Magnetic Characterization & Initial Shimming Results of an APPLE-X Knot Undulator

Insertion Devices for Future Light Sources Workshop

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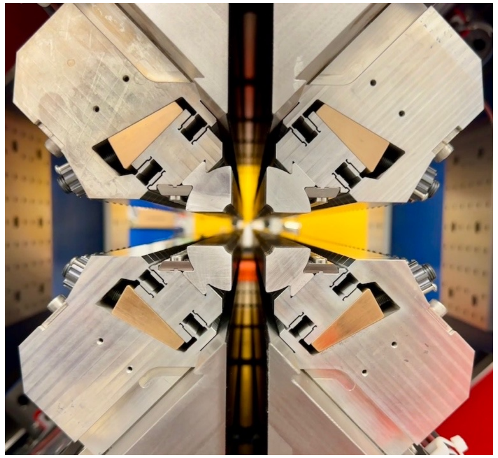
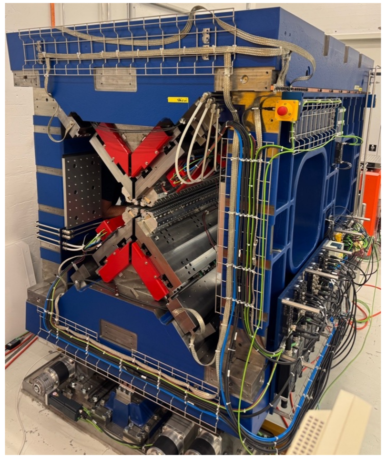
PSI Center for Photon Science
Deauville, France – 15/05/2026

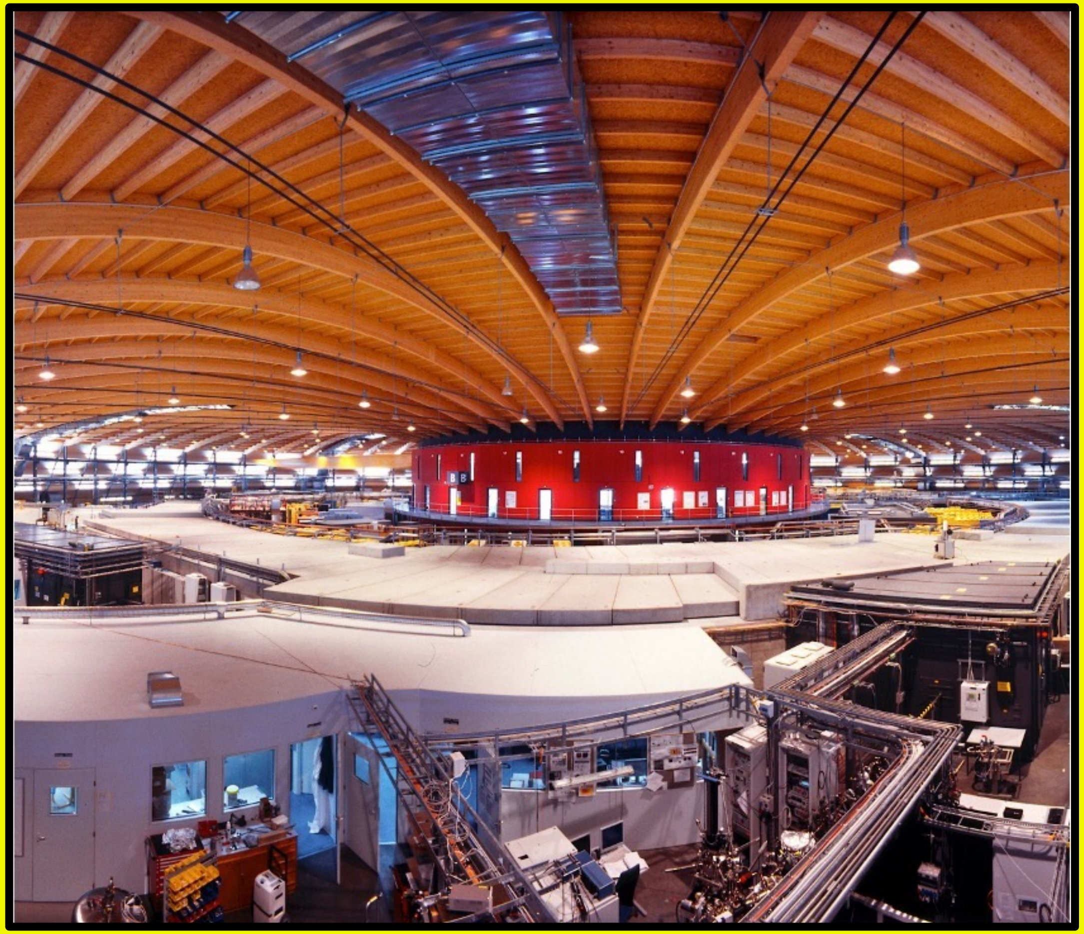
Outline

- The SLS 2.0 Upgrade
- The first APPLE-X knot: UE36kn
  - Undulator & Magnet Design
  - Shimming Strategy & Results
  - Magnetic Characterization
- Conclusion & Outlook





The SLS 2.0 Upgrade



The SLS 2.0 Upgrade: Impressions

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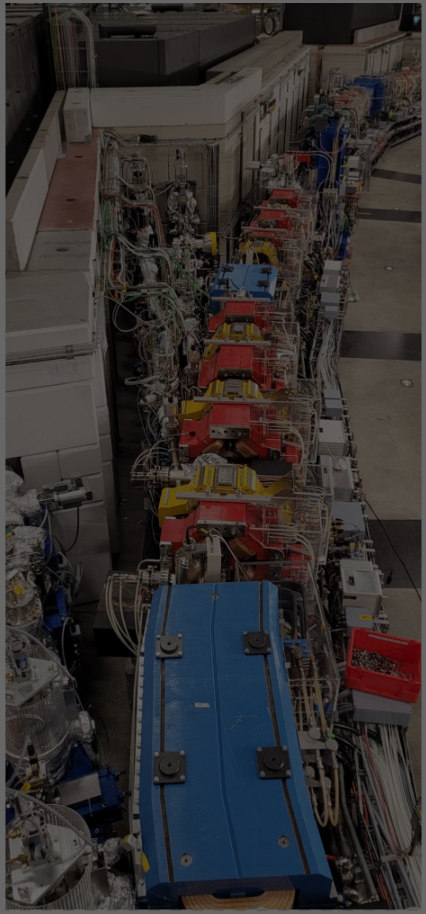
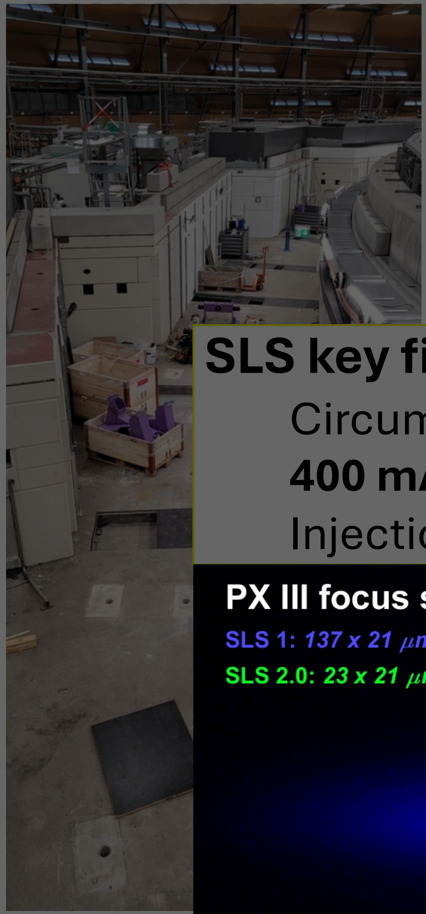
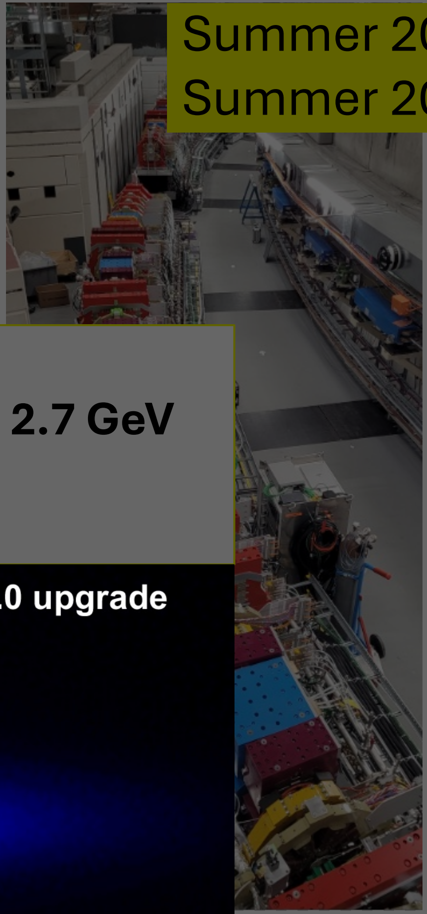






Summer 2025: First test users
Summer 2026: User operation

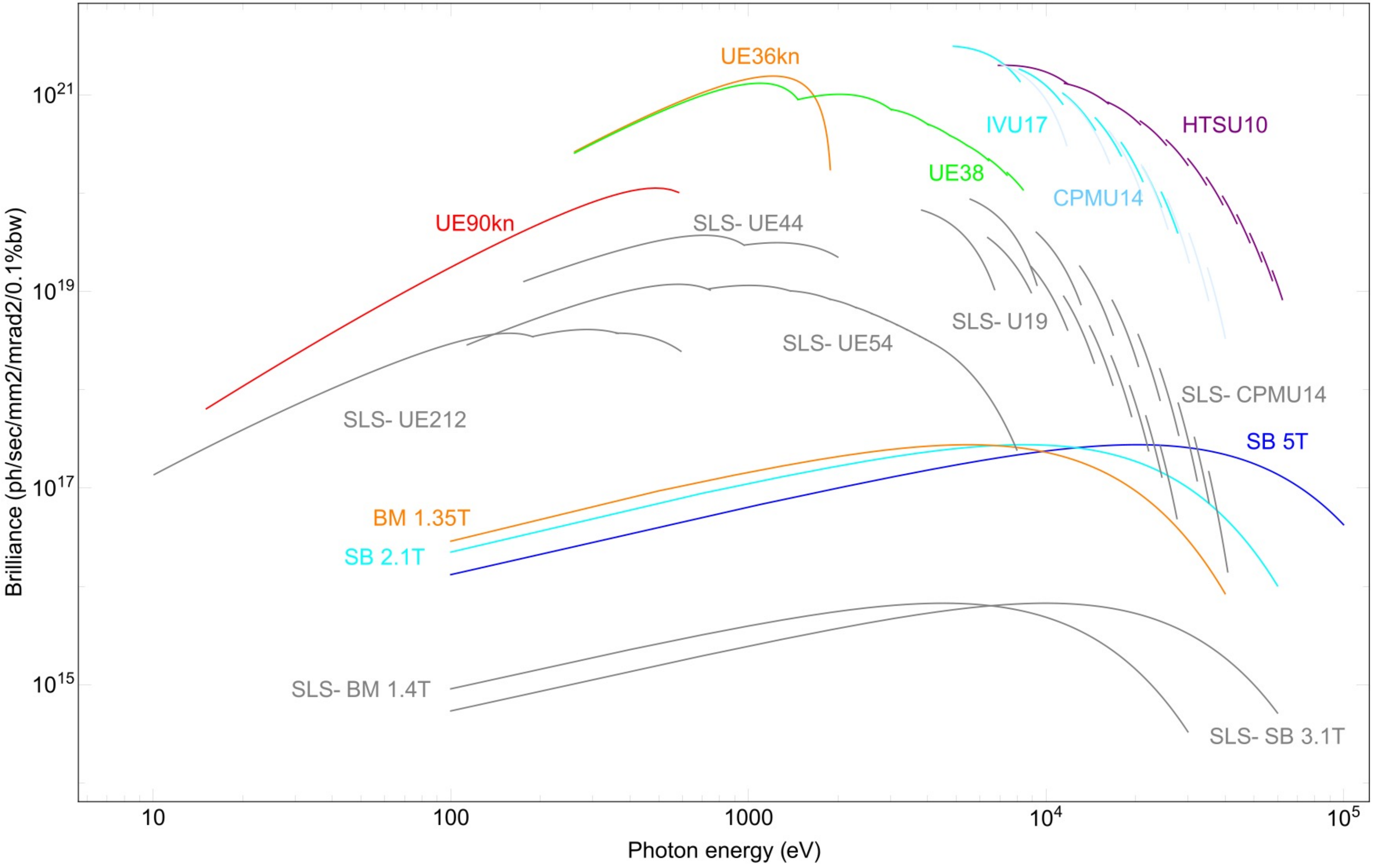
SLS key figures today:

Circumference, Energy: **288 m, 2.7 GeV**
400 mA, lifetime ~ **12 h**
Injection every 5 min for 20 s

03.10.2023 **28.1** **2024** **03.09.2024**

[1] Rosner, B. *et al.*, J. Synchrotron Rad. 33, 580-584, 2026.

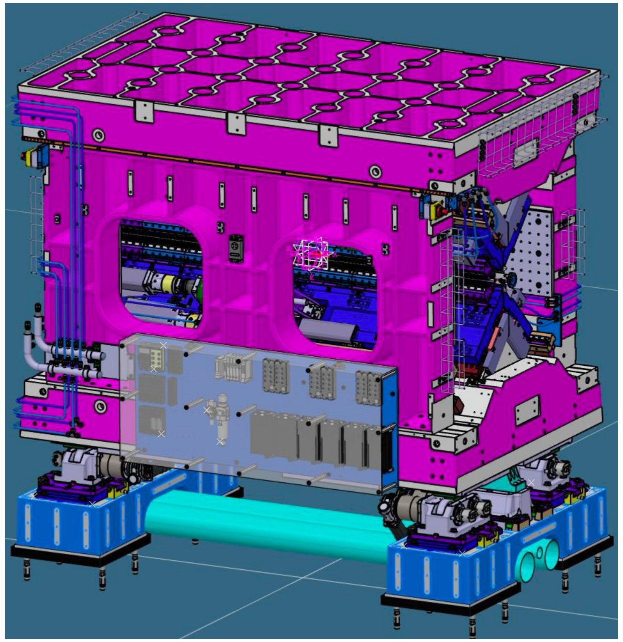
The SLS 2.0 Upgrade: Brilliance Comparison SLS

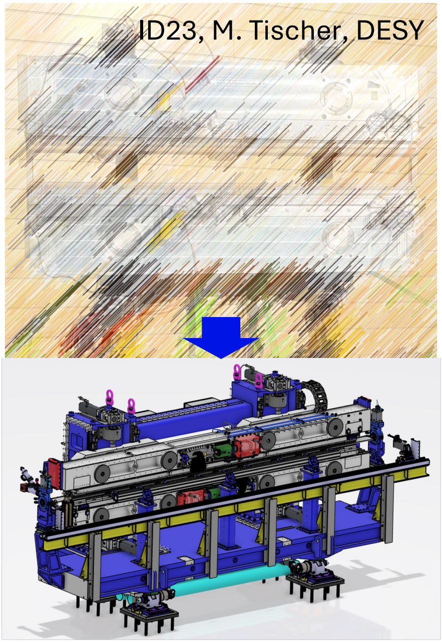


The SLS 2.0 Upgrade:
Soft & Hard X-ray Undulator Upgrade

today

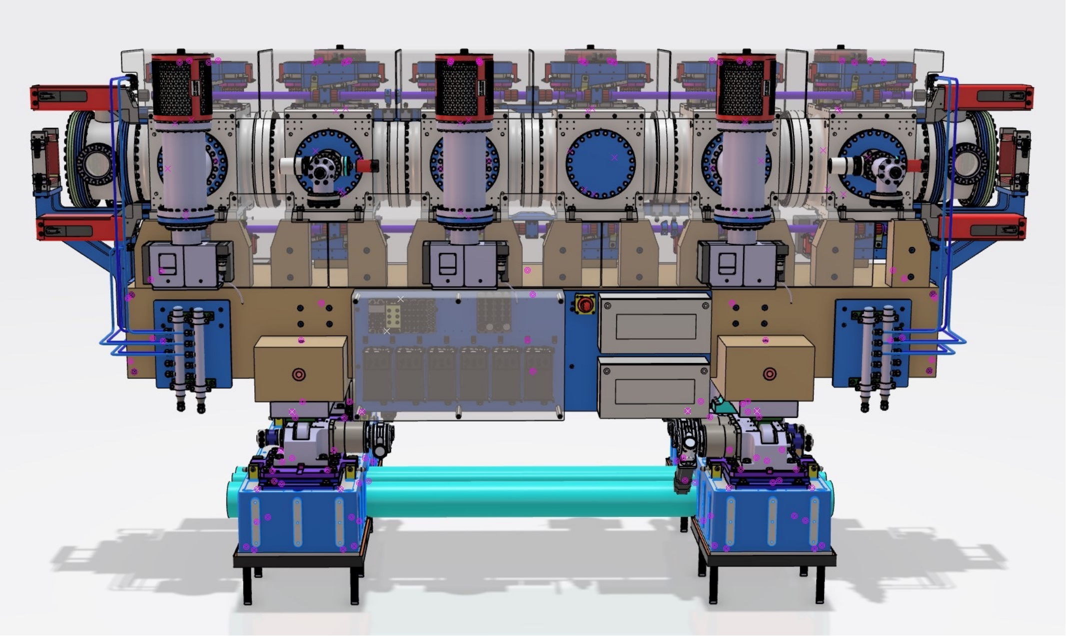
Soft X-ray
- 2x UE36kn (APPLE-X knot, 2 m each)
- 1x UE38 (APPLE-X, 2 m)
- 1x UE38kn (APPLE-III knot, 4 m)
- 1x UE90kn (APPLE-III knot, 4 m)





IPAC'26: THP2158

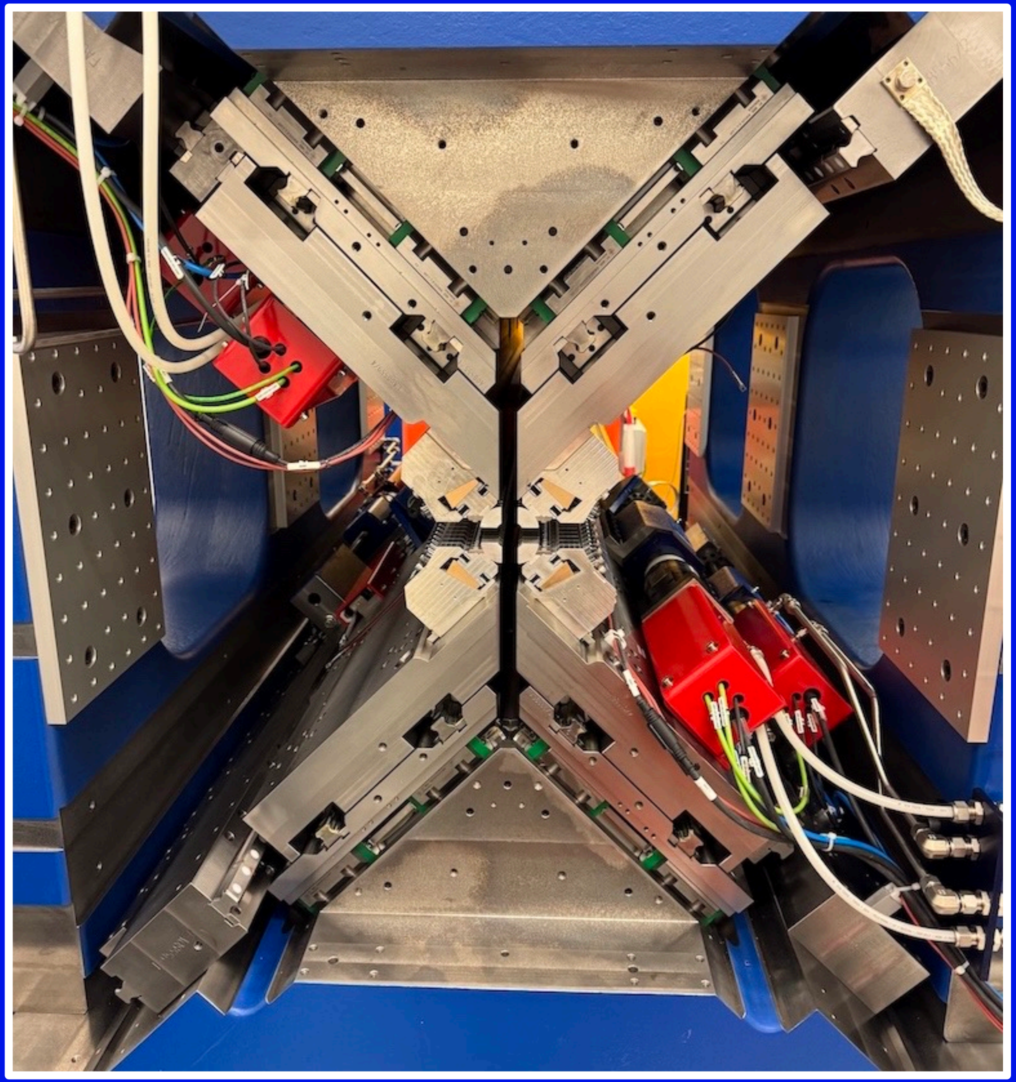
Hard X-ray
- 1x U15 (planar, 2 modules, 1 m)
- 4x U17 (planar, 6 modules, 3 m each)
- 1x HTSU10 (planar, HTS Bulks, 1 m)



IPAC'26: THP2159

The APPLE-X knot Undulator

- Undulator & Magnet Design
- Shimming Strategy & Results
- Magnetic Characterization



APPLE-X knot Undulator

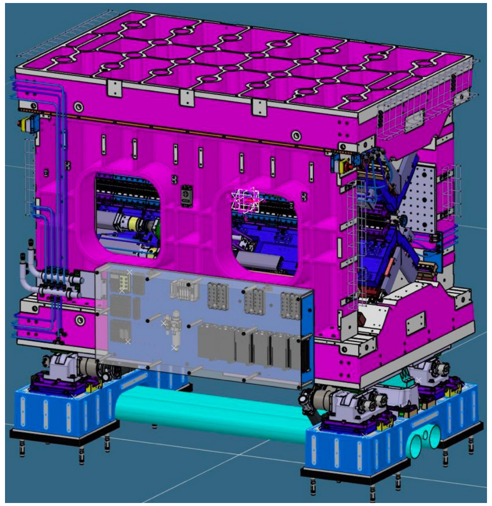
Advanced **P**lanar **P**olarized **L**ight **E**mitting (APPLE) Undulator

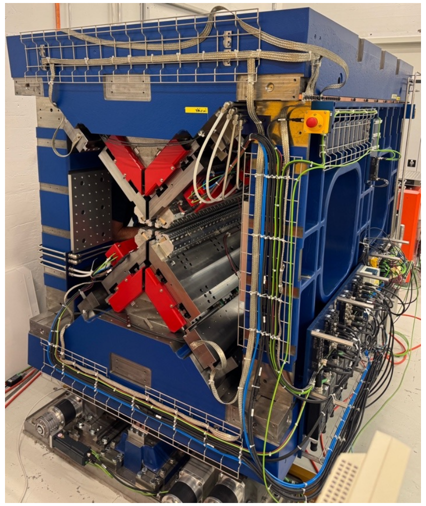
Modified PSI SwissFEL APPLE-X undulator [2], [3]

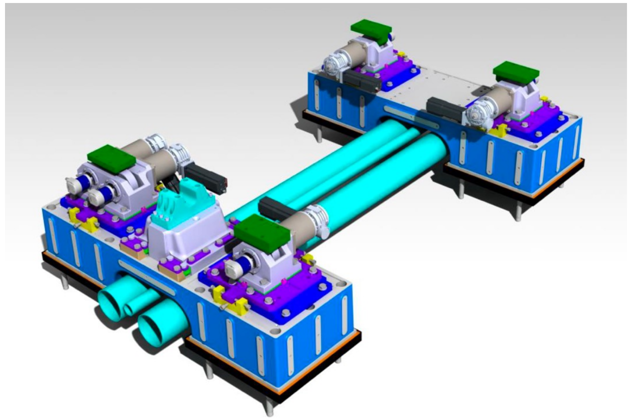
- 5-axis camshaft movers
- Cast iron main support frame
- Wedge-driven radial gap shift
- Pneumatic brakes, lead shields
- Motors with integrated controls
- Vacuum chamber (↔ Eu-XFEL): extruded Al, water-cooled, *round*

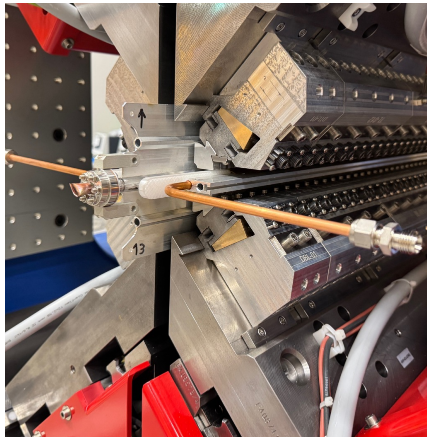
  ⇔ almost on-axis injection (!)

European XFEL MIFA® PRECISION EXTRUSION PRODUCTS









[2] T. Schmidt and M. Calvi, "APPLE X Undulator for the Swiss-FEL Soft X-ray Beamline Athos", in *SRN*, vol. 31, 3, 2018
[3] S.C. Richter, *et al.*, "First magnetic experience with APPLE X knot undulators for SLS 2.0", *Proc. IPAC2025*

APPLE-X knot Undulator

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Manufacturing

- Demanding tolerances for thin magnets (≤ 4.5 mm, e.g., end-fields)
- Amount/Cost: 4x8 = 32 magnets / λ_u
- Material: NdFeB with B_r = 1.31 T

VAC VACUUMSCHMELZE

Measurements and Optimization

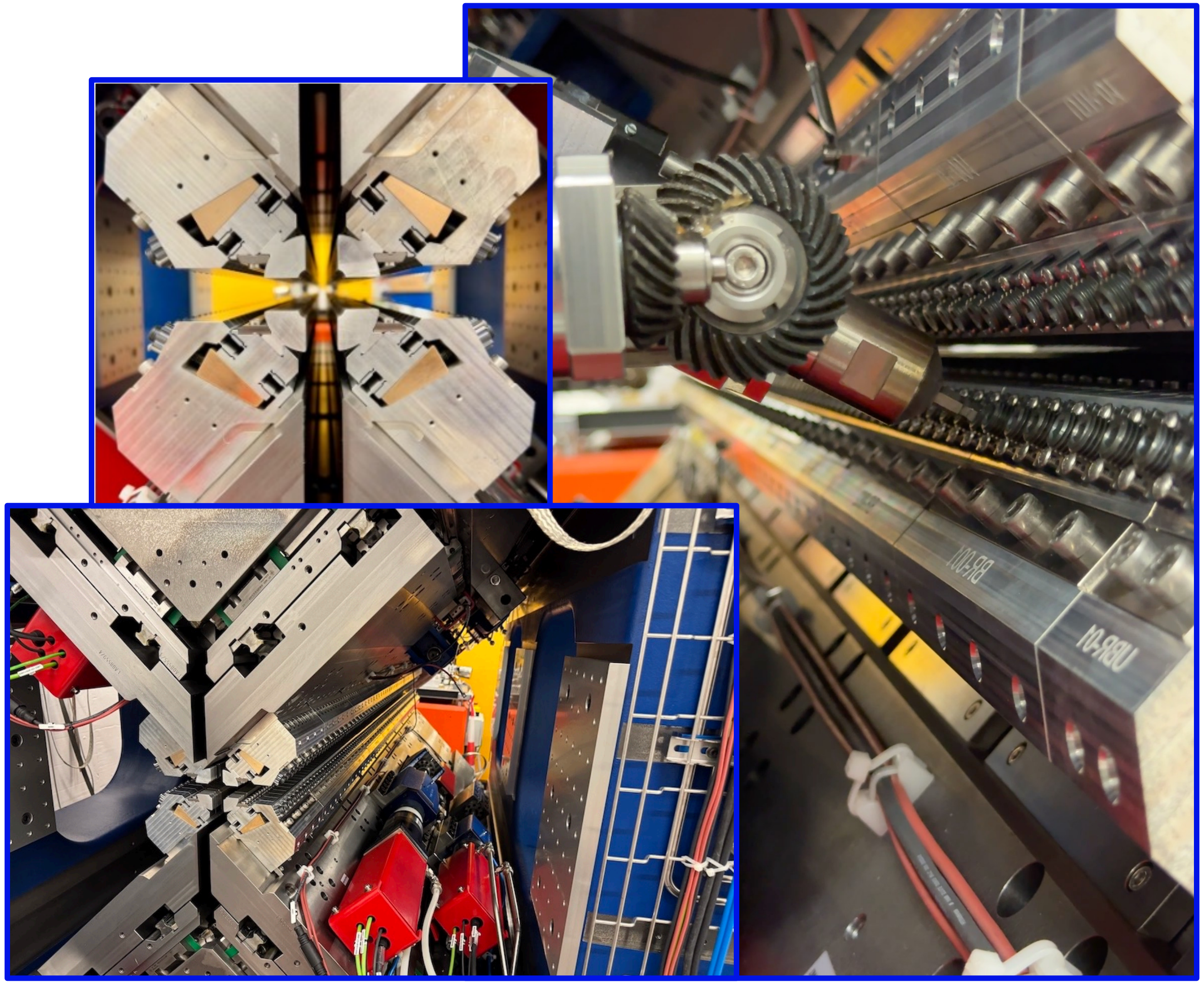
- Electrical driving system

  BECKHOFF

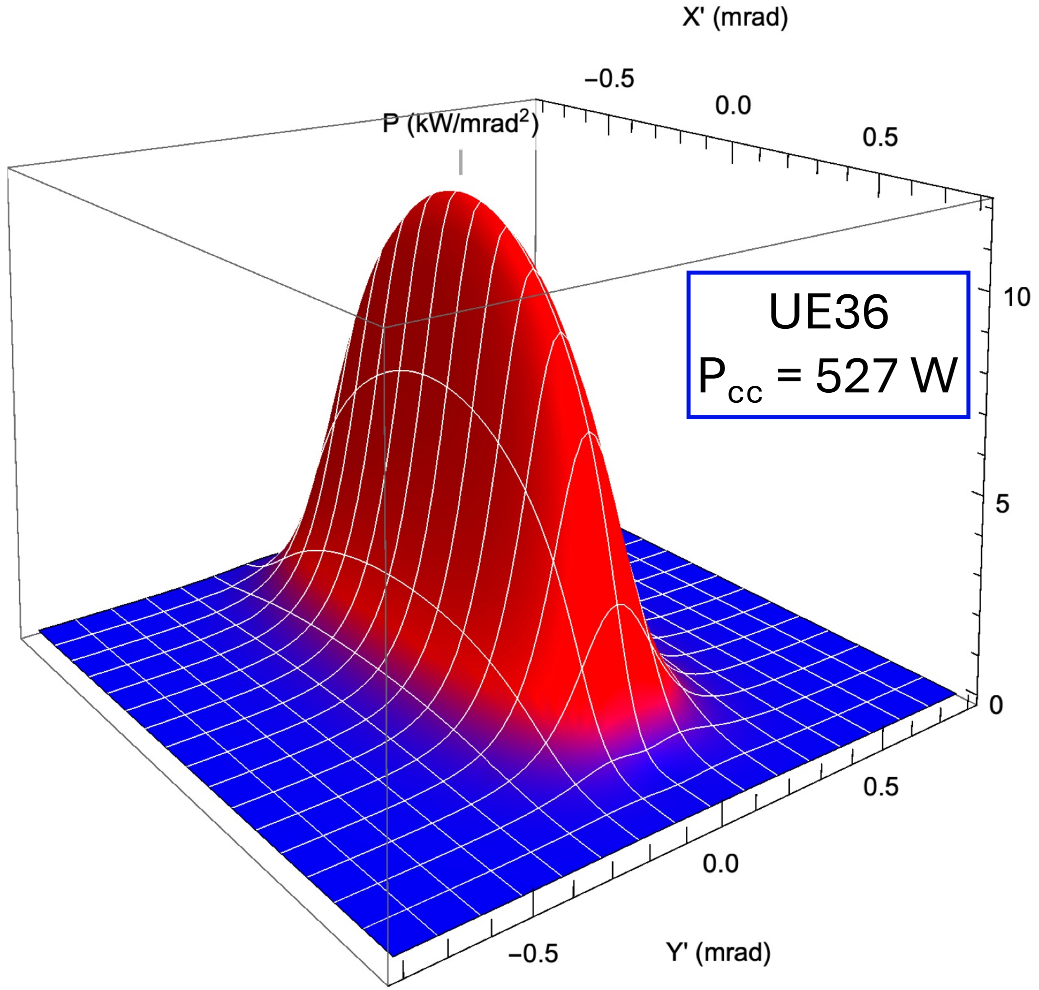
- 3-axes Senis Hall probe

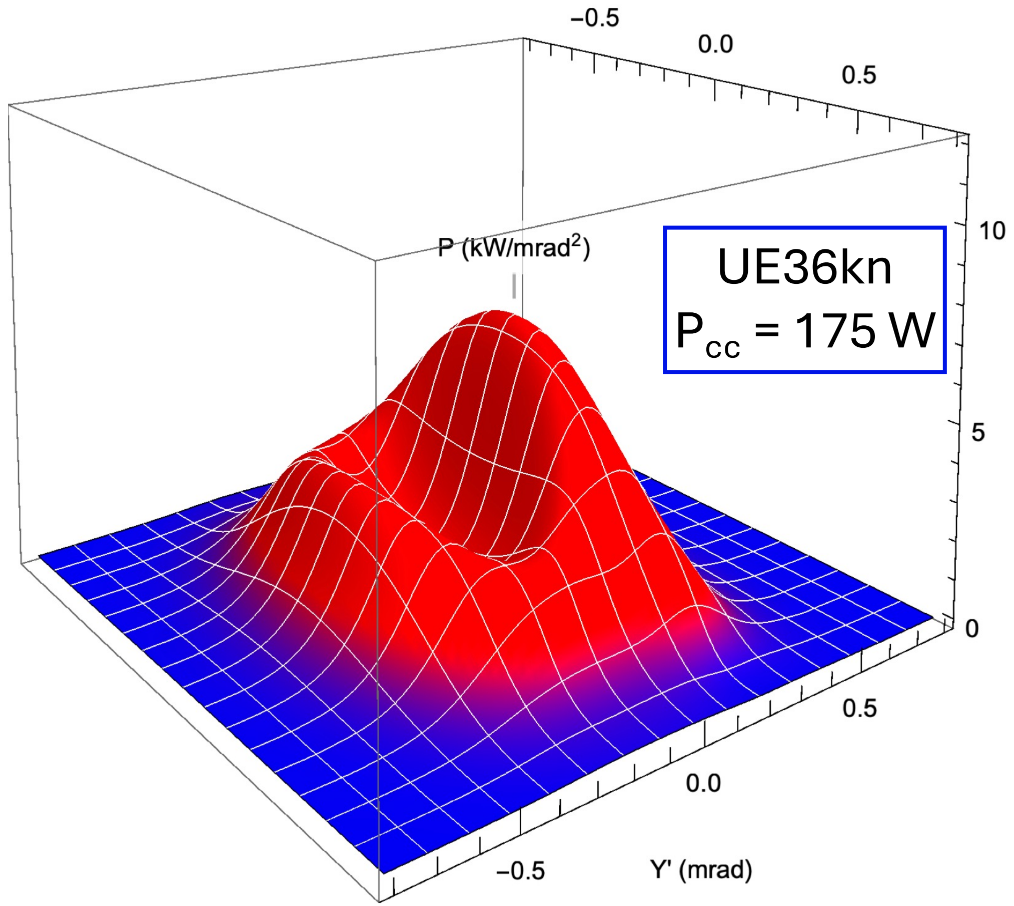
  SENIS magnetic & current measurement

- Laser guiding rails
- Screwdriving Robots
  - Shimming w.r.t. local k_i



APPLE-X knot Undulator – why *knot*?





+ Symmetry of the APPLE-X with round beam pipe

$\text{kn} \stackrel{\text{def}}{=} \text{knot}$

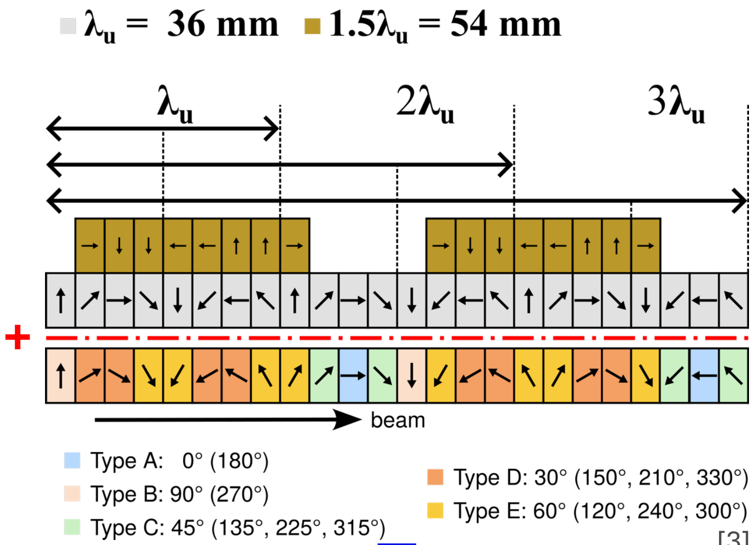
APPLE-X knot Undulator: Magnet Design

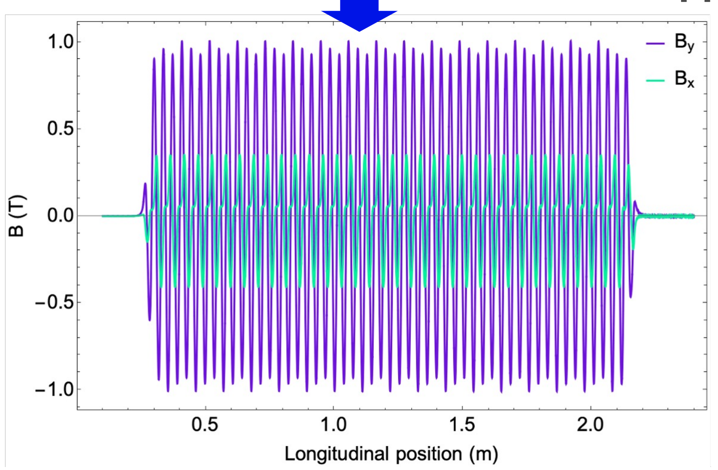
Issue: heat load on beamlines' optics

→ ≧ 60 % reduction by adapting a knot (kn) scheme [4], [5]

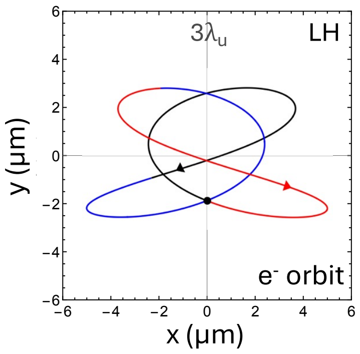
- Undulator period λ_u is combined with $1.5\lambda_u$
- PSI APPLE-X knot: varied scaling factor* for $1.5\lambda_u$,
  + adjustment of single angles

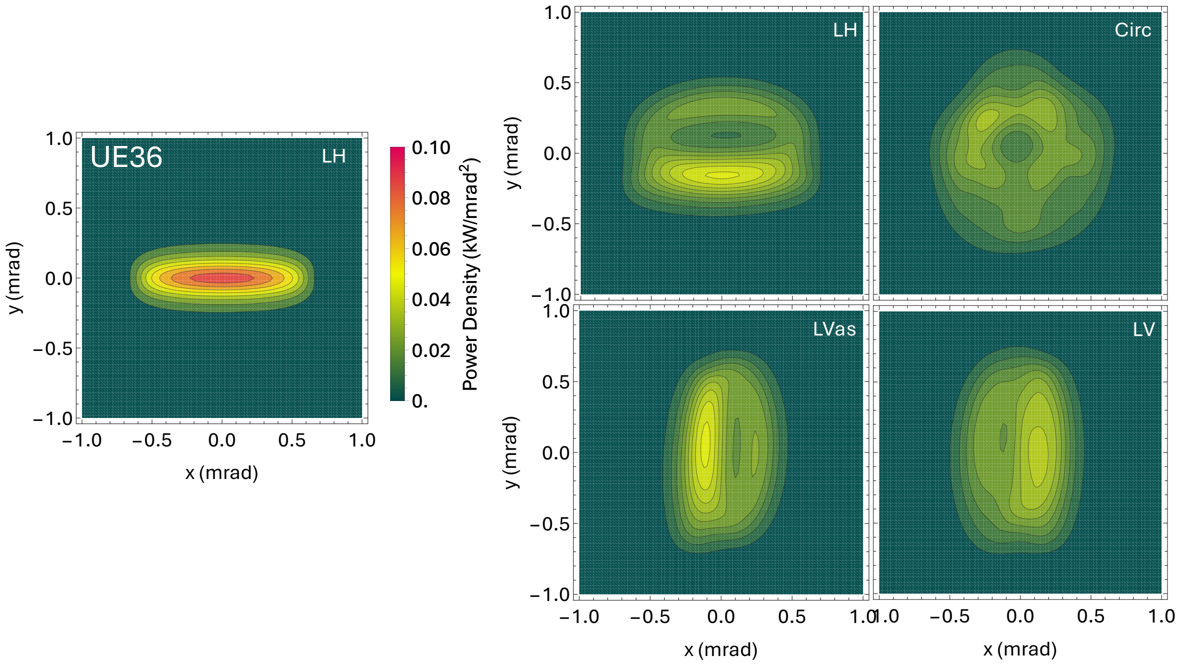
* tan(30°) ≈ 0.58





The PSI *knot*



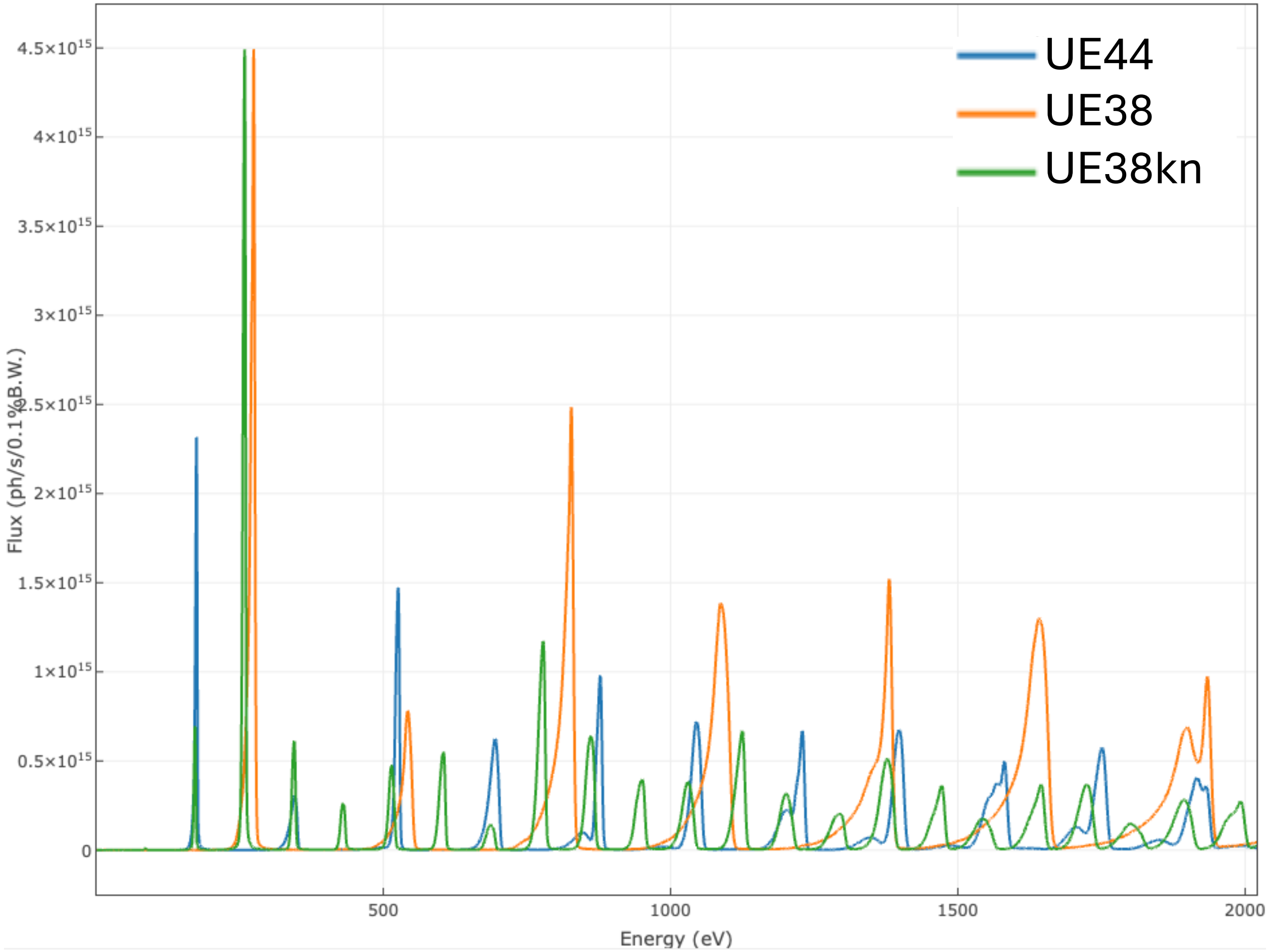


[4] S. Sasaki, A. Miyamomo, S. Qiao, "Design study of Knot-APPLE undulator for PES-beamline at SSRF", Proc. PAC2013
[5] F. Ji, et al., "Design and performance of the APPLE-Knot undulator", in Journal of Synchrotron Radiation, vol. 22, 4, 2015

APPLE-X knot Undulator: Magnet Design
Photon Spectra Calculation

- More peaks than usual
  - Superposition of two λ_u
  - "Sub-harmonics"
  - → Potential:
    Access to lower/higher energies with the same harmonic
  - → Interesting:
    Usable polarization of sub-harmonic
- No real higher harmonics
  - i.e., not usable
- Polarizations ≧ 98.5 %

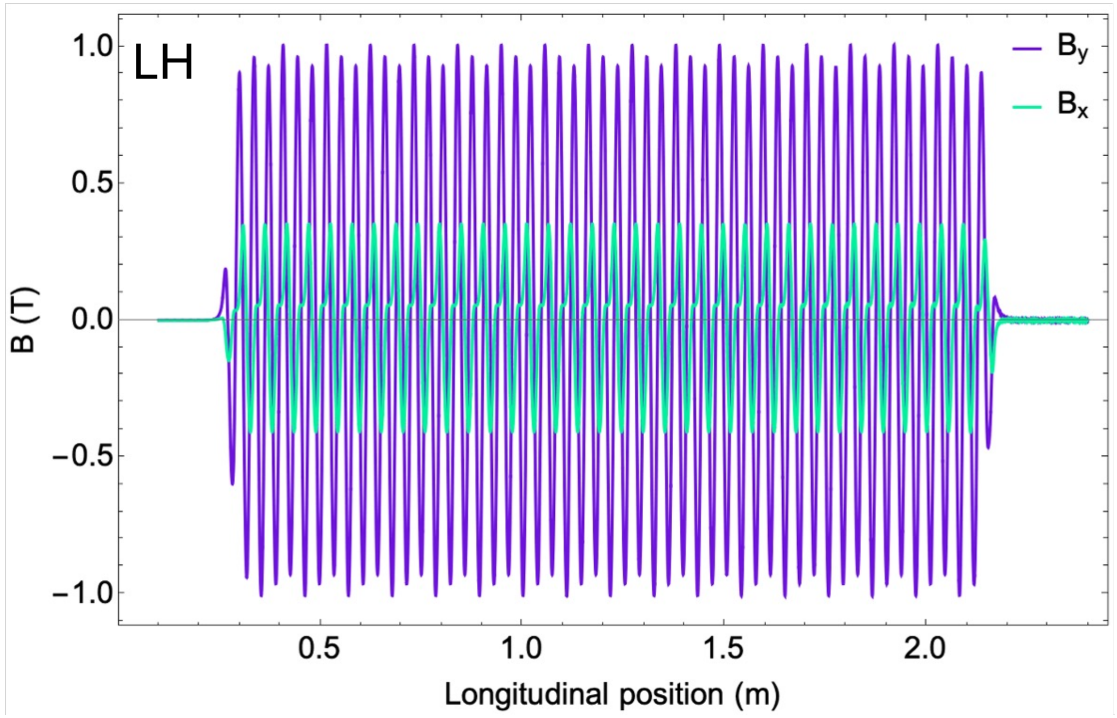
@20 m, linear horizontal (H1, LH, SLS2.0)



Comparison for a 4m-long APPLE-X undulator

APPLE-X knot Undulator: Optimization
Defining *K*

$$K \propto \frac{\lambda_u \cdot B}{m_e c}$$



$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

Doing justice to the superperiod of $3\lambda_u$:

$$3\lambda = \frac{1}{2\gamma^2}\left[3\lambda_u + \left(\frac{e}{mc}\right)^2 \int_0^{3\lambda_u} (I_x^2(z') + I_y^2(z'))\, dz'\right]$$

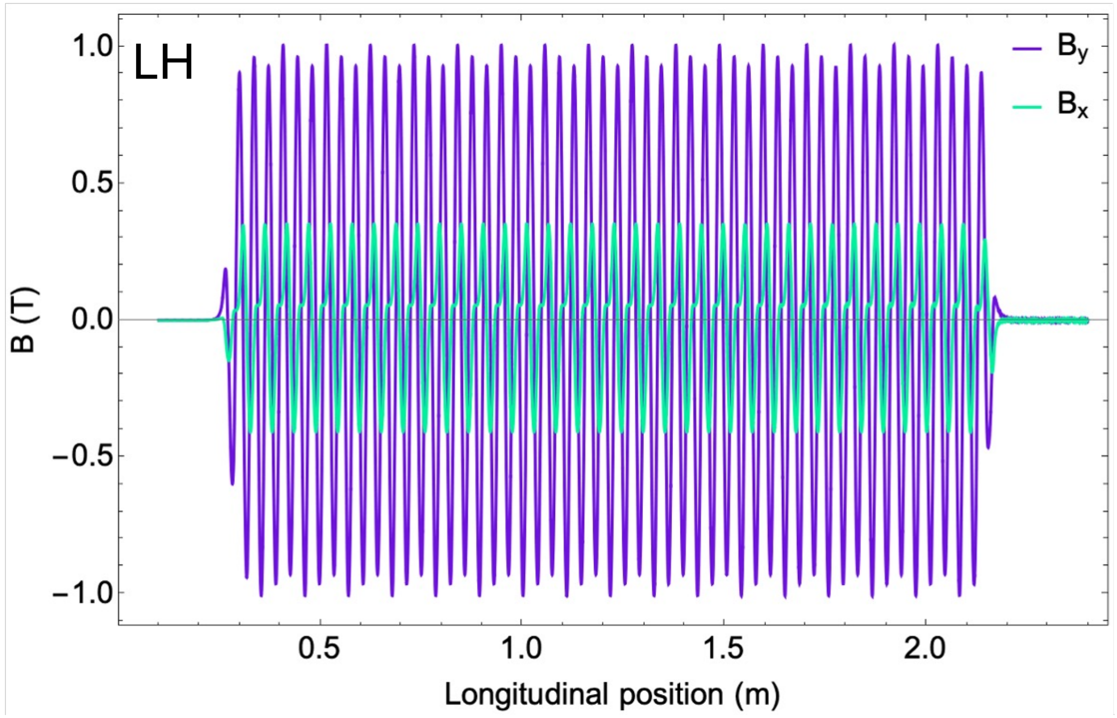
with $$I_{x/y}(z) = \int_{-\infty}^{z} B_{x/y}(z')dz'$$

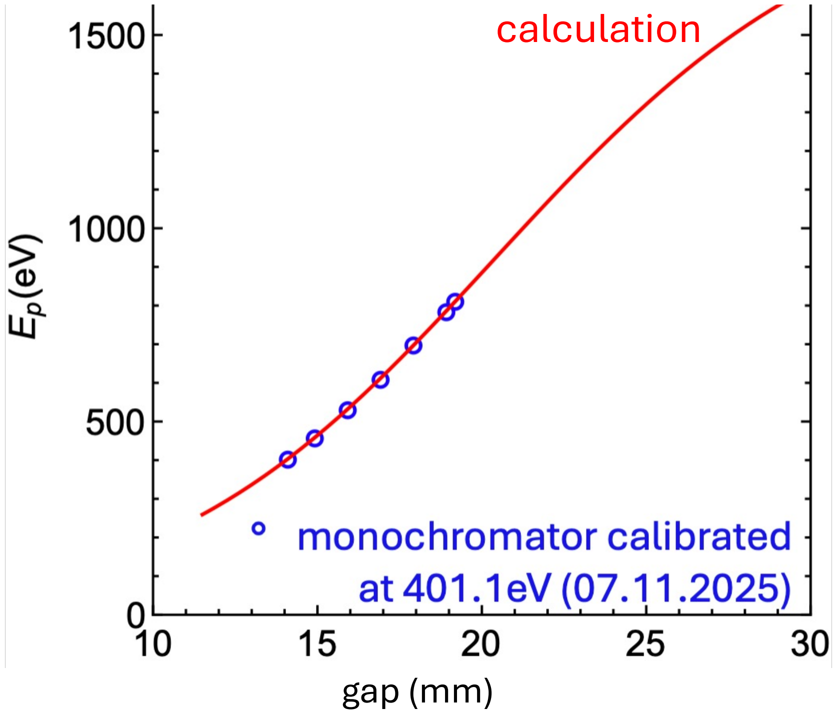
$$K = \frac{e}{mc}\sqrt{\frac{2}{3\lambda_u}\int_0^{3\lambda_u} I_x^2(z') + I_y^2(z')dz'}$$

[6] M. Calvi, S.C. Richter, *Magnetic Assessment of a Knot Apple X Undulator,* PSI Internal Report, 2024

APPLE-X knot Undulator: Optimization
Defining *K*

$$K = \frac{e}{mc}\sqrt{\frac{2}{3\lambda_u}\int_0^{3\lambda_u} I_x^2(z') + I_y^2(z')dz'}$$



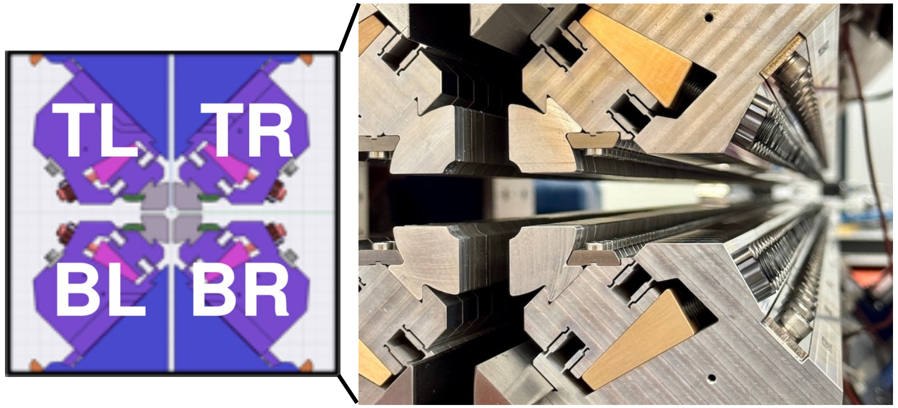


Courtesy of A. Kleibert

APPLE-X knot Undulator: Optimization

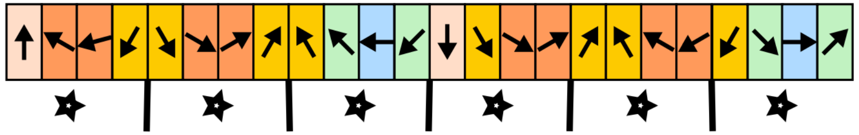
Goals:

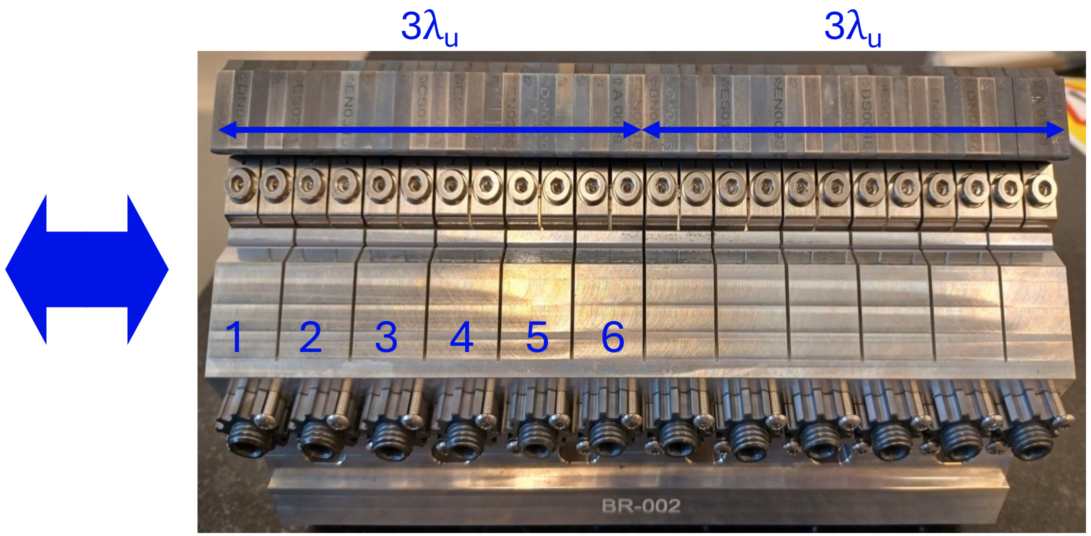
- Making the field as uniform as possible
- → Minimizing the phase error
- Reducing kicks to the beam

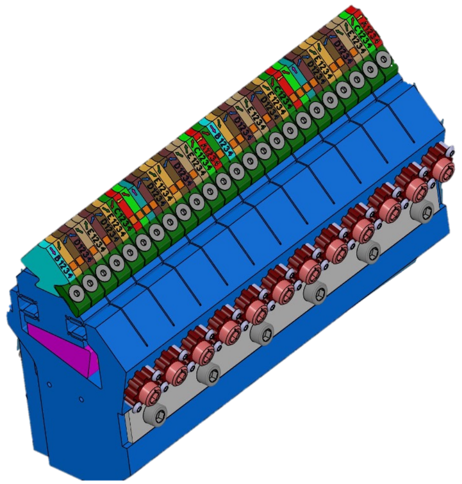


6 shimming knobs per superperiod $\Lambda = 3\lambda_u$

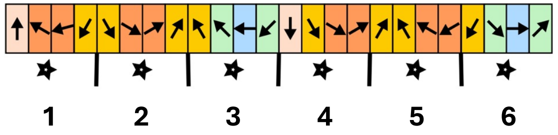
- Each moves a pack of 4 magnets
- Different ”fingerprints”
- µm-precise adjustment



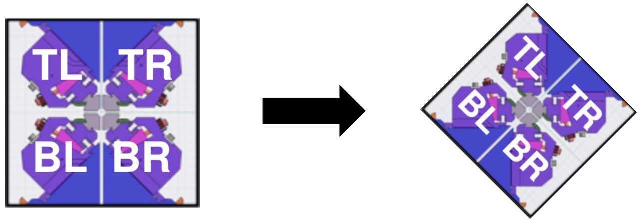




APPLE-X knot Undulator: Optimization

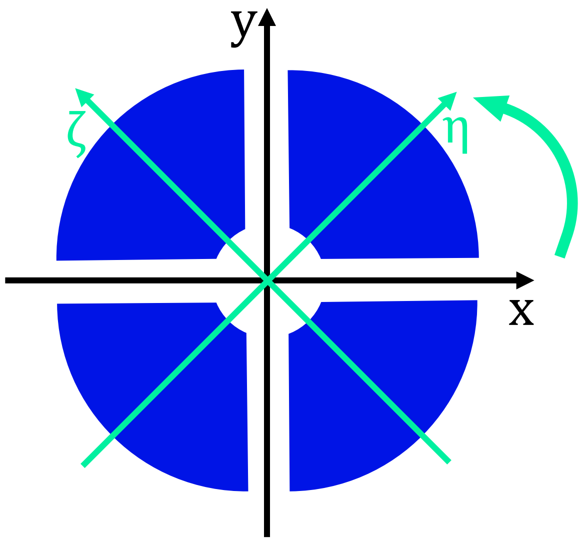


"Decoupling" of the axes for simplified reference frame

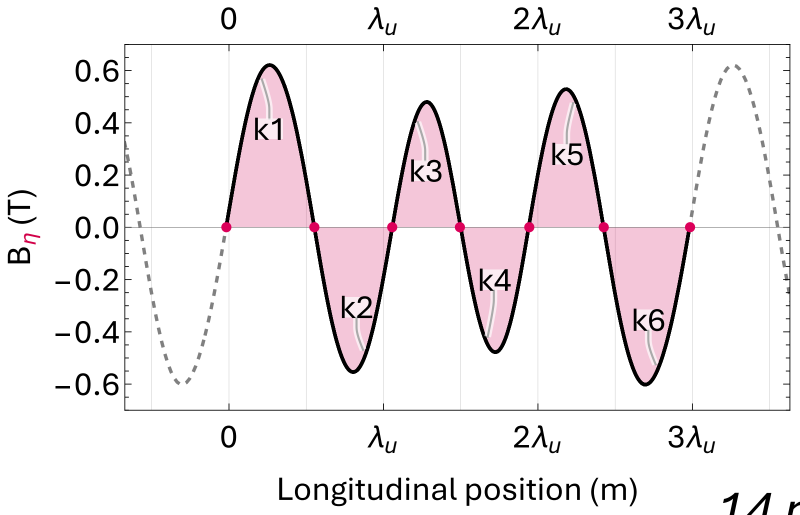


coordinate system transformation of a -45 ° rotation around z (x → +)

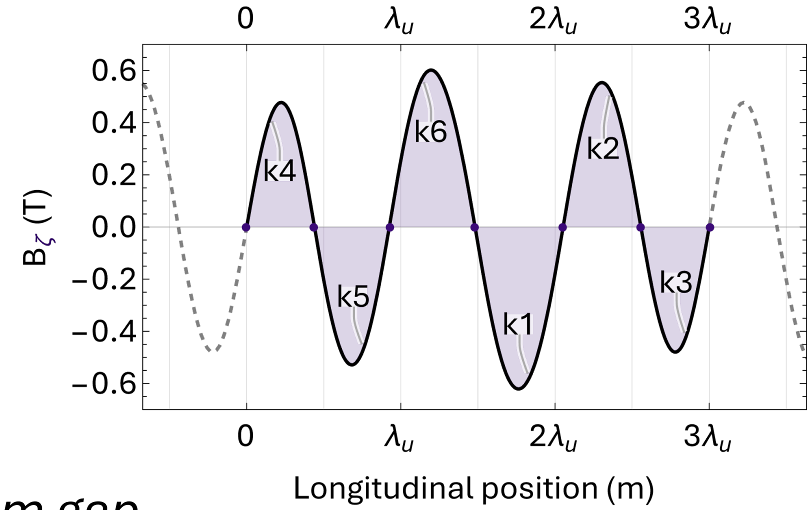
(x, y) → (η, ζ)



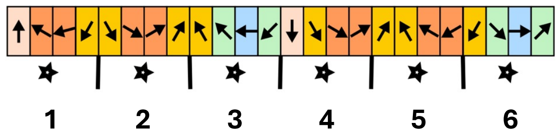
The (η, ζ)-*B-fields*:



14 mm gap



APPLE-X knot Undulator: Optimization
Methodology of local k_i analysis



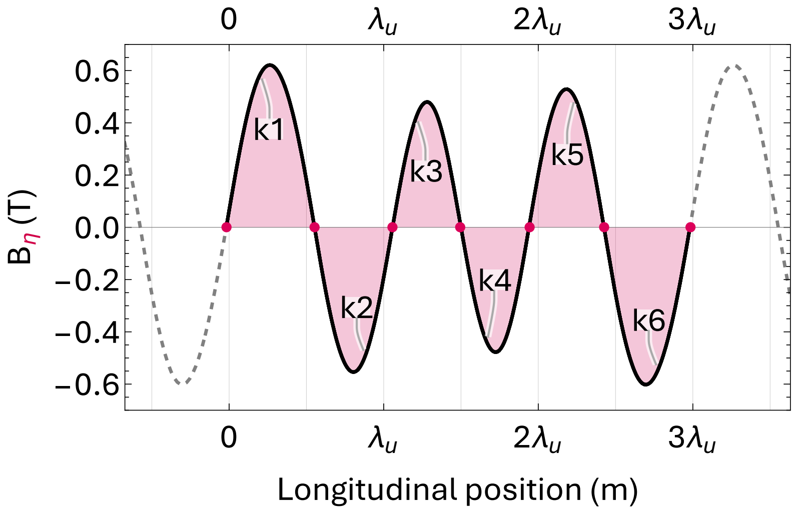
Ideal calculated values

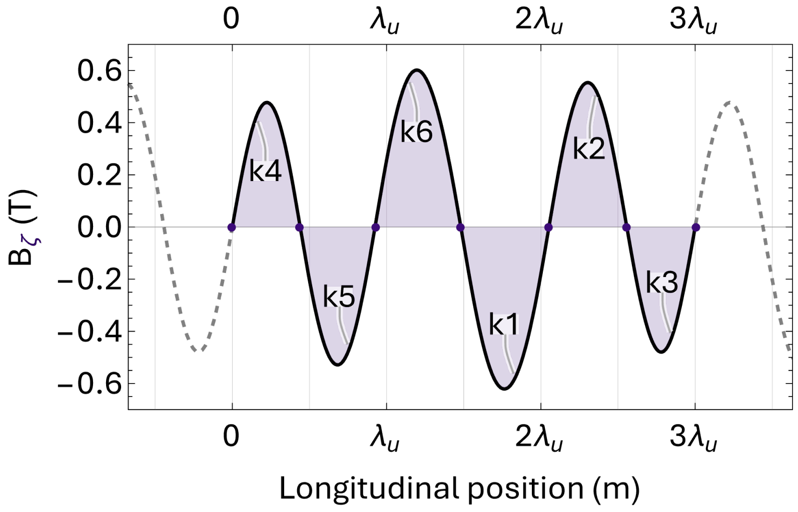
i	η	ζ
$\|k_2/k_1\|$	0.782	0.782
$\|k_3/k_1\|$	0.593	0.593
$\|k_4/k_1\|$	0.589	0.589
$\|k_5/k_1\|$	0.721	0.721
$\|k_6/k_1\|$	0.941	0.941
mean values		
k_1	8.189	-8.189
k_2	-6.410	6.410
k_3	4.857	-4.856
k_4	-4.822	4.821
k_5	5.902	-5.901
k_6	-7.709	7.708
Total	0.0	0.0

Spoiler!

Exp. measured values

i	η	ζ
$\|k_2/k_1\|$	0.778	0.777
$\|k_3/k_1\|$	0.589	0.588
$\|k_4/k_1\|$	0.583	0.581
$\|k_5/k_1\|$	0.715	0.714
$\|k_6/k_1\|$	0.943	0.941





APPLE-X knot Undulator: Optimization

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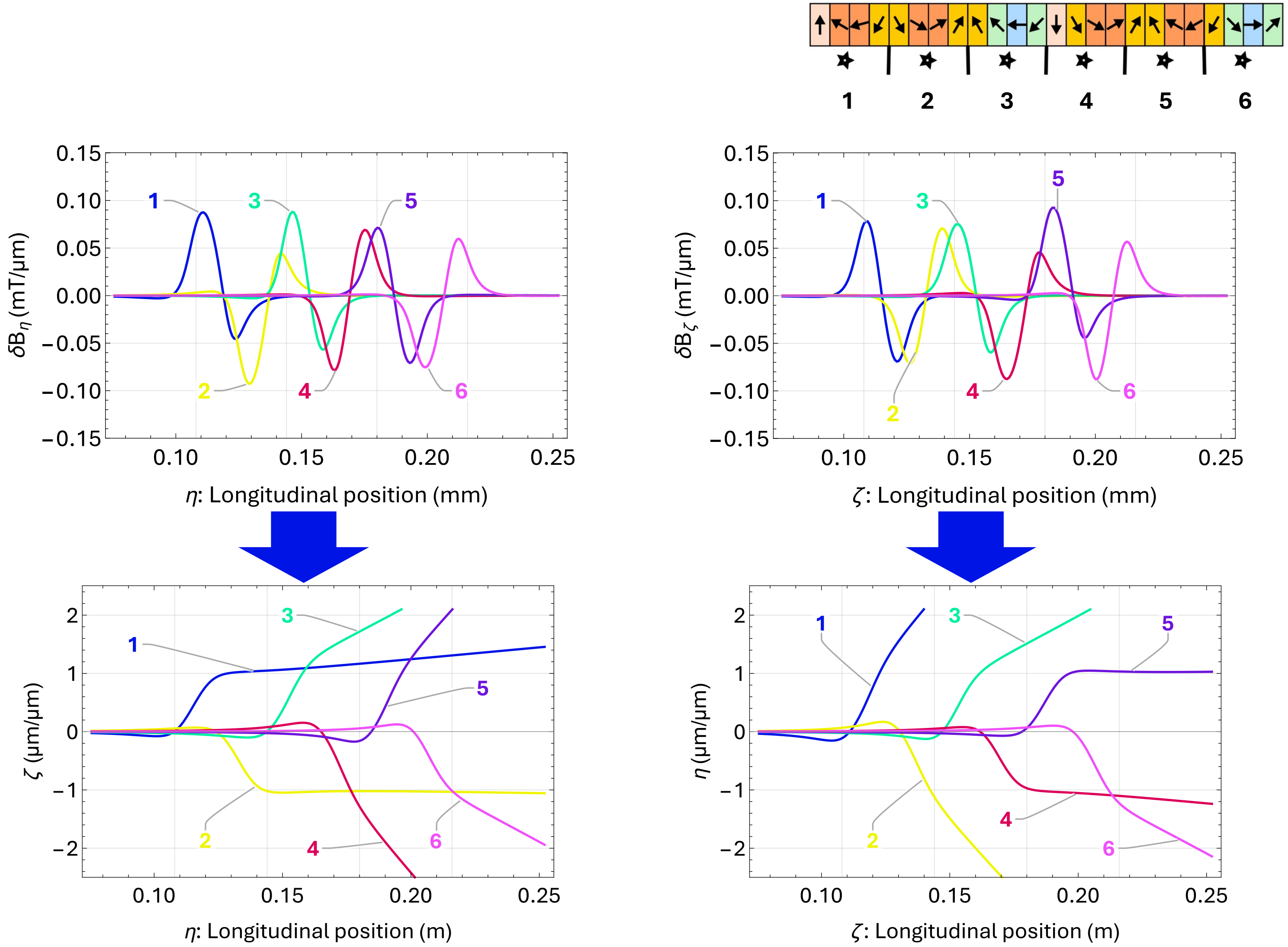
(η, ζ)- Shimming the knobs *n*:
Six different knobs per superperiod Λ = 3λ:

- **4 “good”**
  η: 3, 4, 5, and 6
  ζ: 1, 2, 3, and 6

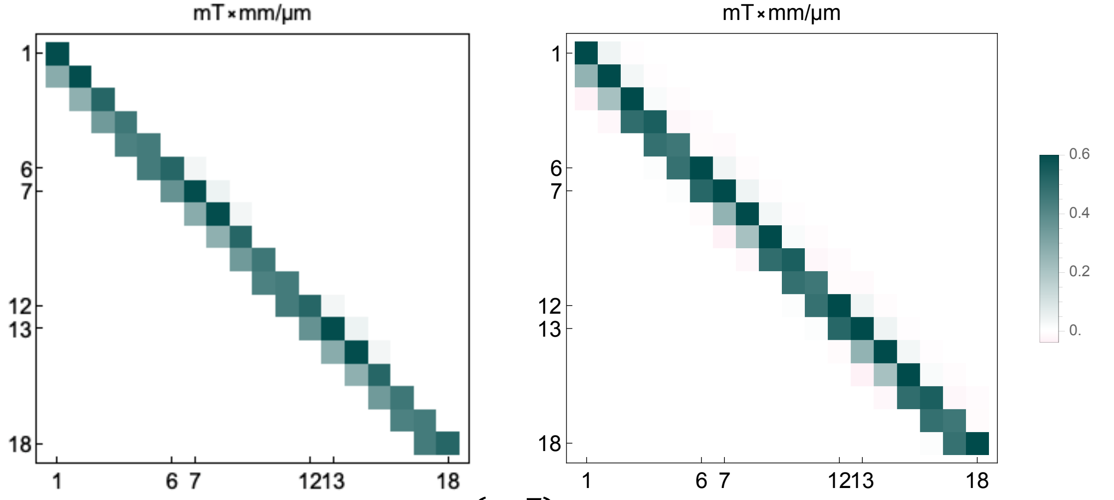
- **2 “bad”**
  η: 1 and 2
  ζ: 4 and 5



APPLE-X knot Undulator: Optimization

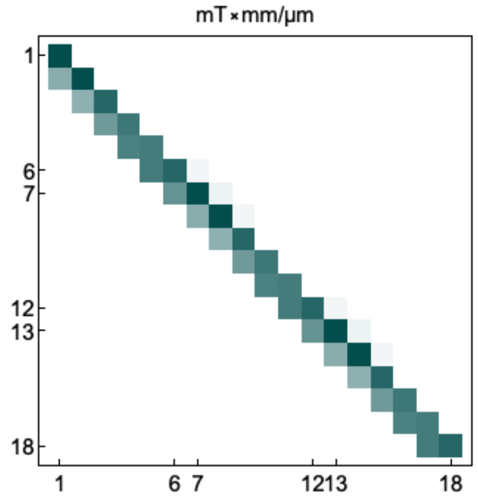
Coupling Matrices can be created for a superperiod and then upscaled to the entire undulator:

- Influence on the two nearest neighbours
- Per superperiod within the (η,ζ)-frames
- Δk_{i} : k_i variation (vector)
- $\Delta knob_{\mathrm{i}}$: knob height variation (vector)

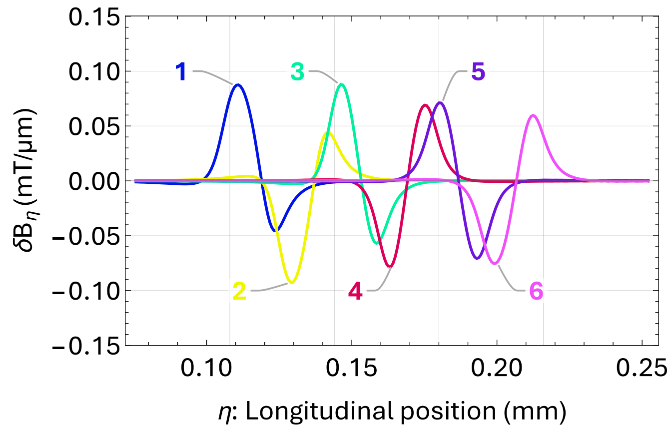


(η,ζ)

$\Delta k_{\mathrm{i}} =$



$\times\, \Delta knob_{\mathrm{i}}$



APPLE-X knot Undulator: Optimization

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- Influence on the two nearest neighbours
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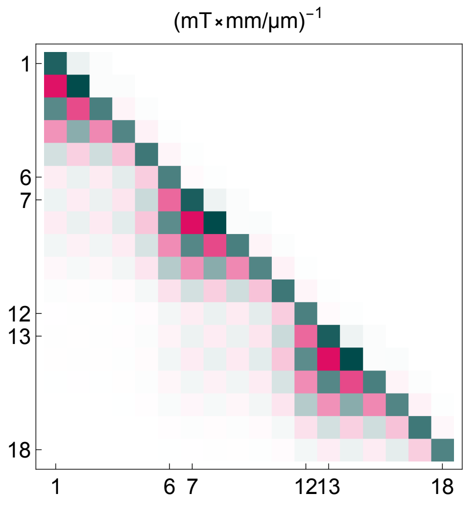
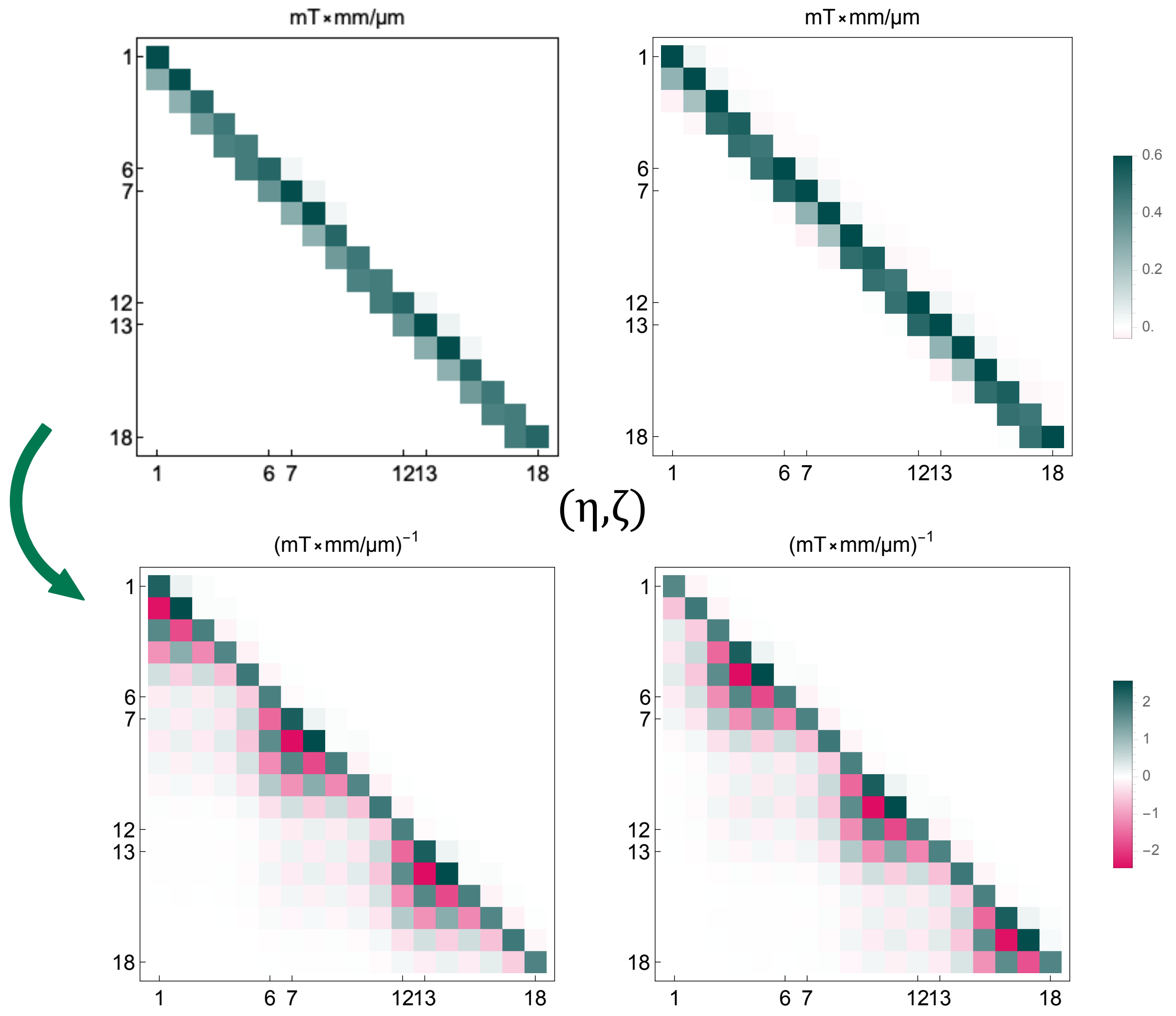
- $\Delta knob_{\mathrm{i}}$: knob height variation (vector)

$\Delta knob_{\mathrm{i}} =$

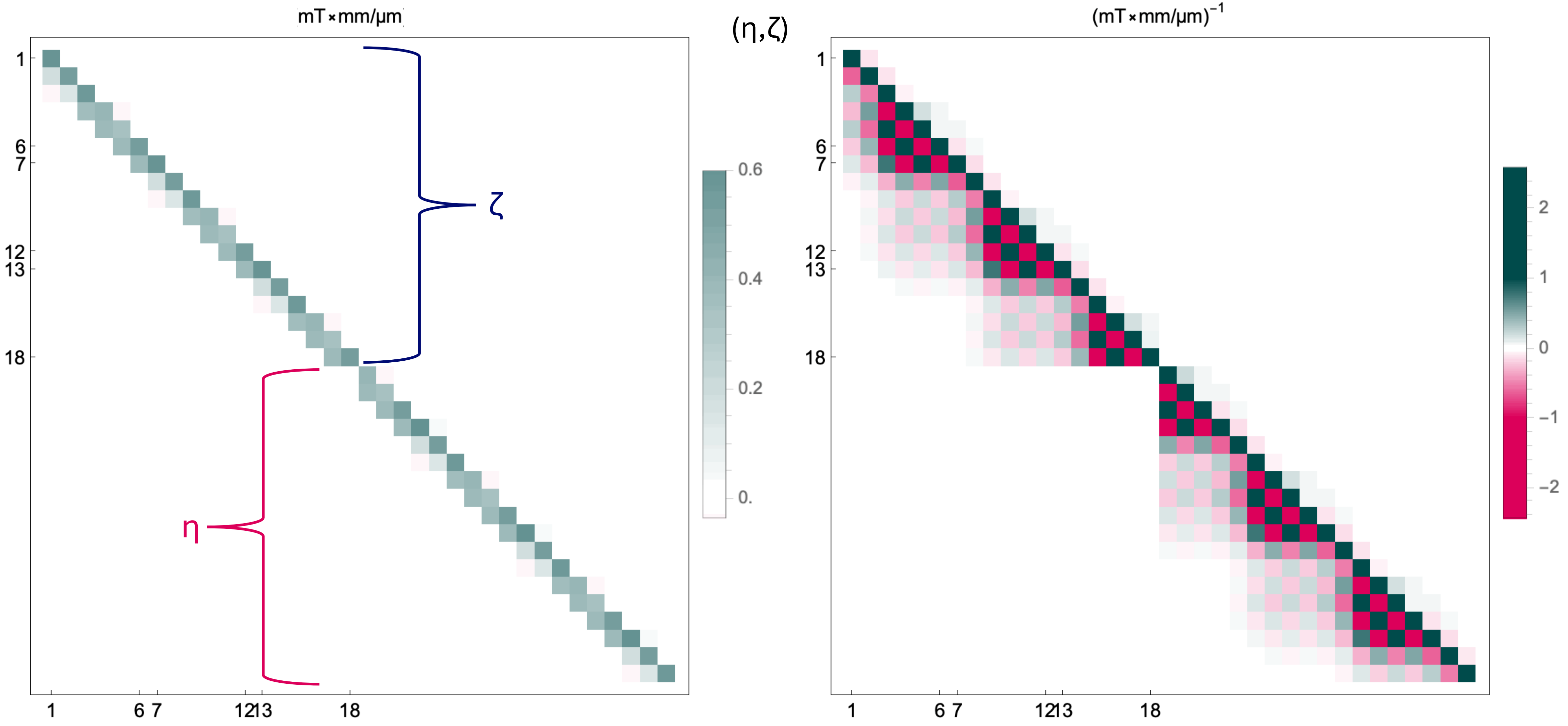


$\times\, \Delta k_{\mathrm{i}}$

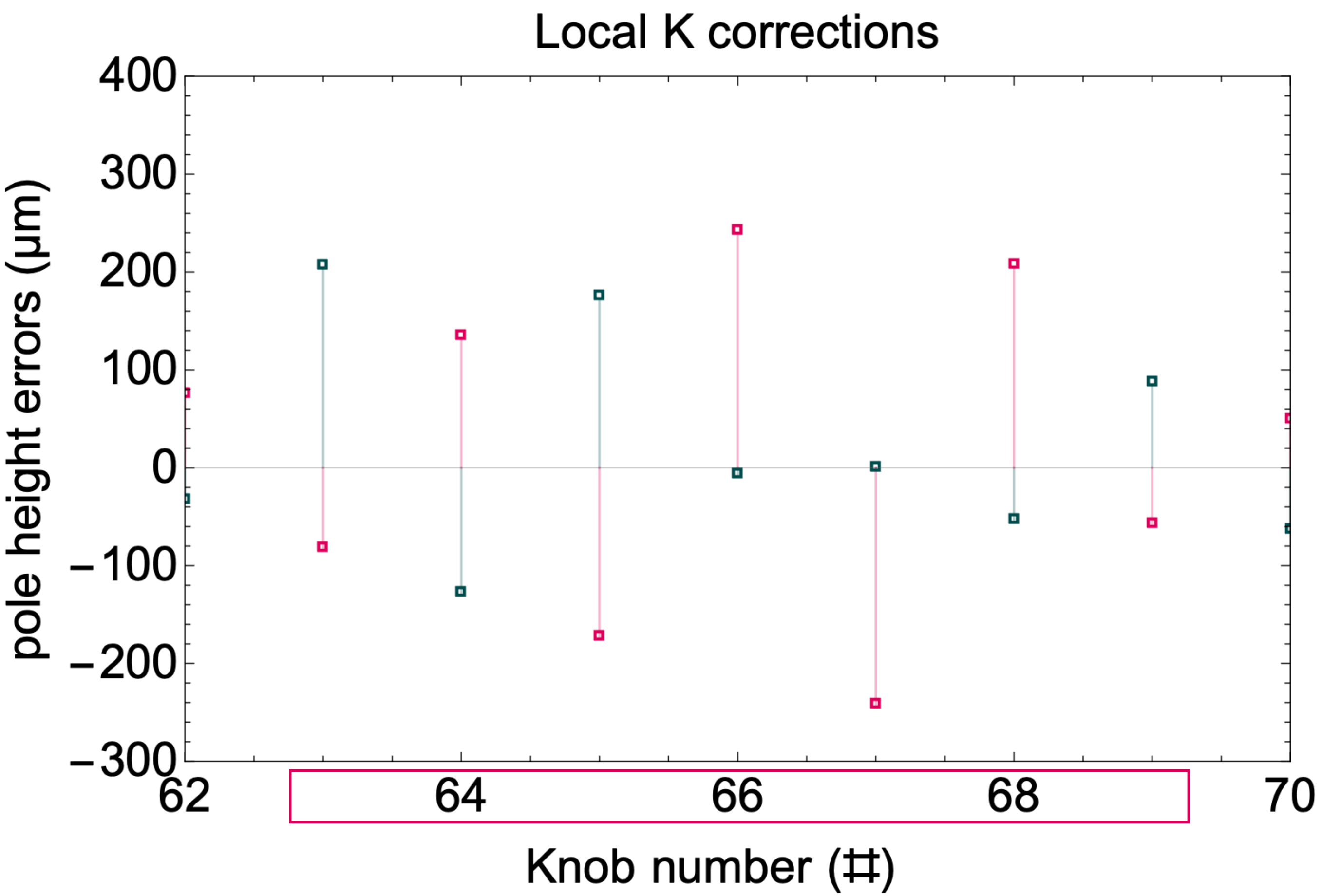
inversing

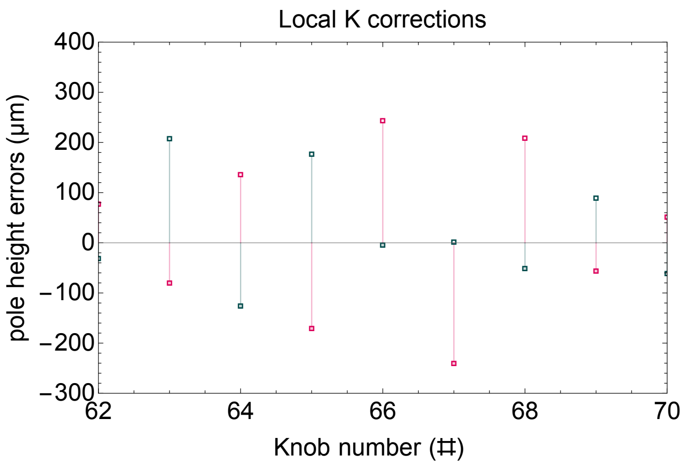


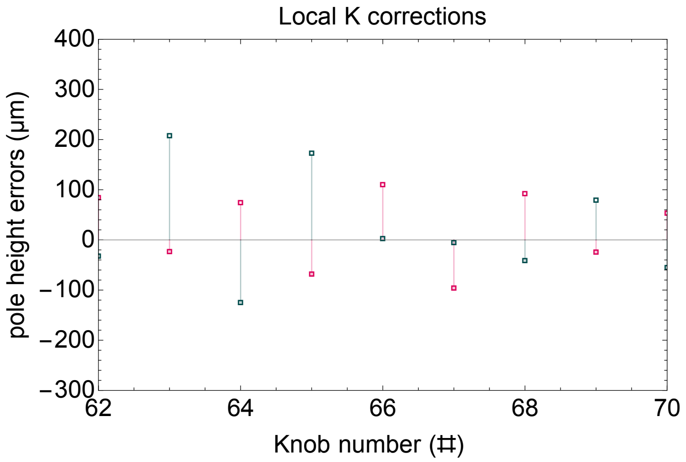
APPLE-X knot Undulator: Optimization Coupling Matrices



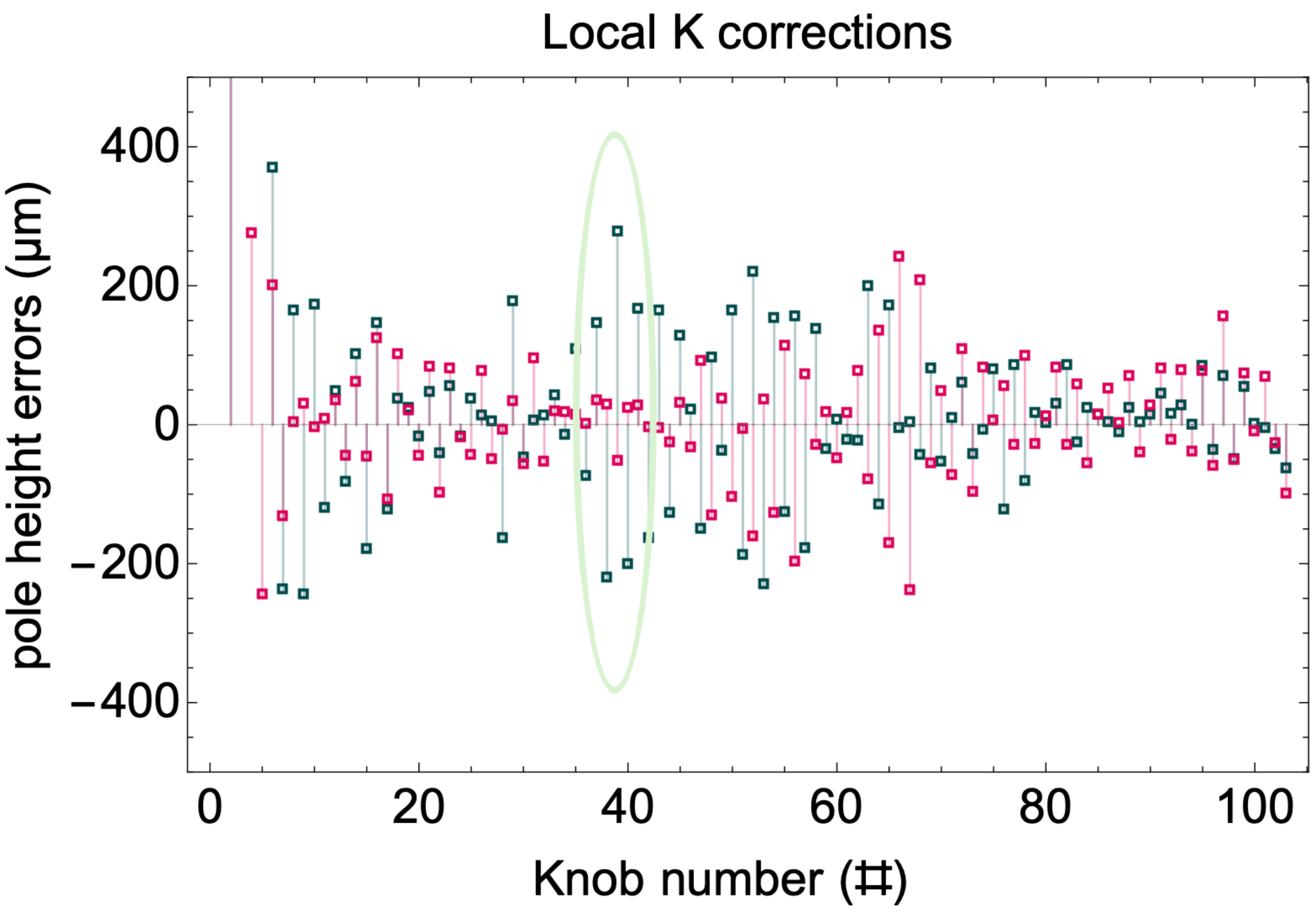
APPLE-X knot Undulator: Optimization Shimming Example (63 to 69)

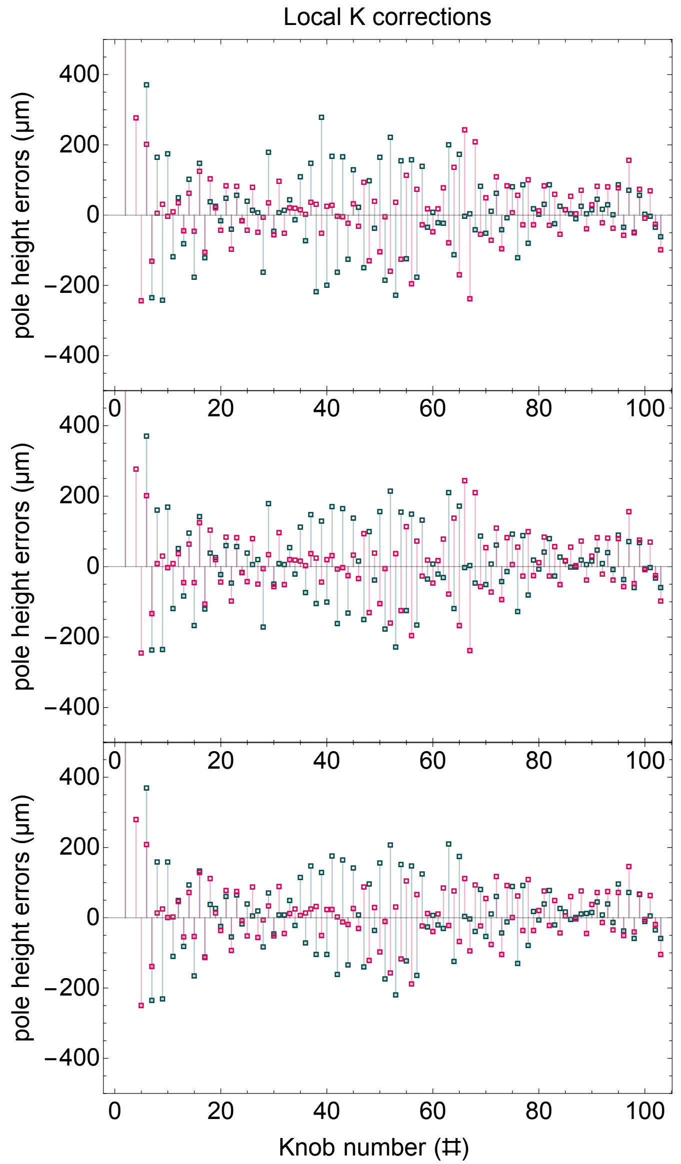




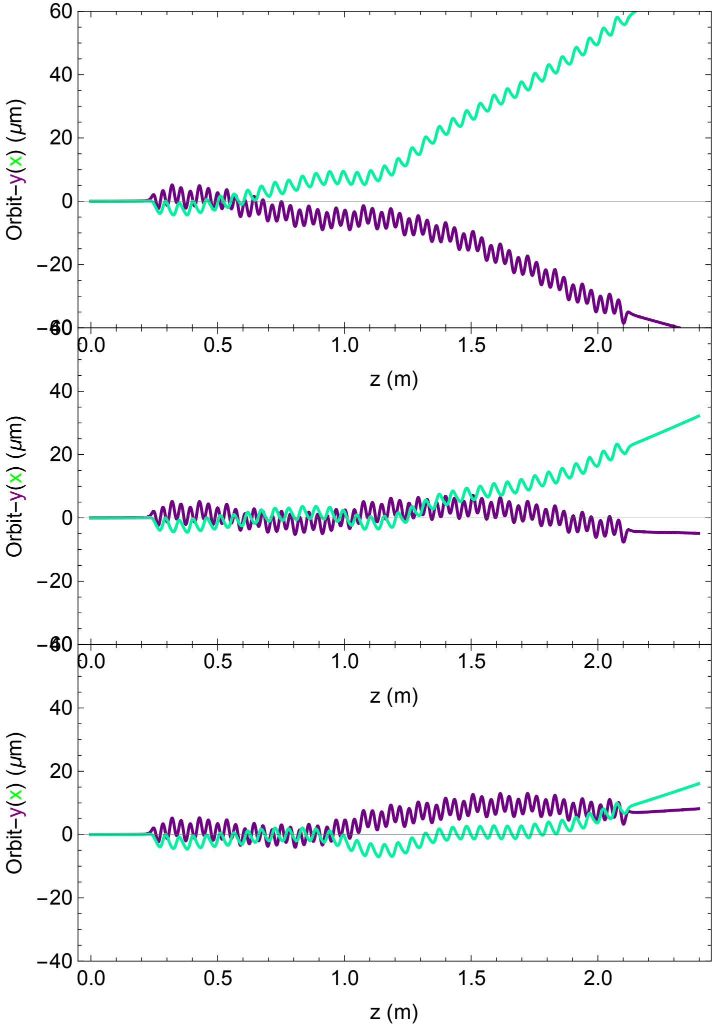


APPLE-X knot Undulator: Optimization Shimming Example Groups



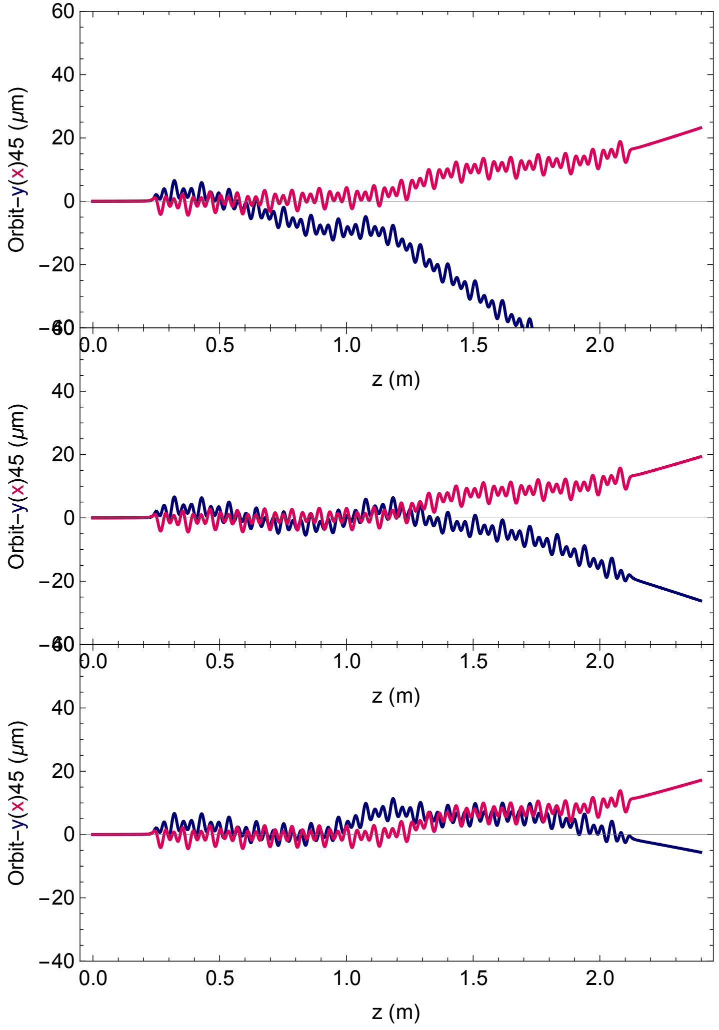


APPLE-X knot Undulator: Optimization Trajectories in x-y and η-ζ

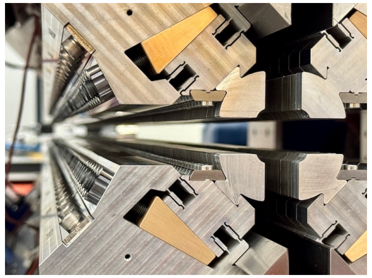


Manual shimming of knobs

Decreased orbits and kicks



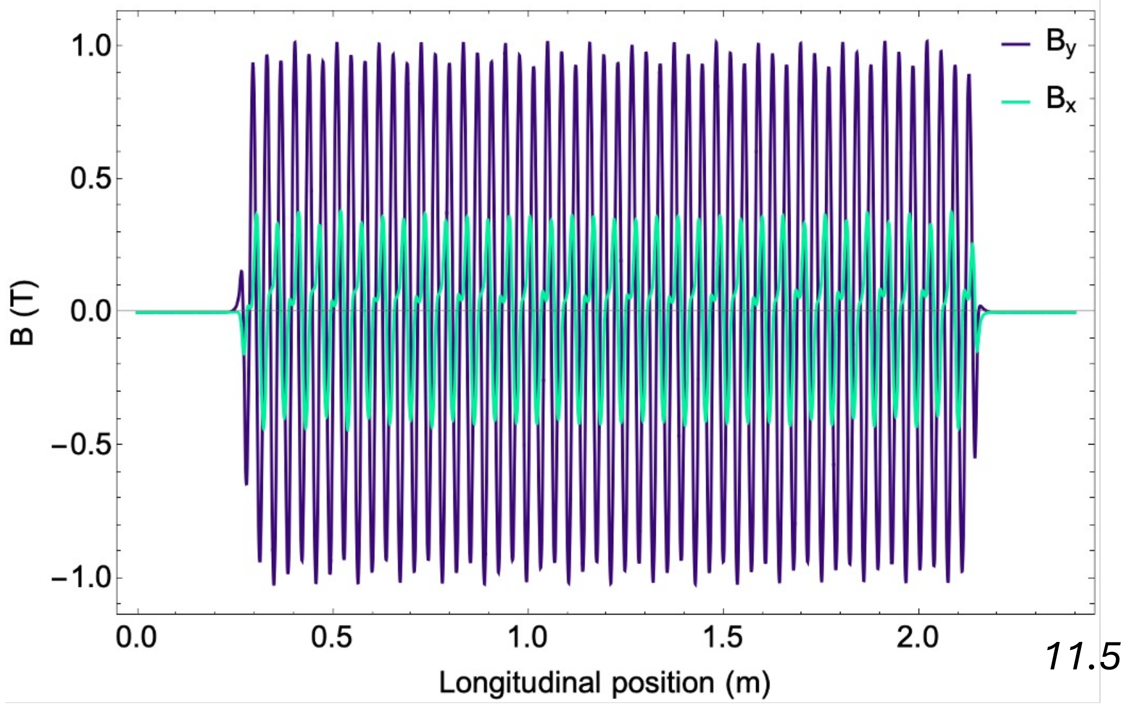
APPLE-X knot Undulator: Magnetic Characterization



- *Main Field:* Qualitative agreement (here: B_y)
- *Knot Field:* Very sensitive to roll angles (here: B_x)
  - Negligible deviations detected

→ IDs deliver the defined output (flux, polarization)

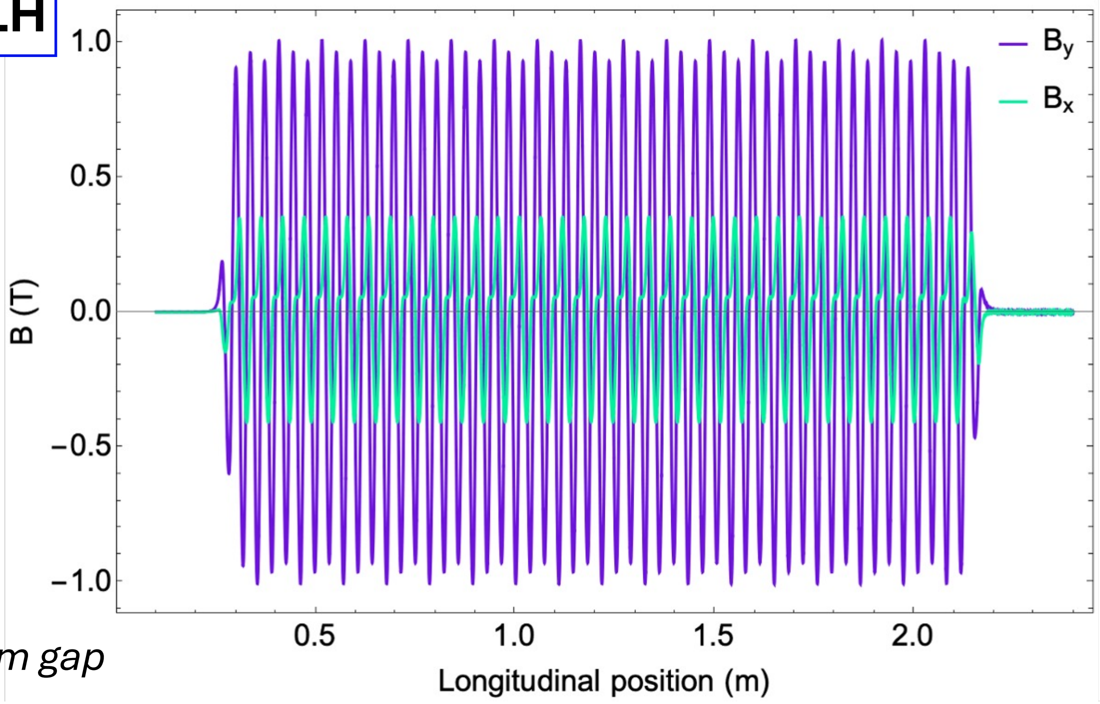
Measurement



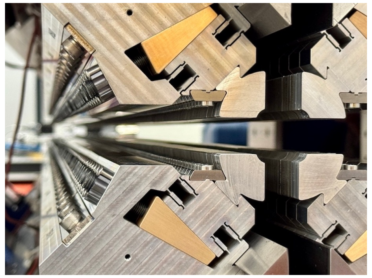
LH

11.5 mm gap

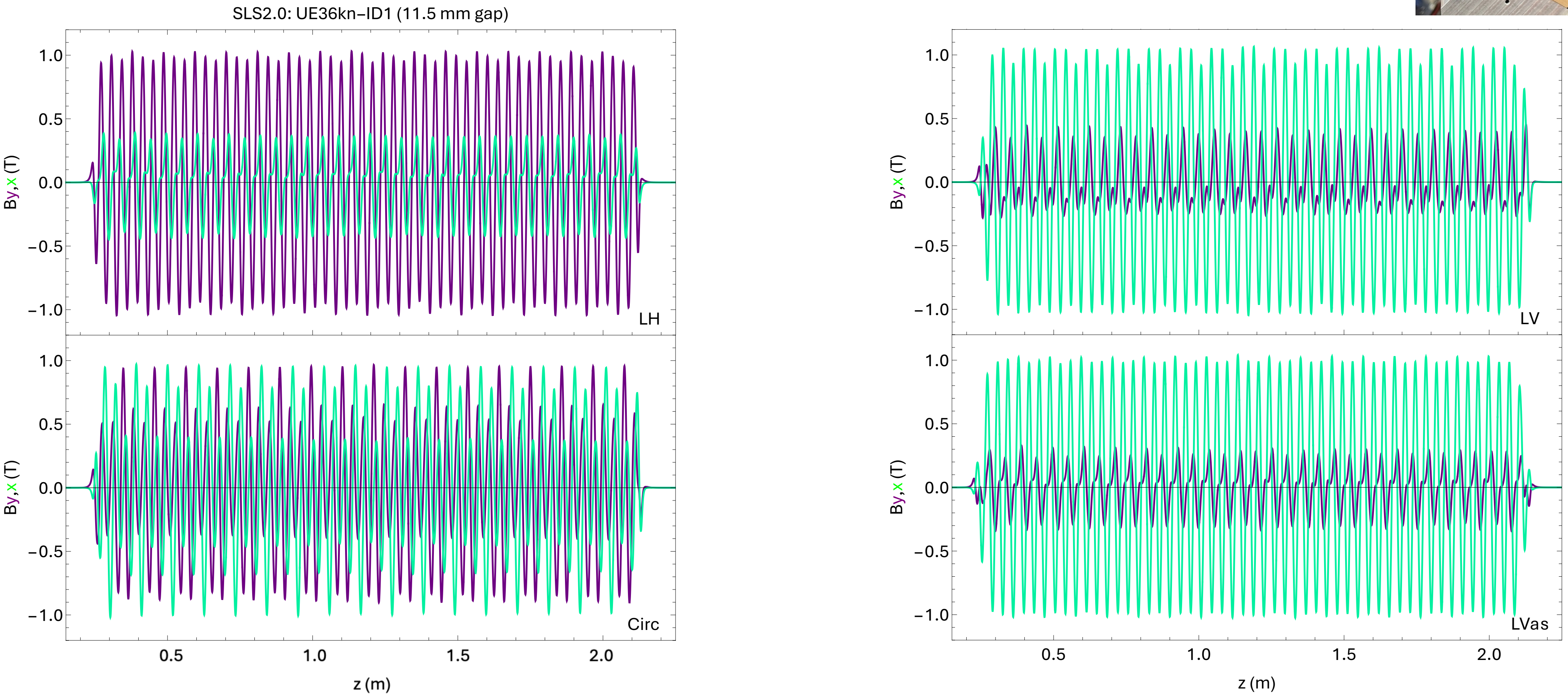
Calculation



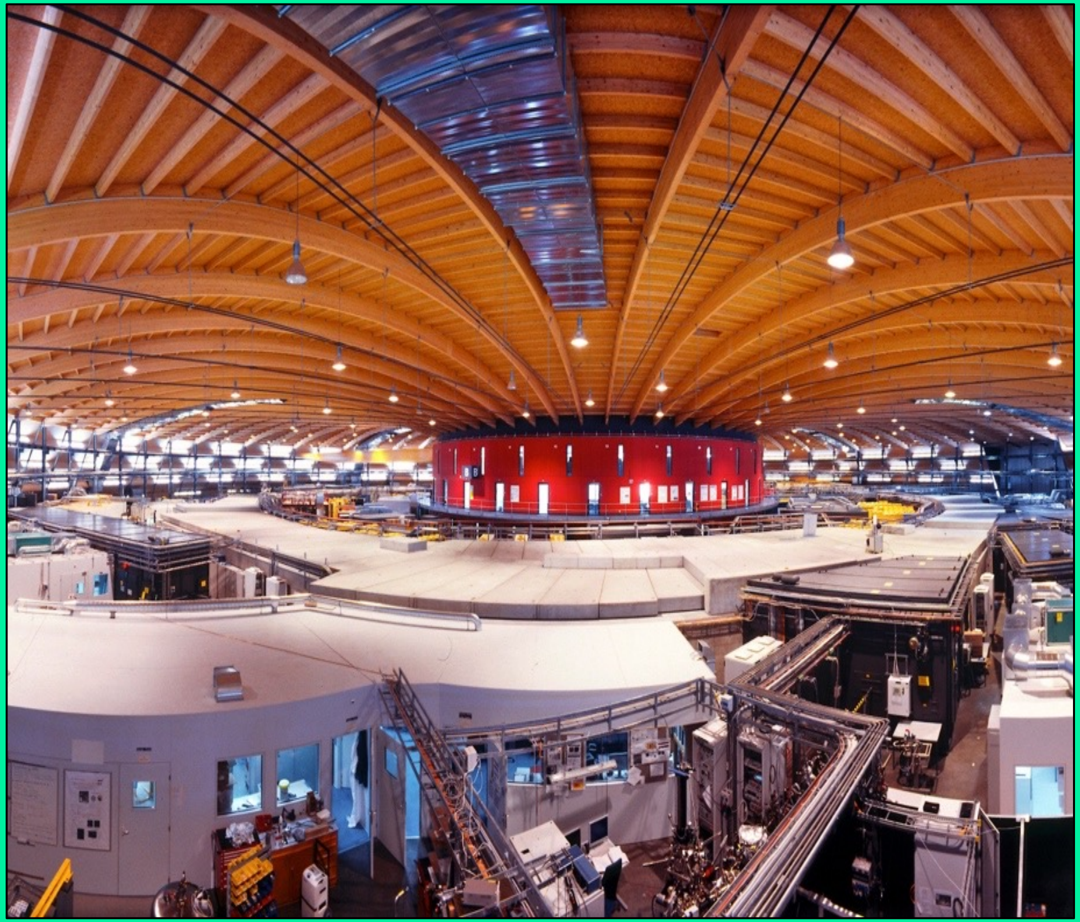
APPLE-X knot Undulator: Magnetic Characterization



Measurement Results UE36kn @ 11.5 mm gap



Summary & Outlook



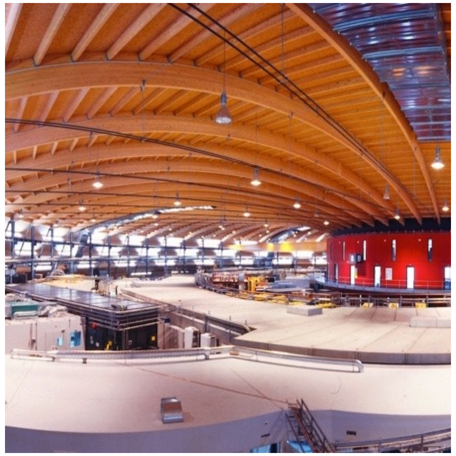
Summary & Outlook

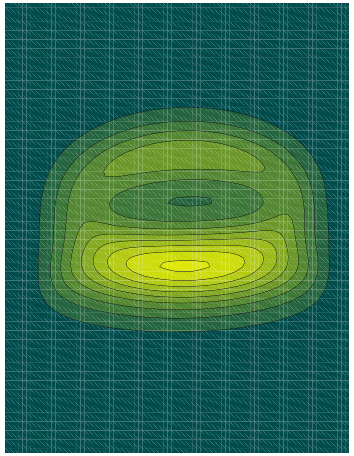
PSI

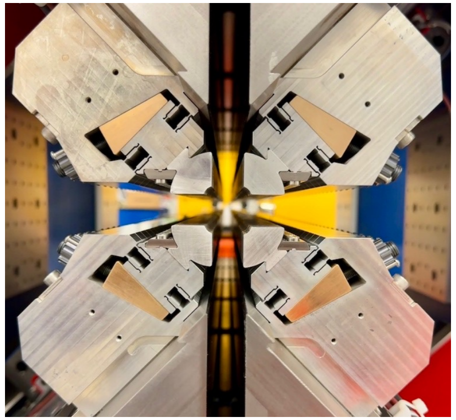
- SLS 2.0 commissioning is going well – exciting new IDs!
- A complex APPLE-X *knot* magnet scheme was realized
  - First automated shimming demonstrated
  - Performance according to calculations
    - Conventional polarization modes perform well
    - On-axis power reduction of over 65 %
  - Measurements and first operations look promising

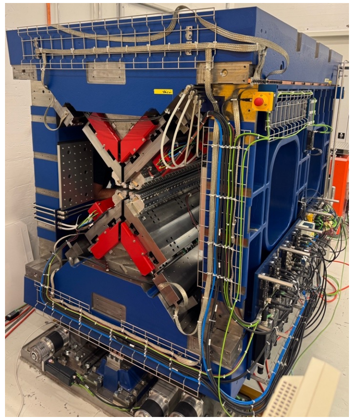
Upcoming work:

- Polarization purity and on-axis power measurements
- Beamline optics alignment, then user operation (mid 2026)
- Two more IDs are planned: APPLE-III *knot*
  - Incl. force compensation magnets: ~ 54 magnets / λ_u









Bring on the e^-beam!

Many thanks to
the ID-Group @PSI!

Magnetic Characterization & Initial Shimming Results of an APPLE-X Knot Undulator

Insertion Devices for Future Light Sources Workshop

sebastian.richter@psi.ch
PSI Center for Photon Science
Deauville, France – 15/05/2026

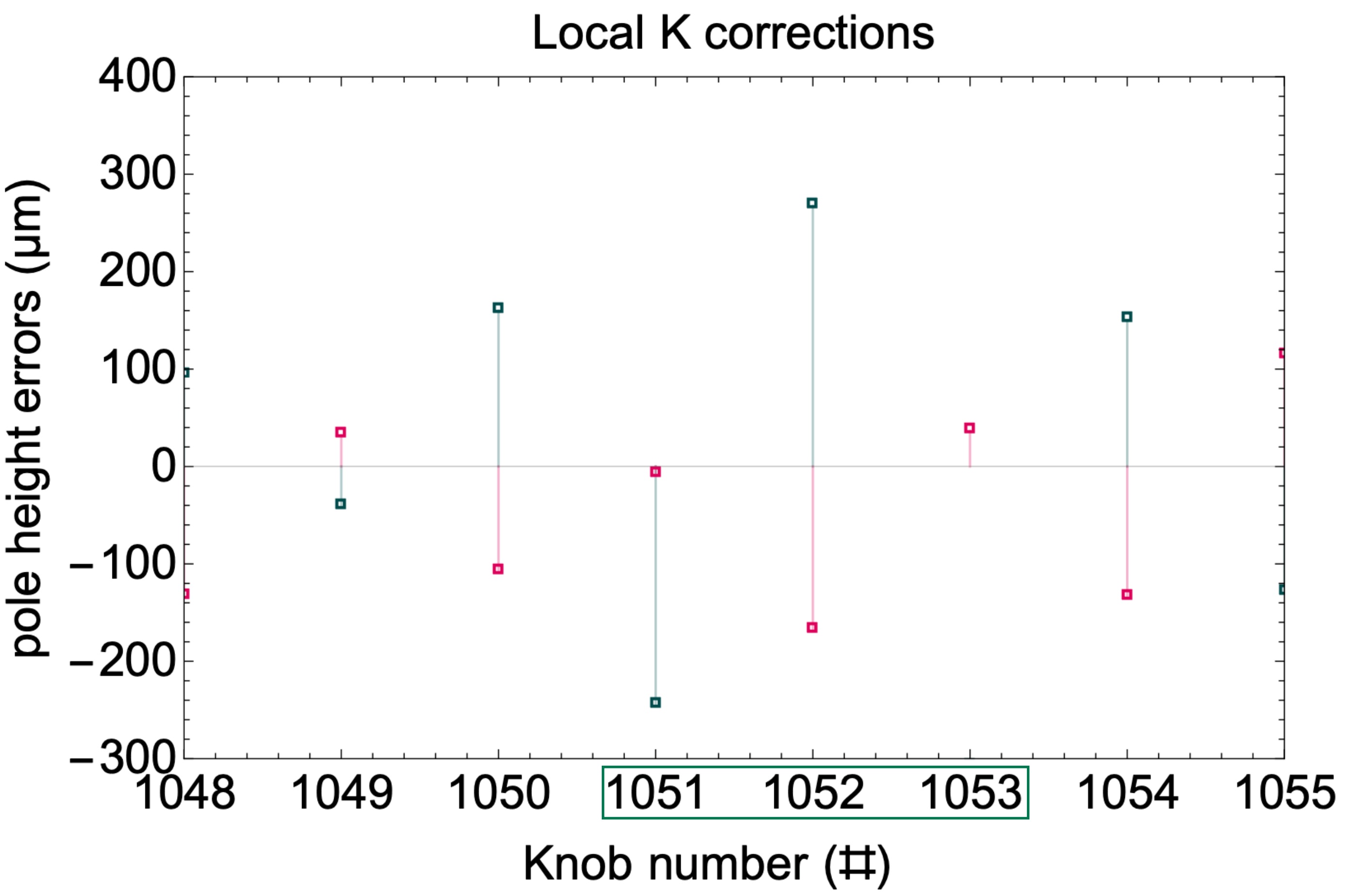
Thank you for your attention!

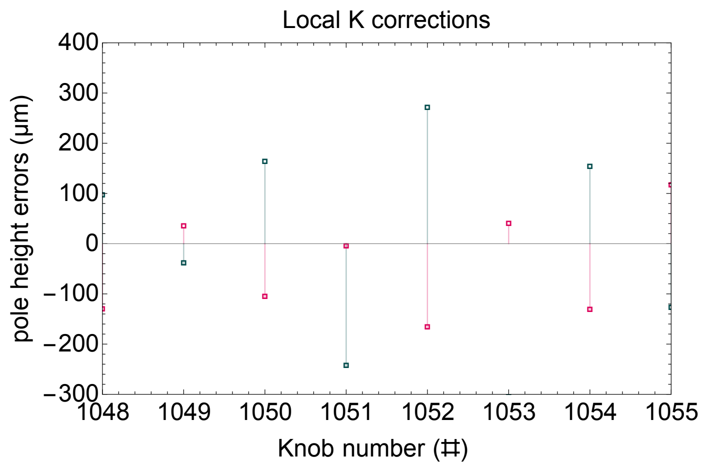
Appendix

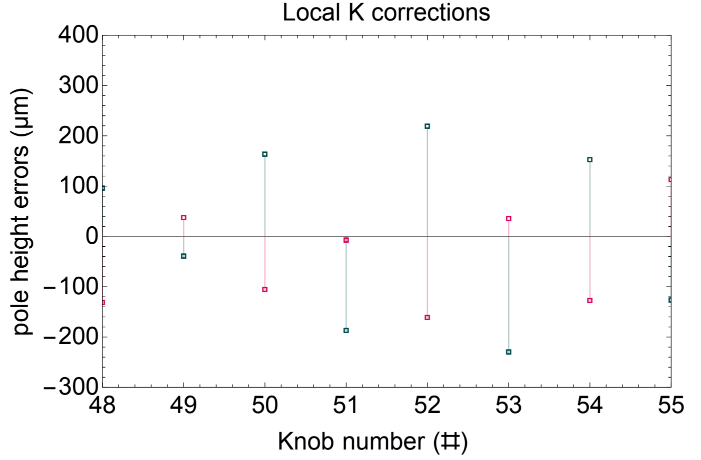
Appendix: UE36kn Main Parameters

Parameter	Value	Unit
Magnet material	$Nd_2Fe_{14}B$	
Period length λ_u	36	mm
Super period $3\lambda_u$	108	mm
max. B	1	T
max. K	3.6	
Min. gap	11.5	mm
Hor./vert. slit	3	mm
Electron energy	2.7	GeV
Photon energy	260 to 1800	eV
Magnetic length	1.836	m
Module length	2.25	m
Number of periods	51	

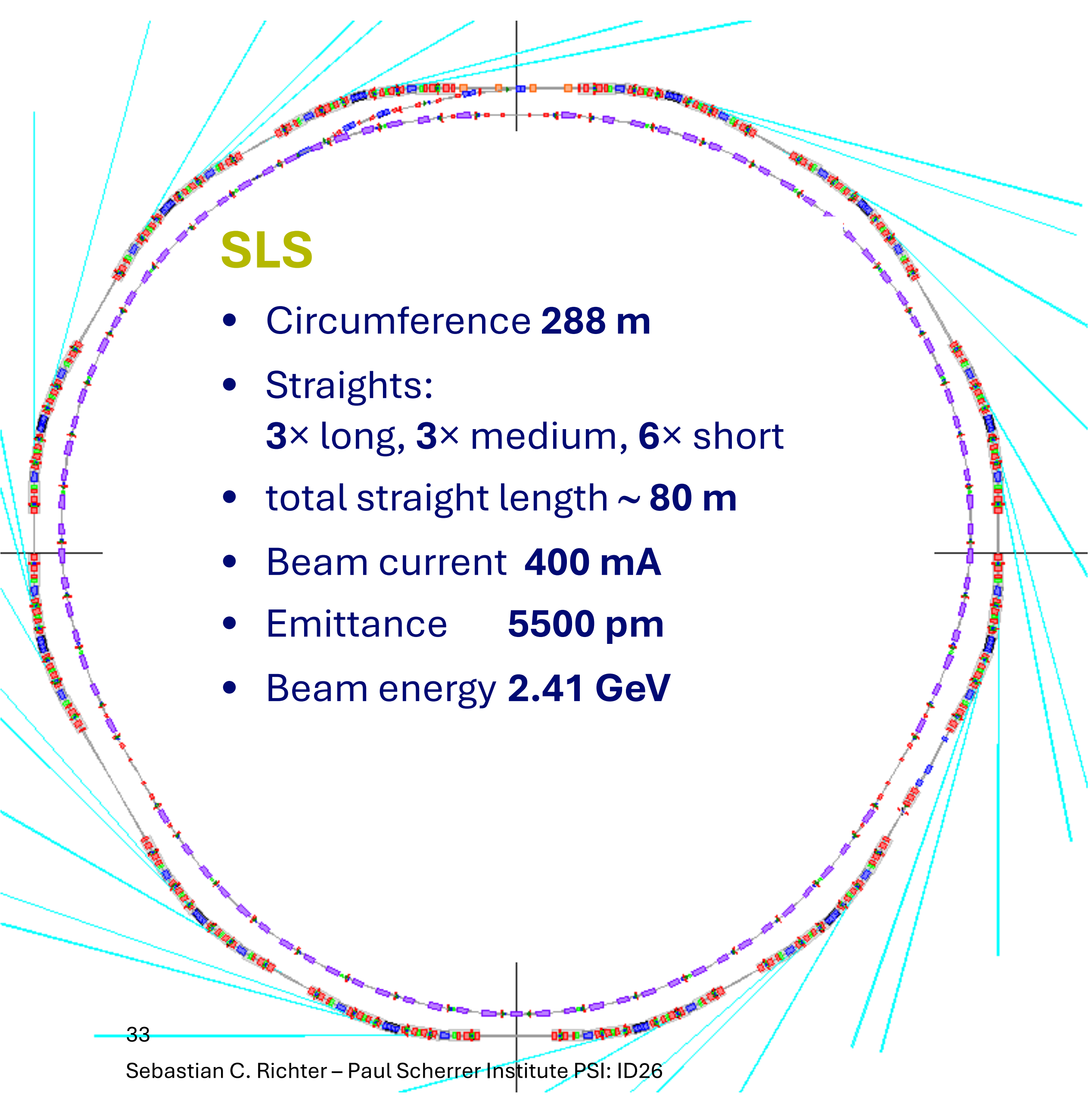
Appendix: APPLE-X knot Undulator: Optimization Shimming Example (1051 to 1053)





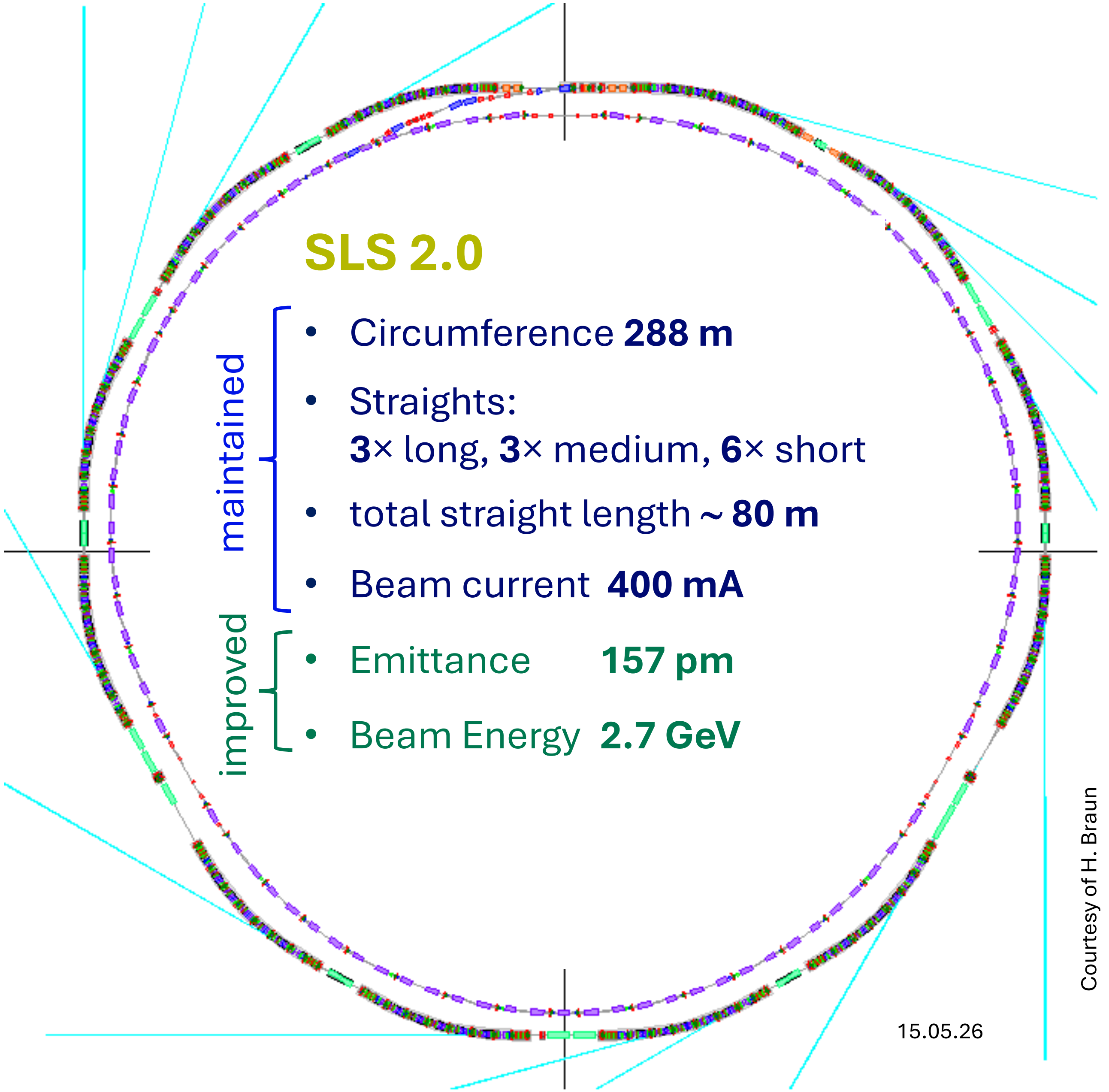


Appendix: The SLS 2.0 Upgrade



SLS

- Circumference **288 m**
- Straights:
  3× long, **3**× medium, **6**× short
- total straight length ~ **80 m**
- Beam current **400 mA**
- Emittance **5500 pm**
- Beam energy **2.41 GeV**



SLS 2.0

maintained:

- Circumference **288 m**
- Straights:
  3× long, **3**× medium, **6**× short
- total straight length ~ **80 m**
- Beam current **400 mA**

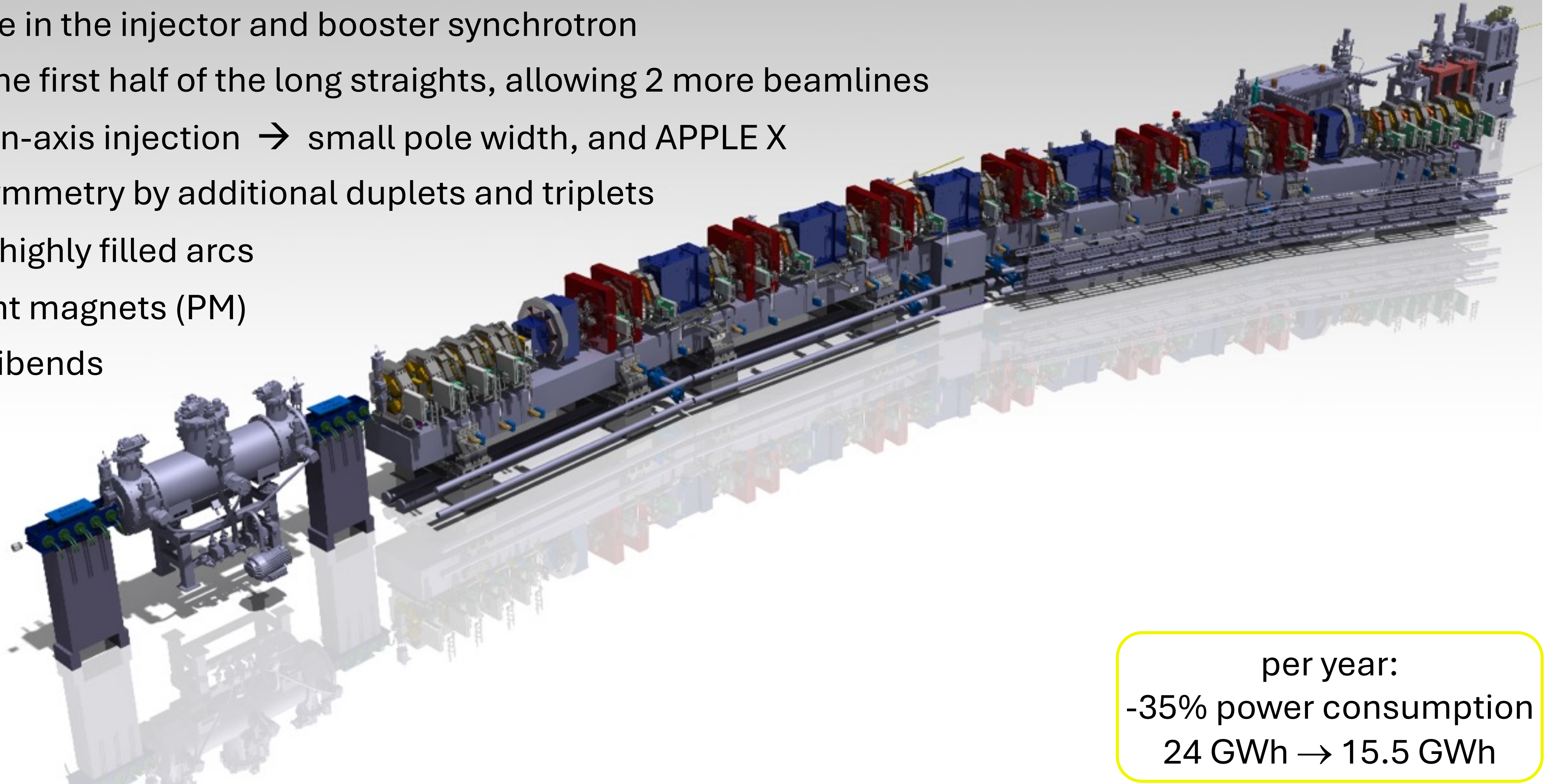
improved:

- Emittance **157 pm**
- Beam Energy **2.7 GeV**

Courtesy of H. Braun

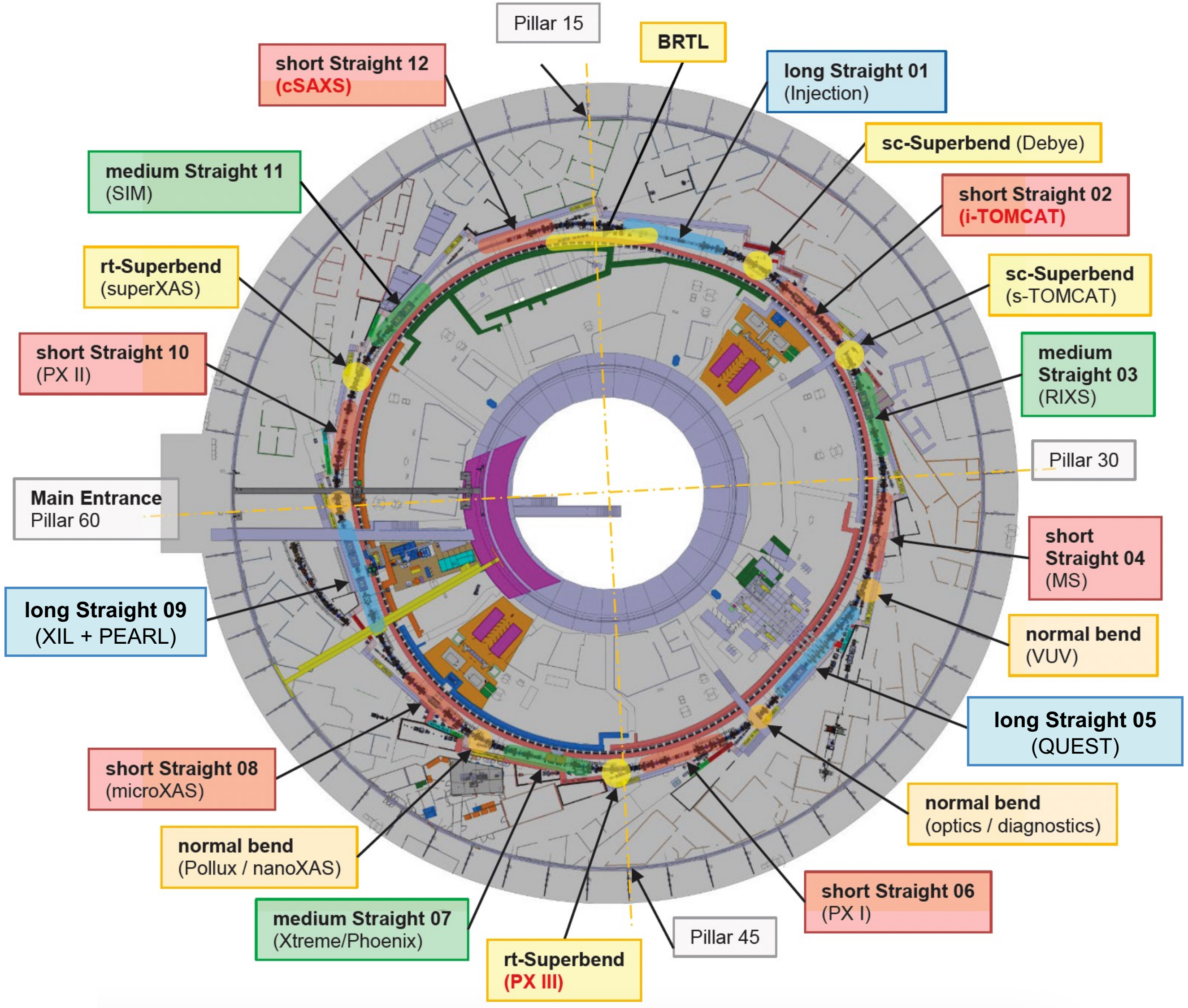
Appendix: The SLS 2.0 Upgrade
Key Figures

- No change in the injector and booster synchrotron
- All RF in the first half of the long straights, allowing 2 more beamlines
- close to on-axis injection → small pole width, and APPLE X
- 12-fold symmetry by additional duplets and triplets
- Tight and highly filled arcs
- Permanent magnets (PM)
- 7BA + antibends



per year:
-35% power consumption
24 GWh → 15.5 GWh

Appendix: SLS 2.0 Beamlines



12 fold symmetry due
to dubletts and tripletts