OPTICAL TRANSITION RADIATION DIAGNOSTICS FOR CHARGED PARTICLE BEAMS

Dr. Ralph Fiorito
IREAP
University of Maryland

USPAS June 20, 2008

What is Transition Radiation?

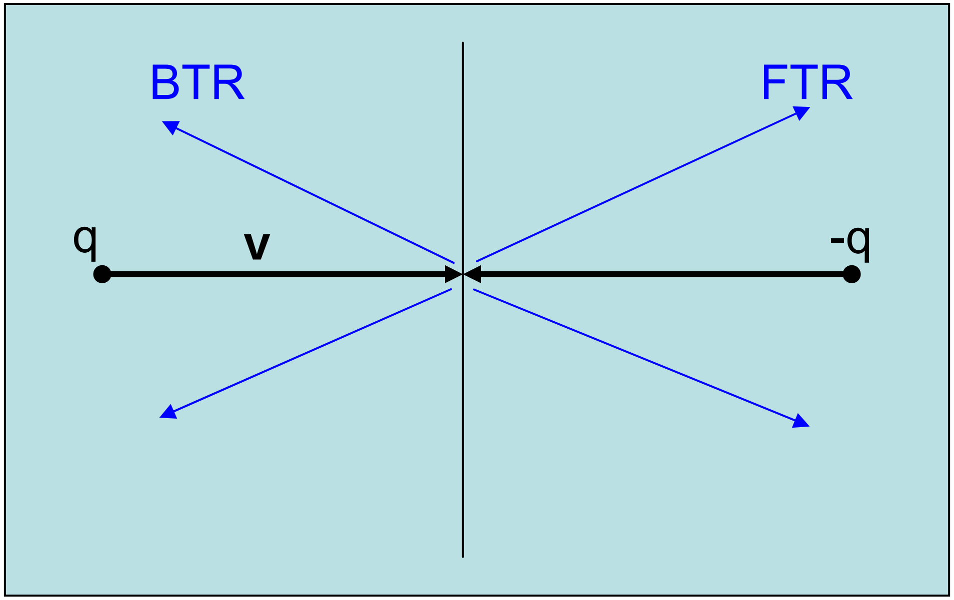
Definition: Radiation which occurs when charge moving at constant velocity crosses a boundary between media with different dielectric constants

a) simple idea: Radiation from collapsing dipole formed by moving charge and its image

b) more exact: Radiation formed by suddenly disappearing (LHS) and appearing (RHS) surface charge distribution as charge crosses boundary (femtosec time scale)

c) virtual photon: picture Reflection and refraction of virtual photons of all frequencies (up to plasma frequency) at the interface

What is radiating? The image charge current (Important to remember)



Brief History of TR and TR beam diagnostics

1919 " Lilienfeld radiation" observed near anode of CRT's - flat spectrum, unknown origin
1945 Tamm and Frank develop theory of TR
1959 Goldsmith and Jelley experimental verify TR in optical regime using 5 MeV protons
1960 Elridge, Ritchie and Ashley (ORNL), and others theoretically and experimentally study properties of optical TR, Bremsstrahlung and plasmon radiation from low energy (10's of keV) electrons
1960 Aitkin images far field angular pattern of OTR and uses it to measure beam energy
1970's Wartski, carefully examines OTR properties and develops OTR diagnostics for profiling and measuring energy of relativistic e beams; invents OTR interferometer, uses it to measure energy to 1% and shows that visibility of OTRI is sensitive to beam scattering
1980's Fiorito/Rule show that OTR and OTRI can be used to determine x and y rms emittances of relativistic electron beams; deliver their first paper on this subject: *"OTR Diagnostics for Intense Beams", at the Werner Brandt Workshop on Charge Penetration Phenomena in Materials, ORNL, 12-13 April, 1984*
1985 Bosser, et. al. use OTR to profile high energy (450 GeV) proton beams at CERN
1990's F/R devise optical transverse phase space mapping method using OTR
1990's Barry devises CTR interferometry technique to measure bunch length; Lihn proves out method experimentally, further developed by Sievers, Blum, Happek, Nakazato, Shibata; now a standard bunch length measurement technique
2000's Explosion of work on OTR, ODR diagnostics for relativistic beams; OTR becomes the gold "standard" imaging method for relativistic beams
Scarpine, Lumpkin, et. al. revisit OTR to image 120 GeV proton beam
Bravin, LeFevre (CLIC) and Feldman, Fiorito & Casey (UMER) use OTR to image low energy (10 - 80 keV) electron beams

Diagnostics of beam observables and resolutions using TR

Incoherent TR ($\lambda << d$)

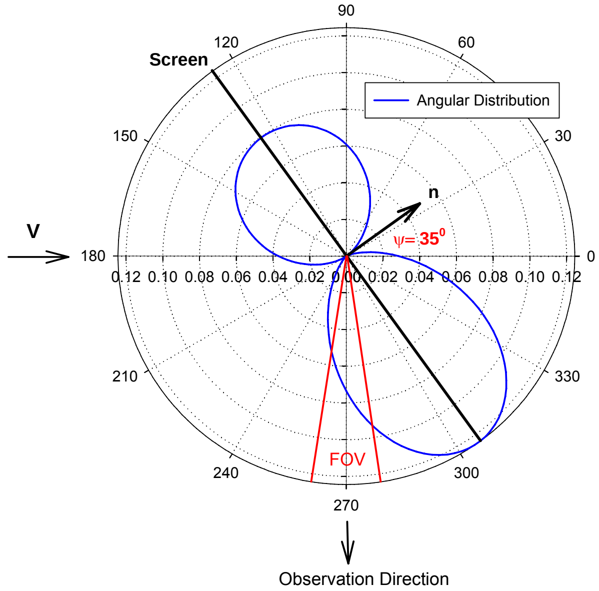
1-Near Field Imaging (spatial distribution)
size (x, y)
position (x, y) (offset)
spatial resolution (independent of energy and close to diffraction limit of optics)

2-Far Field Imaging (angular distribution)
divergence (x', y') [angular resolution < $0.01/\gamma$]
trajectory angle (X',Y') [<$0.01/\gamma$]
energy (average) and energy spread [<0.01]

Coherent TR ($\lambda \sim d$) (e.g. 1ps bunch : FIR-mm)

1- Spectra
bunch length + possibly longitudinal distribution
2- Angular Distribution
divergence, beam transverse size (possible)
bunch length +possibly long. distrib.(new)

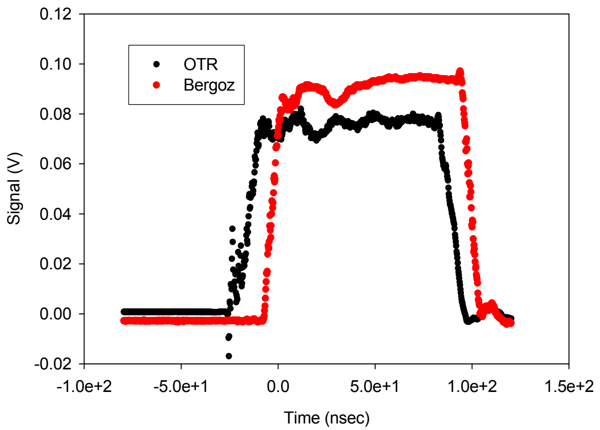
Non relativisitic OTR from 10 keV UMER electron beam ($\beta = 0.139$)

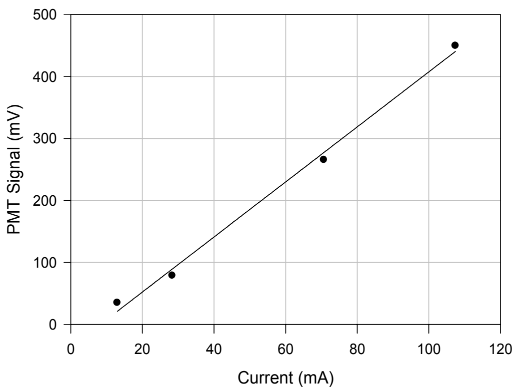


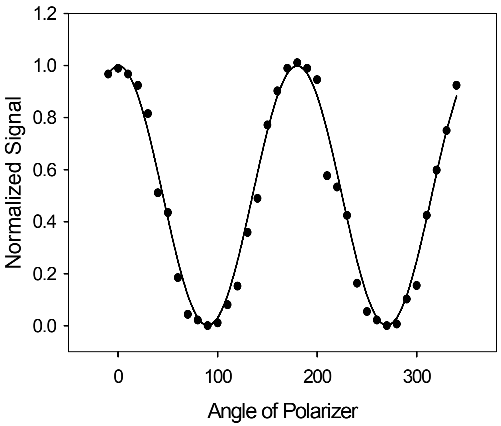
Photon yield

Theory: $dN = (1.4 \cdot 10^{-5}) \frac{d\lambda}{\lambda} d\Omega$

Measured: $dN = (2-5) \cdot 10^{-5} \frac{d\lambda}{\lambda} d\Omega$

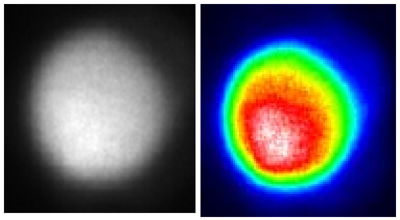




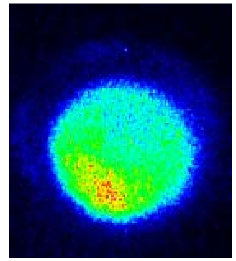


Time Resolved Beam Imaging with OTR and Gated ICCD Camera at UMER
(10 keV, 20 mA)

Phosphor: 1200 frames

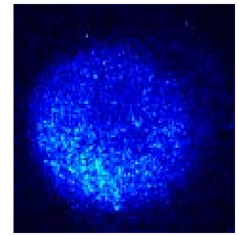


OTR: 0-100ns



7200 frames

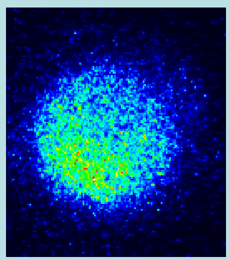
OTR: 3ns gate (10-20ns)



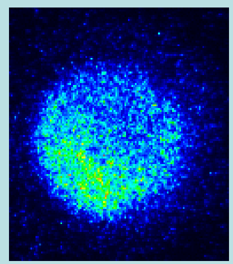
36000 frames

10ns gate
7200 frames

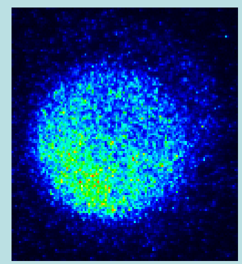
0-10ns



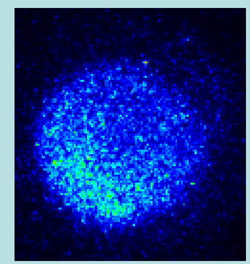
10-20ns



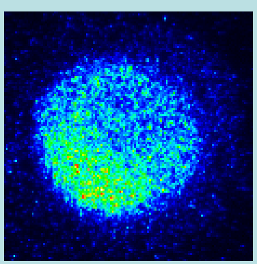
20-30ns



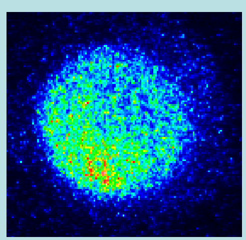
30-40ns



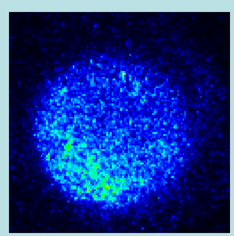
40-50ns



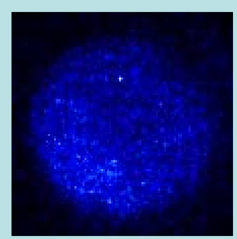
50-60ns



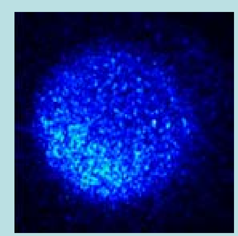
60-70ns



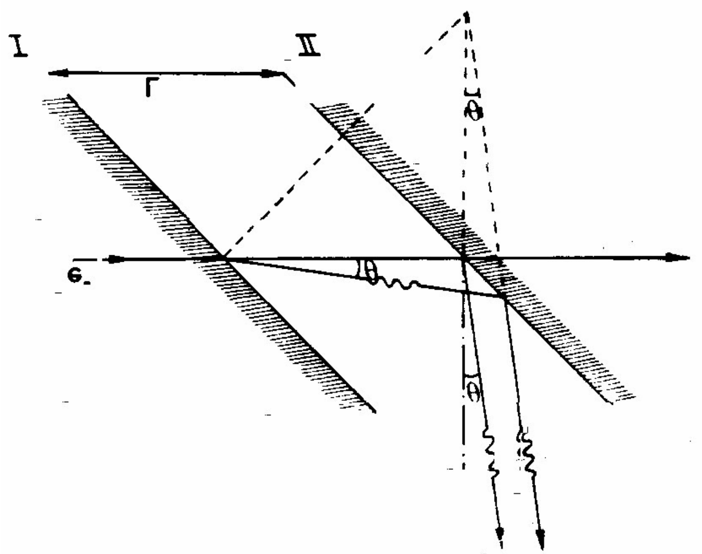
70-80ns



90-100ns



OTR Interferometry beam emittance diagnostics for tune up operations

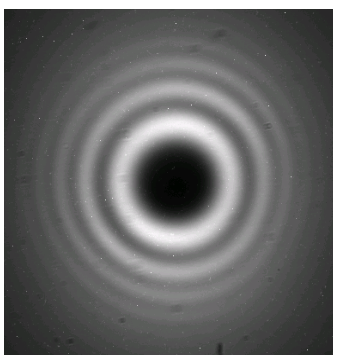


$$\frac{d^2 I_{TOT}}{d\omega d\Omega} = \left[\frac{e^2}{\pi^2 c} \frac{\theta^2}{(\gamma^{-2} + \theta^2)} \right] 4 \left| 1 - e^{i\phi} \right|,$$

where: $\phi = L / L_V,$
(e-photon phase difference)

and: $L_V = (\lambda / \pi)(\gamma^{-2} + \theta^2)^{-1}$
(vacuum coherence length)

θ_x



θ_y

Diagnostics

- **Center of pattern measures trajectory angle of particle**
- **Visibility of OTRI measures beam divergence** ***(and/or ΔE/E)***
- **Radial Polarization of OTRI can be used to *separately* measure x' and y'**
- ***Fringe position also measures beam energy (E)***

Advantages of Optical Transition Radiation Interferometry (OTRI)

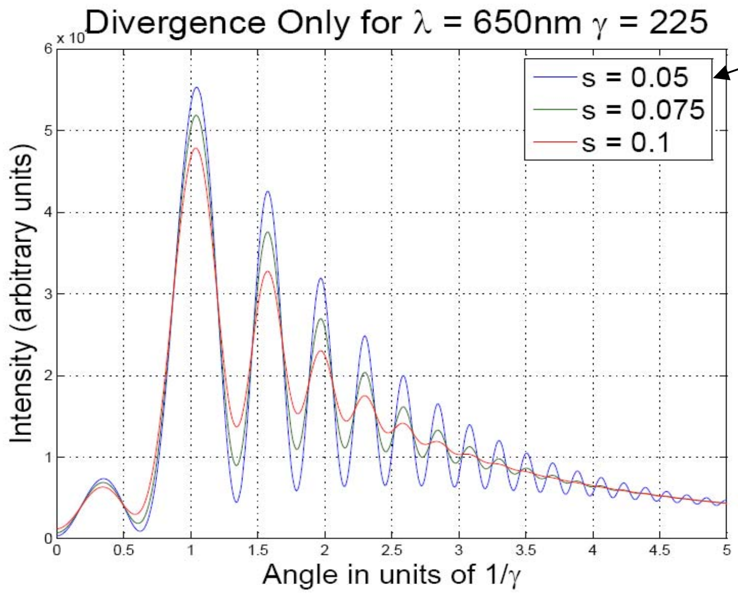
1. Single shot data acquisition for beam property measurements
2. Single position emittance monitoring
3. Ability to measure multiple beam components
4. Can be fitted with mesh front foil to access lower divergence beams i.e. ODR-OTRI
5. Ability of OTR to measure multiple beam parameters with high precision

Electron *Beam* OTRI

Jefferson Lab estimated beam parameters

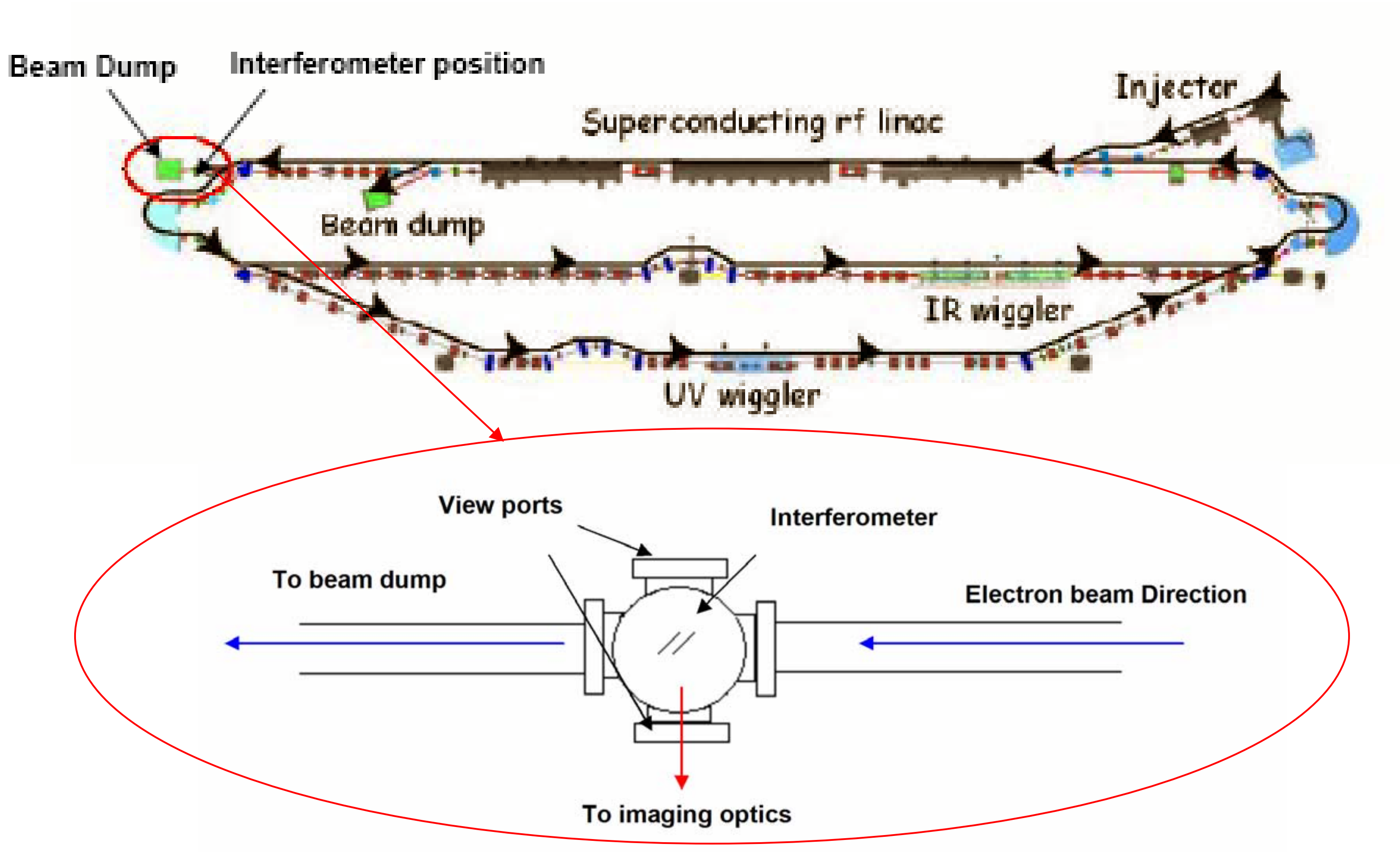
- *Energy = 115 MeV*
- *Energy spread ~ 2%*
- *Emittance ~ 5 mm-mrad – 10 mm-mrad*
- *Rms Beam size at a waist ~ 0.1 mm*

Effect of foil scattering and energy spread on OTRI negligible for JLAB

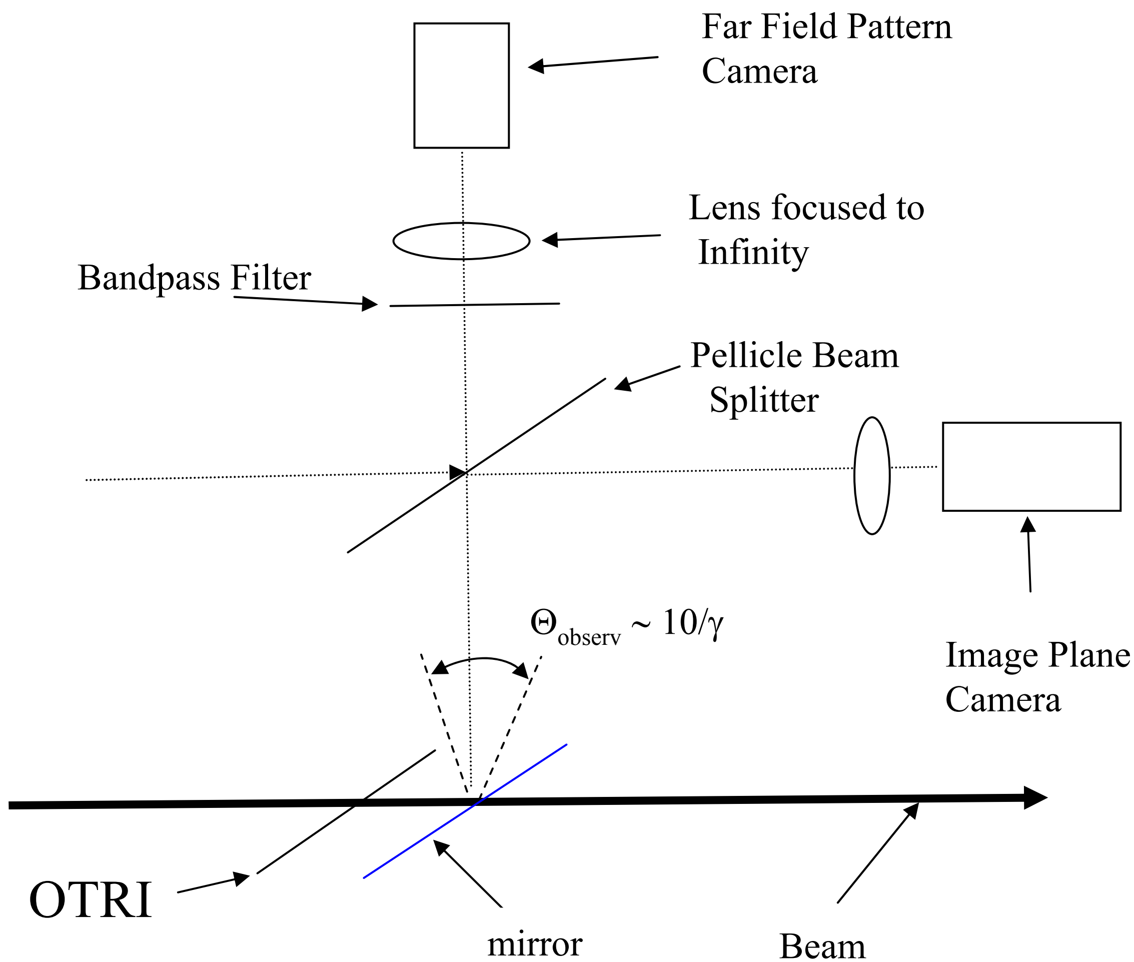


Sensitivity improved by an order of magnitude compared to single foil OTR

Interferometer Location at JLAB FEL

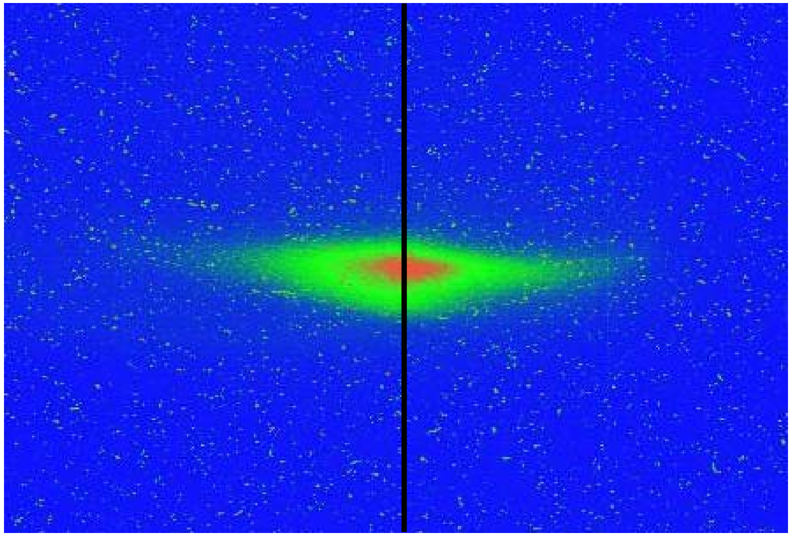


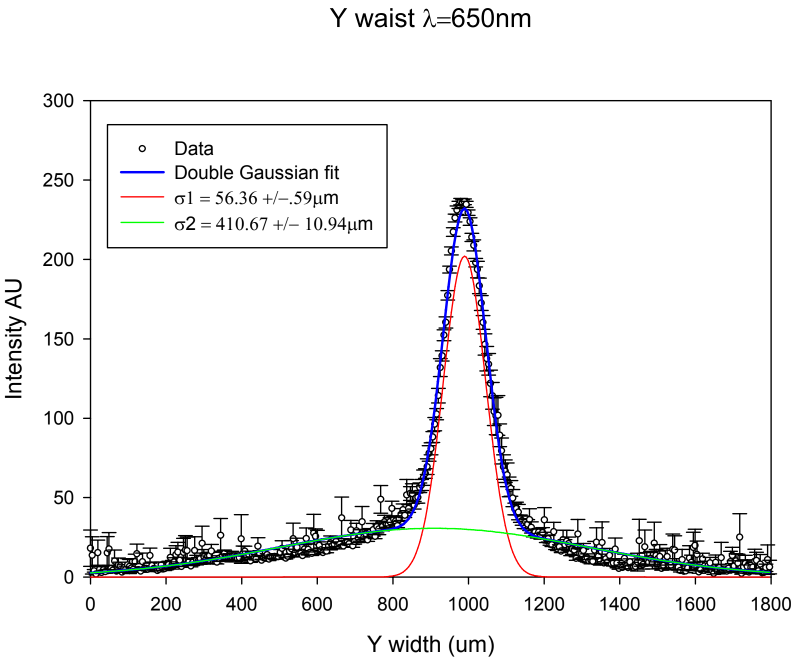
OPTICS Setup for OTR RMS Emittance Measurement



Beam magnetically focused to x or y waist condition

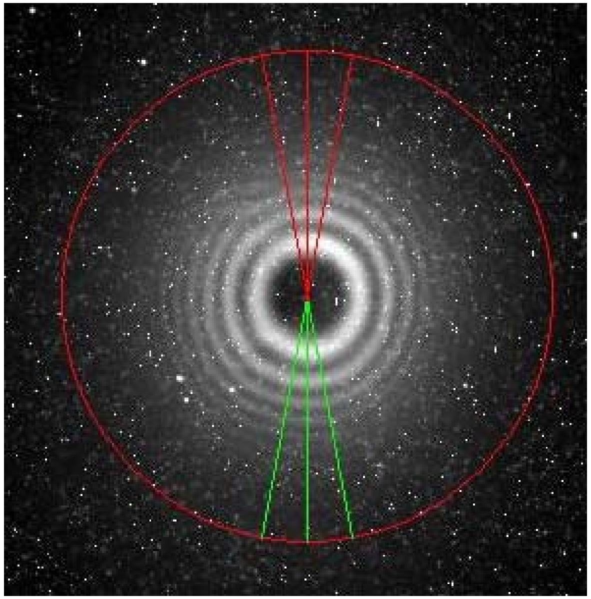
Nearfield Measurements at JLAB Show Two Components

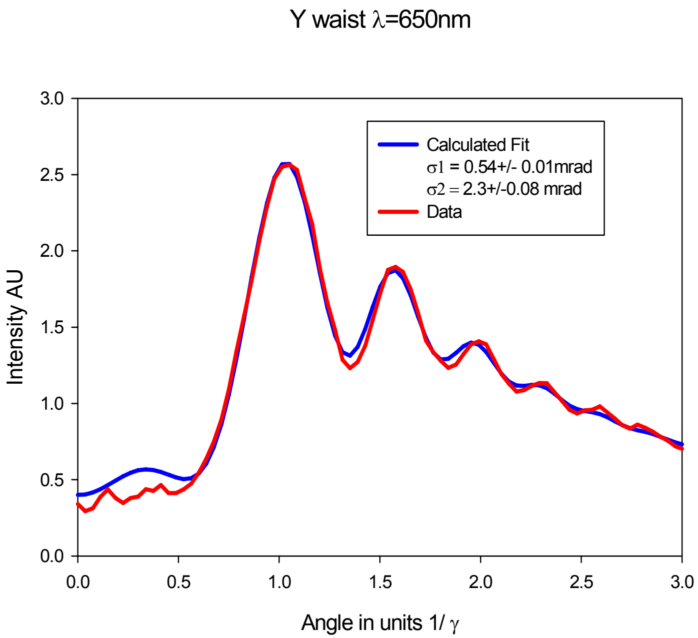




	Wavelength	**σ1** (μm)	**σ2**(μm)	**# of pictures averaged**
X	650 nm	134.39+/-1.38	380.09+/-5.61	10
X	450 nm	174.96+/-2.6	508.72+/-16.87	2
Y	650 nm	56.36+/-.59	410.67+/-10.95	10
Y	450 nm	49.43+/-1.01	380.45+/-14.81	3
X (y scan)	650 nm	46.17+/-.61	375.04+/-9.42	10
X (y scan)	450 nm	45.48+/-1.05	353.82+/-11.98	2

Farfield Measurements also show Two Components





Waist	λ	σ1 (mrad)	σ2 (mrad)	%Intensity σ1	%Intensity σ2	D(A)
Y	650 nm	0.54+/-0.01	2.3+/-0.1	68.9 %	31.1 %	3.23%
Y	450 nm	0.55+/-0.01	2.4+/-0.08	69.9%	30.1%	4.25%
X	650 nm	0.43+/-0.01	1.37+/-0.08	67.1%	32.9%	5.42%
X	450 nm	0.45+/-0.01	1.28+/-0.07	67.6%	32.4%	5.39%
X(y scan)	650 nm	0.49+/-0.01	1.59+/-0.08	67.1%	32.9%	5.18%
X(y scan)	450 nm	0.45+/-0.01	1.56+/-0.08	67.6%	32.4%	3.75%

Core-Halo RMS Emittance Measurements

$$\tilde{\varepsilon}_x = (\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2)^{\frac{1}{2}}$$

At a beam waist

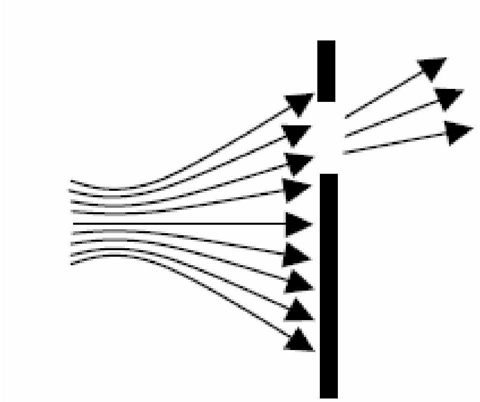
$$\tilde{\varepsilon}_x = x_{rms} x'_{rms}$$

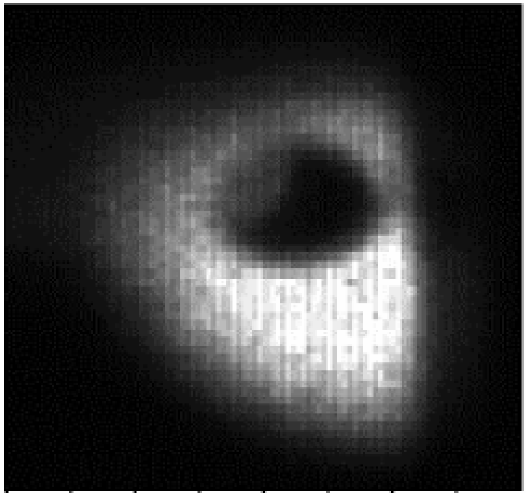
where: $x_{rms} = \sqrt{\langle x^2 \rangle}$, and $x'_{rms} = \sqrt{\langle x'^2 \rangle}$

Waist	λ	Core emittance (mm-mrad)	Halo emittance (mm-mrad)
X	650nm	13 +/-.43	117.2 +/- 7.72
X	450nm	17.7+/-.66	146.5 +/- 14.02
X (y scan)	650nm	5.1 +/-.17	134.2 +/- 10.11
X (y scan)	450nm	4.6 +/-.21	124.2 +/-10.57
Y	650nm	6.8 +/-.2	212.5 +/- 14.89
Y	450nm	6.0 +/-.23	205.4 +/- 14.85

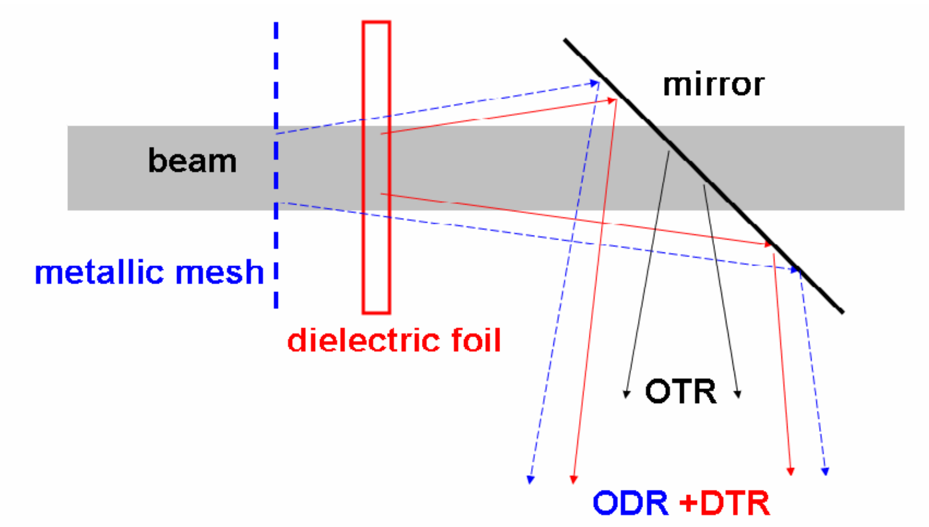
Future Work

- Better determination of the beam waist
- Confirming the Halo-Core Model
- Optical Phase Space Mapping

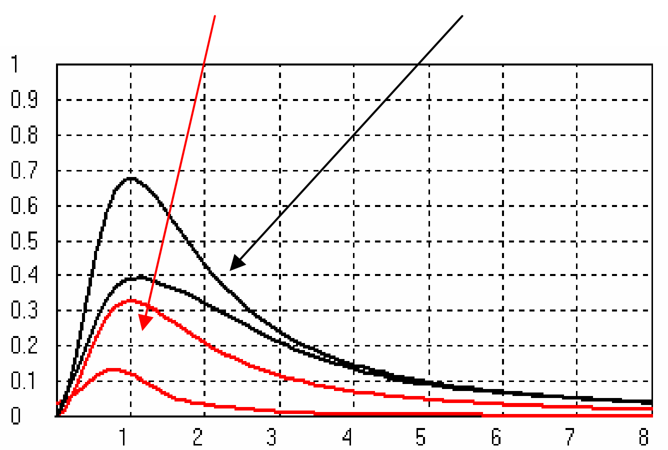




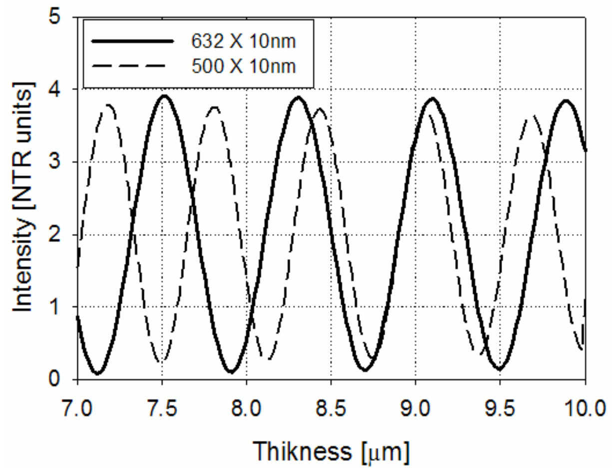
OPTICAL DIFFRACTION-DIELECTRIC FOIL RADIATION INTERFEROMETRY EMITTANCE DIAGNOSTIC FOR INJECTOR



DR from mesh TR from foil

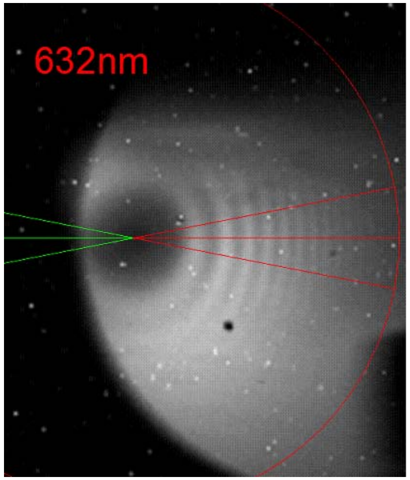


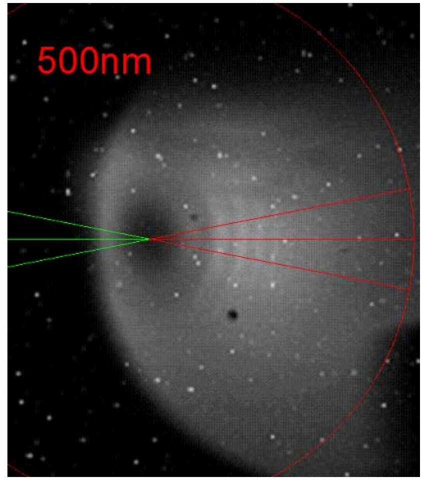
Radiation from dielectric foil

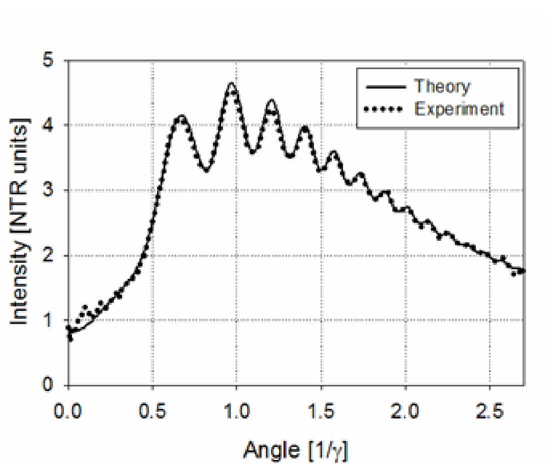


amplitude factor = 3.7
thickness 9.03 µm,
refraction index 1.8.

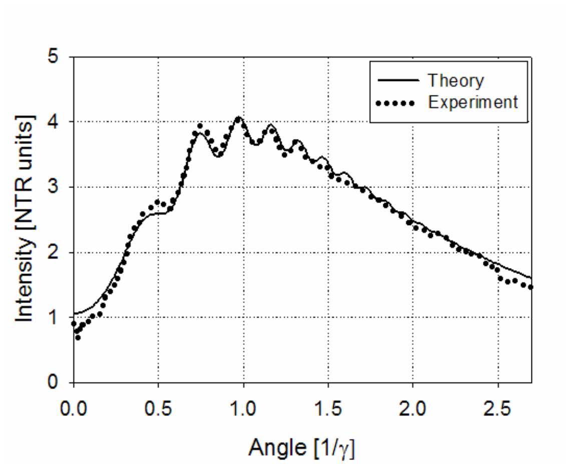
First Phase Measurements: ANL AWA 14 MeV







RMS=0.96%



RMS=1.97%

Best fit parameters :

Beam energy = 13.7MeV,
Foil spacing = 1.88mm,
RMS angular divergence of the scattered fraction = 8.8mrad,
RMS angular divergence of the unscatterd fraction = 1.23mrad.

Non Interceptive Bunch Length Diagnostics: Coherent TR, DR

$$\frac{d^2 I}{d\omega d\Omega} = \frac{d^2 I_e}{d\omega d\Omega}\{N + N(N-1)S_\perp(k_\perp, \sigma_T)S_z(\sigma_z, k_z)\}$$

$$S_{\perp,z} = \left|F(\rho_{\perp,z})\right|^2$$

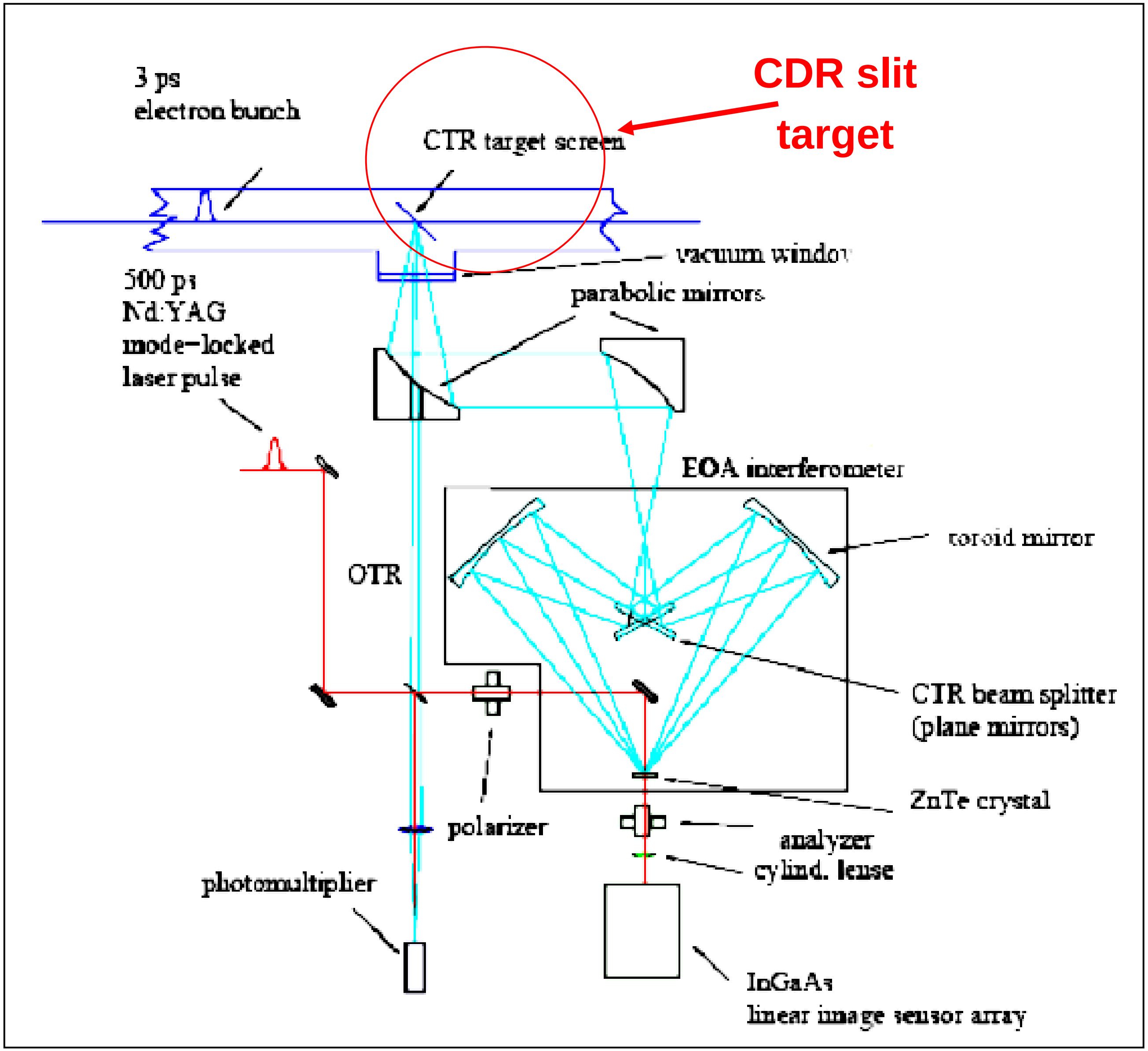
If transverse and longitudinal bunch distributions $\rho_{\perp,z}$ are Gaussian and $\theta \sim \gamma^{-1} \ll 1$, $\mathrm{k}_\perp \simeq \mathrm{k}\theta \simeq \mathrm{k}/\gamma$ and $\mathrm{k}_z \simeq \mathrm{k}$

$$S_\perp = \left|F(\rho_\perp)\right|^2 = \exp[-(\sigma_r k\theta)^2] \rightarrow \exp[-(\sigma_r / \gamma \lambda\!\!\!^{-})^2] \sim 1$$

$$S_z = \left|F(\rho_z)\right|^2 = \exp[-(\sigma_z k)^2] \rightarrow \exp[-(\sigma_z / \lambda\!\!\!^{-})^2]$$

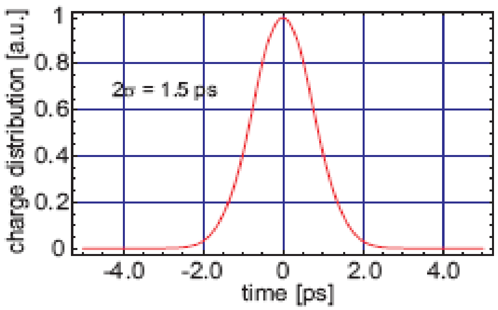
Standard single shot autocorrelator pulse length diagnostic

(PSI Swiss Light Source Linac 100 MeV)

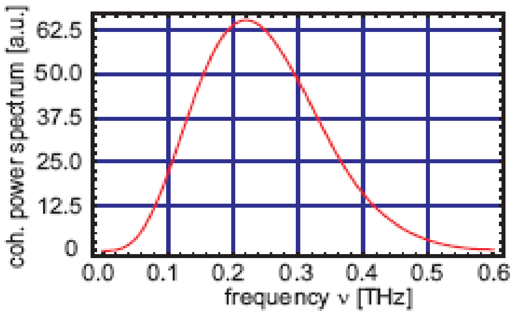


Single Shot **CTR** Autocorrelation Results:
(Swiss Light Source 100 Mev LINAC Injector)

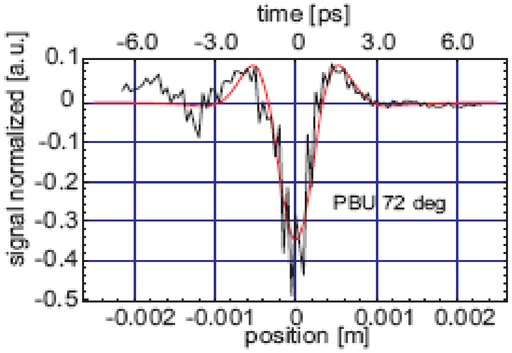
Gaussian pulse



CTR Spectrum

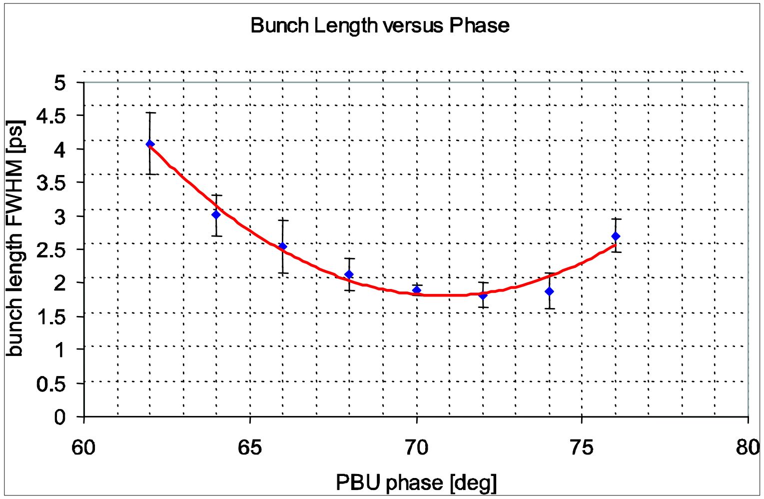


Fit to A.C. data



Bunch lengths versus phase of bunching cavity shows time resolution;

$2\sigma_{\min} = 200\ \mathrm{fs}$



Novel Angular Distribution Bunch Length Diagnostic Method

(goals: simple, robust, low cost, high accuracy)

$$J(\omega, p) = \left| E(\omega, p) \right|^2$$

Frequency Dependent Projected AD

$$S_z(\omega) = \left| \int_{z1}^{z2} \rho(z) \exp(i\omega z / V) dz \right|^2$$

Bunch longitudinal form factor

Energy distribution of CDR from bunch at point p

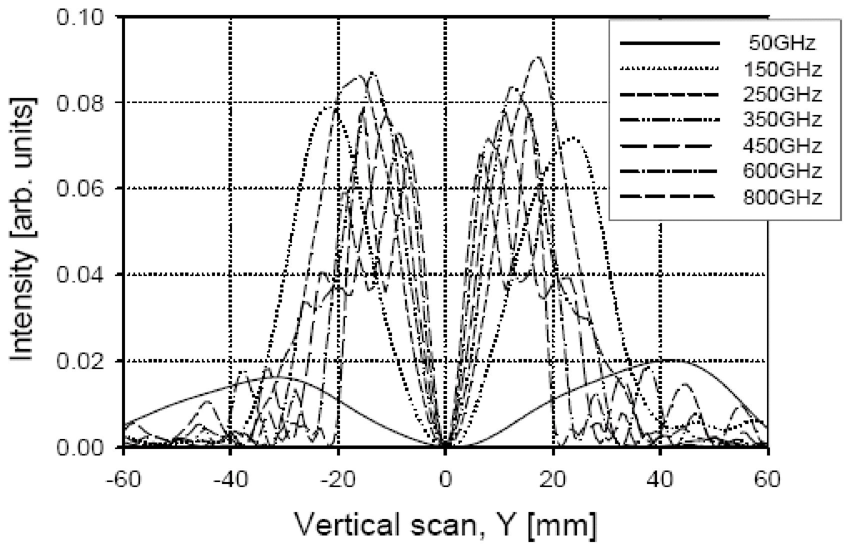
$$W(p) = \int_{\omega 1}^{\omega 2} J(\omega, p) S_z(\omega) d\omega$$

Frequency integrated AD projected on plane

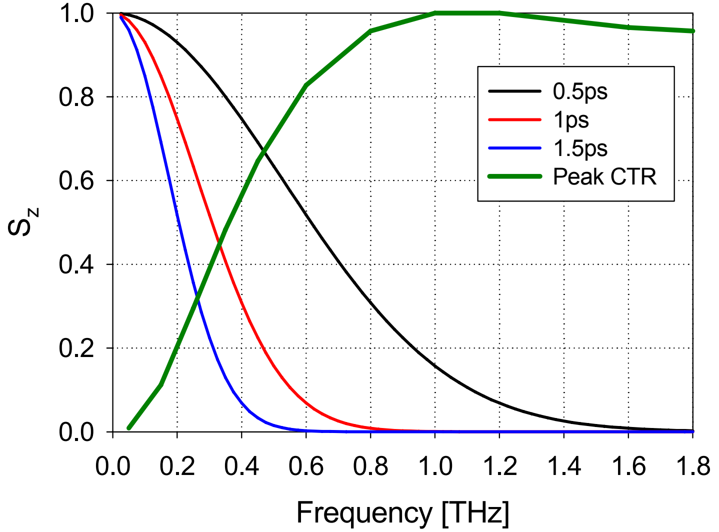
Angular distribution of CDR from Disk

E=100 MeV

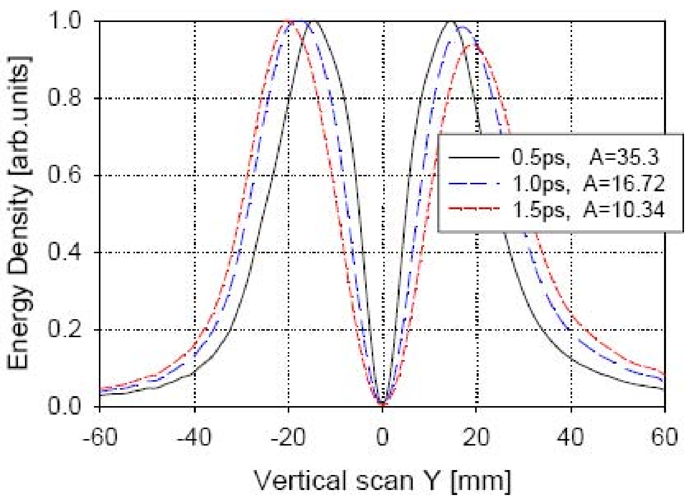
Angular Distributions



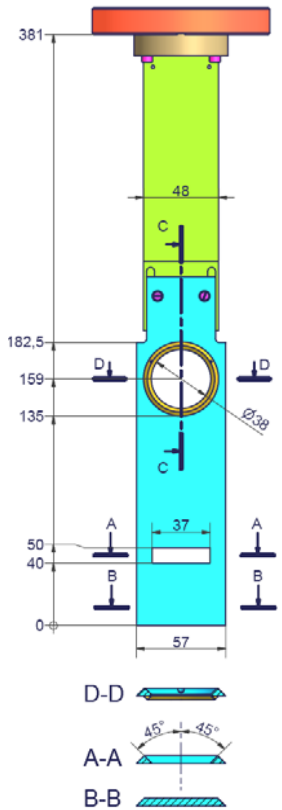
Bunch Form factors and CDR spectrum



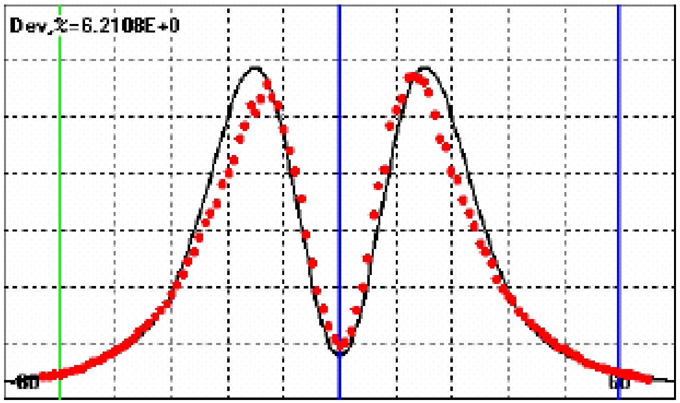
Frequency Integrated AD



Proof of Principle Experiment at Paul Scherrer Institut's 100 MeV LINAC

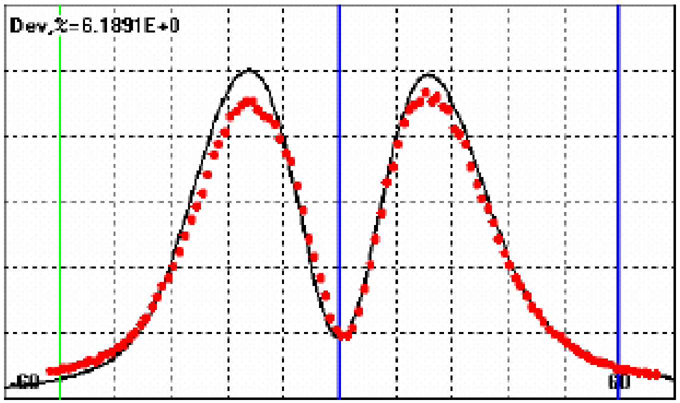


CTR



-60mm 60mm

CDR



-60mm +60mm

Single Gaussian beam bunch fitted parameters

Method	Tune	T(ps)
AD CTR/CDR	PBU-0	0.7
E-O technique	PBU-0	0.75
AD CTR/CDR	PBU+3	1.0
E-O technique	PBU+3	1.0