

Optical Diagnostics for Intense Electron Beams

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Optical beam based radiation diagnostics

- OTR, ODR, OSR, OER all hold promise for mildly intercepting to completely non intercepting diagnostics for FELS, ERLs and other high average power, low emittance charged particle (e, p ..) beams
- Spatial, angular and spectral densities of these radiations are dependent on beam parameters (size, trajectory, divergence emittance, energy spread,etc.) in different ways
- Both incoherent ($\sigma_{t,I} \ll \lambda$) and coherent ($\sigma_{t,I} \sim > \lambda$) radiation can be used; each has its advantages, disadvantages for measuring different beam parameters.

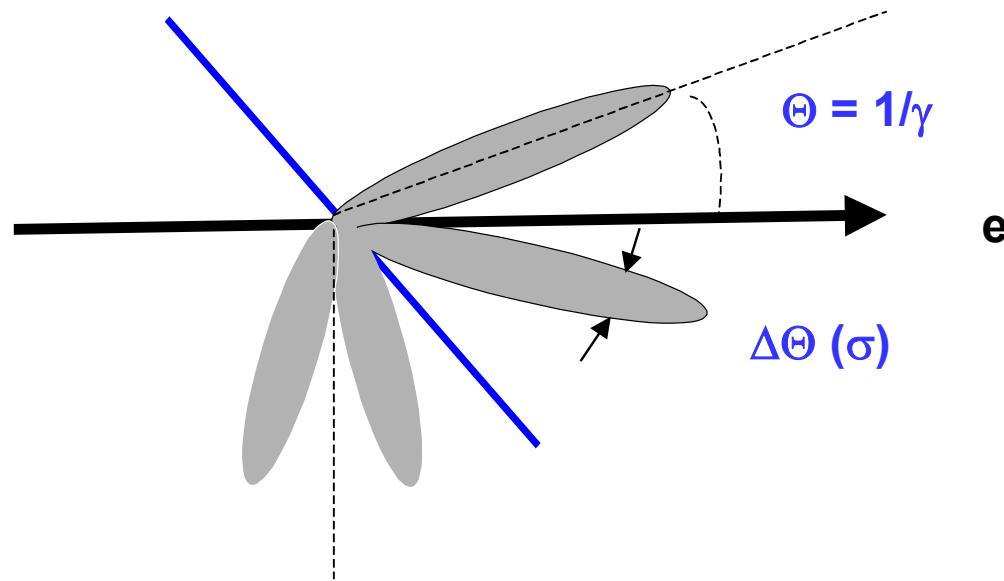
Transverse Phase Space Diagnostics using Incoherent Optical Radiation

- beam size (x, y) (spatial distribution)
- divergence* (x', y') (angular-spectral distribution)
- emittance* (e_x, e_y) (combination of spatial and angular distributions)
- beam trajectory angle (angular distribution)

*rms measurements require focusing to a beam waist;
local measurements can be done at any beam position >OPSM

Examples

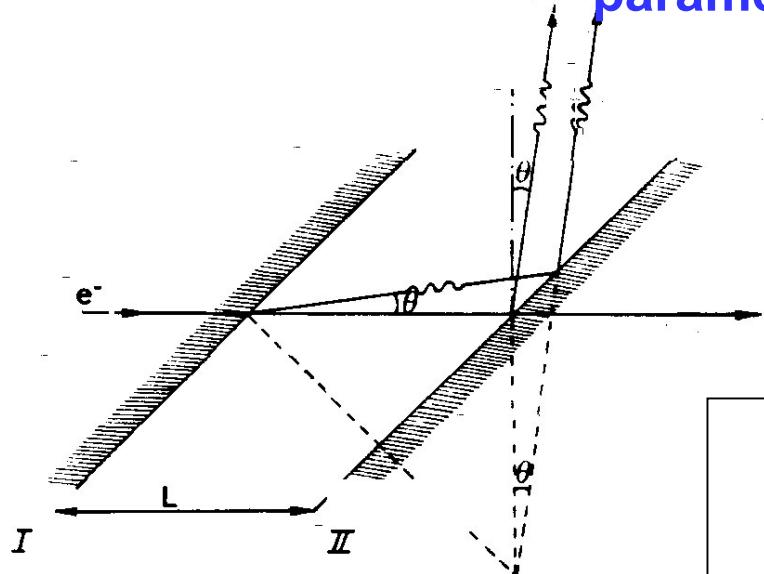
Beam Divergence Measurements using Angular Distribution of OTR from a Single Foil



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

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

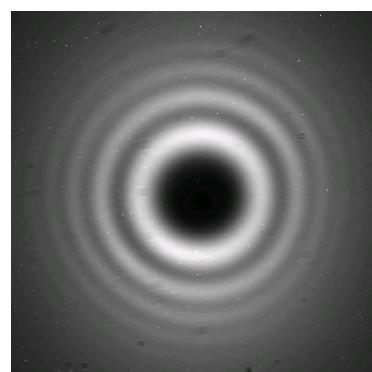
Interference of OR from two sources provides greater sensitive to beam parameters: e.g. OTRI



$$\frac{d^2 I_{TOT}}{d\omega d\Omega} = \frac{4\alpha}{\pi^2 \omega} \frac{\theta^2}{(\gamma^{-2} + \theta^2)} \sin^2(L/2L_V)$$

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

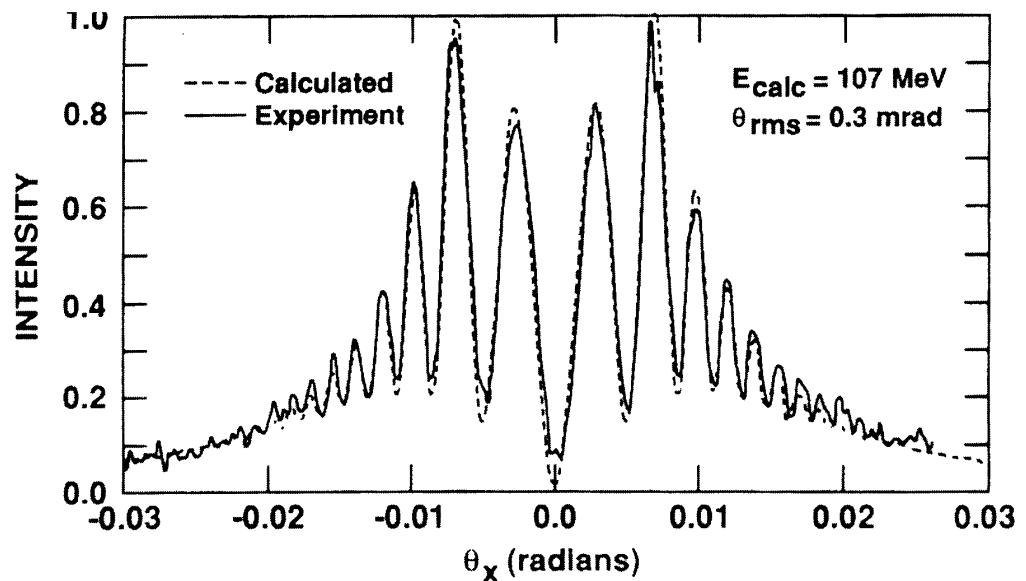
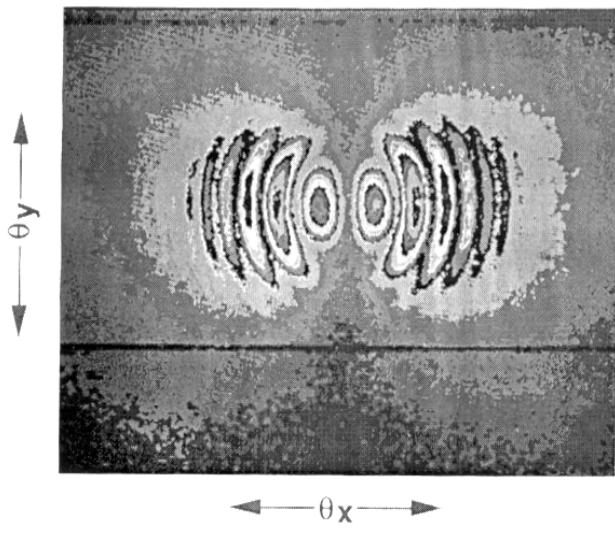
is the “formation” or coherence length
NOTE: common to all relativistic beam OR



- 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'

Polarized OTRI Distinguishes vertical and horizontal components of rms beam divergence

Horizontally (x) Polarized OTRI

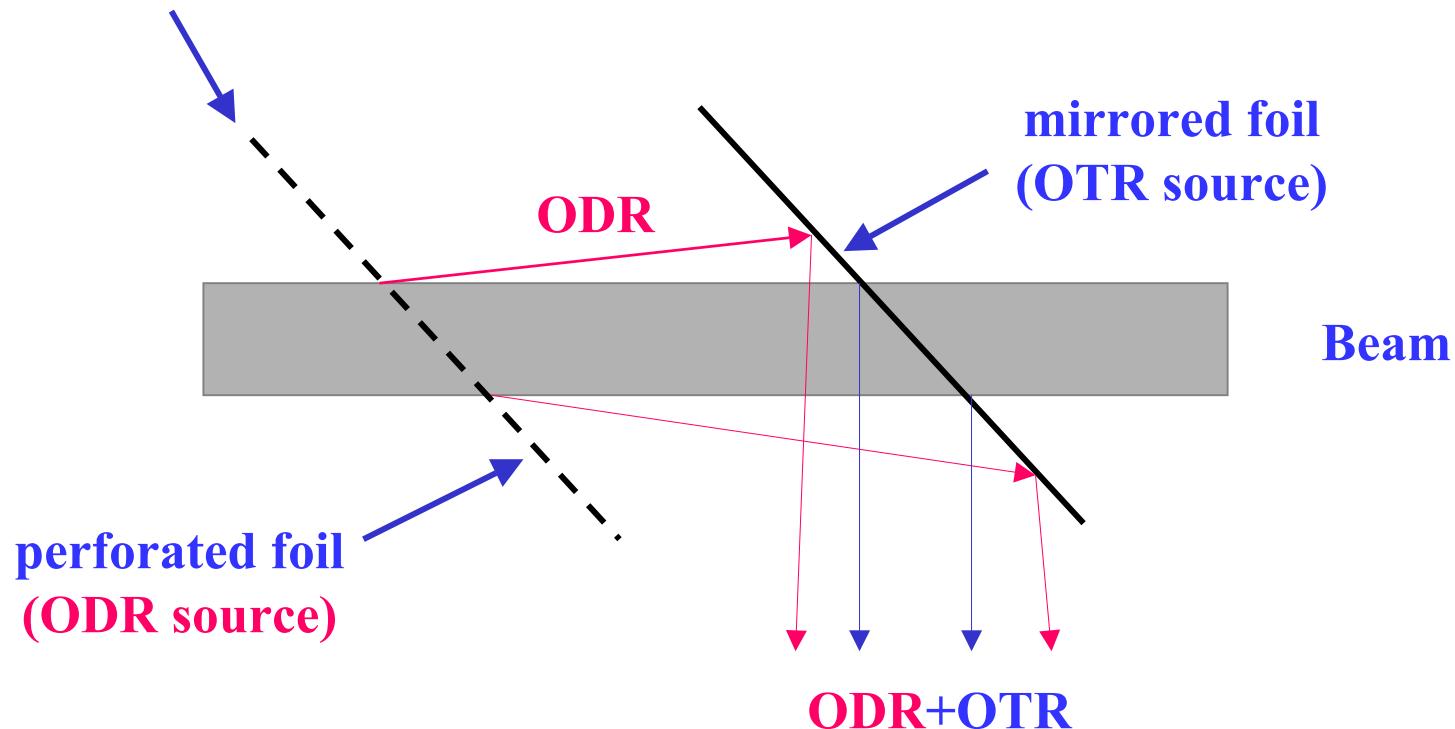


Fit to data typically gives: $E \sim 1\%$ and $\sigma_{rms} \sim 10\%$ precision.

Optical Diffraction-Transition Radiation Interferometry

Extends OTRI diagnostics to low energy and/or low emittance

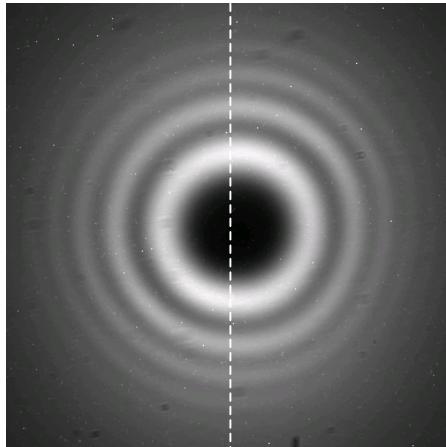
Perforated first foil overcomes scattering limit of conventional OTRI



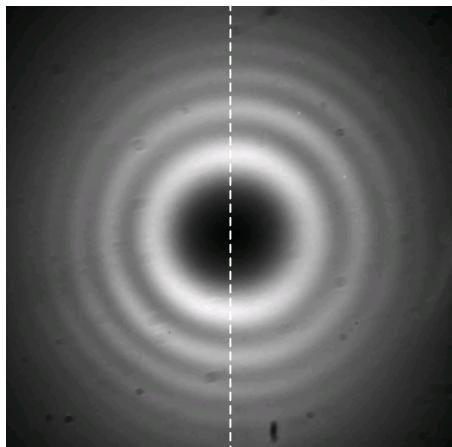
Comparison of OTR and ODTR Interferograms

Vertical (y) beam waist, $E = 95 \text{ MeV}$, $I = 1 \mu\text{A}$, $\lambda = 650 \times 70 \text{ nm}$

θ_y

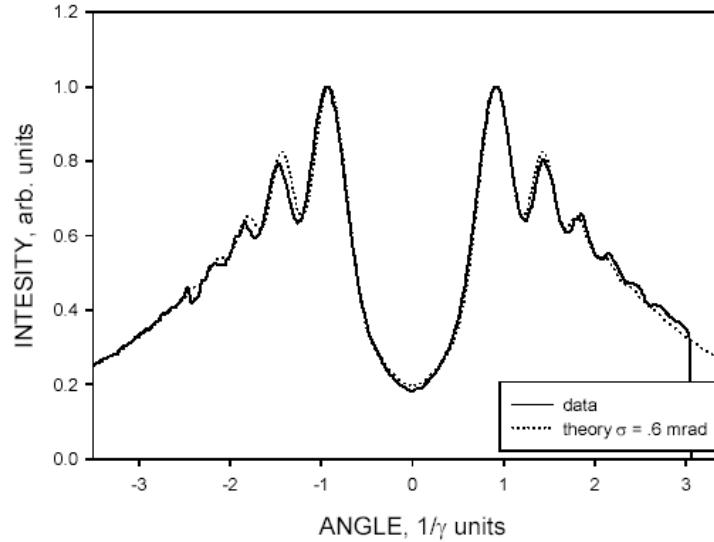
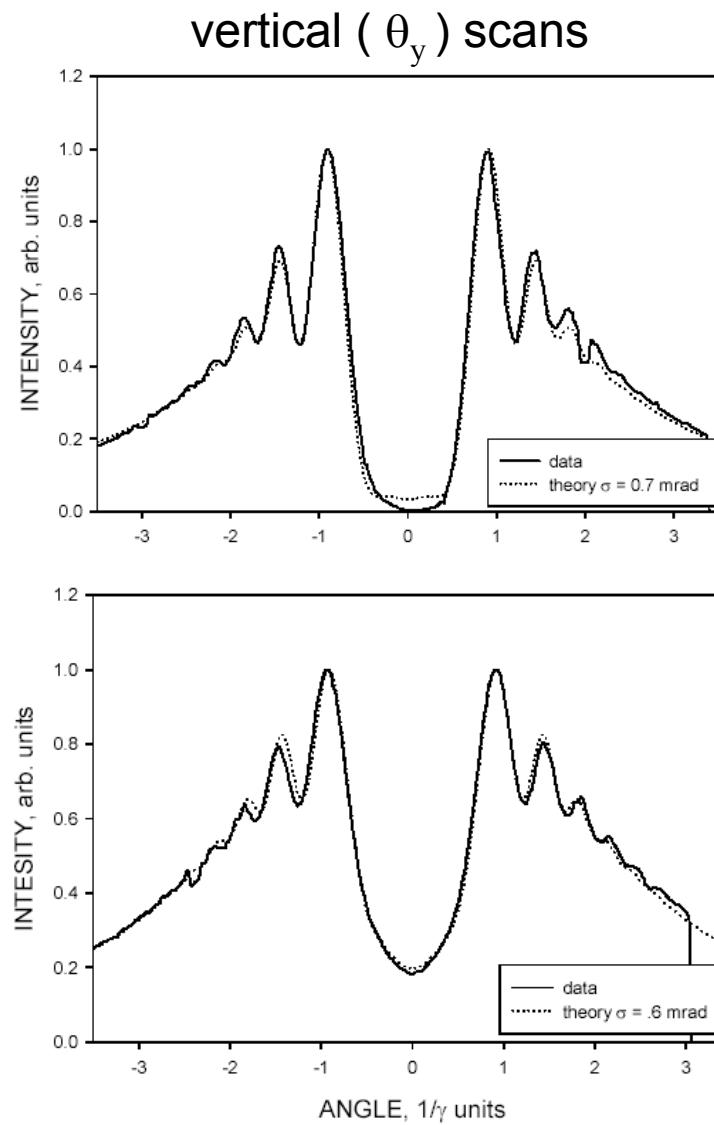


OTRI
 $\tau = 60\text{s}$



ODTRI
 $\tau = 90\text{s}$

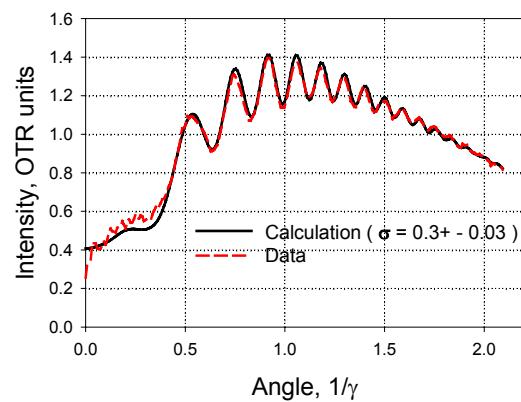
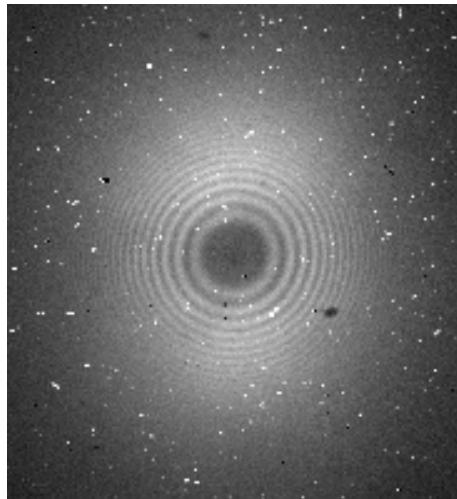
θ_x



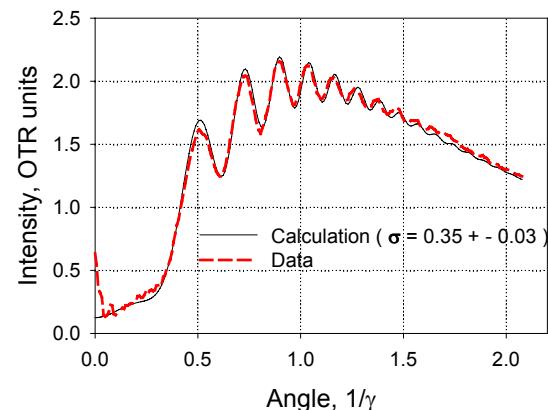
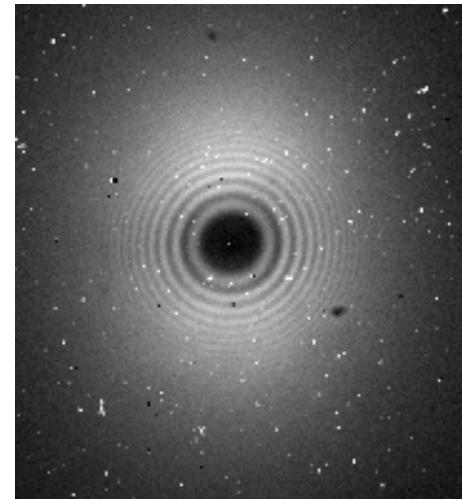
Comparison of Horizontal Divergence Measurements using ODTRI and OTRI on the 50 MeV ATF Electron Beam

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

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



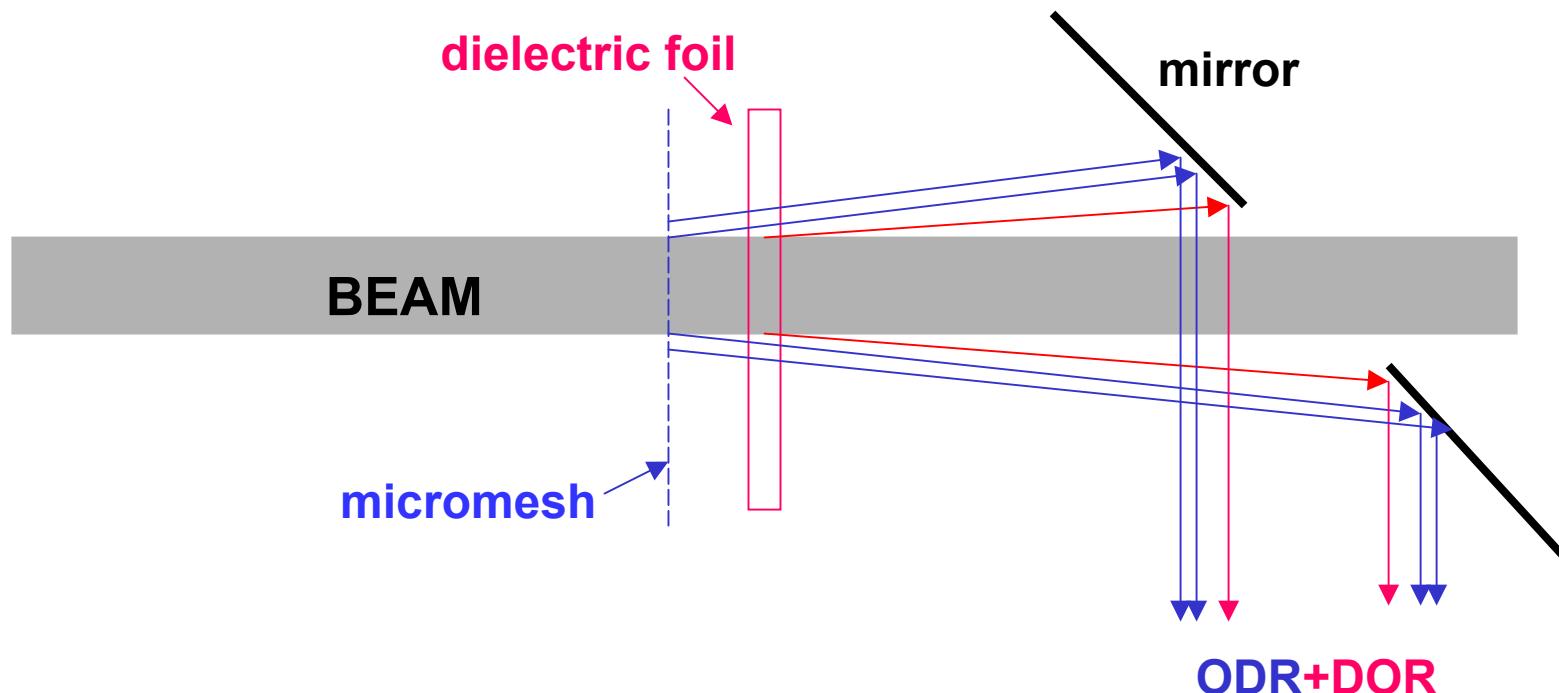
OTRI $\tau = 360\text{s}$



Low Energy (Injector) Diagnostics using ODR and OR from Dielectric Foil

PROBLEM: for low energy beams the inter-foil spacing L required is too small to directly observe backward reflected OTR or ODR from a mesh - metal foil e.g. $L (8 \text{ MeV}, 650 \text{ nm}) \sim \gamma^2 \lambda \sim 1 \text{ mm}$

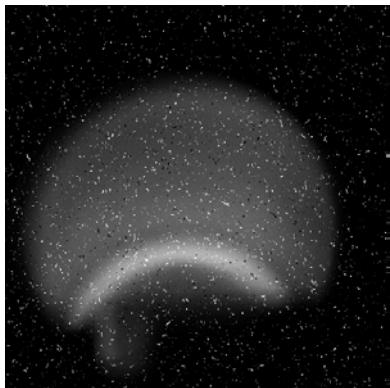
SOLUTION: observe interference between forward directed ODR from mesh and forward dielectric optical radiation (DOR).



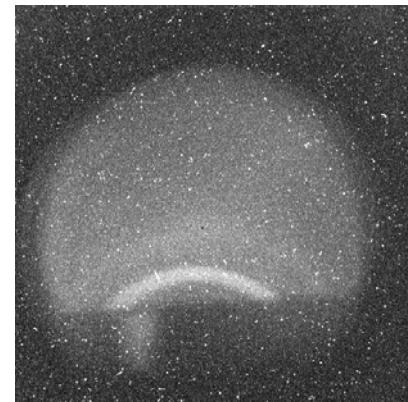
Preliminary Results: ODR-ODFR Interferences from the 8 Mev ANL AWA

(Kapton foil ($t = 13 \mu\text{m}$), mesh-dielectric spacing = 1.36 mm)

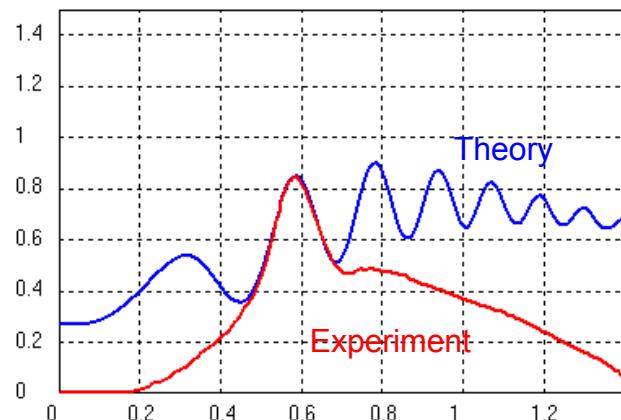
666 nm x 80 nm



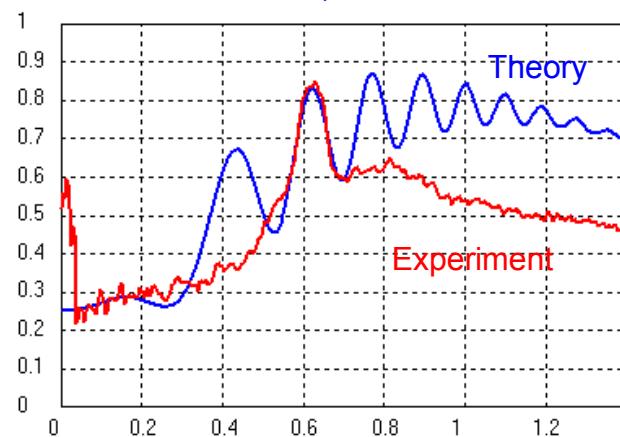
Filter 505 x 10 nm



Fit: $\lambda = 660 \text{ nm}$, $\sigma = 2 \text{ mrad}$



Fit: $\lambda = 505 \text{ nm}$, $\sigma = 1.8 \text{ mrad}$



FOV (theory): $0.3/\gamma$ (reflector) to $1.7/\gamma$

Actual FOV: $0.5/\gamma$ (reflector) to $0.7/\gamma$ (beam offset)

Optical phase space mapping

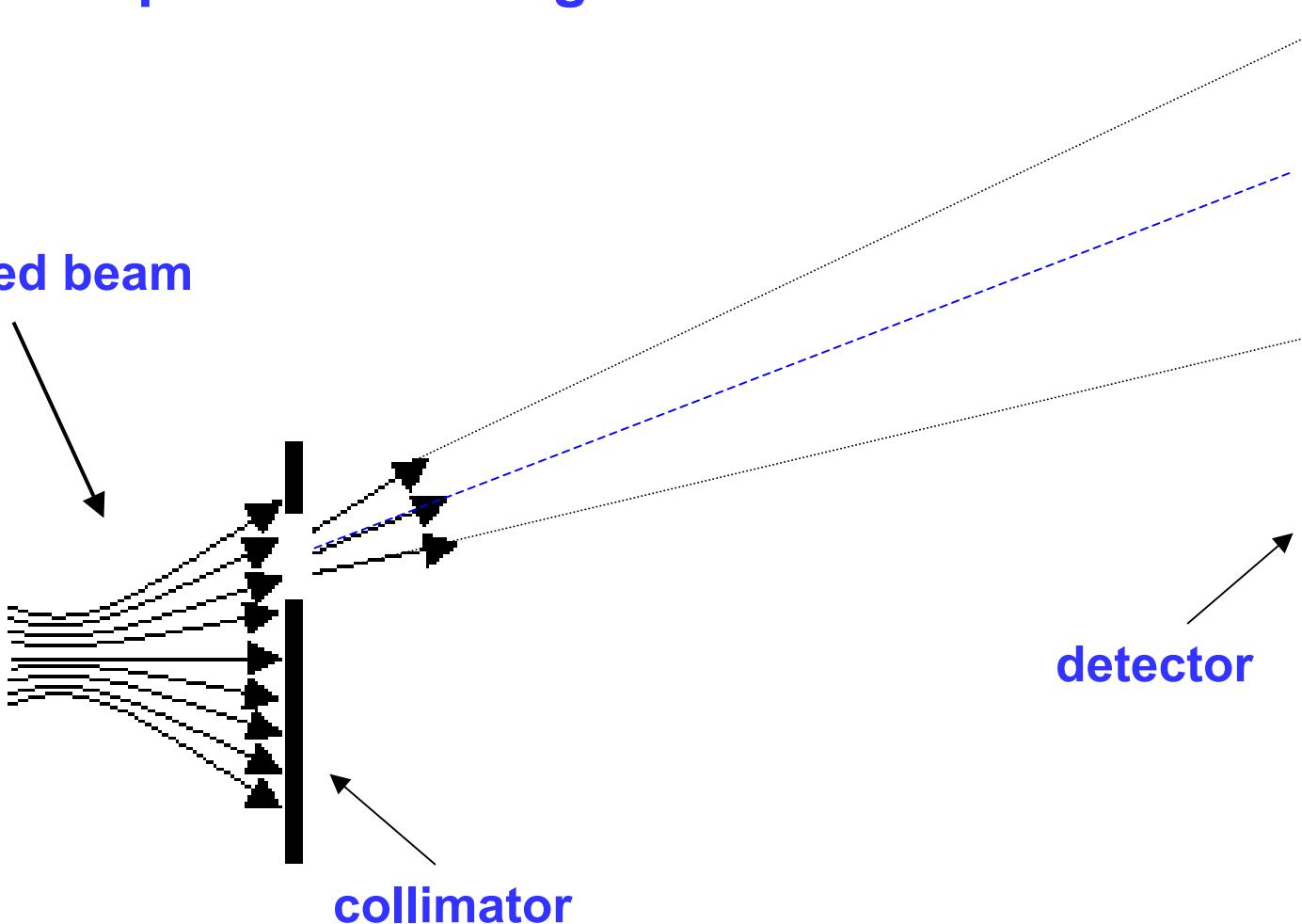
Concept: Optical radiation (e.g. OTR, ODR, OSR) and an optical mask are used to map the transverse phase space of the beam (localized beam divergence and trajectory angle measurements analogous to standard pepper pot method)

Conventional PSM: pepper pot collimates beam into beamlets whose trajectories and spread are monitored as a function of position within the beam. Not practical for high energy beams - collimation doesn't work, beams too small.

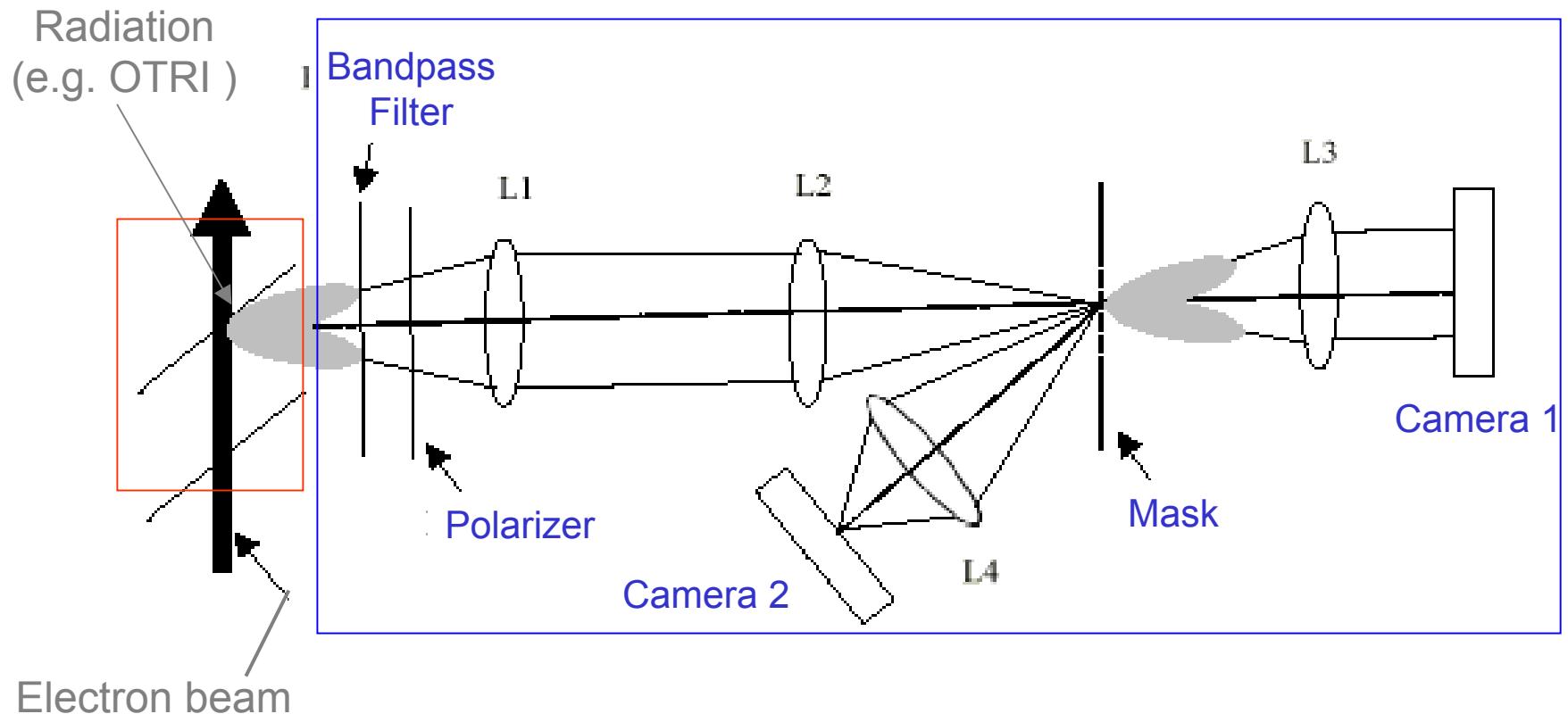
*R.B. Fiorito, A.G. Shkvarunets, and P.G. O'Shea, "Optical method for mapping the transverse phase space of a charged particle beam" in AIP Conf. Proc. No. 648, G. Smith and T. Russo eds., (2002).

Pepper pot Collimator Method For Mapping the Phase Space of a Charged Particle Beam

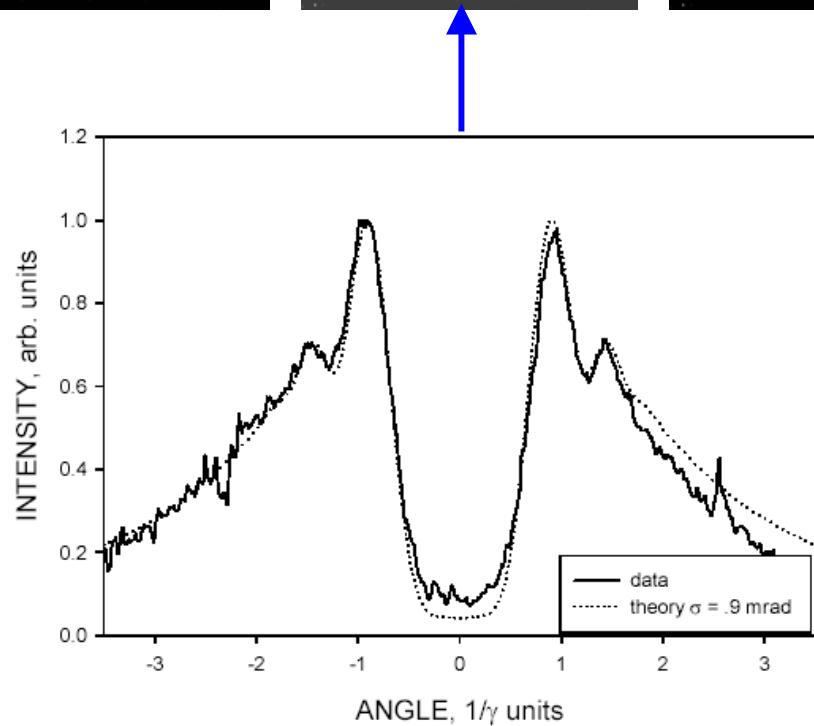
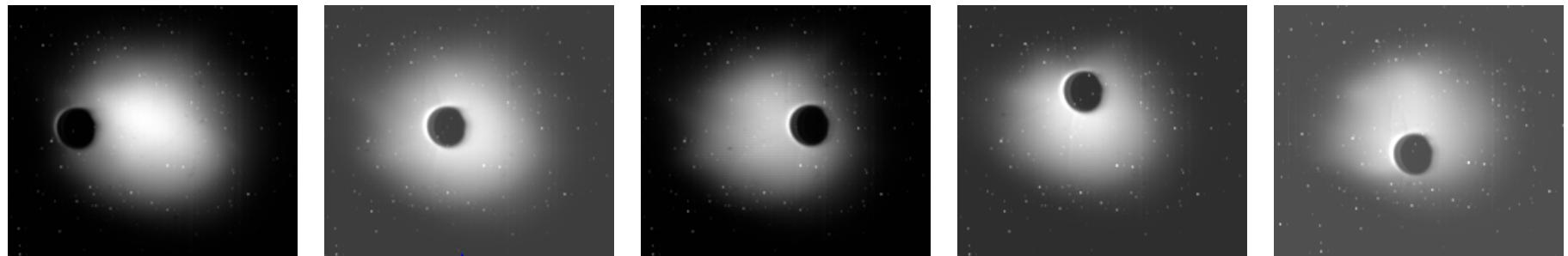
Unfocussed beam



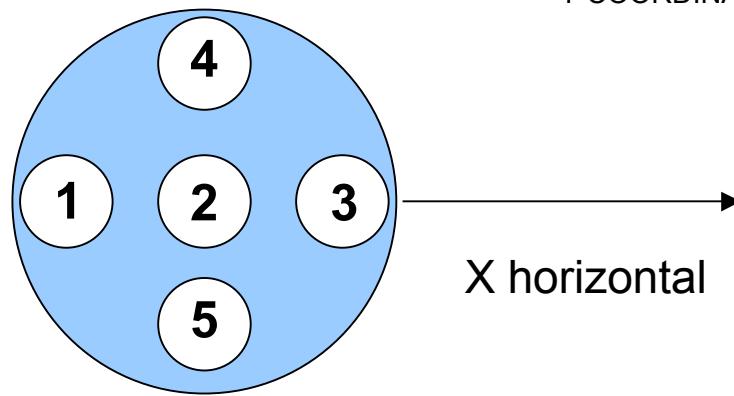
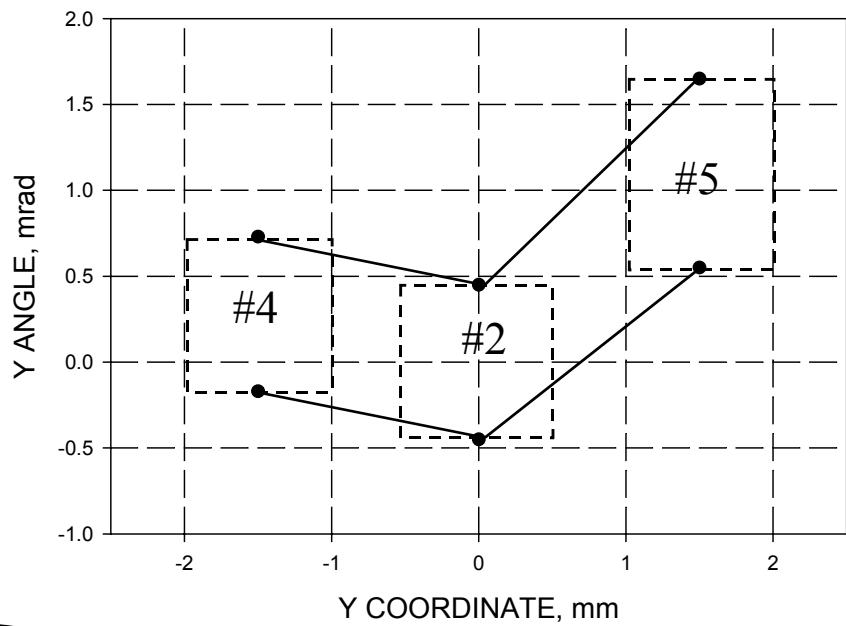
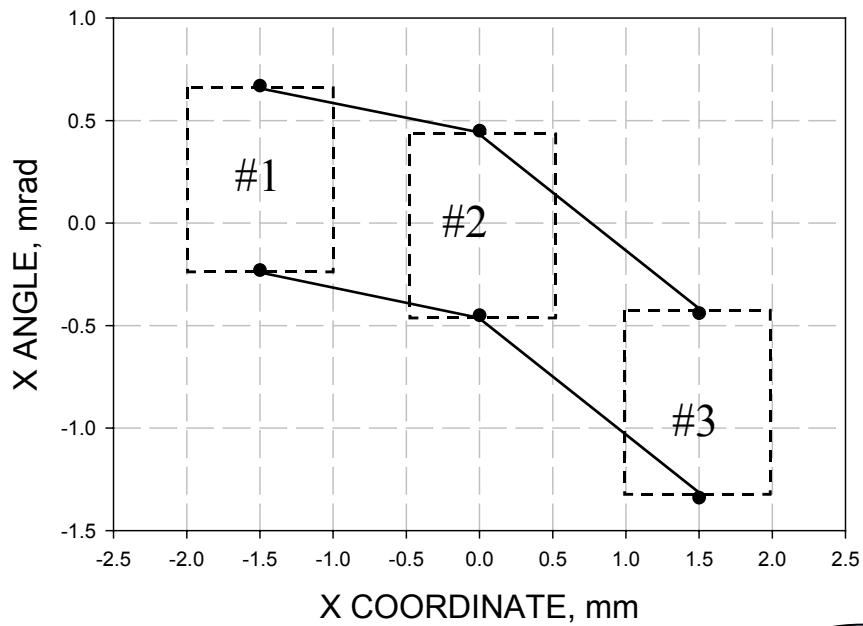
OTR Phase Space Mapping



OTR Phase Space Mapping with a scanning 1mm pinhole



x , x' and y , y' OTR Phase Space Maps using 1 mm Pinhole



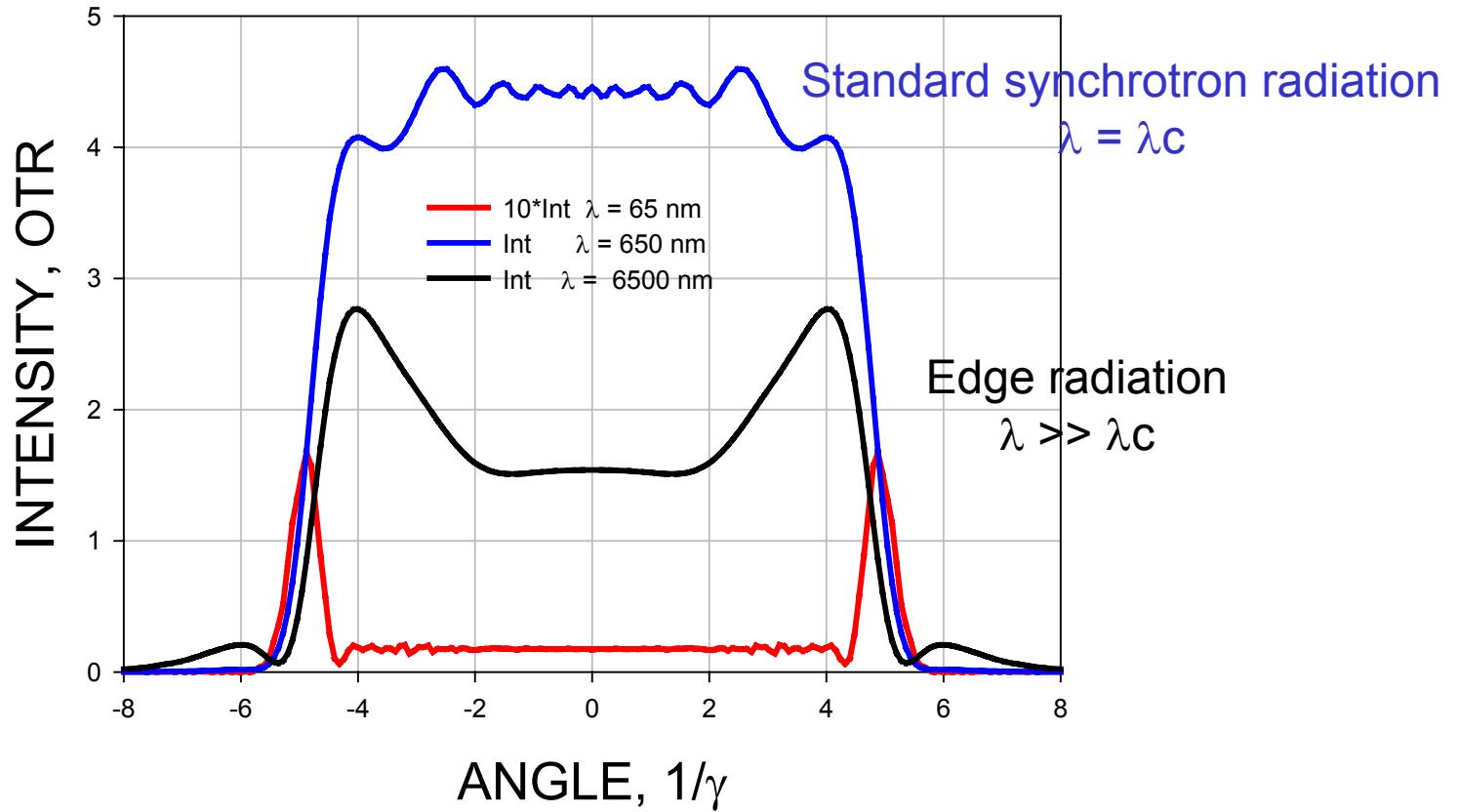
OSR beam emittance/phase space diagnostics

Advantage of OSR :

- 1) Non Intercepting.
- 2) Useful for ERL's, microtrons and, in general, any beam line or structure which produces OSR (e.g. end magnets, chicanes, wigglers, etc).

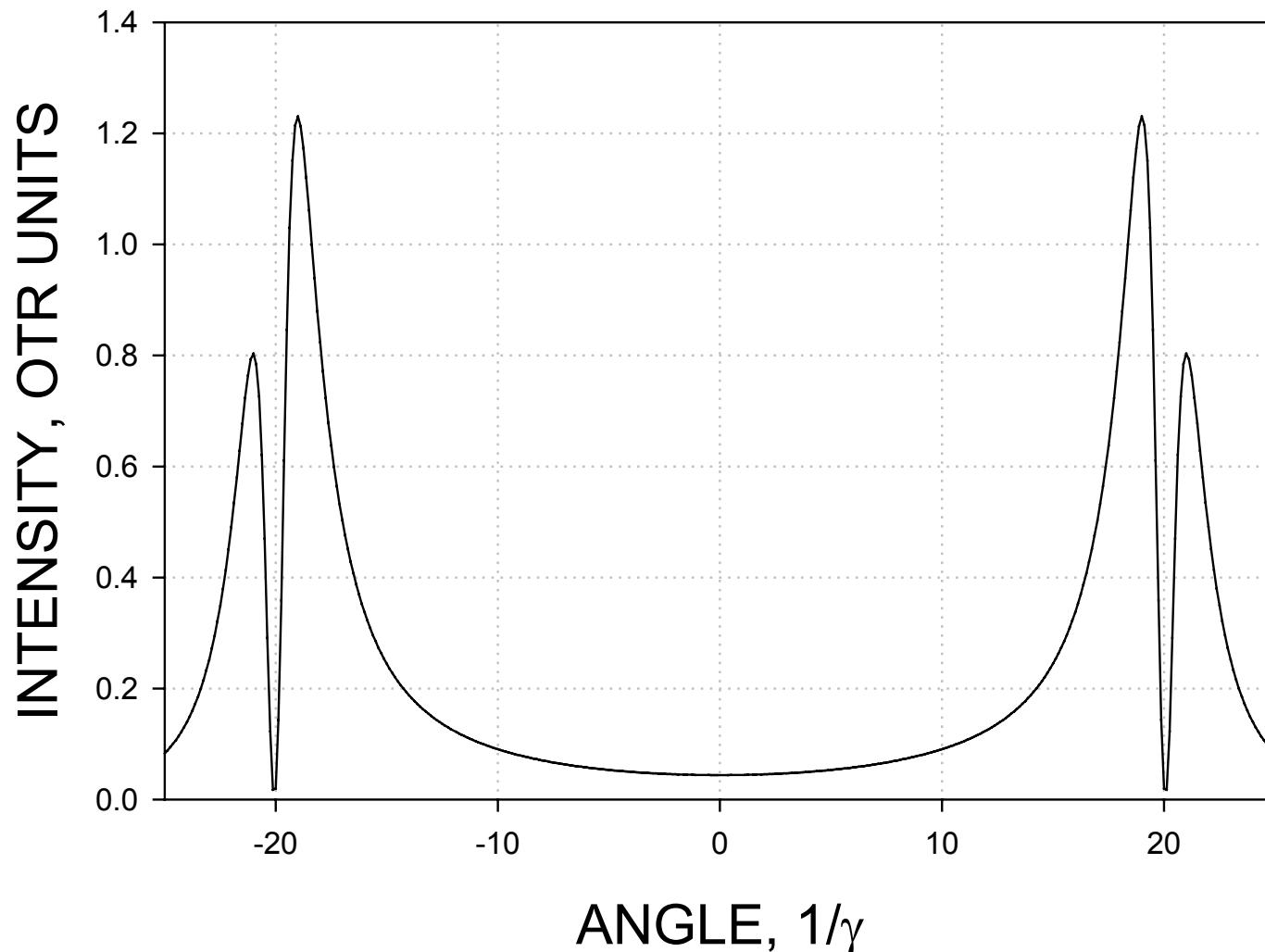
Synchrotron Radiation from a Finite Arc:

x scan, x polarization $\lambda=65$; $\lambda_c=650$; $\lambda = 6500$ nm,
(100 MeV, R=1m, $\Delta\theta = 10/\gamma$)



OER from 2.5 GeV electrons
(x plane, $R = 4\text{m}$, $\lambda = 400\text{nm} \gg \lambda_{\text{cr}} = 1.4\text{nm}$)

(O.Chubar, N.Smoliakov configuration; analysed by UMD OSR simulation Code)



Question: Can we use OSR to make **non intercepting divergence** measurements using farfield OSR in a way similar to what is done with OTR and use it for rms divergence and OPSM?

Test: TJNAF FEL Phase I beam parameters (old but good for rough estimates)

Emittance: 13 mm mrad

Beam Size: 0.5 mm

Energy: 40 MeV

1/gamma: 12.5 mrad

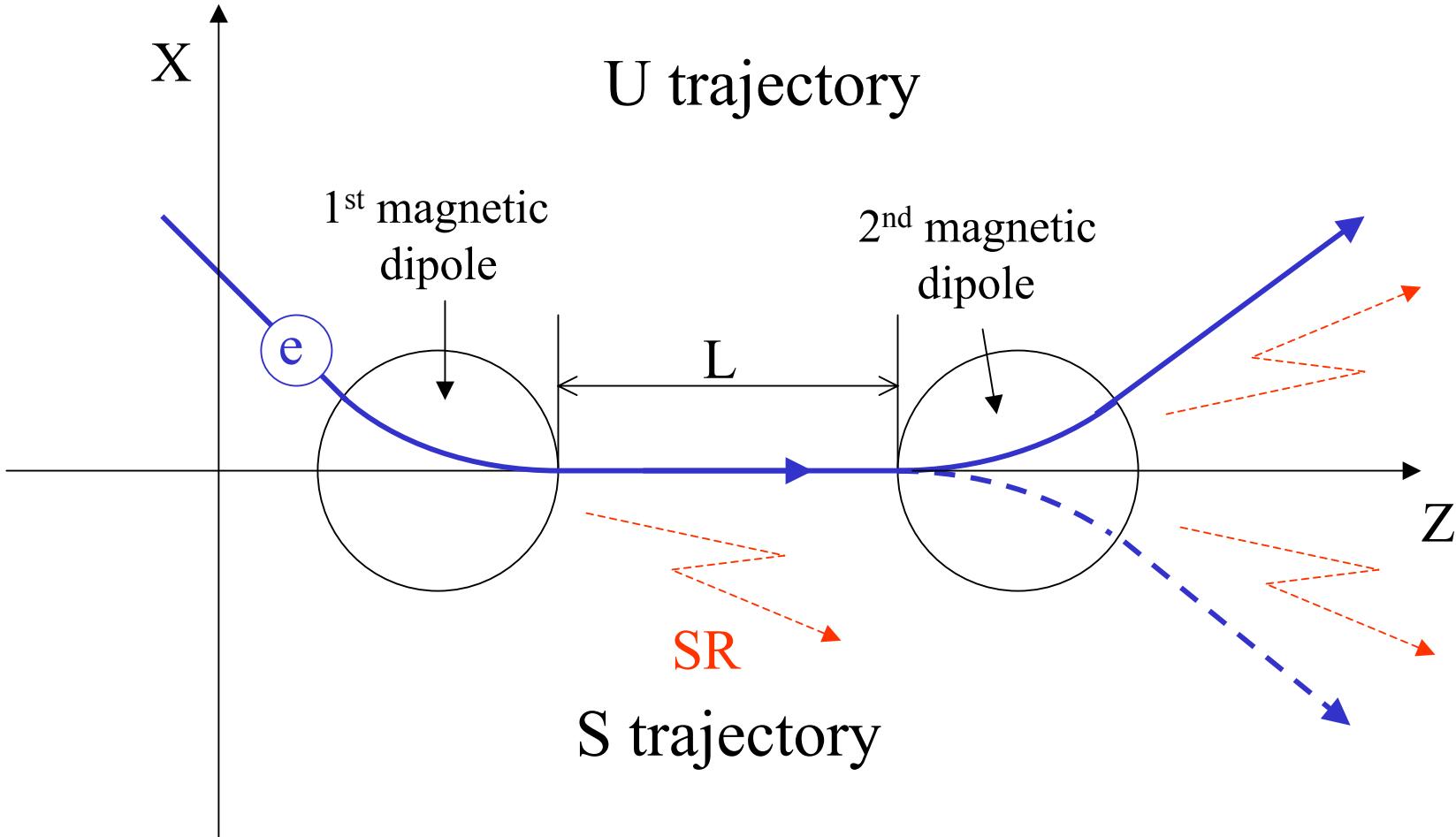
Divergence: 0.325 mrad

Normalized Divergence ($\gamma\theta$): 0.025 (Single arc OSR farfield pattern)

Need factor of 10 increase in sensitivity to measure the divergence
→ OSR from two interfering arcs or edges (OER) separated by the coherence length L_v

Optical Synchrotron Interferences (OERI)

From Two Bending Magnets Separated by Distance L



2 EDGES SYNCHROTRON RADIATION INTERFEROMETER
2.5 GeV, $R=4\text{m}$, $\lambda=400\text{ nm}$, $L=10\text{m}$

(UMD simulation code)

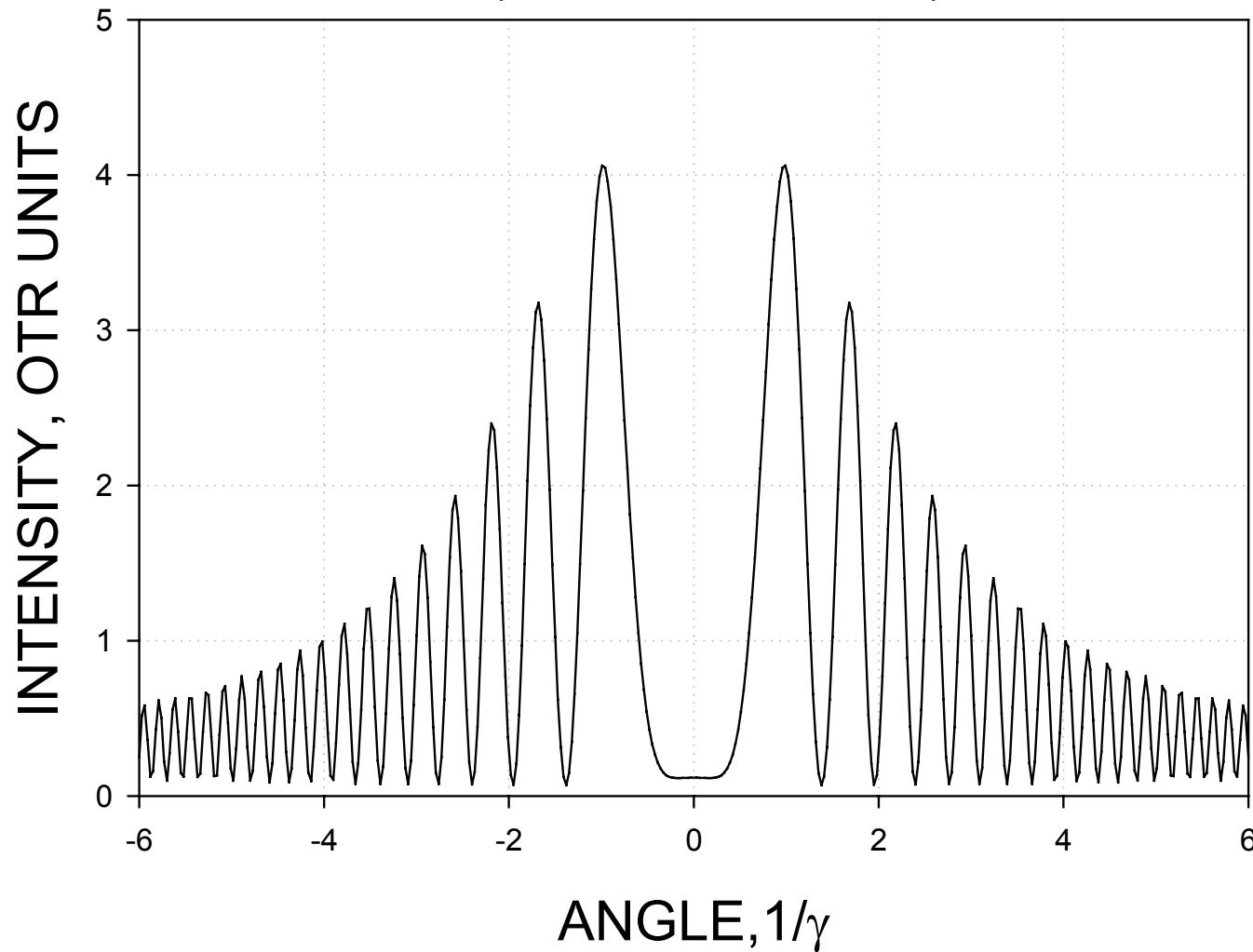
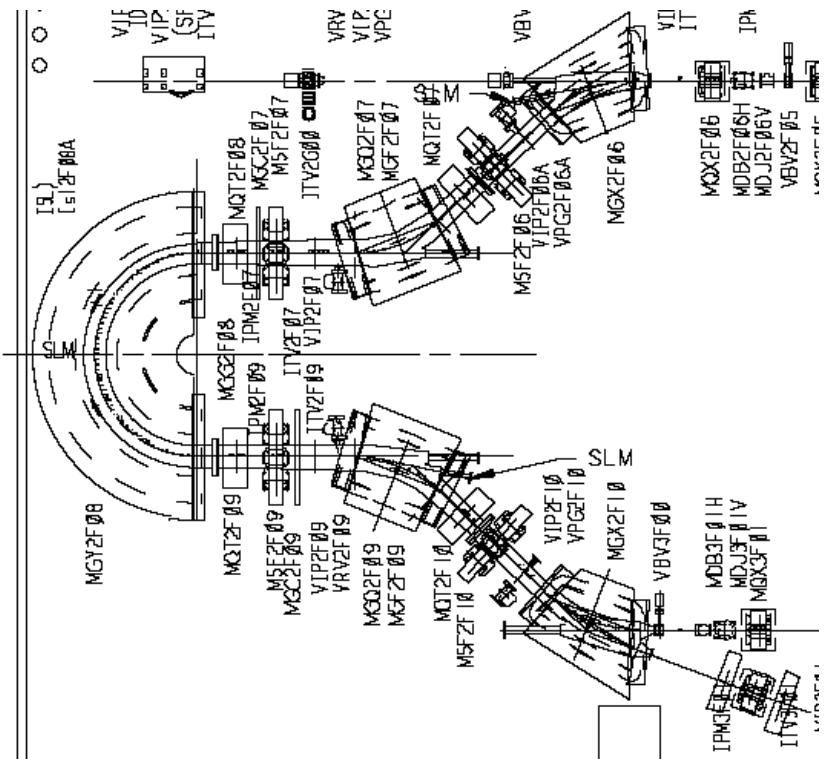
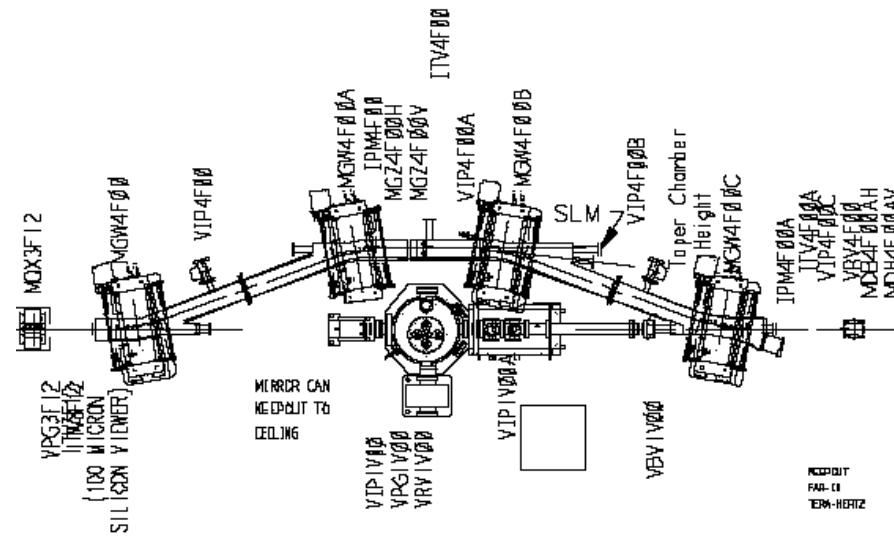


Diagram of TJNAF Bending Magnets Segments where OSR or OER Experiments Might Be Done

End Station



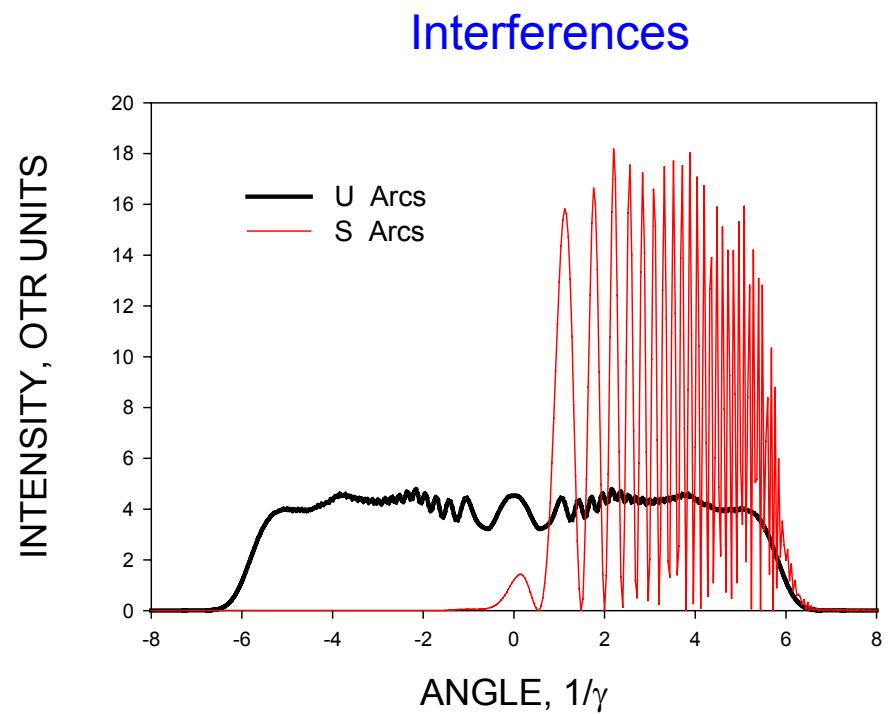
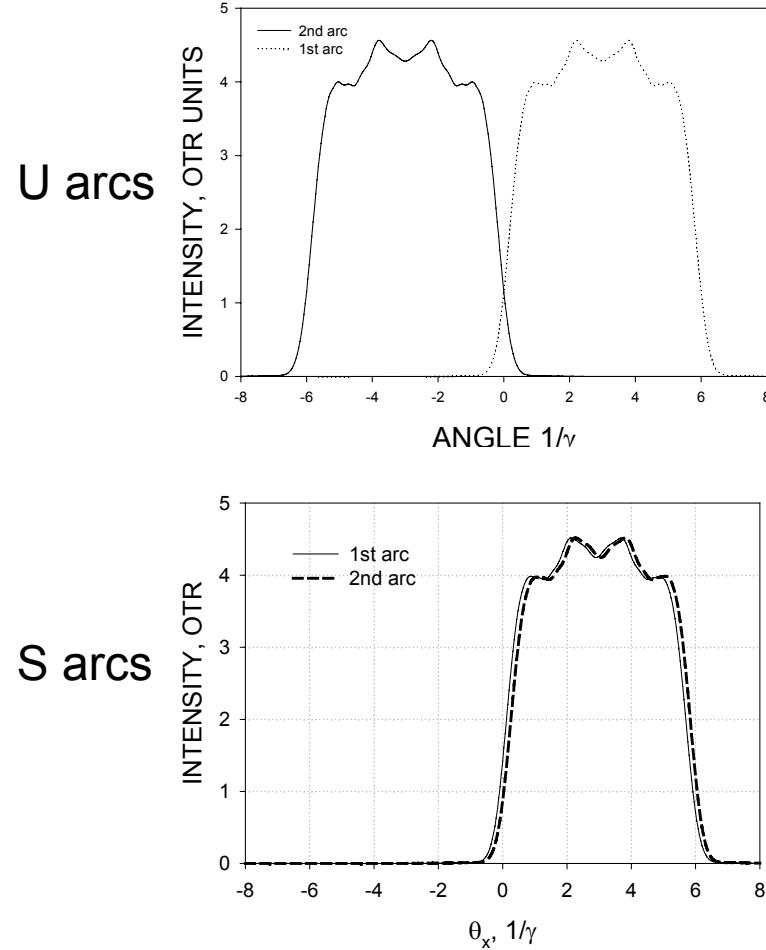
Wiggler Section



→ e beam

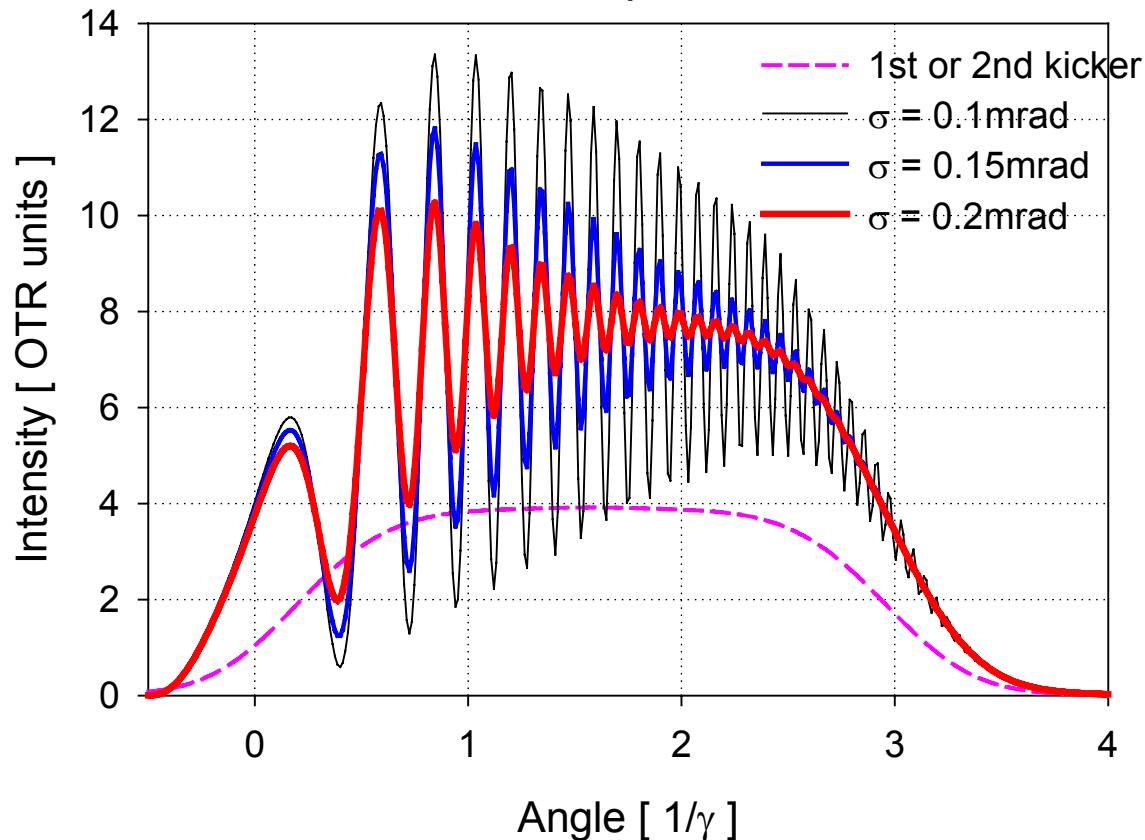
Interference of Synchrotron Radiation from Two Arcs

($E = 100 \text{ MeV}$, $R = 1.09 \text{ m}$, $\lambda = 600 \text{ nm}$, $L = 46 \text{ mm}$, $\Delta\theta = 6/\gamma$, $\theta_e = 0$)



S trajectory. Jefferson NL FEL (proposed double S kicker)

Horizontal scan Xo, horizontal polarization, 100 MeV,
double S kicker, electron deflection = $3.2 / \gamma = 16.3$ mrad
 $\lambda=\lambda c=600\text{nm}$, separation = 100mm



Sensitivity : normalized divergence, $\gamma\sigma \sim 0.01$
Reference: Shkvarunets and Fiorito, Proc.of BIW04

Effect of Divergence on OERI at CESR (1.9 GeV)

Horizontal scan of horizontally polarized OERI
 $L = 20\text{m}$, $\sigma_y = 4\mu\text{rad}$, $\lambda = 600 \text{ nm}$

