Part I : Accelerator light source
Part II : Magnetic field, material and Magnet
Part III : Technology and conventional insertion devices

TingYi Chung (鍾廷翊)
Chung.albert@nsrrc.org.tw

National Synchrotron Radiation Research Center (NSRRC)

Short Bibliography

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Part I : Accelerator light source

What is accelerator light source (加速器光源)？

An electromagnetic wave emitted by a relativistic electron beam deflected by an magnetic field.

生活周遭好多光源:太陽光、燈泡、電視機、手機螢幕、LED、雷射投影筆.........

There are more than 50 light sources in the world (operational, or under construction).

- Low energy storage rings : ALS, TLS, BESSYII
- Medium energy storage rings : SOLEIL, DIAMOND, CLS, ALBA, TPS, Australian

Why the world needs accelerator light source?

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Biotechnology Advances 26 (2008) 246–265

BIOTECHNOLOGY ADVANCES

www.elsevier.com/locate/biotechadv

Research review paper

Biological degradation of plastics: A comprehensive review

Aamer Ali Shah *, Fariha Hasan, Abdul Hameed, Safia Ahmed

Department of Microbiology, Quaid-i-Azam University, Islamabad, Pakistan

Received 22 November 2007; received in revised form 31 December 2007; accepted 31 December 2007
Available online 26 January 2008

Plastics are man-made and continuously to improve stability and durability since 1990. (2019 produce : 353 million tons per year)
=> 自然界還沒微生物，可以創造出酶來分解塑膠。

我們的生存正面臨很多的危機，其中之一Plastic pollution(塑膠汙染)

Hung-Hsuan Chao, Greenpeace, Taiwan

埔里鎮垃圾問題，佟振國(自由時報)，2023
https://news.ltn.com.tw/news/life/breakingnews/4198513

Bringing Science Solutions to the world

NATIONAL GEOGRAPHIC
國家地理

這隻狀似蝦子的微小深海端足類動物，把微小的塑膠碎片和微纖維吃下肚。 PHOTOGRAPH BY DAVID SHALE, MINDEN PICTURES

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NATIONAL GEOGRAPHIC
國家地理

在葉門附近的亞丁灣，一條鯨鯊在塑膠袋旁游泳。雖然鯨鯊是海洋中最大的魚類，但仍然受到吞食塑膠碎片的威脅。 PHOTOGRAPH BY THOMAS P. PESCHAK, NAT GEO IMAGE COLLECTION

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文・黃家慧

2024-03-12

《全球塑膠公約》大事記

力的

業變

未來，企業出口不只得考量碳費、碳稅，可能還要考量各國的「**塑膠稅**」。2022年4

月，英國 … 針對不

可重複使用 …

不僅如此，… 目標，

執行進度也 … 僅4%

為塑膠，且積極採用再生塑料。

另一家消費龍頭可口可樂，也宣布2030年達成至少25%包裝可重複使用；聯合利華更打算在2025年之前，做到100%塑料包材可回收或可分解，同時減半原生塑膠用量。

除了減塑，
我們還可以怎麼做?

Bringing Science Solutions to the world

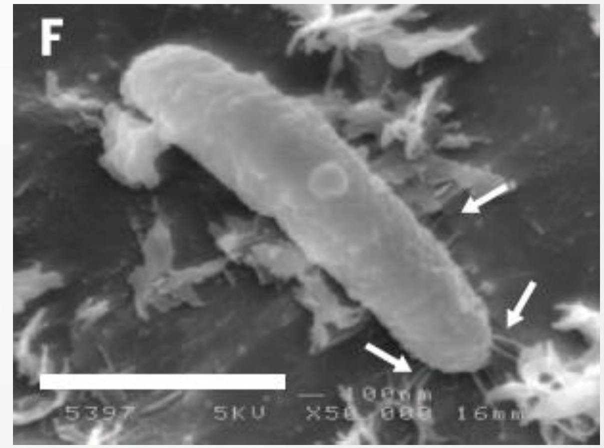
RESEARCH | *REPORTS*

BIODEGRADATION

A bacterium that degrades and assimilates poly(ethylene terephthalate)

Shosuke Yoshida,[1,2*] Kazumi Hiraga,[1] Toshihiko Takehana,[3] Ikuo Taniguchi,[4] Hironao Yamaji,[1] Yasuhito Maeda,[5] Kiyotsuna Toyohara,[5] Kenji Miyamoto,[2†] Yoshiharu Kimura,[4] Kohei Oda[1†]

sciencemag.org SCIENCE 1196 11 MARCH 2016 • VOL 351 ISSUE 6278



Ideonella sakaiensis 201-F6, that is able to use PET as its major energy and carbon source.

大阪堺菌

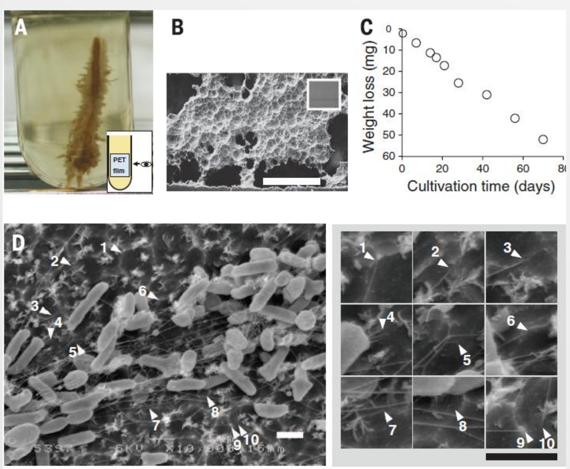
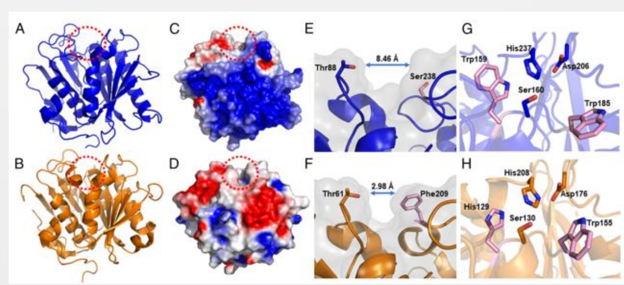


Fig. 1. Microbial growth on PET. The degradation of PET film (60 mg, 20 × 15 × 0.2 mm) by microbial consortium no. 46 at 30°C is shown in (A) to (C).

需要研究與產生更多的酶(大分子生物催化劑)來加速化學反應。



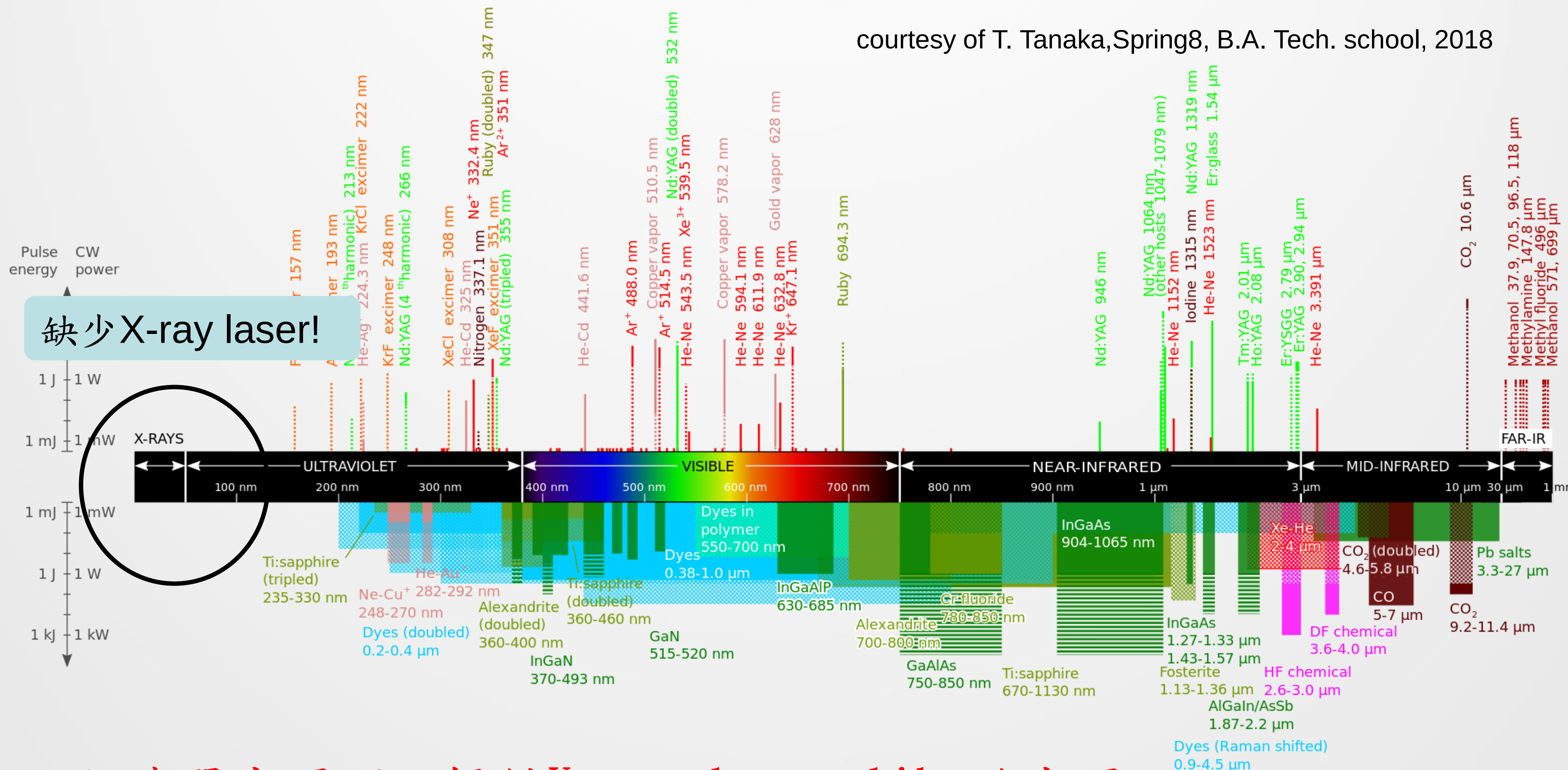
需要高亮度且短波長(≤ nm)的光源進行研究。

TingYi Chung 鍾廷翊, 2026, FEL

Lasers in X-ray Region ?

至今可取得的雷射

courtesy of T. Tanaka,Spring8, B.A. Tech. school, 2018



加速器光源可以提供X-ray laser-like的光源

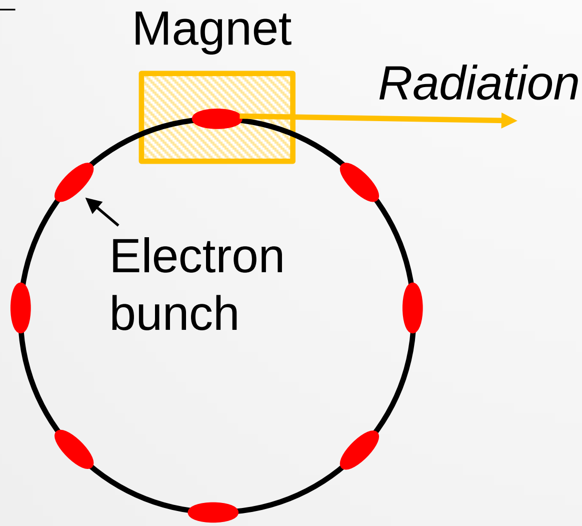
TingYi Chung 鍾廷翊, 2026, FEL

What is accelerator light source (加速器光源)？

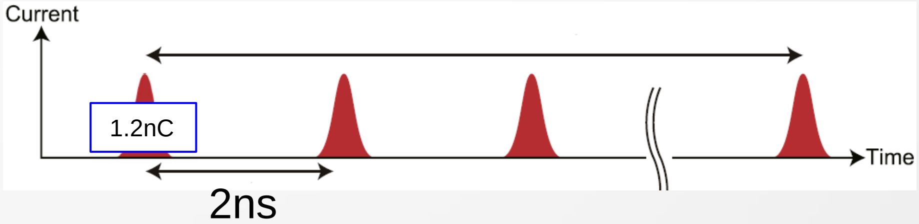
An electromagnetic wave emitted by a relativistic electron beam deflected by an magnetic field.

Light from a relativistic electron beam

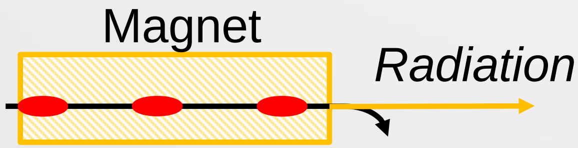
Ring_Synchrotron Radiation

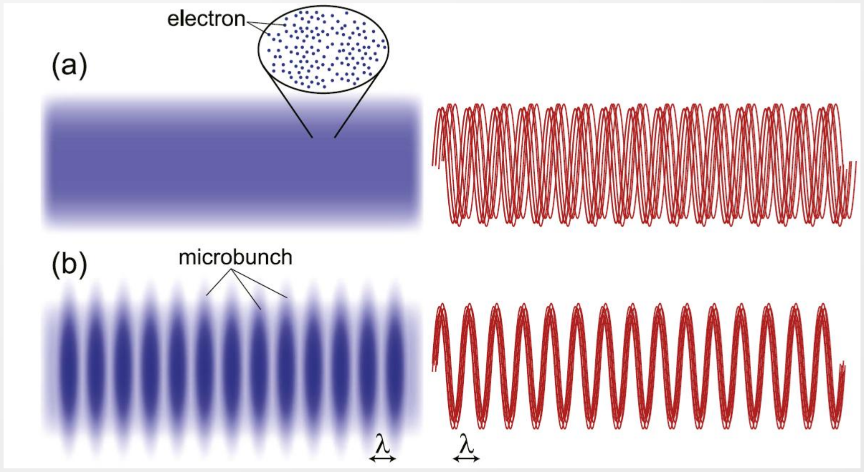


TPS : One bunch has ~10^{10}electrons



Linear_Linac, Free Electron Laser





TingYi Chung 鍾廷翊, 2024,加速器科技

A relativistic electron

Lorentz Factor γ

Electron Total Energy $E = \gamma m_0 c^2 = \gamma E_0$

Electron rest energy
$E_0 = 0.511\ MeV$

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1}{\sqrt{1-\beta^2}} \Leftrightarrow \beta = \frac{v}{c} = \sqrt{1-\frac{1}{\gamma^2}} \approx 1 - \frac{1}{2\gamma^2}$$

Electron velocity

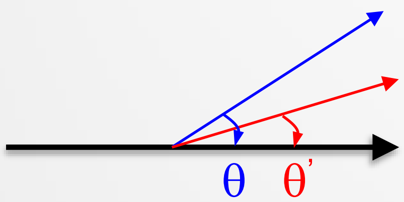
E	γ	β
1 MeV	1.95	0.869
100 MeV	195	0.9999869
1 GeV	1956	0.999999869
3 GeV	5870	0.99999998549

Speed of light in vacuum:
c = 299792.45 m/s

Any particle with non zero mass cannot exceed speed of light.

Light from a relativistic electron

Radiation cone(空間)

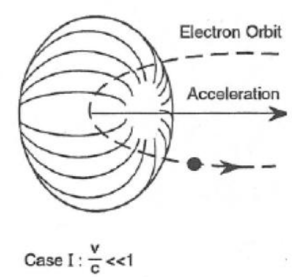


Lorentz (Length) contraction

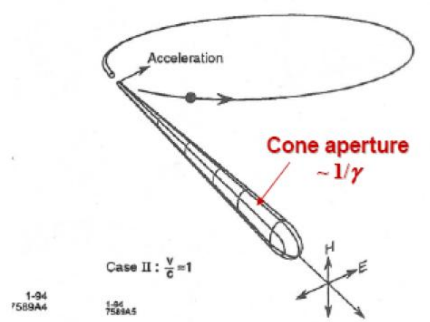
$$\tan\theta' = \frac{1}{\gamma}\frac{\sin\theta}{\cos\theta + \beta}$$

- For a rest electron, isotropic emission.
- For a relativistic electron $\beta \approx 1$, the radiation power is condensed to a narrow forward cone with a vertical angle of $\frac{1}{\gamma}$.

1/γ=0.17mrad for 3GeV electron



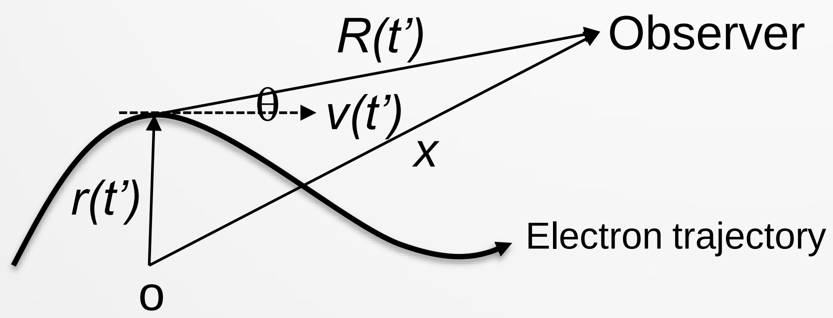
At low electron velocity (non-relativistic case) the radiation is emitted in a non-directional pattern

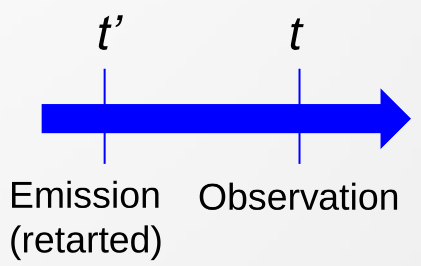


When the electron velocity approaches the velocity of light, the emission pattern is folded sharply forward.

Light from a relativistic electron

Time squeezing (時間)





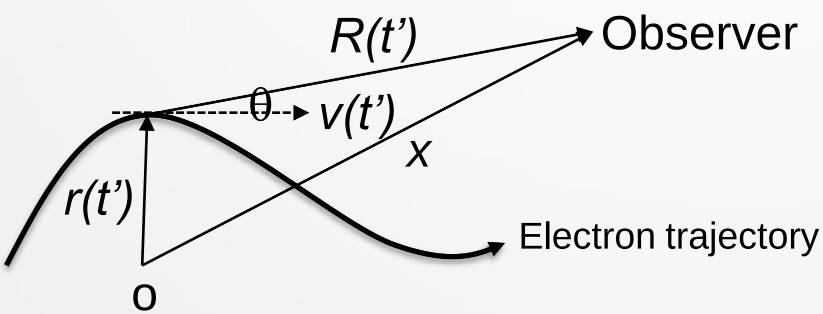
$$t = t' + \frac{R(t')}{c}$$

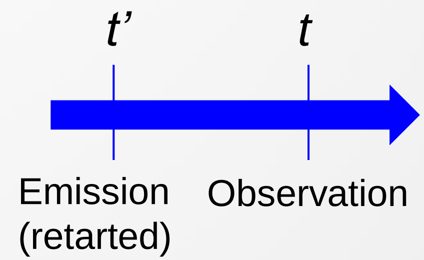
$$\frac{dt}{dt'} = 1 + \frac{1}{c}\frac{dR(t')}{dt'} = 1 + \frac{\vec{R}(t')}{R(t')} \cdot \frac{-\vec{v}(t')}{c} = 1 - \vec{n}(t') \cdot \vec{\beta}\,(t')$$

For $\theta = 0$(on-axis observation), $$dt = \frac{dt'}{2\gamma^2}$$ Time squeezing

Light from a relativistic electron

Time squeezing (時間)





For $\theta = 0$(on-axis observation), $$dt = \frac{dt'}{2\gamma^2}$$ Time squeezing

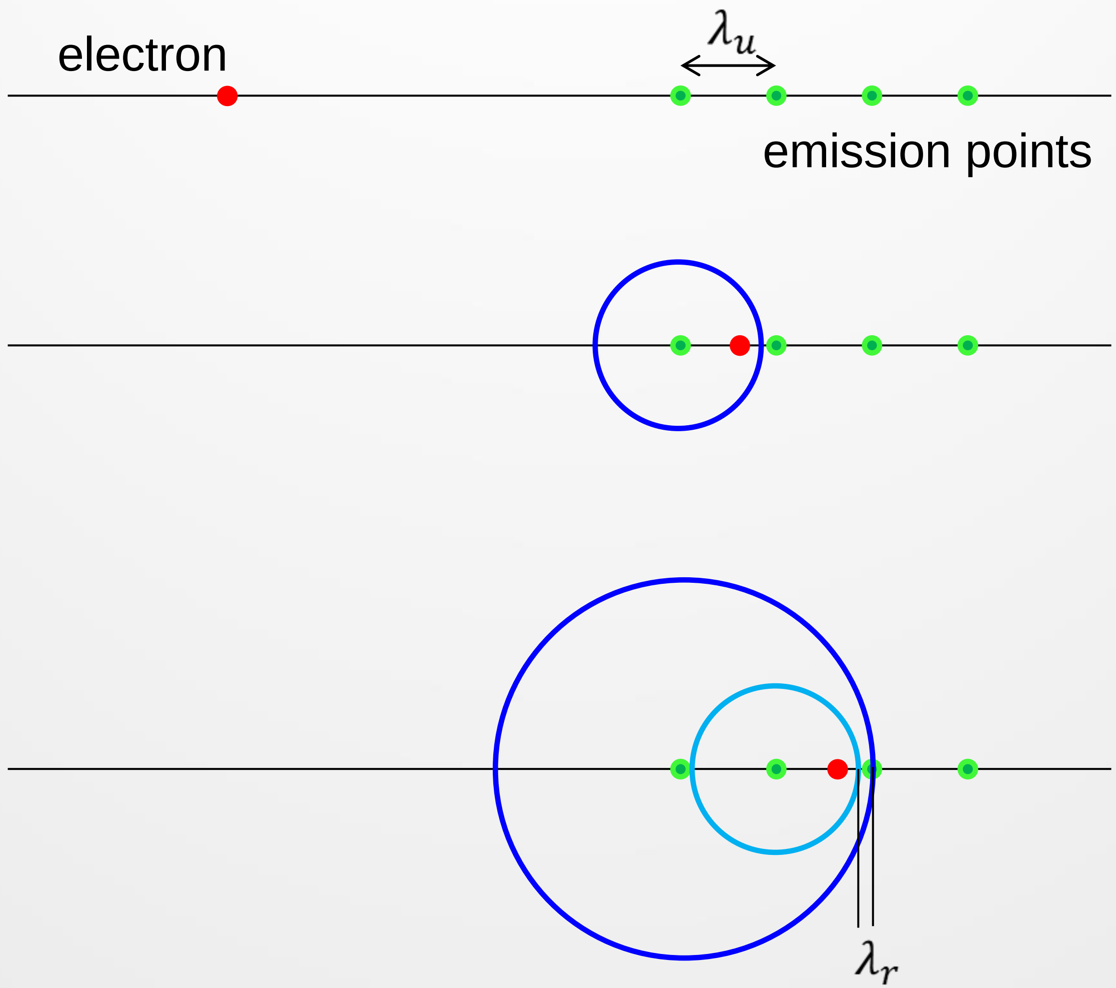
《西遊記》第四回：
孫悟空不滿玉帝所封的弼馬溫一職重返花果山，見到猴子後發出了疑問，而花果山的猴子回答說“天上一天，人間一年”

dt'= one year (3.15x10^7 sec)

γ=5870 for 3GeV electron

dt=0.45 sec

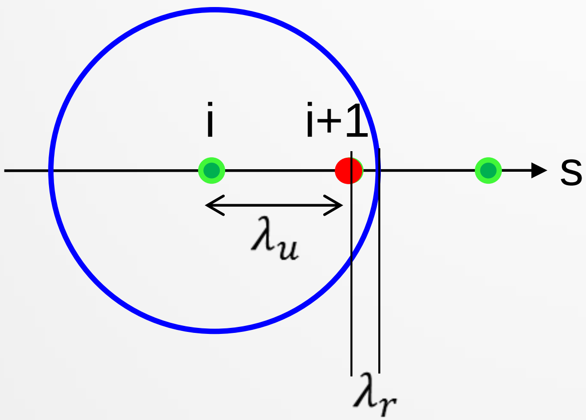
Periodic emitter



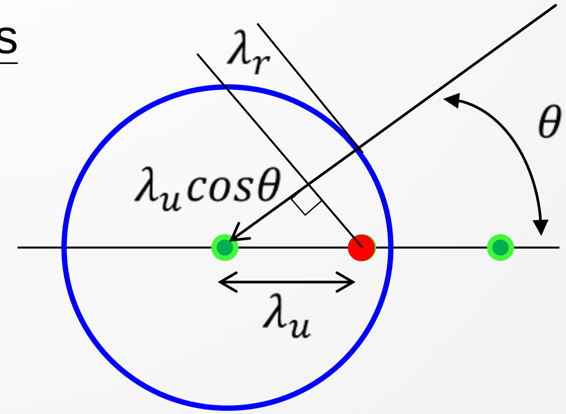
What is the relation between λ_u and λ_r ?

Periodic emitter_Wavelength

On axis



Off axis



Time taken by the electron to move from point i to point i+1: $\Delta t = \frac{\lambda_u}{\beta_s c}$

During this period the wavefront created at point i has expand by c $\cdot \Delta t = \frac{\lambda_u}{\beta_s}$ *light*

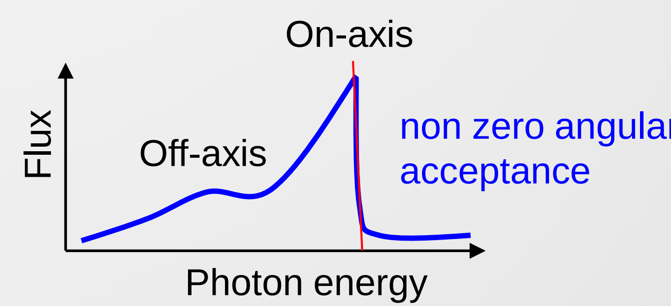
Therefore: $\lambda_r = \frac{\lambda_u}{\beta_s} - \lambda_u \approx \frac{\lambda_u}{2\gamma^2}$ ------------------ on axis

TPS 3 GeV, λ_u=48 mm, λ_r = 7Å

$$\lambda_r(\theta) = \frac{\lambda_u}{\beta_s} - \lambda_u cos\theta \approx \lambda_u\left(1 - cos\theta + \frac{1}{2\gamma^2}\right)$$

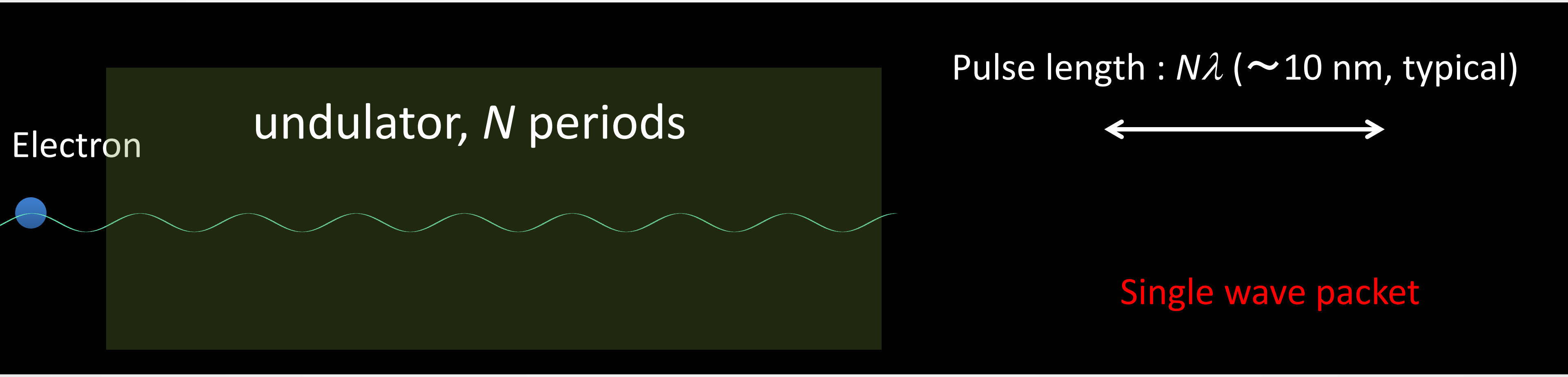
For small angle : $cos\theta \approx 1 - \frac{\theta^2}{2}$

$\lambda_r(\theta) \approx \frac{\lambda_u}{2\gamma^2}(1 + \gamma^2\theta^2)$ ------------------------------ off axis



Wave packets generated from undulator

Single electron snaking in the undulator generates single wave packet.



Trajectory in a planar ID

Equation of motion of an electron in a magnetic field *B*,

$$\frac{d\vec{p}}{dt} = e\vec{v} \times \vec{B}$$

In the coordinate frame,
small angle approx. $\dot{x}, \dot{y} \ll 1$
electrons travelling in the z

$$\ddot{x} = \frac{d^2x}{dz^2} = \frac{e}{\gamma mc}(B_y - \dot{y}B_z)$$

$$\ddot{y} = \frac{d^2y}{dz^2} = \frac{e}{\gamma mc}(\dot{x}B_z - B_x)$$

For a planar ID, the on-axis field: $\left(B_x, B_y, B_z\right) = \left(0, B_0 \sin\left(\frac{2\pi}{\lambda_u} z\right), 0\right)$

Deflection angle:
(First field integral)

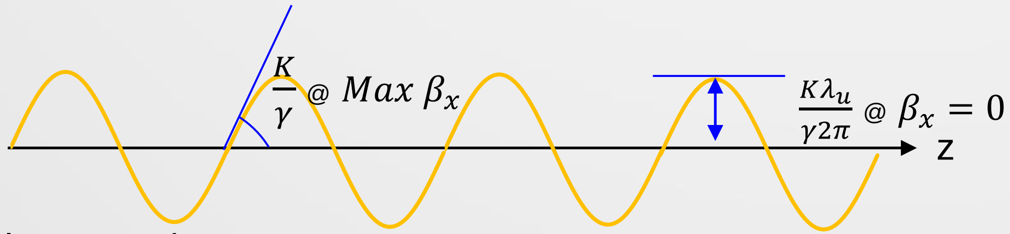
$$\dot{x} = \int \ddot{x}\, dz = \frac{B_0 e}{\gamma mc}\frac{\lambda_u}{2\pi} cos\left(\frac{2\pi z}{\lambda_u}\right) = \frac{K}{\gamma}\cos\left(\frac{2\pi z}{\lambda_u}\right)$$

Position:
(Second field integral)

$$x = \int \dot{x}\, dz = \frac{K}{\gamma}\frac{\lambda_u}{2\pi}\sin\left(\frac{2\pi z}{\lambda_u}\right)$$

$$K = \frac{eB_0\lambda_u}{2\pi mc} = 0.9337 B_0[T]\lambda_u[\mathrm{cm}]$$

Deflection parameter
(Multiple times the natural divergence angle $1/\gamma$)



Electron trajectory

TPS 3 GeV, λ_u=48 mm, *K*=2,
peak deflection =0.34 mrad, max dis.=2.6 μm.

TingYi Chung 鍾廷翊, 2026, FEL

Undulator Radiation

Transverse velocity : $\beta_x = \frac{dx/dt}{c} = \frac{dx}{dz} = \dot{x} = \frac{K}{\gamma}\cos(\frac{2\pi z}{\lambda_u})$

Longitudinal velocity : $\beta_z = \sqrt{\beta^2 - \beta_x^2} \approx 1 - \frac{1}{2\gamma^2} - \frac{K^2}{4\gamma^2} - \frac{K^2}{4\gamma^2}\cos(\frac{4\pi z}{\lambda_u})$

Oscillating term

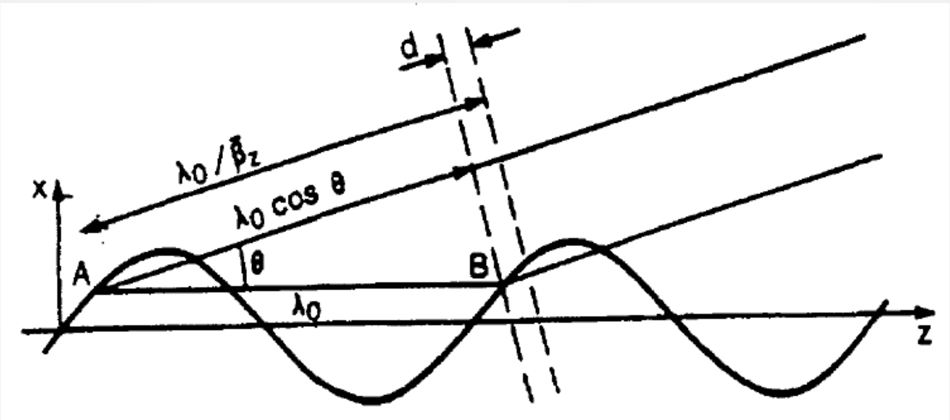
$\overline{\beta_z}$
Average velocity

The average velocity can be adjusted by the magnetic field strength.

K can be understood as how much the longitudinal velocity is slowed down due to the undulator magnetic field.

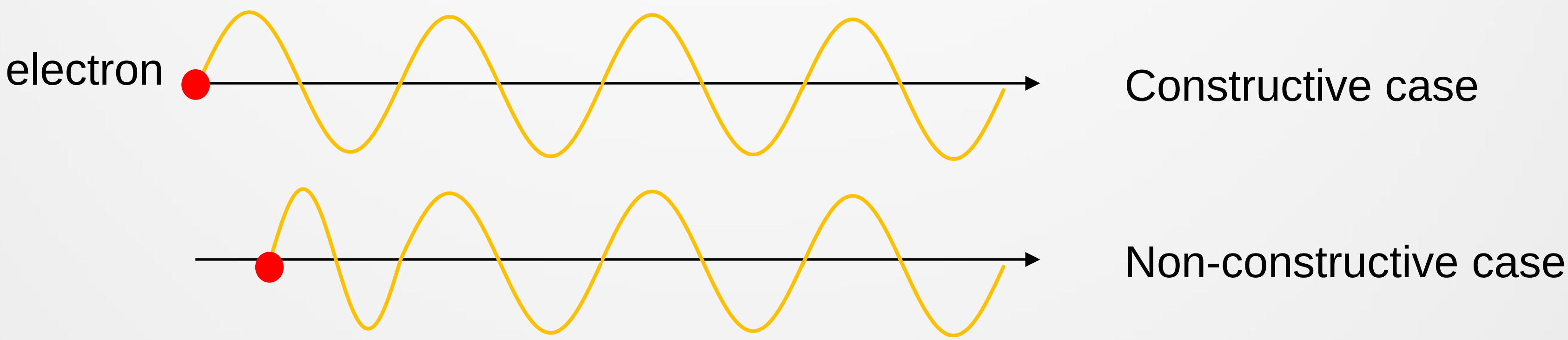
A slippage of an electron behind the wavefront over one period : $\mathrm{d} = \frac{\lambda_u}{\overline{\beta_z}} - \lambda_u cos\theta$

θ : observed angle



Undulator Radiation

For constructive interference between wavefronts emitted by the same electron, the slippage of **the electron must be by a whole number of wavelengths** over one period.



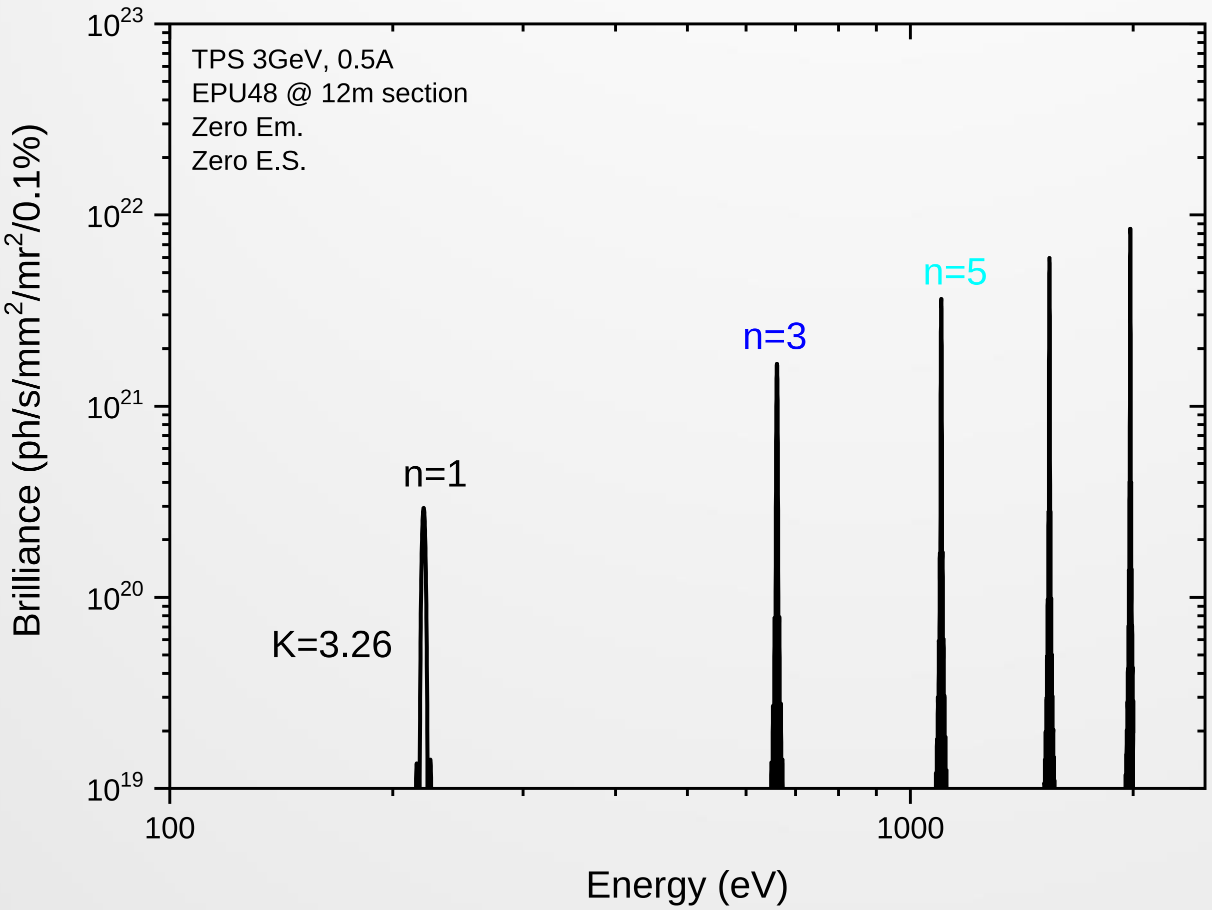
$$\lambda_r = \frac{\lambda_u}{n2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$ Undulator eq.

n: harmonic number

- A magnetic field dependent wavelength.
- Increase *B*(also increase *K*), the output wavelength increase (photon energy decrease).

Spectrum of Undulator Radiation

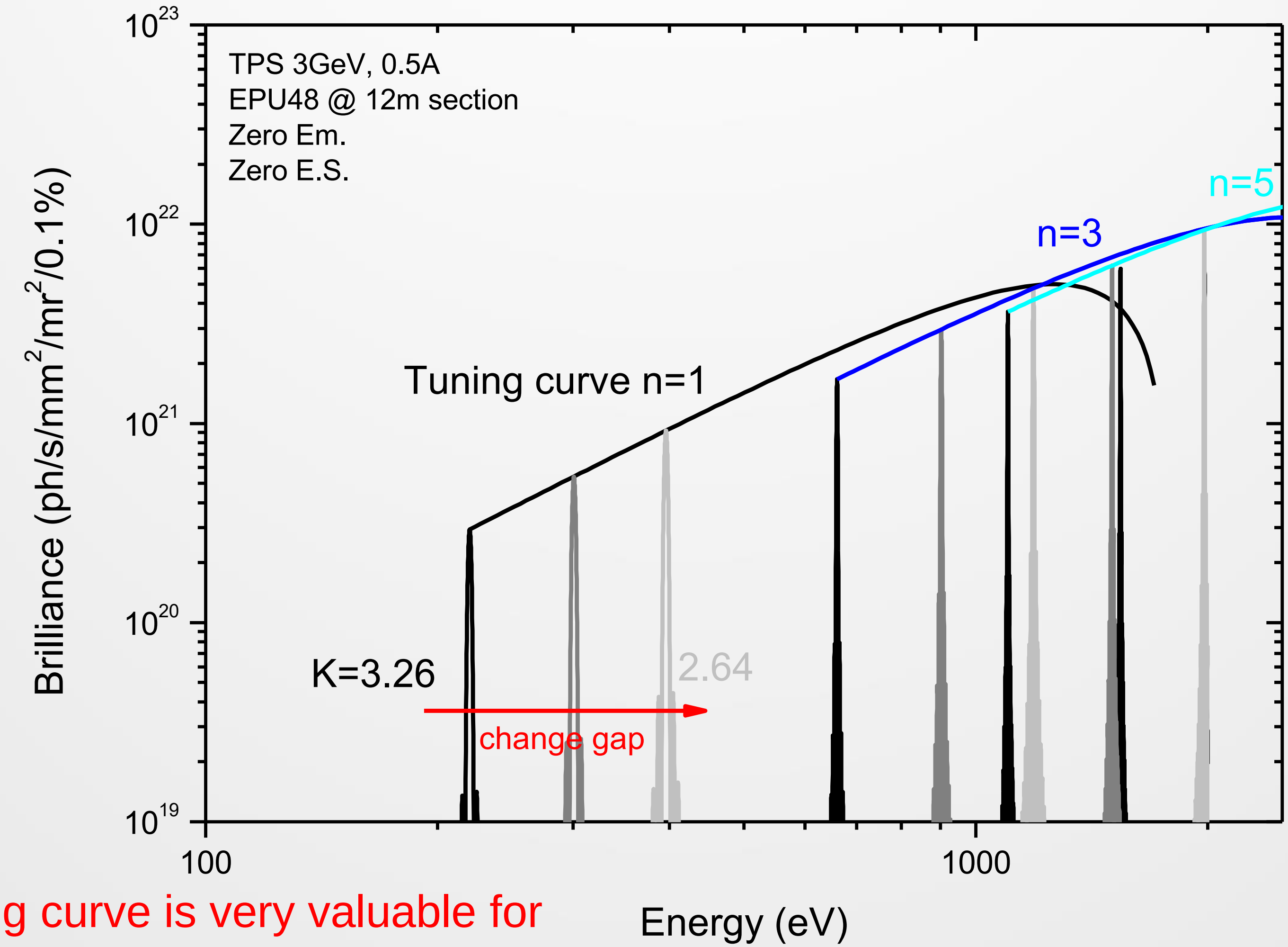
Only wavelengths that are integer multiples and satisfy the slippage condition will result in constructive interference, producing light.



- only even harmonic?
- Peak height of n=5 > n=1?

Tuning curve

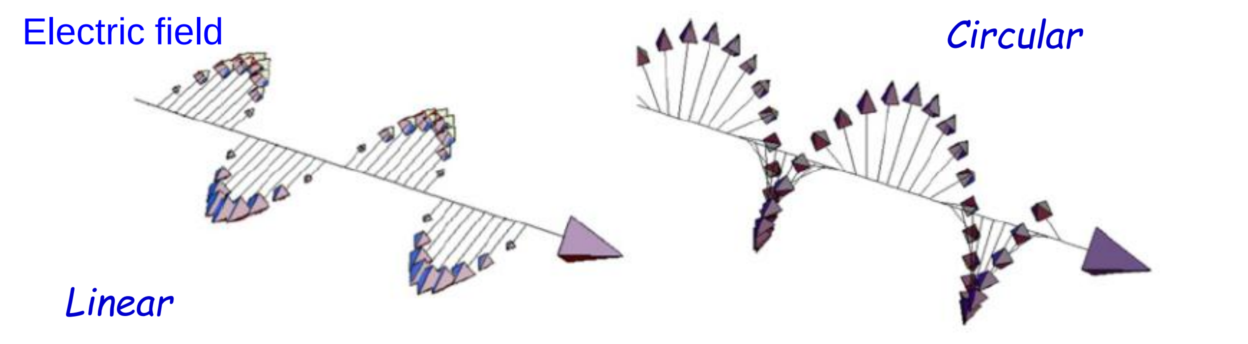
Scan a photon energy range => shift harmonic peak => tuning K generally via a gap change.



The tuning curve is very valuable for end users.

Polarization

- Polarization is described by the relationship between two orthogonal components of the Electric field.
- However, the amplitude and the phase difference cannot be measured directly.



$$E_x = E_{x_0}\sin(\omega t)$$

$$E_y = E_{y_0}\sin(\omega t + \underline{\varphi})$$

Phase difference

$\varphi = 0$ $\quad$ $E_{x_0} = E_{y_0}, \varphi = \pi/2$

Stokes Parameters

The intensity can be measured for different polarization directions:

$$S_0 = I_x + I_y = I_{45^o} + I_{135^o} = I_R + I_L$$

$$S_1 = I_x - I_y$$

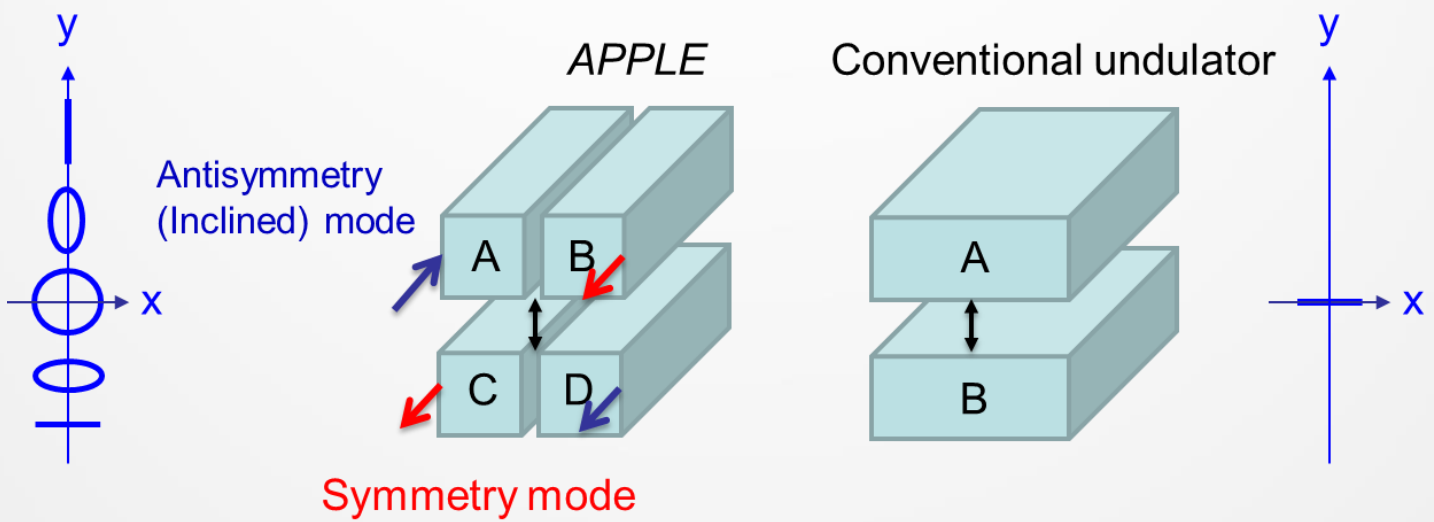
$$S_2 = I_{45^o} - I_{135^o}$$

$$S_3 = I_R - I_L$$

Intensity of :

Linear erect	$I_{x,y}$
Linear skew	$I_{45^o,135^o}$,
Circular	$I_{R,L}$

Elliptically polarized undulator (EPU)



Elliptically polarized undulator (EPU)

- Planar undulator (vertical field) produces only linear polarization.
- Elliptical undulator (vertical and horizontal field),

Magnetic field $$\left(B_x, B_y, B_z\right) = \left(B_x \sin\left(\frac{2\pi}{\lambda_u} z + \varphi\right), B_y \sin\left(\frac{2\pi}{\lambda_u} z\right), 0\right)$$

Velocity $$\left(\beta_x, \beta_y, \beta_z\right) = \left(\frac{K_x}{\gamma} \cos\left(\frac{2\pi z}{\lambda_u}\right), \frac{K_y}{\gamma} \cos\left(\frac{2\pi z}{\lambda_u} + \varphi\right), 1\right)$$

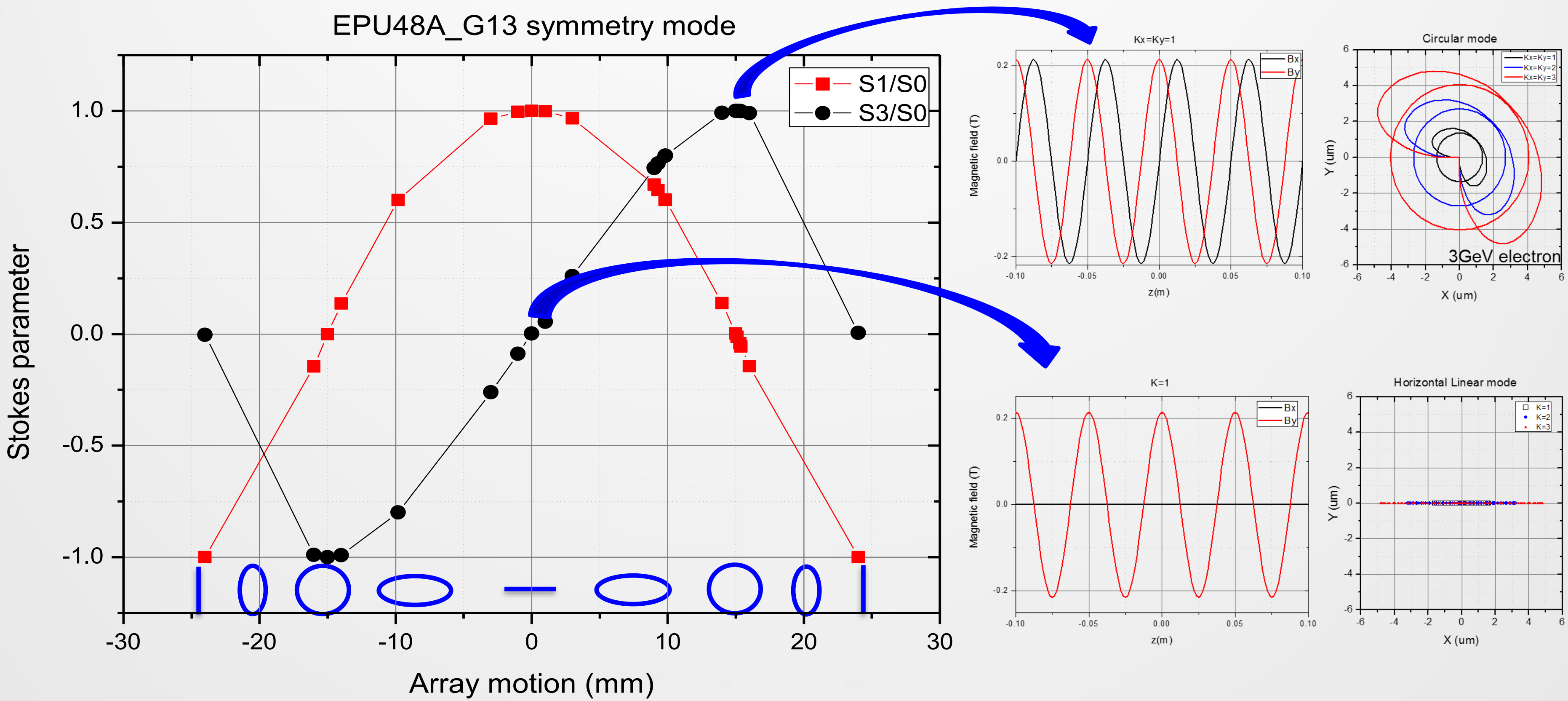
Longitudinal velocity : $$\beta_z = \sqrt{\beta^2 - \beta_x^2 - \beta_y^2} \approx 1 - \frac{1}{2\gamma^2} - \frac{K_x^2}{4\gamma^2} - \frac{K_y^2}{4\gamma^2} \qquad \overline{\beta_z}$$

Wave length： $$\lambda_r = \frac{\lambda_u}{n 2\gamma^2}\left(1 + \frac{K_x^2}{2} + \frac{K_y^2}{2} + \gamma^2\theta^2\right)$$

- The wave length is independent on the phase between the field.
- Similar to the planar undulator

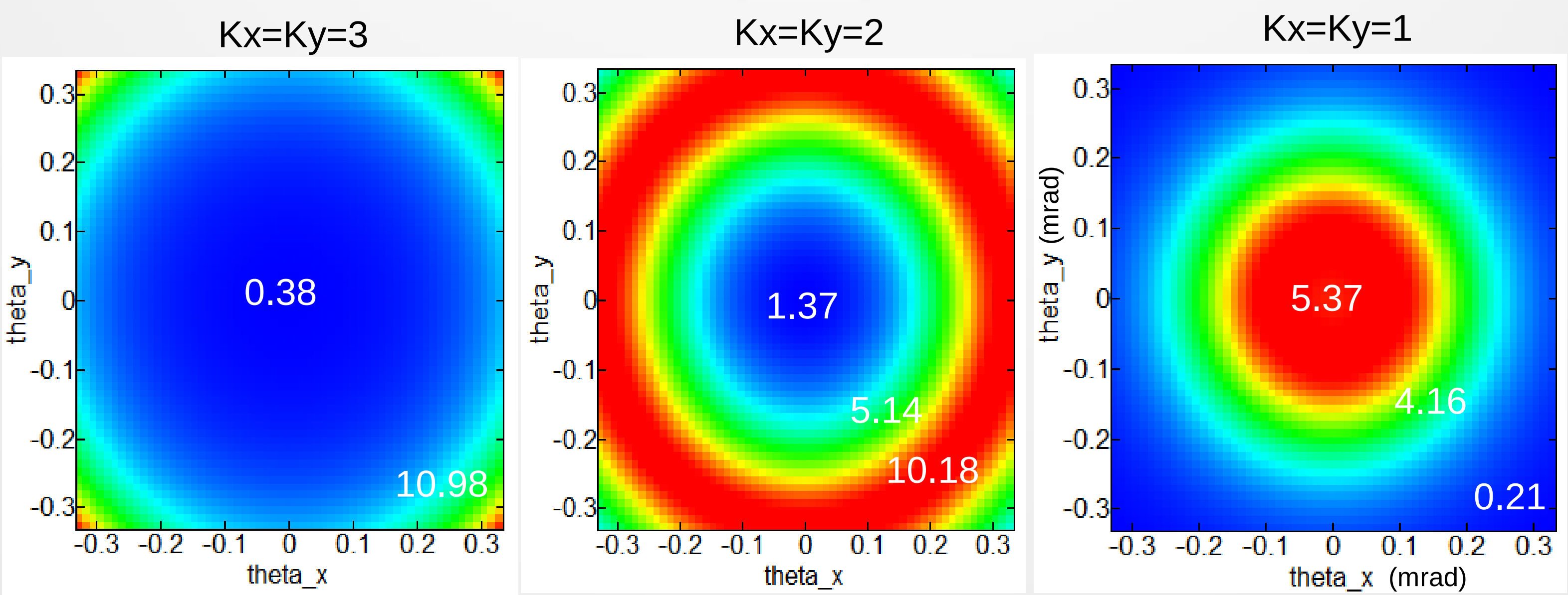
EPU radiation

- $B_x = B_y$, the circular trajectory, pure circular polarization.
- On axis, only the first harmonic, a continuous electric field observed.



Total power and Angular power density

- Total power is double that produced by a planar undulator with the same magnetic field.
- The maximum power density is located at K/γ.
- The width ~ $1/\gamma$
- larger K, lower on-axis power density but greater total power.



TPS 3GeV, 0.5A, 4m

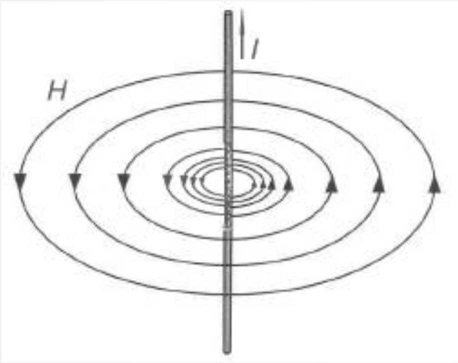
kW/mrad^2

Part II : Magnetic field, material and Magnet

Magnetic field

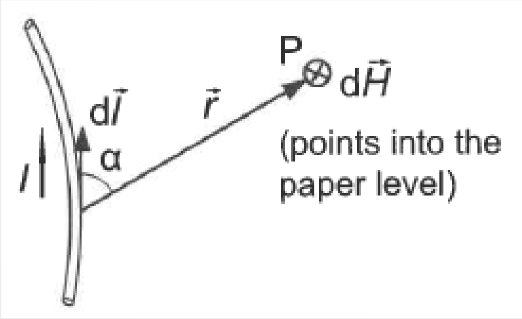
- Magnetic field are always the result of an electric charge in motion.

- Electric current flowing through a wire.



Ampere's law

$$curl\ \vec{H} = \vec{J} \Rightarrow \oint \vec{H} \cdot d\vec{l} = \int J \cdot dA \Rightarrow H = \frac{I}{2\pi r}$$ Straight wire



Biot Savart law

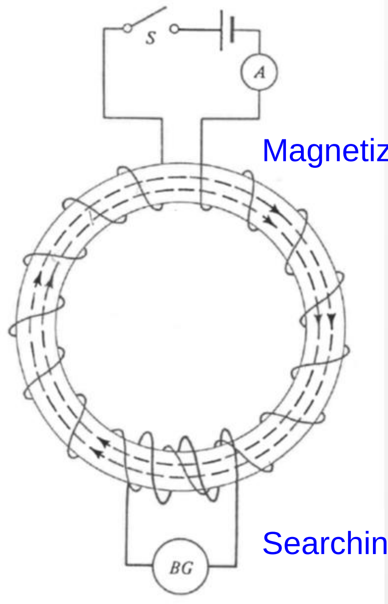
The magnetic field at a point P results from the superposition of the contribution from *dl*.

$$dH = \frac{1}{4\pi r^2} \cdot I \cdot dl \cdot sin\alpha \Rightarrow H = \frac{I}{2r}$$ Single current loop

⇨ Uniform magnetic field

- A pair of Helmholtz coils with diameter 2r and arranged by r.
- A solenoid.

Magnetic material



Rowland ring method (closed loop method)
-Entirely confined flux within the coil.
-Material of a ring without forming poles.

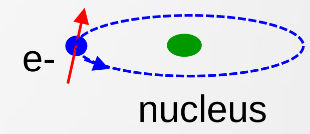
- A ring specimen changes the flux circulation $\phi_{current}$, created by the magnetizing winding.
- The flux ϕ_{obs} is observed by the searching winding.

$\phi_{obs} < \phi_{current}$: diamagnetic
$\phi_{obs} > \phi_{current}$: paramagnetic and antiferromagnetic
$\phi_{obs} \gg \phi_{current}$: ferromagnetic

- 每一種物質都有磁性質，只是需要區分為哪一類
- Magnetic field is always the result of an electric charge in motion.
  => Correct in matter ?

Magnetic material_微觀

- The *orbital motion* of an *electron* around the nucleus may be likened to a current in a loop of wire.
- The *spin* of an *electron*.



Calculating magnetic moment of an electron according to Bohr model

$$\mu_B = (area\ of\ loop)(current) = \frac{eh}{4\pi m} = 9.274 \cdot 10^{-24} Am^2$$

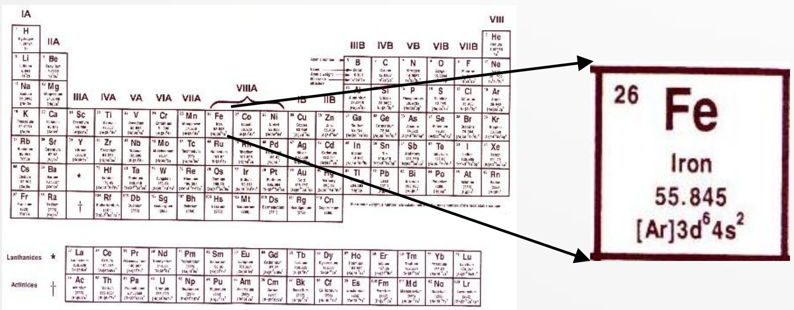
Bohr magneton: natural unit of magnetic moment
The magnetic moment of an electron in the first (n=1) Bohr orbit.
The magnetic moment due to its spin to $1.001 \cdot \mu_B$

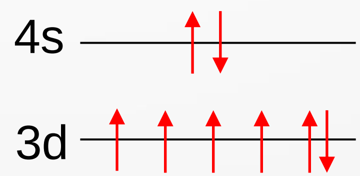
The magnetic moment of the *atom* is the vector sum of all its electronic moments.

- The magnetic moments of all the electrons cancel out, the atom no net magnetic moment: diamagnetism.
- Partial cancellation, the atom is left with a net magnetic moment: the others.

Magnetic material_微觀

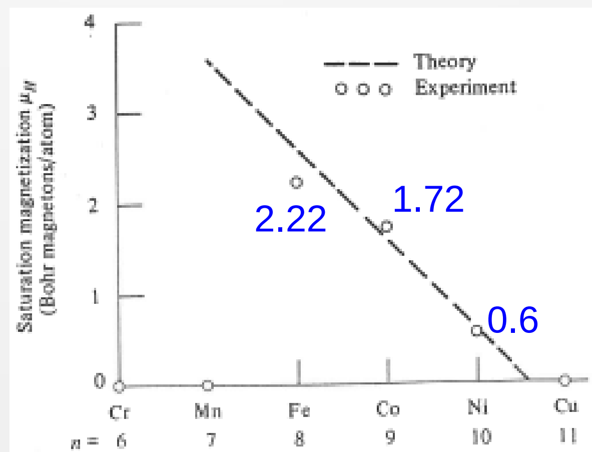
The magnetic moment of an *free* iron (Fe) atom,



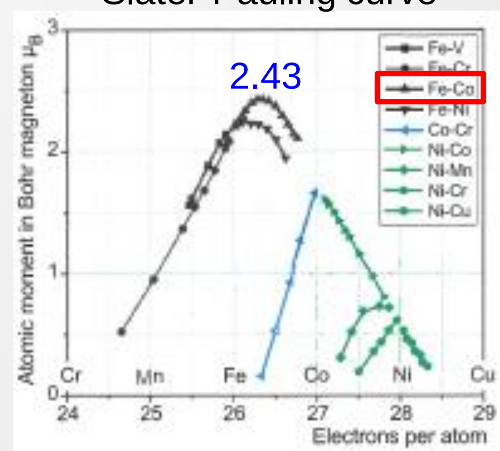


$$\mu_{free}^{Fe} = 4\mu_B$$

- In a *solid*, the energy levels of an atom are modified to a band structure.
- No longer an integer.
- The magnetic moment is influenced by *crystal structure.*



Slater-Pauling curve



=> the origin of the magnetic moments is from spin and orbital moment in incomplete shells.

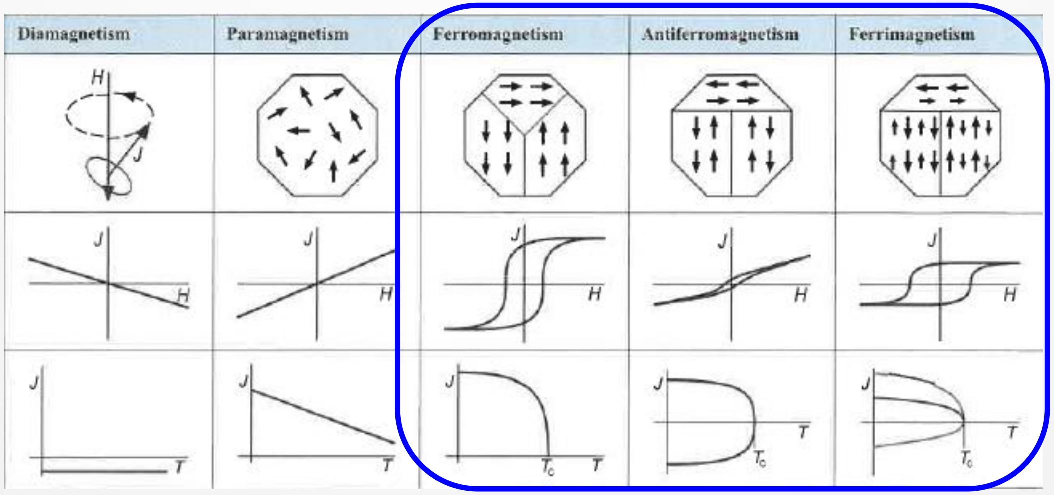
The magnetic moment of an atom has a maximum for a iron-cobalt alloys, reflects the max saturation magnetization of the material.

Magnetic material_巨觀

Arrangement of magnetic moments

J(=μ_0*M*)*H*/*MH* curve,
Magnetic polarization *J*
Magnetic field strength *H*
Magnetization *M*

MT curve
Temperature *T*



Magnet application,

- High *J* at a small external field.
- Permanent magnet.

In addition to the external field, *J* depends on *T*.

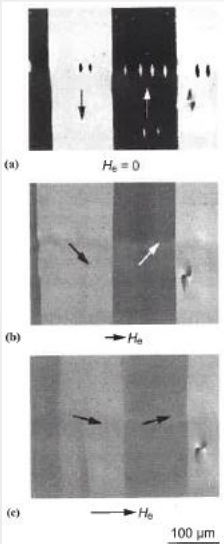
At the Curie temperature *Tc*, the ferromagnetism becomes paramagnetism, the remanence and coercivity get zero.

Fe, Co and Ni are the main components for the magnet application.

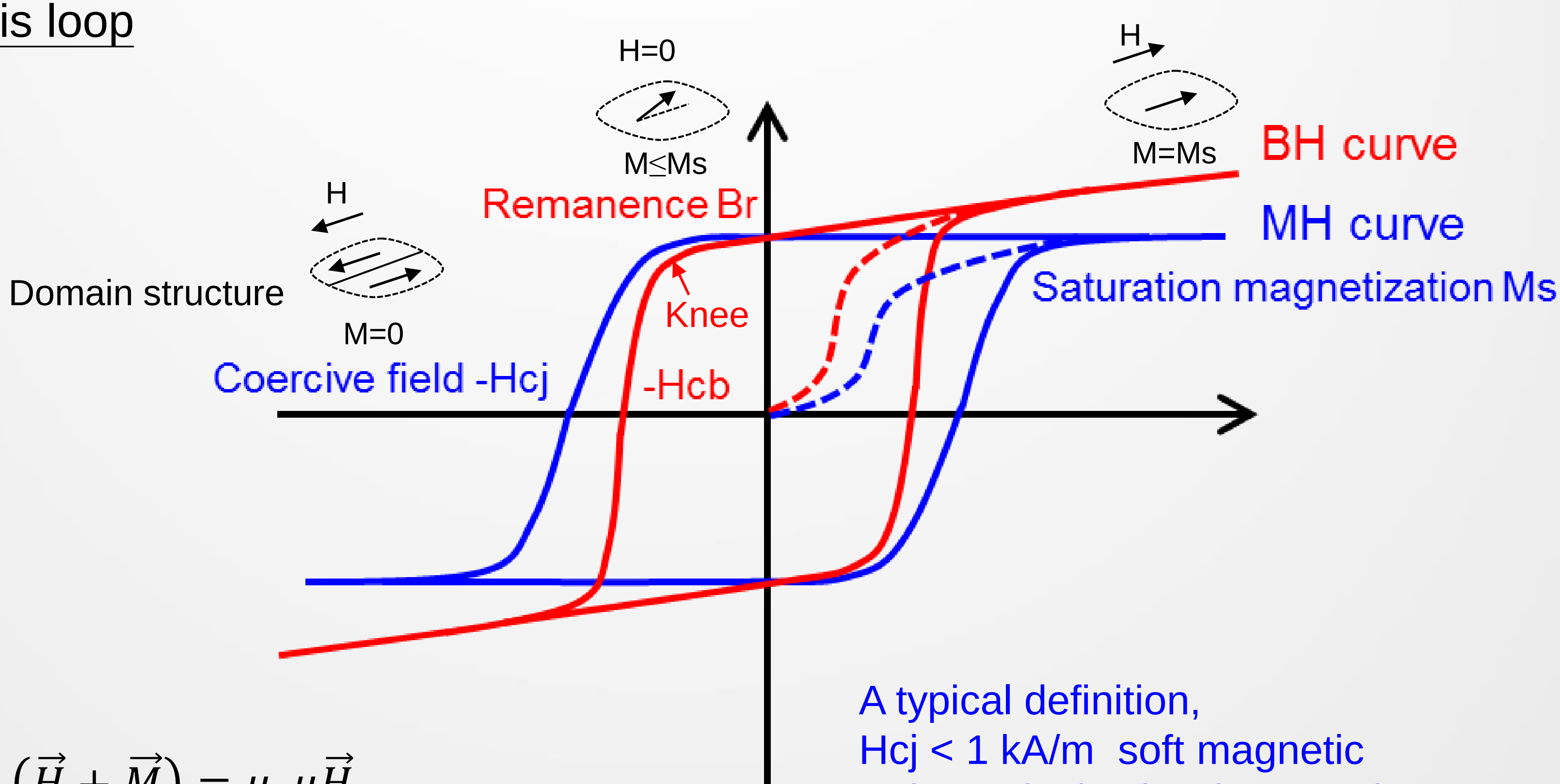
Material	*Tc* (° C)	Material	*Tc* (° C)
Iron (Fe)	770	$Nd_2Fe_{14}B$	310
Cobalt (Co)	1125	$SmCo_5$, Sm_2Co17	700-800
Nickel (Ni)	360	AlNiCo	850
Gadolinium (Gd)	19	Permalloy	360-500
Terbium (Tb)	-54	Vanadium Permendur $Co_{49}Fe_{49}V_2$	950
Dysprosium (Dy)	-188	SiFe	500-750

Ferromagnetism characteristics

Hysteresis loop



MOKE image



$$\vec{B} = \mu_0(\vec{H} + \vec{M}) = \mu_0 \mu \vec{H}$$

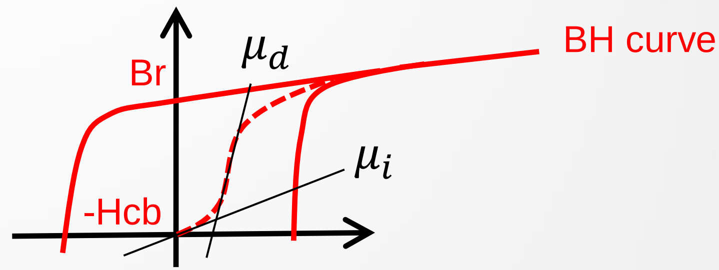
Flux density *B*, 1 T=1 Vs/m^2
Field strength *H*, A/m
Magnetization *M*, A/m
Permeability in free space $\mu_0 = 4\pi \cdot 10^{-7}$ Vs/Am(=H/m)
Relative permeability μ,
In air $\mu \approx 1$, *H* : 1 A/m = 1.25 μT : *B*

A typical definition,
Hcj < 1 kA/m soft magnetic
Hcj > 10 kA/m hard magnetic
(permanent magnets)
location of the knee of *B*:
- 2nd quadrant for soft magnetic
- 3rd quadrant for permanent magnets

Permeability

Permeability

- The ratio of *B* to *H.*
- Function of *H* and hence different terms in whole region.
- One of two important terms for the soft magnetic application, the other is *Ms*



μ_i initial permeability
μ_d differential or maximum permeability

- Hard magnetic :
  NdFeB, $\mu_{\parallel} = 1.04, \;\; \mu_{\perp} = 1.17$

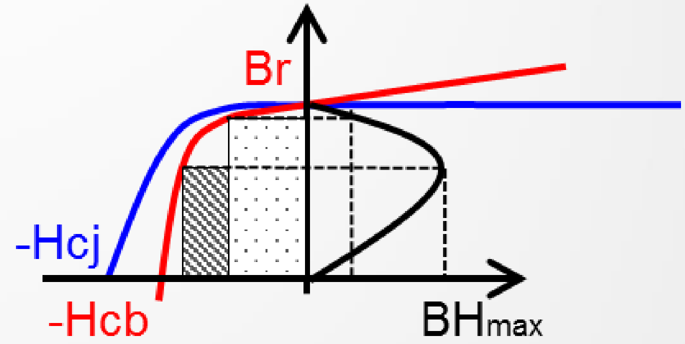
- Soft magnetic :

Name	Approximate composition (weight percent) Ni	Fe	Other	Initial permeability	Maximum perme-ability	Coercivity H_c (Oe)	B_s (gauss)	T_c (°C)	Resistivity (microhm-cm)
				Low-Cost Alloys					
Iron	–	100	–	150	5,000	1.0	21,500	770	10
Silicon iron	–	96	4 Si	500	7,000	0.5	19,700	690	60
Grain-oriented silicon iron	–	97	3 Si	1,500	40,000	0.1	20,000	740	47
				High-Permeability Alloys					
78 Permalloy	78	22	–	8,000	100,000	0.05	10,800	580	16
Hipernik	50	50	–	4.000	70,000	0.05	16,000	500	45
4-79 Permalloy	79	17	4 Mo	20,000	100,000	0.05	8,700	460	55
Mumetal	77	16	5 Cu, 2 Cr	20,000	100,000	0.05	6,500		62
Supermalloy	79	16	5 Mo	100,000	1,000,000	0.002	7,900	400	60
				High-Saturation Alloys					
Permendur	–	50	50 Co	800	5,000	2.0	24,500	980	7
2V-Permendur	–	49	49 Co, 2 V	800	4,000	2.0	24,500	980	27
Hiperco	–	64	35 Co, 0.5 Cr	650	10,000	1.0	24,200	970	28
Supermendur	–	49	49 Co, 2 V		60,000	0.2	24,000	980	27

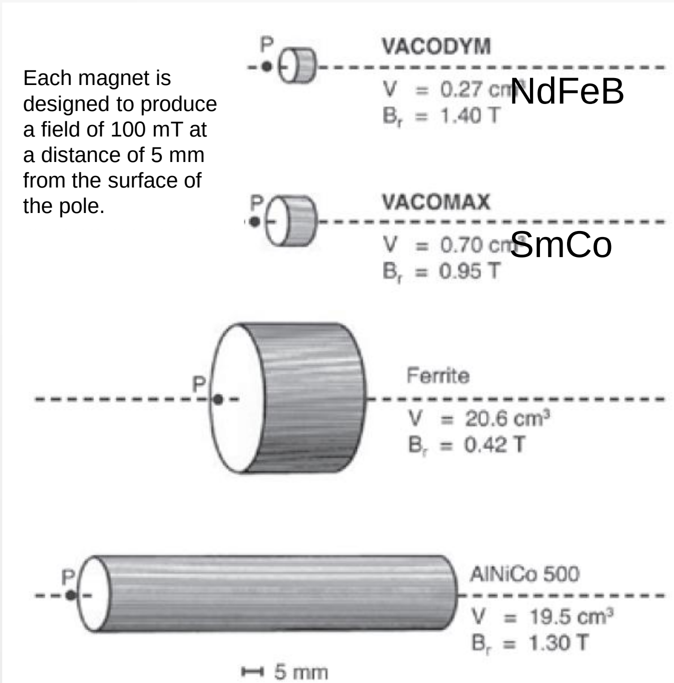
Energy product

Energy product

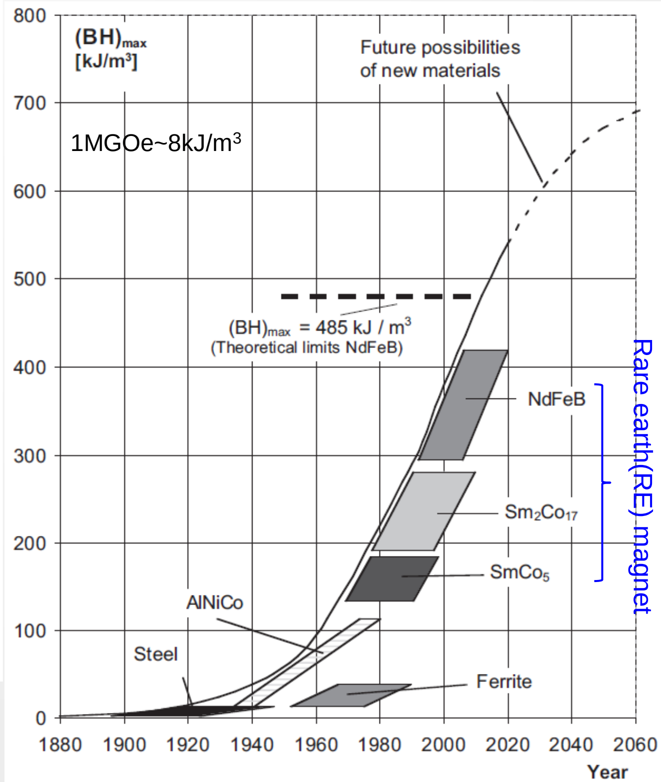
- Energy density and a volume independent magnetic characteristic.
- The largest rectangle under the BH curve.
- The main characteristic for a hard material (permanent magnet).



- ✓ Application generally in air.
- ✓ Higher energy product allows for a reduction in the magnet volume.
- ✓ Working at BH_{max}, the highest efficiency, the highest Induction level at the smallest volume, but not the highest field, larger volumes of the magnet will produce larger magnetic fields.



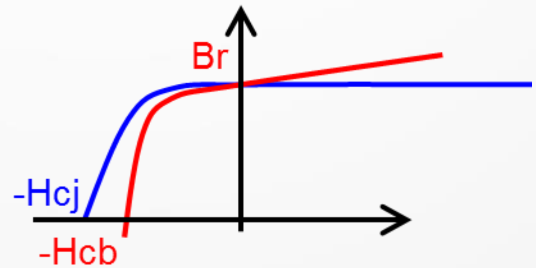
Vacuumschmelze GmbH & Co. KG

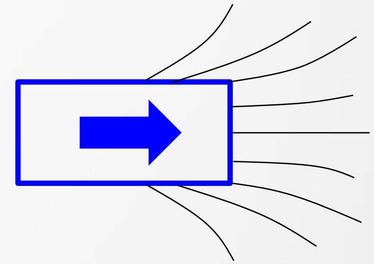


Hard magnetic material

Magnet type I
- Hcj < Br
- μ>>1

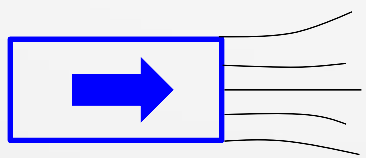
e.g. Alnico
=> High leakage flux, much energy stored in leakage field, not usable.

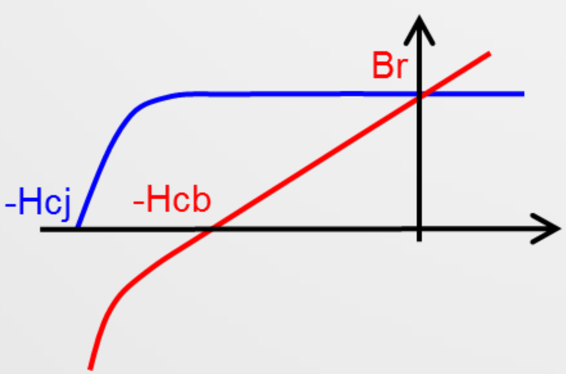


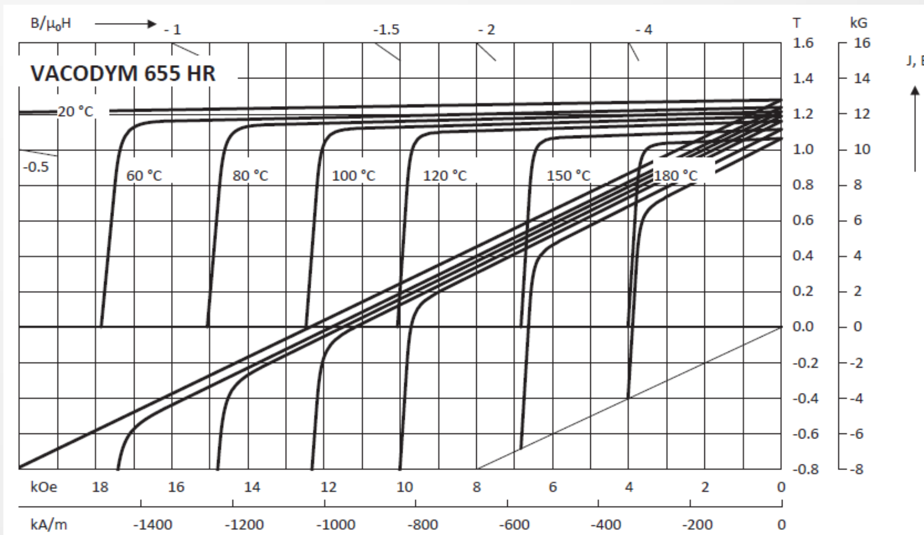


Magnet type II
- Hcj > Br
- μ~1

e.g. RE-magnet
=> Low leakage flux.







Vacuumschmelze, Data leaflet

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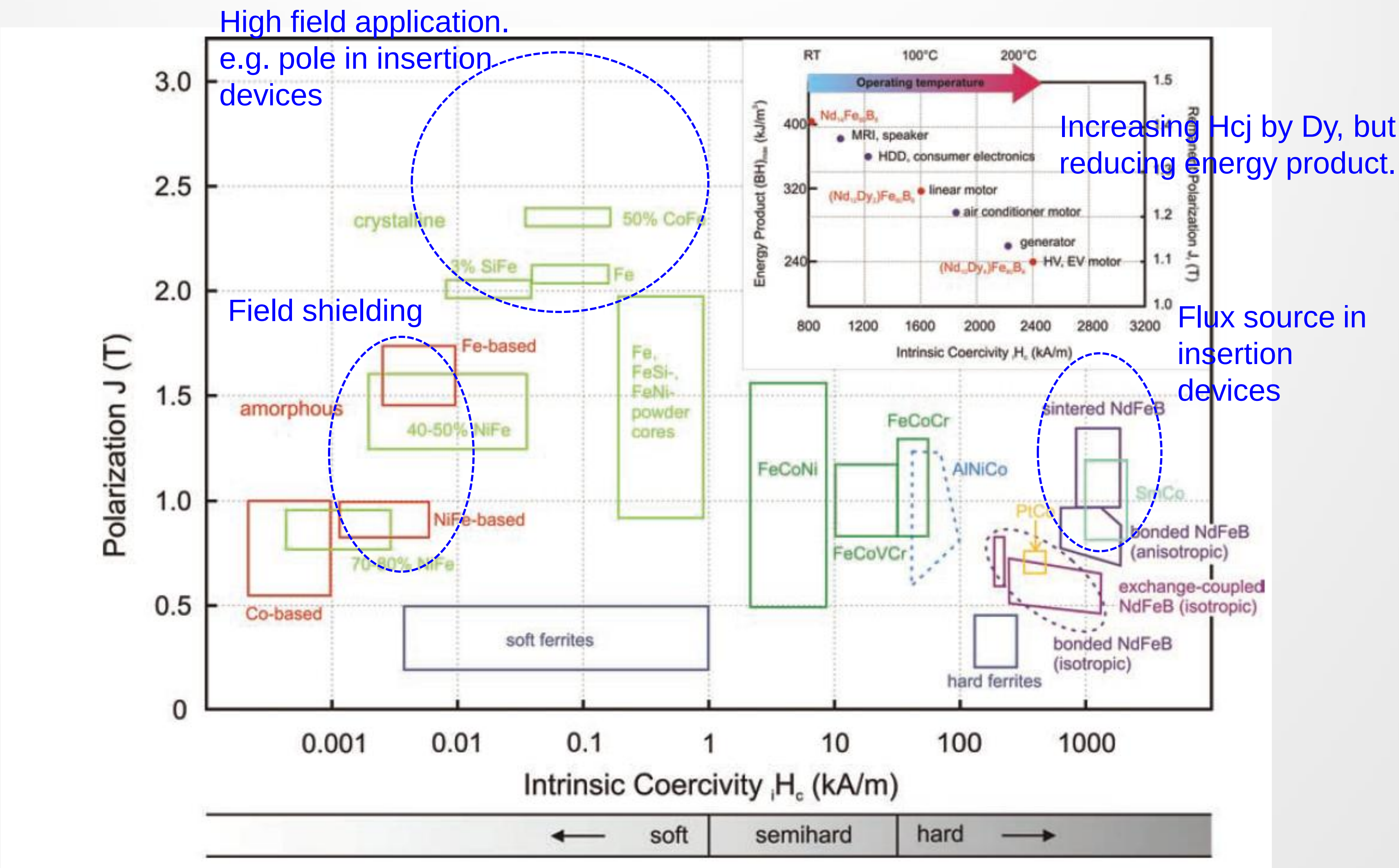
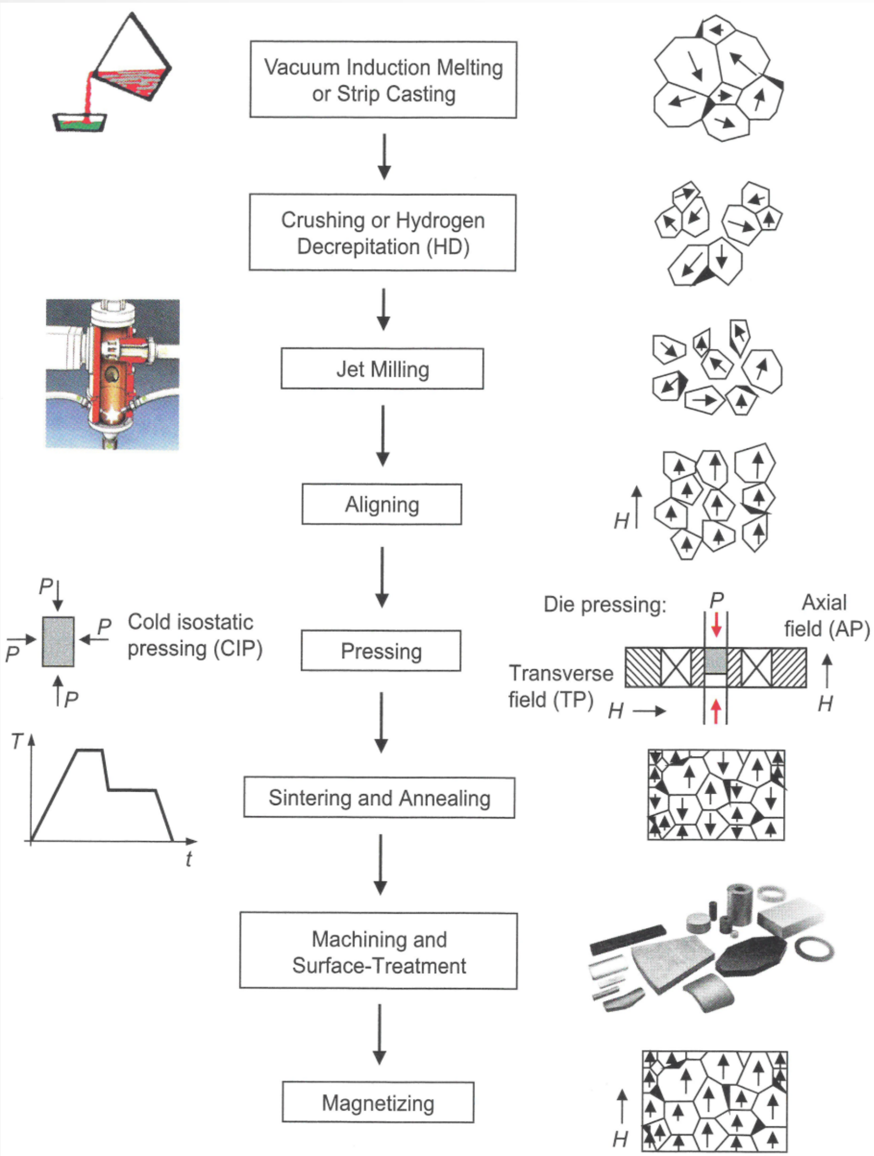
Magnetic material_Summary



Oliver Gutfleisch at.al., Adv. Mater. 23, 821 (2011).

Sintered NdFeB



Courtesy of Vacuumschmelze

- The Hcj increases with smaller grain size
- Die pressing process:

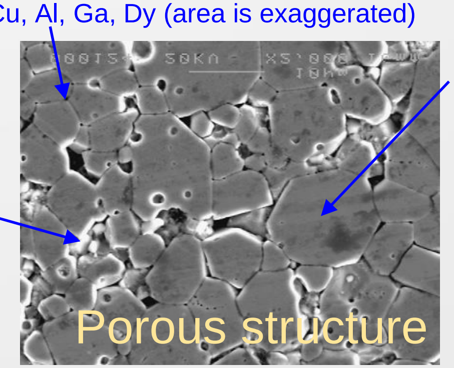
Br : isostatic > transverse > axial

Dipole errors: isostatic > transverse, axial

- Hydrogen decrepitation(燃燒) destroys magnetic material.

Nd+H_2O>>NdOH+H, H+Nd>>NdH

appropriate chemical additions between grains and coating on the surface avoid Hydrogen decrepitation.



Part III : Technology and conventional insertion devices

ID design_Halbach type

Sinusoidal along z.

$$\tilde{B} = B_y + iB_z$$

$$= 2B_r \sum_{n=1,p+1,2p+1\ldots} \sin\left(2n\pi\frac{z+iy}{\lambda_0}\right)\cdot\exp\left(-n\pi\frac{g}{\lambda_0}\right)\cdot\frac{\sin[(n\pi/p)-(n\pi\delta/\lambda_0)]}{(n\pi/p)}\cdot\left[1-\exp\left(-2\pi n\frac{t}{\lambda_0}\right)\right]$$

Field decreasing with increasing gap and decreasing period

Harmonic field effect

Block size effect

Derived by K. Halbach

t : thickness of block

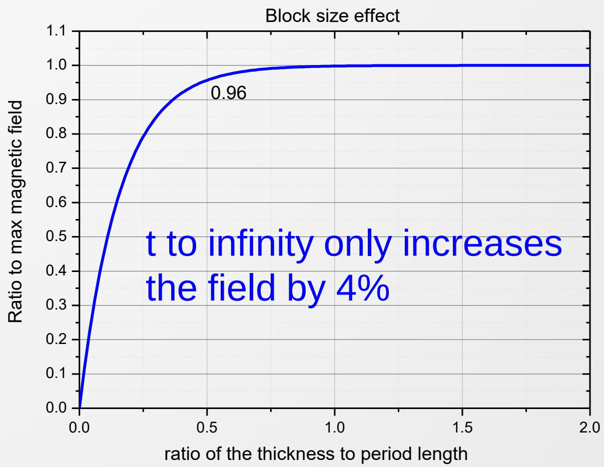
δ : the air gap between block

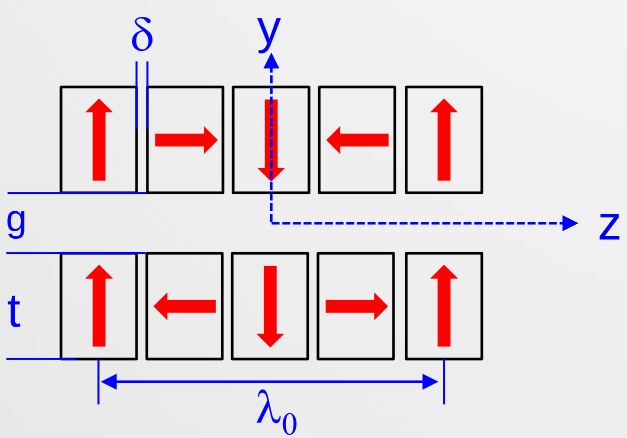
g : gap

λ_0 : period length

p : blocks per period

If $\delta=0$, sinc function, high harmonic decreasing.
Larger p, the less harmonics in the field.





p = 4,
The field only contains harmonics n = 1,5,9…. but dominated by the fundamental harmonic (n=1).

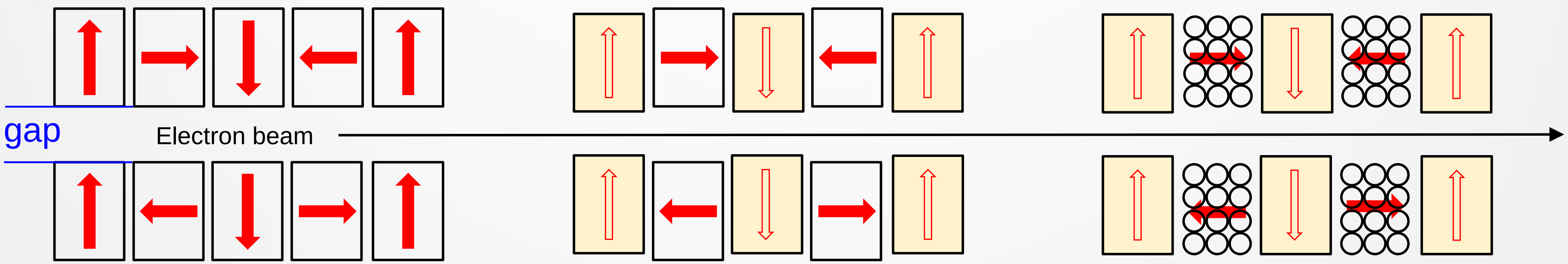
If $t > \lambda_0/2 \Rightarrow \left[1-\exp\left(-2\pi n\frac{t}{\lambda_0}\right)\right] \sim 1 \Rightarrow b_1 = 0.9, b_5 = -0.18.$

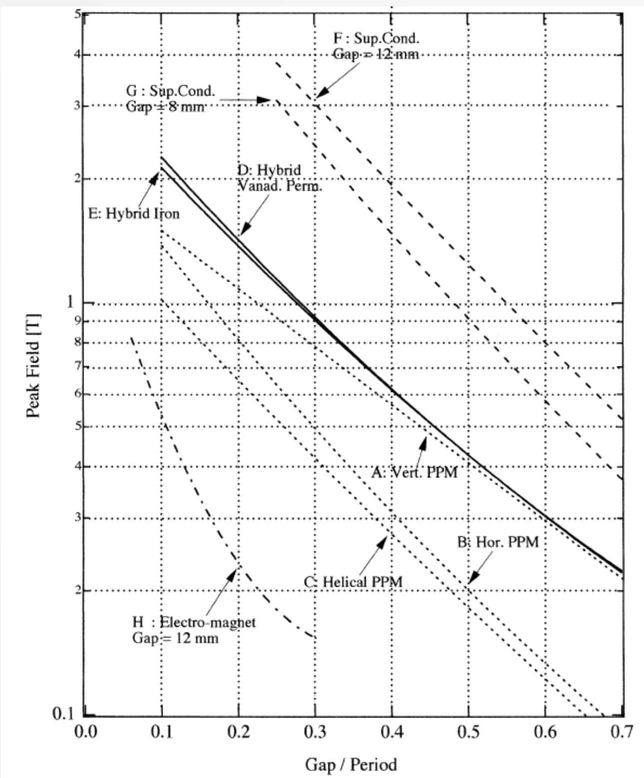
$\Rightarrow$ n=1 dominates

$$B_y(z,0) = 1.8\cdot B_r\cdot\exp\left(-\pi\frac{g}{\lambda_0}\right)\cdot\sin\left(2\pi\frac{z}{\lambda_0}\right)$$

Various technologies

Pure permanent magnet (PPM) | Hybrid, magnet + Iron | Electro-magnet (EM), wire + Iron





$$B_{peak} \approx \mathrm{a} \cdot \exp[\mathrm{b} \cdot \frac{g}{\lambda_0} + \mathrm{c} \cdot (\frac{g}{\lambda_0})^2]$$

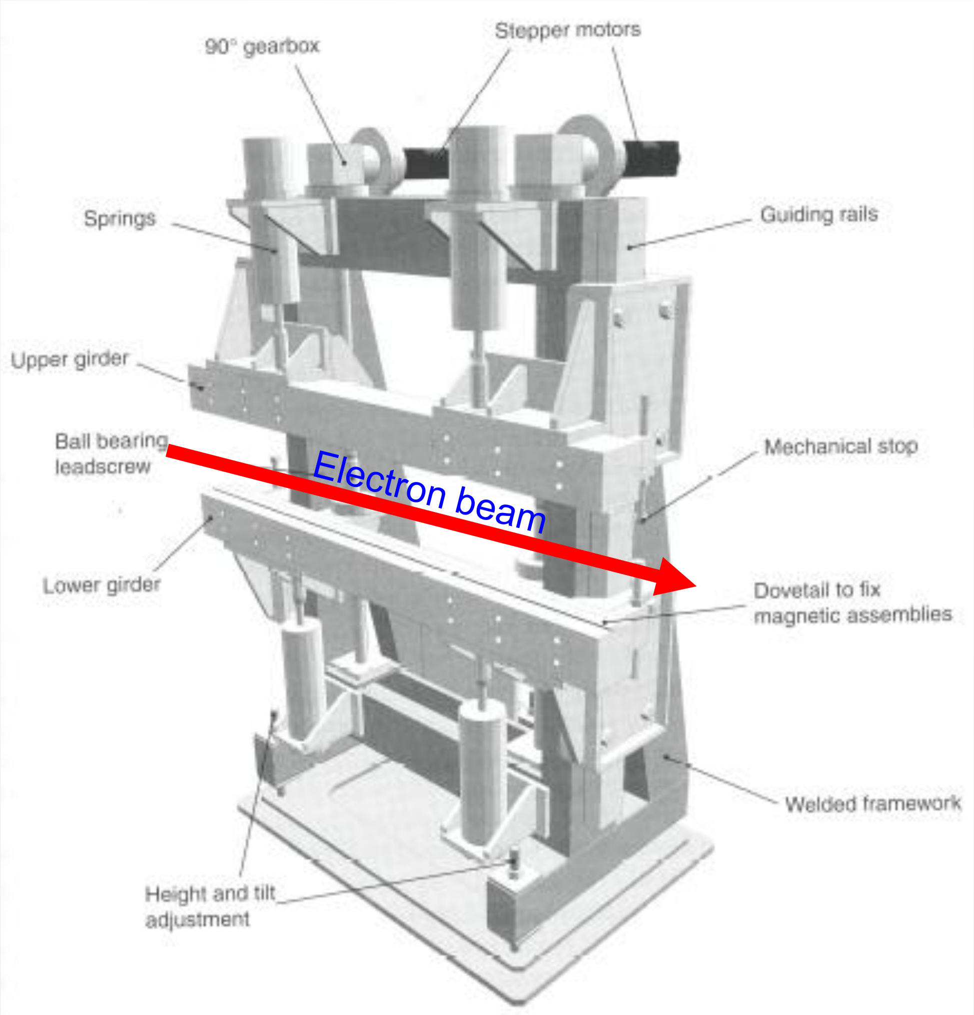
	a	b	c
PPM	2.1	-3.2	0
Hybrid	3.7	-5.1	1.52
EM	1.8	-14.3	20.3

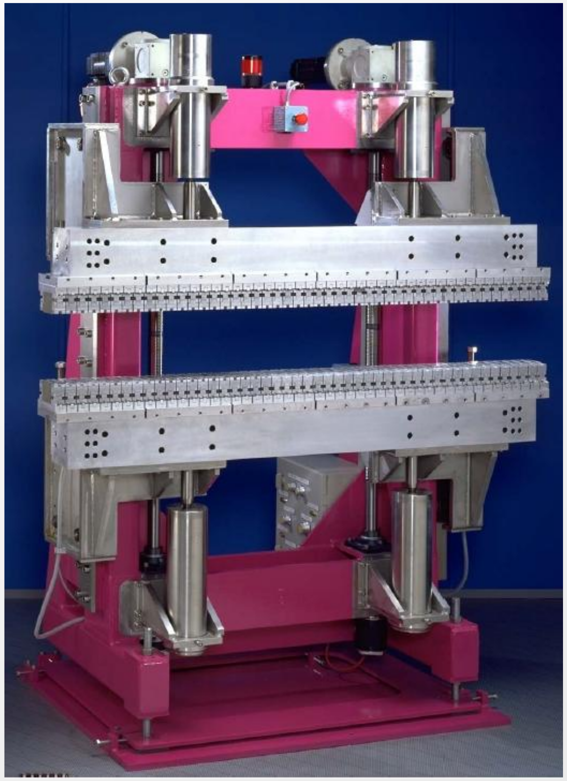
Derived by P. Elleaume

The performance of
the Hybrid type is enhanced by the cryogenic technology;
the EM type by the superconducting technology.

Typical structure

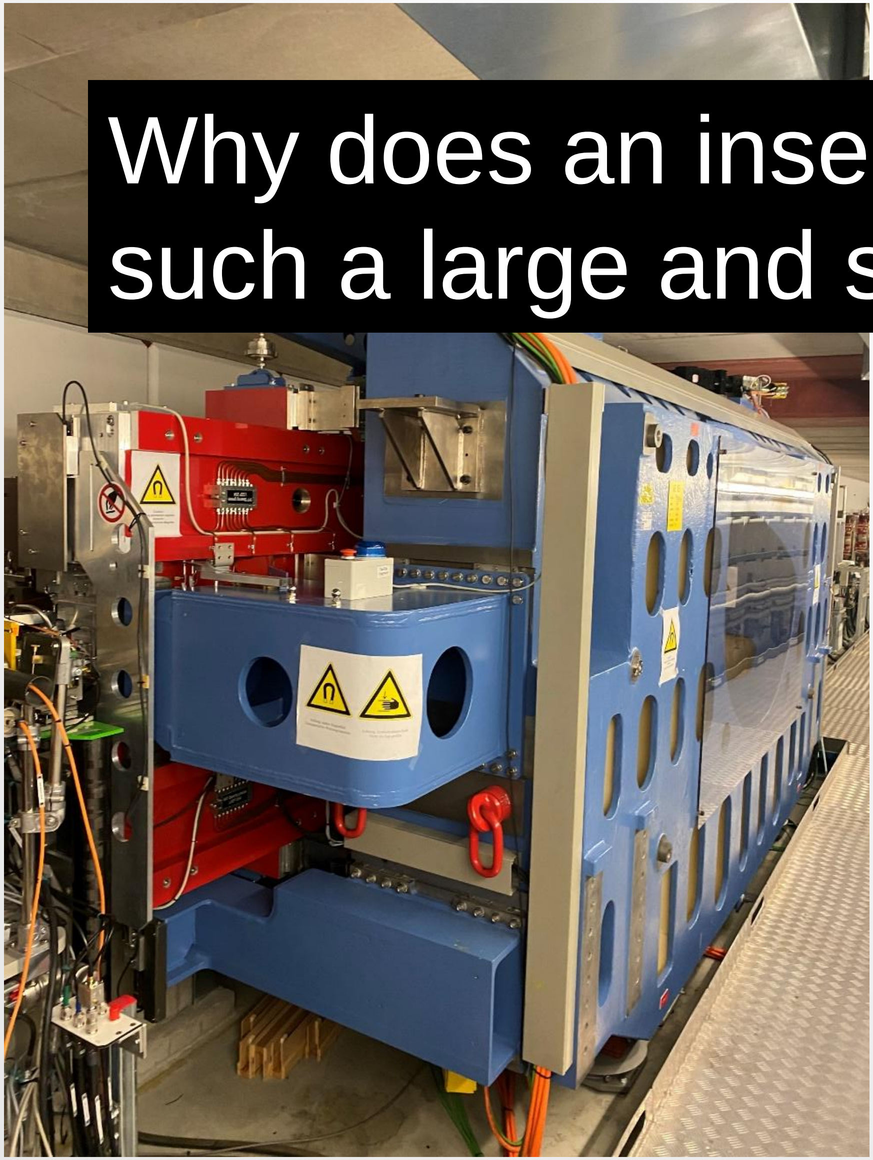
The ESRF standard support structure

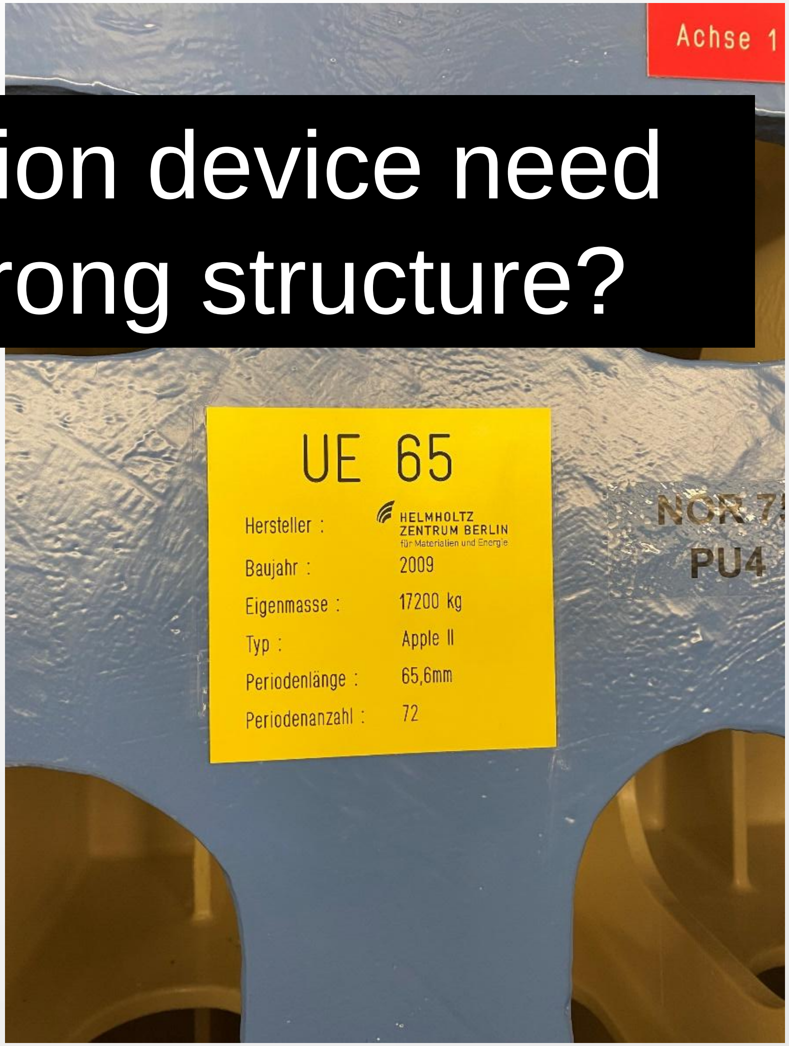




Courtesy of J Chavanne. ESRF

Why does an insertion device need such a large and strong structure?





Magnetic force

Starting from the Lorentz force law and substituting by Gauss's law and Ampère's circuital law.

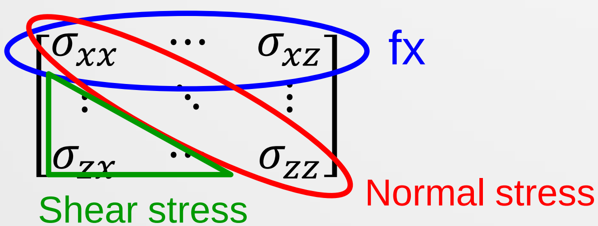
$$\Longrightarrow \qquad \vec{f} + \epsilon_0 \mu_0 \frac{\partial \vec{s}}{\partial t} = \vec{\nabla} \cdot \sigma$$

f : the force per unit volume
s: Poynting vector
σ : stress tensor

In the magnetostatic condition,

$$\Longrightarrow \qquad \vec{f} = \vec{\nabla} \cdot \sigma, \qquad \sigma_{ij} = \frac{1}{\mu_0} B_i B_j - \frac{1}{2} \left(\frac{1}{\mu_0} B^2 \right) \delta_{ij}$$

B : magnetic field



Force on the median plane(electron oscillation plane)

$$\Longrightarrow F_{x,y,z} = \int \sigma_{(x,y,z)y} w dz$$

w : the width of magnet block

$$\Longrightarrow F_y = \frac{w}{2\mu_0} \int_0^L \left(\mathrm{B}_y^2 - B_z^2 \right) dz$$

$$\Longrightarrow F_y = \frac{w B_o^2 L}{4\mu_0}$$

$B_z = 0, B_y = B_0 \sin(2\pi \frac{z}{\lambda})$,
L : the length of ID

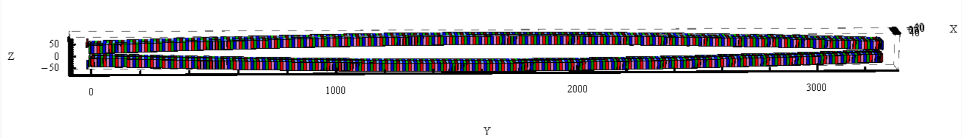
For a sinusoidal field with peak field B_0, force between upper and lower girders.

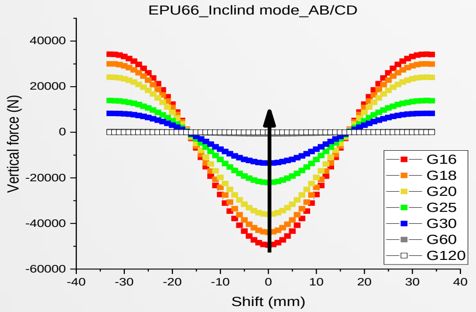
	B	W	L	F
	[T]	[mm]	[m]	[kN]
Undulator	0.8	40	1.6	8.1
Wiggler	1.5	120	1.6	85.9

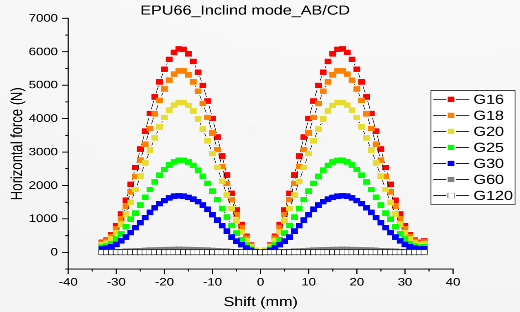
Construction challenges

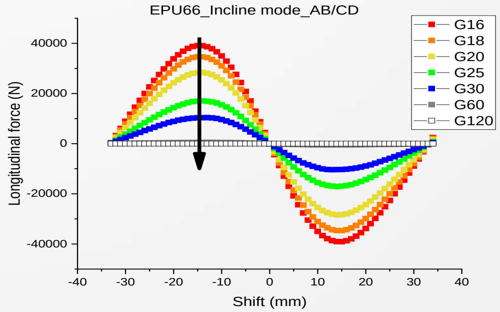
EPU suffers three dimensions of attractive or repulsive forces.

⇒ In addition to mechanical lifetime, mechanical deformation causes systematic errors in the magnetic field.

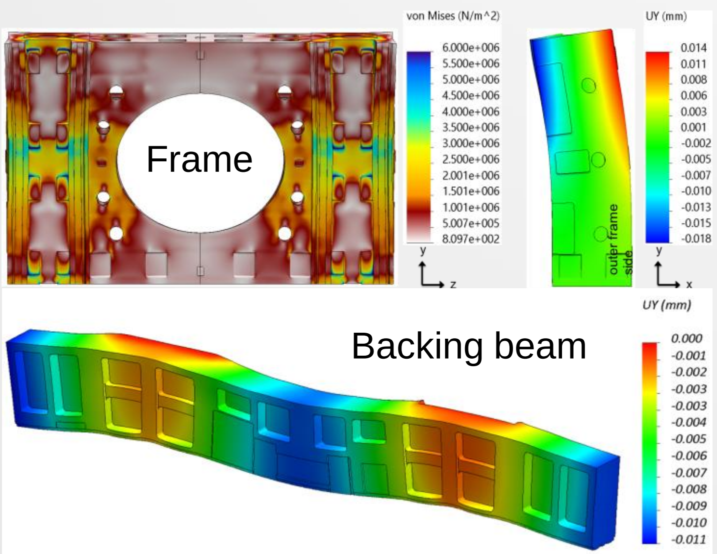


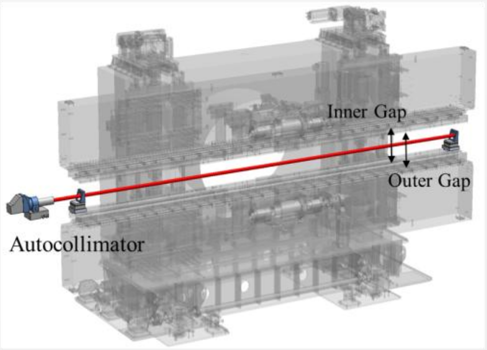


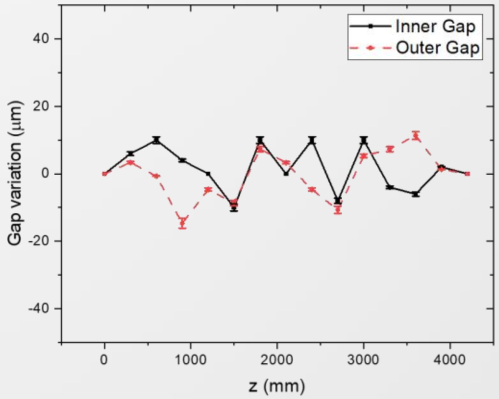




Maximum magnetic force exceeds 5 tons in TPS EPU.







- Optimize mechanical structure: dimensions, supporting points, material..etc.
- Gap variation < 20µm.

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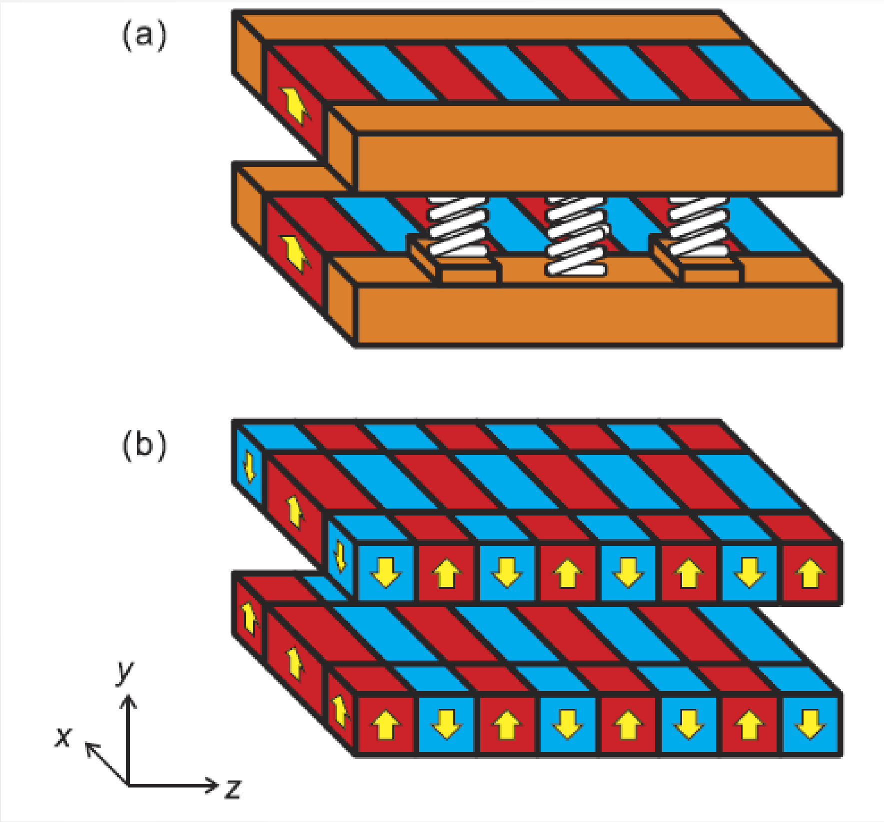
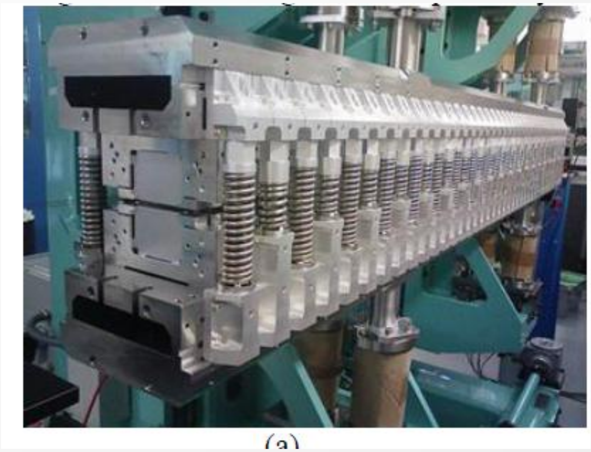
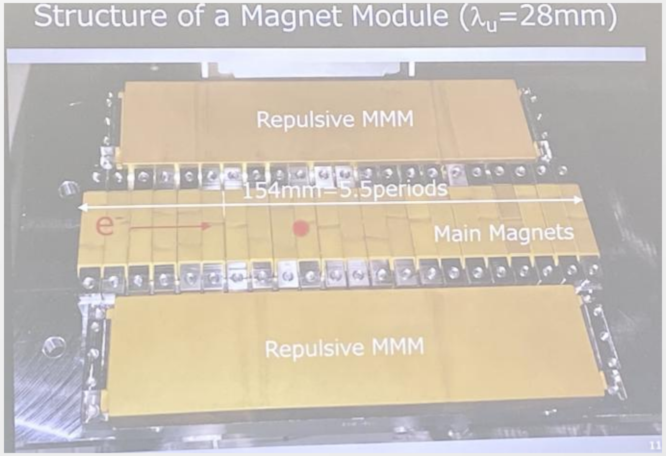




Soleil



Spring8

End pole design

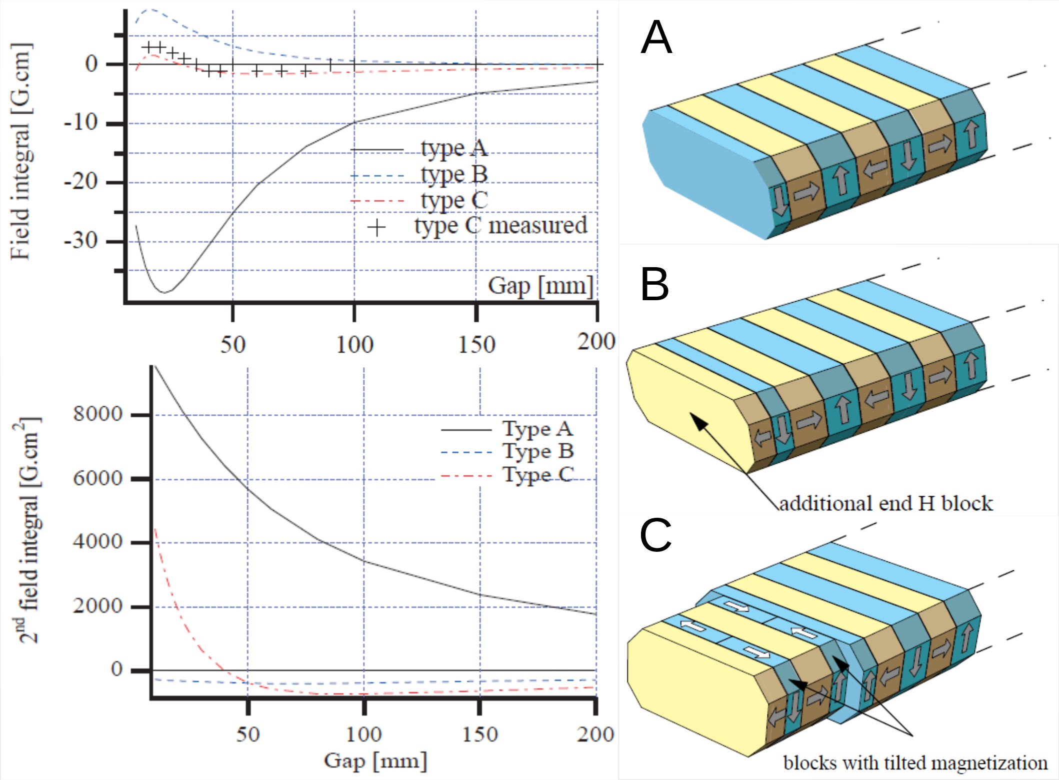
An ideal ID no perturbs the closed orbit and the dynamics of the electron beam in a storage ring for any operation.

- No net kick => No net First field integral
- No net offset => No net Second field integral

The conditions are realized by an optimized end pole design.

For an antisymmetric field with respect to the center of an ID,

- Principally, the first field integral is intrinsic zero.
- A more sophisticated entrance and exit configuration to eliminate the second field integral.

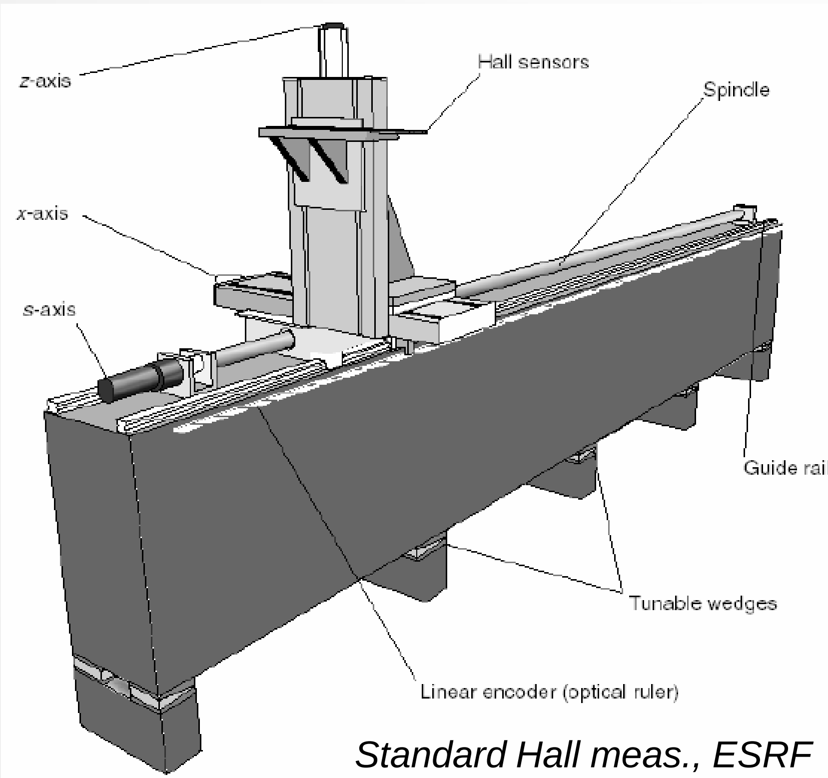


J. Chavanne, PAC(1999)

TingYi Chung 鍾廷翊, 2026, FEL

Typical magnetic field measurement system

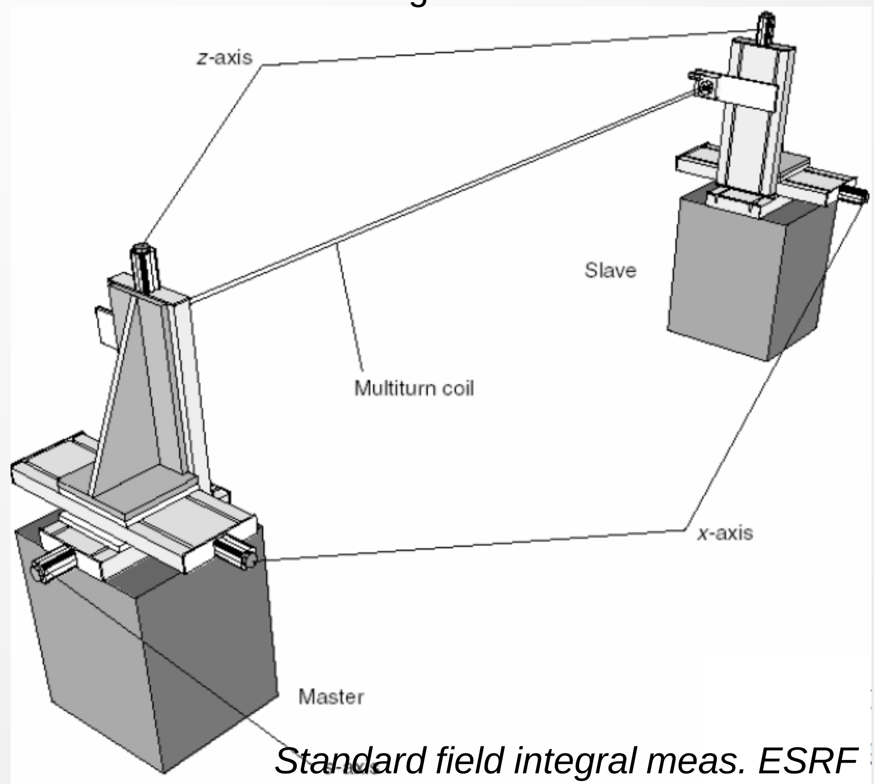
Local field measurement



Standard Hall meas., ESRF

- Hall probe sensor
- On-the-fly scanning
- Laser Encoder
- Essential for phase shimming

Field integral measurement

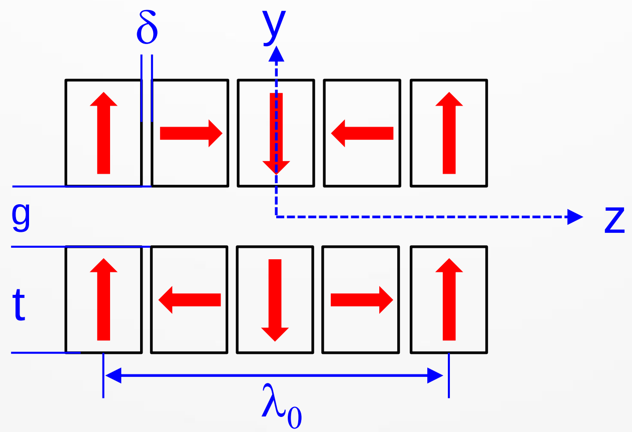


Standard field integral meas. ESRF

- Rotating multiturn coil or Moving stretched wire
- Horizontal and Vertical first and second field integrals
- Essential for multipole shimming

EPU48 at Hall probe and field integral measurement benches, 2015, TPS

Magnetic field error



有誤差才是正常的。
不完美才是真實的。

Error sources:

- Non uniform magnetization of the magnet blocks (poles).
- Dimensional and Positional errors of the poles and magnet blocks.
- Interaction with environmental magnetic field.

Influences:

- Disturbing the electron dynamics in the storage ring => multipole error
- Reduction in the SR intensity. => phase error

Solution:

- High quality blocks. Requiring small variation in, for example dipole error, magnetic flux density of north/south side and mechanical dimensions…
- Efficient sorting and shimming algorithms, which are more important for a mass production of IDs for FEL.

Phase error

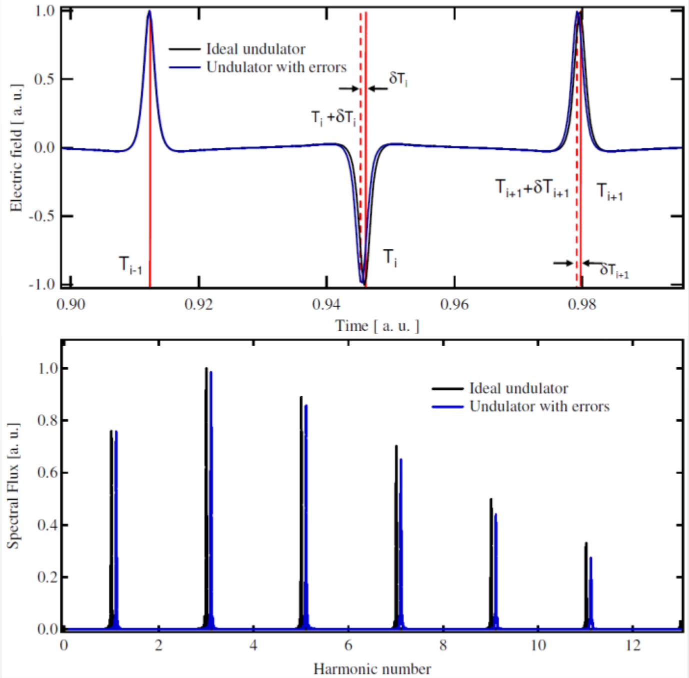
- An ideal ID, 2N peaks of the electric field with equally space of T_i go to the observer.

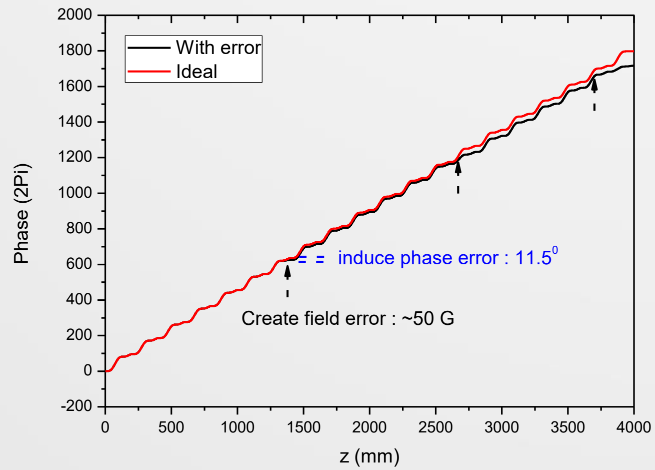
$\overset{F.T.}{\Longrightarrow}$ Numerous harmonics.

- Magnetic field error shift T_i .

$\overset{F.T.}{\Longrightarrow}$ Change the fundamental frequency and introduce destructive interference.

- Calculating the phase ϕ_i, the slippage of one optical wavelength between the electron and the light.
- Magnetic field error => change the longitudinal velocity of an electron => create phase error $\delta\phi_i$





For randomly distributed $\delta\phi_i$, the reduction of flux and brilliance on the spectrum harmonic is given by

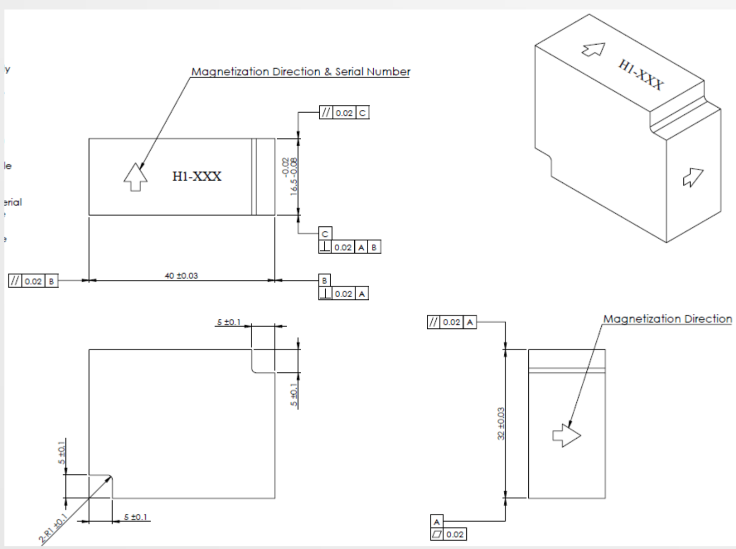
$$I_n(\sigma) = I_n(0)\exp(-n^2\sigma^2)$$

σ : r.m.s. phase error

需求規格

Table 1. Overview of magnets for EPUT66.

Item	Magnet type	Number of Blocks
1	H1	350
2	V1	350
3	H2	350
4	V2	350
5	H1E1	20
6	H1E2	20
7	H2E1	20
8	H2E2	20
9	V1E	20
10	V2E	20
11	MF-CY	4200



實際數據

Magnet Type	H1 for BEAMLINE33 (BL33) – EPUT66				
Number of Blocks	350				
Parameter	Specification	Minimum	Average	Maximum	Accept
ΔJr	±1 %	-0.37 %	1.2552 T	0.56 %	YES
Δα	±1 °	-0.3 °	0.1 °	0.4 °	YES
Δβ	±1 °	-0.3 °	0.1 °	0.5 °	YES
N/S	N/A	N/A	N/A	N/A	YES
Height	32.0 mm	31.976 mm	31.998 mm	32.010 mm	YES
Width	40.0 mm	39.976 mm	39.997 mm	40.013 mm	YES
Thickness	16.5 mm	16.422 mm	16.434 mm	16.440 mm	YES

Magnet Type	H2 for BEAMLINE33 (BL33) – EPUT66				
Number of Blocks	350				
Parameter	Specification	Minimum	Average	Maximum	Accept
ΔJr	±1 %	-0.37 %	1.2540 T	0.44 %	YES
Δα	±1 °	-0.5 °	-0.1 °	0.3 °	YES
Δβ	±1 °	-0.3 °	0.0 °	0.4 °	YES
N/S	N/A	N/A	N/A	N/A	YES
Height	32.0 mm	31.982 mm	31.997 mm	32.011 mm	YES
Width	40.0 mm	39.978 mm	39.999 mm	40.008 mm	YES
Thickness	16.5 mm	16.428 mm	16.434 mm	14.440 mm	YES

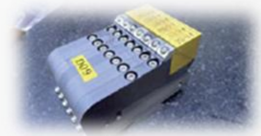
Magnet Type	V1 for BEAMLINE33 (BL33) – EPUT66				
Number of Blocks	350				
Parameter	Specification	Minimum	Average	Maximum	Accept
ΔJr	±1 %	-0.40 %	1.2550 T	0.42 %	YES
Δα	±1 °	-1.0 °	-0.1 °	1.0 °	YES
Δβ	±1 °	-0.2 °	0.2 °	0.4 °	YES
N/S	N/A	N/A	N/A	N/A	YES
Height	32.0 mm	31.978 mm	31.995 mm	32.020 mm	YES
Width	40.0 mm	39.982 mm	39.997 mm	40.016 mm	YES
Thickness	16.5 mm	16.432 mm	16.440 mm	16.447 mm	YES

Magnets Sorting

EPU is composed of more than 1000 “non-identical” magnets, with errors of magnetic moments.

⇒ To reduce random error, a strategy of magnet sorting and shimming process are developed in NSRRC.

⇒ To ensure good light’s quality.



The cost function consists of terms for multipole error and phase error, which means it takes into account the major influences on the electron beam and the spectrum.

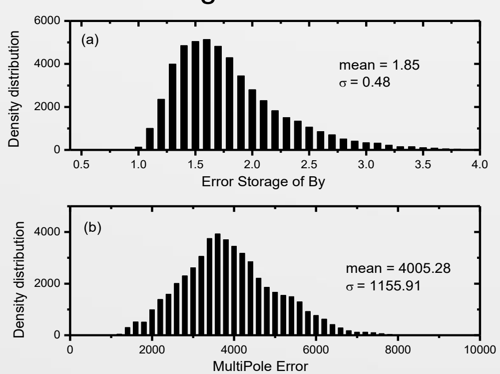
$$E = aMP + bESy + cESx + dFSy + eFSx$$

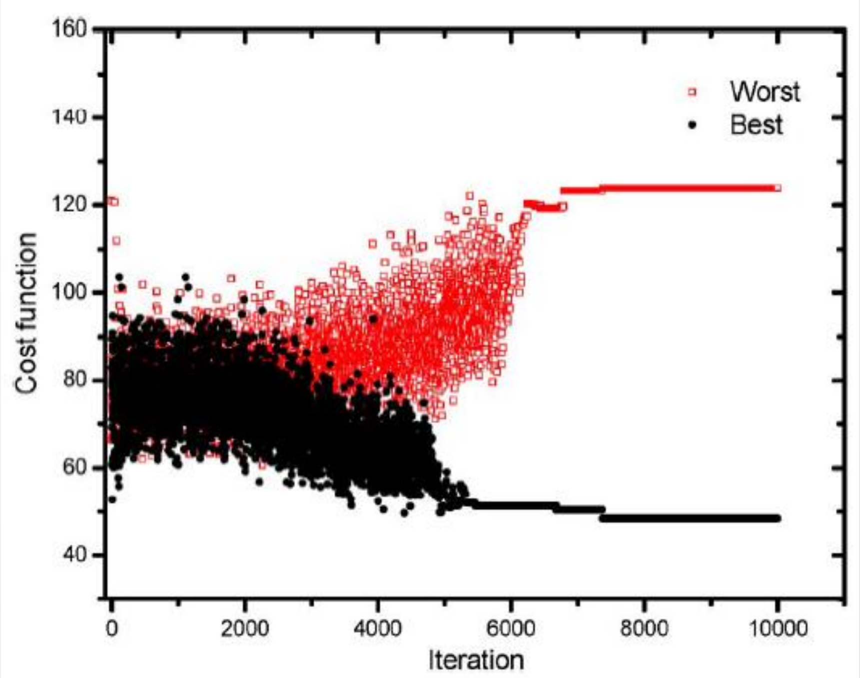
$$MP = \sum_{m=1}^{N} (SQ^2 + NQ^2)_m$$

$$FS = \sum_{m=1}^{n} \frac{I_n - (-1)^n < I >}{< I >}$$

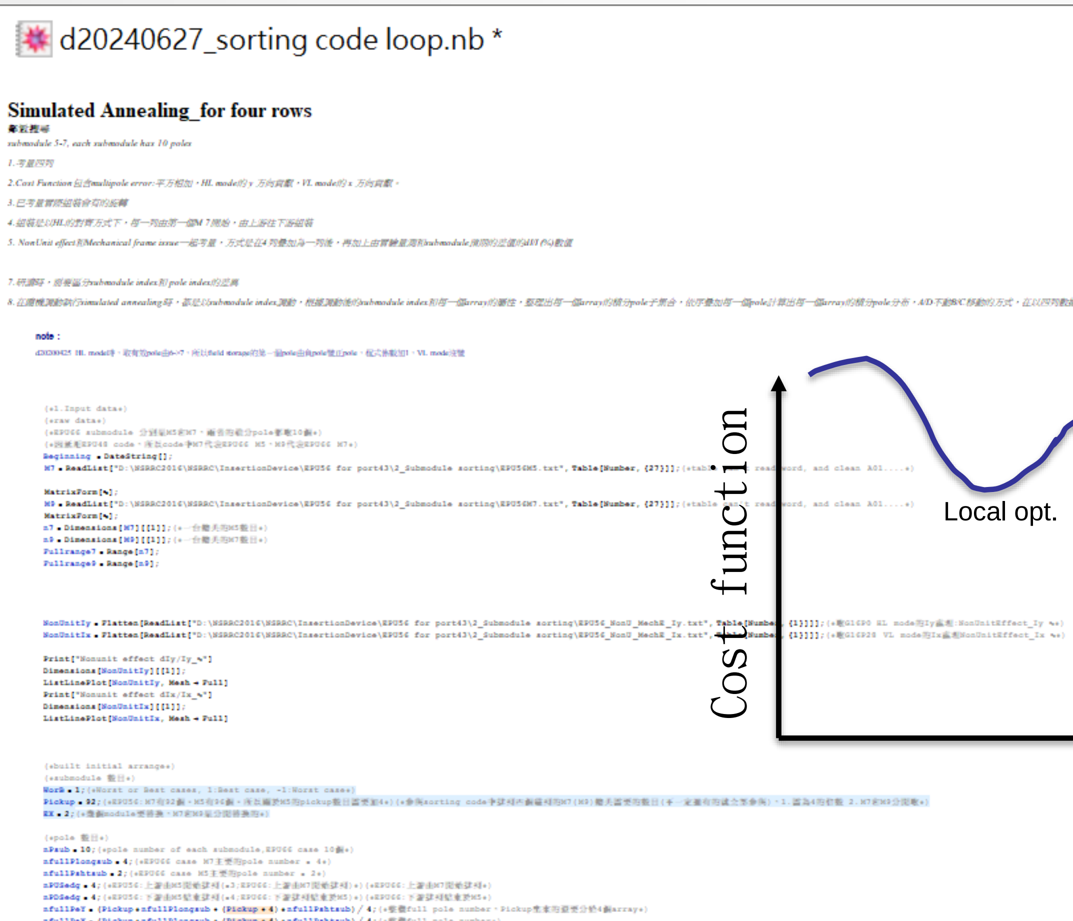
$$ES = \sum_{m=1}^{n} \left(\frac{|I_n| - < I >}{< I >} \right)_m$$

Weight factor

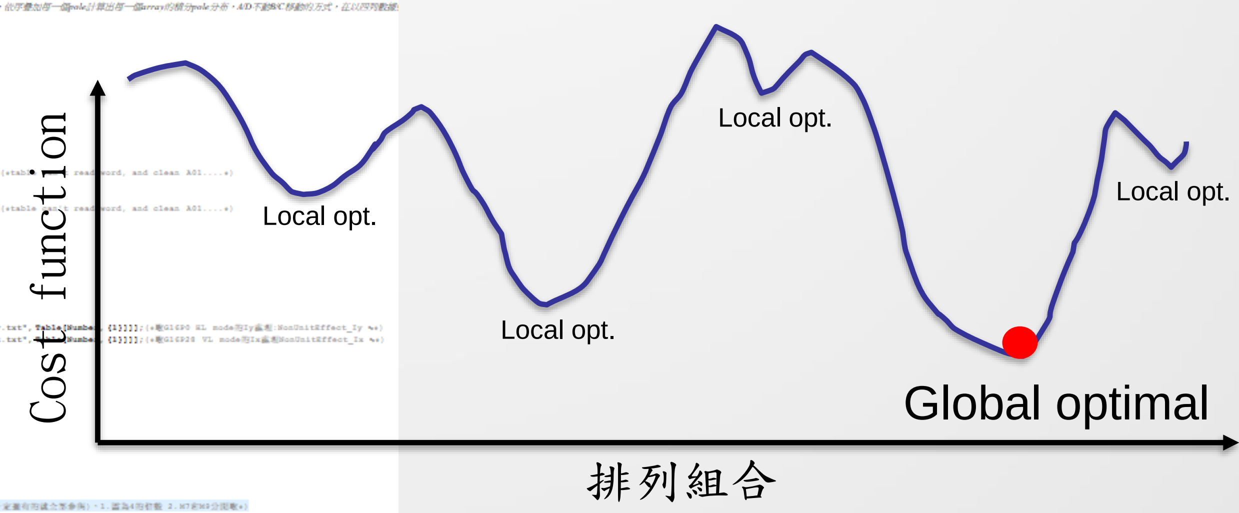




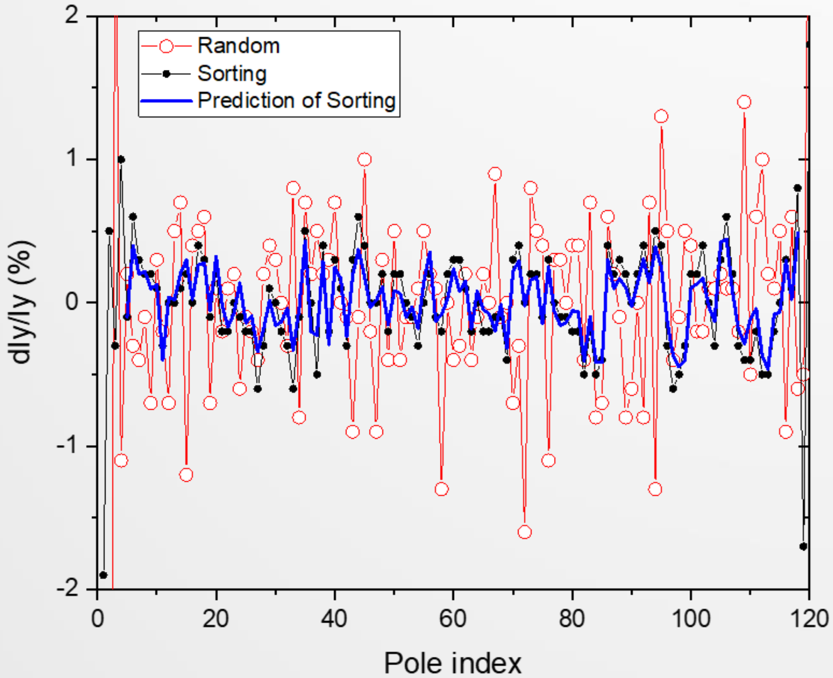
The optimization of the magnet sorting is based on simulated annealing [12]. This method is similar to a gradual cooling of liquids to form a crystalline state, as opposed to an amorphous state after a sudden cooling.



- 隨機方式:後半的最佳化沒效率，越難找到最佳解，即便是找local optimal。
- 局域尋找:很容易受限於初始條件，而只能找到鄰近的local opt.

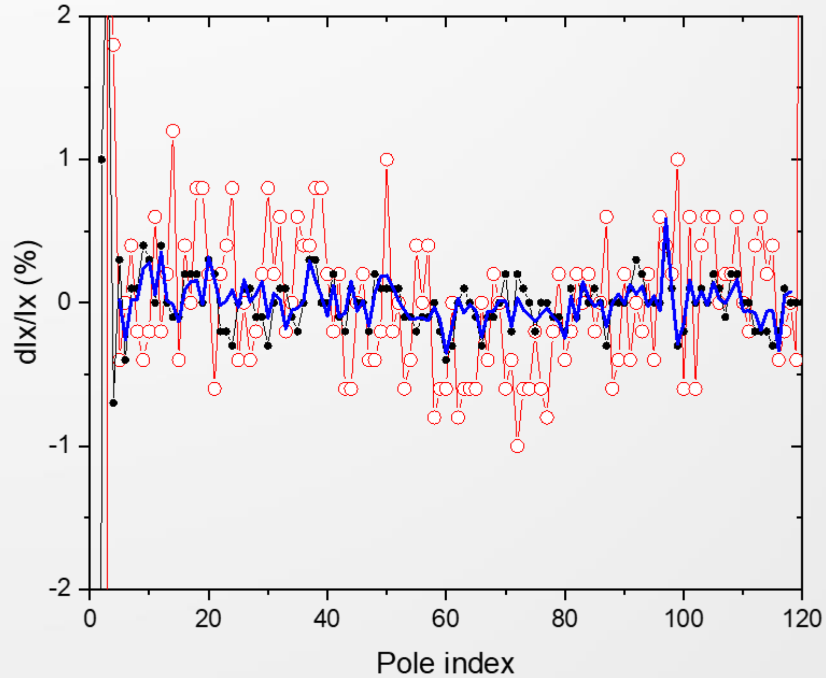


(a)



Random
Sorting
Prediction of Sorting
dIy/Iy (%)
2
1
0
-1
-2
0
20
40
60
80
100
120
Pole index

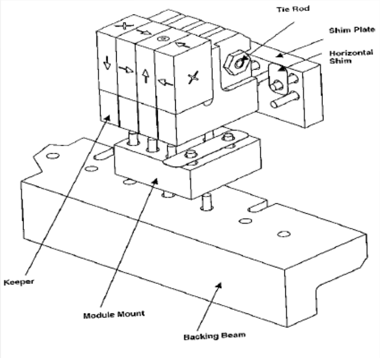
(b)



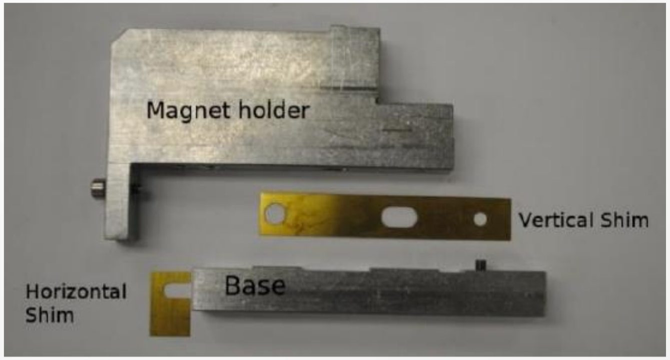
dIx/Ix (%)
2
1
0
-1
-2
0
20
40
60
80
100
120
Pole index

Field shimming

- Mechanical: Moving permanent magnet or iron pole vertically or horizontally.



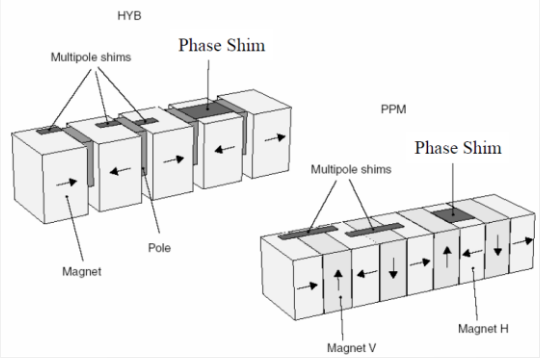
S.Mark, ALS (1998)



NSLSII,(2016)

- Magnetic: Add thin iron piece at the surface of the blocks.

LCLS, (2004)



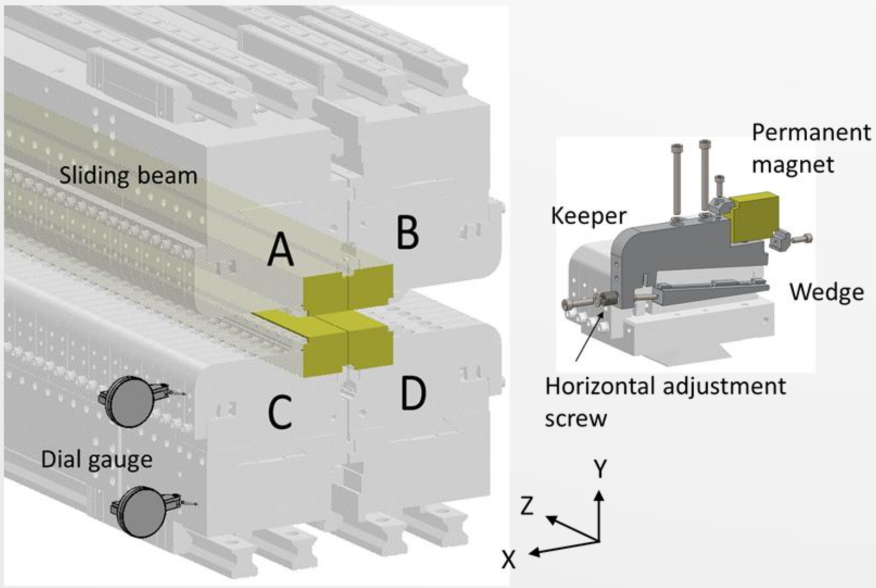
ESRF, standard Undulator

- Swapping/flipping blocks: Important to maintain the flat surface of a magnet array, especially in IVU.

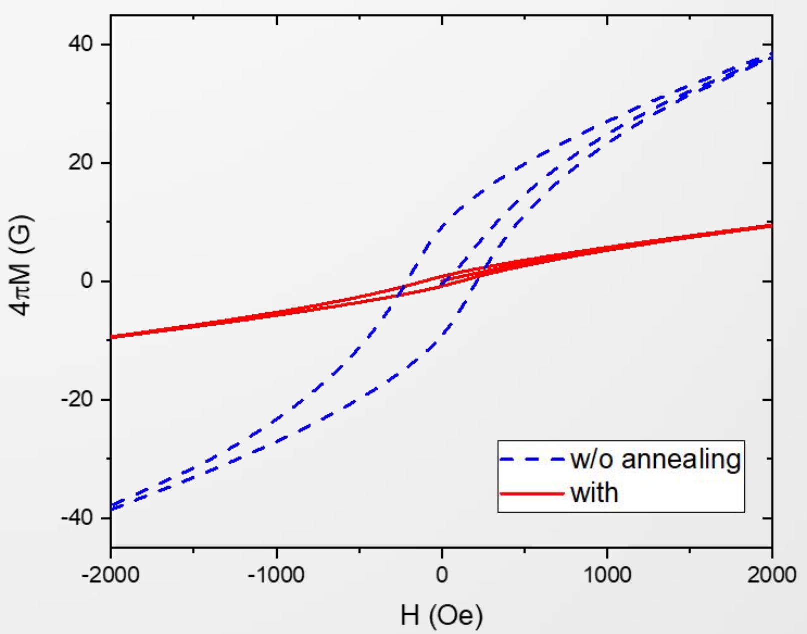
Field shimming

- Mechanical: Moving permanent magnet pole vertically or horizontally.

(a)

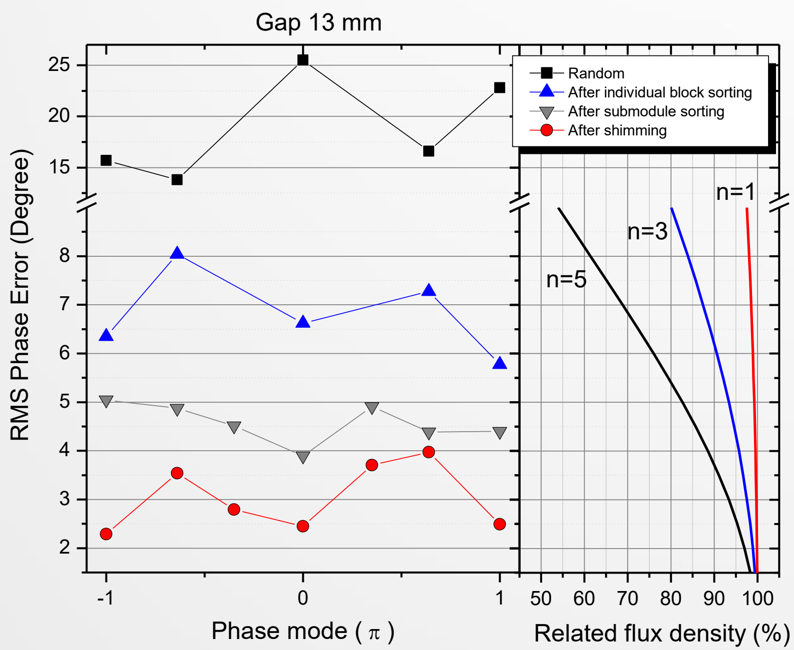


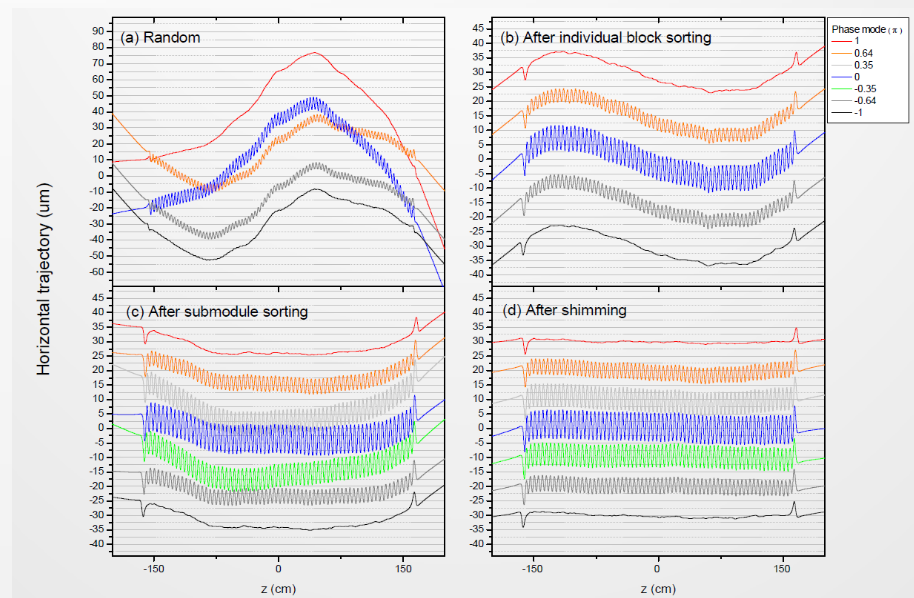
(b) Demagnetizing by annealing



BH curve measurement by VSM

Field performance of ID at NSRRC



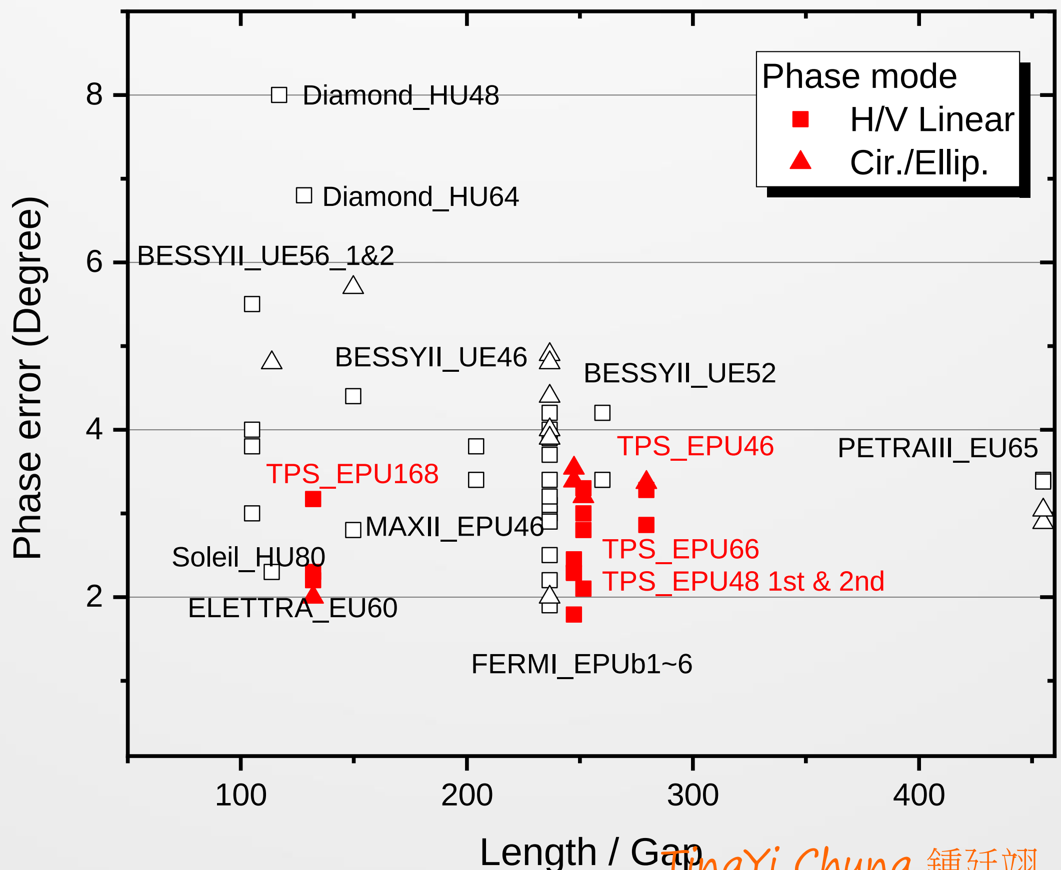


- Efficient sorting and shimming can significantly shorten the construction time.
- The flux density of high harmonics is greater than 95% of an ideal value.
- Straightness of trajectories satisfies the FEL requirement.

Field performance of ID at NSRRC

Position in EPU map:

- Constructing a longer and smaller gap of EPU is much difficult.
- Stiff mechanical structures and good quality magnets are essential.
- Mechanical arts and magnetic field treatments are equal important for a high performance EPU.



Trends in undulator for FEL and Storage ring

To reach the highest photon energy at a fixed electron energy
To increase the Brilliance for a compact device
⇒ the period should be made as short as possible.

$$\lambda_r = \frac{\lambda_u}{n2\gamma^2}(1 + \frac{K^2}{2} + \gamma^2\theta^2)$$

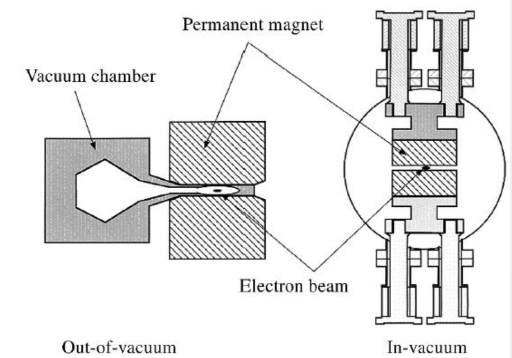
In general, we can't just have short period and accept very small K, because

- The tuning range is too small, a sufficient overlap between n=1 and 3, K ≥ 2.2.
- The FEL coupling too low (undulator length has to be very long to reach saturation), K ≥ 1 (this is just a guide, not physics)

How to shorten the period length, and keep the K value?
In other words, how to create a large magnetic field in a short period?

In-vacuum Undulator

- The minimum magnet gap, which is generally set by the vacuum chamber, limits the magnetic field of an ID.
- To put the undulator magnet inside the vacuum chamber.
- Simple idea, but a lot of difficulties should be overcome to realize the IVU.



H Kitamura, Spring-8

- IVU was developed beginning from KEK and matured by Spring-8.
- Up to date, required by many light sources.

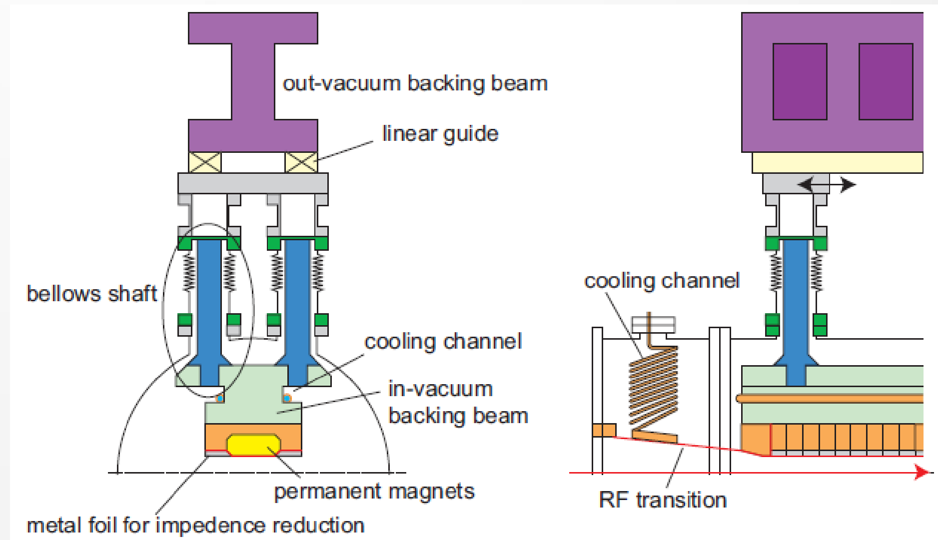
Year	Facility	Contents	Remarks
1990	KEK	λ_u = 40mm, $G_{\rm min}$=10mm, L = 3.6m	1st IVU that works regularly
1996	SPring-8	λ_u = 32mm, $G_{\rm min}$=7mm, L = 4.5m	1st IVU for SPring-8
1996	SPring-8 & ESRF	λ_u = 24mm, $G_{\rm min}$=5mm, L = 1.5m	Beam test of IVU at ESRF
1997	SPring-8	1st on-beam commissioning	4 IVUs have been installed from the beginning
1997~	SPring-8	IVUs with exotic PM configurations	Vertical, helical and figure-8
1997	SPring-8 & NSLS	λ_u=11mm, $G_{\rm min}$=2mm, L=0.3m	
1999~	SPring-8 & PLS	Demagnetization test of PM material	2GeV linac (PLS), 8GeV synchrotron (SPring-8)
2000	SPring-8	λ_u=32mm, $G_{\rm min}$=12mm, L=25m	IVU for the long straight section in SPring-8
2000	SPring-8 & SLS	λ_u=24mm, $G_{\rm min}$=5mm, L=1.5m	Same as that tested at ESRF(magnet refreshed)
2000	SPring-8	λ_u=6,15,20,24mm, L=1m	Revolver undulator (installed in PLS in 2003)
2001	ESRF	λ_u=17~23mm, $G_{\rm min}$=6mm, L=2m	Sm_2Co_{17} is employed (lower radiation damage)
2003	SPring-8	λ_u=15mm, $G_{\rm min}$=2mm, L=4.5m	for SCSS project
2003	KEK	λ_u=40mm, $G_{\rm min}$=10mm, L=3.6m	Tapered undulator
2003	SLS	λ_u=19mm, $G_{\rm min}$=5mm, L=1.9m	Assembled at SPring-8
2004	ALS	λ_u=30mm, $G_{\rm min}$=5mm, L=1.5m	Assembled at SPring-8
2006	SSRL	λ_u=22mm, $G_{\rm min}$=5mm, L=1.5m	Assembled at SPring-8

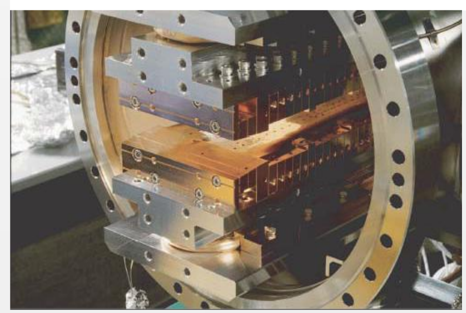
T. Tanaka et. al. FEL (2005)

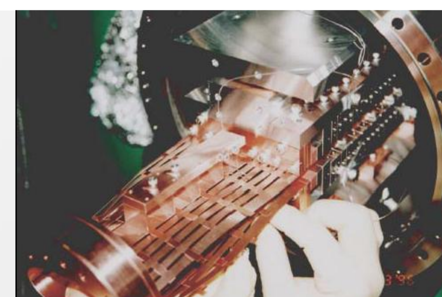
In-vacuum Undulator

Technical challenges in IVU,

- Vacuum condition: In addition to sufficient pumping speed, a TiN coating on PM needs to suppress the outgassing from a porous structure of PM.
- To against the irreversible demagnetizing of PM during bakeout, PMs with higher coercivity (>2000 kA/m) is required.
- Impedance reduction: the metal sheet covers the magnet surface; the RF transition to connect the magnet end and adjacent vacuum duct smoothly.
- Field correction, thermal expansion during bakeout……….

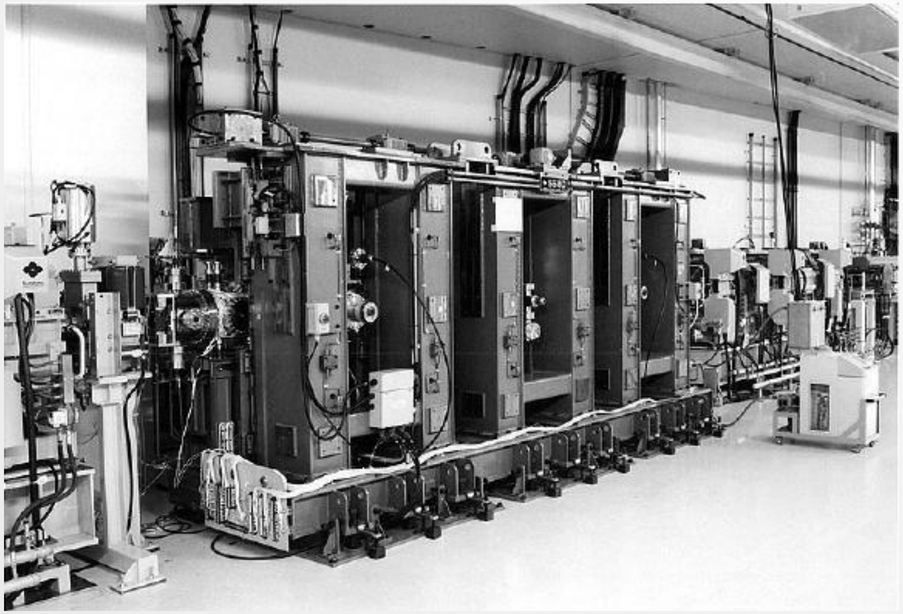






T. Tanaka et. al. FEL (2005)

Installation in the Ring_IVU



IVU32 installation, 1998, Spring8

IVU22 installation, 2015, TPS

Cryogentic Permanent Magnet Undulator

- Increasing the magnetic field by lowering the temperature of PM.
  Incidental benefits:
- ✓ Hcj increasing, robustness for against demagnetizing in operation.
- ✓ Work as cryopumps.
- CPMU are a natural evolution of IVU.
- In addition to the technologies in IVU, CPMU must overcome the new challenges due to a low temp. operation.

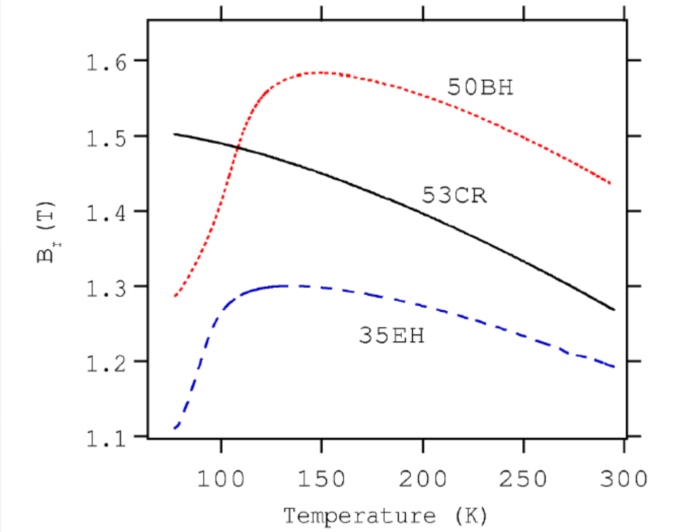


FIG. 2. (Color) Temperature dependence of the remanent fields (B_r) of sintered NdFeB magnets (35EH and 50 BH) and a PrFeB magnet (53CR).

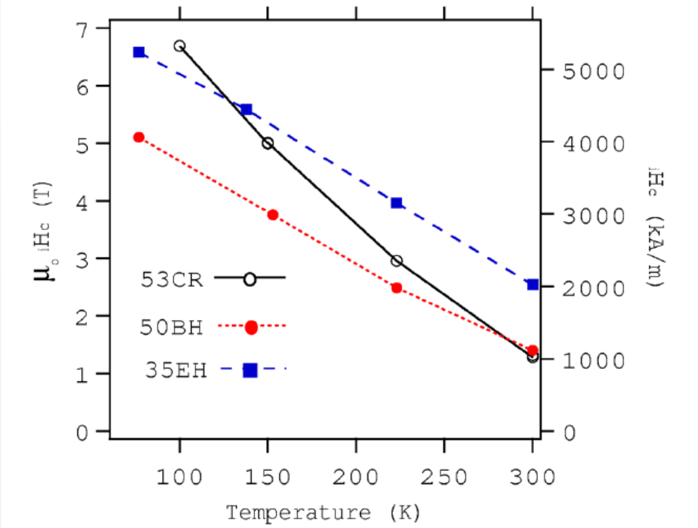
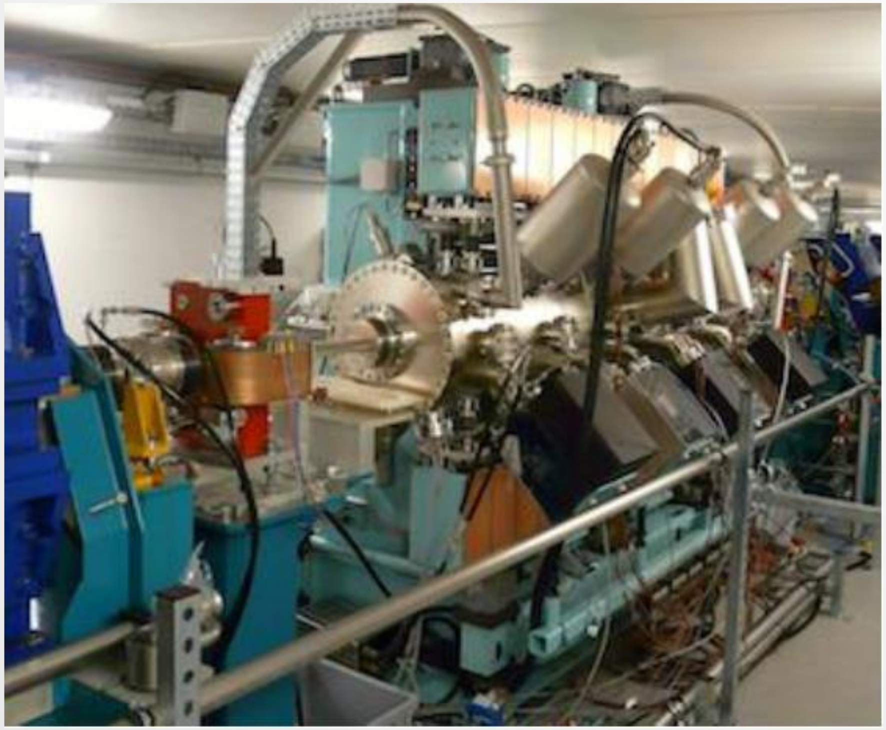


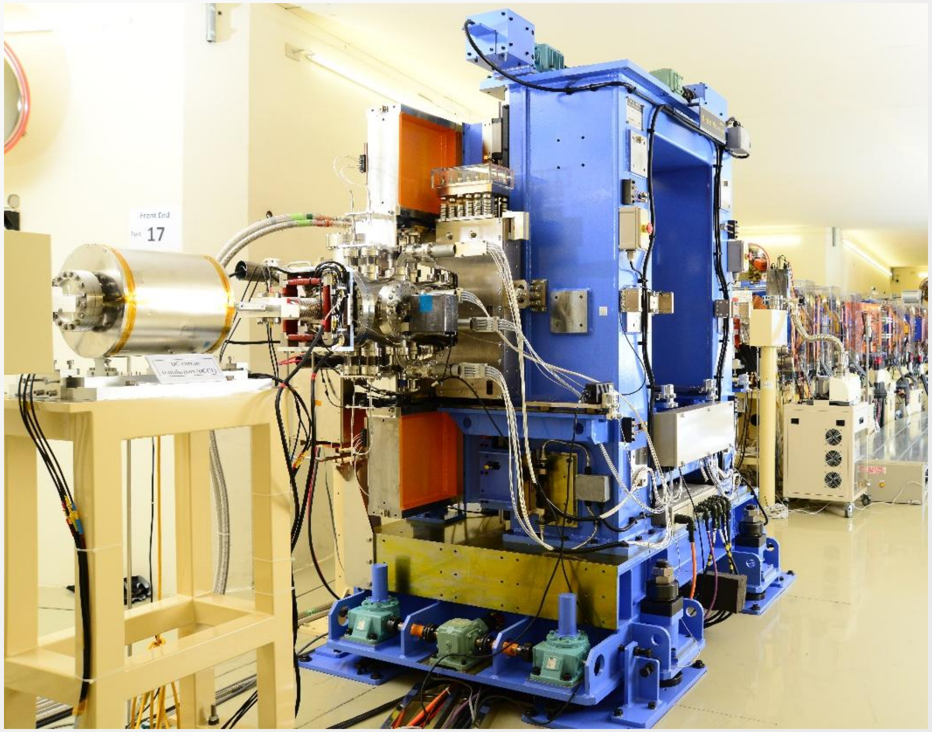
FIG. 3. (Color) Temperature dependence of the coercivity (${}_iH_c$) of sintered NdFeB magnets (35EH and 50 BH) and a PrFeB magnet (53CR).

T. Hara et. al. PRSTAB (2004)

Installation in the Ring_CPMU



CPMU18, Soleil, PRSTAB (2017)

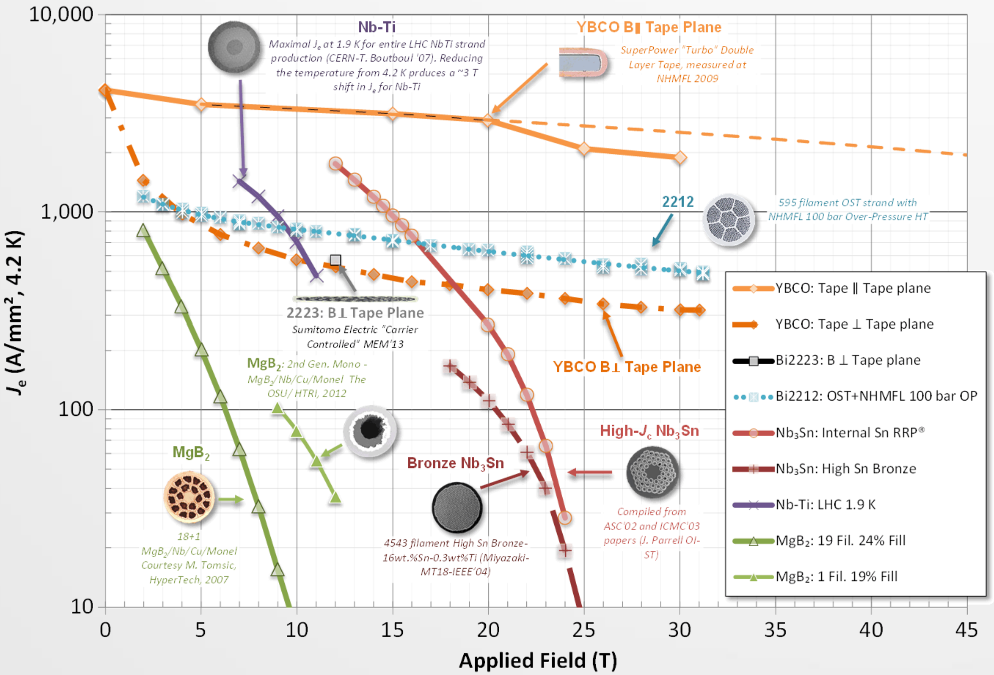


CPMU15, TPS

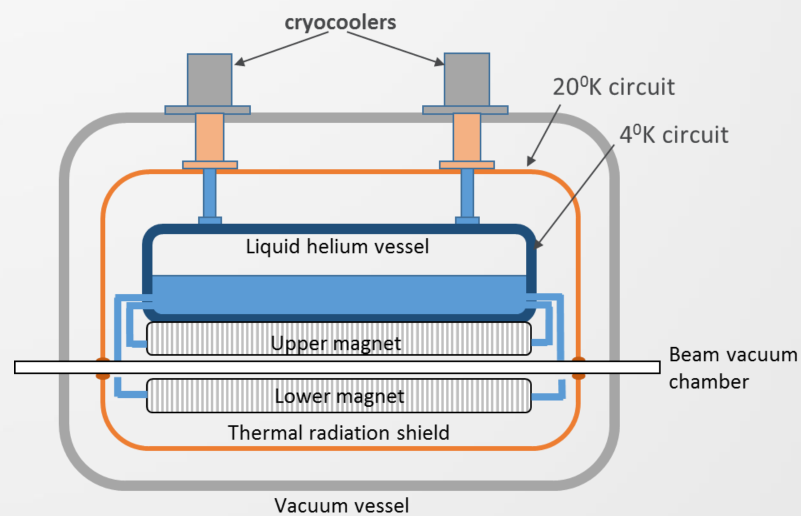
Superconducting undulator

Superconductive wires winding around poles with soft ferro- material.

- Four critical parameters of wires: critical current density, field, temperature and mini bending radius, limit the performance of the SU.
- Cooling technology: direct, indirect or crycooler.



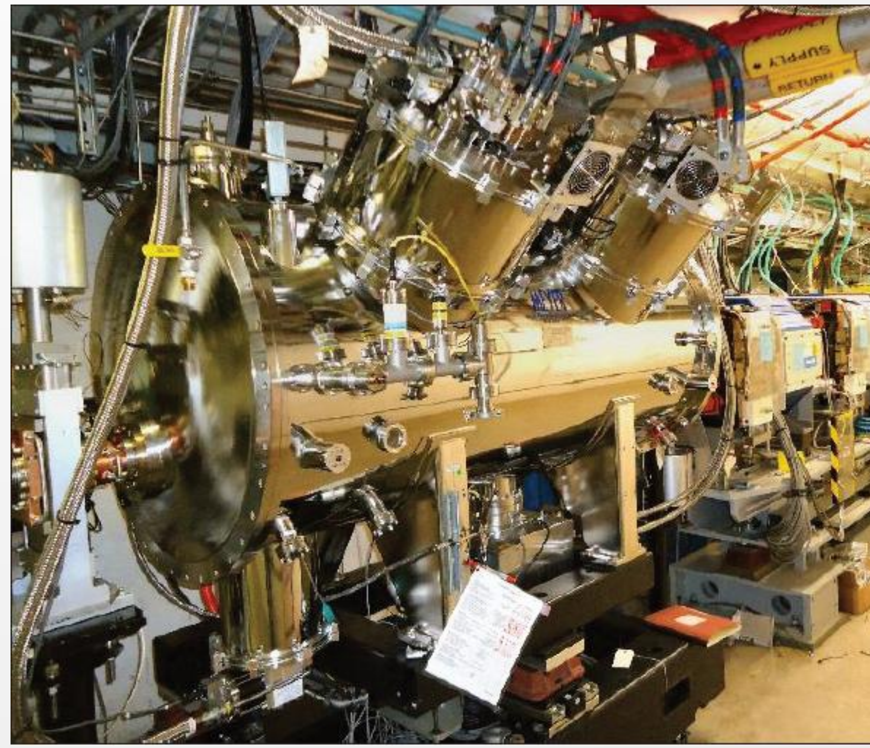
National High Magnetic Field Laboratory (2011)



Indirect cooling, E. Gluskin, APS (2018)

Installation in the Ring_SU

Karlsruhe Institute of Technology (KIT)



Planar SU installed in the APS ring, Sector 1.

Generating various polarization

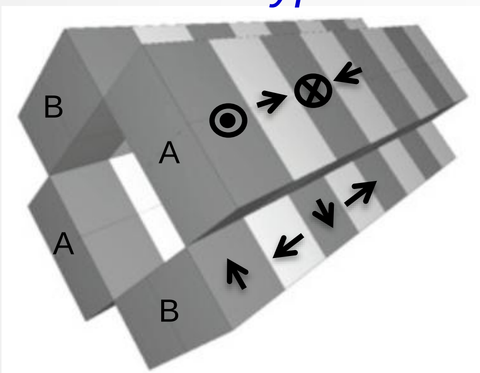
Electromagnet, superconducting magnet, asymmetric wiggler, and permanent magnet are all available to be a variably polarized device.

Permanent Magnet

- 1984 Crossed Undulator concept by K. J. Kim.
- 1986 Two Orthogonal Planar type by H. Onuki.
- 1990 Helios type by P. Elleaume. similar one by B. Divianco & R. Walker.
- 1992 Apple-I type was proposed by S. Sasaki.
  Crossed undulator was demoed at BESSYII.
- 1993 First Apple-I type device was operated at JAERI Storage Ring.
- 1994 Apple-II type was proposed by S. Sasaki.
  First Apple-II was tested at SPEAR storage ring.
  Concept of QPU was proposed by Sasaki & Hashimoto.
- 1995 Six magnet arrays type was proposed by Kitamura.
- 1997 One Apple-II and Dual Helical IDs with orbit switching scheme,
  were installed at SPring-8.
- 1999 One Apple-II was installed at TLS.
  (Apple-II was widely used at synchrotron radiation facilities)
- 2008 Delta undulator was proposed for FEL.
- 2011 12 Apple-II total were built for Fermi@Elettra FEL project.

Permanent variable polarization devices

Onuki type



H.Onuki, Nucl. Instr. Meth., A246,94 (1986)

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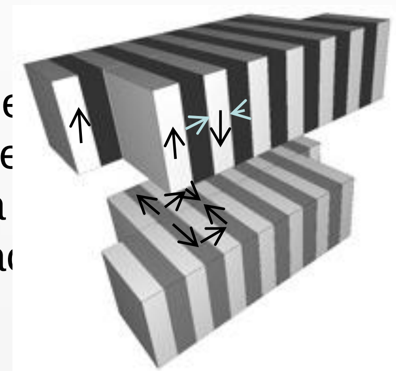
Helios



P.Elleaume, J. Synch. Rad.,1,19 (1994)

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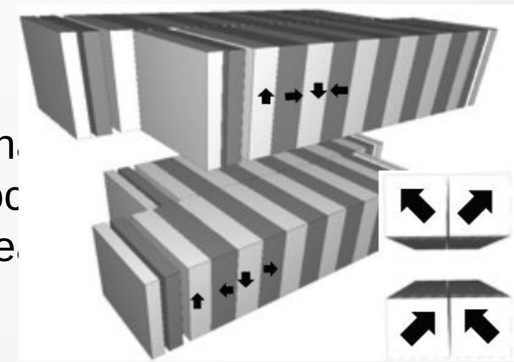
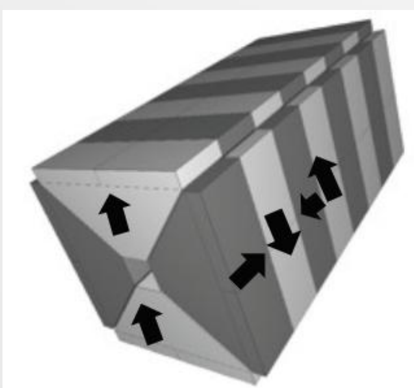
APPLE-I



S.Sasaki et al, Jpn.J.Appl.Phys.,31,L194 (1992)

Magnet blocks with a 45^0 magnetization. Field is symmetry and has a higher a

Delta



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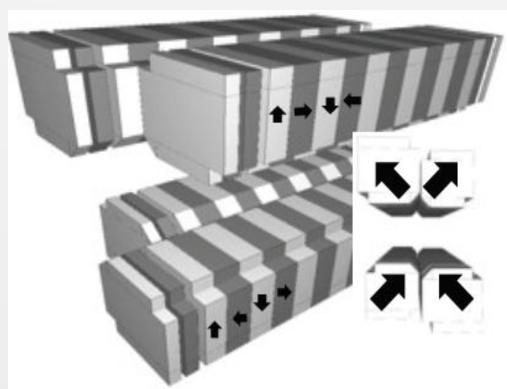
A.B. Temnykh, P.R.S.T.A,11,120702(2008)

APPLE-III



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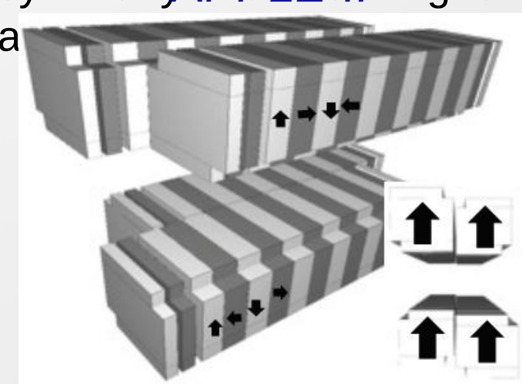
J. Bahrdt et al, 2004 FEL conference

APPLE-II



S.Sasaki et al, Nucl. Instr. Meth., A347,87 (1994)

TingYi Chung 鍾廷翊, 2026, FEL

APPLE-II

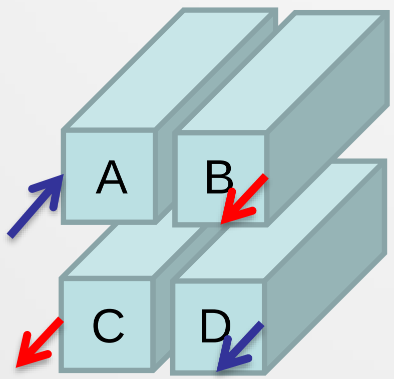
Why APPLE-II?

- Generating any polarization (linear, elliptical, circular)
- High linear/helical magnetic field
- For FEL or USR, Delta-type is the best performance to generate any polarization.

What is APPLE-II?

APPLE (Advanced Planar Polarized Light Emitter)

Antisymmetry(Inclined) mode



Symmetry mode

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

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

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

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

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

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

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

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

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

C.S.Hwang, Nucl. Instr. Meth., A420,29 (1999)

Installation in the Ring_EPU

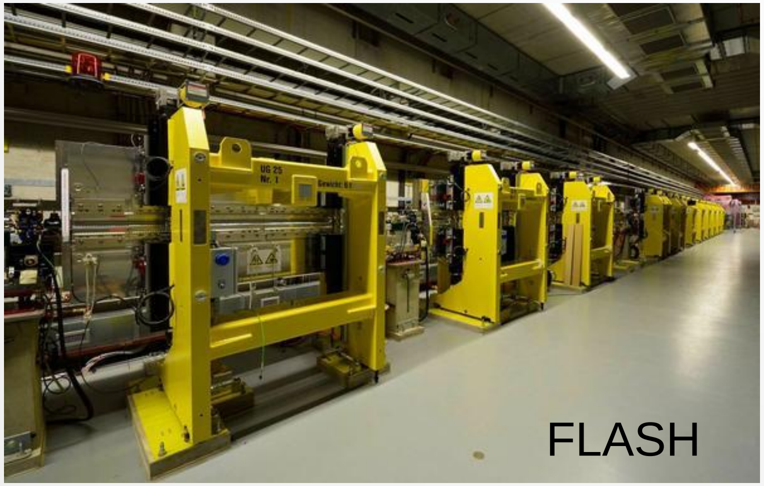
EPU56 installation, 1999, TLS

EPU48 installation, 2015, TPS

Undulator system in FEL

Hybrid/PPM undulators dominate FELs

Hybrid
9,
31.4,
2.87.



IVU
3.5,
18,
2.2

Hybrid
6.8,
30,
3.5.

APPLEII
10,
55.2/ 34.8,

Type
Gap mini,
Period,
K max

Undulator system in FEL

Trend(similar to the application in SR)
Pursuing high K (B field) at small periods to minimize electron energy E.
⇒ Narrowing gap to increase B, but compromised by
⇒ The wakefields which can disrupt lasing, increase the risk of radiation damage to the magnet, and make vacuum harder to achieve.

Specific requirements
FEL radiators are made of a number of modules.

- Tight K variation: all modules need to emit the same wavelength, sets tight limits on reproducibility of period and K – also E decreases along FEL so K from module to module may be adjusted (slightly) to allow for this (tapering).
- Tight straightness of a trajectory (second field integral): Need close control of electron trajectory within undulators to ensure constant overlap of light with electrons.
- Tight survey alignment: alignment of all modules to μm level tolerances over ~100m
- Loose phase error: phase error less important as work at first harmonics only.