Electron Laser interaction

System consists of

Relativistic electron beam

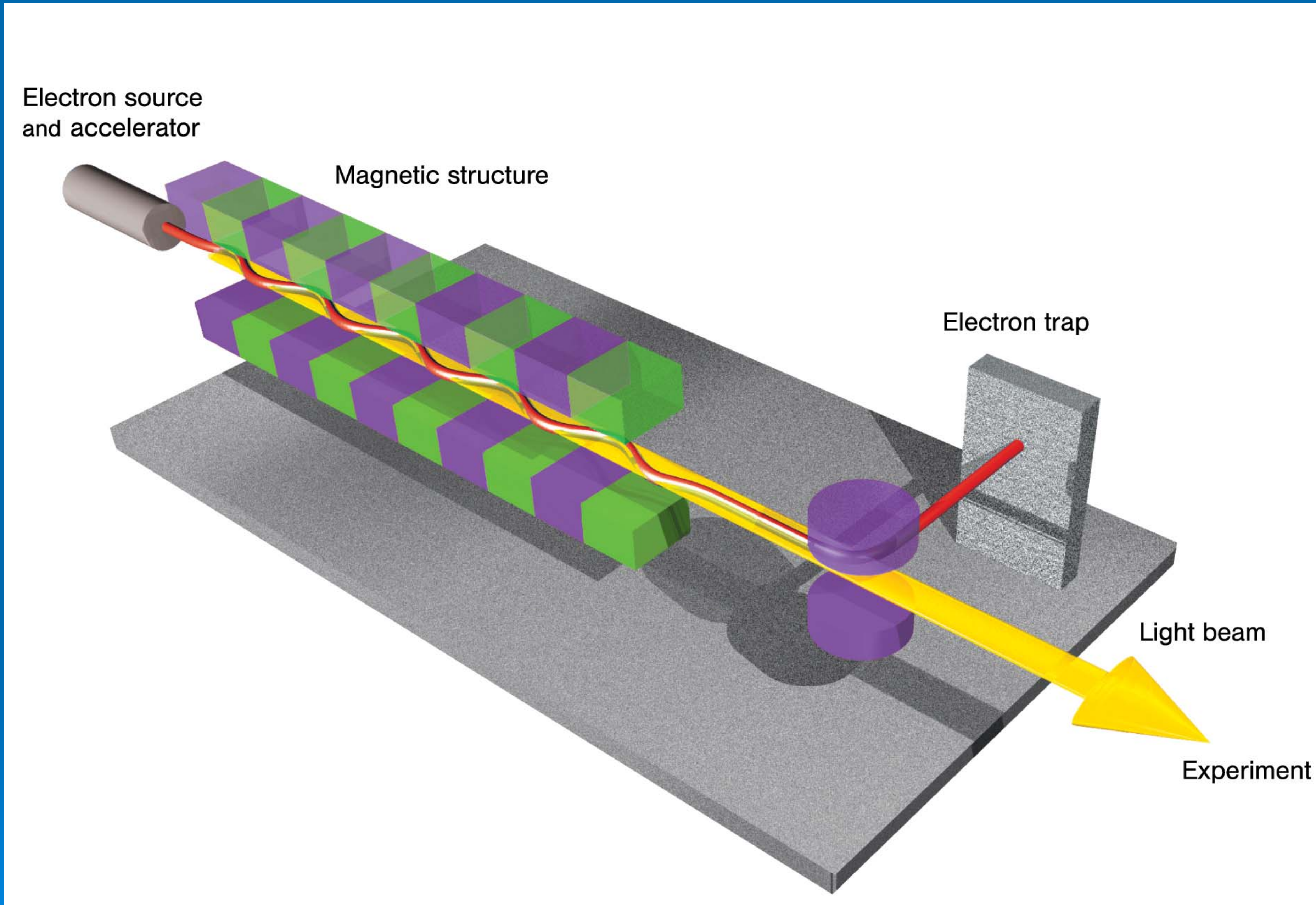
Magnetic field

Laser beam

Following section describes interaction of the electron beam with either magnetic field, laser beam or both

References:

Classical Electrodynamics, Jackson, Ch. 9, 12, 14,
Free Electron Lasers, C. H. Brau, Ch.1, 2
High energy free electron laser accelerator, E. D. Courant, C. Pellegrini, W. Zakowicz, Phys. Rev A 32(1985) 2813


Electron source
and accelerator
Magnetic structure
Electron trap
Light beam
Experiment

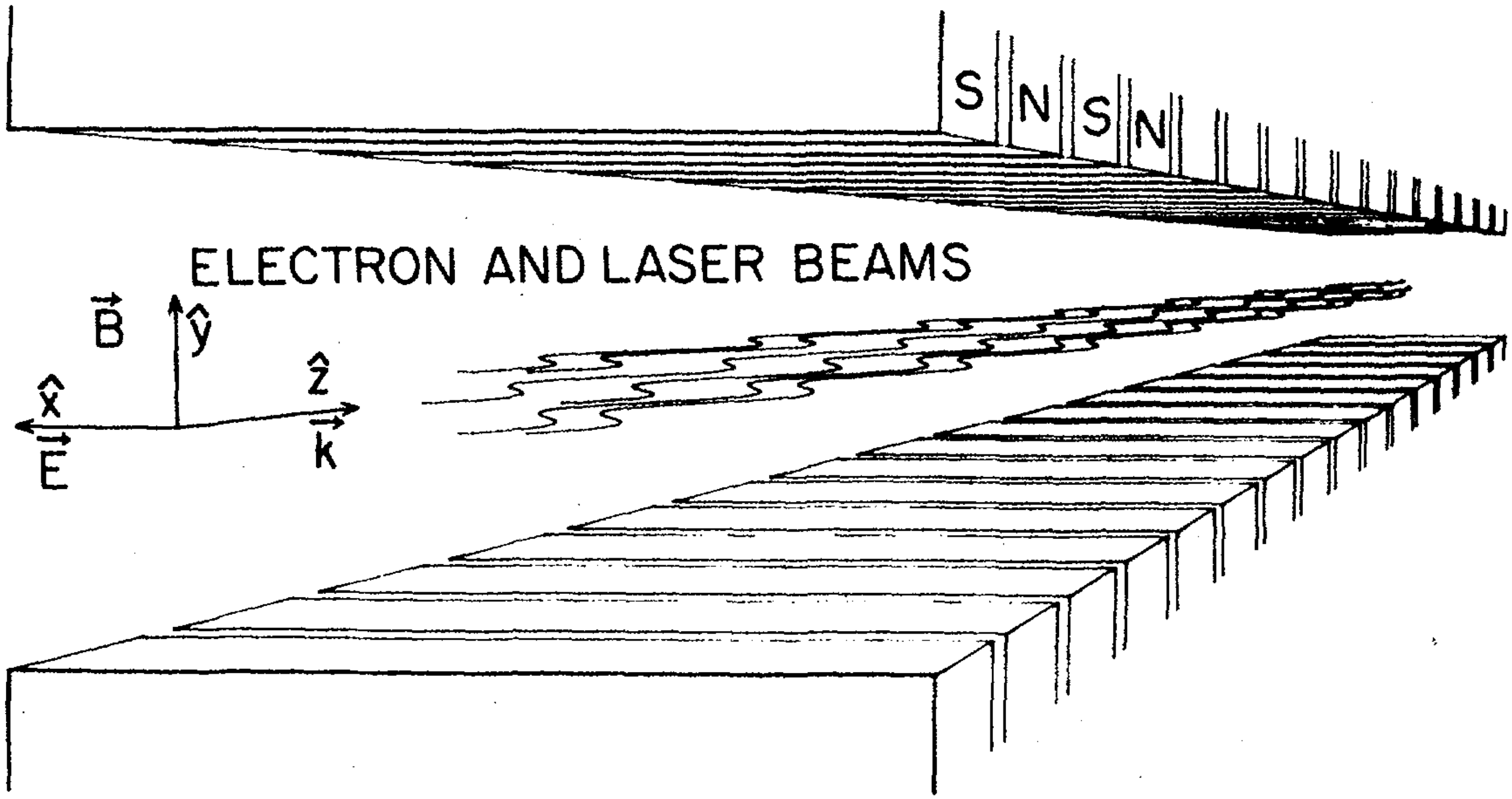


FIG. 1. Schematic view of IFEL accelerator.

Let us consider a system where relativistic electrons are moving along a magnetic wiggler in the filed of a laser. Let us further assume that the Poynting vector of the laser, the electron propagation direction, and the wiggler axis are parallel. The Lorentz equation of motion of the electron, including the force of radiation reaction, F_{reac} ,can be written as

$$m\frac{d(\gamma\vec{v})}{dt} = e\left[\vec{E}_l + \frac{\vec{v}}{c}\times\left(\vec{B}_l + \vec{B}_w\right)\right] + \vec{F}_{reac}$$

$\vec{E}_l$ Is the electric field of the laser,

$\vec{B}_l$ & $\vec{B}_w$ are the magnetic field associated with the laser and the wiggler respectively,

$\gamma = (1-\beta^2)^{-1}$ and $\beta = v/c$

For a transverse EM wave such as the laser beam,

$$\vec{B}_l = \vec{k} \times \vec{E}_l = \vec{z} \times \vec{E}_l$$

$$m\frac{d(\gamma\vec{w})}{dt} = e\left[\vec{E}_l(1-\beta_z) + \hat{z}\left(\vec{\beta} \bullet \vec{E}_l\right) + \vec{\beta} \times \vec{B}_w\right] + F_{reac}$$

For

$$\beta_T << \beta_z << 1$$

the laser field is not extremely strong

the radiation loss (due to) is small compared to the electron energy

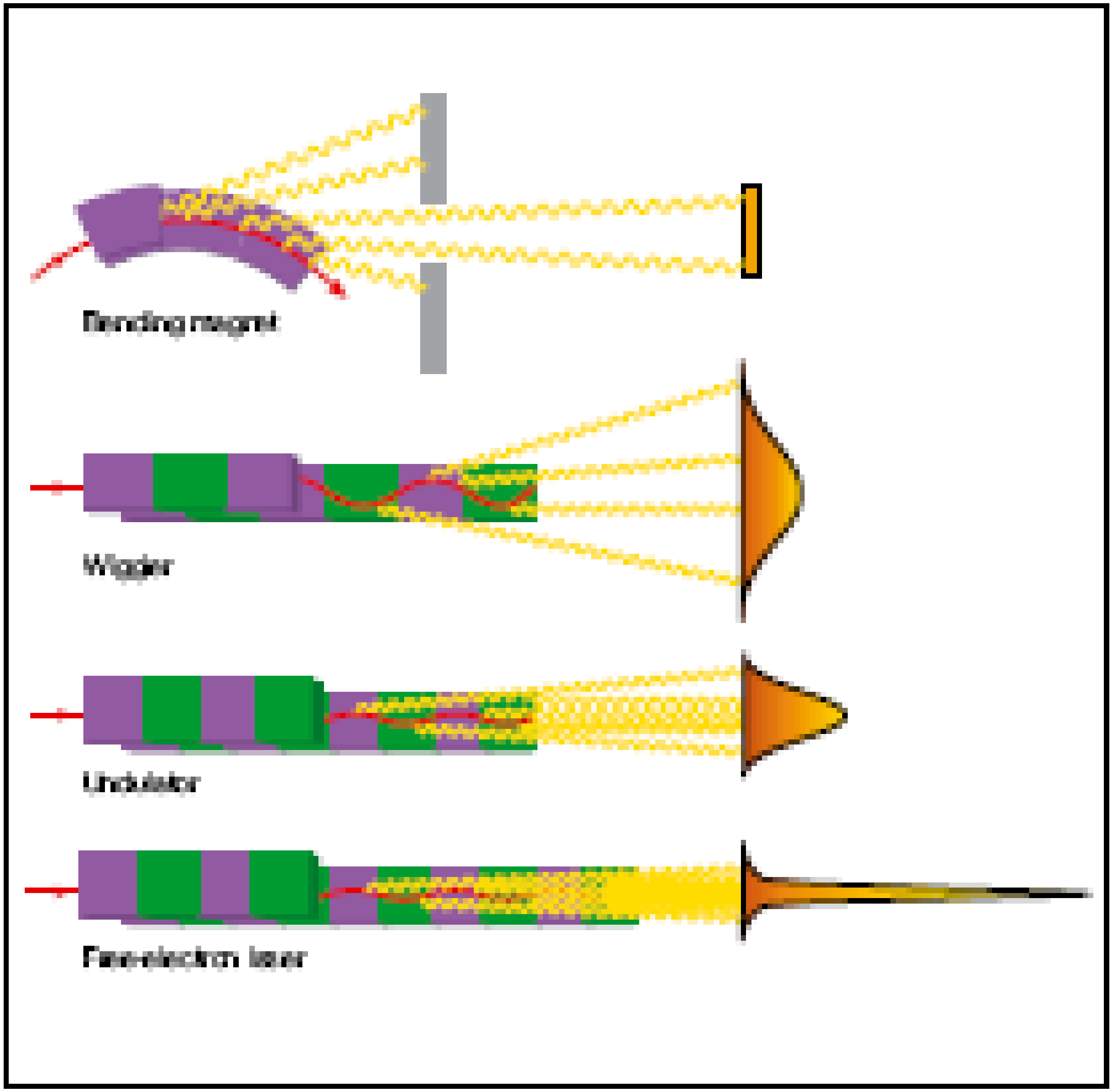
Conservation of canonical transverse momentum dictates

$$p_T = m\gamma v_T + e(A_l + A_w) = const$$

The longitudinal component describes the change in the energy of the electron and can be written as

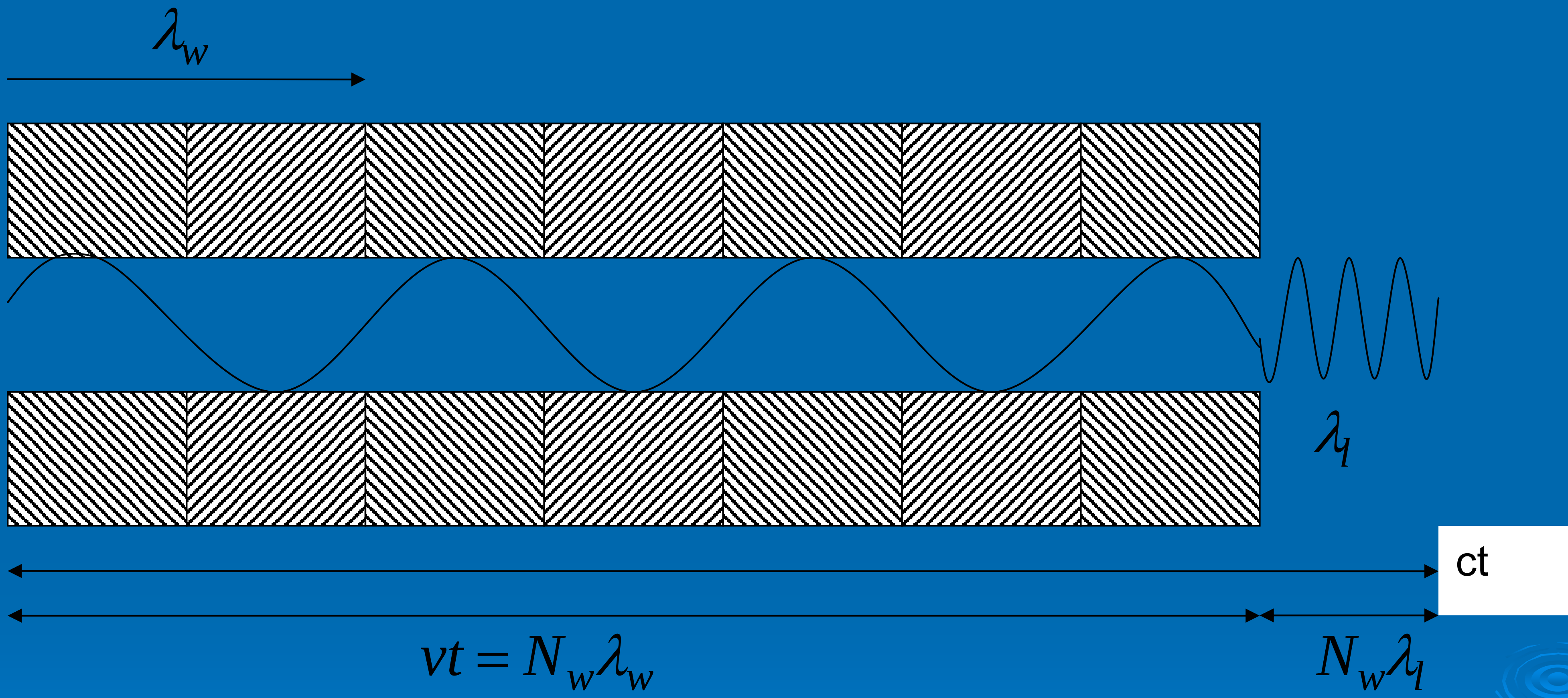
$$mc^2 \frac{d\gamma}{dt} = e\vec{v}_T \bullet \vec{E}_l - \frac{dP_{rad}}{dt}$$

$$\frac{dP}{dt} = \frac{2}{3}\frac{e^2}{c}\gamma^6\left[\dot{\vec{\beta}}^2 - (\vec{\beta}\times\dot{\beta})^2\right]$$



Generation of radiation in various types of

Spontaneous radiation in a wiggler



EM field can be assumed to be negligible and the radiated intensity per unit solid angle $d\Omega$ per unit frequency $d\omega$ can be expressed as

$$\frac{d^2 I}{d\Omega d\omega} = \frac{e^2\omega^2}{4\pi^2 c}\left|\int_{-\infty}^{+\infty} \vec{n}\times\left(\vec{n}\times\vec{\beta}\right)e^{i\omega\left(t-\vec{n}\bullet\frac{\vec{r}}{c}\right)}dt\right|^2$$

$$\lambda_l \approx \frac{\lambda_w}{2\lambda^2}$$

$$\lambda_l = \frac{\lambda_w}{2\gamma^2}\left(1+\left(\frac{eB_w\lambda_w}{mc^2}\right)^2\right)$$

Intensity Spectrum is given by

$$I(\omega) \propto \left| \int_0^{N_w \lambda_l / c} e^{(-i(\omega-\omega_l)t} dt \right|^2$$

Line width is $\propto N_w^{-1}$

Linear Thomson scattering: Laser counter propagating to e beam

Assume the system to be the electrons moving in the EM field of the laser. The transverse field of the laser is equivalent to the wiggler with wiggler period equal to the periodicity of the laser (is the length of the one period of the wiggler). Since the laser and the electron beam are counter propagating, the wavelength of the scattered radiation in the forward direction (direction of motion of the electron) is now modified to

$$\lambda_l = \frac{\lambda_{laser}}{4\gamma^2}$$

The power radiated by a single electron interacting with the laser beam is

$$P_s = 21.3\gamma_0{}^2\left(\frac{r_e}{r_0}\right)^2 P_0$$

γ_0 is the initial energy of the electron in units of its rest mass

r_e is the classical electron radius = 2.82*10-9 μm

r_0 is the spot size of the laser beam

$$P_0(GW) = 21.5\left(\frac{a_0 r_0}{\lambda_l}\right)^2$$

$a_0 = |e|\dfrac{A_0}{m_0 c^2}$ is the normalized peak amplitude of the vector potential A_0 and is analogous to the wiggler strength parameter

Courtesy: P. Sprangle, A. Ting, E. Esarey, and A. Fisher, J. Appl. Phys. **72**, 5032 (1992).

The total radiated power in practical unit can be given as

$$P_T(W) = 2.11 * 10^{-2} \frac{L_0}{Z_R} \lambda_l(\mu m) I_b(A) E_b^{\,2}(MeV) P_0(GW)$$

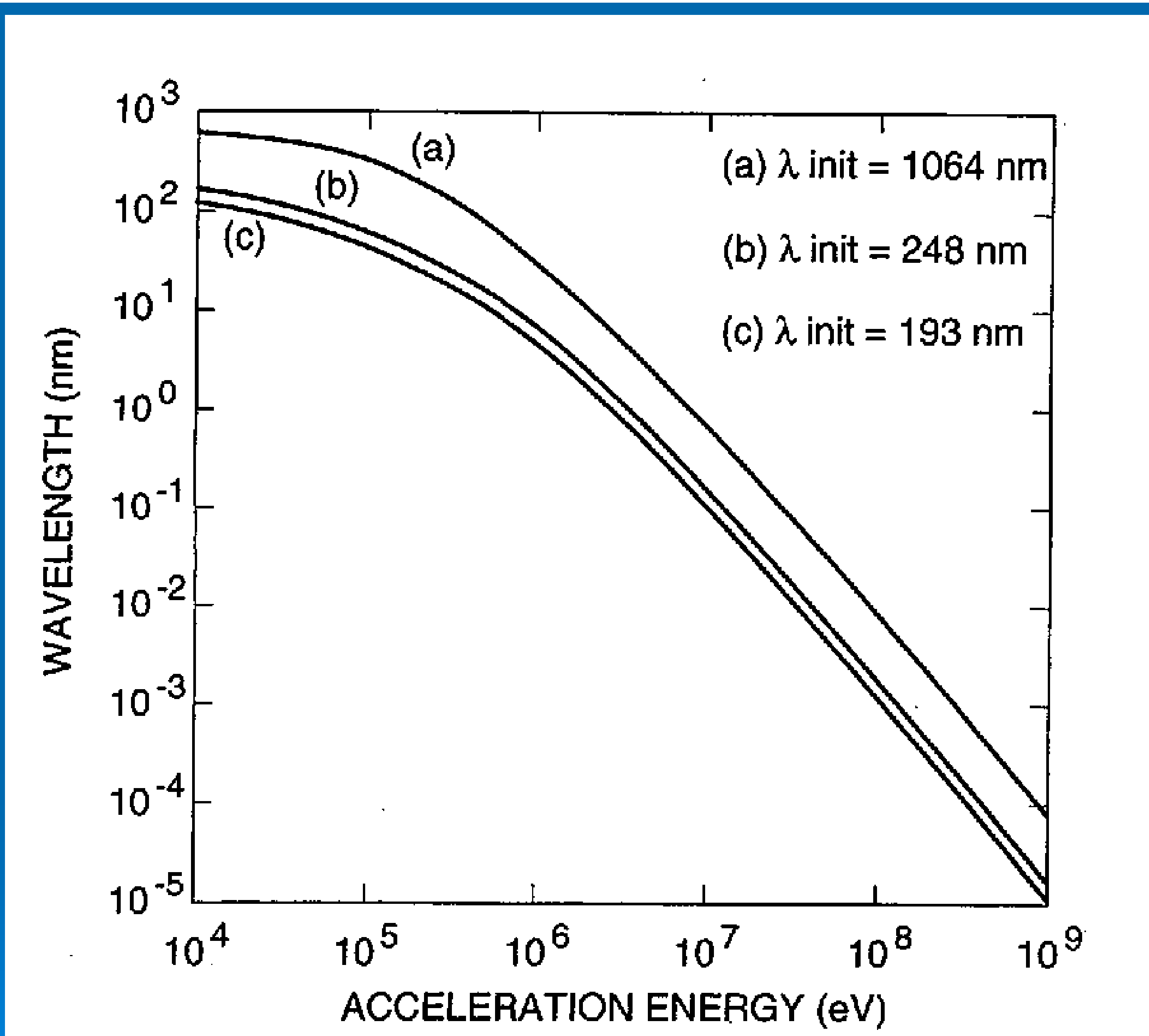
L_0	is the laser pulse length,
Z_R	is the Rayleigh length of the incident laser,
I_b	is the electron beam current in Amperes,
E_b	is the electron energy in MeV
P_0	is the laser power in GW

This radiation is emitted in a cone angle $\theta = \frac{1}{\gamma_0}$

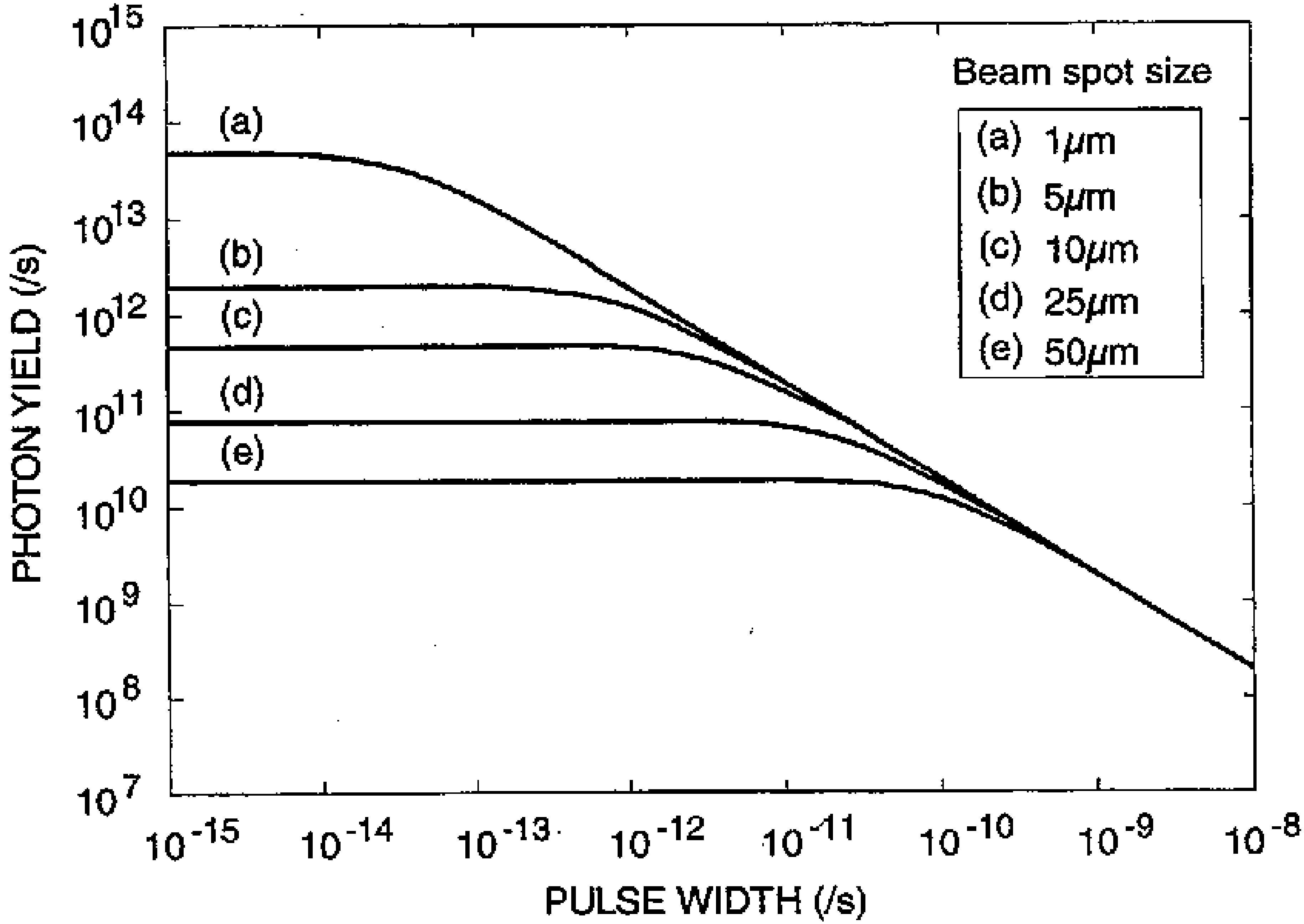
The contribution to the spectral width of the radiation comes from three sources: the finite number of wiggler period $N_w = L_0 / \lambda_l$, emittance of the electron beam ε_b and the energy spread of the electron beam δE.

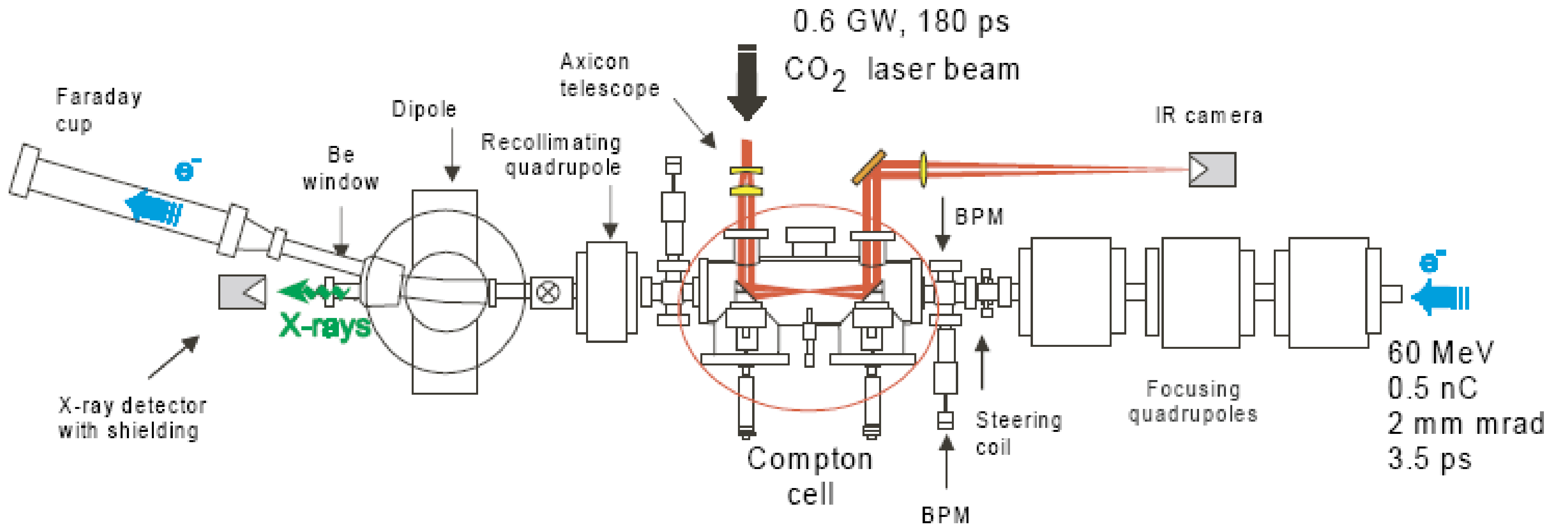
The total width can be written as

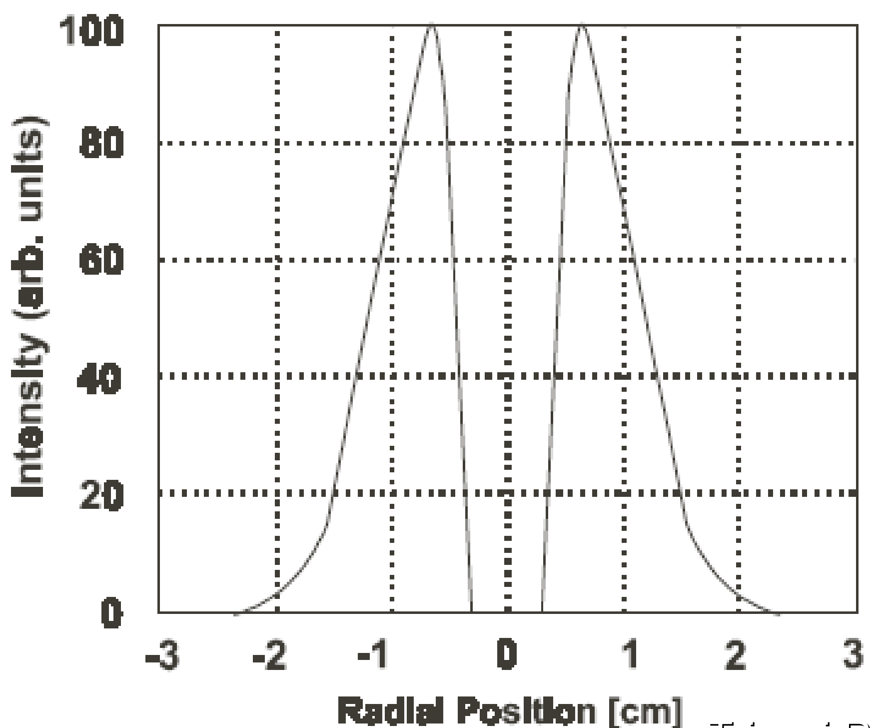
$$\left(\frac{\delta\omega}{\omega}\right)_T = \left(\frac{1}{N_w^{\ 2}} + \frac{\varepsilon^4}{r_b^{\ 4}} + 4\frac{\delta E^2}{E^2}\right)^{1/2}$$



Courtesy: Jpn. J. Appl. Phys. Vol. 37 (1998) pp. L 184–L 186 Part 2, No. 2A, 1 February 1998


Beam spot size
(a) 1μm
(b) 5μm
(c) 10μm
(d) 25μm
(e) 50μm
(a)
(b)
(c)
(d)
(e)
PHOTON YIELD (/s)
PULSE WIDTH (/s)
10^15
10^14
10^13
10^12
10^11
10^10
10^9
10^8
10^7
10^-15
10^-14
10^-13
10^-12
10^-11
10^-10
10^-9
10^-8





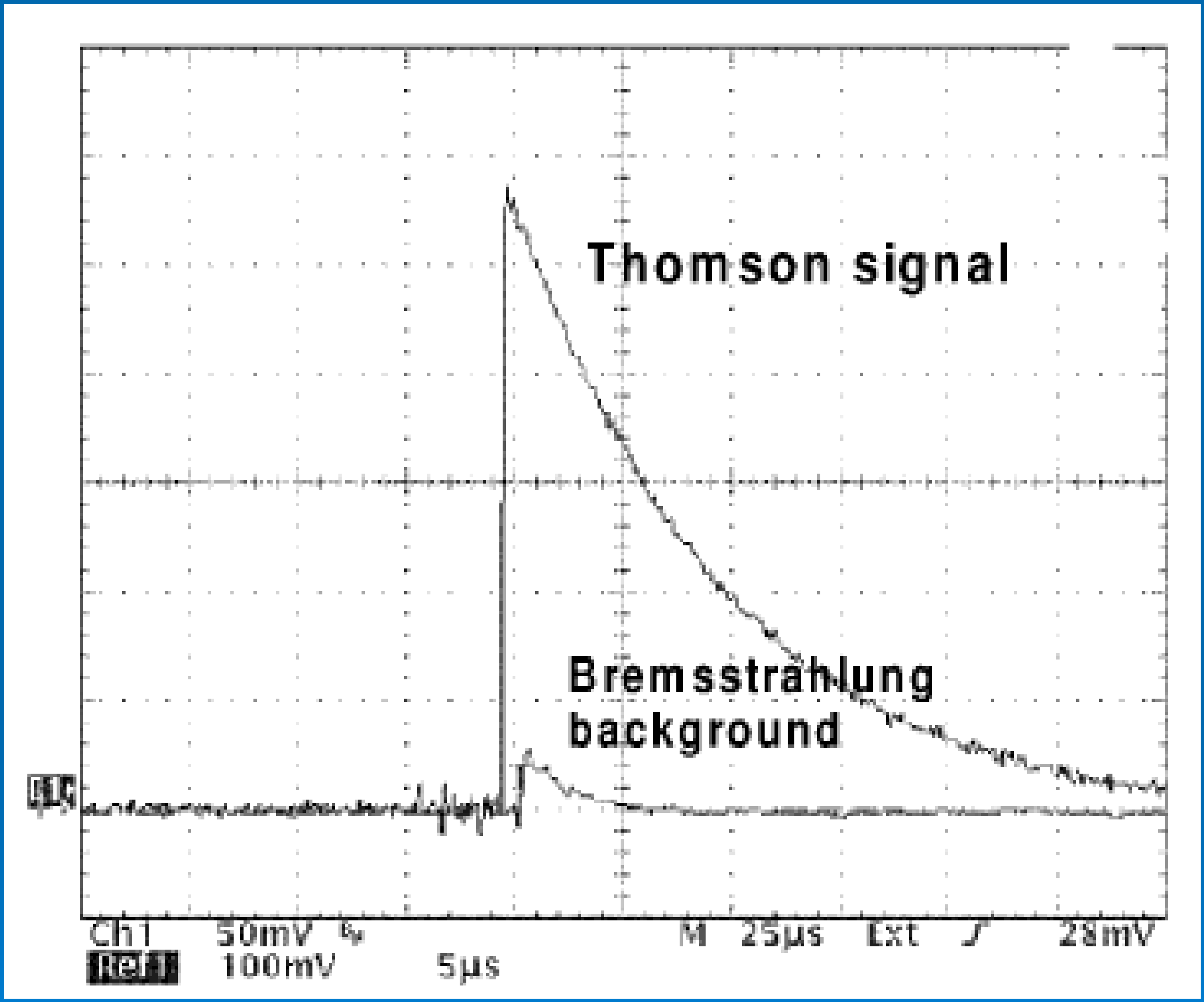
e^-:

60 MeV, 0.5 nC, 140 A, 3.5 ps, 2 mm mrad, 32 µm spot

Laser:

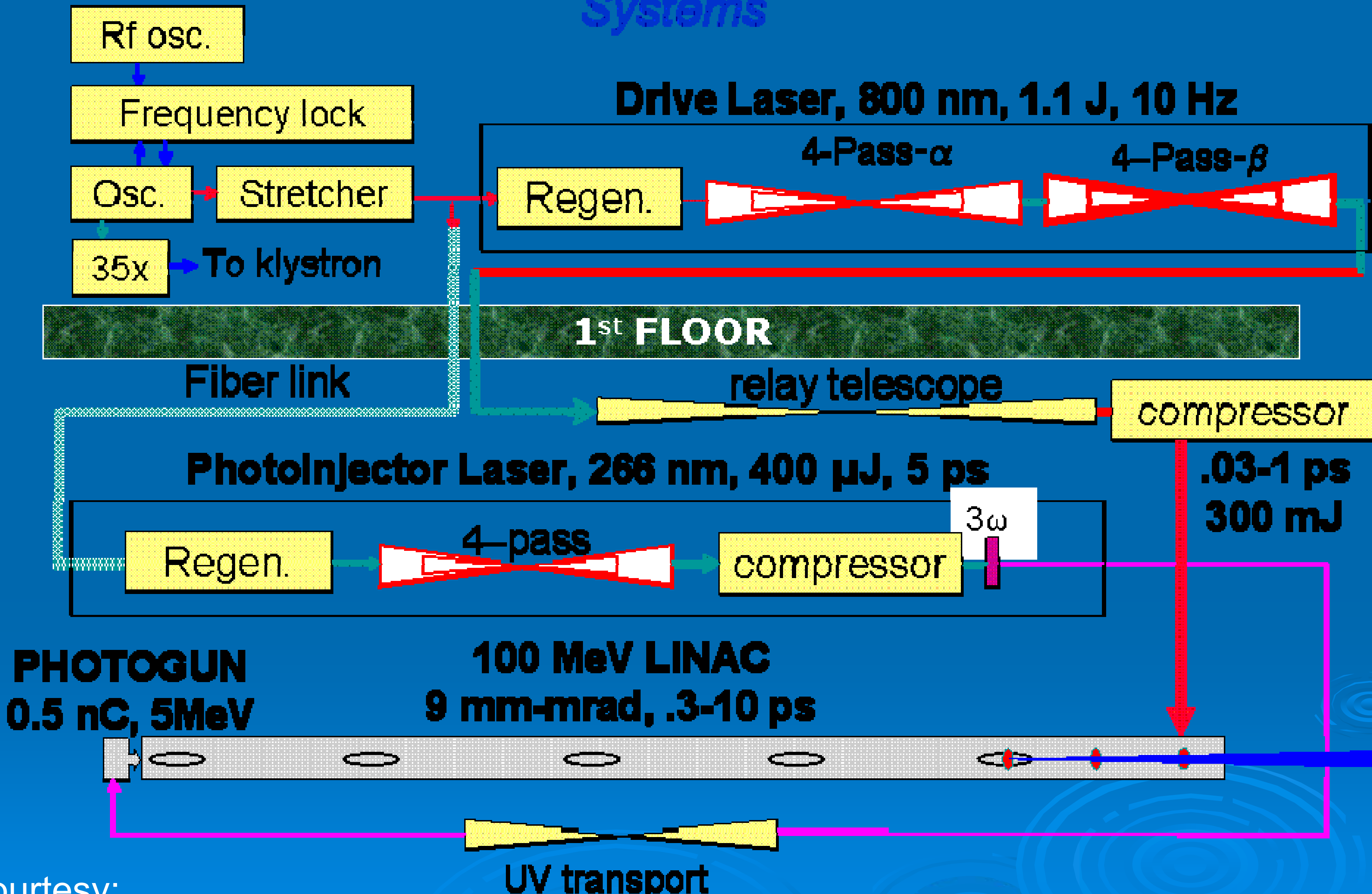
10.6 µm, 600 MW, 180 ps, lin. Pol., 32 µm annular spot

Courtesy: I. Pogorelsky et al PHYSICAL REVIEW SPECIAL TOPICS – AB, VOLUME 3, 090702 (2000)

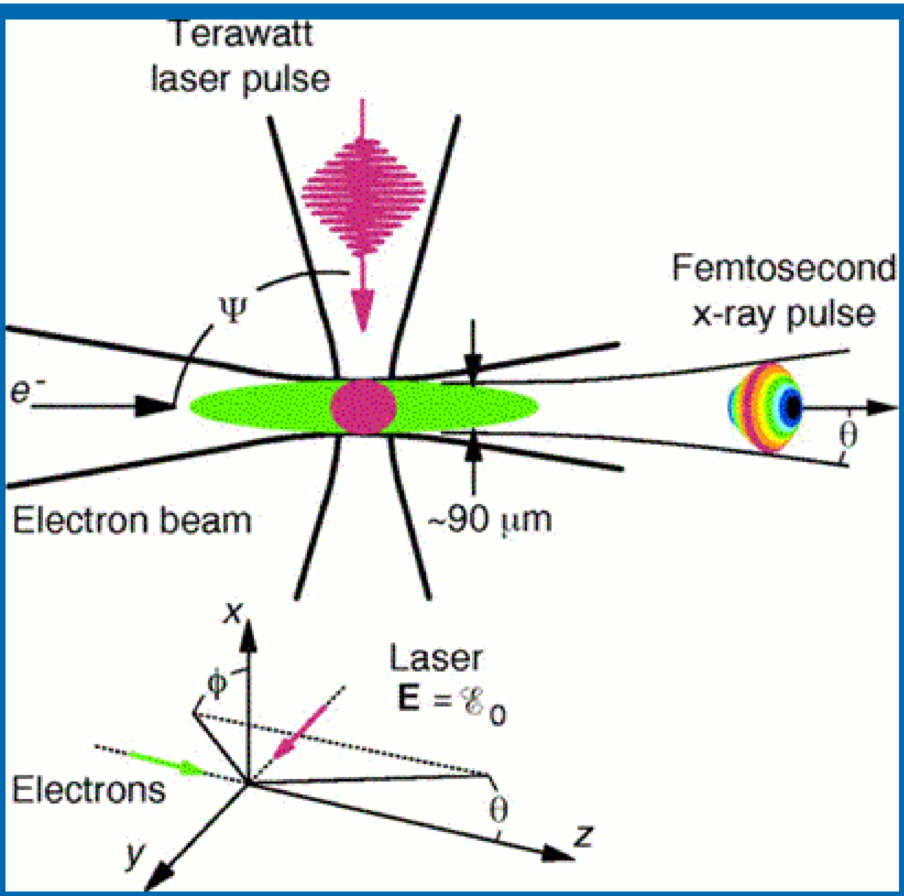


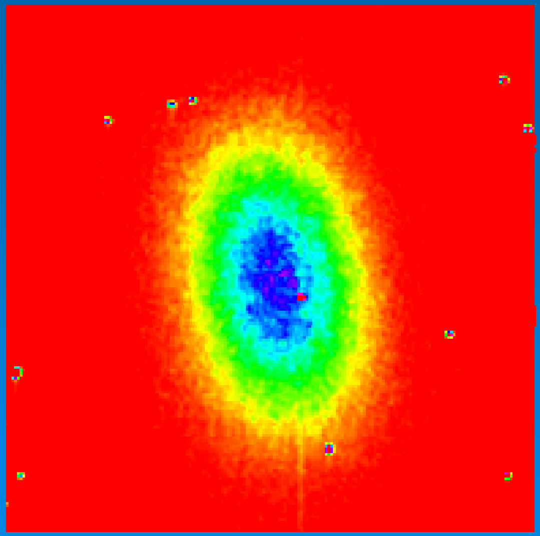
λ	= 1.8 Å
t	=3.5 ps
n/pulse	$=2.8*10^{7}$
n_{pk}	$=8*10^{18}$

Terawatt Falcon Laser & Linac Photoinjector Laser Systems



Courtesy:
http://pbpl.physics.ucla.edu/Research/Experiments/Beam_Radiation_Interaction/Thomson_Scattering/





<u>Laser Parameters:</u>

170 mJ

50 fs FWHM

36 μm $1/e^2$ diameter

$M^2 = 1.4$

<u>Electron Beam Parameters:</u>

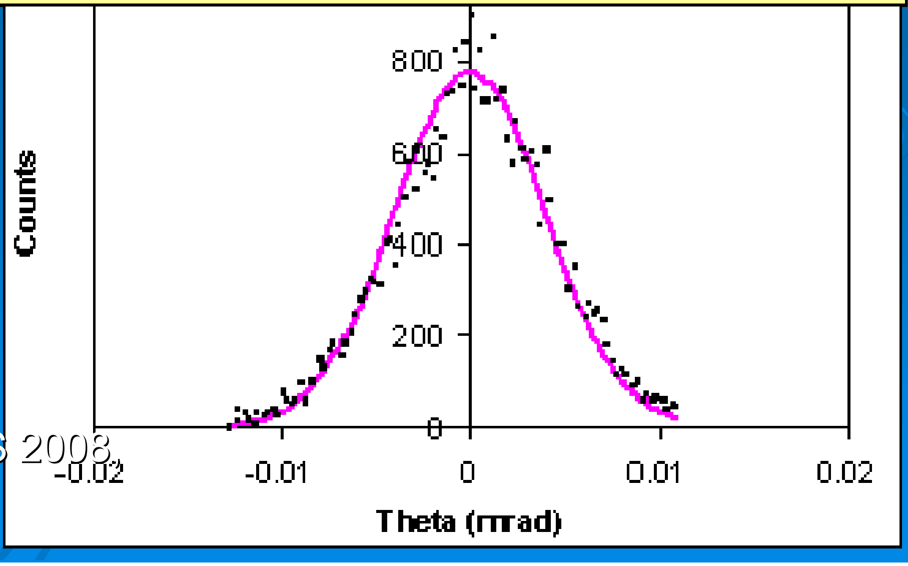
57 MeV

0.275 nC

$\sigma_x = \sigma_y = 70\ \mu m$

$\varepsilon_n = 10$ mm-mrad

Integrated Dose: 2.3 x 10^6 photons



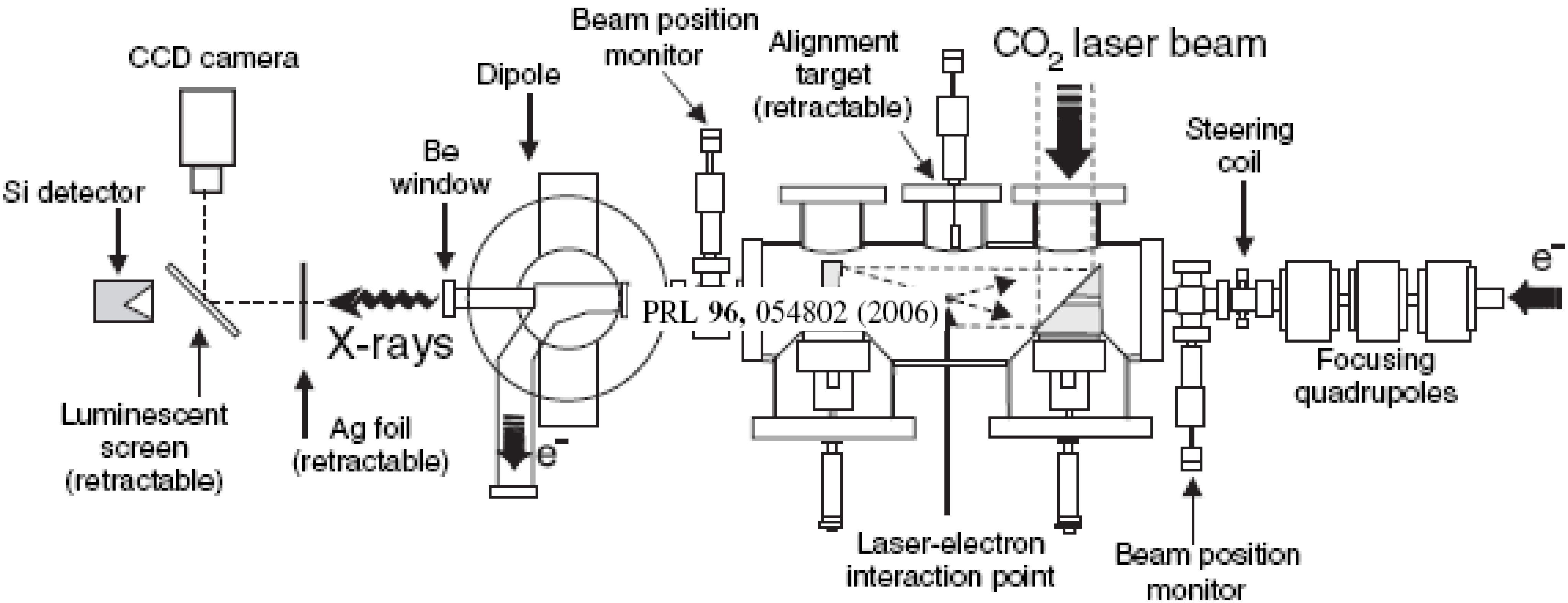
Nonlinear Thomson Scattering

When the strength of the laser field is large, nonlinear effects can be seen.
Laser strength parameter a_0 is defined as

$$a_0 = eA_0/m_e c^2$$

$$= 0.85*10^{-9}*\lambda(\mu m)*\sqrt{I_0(W/cm^2)}$$

$a_0 << 1$:Linear Thomson scattering: radiation at fundamental frequency
$a_0 \approx 1$, Nonlinear Thomson scattering: radiation at harmonic frequencies



Courtesy: M. Babzein et al. Phys . Rev. Lett. 96, 54802 (2006)

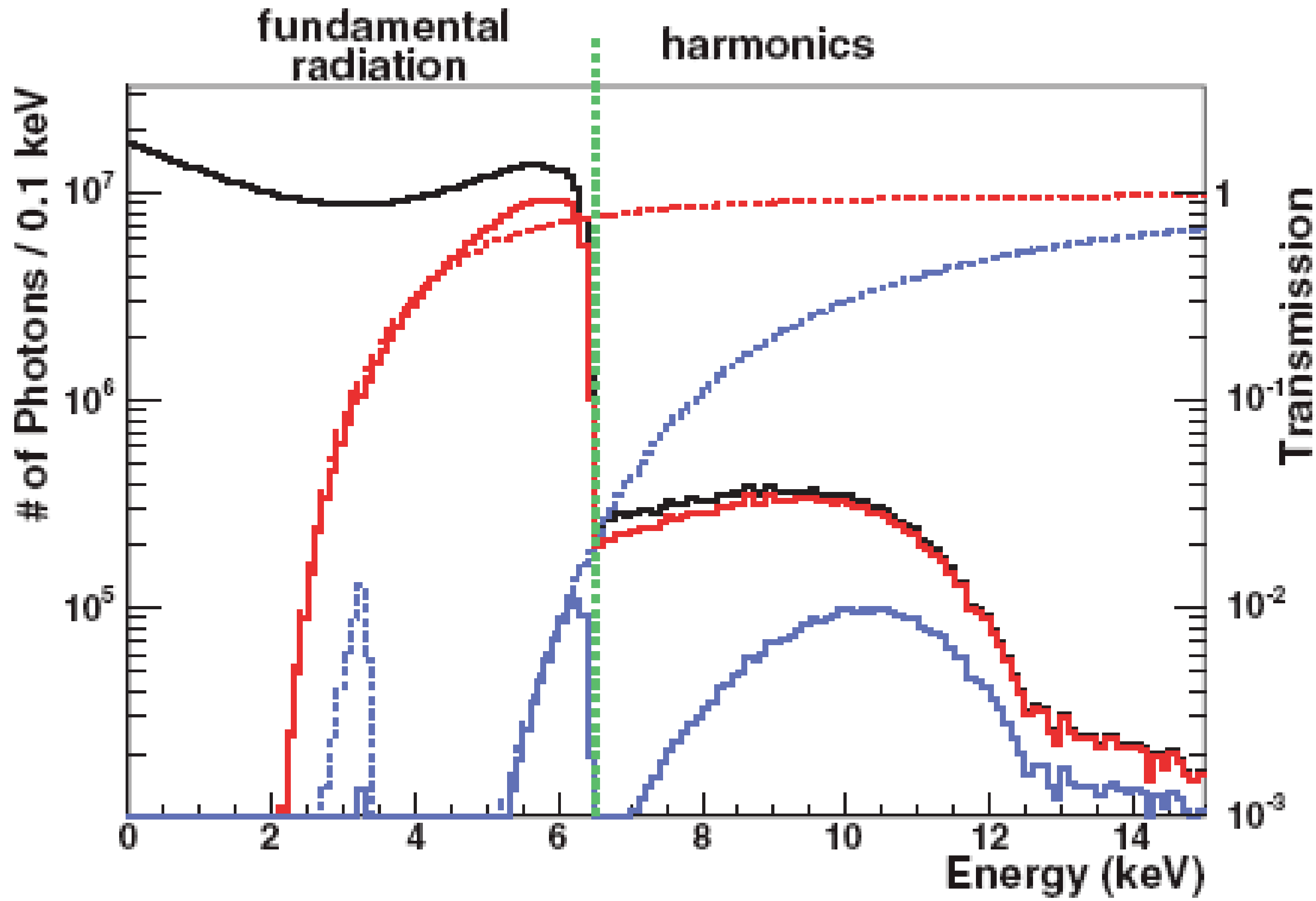


FIG. 2 (color). Simulated energy spectra of Thomson x rays. Solid lines: (black line) at the interaction point; (red line) on the detector after attenuation in the Be window and air; (blue line) filtered by a 10 μm Ag foil. Dashed lines show combined spectral transmission of the Be window with air (red line) and Ag foil (blue line). A green line shows the high-energy edge (6.5 keV) for the linear Thomson scattering.

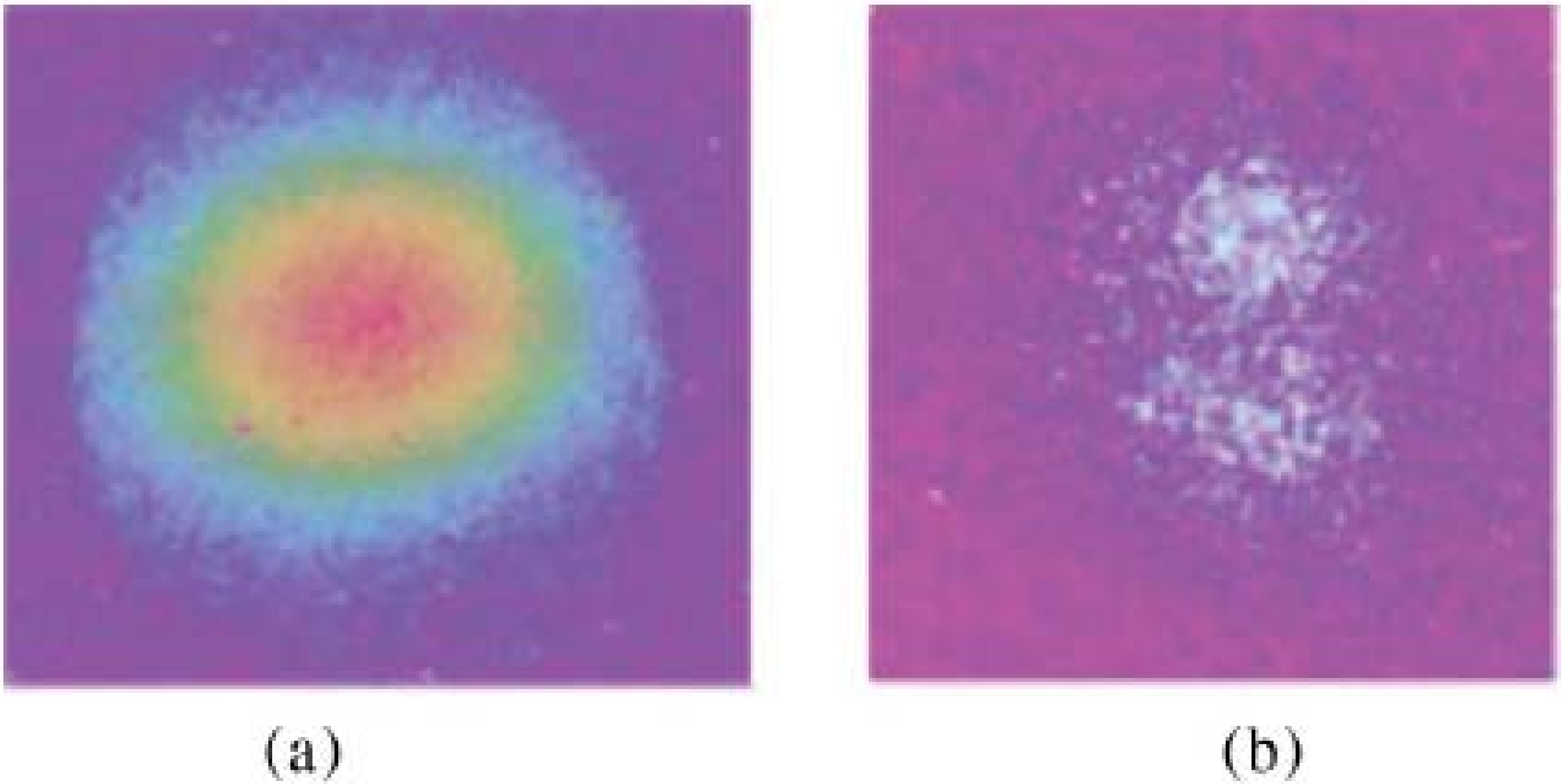


FIG. 3 (color). X-ray images observed on a luminescent screen: (a) without the Ag foil, and (b) with the 10 μm Ag foil filter.

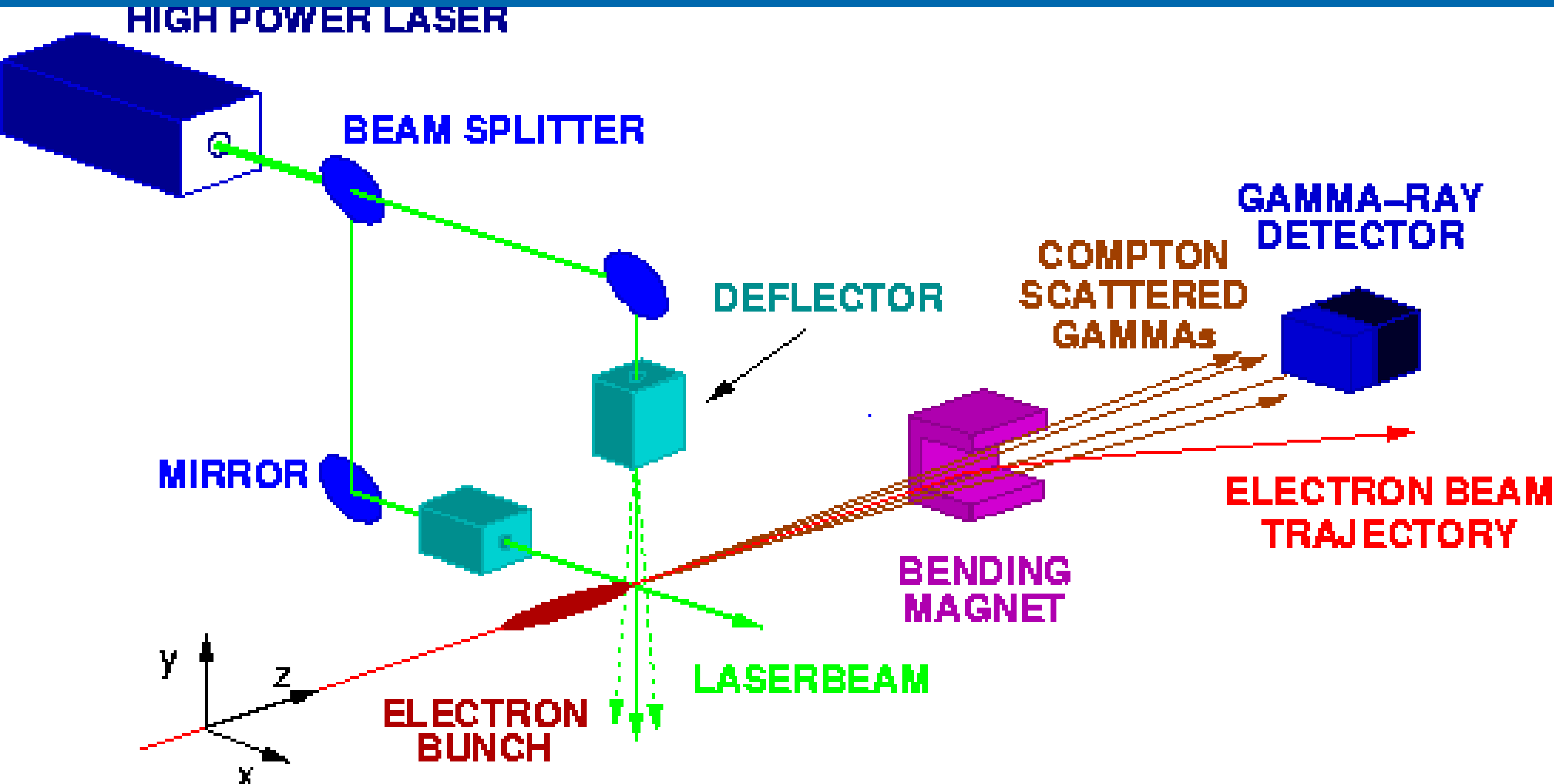
Advantages of Thomson scattering:

- Mono-energetic: no need for spectrometer
- Tunable with laser wavelength and electron beam energy
- High Brightness
- Short pulse
- Lower electron energy

Disadvantage:

- Typically lower repetition rate: average photon flux
  - Multiple interactions to increase the repetition rate

Laser Wire for e beam diagnostics



Courtesy: http://www.hep.ph.rhul.ac.uk/~kamps/lbbd/welcome.html#ScientificCase

Linear Thomson Scattering: Laser propagating transverse to e^- Beam

Similar to counter propagating, but

- ➢Wavelength of the emitted radiation is *2
- ➢Number of interacting electrons and photons is low
  - Low signal- may be as low as 10^{-3} per interaction
  - Need very high power laser
  - Need large electron density
  - Highly optimized laser transport

Courtesy: http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-pub-8057.pdf

Laser Beam intensity:

Let the laser beam with Gaussian profile propagate along z. The intensity at (x, y, z) is

$$I_l(x,y,z) = I_{l,0} e^{-\left[\frac{(x-x_l)^2}{\omega^2(z-z_l)} + \frac{(y-y_l)^2}{\omega^2(z-z_l)}\right]} \left[\frac{\omega_0}{\omega(z-z_l)}\right]^2$$

$I_{l,0}$ is a constant and the waist ω_0 is at x_l, y_l, z_l

Total laser intensity is given by

$$I_{l,tot} = \pi \omega_0^2 I_{l,0}$$

Electron Beam Intensity

In the same coordinate system, the intensity of electron beam with a Gaussian distribution can be written as

$$I_e(x,y,z) = I_{b,0} e^{-\left[\frac{(x-x_b)^2}{\sigma_x^2} + \frac{(y-y_b)^2}{\sigma_y^2} + \frac{(z-z_b)^2}{\sigma_z^2}\right]}$$

$I_{b,0}$ is a constant, (x_b, y_b, z_b) is the center of the electron beam and σ_x, σ_y, and σ_z its size along x,y,and z respectively

Total electron beam intensity is

$$I_{b,tot} = \pi^{3/2} \sigma_x \sigma_y \sigma_z I_{b,0}$$

Courtesy: Nicolas Delerue, University of Oxford
http://nicolas.delerue.org
http://www-pnp.physics.ox.ac.uk/~delerue/

Beams Overlap

$$N_{tot} = I_{l,0} I_{b,0} \times$$

$$\int \left[\frac{\omega_0}{\omega(z - z_l)} \right]^2 e^{-\frac{(x_l - x_b)^2}{\omega^2(z-z_l)+\sigma_x{}^2}} \sqrt{\pi \left[\frac{\sigma_x{}^2 \omega^2 (z - z_l)}{\sigma_x^2 + \omega^2 (z - z_l)} \right]}$$

$$\times e^{-\frac{(y_l - y_b)^2}{\omega^2(z-z_l)+\sigma_y{}^2}} \sqrt{\pi \left[\frac{\sigma_y{}^2 \omega^2 (z - z_l)}{\sigma_y^2 + \omega^2 (z - z_l)} \right]} \times$$

$$e^{-\left[\frac{(z-z_b)^2}{\sigma_z^2} \right]} dz$$

$$N_{tot} = \pi^{3/2} I_{l,0} I_{b,0} \sigma_x \sigma_y \sigma_z \omega_0^2 \times$$

$$\frac{e^{-\frac{(x_l - x_b)^2 \times (y_l - y_b)^2}{\left[\omega^2 (z_b - z_l) + \sigma_x^2\right] \times \left[\omega^2 (z_b - z_l) + \sigma_y^2\right]}}}{\sqrt{\left[\omega^2 (z_b - z_l) + \sigma_x^2\right] \times \left[\omega^2 (z_b - z_l) + \sigma_y^2\right]}}$$

Laser Requirements:

Machine	sigma x microns	sigma y microns	Required Wavelength: microns
TESLA (Diagnostic section 250GeV)	120um	7um	0.67 um
JLC 500GeV	10	3	1.3 um
NLC 500GeV	10	1.25	0.22 um
NLC 1TeV	7.5	0.9	0.15 um

- Wavelength: Significantly smaller than the e spot size
  Minimum laser spot size set by diffraction limit
- Power: Tens of MW
  Efficiency ~10^{-3}
- Laser transport: Spot size diffraction limit
  Rayleigh length > other transverse dimension
- Damage threshold

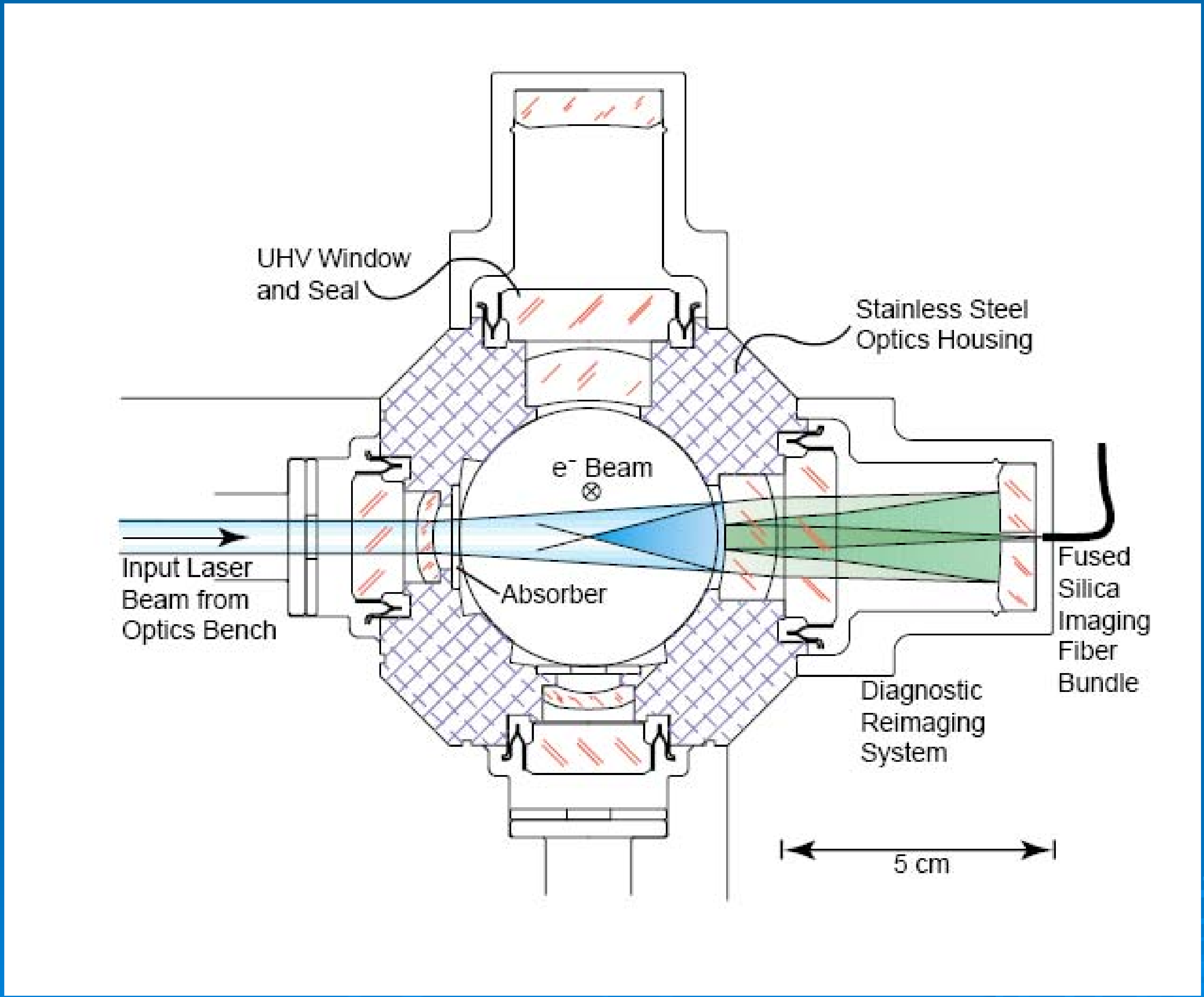
Typical Issue

- The laser beam has a diameter of several millimeters.
- We want a wire size of only a [few] micrometers
- The laser light must be focused by wide aperture lens.
- No commercial lens seems to suits our needs

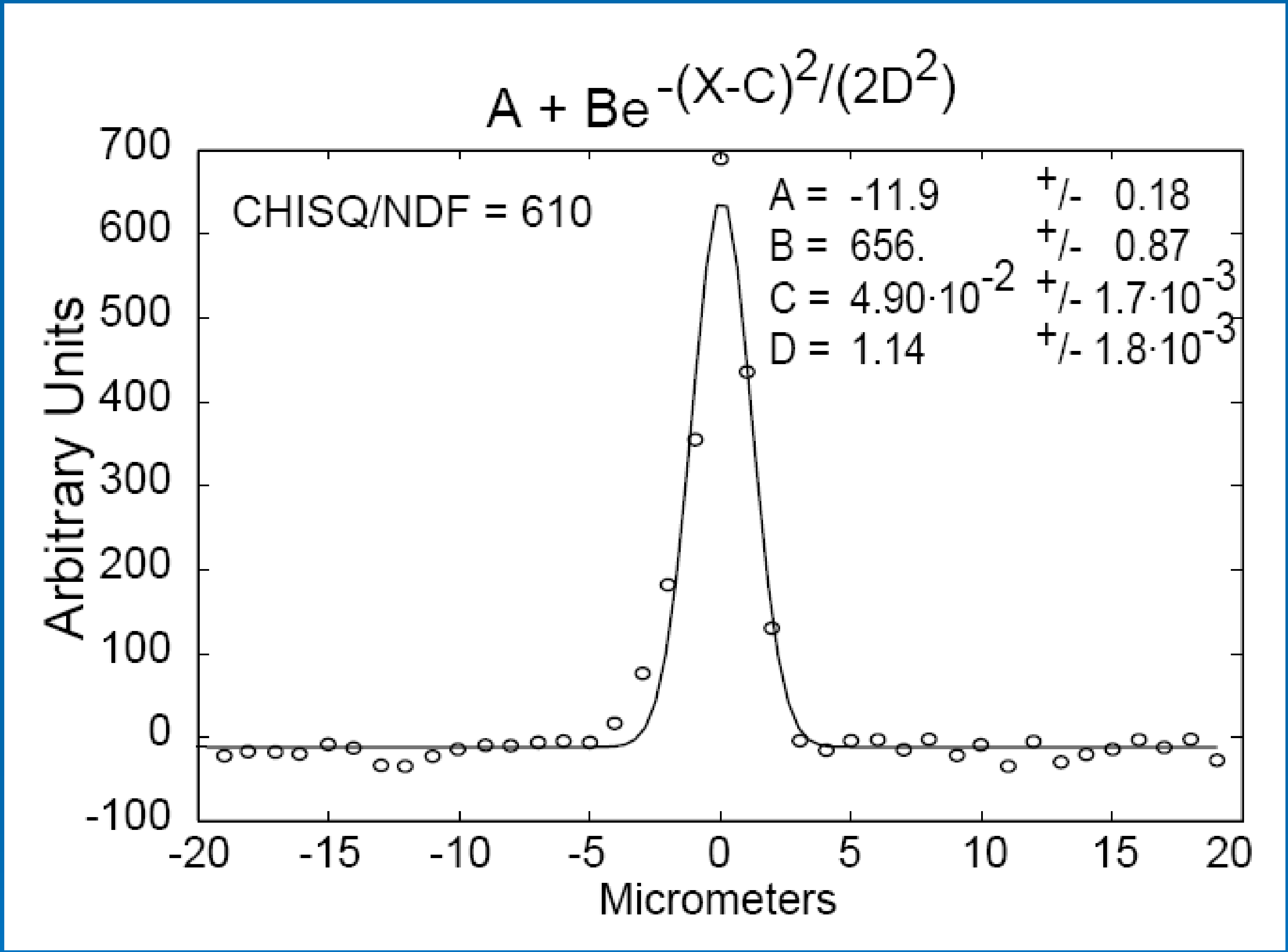
=> Custom design

Courtesy Nicolas Delerue, University of Oxford
http://www-pnp.physics.ox.ac.uk/~de…

- Goal: concentrate as much energy as possible in the smallest possible radius (gives the best performance).
- As the laser beam will be scanned across the lens, the size of the spot must remain constant over the scanning range.
- As the lens will be used with a high power laser, it must have no first order ghosts and as few second order ghosts as possible.
- To facilitate the alignment of the lens, aberrations must be kept as low as possible.
- Effect of a tilt of one element of the lens with respect to the others must be studied carefully



Courtesy: P. Tenenbaum, T. Shintake, SLAC Pub 8057



Signal from Laser wire. λ= 350 nm, spot size 1μm, power10 MW