Beam size diagnostics using diffraction radiation

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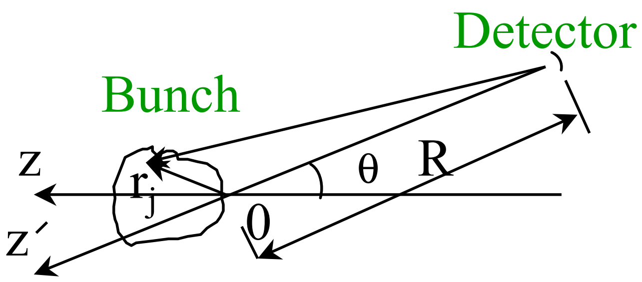
Motivation:

- "Non-intercepting electron beam size diagnostics using diffraction radiation from a slit", proposal for NSF/UCLC.
- Diagnostics of the longitudinal and transverse beam sizes.
- Potential application to diagnose the beam position, beam energy and emittance.

Why use diffraction radiation?

- Non-invasive: Diffraction radiation through a slit.
- Beam size diagnostics: longitudinal and transverse
- Beam position monitor: radiation intensity vs. beam position
- More beam information: beam energy and emittance
- Intensity proportional to the square of beam energy
- In the limit of zero slit width DR$\rightarrow$TR

Coherent Radiation



Intensity of radiation from number of N electron:

$$I_{tot}(\omega) = I_1(\omega)\left|\sum_{j=1}^{N} \exp\left[i\frac{\omega}{c}\vec{n}\bullet\vec{r}_j\right]\right|^2$$

$$= I_1(\omega)\left[N + N(N-1)F(\omega)\right]$$

Bunch Form Factor:

$$F(\omega) = \left|\int d\vec{r}\,S(\vec{r})\exp\left[i\frac{\omega}{c}\vec{n}\bullet\vec{r}_j\right]\right|^2 \quad , \text{ where}\left|\int d\vec{r}\,S(\vec{r})\right| = 1$$

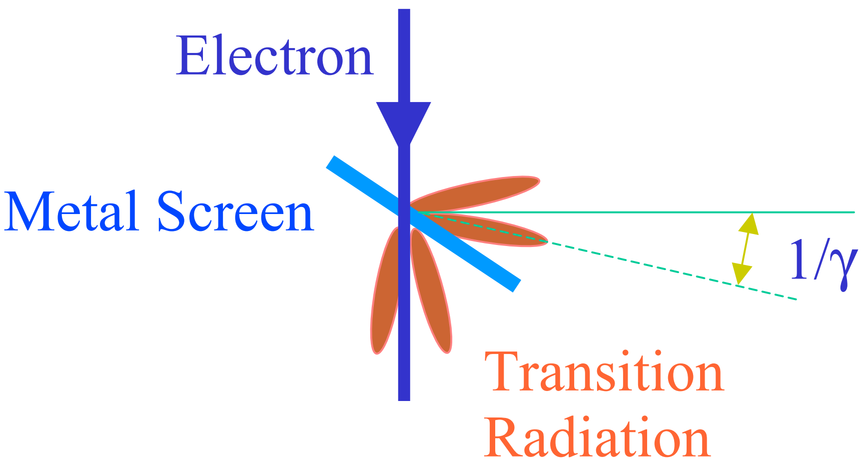
$$\text{for } \theta \to 0,\; F(\omega) = \left|\int dz S(z)\exp\left[i\frac{\omega}{c}z\right]\right|^2$$

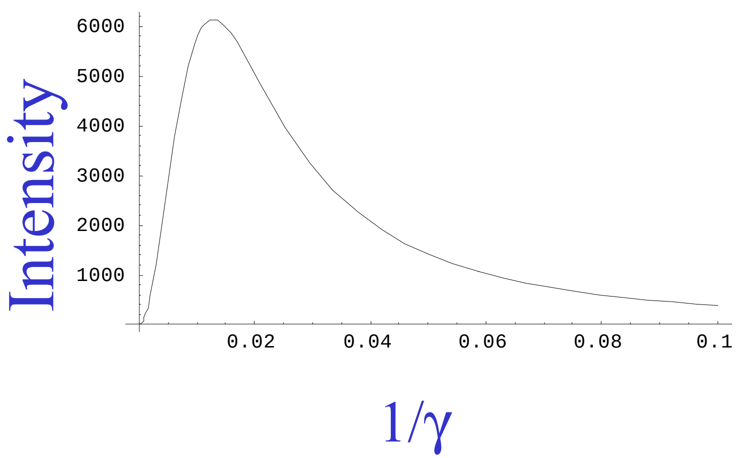
The first term is the incoherent emission component.

The second term is the coherent part which takes into account the phase relation between the different particles. The coherent radiation power is proportional to the square of electron number in a bunch rather than the electron number in case of incoherent radiation.

A measurement of the coherent emission gives the longitudinal bunch form factor F(ω) and therefore provides information about the longitudinal bunch distribution S(z).

Transition Radiation





An electron emits transition radiation when it passes through a metal foil.

- Forward TR
- Backward TR

TR intensity angular distribution

$$I(\omega,\theta)=\frac{\beta^2 e^2}{\pi^2 c}\frac{\sin^2\theta}{(1-\beta^2\cos^2\theta)^2}$$

Diffraction Radiation from a circular aperture

The intensity emitted from a relativistic electron passing through a circular aperture in an ideally conducting screen is given by

$$P(d,\lambda,\theta) = \frac{\alpha}{\pi^2 \lambda} \frac{\beta^2 \sin^2 \theta}{(1-\beta^2 \cos^2 \theta)^2} \bullet J_0\left(\frac{\pi d \sin\theta}{\lambda}\right) \frac{\pi d}{\beta\gamma\lambda} K_1\left(\frac{\pi d}{\beta\gamma\lambda}\right)$$

where the first part is the intensity of transition radiation emitted from the electron passing through the ideally conducting screen in vacuum, d the diameter of the aperture, θ the direction angle measured from the beam axis. The functions J_0 and K_1 are the Bessel function of zeroth order and the modified Bessel function of first order.

The second part corresponds to the diffraction radiation. When in the limit of small aperture, it tends to unity.

Bunch Shape Measurement

Intensity of coherent radiation from a short bunched electron beam

$$I_{coh} \approx N^2 F(\omega) I_{incoh}(\omega)$$

$$F(\omega) = \left| \int dz S(z) \exp\left[i \frac{\omega}{c} z \right] \right|^2$$

In case of symmetric electron bunch:

$$S(z) = \frac{1}{\pi} \int_0^\infty d\omega \sqrt{F(\omega)} \cos\left(\frac{\omega z}{c} \right)$$

In case of asymmetric electron bunch:

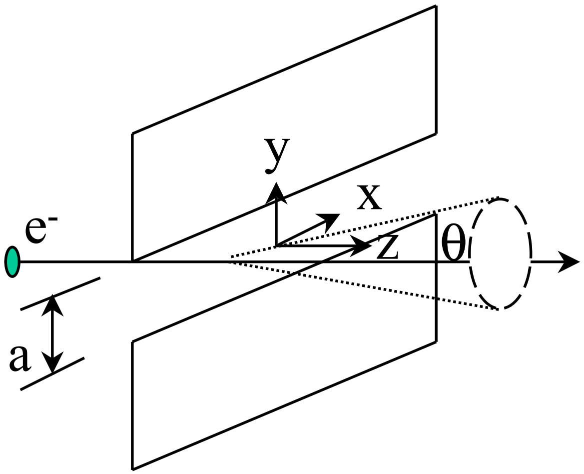
$$S(z) = \tfrac{2}{\pi} \int \left[f(\sigma) \right]^{1/2} \cos[2\pi\sigma z - \Psi(\sigma)] d\sigma$$

where σ is the wave number of radiation, Ψ(σ) the phase calculated from the observed form factor by the Kramers-Kronig relation:

$$\Psi(\sigma) = -(\sigma / \pi) \int \ln\left[f(t) / f(\sigma) \right] / \left(t^2 - \sigma^2 \right) dt$$

Diffraction Radiation from a Slit

- The intensity emitted by an electron passing through the center of a slit along the x-axis and of width a is described as



$$I = 4\pi^3 \frac{k^2 c}{\omega h}\left[\left|E_x^2\right| + \left|E_y^2\right|\right]$$

where

$$E_x(k_x, k_y) = \frac{iek_x}{4\pi^2 cf}\left\{\frac{\exp[-a(f - ik_y)/2]}{f - ik_y} + \frac{\exp[-a(f + ik_y)/2]}{f + ik_y}\right\}$$

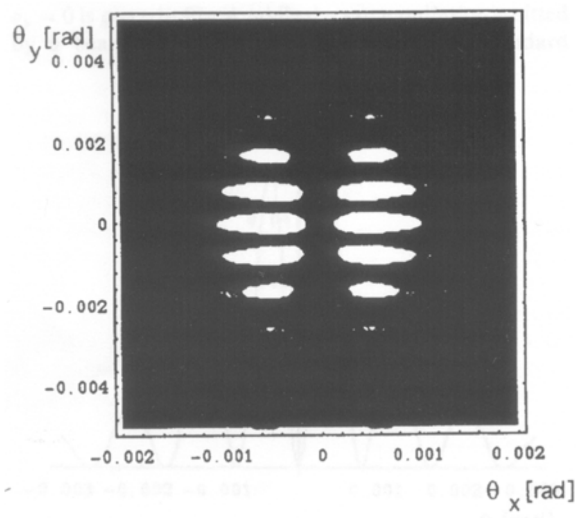
$$E_y(k_x, k_y) = \frac{e}{4\pi^2 c}\left\{\frac{\exp[-a(f - ik_y)/2]}{f - ik_y} - \frac{\exp[-a(f + ik_y)/2]}{f + ik_y}\right\}$$

$$f = \sqrt{k_x^2 + \left(\frac{k}{\beta\gamma}\right)^2}$$

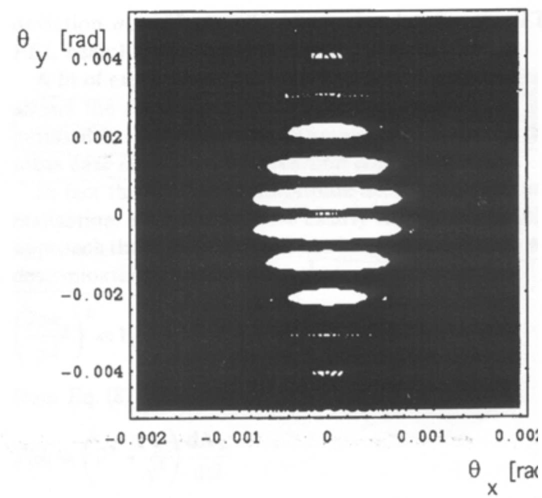
$$k_x = k \sin\theta \cos\varphi$$

$$k_y = k \sin\theta \sin\varphi$$

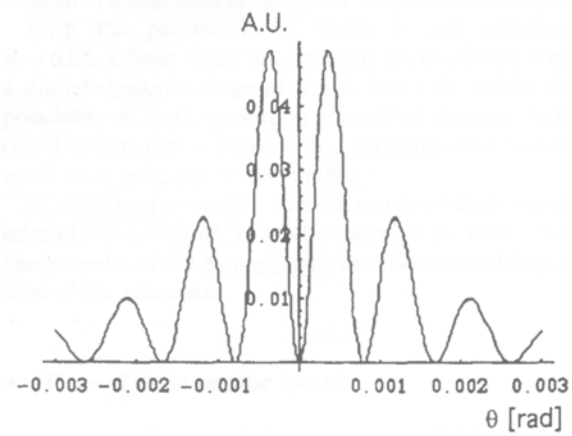
Angular distribution from DR



Parallel polarization
(500MeV, 1mm slit)



Normal polarization



M.Castellano, NIMA 394(1997)275

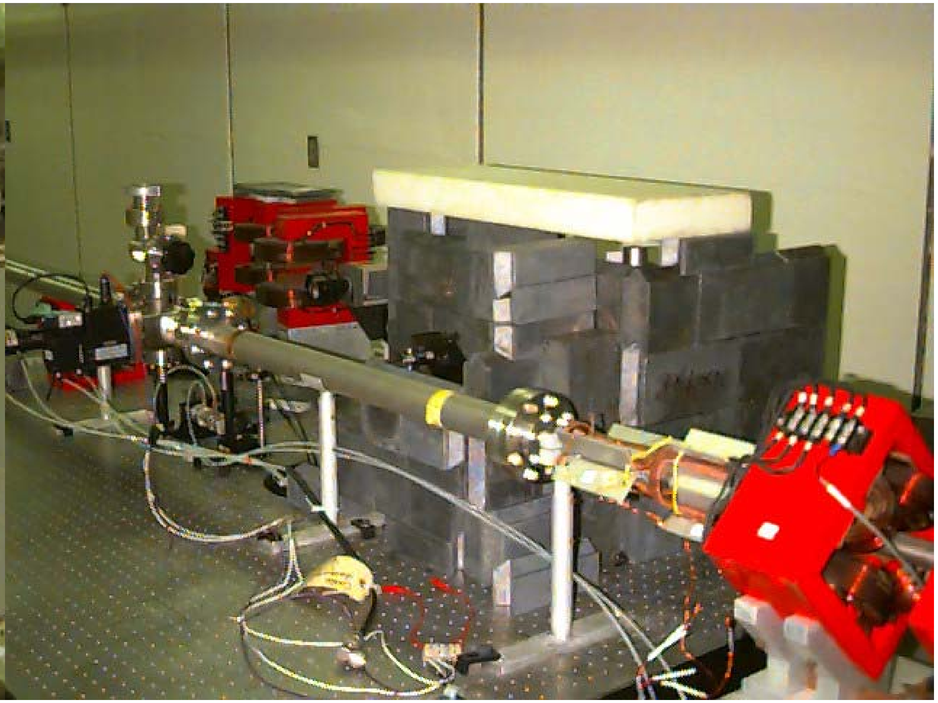
Properties of diffraction radiation can be used to measure beam divergence, energy, position, transverse beam size and emittance

“Diffraction radiation diagnostics for moderate to high energy charged particle beams”, R. B. Fiorito and D.W. Rule, NIMB 173(2001)67

Diffraction Radiation:

- The angular distribution of the DR from a electron beam passing through a slit in a metal foil appears polarization properties because of the interference effects between the two half planes of the radiator.
- The polarization shows different properties with the electric field parallel and normal to the plane of slit.
- Analyzing the whole angular distribution in the normal plane, and fitting with the expression of theoretical calculation on the experimental distribution allows us to determine the transverse dimension of electron beams.
- The total intensity of normal angular distribution has a minimum value when the beam passes through the center of slit. In practice, this can be used to center the electron beam in the slit.
- Angular polarization of the DR can be measured by a simple CCD camera.

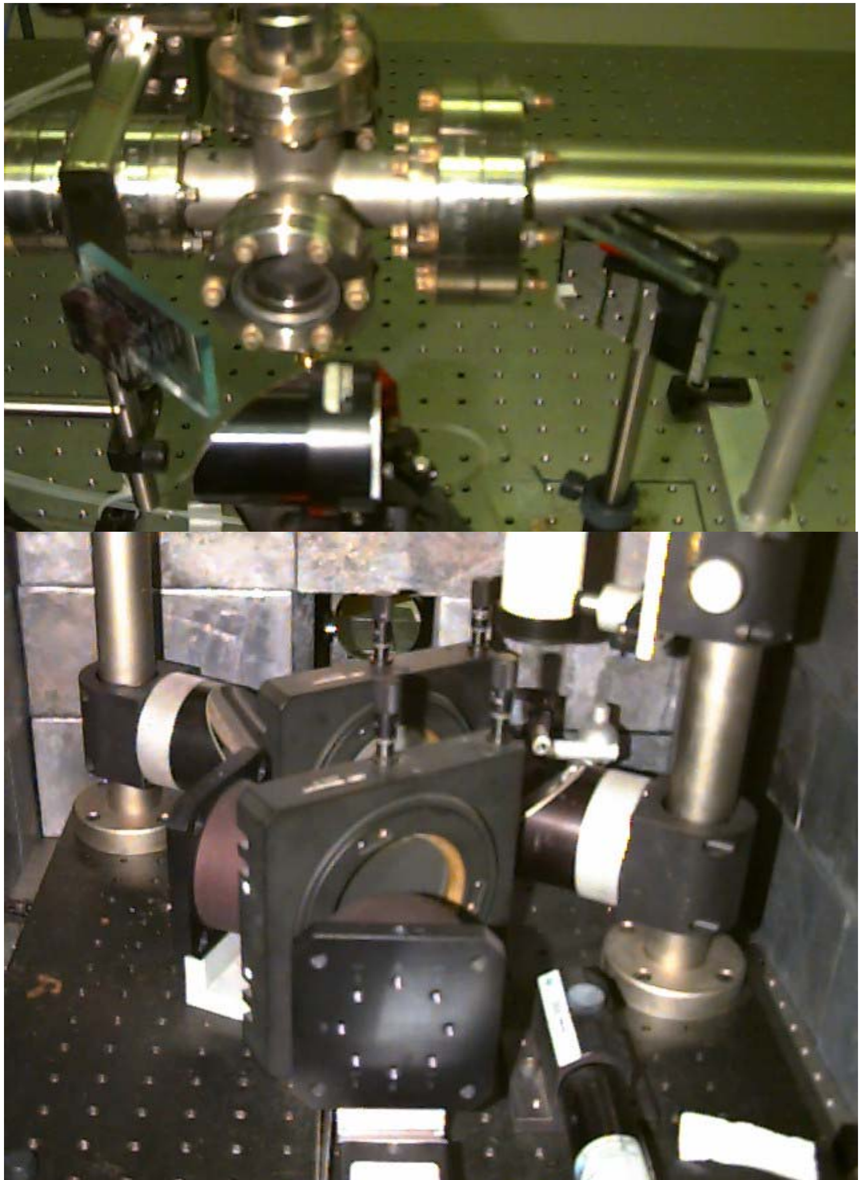
Experiments of coherent transition radiation

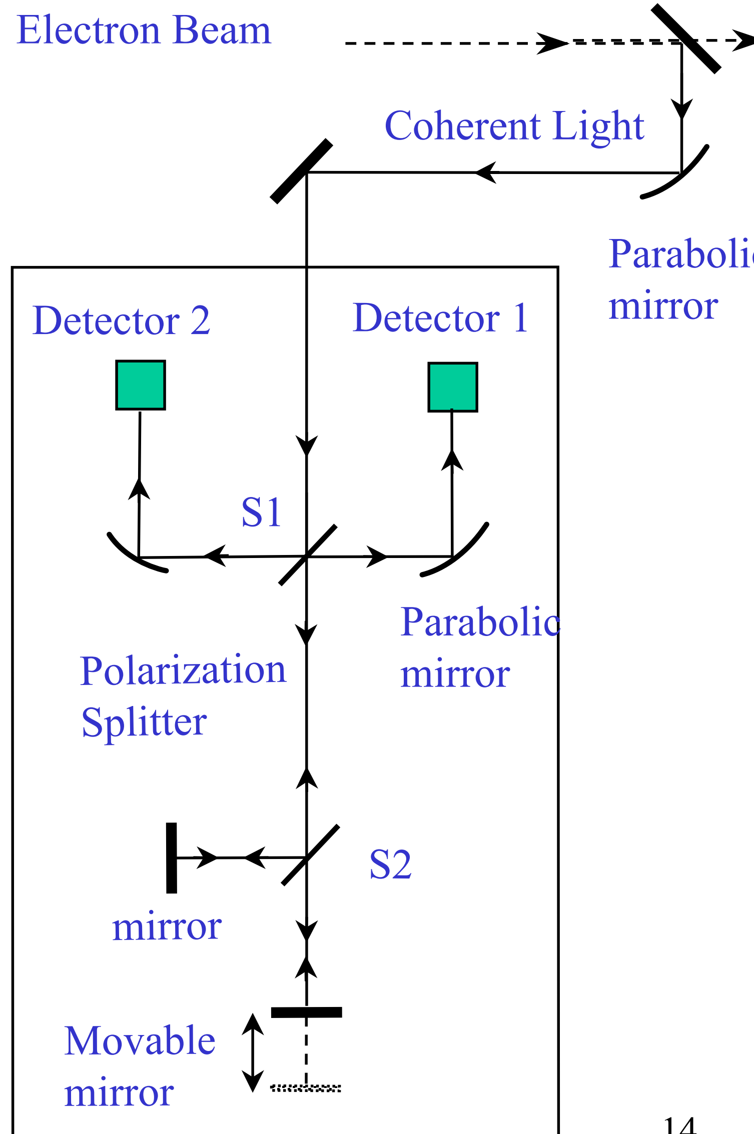


Parameters of the VU FEL

Accelerator:	
Electron energy	20-45 MeV
Energy spread	0.5 %
Normalized emittance	$10\pi \times 30\pi$ mm mrad
Macropulse average current	~ 250 m
Micropulse duration	0.8 ps
Macropulse duration	8 μs
Wiggler:	
Wiggler Period	23 mm
Period number	46
Maximun wiggler field	0.44 T
Laser:	
Wavelength	2 ~ 10 μm
Macropulse energy	50~100 mJ
Macropulse repetition rate	1~30 Hz

Setup of Martin-Puplett interferometer

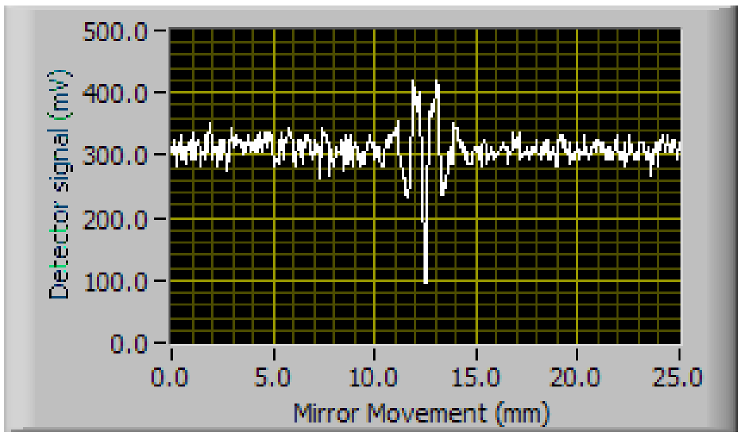




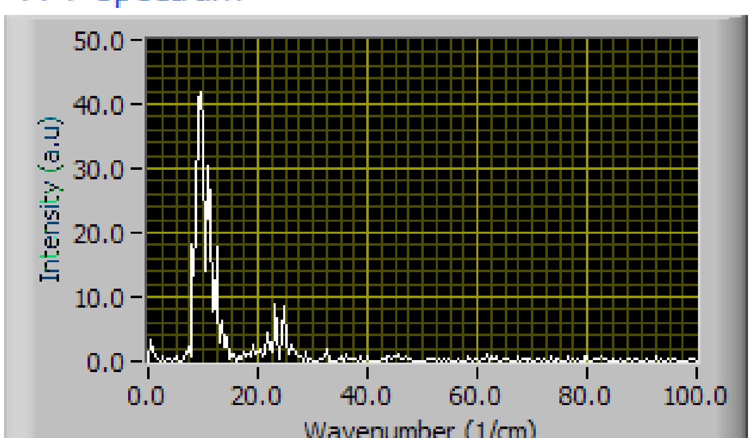
Typical interferogram for radiation from the short electron bunches

25MeV,Ib=228mV (30707_6)

Interferogram

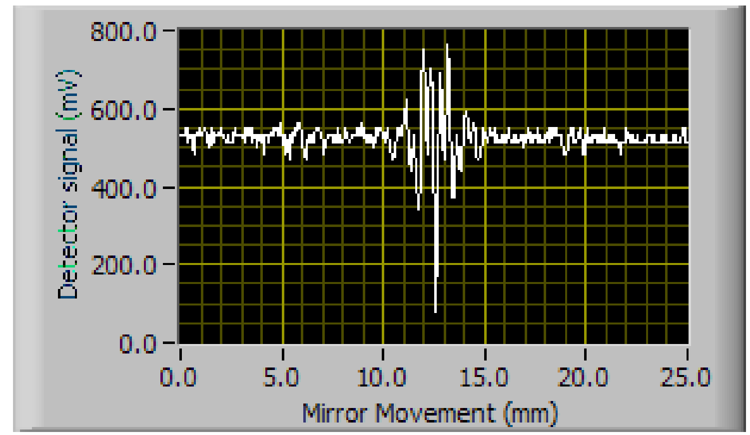


FFT Spectrum

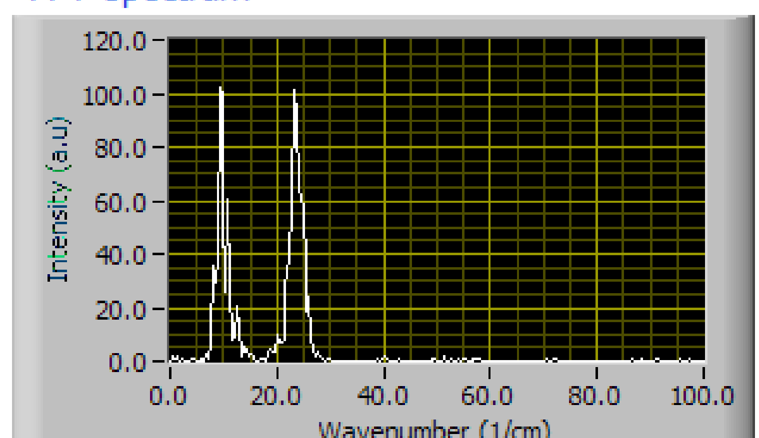


Eb=28.8MeV, Ib=300mV (30707_1)

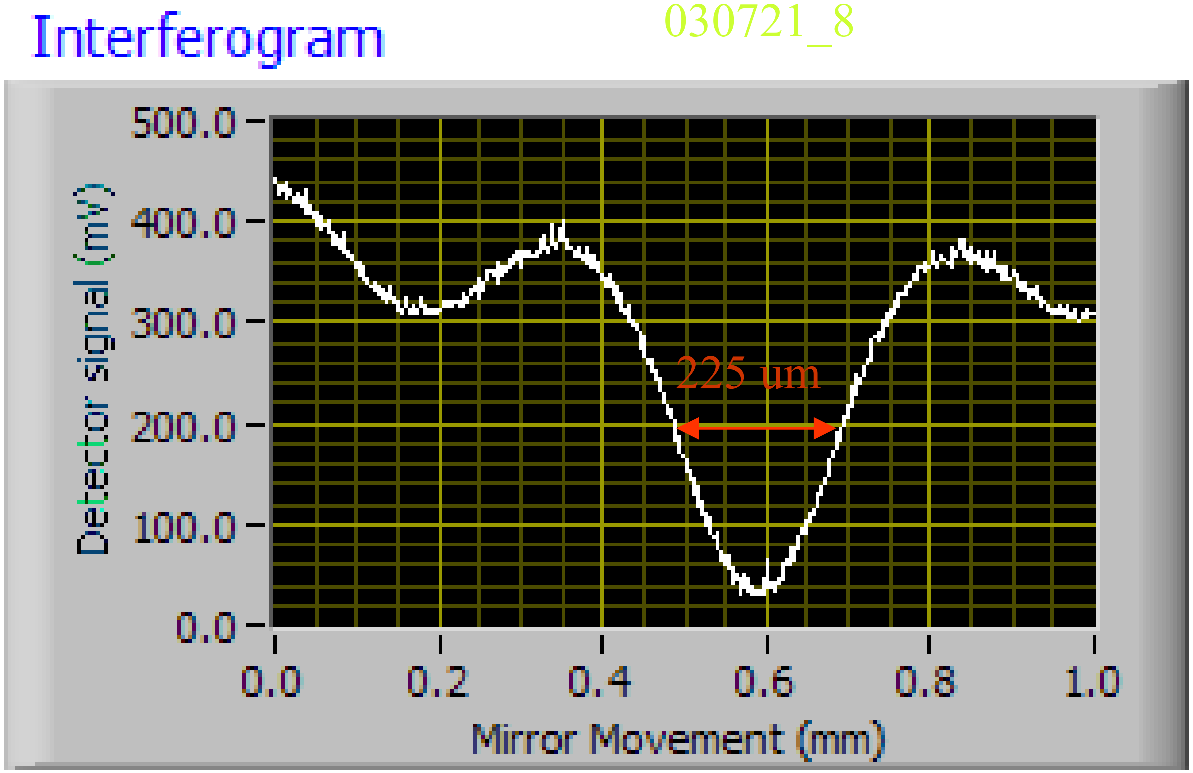
Interferogram



FFT Spectrum



Bunch length estimation



Eb=28MeV
lb=0.75ps

The width of the main peak in the interferogram is equal to the bunch length for a rectangular particle distribution. For a Gaussian distribution the equivalent bunch length is given by 1.5 FWHW

Status and Plan

- Studies of diffraction radiation
- Design and build a interferometer
- Radiator: vacuum chamber and slit actuator
- Longitudinal bunch length experiments
- Measurement of DR angular distribution
- Transverse beam dimension experiments

THE END