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

SUNDAY OCTOBER 31st
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 Wiggles.
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 Wiggler at HASYLAB and its Beamline Interface

9.40
B. Craft
CAMD
The Design of an Asymmetric Wiggler
Variably Polarized Radiation can be Generated with Crossed Undulators in Low Emittance Storage Rings

no longitudinal motion
fast polarization switching (electromagnetic)
Independent Proposals of Crossed Undulator Design

Polarization change of ondulator radiation
Moiseev, Nikitin, Fedosov

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

English translation
  21, 3 (1978) 332-335

Ideal parameters, no limiting factors discussed such as
- emittance
- energy spread
- beamline acceptance
- length of modules (# of periods)

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


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 double undulator producing circularly polarized synchrotron radiation are presented. The observed variation of the photon energy is discussed. A strong dependence on the exact details of the tuning of the two undulators is evident. This probably accounts for the measured deviation from the expected.

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


**OPHELIE @ Super-ACO**  
Period length 250mm  
Number of periods 10  
Magnetic gap 110mm  
Polarization switching 1Hz  
Design electromagnet

Crossed Undulator –
Onuki Undulator – APPLE II

Onuki-Undulator (tilted by 45°)
Phase shifter

Analyses for a planar variably-polarizing undulator

Shigemi Sasaki
Department of Synchrotron
Ibaraki 319-11, Japan

A new undulator for generating linearly polarized radiation was designed and fabricated. This device consists of two pairs of planar permanent magnet rows above and below the electron orbit plane. The magnetic field generated with this undulator, stronger than any other existing planar helical device, 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

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

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

Original paper of Kim

Energy spread & monochromator

Lower figure of merit due to less periods

Larger figure of merit due to big S3 (helical)

\[ E = 1.72 \text{GeV} \]

\[ \lambda_0 = 56 \text{mm} \]

Emittance = 0

Solid: \( \sigma_e = 0.0 \)

Dashed: \( \sigma_e = 0.001 \)

Crossed undulator: 2 x 30 periods

APPLE II: 1 x 60 periods

Big loss due to energy spread
Segmented Undulator: Enhancement of Polarization Degree

- Increasing the degree of polarization with more segments

\[
I = 4 \left( \frac{2\pi MN}{\omega_1} \right)^2 S_NS_M
\]

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

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

similarly:

\[
I = 4 \left( \frac{2\pi MN}{\omega_1} \right)^2 S_NS_M
\]

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

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

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

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

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

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

Simulations with WAVE, Michael Scheer, HZB

 Flux density

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

<table>
<thead>
<tr>
<th>M=1</th>
<th>M=2</th>
<th>M=3</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
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**Polarization degree**

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

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

PS1

PS2

PS1

0° staggered array 90° staggered array 0° staggered array 90° staggered array
crossed undulator crossed undulator
crossed undulator

segmented crossed undulator

superconducting coil
- 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
S. Sasaki, IPAC Taipei, Taiwan 2018
(concept for variable polarization)

Knot undulator

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
Broad Band Polarization Changes via Beamline Components Below 100 eV

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

circular polarization at the experiment

\[ \tan(\Psi_0) = \left| \frac{T_{y}^{BL}}{T_{x}^{BL}} \right| \]

transmissions of field amplitudes

\[ \Delta = \phi_{y}^{BL} - \phi_{x}^{BL} \]

phase difference of electric field components

but also cases where polarization degree is spoilt in beamline

no recovery possible

Prediction of Undulator Photons with Orbital Angular Momentum

Off axis radiation of higher harmonics of a helical undulator

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

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

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

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

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

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

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 harmonic of planar ID

OAM-Experiment at BESSY, Results

Measurement

Simulation

Mod. Phase 1

Mod. Phase 2

Helicity reversed

dashed line depicts equal phase

\[ \varphi = \pm \left( -\frac{\pi d}{y^2 \lambda} + \frac{\pi d}{L^2 \lambda} r^2 \right)/(n - 1) \]
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 Experiment

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

- Wigner function (brightness) of real sources

- 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
  Source code on github:  https://github.com/flechsig/phase
Propagation of electric fields along a single optical element is based on power series expansions of:
- coordinate transformation
- path length
- determinants
- …

\[
E(y',z') = \frac{\sqrt{\cos(\alpha)} \sqrt{\cos(\beta)}}{\lambda^2} \int \int E(y,z) \left\{ \int \frac{1}{r \cdot r'} e^{i k PL} dw \cdot dl \right\} \left| \frac{\partial (y,z)}{\partial (dy',dz')} \right| ddy' \cdot ddz'
\]

2nd order expansion of path length (PL)

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

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