APPLE III developments at DESY

Variable polarisation for FLASH

Kathrin Götze (DESY Undulator group)
ID26 workshop Deauville, 15th May 2026

On behalf of: Markus Tischer, Pavel Vagin, Andreas Schöps, Paul Neumann, Thorsten Vielitz, Philip Eckoldt and the other members of the ***DESY undulator group****, and with thanks to colleagues at the* ***central mechanics*** *and* ***mechanical design groups*** *and at* ***FLASH machine and controls***

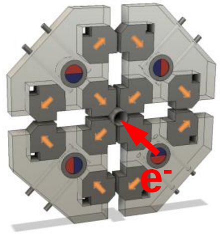
HELMHOLTZ

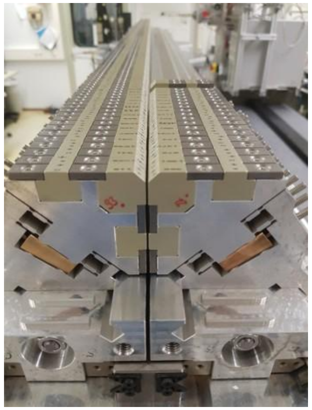
DESY.

Outline

APPLE III developments at DESY

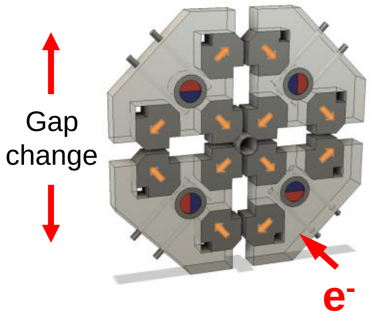
- APPLE III concept
- The “prototype”: APPLE III Afterburner for FLASH2, UE17.5
- The seeding upgrade: Six UE35 APPLE III for FLASH1
- Lessons learnt
- Summary and outlook

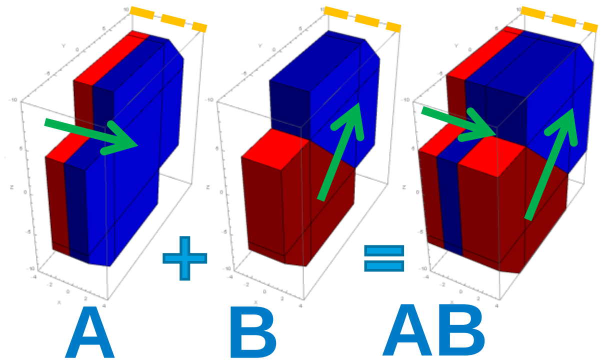


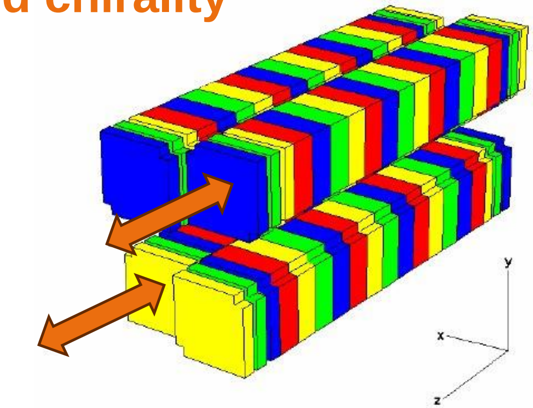


APPLE III concept

Variable polarisation for investigating magnetism and chirality



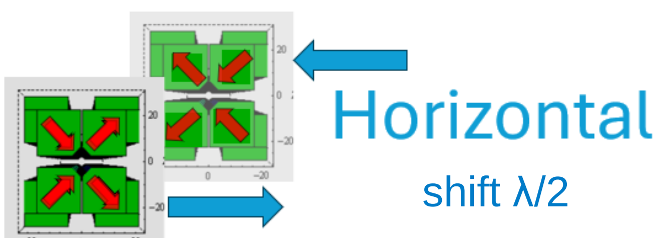


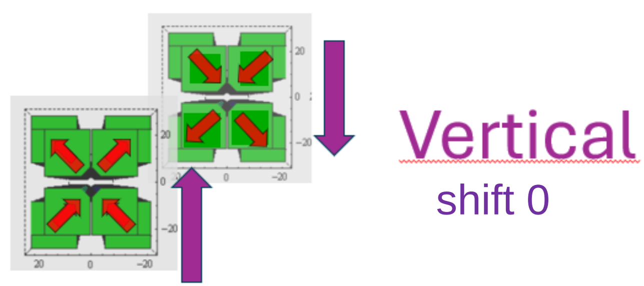


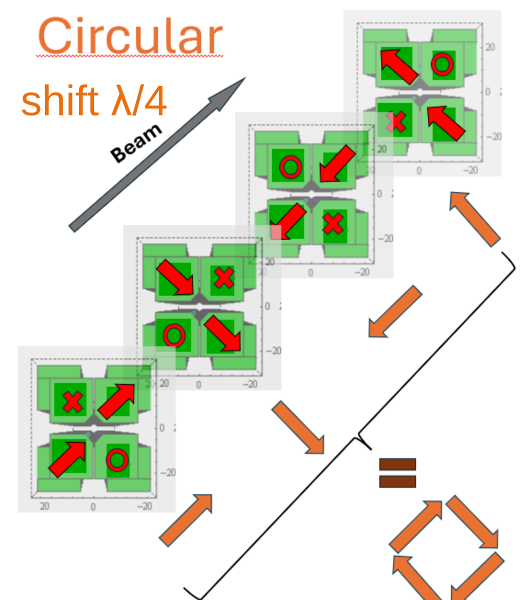
Shift drive for different polarization modes

- APPLE III: highest field, less bulky, cost efficient
- Force reduction up to factor of 8 - reuse of planar undulator support structures

Variable field direction:





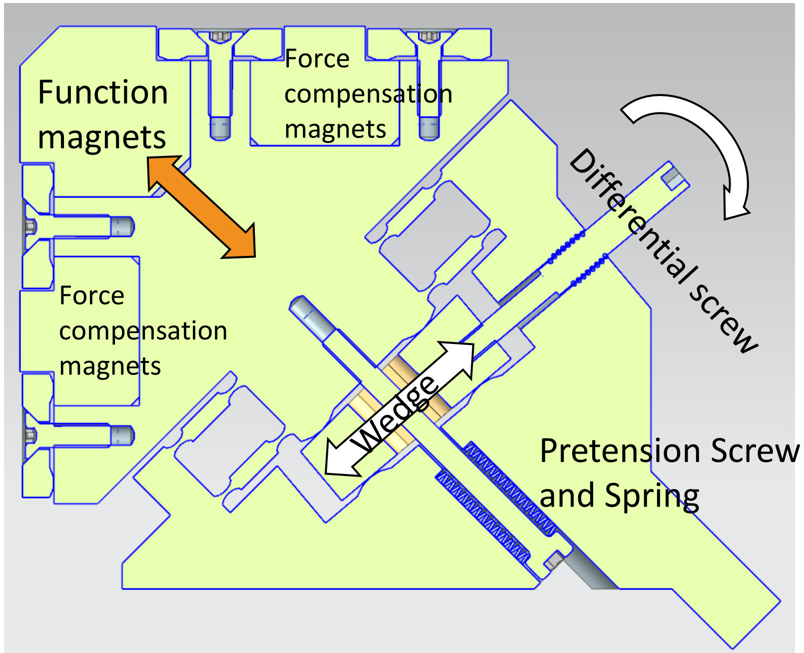


APPLE III design: *Bahrdt J, Frentrup W, Gaupp A, Kuske B, Meseck A, and Scheer M 2004 Proc. SRI Conference 2003 AIP CP 705 215–18*
Source shift drive picture: Hannon, F.E., *et al., Proceedings of EPAC*. 2004.

APPLE III concept

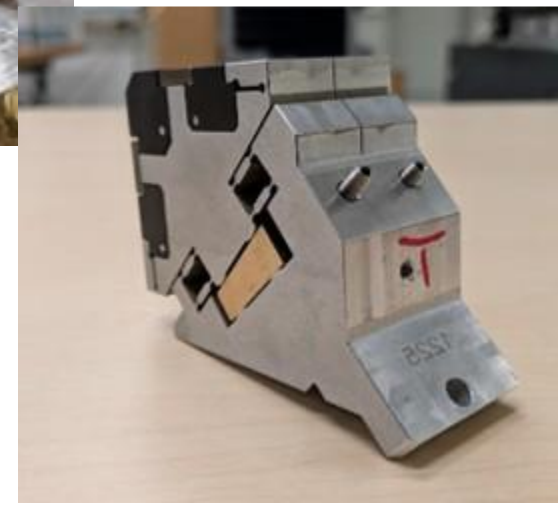
Magnet and keeper design

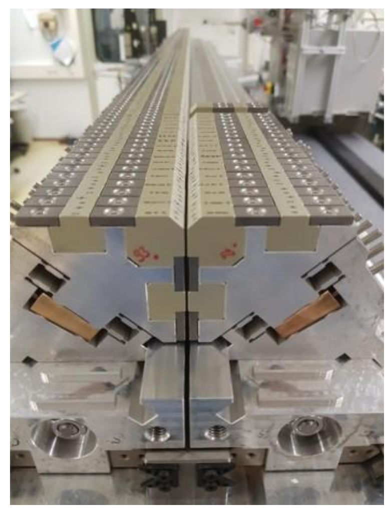
Full period (17.5 or 35mm) keepers



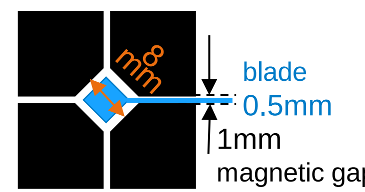
◀FLASH2 Afterburner keeper 17.5mm period length

FL1 radiator keeper ▶ 35mm period length





Vacuum chamber:

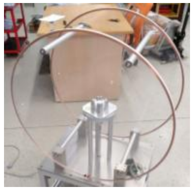


- Field tuning by virtual shimming
- Keeper body: aluminium, wedge: copper tin bronze $CuSn_2$.
- Differential screw (M3/M4 thread)
- One full period per keeper, separated by cut in keeper body for individual tuning of half periods.

APPLE III concept

Magnet and keeper characterisation

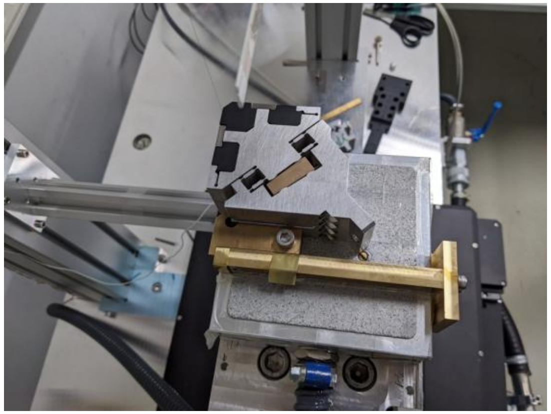
Glued AB magnets measured individually by Helmholtz coil



Magnets sorted into pairs and mounted into keepers

(one keeper=one period=two function magnet pairs)

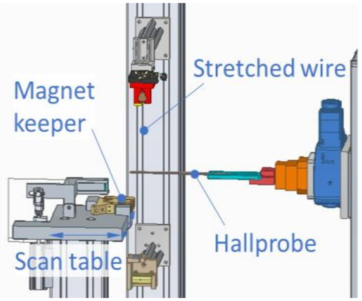
Stretched-wire and Hall measurements of all individual keepers



Sorting list for each device based on these data

Assembly onto girders/support structures

◀ ▲ *Keeper on measurement stand*



Measurement stand scheme

Measurement and tuning of complete device with Hall probe and stretched-wire set-up

APPLE III Afterburner

Circularly polarised SASE radiation at FLASH2.

- Period length 17.5mm
- Wavelength range FLASH1: 3.3 – 90 nm (3rd Harmonic Wavelength down to 1.7 nm)
- Radiates on the third harmonic of the SASE section to provide photon energies around the L-edges of iron, cobalt and nickel (890-700 eV or wavelength range 1.33--1.77 nm) for studies of ultrafast magnetisation dynamics.
- Installed August 2023
- First publication May 2025

RESEARCH ARTICLE | MAY 08 2025

First experiments with ultrashort, circularly polarized soft x-ray pulses at FLASH2

Special Collection: Celebrating the work and the achievements of Jo Stöhr

S. Marotzke ; D. Gupta ; R.-P. Wang ; M. Pavelka ; S. Dziarzhytski ; C. von Korff Schmising ; S. Jana ; N. Thielemann-Kühn ; T. Amrhein ; M. Weinelt ; I. Vaskivskyi ; R. Knut ; D. Engel ; M. Braune ; M. Ilchen ; S. Savio ; T. Otto ; K. Tiedtke ; V. Scheppe ; J. Rönsch-Schulenberg ; E. Schneidmiller ; C. Schüßler-Langeheine ; H. A. Dürr ; M. Beye ; G. Brenner ; N. Pontius

Check for updates

Struct. Dyn. 12, 034301 (2025)
https://doi.org/10.1063/4.0000298

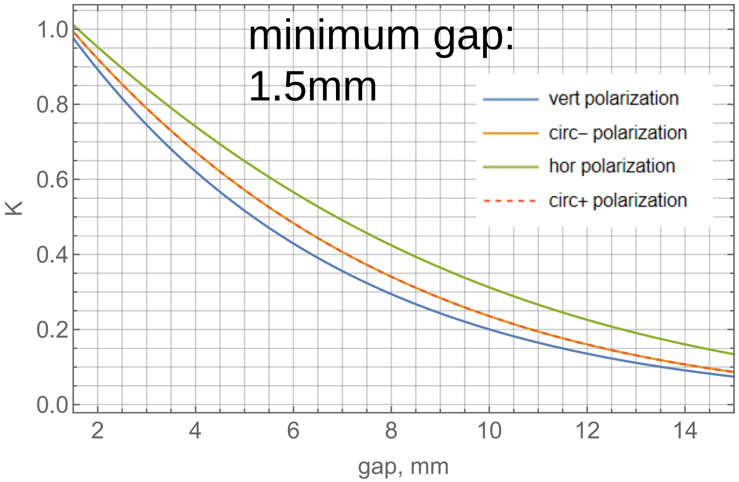
https://doi.org/10.1063/4.0000298

APPLE III Afterburner for FLASH2

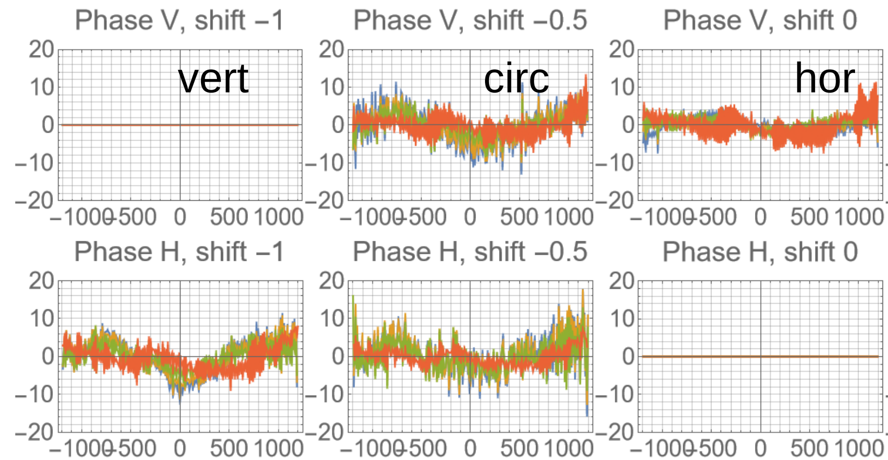
see also Markus Tischer *et al.* 2025 *J. Phys.: Conf. Ser.* **3010** 012045
DOI 10.1088/1742-6596/3010/1/012045

Characteristics and results

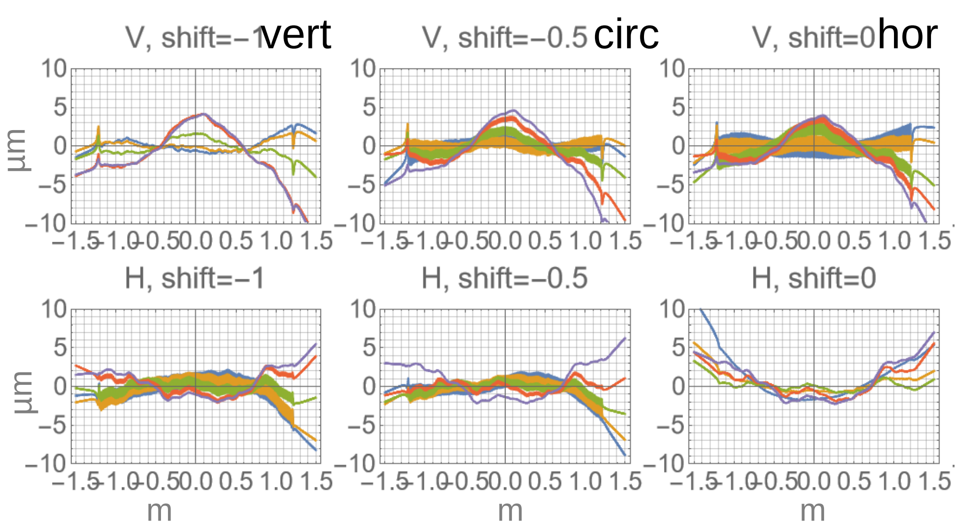
K value



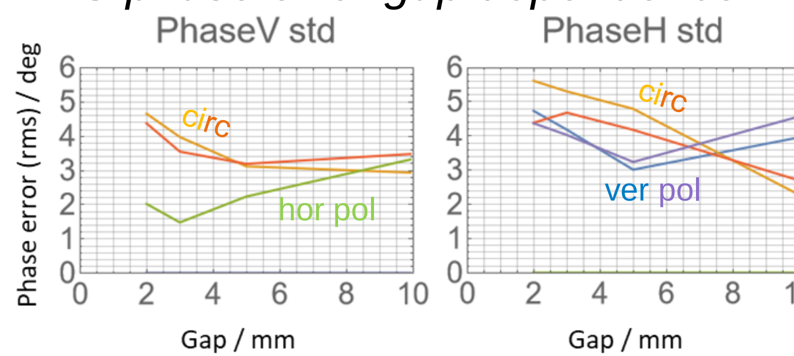
Phase error



Trajectories (@1.35GeV)



RMS phase error gap dependence



<6deg after tuning.
Taper-corrected: <5deg.

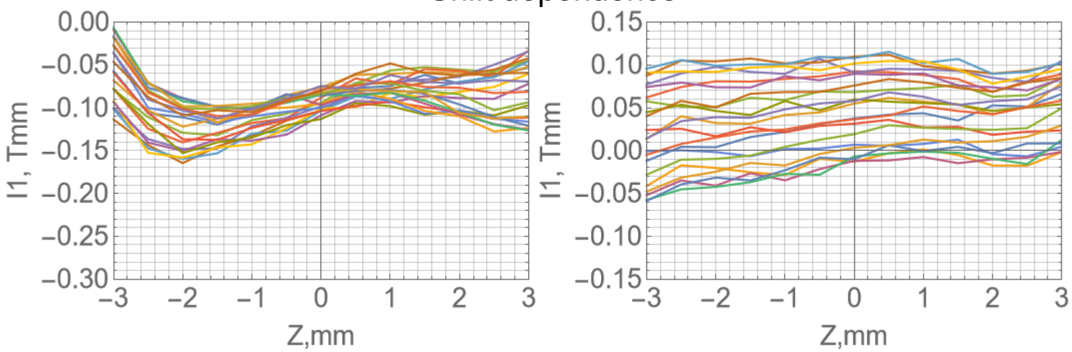
APPLE III Afterburner for FLASH2

see also Markus Tischer *et al.* 2025 *J. Phys.: Conf. Ser.* **3010** 012045 DOI 10.1088/1742-6596/3010/1/012045

Characteristics and results

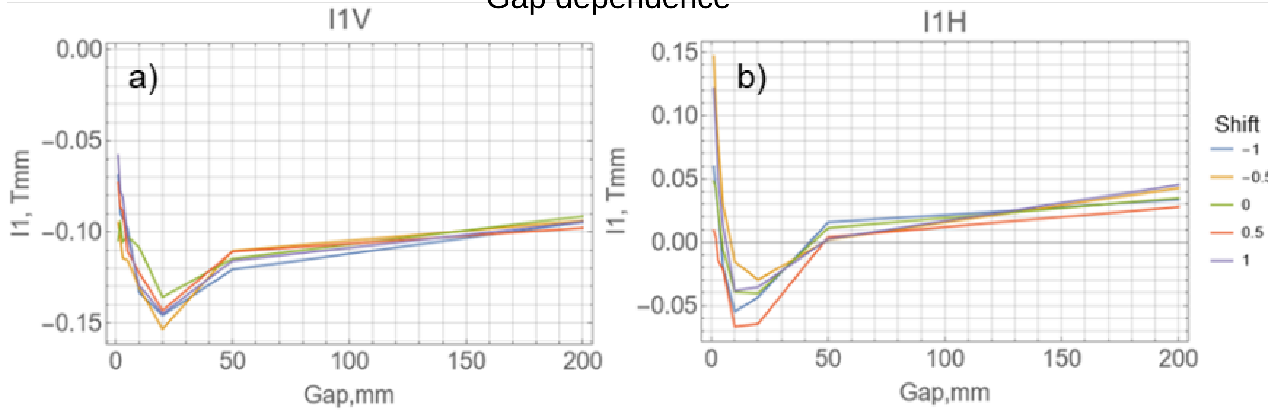
Kick errors and multipoles

Shift dependence



Transverse dependence of vert. and horiz. field integrals at gap = 2mm

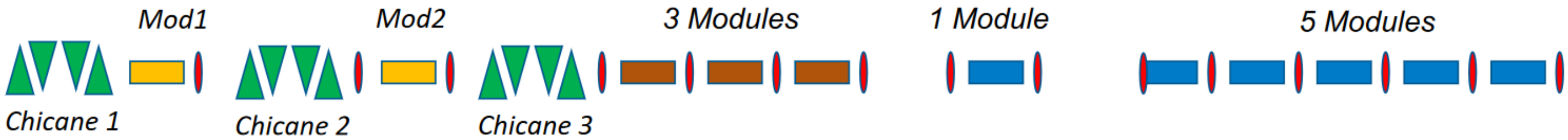
Gap dependence



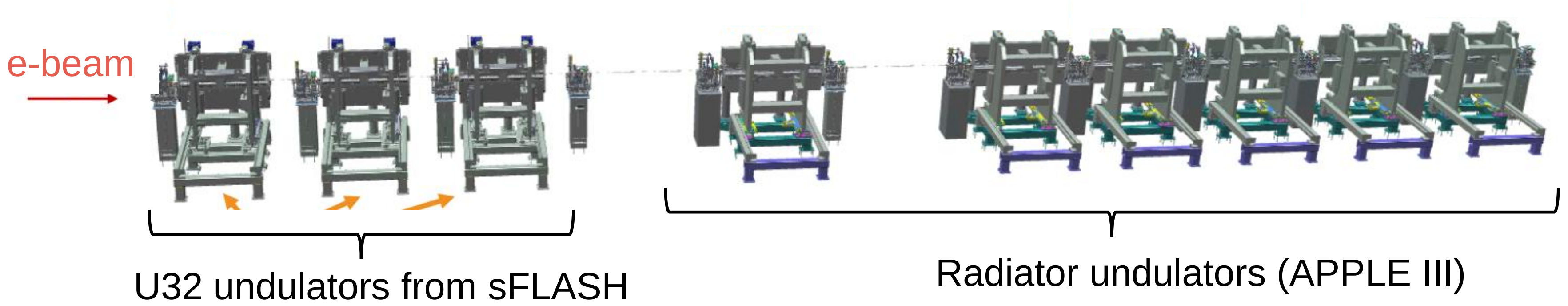
- Dipoles: ±50 Gcm gap dependence plus shift-dependent kick error of similar size.
- ➢ Corrected in a feed-forward by small air coils.
- Only small quadrupole contribution.

FLASH1 Seeding upgrade

General layout of the radiation section



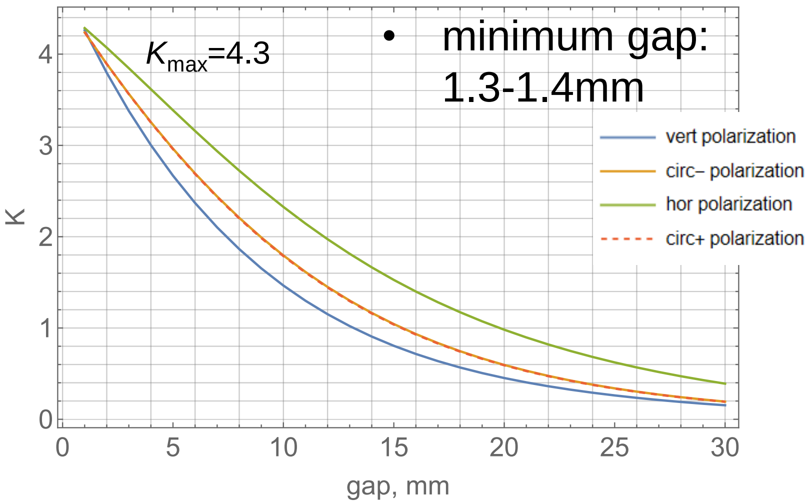
- 2 Modulator undulators with 84mm period length and hybrid (magnets&poles) structure.
- 3 refurbished planar U32 undulators from sFLASH to increase the pulse energy at short wavelengths.
- 6 radiator undulators of APPLE III type UE35.
- Wavelength range: 4 – 60 nm



Six UE35 APPLE III for FLASH1

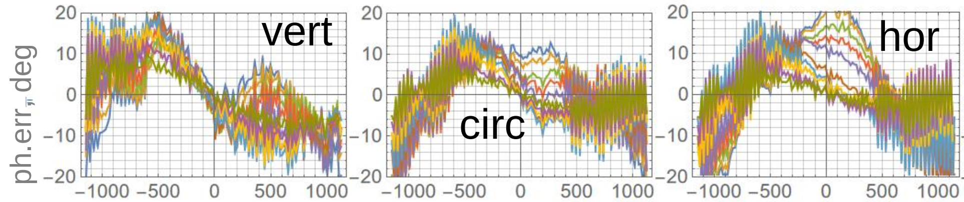
Characteristics and results

K value

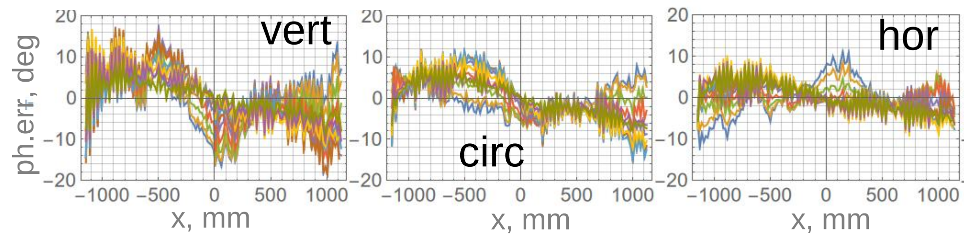


Phase error

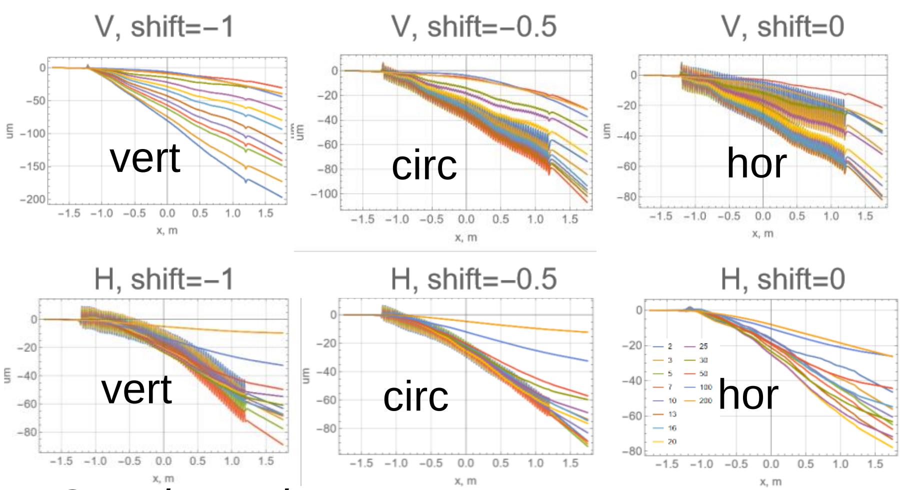
without taper correction & long coil



with taper correction & long coil

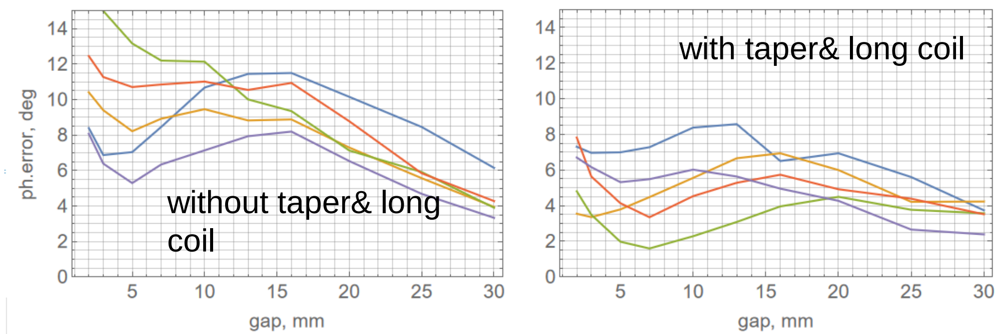


Trajectories (@1.35GeV)



Gap dependence

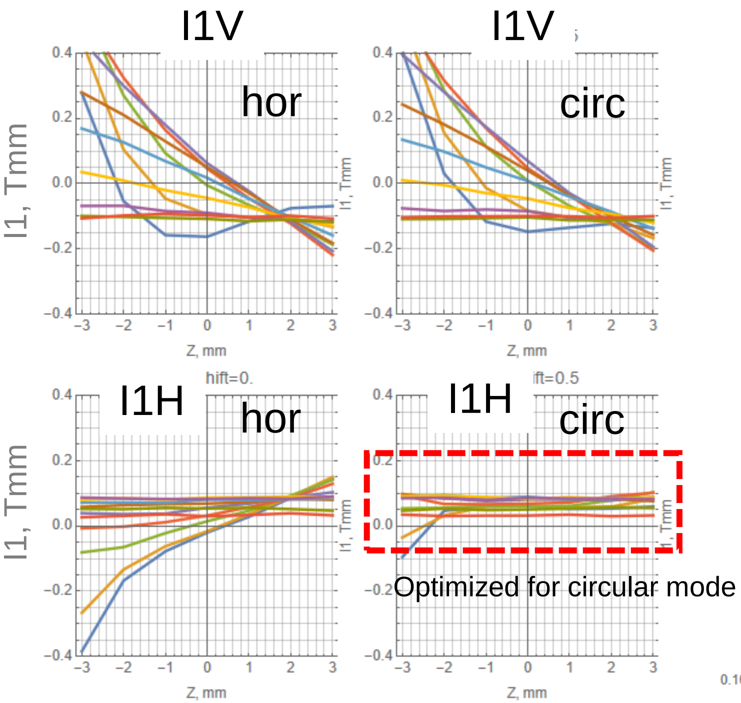
RMS phase error gap dependence



Significant variation of phase error for different polarisation modes. Correction by taper and resistive long coil.

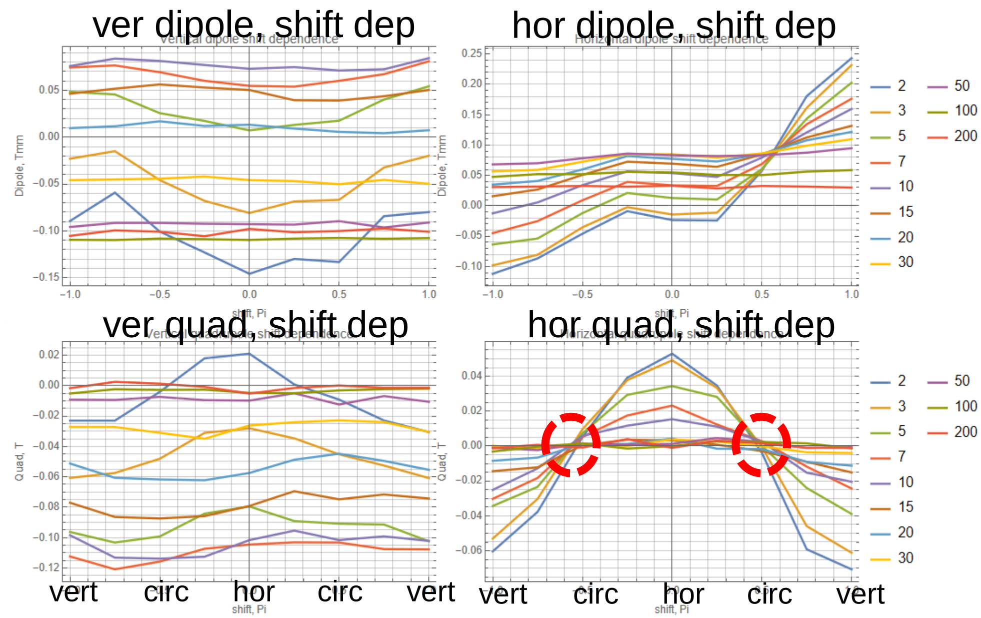
Six UE35 APPLE III for FLASH1

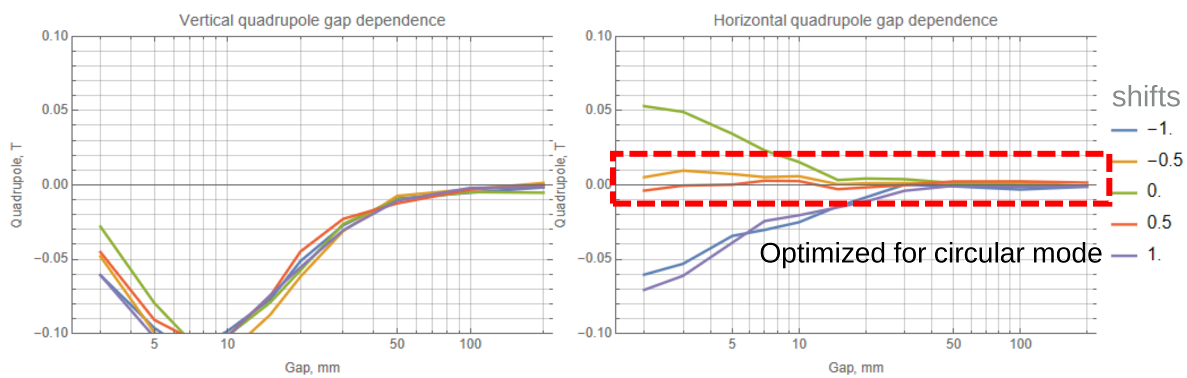
Characteristics and results



Transverse dependence of vert. and horiz. field integrals for shift 0 (hor pol) and shift 0.5 (circ) at different gaps

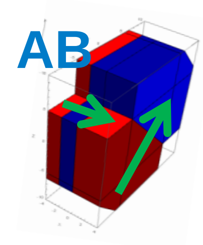
Multipoles errors



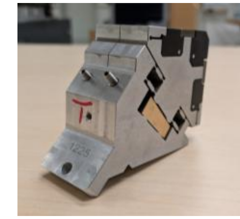


Shift and gap dependence of vert. and horiz. quads

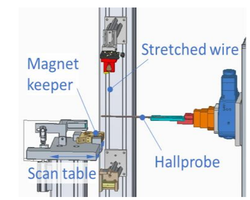
Lessons learnt



- Gluing of magnets to AB-pairs



- One-period keepers for UE35 (and for UE17); longer super-structures (e.g. like SwissFel Apple-X) could be good option for future. Single keeper flipping/swapping was not necessary.



- Pre-characterisation at several stages in the assembly process (magnets separately, single keepers, sub girders mechanically) costs time but is worth it.

- Additional linear encoder for shift drive regarded as mandatory; helped to detect deficiencies with the shift drive.

- Shift drive design needs substantial safety margins in terms of load. Exceeding manufacturing tolerances will quickly use up any buffer on the parameters of the drive train assembly (motor, coupling, bearings, spindle nut).

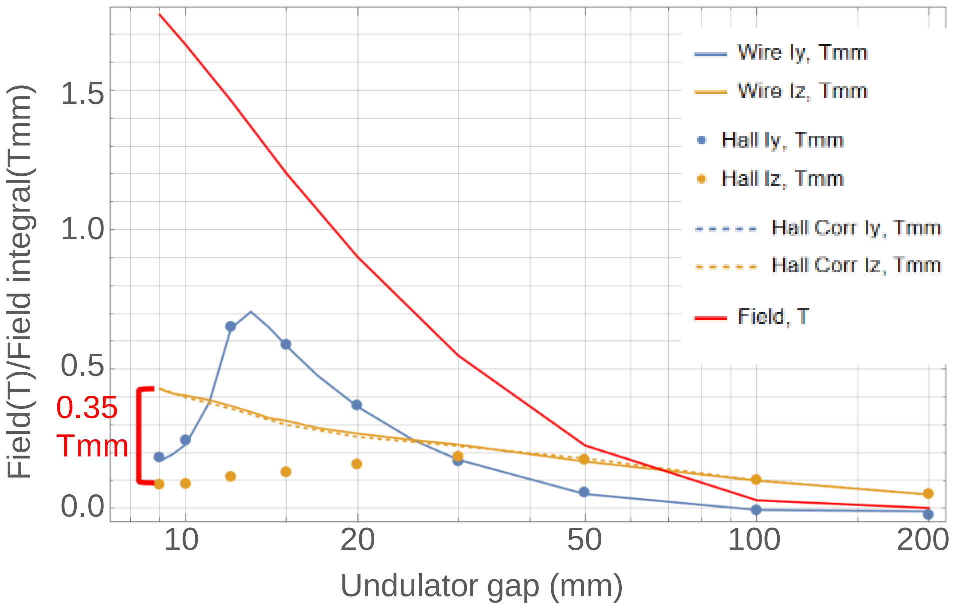
- Focusing properties of Apple-3/X structures: need sufficient awareness on the beam physics side.

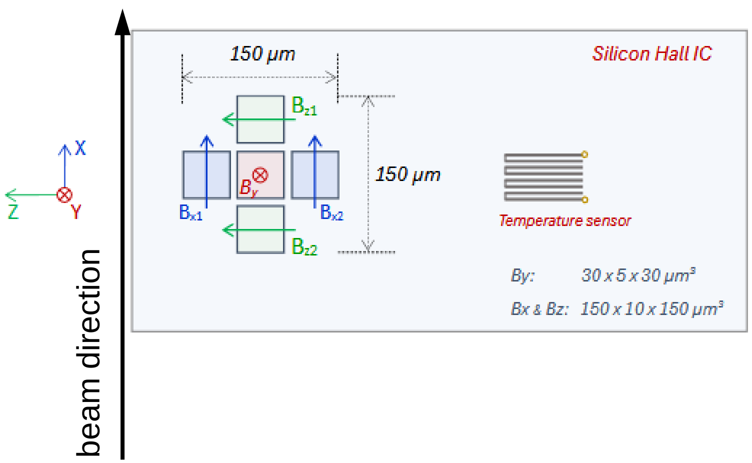
Lessons learnt

https://www.senis.swiss/wp-content/uploads/2024/10/Datasheet-F3A-Magnetic-Field-Transducer_rev.1.2.pdf

“Planar” Hall effect: Hall measurements show an unusual behaviour of the transverse field for the U84 modulators

- Large discrepancy between Hall probe and stretched-wire measurements for transverse direction that cannot be explained by misalignment, mispositioning or wire sag. Adjusted the Hall calibration polynomial by B_z+=0.00011B_y^2 (dashed). But: correction should be checked/recalibrated by stretched wire for different devices.
- If sensor is rotated by 90 deg around horizontal axis, difference to the wire is significantly reduced. → Horizontal sensors are vertically displaced and there is no vertical gradient of the vertical field.



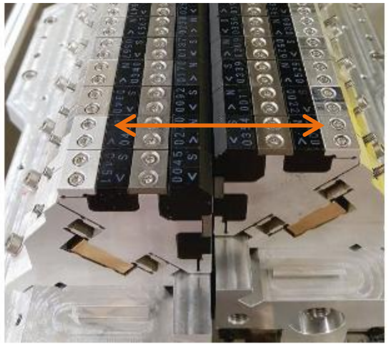


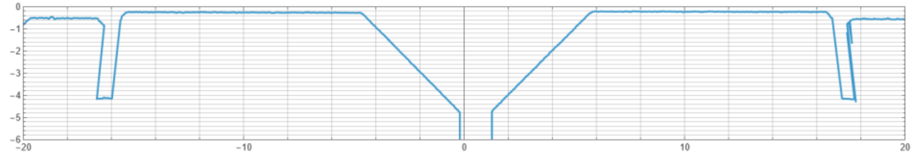
Lessons learnt

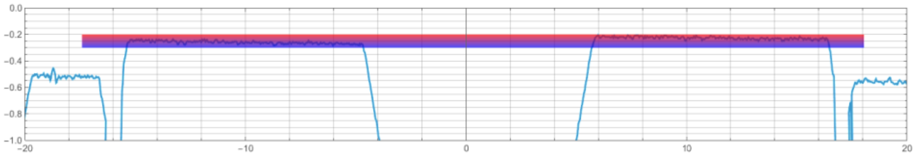
Skew quad investigation:

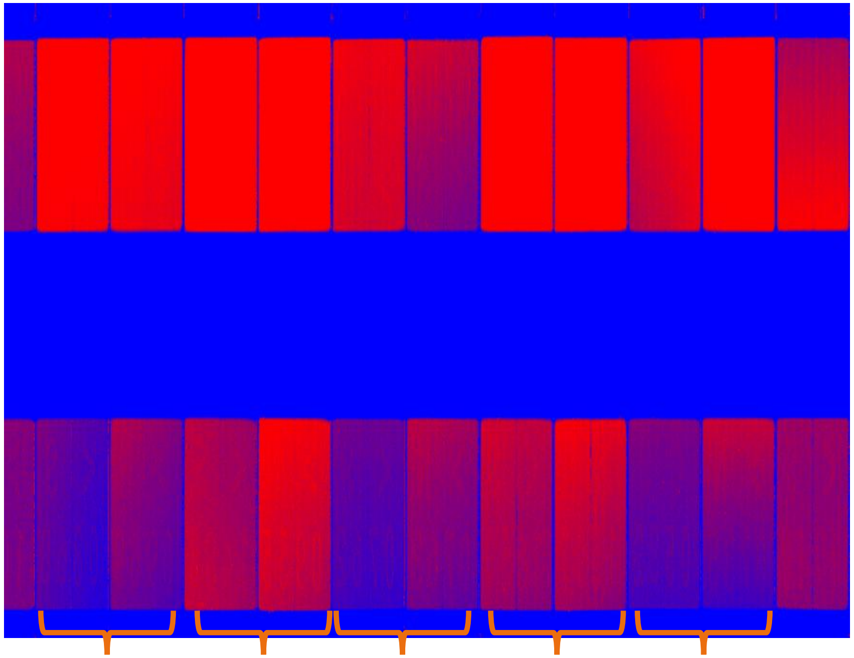
- Conducted optical measurements of local mechanical movement of the magnets during shift movement (resolution <1um)
- Magnets on one keeper move by about 25um and 0.1mrad in pitch angle during one shift cycle.
- Difference between magnet pairs on one keeper: 5-7um and 1E-5rad.

➢ Small but systematic difference for "positive" / "negative" halfperiods most probably causes multipoles shift dependence.









shift moving from
-1…….-0.5.......0.......+0.5……+1

Lessons learnt

Skew quad investigation:

- Conducted optical measurements of local mechanical movement of the magnets during shift movement (resolution <1um)
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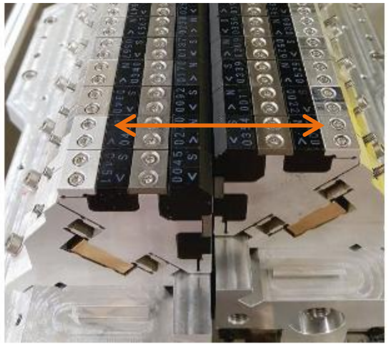
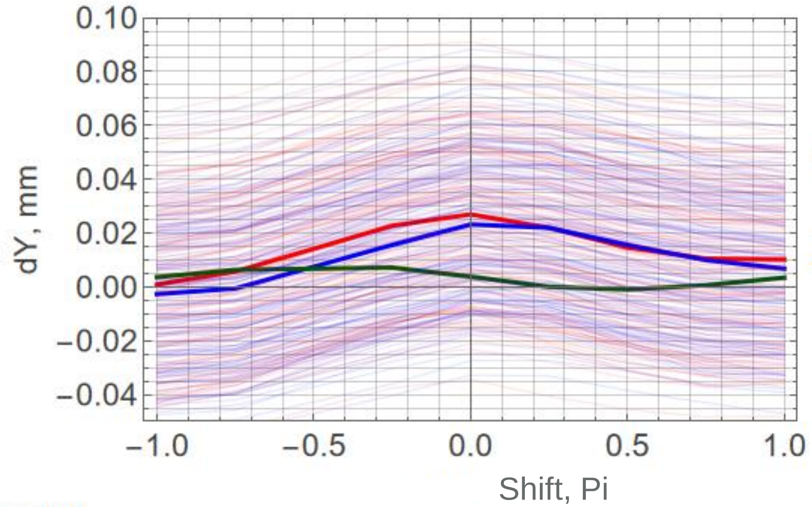
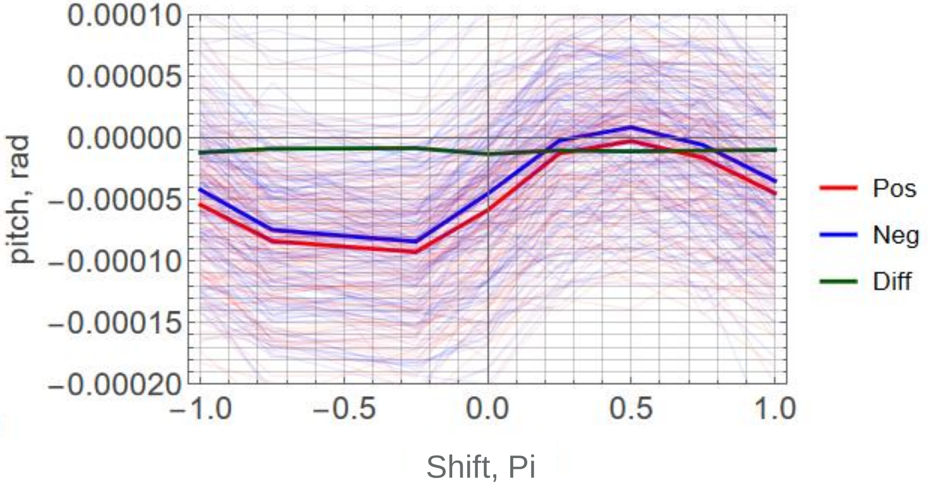






Summary and Outlook

- We successfully designed, manufactured and tuned **six APPLE III UE35** and one **afterburner APPLE III UE17** for the free-electron laser FLASH.

- Devices were tuned by **virtual shimming** (wedge movement on the keepers), **magic fingers**, (shift dependent) **taper and resistive long coils**.

- **Phase error between 2 and 10 deg for UE35 and <5deg for UE17 afterburner**.

- **Hall measurements** show an **unusual behaviour of the transverse field** for very high vertical fields (gradients), calibration function needs to be adapted.

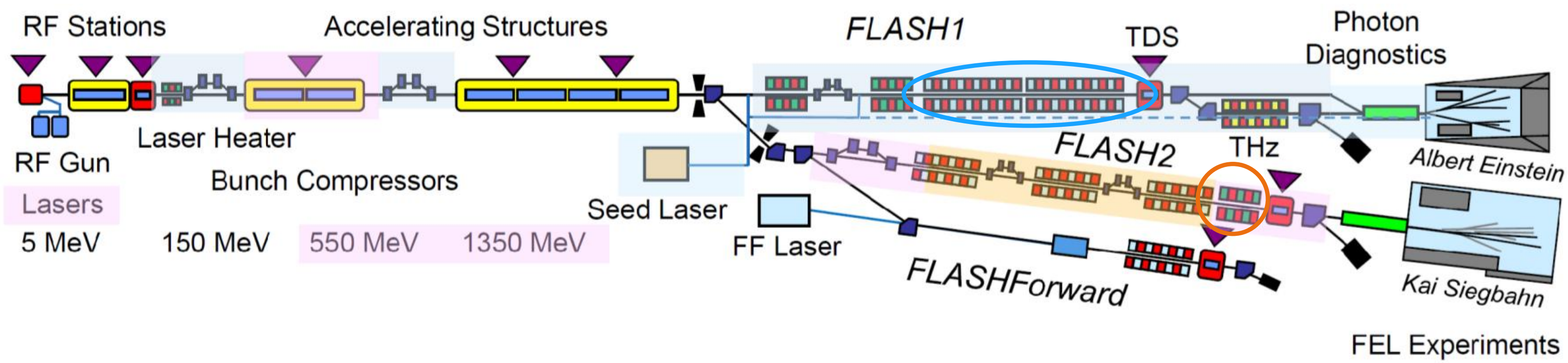
- UE35: **Skew quads minimized for circular mode**. Might be caused by **keeper deformation/movement of halfperiods**. Further investigation by optical measurement of magnet displacement during shift movement planned.

Back up

Additional slides

The FLASH2020+ upgrade

The future high repetition rate XUV and soft X-ray FEL facility

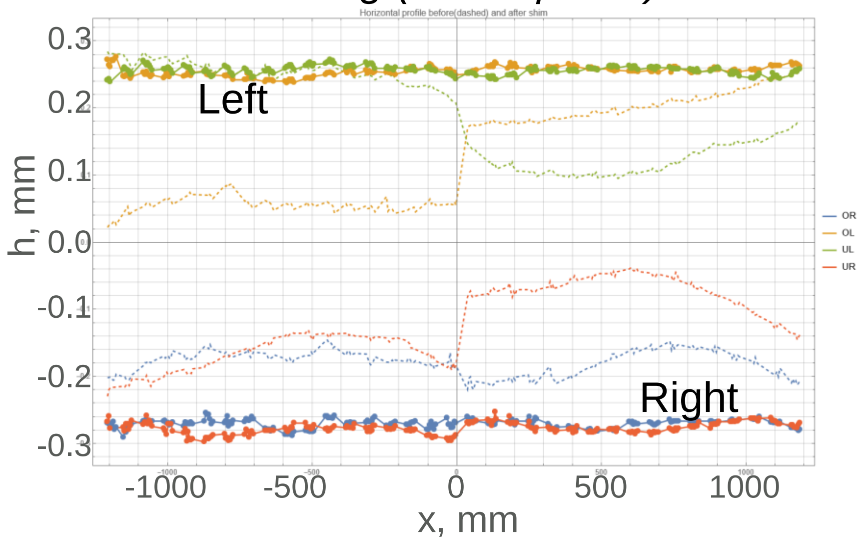


- Small increase in electron beam energy to 1.35 GeV
- Tunable undulators at FLASH1 allow fully parallel operation of two FEL lines.
- FLASH1 fully externally seeded with full repetition rate that FLASH can provide in burst mode.
- Afterburner for FLASH2 to provide circularly polarised light
- Extended the wavelength reach of the fundamental harmonics to the oxygen K-edge and L-edges of Fe, Co, and Ni.
- FL1: 4 – 60 nm, FL2: 3.3 – 90 nm (3rd Harmonic Wavelength down to 1.7 nm)

Six UE35 APPLE III for FLASH1

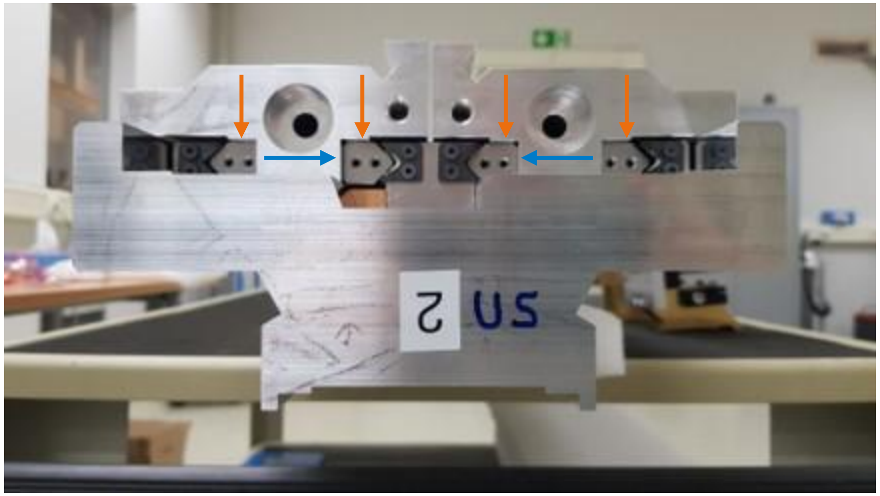
Mechanical shimming

Horizontal profile before (dashed) and after shimming (Touch probe)



Manual shimming of subgirders to even out differences in height of up to 200um ("chain of tolerances")

Support structures

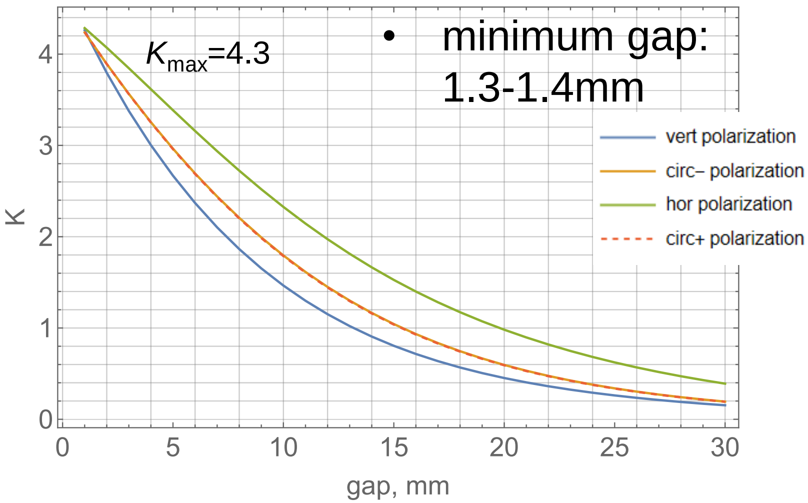


Position of shims for vertical and horizontal shimming

Six UE35 APPLE III for FLASH1

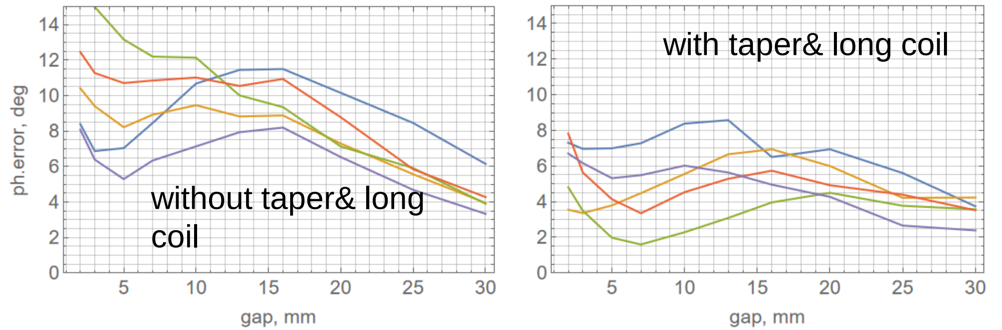
Characteristics and results

K value



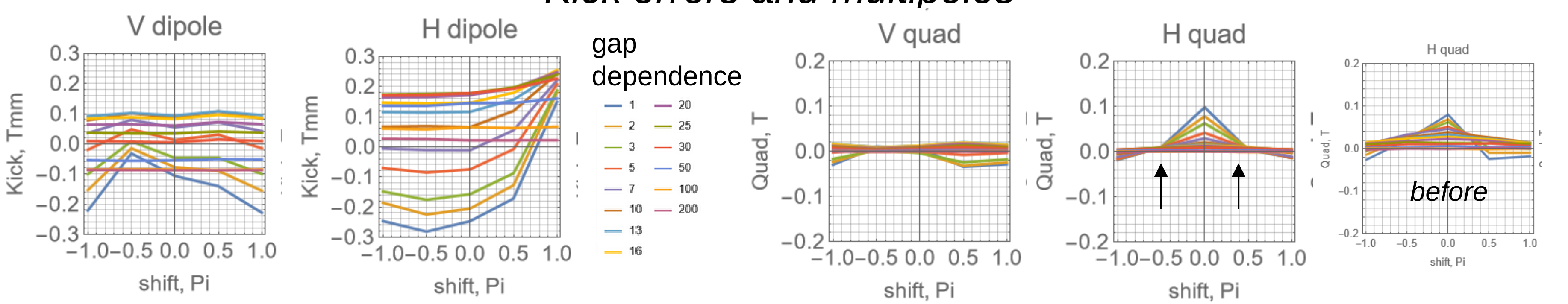
- minimum gap: 1.3-1.4mm

Phase error



- Significant variation of phase error for different polarisation modes. Correction by taper and resistive long coil.

Kick errors and multipoles



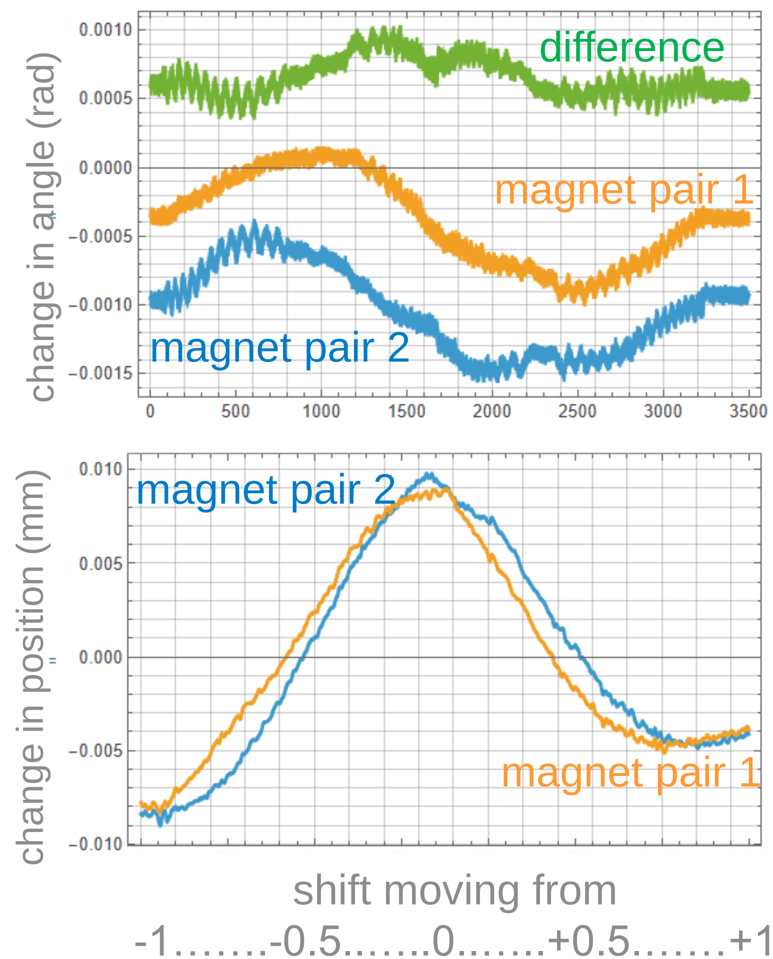
- After multipole tuning and magic fingers: ±0.15Tmm (ver), ±0.25Tmm (hor)
- Skew quad optimised for circular mode

Lessons learnt

Skew quad investigation:

- Conducted optical measurements of local mechanical movement of the magnets during shift movement (resolution <1um)
- Magnets on one keeper move by about 20um and up to 1mrad in angle during one shift cycle.
- Difference between magnet pairs on the keeper: 2-3um.

➢ Small but systematic difference for "positive" / "negative" halfperiods most probably causes multipoles shift dependence.

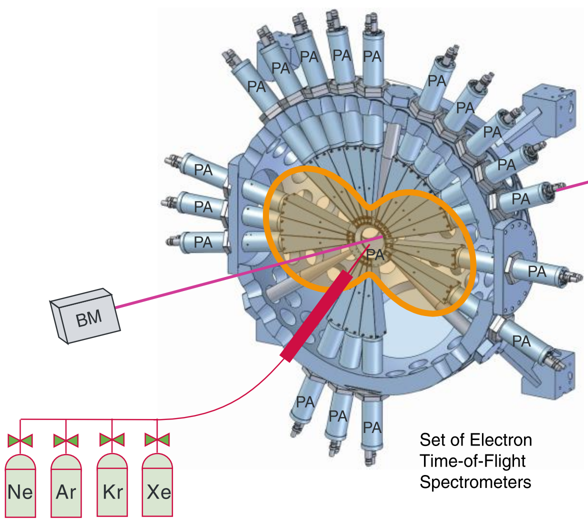


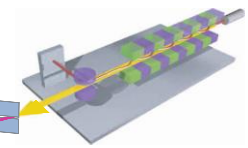
APPLEIII Afterburner for FLASH2

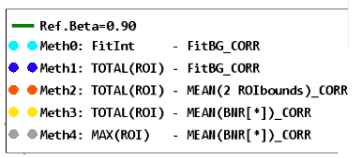
In operation

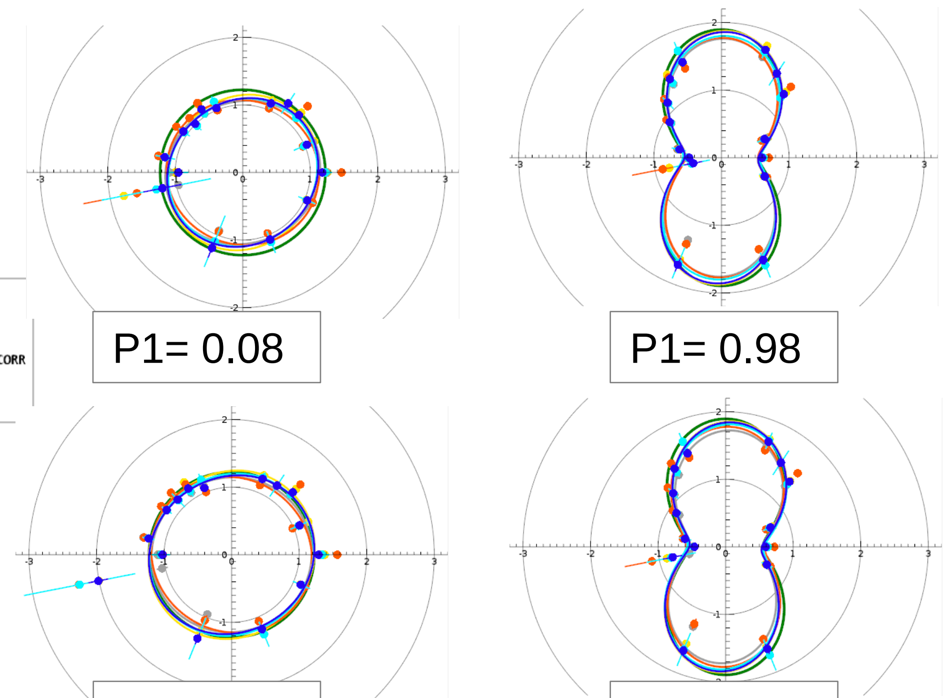
E_{ACC} = 880 MeV
hv = 104.6 eV / 313.8 eV

FLASH 2 afterburner









P1= 0.08

P1= 0.98

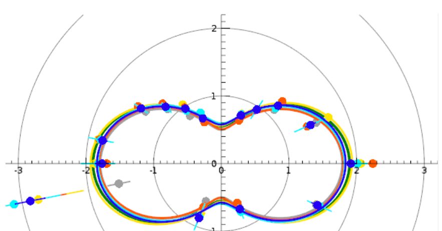
P1= 0.06

P1= 0.98

ABU shift = +/- 0.25

ABU shift = +/- 0.5

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



P1= 0.99

ABU shift = 0.0

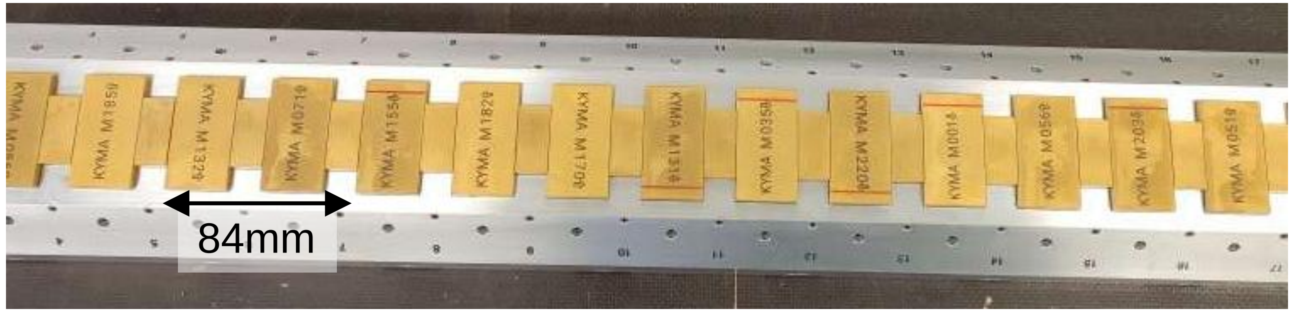
- Circularly polarized light down to 1.46 nm generated
- First successful user experiments

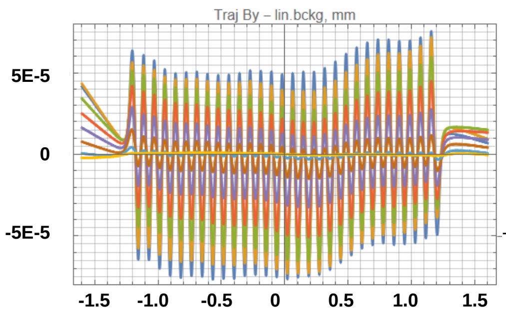
Courtesy M. Braune, K. Tiedke, J. Rönsch-Schulenburg and colleagues

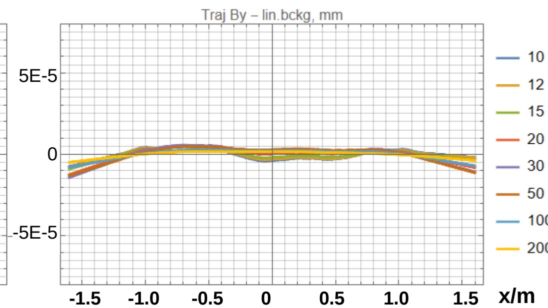
Modulators

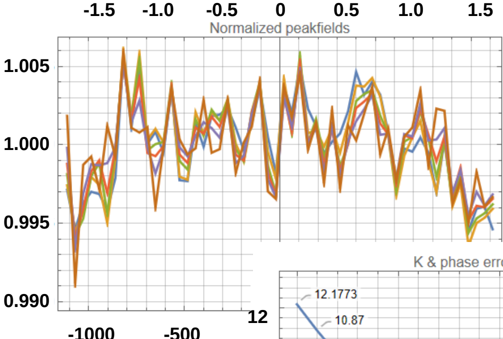
Two U84 planar undulators with hybrid structure (magnet and poles)

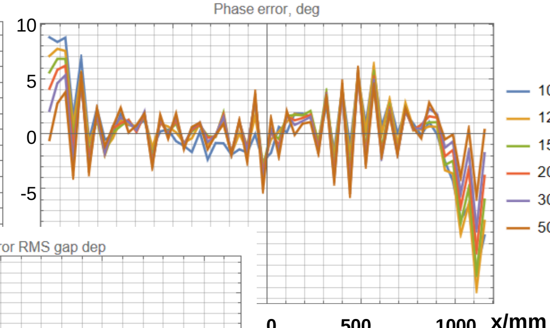
- Length = 2.5m
- Period = 84mm
- Min. gap = 9mm
- B_{max} = 1.8T
- Specs: K=11, achieved: K = 12.9

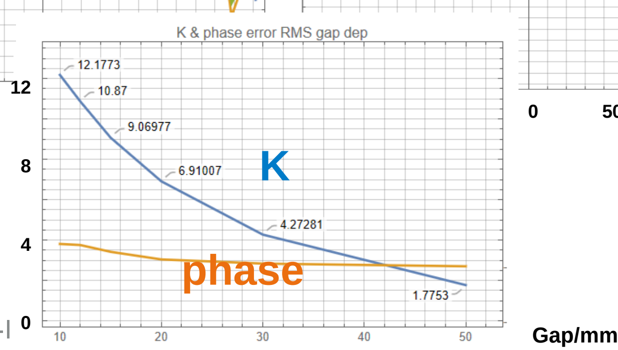












- Sorting of magnets based on novel Hall mapper reduces amount of pole tuning
  - ➢ Parameters were within specs without any pole tuning (straight trajectory, phase error <4°).
- Additional girder curvature spoiled phase error
- Strong fields
  - ➢ Strong forces
  - ➢ Reaching limits of sensor calibration

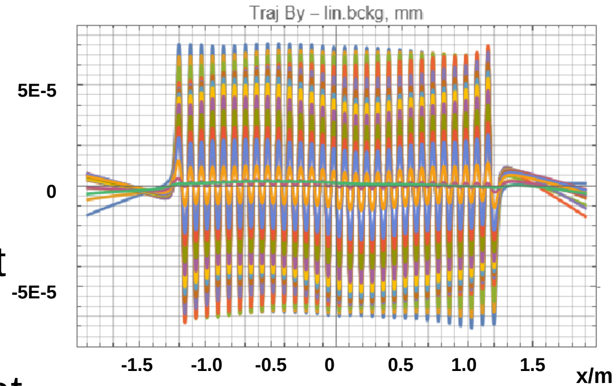
Modulators

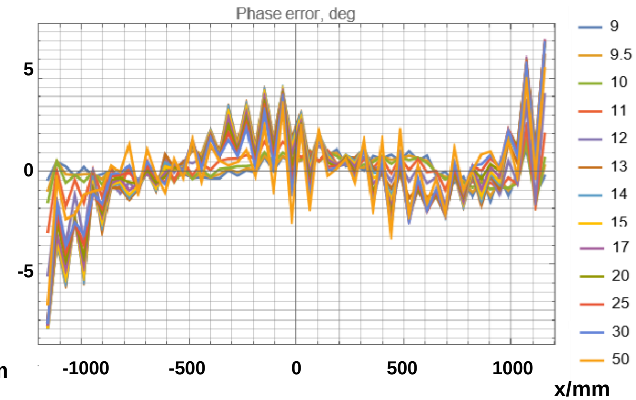
Two U84 planar undulators with hybrid structure (magnet and poles)

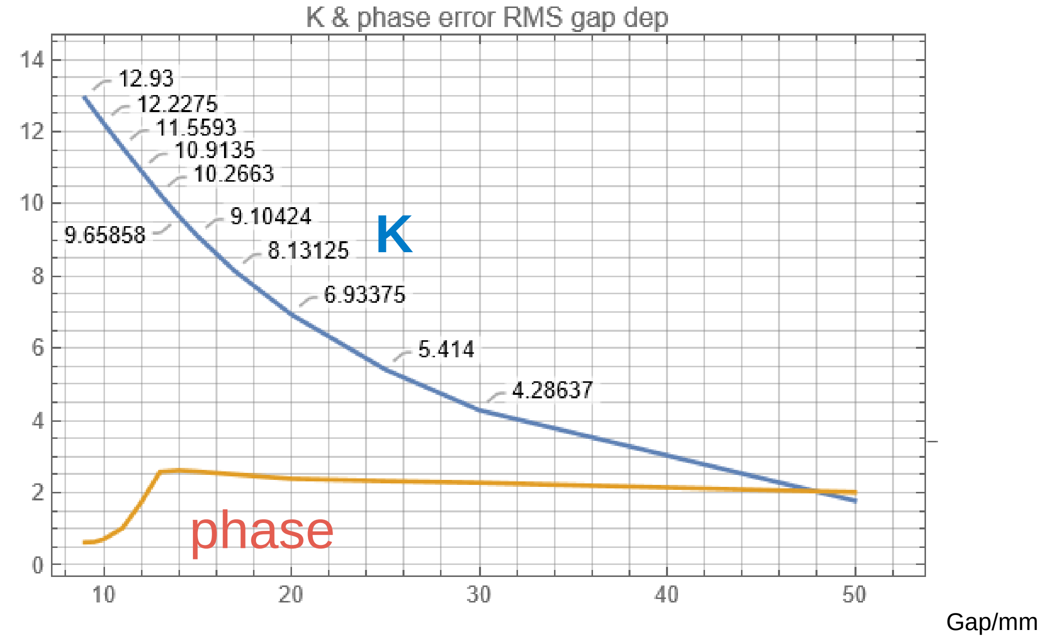
After tuning

- 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.





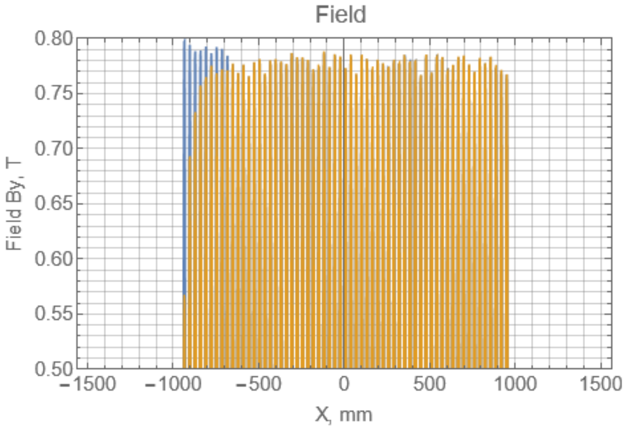


Refurbished U32s from sFLASH

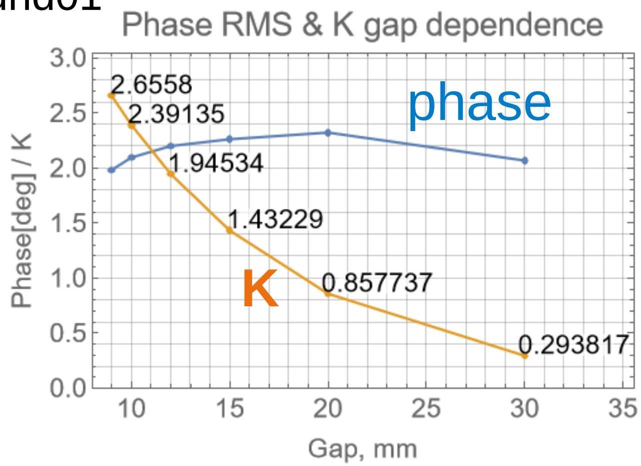
Three devices for the interim to increase pulse energy at short wavelengths

- Three planar devices with 32mm period length from the former sFLASH experiment were 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.

sfund01

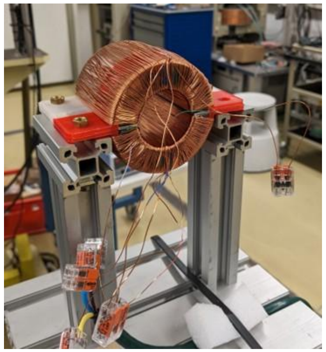


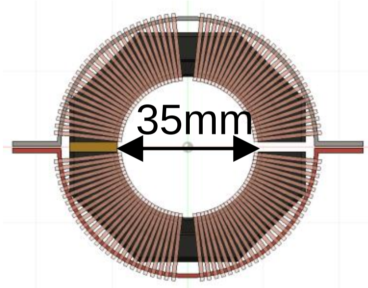
-- Field before
-- Field after flipping 18 magnets US

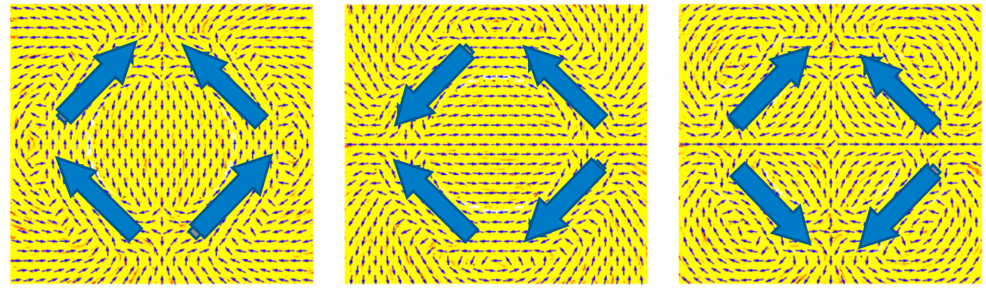


Resistive coils with variable field direction

Ferrite enforced steerer/corrector coils (air-cooled)





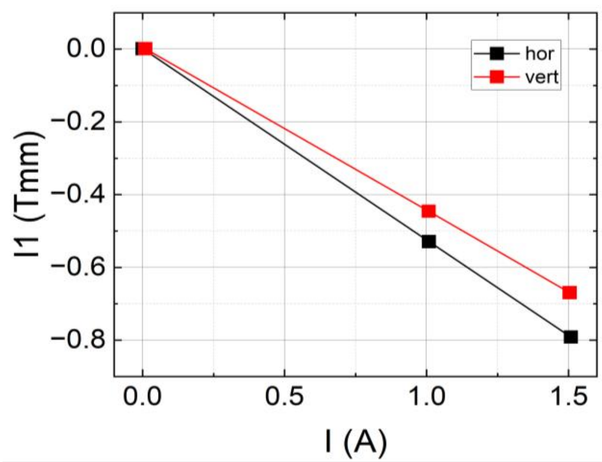


vertical horizontal quadrupole

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



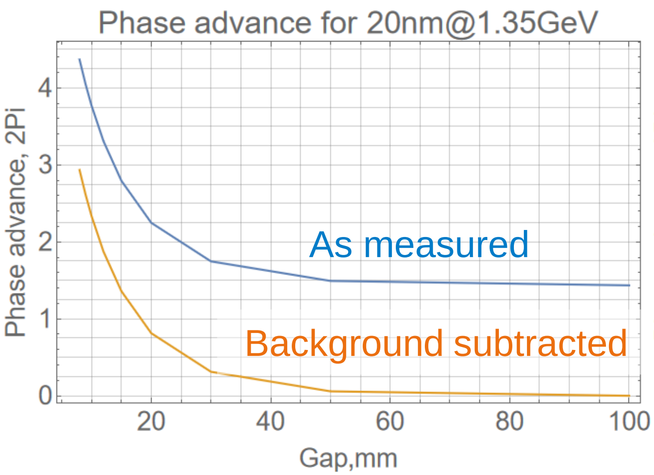
On-axis first field-integral as a function of current (hor/vert field).

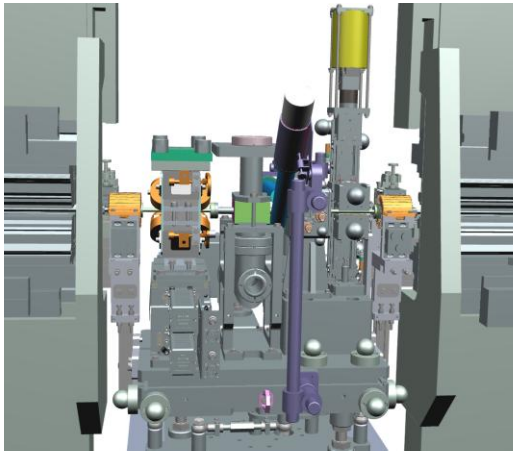
Stored coils

Phase shifters

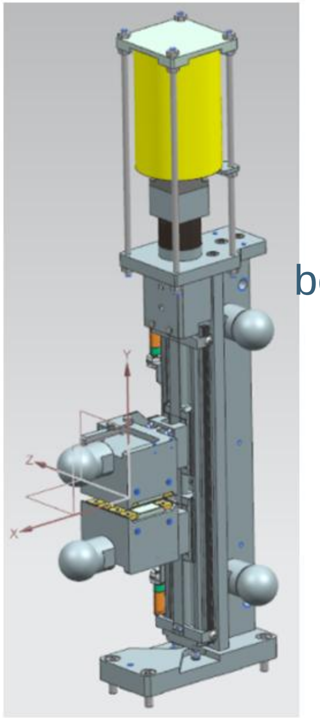
Compact, permanent magnet-based phase shifters on intersections

- 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

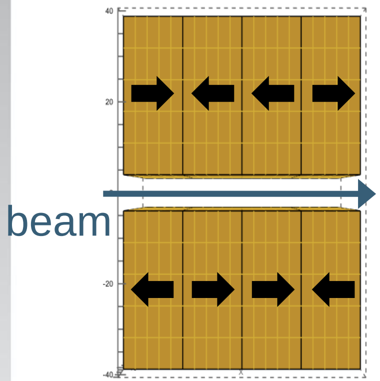




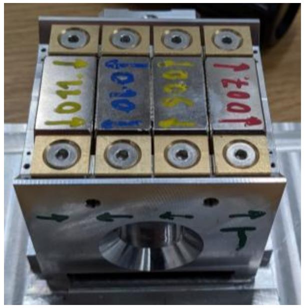
Intersection



Phase shifter



Magnetic set-up



Magnet blocks.
Size: 35x35x15mm^3

➢ Phase advance as a function of gap.

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

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.