Study of X-ray Harmonics of the Polarized Inverse Compton Scattering Experiment at UCLA

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Introduction

$$a_0 = \frac{e\,A_0}{m_e\,c^2}$$

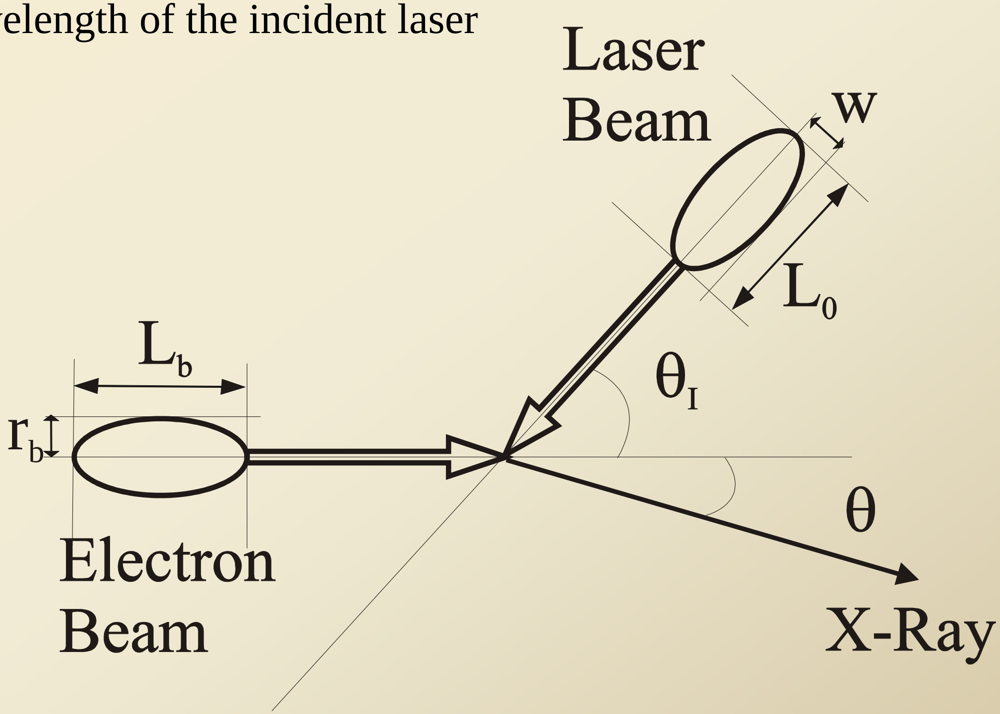
a_0 is the normalized amplitude of the vector potential of the incident laser field (just like K, undulator parameter)

$$a_0 = 0.85\,10^{-5}\,\lambda_0[m]\sqrt{I_0[W/m^2]}$$

I_0 is the intensity and λ_0 is the wavelength of the incident laser

$$\omega = \frac{\omega_0\,2\,\gamma_0^{\;2}\,(1+\beta_{z0})}{1+\frac{a_0^{\;2}}{2}+\gamma_0^{\;2}\,\theta^2}$$

Frequency of the scattered photons where ω_0 is the frequency of the incident laser, γ_0 is the relativistic factor of electron beam, β_{z0} is component of the electron initial velocity in the direction of laser pulse. (β_{z0}=1 for head on scattering and β_{z0}=0 for 90^o scattering.



ICS Calculations

$$N = \frac{\pi}{3} \alpha N_0 a_0^2 \frac{(1 + a_0^2/2)(1 + \beta_{z0})}{(1 + \bar{\beta}_z)}$$

The total number of photons radiated by a single electron

$$N_0 = \frac{(1 + \bar{\beta}_z) c T}{\lambda_0}$$

Where N_0 is the number of periods of the laser field with which electrons interacts

$$\bar{\beta}_z = \frac{\beta_{z0} - a_0^2/4\gamma_0 h_0}{1 + a_0^2/4\gamma_0 h_0}$$

the average axial electron velocity

$\alpha = 1/137$ Fine structure constant

$$h_0 = \gamma_0 (1 + \beta_{z0})$$

$$T = \frac{1}{c} \min\left(\frac{L_0}{1 + \bar{\beta}_z}, \frac{2 Z_r}{\bar{\beta}_z}, \frac{2 w_0}{\beta_{\perp 0}}\right)$$

Interaction time

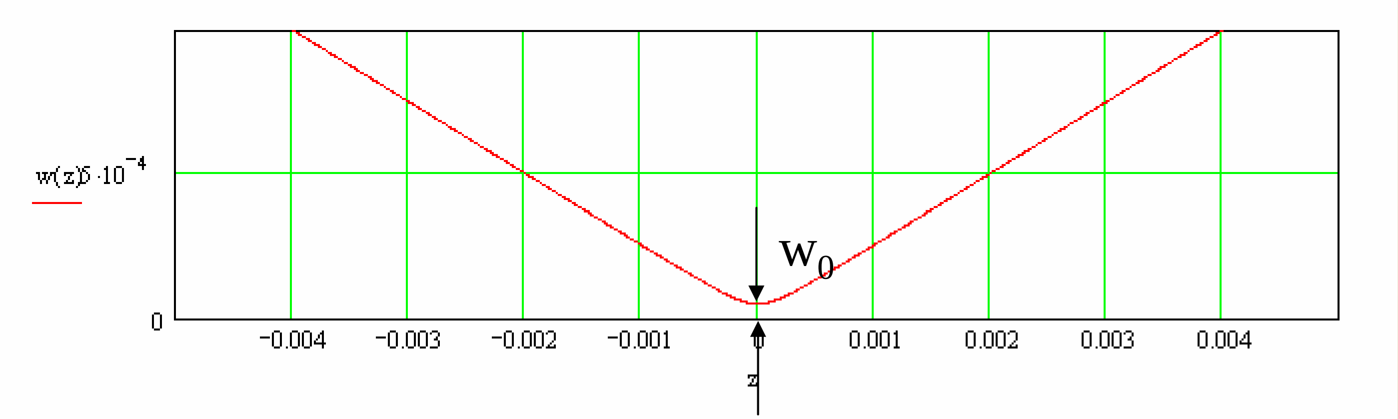
$$Z_r = \frac{\pi w_0^2}{\lambda_0}$$

Rayleigh range where w_0 is the waist radius of the laser

Gaussian beam

$$I(r) = I_0 e^{-2r^2/w^2} = \frac{2P}{\pi w^2} e^{-2r^2/w^2},$$

$$w = 2\sigma$$



$$w(z) = w_0 \sqrt{1 + \left[\frac{z M^2}{Z_r}\right]^2}$$

$$F_\# = \frac{1}{2M^2}\sqrt{\frac{\pi Z_r}{\lambda_0}}$$

F number is f/D
~z/2w(z)

Radius of the beam

Incident Laser focusing properties

75 μm waist radius using an F3 and 50 μm waist radius using F2 focusing geometries are achieved experimentally in Neptune.

The M factor is estimated to be 1.93.

For F2 geometry the Rayleigh range is 0.75 mm. 500 GW laser yields an intensity of $1.25\text{x}10^{16}$ W/cm^2 and $a_0 \cong 1$. Since a_0 is proportional to λ_0 wavelength it is advantageous to use CO_2 laser compared to YAG lasers.

For F3 geometry the Rayleigh range is 1.7 mm. 500 GW laser yields an intensity of $5.5\text{x}10^{15}$ W/cm^2 and a0 $\cong 0.67$.

Time duration of the scattered photons

For head configuration the pulse duration will be determined by either the electron bunch length if $L_b < L_0$, Z_r or by the pulse length of the laser pulse if electron bunch length is longer than the laser pulse length. So we can express the duration of the scattered photons as

$$\tau_\gamma = \frac{1}{c}\min[L_b, (4Z_r + L_0)]$$

For transverse scattering duration of the scattered photons is again determined by electron bunch length if electron is short or by transverse dimension and Rayleigh range of the laser pulse along with the pulse length if electron is long. Thus we can express duration of scattered photons as

$$\tau_\gamma = \frac{1}{c}\min[L_b, 2Z_r + L_0, L_0 + 2r_b]$$

Inverse Compton Scattering Experiment Design Parameters

Electron and Laser Beam Parameters

TABLE 1). Electron and Laser Beam Parameters

Parameter	Value
Electron Beam Energy	14 MeV
Beam Emittance	5 mm-mrad
Electron Beam Spot size (RMS)	25 μm
Beam Charge	300 pC
Bunch Length (RMS)	4 ps
Laser Beam size at IP (RMS)	25 μm
CO_2 laser wavelength	10.6 μm
CO_2 laser Rayleigh range	0.75 mm
CO_2 laser power	500 GW
CO_2 laser pulse length	200 ps

Design Scattered Photon Properties

Head-on scattering	
Parameter	**Value**
Scattered photon wavelength	5.3 nm
Scattered photon energy	235.3 eV
Scattered photon pulse duration (FWHM)	10 ps
Interaction time	5 ps
Number of periods that electrons see (N_0)	283
Number of photons emitted per electron (N)	3.34
Total number of photons	$6.3.10^9$
Half Opening Angle	2.7 mrad
Bandwidth	10 %

Transverse scattering	
Parameter	**Value**
Scattered photon wavelength	10.7 nm
Scattered photon energy	117.7 eV
Scattered photon pulse duration (FWHM)	10 ps
Interaction time	0.33 ps
Number of periods that electrons see (N_0)	10
Number of photons emitted per electron (N)	0.11
Total number of photons	2.10^8
Half Opening Angle	15 mrad
Bandwidth	10 %

Nonlinear Harmonics

$$\frac{\Delta\omega}{\omega_n} = \frac{1}{n N_0}$$

Bandwidth where N_0 is the number of periods that electrons interact.
10% bandwidth is estimated for the fundamental

$$\Delta\theta = \sqrt{\frac{(1 + a_0^2 / 2)\Delta\omega}{\gamma^2 \omega_n}}$$

Half opening angle of the harmonics
15 mrad half angle is estimated

$$\omega_n = \frac{\omega_0 \, n \, 2 \gamma^2 (1 + \beta_{z0})}{1 + \frac{a_0^2}{2} + \gamma^2 \theta^2}$$

Frequency of harmonics

$$\lambda_n = \frac{\lambda_s}{n}$$

Wavelength of harmonics

Double Differential Spectrum of Nonlinear Harmonics

$$\frac{d^2 I_n}{d\omega\, d\Omega} = \frac{e^2 k_0^{\,2}}{\pi^2 c}\left[\frac{\sin \bar{k}\eta_0}{\bar{k}}\right]^2 [A_1 J_n^{\,2} + A_2 (J_n' / b_t)^2]$$

Radiation Spectrum for circularly polarized laser beam*

$$\frac{d^2 I_{\theta n}}{d\omega\, d\Omega} = \frac{e^2 k_0^{\,2}}{4\pi^2 c}\left[\frac{\sin \bar{k}\eta_0}{\bar{k}}\right]^2 [\frac{k}{k_0}\frac{\partial g}{\partial\theta} B_0 - \frac{\partial b_1}{\partial\theta} B_1 + 2\frac{\partial b_2}{\partial\theta} B_2]^2$$

$$\frac{d^2 I_{\phi n}}{d\omega\, d\Omega} = \frac{e^2 k_0^{\,2}}{4\pi^2 c}\left[\frac{\sin \bar{k}\eta_0}{\bar{k}}\right]^2 [\frac{\partial b_1}{\partial\phi}\bigg|_{\phi=\frac{\pi}{2}} B_1 - 2\frac{\partial b_2}{\partial\phi}\bigg|_{\phi=\frac{\pi}{2}} B_2]^2$$

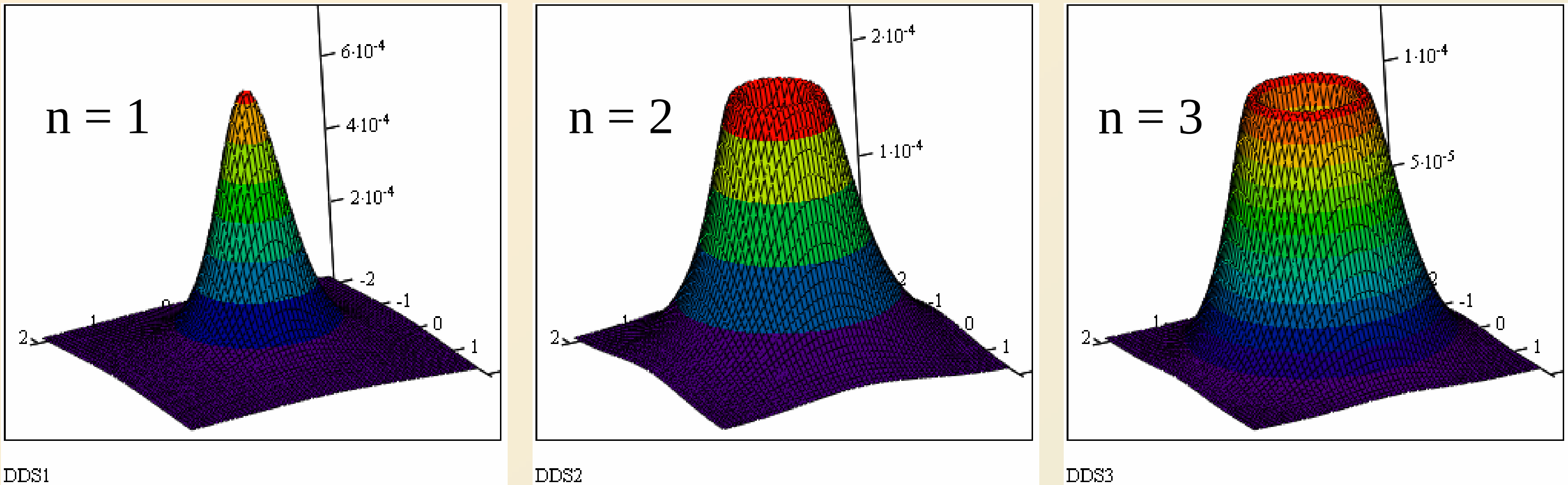
$$\frac{d^2 I_n}{d\omega\, d\Omega} = \frac{d^2 I_{\phi n}}{d\omega\, d\Omega} + \frac{d^2 I_{\theta n}}{d\omega\, d\Omega}$$

Radiation Spectrum for linearly polarized laser beam*

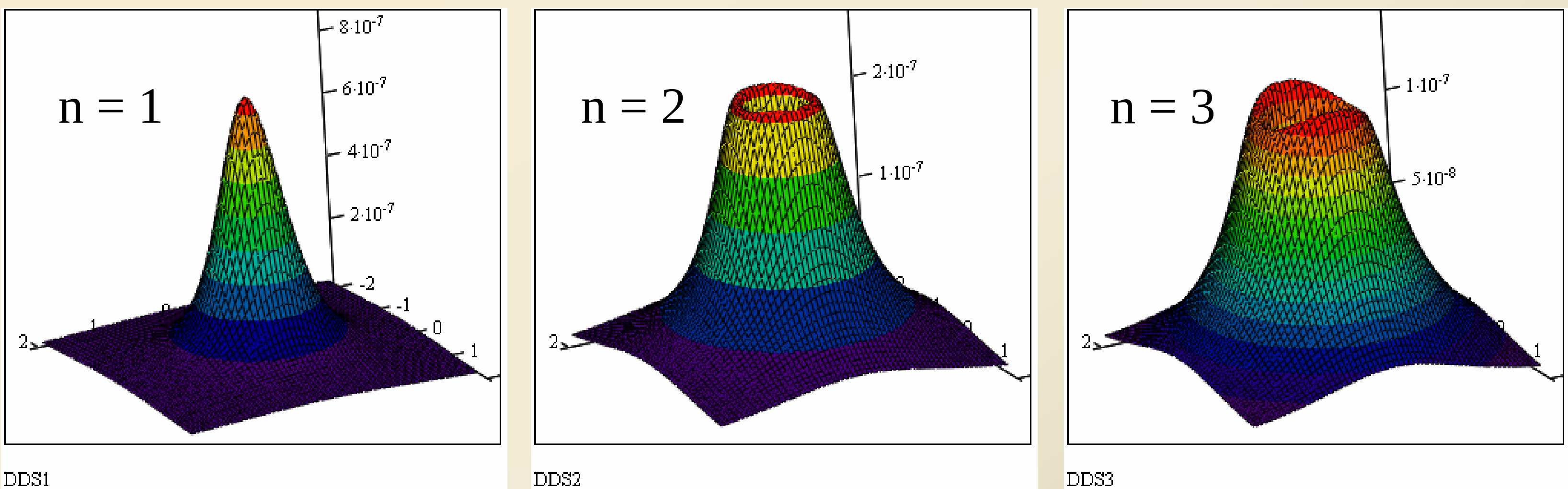
*Ride, Esarey, Baine, Phys. Rev. E, Vol 52, p 5425 (1995)

Note: All the variables are defined in the paper

DDS plots for circularly polarized laser

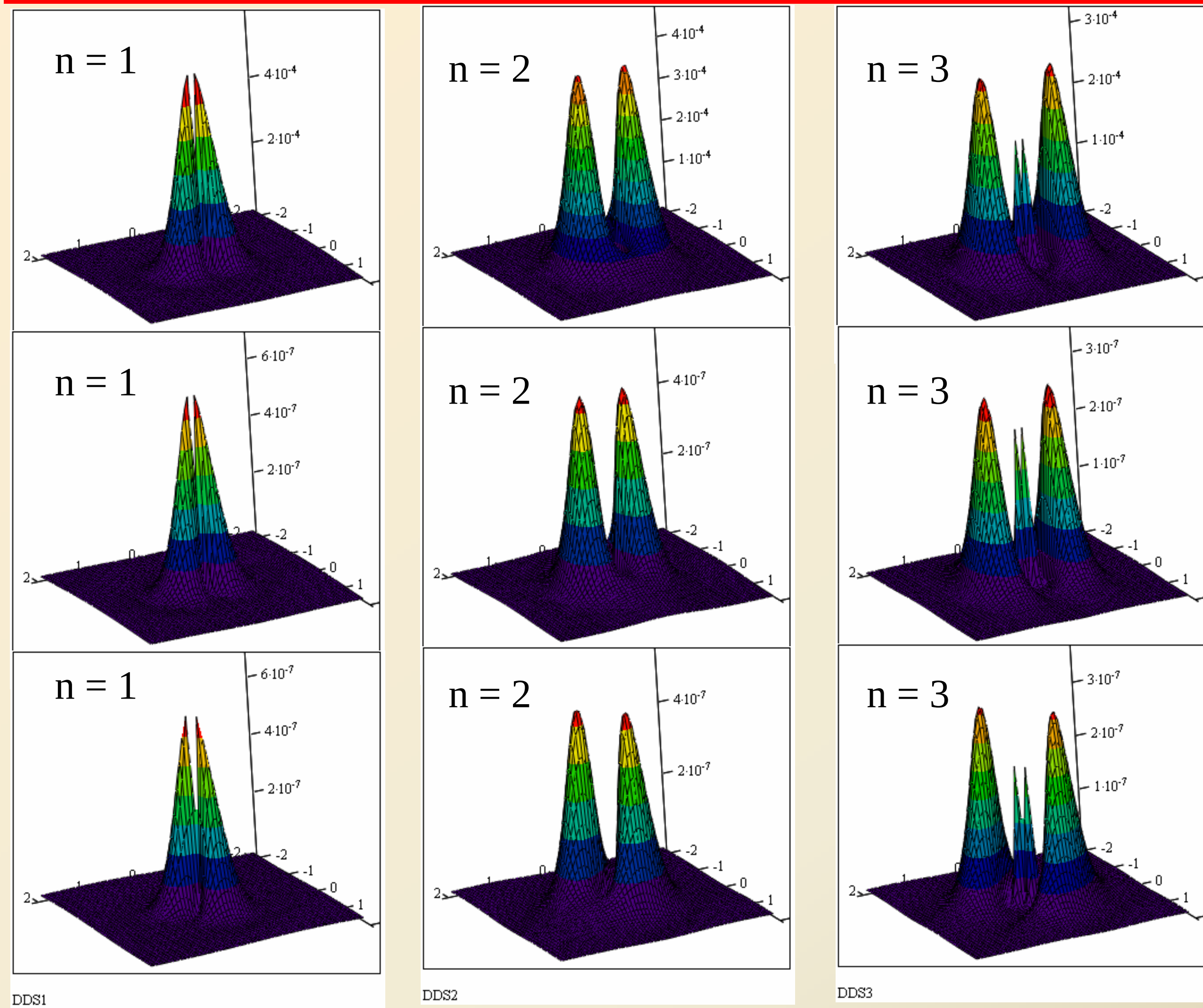


180^0 geometry



90^0 geometry

DDS plots for linearly polarized laser

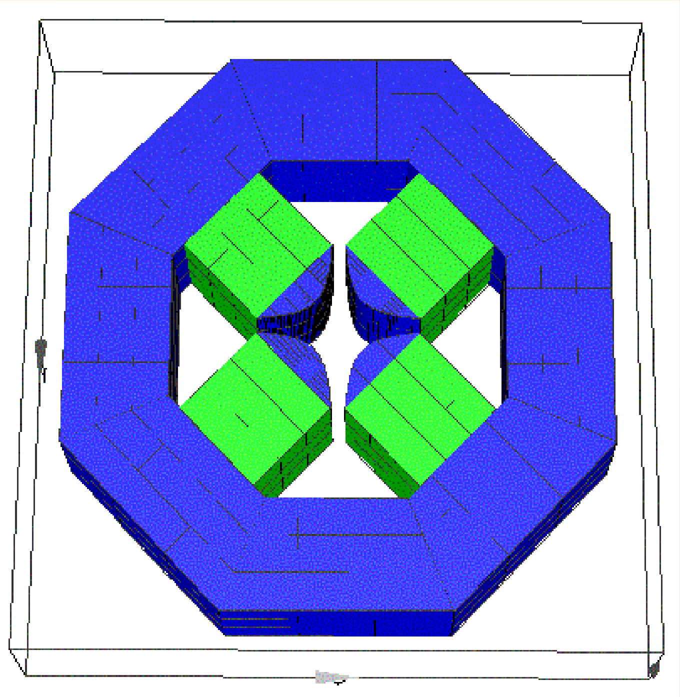


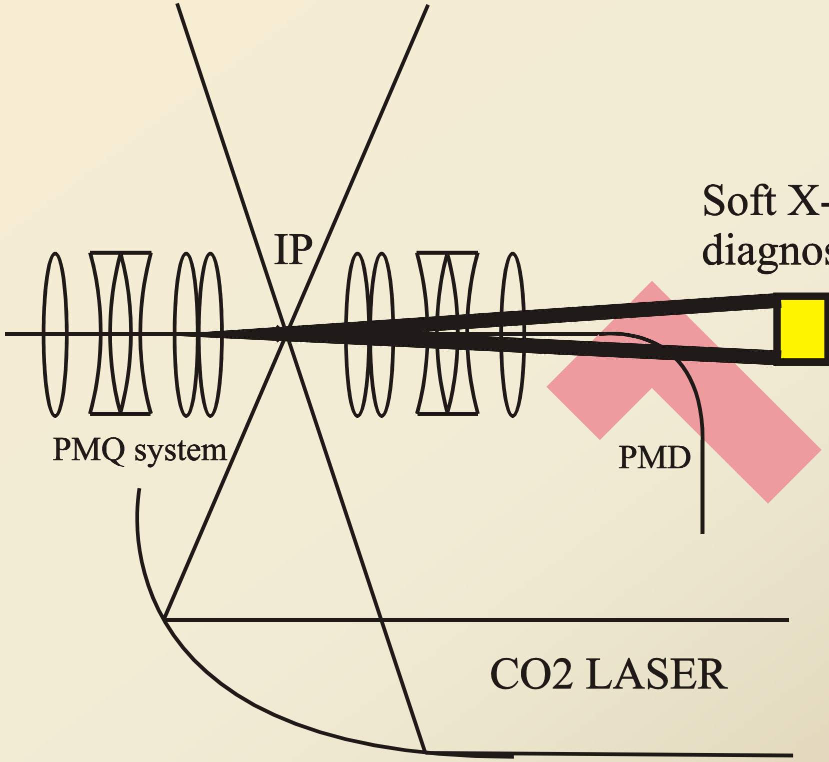
180^0 geometry

90^0 geometry parallel polarization

90^0 geometry perpendicular polarization

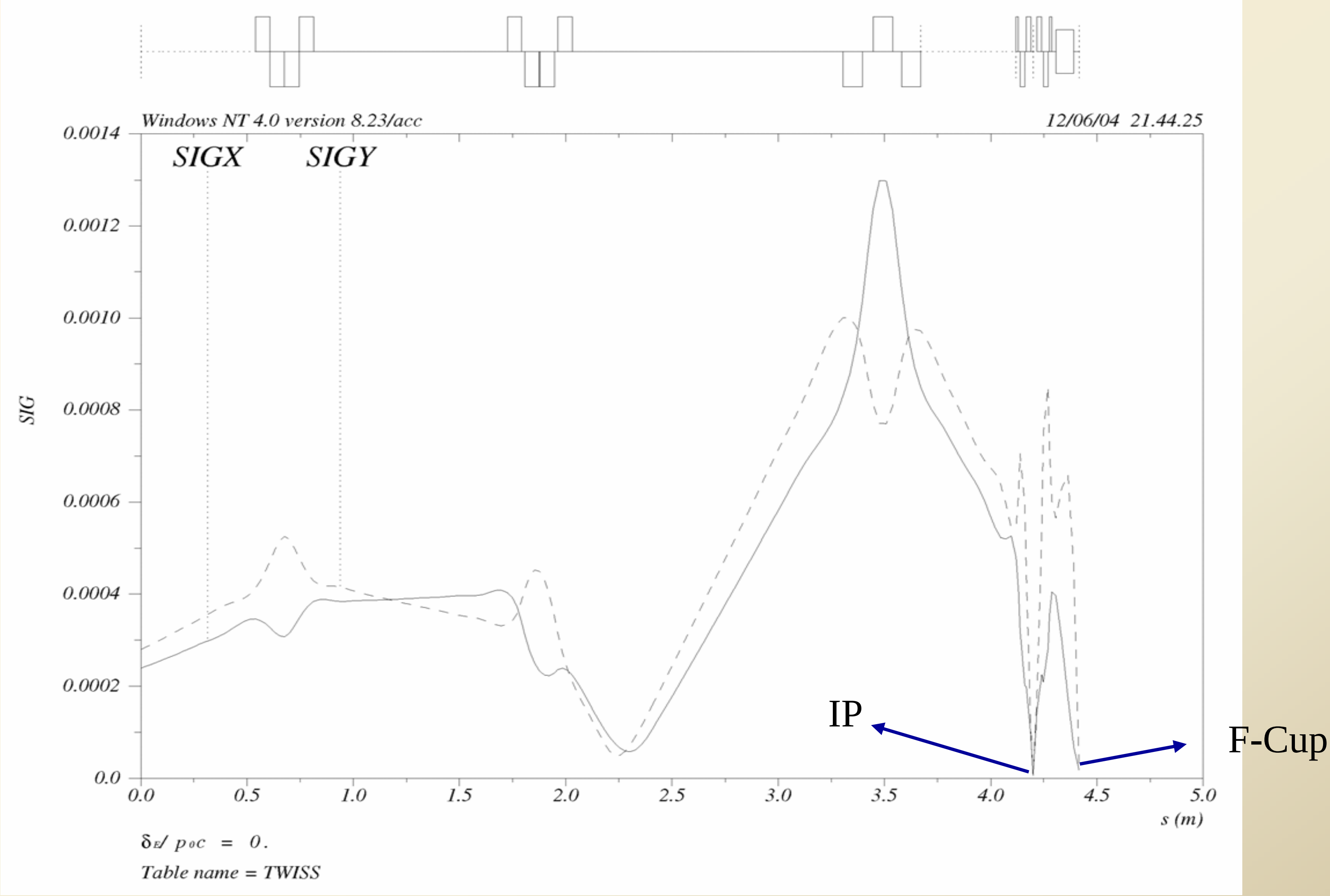
Permanent Magnet Quadrupole (PMQ) System for Final Focus



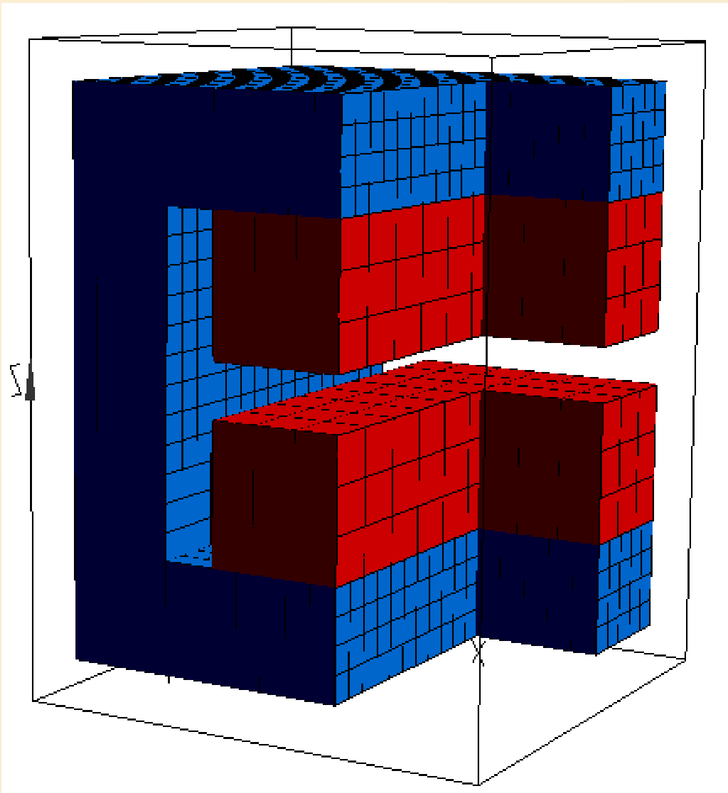


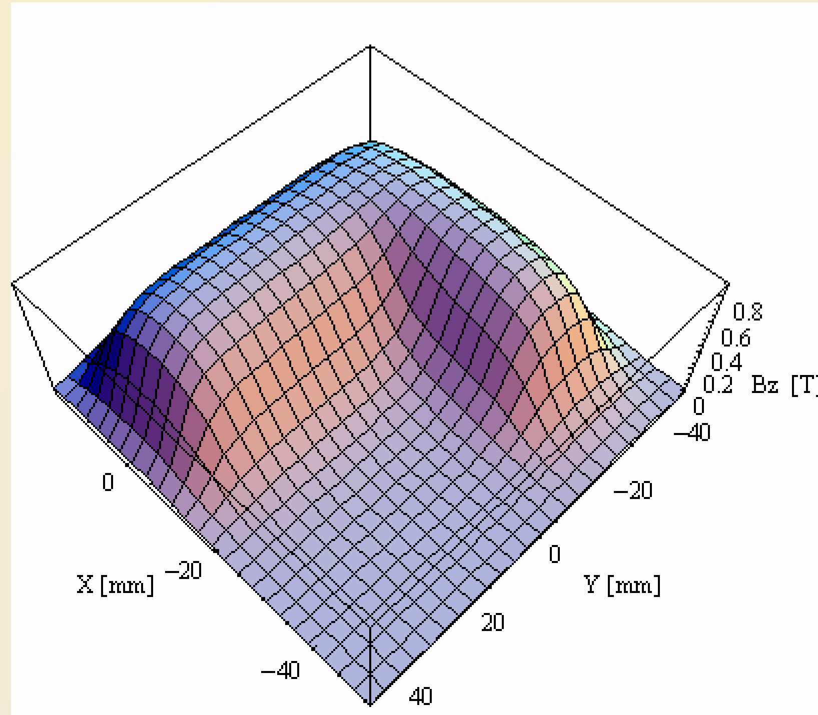
Four permanent magnet cubes (NdFeB) are positioned to produce Quadrupole field at the axis. Radia Program is used to design the magnet to produce 110 T/m gradient. Octagonal iron yoke provide proper field flow and hyperbolic iron tips produce perfect quadrupole field inside the magnet. The prototype was build and it is good agreement with the simulation. 1% field error in the magnetization of the cubes in worst orientation causes 10 μm axis offset which is quite reasonable. The cubes are measured and sorted to reduce possible errors.

Beam Transport for Inverse Compton Scattering



Permanent Magnet Dipole (PMD) for Energy Spectrometer





Field distribution inside the PMD gap simulated by Radia

A Permanent magnet Dipole is designed to serve as energy spectrometer and dump for the electron beam. It bends the beam by 90^{o}. The geometry is chosen so that beam always exits the dipole at 90^{o} for various energies only with some offset.

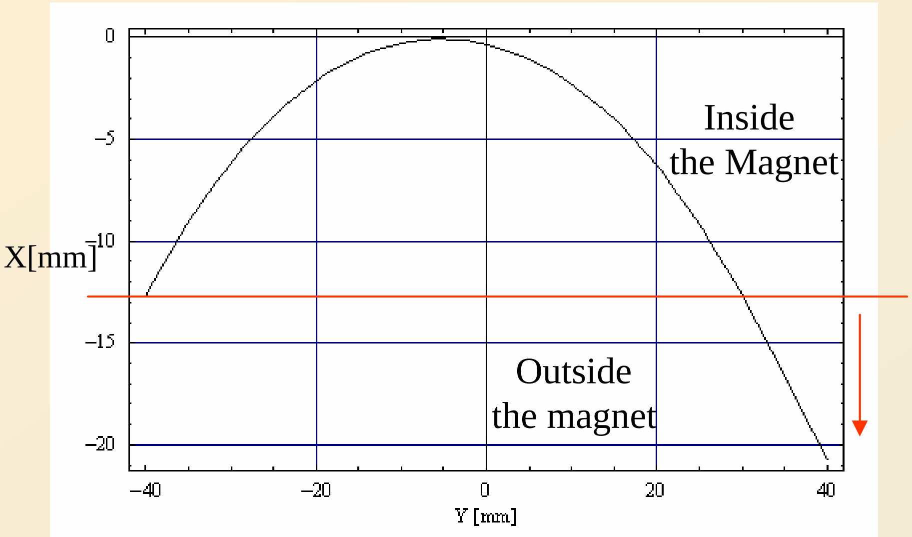
Iron Yoke is designed for proper field flow

Magnets are made out of NdFeB high grade magnets which can yield 1.2-1.4 T magnetization.

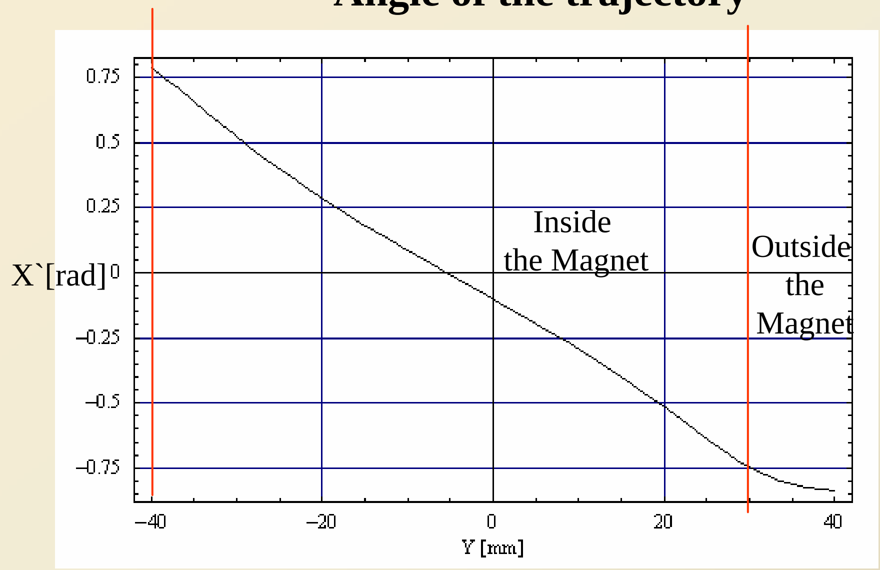
The Magnetic field inside the gap is ~0.85 T. For 14 MeV energy design electrons the bend radius is about 55mm

Trajectory in the PMD

Trajectory of the electron beam in PMD



Angle of the trajectory



Trajectory of the 14 MeV electron beam in the PMD gap. Beam enters the magnet by 45 º angle and exits by 45 º angle. Y axis is the length of the magnet and x axis is width.

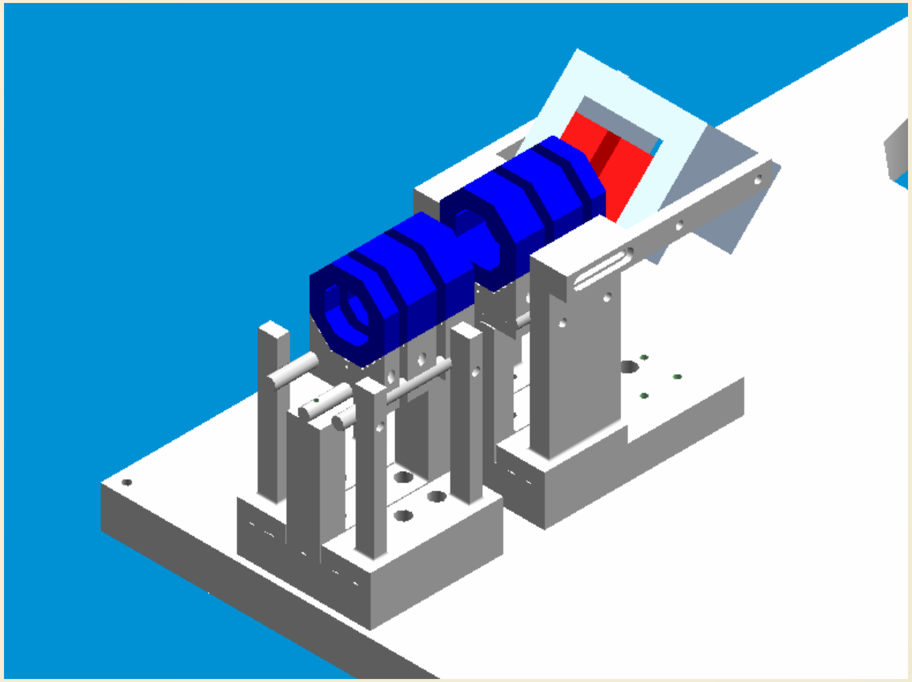
Angle of the 14 MeV electron trajectory in the PMD gap. Angle linearly changes from π/4 to -π/4 inside the magnet.

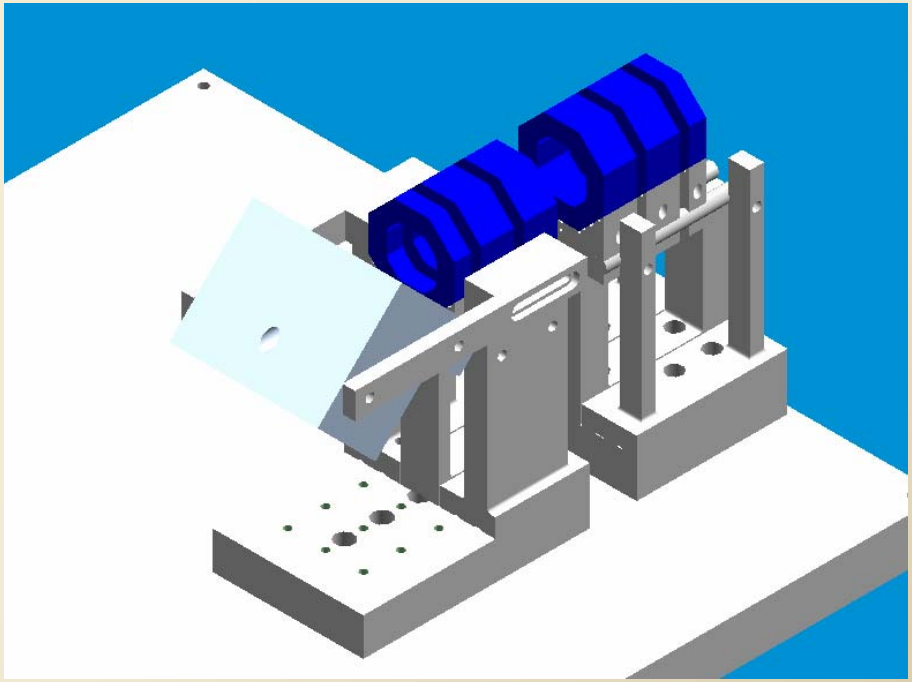
$$\omega_c = \frac{3}{2}\gamma^3 \omega_0 = \frac{3}{2}\gamma^3 \frac{c}{\rho}$$

Synchrotron radiation wavelength is 7.6 μm

$$\lambda_c = \frac{4\pi}{3}\frac{\rho}{\gamma^3}$$

ICS Box design





Current Status

- PMQ design is complete and manufacturing is underway
- PMD design is complete and manufacturing is in progress
- Box design is in progress
- Soft X-ray camera may come from Argonne
- Polarization measurement is being researched