HIROSHIMA UNIVERSITY

HiSOR

Beam Physics 2013
OIST Main Campus, Seminar Room B250
28 November 2013

Recent Progress:
UNDULATOR RADIATION CARRYING LIGHT'S ORBITAL ANGULAR MOMENTUM

Shigemi Sasaki

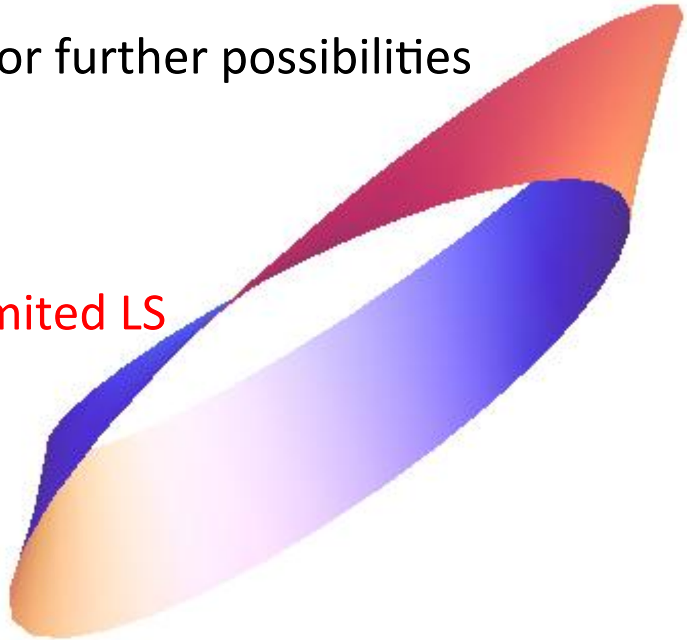
Hiroshima Synchrotron Radiation Center

Hiroshima University

Introduction

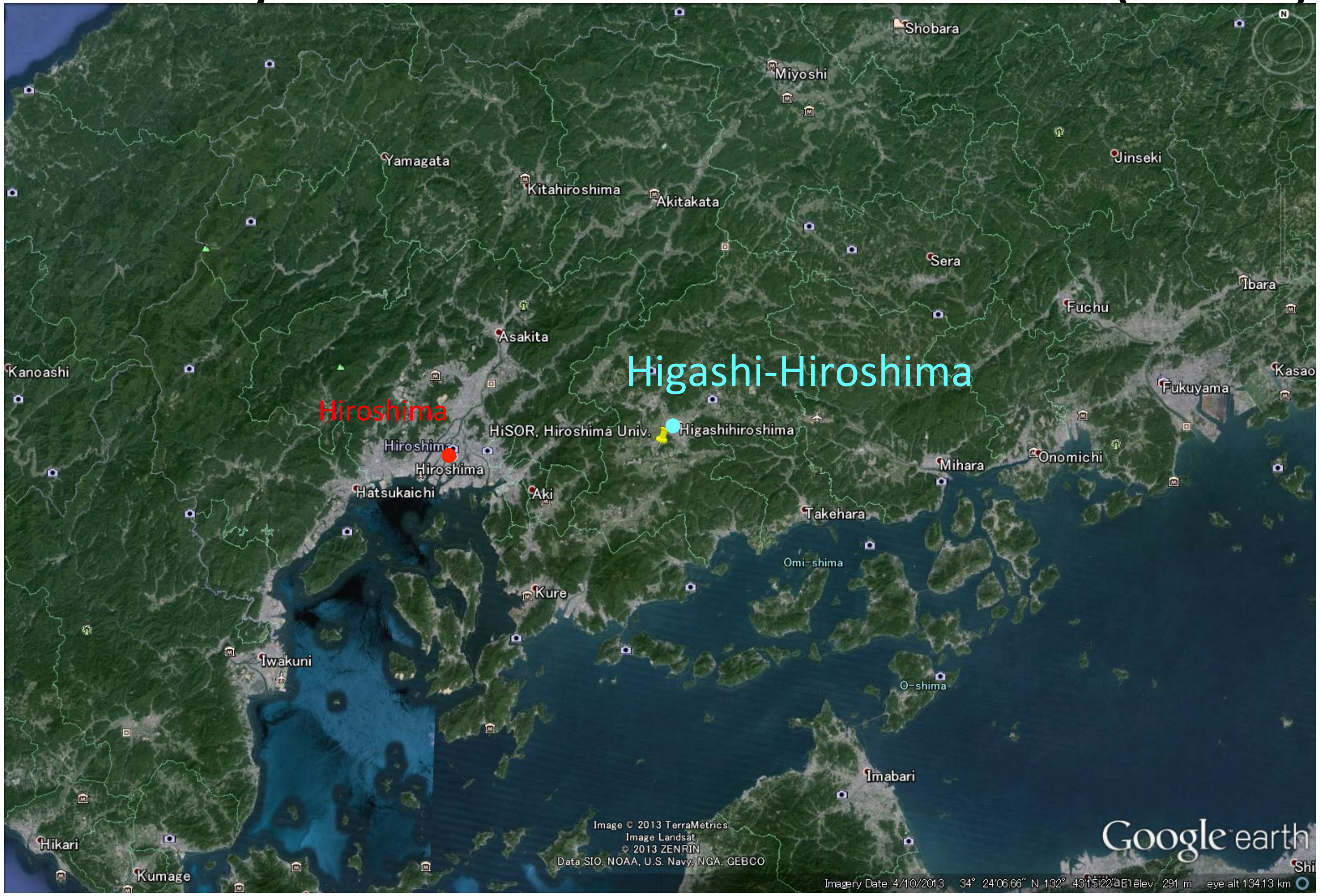
Need diffraction limited light source for utilizing OAM

- Present status of light source ring HiOR at HSRC
- Upgrade plan of HiSOR ring: HiSOR-II+
- Limitations of compact ring and search for further possibilities
- **New lattice**
- HiSOR-II plus ⟶ close to diffraction limited LS



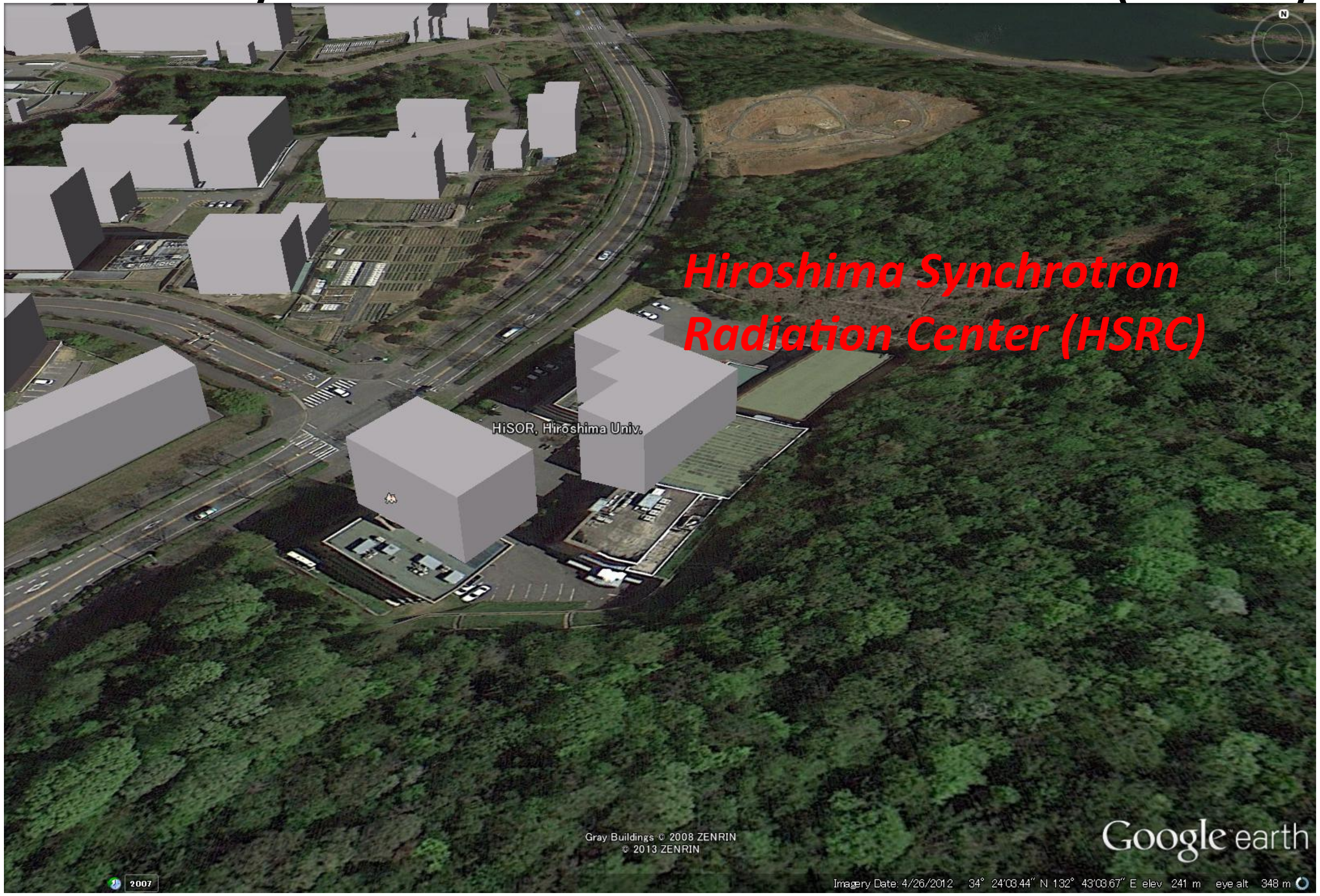
HSRC, Hiroshima University

- Hiroshima, Japan
- Hiroshima Synchrotron Radiation Center (HSRC)



HSRC, Hiroshima University

- Hiroshima, Japan
- Hiroshima Synchrotron Radiation Center (HSRC)



Government Funded SR Users' Facilities in Japan

Hard x-rays

Research in a wide range of fields

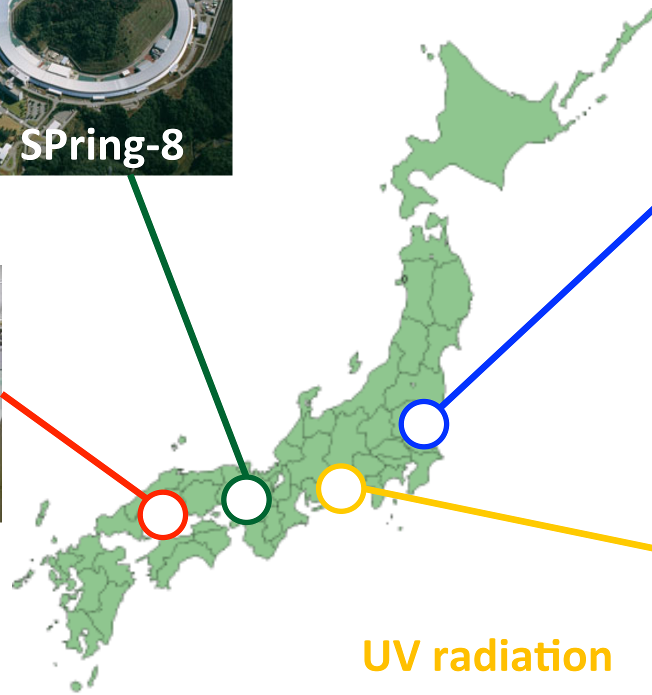
X-rays

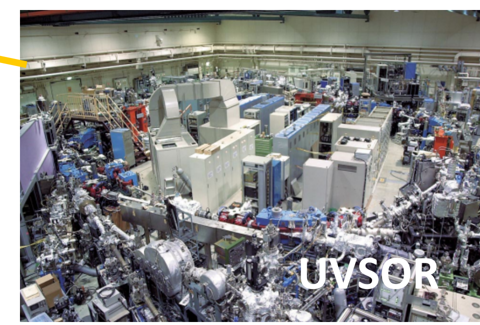
Research in a wide range of fields

UV radiation

Materials science research

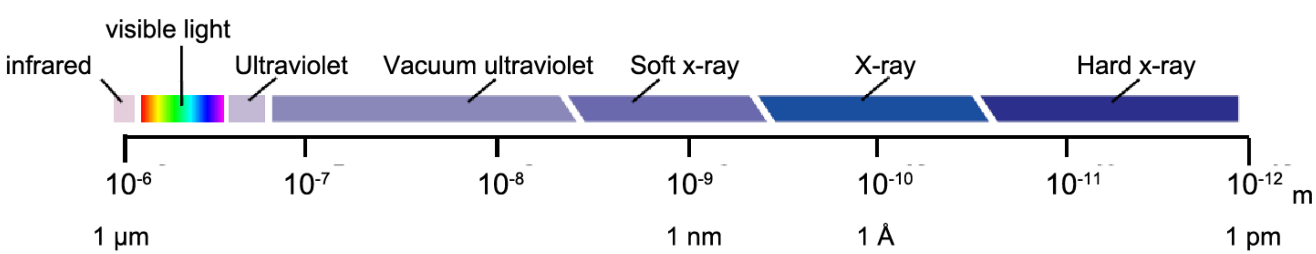
Education



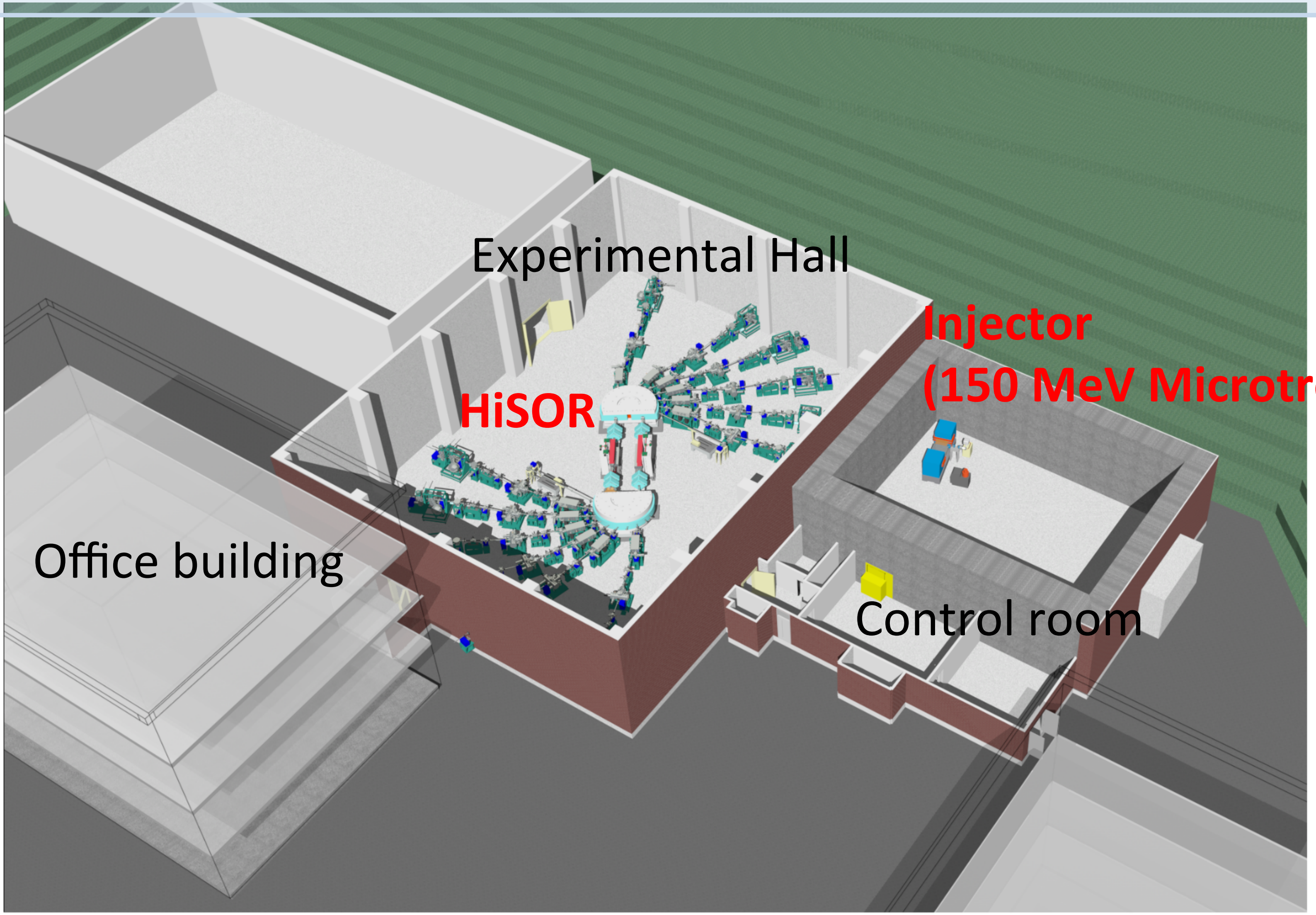


UV radiation

Molecular science research



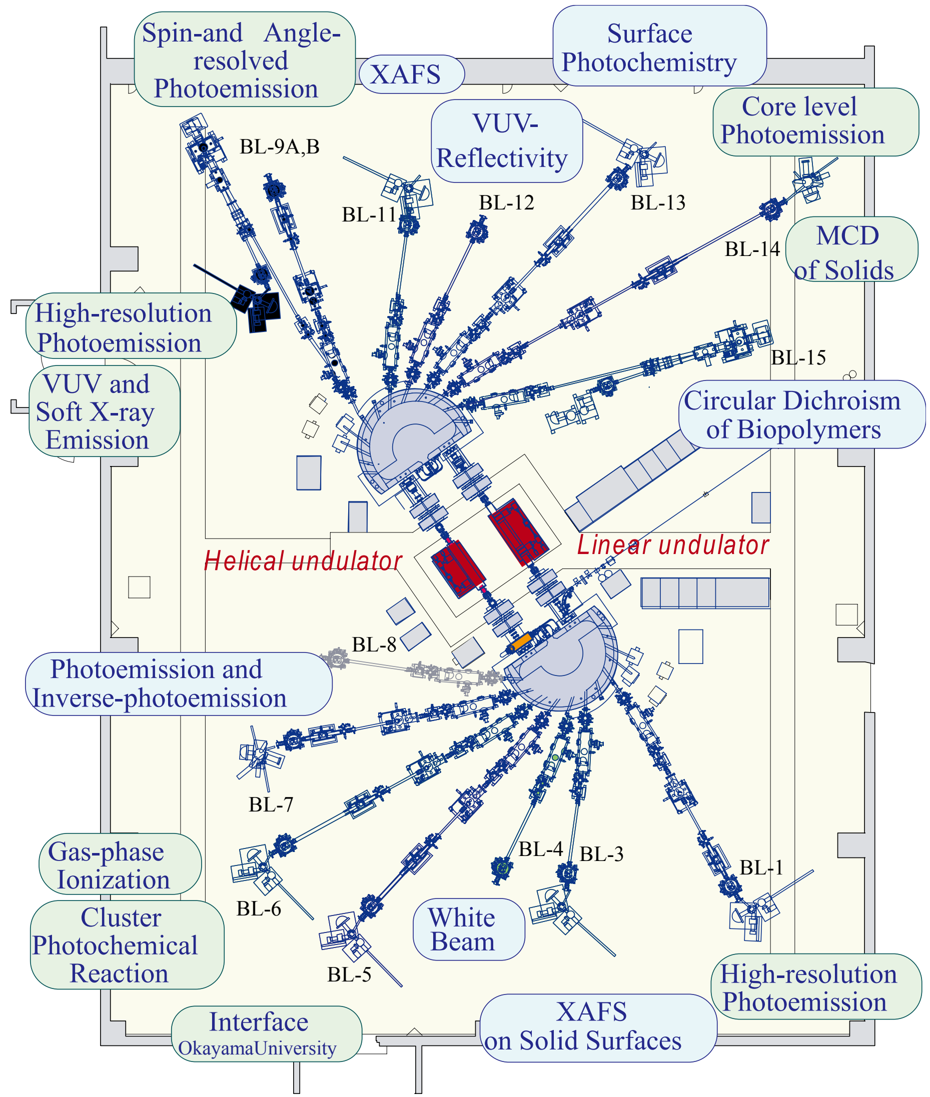
HSRC, Hiroshima University



HiSOR is a nickname of our ring.

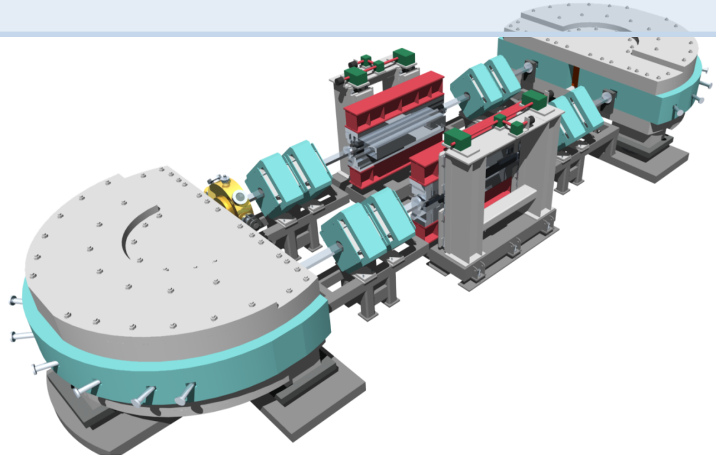
HiSOR Beamline Stations and Experiments

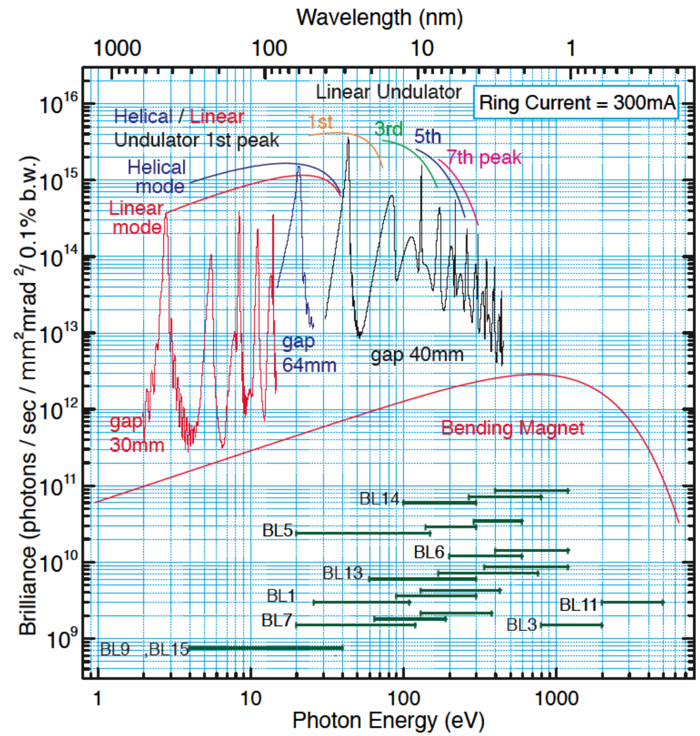
- 15 beamlines
  - Undulators (2)
    - Linear and Helical
    - High resolution VUV-SX
  - Bending section (11)
    - XAFS, ARPES, PEEM, PES, VUV-CD, MCD, etc.
  - Beam diagnostics (2)



Compact SR source, HiSOR

Circumference [m]	21.95
Type	Racetrack
Bending radius [m]	0.87
Beam energy [MeV] Injection/Storage	150/700
Maximum magnetic field [T]	2.7
Betatron tune	1.72, 1.84
RF frequency [MHz]	191.244
Harmonic number	14
RF voltage [kV]	200
Stored current [mA]	350
Natural emittance [π nmrad]	~400
Beam lifetime [hours@200mA]	~10
Critical wavelength [nm]	1.42



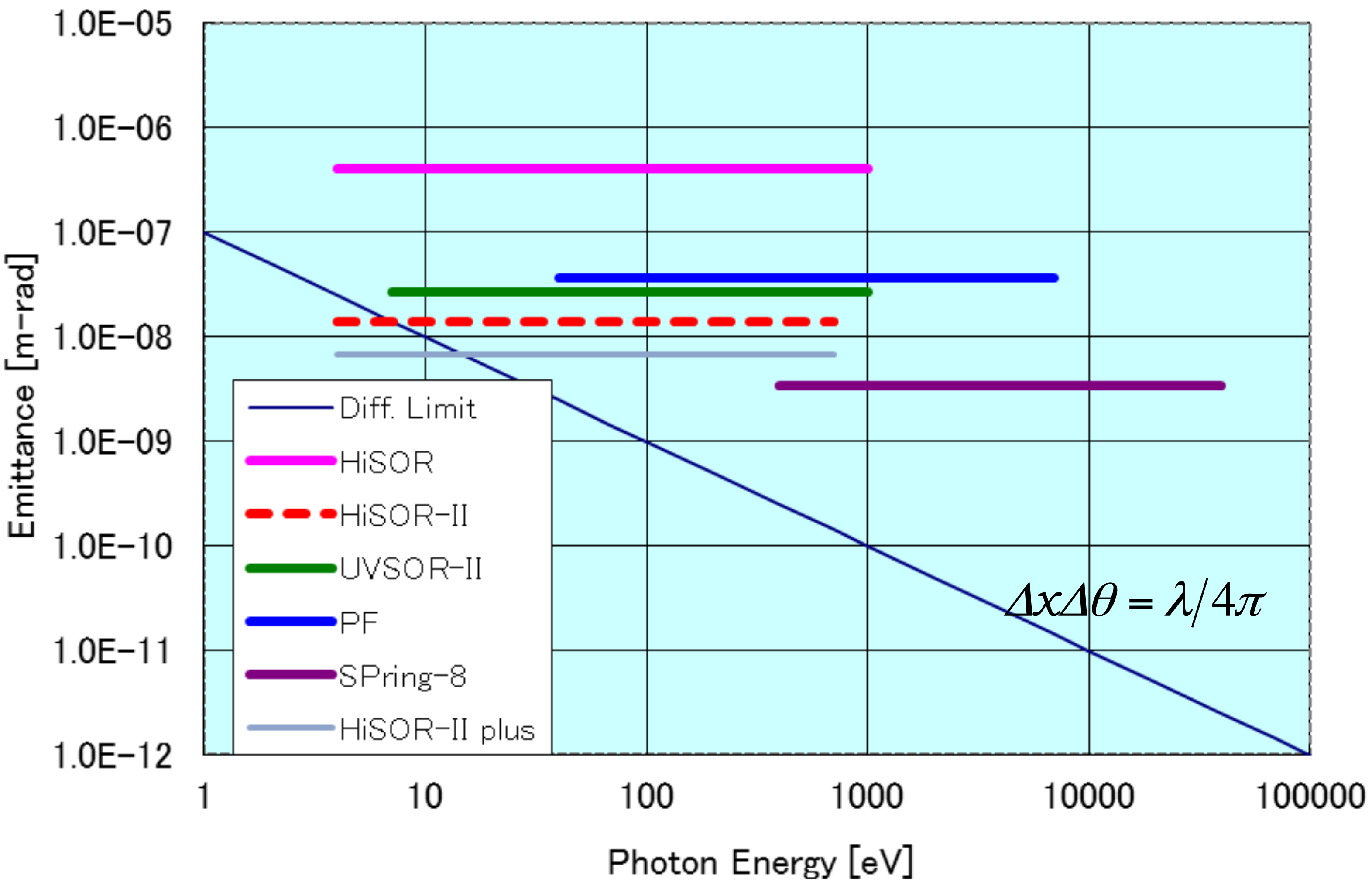


HIROSHIMA UNIVERSITY

Lightsource Rings in Japan

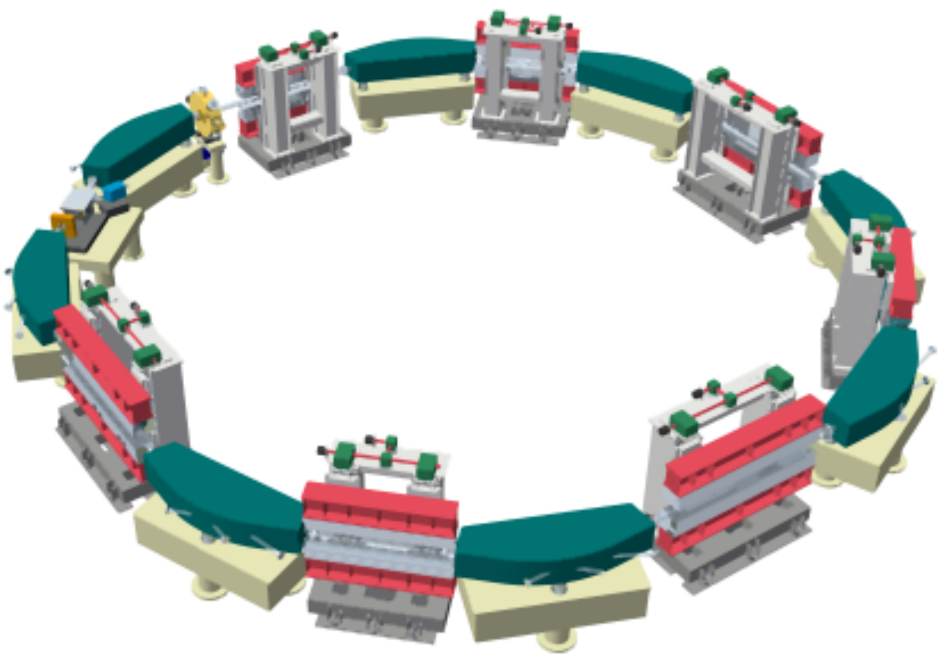
Facility	Energy [GeV]	Emittance
SPring-8	8	3.4
PF	2.5	36
SagaLS	1.4	25
NewSubaru	1-1.5	37
UVSOR-II	0.75	27
HiSOR	0.7	400
NagoyaLS	1.2	53
HiSOR-II plus	0.7	<10
Tohoku LS	3	<1
MAX III	0.7	13

Diffraction Limit and Emittance



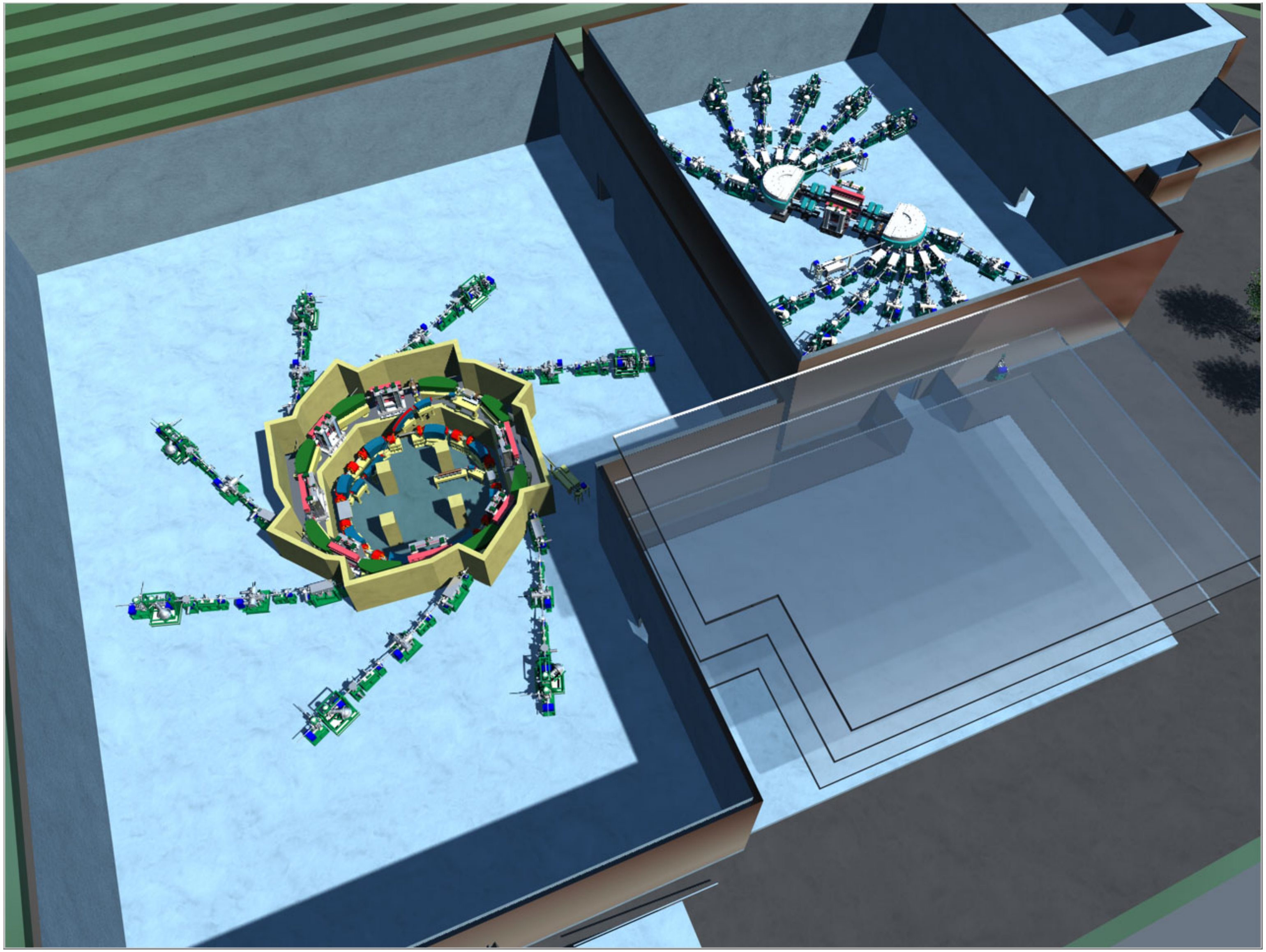
HiSOR-II

Beam energy [MeV]	700
Circumference [m]	40.079
Betatron tune	3.761, 2.846
Natural emittance [nmrad]	13.57
Momentum spread	5.79e-04
Momentum compaction	0.0319
Bunch length [mm]	37.0
Harmonic number	7
RF frequency [MHz]	52.4
Radiation dumping time [msec]	L:11.44 H: 8.57 V:14.70
Touschek lifetime [hour]	2.7
Straight sections	3.4 m × 4 2.0 m × 4



HIROSHIMA UNIVERSITY

Designer's View of HiSOR



Limitations of Compact SR Ring?

1. Limitation of achievable lowest emittance（MAX III holds the World record?）

2. Limitation of usable straight sections for insertion devices

3. Limitation to increase the 'bunch –to-bunch' interval due to the short circumference of the ring (Example： Longest bunch interval is 133 nsec, 7.5 MHz for C=40 m)

For example, ARTOF Photoelectron Spectroscopy experiment cannot be performed with a small circumference (< 100 m) ring.

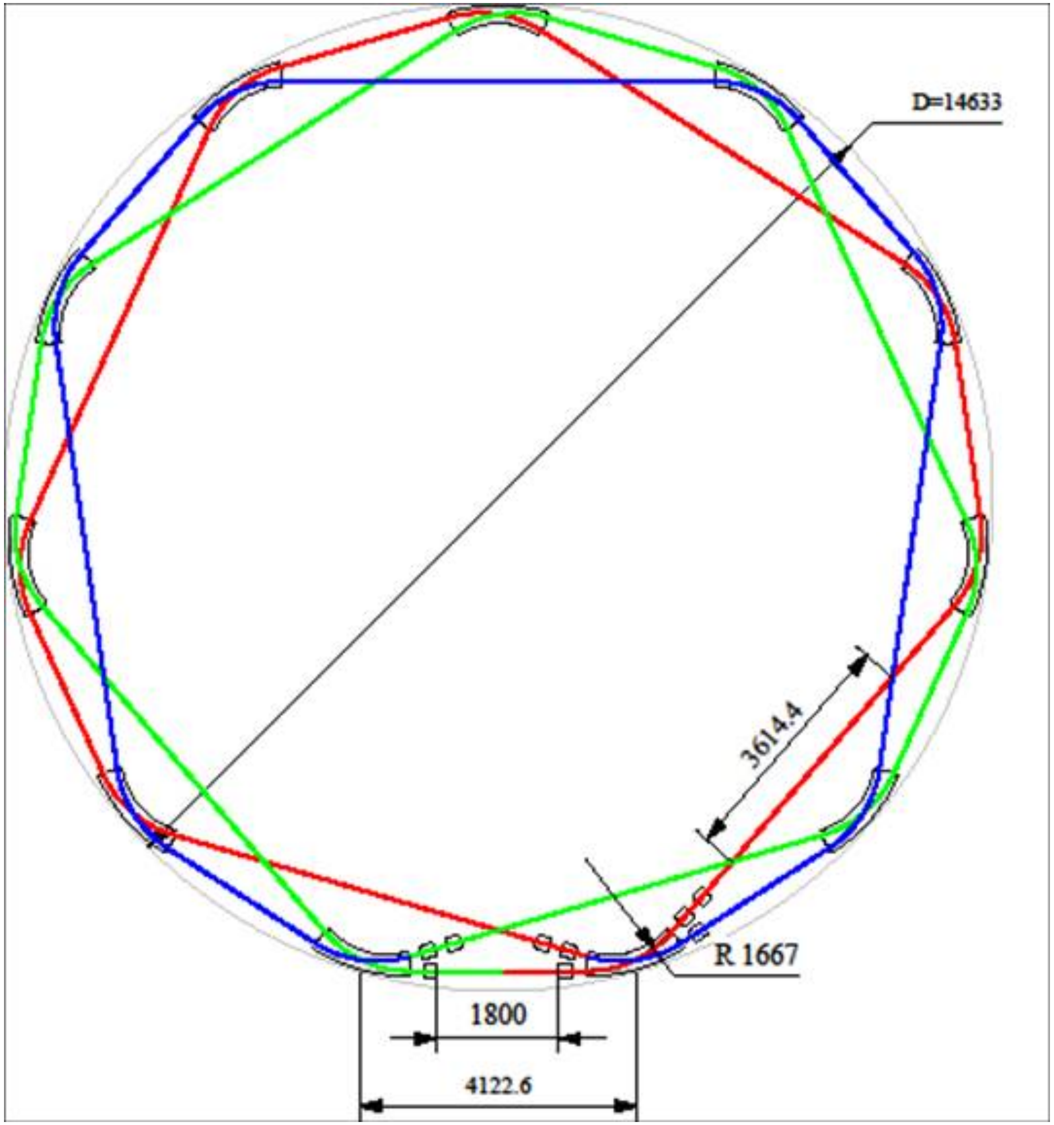
Need to seek some other possibilities

HIROSHIMA UNIVERSITY

Example of HiSOR II+ Lattice

11-fold symmetry

Return to original position after 3 turns

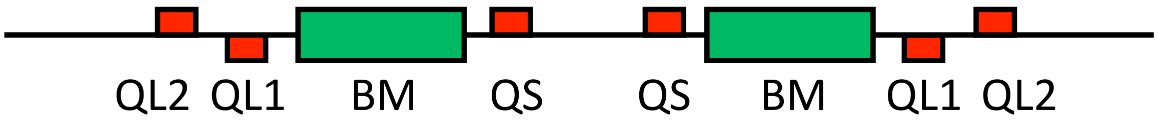


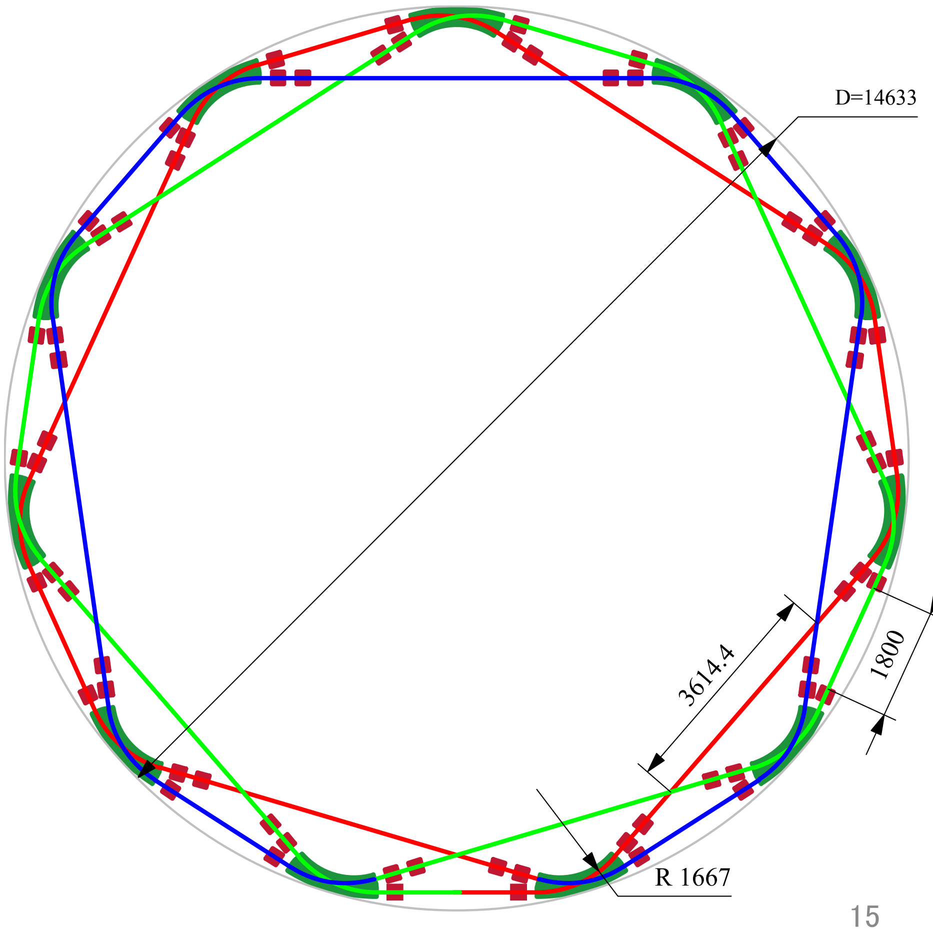
Length of orbit 130.3 m

Circumference 43.4 m

Lattice for HiSOR-II

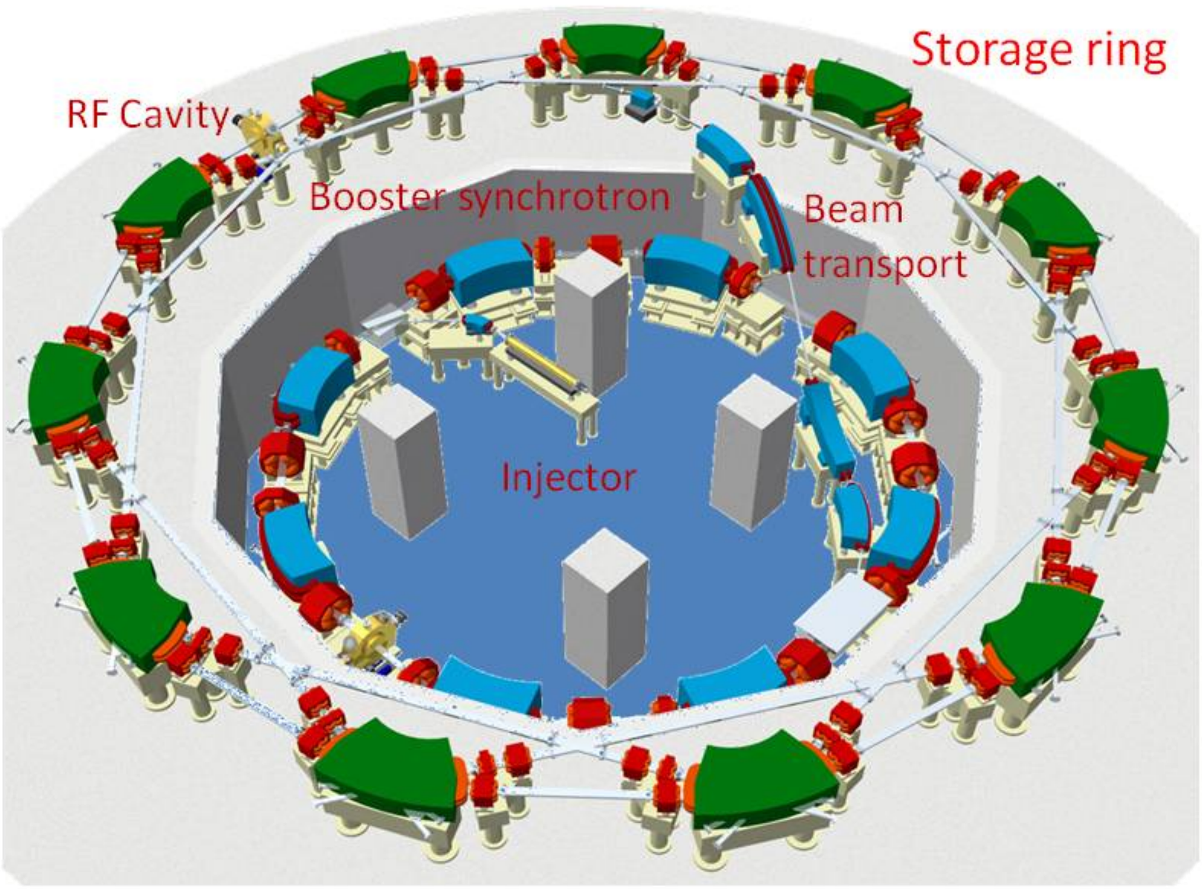
- Lattice Type
  - MAX-III / DBA
- 11 straight sections
  - Most straight sections can be used for IDs
  - Injection, RF-cavity can be installed in short straight sections
- 3-turen orbit
  - Compare with a conventional ring, 3-times longer:
    - Closed orbit
    - Circulation time





HIROSHIMA UNIVERSITY

Layout of HiSOR-II plus Accelerator System



Diffraction limited light

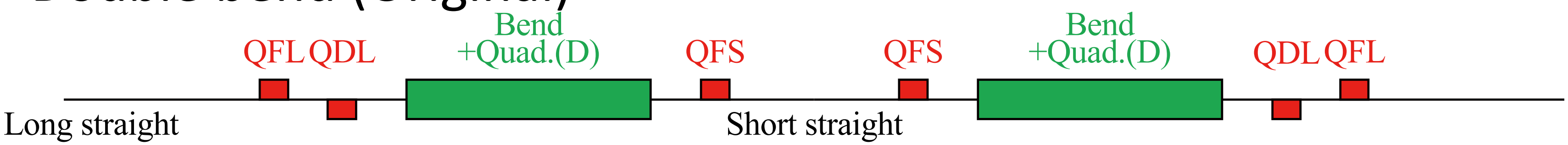
- Recent trend: 'Diffraction limited light source'
  - Multi-bend lattice
    - Short bend and focusing quadrupole
    - Low dispersion function in the bending magnet
- Required emittance for VUV light source ring
  - Emittance $\varepsilon \leq \lambda/4\pi$
  - Photon energy E_γ ~ 10 eV
    - From typical undulator of HiSOR

$$\varepsilon \leq 10 \ [nmrad]$$

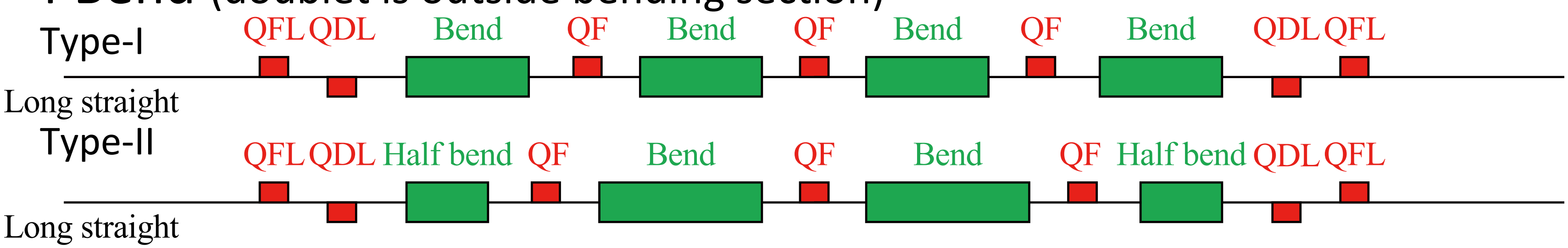
It is not too difficult !!

Multi-bend lattices

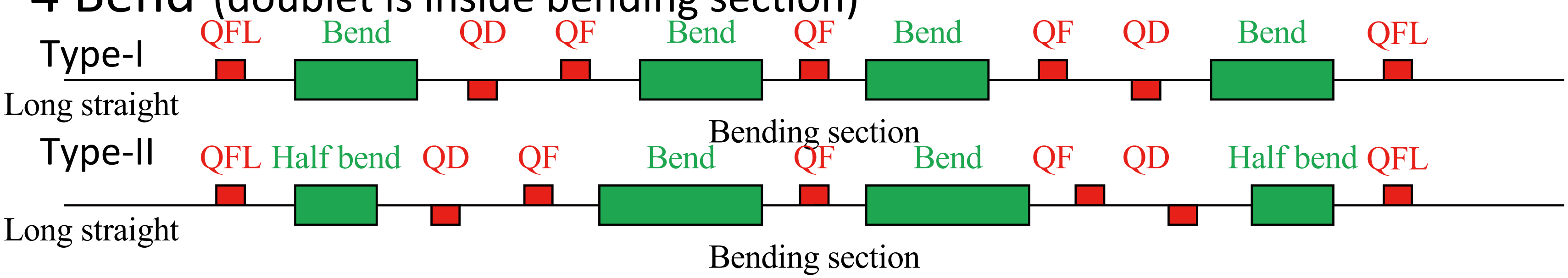
- Double bend (Original)



- 4 Bend (doublet is outside bending section)



- 4 Bend (doublet is inside bending section)



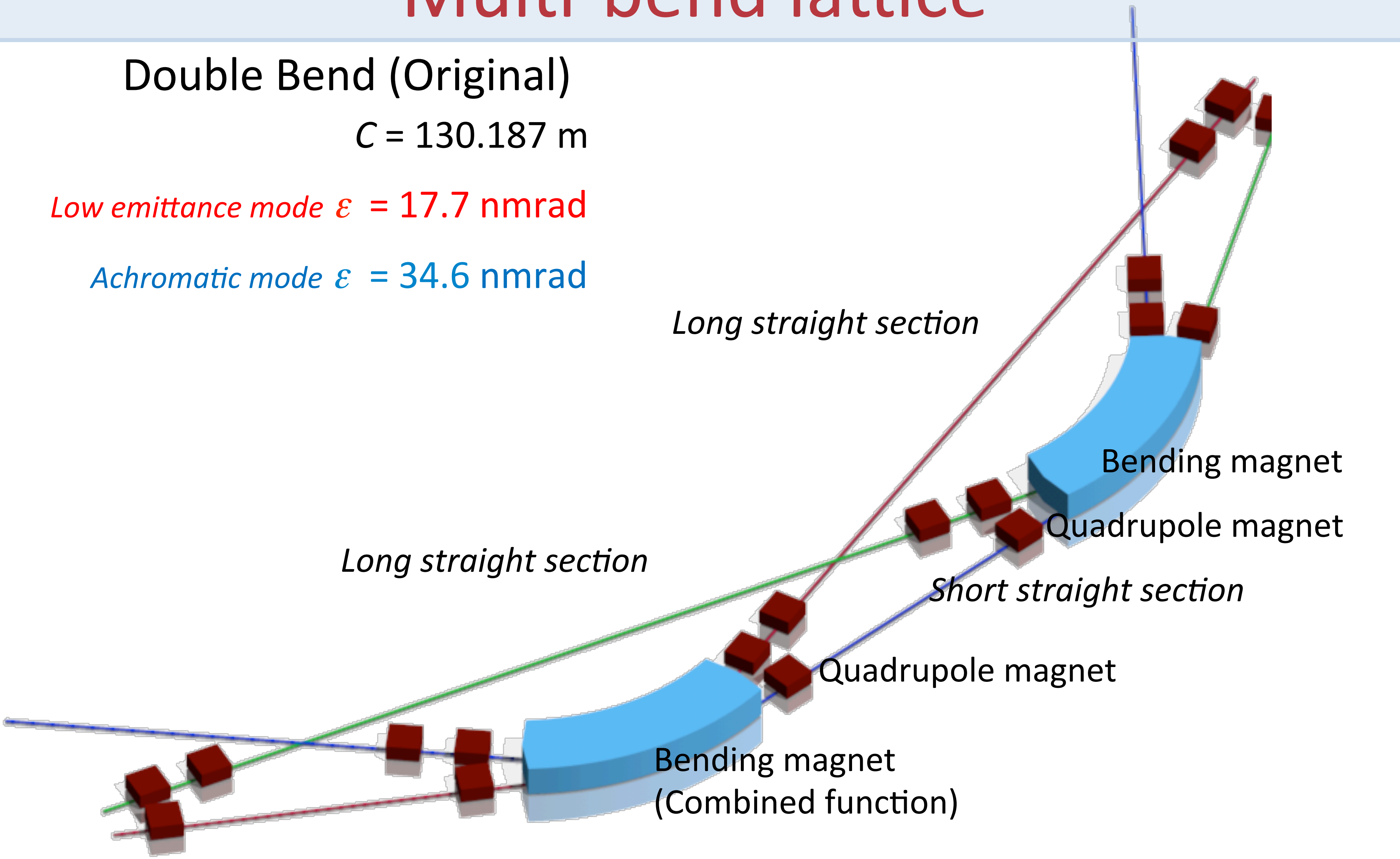
Multi-bend lattice

Double Bend (Original)

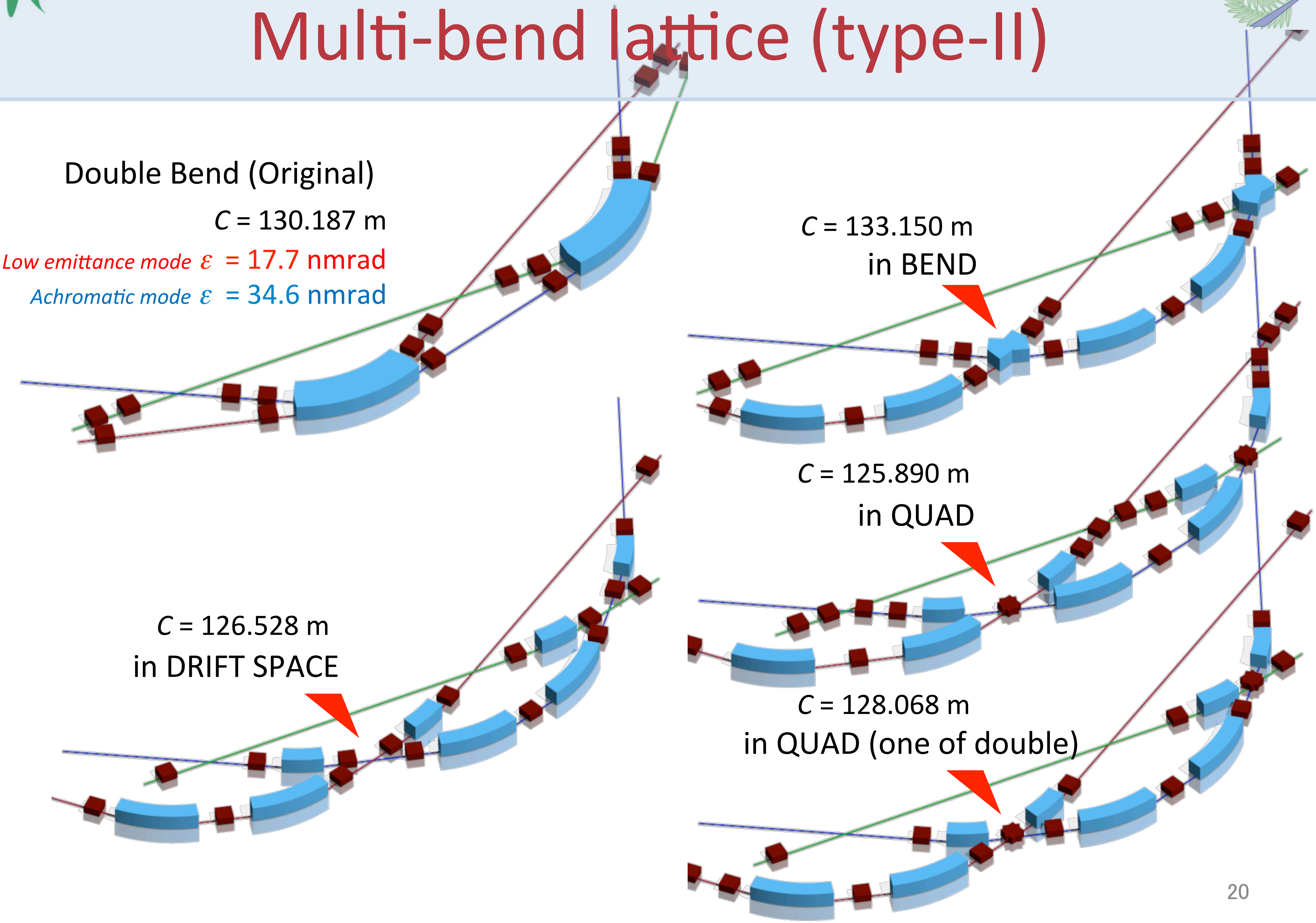
C = 130.187 m

Low emittance mode ε = 17.7 nmrad

Achromatic mode ε = 34.6 nmrad



Multi-bend lattice (type-II)



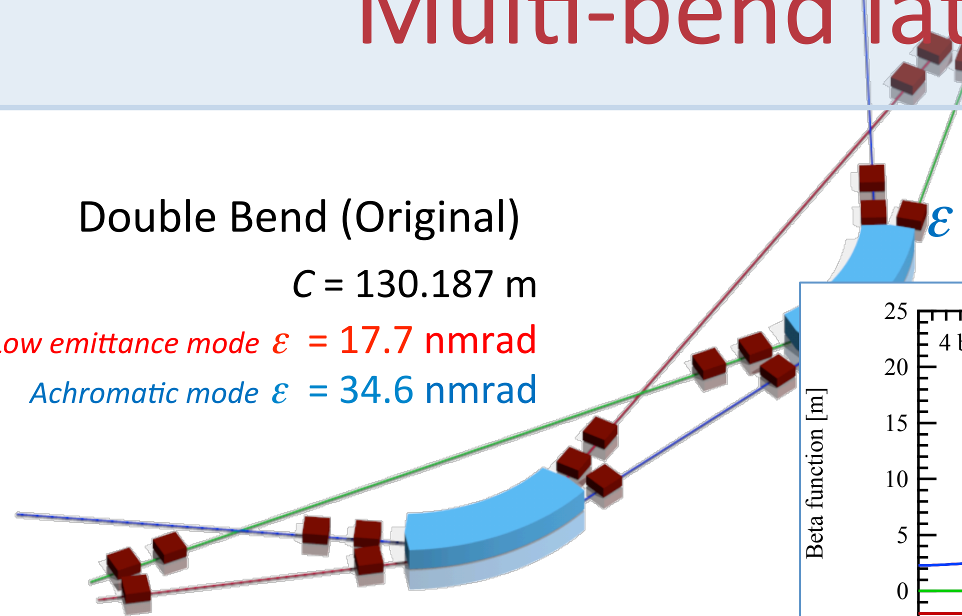
Multi-bend lattice (type-II)

Double Bend (Original)

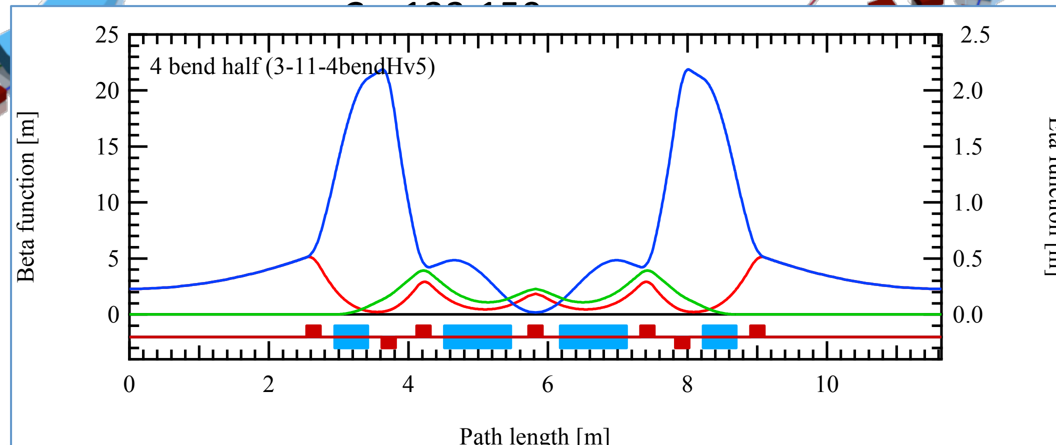
C = 130.187 m

Low emittance mode ε = 17.7 nmrad

Achromatic mode ε = 34.6 nmrad

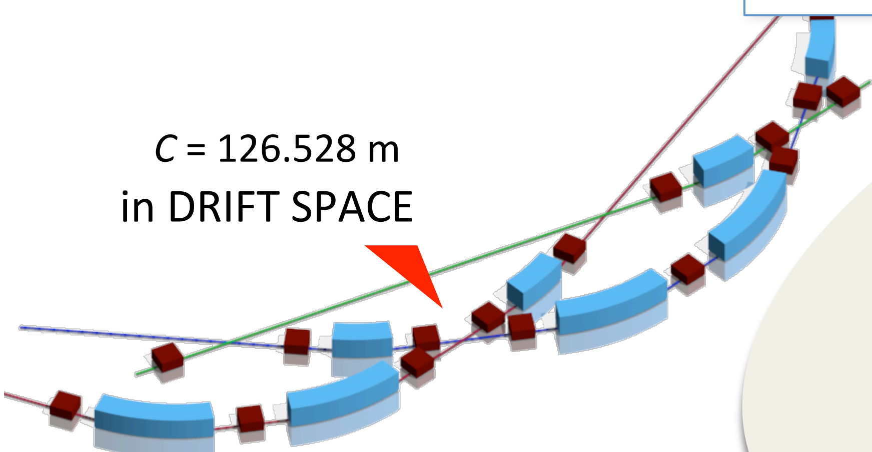


ε = 10.91 nmrad



C = 126.528 m

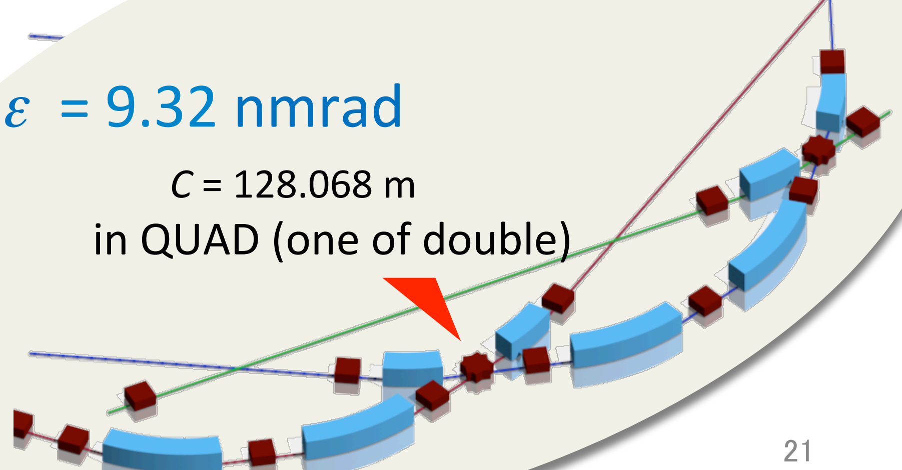
in DRIFT SPACE



ε = 9.32 nmrad

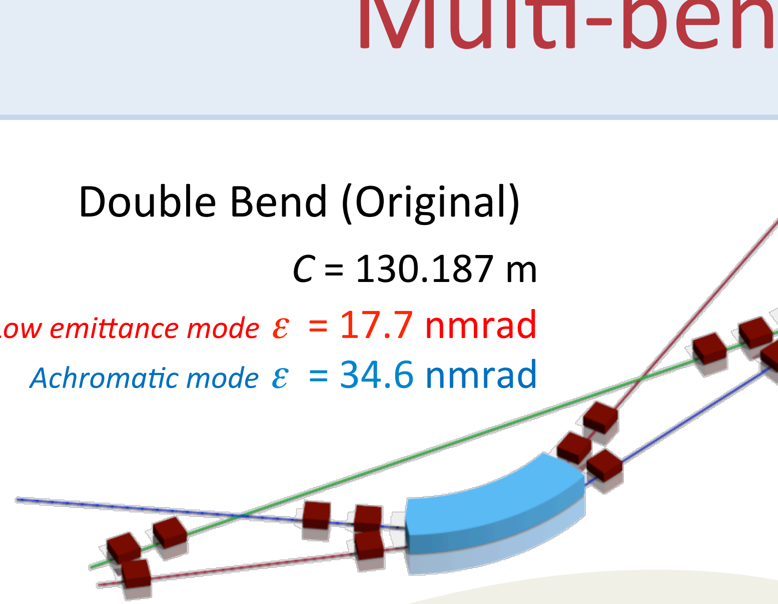
C = 128.068 m

in QUAD (one of double)



HIROSHIMA UNIVERSITY

Multi-bend lattice (type-II)

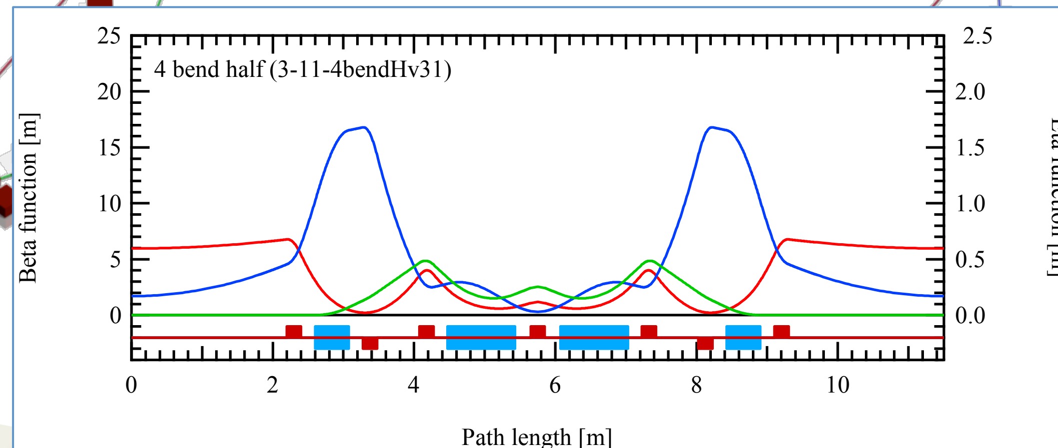


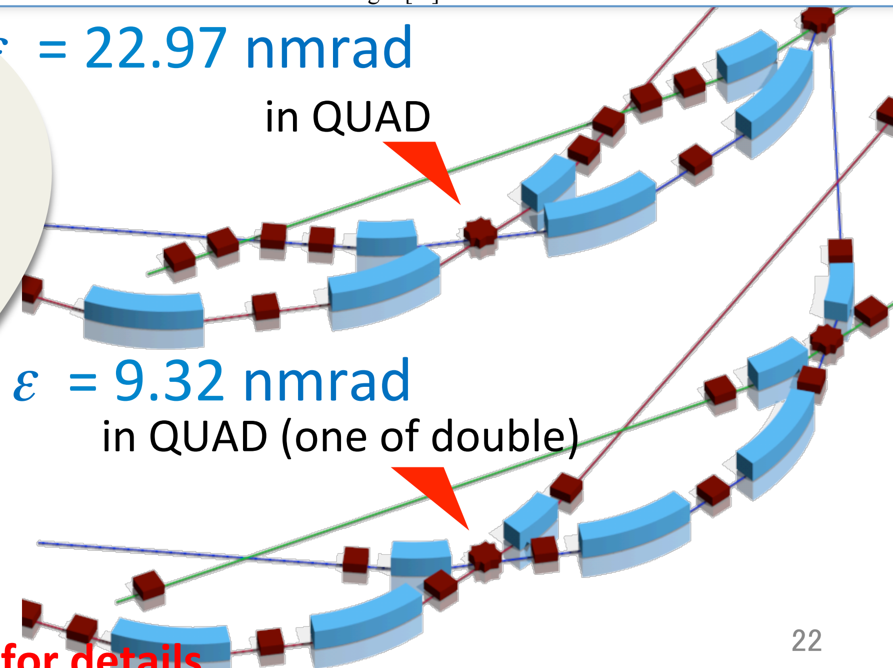
Double Bend (Original)

C = 130.187 m

Low emittance mode ε = 17.7 nmrad

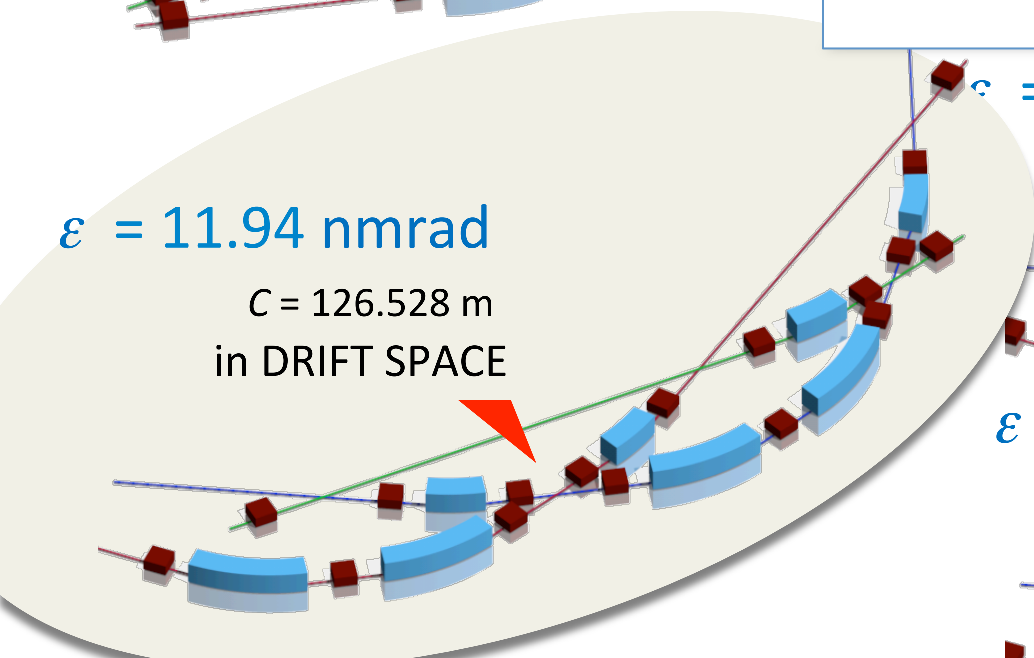
Achromatic mode ε = 34.6 nmrad





ε = 22.97 nmrad

in QUAD



ε = 11.94 nmrad

C = 126.528 m

in DRIFT SPACE

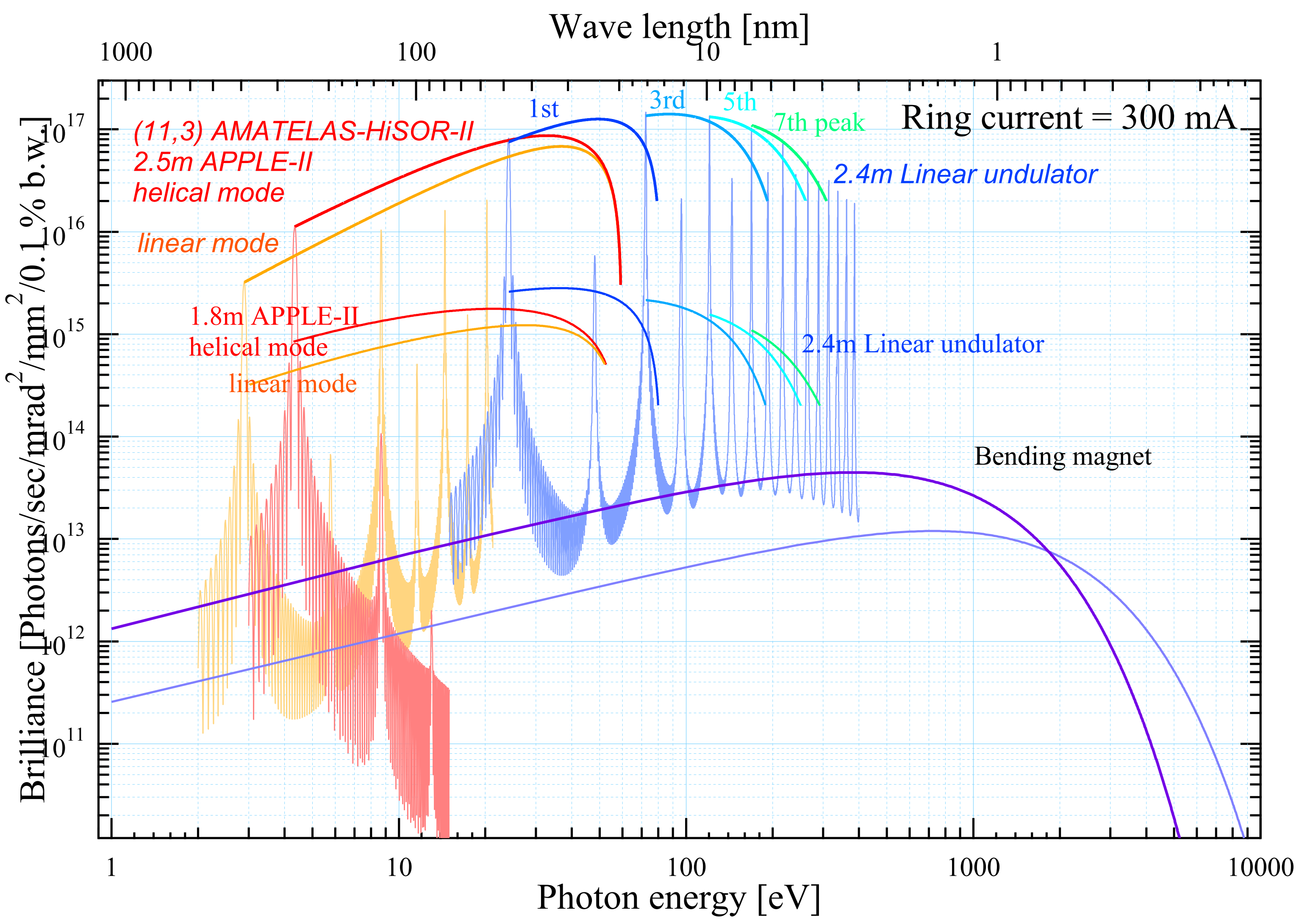
ε = 9.32 nmrad

in QUAD (one of double)

Visit poster presentation, YP19 by A. Miyamoto for details

HIROSHIMA UNIVERSITY

Expected Brilliance of HiSOR-II plus



Outline of main parts

- Optical donuts: solutions to the wave equation
- Light vortices（光渦）
- Helical undulators
- Experiments at HZB/BESSY II and HiSOR
- Recent activities in the World

Maxwell's equations

$$\nabla \bullet \mathbf{E} = 0 \qquad \nabla \times \mathbf{E} + \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} = 0$$

$$\nabla \bullet \mathbf{B} = 0 \qquad \nabla \times \mathbf{B} - \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} = 0$$

source-free, in vacuum

$$\mathbf{S} = \frac{c}{4\pi}\mathbf{E}\times\mathbf{B} \qquad \mathbf{J} = \frac{1}{4\pi c}\int \mathbf{r}\times(\mathbf{E}\times\mathbf{B})\, d\mathbf{r}$$

Poynting vector **Total angular momentum**

$$\mathbf{J} = \frac{1}{4\pi c}\int\left[(\mathbf{E}\times\mathbf{A}) + \sum_{i=1}^{3} E_i(\mathbf{r}\times\nabla)\right] d\mathbf{r}$$

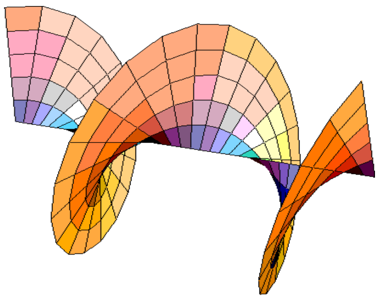
where $\mathbf{B} = \nabla\times\mathbf{A}$

Spin ***S*** **Orbital** ***L***

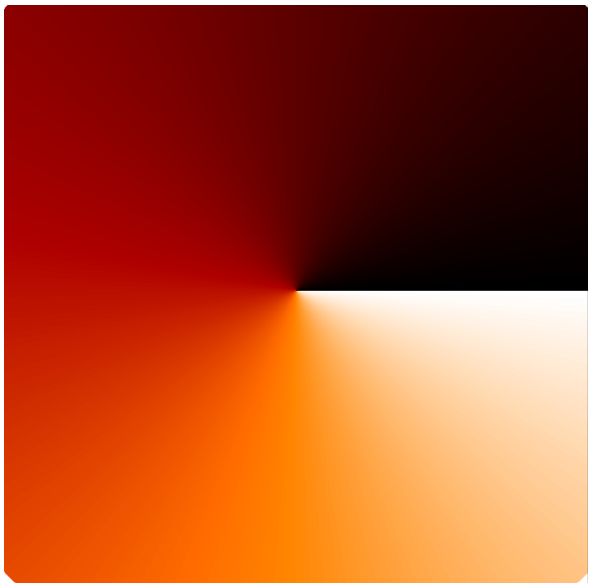
Optical "donuts"

- **Laguerre-Gaussian mode (azimuthal phase):**

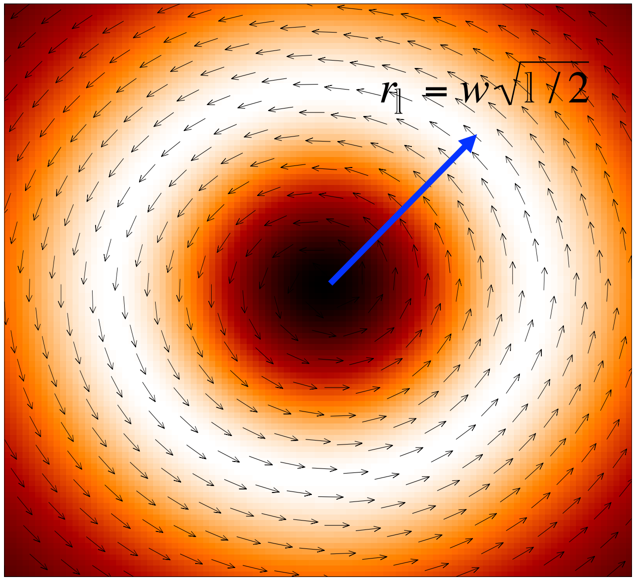
$$a_p^{\ell}(r,\phi,z) = A_p^{\ell}(r,z)\ \exp\left[-i\Phi_p^{\ell}(r,z)\right]\ \exp(-i\ell\,\phi)$$



- **The Poynting vector completely specifies the field**



Phase

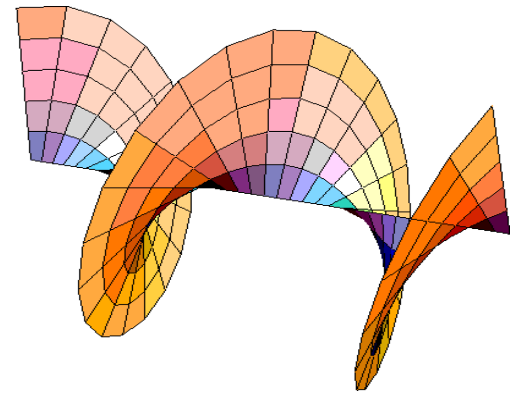


Magnitude

Phase singularities

Laguerre-Gaussian beams

- On-axis singularity characterized by helical phase front
- Poynting vector follows wavefront as beam propagates
- Gives rise to orbital momentum component
- Intensity is zero on-axis (optical donut)



Orbital angular momentum

- Distinct from spin AM associated with circular polarization
- Has magnitude of $\ell\hbar$ per photon, where topological "charge" ℓ is number of ($2\pi\ell$) phase cycles around beam

$$L = \ell\hbar$$

$$(\ell = \text{integer})$$

L. Allen, PRA 45, 8185 (1992)

HIROSHIMA UNIVERSITY

Photon angular momentum

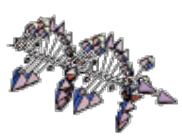
If every polarization vector rotates the light has spin.
If the phase structure rotates the light has orbital angular momentum

- M. Padgett

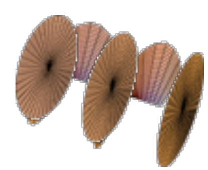
Spin	**Orbital**
linear/circular	**azimuthal**
axis-independent	**axis-dependent**
intrinsic	**intrinsic or extrinsic**
	(on-axis) (off-axis)

$S = 0 \pm 1\hbar$

$L = 0\hbar$



$J = L + S$



Can we produce an *x-ray* vortex?

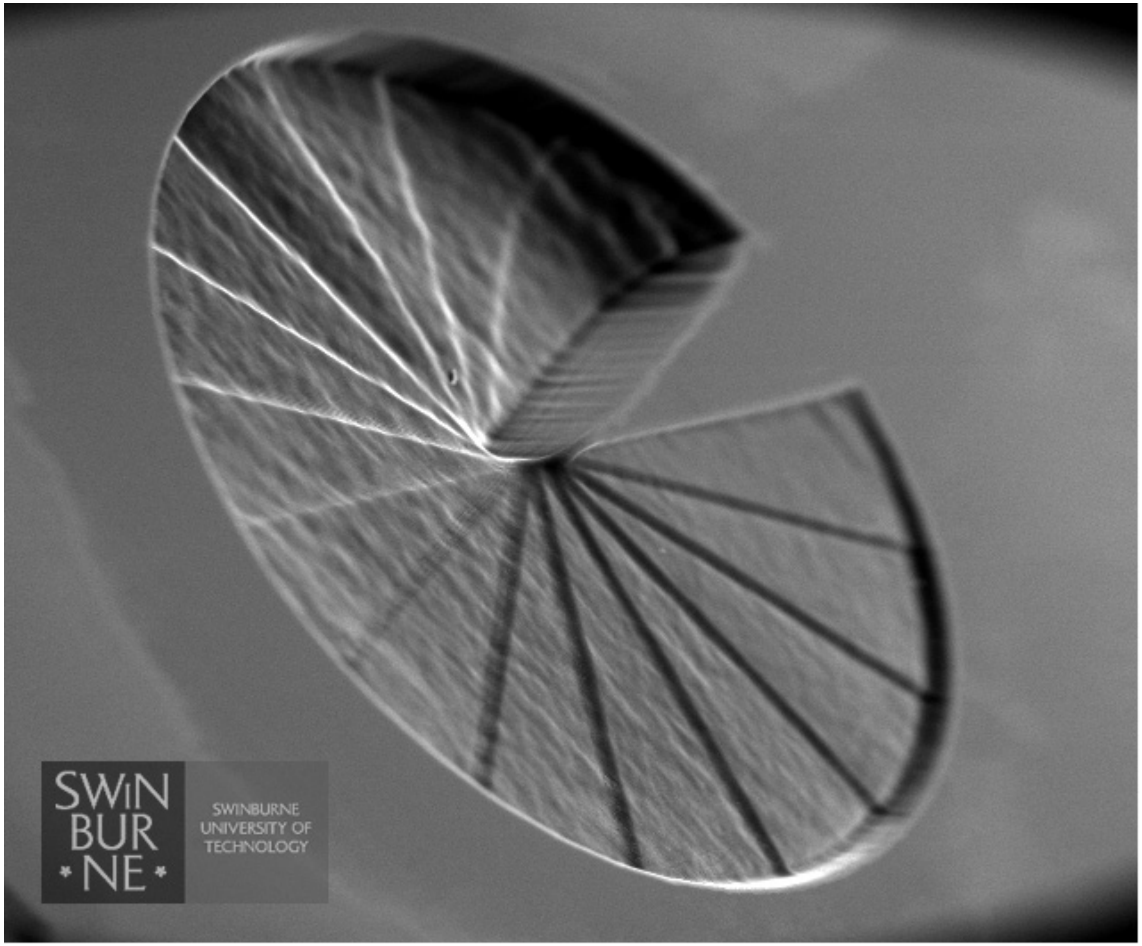
Need:

- **Intense, highly coherent x-ray and VUV beam**
- **Means to generate the helical phase**
- **Means to detect it**

Will it be stable upon propagation, or fall apart due to rapidly varying phases and imperfect optics?

Spiral phase plate

$n = 1 - \delta - i\beta$



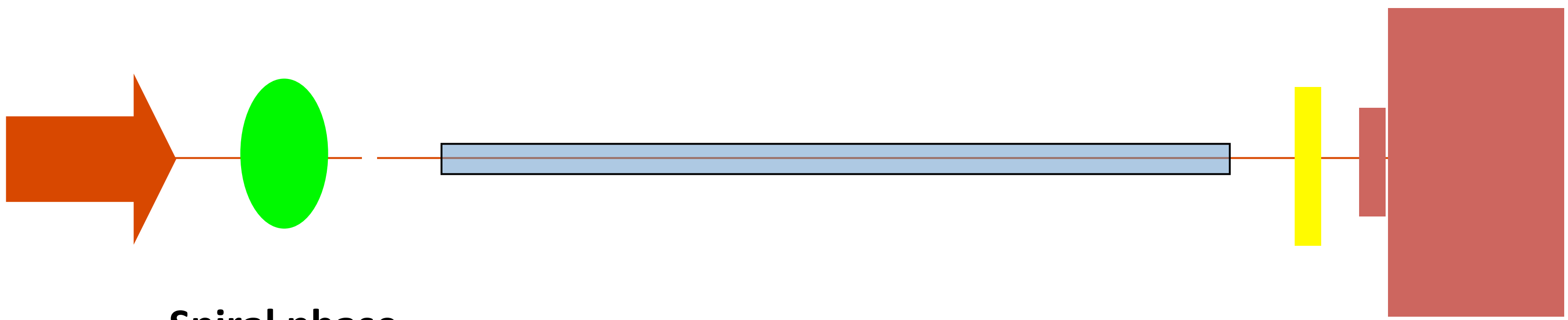
Polyimide phase plate, 34 μm thick, gives ~2π shift at 9 keV

Experiment

Coherent x-ray beam

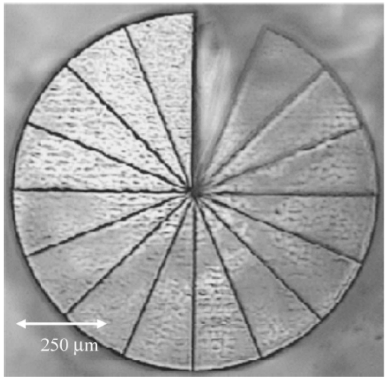
Helium flight path

$CdWO_4$ scintillator



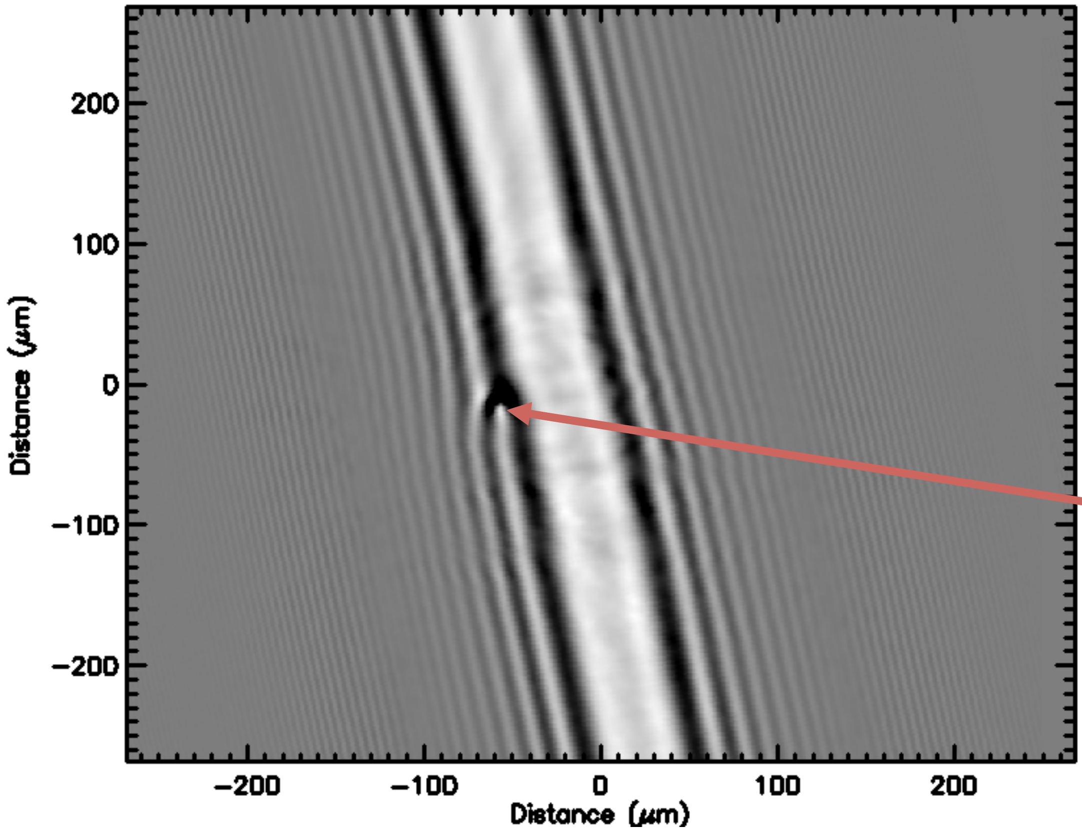
Spiral phase plate

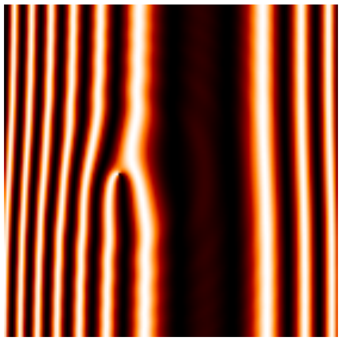
CCD camera



A. Peele, Opt. Lett. 27, 1752 (2002)

"Charge 1" vortex





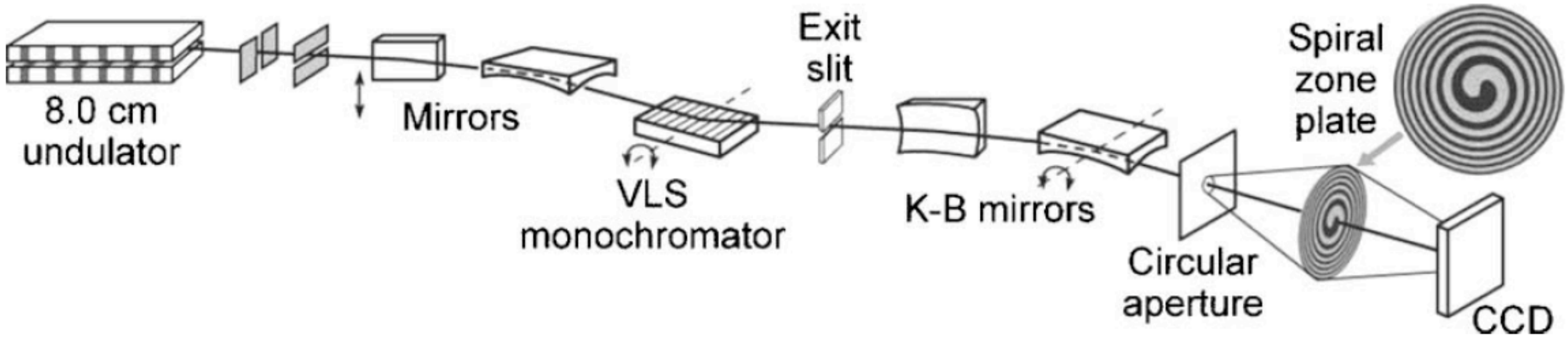
$L = h$

phase singularity

Visualize singularity as split in Fresnel diffraction fringes from a tungsten wire (9 keV)

A. Peele, JOSA A21, 1575 (2004)

Spiral phase contrast x-ray microscopy



Images of 1 μm pinhole at λ= 2.73 nm

ordinary ZP

SZP, ℓ=1

SZP, ℓ=2

Sakdinawat and Liu, Opt. Lett. 32, 2635 (2007)

Optics are fun ... but can we produce vortices directly?

- Brilliant VUV and x-ray sources of beams carrying OAM would provide opportunities for phase contrast imaging and coupling of angular momentum to matter in novel ways.

- Linear undulators do not generate even harmonics on-axis; helical undulators do not generate any on-axis. As a result, the off-axis harmonics (especially even ones) have been considered useless.

- Existence of OAM in infrared FEL radiation has been suspected in experiments at BNL in 2007.

E. Hemsing et al., PAC07, TUPMS036 (2007)

Theory

For a variable polarizing undulator with *N* periods (e.g. APPLE device), the radiated intensity of the *n*th harmonic is

$$\frac{d^2 I}{d\omega d\Omega} = \frac{e^2\gamma^2 n^2 \xi^2}{4\pi\varepsilon_0 c}\left[\left|A_x\right|^2 + \left|A_y\right|^2\right] L(N\Delta\omega/\omega_1),$$

where:

$$A_x = 2\gamma\theta\cos\phi S_0 - K_y(S_1 + S_{-1})$$

$$A_y = 2\gamma\theta\sin\phi S_0 + iK_x(S_1 - S_{-1})$$

$L(N\Delta\omega/\omega_1)$ is the Laue function for fundamental ω_1 and $\Delta\omega=\omega-n\omega_1(\theta)$

$$S_q = \sum_{p=-\infty}^{\infty} J_p(Y) J_{n+2p+q}(X) e^{i(n+2p+q)\Phi}$$

$q = -1, 0, 1$

$$X = 2n\xi\gamma\theta\sqrt{K_y^2\cos^2\phi + K_x^2\sin^2\phi}$$

$$Y = n\xi(K_y^2 - K_x^2)/4 \ , \quad \tan\Phi = (K_y / K_y)\tan\phi$$

$$\xi = 1/(1+\gamma^2\theta^2 + K_x^2/2 + K_y^2/2)$$

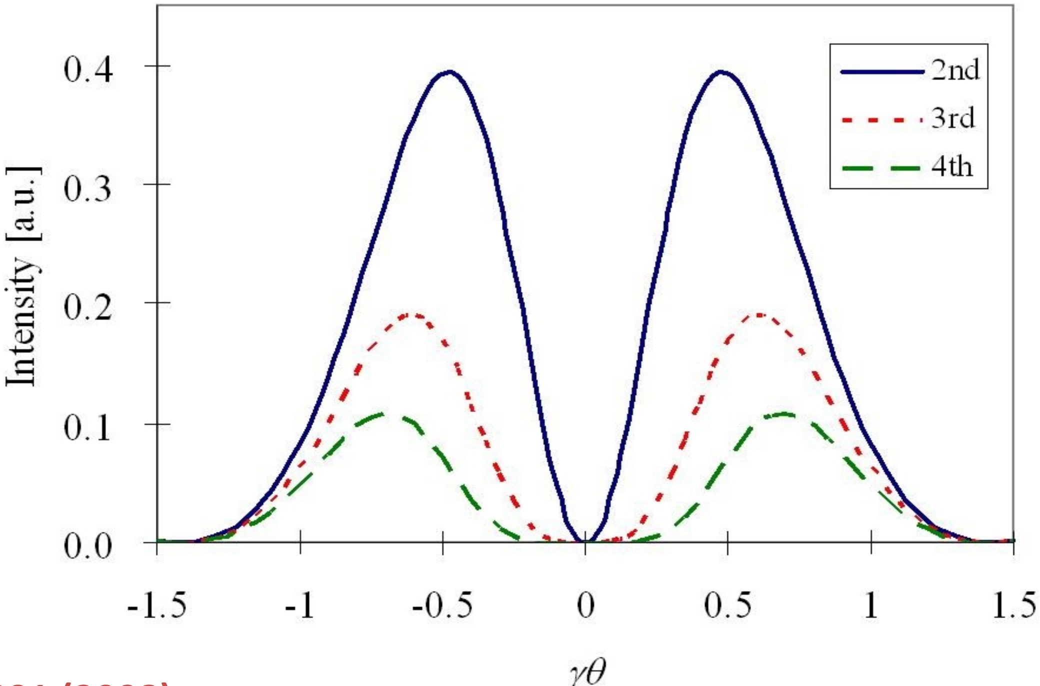
B. Kincaid, JAP 48, 2684 (1977)
R. Walker, CERN Acc. School, 1998

Helical case

In this mode, $K_x = K_y = K$, $X = 2n\xi\gamma\theta K$, $Y = 0$, and $\Phi = \phi$.

$$(A_x - iA_y)/2 = \sqrt{2}\,\boxed{e^{i(n-1)\phi}}\{\gamma\theta J_n(X) - J_{n-1}(X)\}$$

Radiated amplitude has the characteristic central minimum and *exp(iℓϕ)* signature of LG modes



Sasaki and McNulty, PRL 100, 124801 (2008)

Comparisons between two equations

In the circular mode; ***$K_x = K_y = K$, $X = 2n\xi\gamma\theta K$, $Y = 0$, and $\Phi = \phi$.***

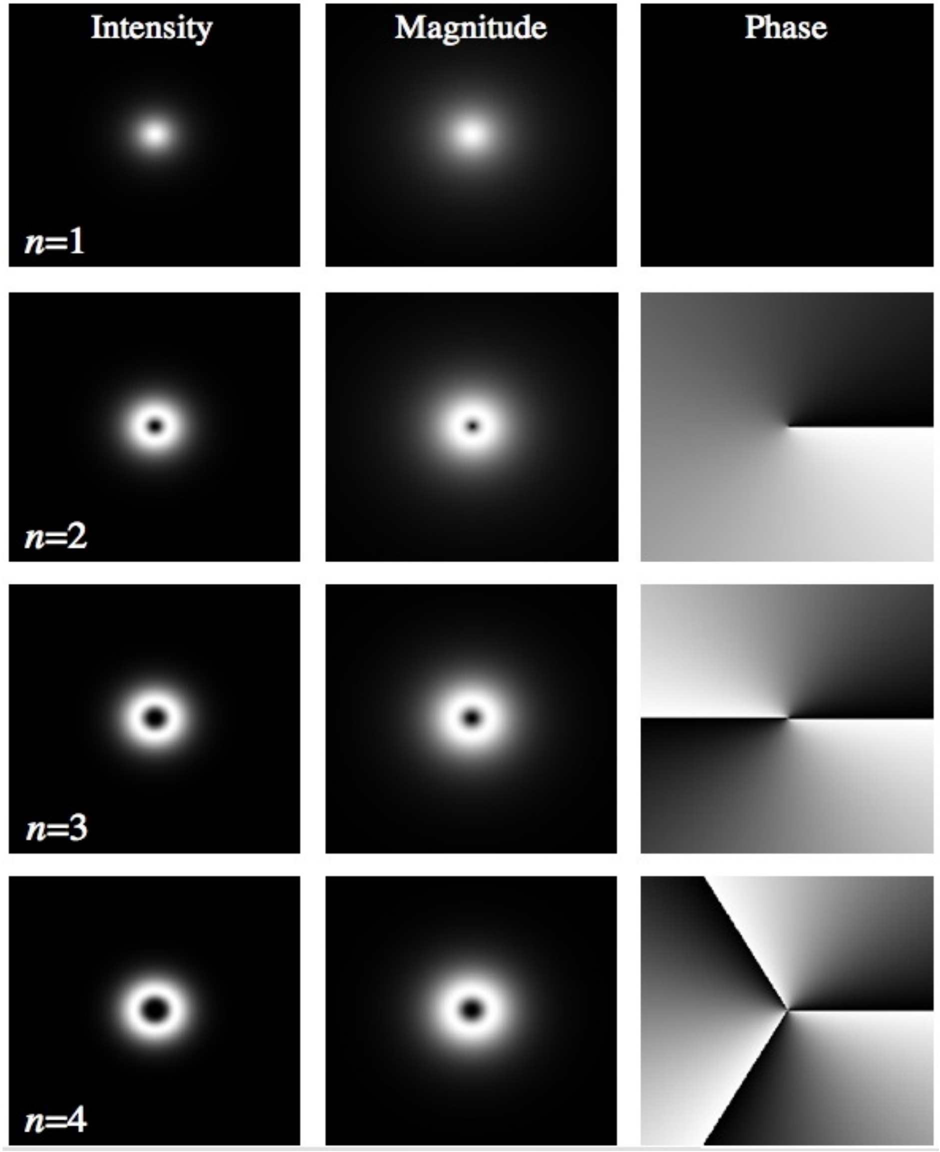
$$(A_x - iA_y)/2 = \sqrt{2}\, \boxed{e^{i(n-1)\phi}} \{\gamma\theta J_n(X) - J_{n-1}(X)\}$$

In Laguerre-Gaussian beam;

$$a_p^{\ell}(r,\phi,z) = A_p^{\ell}(r,z)\ \exp\left[-i\Phi_p^{\ell}(r,z)\right] \boxed{\exp(-i\ell\phi)}$$

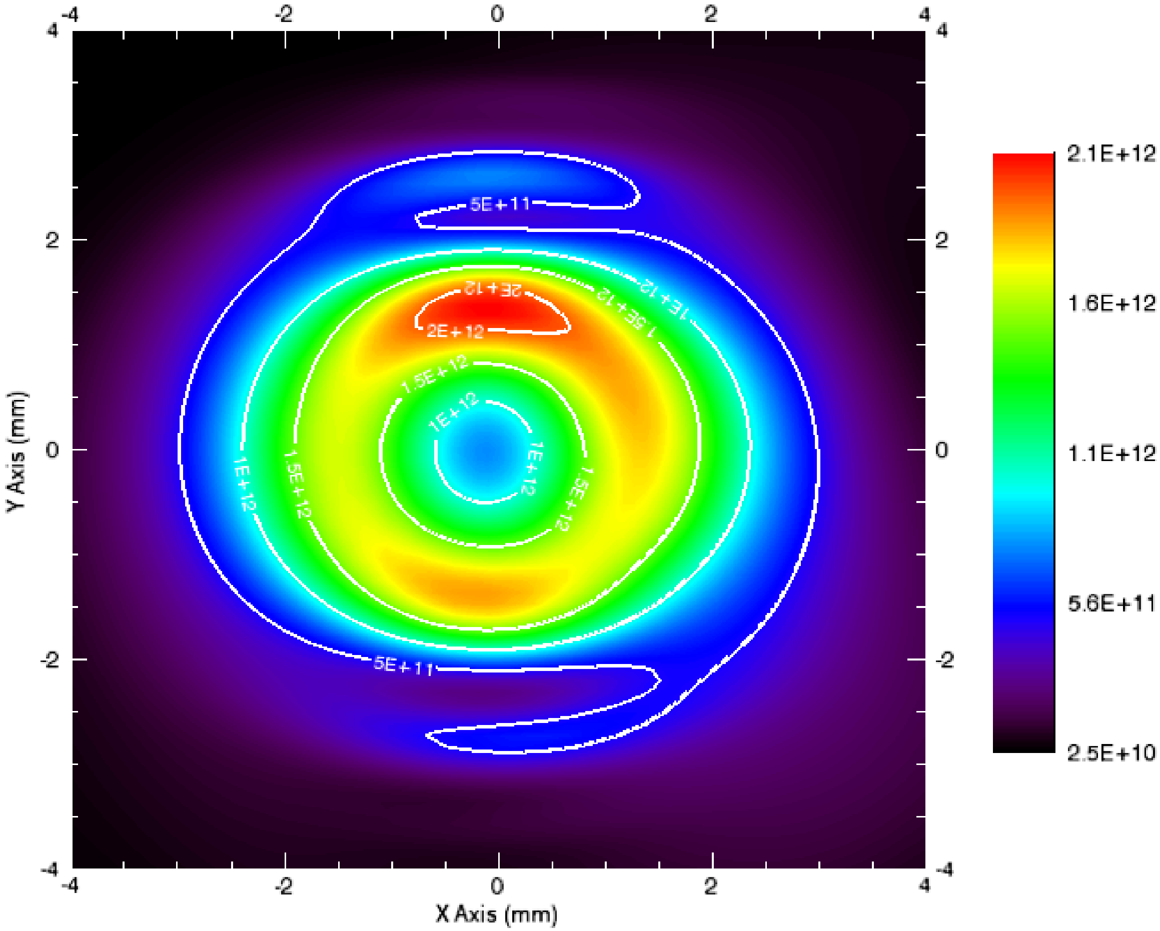
Sasaki and McNulty, PRL 100, 124801 (2008)

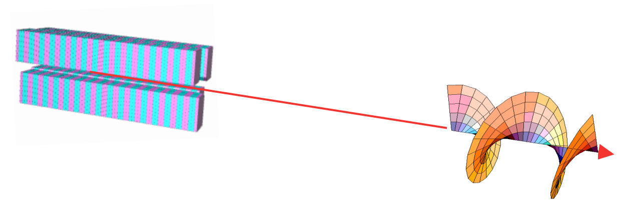
Intensity, magnitude, and phase for the first few harmonics



On safari for "wild" vortices

We aim to detect and characterize these modes in the light from the APS CPU and other

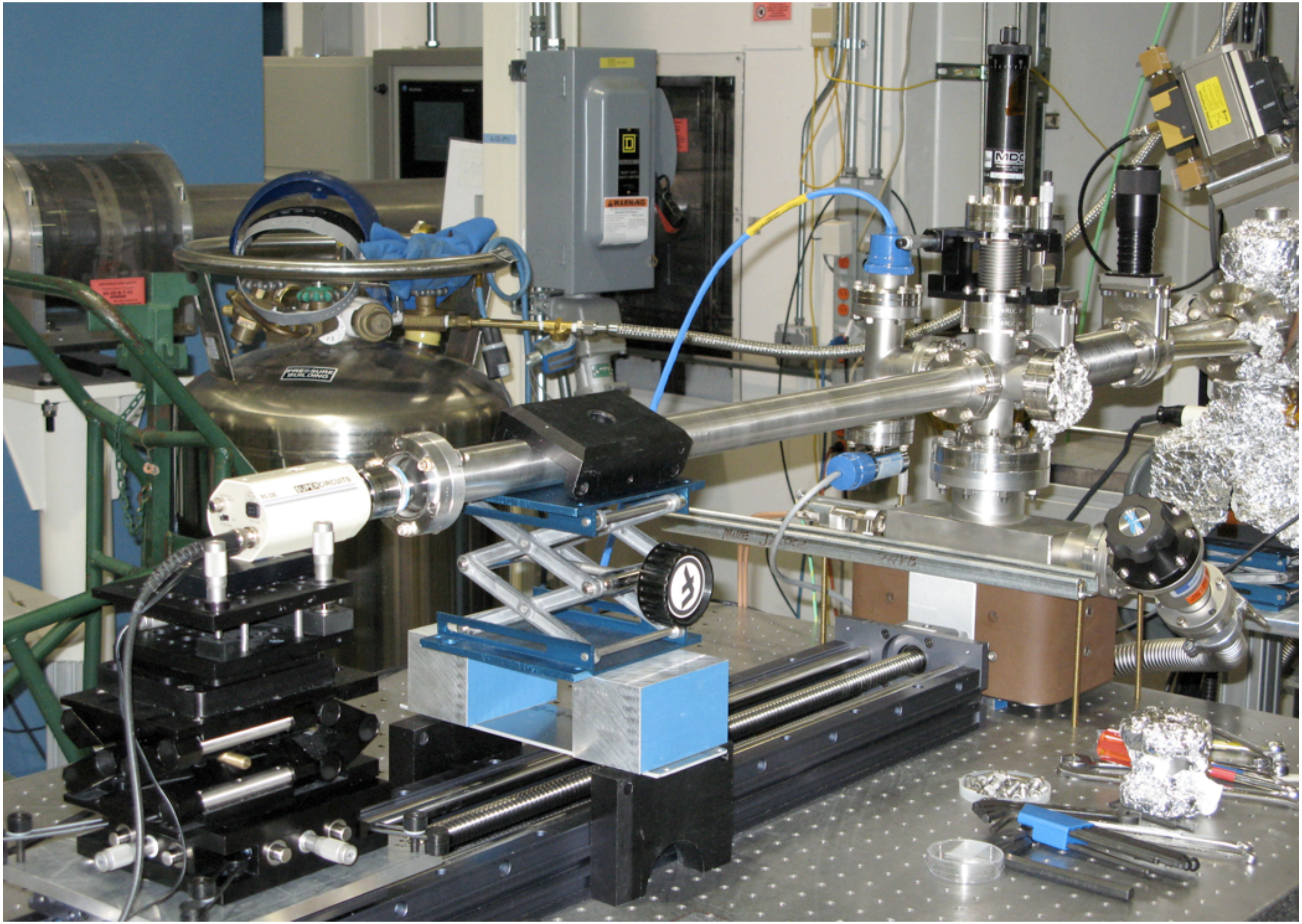




Calculated intensity for the APS Circularly Polarizing Undulator (CPU) at 50 m for K=2.77 and E=830 eV
(2.5 nm-rad, 0.1% coupling)

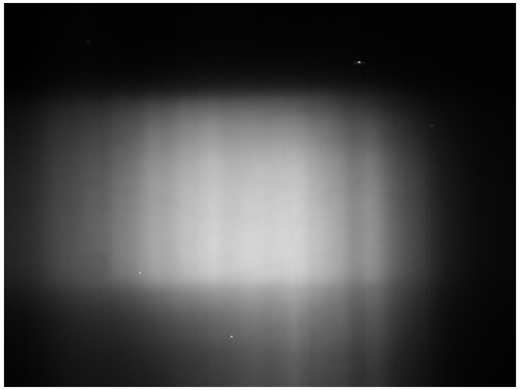
HIROSHIMA UNIVERSITY

Experiment with CPU at APS 4-ID-C beamline

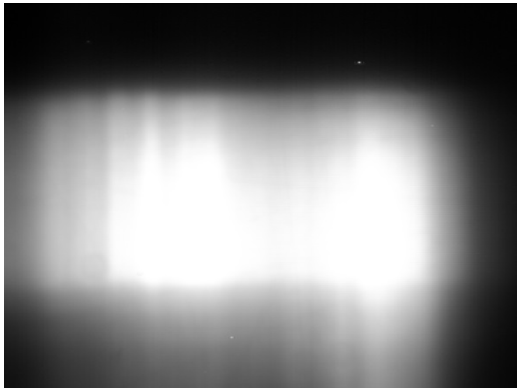


Beamline astigmatism makes life difficult

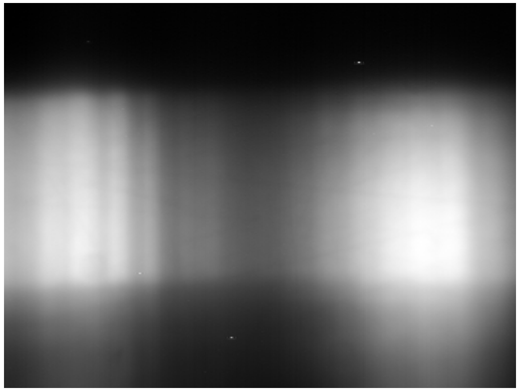
CPU, fundamental = 800 eV, 12 µm entrance, 100 µm exit slit



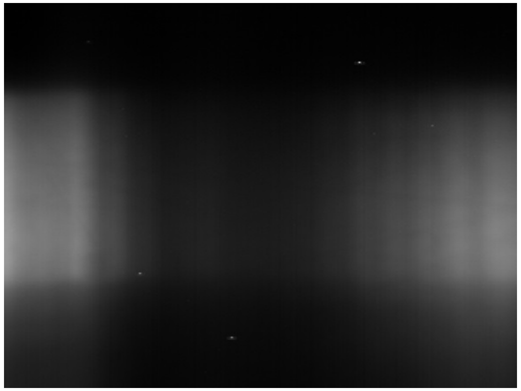
1600 eV



1550 eV



1450 eV

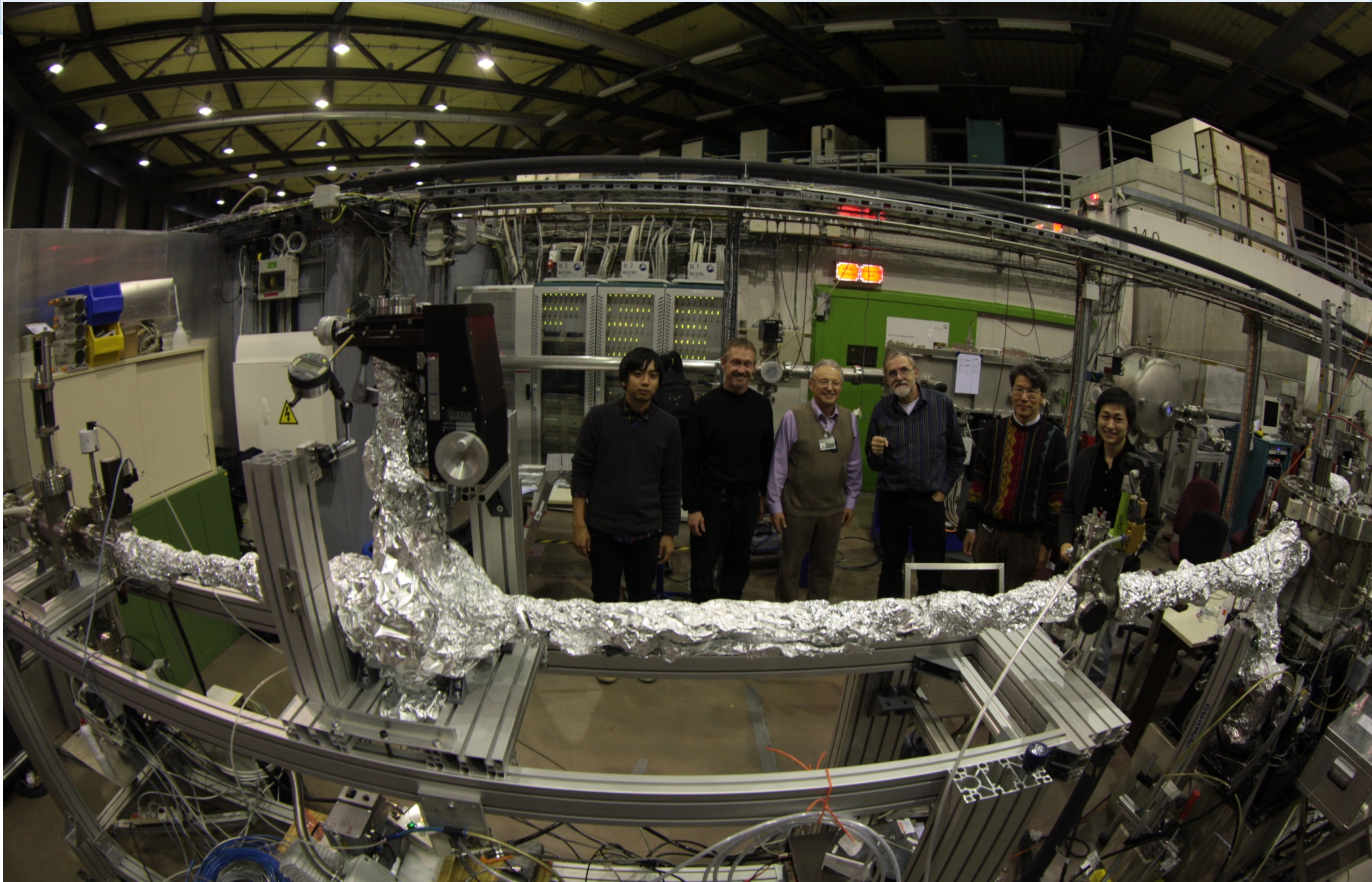


1450 eV

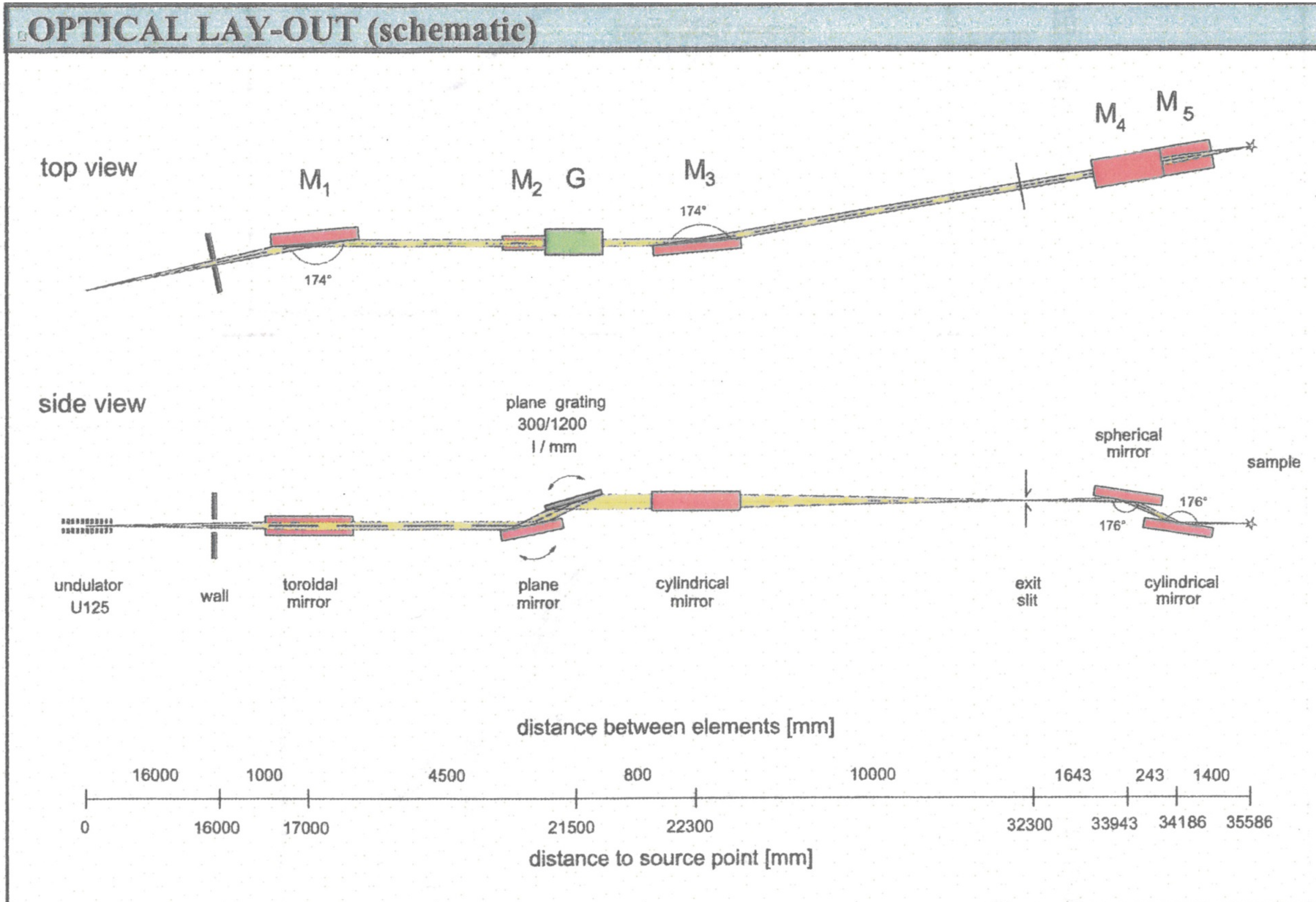
HIROSHIMA UNIVERSITY

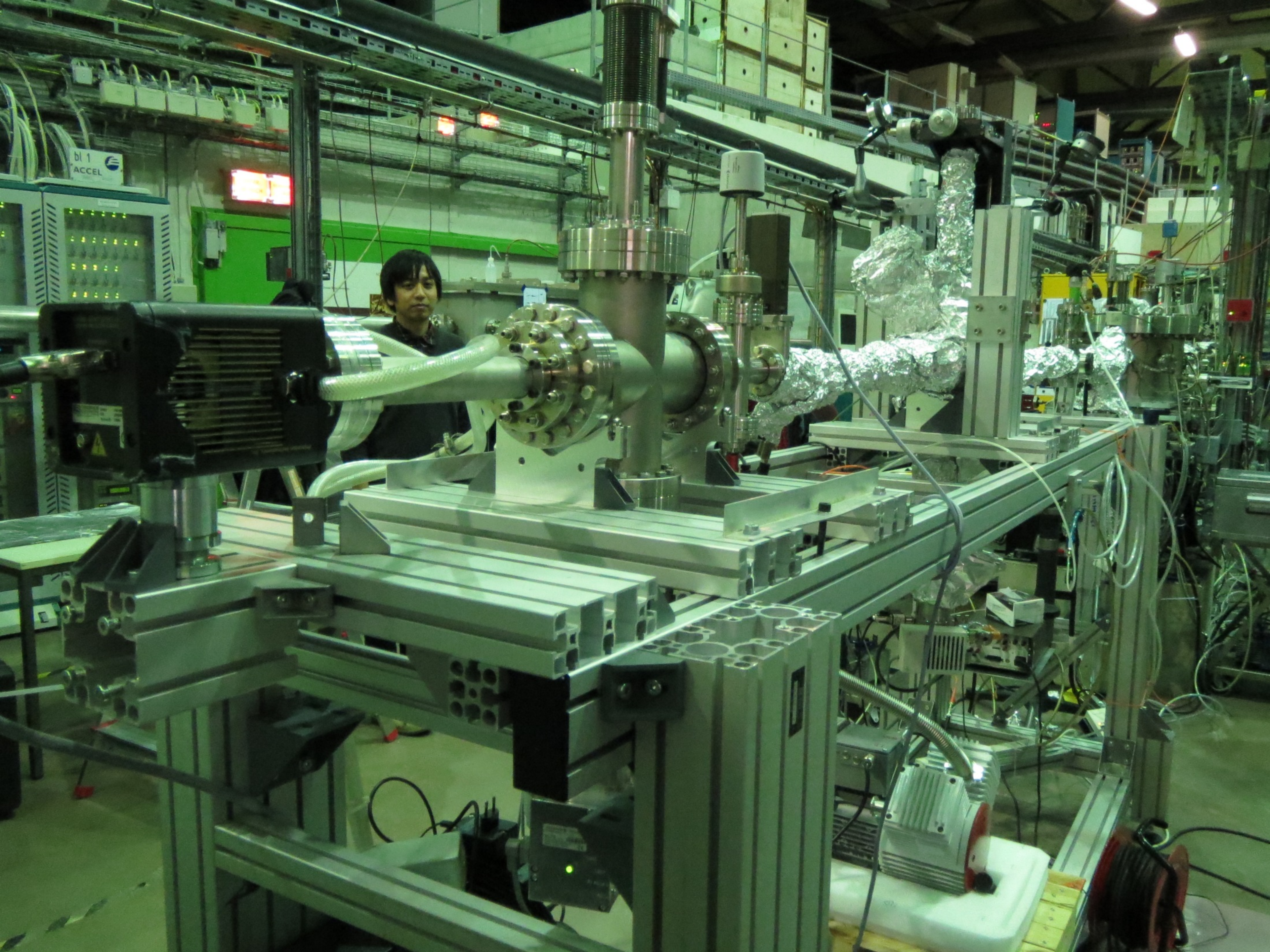
HiSOR

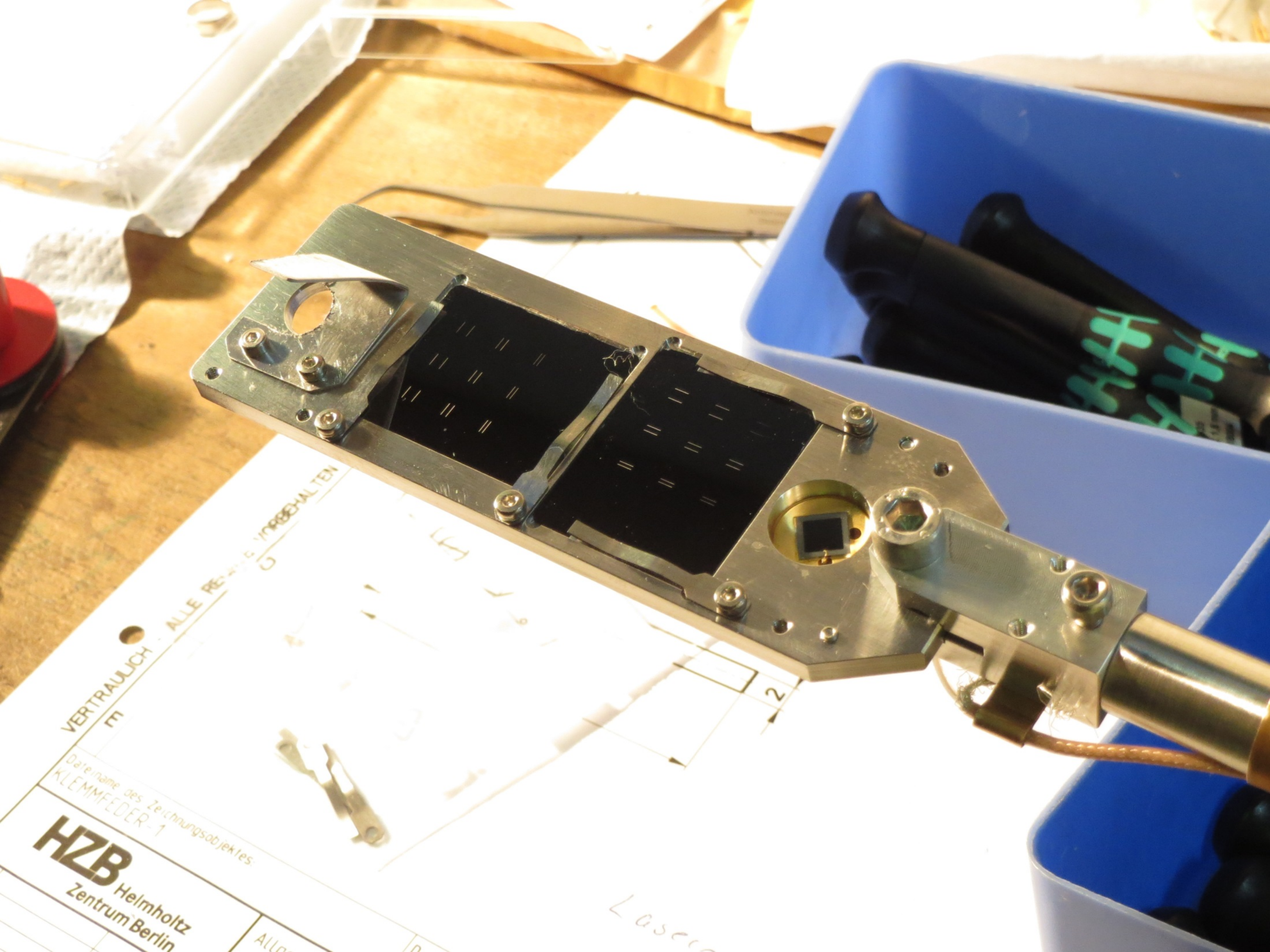
BESSY II Experiment in December, 2012



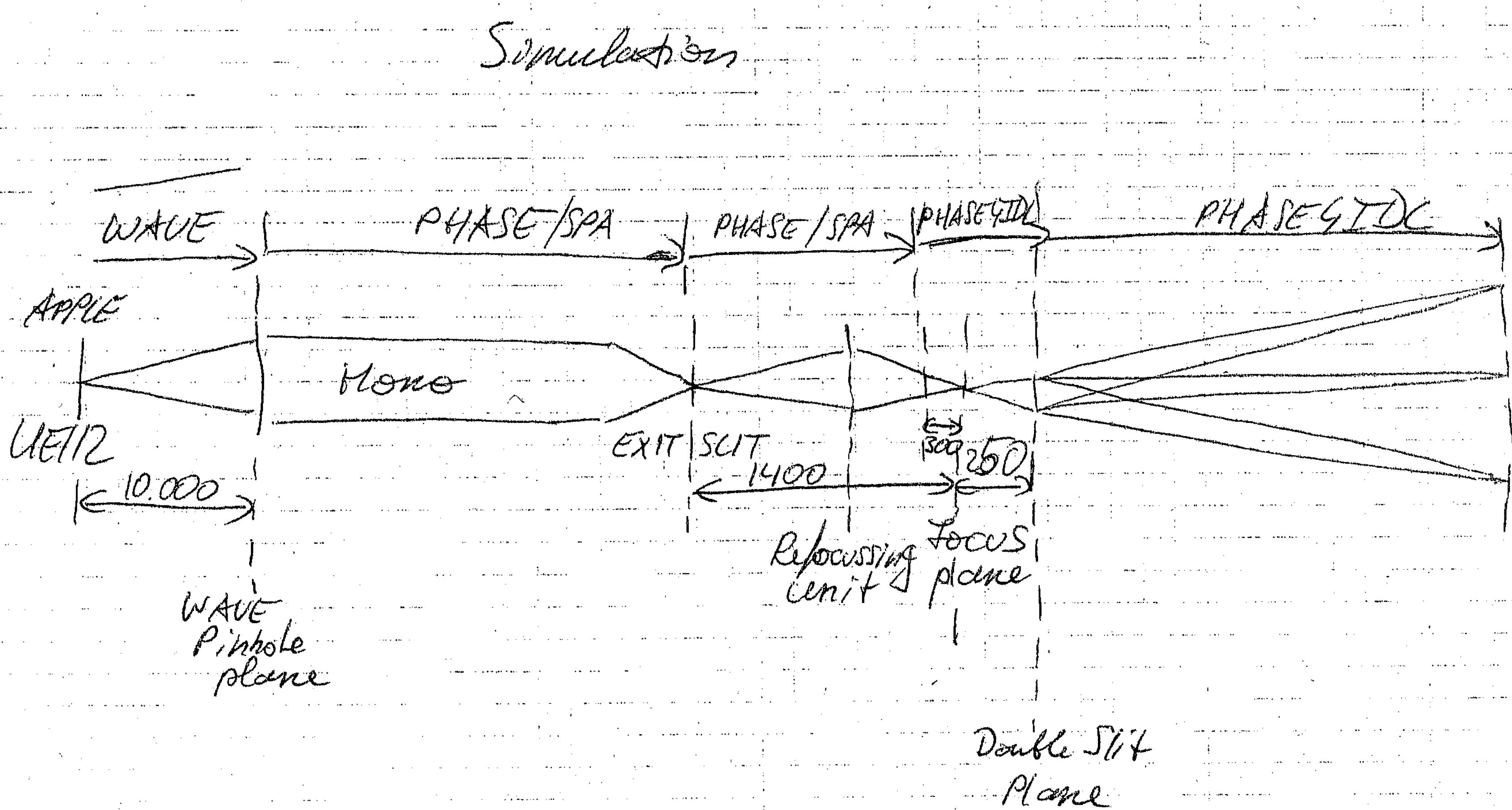
BESSY II UE112 Beamline Lay-out



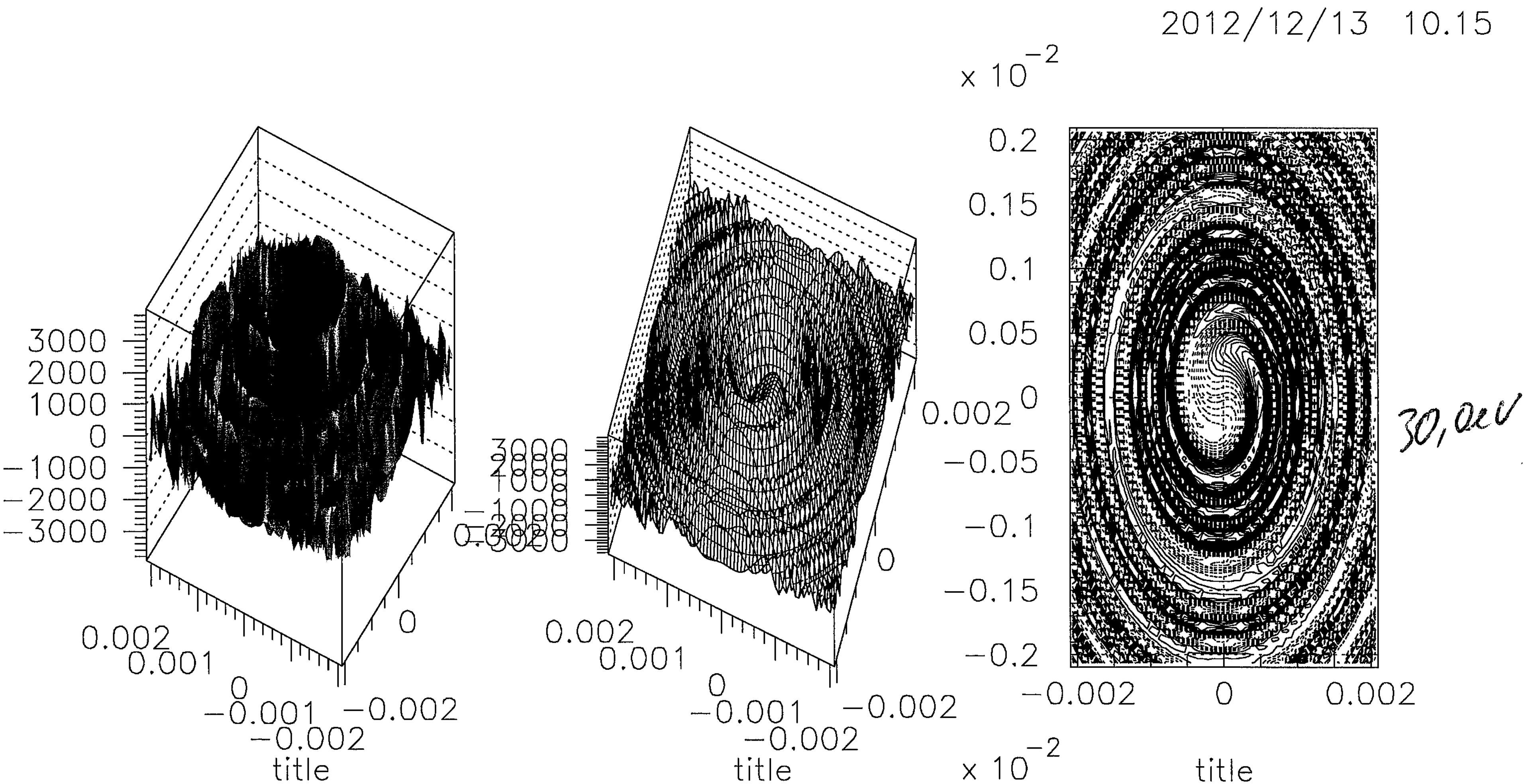

bl 1
ACCEL


VERTRAULICH
Dateiname des Zeichnungsobjektes:
KLEMMFEDER-1
HZB
Helmholtz
Zentrum Berlin
2

Computation procedures with WAVE and PHASE

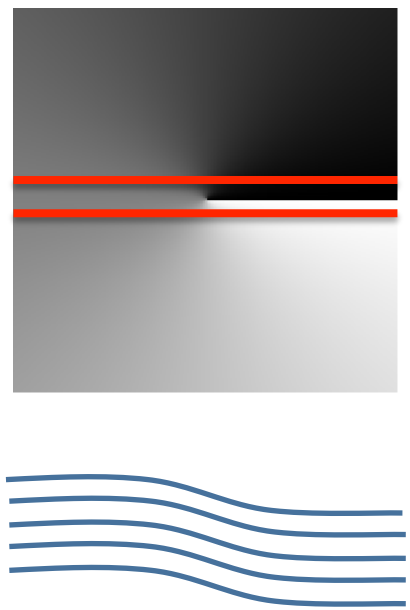


Electric Field Magnitude

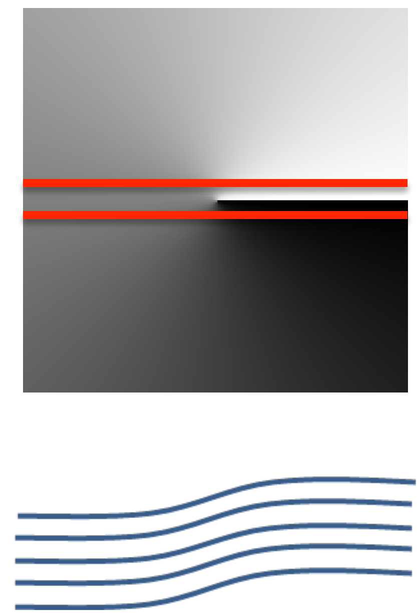


Expected Fringe Pattern

l = 1

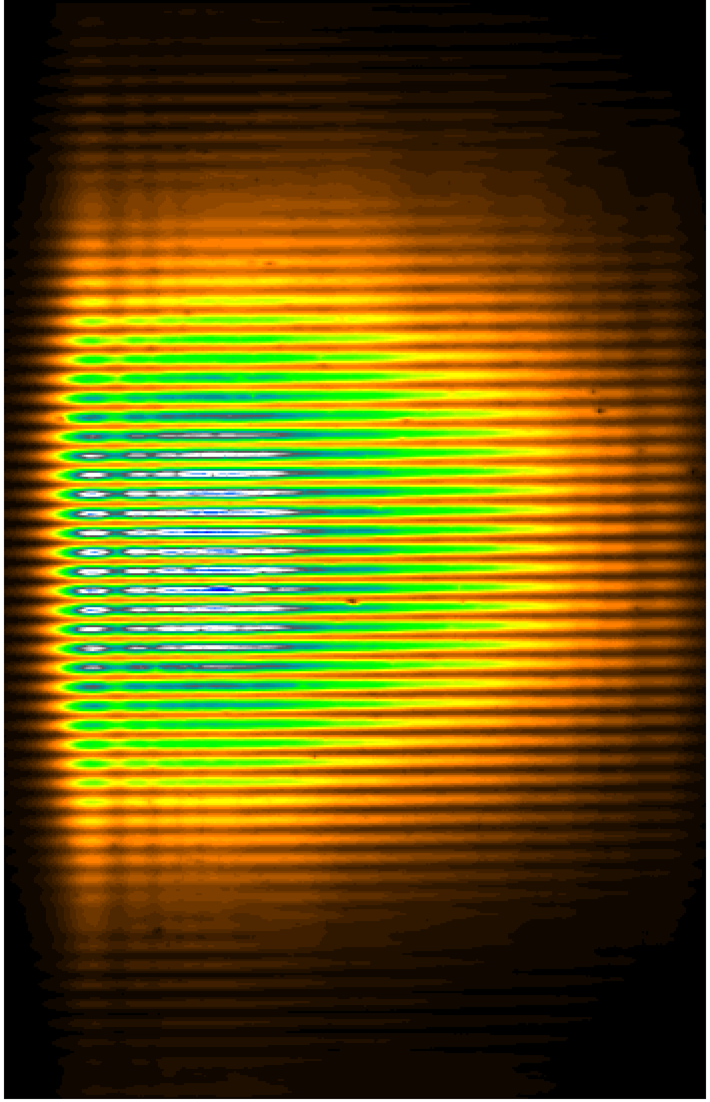


l = -1

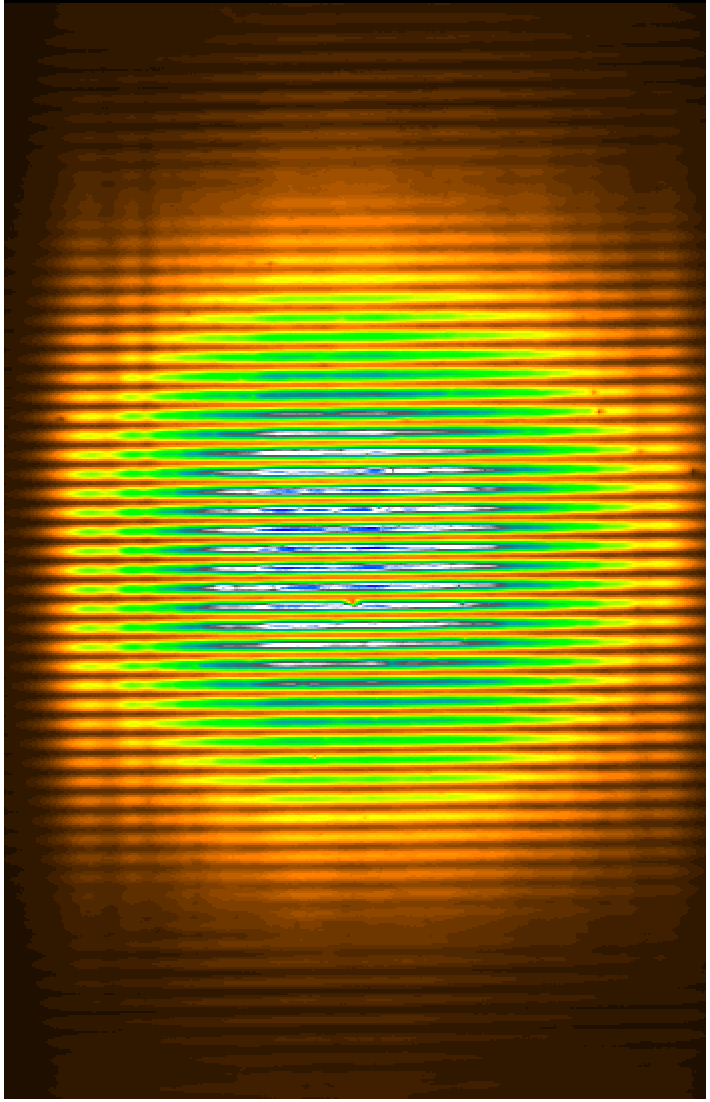


Experimental Result 1

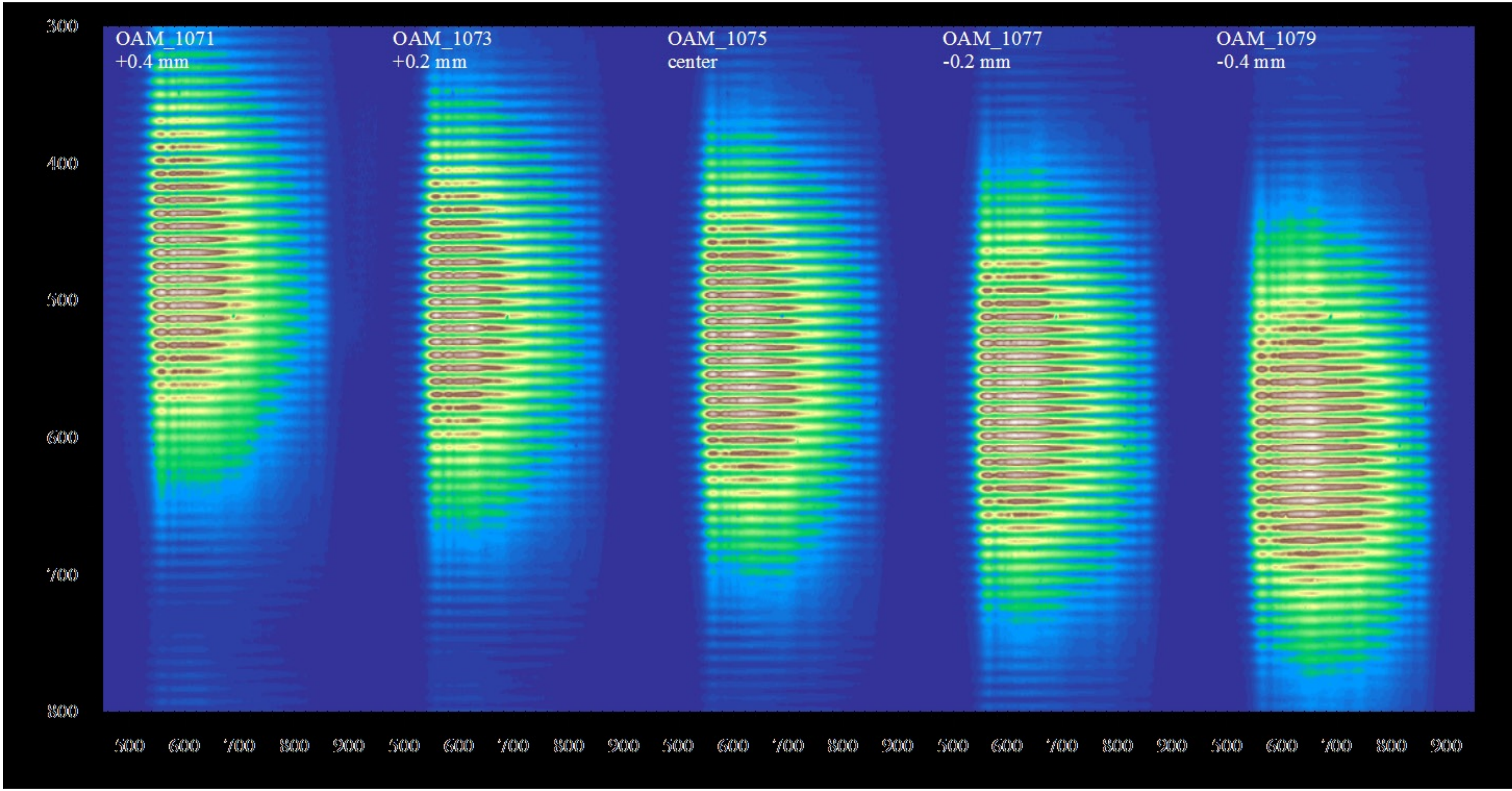
LH polarization



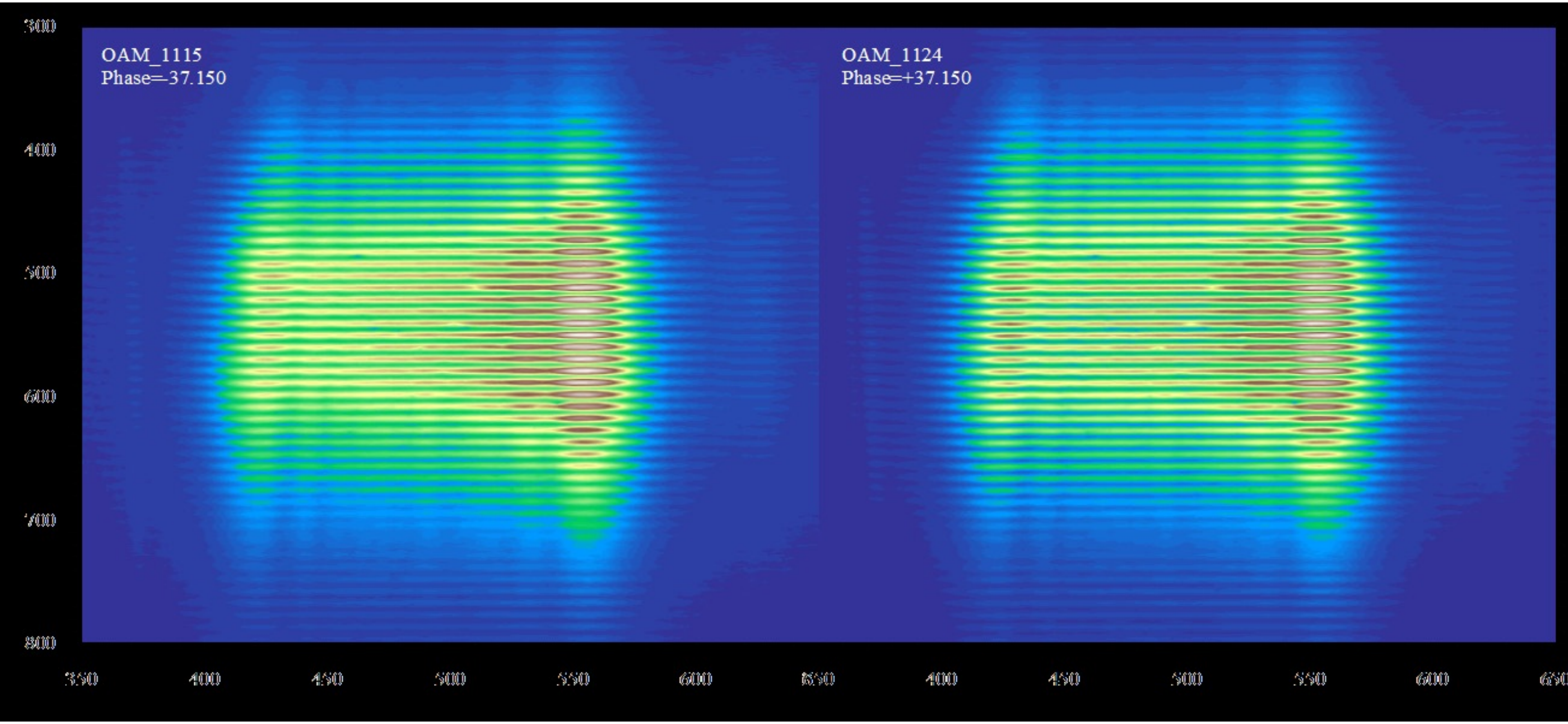
RH polarization



Experimental Result 2



Vertical center = +0.3 mm

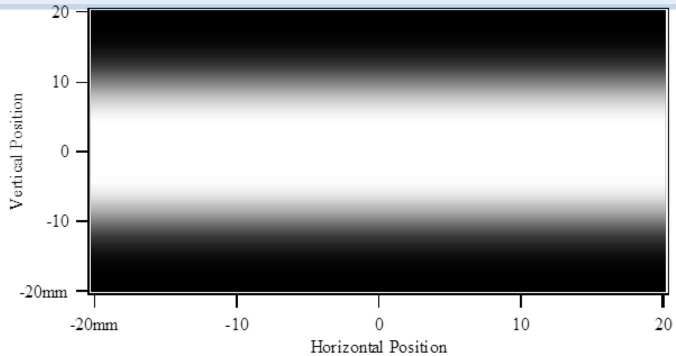


HIROSHIMA UNIVERSITY

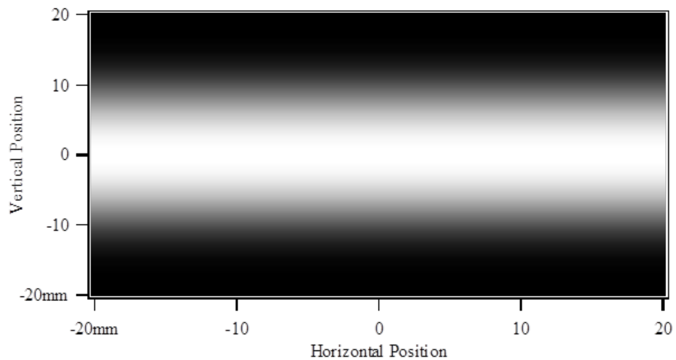
HiSOR

Bending Magnet Radiation Pattern

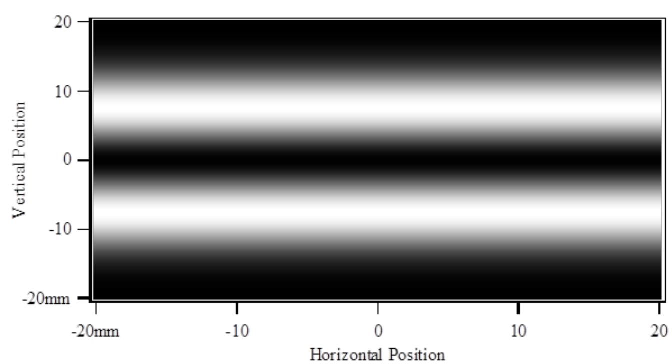
100 eV Total



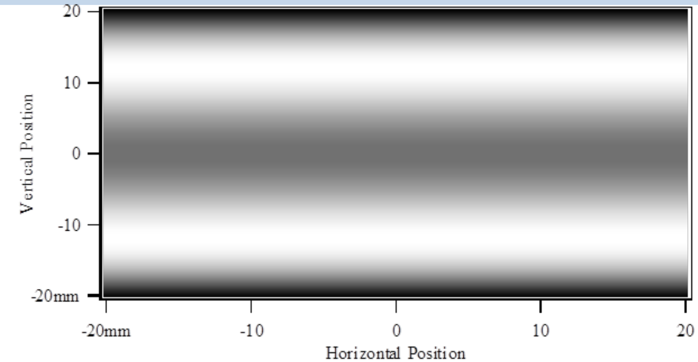
100 eV Hor. linear



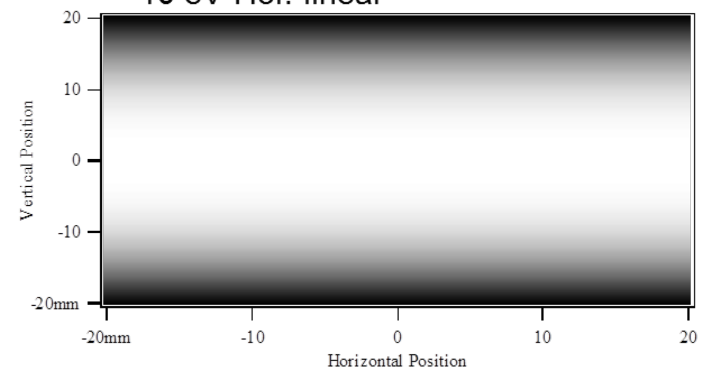
100 eV Ver. linear



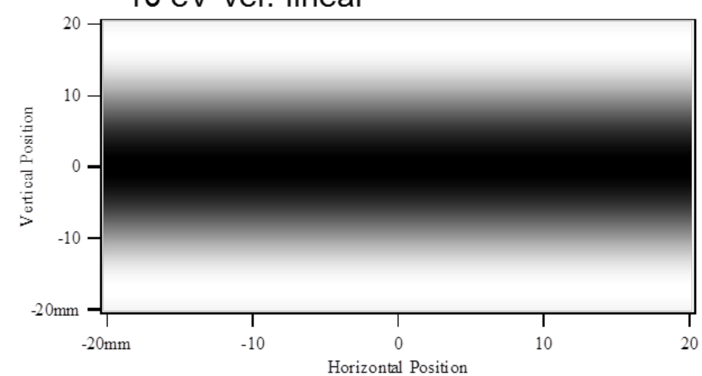
10 eV Total



10 eV Hor. linear

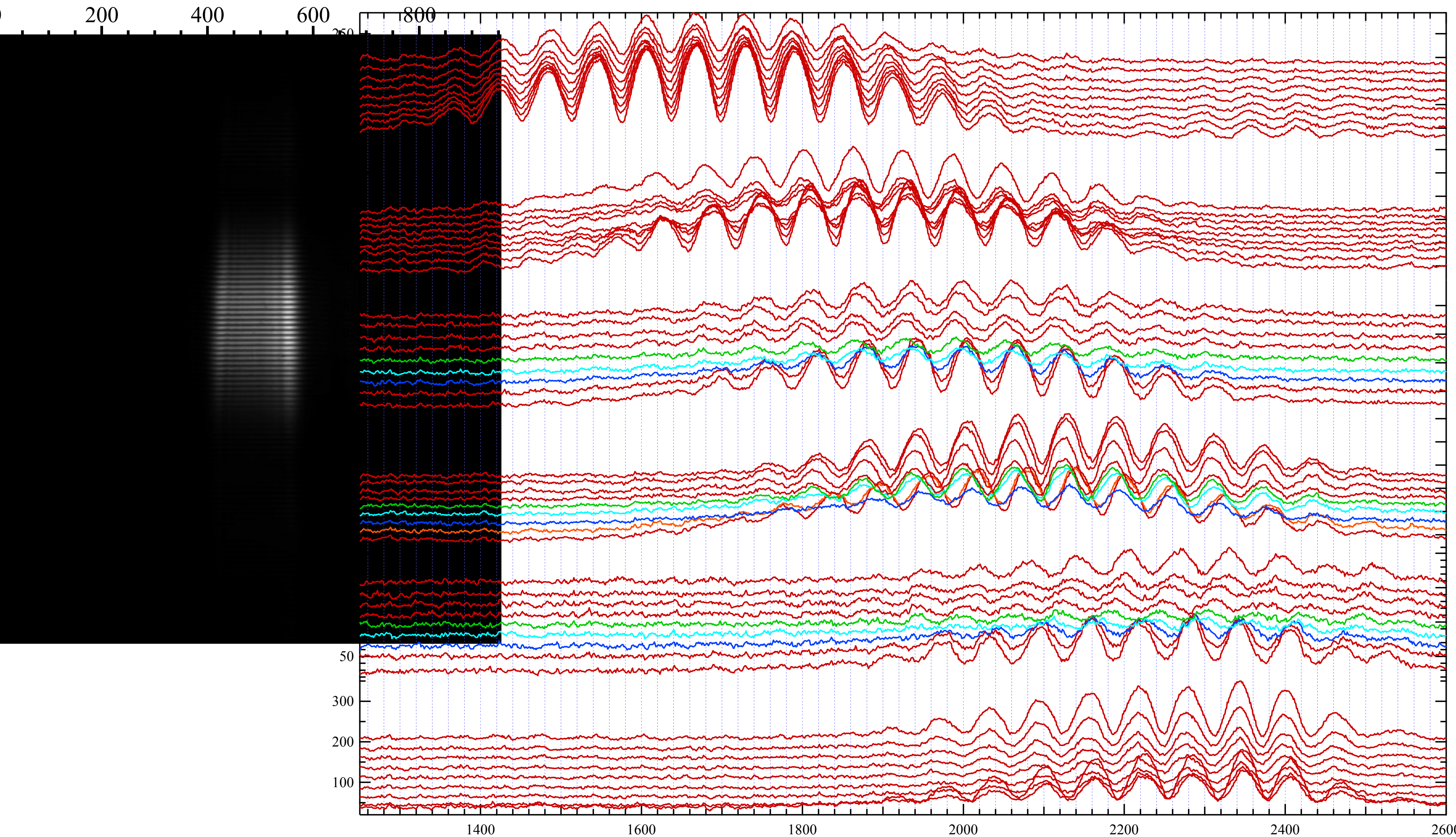


10 eV Ver. linear

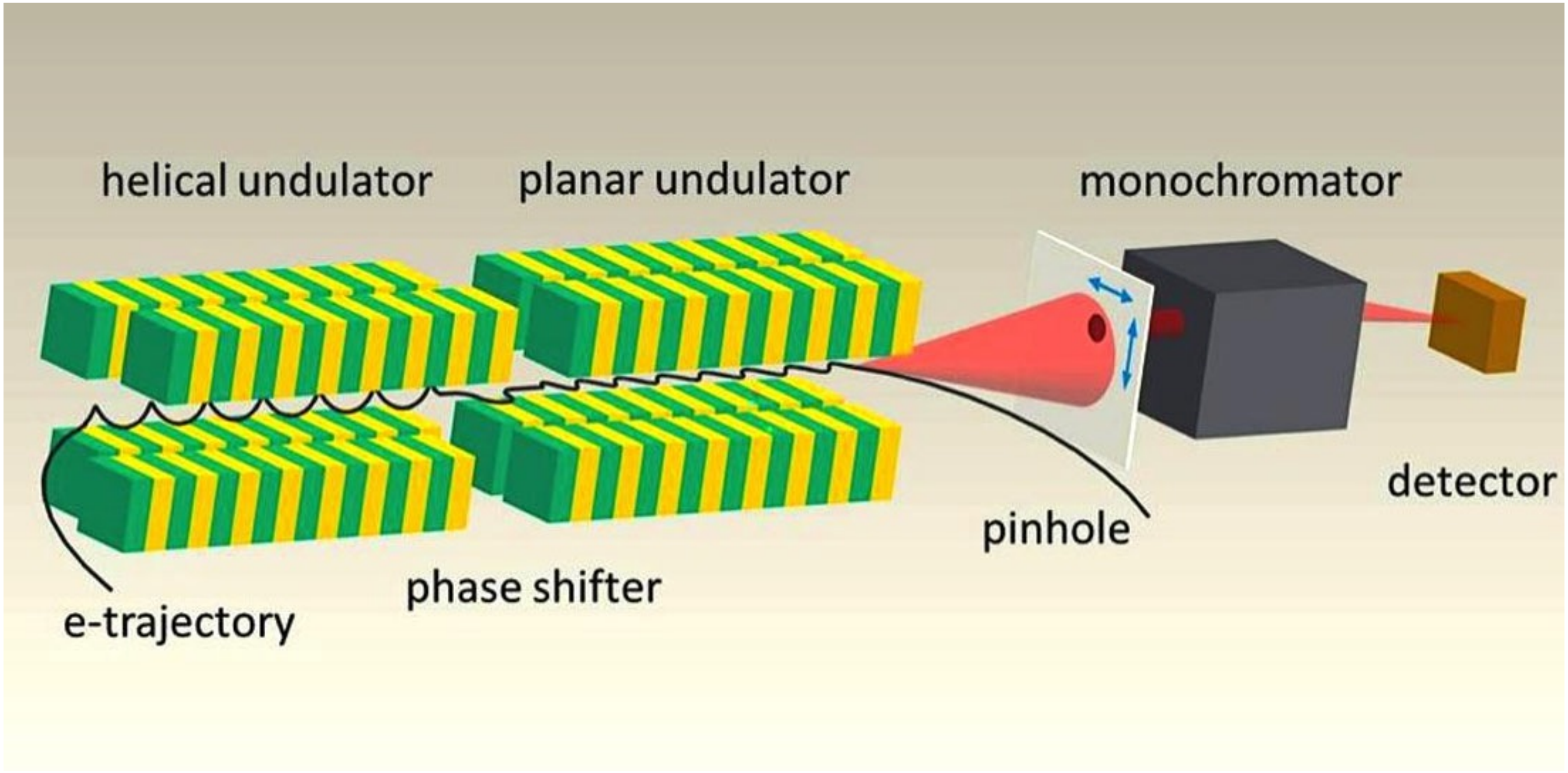


HIROSHIMA UNIVERSITY

Double-Slit Interference Pattern



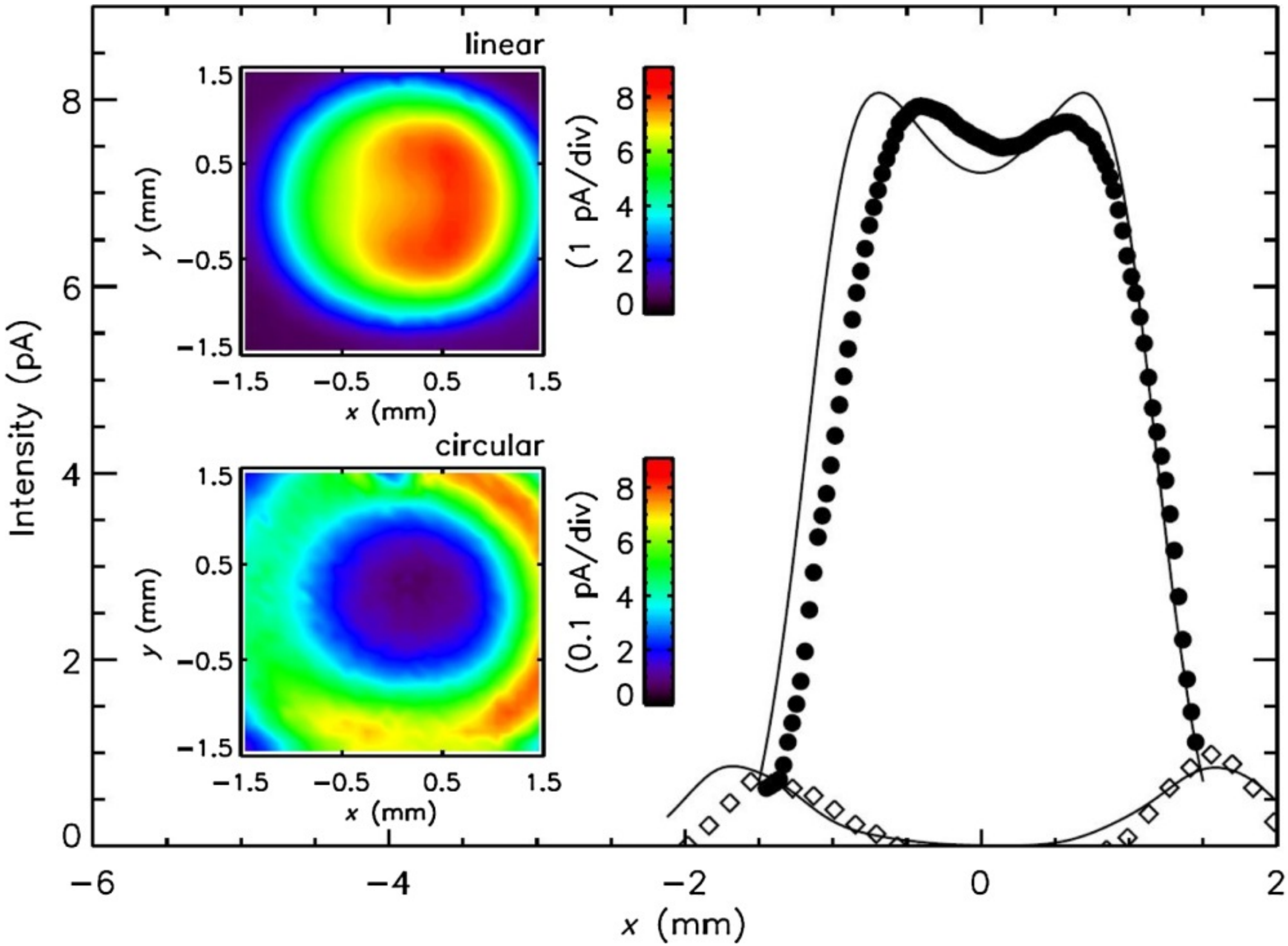
First Observation of OAM



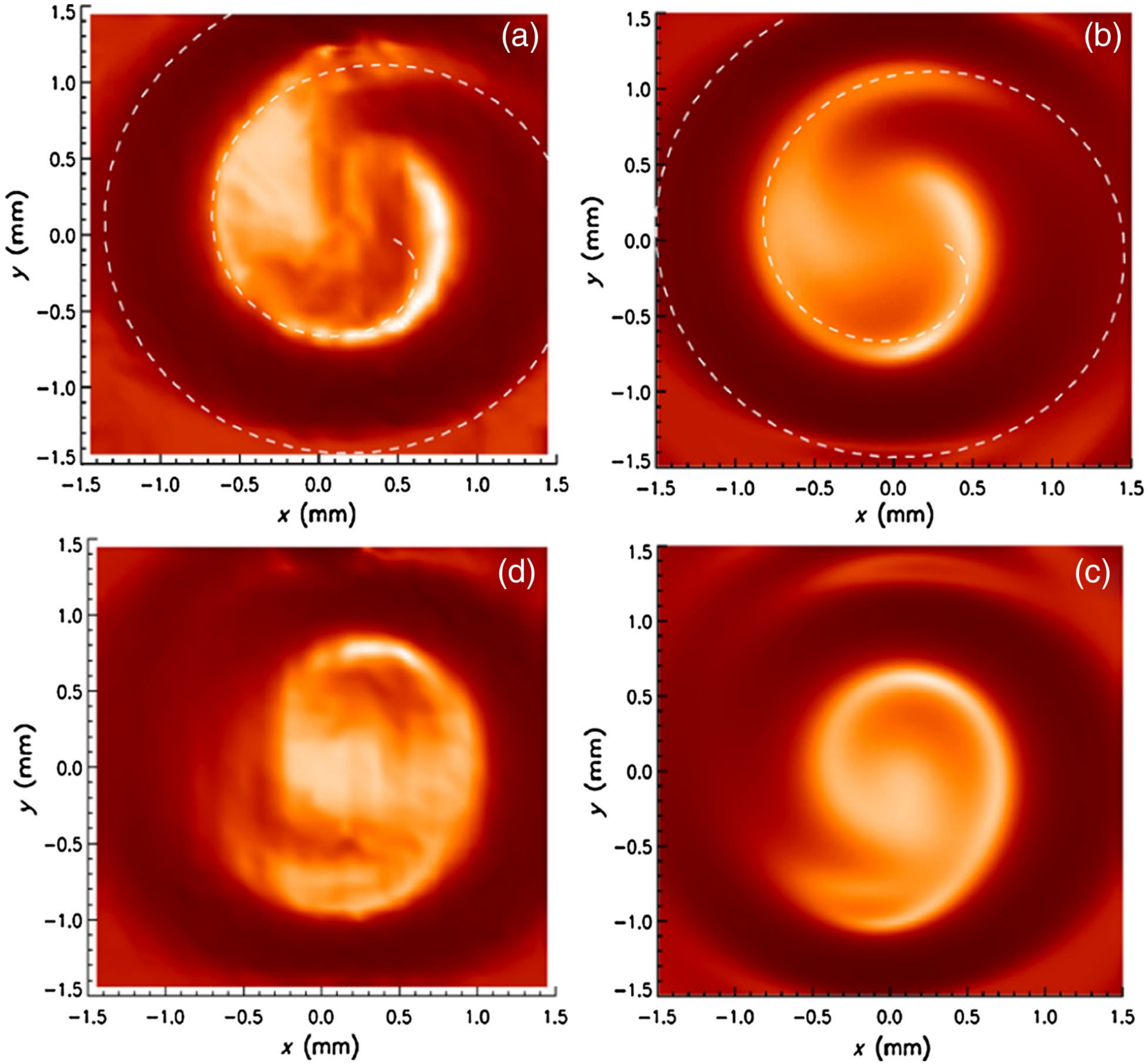
J. Bahrdt, *et. al.* Phys. Rev. Lett. **111**, 034801 (2013).

HIROSHIMA UNIVERSITY

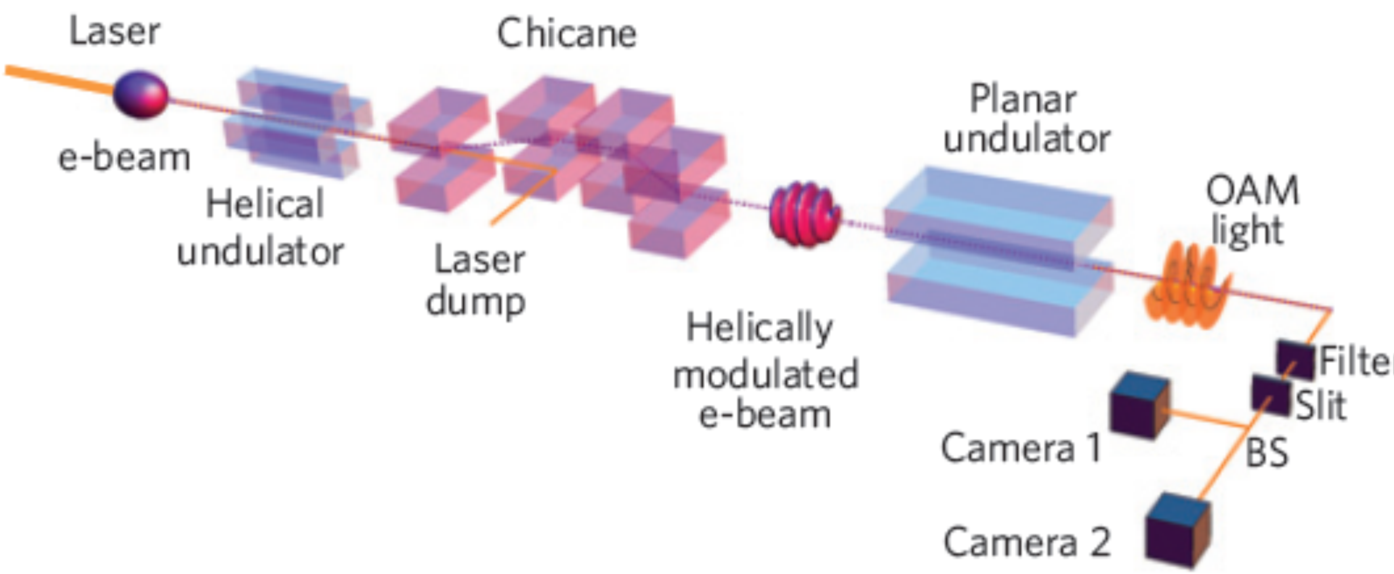
Radiation Profile



Measurement and Simulation



Coherent optical vortices from relativistic electron beams



llustration of the experiment (not to scale). The unmodulated relativistic electron beam interacts with a linearly polarized laser in a helical undulator, which gives the electrons an energy kick that depends on their position in the focused laser beam. The e-beam then traverses a longitudinally dispersive chicane that allows the electrons with higher energy to catch up to those with lower energy (momentum compaction). The result is a 'helically microbunched' beam that then radiates light with OAM at the fundamental frequency in the planar undulator.

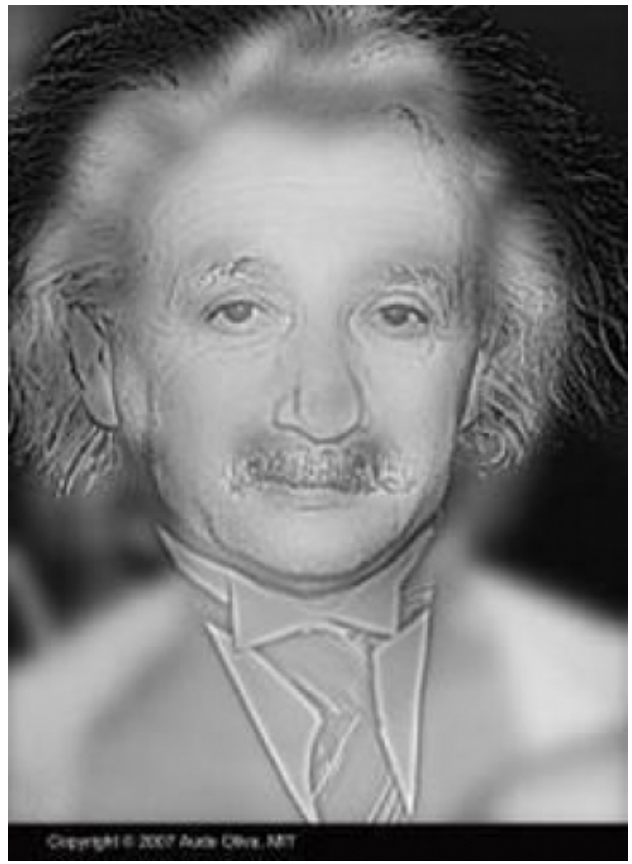
E. Hemsing, *et. al.* Nature Phys. 9, 549 (2013).

Future plans

- Experiments at UVSOR with tandem helical undulators
- Minimal optical components
- See interference pattern between two different LG modes
- Look for possible applications

Summary

A single physical phenomenon may look differently.



THANK YOU FOR YOUR ATTENTION.