Lasers For e Beam Diagnostics

Advantages of using Laser

- Short pulse duration
- Large Bandwidth
- Large EM field
- Accurate phase information

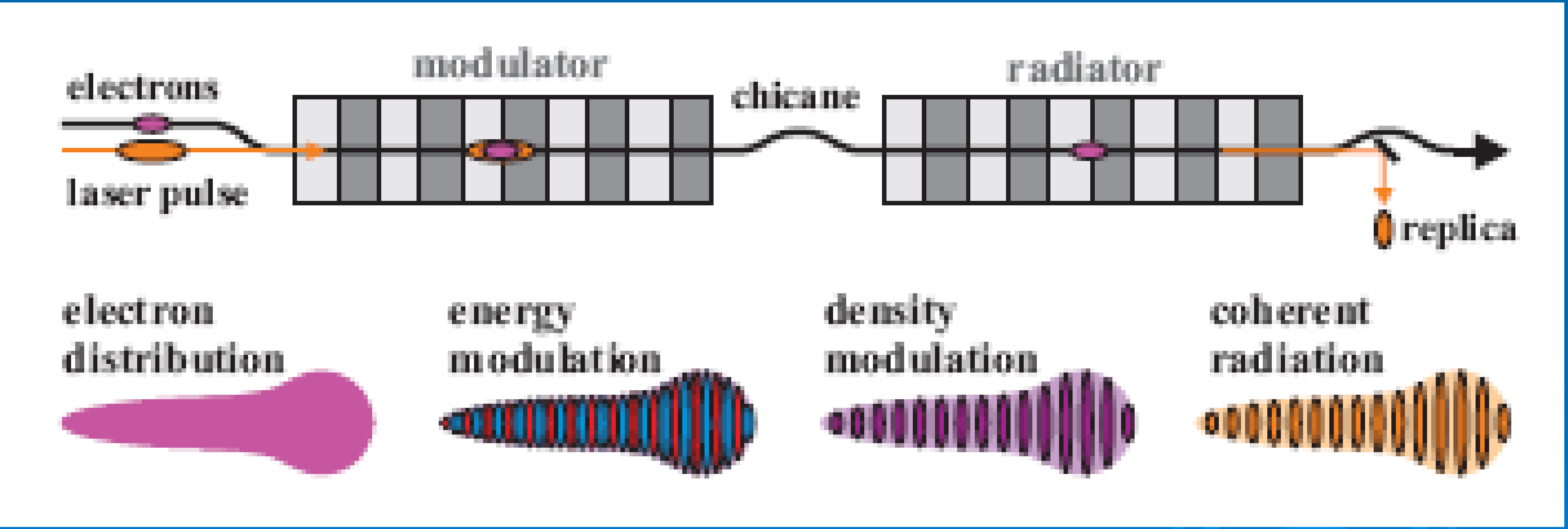
Methods:

- Generated photons
  - FEL
  - Compton Scattering
- Modify laser profile
  - Electro-optic effect

Invasive Techniques

Source of radiation and use of radiation for electron diagnostics

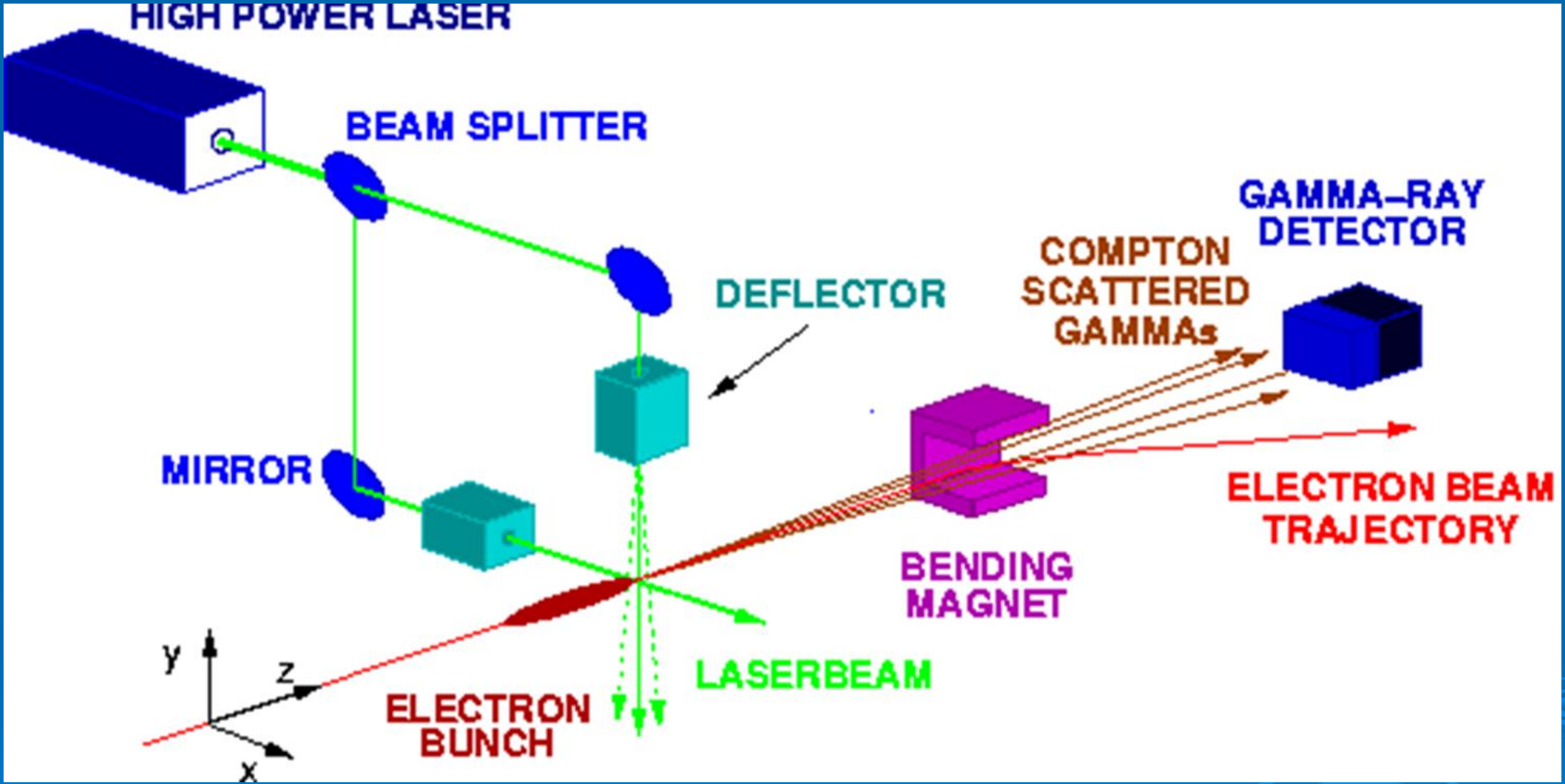
Slice emittance, longitudinal distribution of short (100 fs) electron bunch can not be measured by standard techniques→ generate optical replica of the electron beam



Use standard optical technique to measure beam parameters

Courtesy: E. Saldin et al. Proc. Of PAC 07, P. 965

Laser wire scan

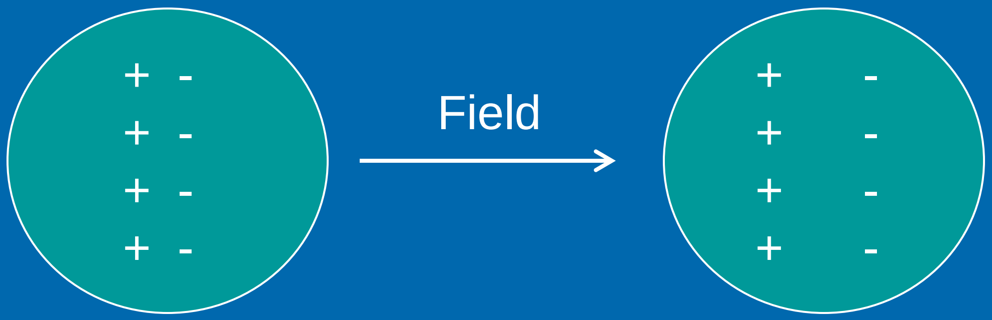


Courtesy:
http://www.hep.ph.rhul.ac.uk/~kamps/lbbd/welcome.html#ScientificCase

Non-invasive Techniques

Electro optic effect as e- beam diagnostics

- What is electro-optic effect?



The electric polarization P can be written as

$$P_i = \varepsilon_0 \sum_{j=1}^{3} \chi_{ij}^{(1)} E_j + \varepsilon_0 \sum_{j=1}^{3} \sum_{k=1}^{3} \chi_{ijk}^{(2)} E_j E_k + \varepsilon_0 \sum_{j=1}^{3} \sum_{k=1}^{3} \sum_{l=1}^{3} \chi_{ijkl}^{(3)} E_j E_k E_l + \ldots$$

ε_0 is vacuum permittivity, $\chi^{(n)}$ n^{th} order tensor electric susceptibility, *I,j, and k* are Cartesian indices, E_i, E_j can have different frequencies

The first term $P = \varepsilon_0\, \chi^{(1)} : E$ applies to all linear optics and leads to optical index of refraction and dielectric constant .

For a linear material, terms with higher order χ vanish and
$P = \varepsilon_0\, \chi^{(1)} : E$

The second term $\varepsilon_0 \sum_{j=1}^{3} \sum_{k=1}^{3} \chi_{ijk}^{2} \vec{E}_j \vec{E}_k$ gives rise to optical mixing ($\omega_1+\omega_2$ and $\omega_1-\omega_2$) and second harmonic generation ($\omega_1=\omega_2$). When one of the fields varies very slowly compared to the other ($\omega_1>>\omega_2$), then it is Pockel's effect where the input and output frequencies are the same and the index of refraction varies linearly with the applied slowly varying field.

$$\vec{P}_i(\omega_1) = \left(\chi_{ijk}^{2} \vec{E}_k(\omega_2)\right)\vec{E}_j(\omega_1)$$

χ^{2}_{ijk} is a 3x3x3 third rank tensor. Since the input and out put frequencies are the same (ω_2~0), it can be contracted notation for (ij) ie. 1=(11), 2=(22), 3=(33), 4=(23), 5=(13), 6= 12). This reduces the number of independent tensor elements from 27 to 18. The crystal symmetry may further reduce it since some of the tensors may be zero. In the contracted form, the 18 elements of χ_{ik} and the components of the polarization vector can be written as

$$\begin{vmatrix} P_x \\ P_y \\ P_z \end{vmatrix} = \varepsilon_0 \begin{vmatrix} \chi_{11}\chi_{12}\chi_{13}\chi_{14}\chi_{15}\chi_{16} \\ \chi_{21}\chi_{22}\chi_{23}\chi_{24}\chi_{25}\chi_{26} \\ \chi_{31}\chi_{32}\chi_{33}\chi_{34}\chi_{35}\chi_{36} \end{vmatrix} \begin{vmatrix} E_x^2 \\ E_y^2 \\ E_z^2 \\ 2E_yE_z \\ 2E_xE_z \\ 2E_xE_y \end{vmatrix}$$

How to relate to measurable quantity?

The index of refraction n(ω) and the dielectric constant ε (ω) are related to the real part of the susceptibility by

$$n_{j,k}^2(\omega) = \frac{\varepsilon_{j,k}(\omega)}{\varepsilon_0} = 1 + \chi_{j,k}^1(\omega)$$

The susceptibility is related to the electro-optic coefficients r_{jk} through the optical impermeability B_{jk}

$$B_{jk} = (1/\varepsilon)_{jk} = (1/n^2)_{jk}$$

$$\Delta B_j = r_{jk}E_k = -\frac{2\Delta n_j}{n_j^3}$$

$$\Delta n_j = -\frac{1}{2} n_j^3 r_{jk} E_k$$

Phase difference and intensity modulation are

$$\delta = \frac{2\pi l \Delta n}{\lambda} \qquad I = I_0 \sin^2(\frac{\delta}{2})$$

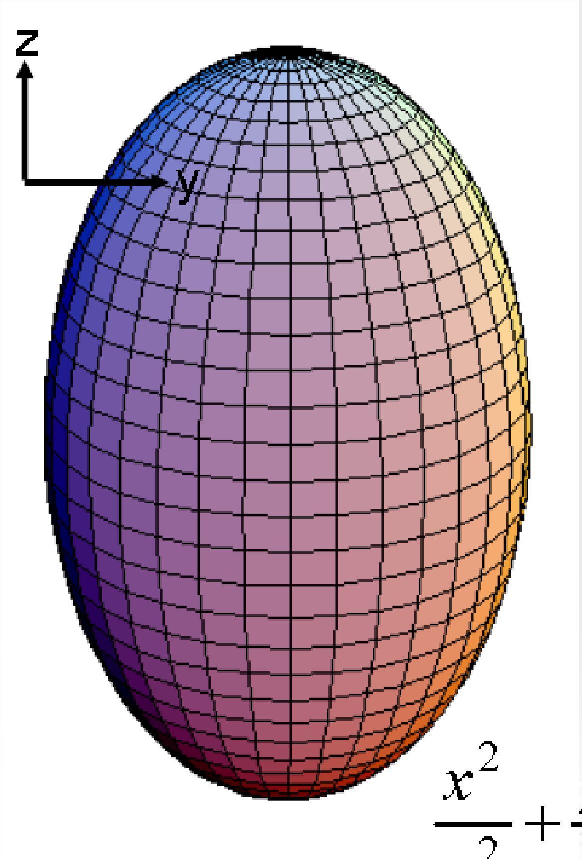
Index of ellipsoid: general

$$\frac{x^2}{N_1^2} + \frac{y^2}{N_2^2} + \frac{z^2}{N_3^2} + \frac{2yz}{N_4^2} + \frac{2xz}{N_5^2} + \frac{2xy}{N_6^2} = 1$$

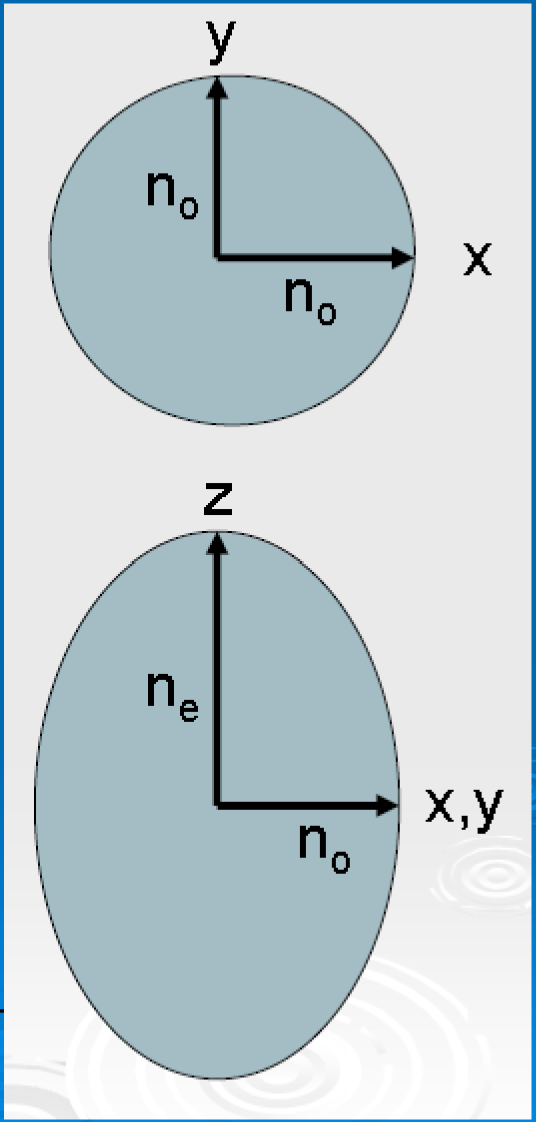
Choose coordinate system appropriately

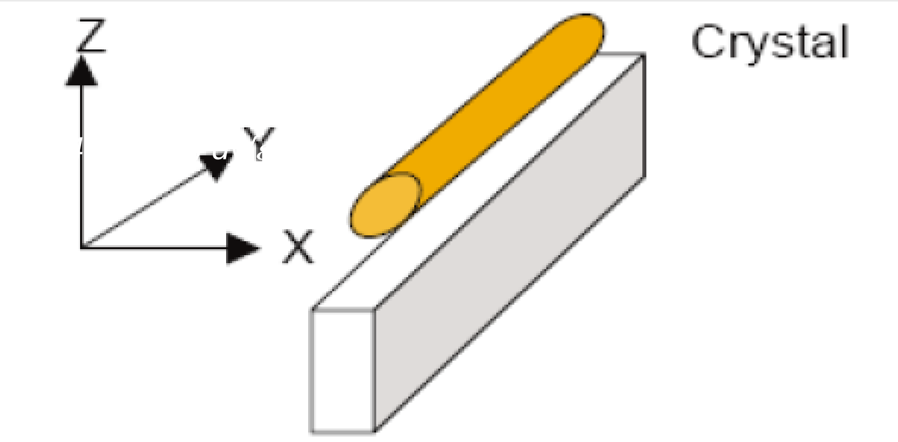
$$\frac{x^2}{n_1^2} + \frac{y^2}{n_2^2} + \frac{z^2}{n_3^2} = 1$$

Index Ellipsoid: Uniaxial crystal



$$\frac{x^2}{n_0^2}+\frac{y^2}{n_0^2}+\frac{z^2}{n_e^2}=1$$





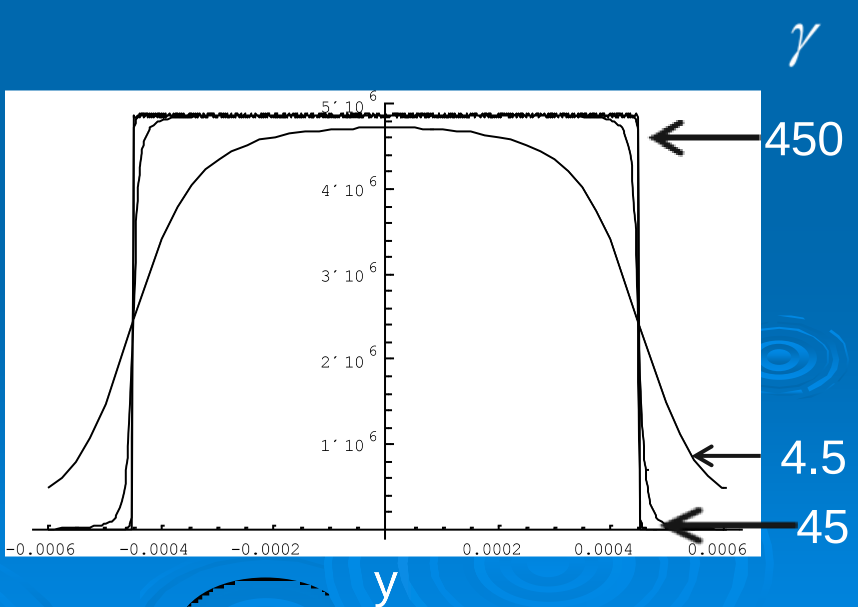
The electric field dE in the crystal with dielectric constant ε at a distance r from the relativistic electron beam due to a charge σdv

$$d\vec{E} = (\gamma/4\pi\varepsilon_0)\,\sigma(y)\,dy/\varepsilon r^2\,\vec{r}$$

The field decays rapidly along the y direction, past the extent of the beam

$dE(x,t) = (\gamma/4\pi\varepsilon_0)\,\sigma(y,t)\,dy/\varepsilon r^2$

$dE(z,t)=(\gamma/4\pi\varepsilon_0)\,\sigma(y,t)\,dy/\varepsilon r^2$



Time dependent field leads to time dependent change in index of refraction and index of ellipsoid

$$\Delta n_j = -\frac{1}{2} n_j^3 r_{jk} E_k$$

$$\frac{x^2}{n_1^2} + \frac{y^2}{n_2^2} + \frac{z^2}{n_3^2} = 1$$

$$x^2\left(\frac{1}{n_1^2} + r_{1j}E_j\right) + y^2\left(\frac{1}{n_2^2} + r_{2j}E_j\right) + z^2\left(\frac{1}{n_3^2} + r_{3j}E_j\right) + 2yz(r_{4j}E_j) + 2xz(r_{5j}E_j) - 2xy(r_{6j}E_j) = 1$$

Redefine the principal axes X_i, calculate the refractive indices N_i and the phase difference δ between the orthogonal components

$$\delta = \frac{2\pi}{\lambda}\int_0^L N_j - N_i dx_k$$

where x_k is the laser propagation direction, L is length of the crystal in that direction and $N_{i,j}$ are refractive indices in directions orthogonal to propagation

$$I = I_o \sin^2(2\theta + 2\phi)\sin^2\frac{\delta}{2}$$

where θ is the angle made by the E vector of the laser beam with the y-z plane, Φ is the field dependent orientation of the new principal axis with the old one

For Lithium Niobate

Rotation ϕ of Principal axes

Direction of propagation of Charge Bunch	Direction of propagation of Laser: x	y	z
x	$\phi \sim \frac{1}{2}\tan^{-1}\left(\frac{36.4\times10^{-12}E_y}{-0.016+3.4\times10^{-12}E_y-21.1\times10^{-12}E_z}\right)$	$\phi \sim 0$	$\phi \sim 0$
y	$\phi \sim 0$	$\phi \sim \frac{1}{2}\tan^{-1}\left(\frac{36.4\times10^{-12}E_x}{-0.016-21.1\times10^{-12}E_z}\right)$	$\phi \sim \pm\pi/4$
z	$\phi \sim \frac{1}{2}\tan^{-1}\left(\frac{36.4\times10^{-12}E_y}{-0.016+3.4\times10^{-12}E_y}\right)$	$\phi \sim \frac{1}{2}\tan^{-1}\left(\frac{36.4\times10^{-12}E_x}{-0.016-3.4\times10^{-12}E_y}\right)$	$\phi \sim \frac{1}{2}\tan^{-1}\left(\frac{E_x}{E_y}\right)$

ϕ Is independent of field for 4 cases, dependent on field along one direction in 1 case

Total Retardation δ experienced by the laser beam for 3 possible directions of the laser and electron beams

		Direction of propagation of Laser		
Direction of propagation of charge bunch		**x**	**y**	**z**
	x	$-(1.19\times10^{6})L$ $-(0.0014)\int_0^L E_z dx + (0.0003)\int_0^L E_y dx$ $-(2.97\times10^{-12})\int_0^L E_y{}^2 dx + (1.95\times10^{-13})\int_0^L E_z{}^2 dx$ $-(1.67\times10^{-14})\int_0^L E_y E_z dx + \ldots$	$-(1.19\times10^{6})L$ $-(0.0014)\int_0^L E_z dy + (0.0003)\int_0^L E_y dy$ $+(1.95\times10^{-13})\int_0^L E_z{}^2 dy - (1.67\times10^{-14})\int_0^L E_y E_z dy$ $-(3.69\times10^{-15})\int_0^L E_y{}^2 dy + \ldots$	$\delta = -(0.0011)\int_0^L E_y dz$ $+(6.69\times10^{-14})\int_0^L E_y E_z dz$ $-(3.51\times10^{-24})\int_0^L E_y E_z{}^2 dz$ $-(9.13\times10^{-25})\int_0^L E_y{}^3 dz + \ldots$
	y	$-(1.19\times10^{6})L$ $-(0.0014)\int_0^L E_z dx$ $+(1.95\times10^{-13})\int_0^L E_z{}^2 dx$ $-(2.51\times10^{-23})\int_0^L E_z{}^3 dx. + \ldots$	$-(1.19\times10^{6})L$ $-(0.0014)\int_0^L E_z dy$ $+(2.96\times10^{-12})\int_0^L E_x{}^2 dy + (1.95\times10^{-13})\int_0^L E_z{}^2 dy + \ldots$	$\delta = -(0.0005)\int_0^L E_x dz$ $+(3.34\times10^{-14})\int_0^L E_x E_z dz$ $-(1.76\times10^{-24})\int_0^L E_x E_z{}^2 dz$ $-(1.14\times10^{-25})\int_0^L E_x{}^3 dz + \ldots$
	z	$-(1.19\times10^{6})L$ $+(0.0003)\int_0^L E_y dx$ $-(2.97\times10^{-12})\int_0^L E_y{}^2 dx$ $-(5.71\times10^{-22})\int_0^L E_y{}^3 dx. + \ldots$	$-(1.19\times10^{6})L$ $-(0.0014)\int_0^L E_z dy + (0.0003)\int_0^L E_y dy$ $-(2.96\times10^{-12})\int_0^L E_x{}^2 dy - (5.92\times10^{-12})\int_0^L E_y E_x dy$ $-(3.69\times10^{-15})\int_0^L E_y{}^2 dy + \ldots$	$\delta = -(0.0005)\int_0^L E_x dz$ $-(0.0007)\int_0^L \frac{E_y{}^2}{E_x} dz$ $-(1.14\times10^{-25})\int_0^L E_x{}^3 dz + \ldots$

Two specific cases

e along y axis, laser along x axis

$$\delta = -(1.19\times10^{6})L - (0.0014)\int_0^L E_z dx + (1.95\times10^{-13})\int_0^L E_z{}^2 dx - (2.51\times10^{-23})\int_0^L E_z{}^3 dx. + \ldots$$

e along z axis, laser along x axis

$$\delta = -(1.19\times10^{6})L + (0.0003)\int_0^L E_y dx - (2.97\times10^{-12})\int_0^L E_y{}^2 dx - (5.71\times10^{-22})\int_0^L E_y{}^3 dx. + \ldots$$

No cross filed terms, Large Static term, Large coefficient for case 1

Need to compensate for the static term

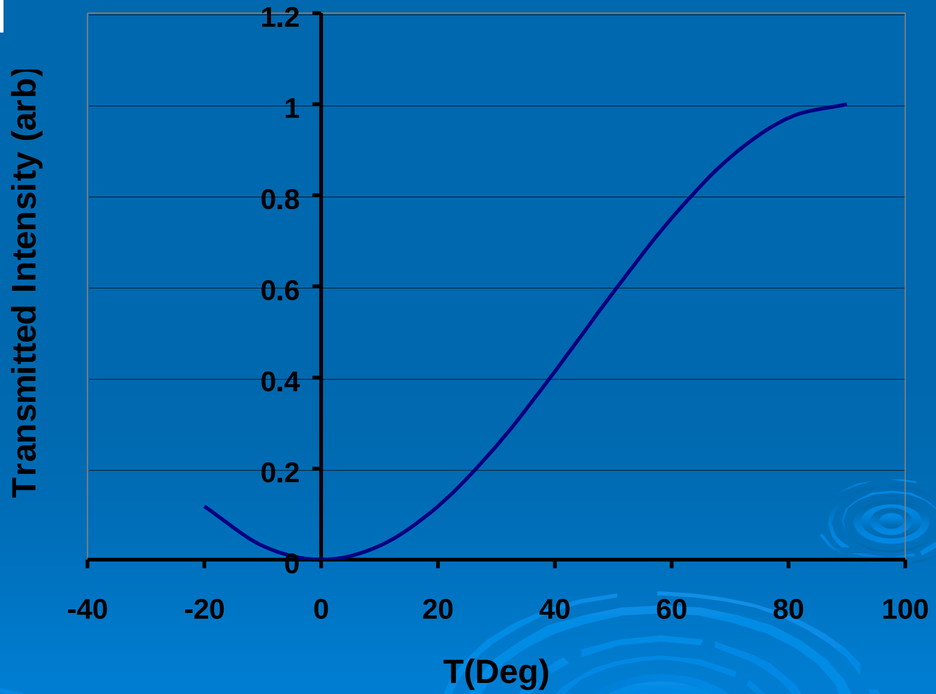
We showed that

$$I = I_o \sin^2(2\theta + 2\phi)\sin^2\frac{\delta}{2}$$

If laser polarization is set at 45˚ to field free optical axis (θ =45˚

$$I(t) \quad = I_0\,[\eta + \sin^2(\delta_b + \delta(t))]$$

where η is the intensity extinction coefficient of the optical arrangement (fraction of the transmitted intensity in the absence of the crystal), δ_b is the static retardation and $\delta(t)$ is the time dependent component of the retardation.



Preset operation in linear regime

For Measurements

- Select type of Crystal
  - E-O coefficient
  - Radiation damage
- Select orientation
  - Rotation
  - Cross & Static terms
- Select laser
  - Polarization
  - CW/Pulsed
  - Power
  - wavelength
- Select Detection scheme
  - Time
  - Spectrum
  - Spatial profile
- Select operating parameters
  - X'tal dimensions
  - Location
  - Laser transport
  - Optical system
  - Diagnostics
  - …

Measurement of Pulse duration in a single shot using CW laser and fast detector

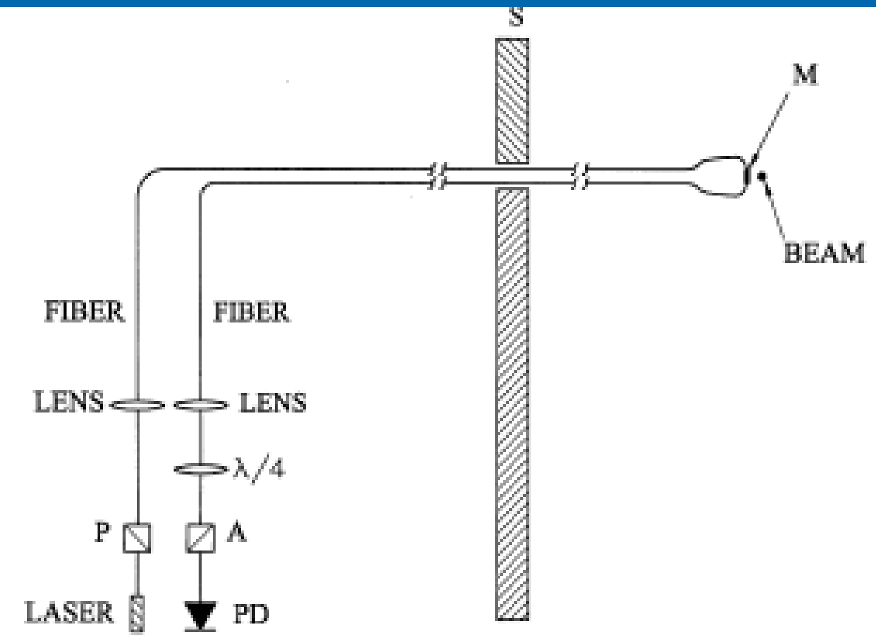
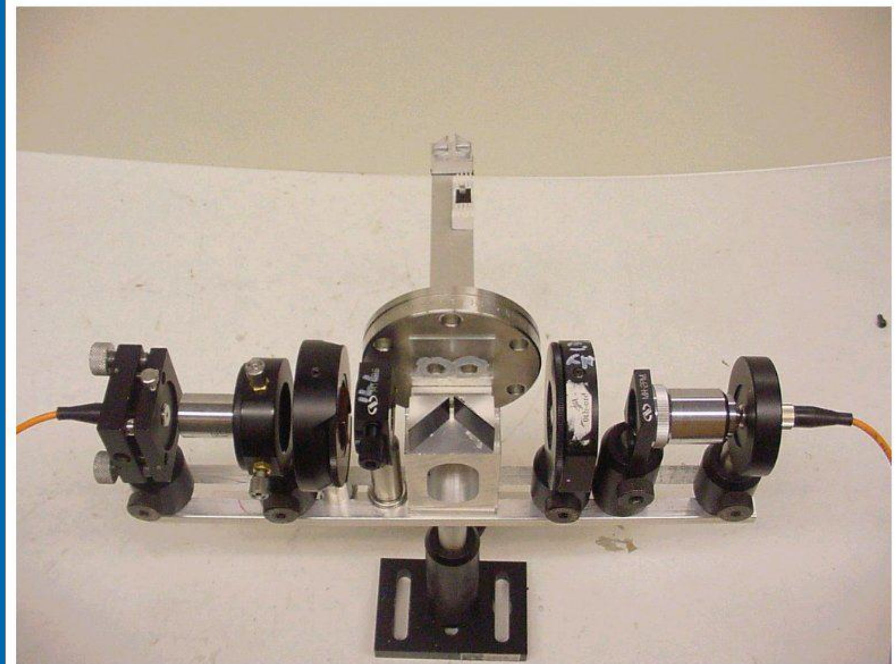
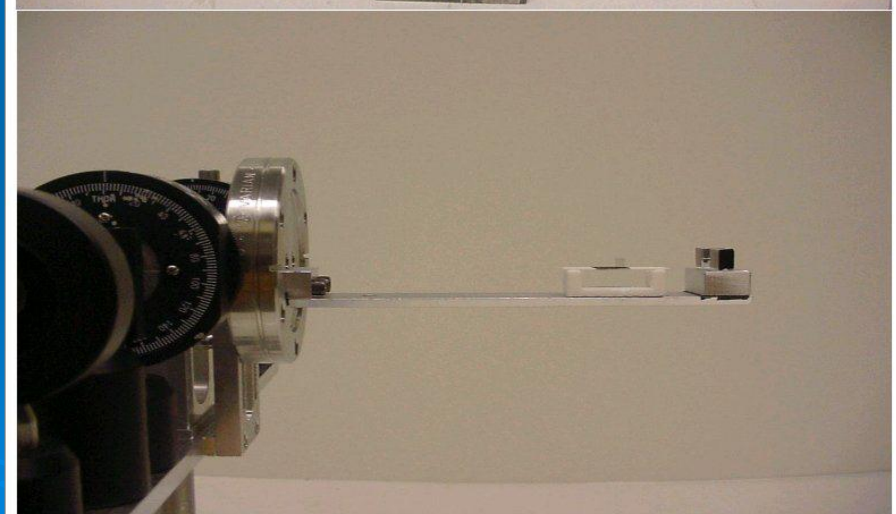
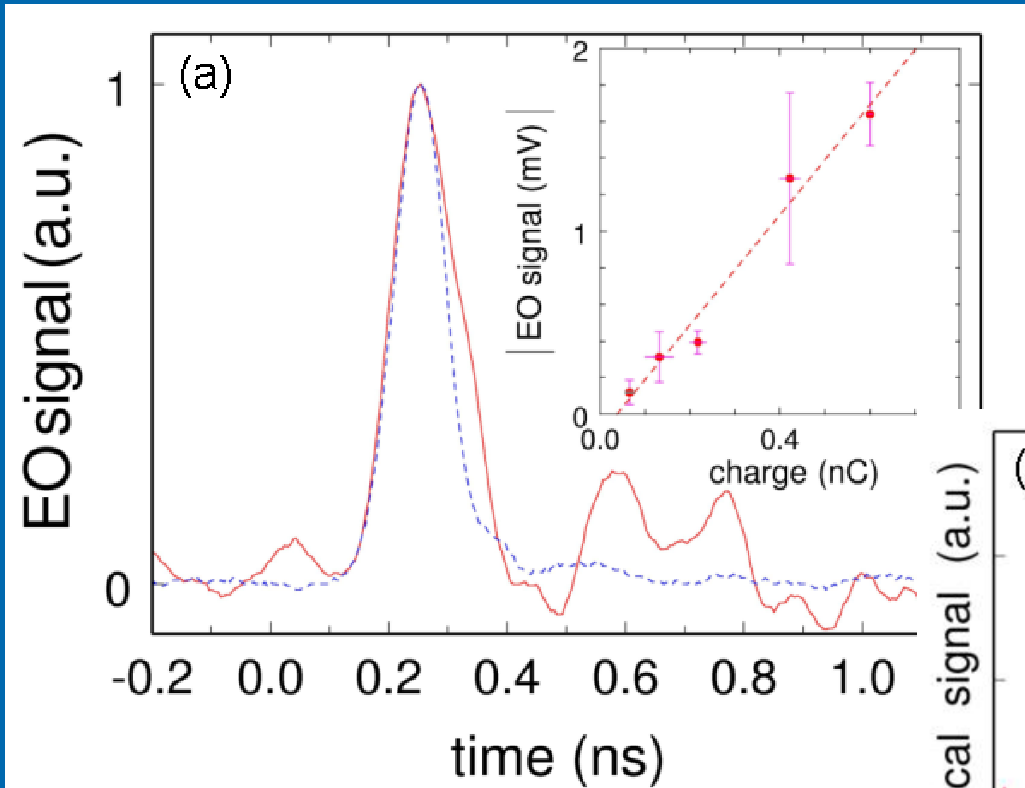


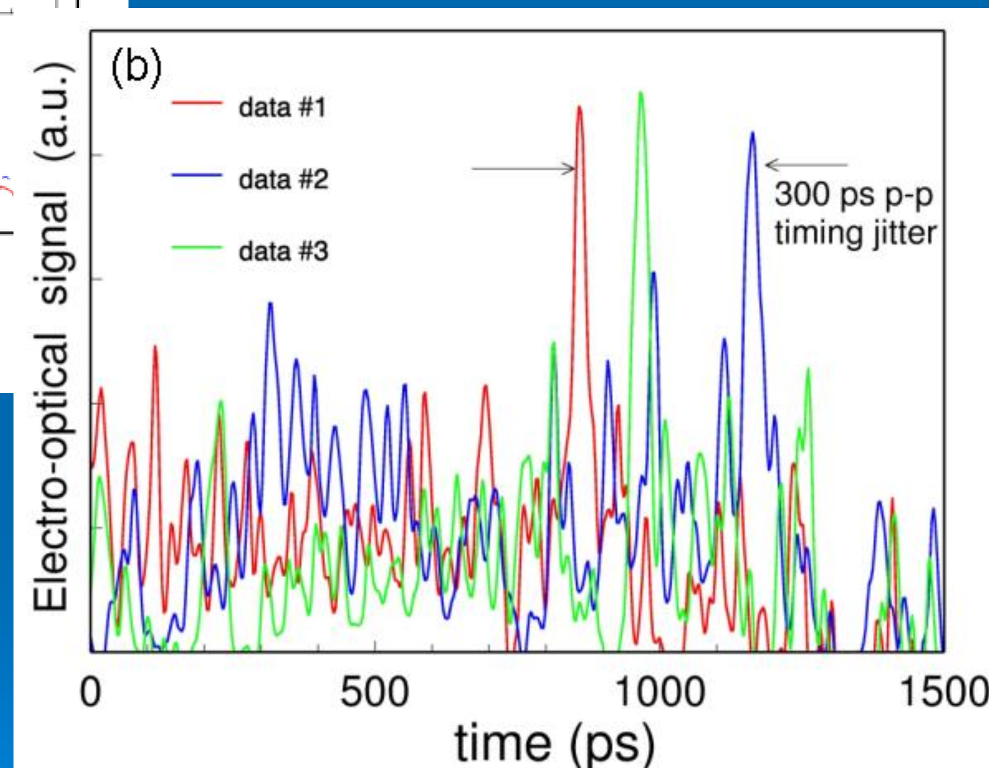
Fig. 1. The experimental setup for detecting a charged particle beam. The $LiNbO_3$ crystal (M) was located in vacuum several mm from the beam position which could be varied over several cm. The beam direction was perpendicular to the plane of the page. The positions of the polarization maintaining fibers, polarizer (P), lenses, $\frac{1}{4}$ wave plate ($\lambda/4$), analyzer (A), shield wall (S) and photodiode detector(PD) are schematically indicated.







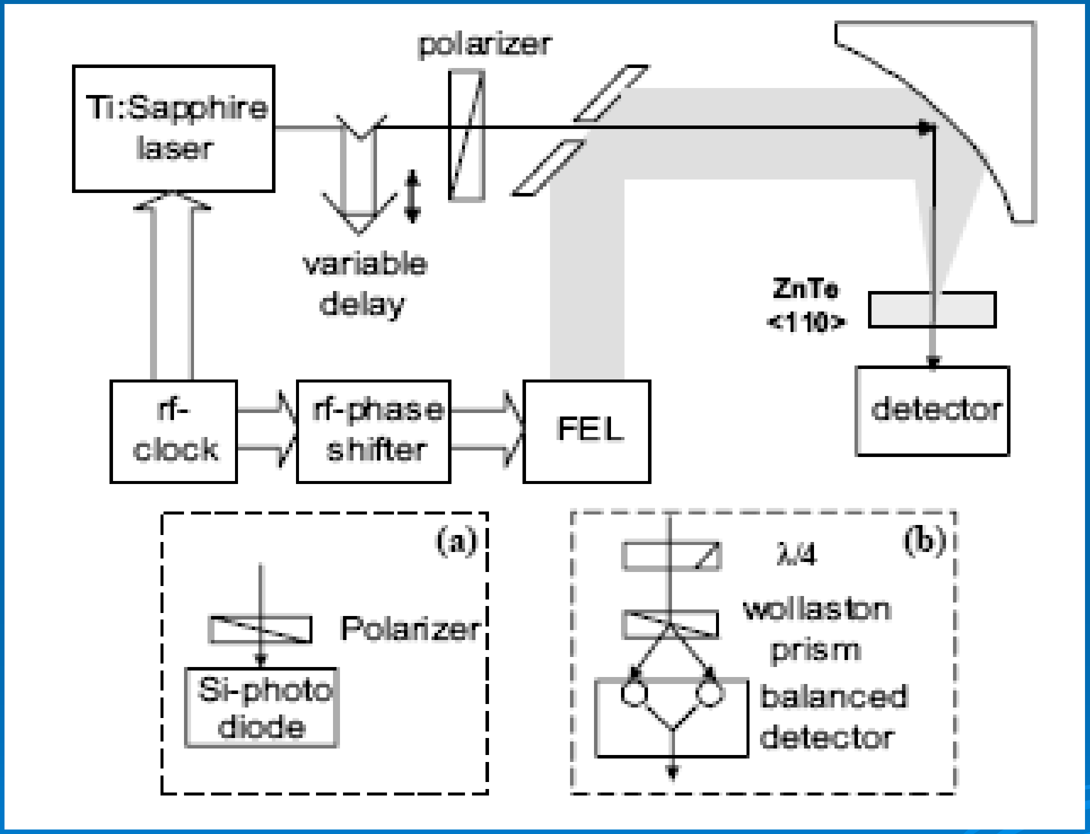
Using Streak Camera, 3 single shot traces superimposed



Using 7 GHz Oscilloscope: Resolution limited by the bandwidth of scope

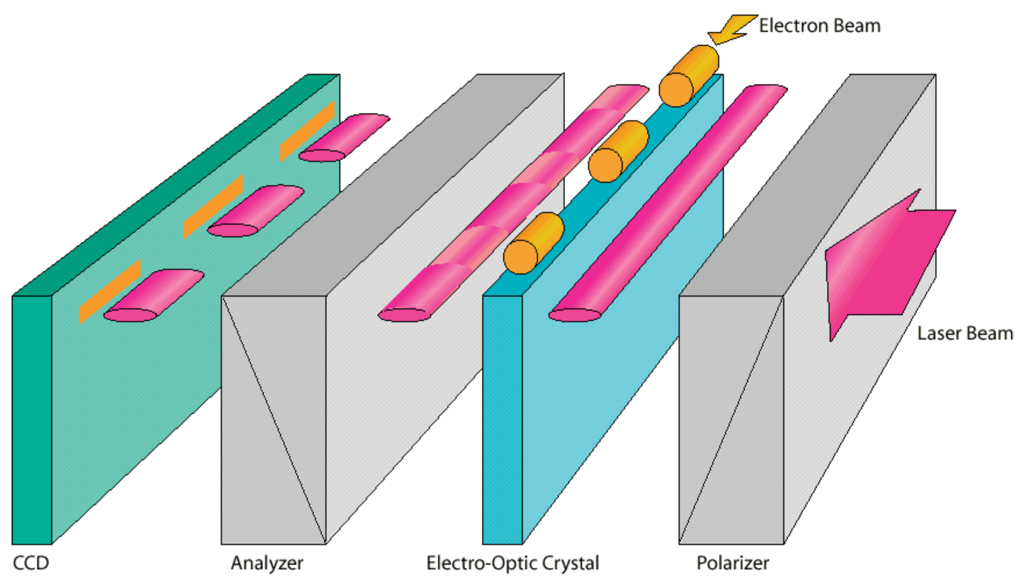
Nuclear Instruments and Methods in Physics Research A 452 (2000) 396–400

Measurement of pulse duration in multiple shots using ultrafast laser (12 fs) and photodiode



NIM A 475 (2001) 504-508

Converting temporal information to Spatial information: Information on pulse duration shape, distribution and timing



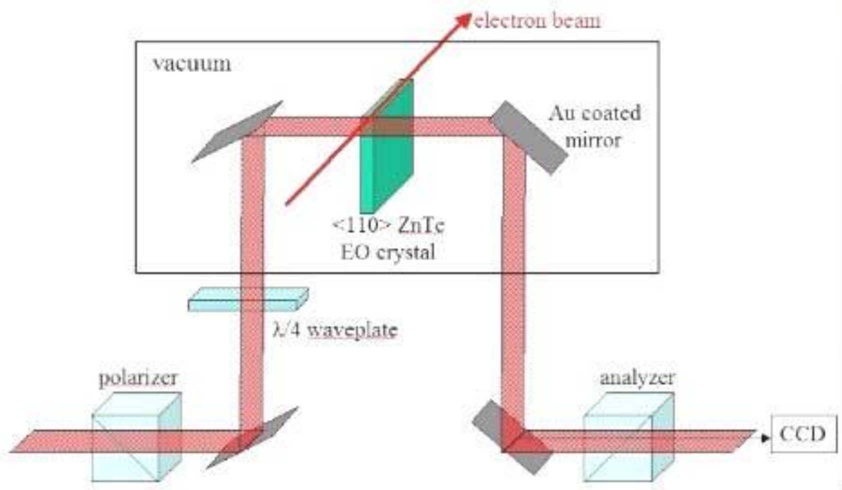


Fig. 1.3 Schematic of EO setup

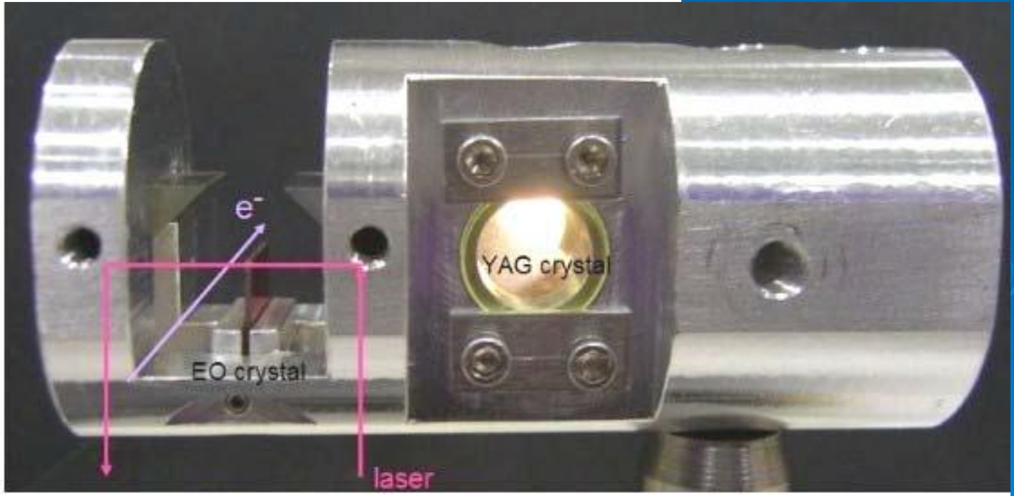
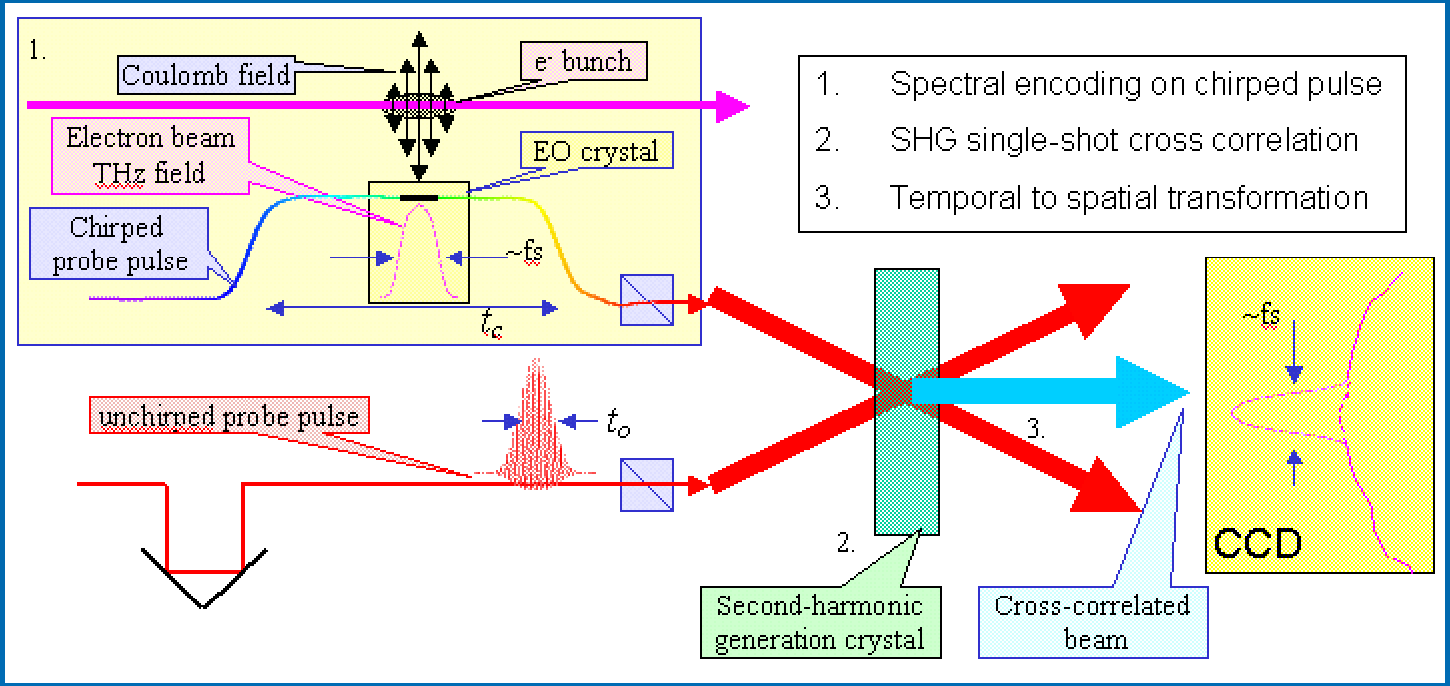


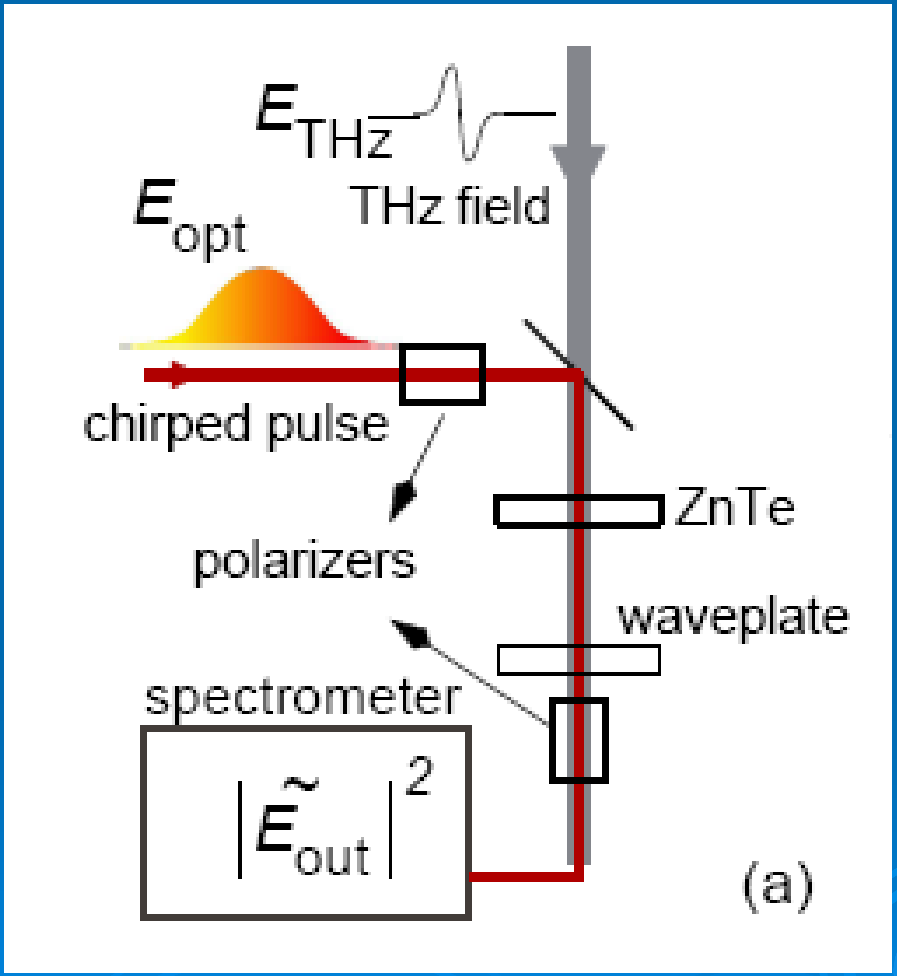
Fig. 1.4 EO-flash detection module

Cross correlation between unchirped and chirped pulse-single shot, information on pulse duration, shape and timing



Replace CCD by spectrometer for spectral encoding of the e beam on chirped pulse

Spectral encoding of electron beam on chirped pulse Single shot



Limitations

- Crystal absorption and dispersion beyond 10 THz (100 fs) regime
- Short distance between e beam and crystal
- Edge effects in low relativistic regime