Part III
Technology of Insertion Devices

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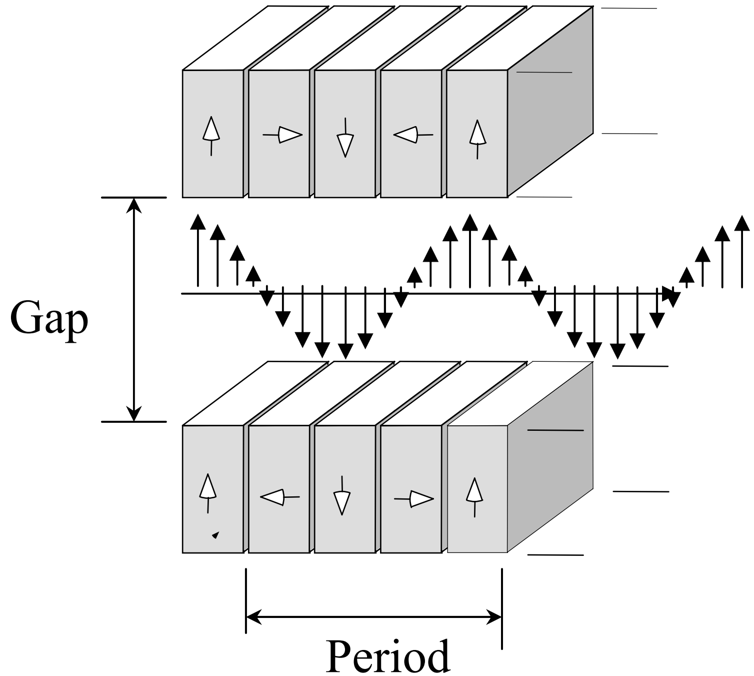
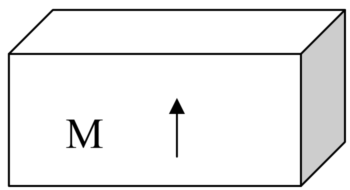
Technology of Undulators and Wigglers

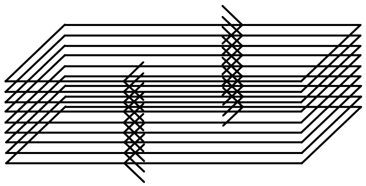


- The main issue in the magnetic design of a planar undulator or wiggler is to produce a sinusoidal field with a high peak field B and the shortest period λ_0 within a given aperture (gap).
- Three type of technologies can be used :
  - Permanent magnets (NdFeB , Sm_2Co_{17})
  - Room temperature electromagnets (iron and coils)
  - Superconducting electromagnets (superconducting coils with or without iron)

Current Equivalent of a Magnetised Material

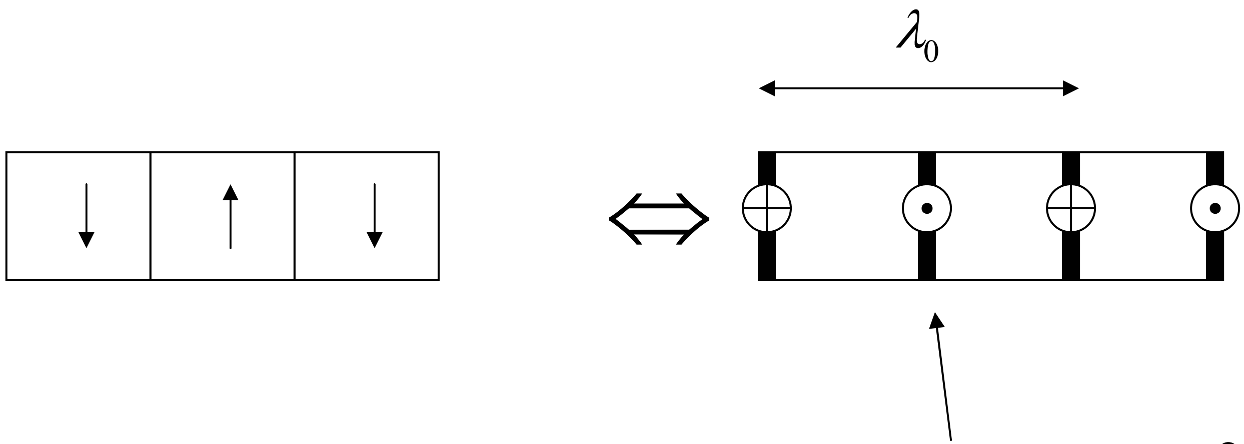


$\Leftrightarrow$



$$\text{Air coil with Surface Current Density[A/m]} \cong \frac{B_r[T]}{\mu_0}$$

Periodic array of magnets



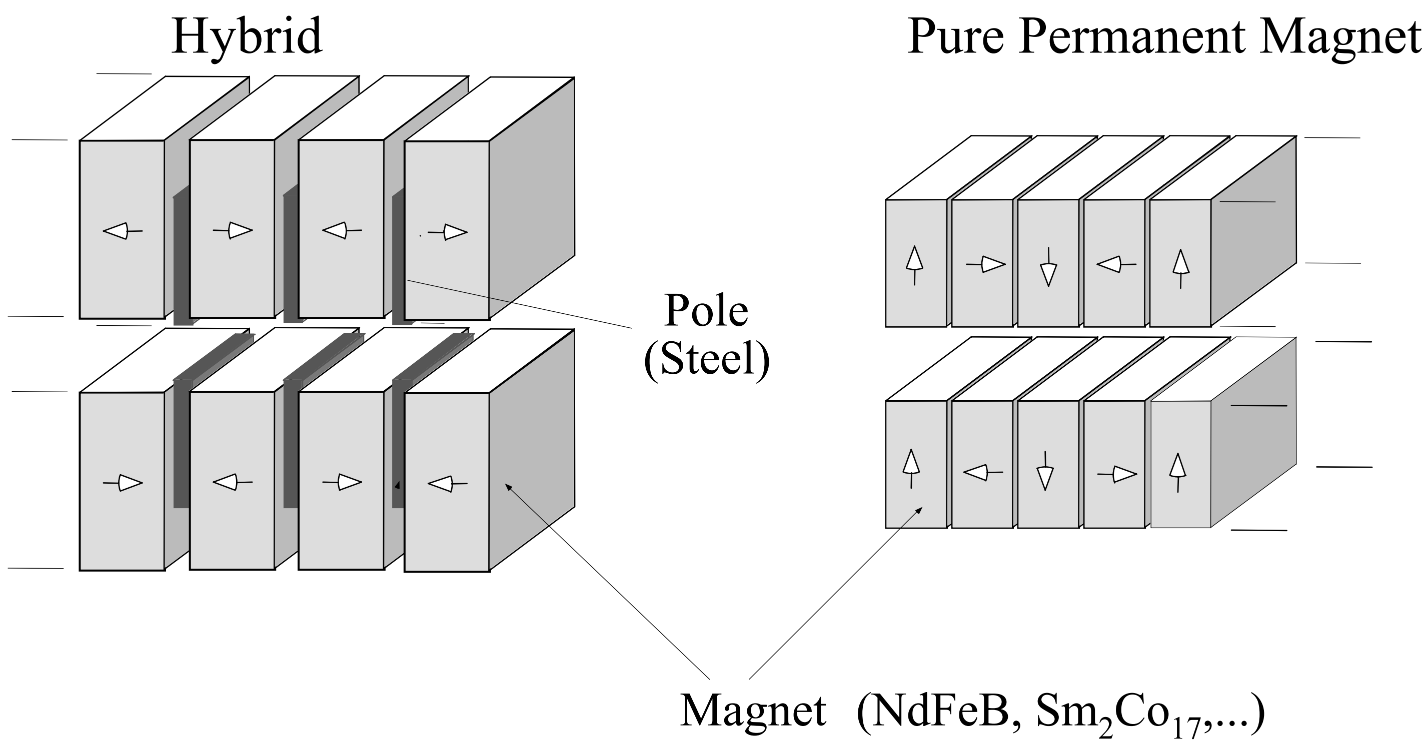
$$\text{Surface Current Density[A/m]} \cong \frac{2B_r[T]}{\mu_0}$$

$$\text{or Current Density[A/m}^2] \cong \frac{4B_r[T]}{\mu_0 \lambda_0}$$

Example: $B_r = 1$ T , $\lambda_0 = 20$mm $\Rightarrow$

Equiv. Current Density=160A/mm^2 !!

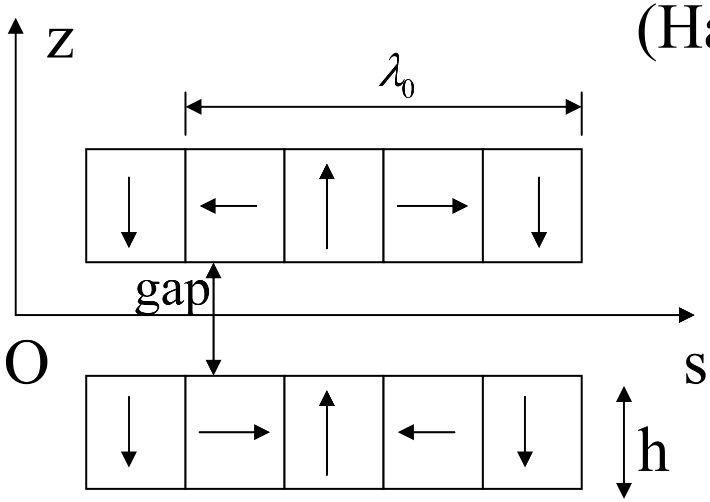
Permanent Magnet Undulator



magnet materials

Material	B_r [T]	$\mu_{r,\parallel}$	$\mu_{r,\perp}$	H_{cJ} [kA/m]	$10^{-2}/°C$
$SmCO_5$	0.9–1.01	1.05		1500–2400	−0.04
Sm_2CO_{17}	1.04–1.12	1.05–1.08		800–2000	−0.03
NdFeB	1.0–1.4	1.04–1.06	1.15–1.17	1000–3000	−0.10

Magnetic Field of a Pure Permanent Magnet Undulator (Halbach Formula)



Assume relative permeability of magnet =1 with remanent field B_r, then the exact field computation gives :

$$B_n = 2B_r \frac{\sin(n\frac{\pi}{4})}{n\frac{\pi}{4}} \exp(-n\pi \frac{gap}{\lambda_0})(1-\exp(2n\pi \frac{h}{\lambda_0}))\cos(2n\pi \frac{s}{\lambda_0})$$

$$\text{if } h > \frac{\lambda_0}{2} \Rightarrow 1-\exp(2n\pi \frac{h}{\lambda_0}) \sim 1$$

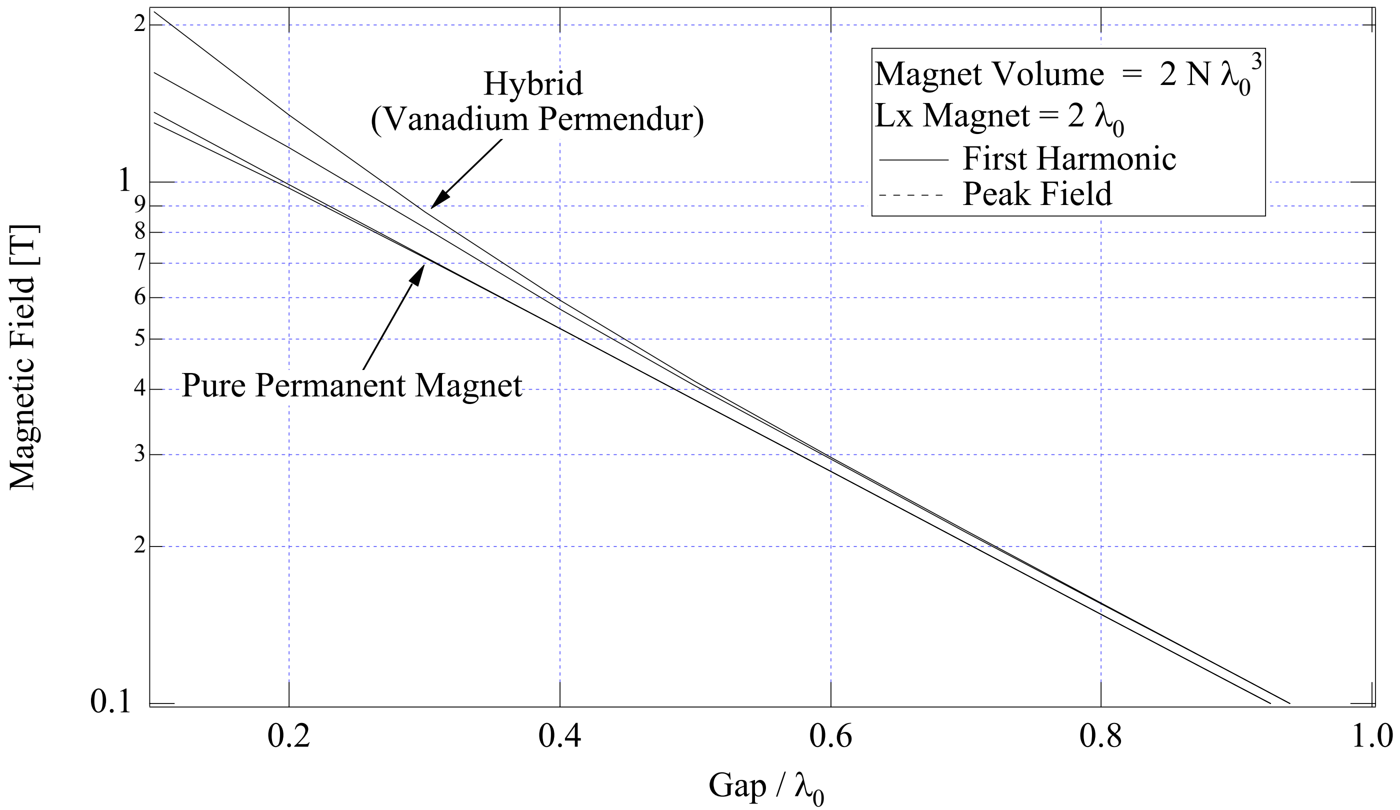
b1	0.90
b3	0.30
b5	-0.18
b7	-0.13

$$\Rightarrow B_n = B_r\, b_n \exp(-n\pi \frac{gap}{\lambda_0})$$

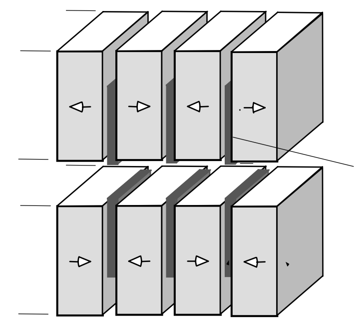
$$\Rightarrow n = 1 \text{ dominates}$$

$$B_z(s) \approx 1.8\ B_r \exp(-\pi \frac{gap}{\lambda_0})\cos(2\pi \frac{s}{\lambda_0})$$

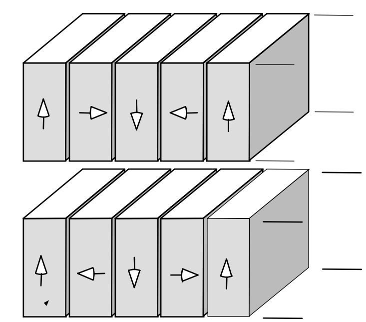
Field from Pure Permanent Magnet vs Hybrid



Hybrid



Pure Perm. Magnet



Numerical Computation of Magnetic Field

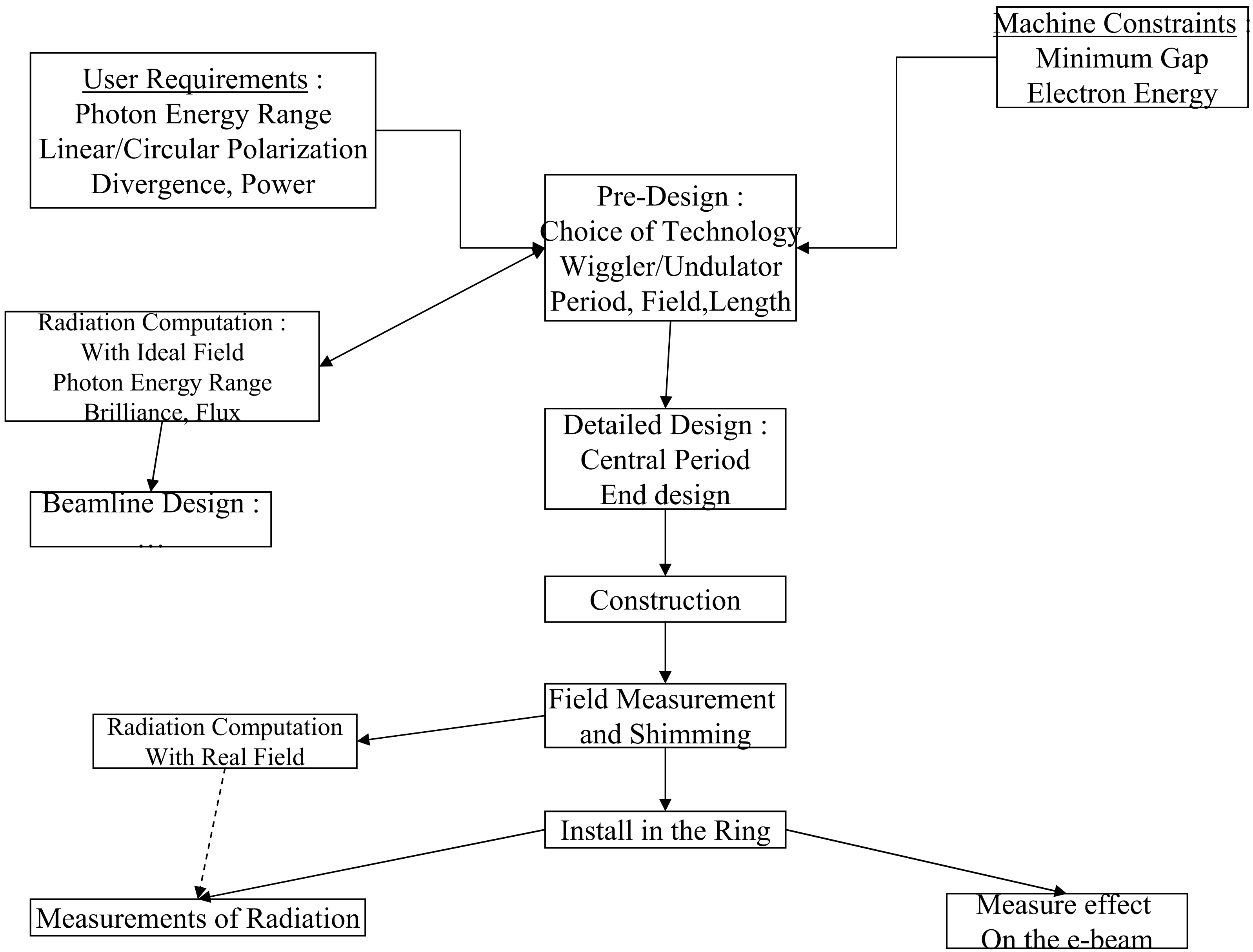
- No Iron (perm. magnet & coil)
  - Integration of Biot and Savart Law

$$\vec{B} = \mu_0 \int I \frac{d\vec{l} \times \hat{u}}{r^2}$$

  - Simple Numerical Methods based on the current sheet or surface charge model. The total field is the linear sum of the field produced by each block. Particularly simple and efficient for parallellepipedic shapes

- With Iron (perm. magnet & coil & iron) : Best solved with numerical methods
  - Finite Element Method
    - Used dominantly for Dipole/Quadrupole/Sextupole … Magnets
    - 2D : POISSON (Public Domain)
      - from http://laacg1.lanl.gov/laacg/services/possup.html
    - 3D : Commercial Codes (TOSCA, FLUX3D, ANSYS,…)
  - Volume Integral Method : Radia
    - Particularly adapted to undulators and Wigglers
    - Compute field and field integral in 3D
    - Public Domain http://www.esrf.fr/machine/groups/insertion_devices/Codes/software.html

Design Process

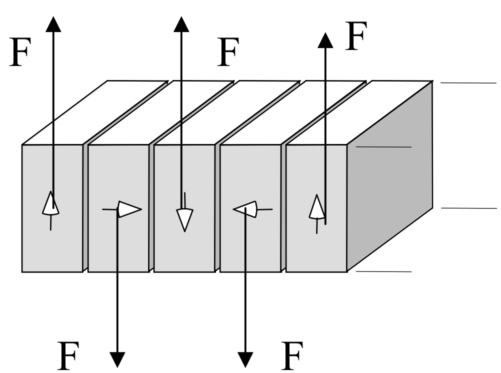


Magnetic Forces

Force between upper and lower magnetic arrays :

$$Force = \frac{\hat{B}^2 W L}{4\mu_0}$$

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

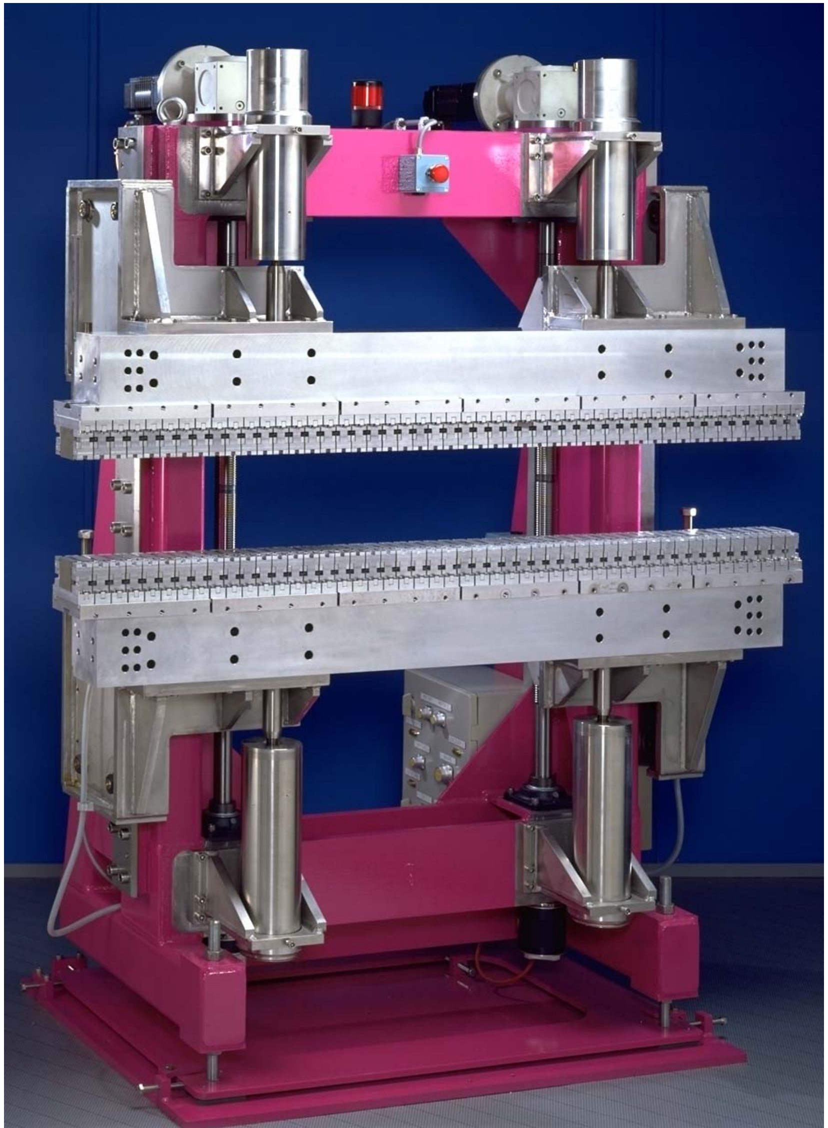


Force on each magnet can be large :

⇒ rigid holding structures

⇒ special assembly tools

ESRF Undulators



Magnetic Force : 1-10 Tons
Gap Resolution : < 1 μm
Parallellism < 20 μm

Undulators are Fundamentally Small Gap Devices

- Like any accelerator magnet, the smaller the magnetic gap the less volume of magnetic material required to reach a specific field geometry.
- The lower the gap the higher the energy of the harmonics in the undulator emission.

$$\lambda_n = \frac{\lambda_0}{2n\gamma^2}(1 + \frac{K^2}{2})$$

with

$$K = 0.0934\, B_0[T]\,\lambda_0[mm]$$

$$B_0 \sim 1.8 B_r \exp(-\pi \frac{gap}{\lambda_0})$$

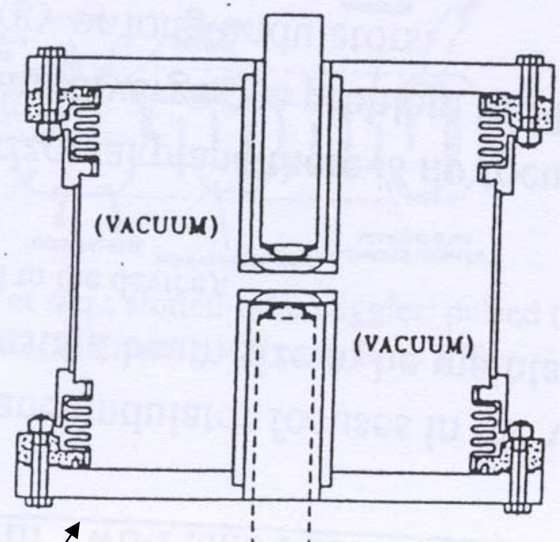
Application : Build a pure permanent magnet undulator with NdFeB Magnets (B_r = 1.2 T)

Undulator with K=1

Gap [mm]	B [T]	Period [mm]	Fundamental [keV] @ 6 GeV	Electron Energy [GeV] Fund = 15.2 keV
5	0.72	15	15.2	6.0
10	0.49	22	10.3	7.3
15	0.38	28	8.2	8.2

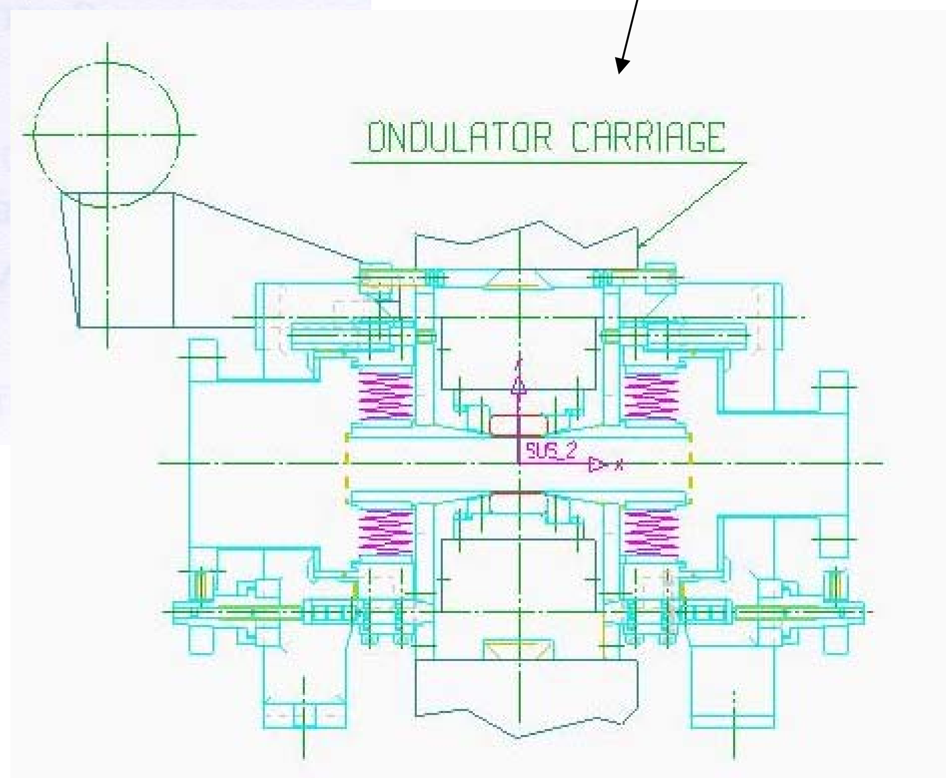
Flexible Chambers

Ring	λ_0 (mm)	L (m)	g_{vac} (mm)	g_{mag} (mm)	K
MAX	24	0.83	6.0	7.6	1.7
NSLS	16	0.32	3.8	7.5	0.7
ESRF	26	0.80	6.0	9.0	1.7

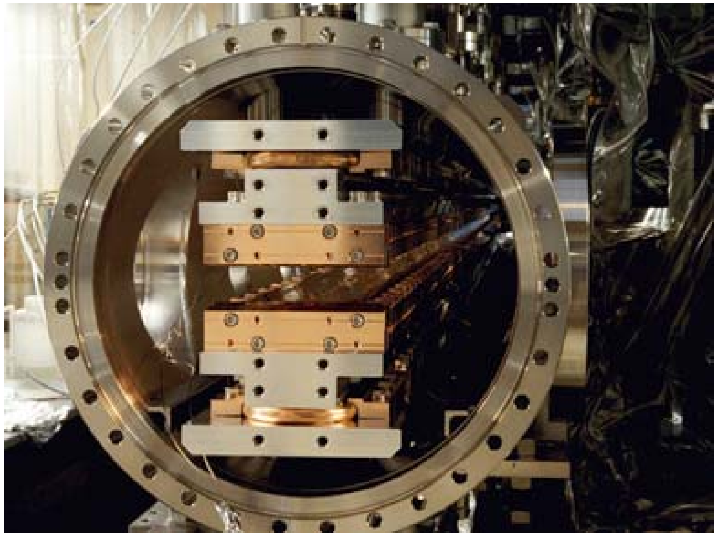


NSLS

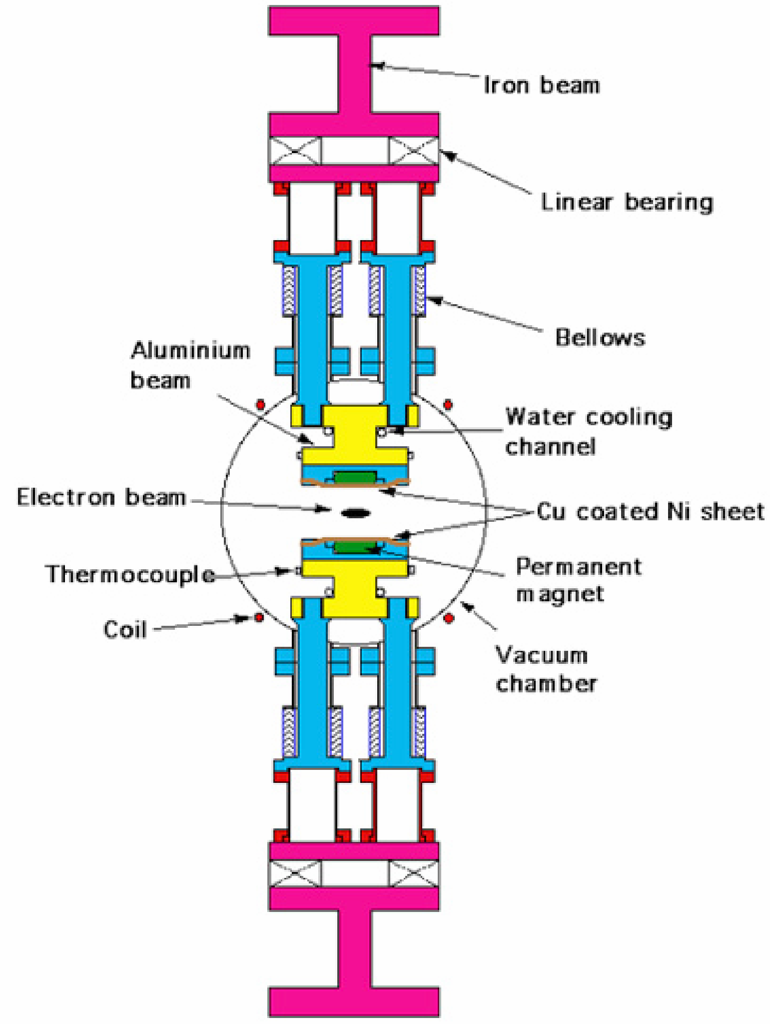
ESRF



In Vacuum Undulators



- Developed at NSLS, Spring-8 , ESRF
- Required by many new light sources (SLS,CLS,LBL,Diamond,Soleil,..)
- Open the gap during injection if needed
- Allow a minimum magnetic gap of 3 to 6 mm



SPring-8 In-Vacuum Undulator

ESRF In-vacuum Undulator

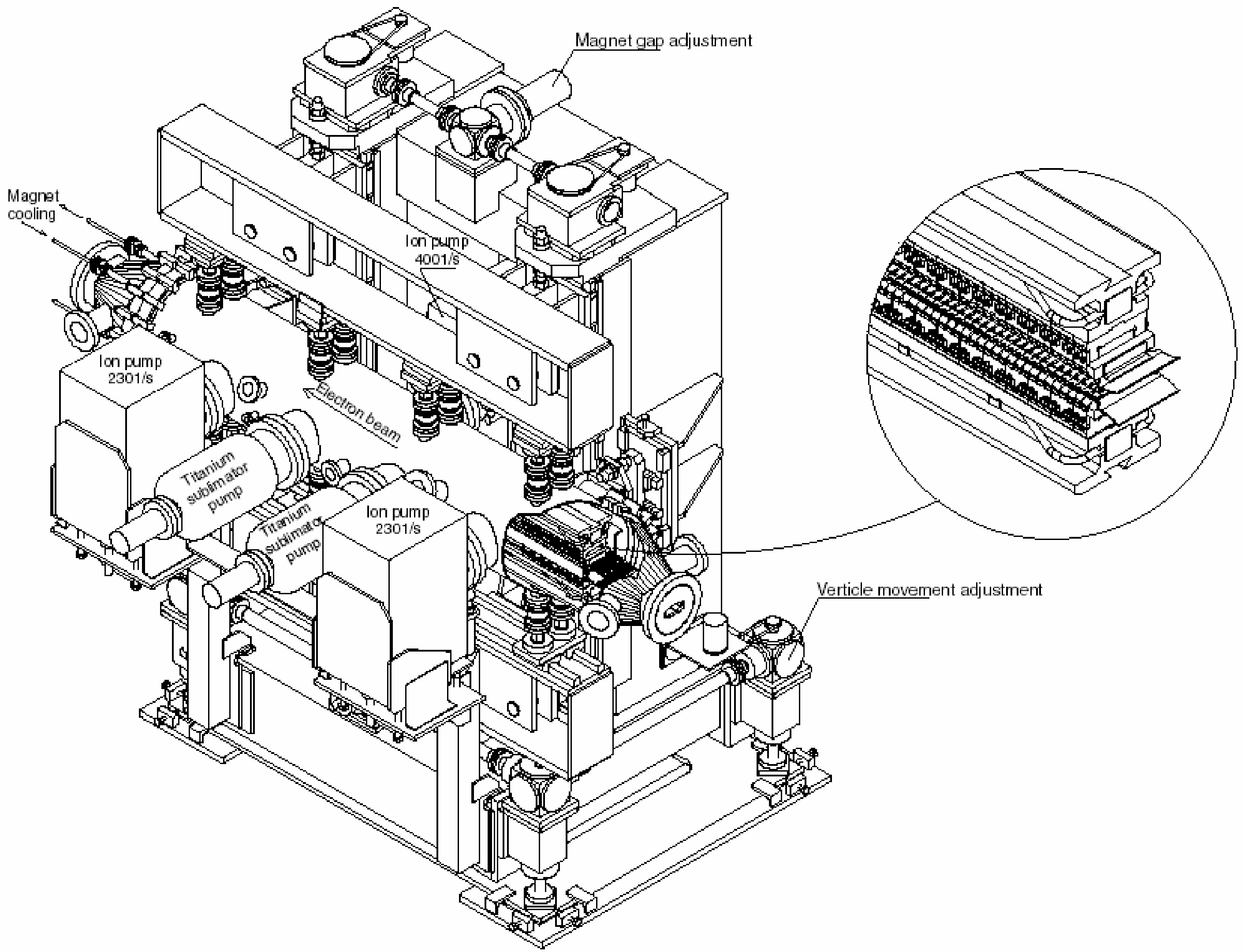
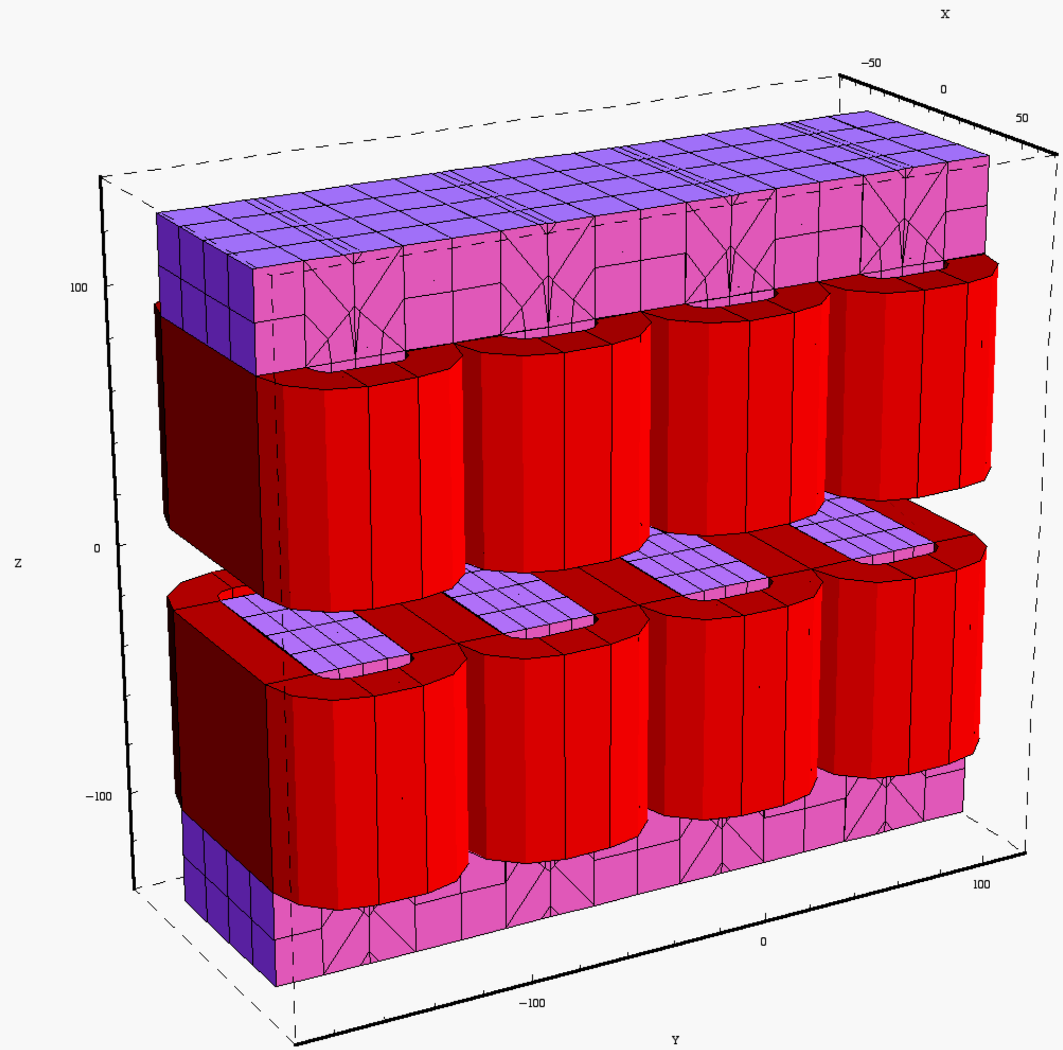


Figure 5.26 3D view of an ESRF in-vacuum undulator.

Electro-Magnet Undulator



-Limited by the electrical power requirement and associated cooling of the coils :
Current Densities < 10-15 A/mm^2

-Only interesting for long periods

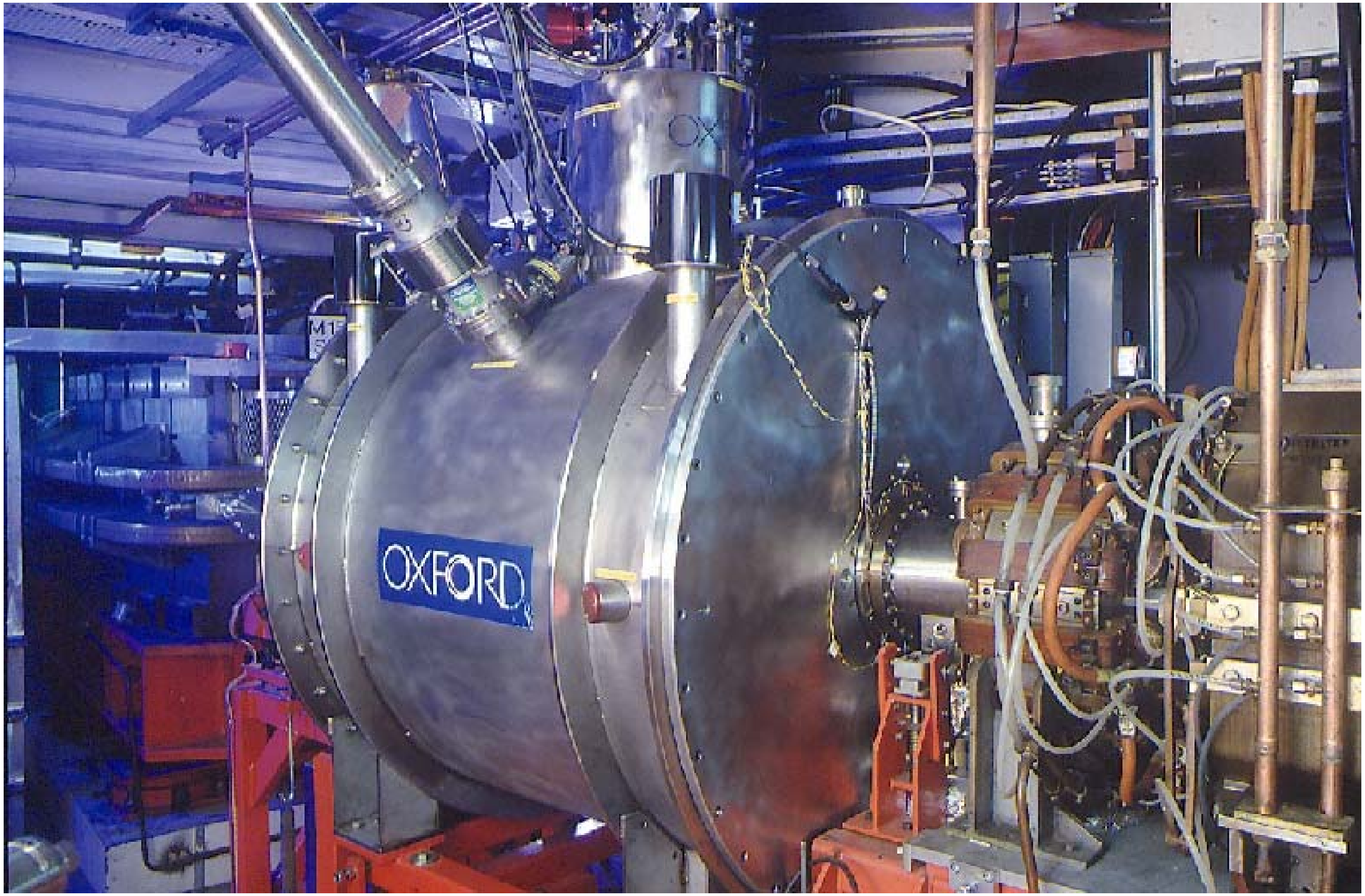
SRC Electro-magnet Undulator (Wisconsin USA)

http://www.src.wisc.edu/research/highlights/undulator/default.html

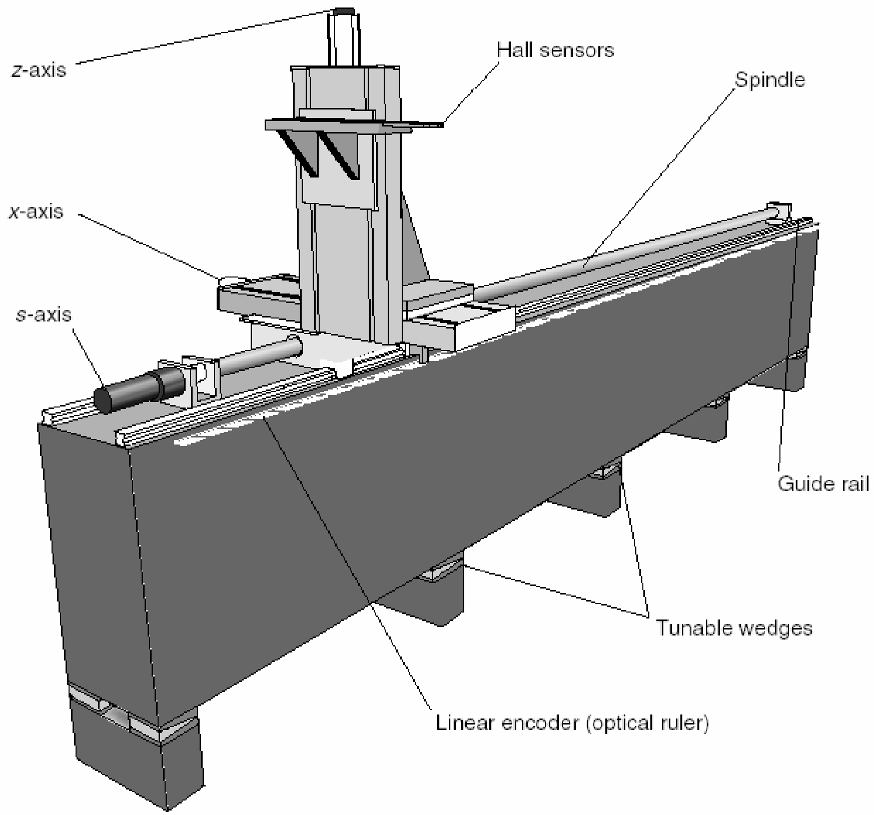
Delta Superconducting Wiggler

- High field : up to 10 T => Shift the spectrum to higher energies
- Sophisticated engineering & high cost

SRS Superconducting Wiggler



Local Field Measuring Bench



Optimized for fast longitudinal field scanning :

- Optical & Laser Encoder
- 3-axis Hall probe sensor
- On-the-fly scanning 2000pts/m
- Measuring length 2-10 m
- Essential for phase shimming

Field Integral Measuring Bench

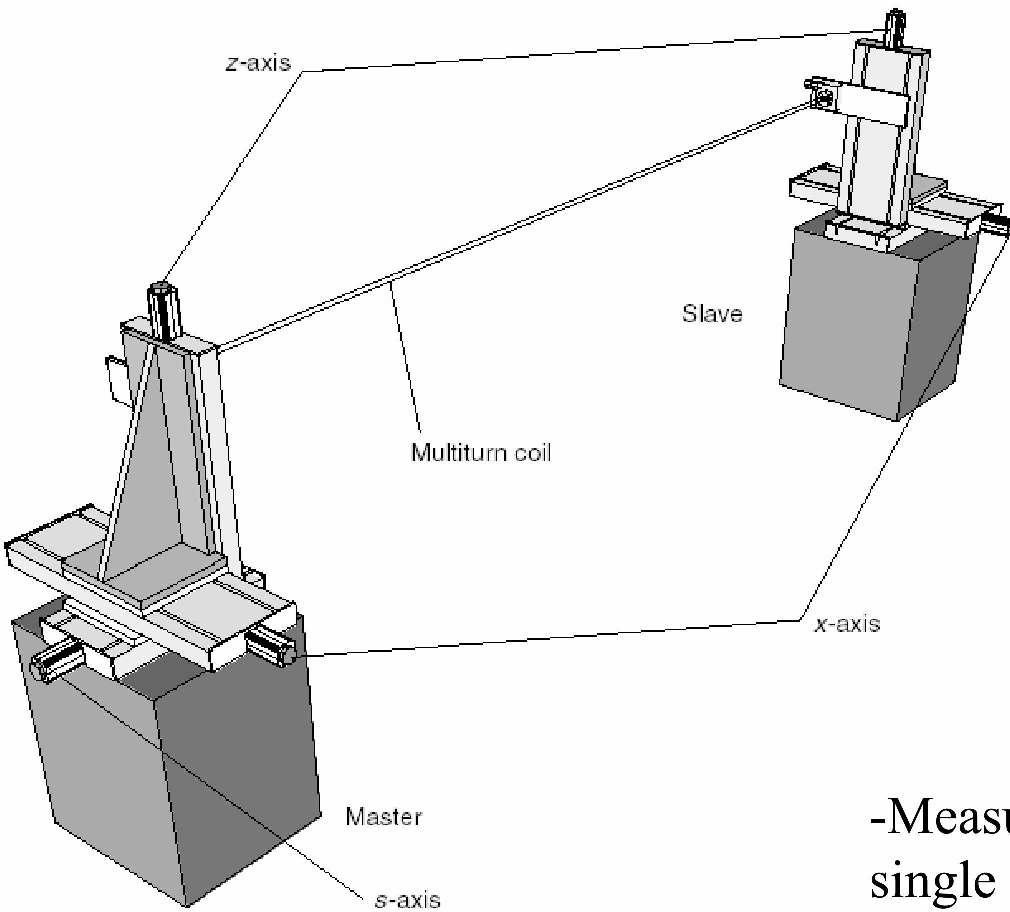


Figure 5.16 View of a field integral measuring bench.

Either :
-Rotating multiturn coil
-Moving stretched wire

-Measure Horiz & Vertical single and double field integrals
- Absolute accuracy < 10 Gcm
- Essential for multipole shimming

Magnetic Field Errors of Permanent Magnet Insertion Devices :

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

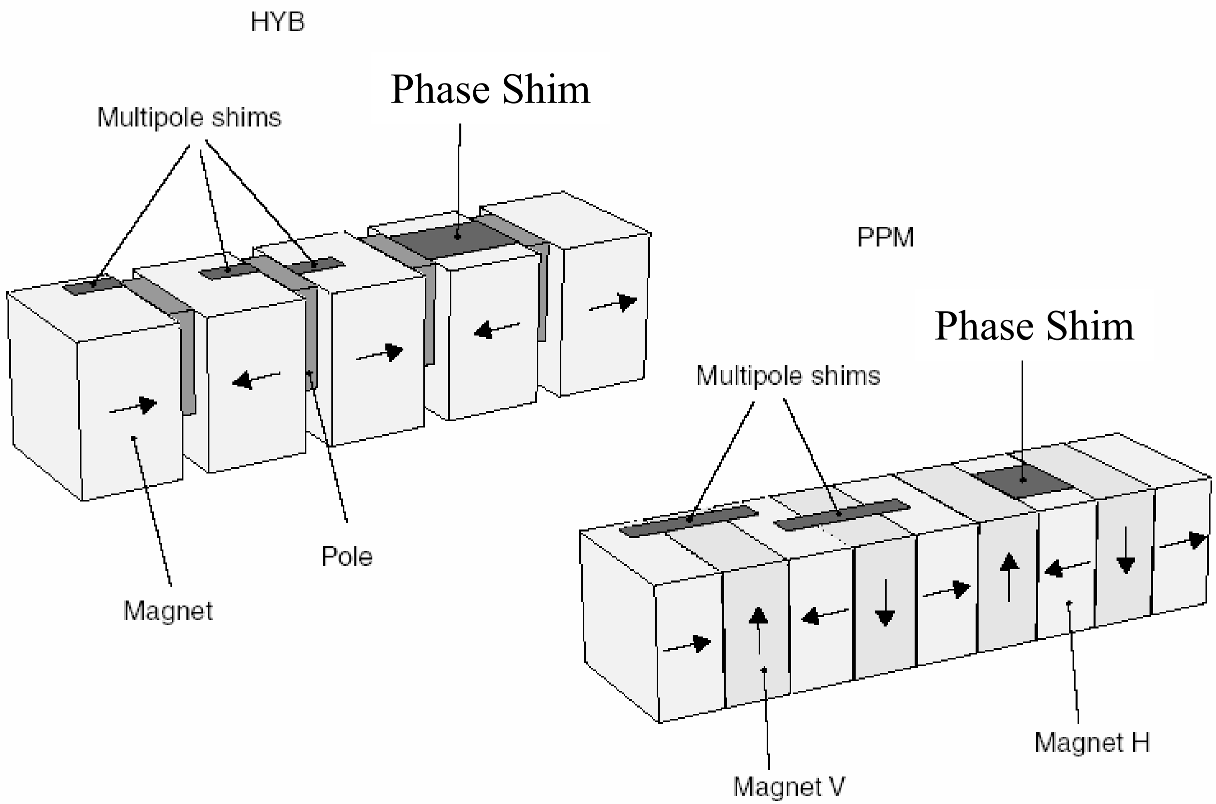
- Need to purchase highly uniformly magnetized blocs and
  - perform a systematic characterization
  - Perform a pairing of the blocks to cancel field integrals
  - but still insufficient .

- Type of Field Errors
  - Multipole Field Errors (Normal and skew dipole, quadrupole, sextupole,…).
  - Phase errors which reduce the emission on the high harmonic numbers

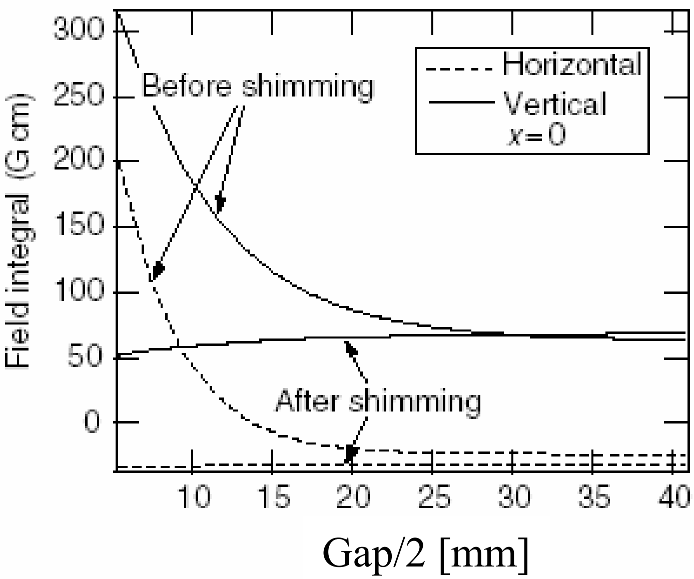
Undulator Shimming

- Mechanical : Moving permanent magnet or iron pole vertically or horizontally
- Magnetic : Add thin iron piece at the surface of the blocks
  - More precise and local
  - Field reduction

Magnetic shims

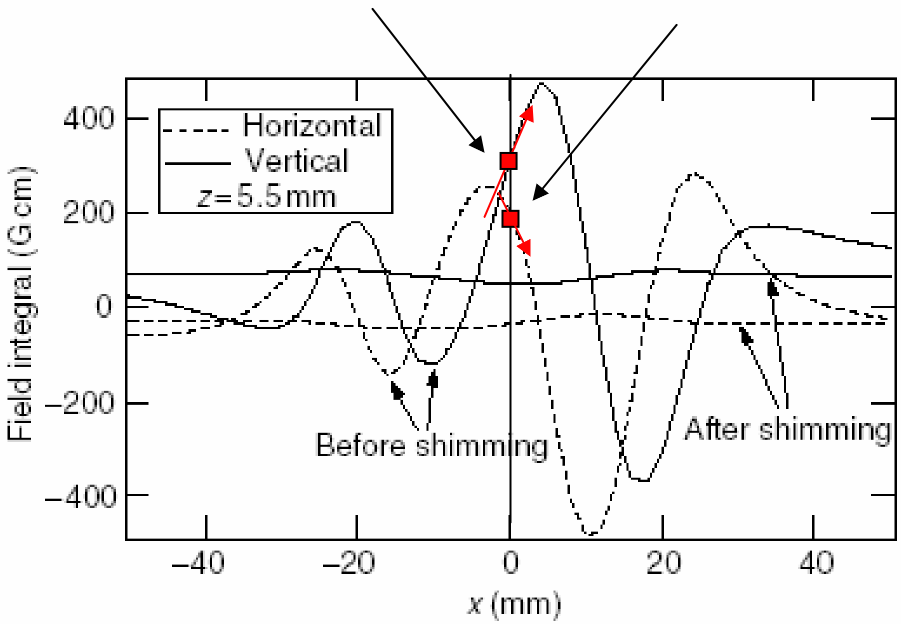


Field Integral and Multipole Shimming

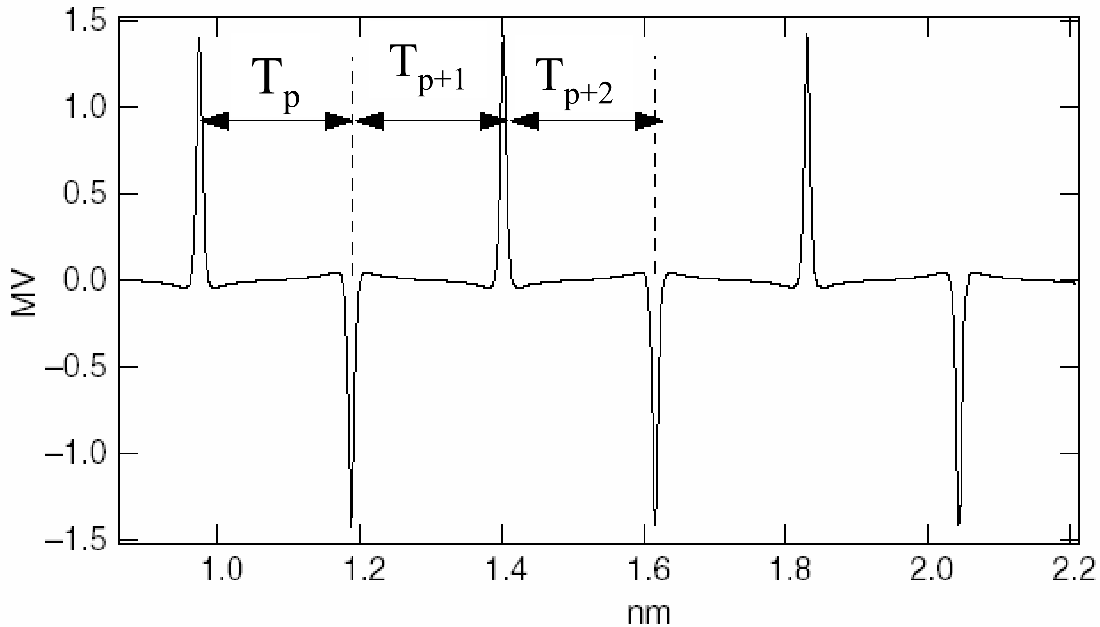


Horizontal Deflection
Quadrupole
Sextupole …

Vertical Deflection
Skew Quadrupole
Skew sextupole …



Phase Error and Phase Shimming



Horizontal electric field produced on-axis by a single 6 GeV electron propagating through an undulator with a 34 mm period and a 0.7 T peak field.

Each pulse interfere constructively If $T_p = T$ for all p and for a wavelength so that $\lambda = 2T/n$ where n is an integer (harmonic number). Real undulators have small field errors which result in fluctuations of T_p. These are also called phase errors.

Assuming: T_p identically independently distributed for every p with :

$$\langle T_p \rangle = T, \quad \langle (T_p - T)^2 \rangle = \sigma_T$$

Then , it is a consequence of the Fourier Transform that :

$$\frac{d\Phi_n}{d\theta_x d\theta_z \frac{d\lambda}{\lambda}}(0,0,\lambda_n) = \frac{d\Phi_n}{d\theta_x d\theta_z \frac{d\lambda}{\lambda}}(0,0,\lambda_n)_{ideal}\, e^{-(n\pi \frac{\sigma_T}{T})^2}$$

independently of the number of period N

The effect is usually characterised by a rms phase error σ expressed

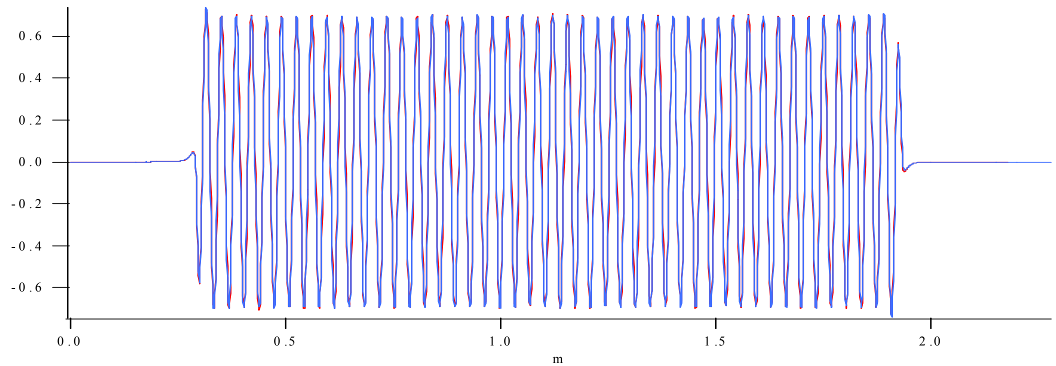
in degrees. $\sigma[\text{deg}] = \frac{1}{180}\frac{\sigma_T}{T}$

On-axis angular flux, flux and brilliance are multiplied by $e^{-(n\pi \frac{\sigma_T}{T})^2}$

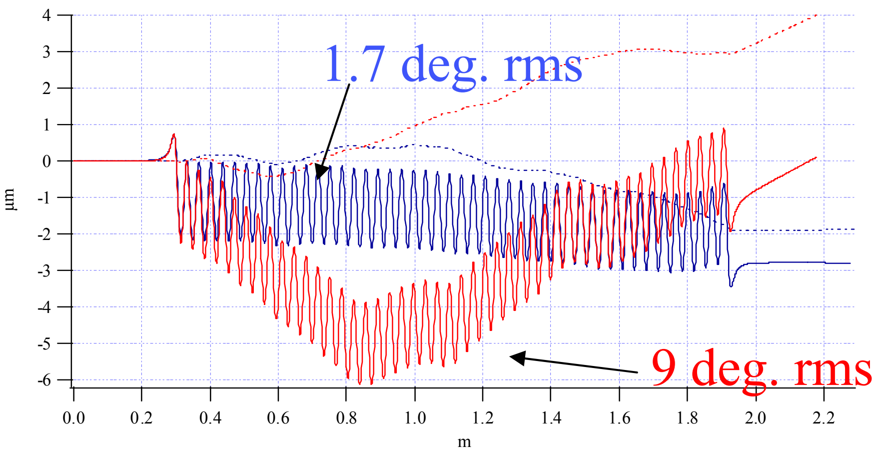
Phase error [deg]	6	1
Harmonic #		
1	0.99	1.00
5	0.76	0.99
9	0.41	0.98
13	0.16	0.95

A Practical Example of Phase Shimming of an ESRF Undulator :
(period 35 mm, N= 46 periods, Gap=11 mm)

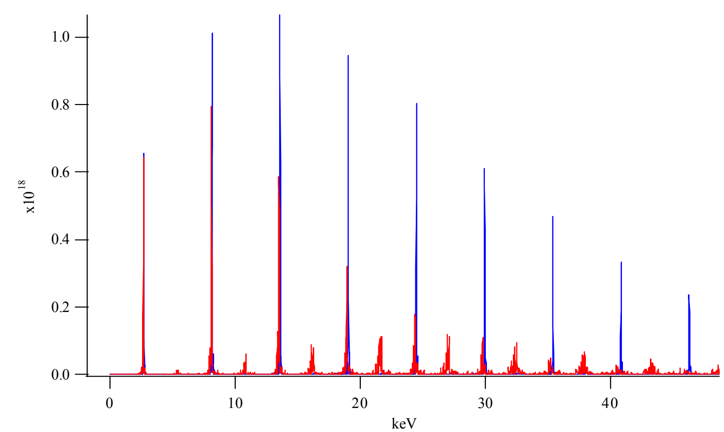
Measured Vertical Field



Calculated Trajectory @ 6 GeV



Calculated on-axis single electron emission spectrum



Remarks on Phase Errors

- Small phase errors may have a large impact on the undulator spectrum in particular on the high harmonic numbers. The associated magnetic field errors can be detected on the field plot where they appear as period and peak field fluctuations. Some of them (generating internal angles) may also be visible from the wandering of trajectory.

- Emittance and energy spread induce a broadening of the peak and may mask a part of the spectral flux lost due to phase errors. Nevertheless, in most cases, even with large emittance and energy spread, low phase error undulators perform much better on the high harmonics.

- They are important for long undulators or undulators intended to be used on a high harmonic number

- They are usually not important in undulators used on the fundamental of the spectrum such as in Free Electron Lasers