Insertion Devices

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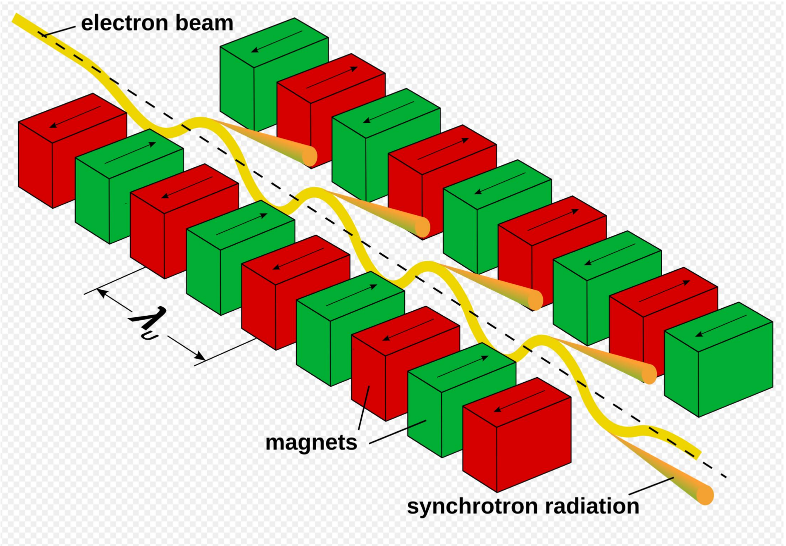
Outline

- Insertion devices to generate radiation
- Types of Insertion devices
- Undulators torwards the future
- Try to design an undulator?

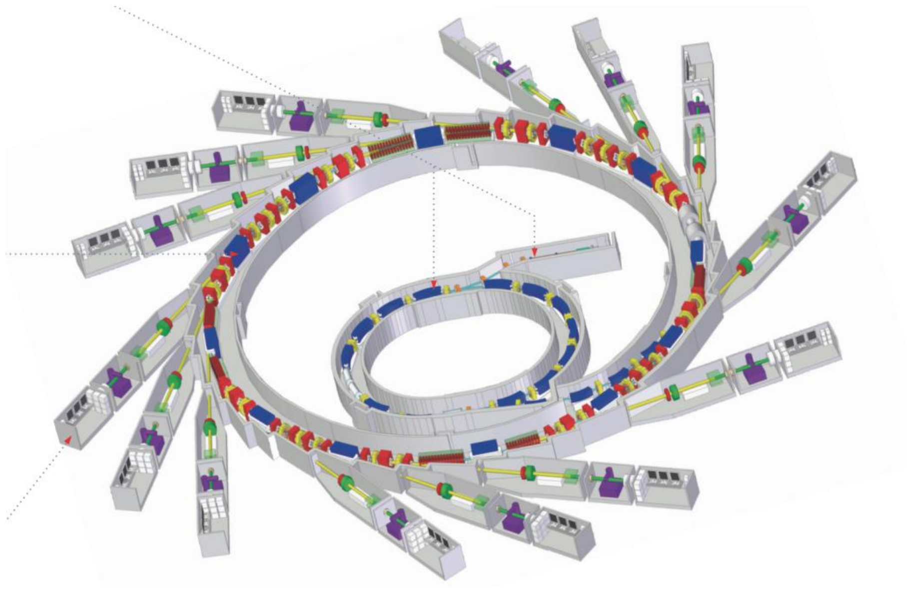
What is an insertion device?

An **insertion device** (**ID**) is a component in modern synchrotron light sources, so called because they are "inserted" into accelerator tracks. They are periodic magnetic structures that stimulate highly brilliant, forward-directed synchrotron radiation emission by forcing a stored charged particle beam to perform wiggles, or undulations, as they pass through the device. This motion is caused by the Lorentz force, and it is from this oscillatory motion that we get the names for the two classes of device, which are known as wigglers and undulators. As well as creating a brighter light, some insertion devices enable tuning of the light so that different frequencies can be generated for different applications.



Key words： synchrotron radiation\periodic magnet structure\inserted\tuning light

Introduction： synchrotron radiation source and IDs



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- The synchrotron radiation source consists of an electron linear accelerator, an electron booster and an electron storage ring.
- Special magnets that are specifically designed to generate synchrotron radiation
- They are quite literally devices that are inserted into an accelerator straight section (drift space)
- Two basic types; Undulators and Wigglers
- Periodic, sinusoidal magnetic field

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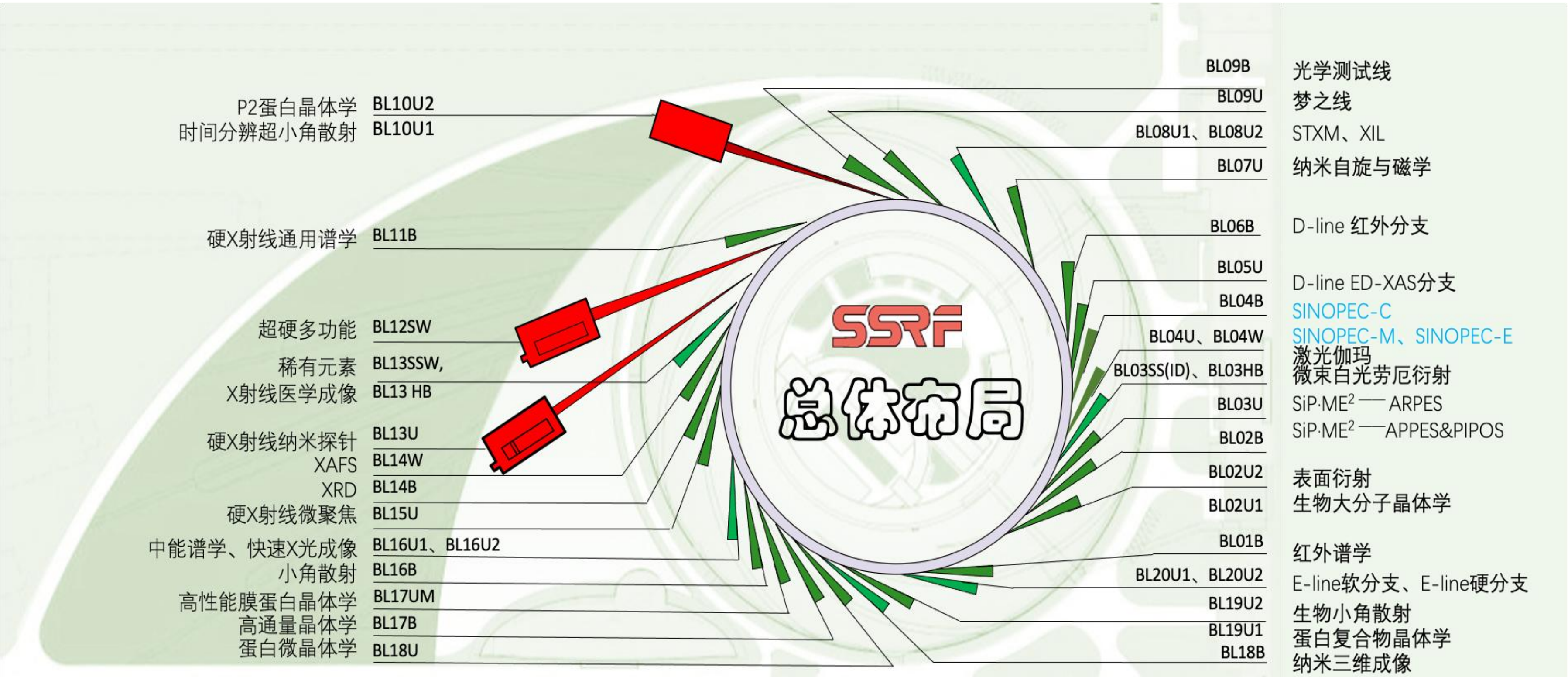
SSRF and SSRF-II



ID type	Number
IVU	12
CPMU	4
Wiggler	3
EPU	4 (+2)
AppleKnot EPU	1
SCW	1

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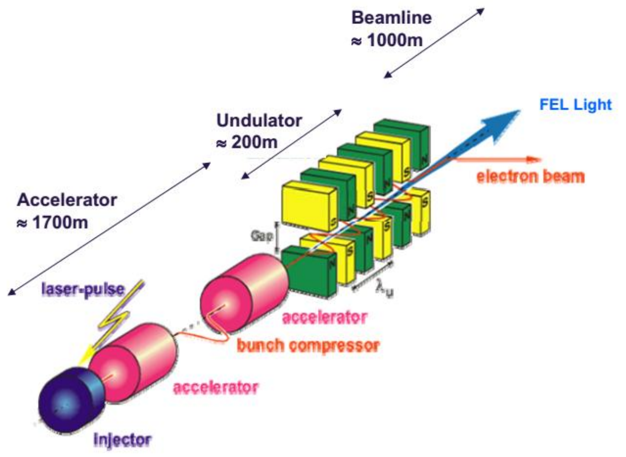
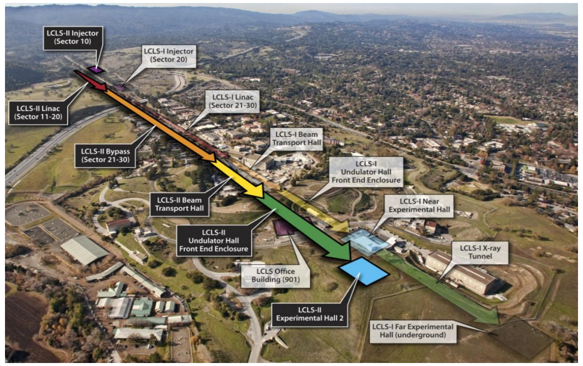
Introduction：FEL facility and undulators

- Free electron laser is a kind of high brightness coherent synchrotron radiation, its brightness can be 9 orders of magnitude higher than the third generation synchrotron radiation.
- In order to achieve saturation of the output power of the high gain free electron laser, tens or even hundreds of meters of undulators are needed.
- At present, Europe, the United States, Japan, South Korea and other countries have built hard X-ray free electron laser devices.
- A total length of 3.2 kilometers, the Shanghai high refrequency hard X-ray free electron laser device (SHINE) is under construction, and the first phase will be the construction of three 300-meter-long undulator lines.



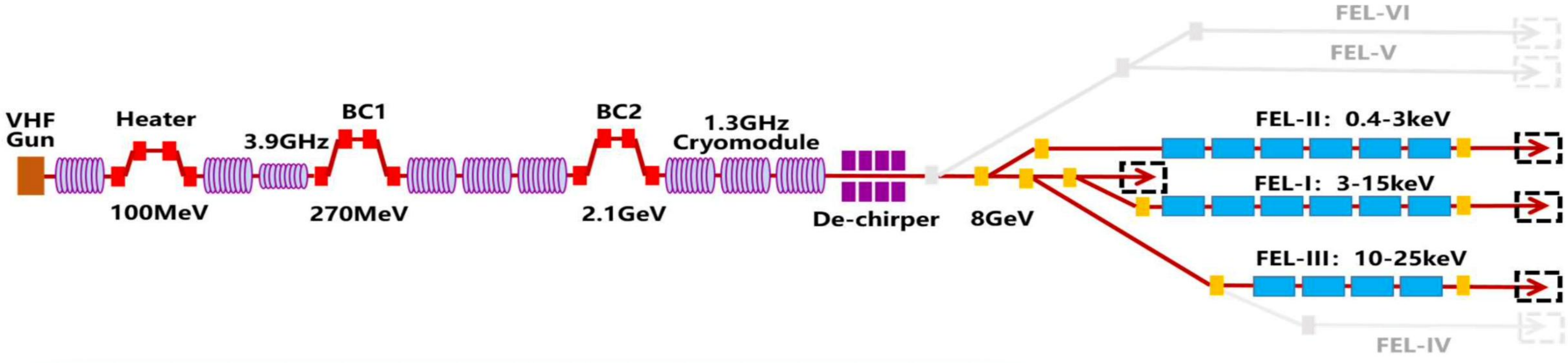
Eu-XFEL（3.5km long）

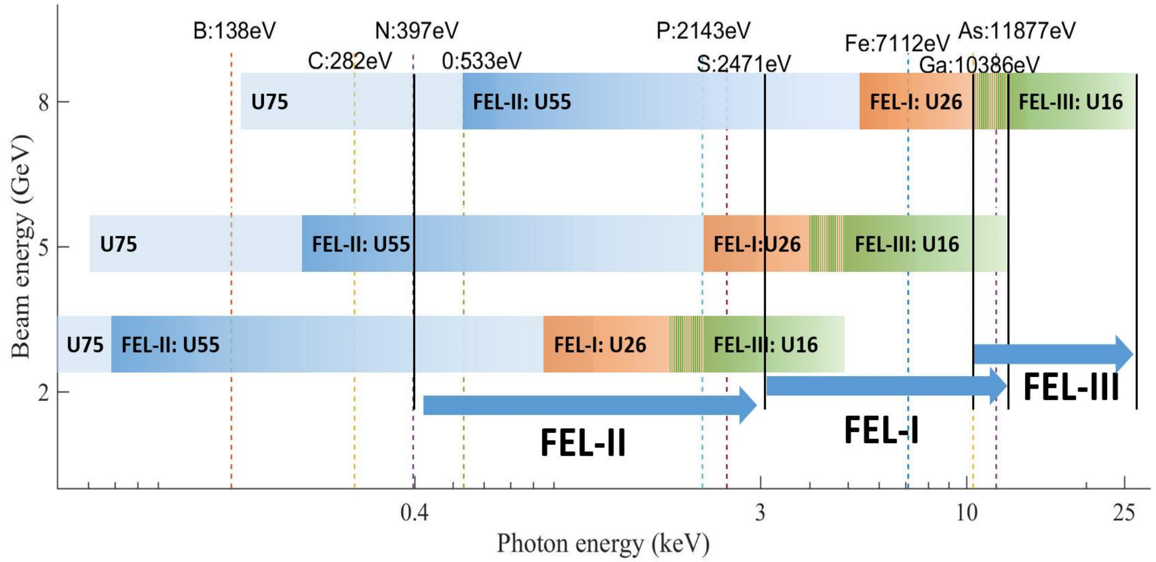


LCLS-I and LCLS-II

SHINE project（3.2km long）

SHINE undulator project





Location	equipments	quantity
Injector	Laser Heater U50, 0.5m	1
FEL-I	Planner U26, 4m	42
	Phase Shifter -U26, 4m	41
FEL-II	Planner U,2.2m	2
	Planner U55, 4m	18
	Phase Shifter -U55	35
	Double Planner U55&U75， 4m	14
	EPU,4m	4
FEL-III	Superconduct Uudulator ,4m	40
	Phase Shifter -U16	39

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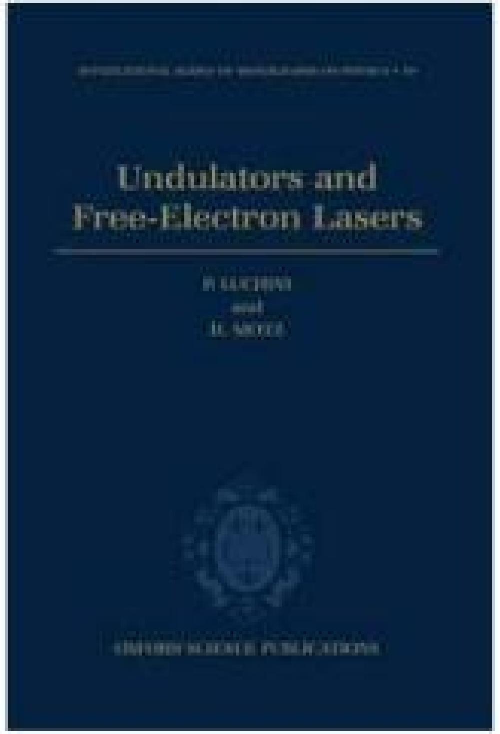
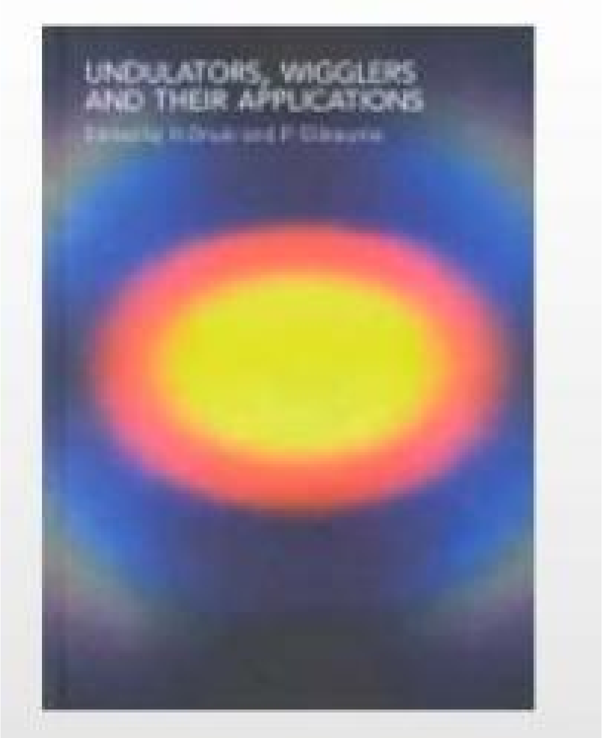
Reference Books of IDs

J. A. Clarke:
“The Science and Technology of Undulators and Wigglers”
Oxford University Press, 2004

Referred to as “Clarke”



P. Luchini, A. Motz:
“Undulators and Free Electron Lasers”
Clarendon Press, Oxford



H. Onuki. P. Elleaume:
“Undulators, Wigglers and their Applications
Taylor & Francis, New York 2003

Referred to as “Onuki”

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Computer codes for undulator/wiggler radiation

Radiation calculation including emittance and energy spread

Name	Authors	Platform	Download
B2E & SRW	O. Chubar, P. Elleaume, ESRF	Mac, Windows	http://www.esrf.fr/machine/groups/insertion_devices/Codes/software.html
URGENT	R.P. Walker, Diamond Light Source	Fortran Source	Contact Author
XOP	M. Sánchez del Río , ESRF & R. J. Dejus, APS	Unix, Windows	http://www.esrf.fr/computing/scientific/xop/
SPECTRA	T. Tanaka, SPring8	Unix, Windows Mac	https://spectrax.org/spectra/

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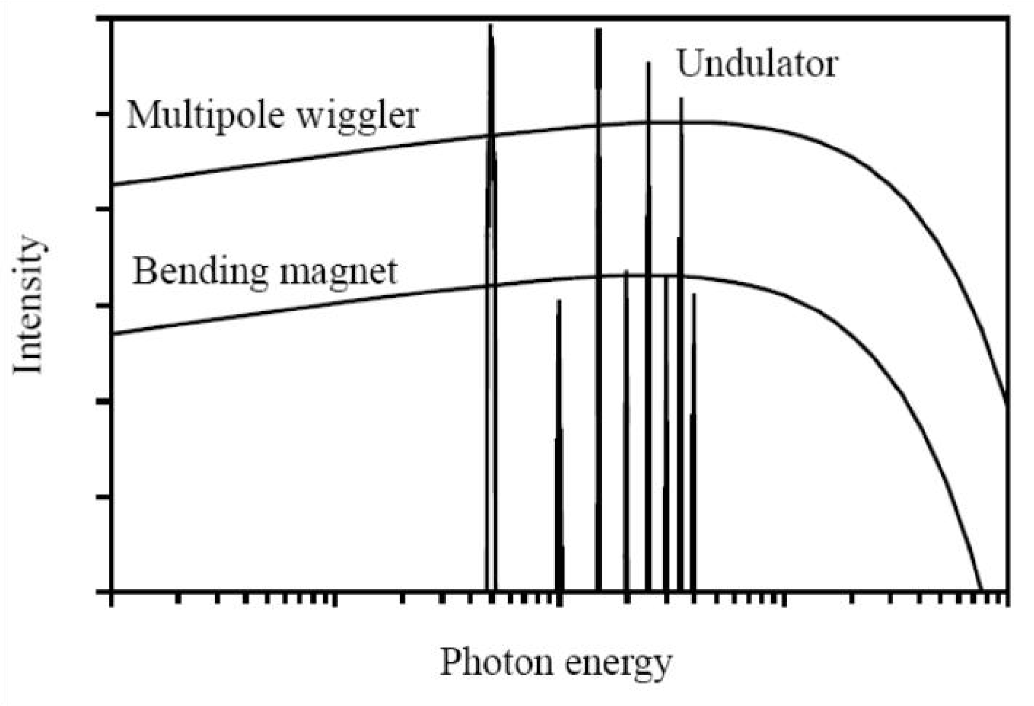
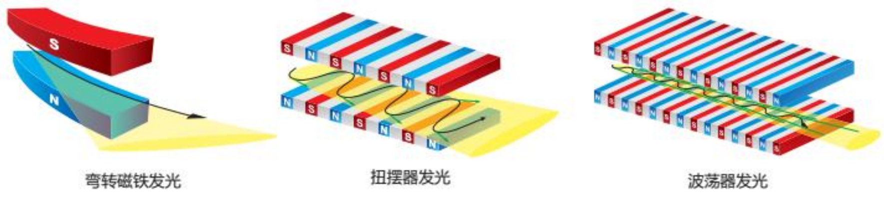
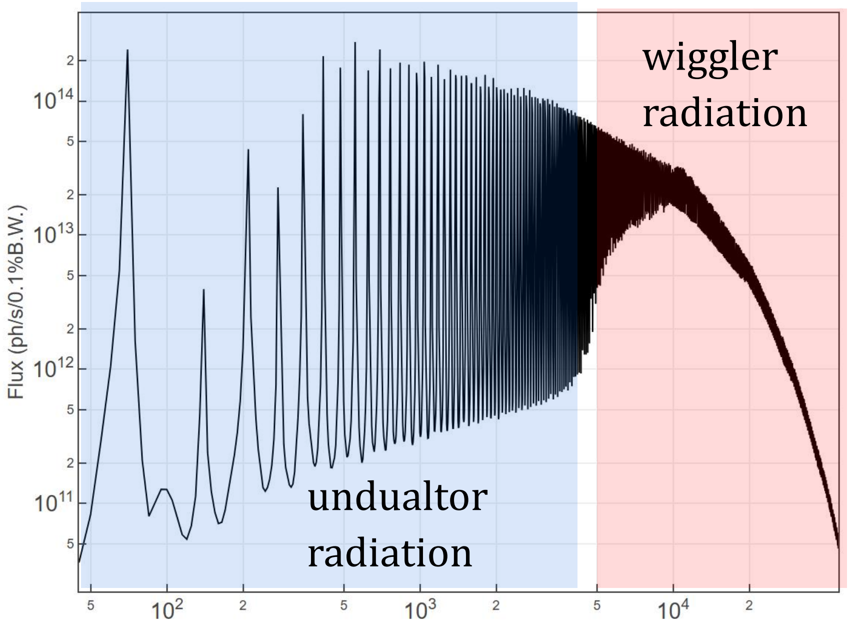
Typical Spectrum of the Three Sources





Researchers typically only use one photon energy or wavelength at a time (they use a monochromator to select this wavelength) for their experiments
undulators, which have the highest intensities, are the most popular sources of SR



3.5GeV, 200mA, Period 100mm,K=5.6

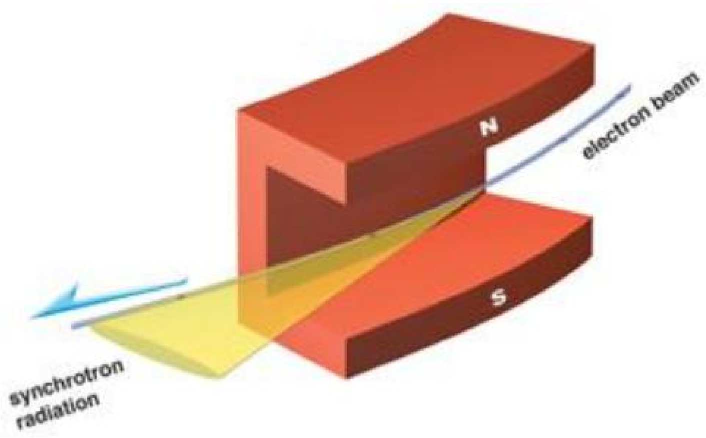
SR from Dipoles

A bending magnet or dipole has a uniform magnetic field

The electron travels on the arc of radius set by the magnetic field strength

Horizontally the light beam sweeps out like a lighthouse - the intensity is flat with horizontal angle

Vertically it is in a narrow cone of angle typically ±1/γ



$$\gamma \approx E / E_0$$

$$\epsilon_c = 665 E^2 B$$

The critical energy is given (in eV)by
where E is expressed in GeV and B is in Tesla and so in more practical units

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SR Power

The average SR power is very high and the **power density is even higher**

The total power emitted by the electron beam in the dipoles is

$$P_{\text{total}} = 88.46 \frac{E^4 I_b}{\rho_0}$$

where the power is in **kW**, E is in GeV, I_b is in A, bend radius is ρ_0 in m. and **power density on axis** (in W/mrad^2)

$$\left.\frac{dP}{d\Omega}\right|_{\psi=0} = 18.08 \frac{E^5 I_b}{\rho_0}$$

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Insertion Devices Power

The total power emitted by a beam of electrons passing through **any magnet system** is

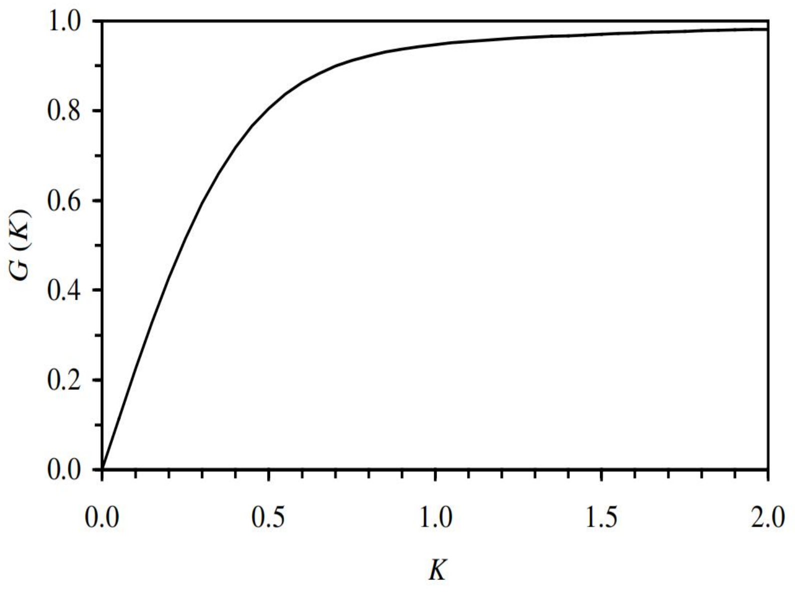
$$P_{\text{total}} = 1265.5\, E^2 I_b \int_0^L B(s)^2 ds$$

For a sinusoidal magnetic field ,wiggler and undulator, the total power emitted is (in W)

$$P_{\text{total}} = 632.8\, E^2 B_0^2 L I_b$$

Power density

$$\left.\frac{dP}{d\Omega}\right|_{\psi,\theta=0} = 1012.5\, \frac{E^4 B_0^2}{K} L I_b G(K)$$



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Power Examples

The RF system must replace this lost power continuously to keep the electrons in an equilibrium state

Dipoles

Light Source	Energy(GeV)	C (m)	Current (mA)	P_total (KW)	SR loss/turn, dipole (KeV)
HEPS	6	1360.4	200	578.4	2891
SLS 2.0	2.7	288	400	276	690
HALF	2.2	480	350	63.7	181.4
SSRF	3.5	432	200	290	1450
TPS	3.0	518.4	400	341	852.7

Wiggler ,26 poles at 1.58T, period of 100mm
Power emitted = 4.26kW
This is equivalent to ~2% all the dipole SR

IVU,400 poles at 0.9T, period of 20mm
Power emitted = 4.97kW
This is equivalent to ~2% all the dipole SR

SSRF case

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Three basic sources of SR

- Dipole

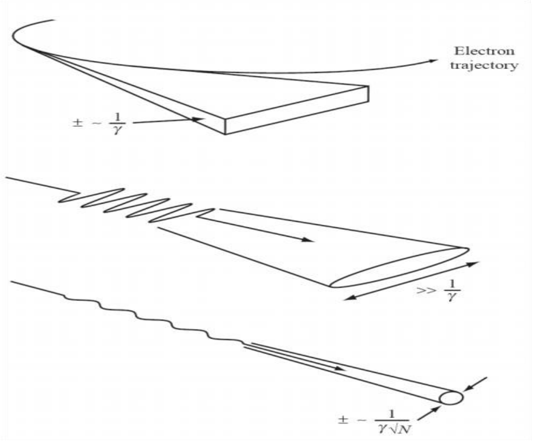
B=1T, L=0.1m

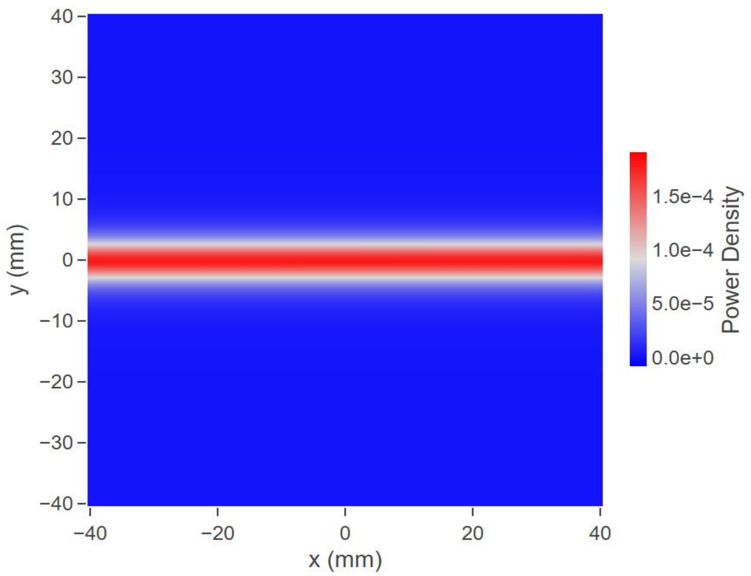
- (Multipole) Wiggler

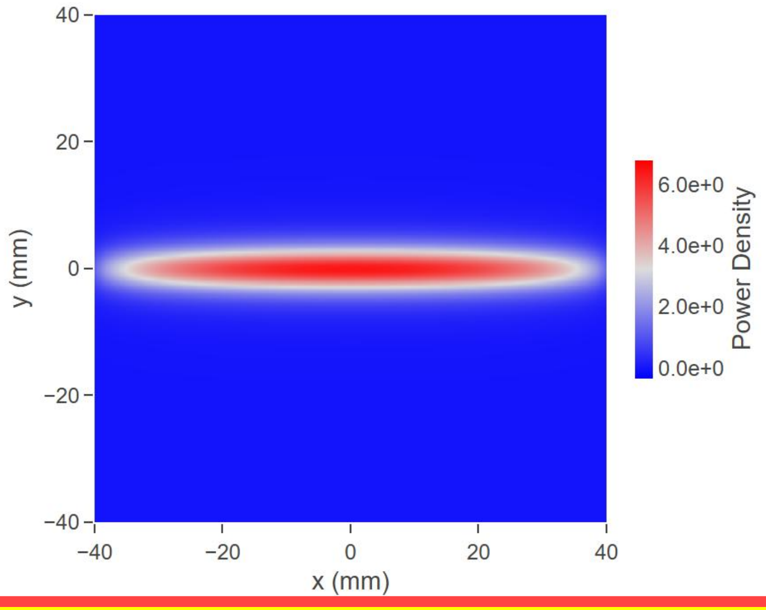
B=1T, Period=100mm,L=2m

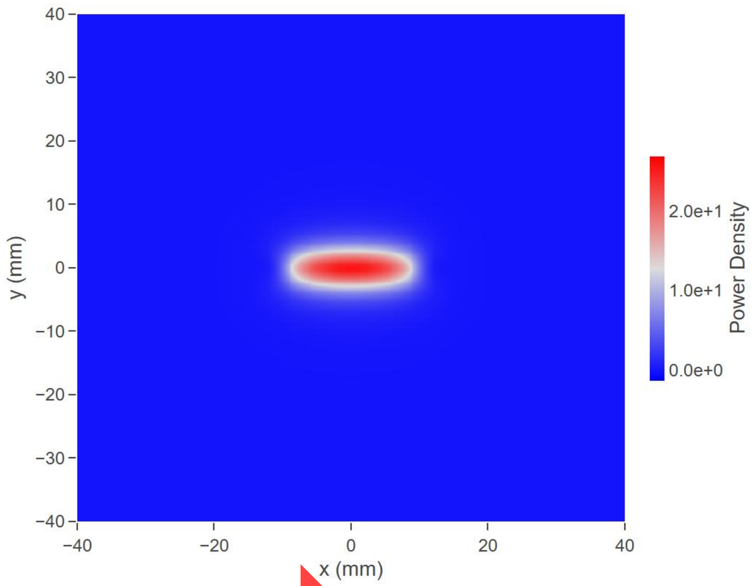
- Undulator

B=1T,Period=25mm,L=2m









power desity increase @3.5GeV，200mA

Trajectory of the Electron in sinusoidal field

$$\ddot{x} = \frac{d^2x}{ds^2} = \frac{e}{\gamma m_0 c}(B_y - \dot{y}B_s)$$
$$\ddot{y} = \frac{d^2y}{ds^2} = \frac{e}{\gamma m_0 c}(\dot{x}B_s - B_x)$$

$$B_y(s) = -B_0 \sin\left(\frac{2\pi s}{\lambda_u}\right)$$

$$\dot{x}(s) = \frac{K}{\gamma}\cos\left(\frac{2\pi s}{\lambda_u}\right)$$

$$x(s) = \frac{K}{\gamma}\int \cos\left(\frac{2\pi s}{\lambda_u}\right) ds = \frac{K}{\gamma}\frac{\lambda_u}{2\pi}\sin\left(\frac{2\pi s}{\lambda_u}\right) .$$

$$K = \frac{B_0 e}{m_0 c}\frac{\lambda_u}{2\pi} = 93.36\, B_0\lambda_u$$

The maximum angular deflection is K/γ

The maximum transverse displacement is $\frac{K}{\gamma}\frac{\lambda_u}{2\pi}$

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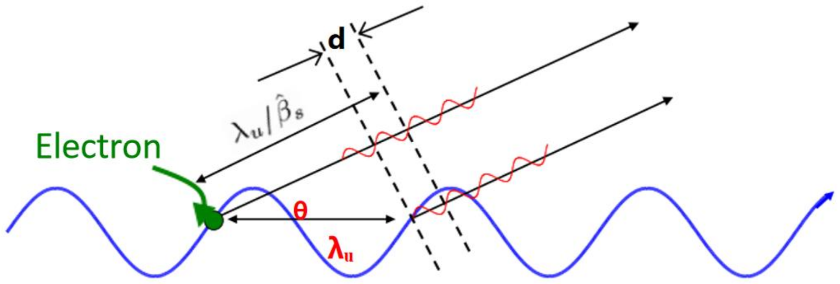
The Condition for Interference and Undulator equation

For constructive interference between wavefronts emitted by the same electron **the electron must slip back by a whole number of wavelengths** over one period



Solving for λ we get the **undulator equation** for constructive interference
The wavelength primarily depends on the period and the electron energy but also on deflection parameter K and the observation angle θ.

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

$$K = \frac{B_0 e}{m_0 c}\frac{\lambda_u}{2\pi} = 93.36\, B_0 \lambda_u$$

If we can change B_0 we can change λ.

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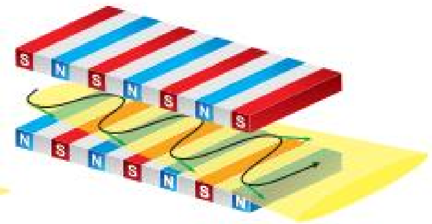
Wiggler Flux

- A Wiggler can be considered a series of dipoles one after the other
- There are two source points per period (two poles per period)
- The flux is simply the number of source points multiplied by the dipole flux for one pole
- The Wiggler has two clear advantages:
  - **The spectrum can be set to suit the science need**
  - **The Flux is enhanced by the number of poles**



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$$\dot{N} = 2.46 \times 10^{13}\, 2N\, E I_b \left(\frac{\epsilon}{\epsilon_c}\right) \int_{\epsilon/\epsilon_c}^{\infty} K_{5/3}(u)\, du$$

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Flux density of undulator

the famous undulator equation

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

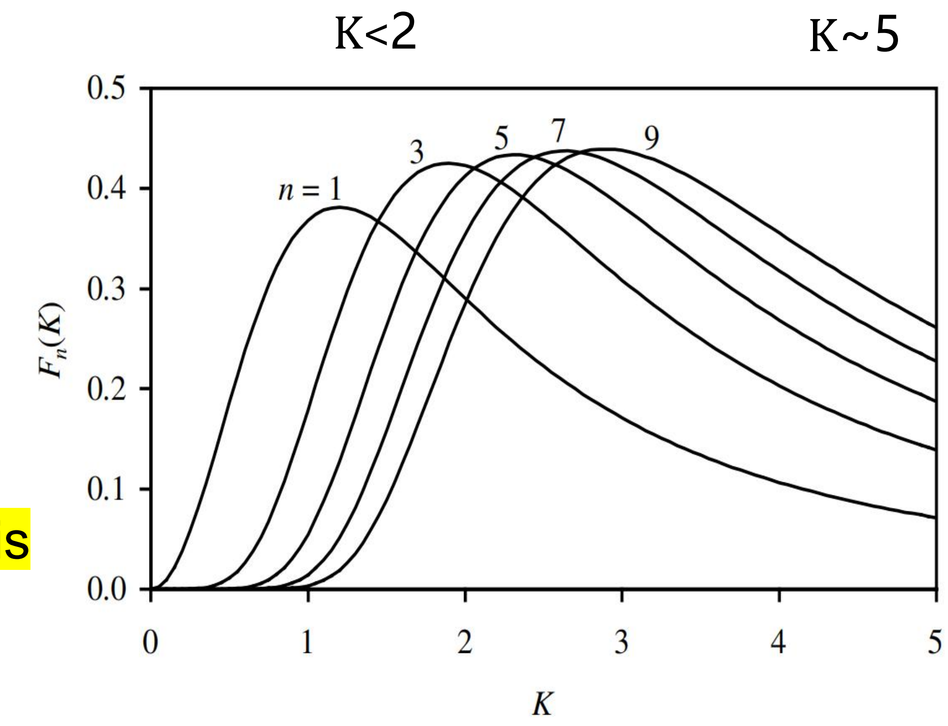
In practical units this gives the number of photons per solid angle per second on-axis for a planar undulator as

$$\left.\frac{d\dot{N}}{d\Omega}\right|_{\theta=0} = 1.74 \times 10^{14}\, N^2 E^2 I_b F_n(K)$$

$$F_n(K) = \frac{n^2 K^2}{(1 + K^2/2)^2}\left(J_{(n+1)/2}(Y) - J_{(n-1)/2}(Y)\right)^2$$

There are *no even harmonics observed on-axis*

For K>5, high harmonic are quite large, mirror heat is heavy,we need suppress

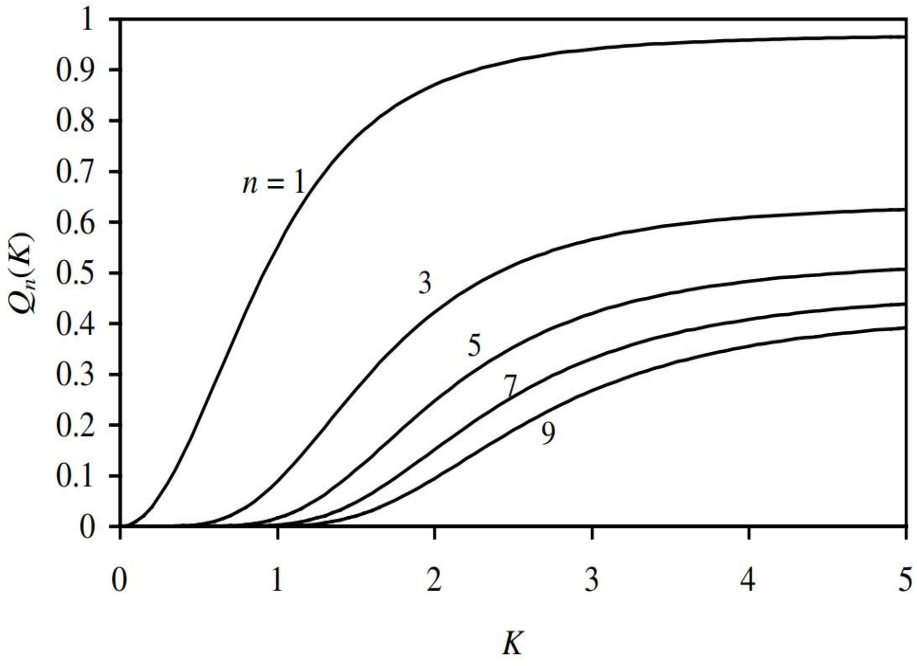


Flux of undulator

$$Q_n(K) = \frac{1 + K^2/2}{n} F_n(K)$$

In practical units of photons per second per 0.1% bandwidth this gives the flux in the central cone as

$$\dot{N} = 1.43 \times 10^{14} \, N I_b Q_n(K)$$



For K<2, high harmonic are quite small, we need more periods N

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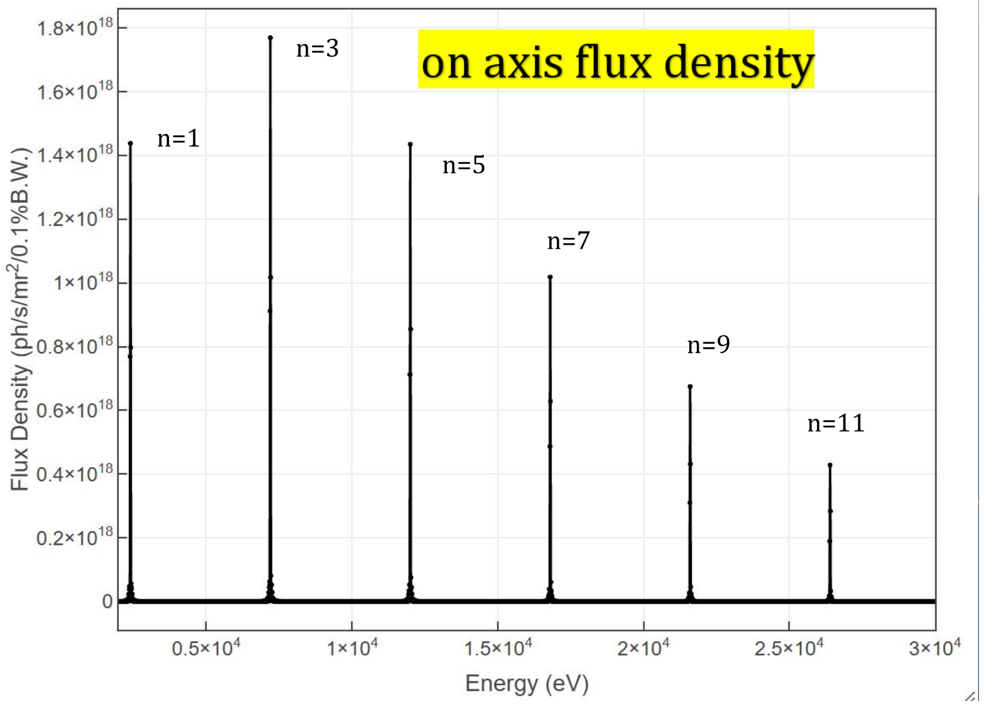
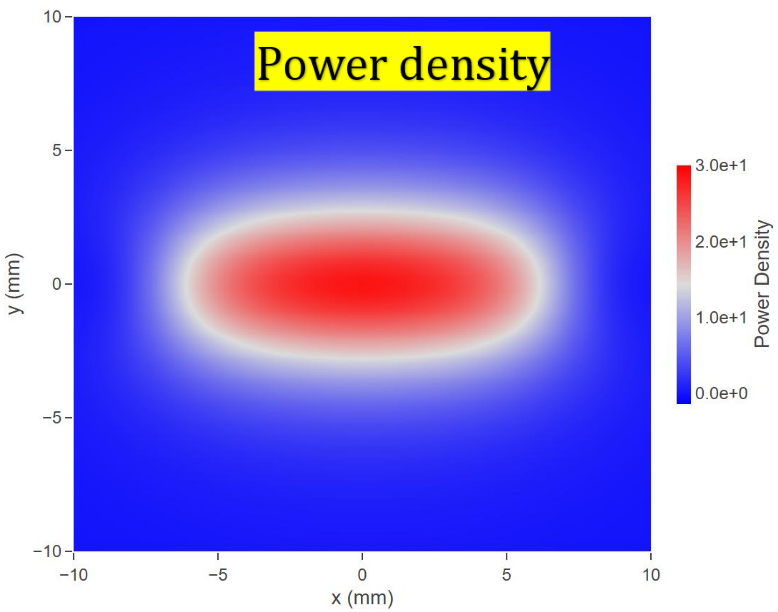
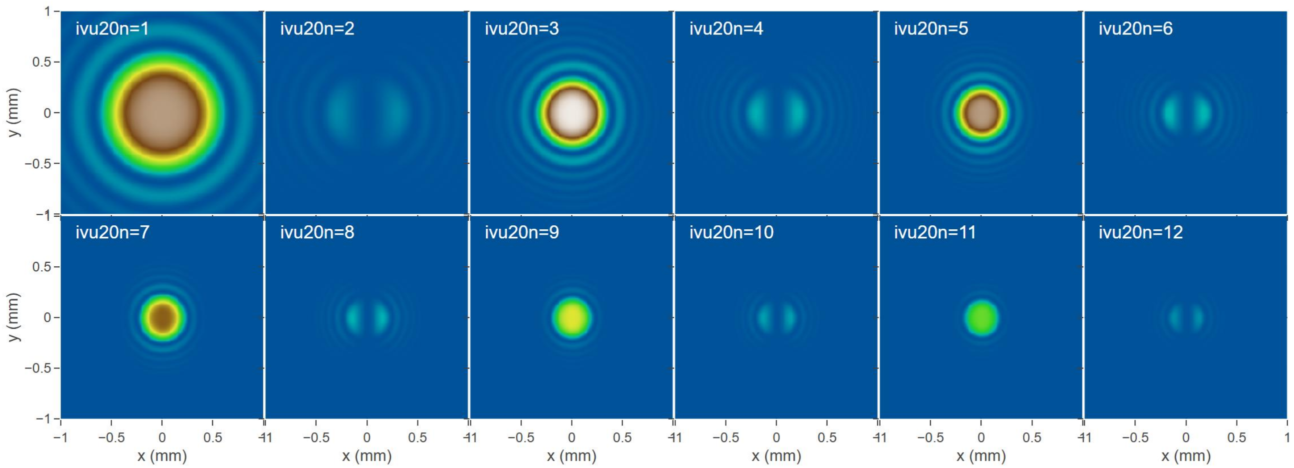
Example K<2, synchrotron radiation

Period 20mm，
B=0.9T,K=1.68 ,3.5GeV,200mA,
source point distance 30m



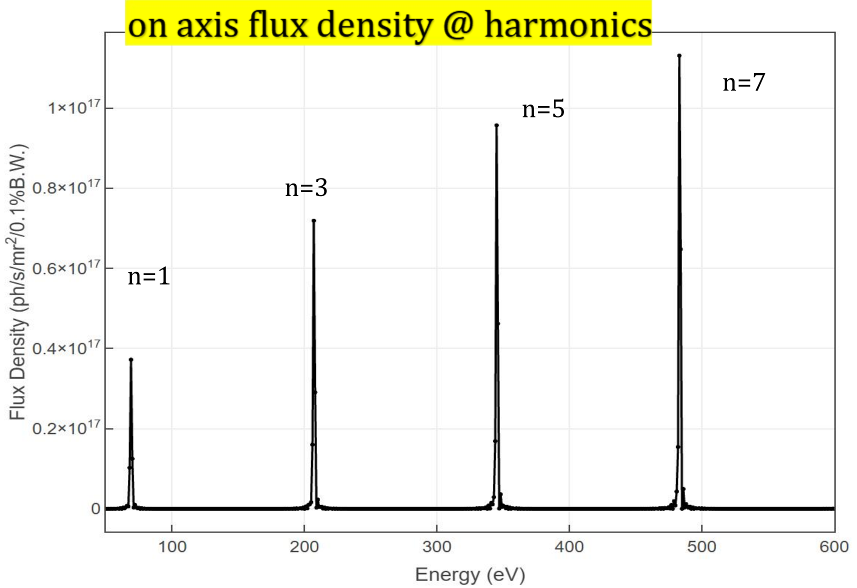


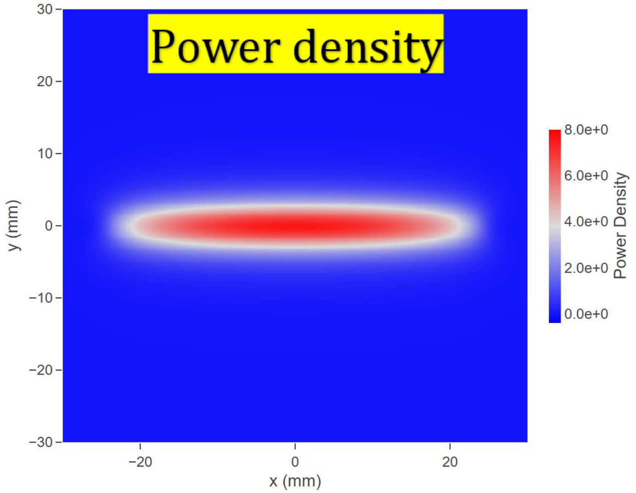


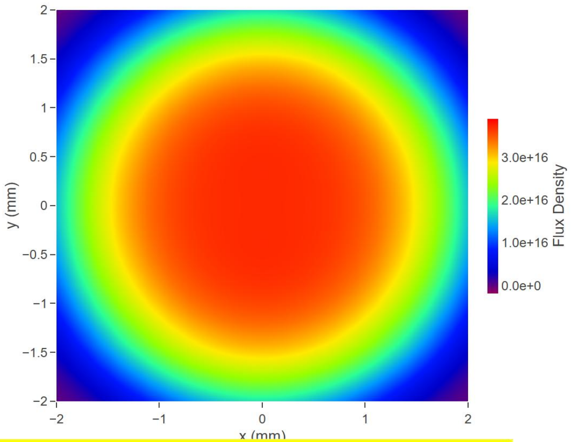
on axis flux density @ harmonics

Example K>5, synchrotron radiation

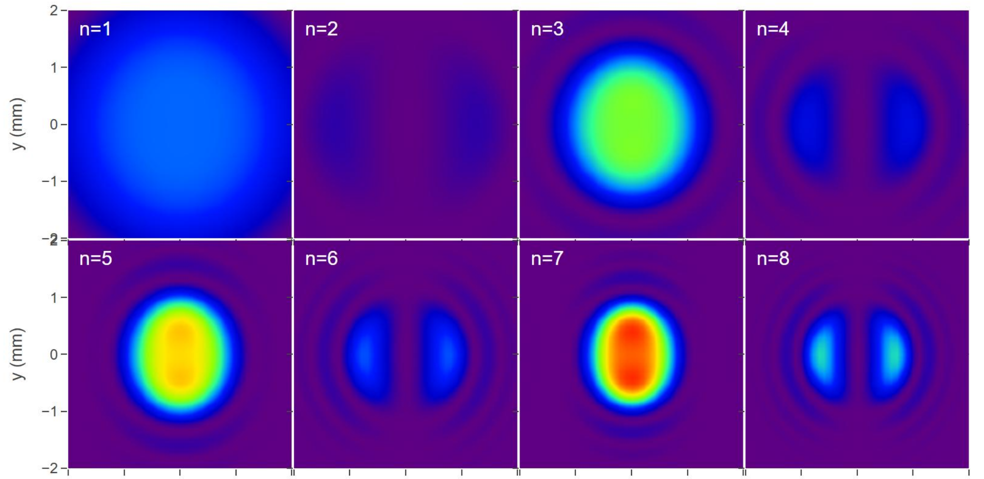
Period 100mm， B=0.6T,K=5.6 ,3.5GeV,200mA, source point distance 30m







on axis flux density @ n=1



on axis flux density @ harmonics

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Harmonic bandwidth

If we calculate at what wavelength destructive interference will occur we can estimate the harmonic bandwidth (width of the harmonic line) to be

$$\frac{\Delta\lambda}{\lambda} \sim \frac{1}{Nn}$$

So, if the undulator has 100 periods then the first harmonic (n = 1) line will have a bandwidth of ~1%

With a harmonic wavelength of 4 nm, the undulator will provide output between approx 3.98 and 4.02 nm

Bandwidth is inversely proportional to the period numbers, better coherent recieved

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Example Angular Flux Density

- An Undulator with 50mm period and 100 periods with a 3GeV, 300mA electron beam will generate:
- Angular flux density of **8×10^{17}** photons/sec/mrad^2/0.1% bw

- For a dipole with the same electron beam we get a value of **~ 5×10^{13}** photons/sec/mrad^2/0.1% bw

- **The undulator has a flux density ~10,000 times greater than a dipole because it scales with N^2**
- N is the number of undulator periods

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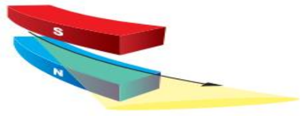
Example Flux

- Undulator with 50mm period, 100 periods
- 3GeV, 300mA electron beam
- Our example undulator has a flux of **4 x 10^{15}** photons/s/0.1% bandwidth
- **The flux is proportional to N**

compared with the dipole flux of **10^{13}** photons/s/0.1%



弯转磁铁发光

$$\dot{N} = 2.46 \times 10^{13}\, E I_b \left(\frac{\epsilon}{\epsilon_c}\right) \int_{\epsilon/\epsilon_c}^{\infty} K_{5/3}(u)\, du$$

扭摆器发光

$$\dot{N} = 2.46 \times 10^{13}\, 2N\, E I_b \left(\frac{\epsilon}{\epsilon_c}\right) \int_{\epsilon/\epsilon_c}^{\infty} K_{5/3}(u)\, du$$

波荡器发光

$$\dot{N} = 1.43 \times 10^{14}\, N I_b Q_n(K)$$

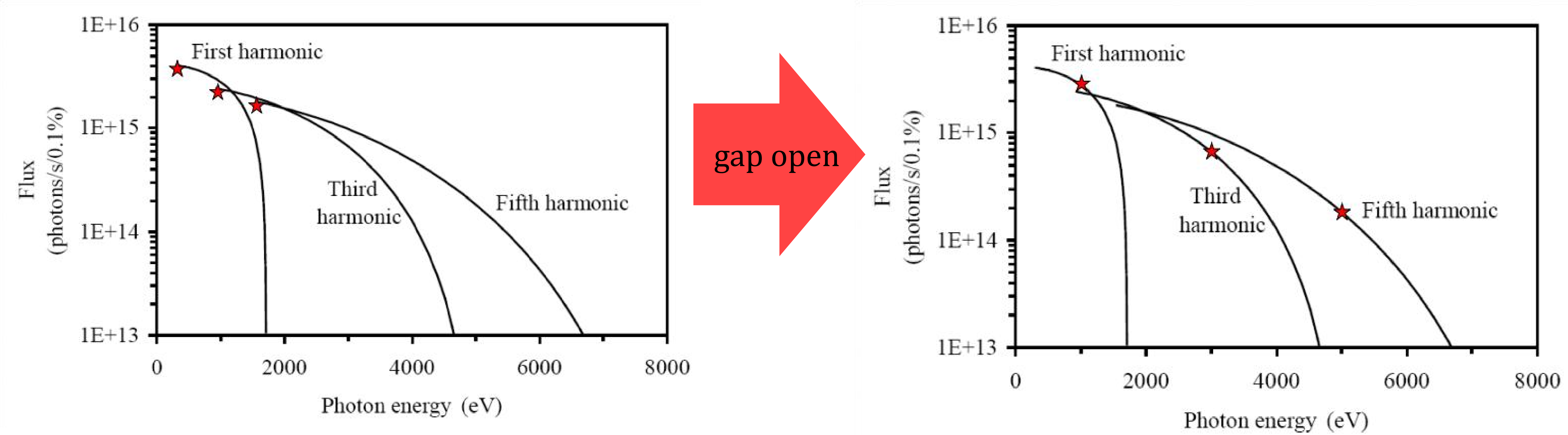
Example Undulator Tuning Curve

Undulator with 50mm period, 100 periods

3GeV, 300mA electron beam

We can tune the wavelength by open the undulator gap

Note: there may be flux@n=5,7 at small gap larger than flux@n=3,5 at bigger gap



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Key words for Insertion Devices

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

Peak magnetic field: Given the period length, the stronger the magnetic field, the lower the radiation energy

Period length: For goal wavelength, the shorter the period length, the more periods that can be obtained in a limit straight section.

Deflection parameter: for a given K, try to increase B

Flux: The smaller the K value, the weaker the higher harmonics, the higher the energy, the small period IVU requires higher harmonics (requires small phase errors)

The flux is proportional to N

Flux density: The greater the K value, the higher the axial flux density at high-order harmonics (linear polarization mode)

Axial power density: K value large undulator, need to reduce the thermal liability of optical crystals; Filtering required (higher harmonics)

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Outline

- Insertion devices to generate radiation
- **Types of Insertion devices**
- Undulators torwards the future
- Try to design an undulator?

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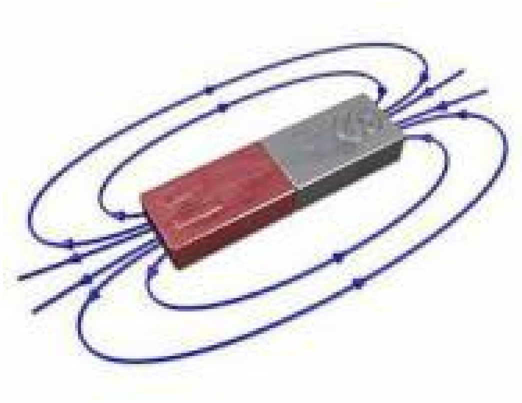
Generating Periodic Magnetic Fields

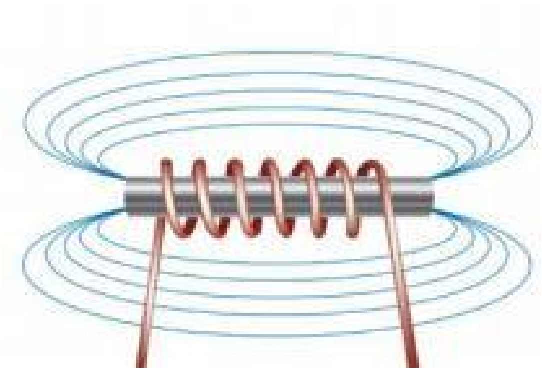
- To generate magnetic fields we can use:

Permanent Magnets



Electromagnets

- Normal conducting
- Superconducting



- **Both types can also include iron to enhance and shape the field**

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Permanent Magnets

- Permanent Magnet materials are manufactured so that their magnetic properties are enhanced along a particular axis

- When a magnetic field, B, is applied to a magnetic material each dipole moment tries to align itself with the field direction
- When B is strong enough (at saturation) all of the moments are aligned, overcoming other atomic forces which resist this
- **A Permanent Magnet maintains this alignment after the external B is removed**

Note： China is the top exporter of permanent magnet materials, with high-quality magnetized blocks gradually dominating the international accelerator market.

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Magnet Materials

Three types of permanent magnet are commonly used for undulators – Samarium Cobalt (SmCo) and Neodymium Iron Boron (NdFeB),a newtype (PrFeB) is also starting to be used for special applications – **these are all very close to ideal in their performance**

	Samarium Cobalt (SmCo)	Neodymium Iron Boron (NdFeB)	Praseodymium iron boron (PrFeB)
Remanent Field	0.85 to 1.1 T	1.1 to 1.4 T @300K about 1.56T @150K	1.3-1.5T @300K 1.6-1.7T @77K
Coercivity	900 to 2400 kA/m	1000 to 2400 kA/m@300K ~5000kA/m@300K	~1500kA/m@300K ~5400kA/m@77K
Relative Permeability	~1.03	~1.05	~1.05
Temperature Coefficient	-0.04 %/。C	-0.11 %/。C	-0.11 %/。C
Max operating temperature	~500K	~400K	<400K

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NdFeB magnet

HPMG High Grade Magnets Development Road Map (2024)

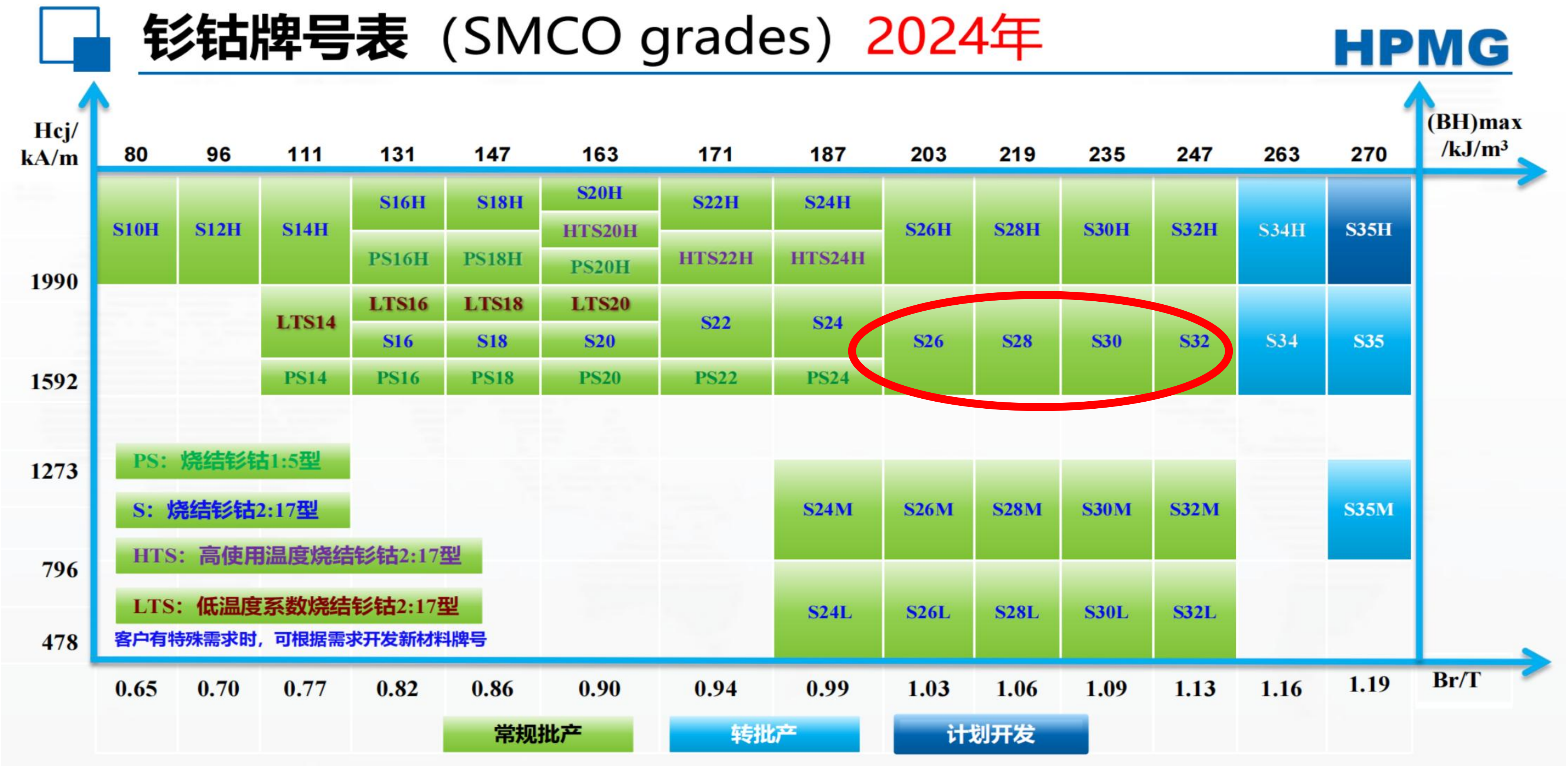
Hcj kA/m	223	239	263	279	302	318	334	358	382	398	414	430	446	462	478	493	(BH)max /kJ/m³ / T°C
3184	28VH	30VH	33VH	35VH													240
2786	28TH	30TH	33TH	35TH	38TH												230
2388	28EH	30EH	33EH	35EH	38EH	40EH	42EH	45EH									200
1990	28UH	30UH	33UH	35UH	38UH	40UH	42UH	45UH	48UH								180
1592			33SH	35SH	38SH	40SH	42SH	45SH	48SH	50SH	52SH						150
1353			33H	35H	38H	40H	42H	45H	48H	50H	52H	54H	56H				120
1114				35M	38M	40M	42M	45M	48M	50M	52M	54M	56M	58M			100
955				N35	N38	N40	N42	N45	N48	N50	N52	N54	N56	N58	N60		80
	1.05	1.08	1.14	1.18	1.23	1.26	1.29	1.33	1.37	1.39	1.42	1.44	1.46	1.49	1.52	1.54	

Free Dy/Tb | Low Dy | Low Tb | Developing

https://www.china-hpmg.com/

SHINE

SmCo magnet



https://www.china-hpmg.com/

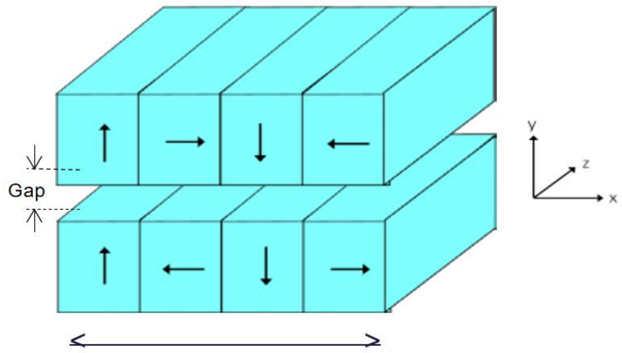
SHINE

Typical magntic array: PPM and Hybrid

The arrows in the blocks are the field directions generated by each block

Over a full period the arrows have rotated by 360 degree

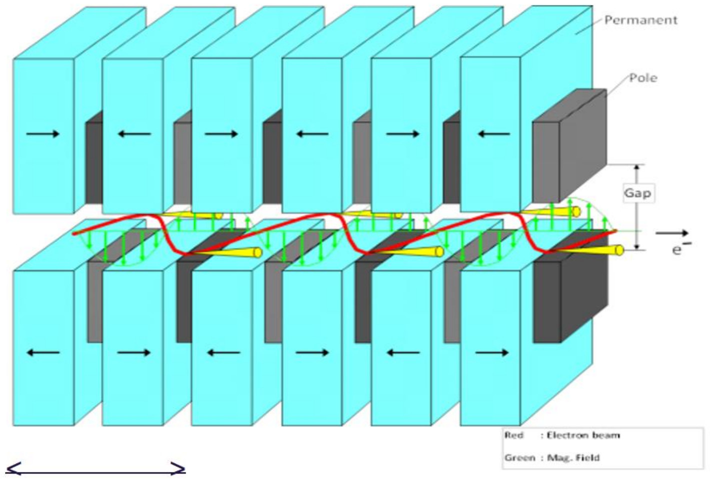
PPM



λ_0

K. Halbach, NIM 187, (1981) 109

Hybrid



λ_0

K. Halbach, Journal de Physique 44, Colloque C1, (1983) 211

$$B_{y_0} = 1.72\, B_r e^{-\pi g/\lambda_u}$$

$$B_0[g, \lambda_u] = 4.22[T] \exp\left(-5.08 \times \left(\frac{g}{\lambda_u}\right) + 1.54 \times \left(\frac{g}{\lambda_u}\right)^2\right)$$

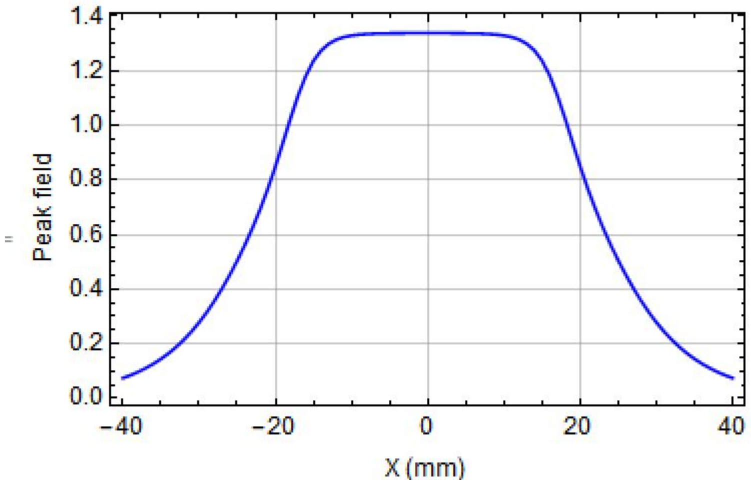
case：LCLS-II、SHINE-U26

SHINE

Undulator Forces

- For a sinusoidal field of length **L** where the **vertical field is constantin x over a width W** (and zero outside of this width) then the **total force between the two arrays is**

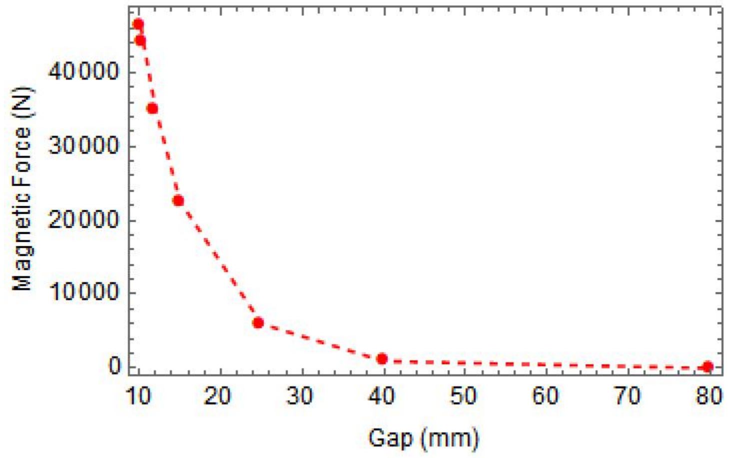
$$F = \frac{B_{y_0}^2 LW}{4\mu_0}$$



- For SHINE project examples
  4m long undulator,55 mm period hybrid structure and 10.4mm gap undulator with remanent field of 1.28T and a horizontal field width of 35mm

The attractive force between the two arrays is ~50kN

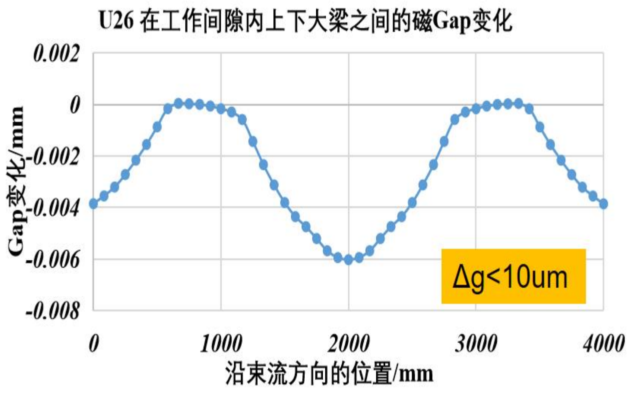
- Note that this force changes rapidly with gap since the field changes exponentially

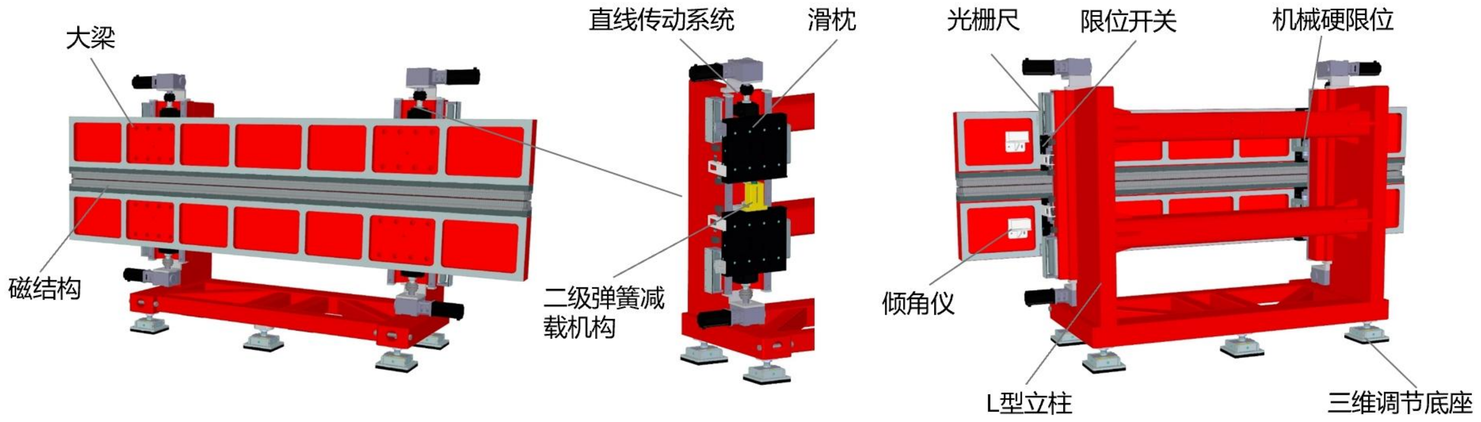


SHINE

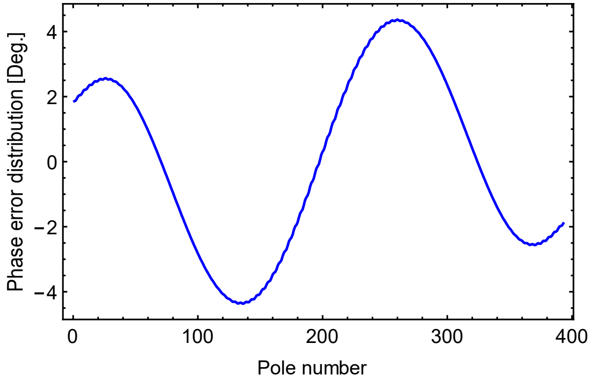
Engineering Issues for all PM Undulators

- **Engineering demands are very high:**
- Very strong magnetic forces are present during assembly and when complete
- Must achieve very high periodicity
- Arrays must be parallel to μm precision and must stay parallel at all gaps



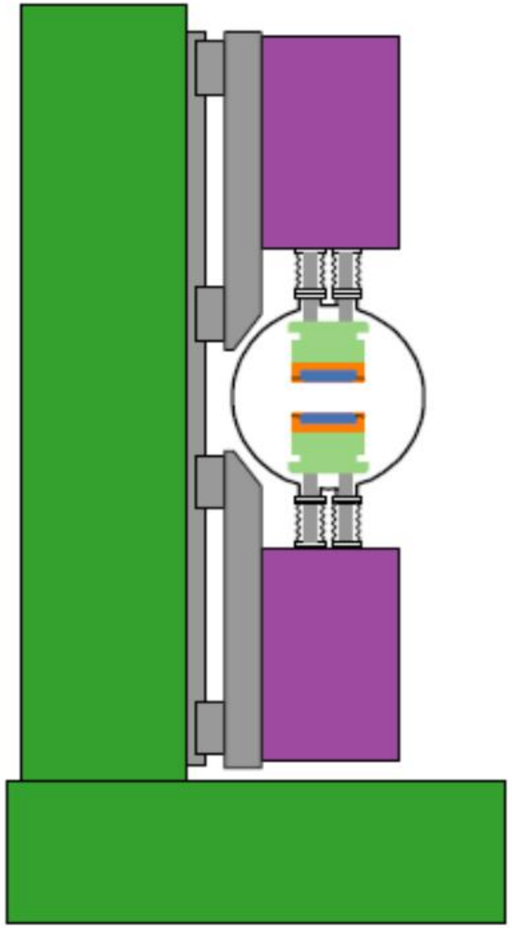


SHINE -U26 Mechanical



Girder deformance
<10 μm, rms phase error ~2.5deg
<20 μm, rms phase error ~5deg

Engineering Issues



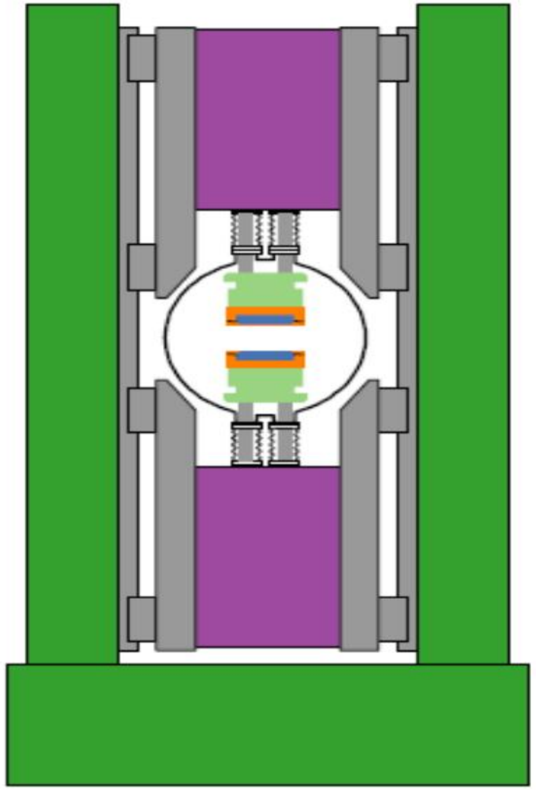
C-shape

C shape :

- Best access for magnetic measurements & Tuning
- Convenient for installation in storage rings or FELs, especially in air undulator.

H Frame:

- Compact, symmetric support, stable
- but not easy to measurements & tuning



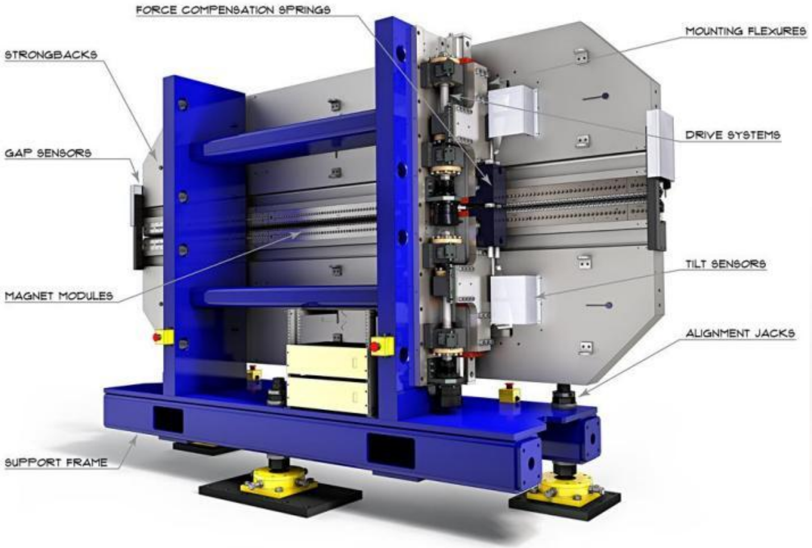
H-Frame

Huge Undulators Project

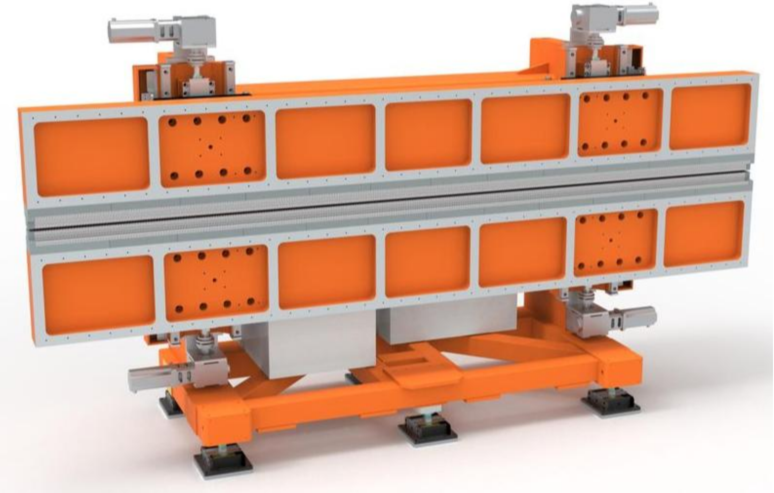
Although the permanent magnet blocks are themselves physically small, the engineering arrangement needed to generate high quality fields and to change the magnet gap in a precise and controlled way means undulators are large and challenging engineering systems

simple- easy series production- low cost

EuXFEL Undulator 5m long, Dessy

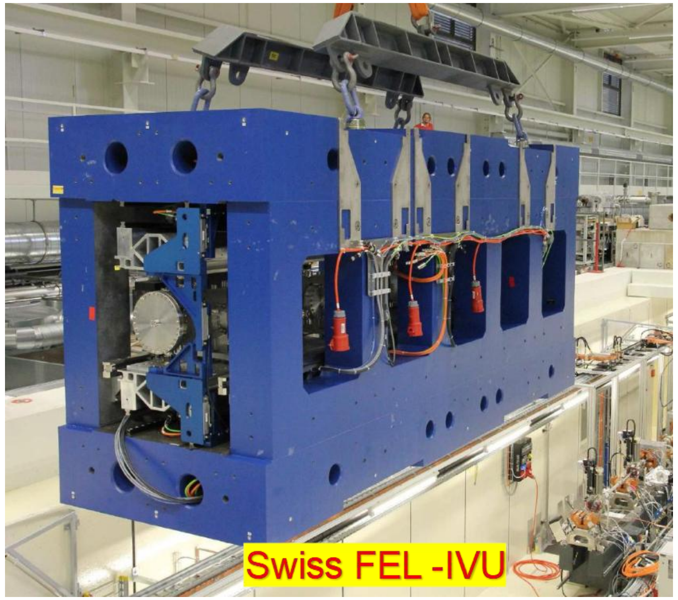


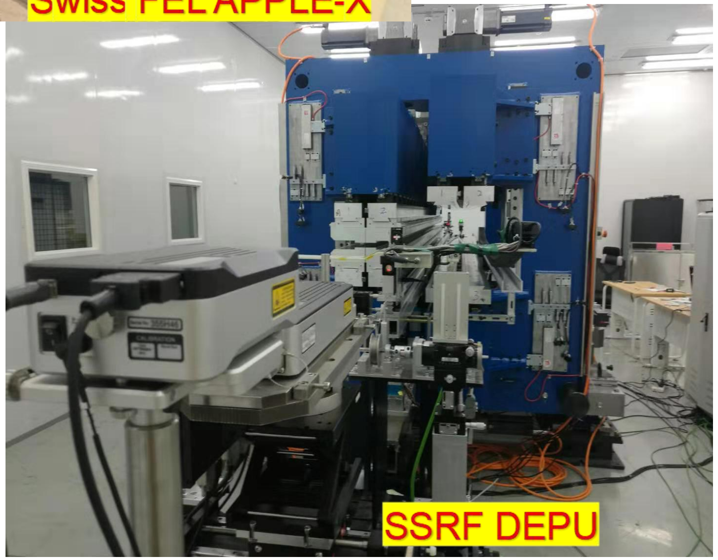
LCLS-II Undulator 3.4m long, LBNL



SHINEUndulator 4m long, SARI

H-Frame

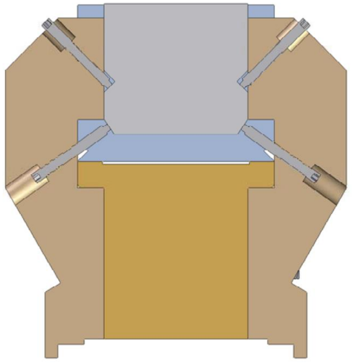




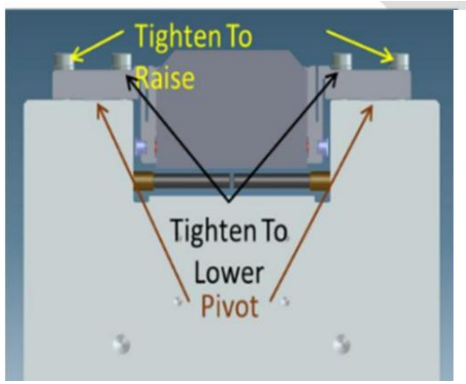
SHINE

Holder on Magnetic Field Shimming

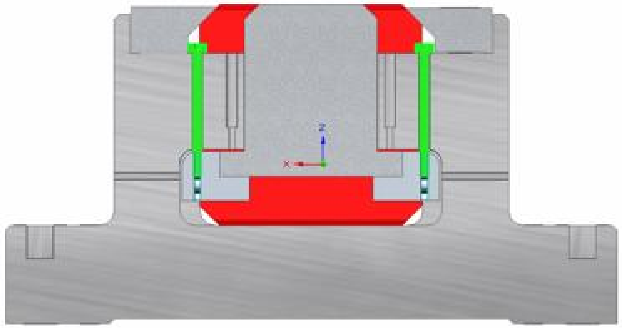
- Precise magnetic measurements of the undulators are (often) made during assembly as well as of the fully assembled device (over the full gap range)
- Local magnetic field shimming are corrected to ensure the field quality of the undulator meets the specification required, magnetic field intensity/phase error/orbit
- End **shimming** is corrected to fullfill the field integrals requirments, including multipole reduction
- Usually pole or magnet position adjusted within ±0.1mm



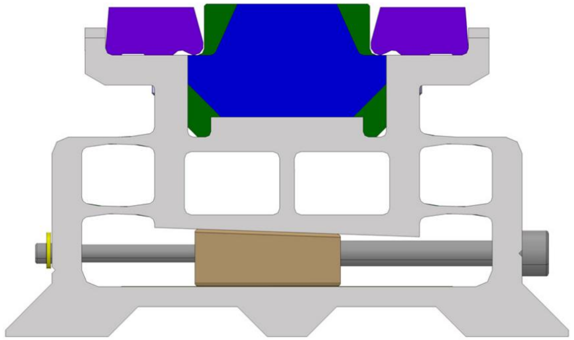
EuXFEL



LCLS-II



SHINE



SWISS FEL -Aramis U15

J. Pflüger, H. Lu, T. Teichmann NIM A429 (1999), 368

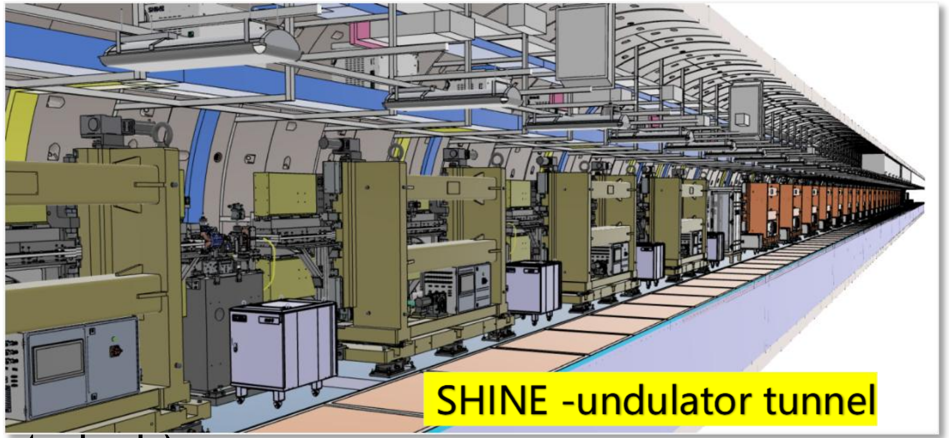
Although shimming is a time consuming task, it is a very important step, since the magnetic errors will be significantly reduced.

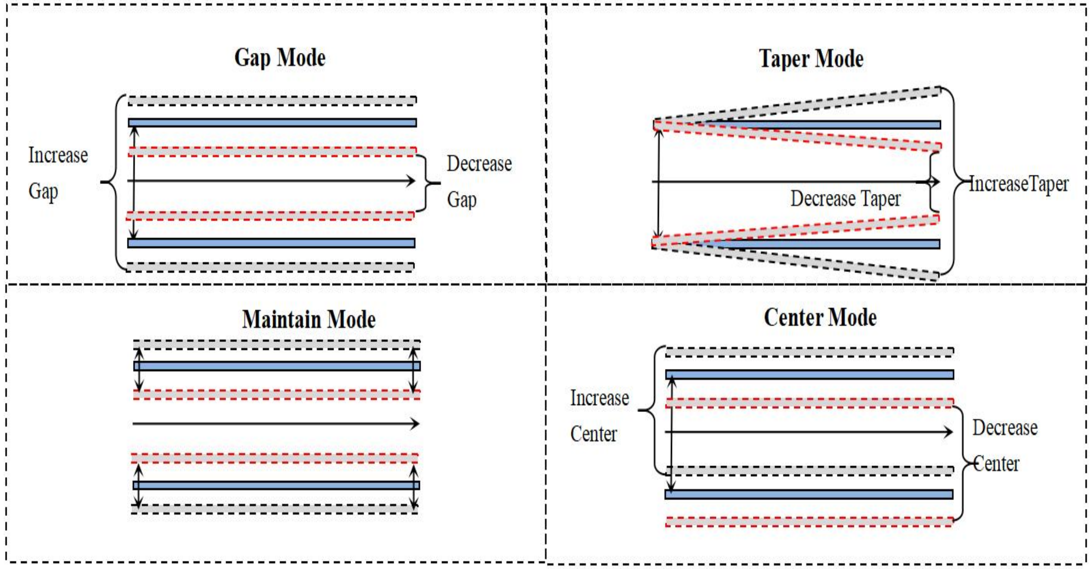
SHINE

Motion Control for IDs

➢ Motion control function

- **four motion control modes**
- Local and remote control function
- Position protection (soft limit, hard limit, electromechanical,
- photoelectric)
- Emergency stop function
- Communication interface based on Modbus TCP
- Other interfaces (temperature monitoring and interlock , external interlock)
- Torque protection





- Gap mode, adjustment of gap of magnetic pole
- Taper mode, adjustment of deviation between the entrance gap and the exit gap and keeping it within a certain range.
- Center mode, adjustment of magnetic pole height.
- Inclined mode

The movements of the four motors are completely independent and can be operated independently

Assembly magnet into Vacuum chamber

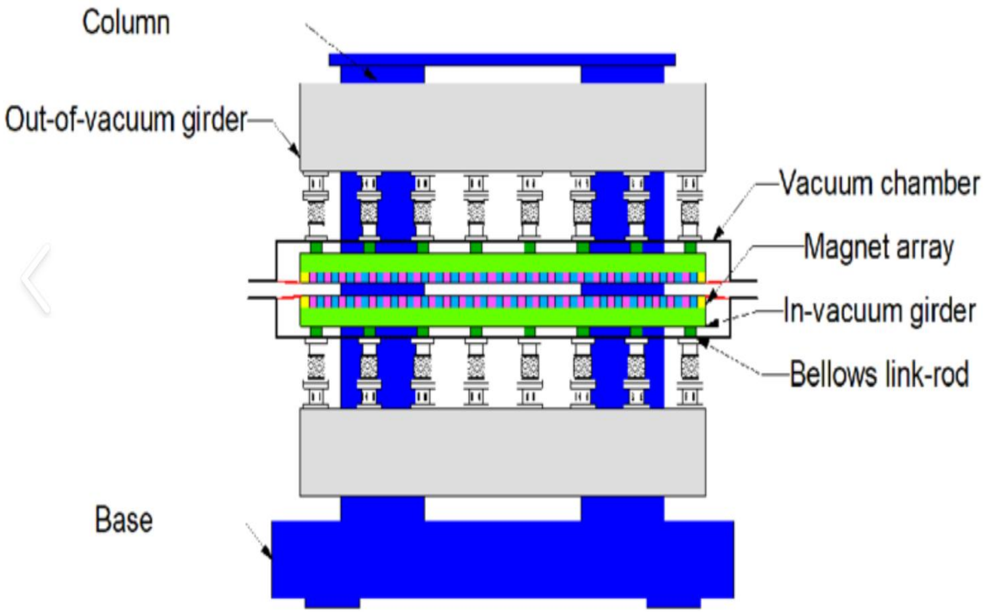
- The minimum magnet gap limits the peak field of an undulator
- The magnet gap is determined by the needs of the electron beam
- In practice this is set by the vacuum chamber
- If an electron beam needs 5mm of vertical space

  For in air undulator

  - The vacuum chamber walls are 0.5mm thick
  - With an allowance for mechanical tolerances of 0.5mm
  - The minimum magnet gap will be at least 5+0.5*2+0.5*2=7mm (LCLS-II case\SHINE case)

  So 2 mm is effectively wasted as far as the magnet is concerned

- Better option is to put the undulator inside the vacuum chamber



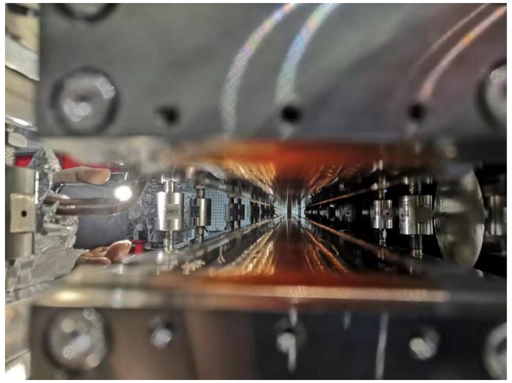
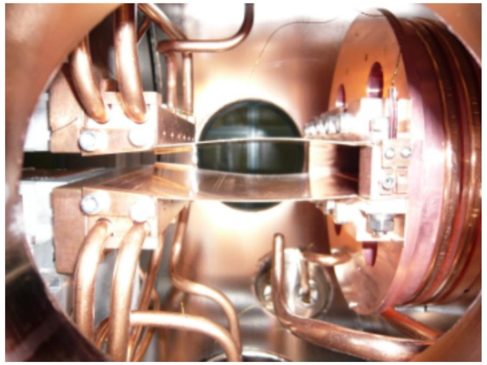
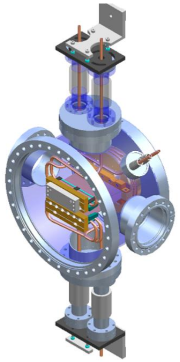
SHINE

In Vacuum Undulators

- **Decrease minimum gap** to 3-6mm
- **coating** of magnets to **reduce outgassing**

  Ti+TiN ion plating of NdFeB or SmCo magnets
- Pick high coercive magnetic material (bakeout less than 120°)
- **NiCu sheet** to reduce image current heating
- (20 Ni + 50 Cu)
- water cooled RF-fingers

  Heat load from **synchrotron radiation and beam impedance**

IVUs have been extensively utilized in the third-generation synchrotron radiation light sources since 1990s and FELs from 2005

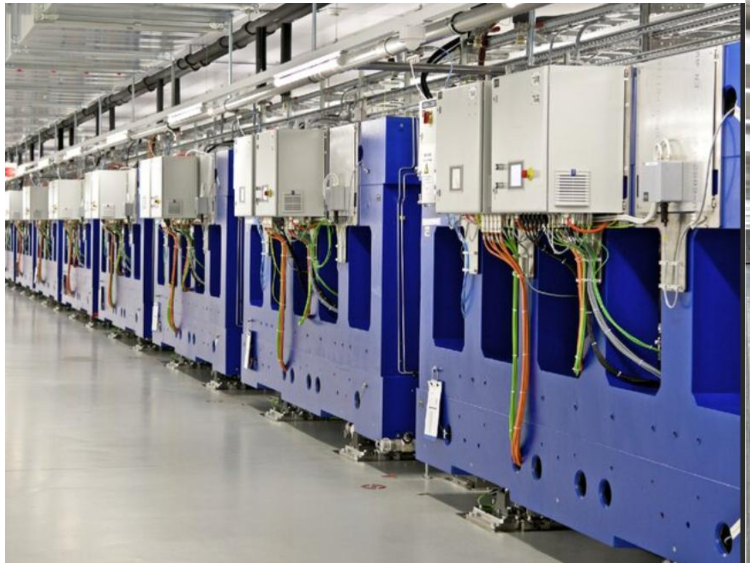
Sirius IVU at SSRF

SHINE

In-Vacuum undulator for FELs

Facility	日本 SACLA	瑞士 Swiss-FEL	上海 SXFEL-SBP
length（m)	5	4	4
period （mm)	18	15	16
number	277	266	243
gap（mm)	3.5	3.2	3.6
peak field（T)	1.57	1.27	1.22
Magnet	NdFeB	NdFeB+Dy	SmCo

SACLA in-vacuum undulators



SWISS FEL IVUs

SXFEL IVUs

SHINE

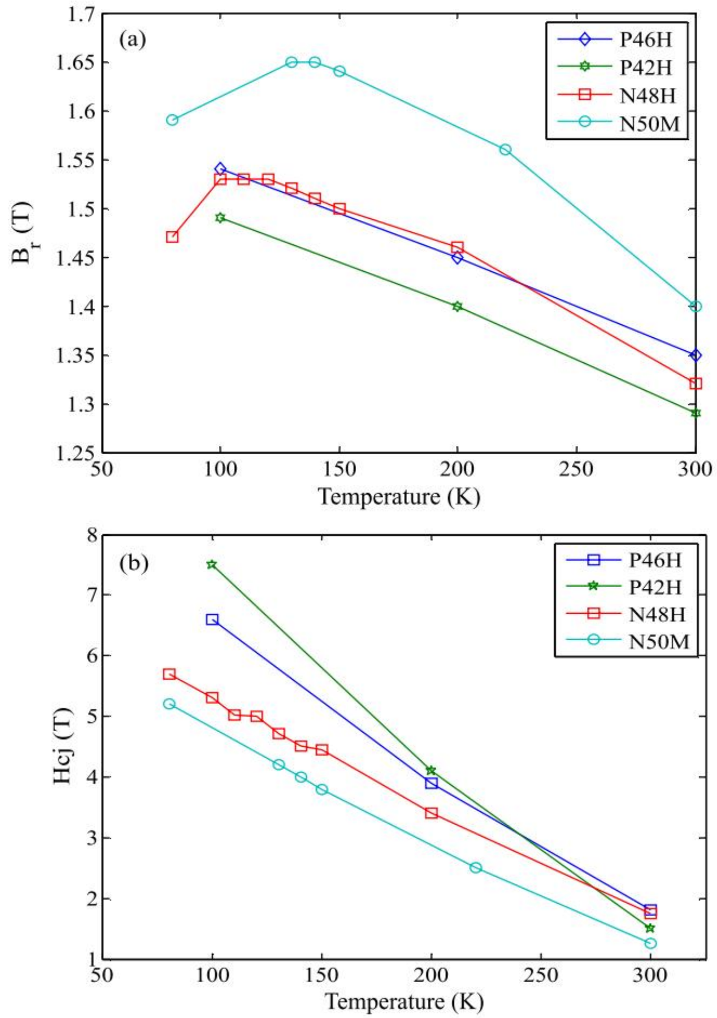
Cryogenic Undulators (CPMUs)

PM Magnetisation increases

- As temperature decreases, coercivity increases even more – selection of stronger grades of PM possible
- The intrinsic coercivity increases also which helps with radiation resistance and allowsselection of stronger grades
- Better magnetic performance, better vacuum performance because cold, better radiation damage resistance

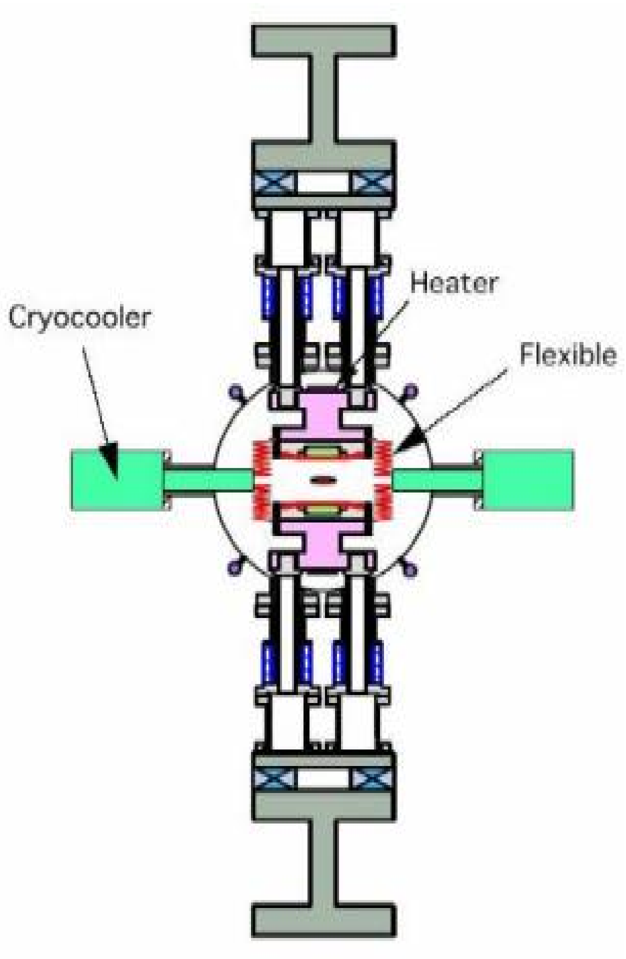
PrFeB is now the material of choice：

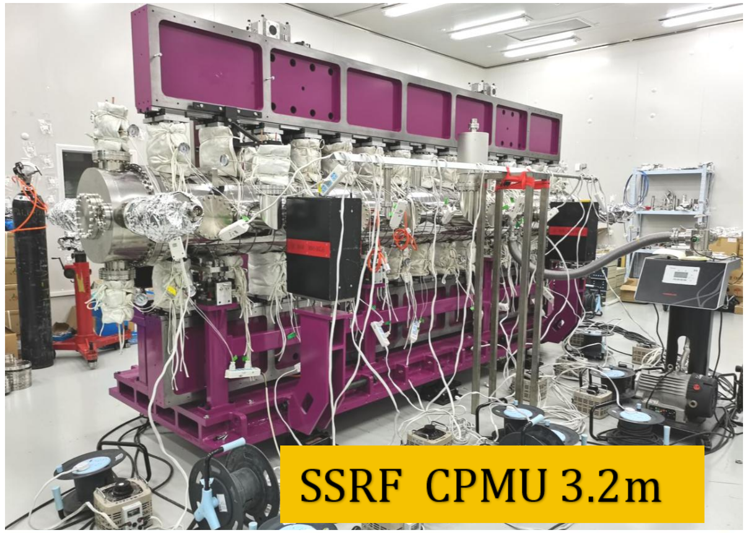
- Basically an in-vacuum device with cryogenic cooling attached
- It is strong (B_r up to ~1.7T) and works at 77K which is a very easy temperature to achieve and maintain with liquid nitrogen
- Need higher temperature stability requirements compared to NdFeB

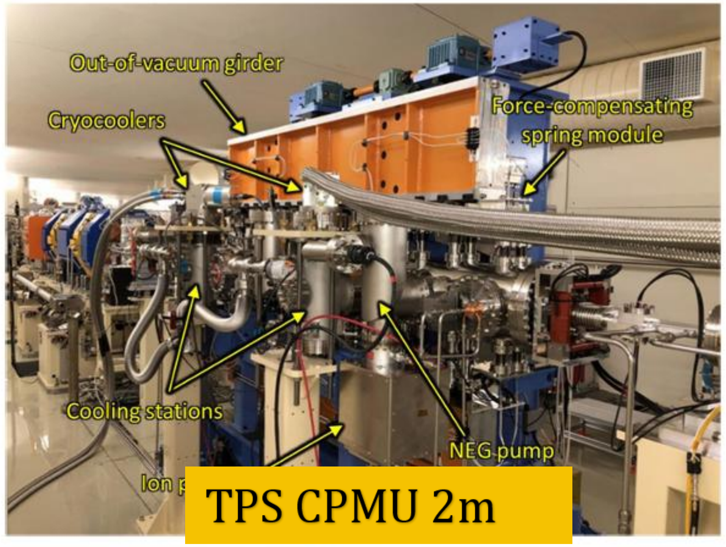


H Kitamura, Spring-8

Cryogenic PM undulators







G. 1. TPS-CPMU, CU15 installed in the TPS storage ring.

SHINE

Measurement facilities for IDs

1、Hall probe system (on-fly measurement)

probe：SENIS H3A，Resolution 0.02GS
granite scan range in z 6500/5000mm, 300mm in x /y
Field strengh/ phase error/ trajectory

2、Flipping coil

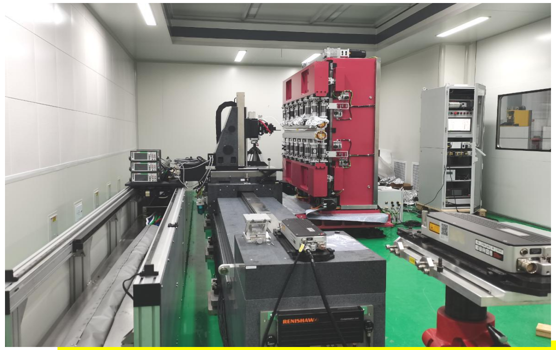
coil length：Max 5m，coil width 2.8mm，repeatability 3Gs.cm
First and second field integral, kick value for undulator

3、Capacitance sensor

can be integrated in the Hall probe scan system
precision：~2μm
Measured magnetic gap

4、Optical displacement meter

can be integrated in the Hall probe scan system
precision：~1μm
Measured girder deformation



Hall ptobe scan system

flipping coil system

Capacitance sensor

Optical displacement meter

SHINE

CPMU Magnetic field measurement system

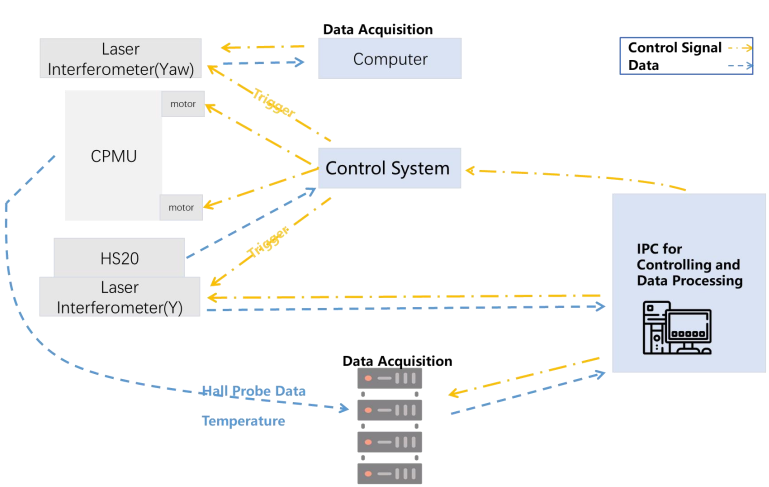


Figure 1: System Structure Diagram

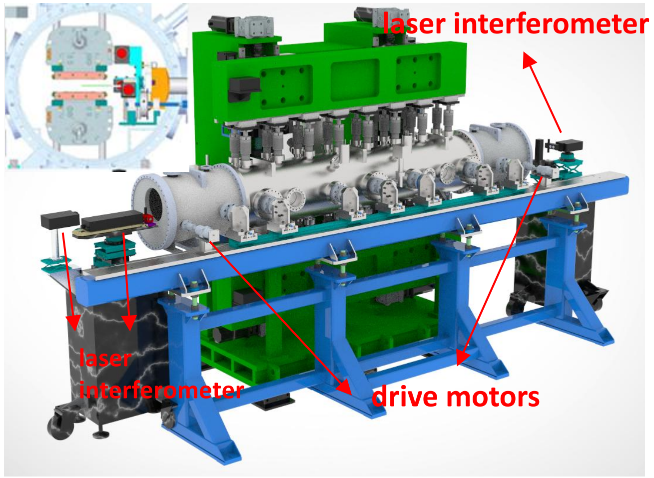


Figure 2: System 3D Diagram

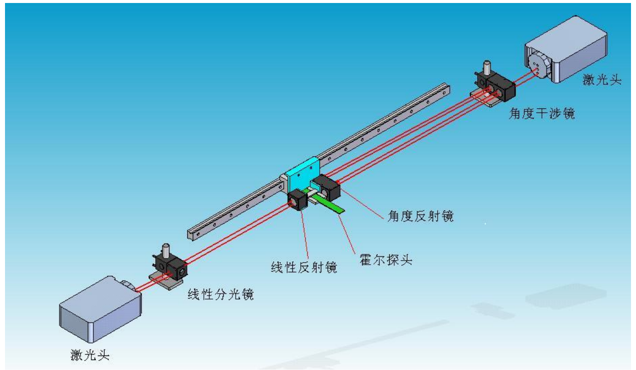


Figure 4: Optical System for Deformation Measurement of Magnetic Measurement Rail inside the Vacuum Chamber

- The test system consists of a deformation measurement optical system, a data acquisition system, and a motion control system.
- Three laser systems are used: a laser interferometer measures the angular deviation (Yaw) and straightness in the Y-direction of the linear guide rail, while a laser distance measurement system is used for beamline positioning in the Z-direction.
- The head and tail motors and magnetic fluid drive the rollers inside the extended chamber, pulling the steel wire rope to move the Hall probe along the linear guide rail. This setup allows for equidistant triggering to obtain Hall probe voltage data, angular deviation, and Y-direction straightness.

SHINE

Elliptical Undulator Example: APPLE-2

This is the most popular elliptical undulator

It consists of **four standard** PPM arrays

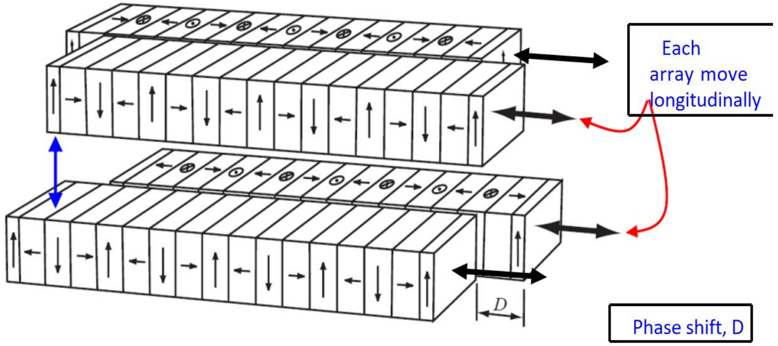
Adjust gap to tune K

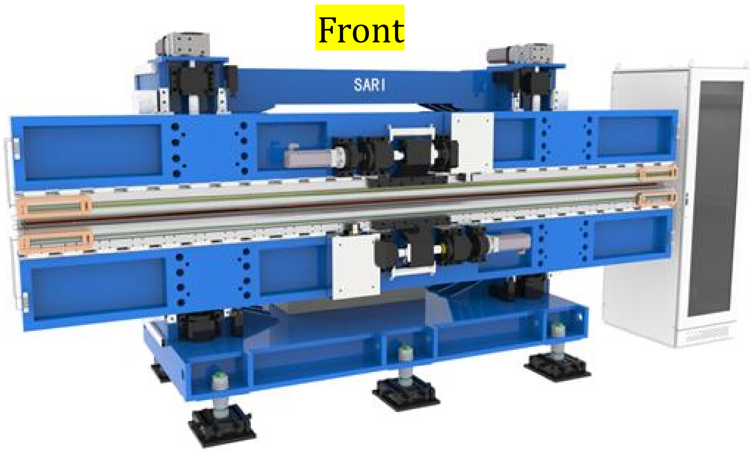
Each magnet array can move longitudinally

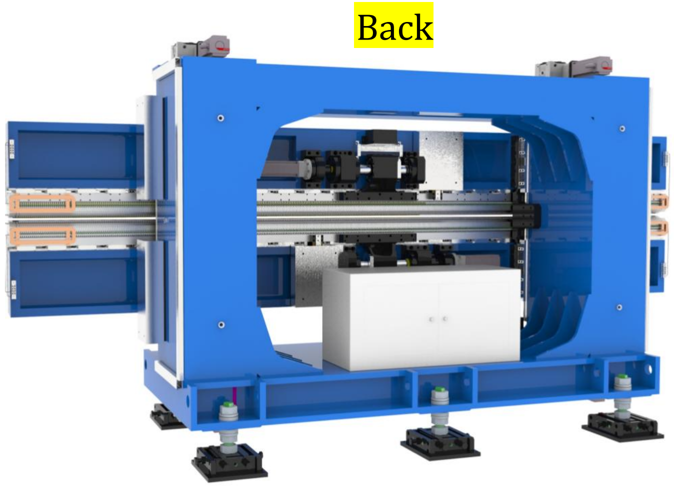
-----From two to four, polarization modes at arbitrary angles

$$B_x = B_{x0} \cos(\frac{2\pi}{\lambda_1} z)$$

$$B_y = B_{y0} \sin(\frac{2\pi}{\lambda_1} z)$$



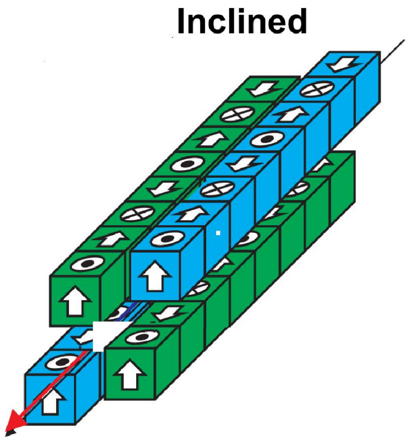


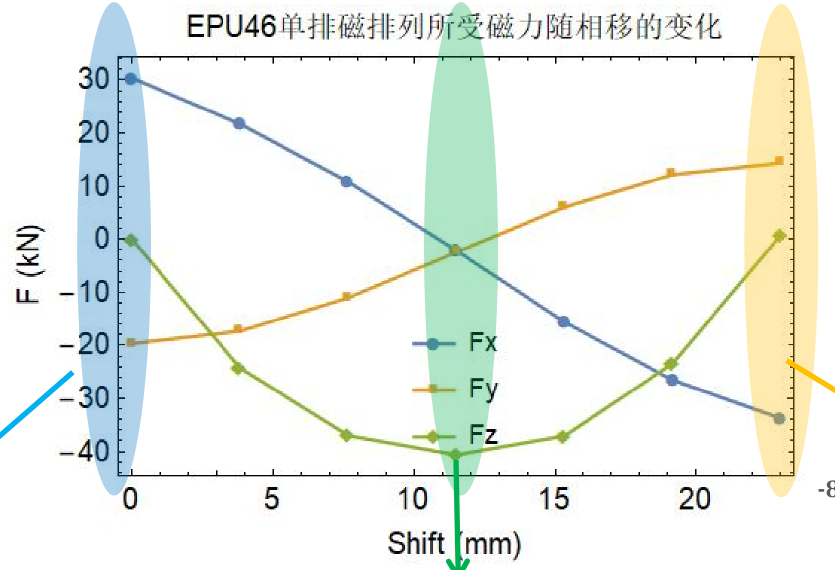


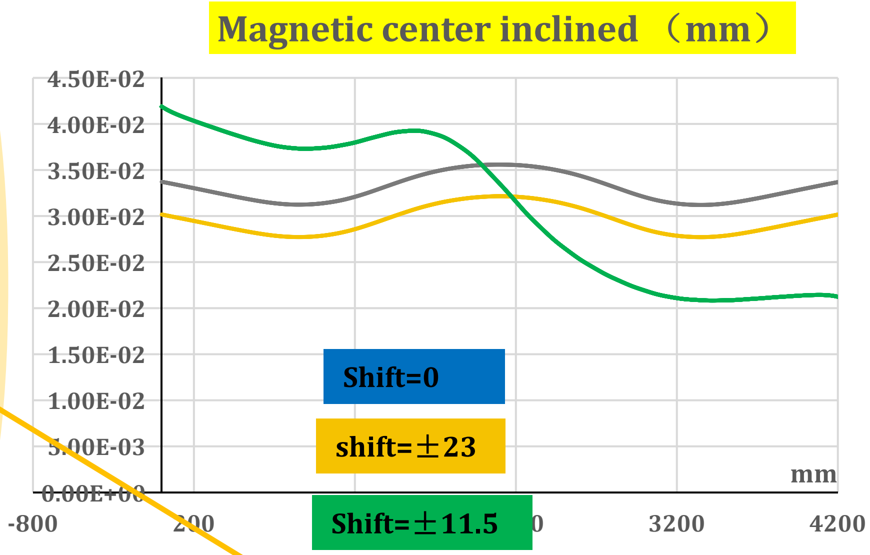
EPU55 for SHINE after burner, 4m long

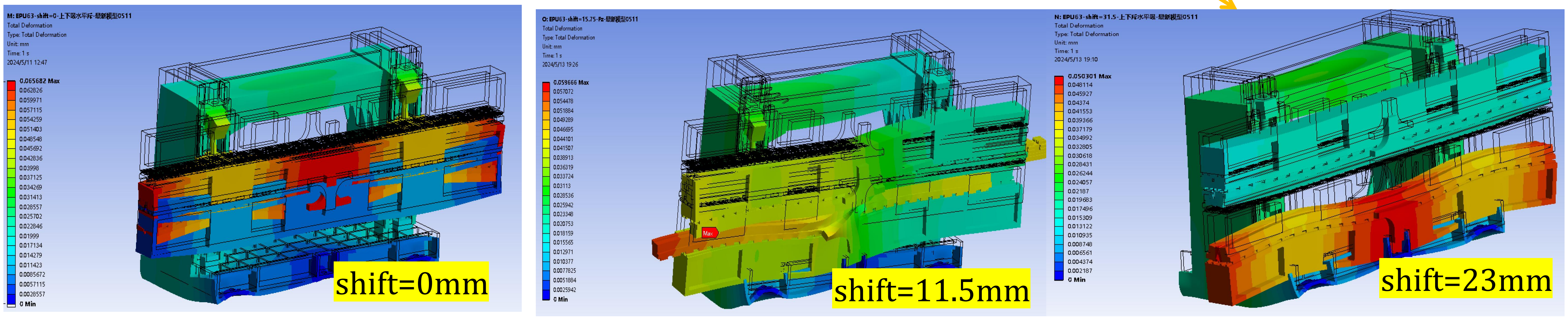
SHINE

Strong mechanical for EPU Inclined-MODE







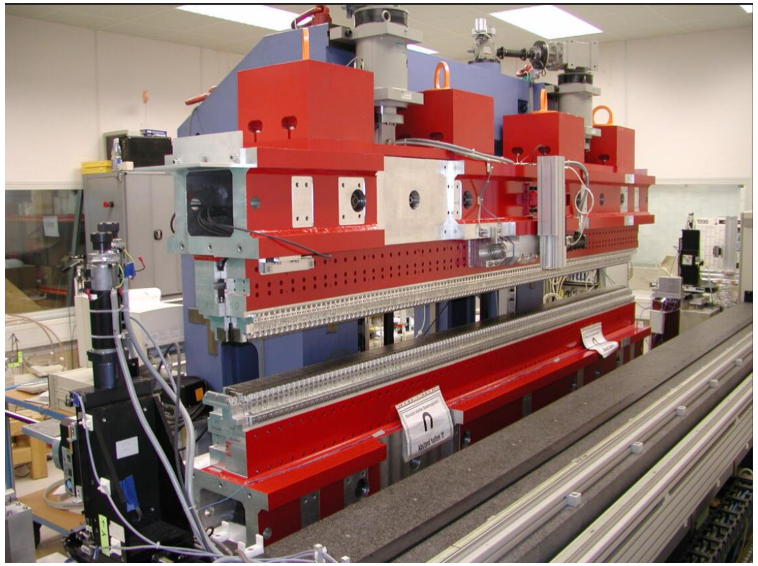


SHINE

EPU with High K，long length

- Length: >4m
- Height: >2.3m
- Weight: >15 tons

TPS EPU, 4m long

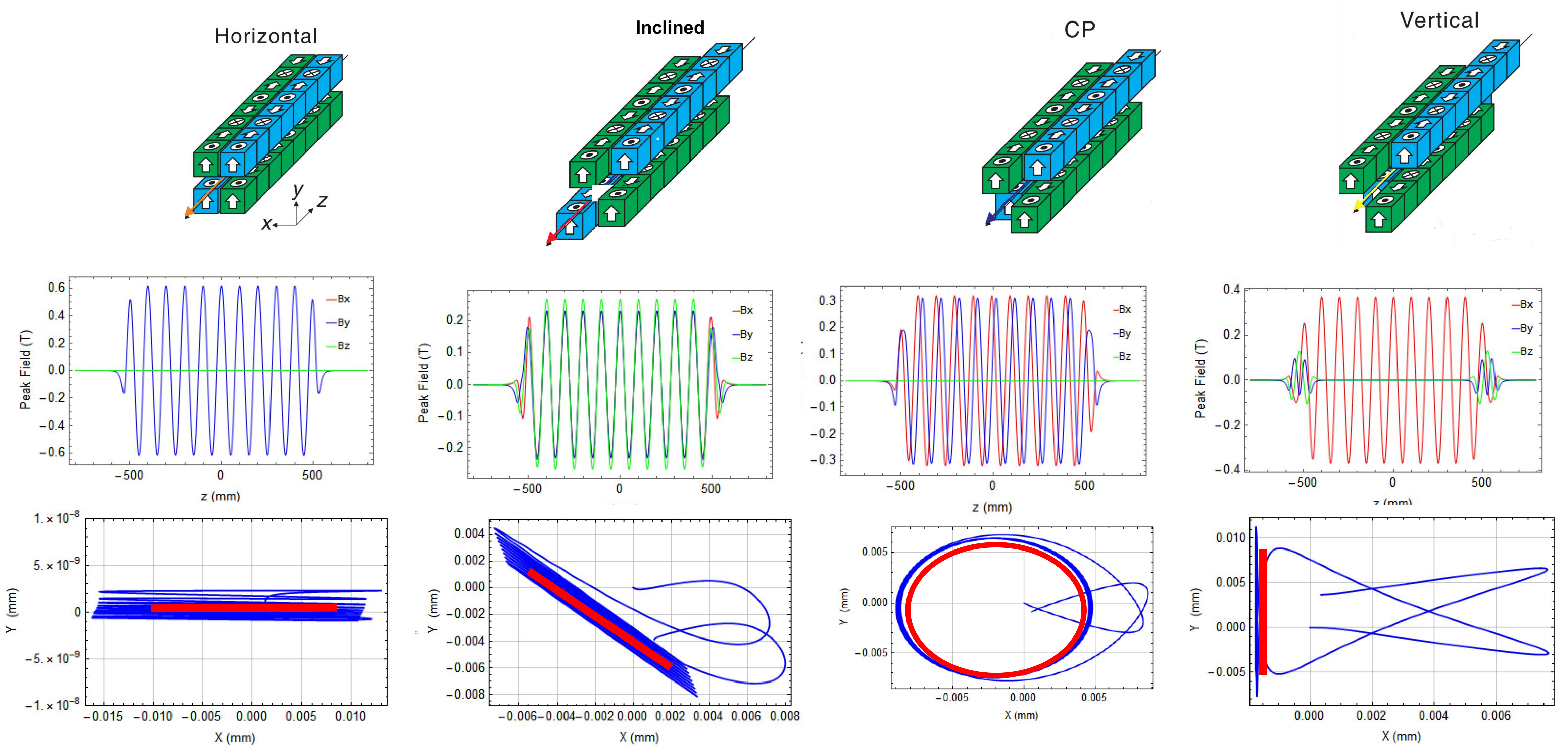


PETRA, 5m long

HALF, 4.2m long

SHINE

Example Trajectories: 3.5GeV, period 100mm APPLE-II EPU

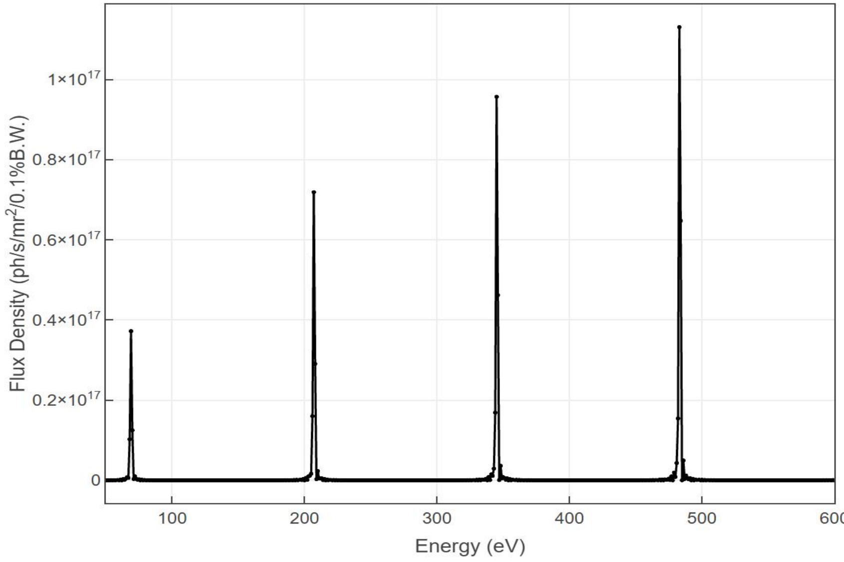


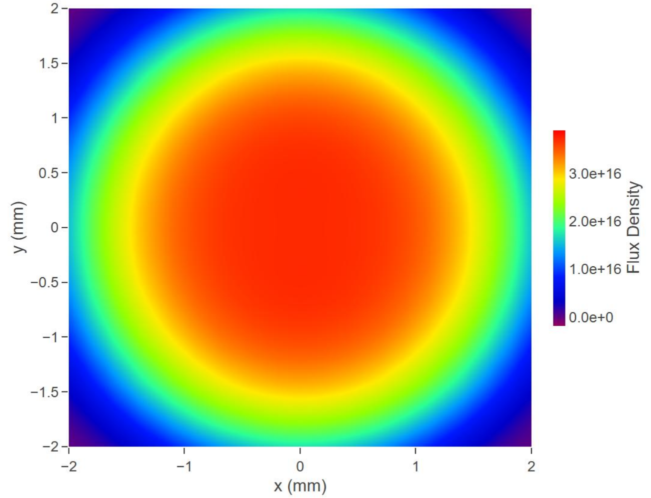
Trajectories viewed head on – as the observer sees them

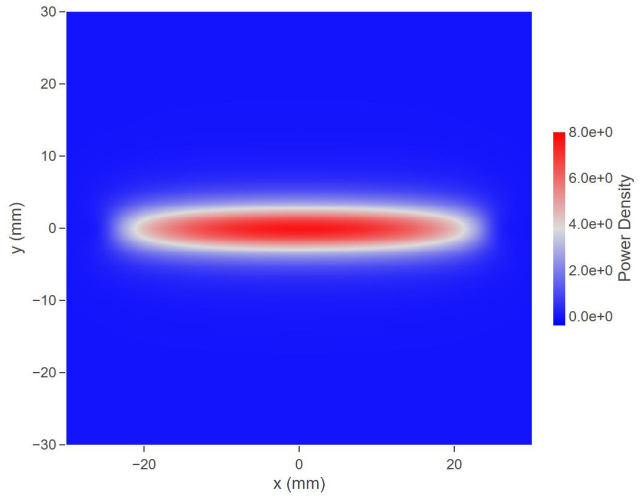
SHINE

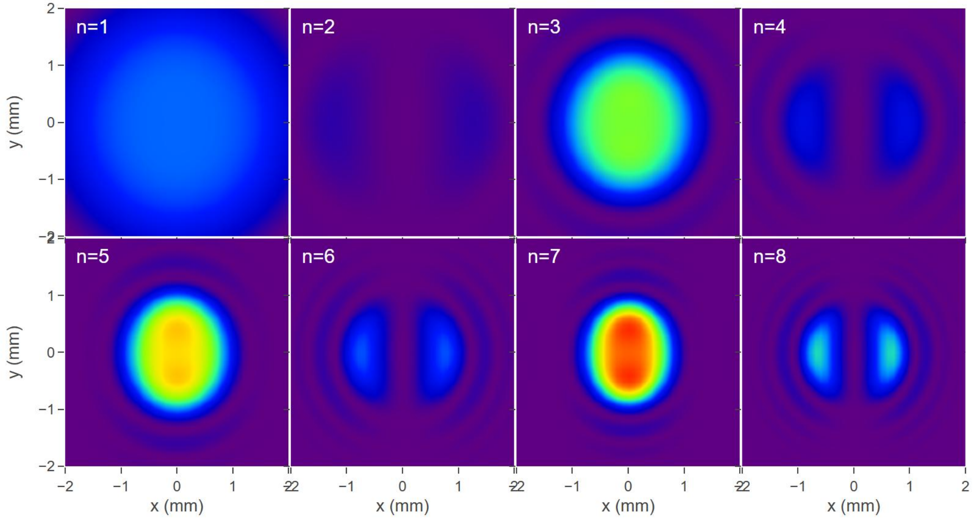
APPLE-II: K =5.6

Period 100mm， B=0.6T,K=5.6 ,3.5GeV,200mA, source point distance 30m







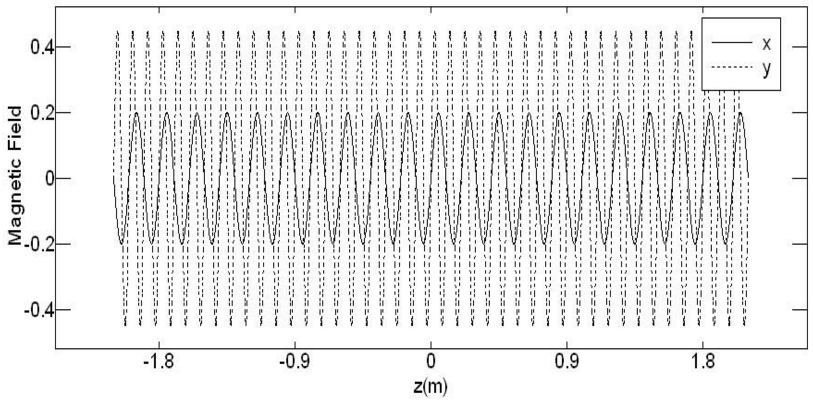


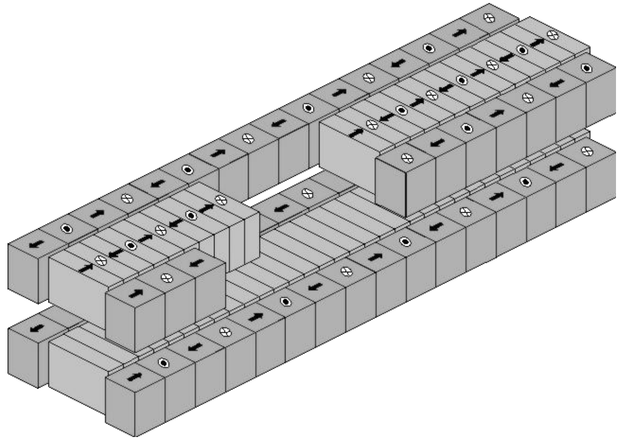
SHINE

Figure-8 undulator: same K

$$B_x = -B_{x0}\sin(\frac{\pi}{\lambda_u}z)$$

$$B_y = B_{y0}\sin(\frac{2\pi}{\lambda_u}z)$$





$$x' = -\frac{e\lambda_u B_{y0}}{2\pi mc\beta_z}\cos\frac{2\pi}{\lambda_u}z$$

$$y' = \frac{e\lambda_u B_{x0}}{\pi mc\beta_z}\cos\frac{\pi}{\lambda_u}z$$

$$x = -\frac{eB_{y0}}{mc\beta_z}(\frac{\lambda_u}{2\pi})^2\sin\frac{2\pi}{\lambda_u}z$$

$$y = \frac{eB_{x0}}{mc\beta_z}(\frac{\lambda_u}{\pi})^2\sin\frac{\pi}{\lambda_u}z$$

$$\beta_z = \frac{\beta}{\sqrt{1+x'^2+y'^2}} \approx \beta$$

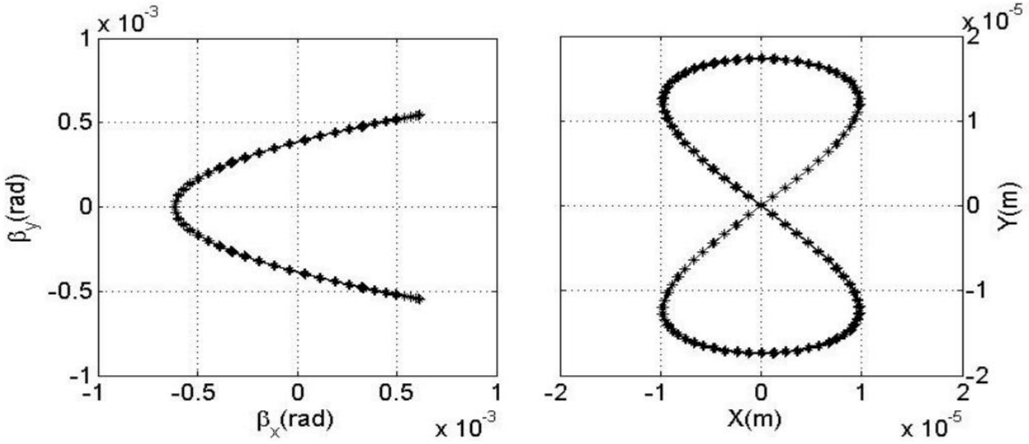
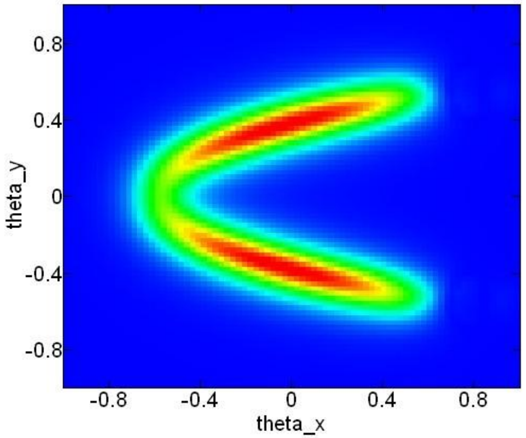


图 2.4 Figure-8 波荡器速度及轨迹在横向的投影



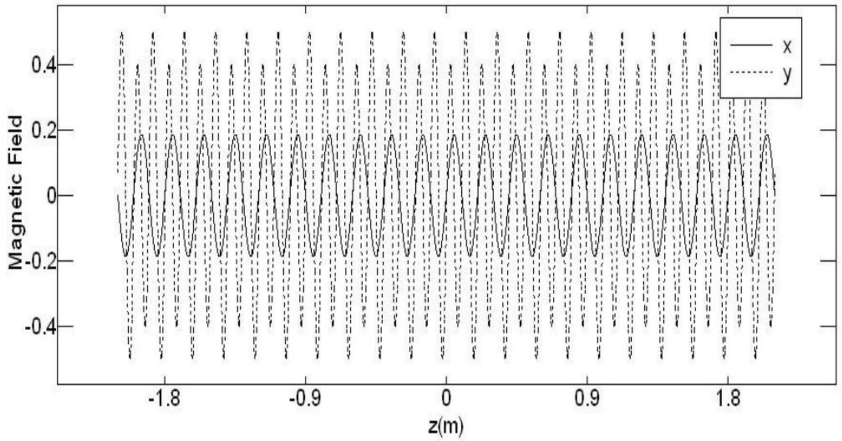
AFigure-8 : same K

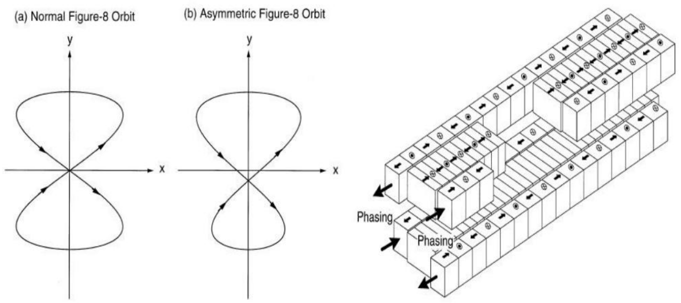
$$B_x = -B_{x0}\sin(\frac{\pi}{\lambda_u}z)$$

$$B_y = B_{y1} + B_{y2}$$

$$B_{y1} = B_{1y}\sin(\frac{2\pi}{\lambda_u}z)$$

$$B_{y2} = B_{2y}\cos(\frac{\pi}{\lambda_u}z)$$





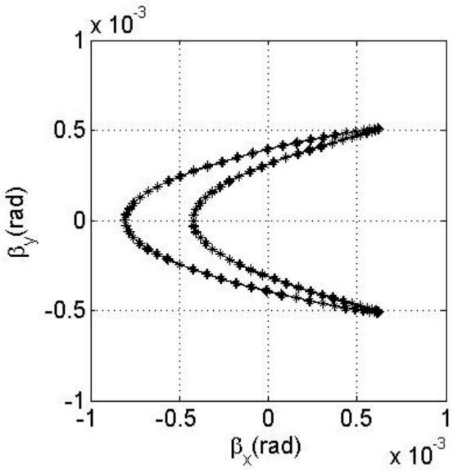
$$x' = -\frac{e}{mc\beta_z}(\frac{\lambda_u}{2\pi})\left[B_{1y}\cos\frac{2\pi}{\lambda_u}z - 2B_{2y}\sin\frac{\pi}{\lambda_u}z\right]$$

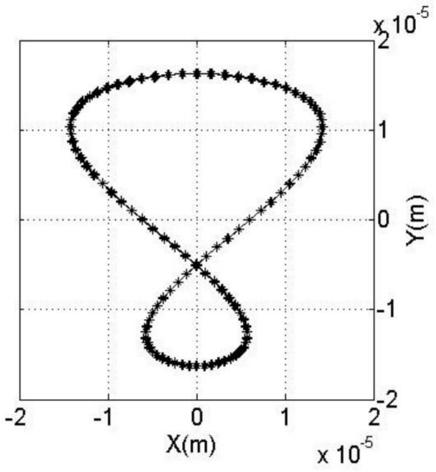
$$y' = \frac{eB_{x0}}{mc\beta_z}(\frac{\lambda_u}{\pi})\cos\frac{\pi}{\lambda_u}z$$

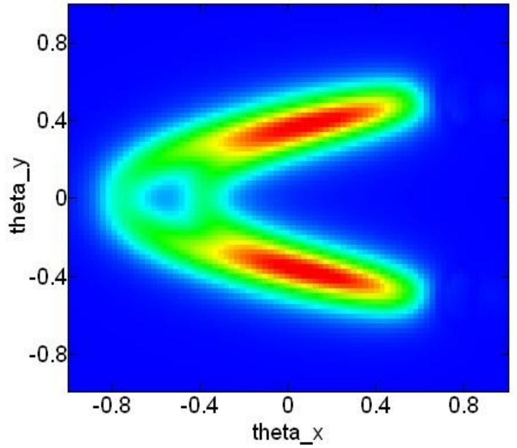
$$x = -\frac{e}{mc\beta_z}(\frac{\lambda_u}{2\pi})^2\left[B_{1y}\sin\frac{2\pi}{\lambda_u}z + 4B_{2y}\cos\frac{\pi}{\lambda_u}z\right]$$

$$y = \frac{eB_{x0}}{mc\beta_z}(\frac{\lambda_u}{\pi})^2\sin\frac{\pi}{\lambda_u}z$$

$$\beta_z = \frac{\beta}{\sqrt{1+x'^2+y'^2}} \approx \beta$$







PERA undulator: same K

$$B_x = -B_{x0}\sin(\frac{2\pi}{\lambda_u}z)$$

$$B_y = B_{y1} + B_{y2}$$

$$B_{y1} = \frac{3}{2}B_{y0}\cos(\frac{2\pi}{2\lambda_u/3}z)$$

$$B_{y2} = \frac{1}{2}B_{y0}\cos(\frac{2\pi}{2\lambda_u}z)$$

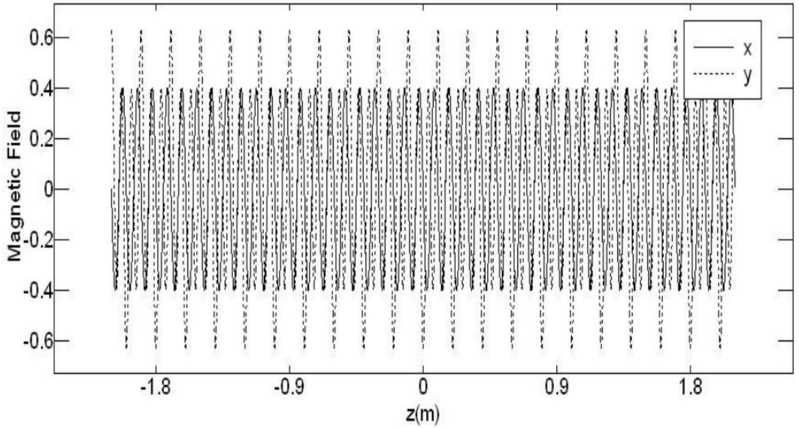
$$x' = \frac{eB_{y0}}{mc\beta_z}(\frac{\lambda_u}{2\pi})\left[\sin\frac{3\pi}{\lambda_u}z + \sin\frac{\pi}{\lambda_u}z\right]$$

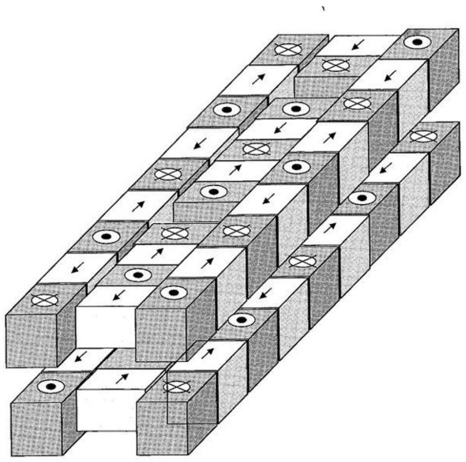
$$y' = \frac{eB_{x0}}{mc\beta_z}(\frac{\lambda_u}{2\pi})\cos\frac{2\pi}{\lambda_u}z$$

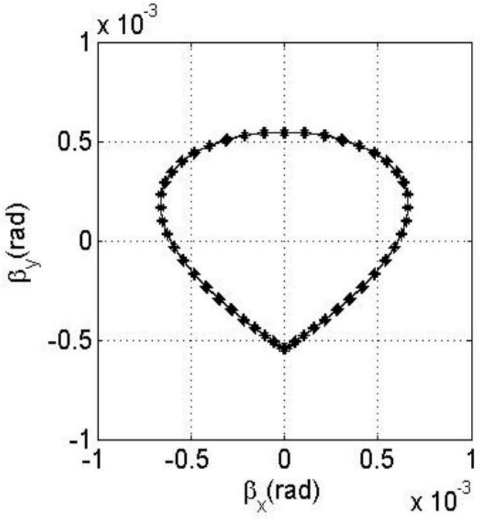
$$x = -\frac{eB_{y0}}{mc\beta_z}(\frac{\lambda_u}{2\pi})^2\left[\frac{2}{3}\cos\frac{3\pi}{\lambda_u}z + 2\cos\frac{\pi}{\lambda_u}z\right]$$

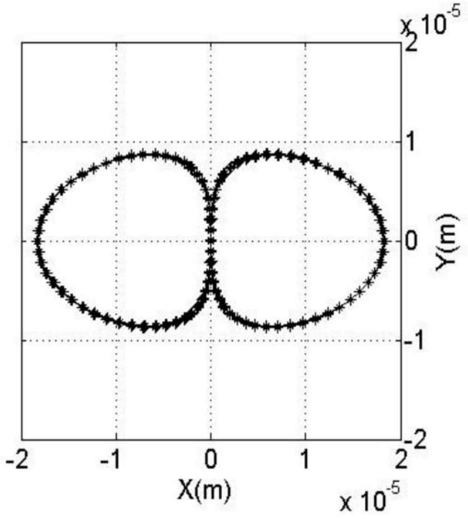
$$y = \frac{eB_{x0}}{mc\beta_z}(\frac{\lambda_u}{2\pi})^2\sin\frac{2\pi}{\lambda_u}z$$

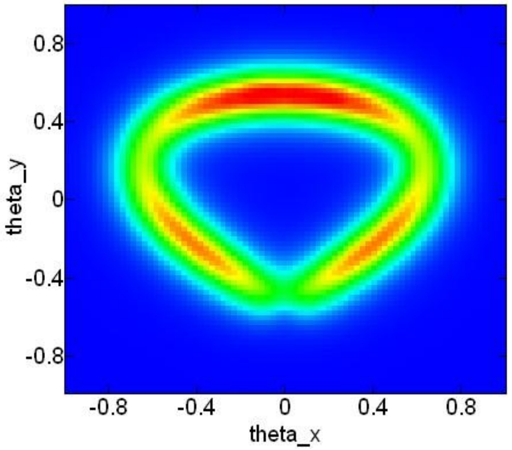
$$\beta_z = \frac{\beta}{\sqrt{1+x'^2+y'^2}} \approx \beta$$











SHINE

APPLE-8

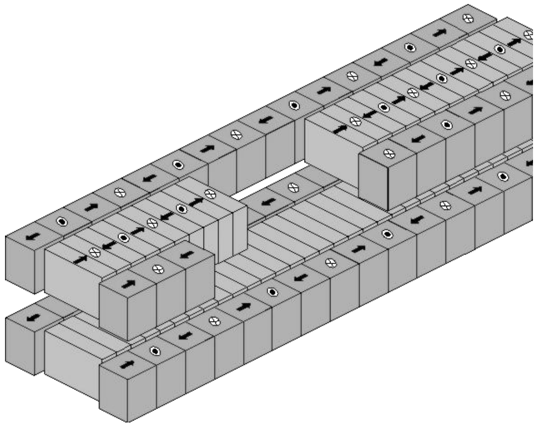
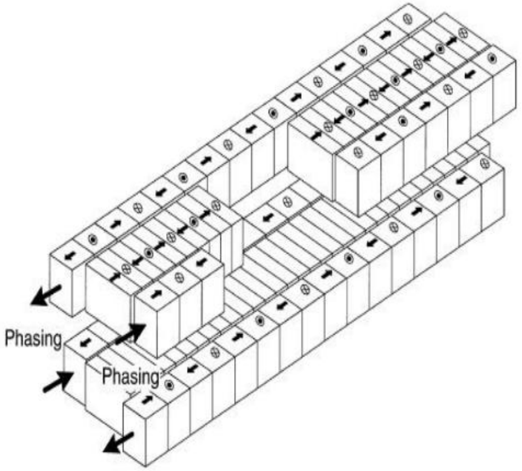
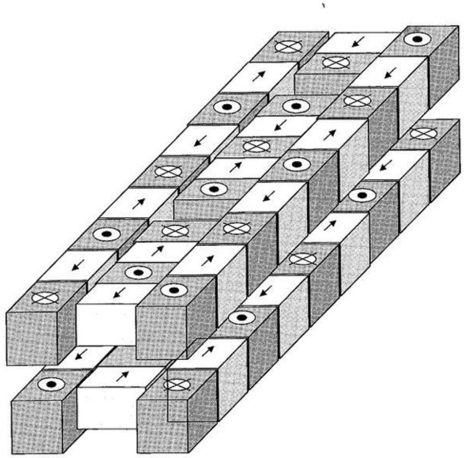


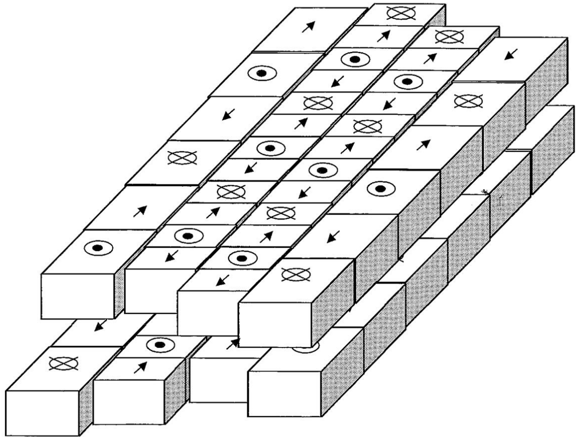
Figure-8



AFigure-8



PERA



APPLE-8

General expression
APPLE-8

$$B_x = B_{x10}\cos(\frac{2\pi}{\lambda_1}z) + B_{x20}\cos(\frac{2\pi}{\lambda_2}z)$$

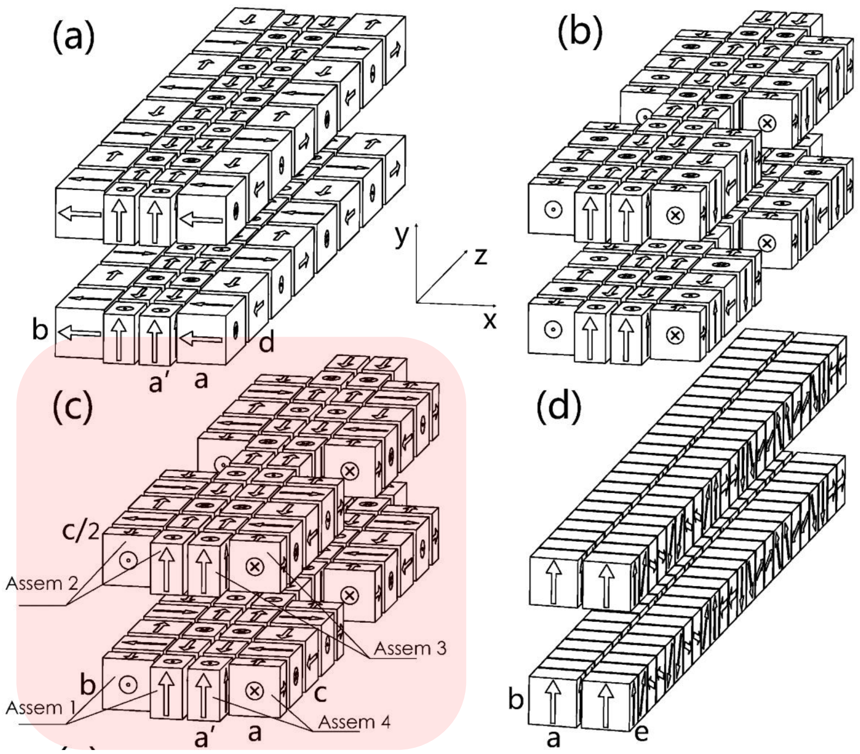
$$B_y = B_{y10}\sin(\frac{2\pi}{\lambda_1}z) - B_{y20}\sin(\frac{2\pi}{\lambda_2}z)$$

inner arrays

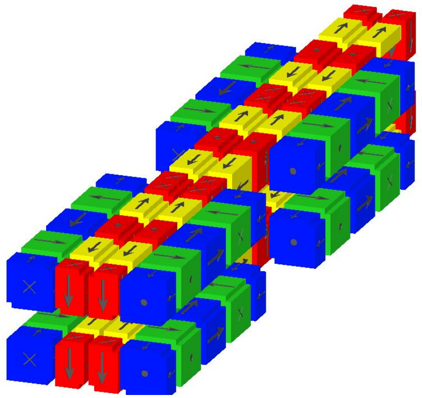
outer arrays

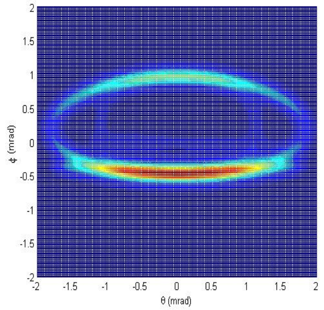
SHINE

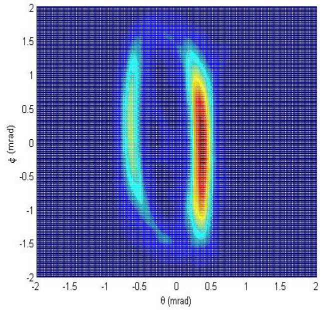
APPLE-Knot

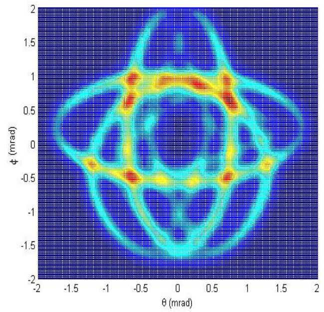


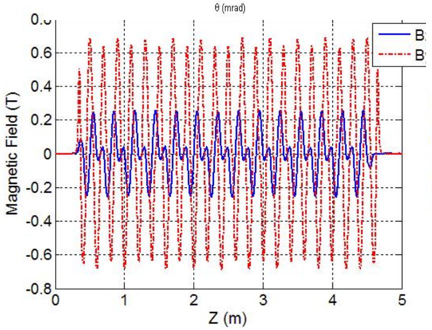
The first APPLE-Knot in the world,2014, SSRF,China

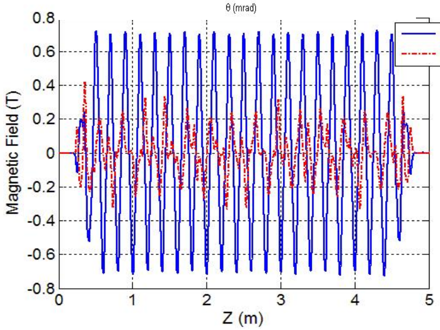


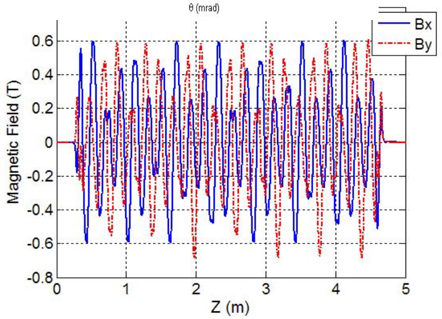




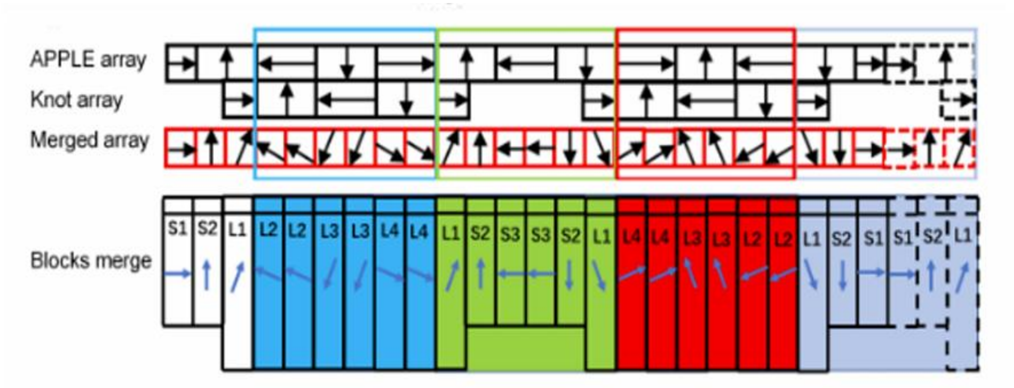




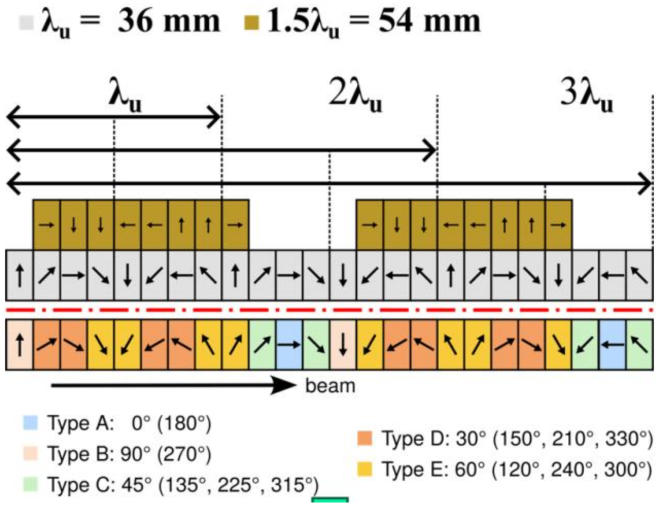




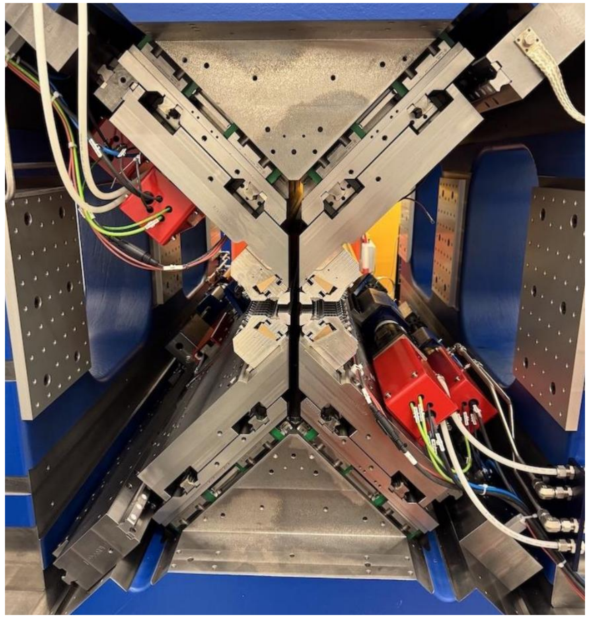
New Knot *Merged four arrays*



APPLEII+Knot
HEPS，China



APPLEX+Knot
SLS 2，PSI



Mango wiggler at HEPS

$$B_x(z) = B_0 \sin\left(\frac{2\pi z}{\lambda_{ux}}\right), \qquad \lambda_{ux} = \frac{L}{N_u \pm (1/4)},$$

$$B_y(z) = B_0 \sin\left(\frac{2\pi z}{\lambda_{uy}}\right), \qquad \lambda_{uy} = \frac{L}{N_u}.$$

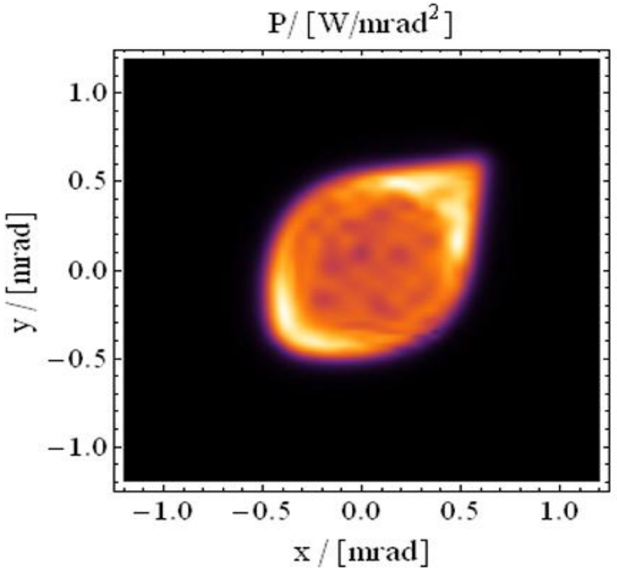
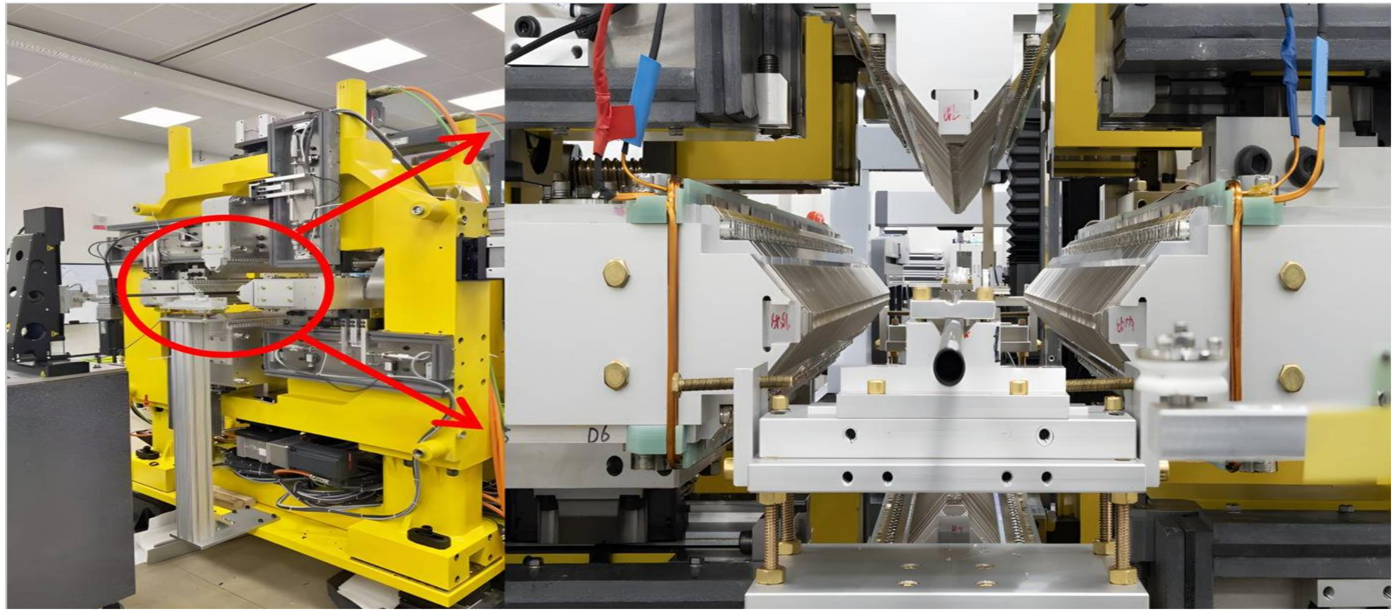


Table 1. Parameters of the Mango wiggler designed for HEPS.

Peak magnetic field strength, B_0	1.0 T (0.2–1.0 T adjustable for the tapered mode)
Period lengths, $\lambda_{ux}/\lambda_{uy}$	50.70 mm/50 mm
Period, N_{ux}/N_{uy}	17.75/18



SHINE

Power density distribution

Standard Planar undulator

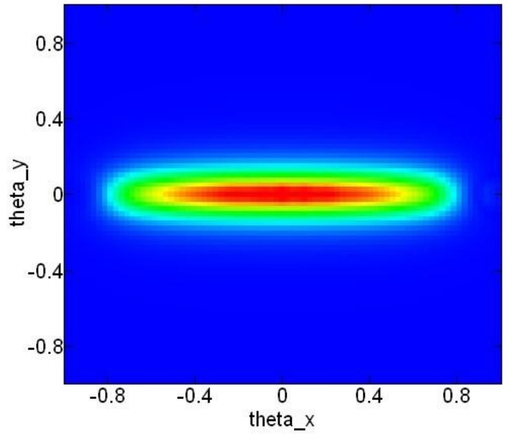
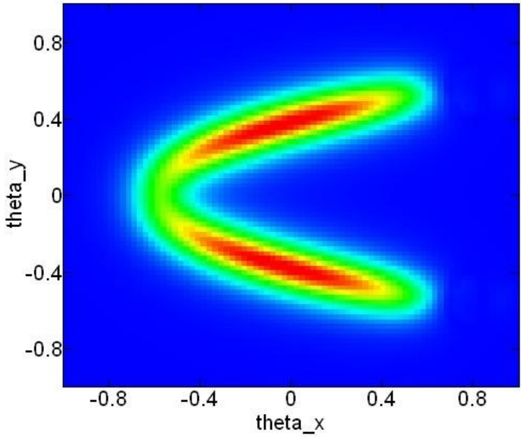
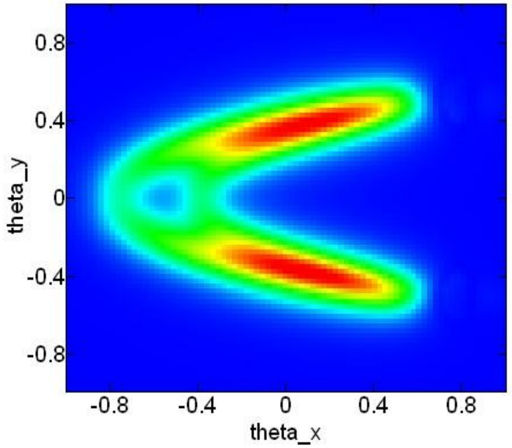


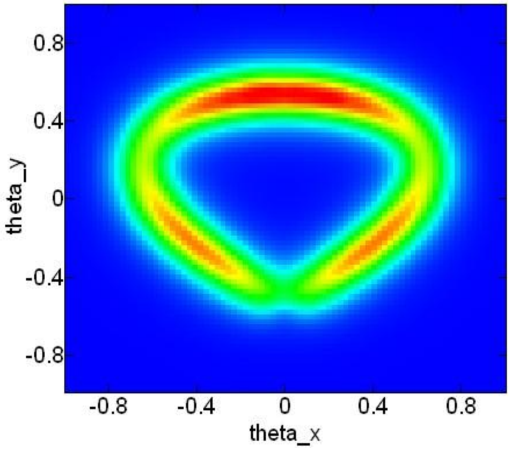
Figure-8



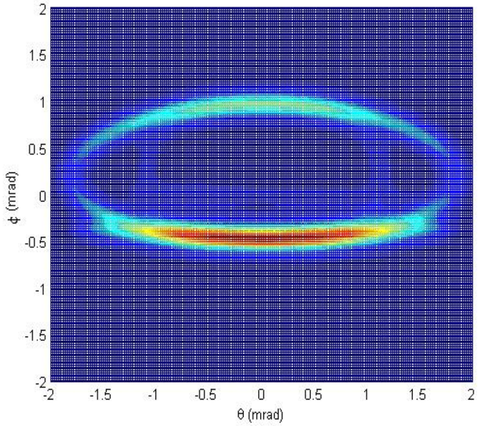
AFigure-8



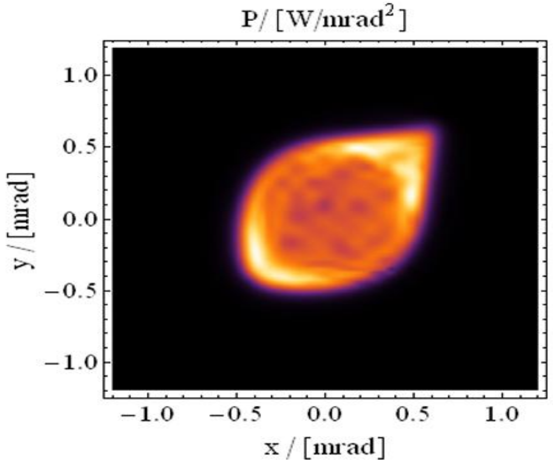
PERA



Knot



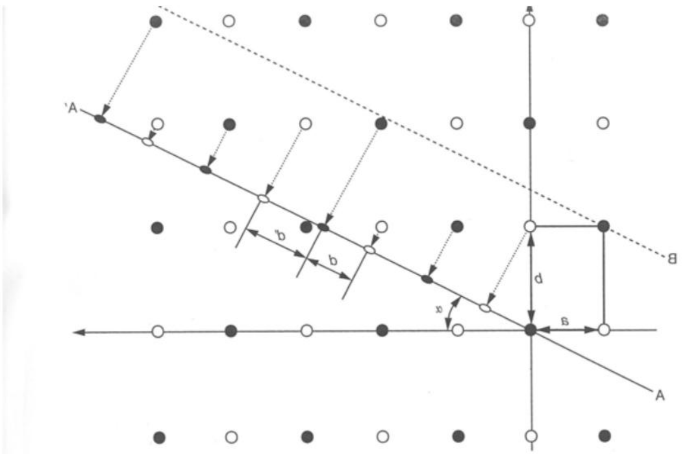
Mango



SHINE

Quasi-periodic Undulators (S. Sasaki)

generate 1D-quasiperiodic lattice



$$z_m = \frac{d}{r \cdot \tan(\alpha)} \cdot \left(m + (r \cdot \tan(\alpha) - 1)\left\lfloor \frac{\tan(\alpha)}{r + \tan(\alpha)} m + 1 \right\rfloor\right)$$

$$r = b / a$$

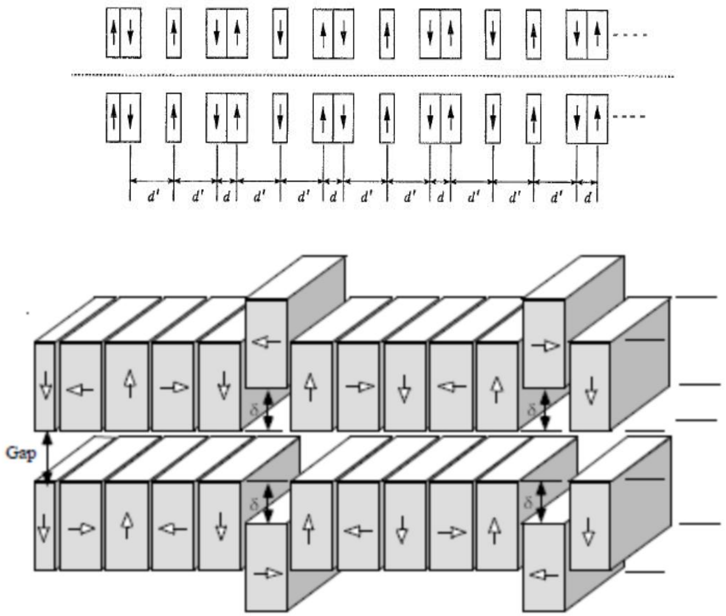


图 3.6 ESRF 准周期结构示意图[11]

Purpose

- The electron beam trajectory changes when passing through a quasi-periodic undulator, resulting in quasi-periodic oscillations.
- The traditional high-order harmonic generated shift to irrational position.
- The irrational harmonic radiation can be filtered out using a monochromator.

SHINE

QEPU Quasi-period example

EU12.5 Quasi-period at ELETTRA

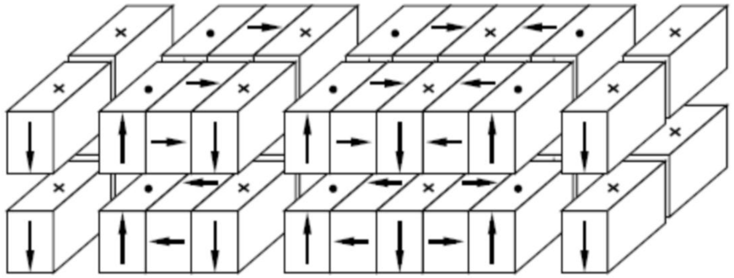
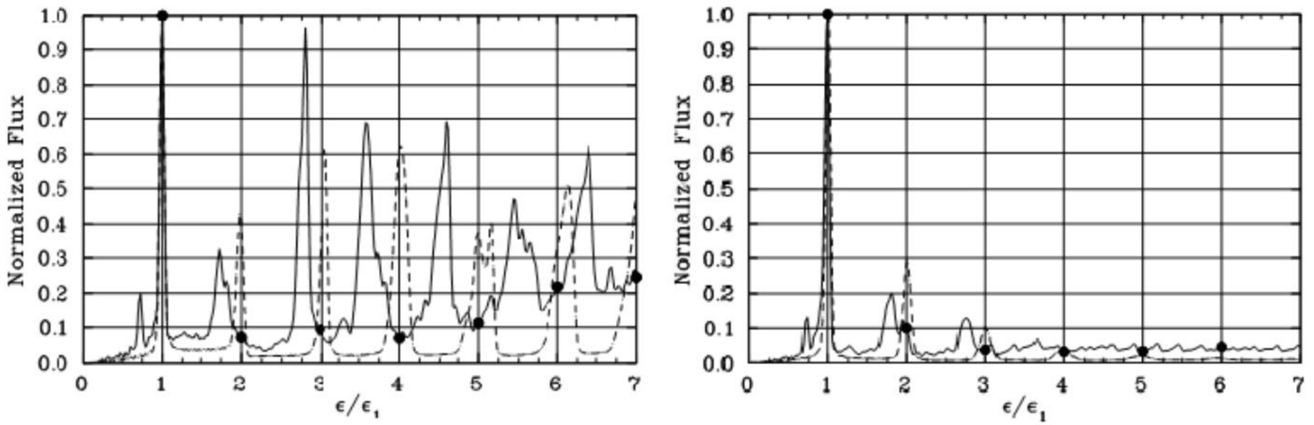
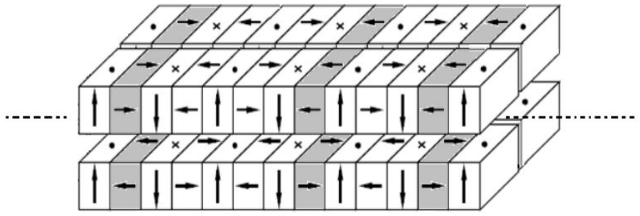


图 3.9 ELETTRA 准周期 APPLE-II 型椭圆波荡器结构示意图[12]



（1）线极化　　（2）圆极化

DEPU Quasi-period at low-EPU, SSRF 2013



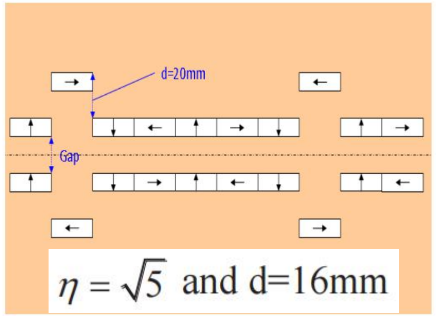
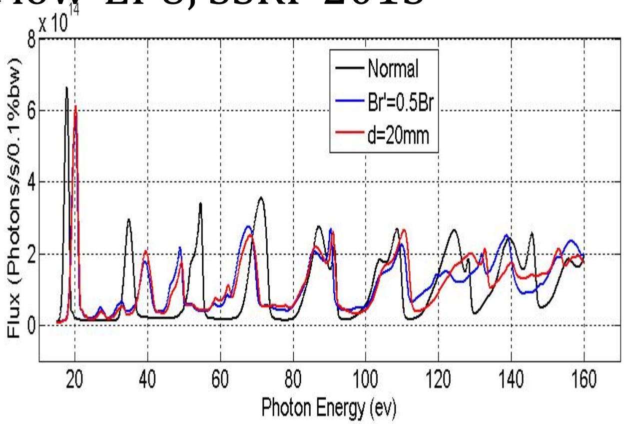


图 3.38 两种不同准周期方案的磁结构示意图



Outline

- Insertion devices to generate radiation
- Types of Insertion devices
- **Undulators torwards the future**
- Try to design a undulator?

Double Period Undulator--extended energy range

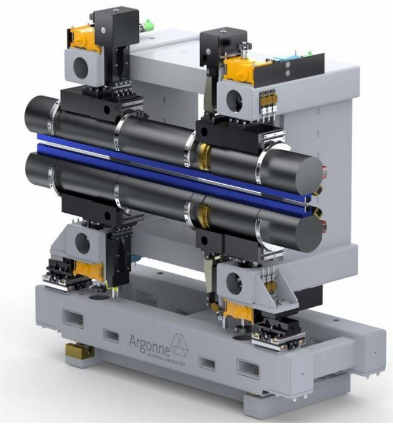
Double Undulator

- Source point remains constant.

Revolver undulator：SPring-8，APS2014，Dessy 2018

DEPU: SSRF 2013,CLS2016

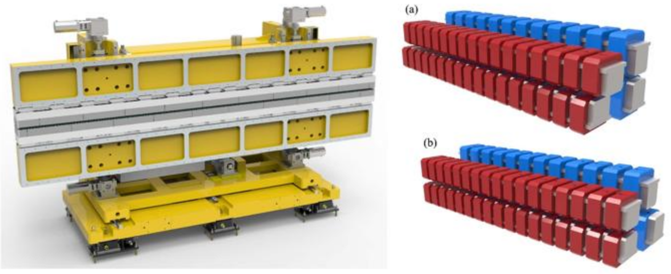
DPU: SXFEL 2018



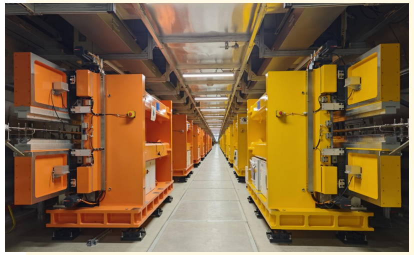
At SHINE project

First prototype 2022.

Double period undulator line，2025



SHINE project
(10.1109/TASC.2023.3346838)

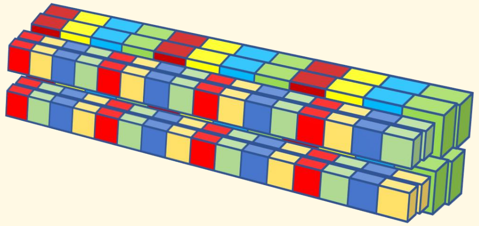


Force compasation technology for DPU

Proposed by BESSY_III

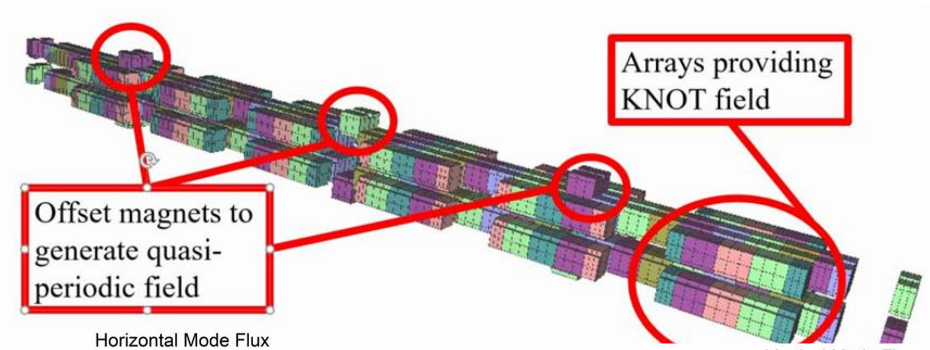
A prospective device to bring two in-vacuum APPLE II arrays side by side.

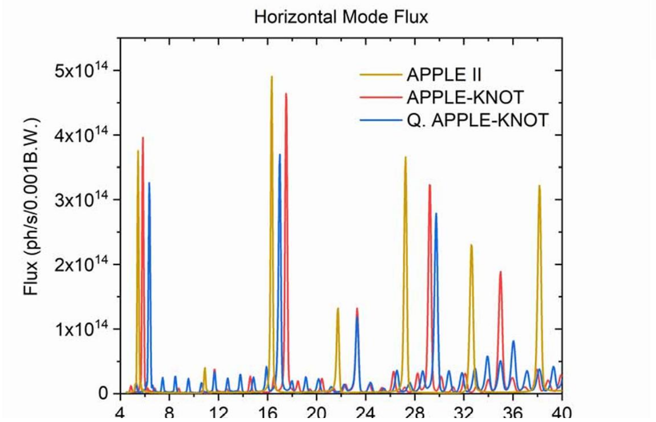
Practical development starting 2026.

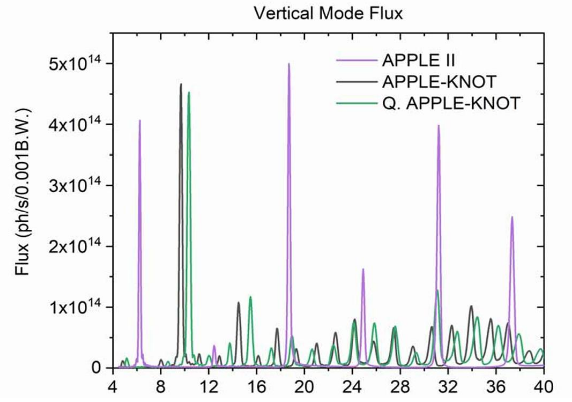


SHINE

APPLE-II+Knot+Quasi：Multi-functional





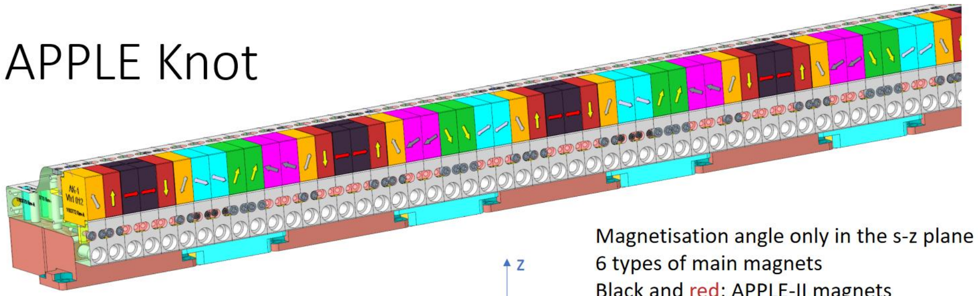


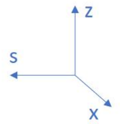
14th International Particle Accelerator Conference, Venice, Italy JACoW Publishing
ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPM103

UNDULATORS FOR BESSY III

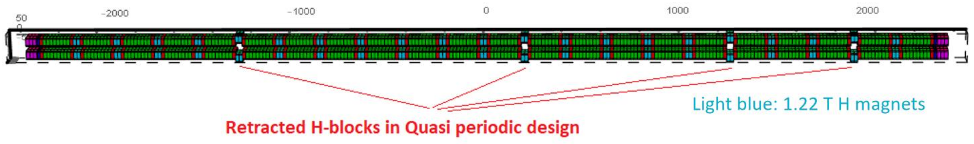
E. C. M. Rial†, A. Meseck[1], J. Bahrdt, J. Bakos, S. Gäbel, S. Gottschlich, S. Grimmer, K. Karimi, C. Kuhn, F. Laube, A. Rogosch-Opolka, S. Schäfer, M. Scheer, M. Strehlke, P. Volz[1]
Helmholtz Zentrum Berlin, Berlin, Germany
[1]also at Johannes Gutenberg University Mainz, Germany

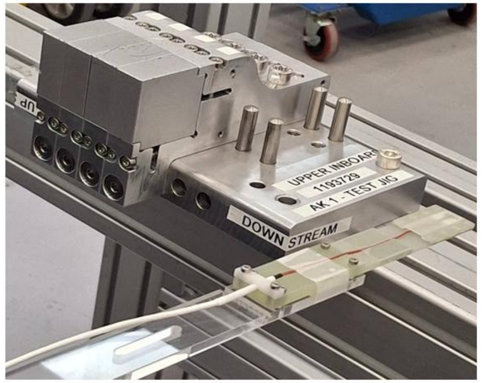
APPLE Knot

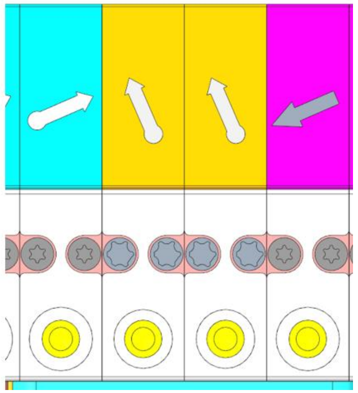




Magnetisation angle only in the s-z plane
6 types of main magnets
Black and red: APPLE-II magnets
Others: merged APPLE-II and APPLE Knot magnets
Orange & green: 23.46° angle from z-axis
Blue & pink: 23.46° angle from s-axis





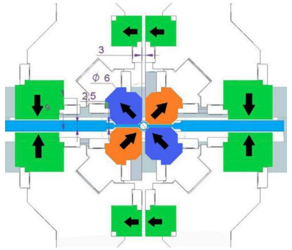


SHINE

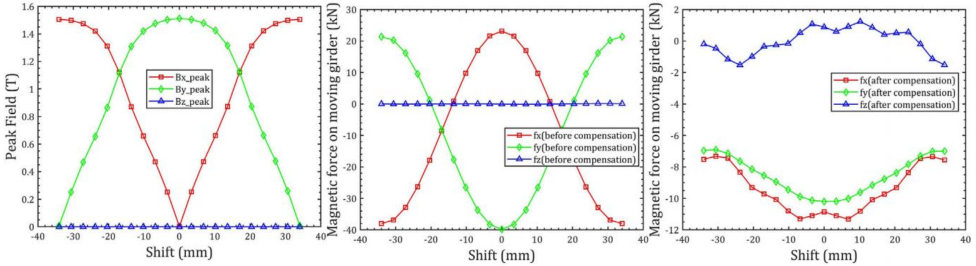
Force Compensation for high field EPU

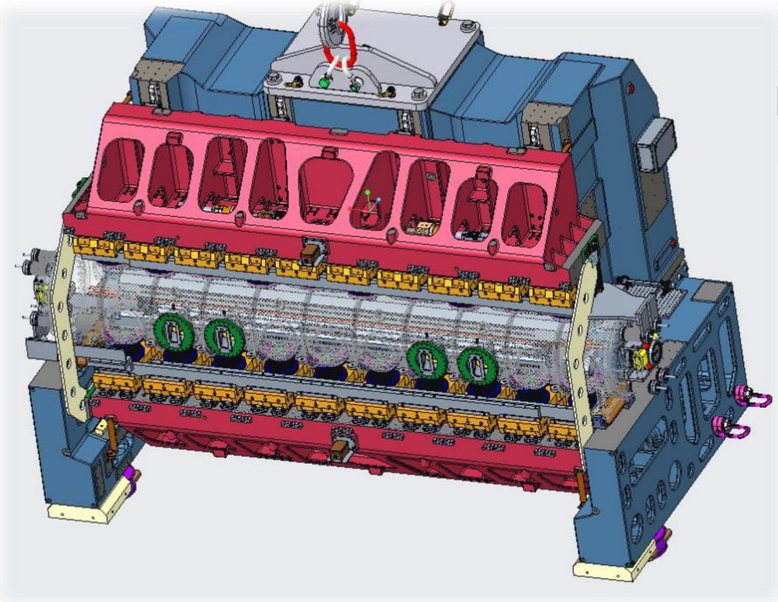
Length： 4 m
Period: 68mm
Peak field： 1.5T
Vertical Gap range： 3.2--150mm

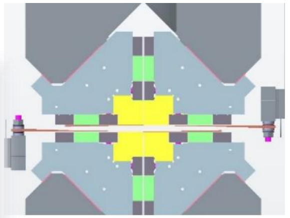
Qiaogen, Z. (2018). Novel Undulators Developed at SINAP. *Synchrotron Radiation News*, *31*(3), 18–23. https://doi.org/10.1080/08940886.2018.1460170



Front. Phys., 27 June 2023
Sec. Interdisciplinary Physics
Volume 11 - 2023 |
https://doi.org/10.3389/fphy.2023.1174620







9th International Particle Accelerator Conference IPAC2018, Vancouver, BC, Canada JACoW Publishing
ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPMF031

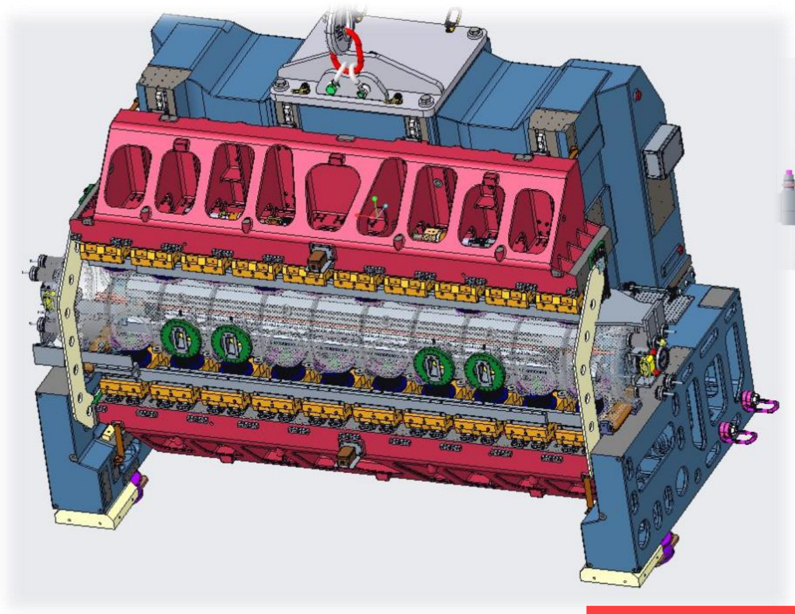
IN-VACUUM APPLE II UNDULATOR

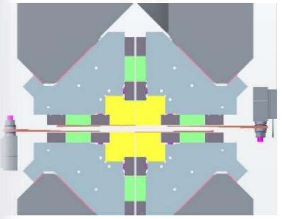
J. Bahrdt, W. Frentrup, S. Grimmer, C. Kuhn, C. Rethfeldt, M. Scheer, B. Schulz, Helmholtz-Zentrum Berlin, 12489 Berlin, Germany

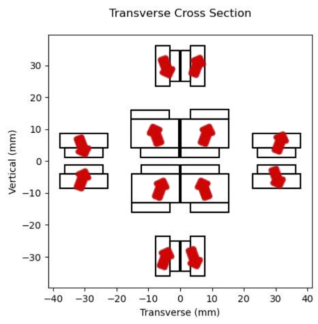
J. Bahrdt, S. Grimmer, in *proc. SRI 2018*, Taipeh, Taiwan, to be published in AIP conference proceeding

SHINE

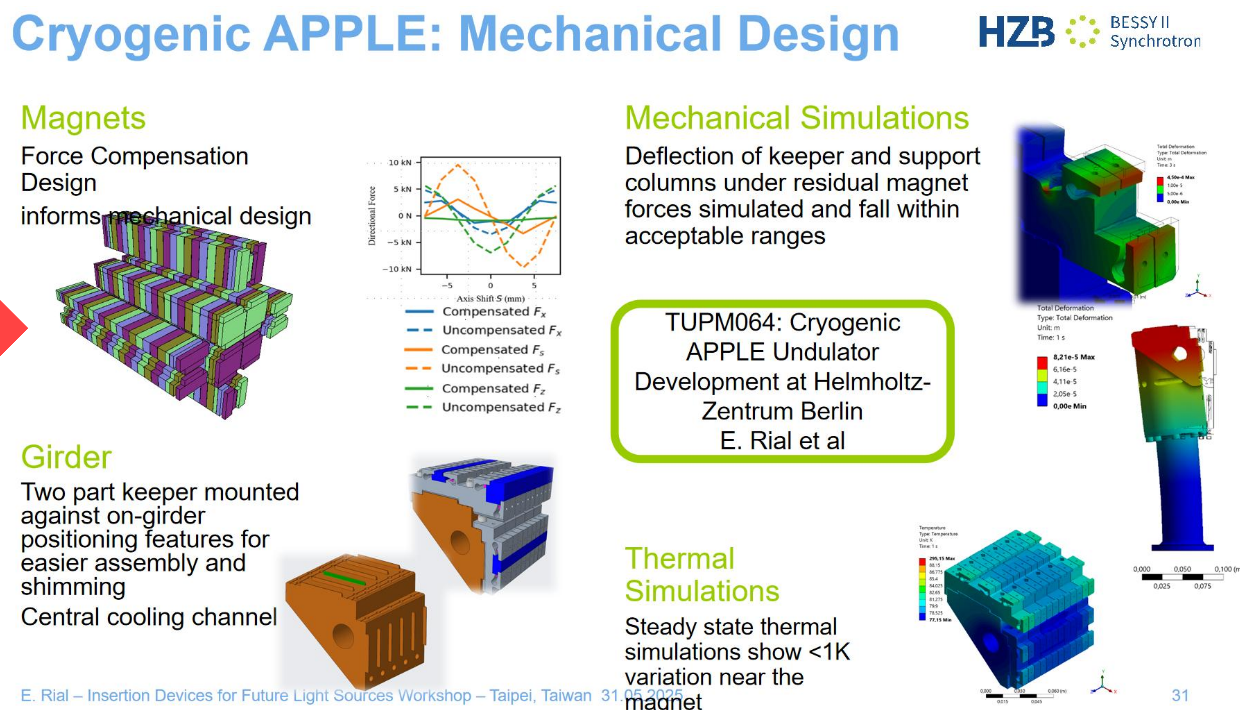
Force Compensation for In vacuum EPU







Cryogenic



J. Bahrdt, S. Grimmer, in *proc. SRI 2018*, Taipeh, Taiwan, to be published in AIP conference proceeding

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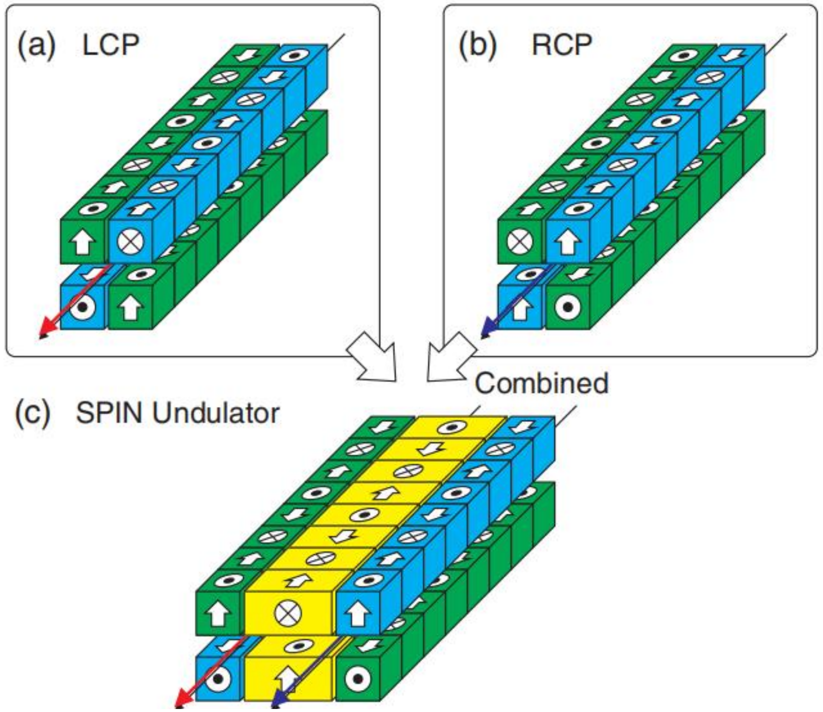
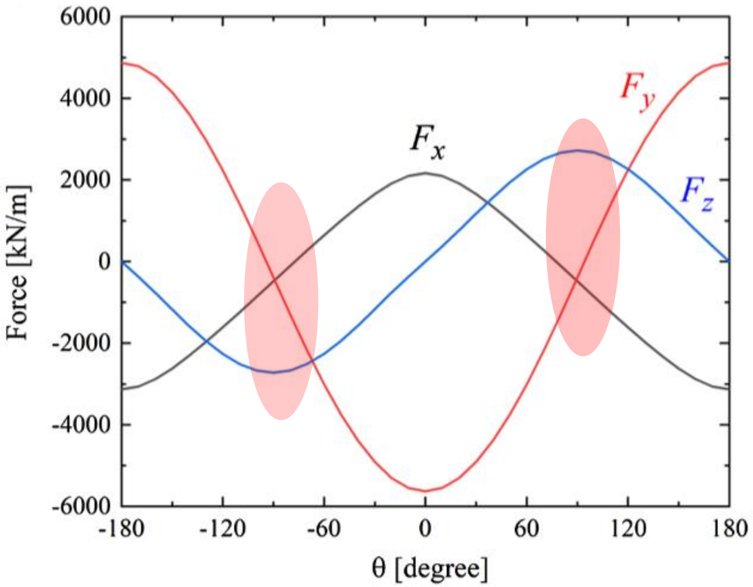
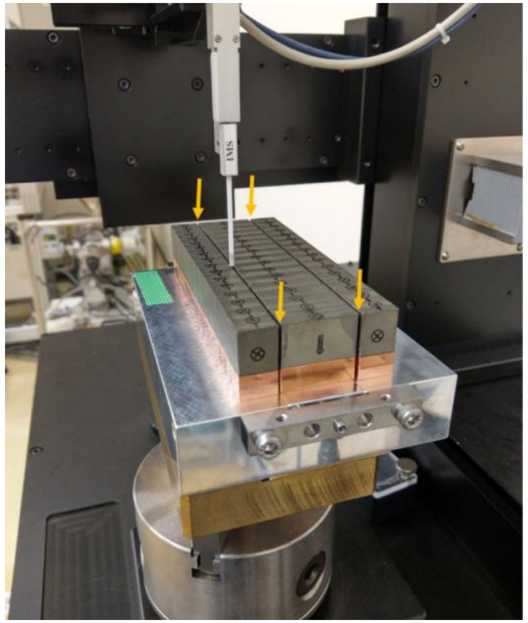
In-vacuum SPIN-EPU







Undulator configuration for helicity switching in in-vacuum undulators

Ryota Kinjo* and Takashi Tanaka

RIKEN SPring-8 Center, 1-1-1, Koto, Sayo-cho, Sayo-gun, Hyogo, 679-5148, Japan

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•DOI: 10.1103/PhysRevAccelBeams.23.020705

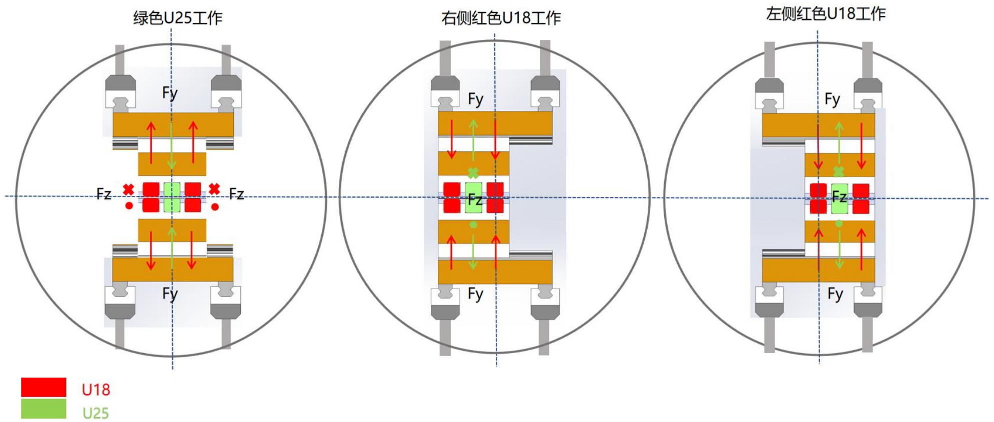
The SPIN configuration

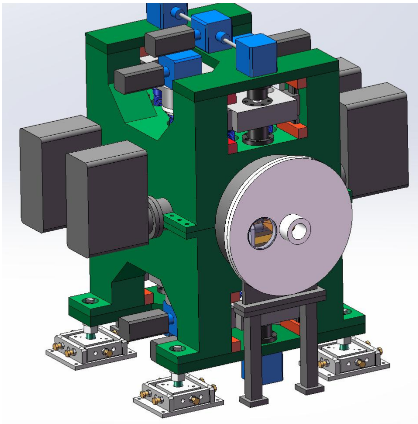
- It is well compatible with IVUs because the phasing operation is not necessary and the magnetic force can be much weaker than conventional undulators.
- It can achieve LC /RC and Horizontal polarization
- Maybe best solution for IVEPU

SHINE

Compact IVU

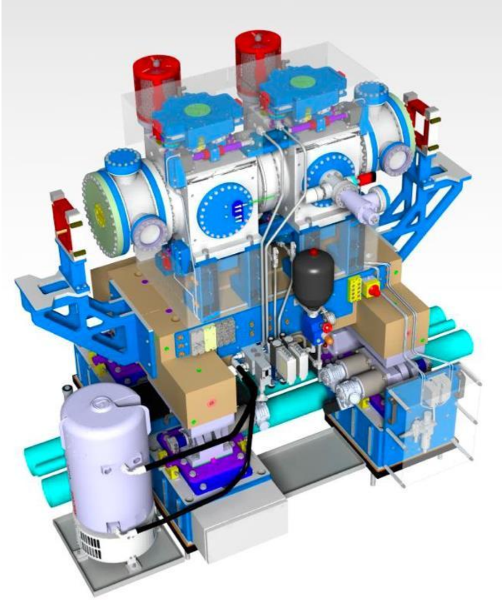
Magnetic force compensation by double or triple periods

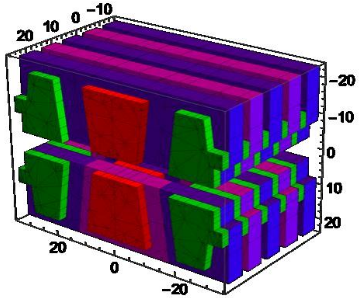


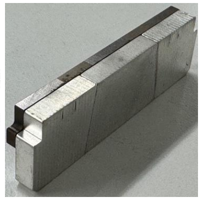


SRI2024,A double-period in-vacuum undulator moving in three directions

Soldering of magnetized Permanent Magnets



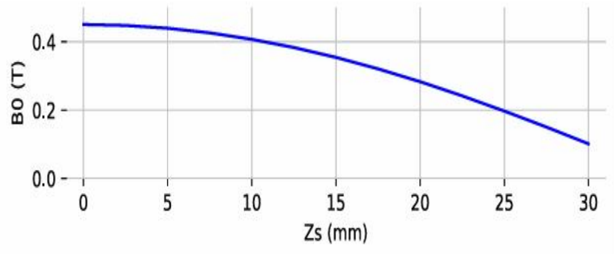




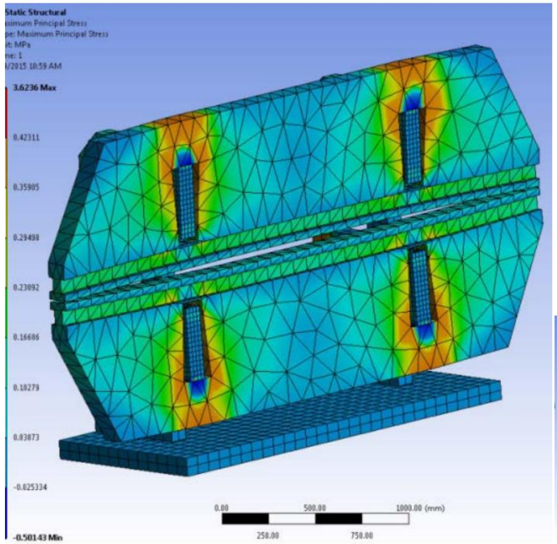
IPAC2025，Sebastian C. Richter – Paul Scherrer Institute PSI: Novel APPLE X knot & Compact Modular in-Vacuum Undulators for SLS 2.0

Fix Gap Compact PMU

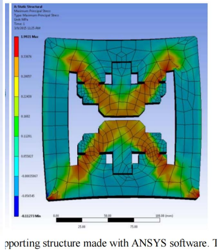
APU: When the phase between up arrays and down arrays changes, the magnetic field will also change

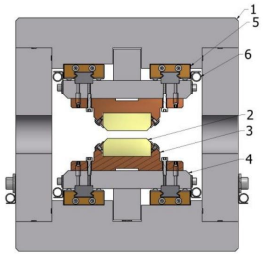


2m height



0.3m height

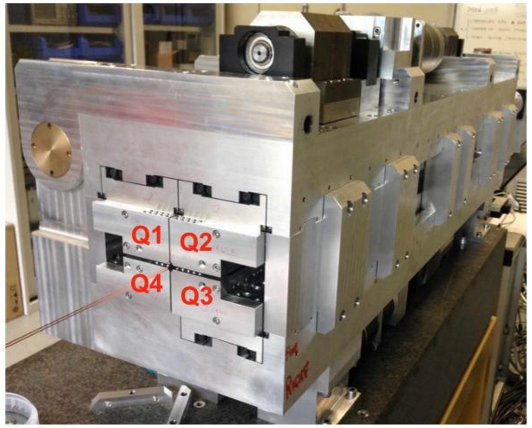




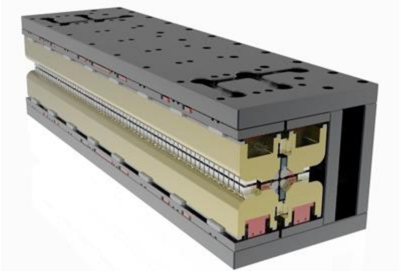
Construction of CHESS Compact Undulator magnets at Kyma

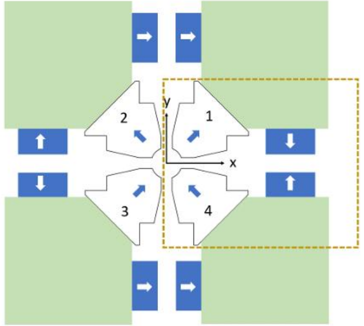
Alexander B. Temnykh[a], Aaron Lyndaker[a], Mirko Kokole[b*], Tadej Milharčič[b], Jure Počkar[b], Raffaella Geometrante[c]
[a]Cornell University, Ithaca, NY, 14850, USA; [b]Kyma Tehnologija, Sežana, Slovenia; [c]Kyma Srl, Trieste, Italy

PU to EPU



Elettra Fix gap EPU

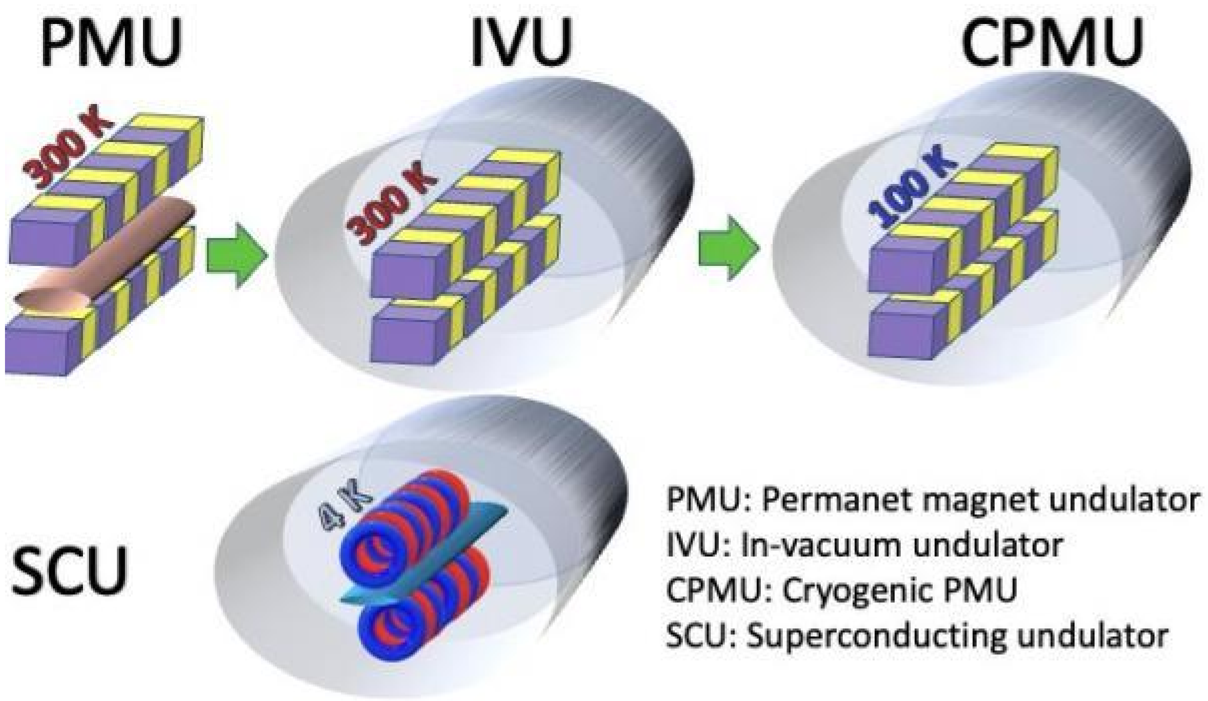


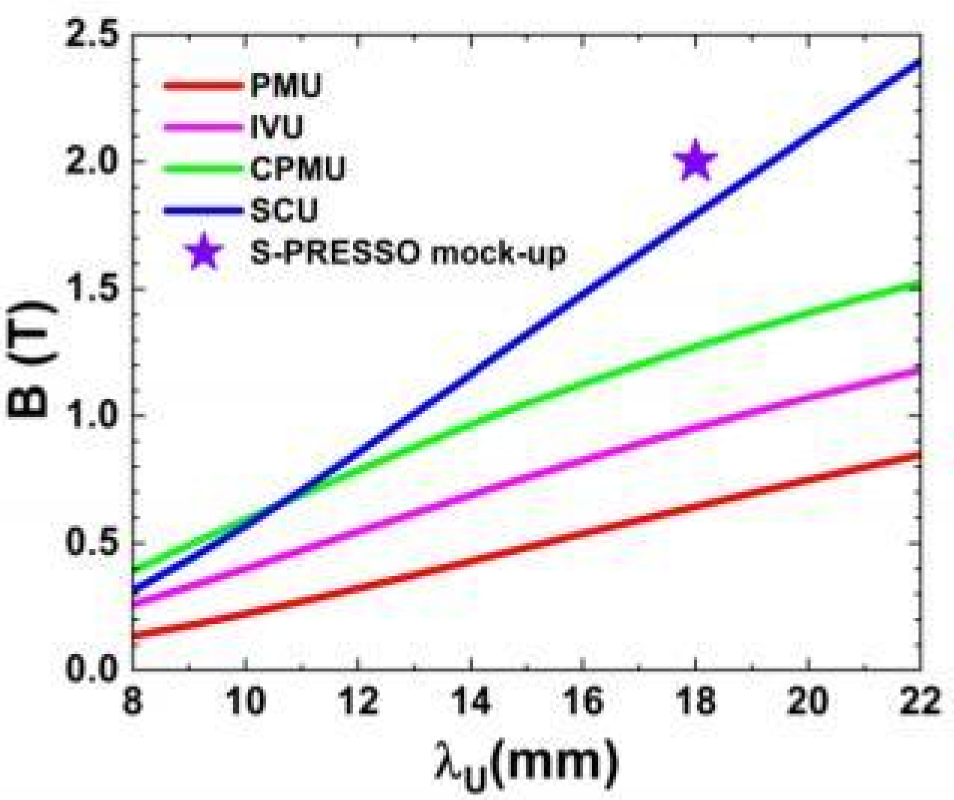


APS Fix gap EPU，based on force compensation

Compact without gap tunable

Superconducting Undulator towards FEL





Why Superconducting Undulator

A superconducting undulator (SCU) is an insertion device that generates periodic magnetic fields using superconducting coils.

Higher Peak Field

Larger gap for same period; shorter period for same gap as PMUs

Broad Spectral Coverage with SC coil current

- Fast, precise tuning of field strength
- Wide spectral range coverage through flexible field adjustment.
- Compact Design, Reduces overall device size and construction costs.

Low sensitivity to radiation damage, comparing to PMs

$$\lambda = \frac{\lambda_U}{2\, n\, \gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

$$K = \frac{e}{2\pi mc} B_0\, \lambda_U = 0.9336\, B_0[T]\, \lambda_U[cm]$$

LTS undulator

- Operate at 1.8 K - 4.2K
- Mature technology (Facility-grade)

HTS undulator

- Operate at 20 K - 70 K
- Frontier research (Lab-scale)

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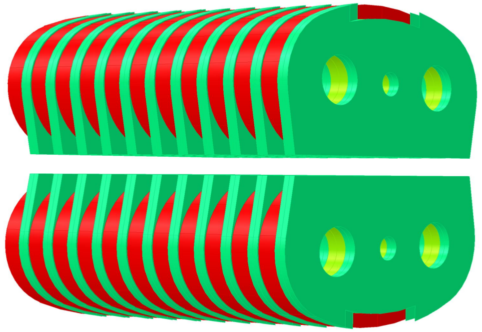
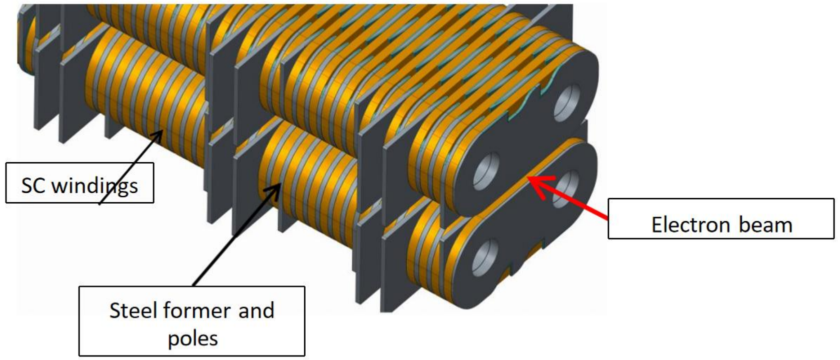
Magnet Design of SCU

The standard solution is very simple – currents flowing perpendicular to the beam axis with iron poles

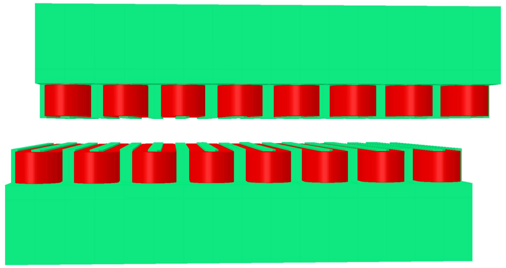
The challenge is the engineering



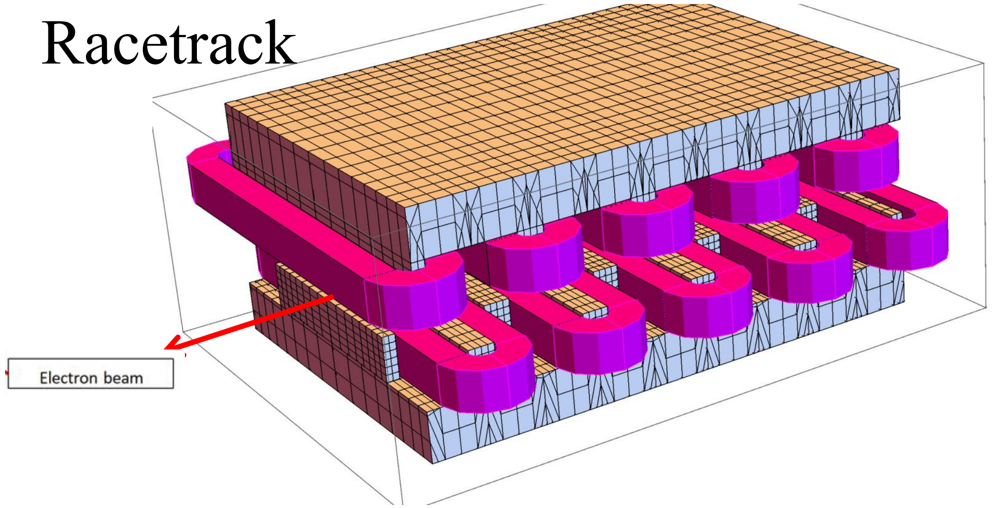
Vertical Racetrack



difficult in small period



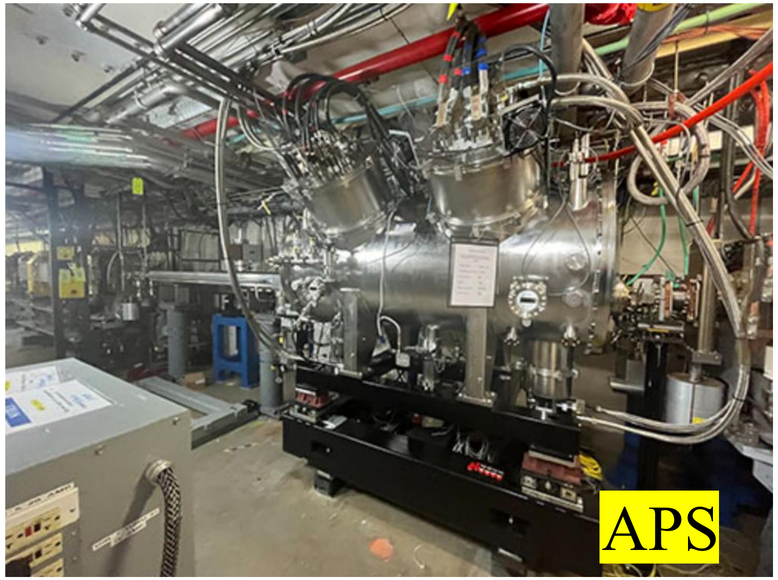
Horizontal Racetrack



Operating SCUs in Storage

TABLE VI. Parameters of storage ring SCUs which have been installed and operated successfully. Gap is the beam chamber vertical aperture.

Facility	λ_u [mm]	N	Gap [mm]	B_{peak}
KIT synchrotron	14	100	8	0.3
KIT synchrotron	15	100.5	7	0.73
KIT synchrotron	20	74.5	7	1.18
APS	16	20.5	7.2	0.8
APS	18	59.5	7.2	0.97
APS	31.5	38.5	8	0.4



KIT

SCUs for FEL

EXFEL: 5 modules (2m+2m)

Prototype work， 1 module finished on 2026

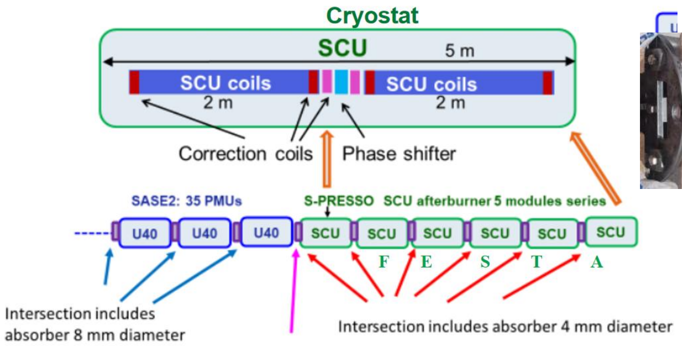
LCLSII: 1 modules (2m+2m)

Prototype work， uncertain

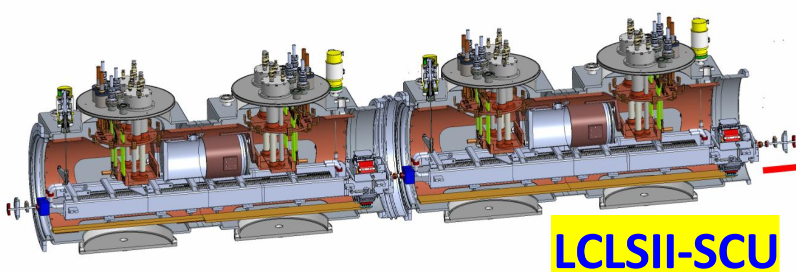
SHINE: 42 modules (from 4m prototype to 3m+3m)

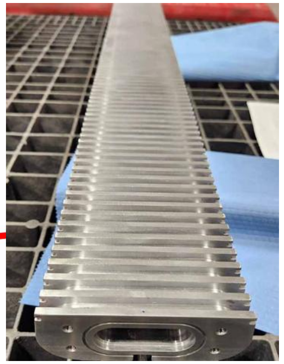
4 m prototype 2025， 3+3 in technical design

Lab.	Period length	Magnetic Length	Magnetic gap	Vacuum gap	Undulator field B0
KIT[2016]	15mm	1.5m	8mm	7mm	0.73 T
APS[2023]	18mm	1.075m	9.8mm	7.2mm	0.97 T
IHEP[2023]	15mm	1.5m	9.5mm	6.5mm	0.5T
SHINE[2023]	16mm	4m	5(4)mm		1.58T
EuXFEL	18mm	(2+2)m	6mm	5mm	1.82T
APS-U	16.5mm	(1.9+1.9)m	8mm	6.3mm	1.1T

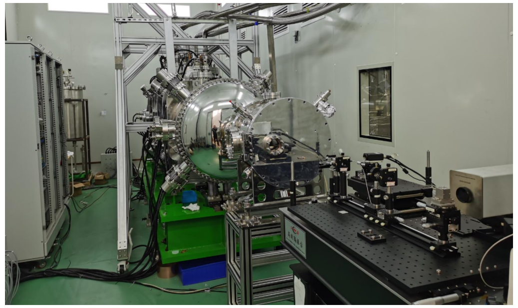


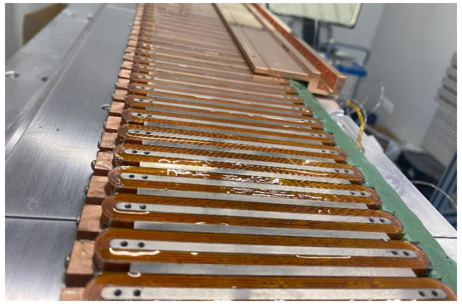
EXFEL-SCU





LCLSII-SCU



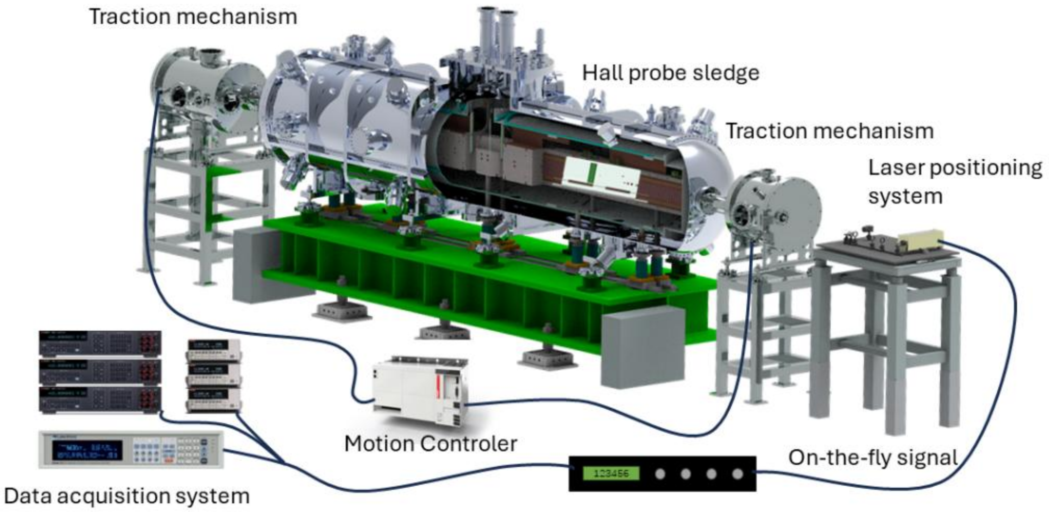


SHINE-SCU

SHINE

Superconducting Undulators Challenges

- The field quality has to be as good as existing undulators and most SC undulator groups do not use any field shimming so the engineering tolerances need to be very precise, pole height\coil dimension\period length\...
- Field measument for >2m long SCU is still a challenge, small gap ,low tem, high peak field
- Beam heat load and superconducting thermal insulation remain challenges for the stable operation of FEL SC.



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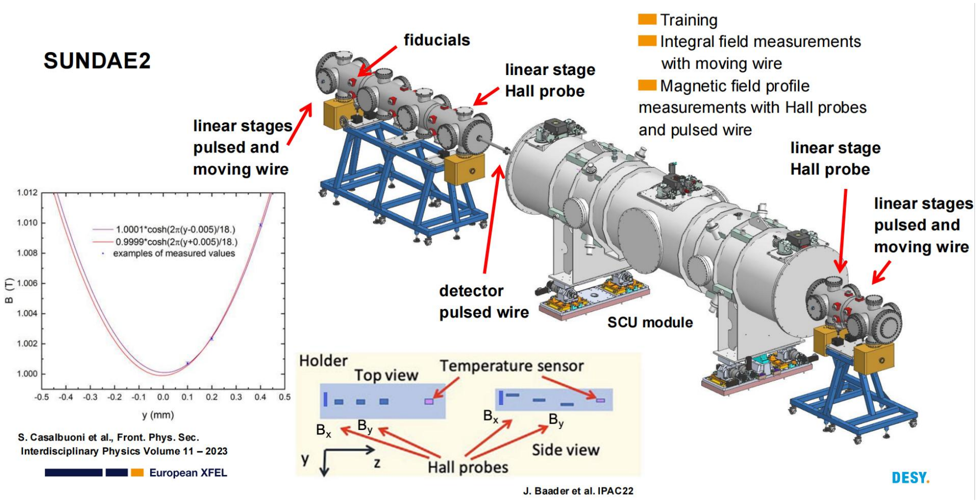
SHINE-SCU prototype



EXFEL-SCU prototype

Try to design an undulator?

Need: What kind of machine/beam/radiation would do the job?

- e-beam energy and current
- photon energy range
- minimum gap limit
- space limit
- photons
- polarizaton

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

$$K = \frac{B_0 e}{m_0 c}\frac{\lambda_u}{2\pi} = 93.36\ B_0\lambda_u$$

PPM $$B_{y0} = 1.72\ B_r e^{-\pi g/\lambda_u}$$

Hybrid $$B_0[g,\lambda_u] = 4.22[T]\exp\left(-5.08\times\left(\frac{g}{\lambda_u}\right) + 1.54\times\left(\frac{g}{\lambda_u}\right)^2\right)$$

SCU $$B = \left(0.28052 + 0.05798\cdot\lambda_U - 0.0009\cdot\lambda_U^2 + 5.10^{-6}\cdot\lambda_U^3\right)\cdot\exp\left(-\pi\cdot\left(\frac{g}{\lambda_U} - 0.5\right)\right)$$

SHINE

Summary

- **Undulator is the key component of SR and FEL.**
  - The core of the undulator generate a periodic magnetic field to produce high performance SR
  - Type of excitation: permanent magnet and electromagnetic
- Permanent magnet undulators: PPM type and hybrid type are relatively popular, more than 95% of the current use.
- **Invacuum---low temperature---superconducting**
  - IVUs can achieve short periods and small gaps, so as to obtain a high peak magnetic field.
  - CPMU can increase the peak magnetic field by 10-20%.
  - Superconducting undulator is a hot topic in recent years, with strong magnetic field, challenge in low stability and measurement . But a good future.
- **Compact EPU with short period, strong magnetic field ,on axis power density suppression is the main development direction.**

SHINE