Optical Beam Diagnostics: Transverse Phase Space Measurements

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Topics : use of beam based optical radiation to measure transverse beam properties

- size, space distribution (x, y) [OTR, OSR]
- divergence (x', y'), [OTR, ODR, OSR interferences]
- trajectory angle "
- rms emittance (e_x, e_y) "
- phase space mapping (x,x'), (y,y') "

Exclusions (will be talked about via other speakers)

- Laser wires
- Coherent optical radiation generated at optical wavelengths due to microbunching
- EO methods, Compton and Thomson scattering
- Longitudinal beam properties

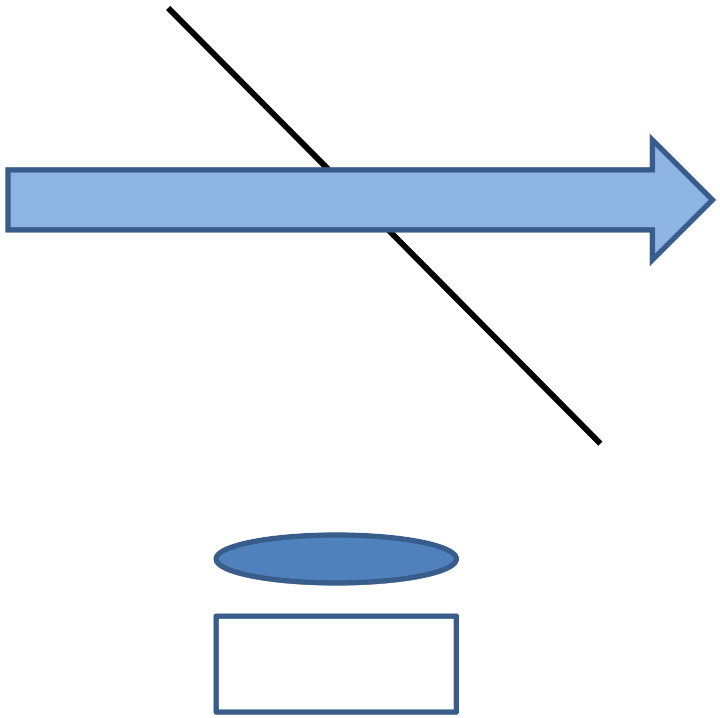
I. Optical Beam Profiling Methods

Traditional Imaging: uses beam based radiations, e.g. OTR ,OSR, ODR, OCR, etc.
or fluorescent screens, e.g. phosphors, YAG crystals, etc.
(width of the PSF limits the resolution of these measurements-
determined by the first few decades of intensity)

High Dynamic Range Imaging: HDR cameras (CMOS, CID),
Segmented HDR imaging with spatial light modulators (e.g. DMD)
(intensity distribution of the PSF limits these measurements)

Indirect Beam Size Measurement: Young's double slit interferometry - measures the
degree of spatial coherence of optical radiation produced by the beam
(depends on the size of the source; first used by Michelson to
measure the size of stars).

Optical Transition Radiation



OTR Beam PSF determines Resolution: 2-3 lens diffraction limit from point source

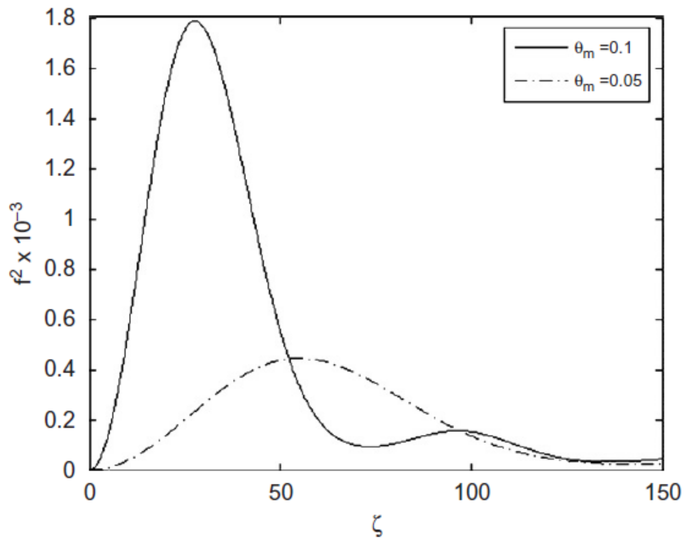


Fig. 2. PSF of a single electron for TR. $\gamma = 1000$.

OTR vs inorganic scintillators at a glance

OTR

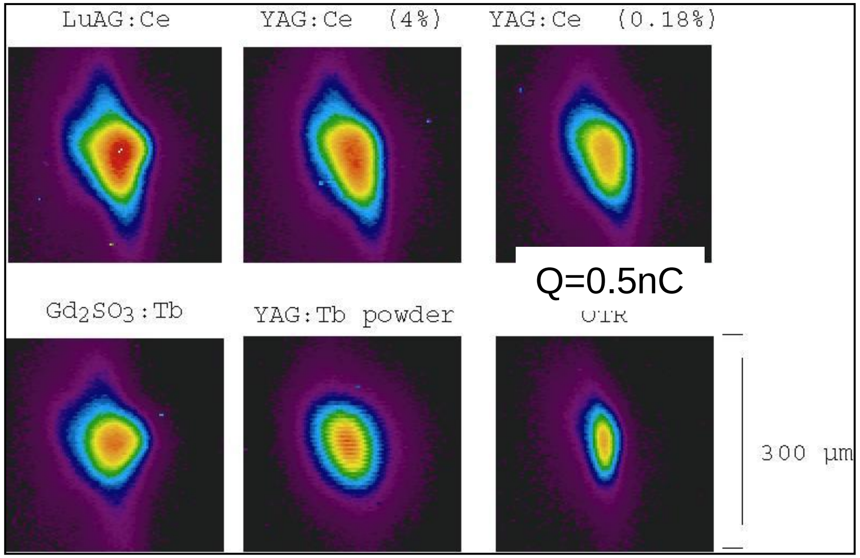
- Rapid (<fs) emission
- linearity (no saturation effects)
- high resolution (PSF ~ point source)
- surface effect: thickness doesn't matter
- small perturbation to the beam (small thickness)
- small radiation background (small thickness)
- can be used in a wide range of γ
- relatively low photon yield (1 photon/137 electrons)

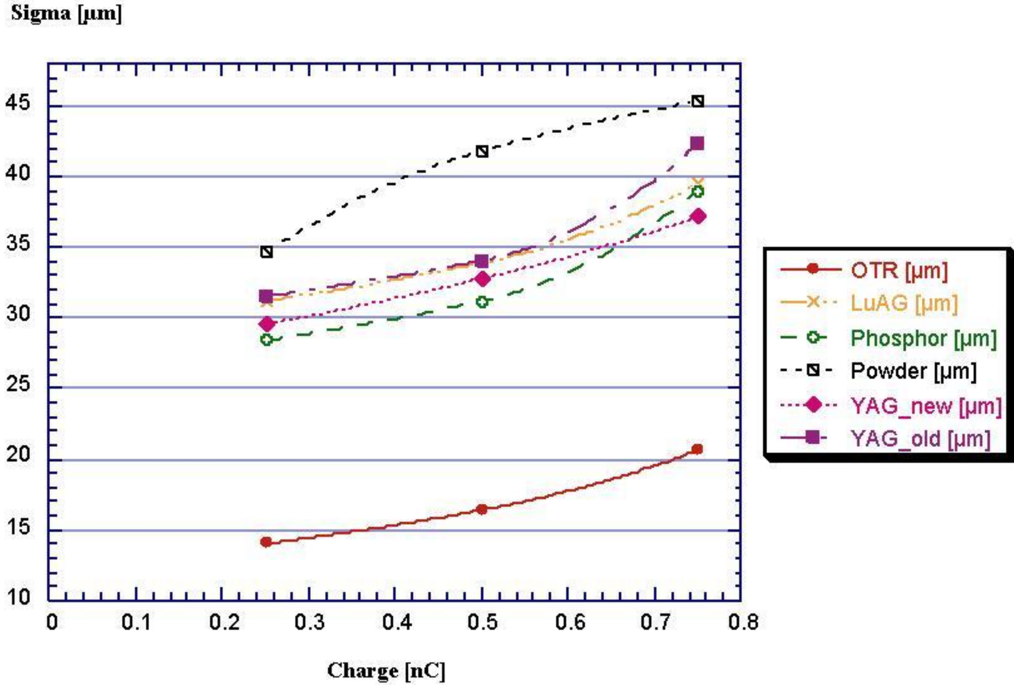
Scintillators (YAG:Ce, YAP:Ce, oth.)

- high sensitivity +yield
- no grain structure
- time response ~ 100ns
- conformance to HV
- radiation resistance
- bulk effect+space charge (cause saturation and limit resolution)

OTR/Scintillator resolution

Experiments at BNL* showed discrepancy in the beam size measurements compared to OTR and wire scans and is charge dependent.

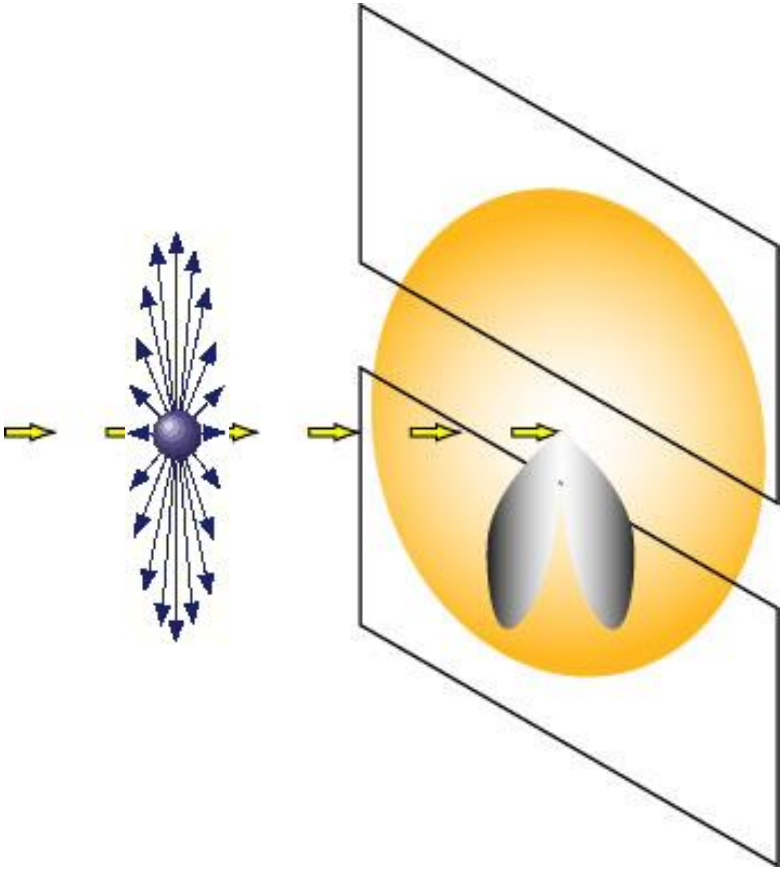




*A.Murokh et al. FEL99

Diffraction radiation

- Diffraction radiation is emitted when a particle passes in the proximity of optical discontinuities (apertures)
- DR characteristics depend on the ratio of the aperture size to the parameter $\lambda\gamma$
- DR intensity strongly suppressed at wavelengths $\lambda<a/\gamma$

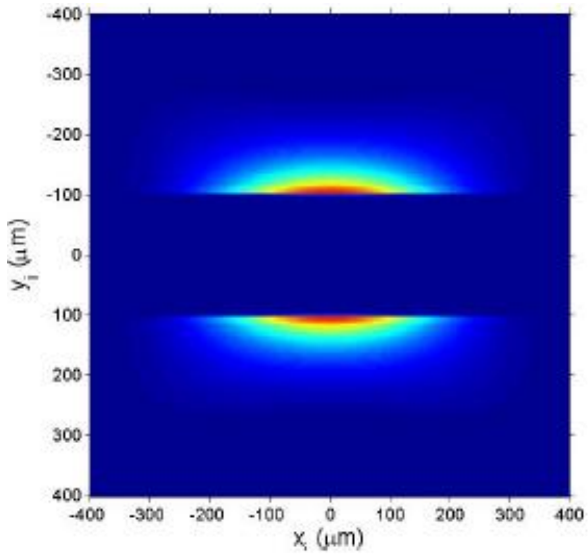


Credit for slide: V. Verzilov, TRIUMP

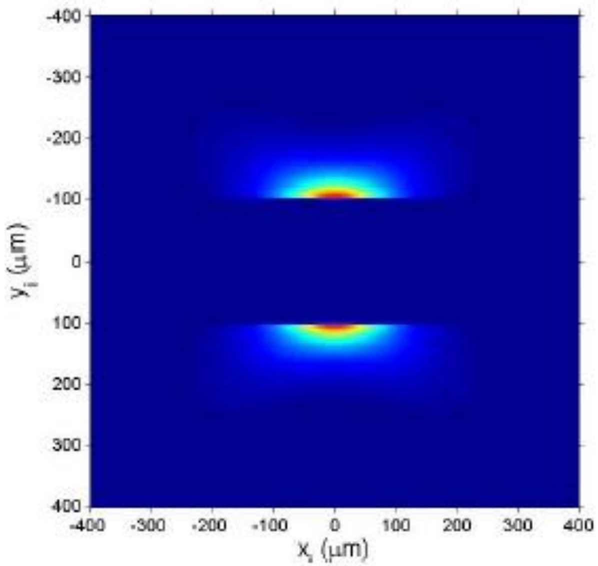
Restoration of Beam Profile from Source Image of ODR*

(example: γ = 2500; λ = 0.5m; θ = 0.1)

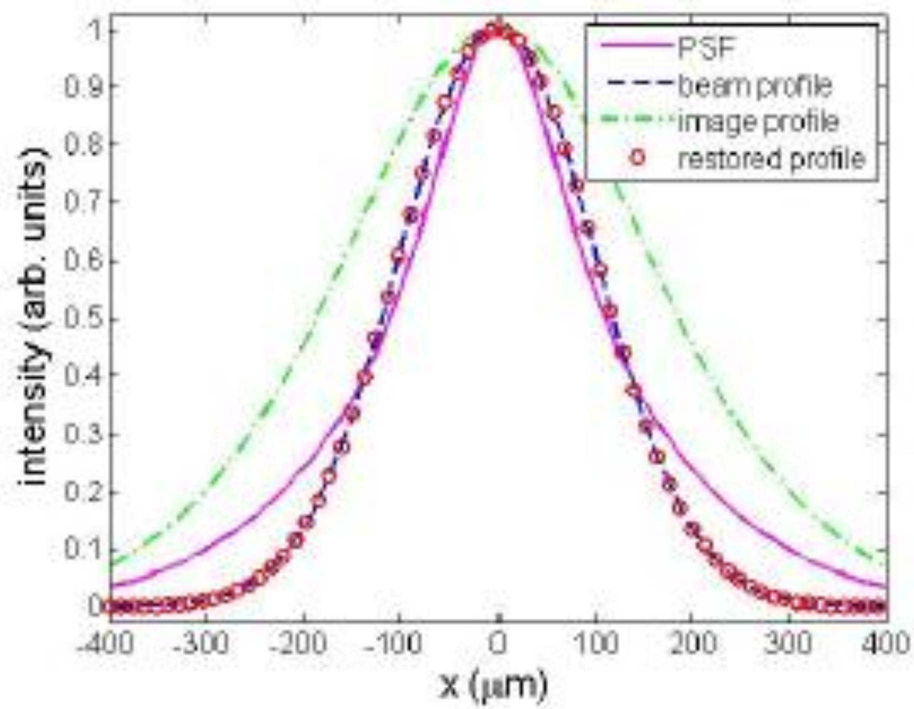
ODR Distribution from Gaussian Beam



PSF



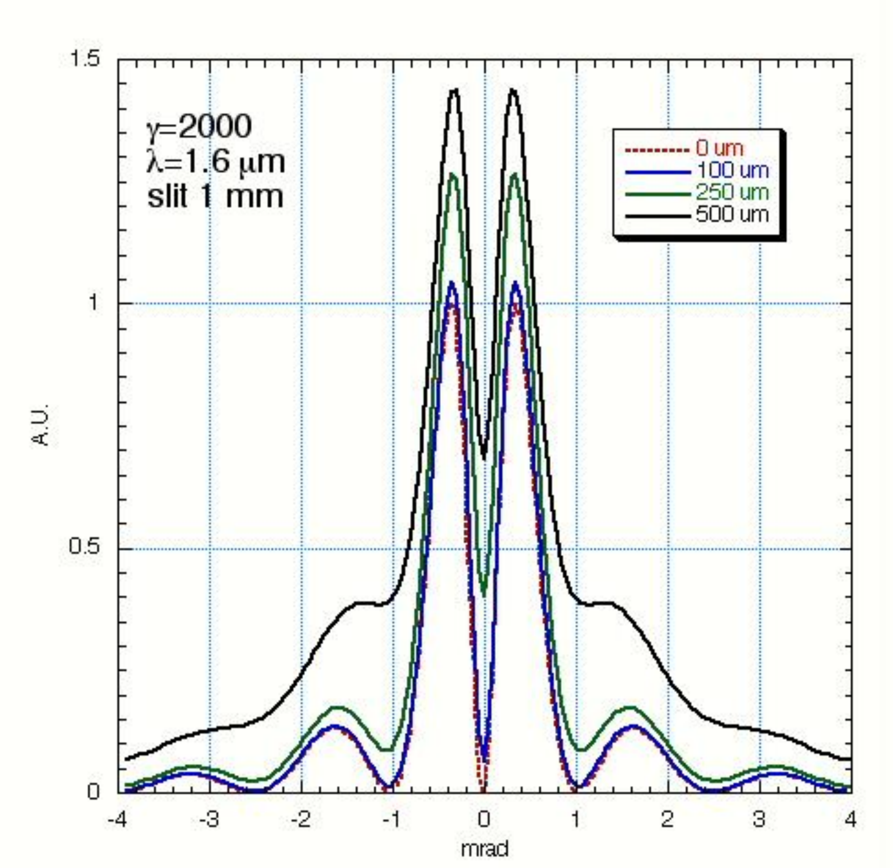
Vertical Profiles



*D.Xiang, et. al. PRSTAB 2007

Effect of the beam size on Far Field ODR

- Angular distribution depends on the relative particle position with respect to the aperture and can be used to measure the beam size
- Energy and angular spread, detector bandwidth are interfering factors



A.Cianchi PhD Thesis

High Dynamic Range Beam/Halo Imaging

OPTIONS

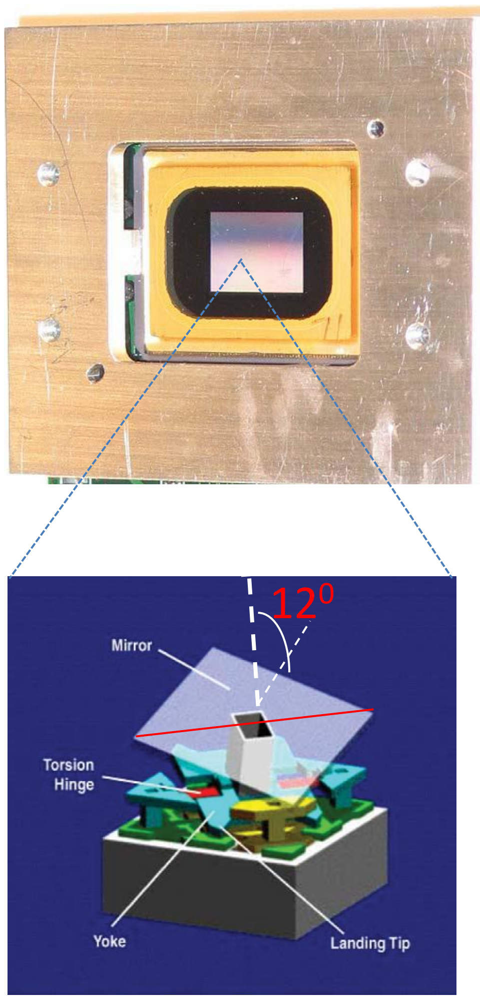
HDR CID or CMOS Cameras: expensive

Saturated/ Unsaturated sensors: cross talk possible in sensor; does not reduce
scattering in optics from central beam core

Digital Micro-array Method: versatile programable masking
reduces scattering of light in primary optics
any type of camera can be used
diffractive imaging possible

DMD Technology

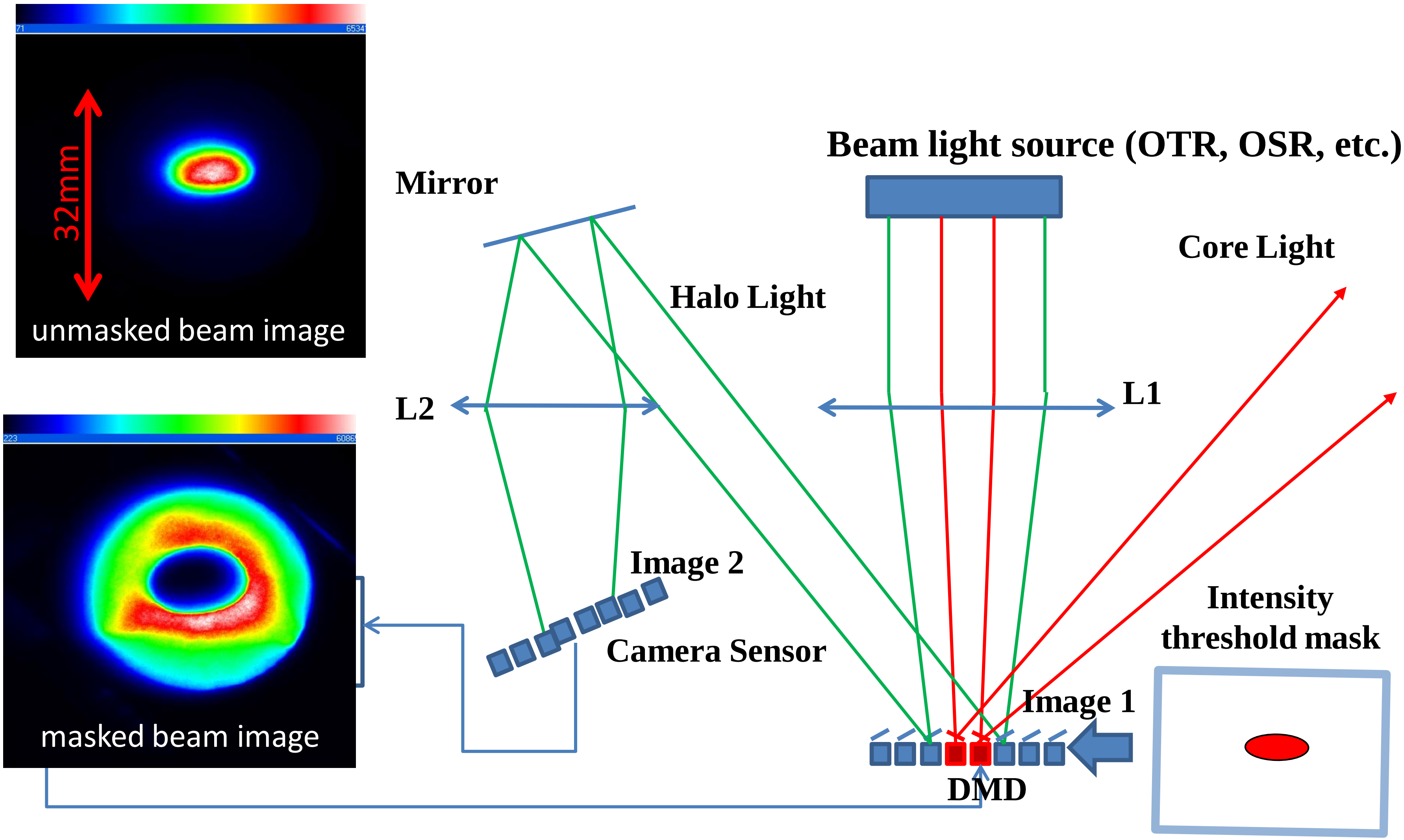
*DLP^{TM} Texas Instruments Inc.



Array dimensions: 14 x 10 mm
Pixels: 1024 x 768,
Pixel dimension: 14x14 μicrons
Switching rate: 9600-32000 fps
Individual pixel addressable

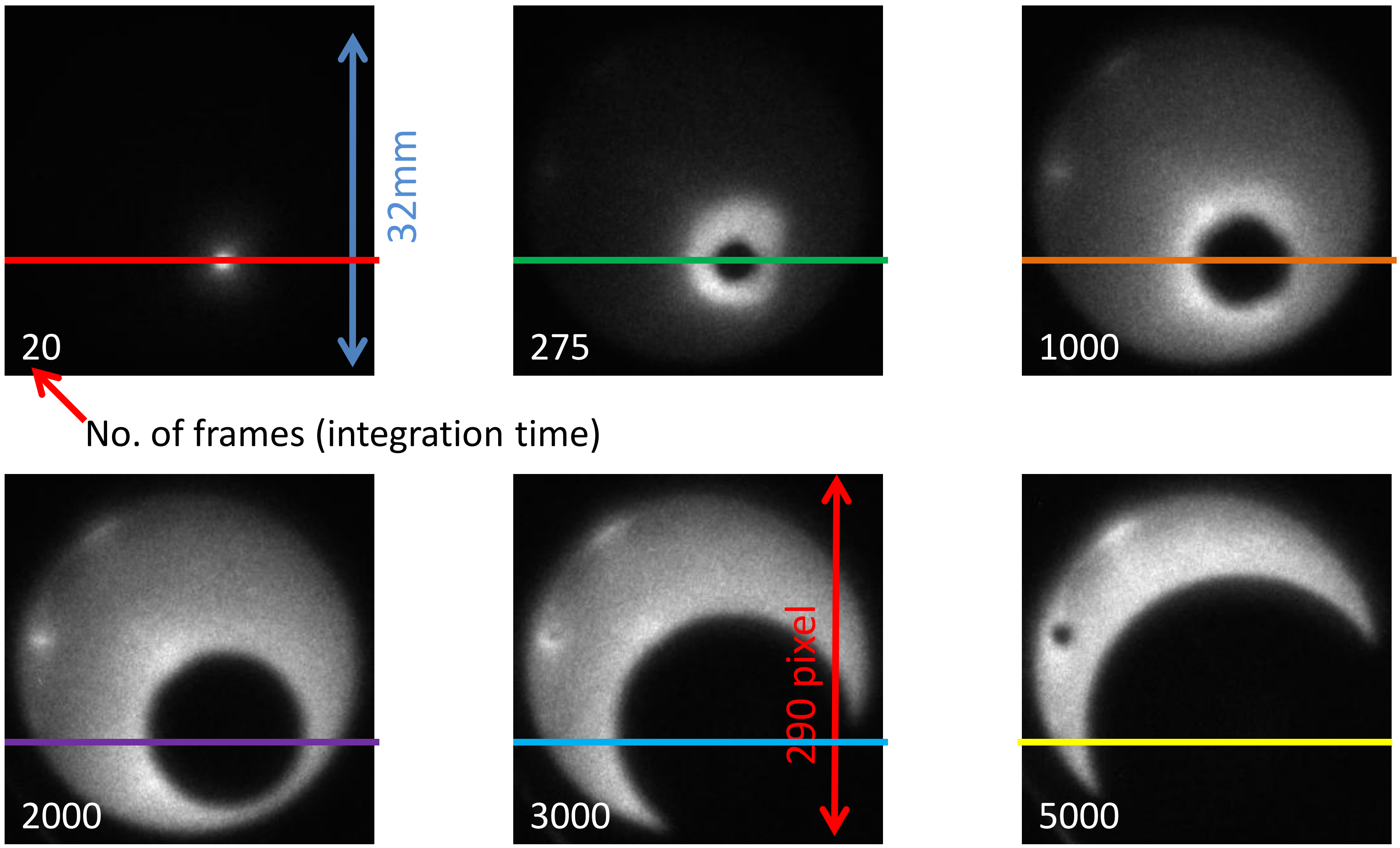
Uses: 1-Spatial light modulator
2-Adaptive optical Mask

Optical Technique for DMD based Beam Halo Imaging*

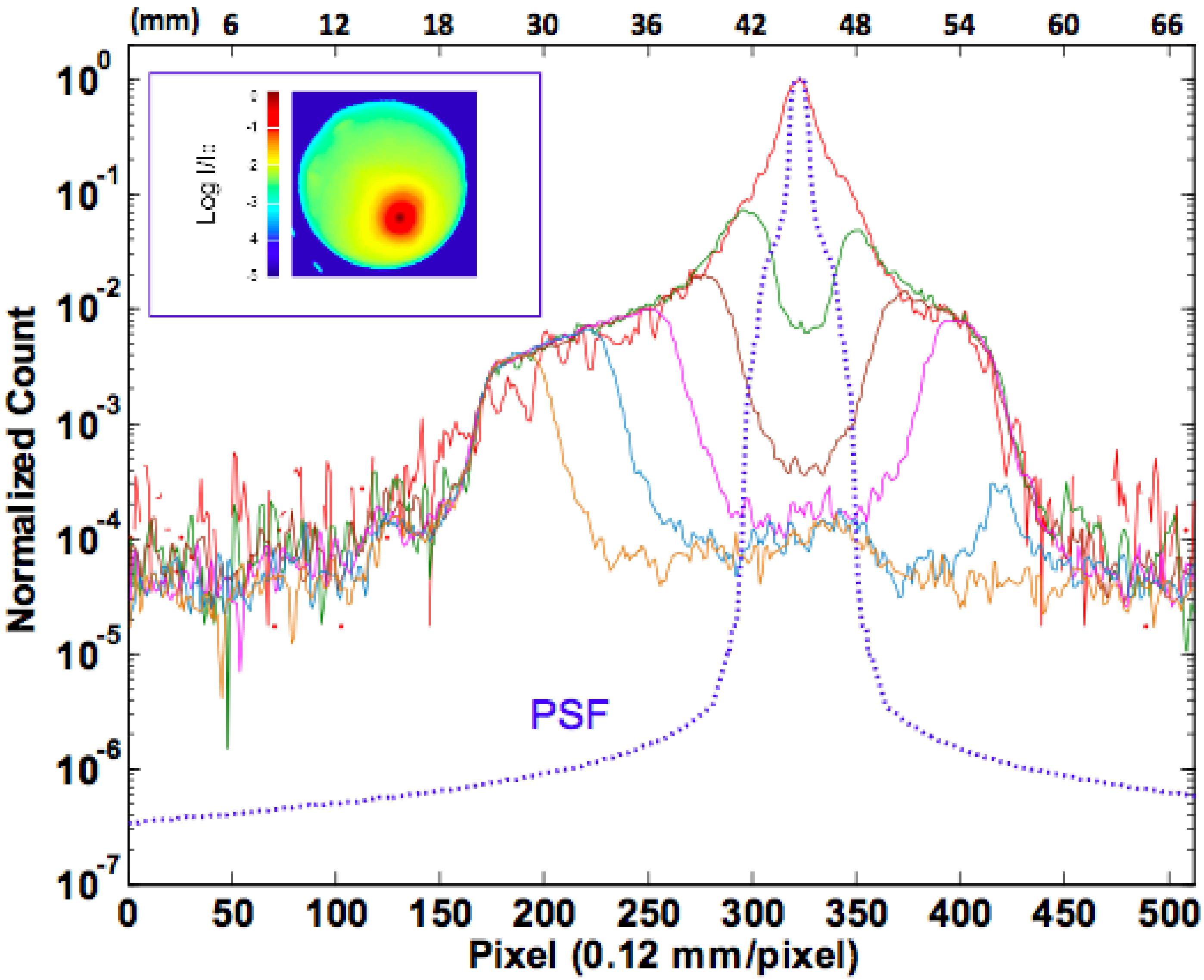


*H. Zhang, et. al. Phys. Rev. ST Accel. and Beams (2012)

Dynamic range measurement of imaging system using DMD as an optical mask with phospor screen (21mA ebeam)



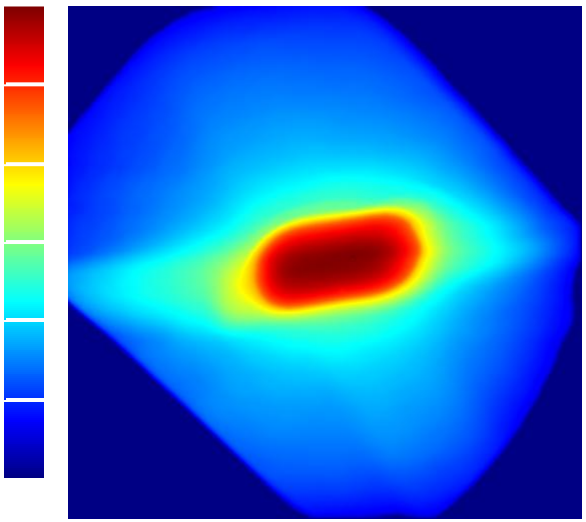
Dynamic Range and Point Spread Function Measurements for UMER



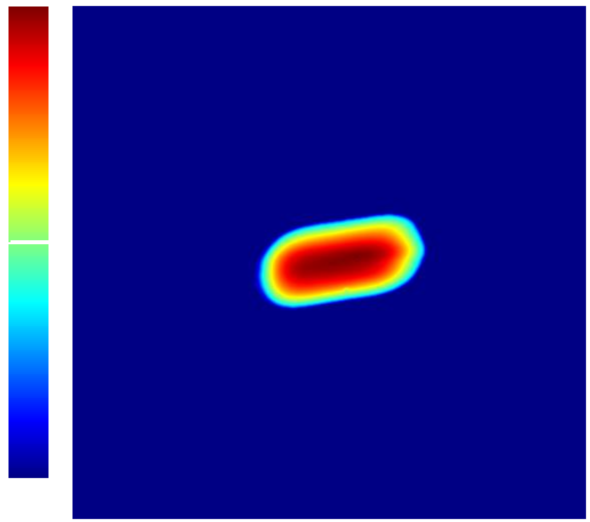
Reconstructed intensity distribution *I(x,y)* and calculated total radiant energy E_{Total}

Assume $I(x,y) \sim J_{beam}(x,y) \Rightarrow E_{total} \sim Q_{beam}$

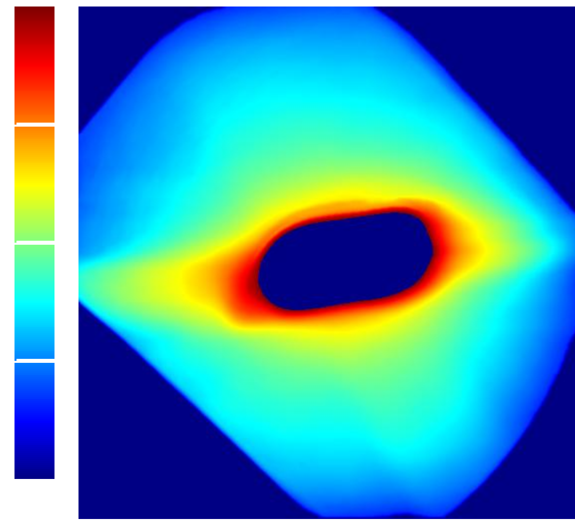
$(1-10^{-6})\, I_{max}$



$(1-10^{-2})\, I_{max}$



$(10^{-2}-10^{-6})\, I_{max}$



$$E_{Total} \equiv \int_S I(x,y)\,dxdy$$

$$E \sim 0.99\, E_{Total}$$

$$E \sim 0.01\, E_{Total}$$

R. Fiorito, et. al. Proc. BIW12; H. Zhang,et. al. Proc.IPAC2012

RMS Emittance measurements

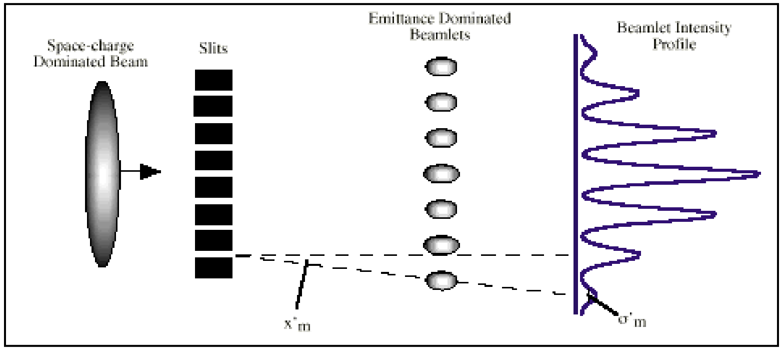
Widely used techniques

- Pepper-pot (multislit)
- Quadscan (beam size vs 1/f)
- 2 or more screens beam size

Space-charge forces

$$R = \frac{I\sigma^2}{2I_0\gamma\varepsilon_n^{\ 2}}$$

Measure of spaces-charge dominance



Transverse rms Emittance using Angular and Spatial Distributions of OTR

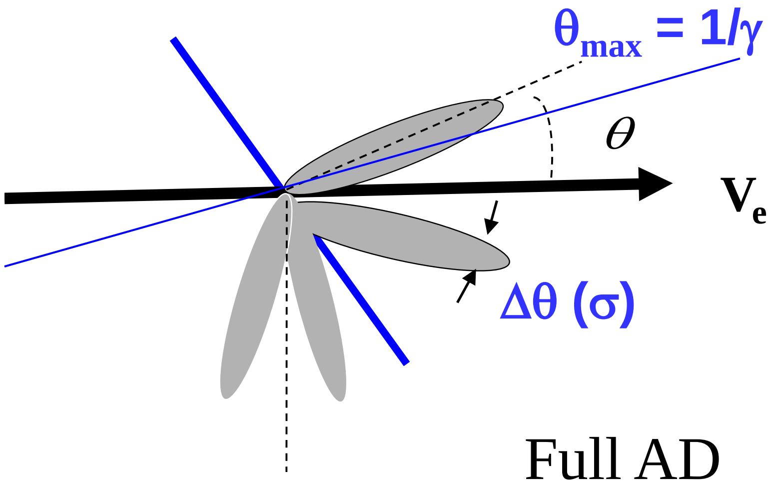
1) Measurements at a beam waist:
In addition to beam profile, measurement of beam divergence is required to construct

$$(\varepsilon_{r=x,y}^{rms})^2 = \langle r^2 \rangle \langle r'^2 \rangle - \langle rr' \rangle^2$$

2) At beam minimum $\langle r\, r' \rangle$ must be retrived via an algorithm employing observables r_{rms} and r'_{rms}.

OTR Angular Distribution Measures Divergence

NOTE: far field OTR independent of beam size or position



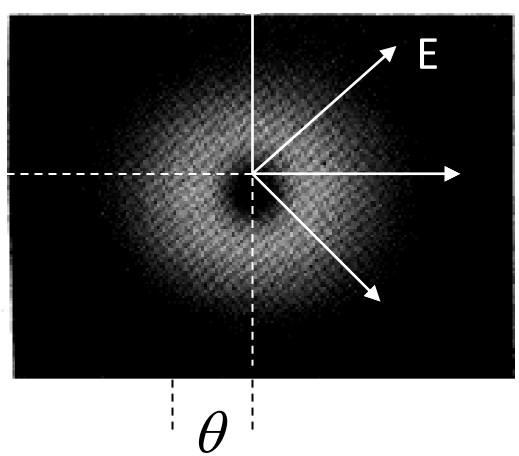
$$\frac{d^2 I^{(S)}}{d\omega d\Omega} = \frac{e^2}{c\pi^2} \frac{\theta^2}{(\gamma^{-2} + \theta^2)^2},$$

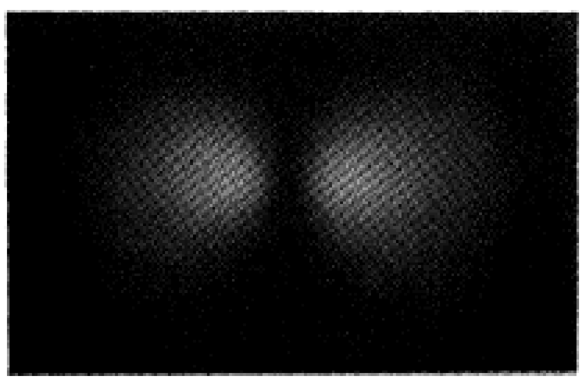
$$\theta \sim \gamma^{-1} << 1$$

Full AD

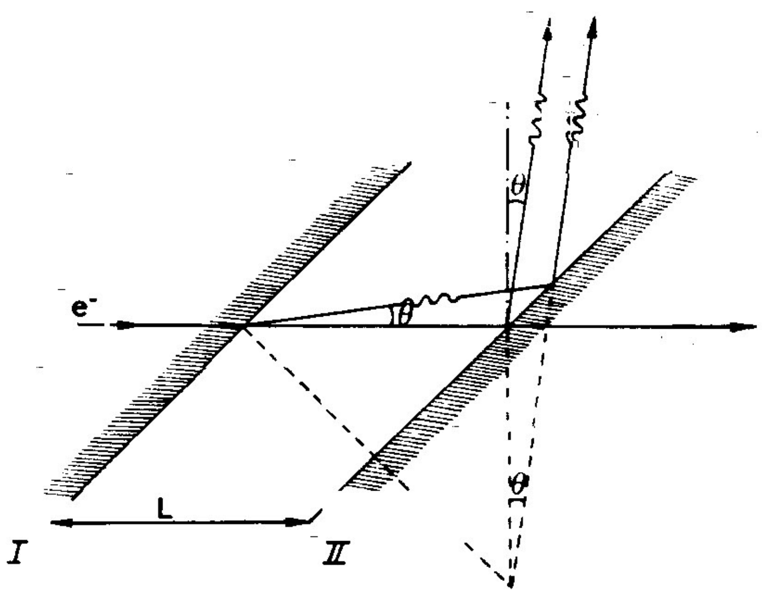
Horizontally Polarized AD

Radially Polarized AD Pattern Centered on Direction of V_e





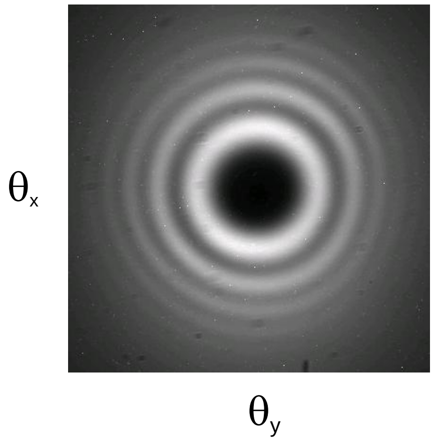
OTR Interferometry provides greater sensitivity to beam divergences x',y', E, ΔE/E



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

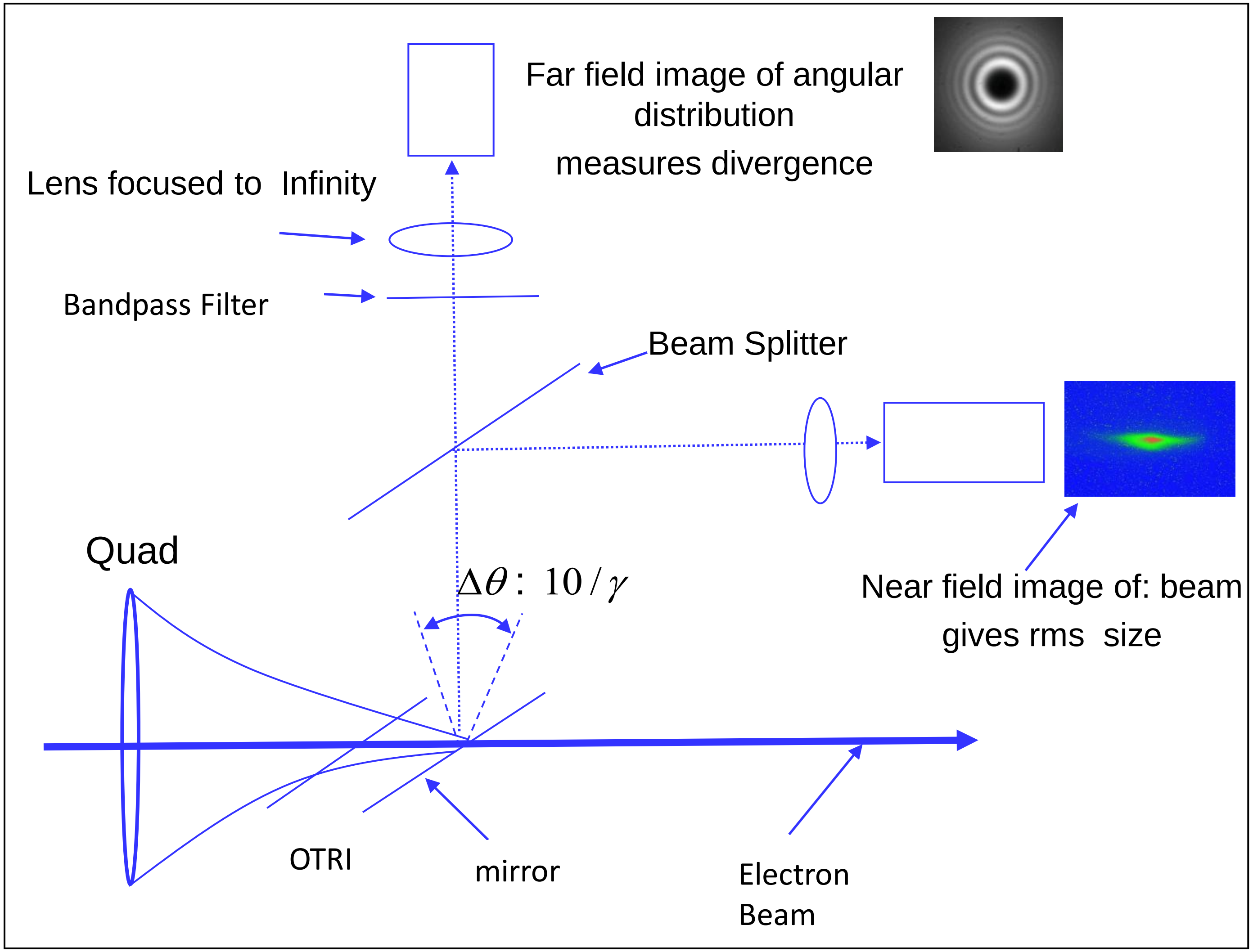
where: $\phi = L / L_V$,
(e-photon phase difference)

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



- Visibility of OTRI measures beam divergence *(and/or ΔE/E)*
- Radial Polarization of OTRI can be used to *separately* measure x' and y' via polarizer
- *Fringe position measures beam energy (E)*

Experimental Setup for OTR RMS Emittance Measurement



New theory predicts correlation term *(<r r'>)* in terms of simple OTR observables x_{rms}, x'_{rms} , y_{rms}, y'_{rms}

Emittance Dominated Beam (C. Papadopolous, R. Fiorito PAC 09)

1) true beam waist:

difficult to achieve, i.e. need to move screen along s

$$\left.\frac{d\left(x(s,f)\right)}{ds}\right|_{f=f_0} = <xx'> = 0$$

2) beam spot minimum:

achievable with a usual quad scan, i.e. vary *f* and image beam with OTR

$$\left.\frac{d\left(x(s,f)\right)}{df}\right|_{s=L} = 0 \quad \rightarrow <xx'> = \frac{1}{L} <x^2>$$

3) divergence minimum:

achievable by varying *f* and maximizing OTRI fringe visibility

$$\left.\frac{d\left(x'(s,f)\right)}{df}\right|_{s=L} = 0 \quad \rightarrow <xx'> = L <x'^2>$$

Theory predicts relative error in emittance measurements at beam size minimum

Example: JLAB 100 MeV, OTR measurement

$$\frac{\Delta\varepsilon}{\varepsilon} = -\frac{1}{2}\frac{\langle yy'\rangle^2}{\langle y^2\rangle\langle y'^2\rangle} = -\frac{1}{2}\frac{\langle y^2\rangle}{L^2\langle y'^2\rangle} \quad \sim 4.4 \times 10(-4)$$

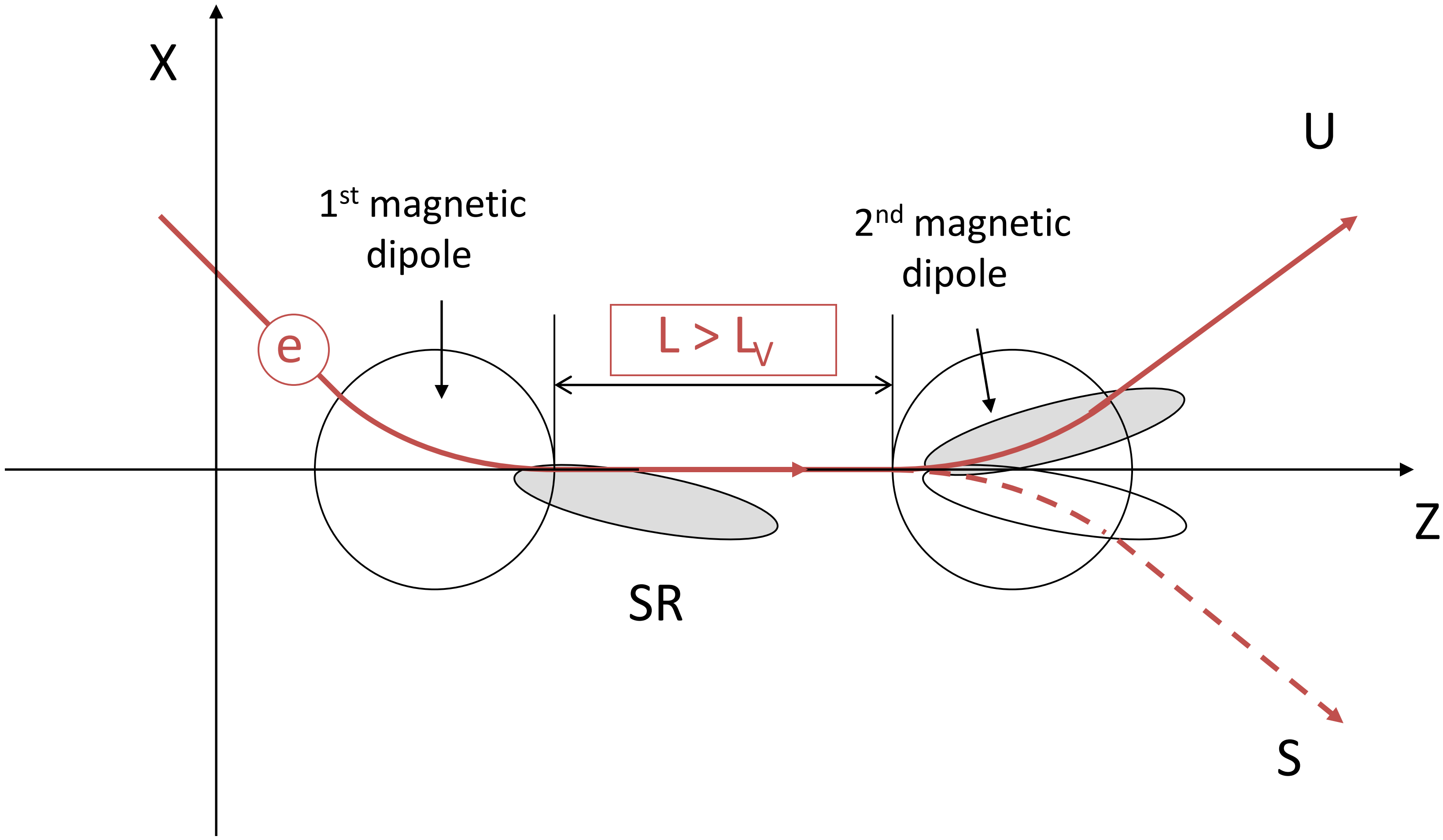
Caveats: 1) in general error may not be small

2) space charge forces neglected in the analysis shown above recent new correlation term algorithm developed that computes correlation terms in the presence of space charge from two measurements of r, r' and 1/f *

*K. Poorrezaie, R. Fiorito, et. al. PRSTAB 20013

Non Invasive Divergence Measurement using Optical Synchrotron Interferences (OSRI)

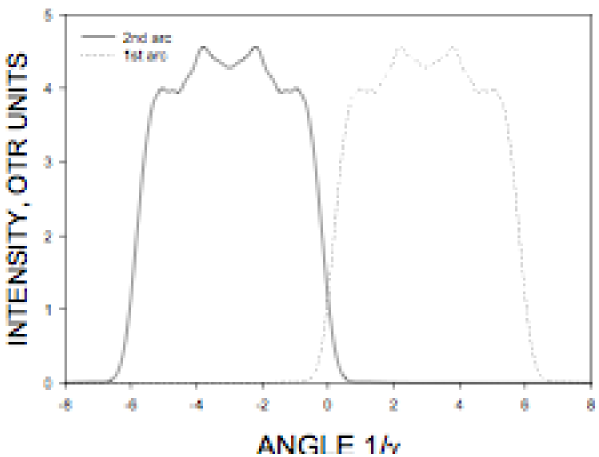
from two magnetic dipoles separated by a straight trajectory



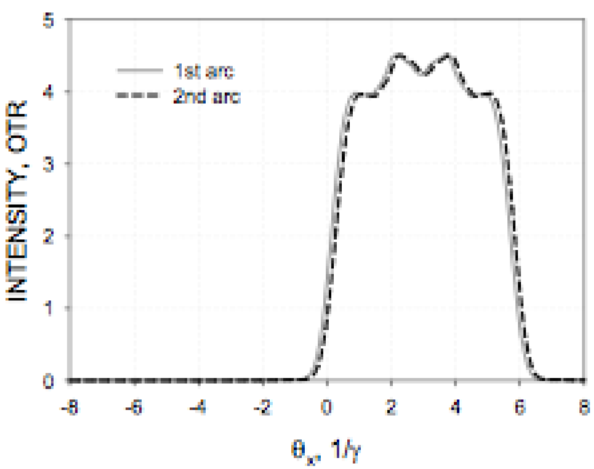
Comparison of OSR from U and S Arcs For the 100 MeV JLAB ERL

(R = 1.09 m, λ = 600 nm, L = 46 mm, $\Delta\theta$ = $6/\gamma$, $\theta_e = 0$)

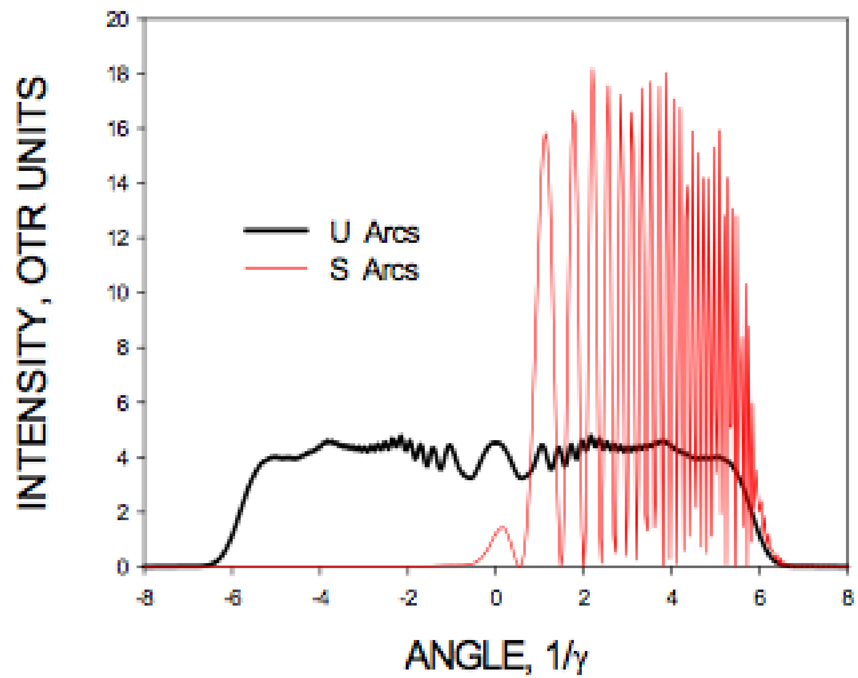
U arcs



S arcs



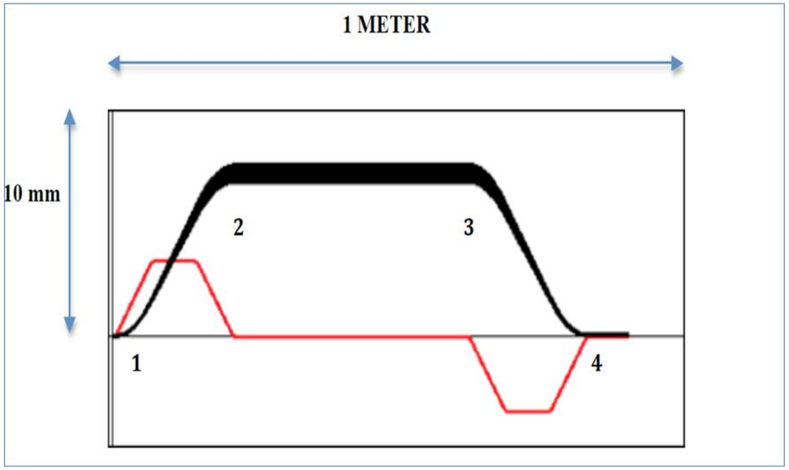
Interferences of OSR



Shkvarunets and Fiorito, Proc. of BIW04

Non Invasive Emittance and Energy Spread Monitor using OSR Interferences

Diagnostic Mini chicane Design with (1,2) 'S' and (2,3) ' U' Interferometers



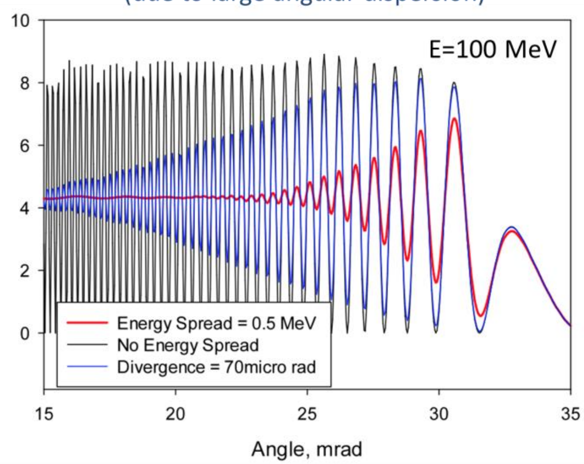
Properties of Chicane:

B (100MeV) = 0.12 Tesla
B(285 MeV) = 0.35 Tesla

L @magnet = 100 mm
L (2,3) = 600 mm
Angle deflection = 35 mrad

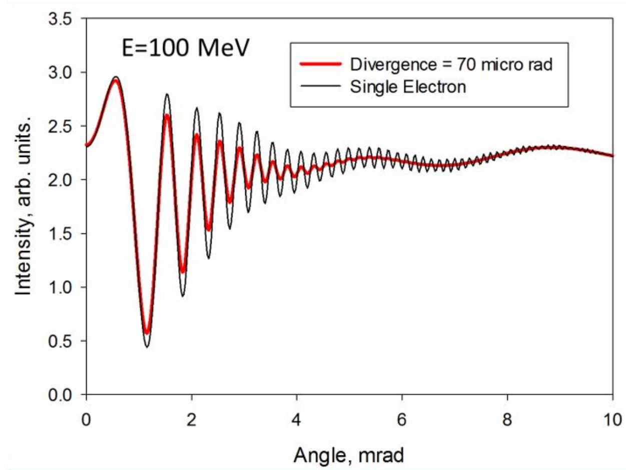
OSR Interferences from (1,2) shows sensitivity to dE/E

(due to large angular dispersion)

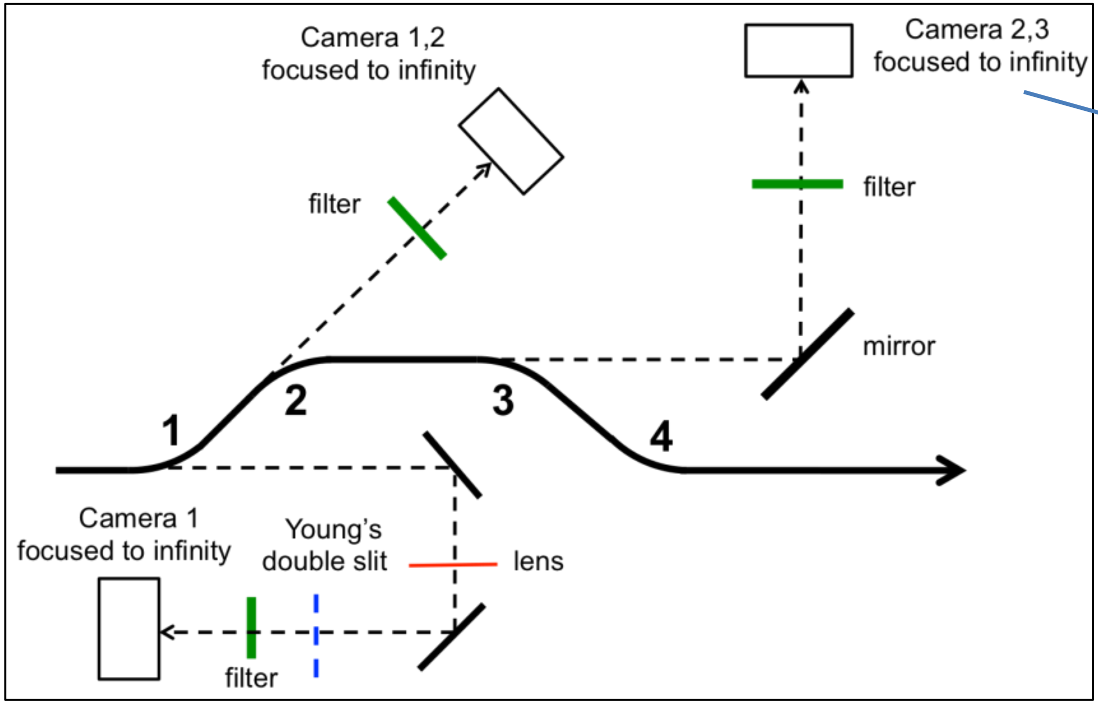


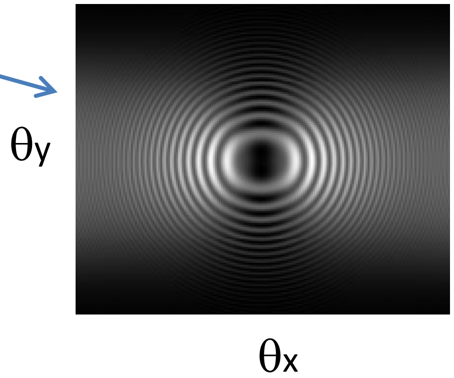
OSR Interferences from (2,3) shows sensitivity to divergence

(and essentially no sensitivity to dE/E)



Optics to Observe Beam Size and Divergence using Optical Synchrotron Radiation Interferences

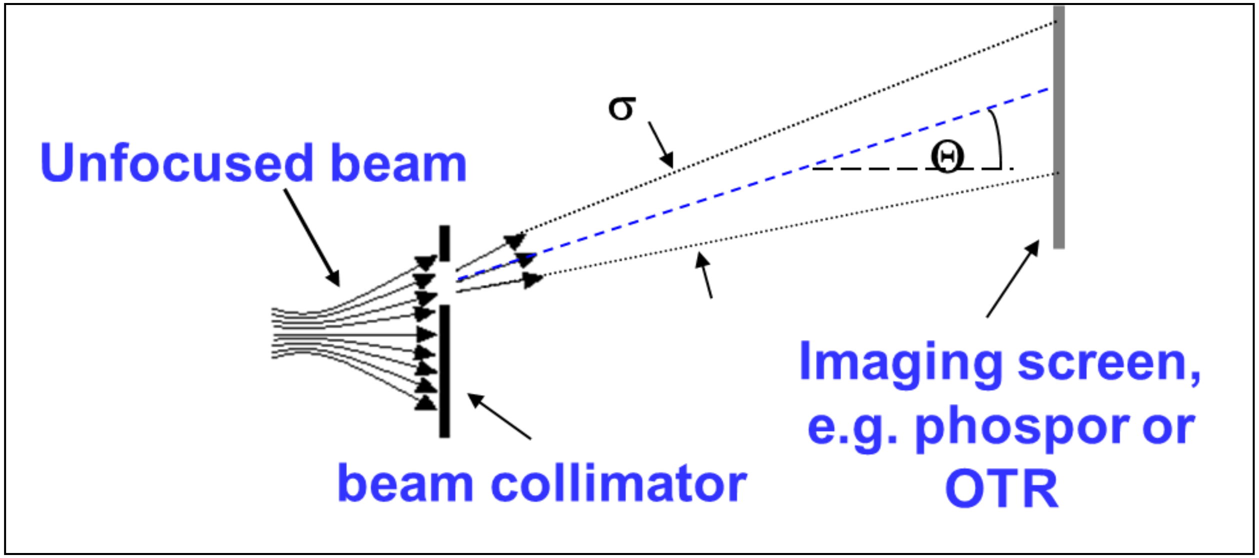




Optical phase space mapping (OPSM)*- the optical equivalent of the pepper pot technique

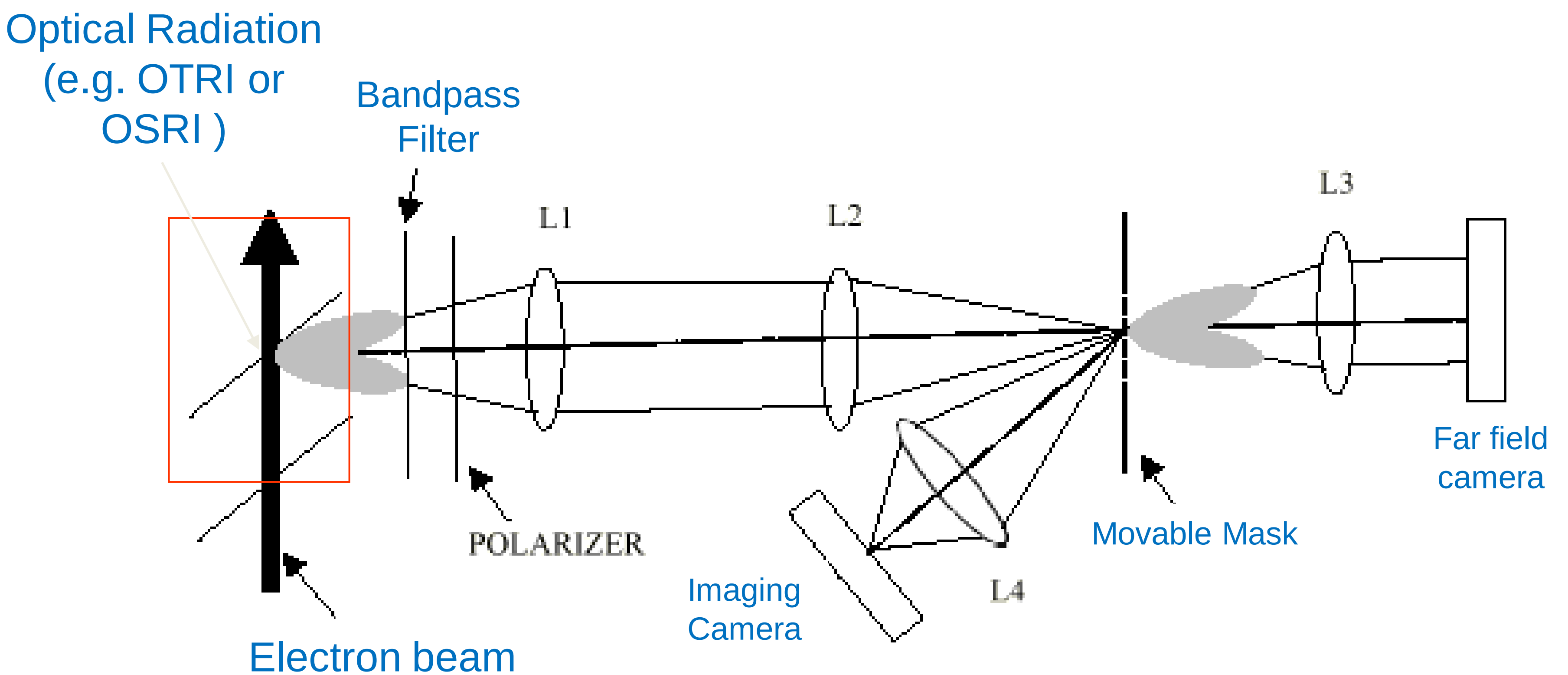
Conventional PSM: uses collimator (slits or pinholes) to segment the beam into beamlets, whose angular trajectories and angular spreads are measured as a function of position within the beam to make a PSM

Problems: *Not practical for high energy beams - collimation doesn't work - beams too small; requires drift space and imaging screens in the beam line.*



* R.B. Fiorito, A.G. Shkvarunets, and P.G. O'Shea, AIP Conf. Proc. No. 648, (2002).

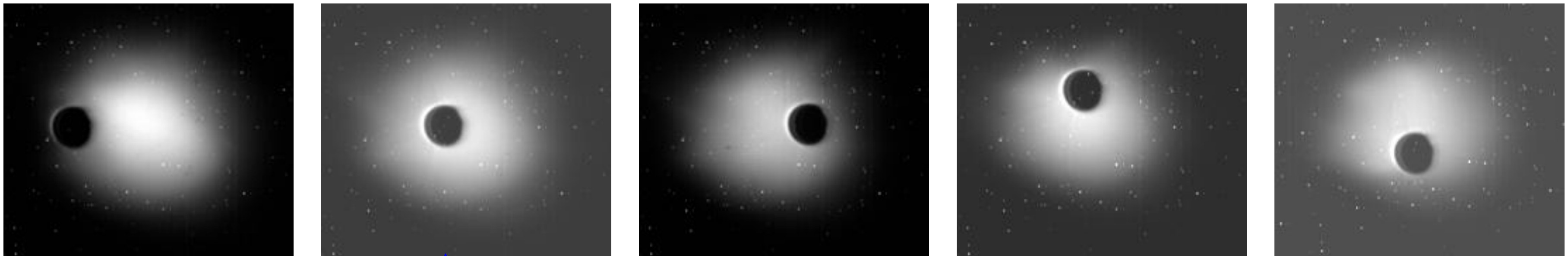
OPSM: uses optical mask to segment beam associated radiation to measured beam divergence and trajectory angle measurements as a function of position within the beam image at one position in space *

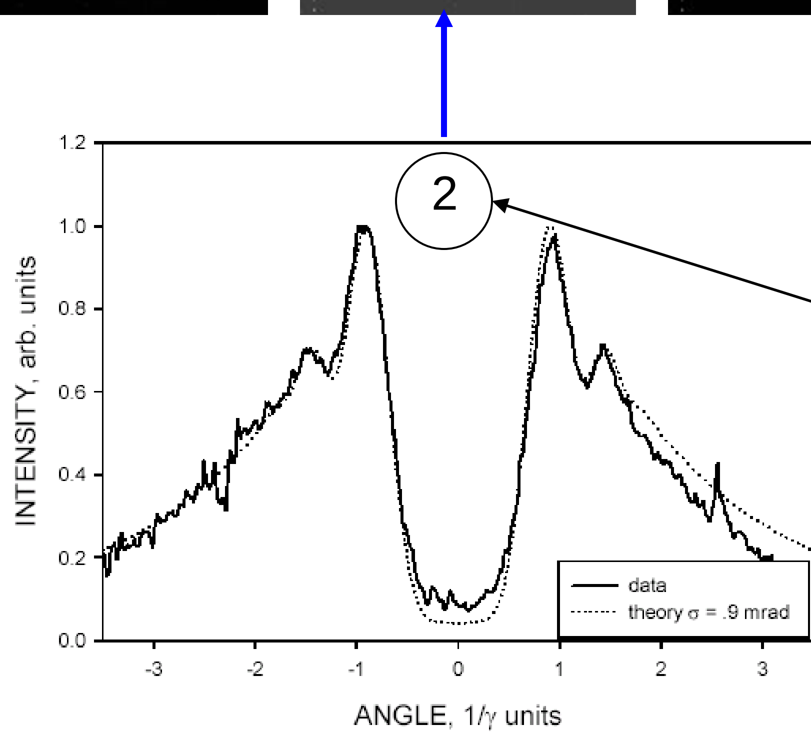


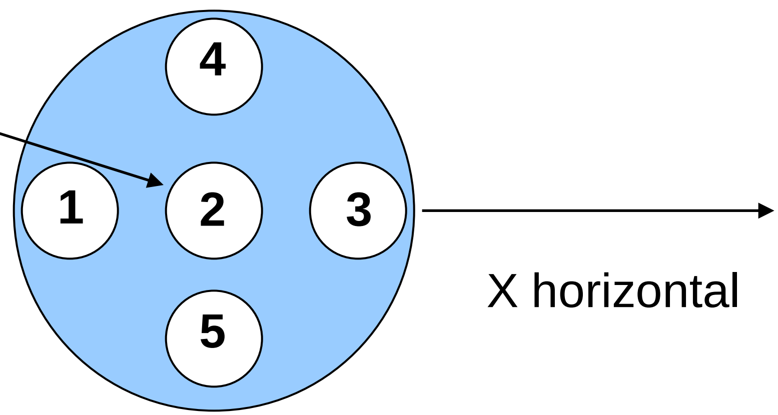
Applications: 1) separate out core and halo emittance
2) create phase (trace) space map of beam

Proof of principle experiment using OTR and a scanning pinhole mask

Done at 95 MeV linac at NPS- Monterrey CA*







R. Fiorito, et. AIP Conf. Proc. 648, (2002) The End: Thanks for your attention.