Elliptically Polarizing Undulators, Quasi-Periodic Undulator, and Other types

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NSLS-II Insertion Device Group Leader
SRI2010 ID Workshop, September 20-21, 2010

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Outline

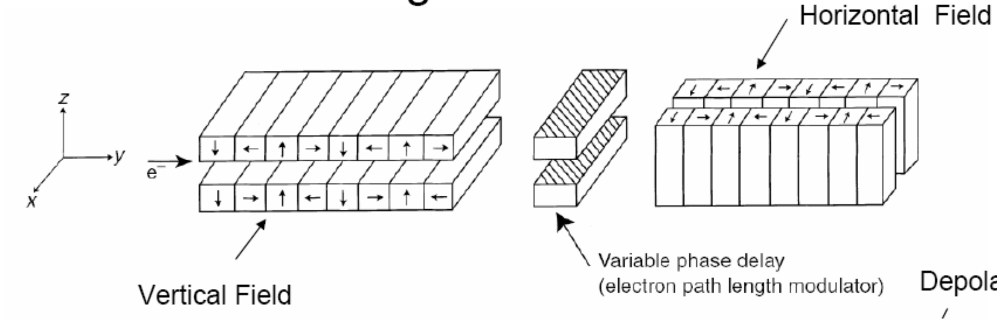
- Brief History of Variable Polarization Devices
- Apple I, II, & III?
- NSLS2 EPU spec & Non-linearity Issues
- Quasi-Periodic Undulator (QPU)
  - Principle
  - QEPU
- Figure-8 and Rhombus Type
- Revolver

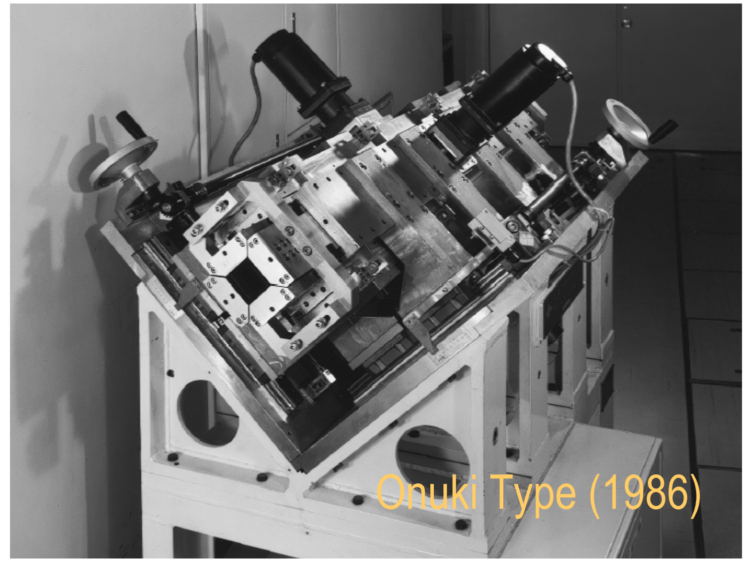
Brief History of EPU(W)s and QPUs

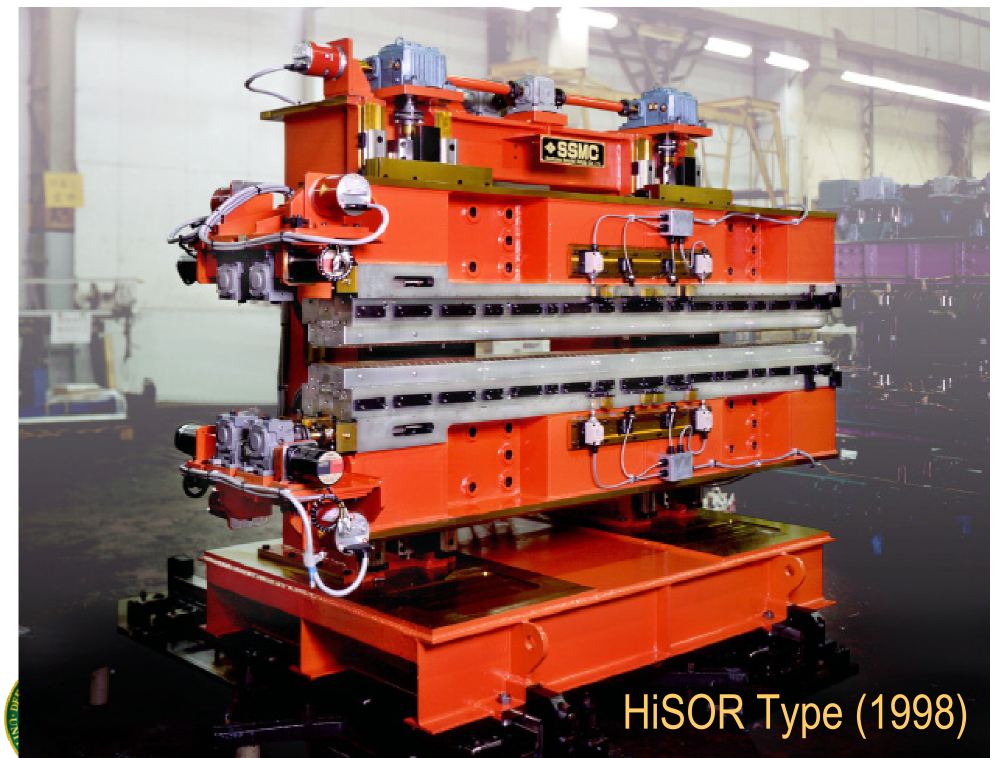
1979 Bifilar SC Undulator was operated for the 1st FEL at Stanford.
1984 Crossed Undulator concept by K. J. Kim (high harmonic on axis)
1986 Two Orthogonal Planar type by H. Onuki
1990 Helios type by P. Elleaume, similar one by B. Divianco & R. Walker
First in-vacuum undulator (IVU) was successfully operated at KEK.
1992 Apple-I type was proposed by S. Sasaki
1993 First Apple-I type device was operated at JAERI Storage Ring (JSR)
1994 First Apple-II type device was tested at SSRL
Hybrid EPW was installed at the NSLS
Concept of QPU was proposed by Sasaki & Hashimoto
1996 First QPU was installed in NIJI-IV ring
1997 One Apple-II, SP8-EPW, Dual Helical IDs with orbit switching scheme, etc. were installed at SPring-8.
2008 New EPU arrangment at KEK

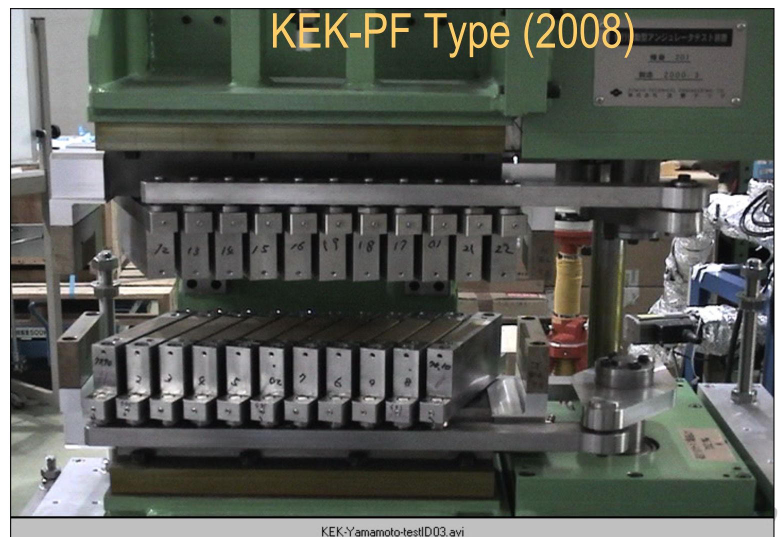
Various EPU Devices

Crossed Undulator (K.J. Kim) (1984)
Fast Switching of Polarisation

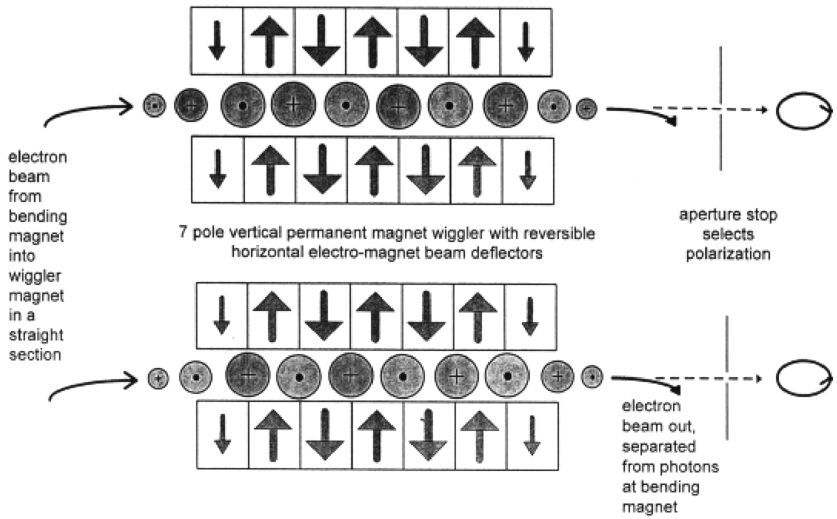


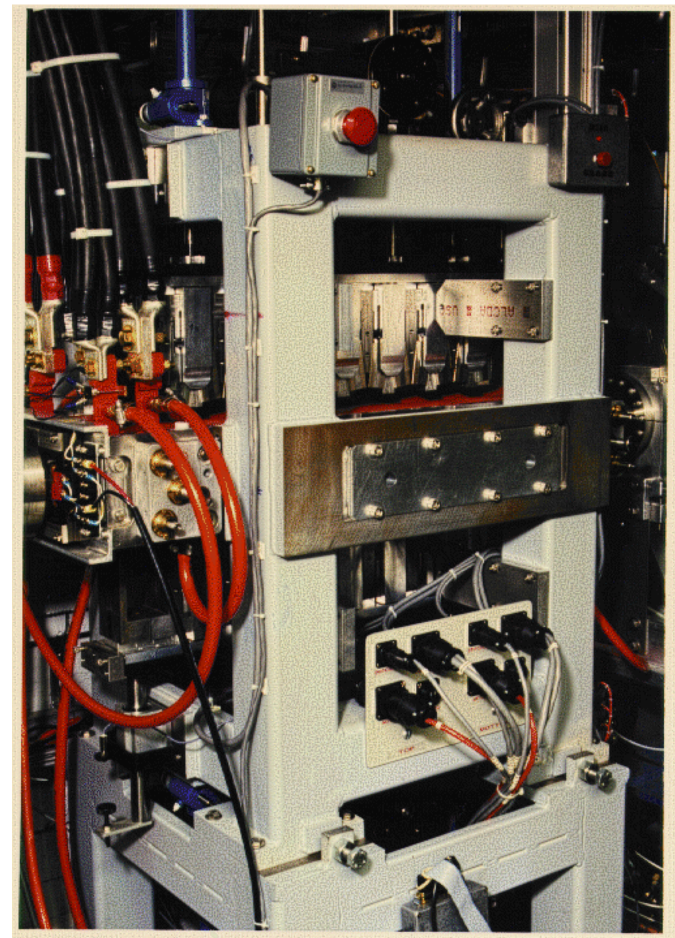






NSLS Hybrid EPW (1994)





PARAMETER	PM	EM
Magnetic period, λ_w [cm]	16	16
Number of full-strength poles, N	5	6
Peak field [T]	0.8	0-0.2
Deflection parameters: K_x, K_y	12	0-3
Magnetic gap [cm]	2.7	5.3
Chamber aperture (vert., horiz.) [cm]	2.5	5.0
Switching frequency [Hz]	0	0-100

Joint design by APS and Budker Inst.

Apple (Advanced Planar Polarized Light Emitter) Type Device

Jpn. J. Appl. Phys. Vol. 31 (1992) pp. L 1794–L 1796
Part 2, No. 12B, 15 December 1992

A New Undulator for Generating Variably Polarized Radiation

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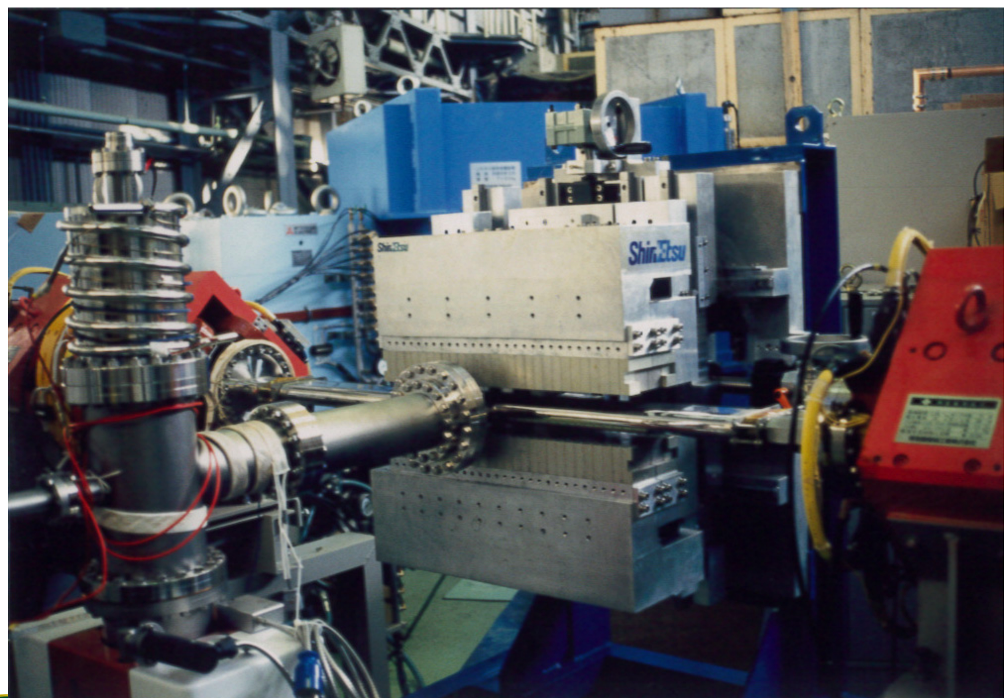
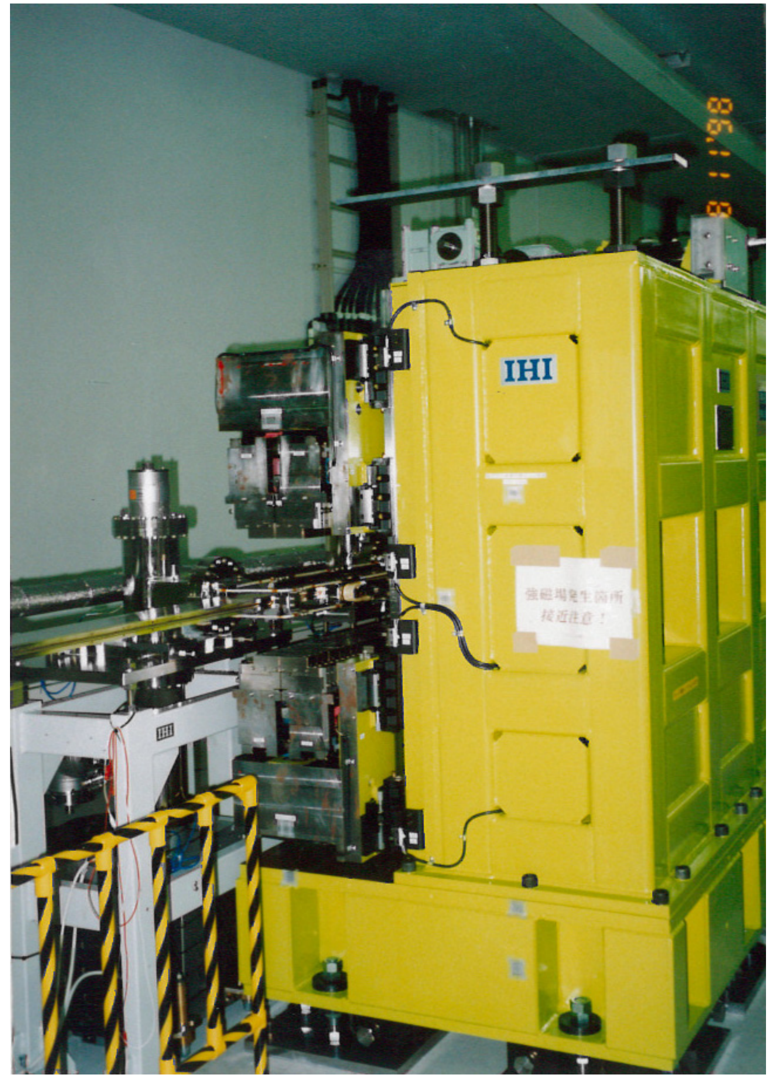
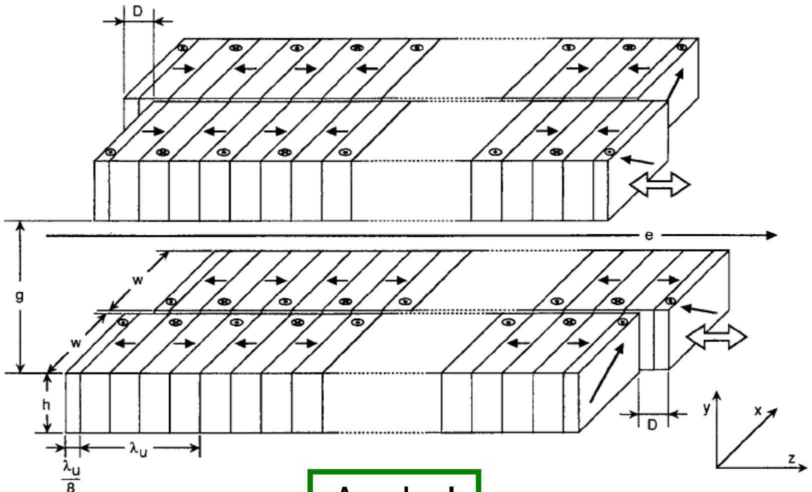


Apple-I at JSR in 1993

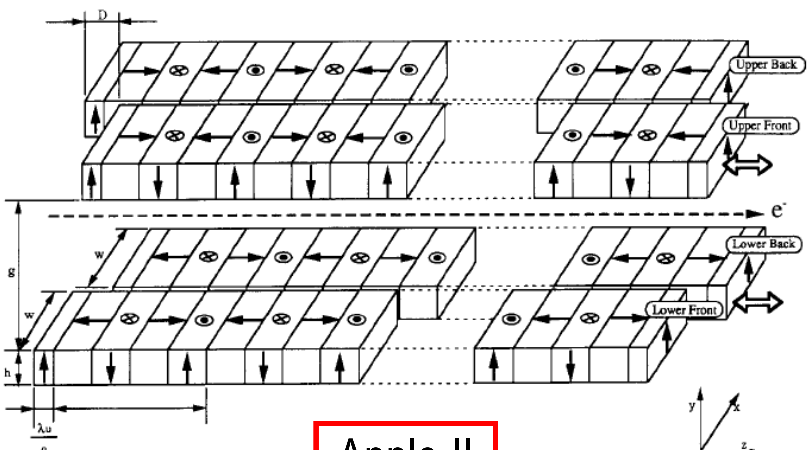


Apple-II at SPring-8
in 1996

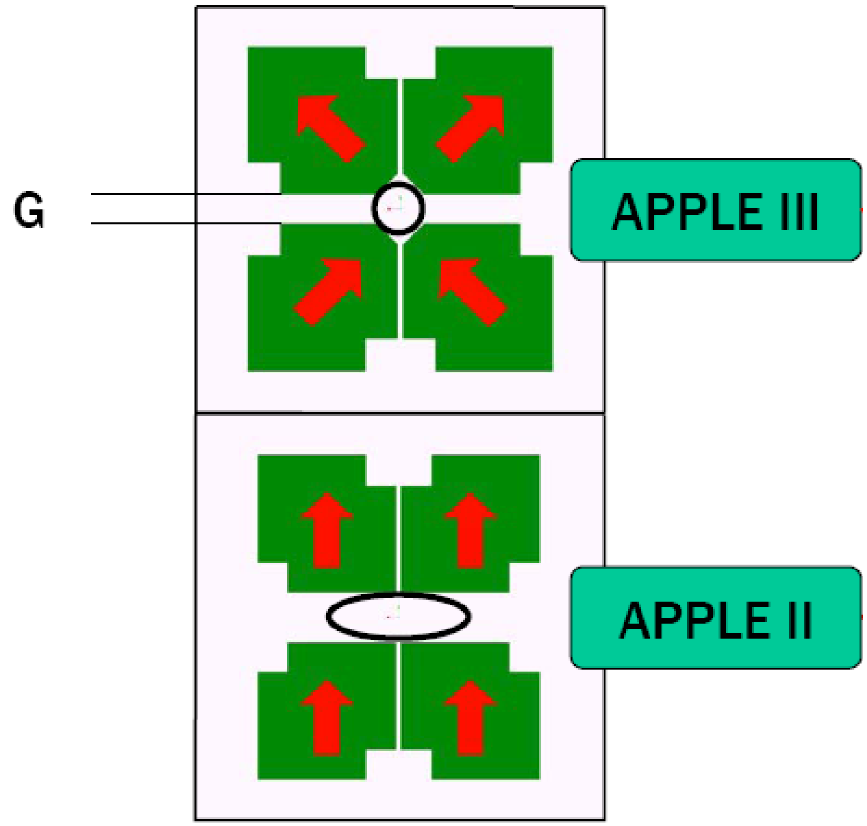
Apple I ≈ III(?)



Apple-I



Apple-II



J. Bahrdt

Two Modes of Operations (Apple-II)

Symmetric Motion : $\varphi_2 = \varphi_1 = \varphi$

$$[B_z(s), B_x(s)] = \left[4B_{z0}\cos(\frac{\varphi}{2})\cos(2\pi\frac{s}{\lambda_0}+\frac{\varphi}{2}), -4B_{x0}\sin(\frac{\varphi}{2})\sin(2\pi\frac{s}{\lambda_0}+\frac{\varphi}{2}) \right]$$

$\varphi = 0 \Rightarrow [B_z(s), B_x(s)] = \left[4B_{z0}\cos(2\pi\frac{s}{\lambda_0}), 0 \right]$: *Vertical*

$\varphi = \pi \Rightarrow [B_z(s), B_x(s)] = \left[0, -4B_{x0}\sin(2\pi\frac{s}{\lambda_0}) \right]$: *Horizontal*

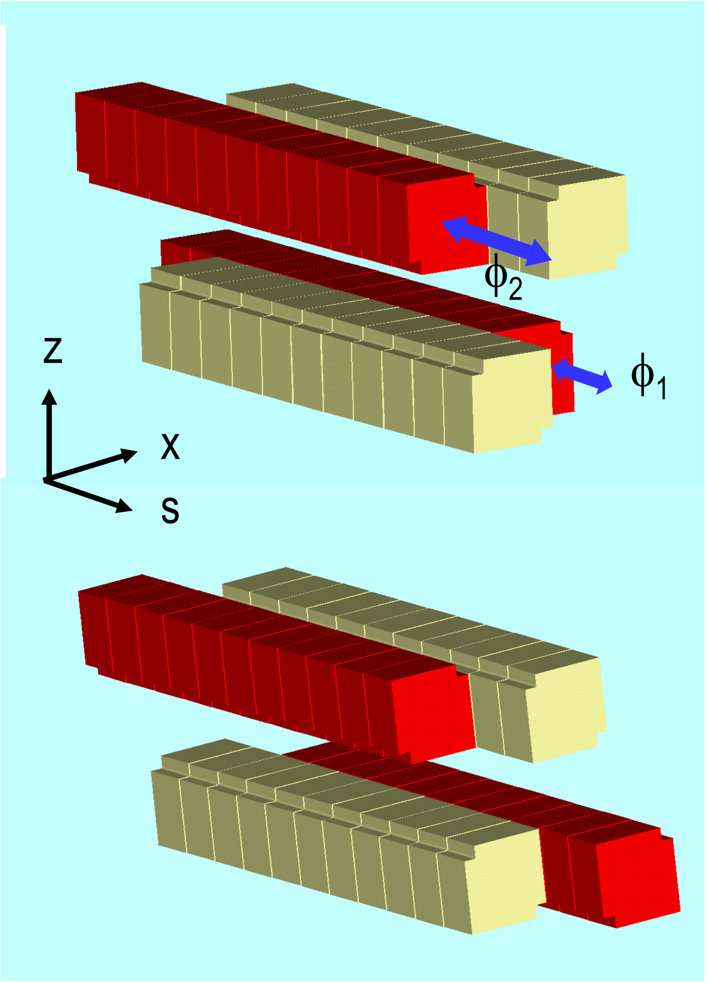
$\varphi = \arctan(\frac{B_{z0}}{B_{x0}}) \Rightarrow [B_z(s), B_x(s)] = 4B\left[\cos(2\pi\frac{s}{\lambda_0}+\frac{\varphi}{2}), -\sin(2\pi\frac{s}{\lambda_0}+\frac{\varphi}{2}) \right]$: *Helical*

Antisymmetric Motion : $\varphi_2 = -\varphi_1 = \varphi$

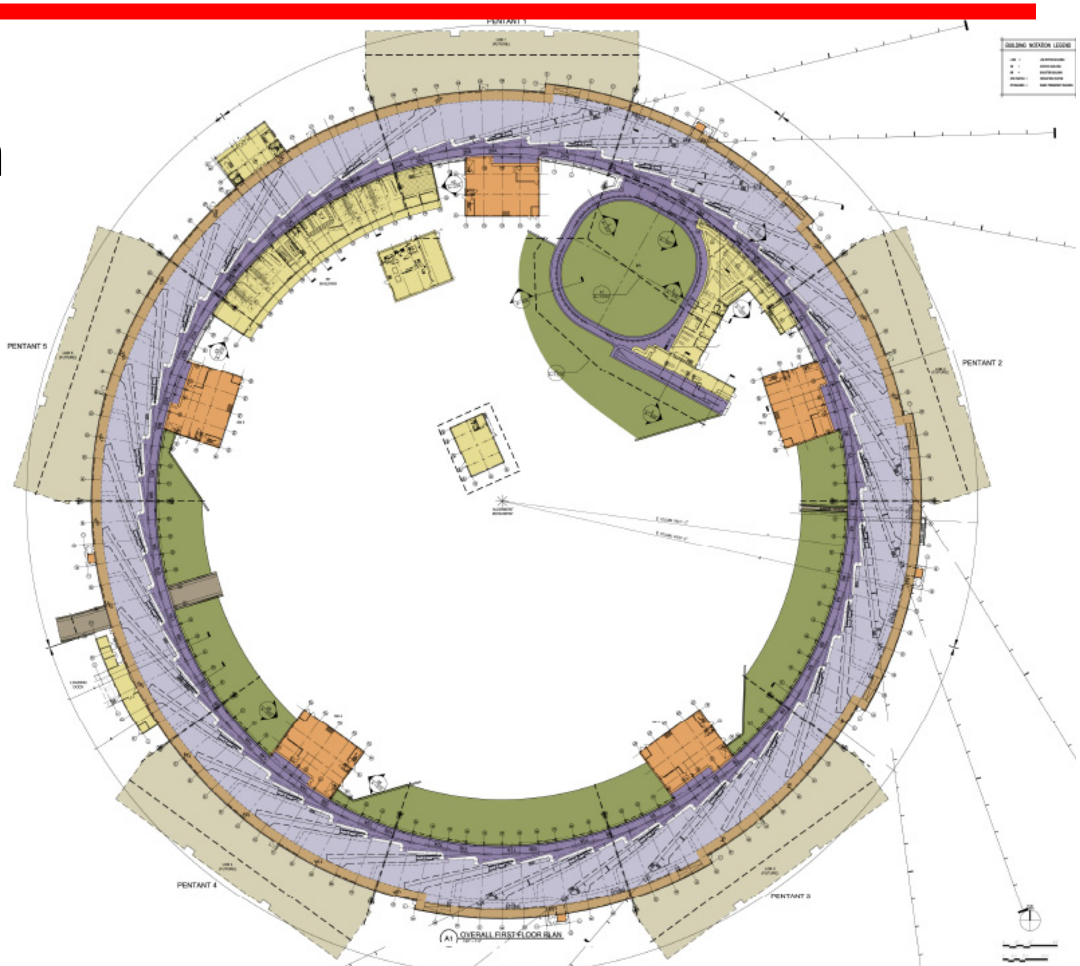
$[B_z(s), B_x(s)] = \left[4B_{z0}\cos^2(\frac{\varphi}{2}), -4B_{x0}\sin^2(\frac{\varphi}{2}) \right]\cos(2\pi\frac{s}{\lambda_0})$: *Linear*

$\varphi = 0 \Rightarrow [B_z(s), B_x(s)] = [4B_{z0}, 0]\cos(2\pi\frac{s}{\lambda_0})$: *Vertical*

$\varphi = \pi \Rightarrow [B_z(s), B_x(s)] = [0, -4B_{x0}]\cos(2\pi\frac{s}{\lambda_0})$: *Horizontal*



NSLS-II Design Features



Design Parameters
- 3 GeV, 500 mA, top-off injection
- Circumference 791.5 m
- 30 cell, Double Bend Achromat
  - 15 high-β straights (9.3 m)
  - 15 low-β straights (6.6 m)

Novel design features:
- Damping wigglers
- Soft bend magnets
- Three pole wigglers
- Large gap IR dipoles

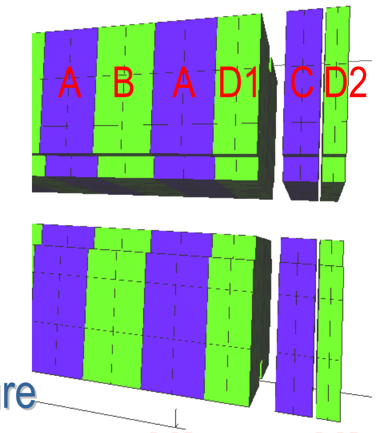
Ultra-low emittance
- ε_x, ε_y = 0.6, 0.008 nm-rad
- Diffraction limited in vertical at 12 keV
- Small beam size: σ_y = 2.6 μm, σ_x = 28 μm, σ'_y = 3.2 μrad, σ'_x = 19 μrad

Pulse Length (rms) ~ 15 psec

NSLS-II: EU49 (Ref-Design) Parameters

Undulator Parameters:

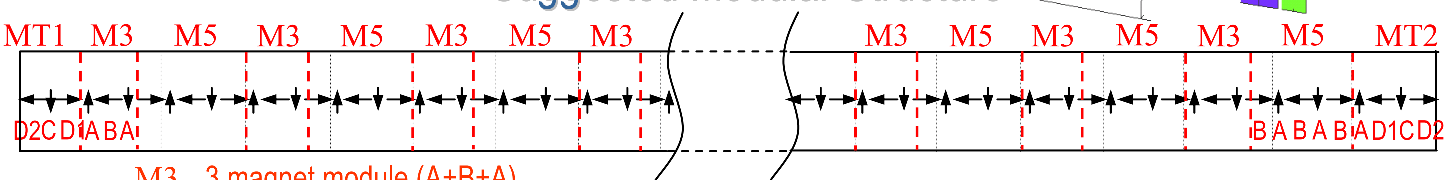
- Br = 1.25 (NdFeB)
- Main Magnet Dimensions: 34 mm (H) x 34 mm (V) x 12.25 mm (L)
- Longitudinal "Air-Gap" between Main Magnets: 50 µm
- Horizontal Gap between Magnet Arrays: 1 mm
- Period: 49.2 mm
- Number of Full Periods: **38**
- Length: ~1930 mm (without "Magic Fingers", ~1960 mm with "MF")
- Minimal Gap: 11.5 mm



Termination Magnet Thicknesses and Spaces:

- Δ_{D1} = 8.15 mm
- $\Delta_{D1\text{-}C}$ = 4.47 mm
- Δ_{C} = 6.11 mm
- $\Delta_{C\text{-}D2}$ = 0.65 mm
- Δ_{D2} = 3.82 mm

Suggested Modular Structure

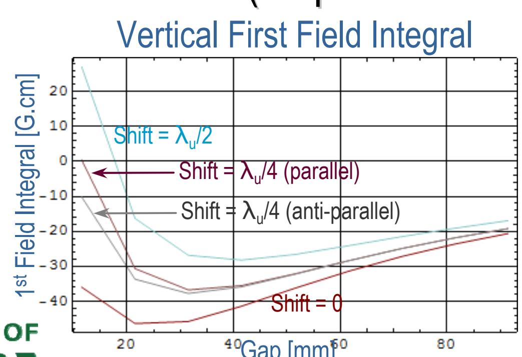


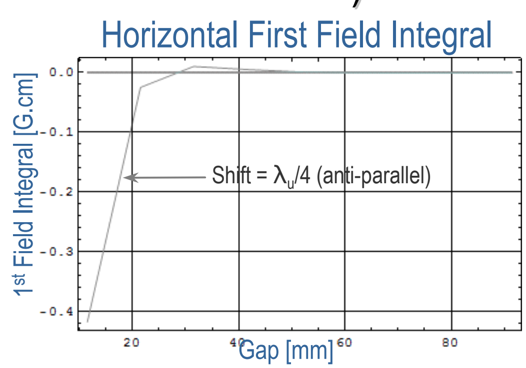
M3 - 3 magnet module (A+B+A)

M5 - 5 magnet module (B+A+B+A+B)

M3 + M5 = 2 periods

Ex. Estimated Residual Field Integrals (40 periods without Correction Coils)



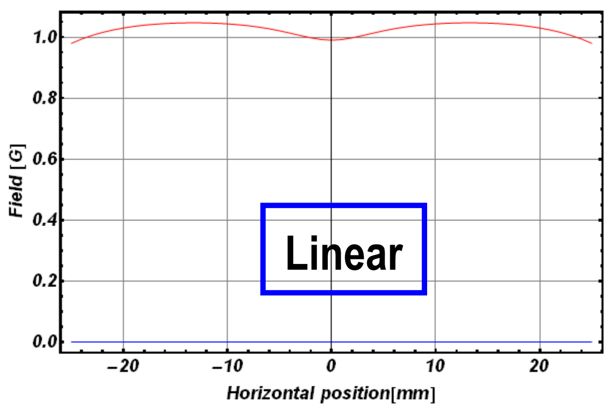


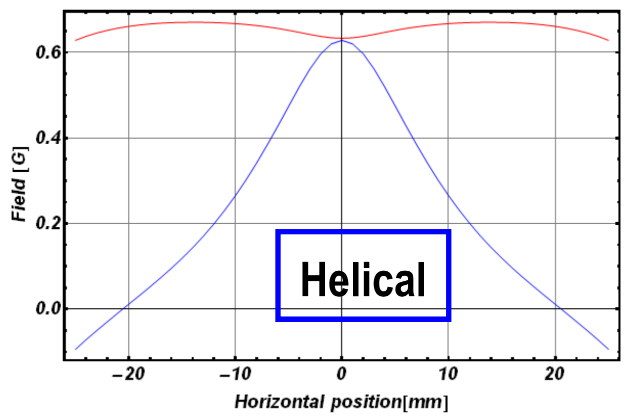
EU49 Magnet Array Specifications

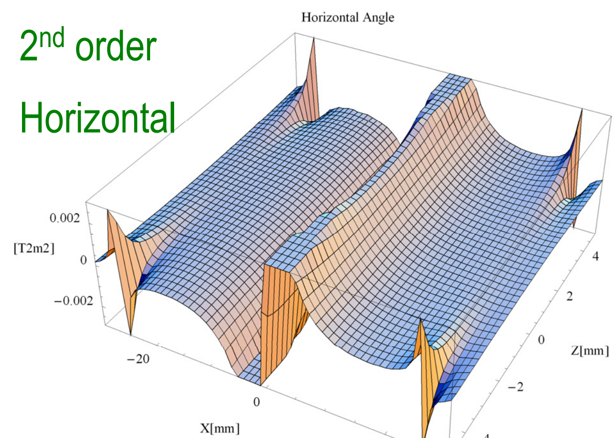
Item	Parameter
Magnet Core length	<2000 m
Period Length	49.2 mm
Minimum Transverse Magnet Size (Width x Height)	34mm x 34mm
Minimum Operational Magnetic Gap (mingap)	11.5 mm
Maximum Operational Magnetic Gap (maxgap)	40 mm
Minimum Fully Open Gap	>220 mm
Lower Energy Limit in linear horizontal mode	172eV
Lower Energy Limit in linear vertical mode	274eV
Lower Energy Limit in helical mode	211eV
Lower Energy Limit in 45 degree inclined linear mode	400 eV
RMS Phase Error in any polarization state	< 4.0 degree
1st and 2nd Integral Error Requirement (|x|<15mm, |y|=3mm), .(mingap ≤gap≤maxgap)	
$\int_{-\infty}^{\infty} By(x,y,z)dz$ (without correction coils)	<±50 G.cm
$\int_{-\infty}^{\infty} Bx(x,y,z)dz$ (without correction coils)	<±30 G.cm
$\int_{-\infty}^{\infty}\int_{-\infty}^{z} By(x,y,z')dz'dz$ (without correction coils)	<±10,000 G.cm.cm
$\int_{-\infty}^{\infty}\int_{-\infty}^{z} By(x,y,z')dz'dz$ (without correction coils))	<±5,000 G.cm.cm
On-axis Electron Trajectory Requirements for E=3GeV at any longitudinal position	|x|<30 μm, |y|<3 μm and |y'|<10 μrad
Integrated Multipole Requirement (|x|<12 mm, y = 0 mm), (mingap ≤gap≤maxgap)	Definition of Multipole Expansion about (x = x0, y = 0)* $\int_{-\infty}^{\infty} dz(B_y + iB_x) \equiv \sum_{n=0}^{\infty}(b_n(x_0) + ia_n(x_0))(x - x_0 + iy)^n$
Normal quadrupole (b1(x0))	≤50 G
Skew quadrupole (a1(x0))	≤50 G
Normal sextupole (b2(x0))	≤50 G/cm
Skew sextupole (a2(x0))	≤50 G/cm
Normal octupole (b3(x0))	≤50 G/cm/cm
Skew octupole (a3(x0))	≤50 G/cm/cm

Issues for Apple-II EPU

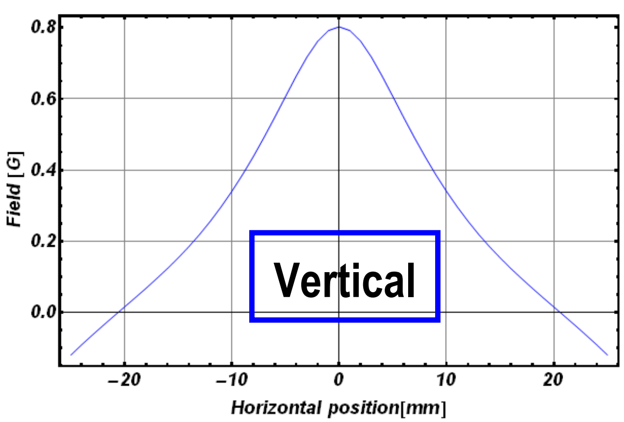
- Strong Horizontal De-focusing due to Narrow Bx good field region
- 2nd Order Kick which is responsible for dynamic multipole becomes non-negligible for low energy machine and/or long period device
- Varying skew quad components with phase change requires skew quadrupole correction
- Difficulty to achieve low phase error (<3 degree) for all the polarization cases

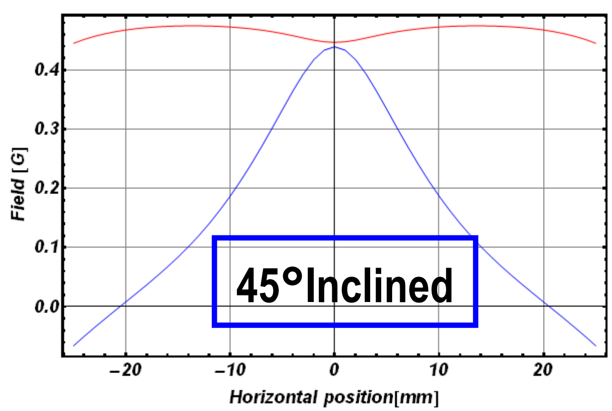


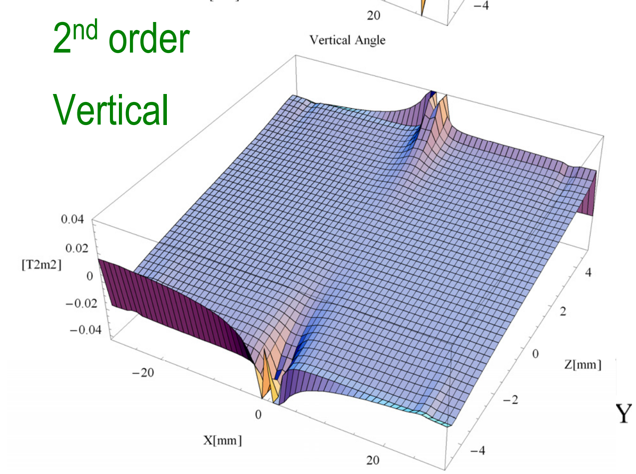




55mm period EPU

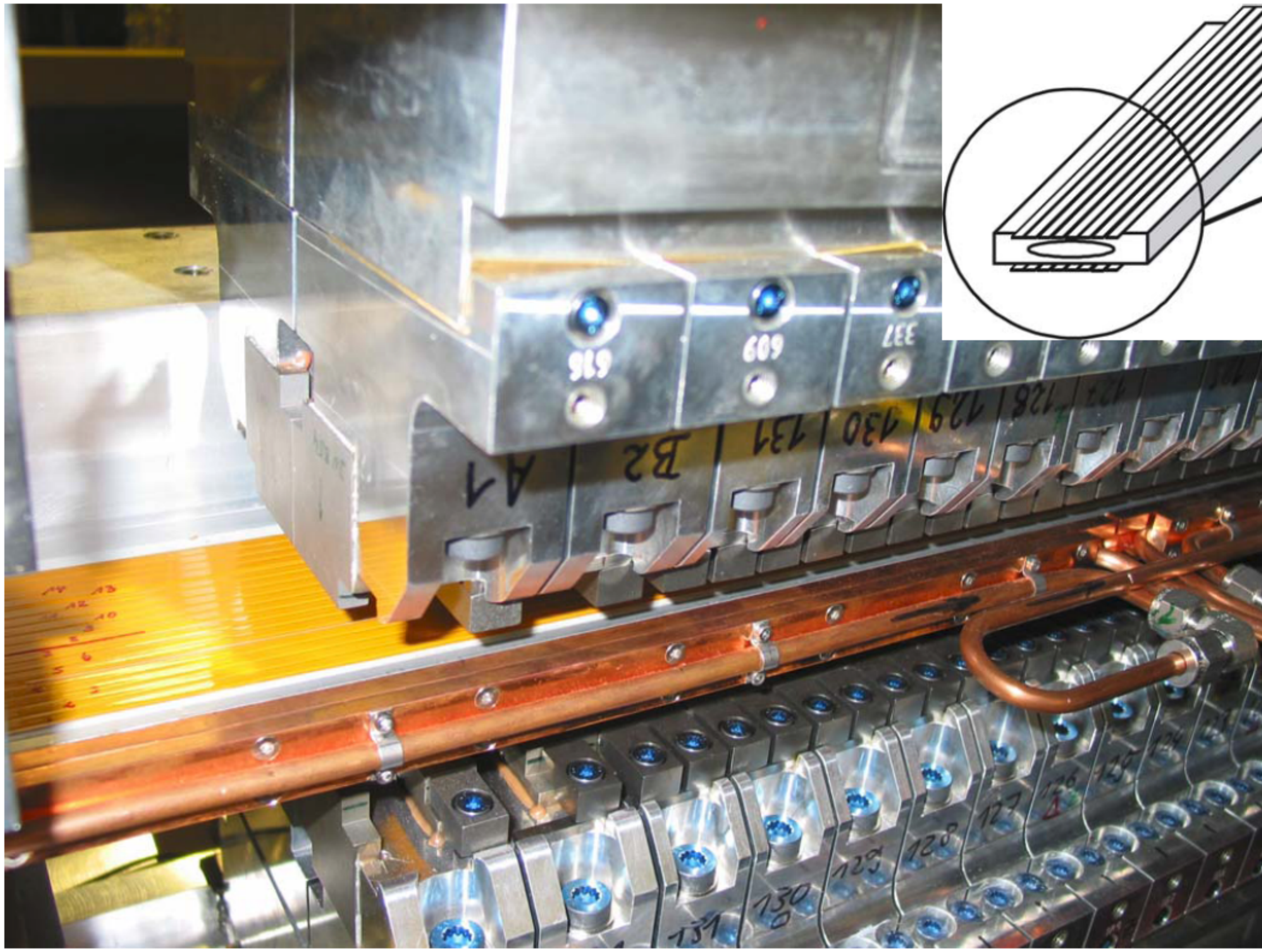


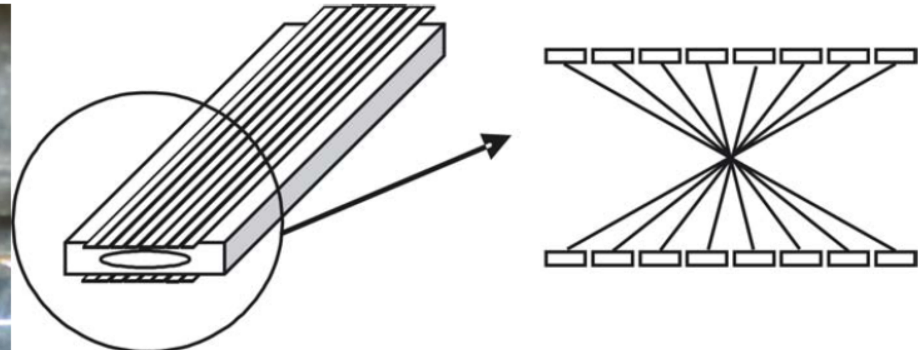




EPU Active Compensation (à la BESSY)

active compensation of dynamic field components in the linear/inclined mode





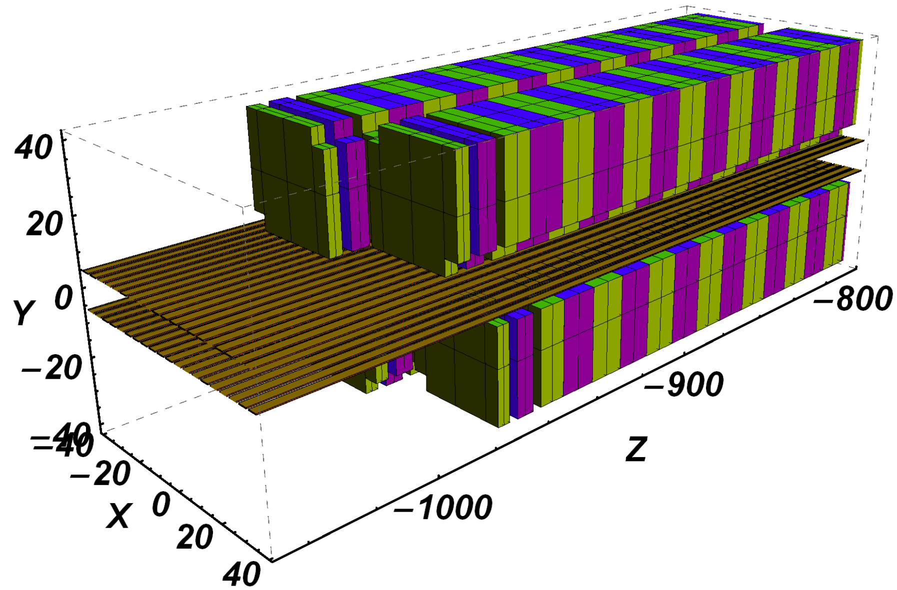
28 flat wires along the ID-chamber with 14 PS

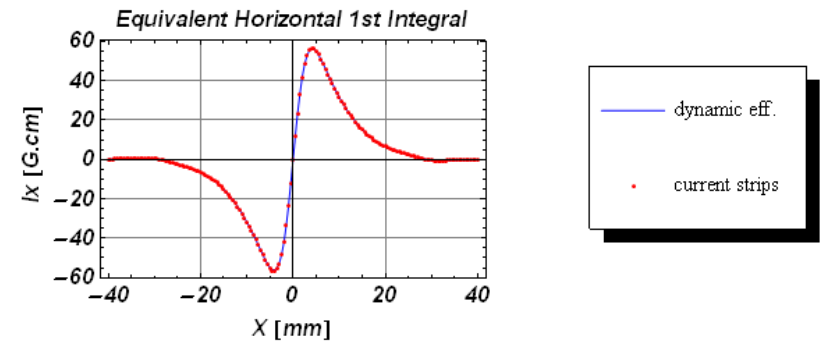
maximum current; 16A,
wire diameter; 3x0.3mm^2
wire separation: 4mm

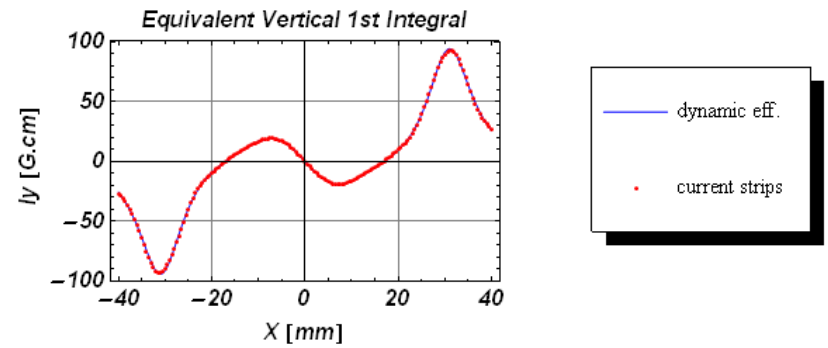
Courtesy of J. Bahrdt

Compensation of 2^{nd} order kicks by current strips

Case1: 45 degree inclined linear polarization







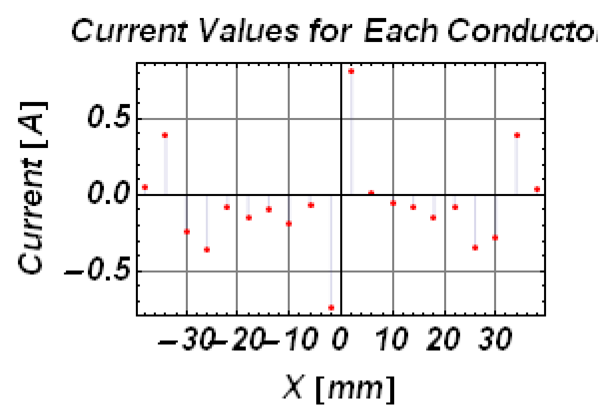
# of strips: 2 x 20

Strip size: 3mm (x) x 0.3mm (y) x 2.1m (z)

Space bet. strips: 1mm

Strip gap: 10.7mm

Magnet size: 35 mm (H) x 35 mm (V)



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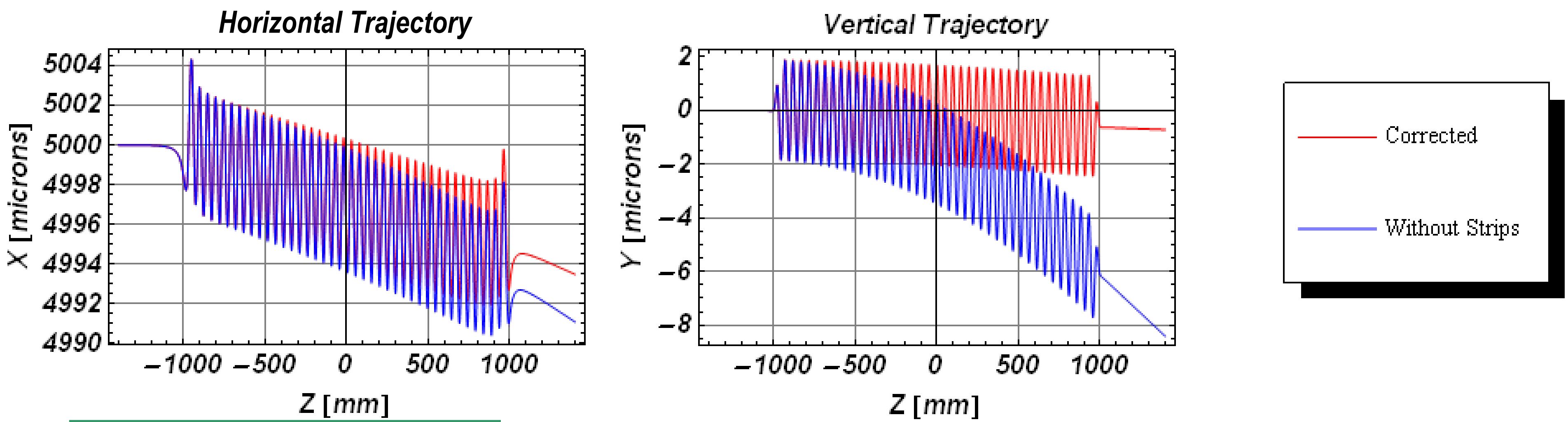
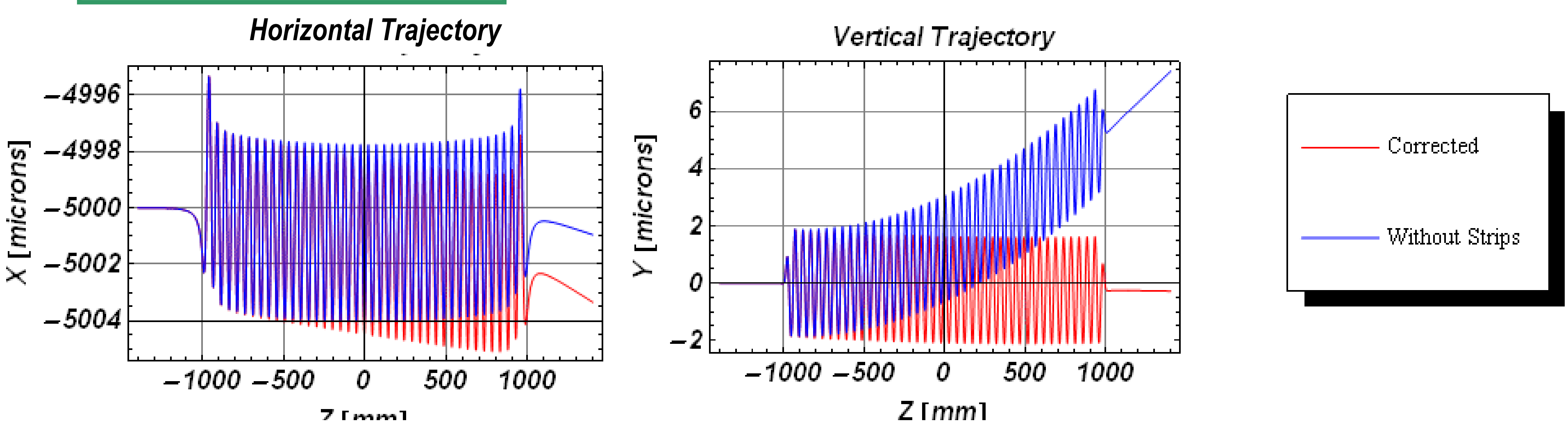
Electron Trajectories w / wo Correction (45 degree inclined)

Horizontal Offset = + 5 mm

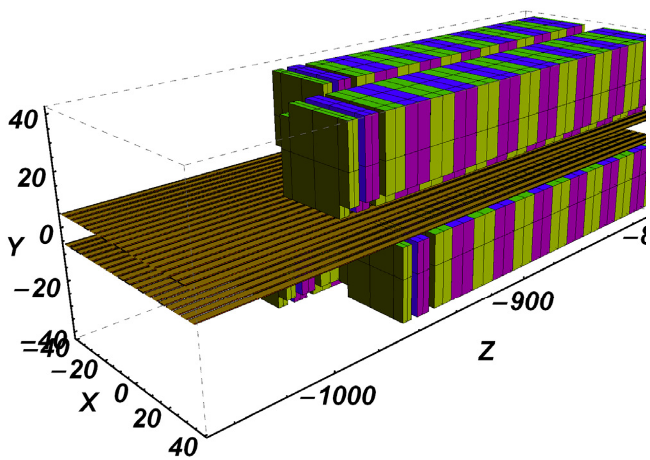


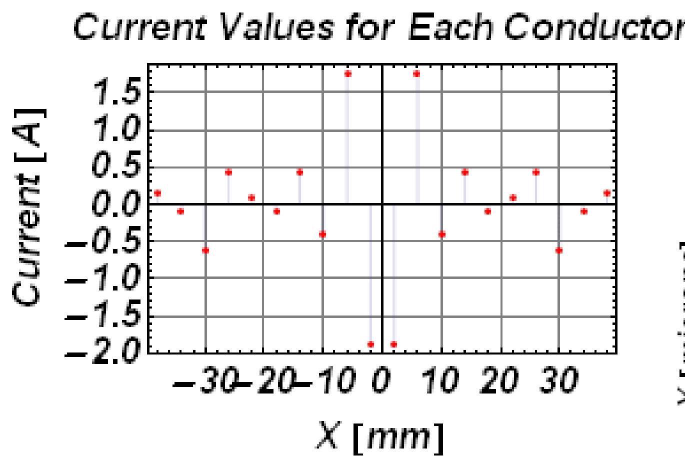
Horizontal Offset = - 5mm



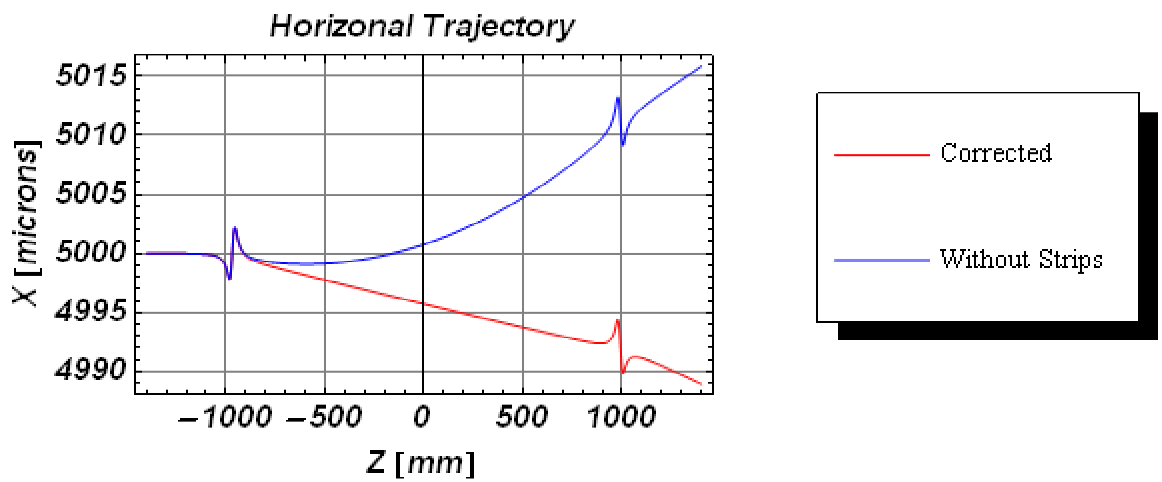
Vertical Linear Mode

Case2: Vertical linear polarization





Horizontal Offset = +5 mm



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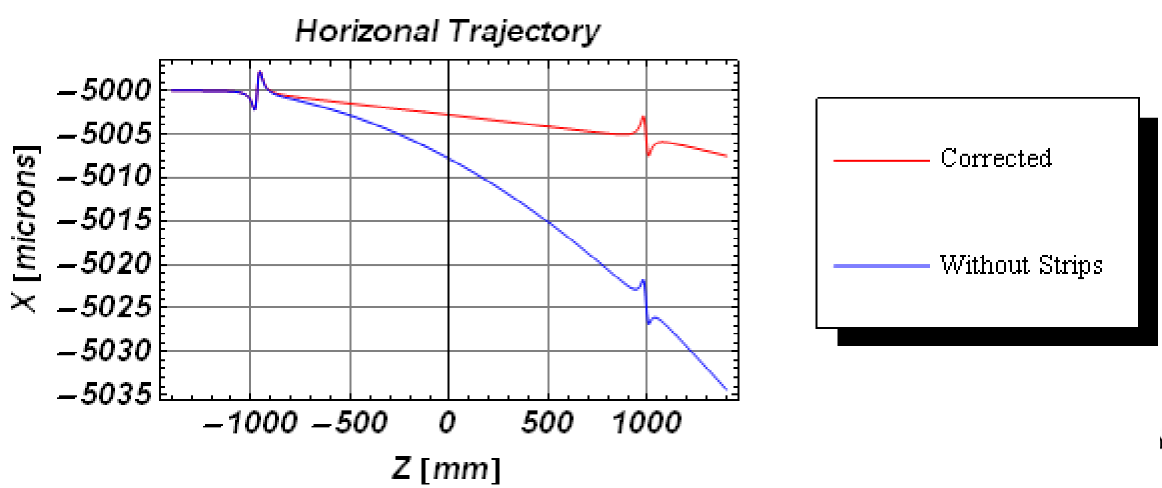

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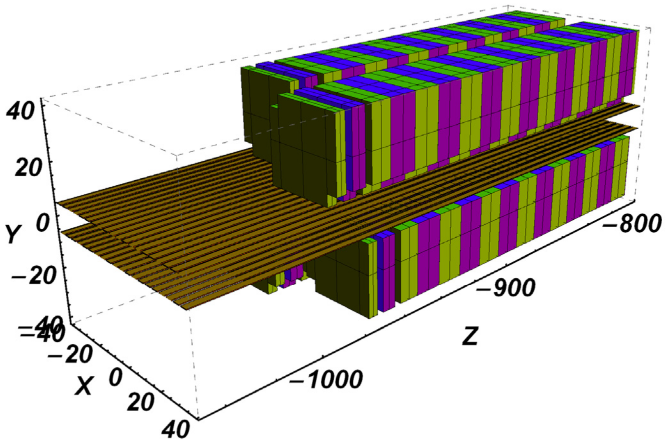
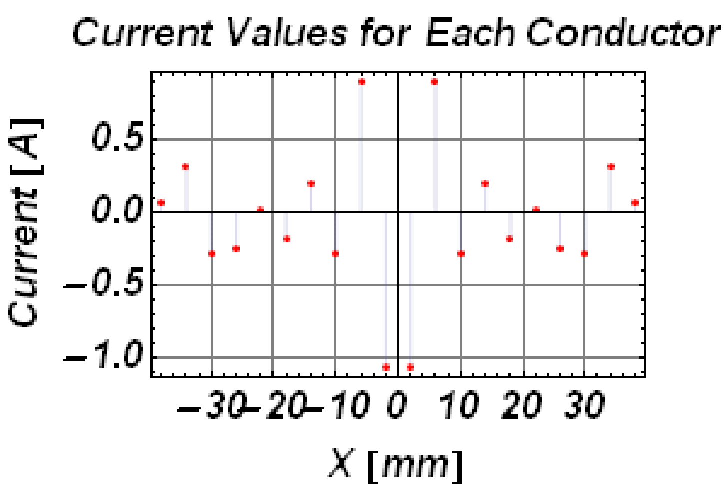
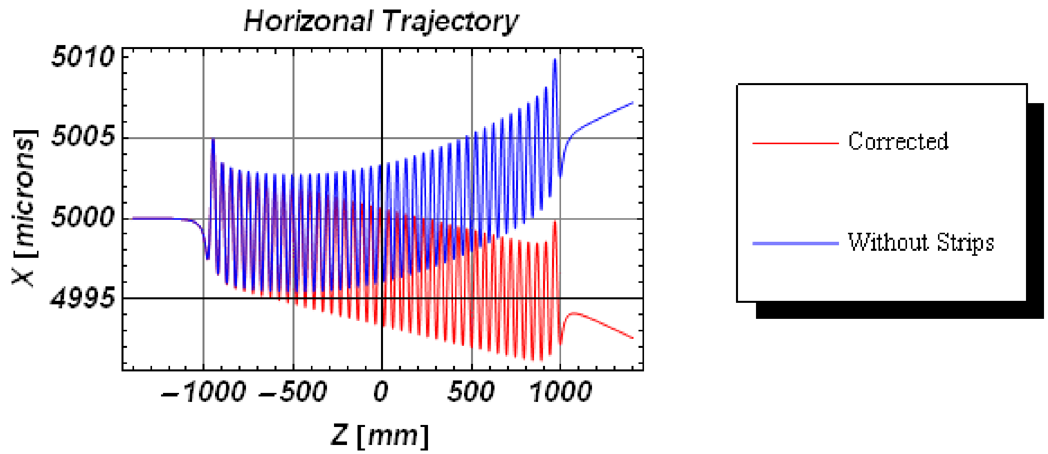
Helical Mode

Case3: Circular polarization

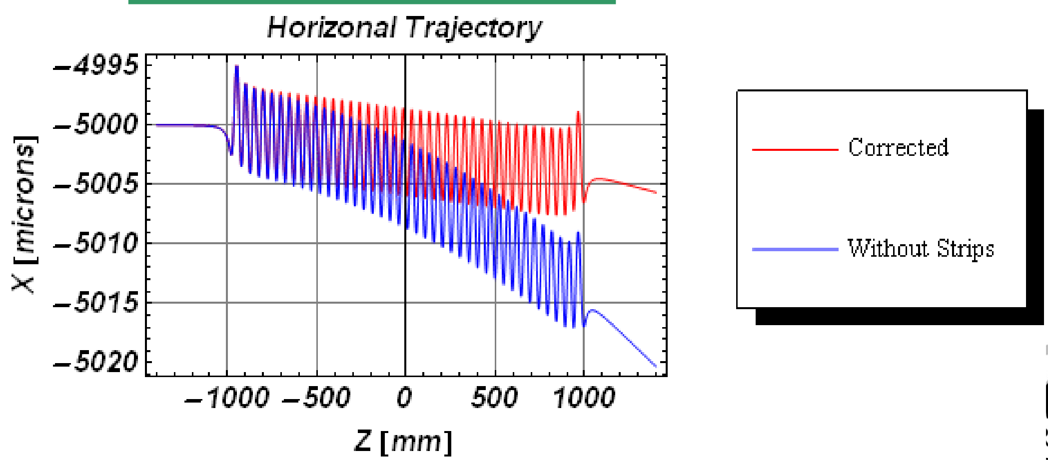




Horizontal Offset = +5 mm



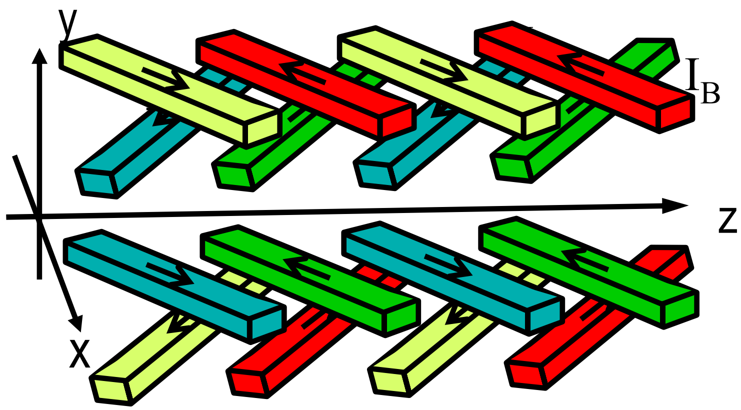
Horizontal Offset = -5mm

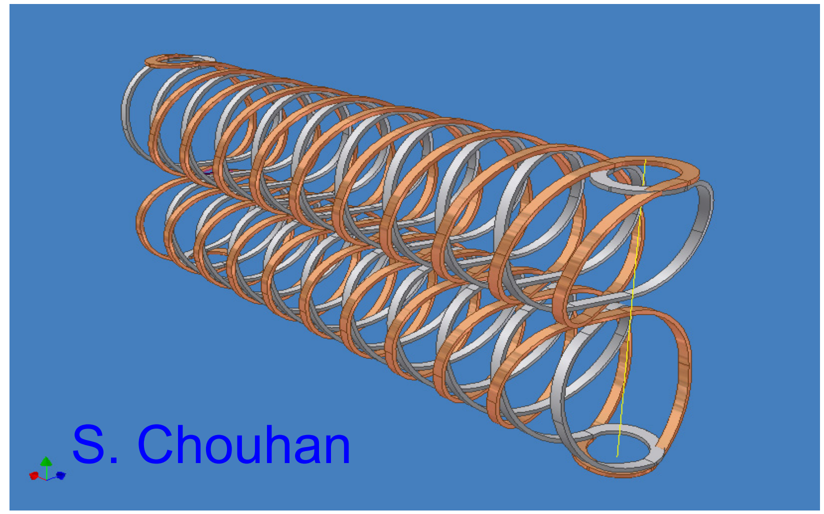


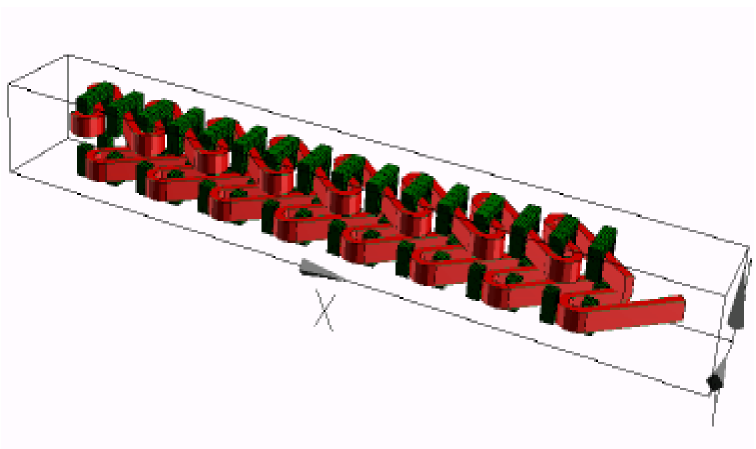
Summary of Calculations of Radiation Power Density on Straight Section Vacuum Chamber Walls (or IVU Ni-Cu Foils) for Different NSLS-II IDs

ID	Intern. Chamber Size / IVU Gap [mm]	Electron Beam Angular Deviation [mrad]	Electron Beam + Chamber Posit. Offset [mm]	Deposited Radiation Power [W] (at I = 0.5 A)	Max. Power Density [W/mm^2]	Max. Temperature [deg. C]
DW100	11.5	0.25	2.0	500	~0.02	75
--||--	--||--	0.25	1.5	235	~0.009	46
EPU49 (helical)	8.0	0.25	2.0	1240	0.5	170
--||--	--||--	0.25	1.5	580	0.27	130
IVU20	5.0	0.25	1.5	780	2.08	
--||--	--||--	0.25	1.25	200	0.41	
--||--	--||--	0.25	1.0	65	0.11	
--||--	--||--	0	2.0	180	0.19	
--||--	--||--	0	1.5	25	~0.02	
IVU22	6.95	0.25	1.5	950	0.71	
--||--	--||--	0.25	1.25	460	0.30	
--||--	--||--	0.25	1.0	240	0.14	
--||--	--||--	0.25	0.75	130	0.067	
--||--	--||--	0.25	0.5	75	0.035	
--||--	--||--	0	2.0	70	~0.02	
--||--	--||--	0	1.5	30	~0.007	

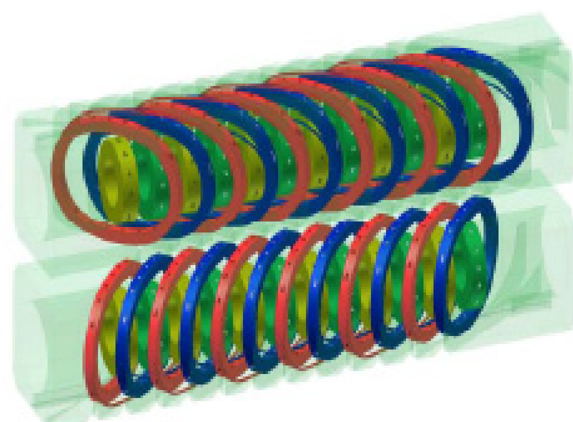
Superconducting EPUs





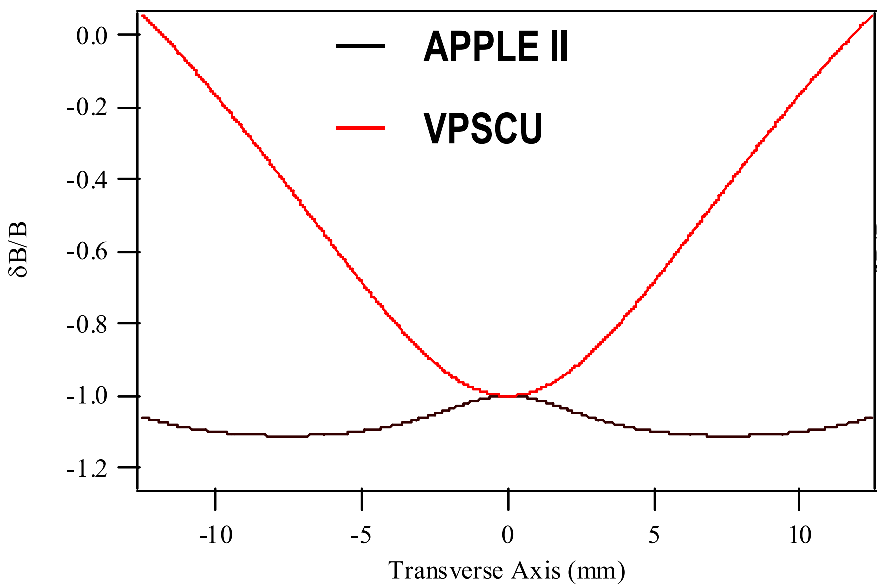


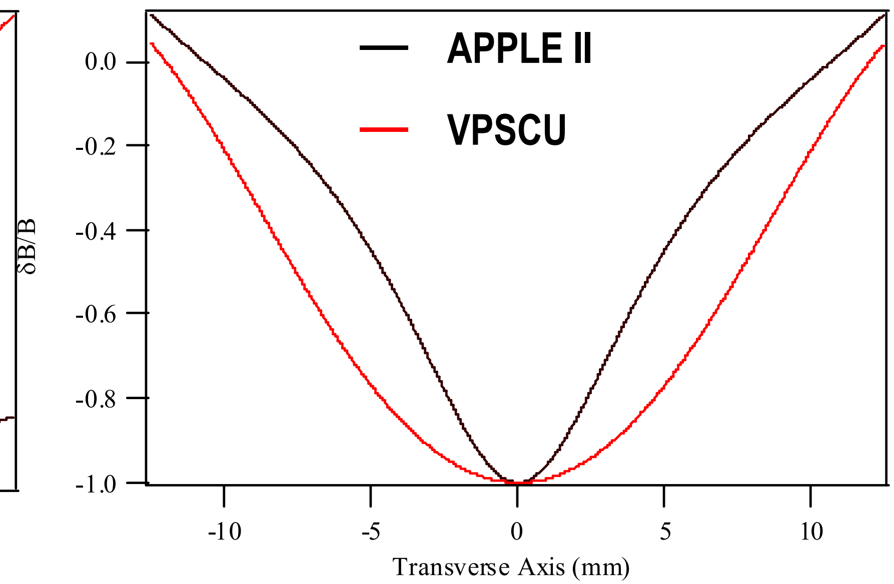
Sasaki Snake



Rossmanith

Transverse field profile in circular mode





- Vertical Field
- Horizontal Field

Quasi-Period Undulator

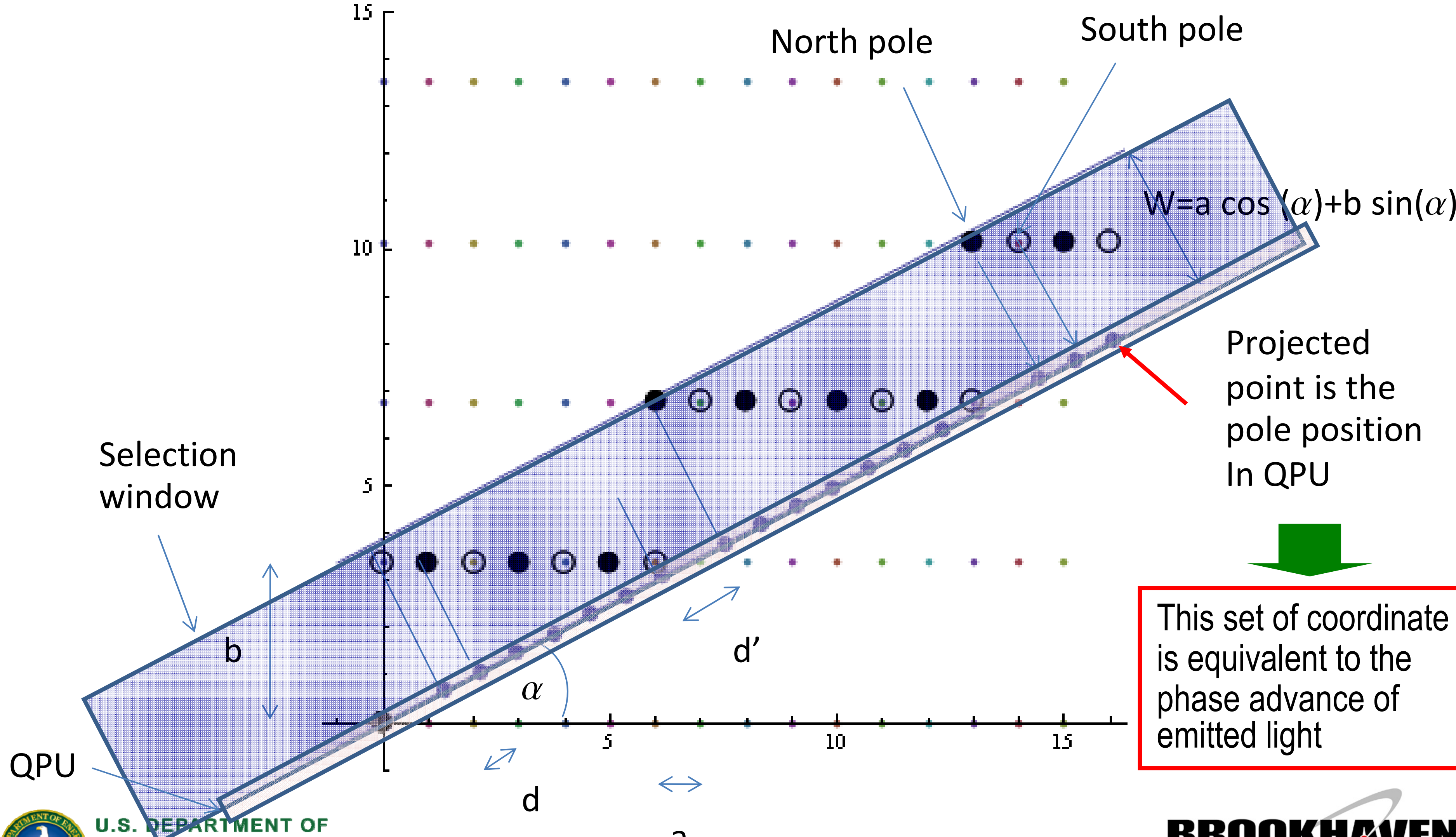
- **Periodic undulator has harmonics**
- **For many users the harmonics are harmful**
- **Quasi-Period Undulators(QPU) can suppress harmonics or select harmonics**
- **The one-dimensional quasi-periodic lattice can be created by projecting lattice points in a window in the two-dimensional rectangular lattice onto a irrationally inclined line.**
- **1-D Spectrum of QPU can be easily calculated to give harmonic contents**
- **It is possible to vary QPU spectrum even though its structure can be fixed**
- **There is a simple formula to determine QP step size for a fixed structure**

References

- S.Sasaki, “Overview of quasi-periodic undulators”
- S. Hashimoto, S.Sasaki, Nucl. Instr. And Methods A361 (1995) p. 611.
- J. Chavanne, P. Elleaume, P. Van Vaerenbergh , “DEVELOPMENT OF QUASIPERIODIC UNDULATORS AT THE ESRF”

Projection of a selected widow in a 2-D lattice on to an inclined axis to form QPU

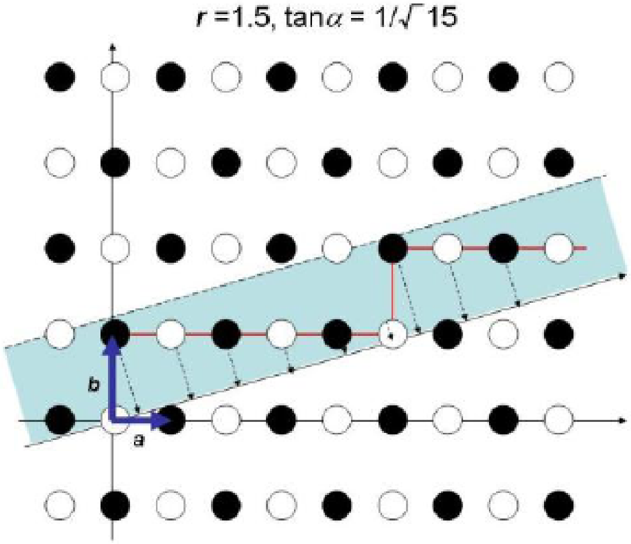
The ratio r=b/a, and angle α can be adjusted to vary the non-periodic spacing d'



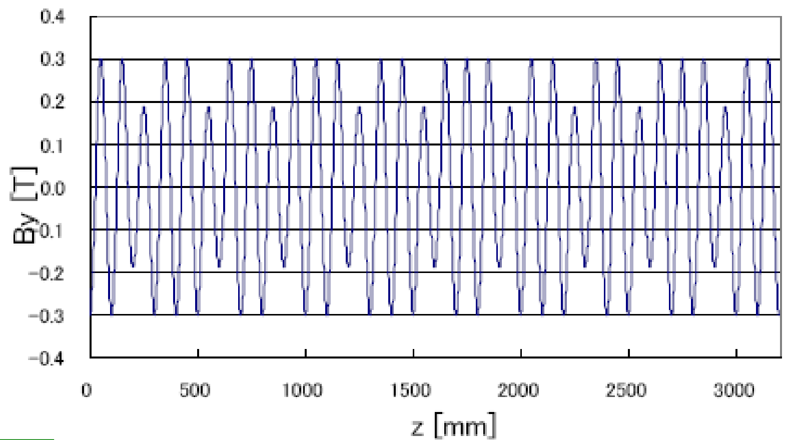
This set of coordinate is equivalent to the phase advance of emitted light

Selected lattice points are within a window of width W

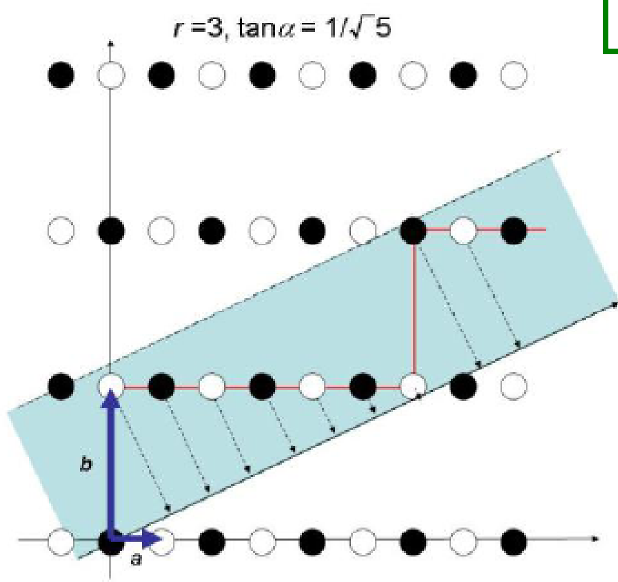
Window Choice and Corresponding Field Profile

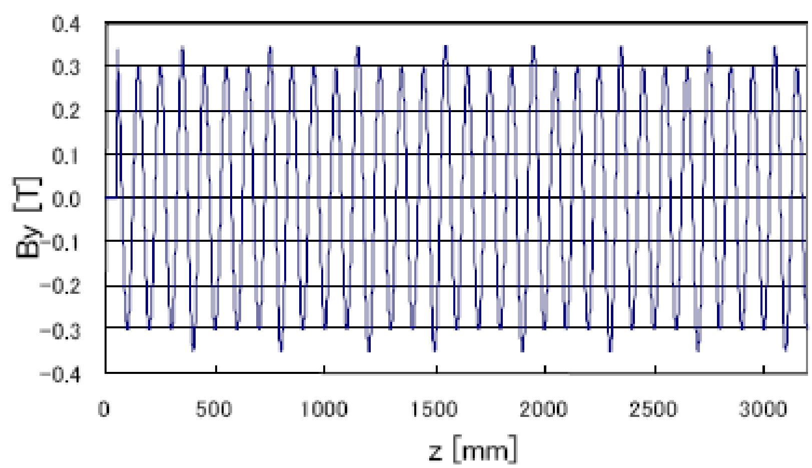


Corresponding Magnetic Field with Constant Period Length



Sasaki, PAC09

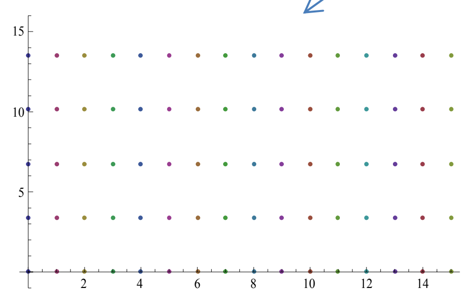


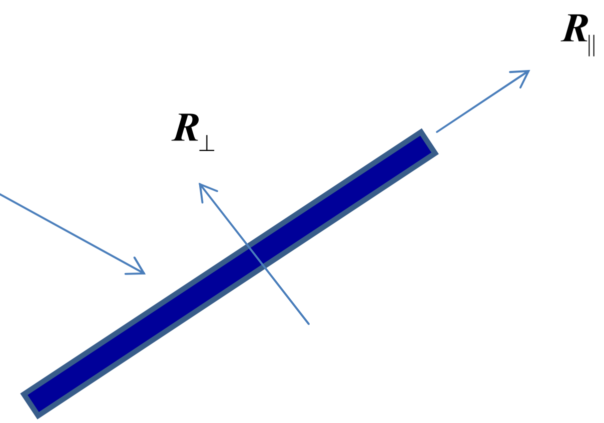


Spectrum of QPU

- Spectrum of QPU is the Fourier transform of its radiation
- Radiation from QPU is a projection of the 2-D lattice onto the inclined axis
- Radiation from 2-D lattice is multiplied by a window of width w:

$$F(\boldsymbol{R}) = \boldsymbol{S}(\boldsymbol{R})\,V(\boldsymbol{R})$$

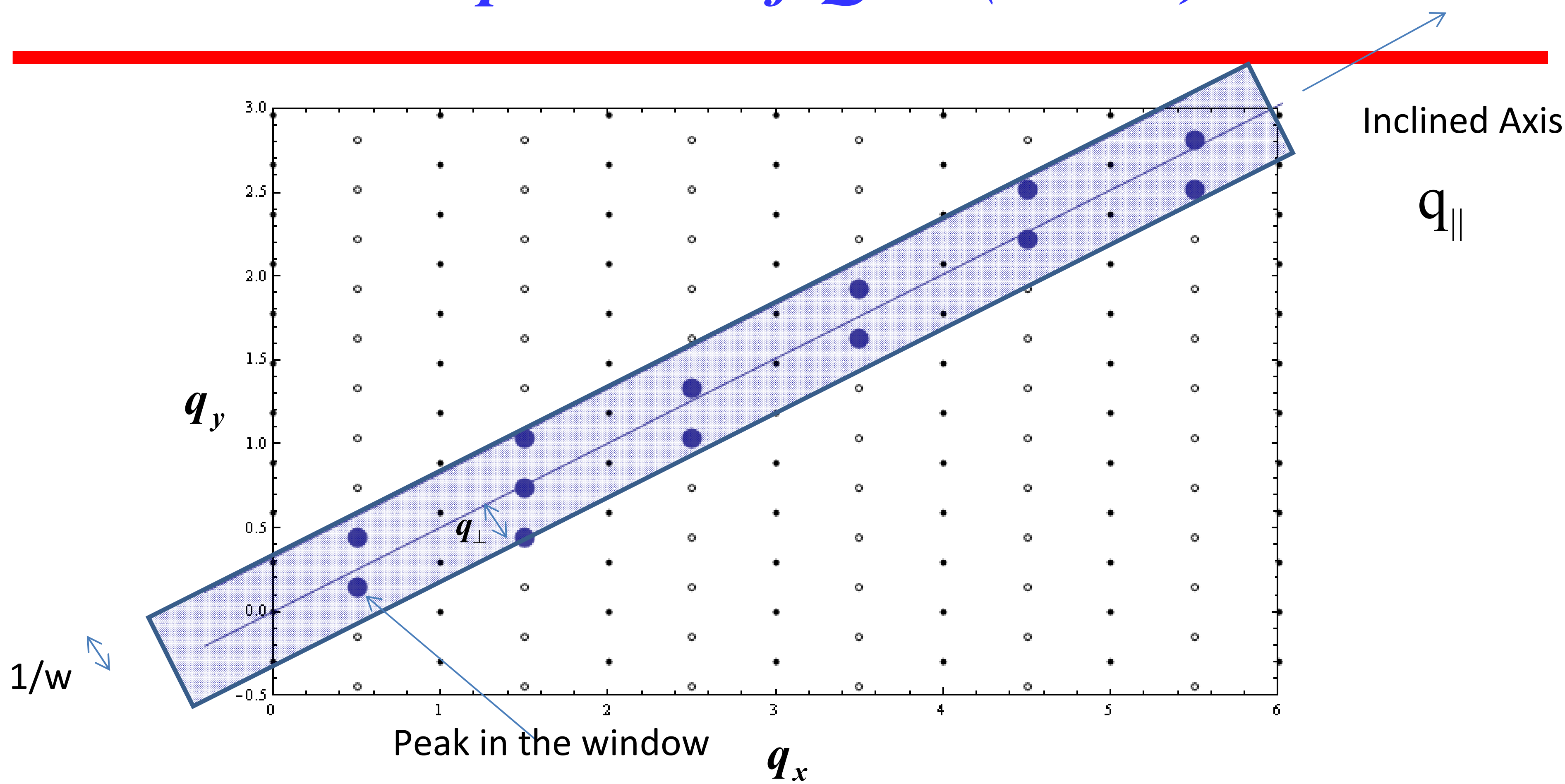




- The Fourier transform of 2-D lattice with the window is the convolution of the two Fourier transforms

$$f(q) = \int s(q - q')\, v(q')\, dq'$$

Spectrum of QPU (cont'd)

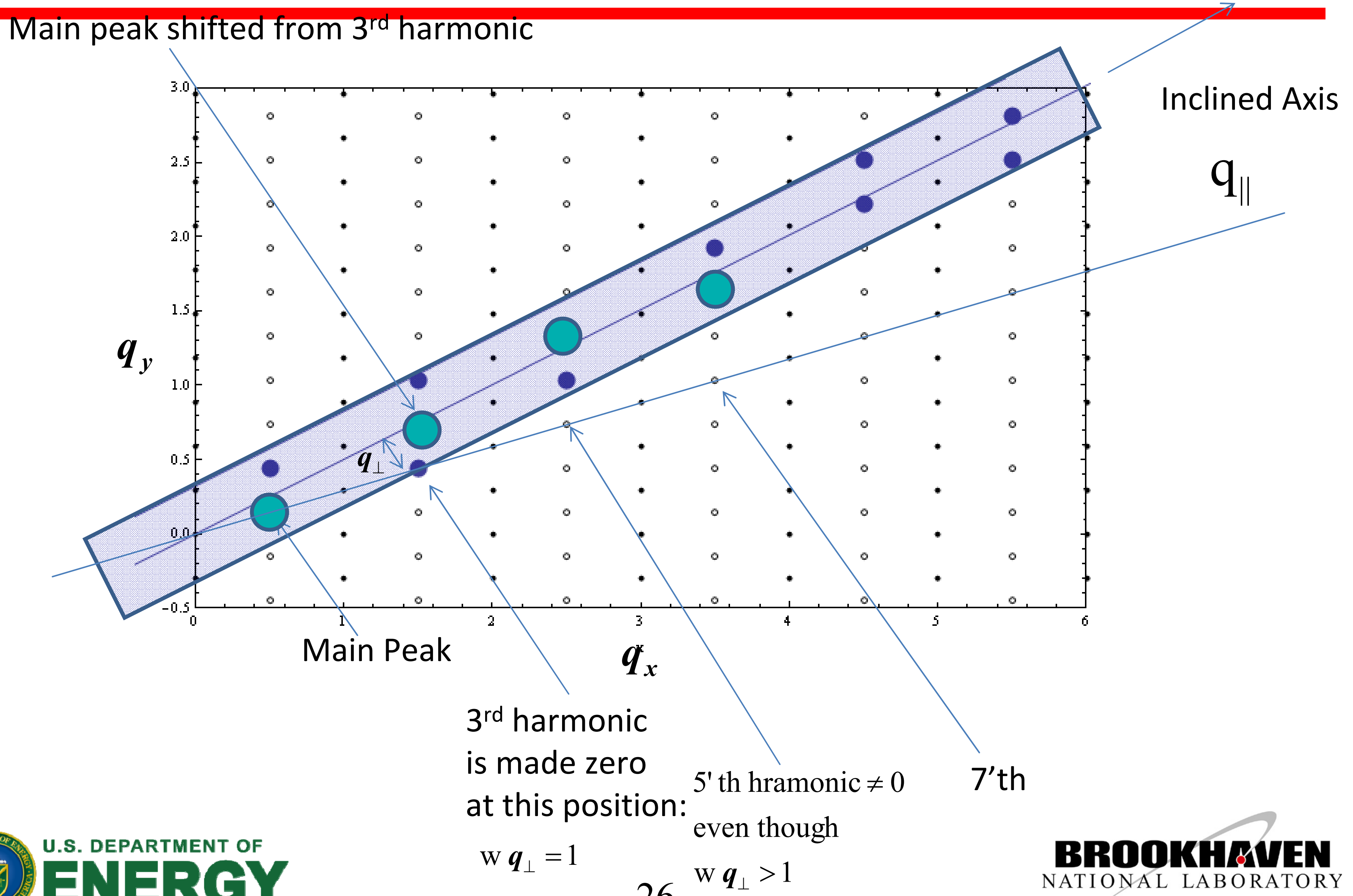


When lattice points are selected within a window of width W inclined by α ,
the bright reciprocal lattice points also lie within a window of width 1/W also inclined by α

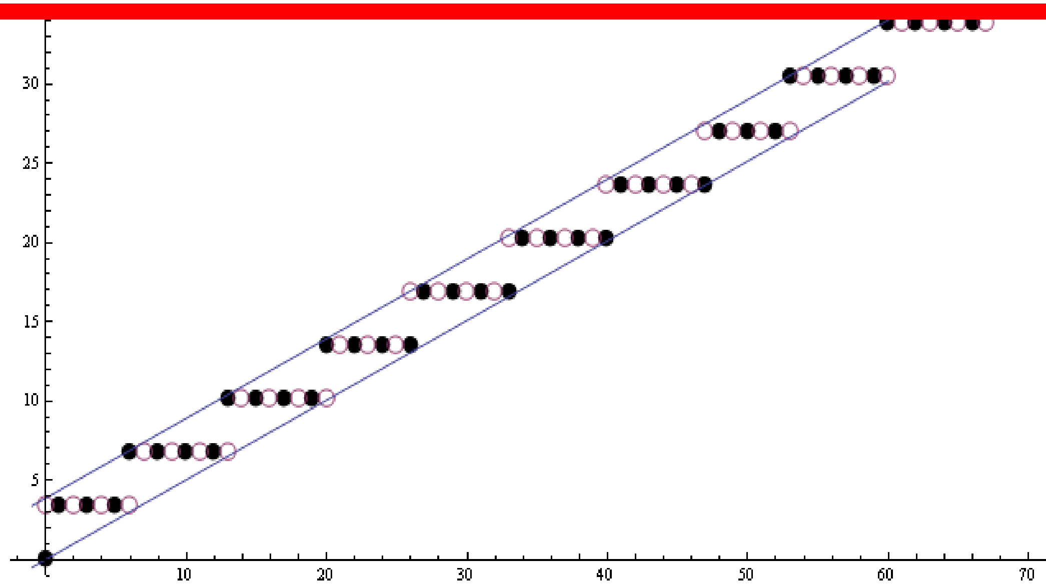
Distance to $q_{||}$ axis is $\boldsymbol{q}_\perp$

$$\text{Intensity} \sim \left(\frac{\text{Sin}(\pi w \boldsymbol{q}_\perp)}{\pi w \boldsymbol{q}_\perp} \right)^2, \text{so when } \boldsymbol{q}_\perp = \frac{1}{\boldsymbol{W}}, \text{it is zero}$$

Main peaks are shifted from harmonics, but exact harmonics still exist



How to vary α without changing the structure?



longitudinal phase as function of pole number:

$$\phi_m = \pi\left(m + (r\tan\alpha - 1)\ \text{IntegerPart}[m\frac{1}{\frac{r}{\tan\alpha}+1}+1]\right)$$

So when $\eta \equiv \frac{r}{\tan\alpha}$ is kept constant, the quasi-period position is fixed

while QP phase advance $\pi r \tan\alpha$ is varied (both r and α are changing)

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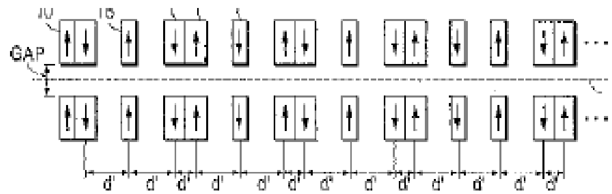
QEPU

- quasi periodicity (reduction of harmonic contamination)
- variable polarisation

Original quasi-periodic structure



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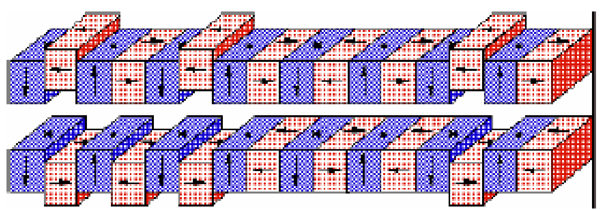
Variation based on displacement/removal of H-blocks



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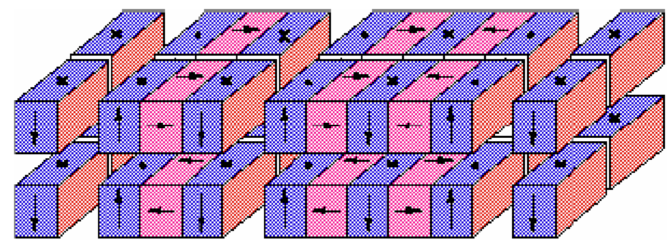

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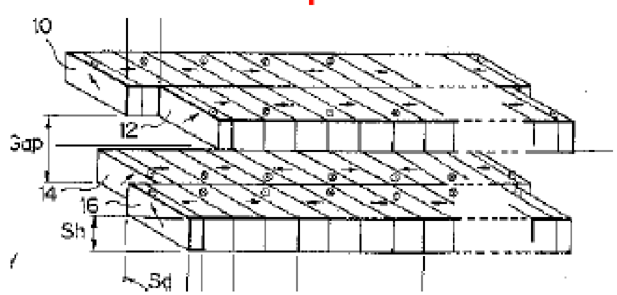
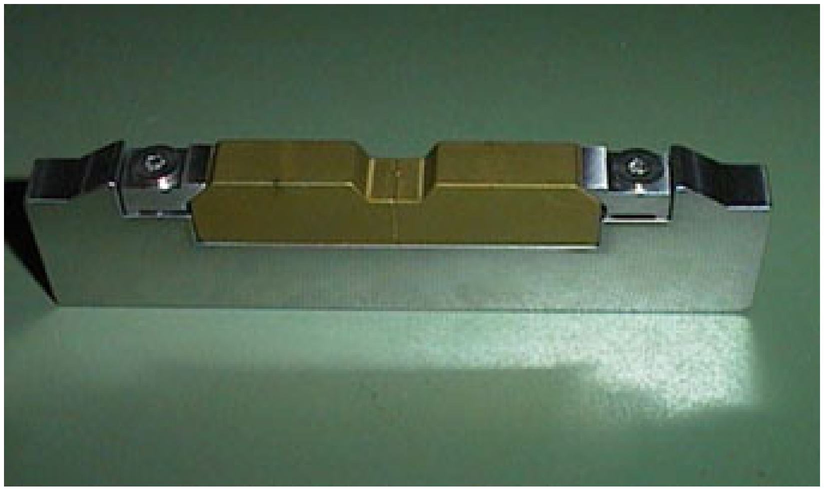
APPLE-II concept



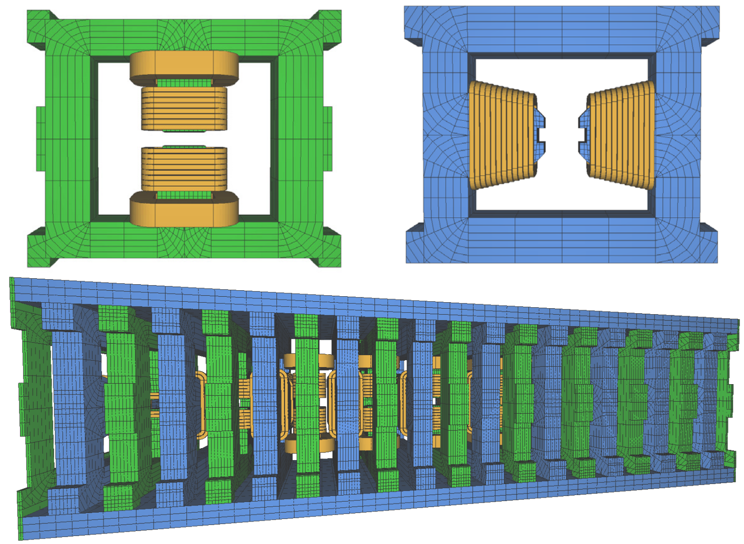
Elettra Example

Other Types of ID

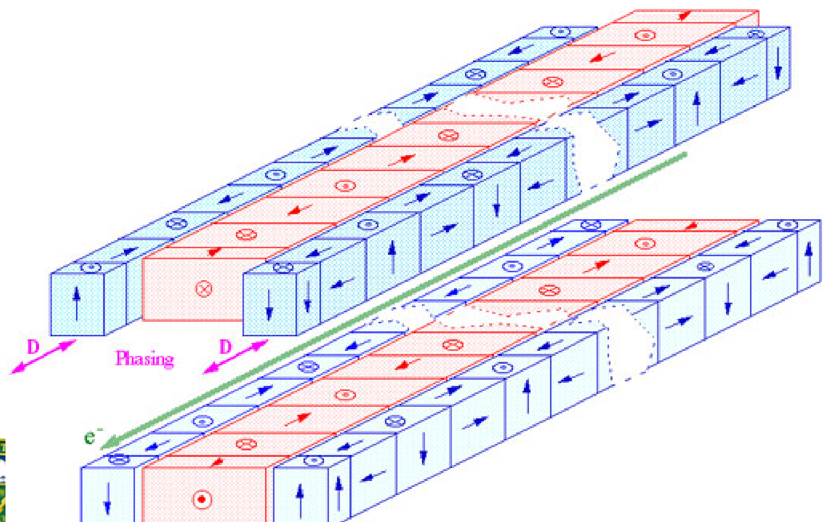
- Vertical IVU



- Soleil EM-EPU (256mm period)

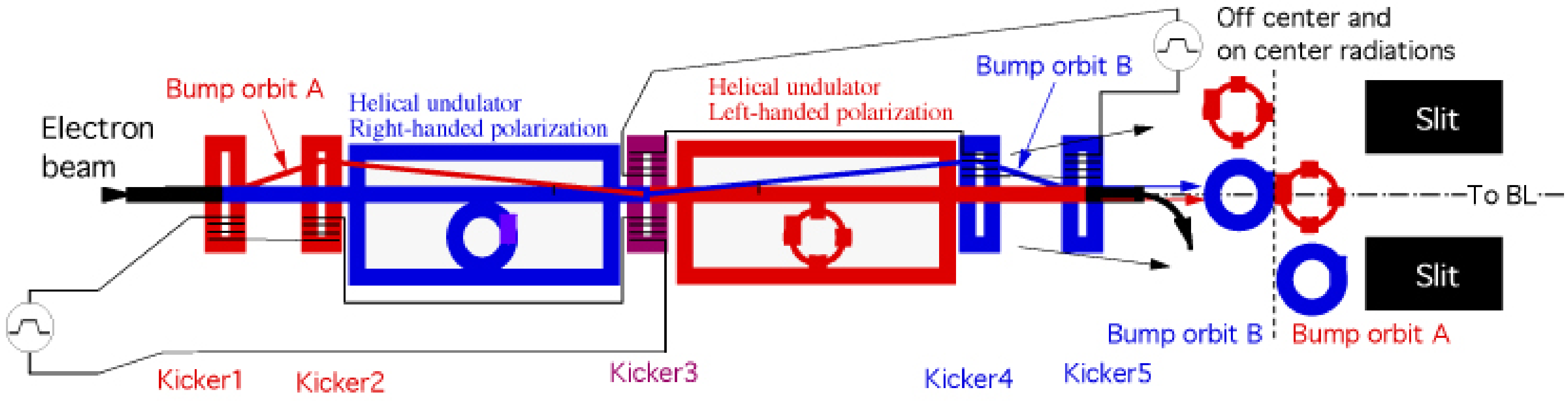


- Elliptical multipole wiggler



More....

- Helical



Twin helical undulator polarization switching

- Figure-8 (low heat load on axis in linear mode)

- Rhombus (helical higher harmonics on axis)

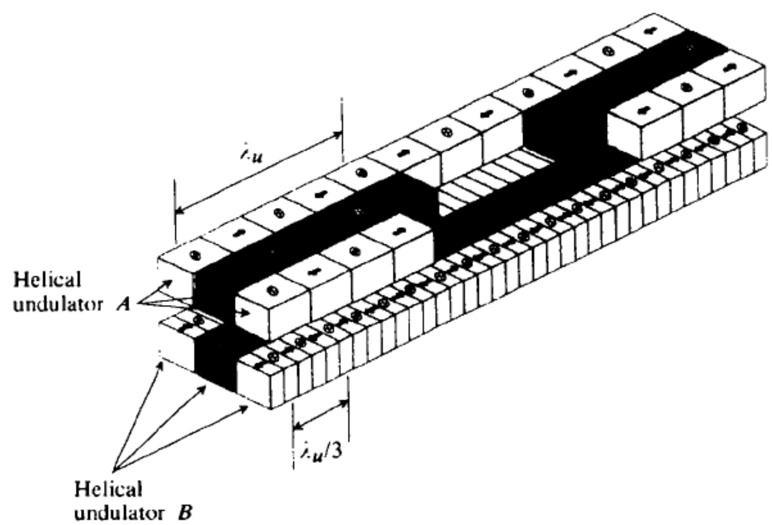
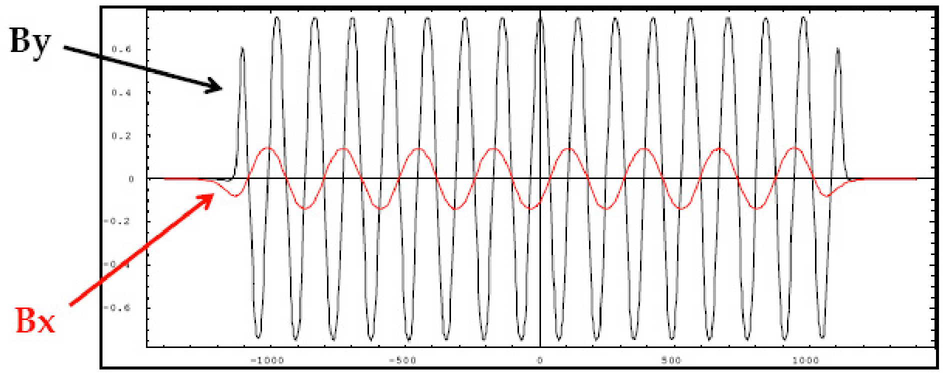
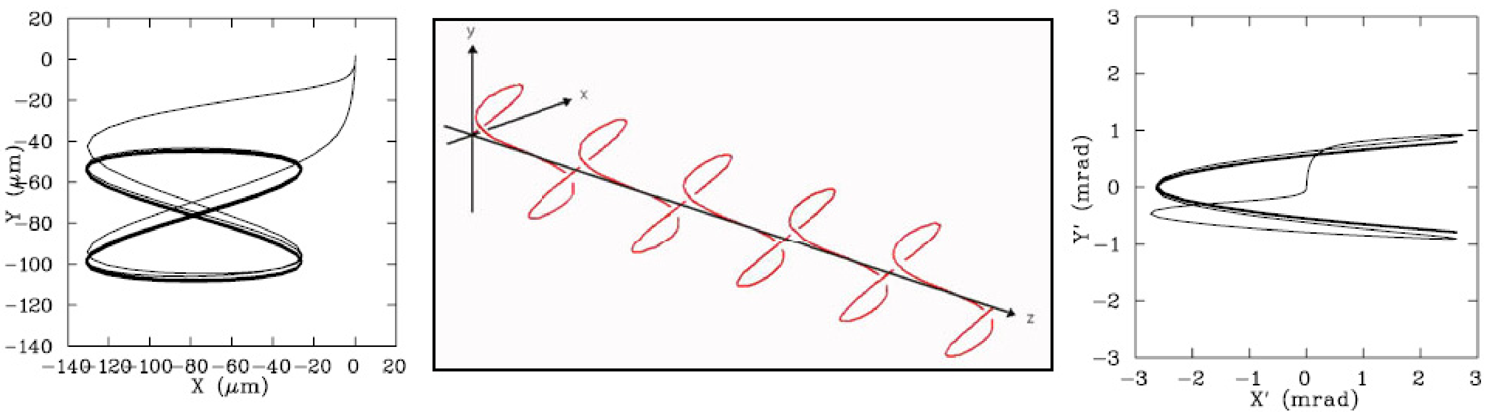


Figure-8 Type

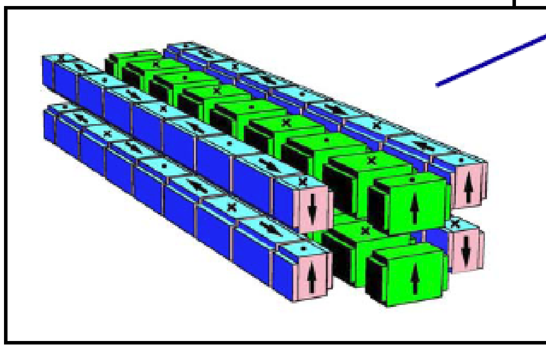


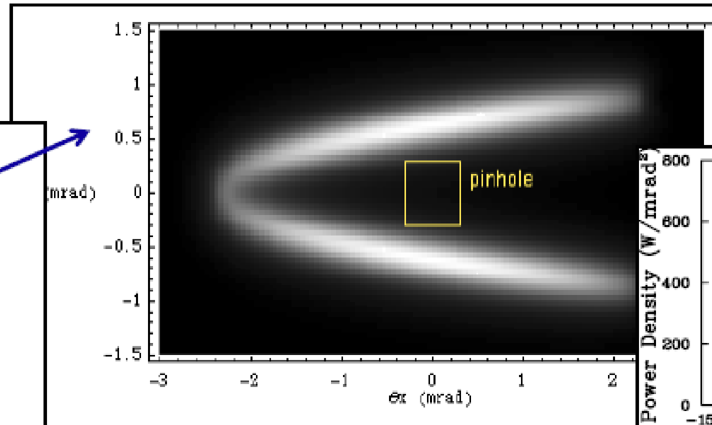


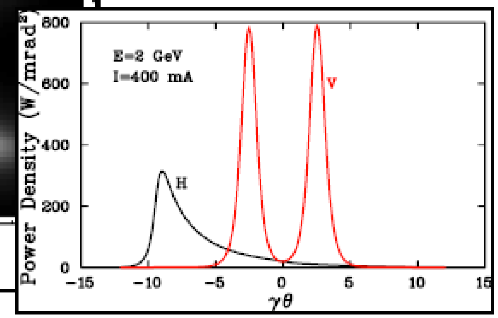
$$\frac{dP}{d\Omega} = \frac{e^2}{(4\pi\varepsilon_0)4\pi c}\left[\frac{\dot{\beta}^2}{\left(1-\vec{n}\cdot\vec{\beta}\right)^3} - \left(\frac{1}{\gamma^2}\right)\frac{\left(\vec{n}\cdot\dot{\vec{\beta}}\right)^2}{\left(1-\vec{n}\cdot\vec{\beta}\right)^5}\right]$$

Power Density Distribution

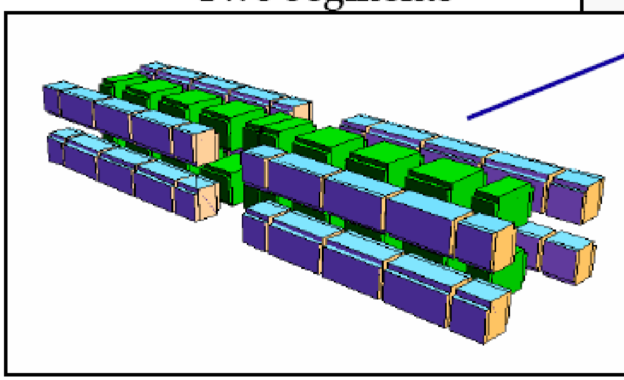
Single segment

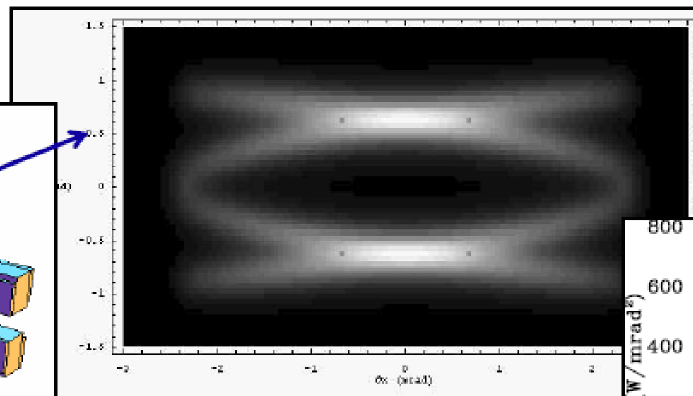


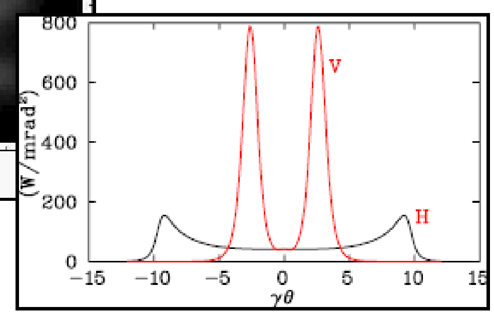




Two segments

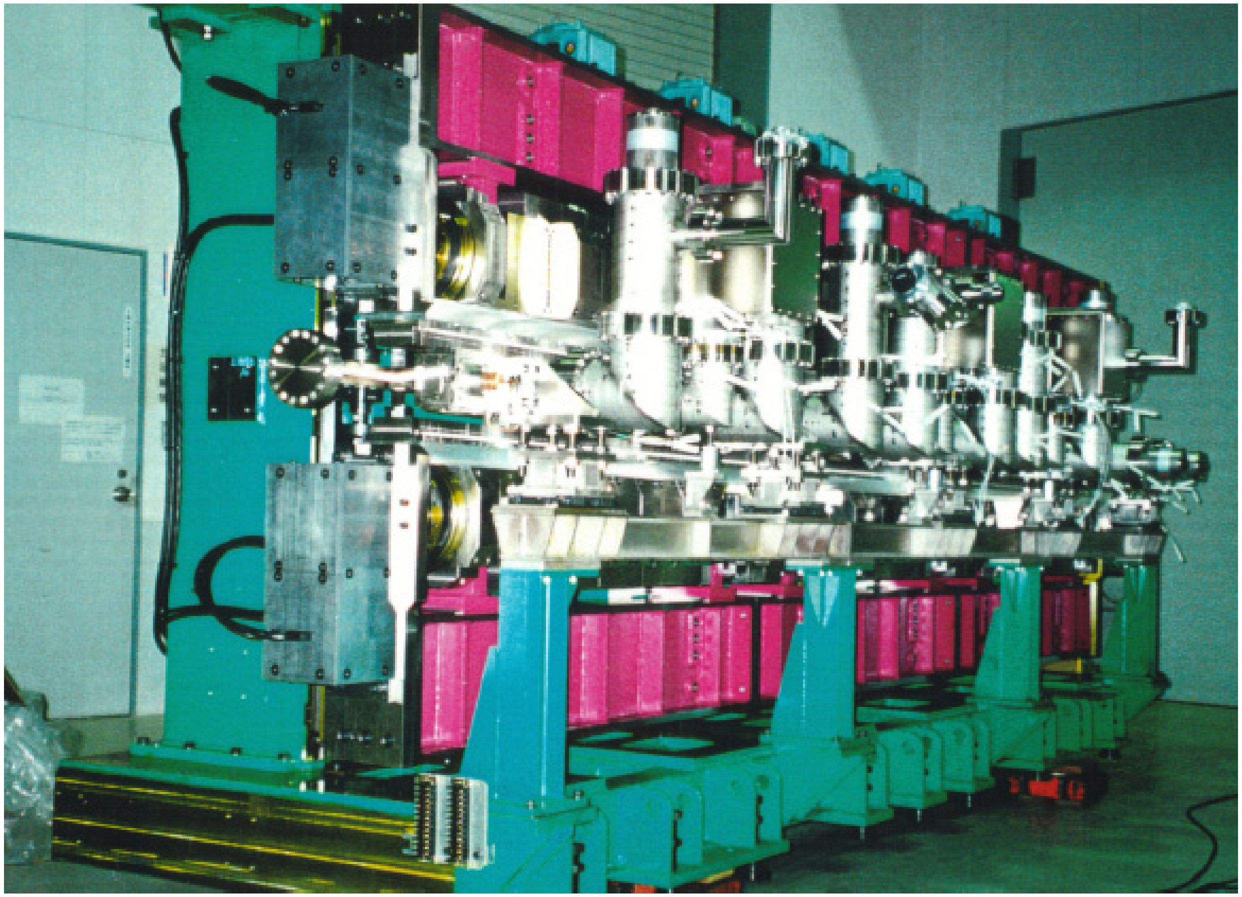




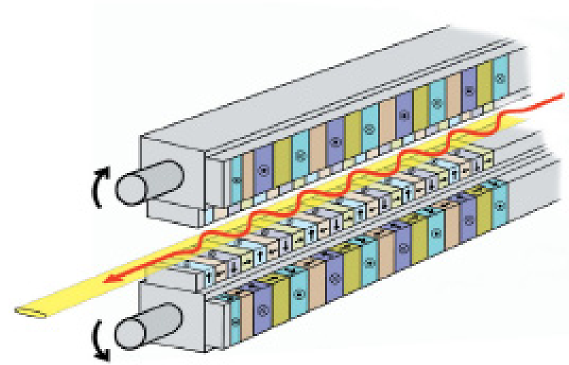


Elletra Example

Revolver Undulator (ESRF, SPring-8)



SPring-8



Planer Undulator

Period : 44mm

Number of Period : 102

Helical Undulator

Period : 92mm

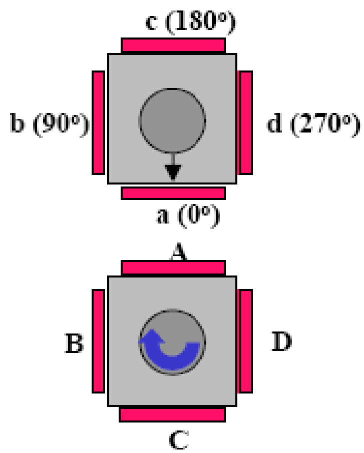
Number of Period : 48

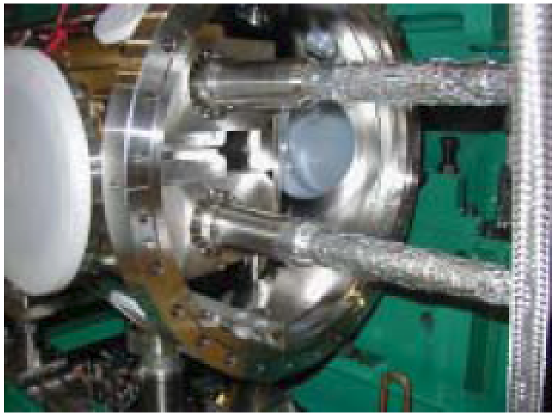
Revolver IVU installed at Pohang LS

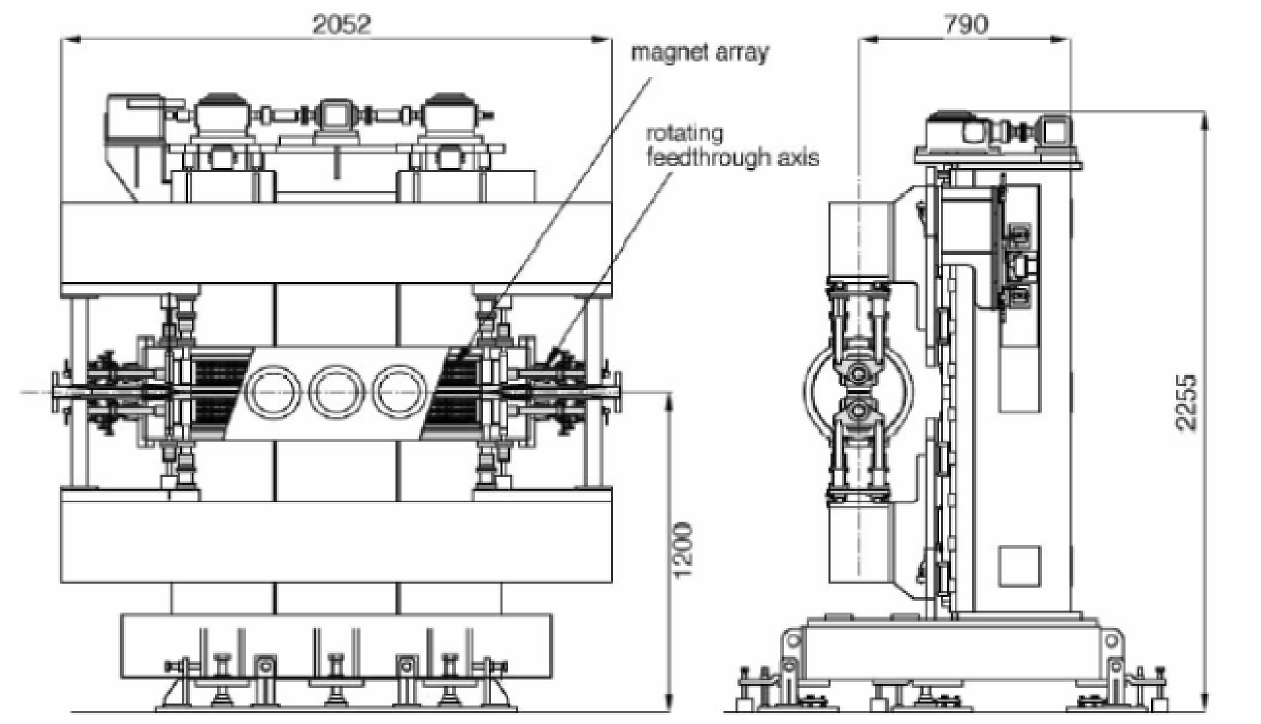
Revolver Type Multi-Undulators

Magnet Periods (Gap)

A, a : 20 (5) mm
B, b : 15 (4) mm
C, c : 10 (3) mm
D, d : 24 (6) mm







designed at Spring-8

Kitamura et al. NIMA 467, 110 (2001)

Summary

- There are many variety of variable polarizing insertion devices.
- Apple-II type EPU has been widely used because of its simplicity and effectiveness
- However, Apple-II EPU has some unfavorable features such as
  - Very small good field region (= high non-linearity off-axis or off-the-midplane)
  - Field correction for all the polarization states cannot be done with passive method such as L-shim → requires active corrections
- QPU can be designed to meet user's demand for rejection of certain harmonics. However, the fundamental radiation also degrades. Total S/N ratio after monochromator must be optimized.
- EM or Hybrid EPU is suitable for fast switching of polarization on axis. They could be suitable choice for the period ~>60mm or more.
- Figure-8, Revolver, etc. have been built to address the special need for the beamline.

NSLS-II Available Positions

- **Associate Physicist (S-2) - Insertion Devices (Term Appointment) -** Please apply to Job ID# 15274. **Job No. 15274**. Log in to the Candidate Gateway to apply for this position.

- **Project Engineer I (P-9) - Mechanical (Insertion Devices)** – Please apply to Job ID# 15275. Job No. **15275**. Log in to the Candidate Gateway to apply for this position.