

Transition, diffraction and Smith-Purcell radiation diagnostics for charged particle beams

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Key Concepts

1) Radiation impact parameter $\alpha = \gamma\lambda/2\pi$

range of the radial E field of the charge: $\mathbf{E}_e \sim \mathbf{K}_1(r/\alpha)$

TR $r \gg \alpha$

DR $r \lesssim \alpha$

2) Coherence Length: distance over which phase of E field and photon field shift by π radians

Vacuum : $L_v(\gamma, \lambda, \theta)$; Dielectric : $L_D(\epsilon, \lambda)$

e.g. OTRI, ODTRI, SPR

3) Resonance radiation: $I \sim (N \text{ radiators})$

resonance condition: $V_{\text{photon}}(\lambda, \theta) = V_e = \beta c$

e.g. XTR from stack of foils, Smith Purcell from a grating

4) Bunch Coherence:

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

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

Applications of TR, DR and SPR

usual, i.e for rf accelerators where $t_{\mu\text{bunch}} \gtrsim \text{ps}$

Incoherent radiation ($\lambda \ll t_{\text{bunch}}$) - optical wavelengths

Near Field Imaging (spatial distribution)

- size (x, y) e.g. OTR, ODR
- position (x, y) (offset) OTR, ODR

Far Field Imaging (angular distribution)*

- divergence (x', y') OTR, OTRI, ODR*, ODTRI
- trajectory angle (X', Y') “
- energy (average) and energy spread “

* ODR AD can be used to measure beam size as well as divergence

Coherent ($\lambda \geq t_{\text{bunch}}$) - FIR-mm wavelength

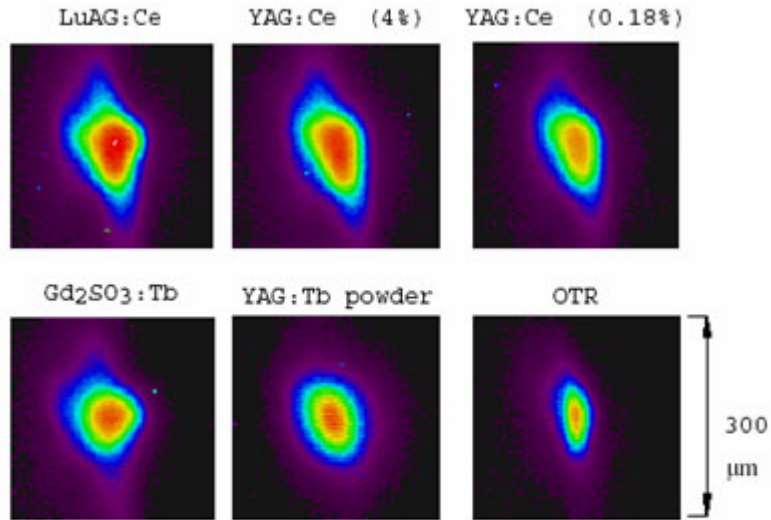
- spectrum: direct, autocorrelation technique - bunch length and shape

* angular distribution can also be used

less common: t_{bunch} in **optical regime** - optical micro bunching, laser plasma interaction - in this regime coherent radiation can be used to diagnose transverse as longitudinal beam properties, e.g. beam size

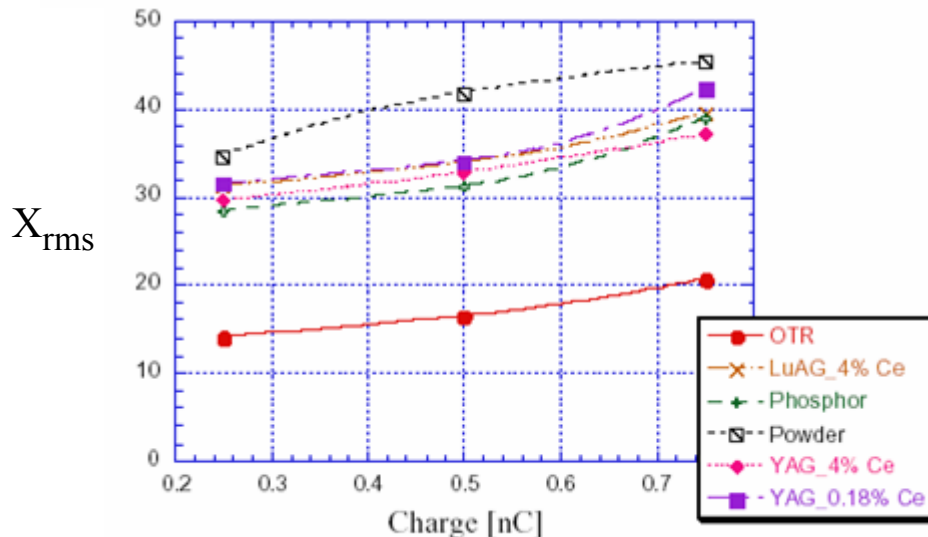
Incoherent OTR: well developed; high spatial and temporal resolution

1) imaging: beam profiling + position



Spatial resolution (sub micron, independent of energy)

< Beam images taken with six different diagnostic screens under the stable experimental conditions ($Q \sim 500$ pC) at the ATF/BNL 40 MeV linac.



High Linearity :

< Electron beam horizontal spot size as a function of charge, measured with scintillating diagnostics and incoherent OTR

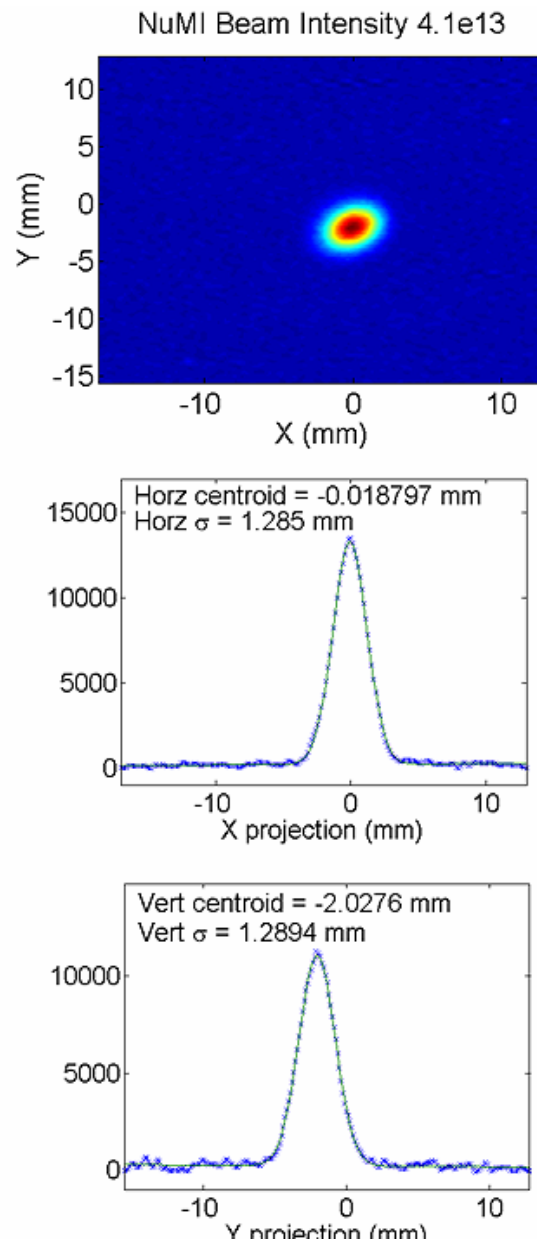
OTR Imaging proven useful over very wide range of beam energies

Highly Relativistic: 30 GeV (SLAC) electron beam
120 GeV (FNAL) proton beams

Non Relativistic: 29 MeV protons (Goldsmith and Jelley 1959)
(first experiment confirmation of TR)
10 keV (UMER): electron beam
50 keV (CLIC) gun test stand: electron beam

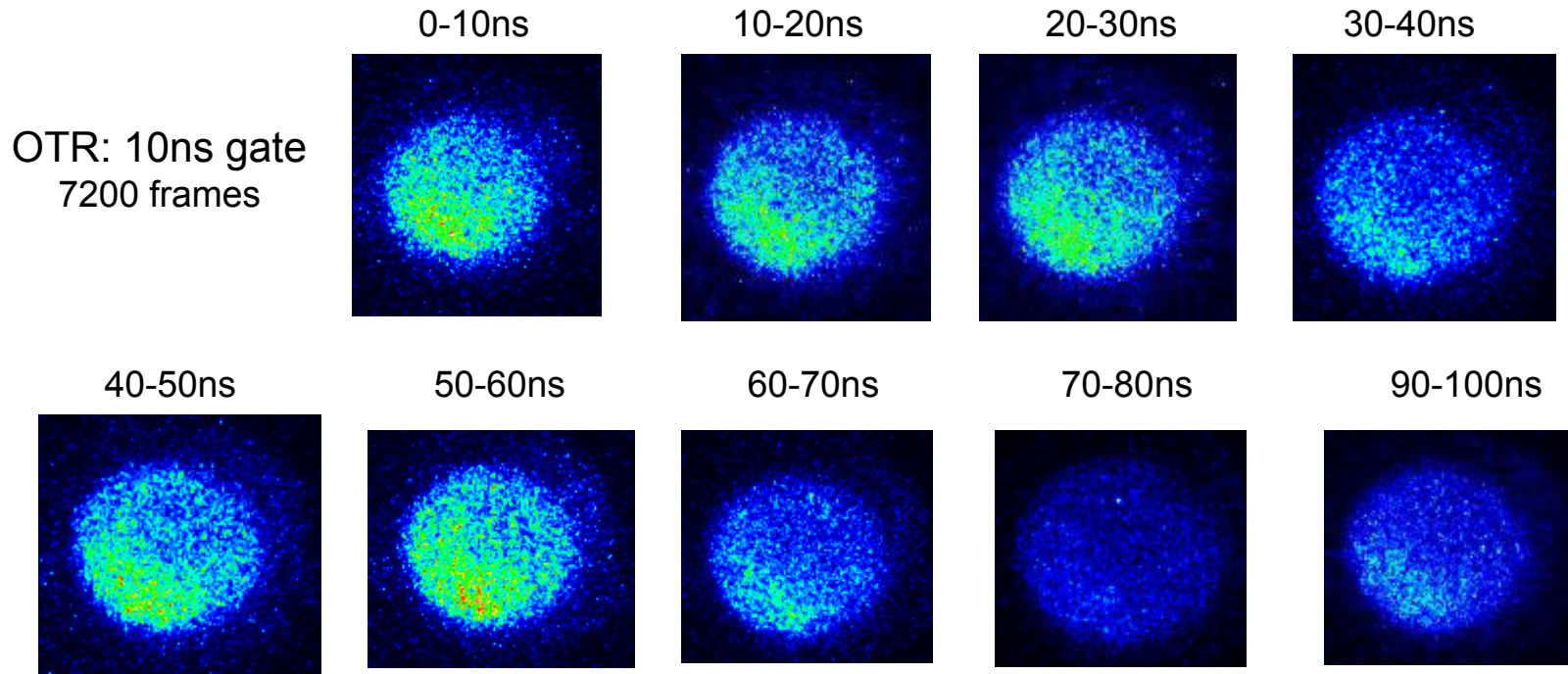
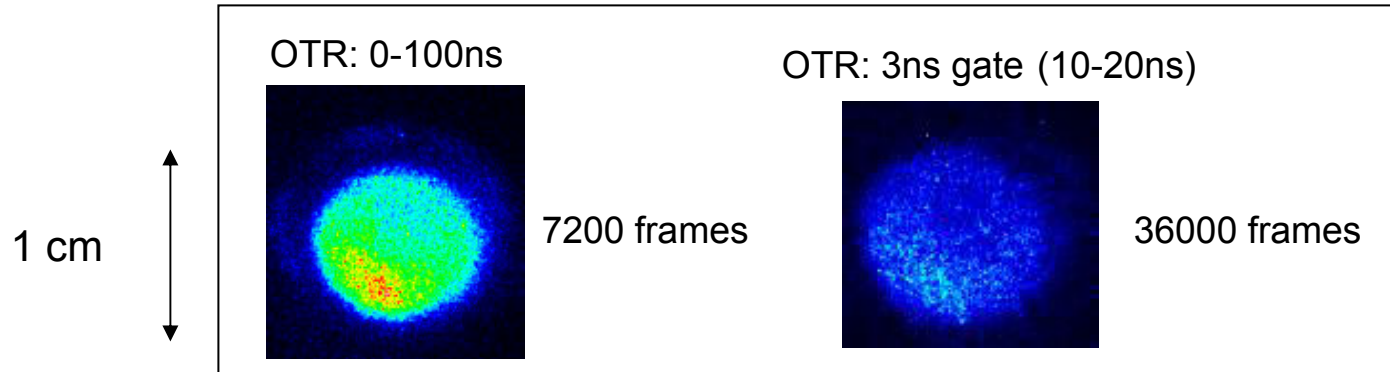
FNAL NuMI Proton OTR Detector

- OTR foil: 6 μm aluminized Kapton
- $N_p \sim 6.5 \times 10^{19}$ protons
- Measure beam shape for every pulse
- Operating at ~ 2 to 4×10^{13} 120 GeV protons per pulse at ~ 0.5 Hz
 - Up to 350 kW beam power



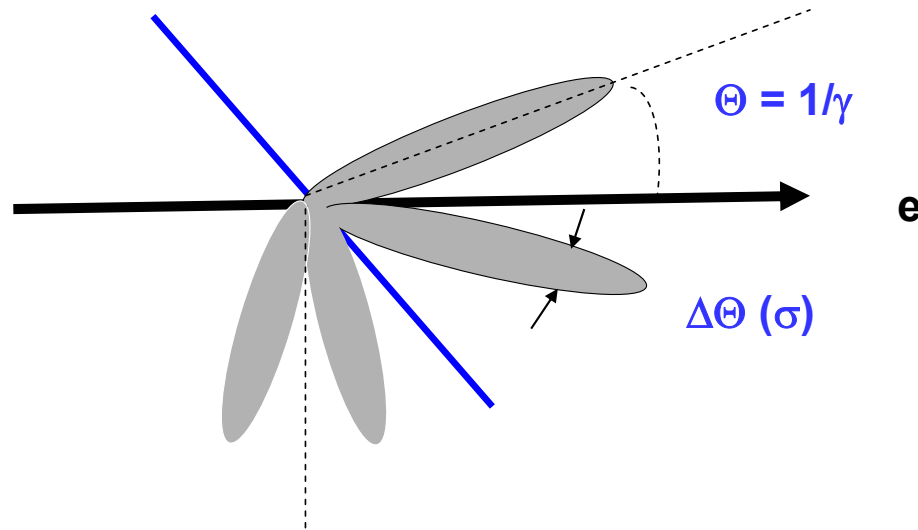
Provided by Vic Scarpine FNAL

Low Energy (10 KeV) electron OTR images of UMER beam using gated ICCD camera
(gun parameters: $\Delta t = 100\text{ns}$ pulse, $I \sim 20\text{ mA}$)



Beam Divergence Diagnostic using Angular Distribution of Single Foil OTR

1) Single Foil

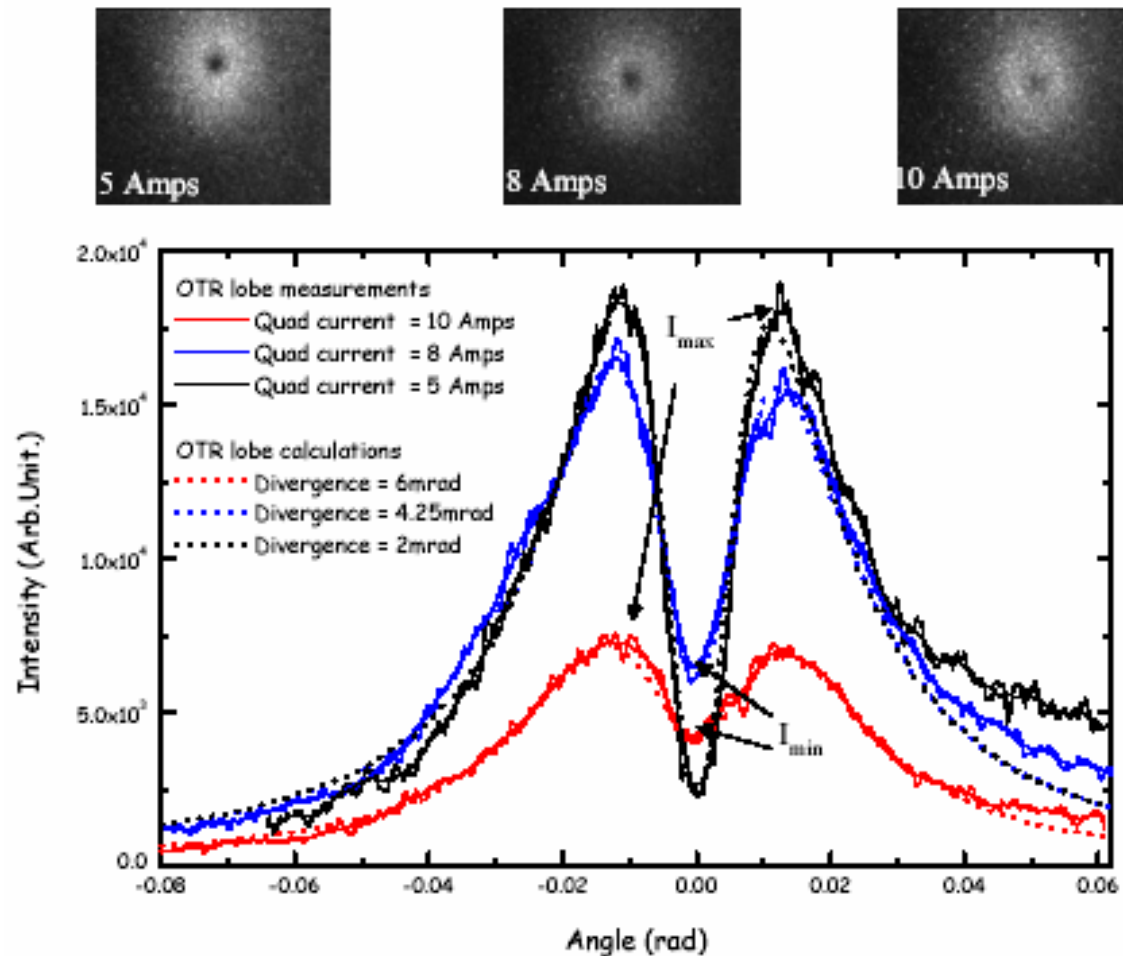


$$\theta \ll \gamma^{-1} \ll 1 \Rightarrow \frac{d^2 I^{(S)}}{d\omega d\Omega} = \frac{e^2}{\pi^2 c} \frac{\theta^2}{(\gamma^{-2} + \theta^2)}$$

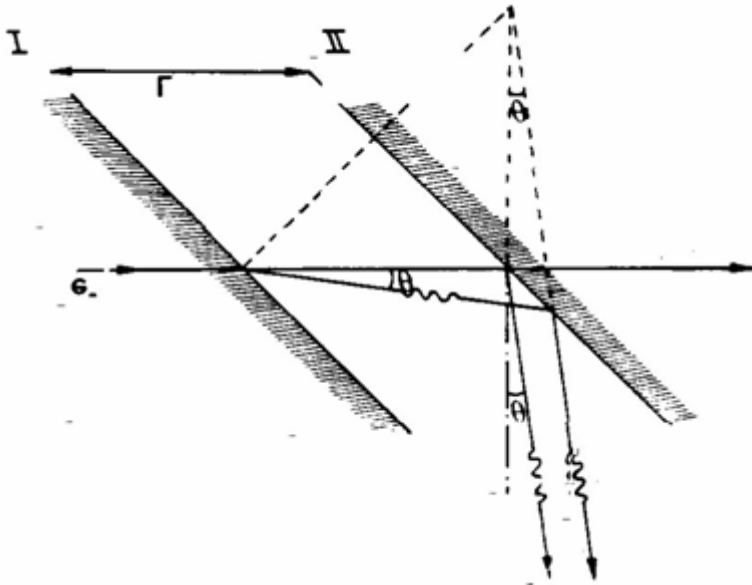
A.D. is a function of angle, energy, angle, divergence
and energy spread but is independent of beam size or position

Effect of Divergence on OTR Angular Distribution and Horizontal Scans

(48 MeV CLIC2 Test Facility Beam)



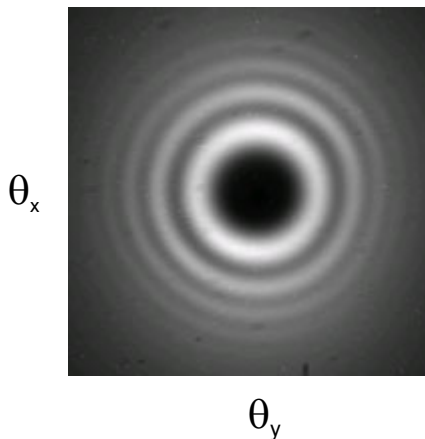
2) Interference OTR : gives greater sensitivity to beam divergence



$$\frac{d^2 I_{\text{TOT}}}{d\omega d\Omega} = 4 \frac{d^2 I^{(S)}}{d\omega d\Omega} \sin^2(L / 2L_V)$$

where: $L_V = (\lambda / \pi)(\gamma^{-2} + \theta^2)^{-1}$

“formation” or coherence length,
which is common to all relativistic beam
interactions.



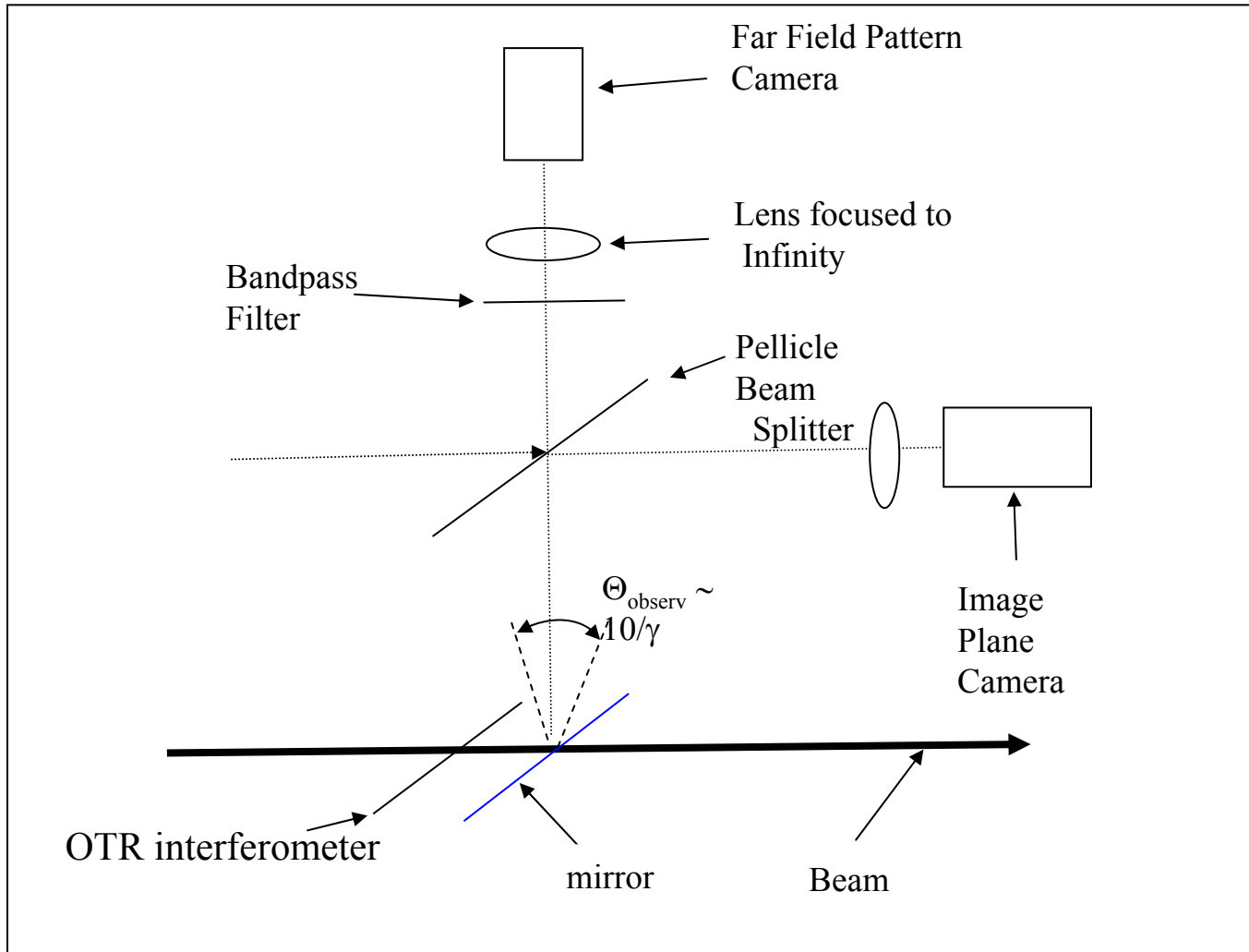
Diagnostics:

- Center of pattern measures trajectory angle of particle
- Fringe position measure beam energy
- Visibility of OTRI measures beam divergence and/or $\Delta E/E$
- Radial Polarization of OTRI can be used to separate and measure x' and y'

Experimental Setup for OTR **RMS Emittance** Measurement

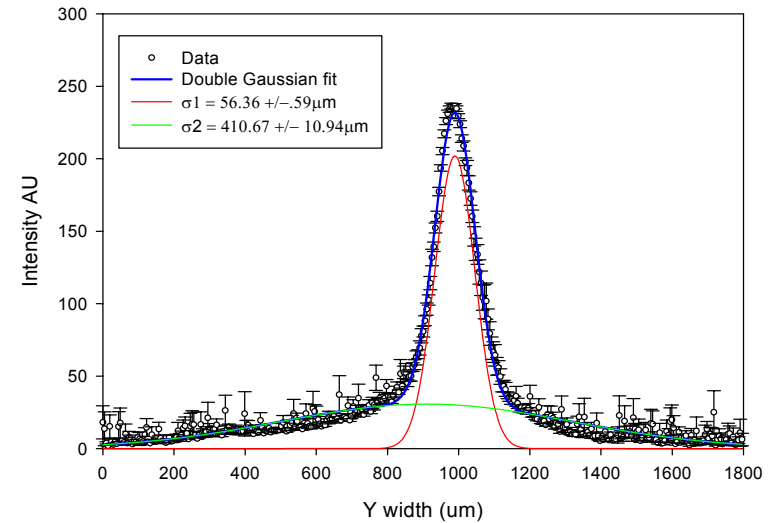
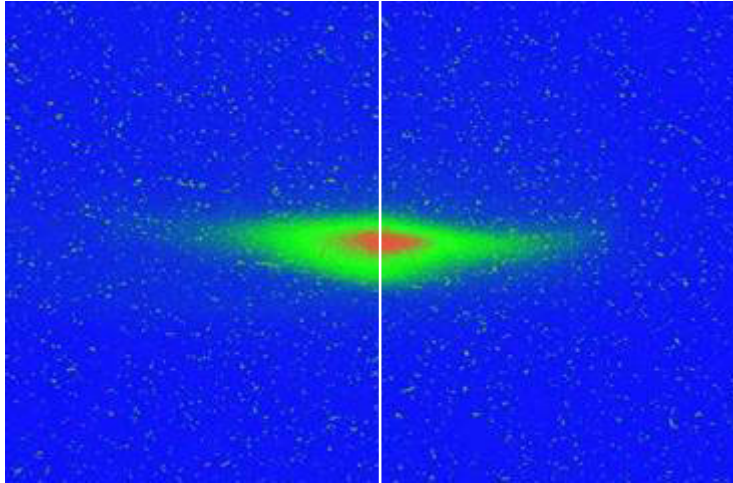
Beam magnetically focused to x or y waist condition at mirror

$$\epsilon_{\text{rms},n} = \beta\gamma\langle x \rangle^{1/2}\langle x' \rangle^{1/2}$$

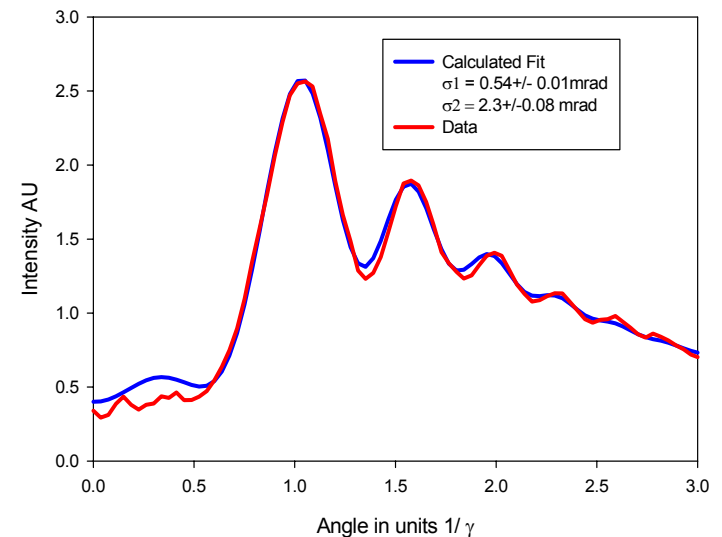
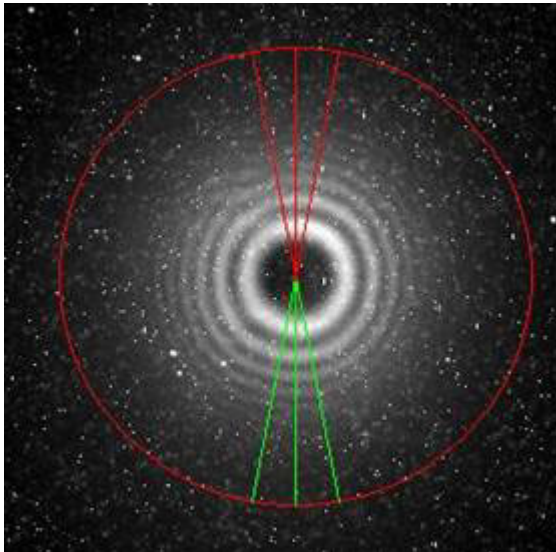


Example: OTR Images and OTRI at JLAB Show Two Beam Components and provide x, y rms emittances at x,y beam waists:

Y waist $\lambda=650\text{nm}$

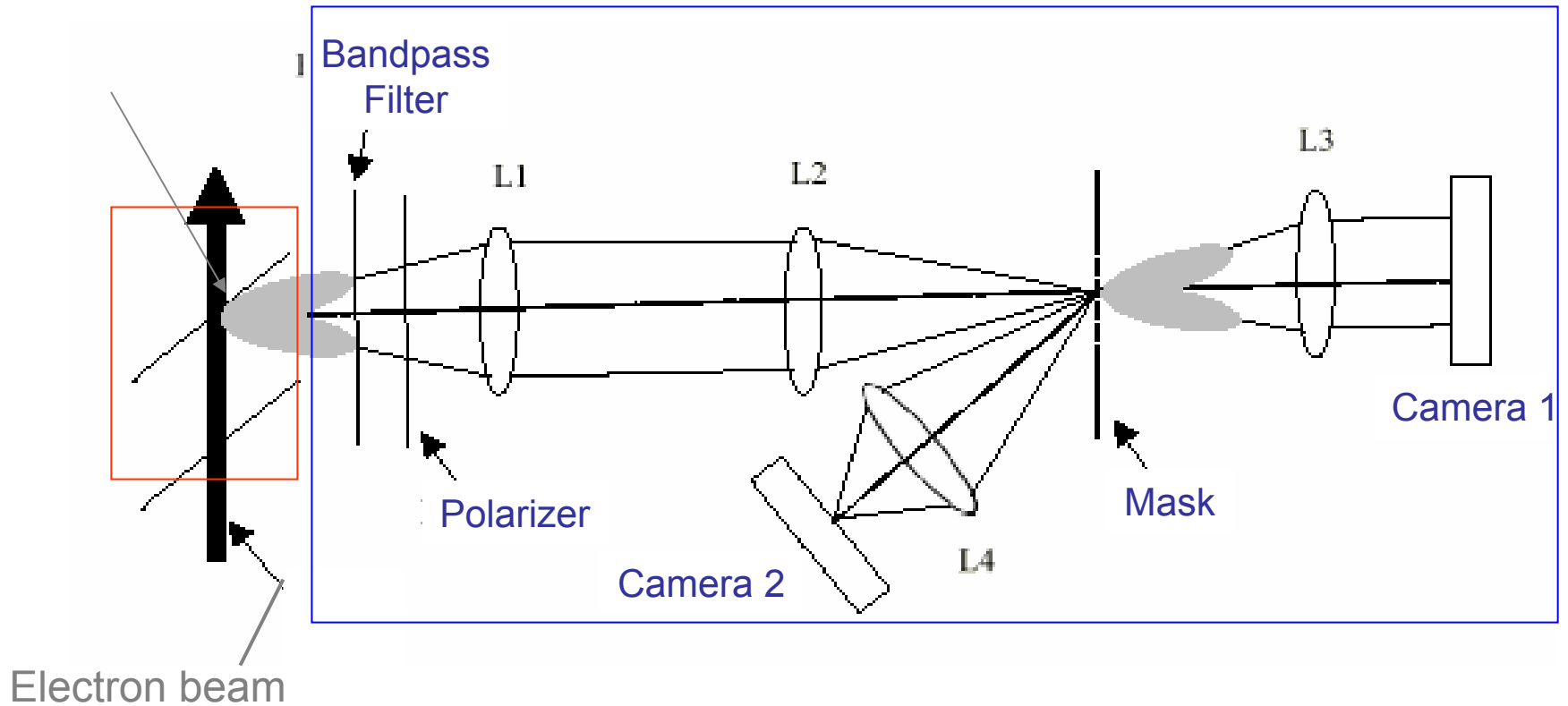


Y waist $\lambda=650\text{nm}$



Optical phase space mapping

Concept: Optical beam radiation e.g. OTR, and an optical mask can be used to map the transverse phase space of the beam
(measure localized beam divergence and trajectory angle: analogous to standard pepper pot method)



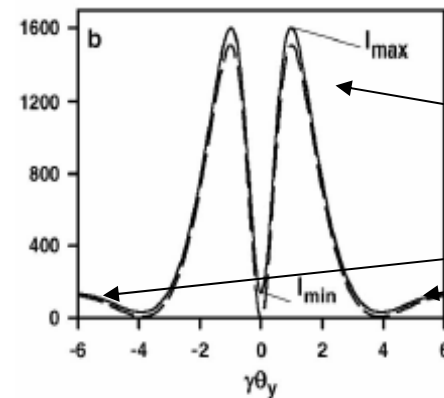
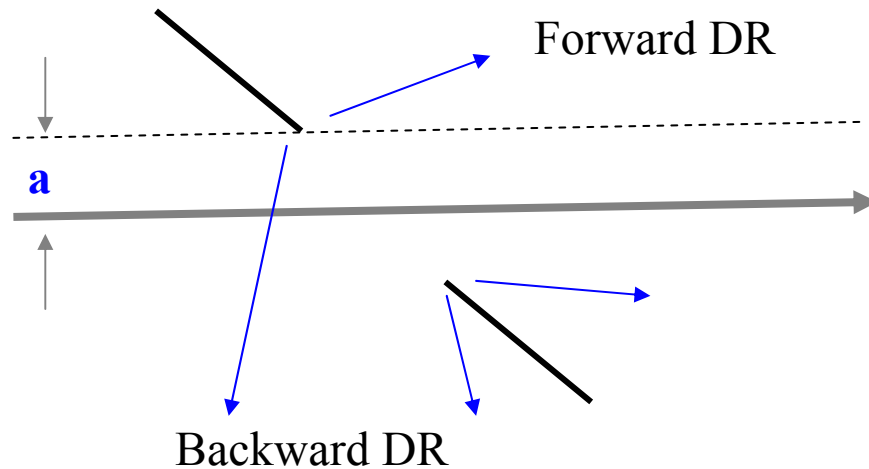
DIFFRACTION RADIATION

(produced by interaction of the field of a constant velocity charge with a boundary)

Impact Parameter: $\alpha = \gamma\lambda/2\pi$,

is the range of the radial field of the charge: $E_e \sim K_1(r/\alpha)$

1) when $a \sim \gamma\lambda$, DR is produced and AD is frequency dependent

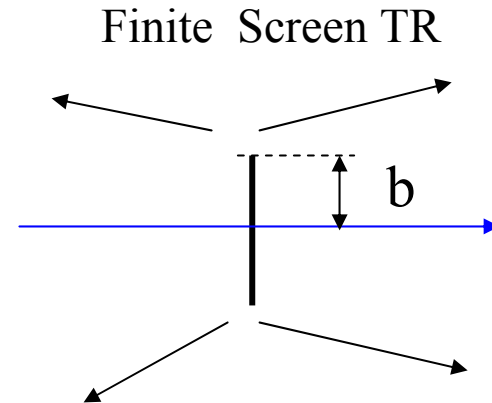
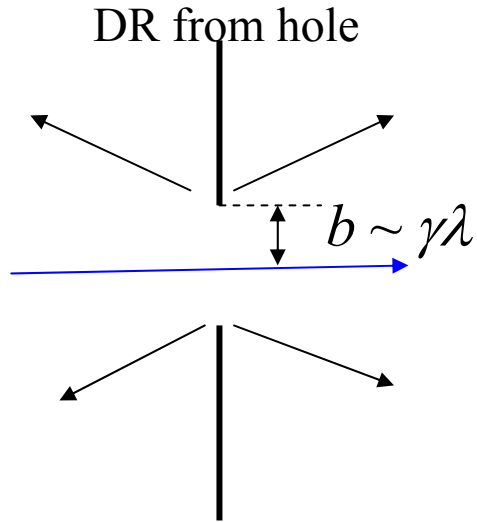


Shift of peaks from $\theta = 1/\gamma$

Diffraction fringes

2) When $a \ll \gamma\lambda$ DR = TR; particle doesn't see hole and no diffraction wings

DR and TR from Finite Screens are Related Phenomena

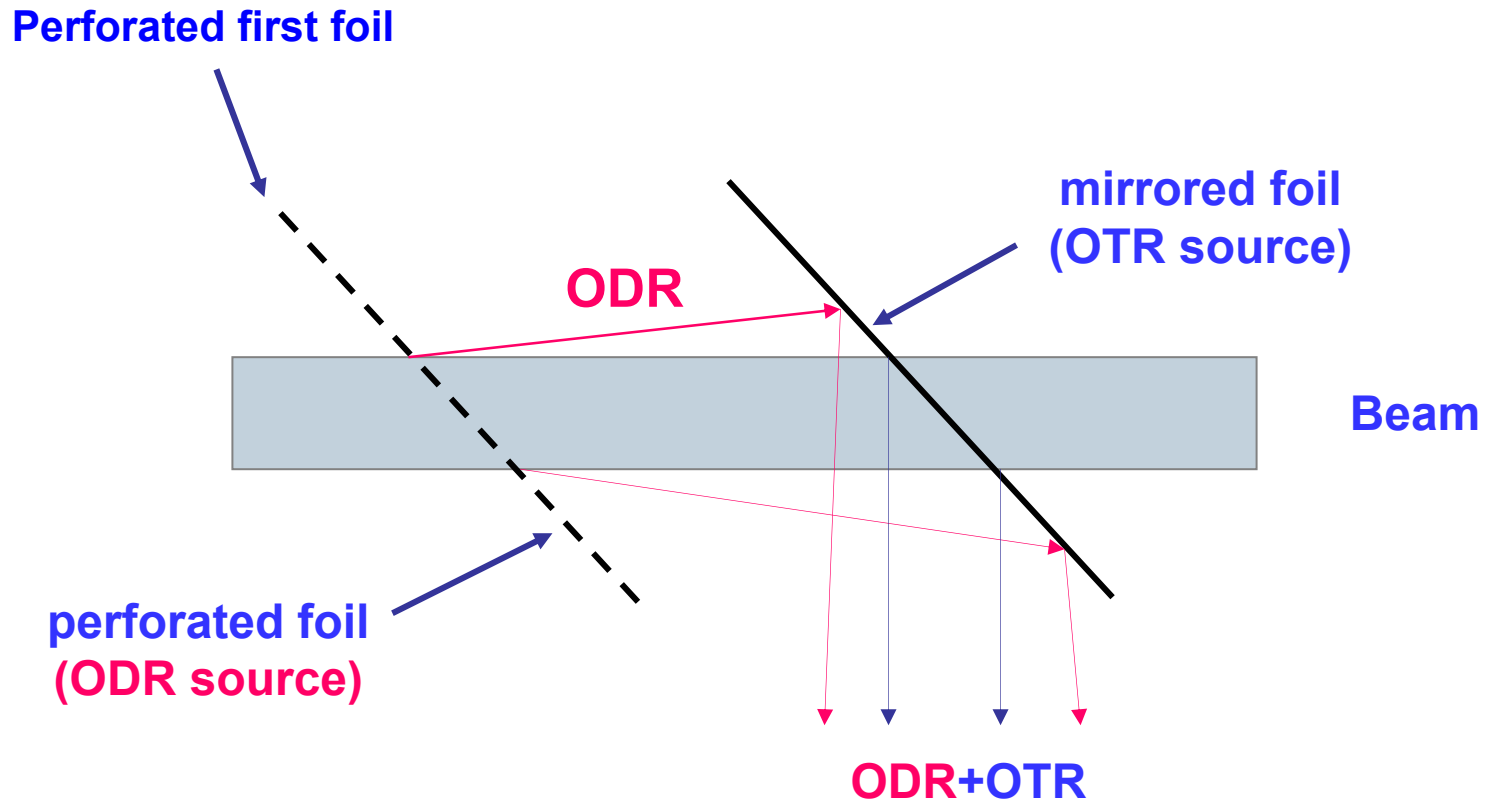


Babinet's Principle applies:

$$E_{\infty Screen}^{TR} = E_{Hole}^{DR} + E_{FiniteScreen}^{TR}$$

Optical Diffraction-Transition Radiation Interferometry

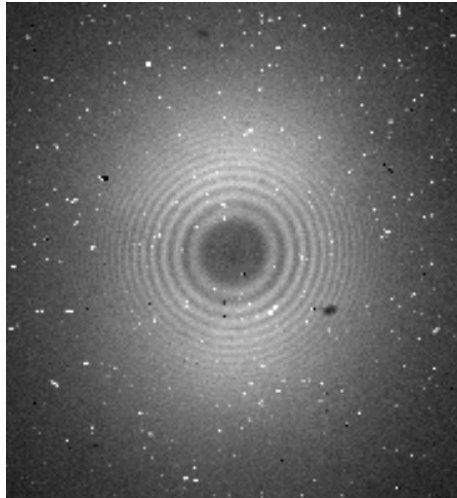
(extends OTRI diagnostics to low energy and/or low emittance beams)



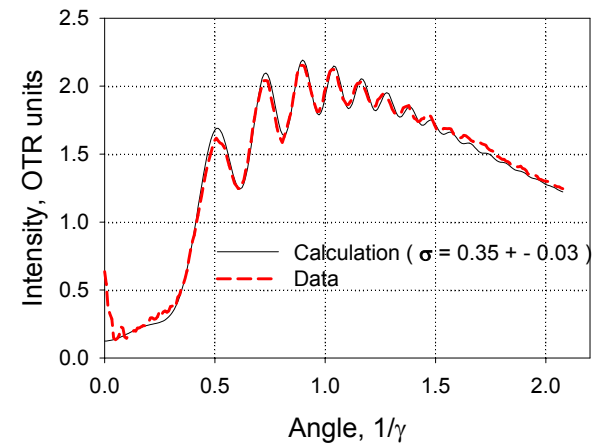
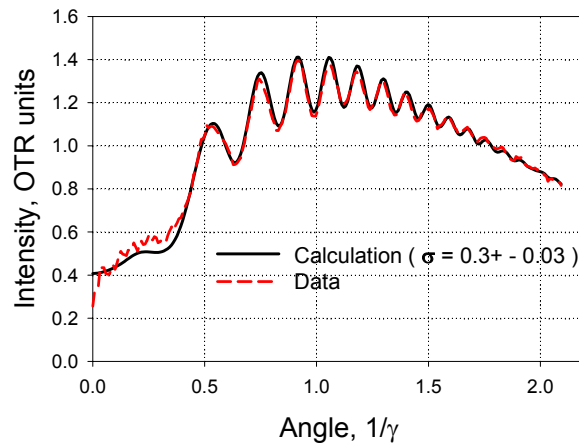
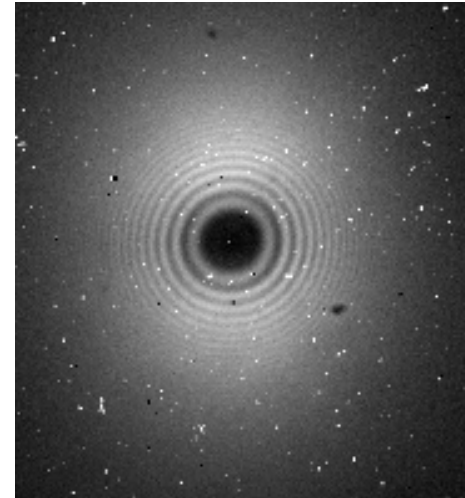
Example: Comparison of Horizontal Divergence Measurements using ODTRI and OTRI on the 50 MeV ATF Electron Beam

($\lambda = 600 \times 10 \text{ nm}$)

ODTRI $\tau = 480\text{s}$



OTRI $\tau = 360\text{s}$



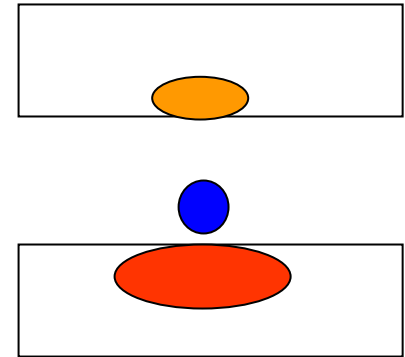
Non Interceptive ODR BPM and size monitors

under intense development in Japan (KEK), Russia (TPI) Italy,(INFN),
USA (APS, SLAC, JLAB)

1) Near field intensity surrounding aperture sensitive to distance from centroid position of beam and its spatial distribution

Resolution of ODR BPM : 40 um measured
10 um (estimated)

Offset beam passing through slit

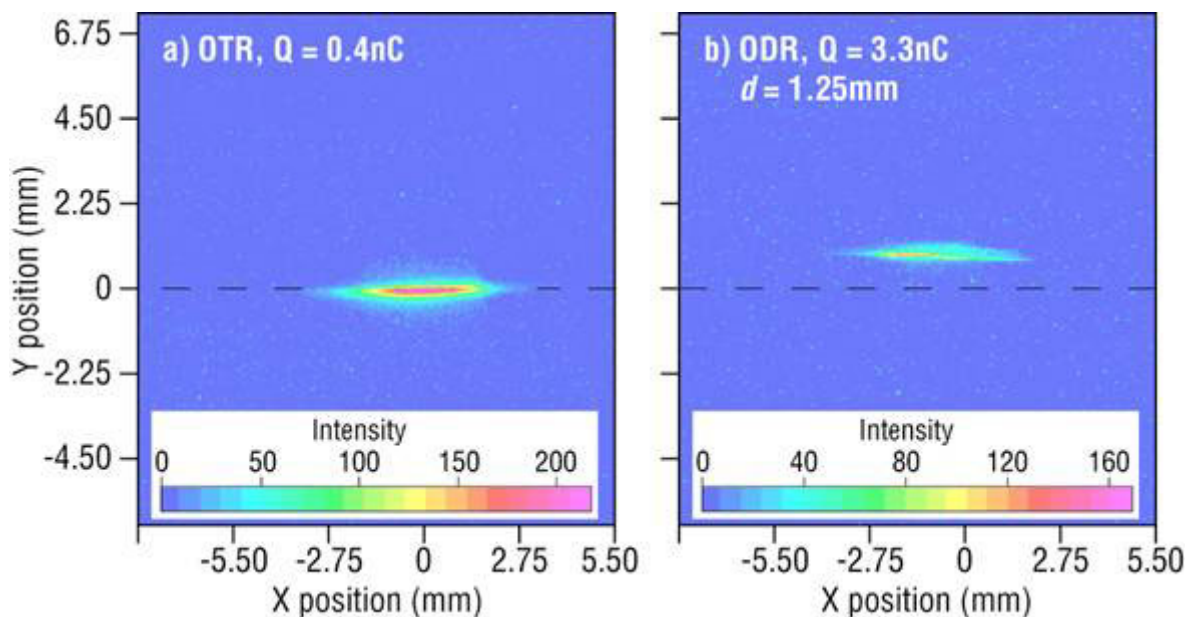


[see contributed talk P. Evtushenko,
#5 today]

Near Field ODR - 7-GeV Beam at APS



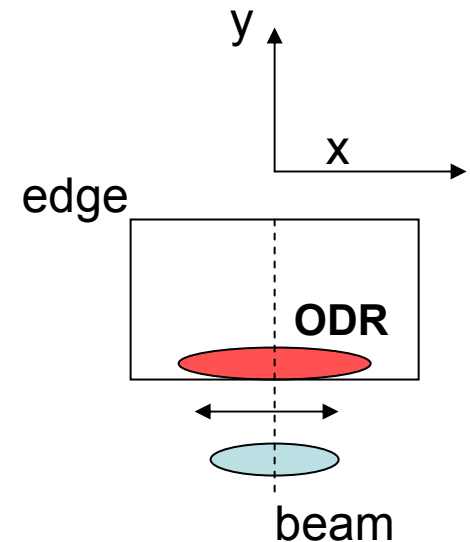
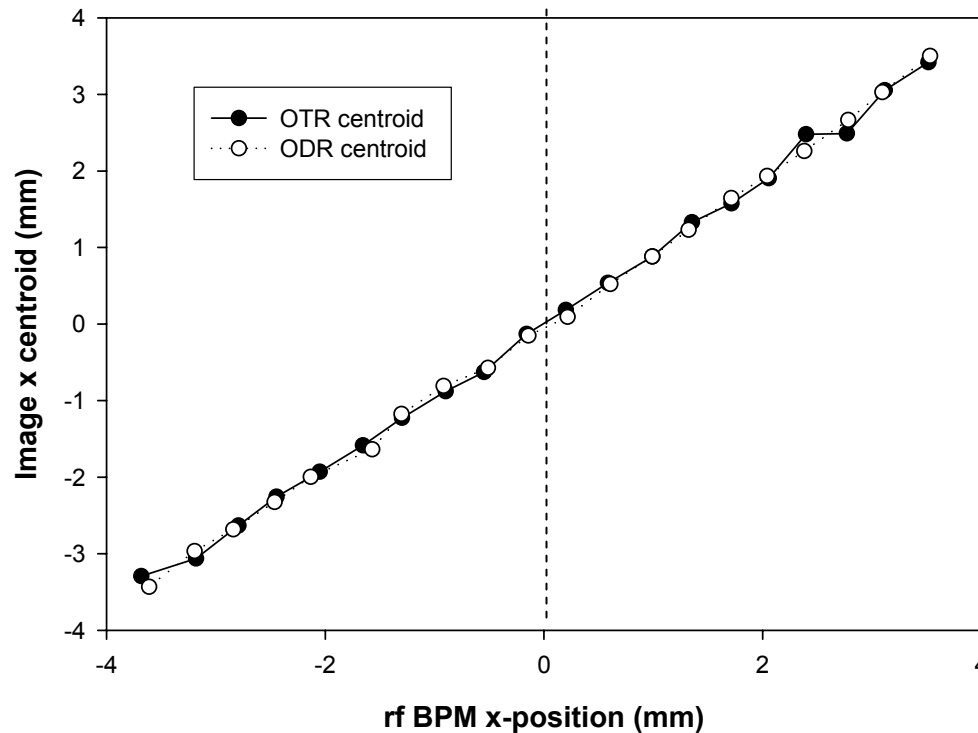
ODR offers the potential for nonintercepting, relative beam-size monitoring with near-field imaging. This is an alternate paradigm to far-field work at KEK and INFN.



ODR Has Good Beam-Position Sensitivity Using Vertical (y) Polarization Component



OTR and ODR Image Centroid versus Horizontal rf BPM values linear.

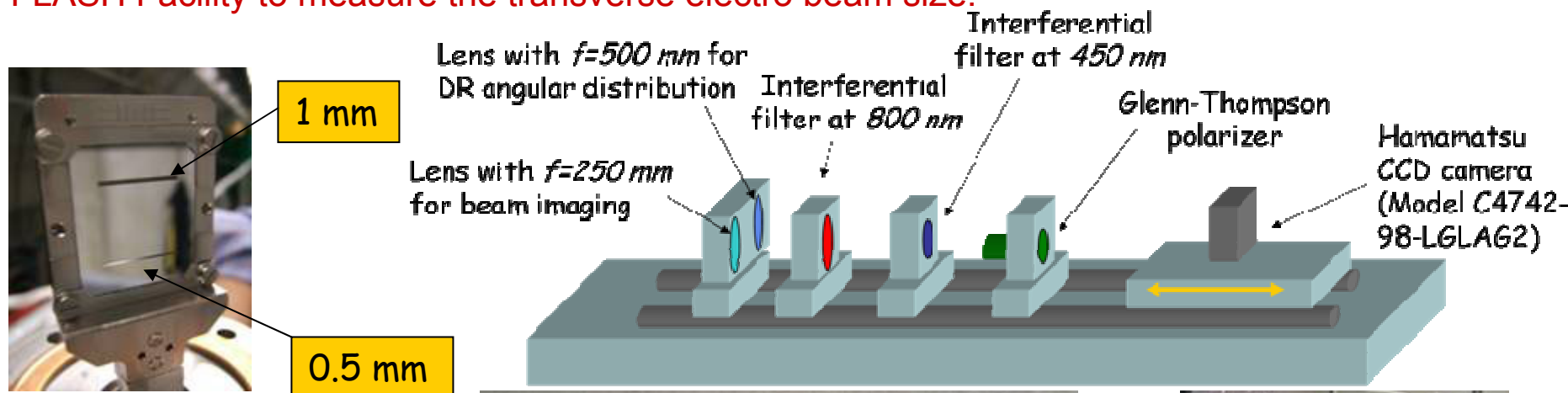




Farfield ODR Beam Size Monitor



An experiment based on the detection of Optical Diffraction Radiation has been set up at DESY FLASH Facility to measure the transverse electro beam size.

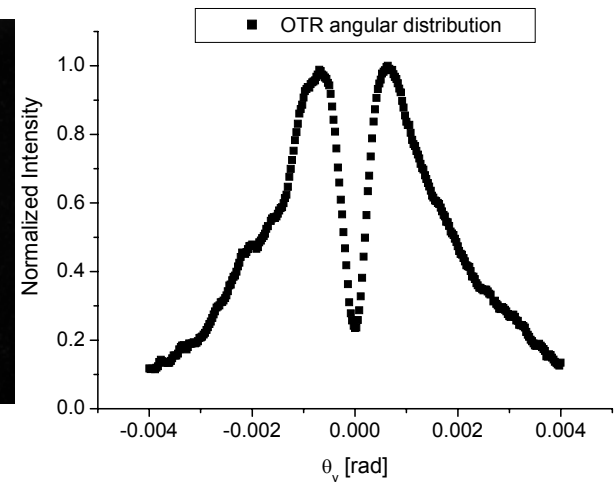
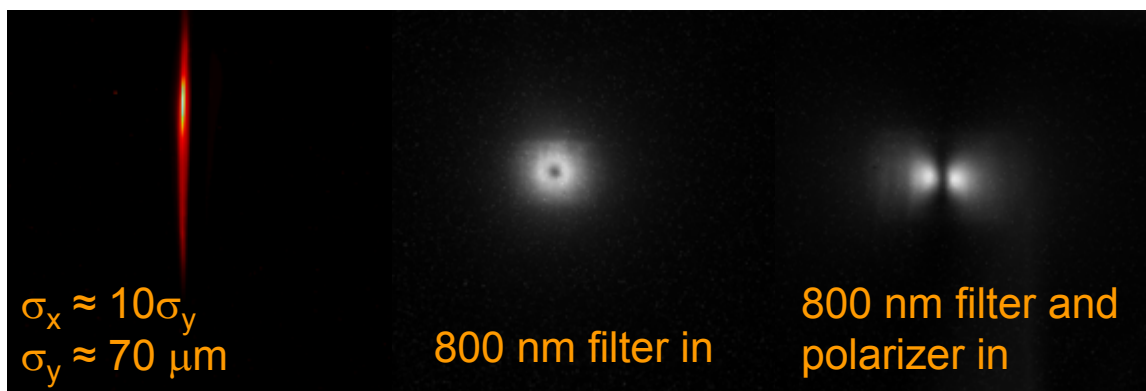


M. Castellano, E. Chiadroni (INFN - LNF)
A. Cianchi (INFN - Roma2)
K. Honkavaara (HH University)
G. Kube (DESY)

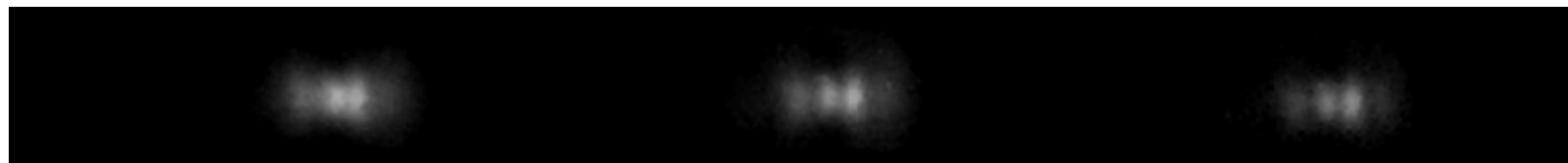


Preliminary Results

Beam and OTR
Optimization



From OTR
to ODR



Approaching one edge of the slit

100 μm with respect to
the center of the slit

Center of the slit

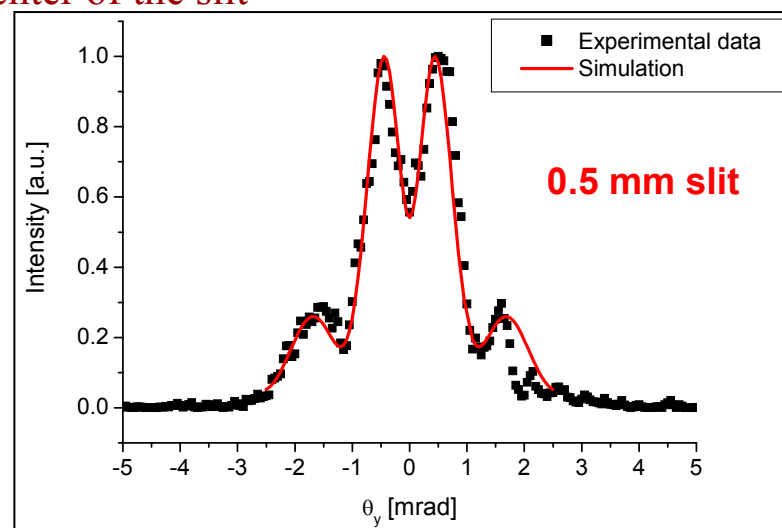
Beam transport optimization

- 0.7 nC
- 25 bunches
- 2 s exposure time
- E_{beam} (nominal) = 680 MeV
- 800 nm filter and polarizer in

Simulation parameters:

- Gaussian distributed beam
- $\sigma_y = 80 \mu\text{m}$
- $\sigma'_y = 125 \mu\text{rad}$

ODR Signature



Radiation Based Bunch Length Diagnostics

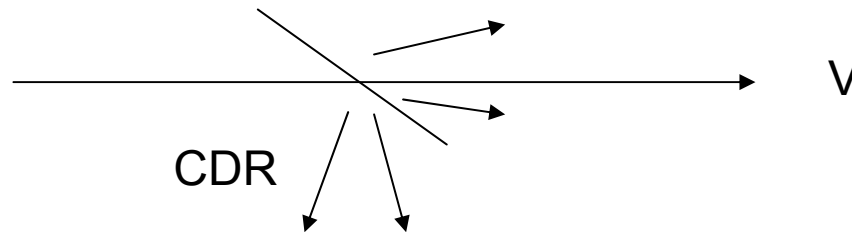
Standard :

- 1) Streak camera using incoherent OTR (limited to about 1ps resolution)
- 2) Direct spectral measurements using CSR, CTR, CDR (difficult to implement, limited band width)
- 3) Autocorrelation of CTR, CDR using Michelson interferometer (Barry and Lihn, Faraday Cup 1996) (no phase info. must be added)
- 4) E-O Sampling techniques (see review by van Tilborg -invited talk #4)

Relatively new: CDR angular distribution method and CSPR method

CDR ANGULAR DISTRIBUTION BUNCH LENGTH MONITOR

1. For small target: $D < \gamma\lambda$, Angular Distribution of DR depends on frequency
2. OPTIMUM SIZE OF RADIATOR FOR GIVEN ENERGY PRODUCES CDR IN FREQUENCY BAND APPROPRIATE TO BUNCH WIDTH $\Delta f \sim 1/\Delta t$



Calculation of Radiated CDR Power for single electron*

$$J(\omega, p) \propto \left| E_{TOT}^e(\omega, p) \right|^2$$

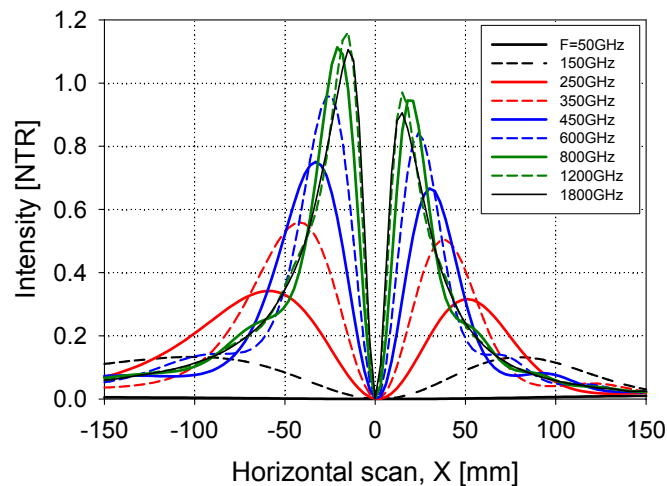
For a bunch*:

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

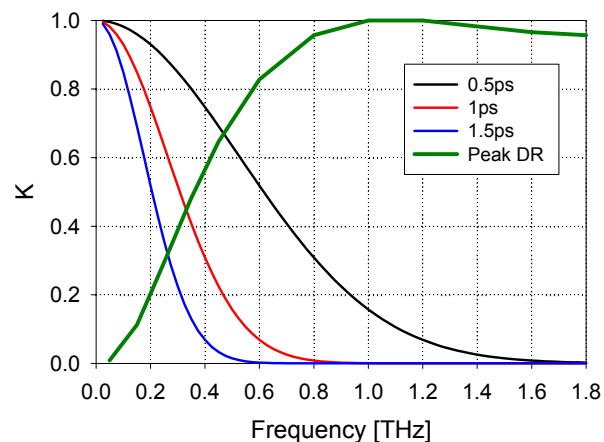
*A. G. Shkvarunets and R.B.Fiorito, PRSTAB , January (2008)

Example: CDR from 8 mm disk produced by a 10 MeV ebeam (optimized for a 2ps bunch observed at a distance of 300mm)

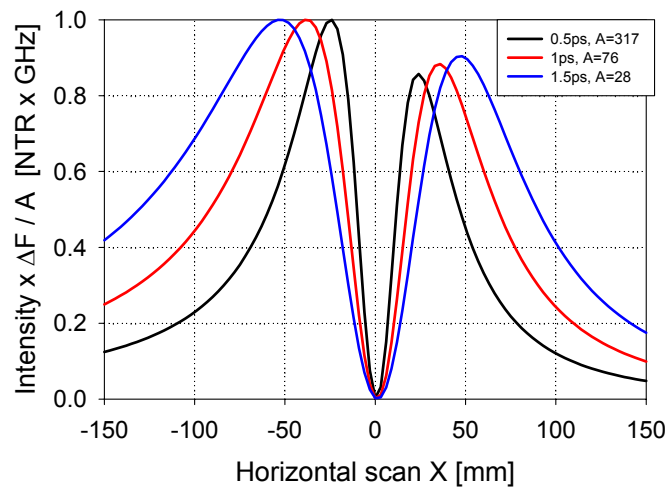
DR/TR from a disc $D=8\text{mm}$, $\Psi=45^\circ$



Formfactor of a relativistic Gaussian bunch.
Peak DR distribution.



Horizontal distribution of CDR

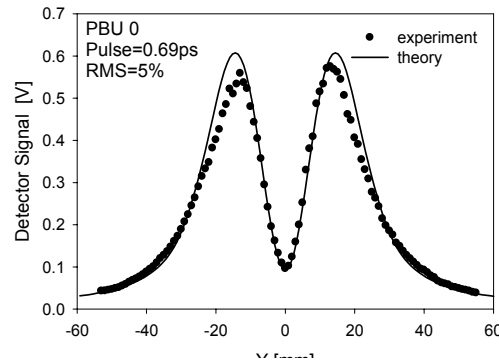


Proof of Principle Experiment at the PSI 100 MeV linac for two bunch compressor tunes

Single Gaussian bunch fit

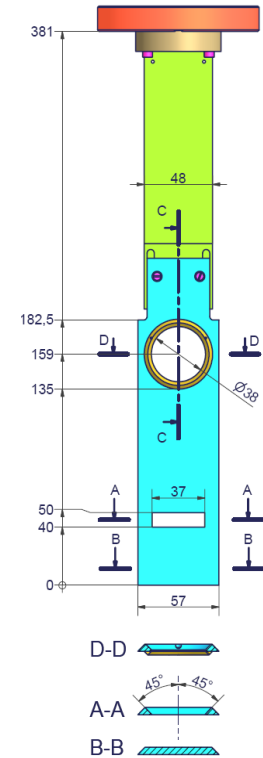
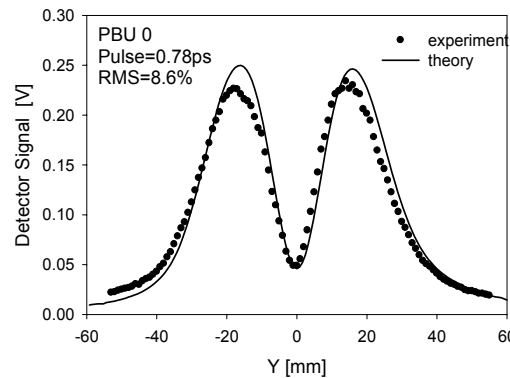
CDR plate

0.69ps bunch, RMS=5%



CDR slit

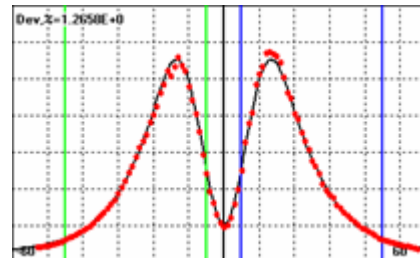
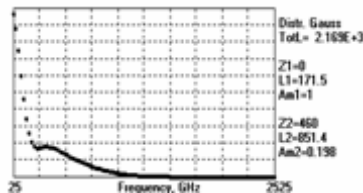
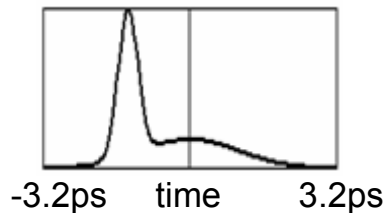
0.78ps, RMS=8.6%



Double Gaussian bunch fit, RMS=1.26%,

0.57ps, Am=1;

2.84ps, Am=0.2, Shift=1.53ps



Coherent Smith Purcell Radiation Bunch Length Monitor

Some (not all) Labs developing CSPR diagnostics:

TPU	6 MeV
MIT-Dartmouth*:	15 MeV
University of Mainz:	900 MeV
Oxford, Essex, SLAC:	multi GeV (up to 30 GeV)

*S. Korbly, et. al., PRSTAB, 9, 022802 (2006) and PRL 94, 054803

Smith-Purcell Radiation:

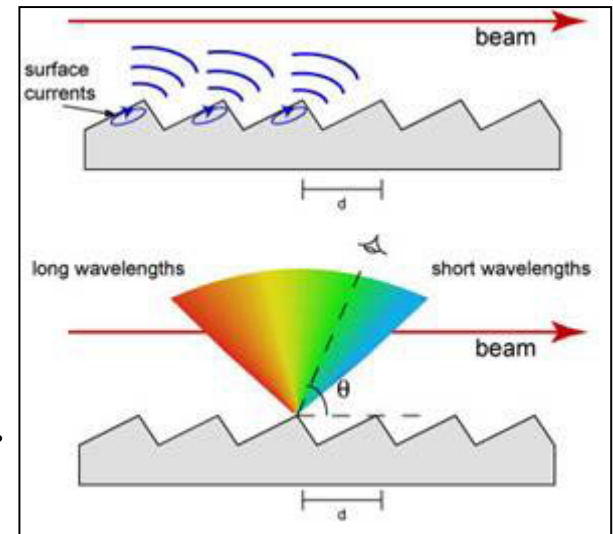
- ♦ Smith-Purcell radiation is produced when a charged particle beam interacts with a periodic metallic structure. (**spatially coherent DR**)
- ♦ The structure, or 'grating', causes an angular dispersion of wavelengths according to the relationship (**radiation resonance condition**):

$$\lambda = \frac{l}{n} \left(\frac{1}{\beta} - \cos \theta \right),$$

where l is the period of the grating, n is the emitted order of radiation, $\beta = v/c$ and θ is the observation angle.

Fig. 1

- ♦ The wavelength range depends upon the grating period, and can be selected.
- ♦ *Coherent enhancement* occurs for bunch lengths shorter than, or equal to, the emitted wavelengths.



Intensity per unit frequency for nth order for single electron

$$\frac{dI_n}{d\omega} = \frac{e^2 N_g l}{8\pi^2 \epsilon_o c^2} \omega \sin\theta \int |R_n|^2 \exp\left[-\frac{2x_o}{\lambda_e}\right] \sin^2(\phi) d\phi,$$

For bunch of N electrons

$$\left(\frac{dI_n}{d\omega}\right)_{N_e} = \left(\frac{dI_n}{d\omega}\right) (N_e S_{\text{inc}} + N_e^2 S_{\text{coh}}(\omega))$$



Longitudinal bunch form factor

Experiment: Measure CSPR AD for two different bunch lengths

