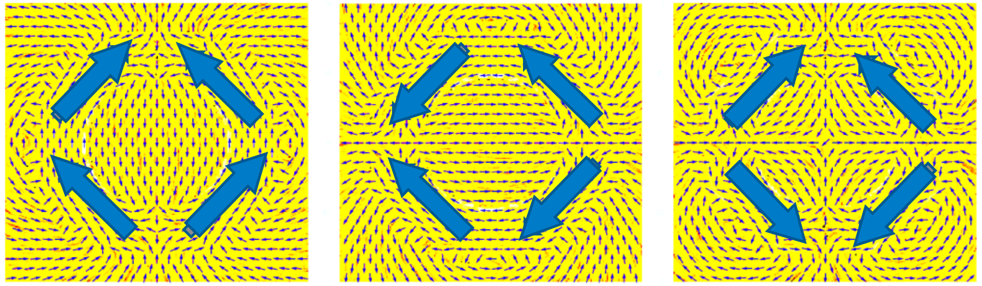


Corrector coils with variable field direction for FLASH1

Ferrite enforced resistive coils (air-cooled)



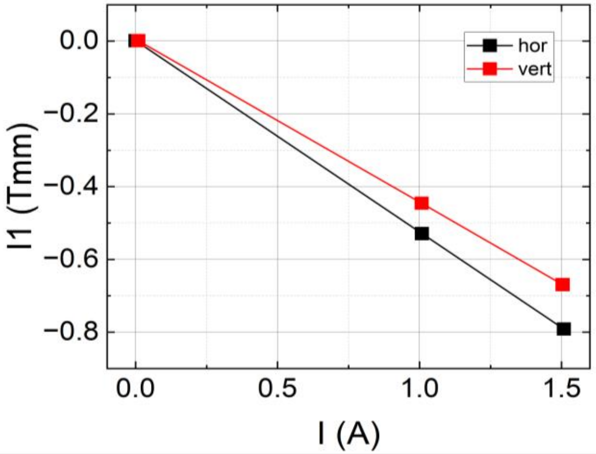




Correct (gap dependent) kick up and down stream of undulators

- In-house design for stronger coils with slow feedback option
- Resistive, air-cooled coils
- Compact and cost-efficient design
- Ferrite-based – 0.55Tmm at 1A
- Four sub-coils per unit – variable field direction
- AC capability

➢ Series of 40 coils manufactured



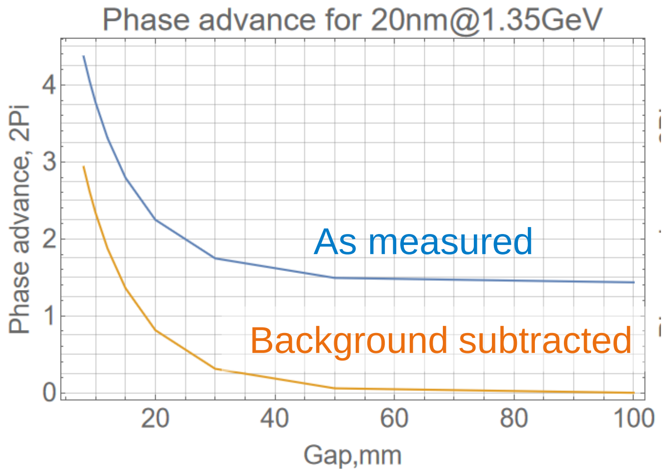
On-axis first field-integral as a function of current (hor/vert field).

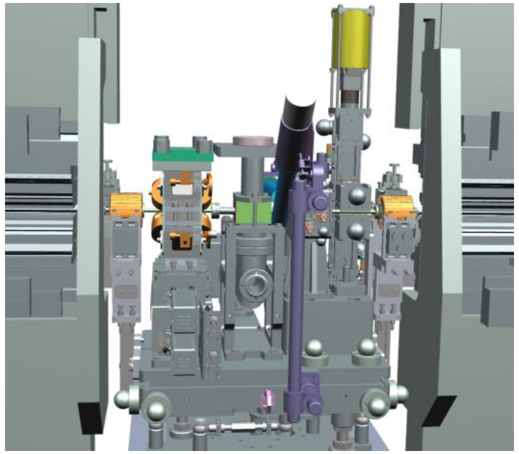
Stored coils

Phase shifters for FLASH1

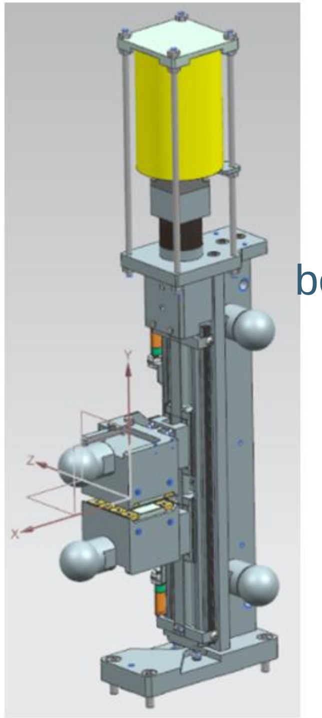
Compact, permanent magnet-based phase shifters on intersections

- Compact, permanent magnet-based design
- Pre-sorting allows for using lower quality, low price magnets
- Series of 10 phase shifters built and tuned
- <0.02Tmm (6µrad) on-axis kick remaining
- high uniformity within series

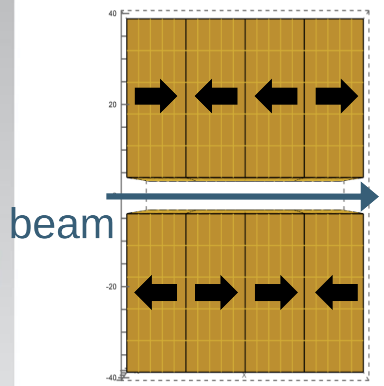




Intersection



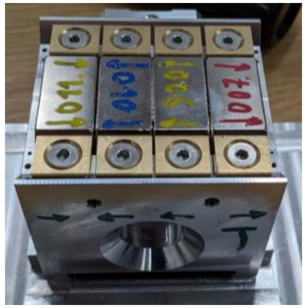
Phase shifter



Magnetic set-up

➢ Phase advance as a function of gap.

All 10 phase shifters achieve at least **2.8*2π** for 20nm@1.35GeV.

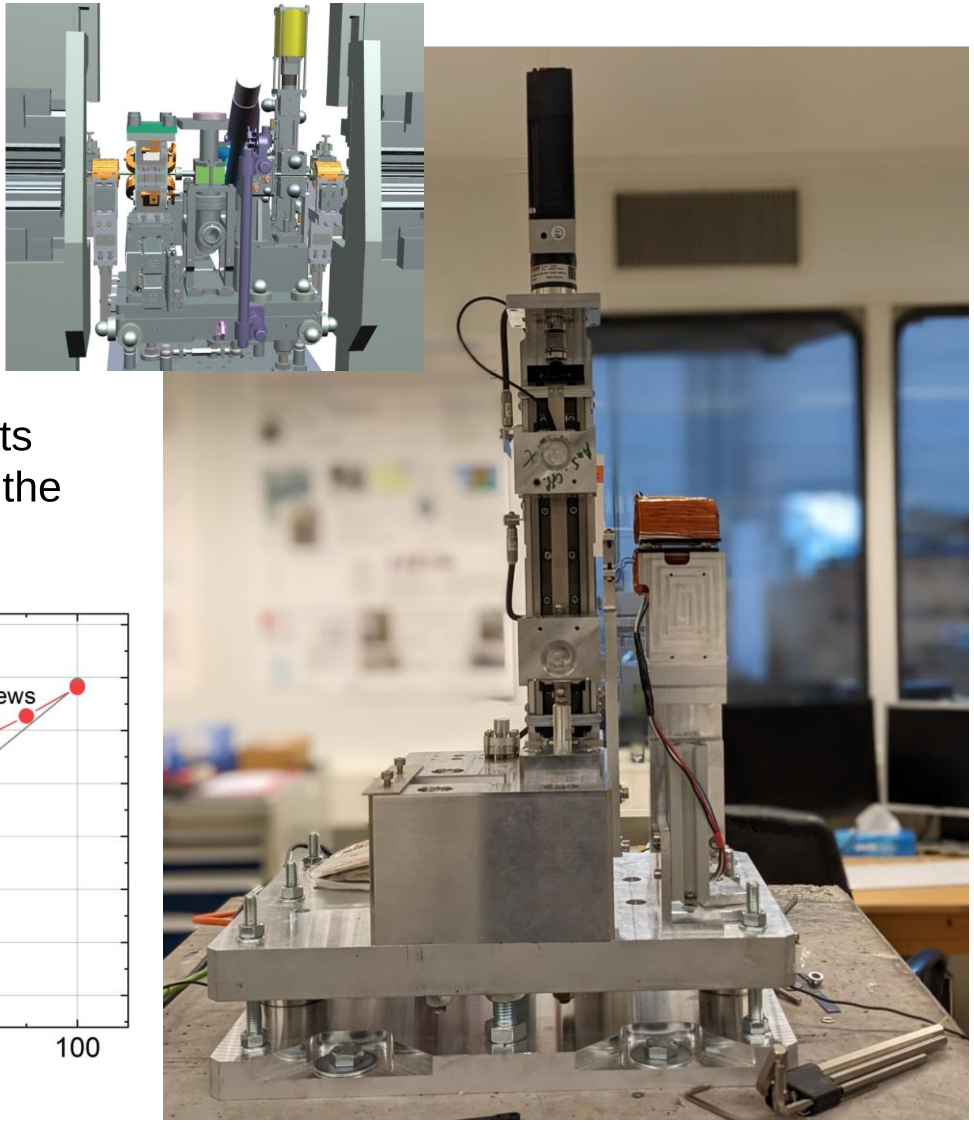


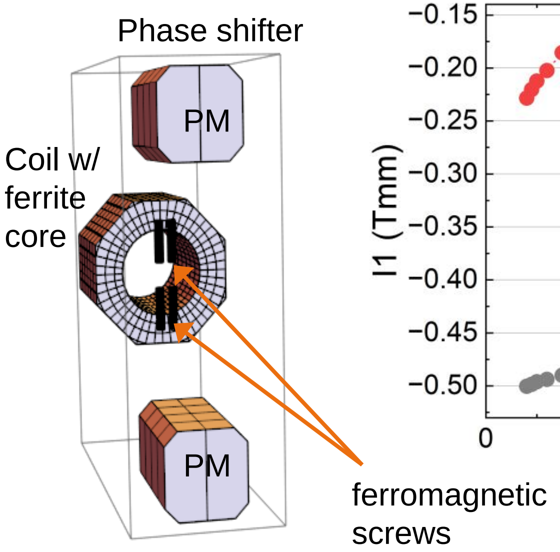
Magnet blocks.
Size: 35x35x15mm^3

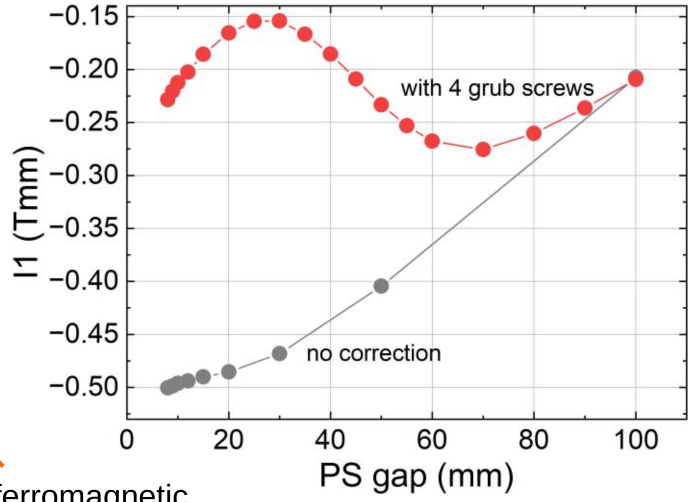
Phase shifters and corrector coils

Managing cross-talk

- Originally only 22mm distance between permanent magnets of phase shifter and ferrite enforced coils
- Strong, unwanted dampening of PS fringe fields due to cross-talk
- ➢ Increased the distance to 30 mm (max)
- ➢ Passive compensation by installing two sets of ferromagnetic screws above and below the beam pipe.



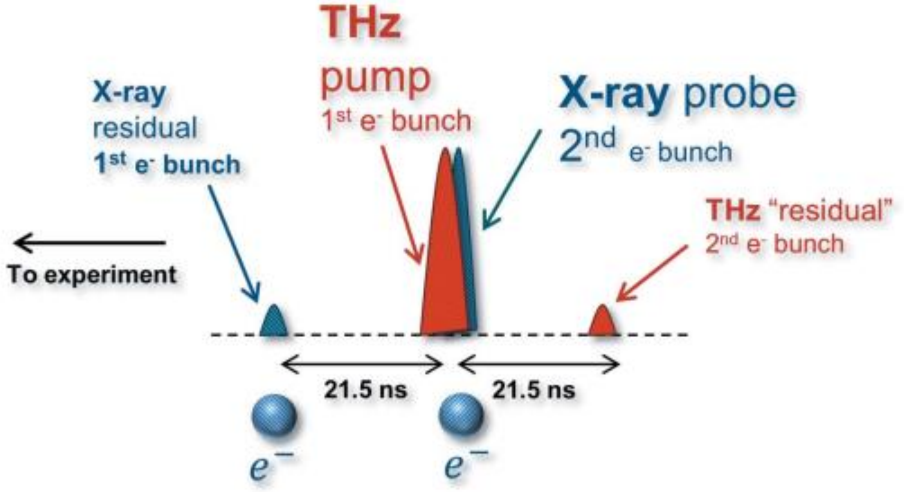




Advanced Lasing tested at FLASH

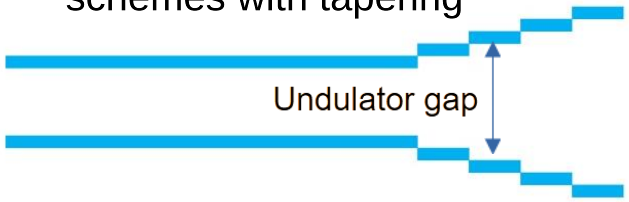
- Various double pulse schemes
- Improved FEL-performace by optimized undulator tapering
- Two color operation
  - Amplification of higher harmonics
  - Optimization of focus points
- Improving longitudinal coherence by single spike SASE

Example double pulses: X-ray and THz pulse arrival times for the double electron bunch scheme.

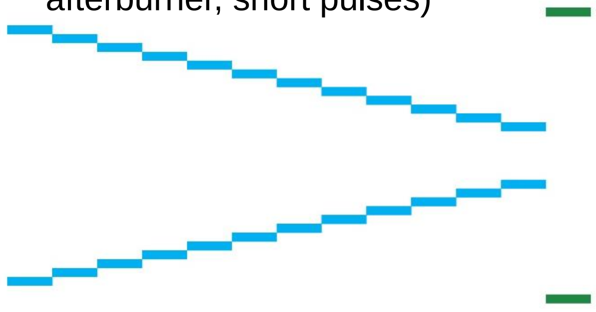


THz pulse doubler at FLASH: double pulses for pump-probe experiments at X-ray FELs
J.Synchrotron Radiat. 25 (2018) 39-43, DOI: 10.1107/S1600577517015442

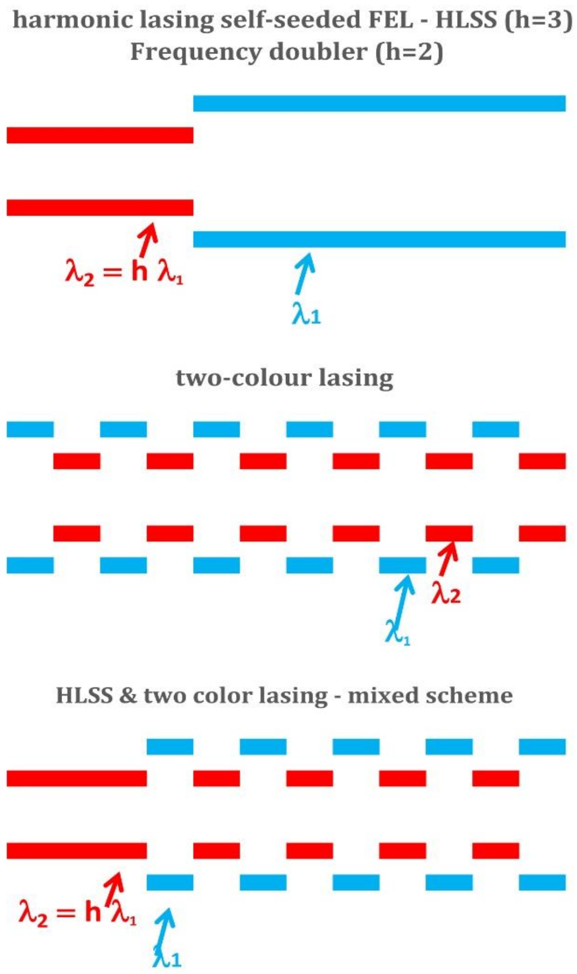
Examples for undulator schemes with tapering



Reverse tapering (for afterburner, short pulses)



Examples for two color undulator schemes



The FLASH Facility: Advanced Options for FLASH2 and Future Perspectives. Applied Sciences. 2017; 7(11):1114. https://doi.org/10.3390/app7111114