Part V
Undulators for Free Electron Lasers

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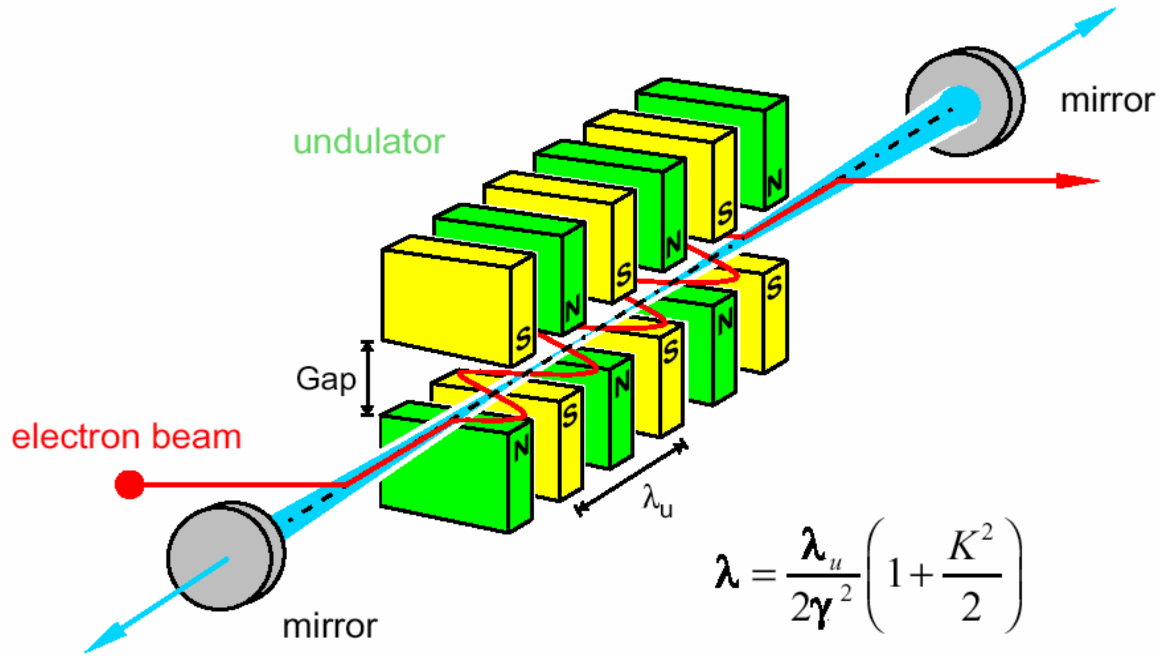
Oscillator-type Free Electron Laser



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

$$\gamma \approx 2E\,(\text{MeV})$$

$$K \approx 0.9\,B_0\,(\text{T})\,\lambda_u\,(\text{cm})$$

Generalities on Undulators for Oscillator-type Free Electron Lasers

- The Laser is usually designed to operate in the fundamental
  - => no need of phase shimming

- To maximize the gain per pass, one must maintain an overlap between the electron beam and the radiation (TEM_{00} eigen mode of the optical cavity) along the undulator length
  - => one must ensure a straight trajectory of the electron in the undulator

Undulators for LINAC based FEL Oscillators

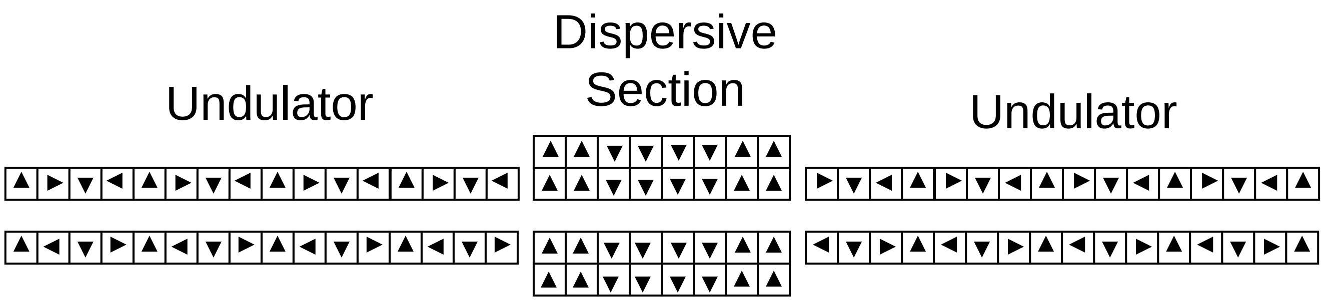
- Use essentially permanent magnet based planar undulators of short length (a few meters, limited by the train duration)
- The electron beam circulates only once in the undulator

  => Field integral and integrated multipole correction are not as essential as in a storage ring

  => A small magnetic gap can be tolerated and is desirable in order to reduce the wavelength of the laser and save on electron energy.
- Other types of undulator technologies have been developed and tried :
  - Pulsed electromagnet
  - Superconducting
  - mini gap (1 - 3 mm)

Undulators for Storage Ring based FEL Oscillator

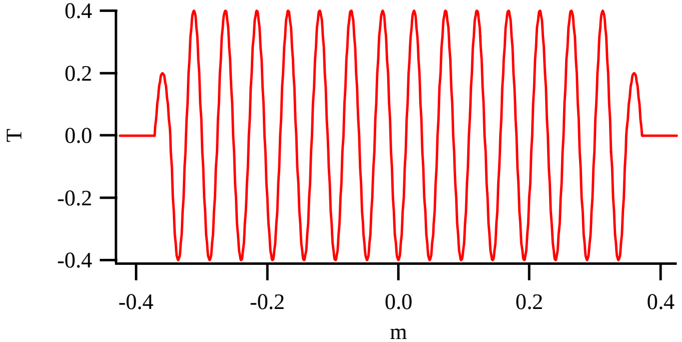
- gain /pass is low (0.1% to 10 %) because :
  - Relatively long bunch length (several10 ps)
  - Straight section length is limited to a few meters
- All storage ring FELs use a modified version of the Undulator called "Optical Klystron"



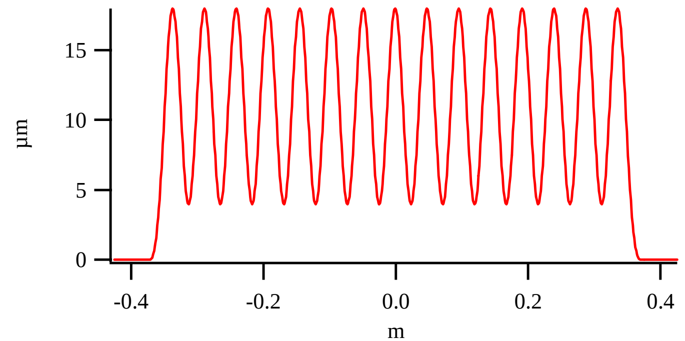
- Magnetic Field Quality : Same requirement as other storage ring IDs in terms of multipole correction and shimming

Undulator Spectrum

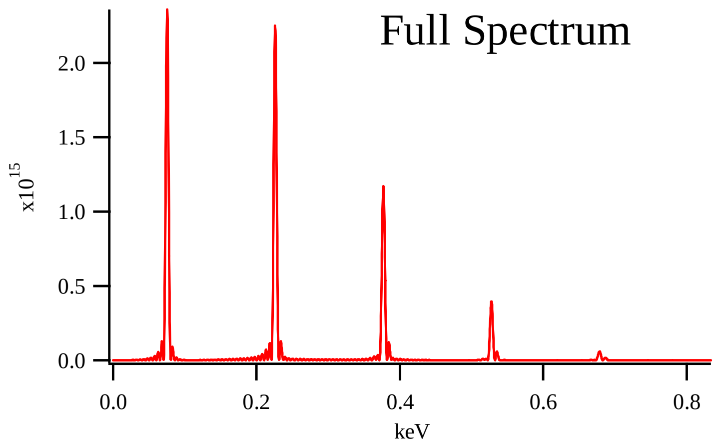
Vertical Field



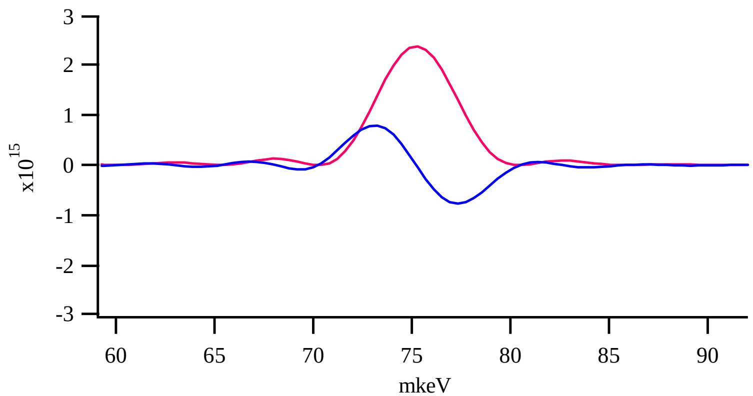
Horizontal Trajectory



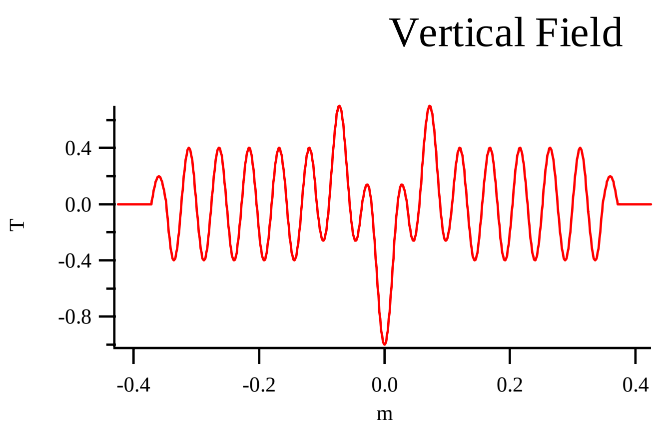
Full Spectrum

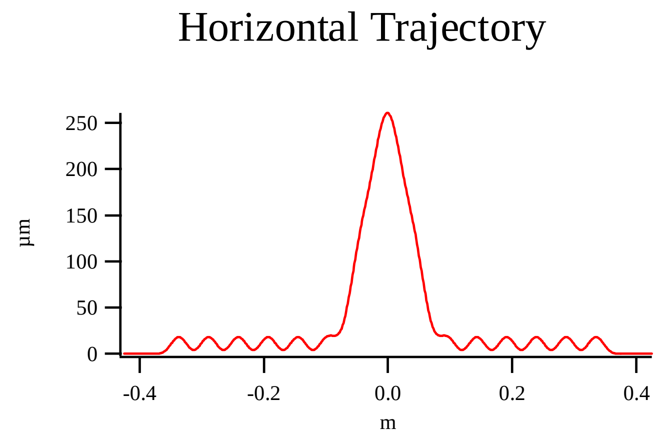


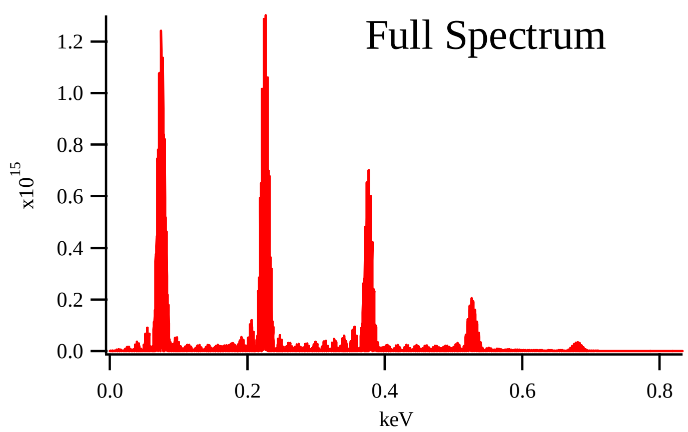
Spectrum of Fundamental

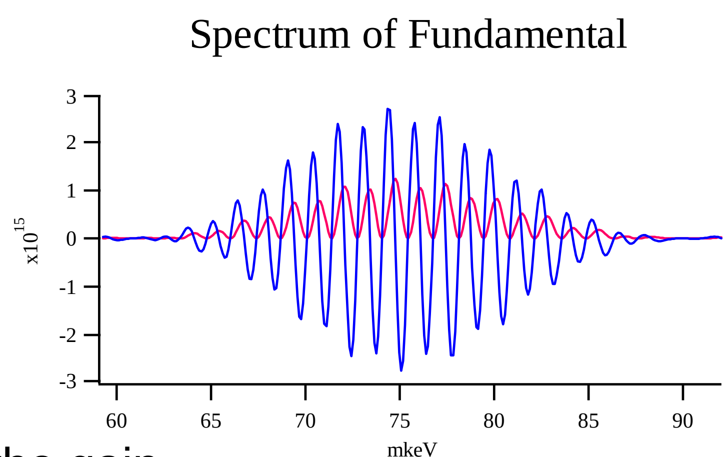


Optical Klystron Spectrum







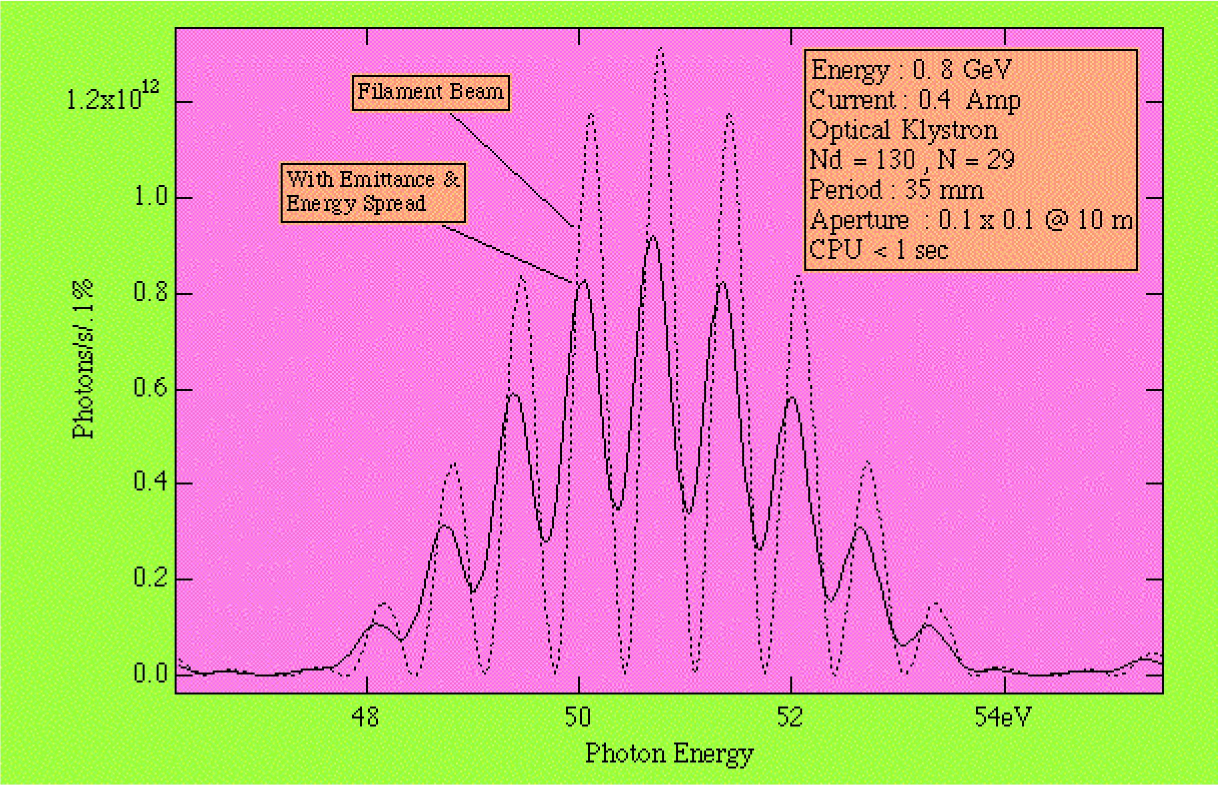


- The Narrower the fringes, the higher the gain.
- Electron energy spread and finite emittance blur the fringes => limits the gain

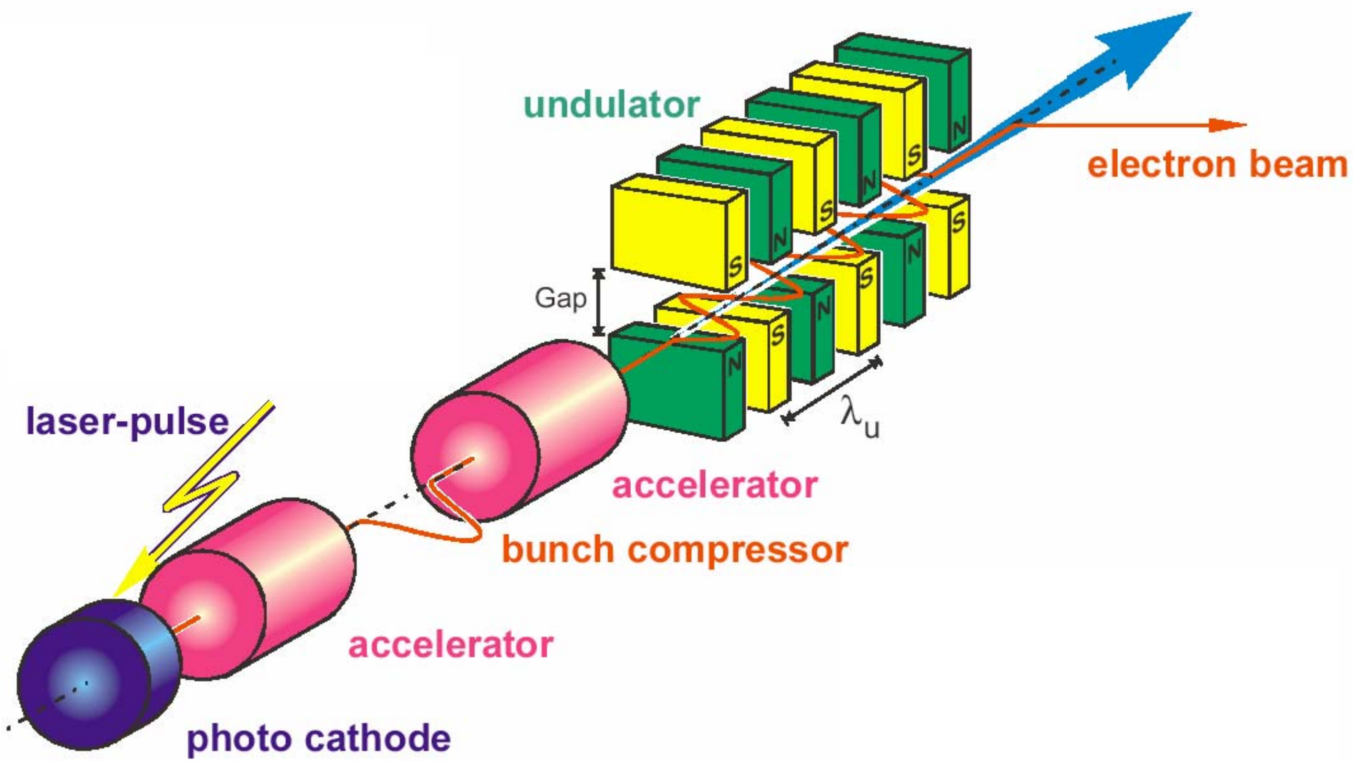
Gain/pass enhancement of 3-10

Fringe blurring induced by electron energy spread and emittance

$$\lambda = \frac{\lambda_0}{2\gamma^2}(1 + \frac{K^2}{2} + \gamma^2\theta^2)$$



Free Electron Laser based on Self Amplified Spontaneous Emission



Electron beam is essentially a single pulse of duration 50-500 fs
With a repetition rate 1-10 kHz

Undulators for SASE FEL

- Requires a gain per pass > 10^6 => Need very long undulators
  - L=10 m in visible
  - L=200 m for 0.1 nm (TESLA)

- Planar Undulators are the first choice because the technology is well mastered.

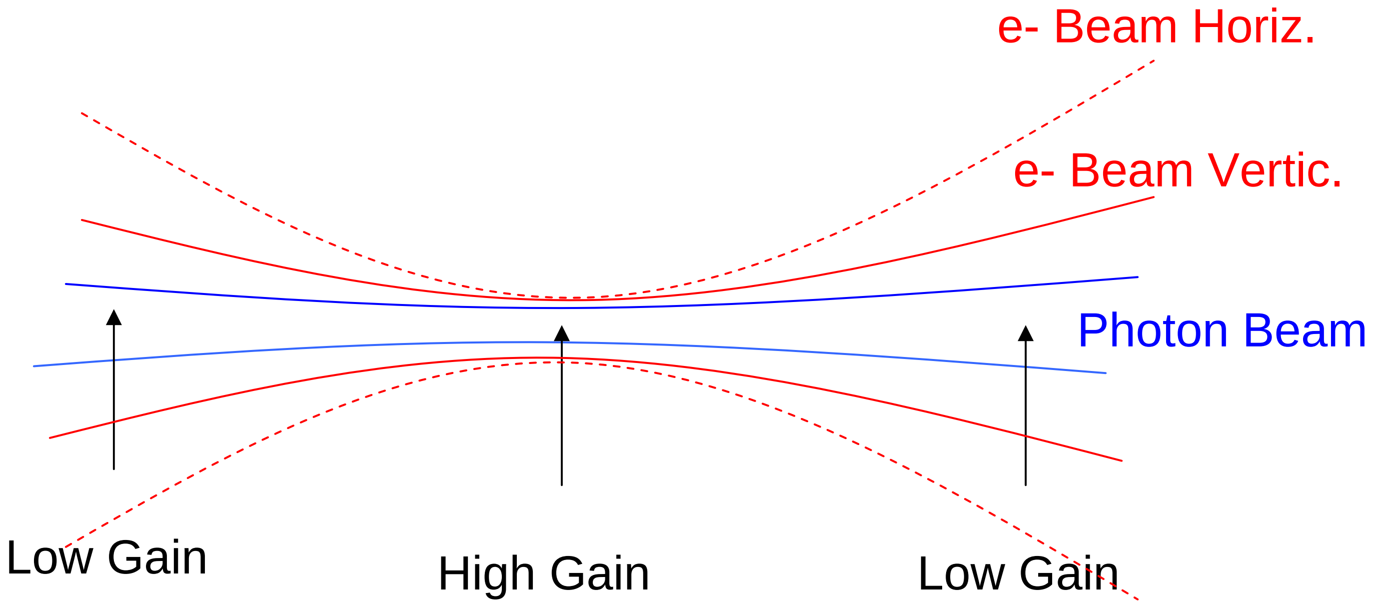
- Helical Undulators can saturate the radiation over a shorter distance
  - more economical
  - more delicate (Field errors, Field measurement)

- Whatever technology is used, what matters is not the length but the number of periods => gap reduction is very important to reduce the period and therefore the undulator length. The smallest usable gap is either determined by the electron beam emittance (low energy) or by the wake field (high energy).
  - L=120 m & gap= 6 mm for the LCLS undulator

Electron and Photon Beam Sizes

To maximize the gain, a high density electron beam must be used and the overlap between the electron and the photon beams maximized. This overlap is limited by diffraction for the photon beam emittance (emit~ $\lambda/4\pi$) and by the electron beam emittance itself.

A vertical field undulator focuses in the vertical plane only



Possible Solutions : **Two Plane Focusing** or **Strong Focusing**

Undulator and Quadrupole Focusing

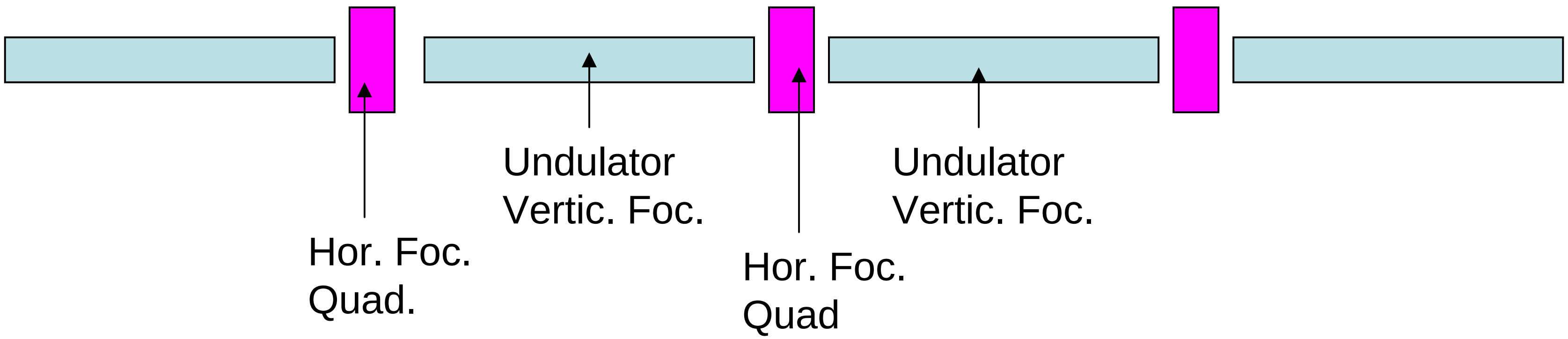
$$K_{Quadrupole}[m^{-2}] \propto \frac{1}{\gamma}\frac{dB_z}{dx}$$

Focusing in one plane
Defocusing in the other plane
Dominates at high electron energy

$$K_{Planar\ Undulator}[m^{-2}] \propto \frac{\hat{B}^2}{\gamma^2}$$

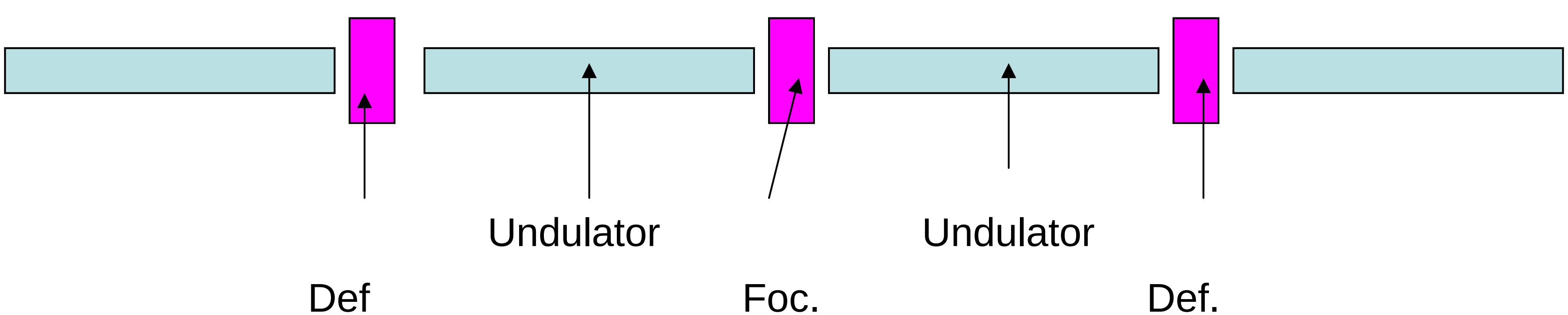
Focusing in Vertical plane
No effect in Horizontal plane
Dominates at low electron energy

Low Energy : TTF, LEUTL, VISA



Opimum distance between quadrupole can be < 1 m at very low energy =>
Require the installation of quadrupole in the undulator (VISA, TTF-1)

High Energy : LCLS, TESLA

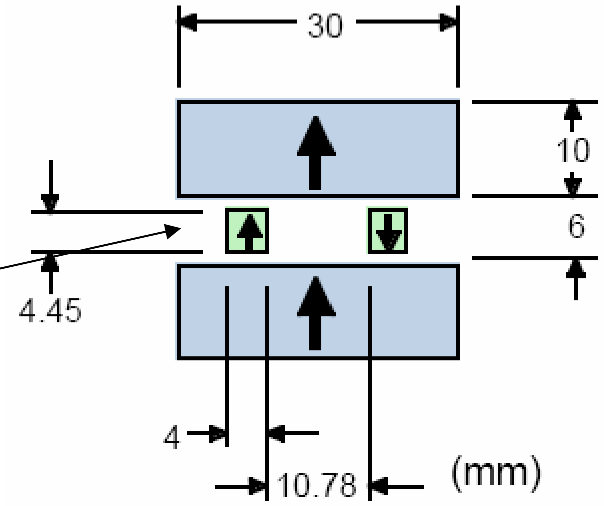


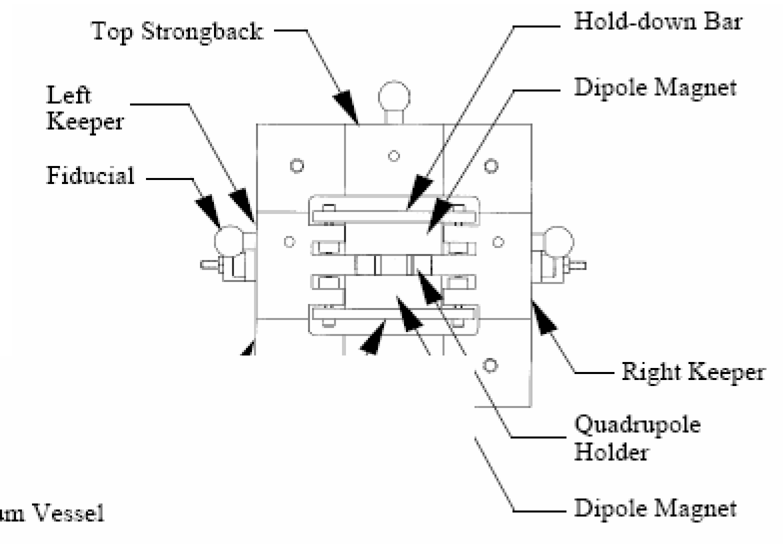
VISA Undulator

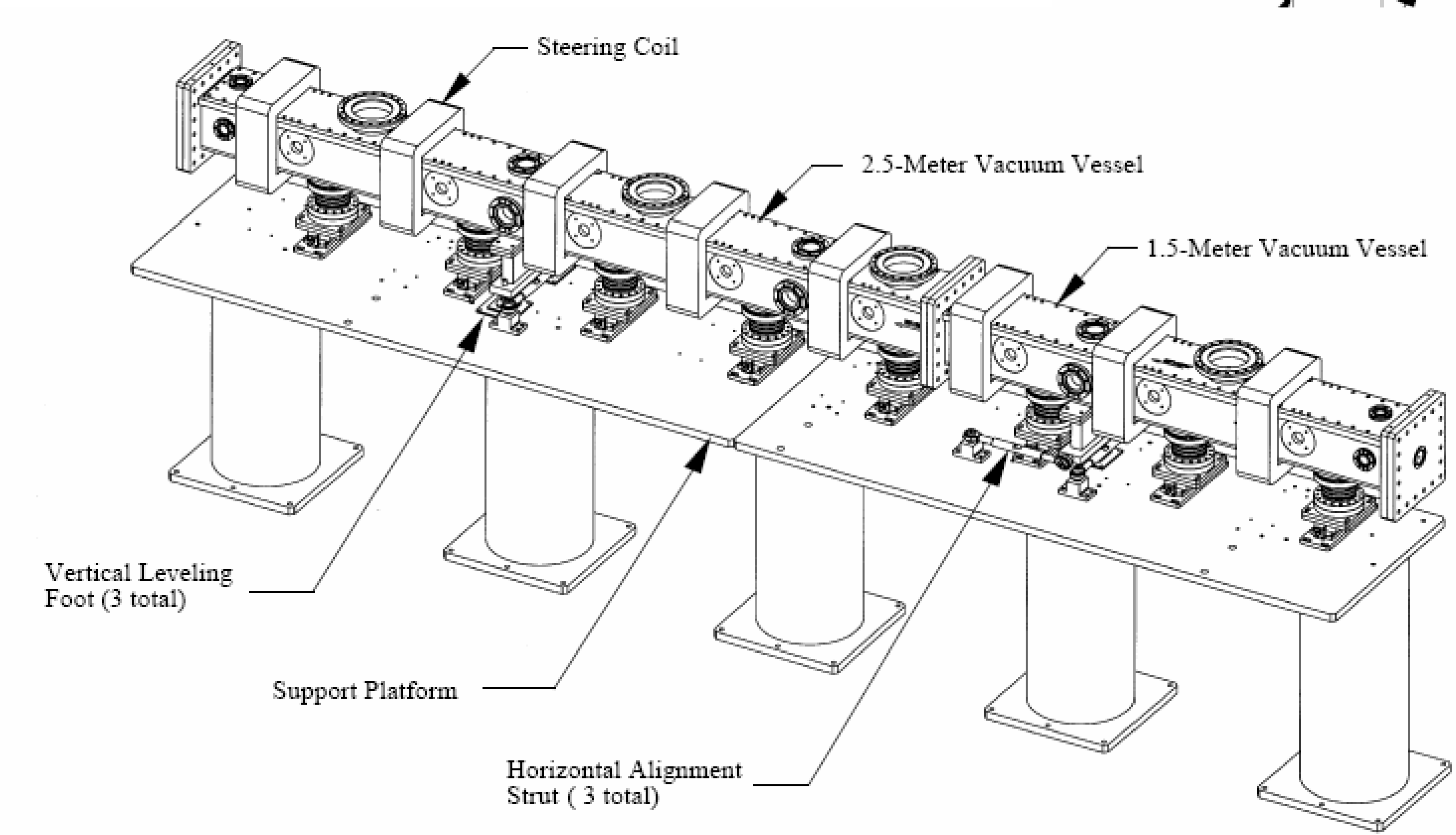
Period	18 mm
Gap	6 mm (fixed)
Block dimensions	30 x 10 x 4.45 mm
Remanence B_r	1.25 T
Intrinsic coercivity H_{ci}	>20 kOe
Peak field B_o	0.75 T
Number of periods	220 (4 x 55/section)

FODO Quadrupole Magnets

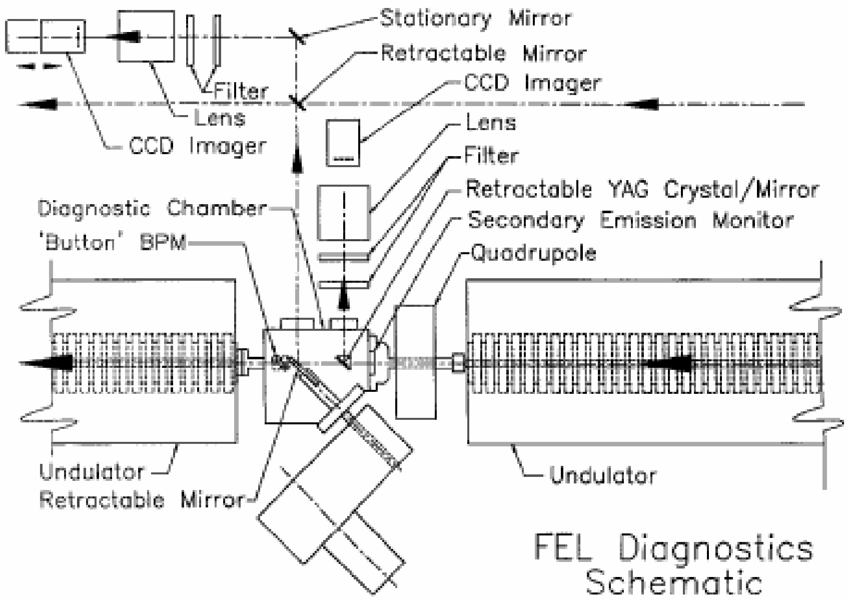
Gradient = 33 T/m




Top Strongback
Hold-down Bar
Dipole Magnet
Left Keeper
Fiducial
Right Keeper
Quadrupole Holder
Dipole Magnet


Steering Coil
2.5-Meter Vacuum Vessel
1.5-Meter Vacuum Vessel
Vertical Leveling Foot (3 total)
Support Platform
Horizontal Alignment Strut (3 total)

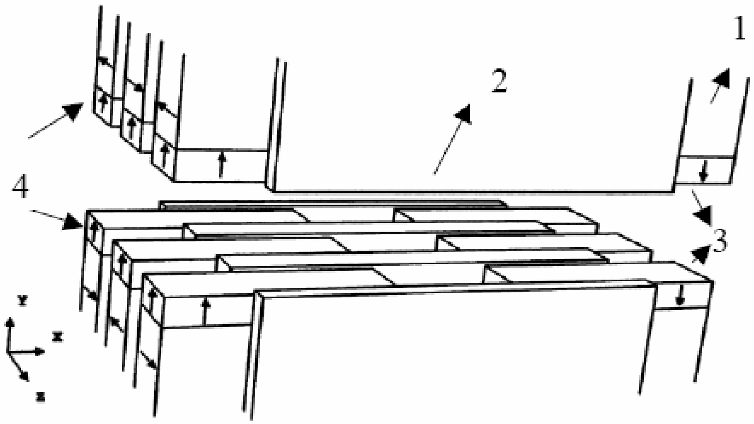
LEUTL Undulator (APS)



Fixed Gap
Period = 33 mm
Gap = 9 mm
Length = 11 x 2.4 m
K= 3.7
Wavelength = 500 to 100 nm

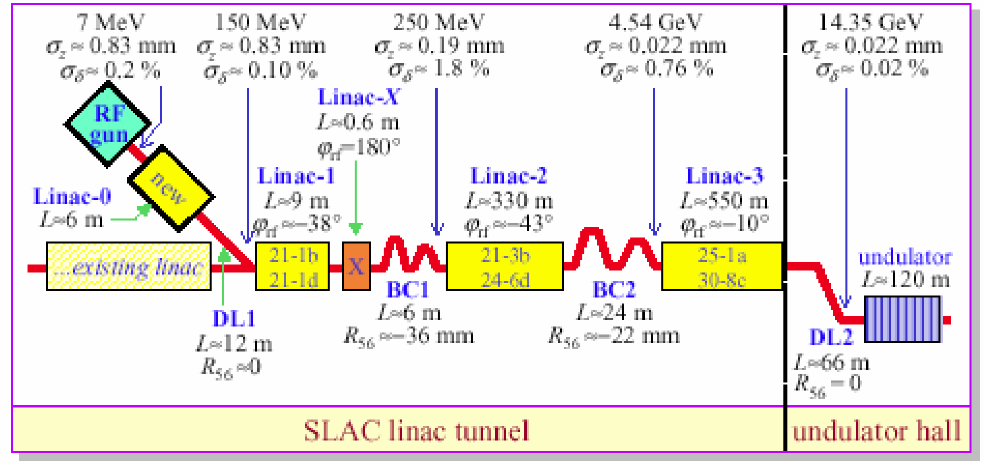
Tesla Test Facility Undulator

		TTF-1	TTF-2
Undulator Period Length	mm	27.3	27.3
Gap	mm	12	12
Peak field	T	0.47	0.47
K-Parameter		1.17	1.17
Electron beam energy	GeV	0.23	1.0
Segment length	m	4.4922	4.4922
Distance between Segments	mm	325	710
Focusing Type		integrated, FODO	separated, Doublet
Quadrupole type		Permanent magnet	Electro-magnet
Quadrupole distance	mm	477.75	5000 / 400
Quadrupole gradient	T/m	17	37
Quadrupole length	mm	163.8	82
Average β function	m	1	4.0
bMax / bMin	m	3.0	3.0
Saturation length	m	12	27
Length	m	15	30

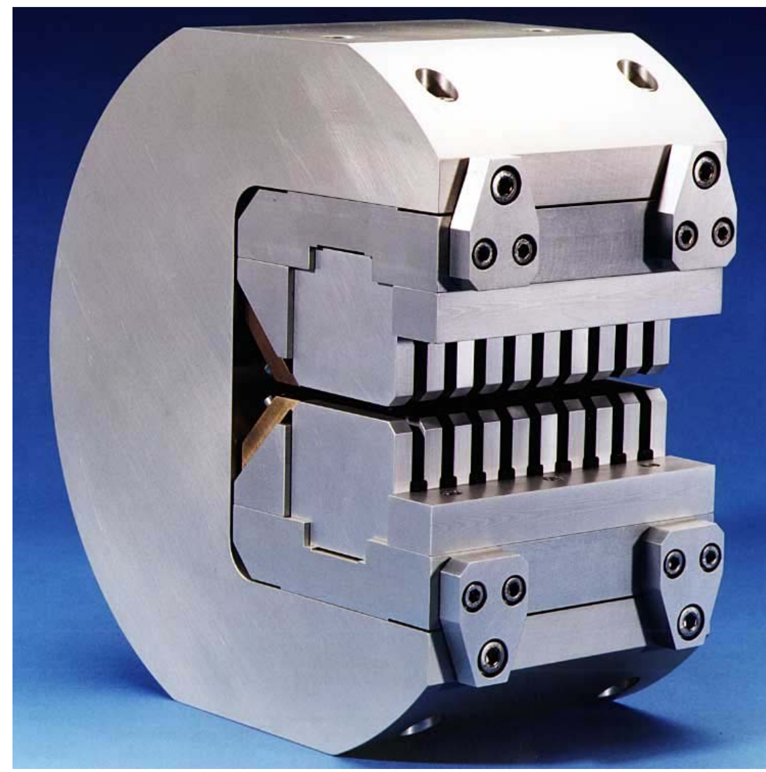


15 GeV Electrons **LCLS** 1.5 Å X-Ray

Linac Coherent Light Source

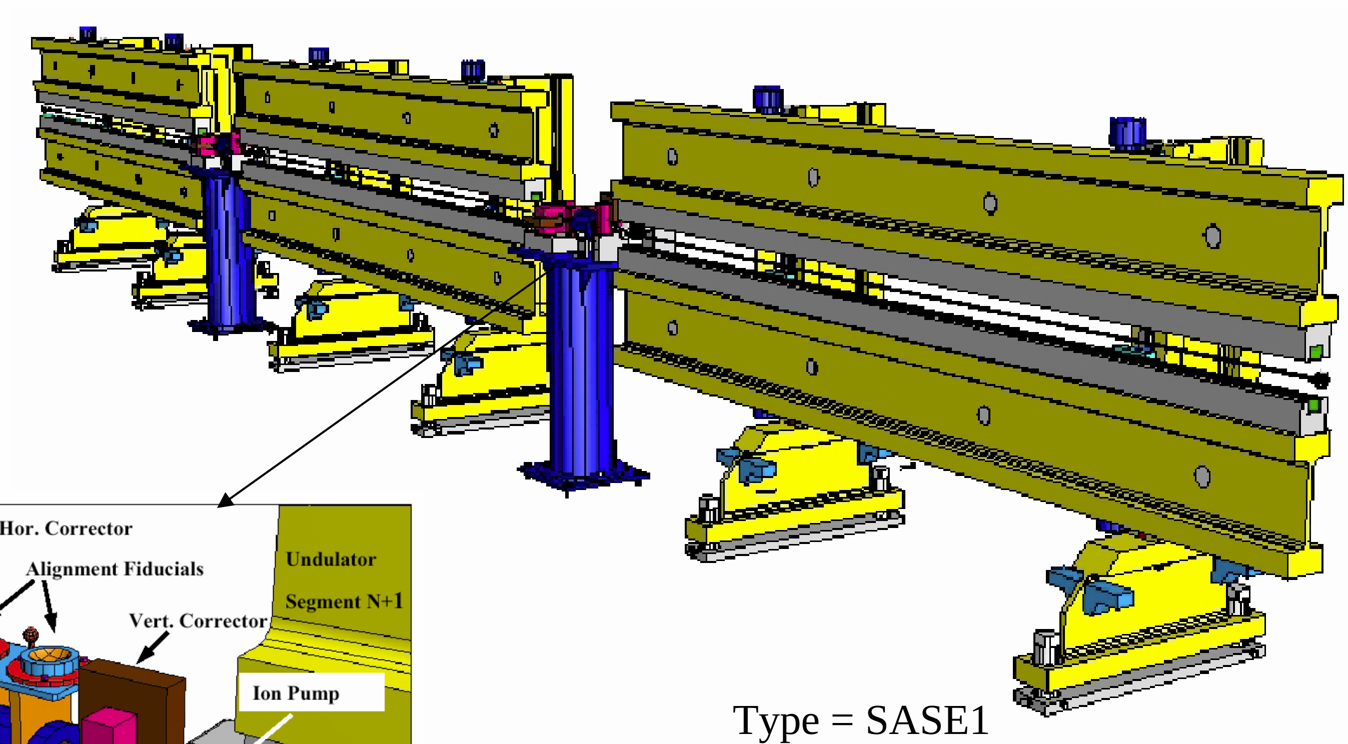


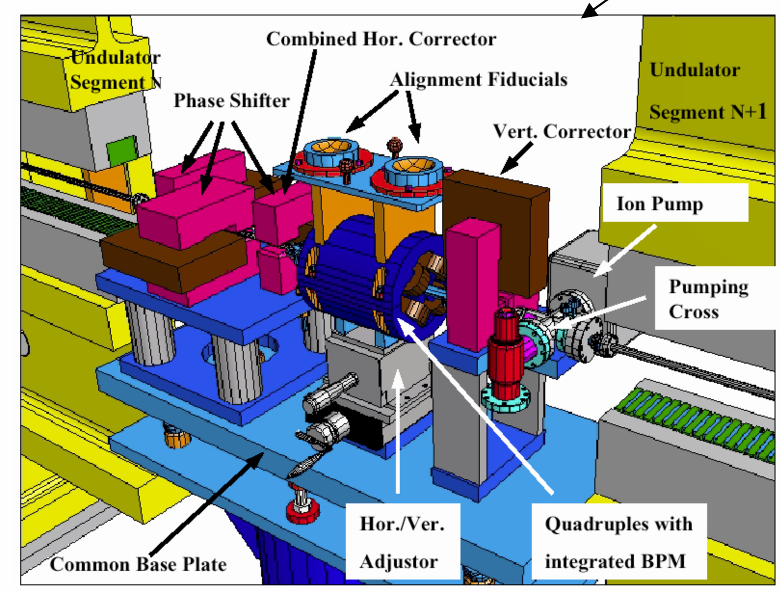
Technology : Hybrid Fixed Gap
Material : NdFeB
Period : 30 mm
Gap : 6 mm
B : 1.325 T
K : 3.711
Segment Length : 3.38 m
Number of Segments : 33
Total Length : 121 m
Fodo type Focusing
Average Beta Function : 8 / 18 m
Electron Energy : 4.5 / 14.4 GeV
Photon Wavelength : 1.5 / 0.15 nm
Photon Energy : 0.8 / 8.2 keV



http://www-ssrl.slac.stanford.edu/LCLS/

TESLA Undulator





Type = SASE1
λ= 0.1-0.35 nm
Energy = 20 GeV
Variable Gap = 19-12 mm
B = 0.66-1.33 T
Period = 60 mm
ß = 45 m
Length ~ 200 m

From TESLA TDR   http://www-hasylab.desy.de/

0.1 nm SASE Undulator

- Undulator Sections
  - All SASE undulators built so far have been planar, even though a helical undulator would saturate over a shorter distance (0.6).
  - The main requirement in field quality in the undulator is a straight trajectory a few micrometers over 10-200 m ! Only achieved by beam based alignment using steerer and beam position monitor in the transition sections
  - To minimize the energy variation along the bunch train induced by wake fields, one must use a copper vacuum chamber with small wall roughness and smoothely varying profile.

- Transition Sections includes
  - Focusing quadrupoles
  - Horizontal and Vertical Steerers
  - Phasing Sections
  - Electron beam Position Monitors