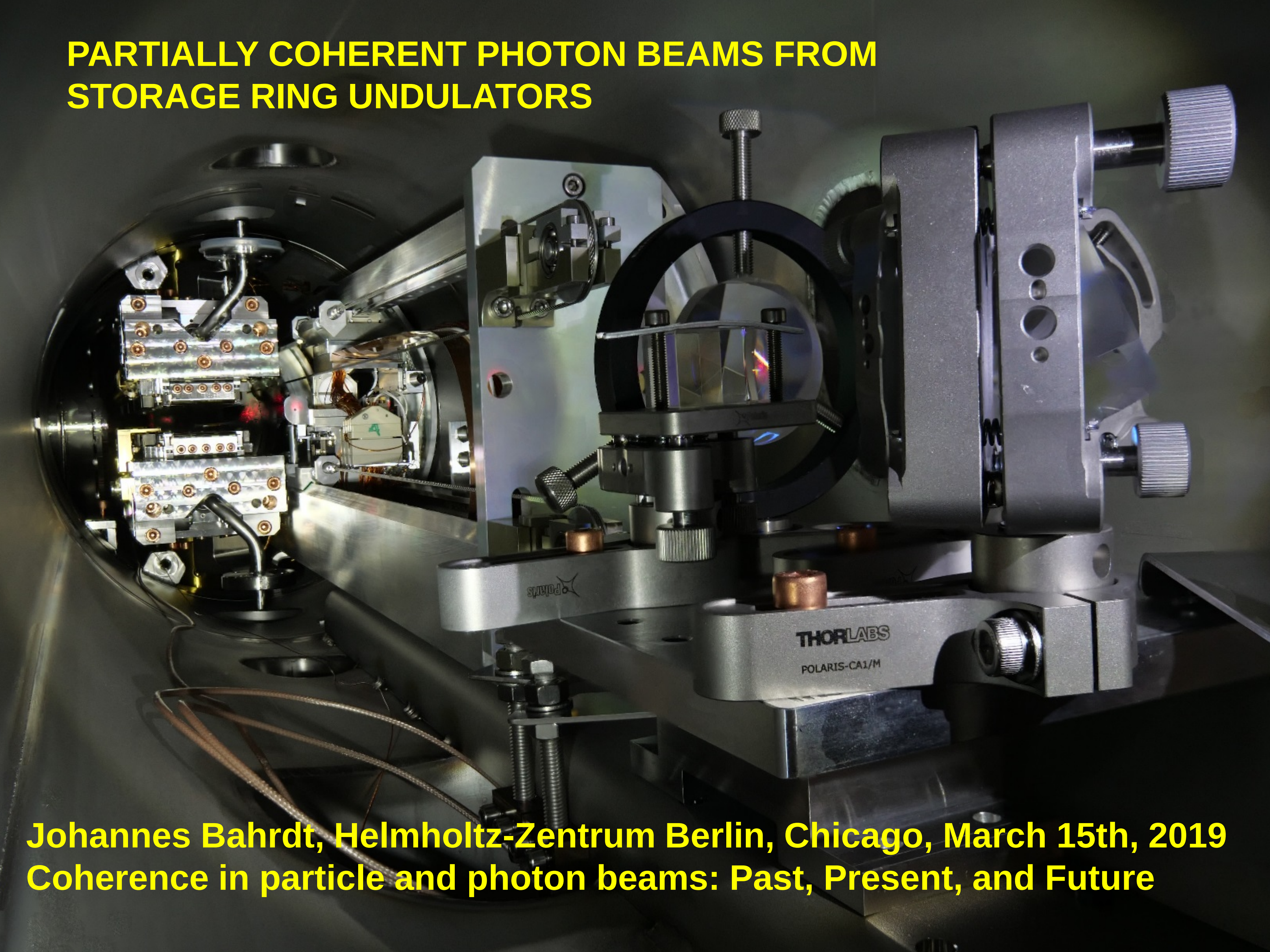
PARTIALLY COHERENT PHOTON BEAMS FROM STORAGE RING UNDULATORS

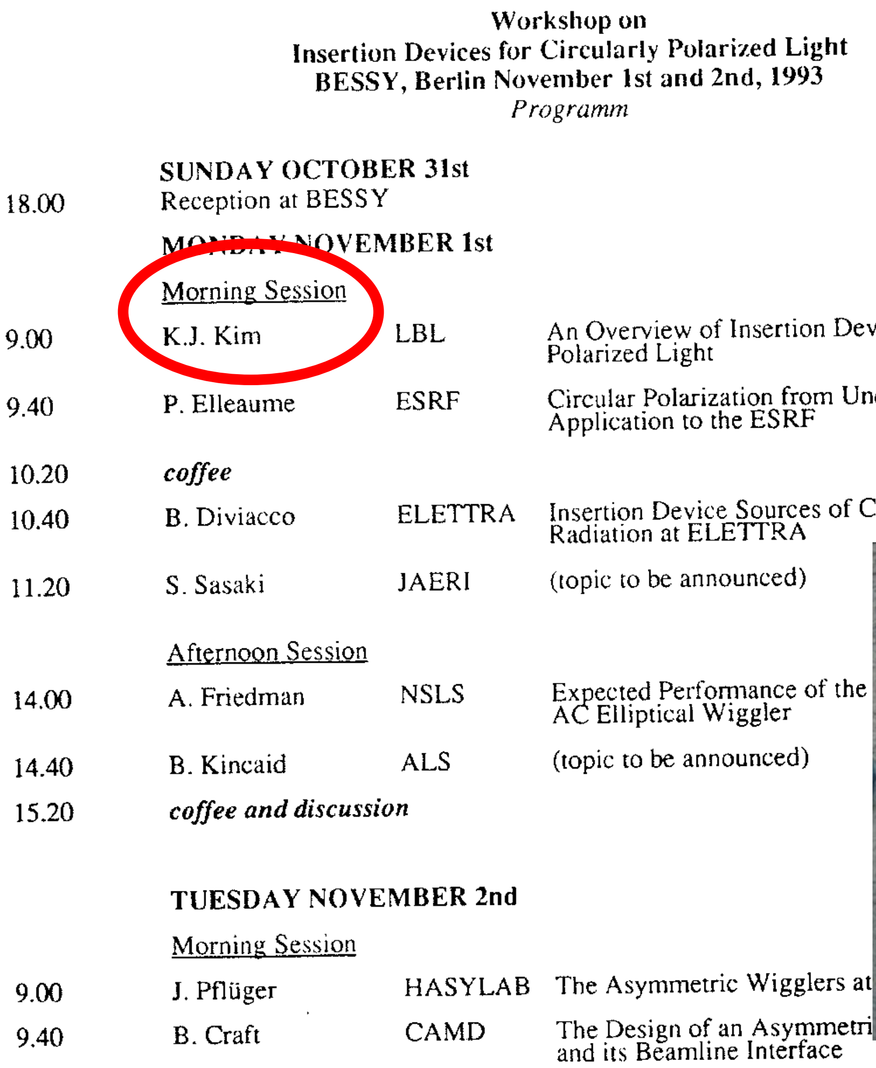


Johannes Bahrdt, Helmholtz-Zentrum Berlin, Chicago, March 15th, 2019

Coherence in particle and photon beams: Past, Present, and Future

Undulator Workshop 1989 @ BESSY

Workshop 1993 @ BESSY



Workshop on
Insertion Devices for Circularly Polarized Light
BESSY, Berlin November 1st and 2nd, 1993
Programm

SUNDAY OCTOBER 31st

18.00	Reception at BESSY		

MONDAY NOVEMBER 1st

Morning Session

9.00	K.J. Kim	LBL	An Overview of Insertion Devices with Variably Polarized Light
9.40	P. Elleaume	ESRF	Circular Polarization from Undulators and Wigglers. Application to the ESRF
10.20	*coffee*		
10.40	B. Diviacco	ELETTRA	Insertion Device Sources of Circularly Polarized Radiation at ELETTRA
11.20	S. Sasaki	JAERI	(topic to be announced)

Afternoon Session

14.00	A. Friedman	NSLS	Expected Performance of the AC Elliptical Wiggler
14.40	B. Kincaid	ALS	(topic to be announced)
15.20	*coffee and discussion*		

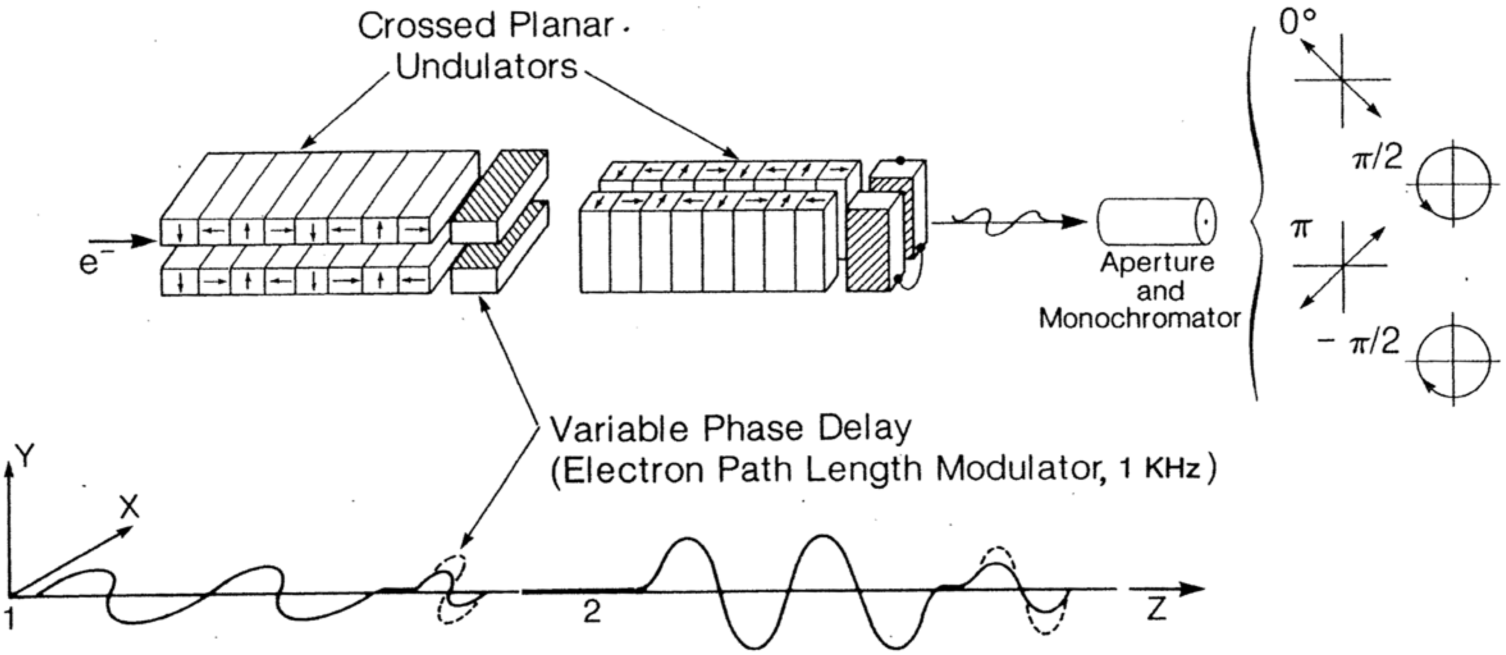
TUESDAY NOVEMBER 2nd

Morning Session

9.00	J. Pflüger	HASYLAB	The Asymmetric Wigglers at
9.40	B. Craft	CAMD	The Design of an Asymmetri and its Beamline Interface

Workshop 1993 @ BESSY

Variably Polarized Radiation can be Generated with Crossed Undulators in Low Emittance Storage Rings



no longitudinal motion
fast polarization switching
(electromagnetic)

XBL 8311-4539-A

BESSY

Independent Proposals of Crossed Undulator Design

Polarization change of ondulator radiation
Moiseev, Nikitin, Fedosov

Russian
Izvestiya Vysshikh Uchebnykh Zavedenij, Fizika; (no.3); p. 76-80, 1978

English translation
Russian Physics Journal, Springer, (former Sov. Phys. J.)
21, 3 (1978) 332-335

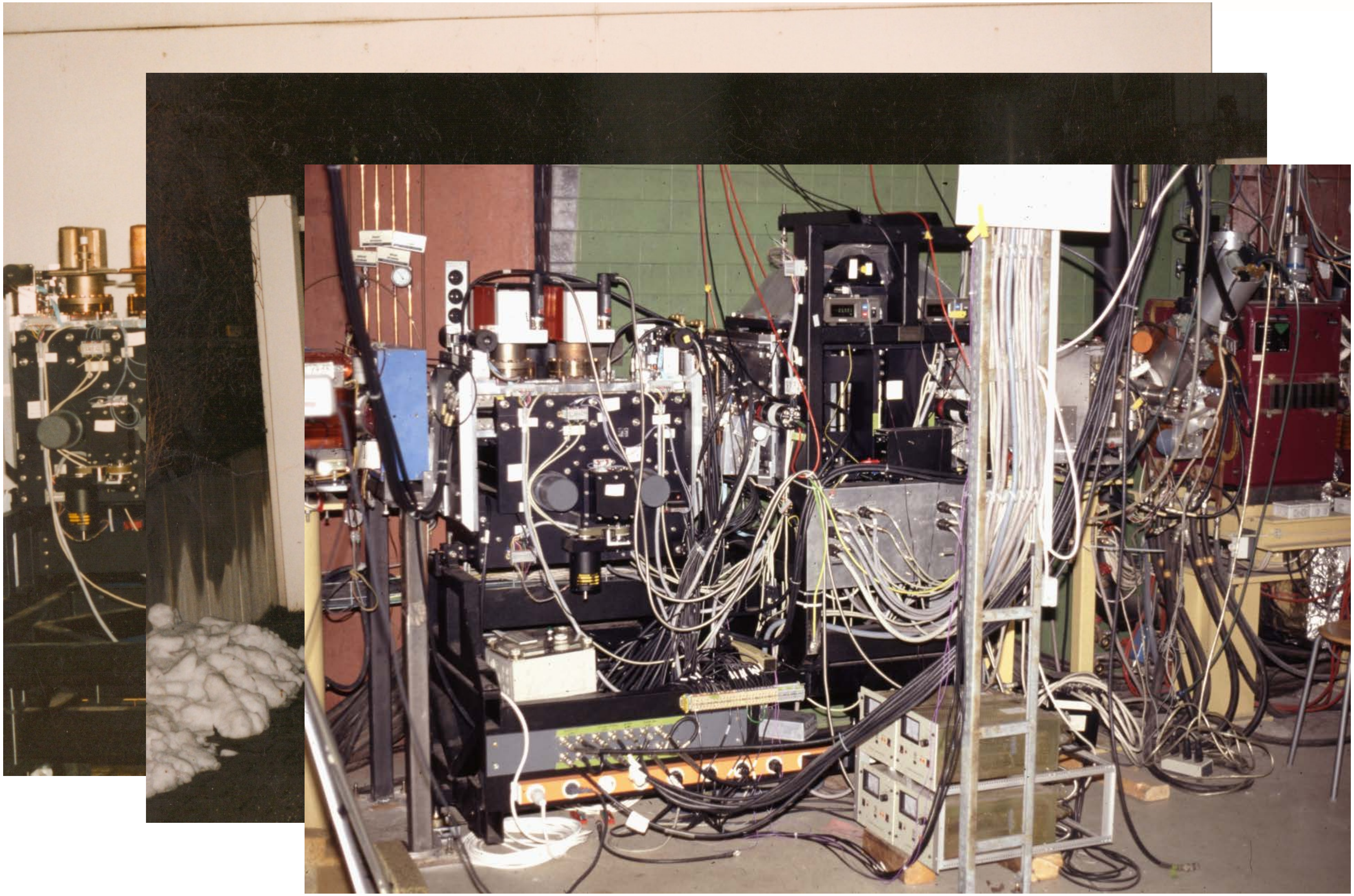
Ideal parameters, no limiting factors discussed such as

- emittance
- energy spread
- beamline acceptance
- length of modules (# of periods)

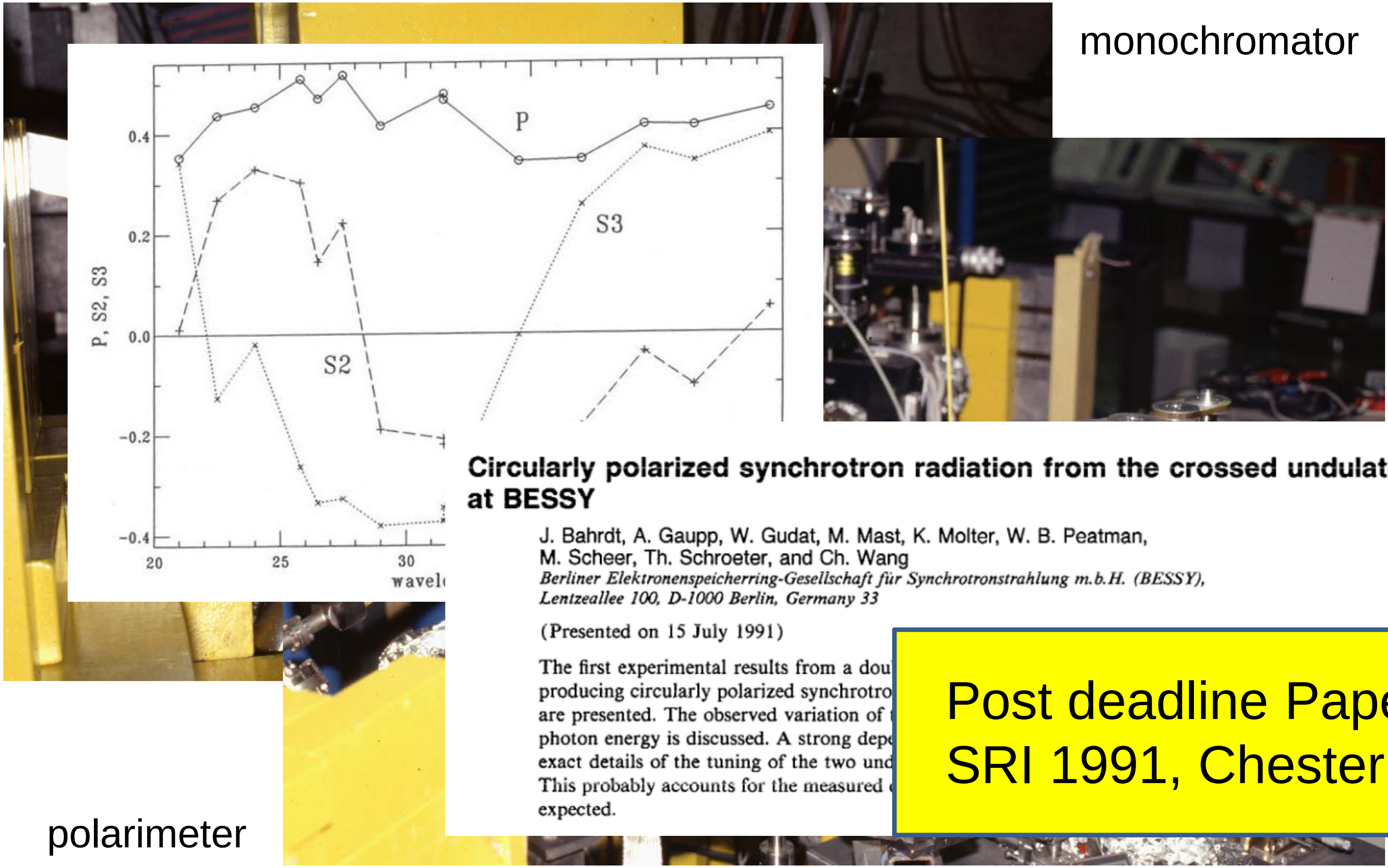
Kwang-Je Kim, NIM **219** (1984) 425-429
Evaluation of effects in old and new rings including

- emittance
- energy spread

The BESSY I Crossed Undulator



Characterization



Circularly polarized synchrotron radiation from the crossed undulator at BESSY

J. Bahrdt, A. Gaupp, W. Gudat, M. Mast, K. Molter, W. B. Peatman,
M. Scheer, Th. Schroeter, and Ch. Wang
Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung m.b.H. (BESSY),
Lentzeallee 100, D-1000 Berlin, Germany 33

(Presented on 15 July 1991)

The first experimental results from a dou
producing circularly polarized synchrotro
are presented. The observed variation of
photon energy is discussed. A strong depe
exact details of the tuning of the two und
This probably accounts for the measured
expected.

polarimeter

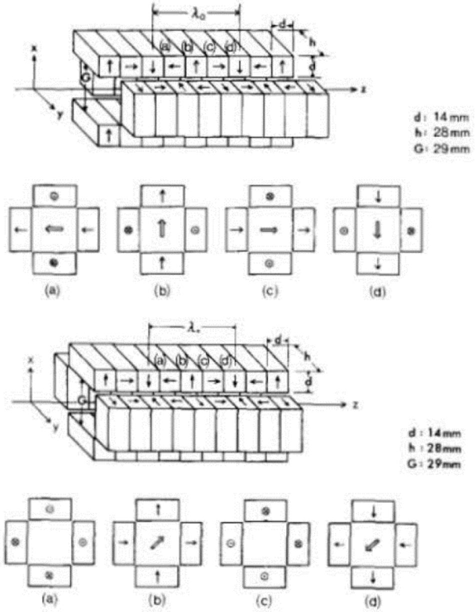
Post deadline Paper
SRI 1991, Chester

Mechanic Polarization Switching I

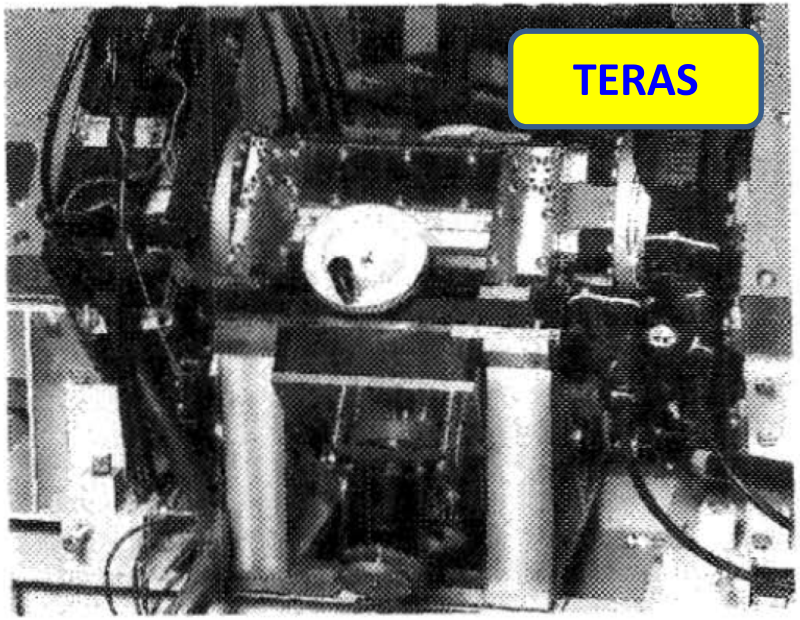
Onuki undulator:

- 1986 proposal
- 1989 realization

Period length	80mm
Number of periods	4
Magnetic gap	57 – 150mm
Polarization switching	**3Hz**
Design	permanent magnet



H. Onuki, NIM A246 (1986) 94-98



H. Onuki et al., RSI 60 (1989) 1838-1841

Mechanic Polarization Switching II

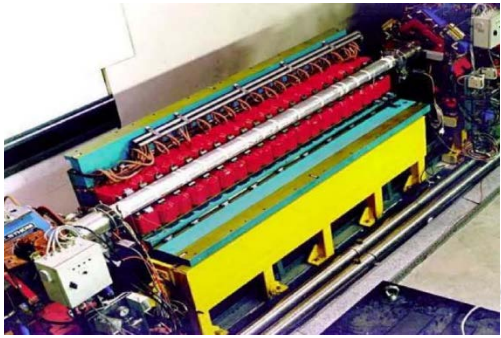
Onuki undulator:

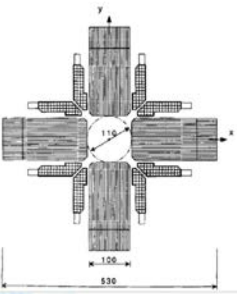
1996 realization at **NIJI-II**

Period length	86mm
Number of periods	15
Magnetic gap	64 – 160mm
Polarization switching	**3Hz**
Design	permanent magnet

T. Yamada, M. Yuri, H. Onuki, S. Ishizakaa, Rev. Sci. Instrum. 66 (2) (1995) 1493-1495
M. Yuri, K.Yagi, T. Yamada, H. Onuki, J. Electron Spectrosc. Relat. Phenom. (1996) 425-428

OPHELIE @ Super-ACO

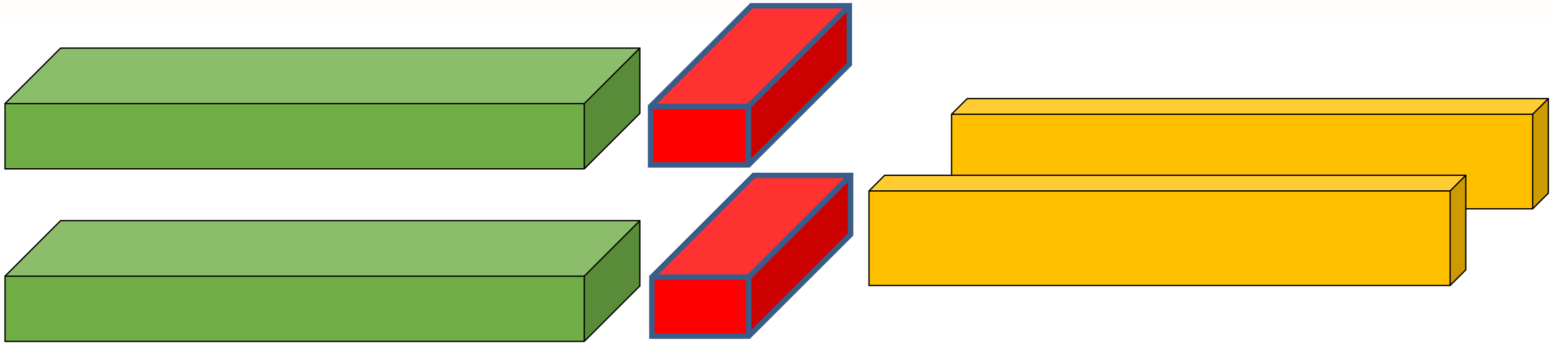




Period length	250mm
Number of periods	10
Magnetic gap	110mm
Polarization switching	**1Hz**
Design	electromagnet

L. Nahon et al., J. Synchrotron Rad. 5 (1998) 428-430
L. Nahon et al., NIM A 447 (2000} 569-586

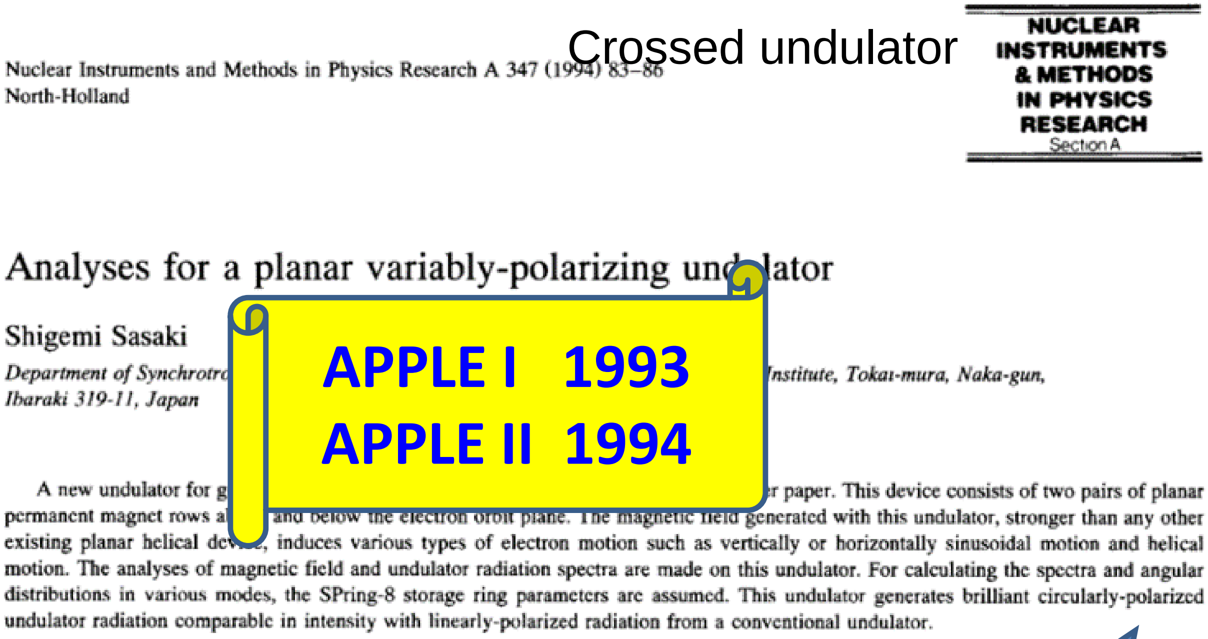
Crossed Undulator – Onuki Undulator – APPLE II



Onuki-Undulator (tilted by 45°)

Phase shifter

Crossed undulator



Nuclear Instruments and Methods in Physics Research A 347 (1994) 83–86
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

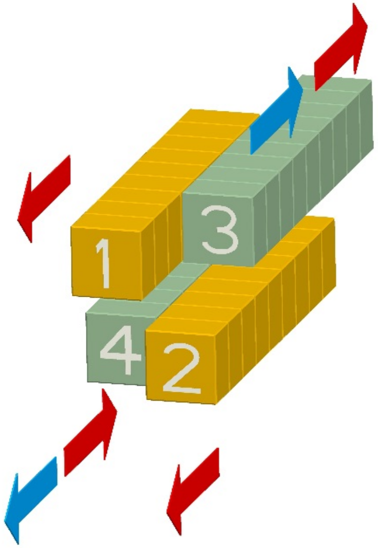
Analyses for a planar variably-polarizing und lator

Shigemi Sasaki

Department of Synchrotro *Institute, Tokai-mura, Naka-gun,*
Ibaraki 319-11, Japan

A new undulator for g r paper. This device consists of two pairs of planar permanent magnet rows a and below the electron orbit plane. The magnetic field generated with this undulator, stronger than any other existing planar helical dev ce, induces various types of electron motion such as vertically or horizontally sinusoidal motion and helical motion. The analyses of magnetic field and undulator radiation spectra are made on this undulator. For calculating the spectra and angular distributions in various modes, the SPring-8 storage ring parameters are assumed. This undulator generates brilliant circularly-polarized undulator radiation comparable in intensity with linearly-polarized radiation from a conventional undulator.

APPLE I 1993
APPLE II 1994



APPLE II: workhorse
at most 3rd generation SR

Crossed Undulator versus APPLE II

$$P = 1 - \frac{\langle(\Delta\alpha)^2\rangle}{2}$$

emittance

original paper of Kim

$$(\Delta\alpha)^2=\left(\alpha_0\frac{\sigma_\lambda}{\lambda}\right)^2+2\left(2\pi\eta\,\frac{\gamma^2\sigma_\theta^2}{1+K^2/2}\right)^2$$

energy spread & monochromator

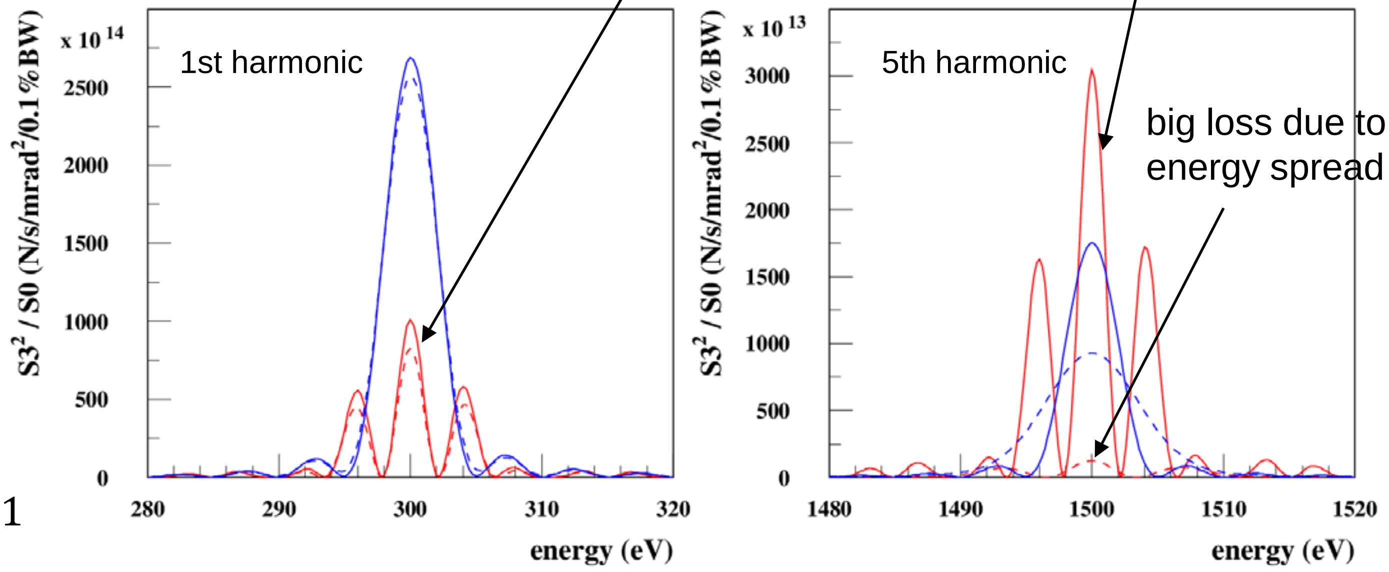
$$E = 1.72GeV$$
$$\lambda_0 = 56mm$$
$$emittance = 0$$

solid: $\sigma_e = 0.0$

dashed: $\sigma_e = 0.001$

lower figure of merit due to less periods

larger figure of merit due to big S3 (helical)



big loss due to energy spread

Crossed undulator: 2 x 30 periods

APPLE II: 1 x 60 periods

Segmented Undulator:
Enhancement of Polararization Degree

- Increasing the degree of polarization with more segments

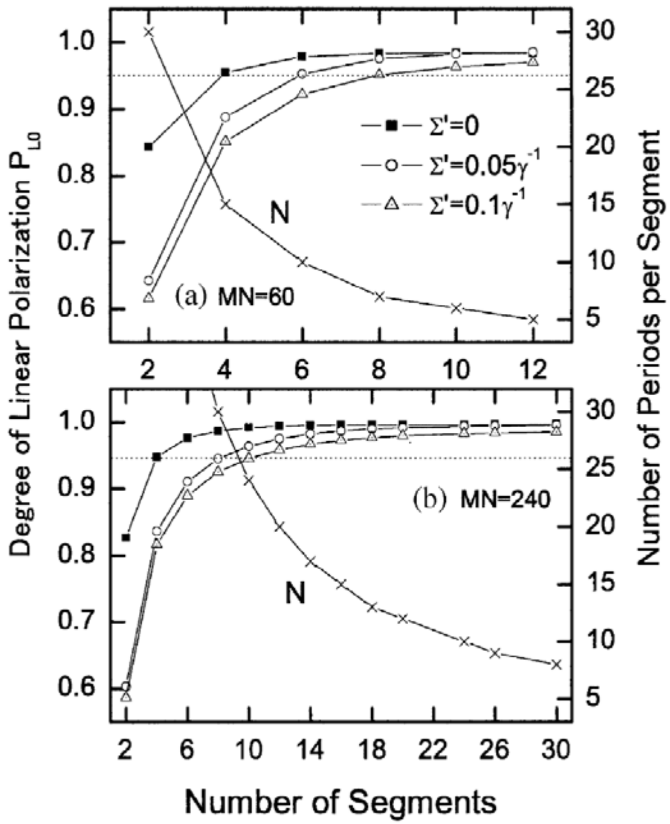
↻ + ↺ ➡ ✛

T. Tanaka, H. Kitamura, NIM A490 (2002) 583-591

$$I = 4\left(\frac{2\pi MN}{\omega_1}\right)^2 S_N S_M$$

$$S_N = \frac{sin^2[\pi N(1-\omega/\omega_1)]}{\pi^2 N^2 (1-\omega/\omega_1)^2}$$

$$S_M = \frac{sin^2[(M/2)(2\pi N + \Phi_1)\,\omega/\omega_1]}{M^2 sin^2[(2\pi N + \Phi_1)\,\omega/\omega_1]}$$



similarly: ↑ + → ➡ ↻ ↺

T. Tanaka, H. Kitamura, SRI 2003, 231-234

Higher order suppression via relative detuning of segments

T. Tanaka, H. Kitamura, JSR 9 (2002) 166-269

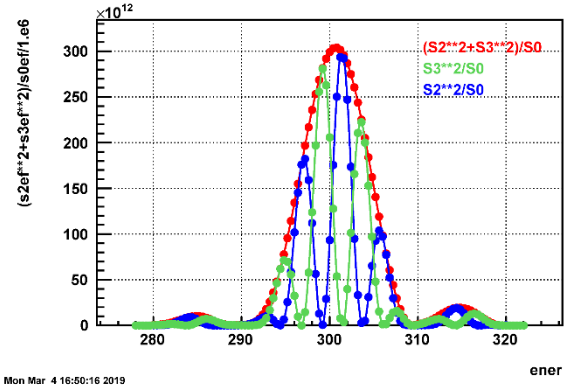
Segmented Crossed Undulator
Idea of Tanaka & Kitamura, 2002

Periode 56mm
M=1, 2, 3
N=30, 15, 10
MN=30

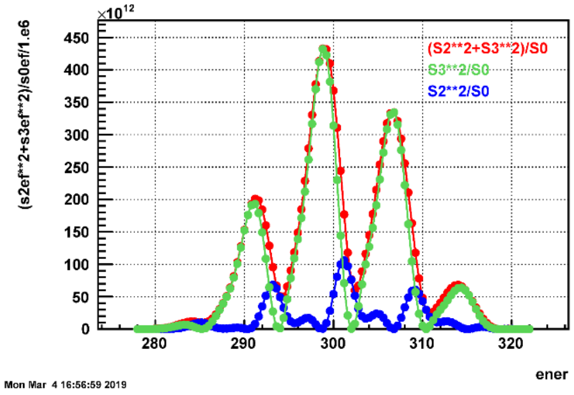
Simulations with WAVE, Michael Scheer, HZB

Flux density

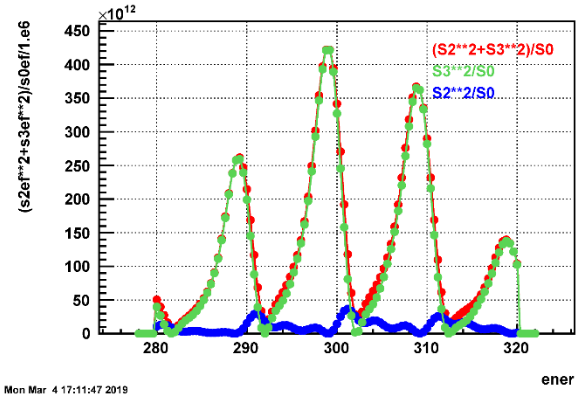
UE56, modular, Run 6637 M=1



UE56, modular, Run 6640 M=2

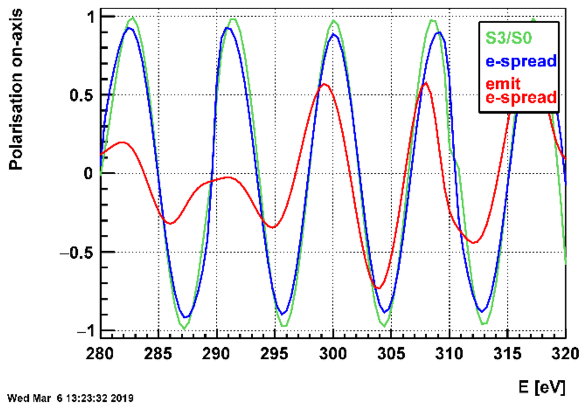


UE56, modular, Run 6654 M=3

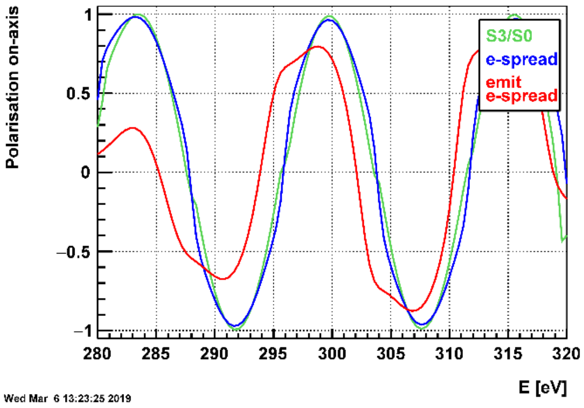


Polarization degree

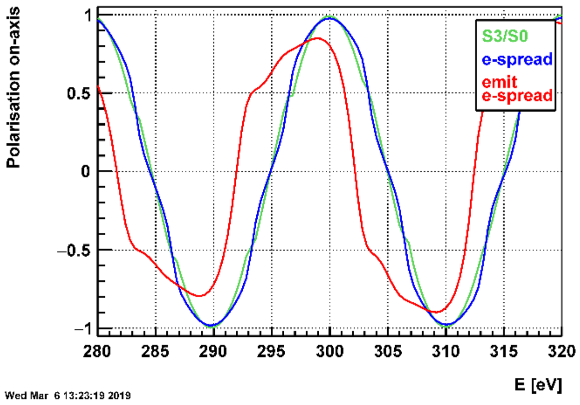
UE56, 2x30 Periods, planar, Run 6637



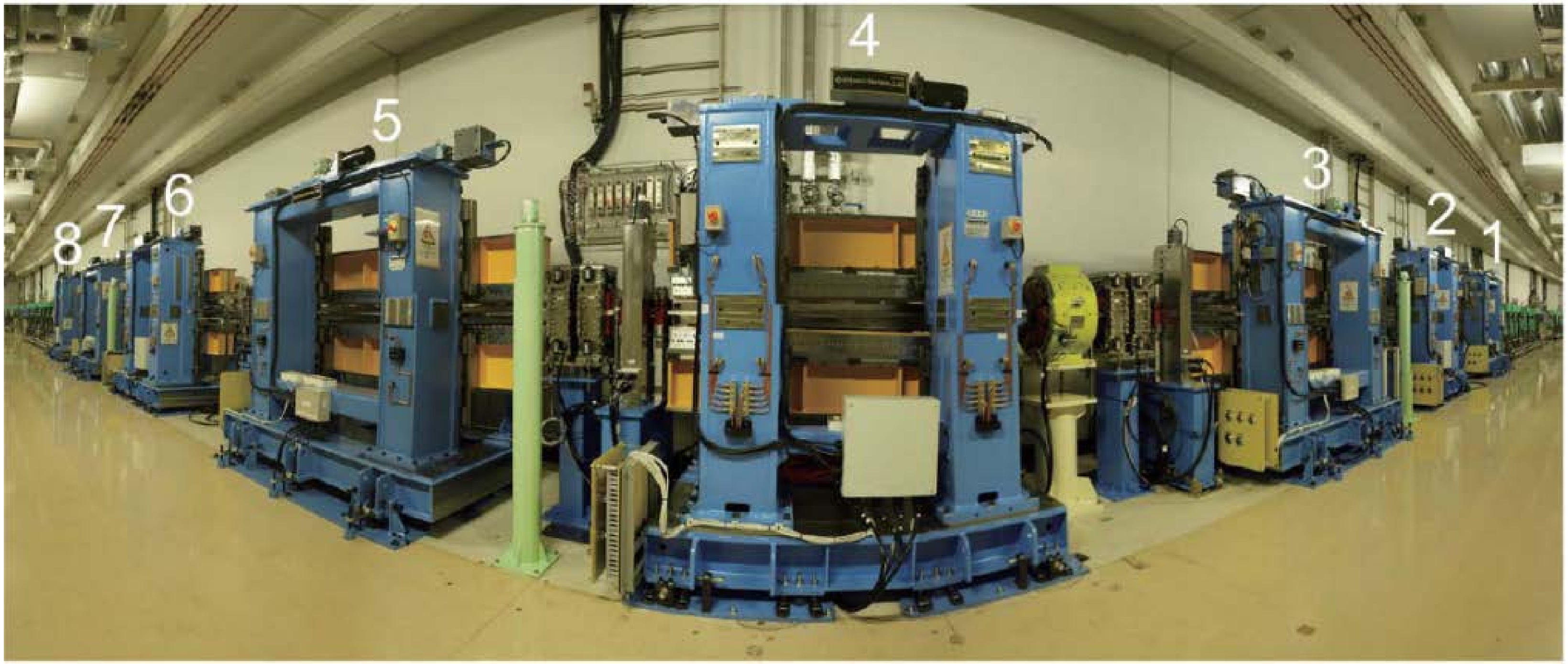
UE56, 2x(2x15) Periods, planar, Run 6640



UE56, 3x(2x10) Periods, planar, Run 6654



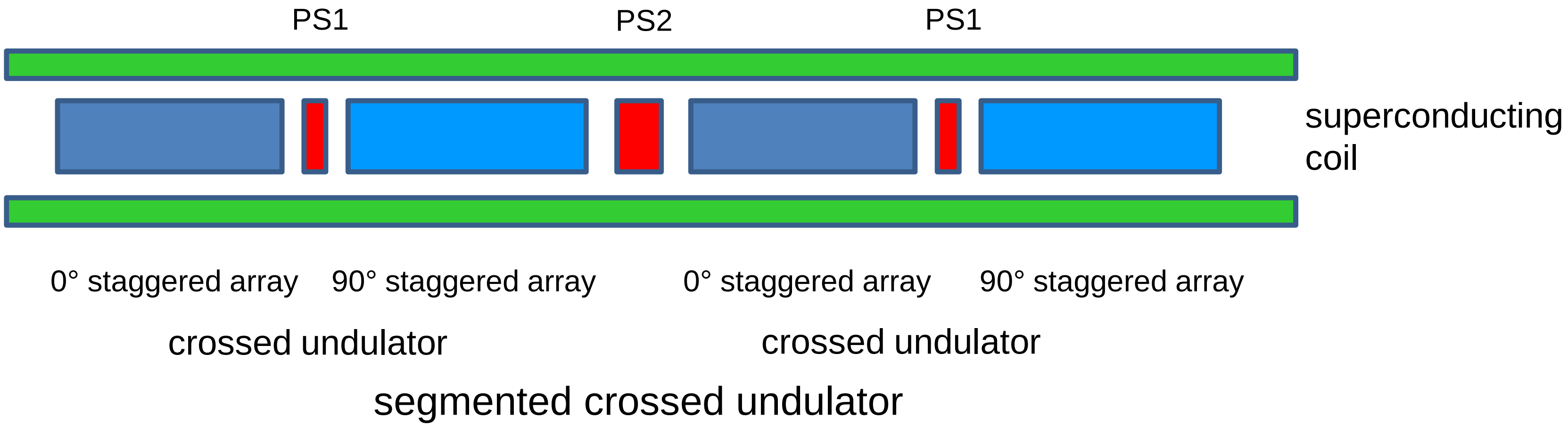
Segmented CU with low on-axis power: 8 Figure-8 Undulators



S. Yamamoto, J. Synch. Rad. (2014). 21, 352–365

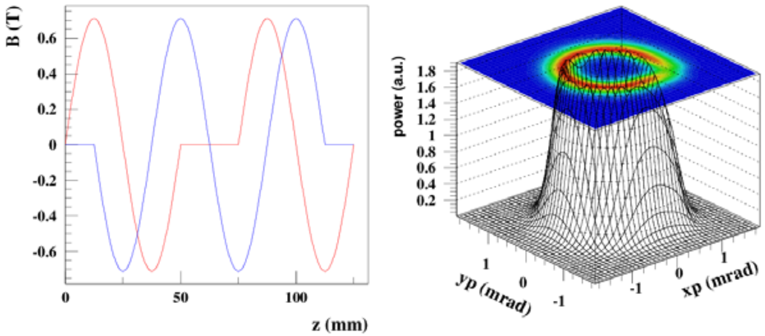
Crossed Undulator as Part of Advanced Short Period Undulators

Highest fields at short periods combined with variable polarization → HTS based staggered array segmented crossed undulator



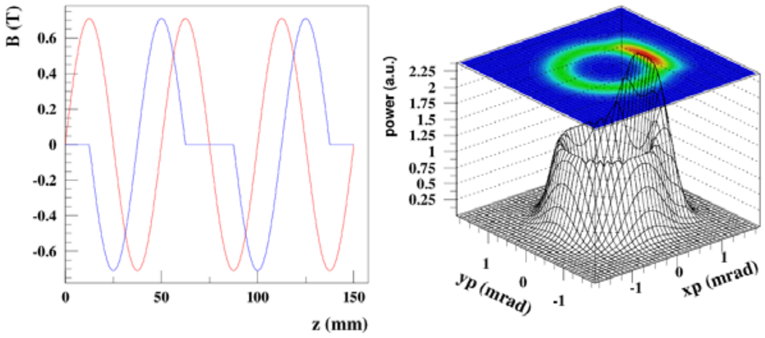
Maximum „Segmentation“ in Single Device

- High degree of polarization
- Linear polarized light without higher harmonics
- Linear polarized light with reduced on-axis power
- Even variable polarization is possible



Leaf undulator

J. Yan, S. Qiao, Rev. Sci. Instrum., ***81 (2010)*** *056101-1-3*
S. Sasaki, IPAC Taipeh, Taiwan 2018
(concept for variable polarization)



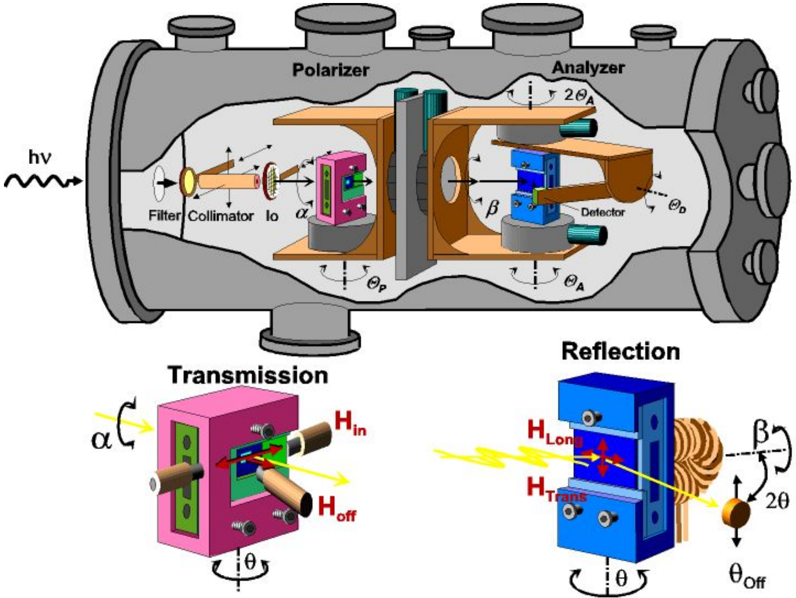
Knot undulator

S. Qiao et al., Rev. Sci. Instrum., ***80*** *(2009) 085108-1-4*

APPLE knot undulator

S. Sasaki et al., NA-PAC, (2013) 1043-1045 (theory)
J. Fuhao et al., JSR, 22 (2015) 901-907 (built at SSRF)
Q. Zhou et al., IEEE TRANS. APPL. SUPERCOND., ***26****,*
(2016) 4101704-1-4 (built at SSRF)

Polarization Characterization, BESSY II



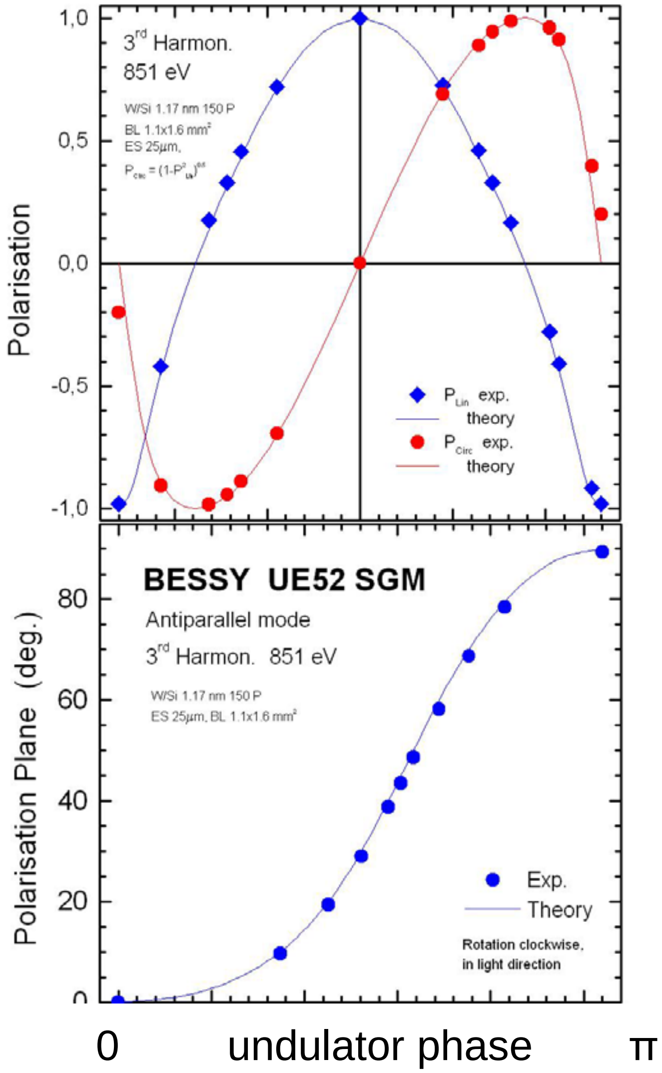
HZB Soft X-ray Polarimeter

Excellent agreement between theory and measurement

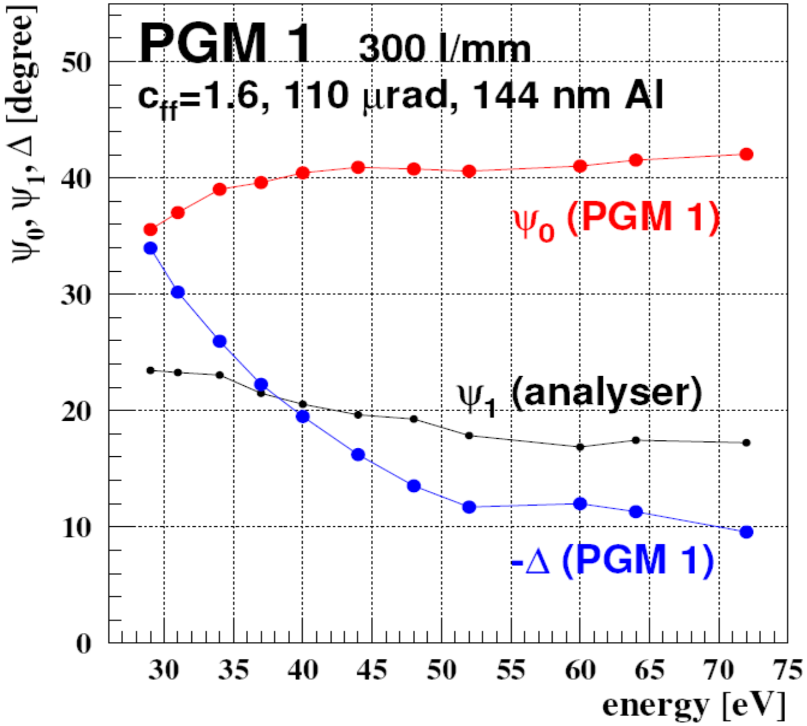
F. Schaefers et al., Applied Optics 38 (1999) 4974

elliptical mode

inclined mode



Broad Band Polarization Changes via Beamline Components Below 100 eV



UE-112 APPLE @ BESSY II

$$\tan(\Psi_0) = \left|T_y^{BL} / T_x^{BL}\right|$$

transmissions of field amplitudes

$$\Delta = \phi_y^{BL} - \phi_x^{BL}$$

phase difference of
electric field components

APPLE II produces any kind of polarization ellipse including a tilt in the so-called „universal mode“

→ circular polarization
at the experiment

but also cases where polarization degree is spoilt in beamline

↓

no recovery possible

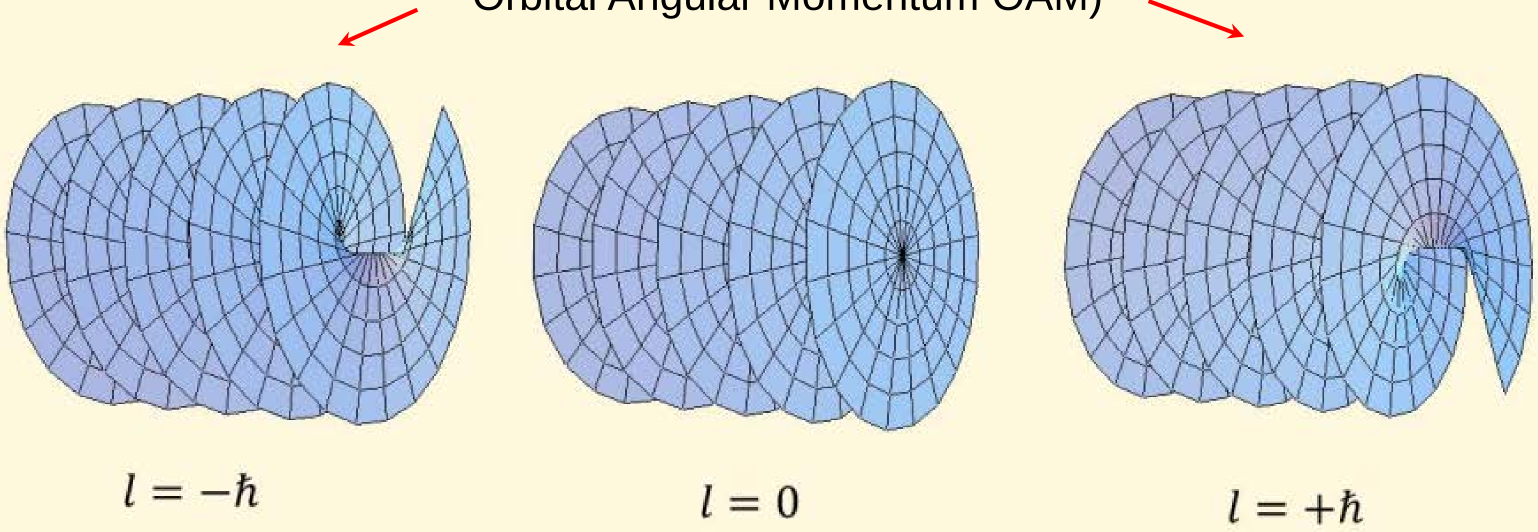
J. Bahrdt et al, Proc. PAC, Vancouver BC, USA (2009) 1162-1164
J. Bahrdt et al, Conf. Proc. 1234 (2010) 335-338

Prediction of Undulator Photons with Orbital Angular Momentum

Off axis radiation of higher harmonics of a helical undulator

$$A \sim \frac{(A_x - iA_y)}{\sqrt{2}} = \sqrt{2}e^{\pm i(n-1)\varphi}\left\{\left(\gamma\theta - \frac{nK}{X}\right)J_n(X) - KJ_n'(X)\right\}$$

Orbital Angular Momentum OAM)



S. Sasaki, I. McNulty and R. Dejus, NIM 582 *A*, 1 (2007) 43-46
S. Sasaki, I. McNulty, PRL 100 (2008) 124801

Demonstration of OAMs with Interference Experiment at BESSY II

helical

$$A(r,\varphi) = \frac{a(r)}{L+d} cos\left(\frac{\pi d}{\gamma^2 \lambda} + \frac{\pi}{(L+d)\lambda} r^2 \pm (n-1)\varphi + \frac{2\pi L}{\lambda} - \omega t\right)$$

planar

$$B(r,\varphi) = \frac{b(r)}{L} cos\left(\frac{\pi}{L\lambda} r^2 + \frac{2\pi L}{\lambda} - \omega t\right)$$

$$I(r,\varphi) = \frac{\omega}{2\pi} \int_0^{\frac{\omega}{2\pi}} (A+B)^2 \, dt =$$

$$\frac{a^2}{2(L+d)^2} + \frac{b^2}{2L^2} + \frac{ab}{L(L+d)} cos\left(\frac{\pi d}{\gamma^2 \lambda} - \frac{\pi d}{L^2 \lambda} r^2 \pm (n-1)\varphi\right)$$

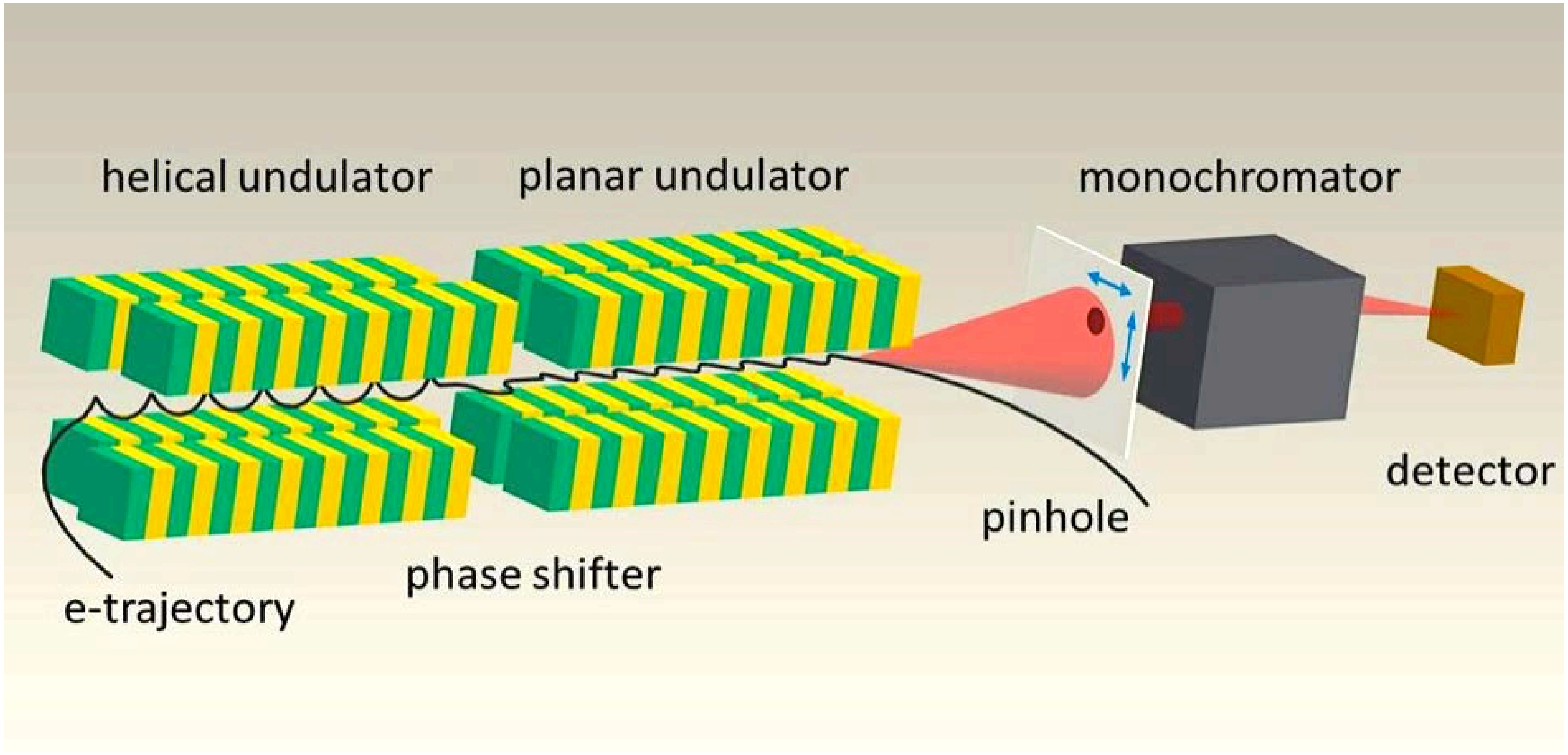
$$\varphi = \pm\left(-\frac{\pi d}{\gamma^2 \lambda} + \frac{\pi d}{L^2 \lambda} r^2\right) / (n-1)$$

This spiral structure of the intensity can be measured

In 2013: Photons with Orbital Angular Momentum

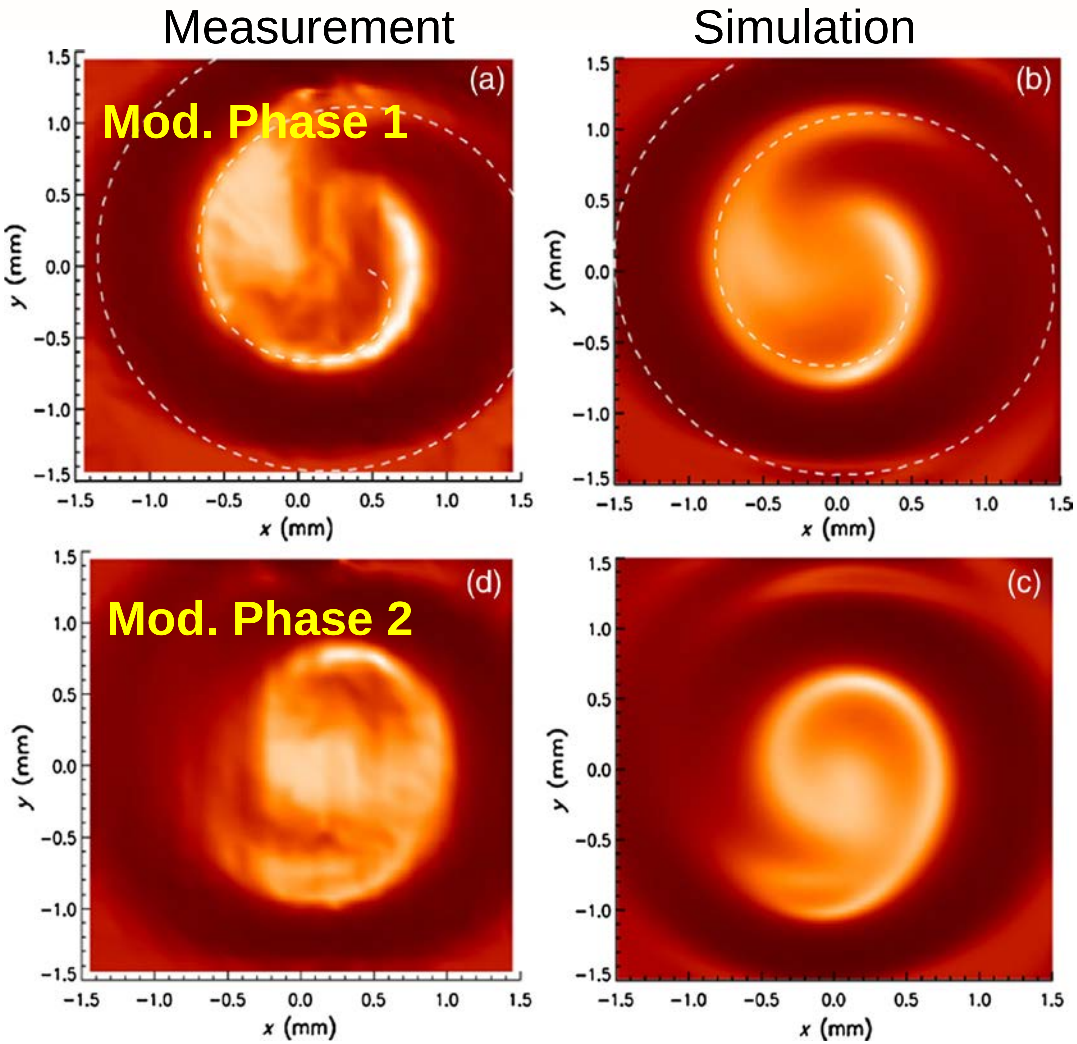
Double APPLE II Undulator UE56
pinhole in 13mm distance, pinhole scans

Spectral and spatial overlap of
2nd harmonic of helical ID & 1st harmnic of planar ID

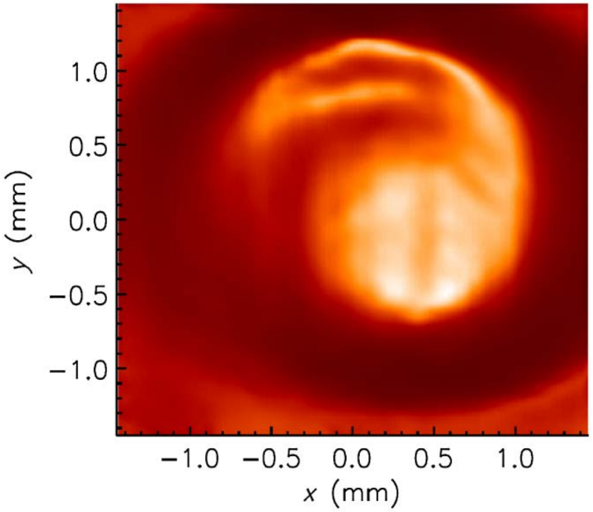


J. Bahrdt et al., Physical Review Letters 111 (2013), p. 034801/1-5

OAM-Experiment at BESSY, Results


Measurement

Simulation



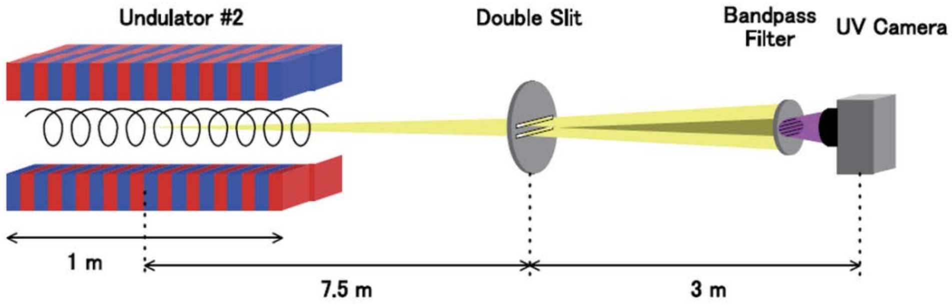
Helicity reversed

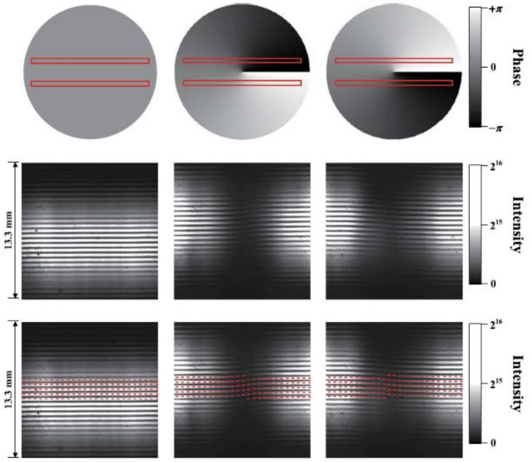
dashed line depicts equal phase

$$\varphi = \pm\left(-\frac{\pi d}{\gamma^2\lambda} + \frac{\pi d}{L^2\lambda}r^2\right)/(n-1)$$

Double Slit Experiment

- Not successful at BESSY UE112 due to optical element quality
- Successful at UVSOR because:
    - larger wavelength: 355nm instead of 12.5nm at BESSY
    - Energy selection with band pass filter instead of monochromator (no degradation due to optical element quality)





Katoh et al., Scientific Reports, 7: 6130 (2017) 1-8

Coherent Beams at the Expeiment

Generation of photon beams with high degree of coherence (ID-shimming)
minimization of electron beam effects (emittance reduction)

Keeping the coherence during propagation to the experiment
pushing the optical element quality further

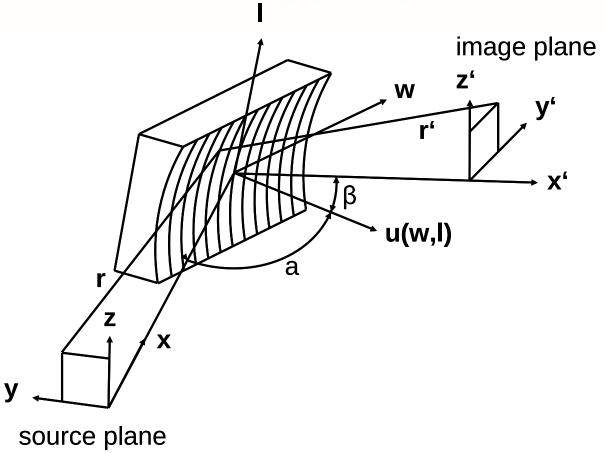
Methods of partially coherent photon beam propagation:

- Fourier Optics (FO), linear systems
  J.W.Goodman, Introduction to Fourier Optics, McGRAWHILL, 1968
- FO + local ray-tracing includig the phase, SRW
  O. Chubar et al., J. of Physics: Conf. Ser. 425 (2013) 162001
- Wigner function (brightness) of real sources
  G. Geloni, V. Kocharyan, E. Saldin, JSR, 22 (2015) 288-316
- Propagation of Wigner function, SPECTRA
  T. Tanaka, PRST-AB, 17 (2014) 060702-1-14
- Stationary phase approximation, PHASE
  J. Bahrdt, PRST-AB, 10 (2007) 060701-1-15
  J. Bahrdt, U. Flechsig, S. Gerhardt und I. Schneider Proc. of SPIE 8141, Advances in Computational Methods for X-Ray Optics II, Bd. 8141, 2011.
  Source code on github: https://github.com/flechsig/phase

2^{nd} Order Stationary Phase Aproximation (SPA), Short Review

Propagation of electric fields along a single optical element is based on power series expansions of

- coordinate tranformation
- path length
- determinants
- …



$$E(y',z') = \frac{\sqrt{\cos(\alpha)}\sqrt{\cos(\beta)}}{\lambda^2} \iint E(y,z) \left\{ \iint \frac{1}{r \cdot r'} e^{ikPL} dw \cdot dl \right\} \left| \frac{\partial(y,z)}{\partial(dy',dz')} \right| ddy' \cdot ddz'$$

2nd order expansion of path length (PL)

$$PL(w_0 + \Delta w, l_0 + \Delta l) = PL_{w_0 l_0} + \frac{1}{2}\frac{\partial^2 PL}{\partial w^2}\bigg|_{w_0 l_0} \Delta w^2 + \frac{1}{2}\frac{\partial^2 PL}{\partial l^2}\bigg|_{w_0 l_0} \Delta l^2 + \frac{\partial^2 PL}{\partial w \cdot \partial l}\bigg|_{w_0 l_0} \Delta w \cdot \Delta l$$

and analytic integration over the optical element surface;
for implementation of emittance & energy spread: integration over phase space

3rd order derivative of PL needs to be implemented

We Wish You for the Future

high brightness sunshine
beautiful non-linear mountain trails
and always great views