Imaging of Charged-Particle Beams with OTR and ODR

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Darmstadt, Germany

OUTLINE

I. Introduction

II. Optical Transition Radiation (OTR)

- OTR results with electrons
- OTR point-spread function (PSF) aspects
- OTR results with protons, hadrons

III. Optical Diffraction Radiation (ODR) as a nonintercepting (NI) beam-size monitor.

- ODR near-field experimental results (APS, CEBAF)
- ODR model results for Gamma=1000, 46000

IV. Summary

Intro to Beam-Size Imaging

- The charged-particle beam transverse size and profiles are part of the basic characterizations needed in accelerators to determine beam quality.
- A basic beam imaging system includes:

  - conversion mechanism (scintillator, optical or x-ray synchrotron radiation (OSR or XSR), Cherenkov radiation (CR), optical transition radiation (OTR), undulator radiation (UR), and optical diffraction radiation (ODR).

  - optical transport (lenses, mirrors, filters, polarizers).

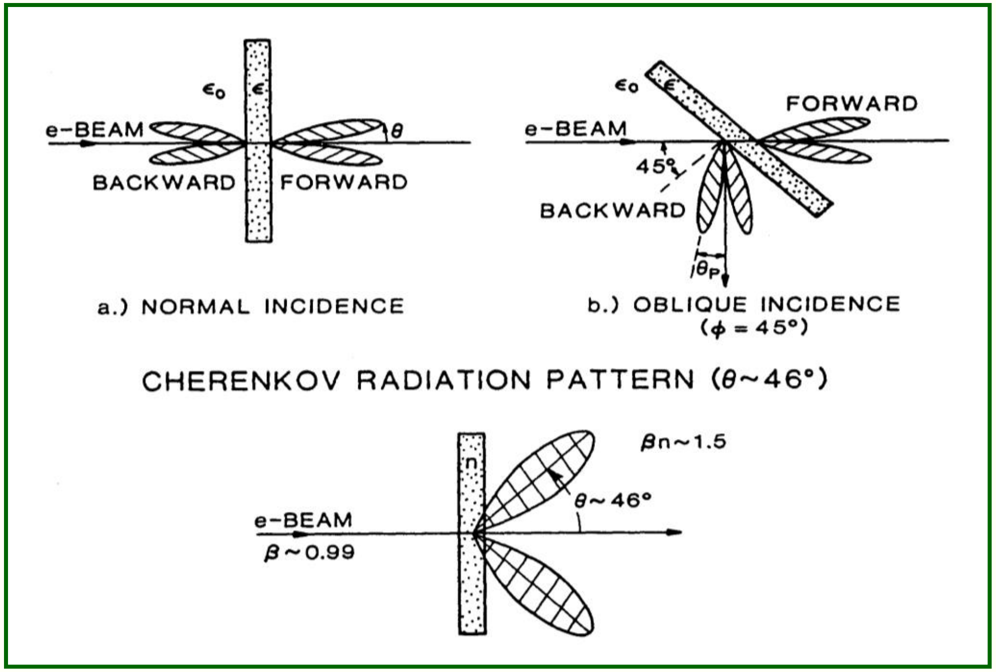
  - imaging sensor such as CCD,CID, CMOS camera, with or without intensifier and/or cooling.

  - video digitizer.

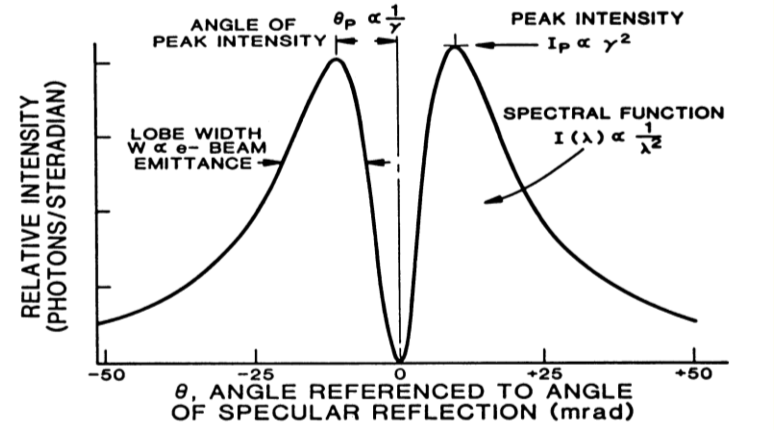
  - image processing software.

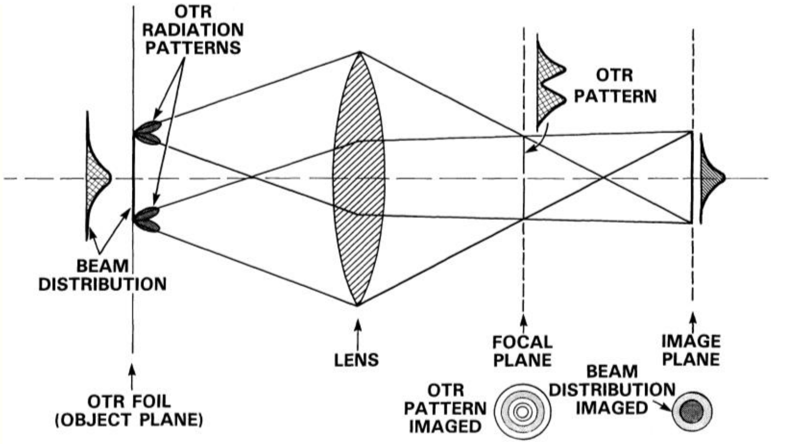
OTR Basics

- **OTR can be used for beam size/profile, position, divergence, energy, relative intensity, bunch length info.**



A.H. Lumpkin et al., NIM A296, 150 (1990)





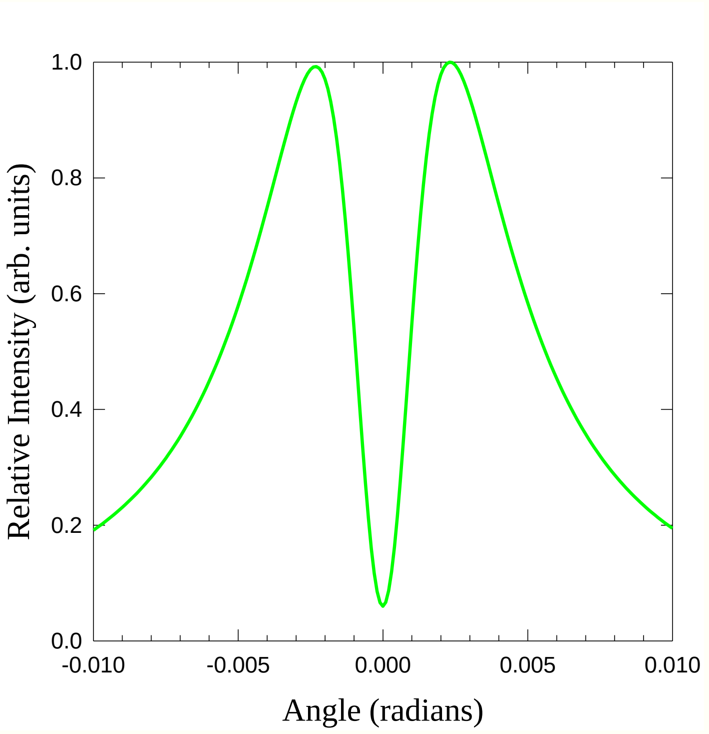
Optical Transition Radiation Interferometry (OTRI) Calculations

Coherent Spectral-Angular Distribution from a Macropulse,

- **Number of Photons per Unit Frequency and Solid Angle**

$$\frac{d^2N}{d\omega d\Omega} = \left| r_{\perp,//} \right|^2 \frac{d^2N_1}{d\omega d\Omega} I(\mathbf{k}) \Im(\mathbf{k})$$

E = 220 MeV $\sigma_{x', y'}$ = 0.2 mrad



Single Particle OTR Spectral-Angular Distribution

$$\frac{d^2N_1}{d\omega d\Omega} = \frac{e^2}{\hbar c} \frac{1}{\pi^2 \omega} \frac{\left(\theta_x^2 + \theta_y^2\right)}{\left(\gamma^{-2} + \theta_x^2 + \theta_y^2\right)^2}$$

From D. Rule and A. Lumpkin, PAC’01

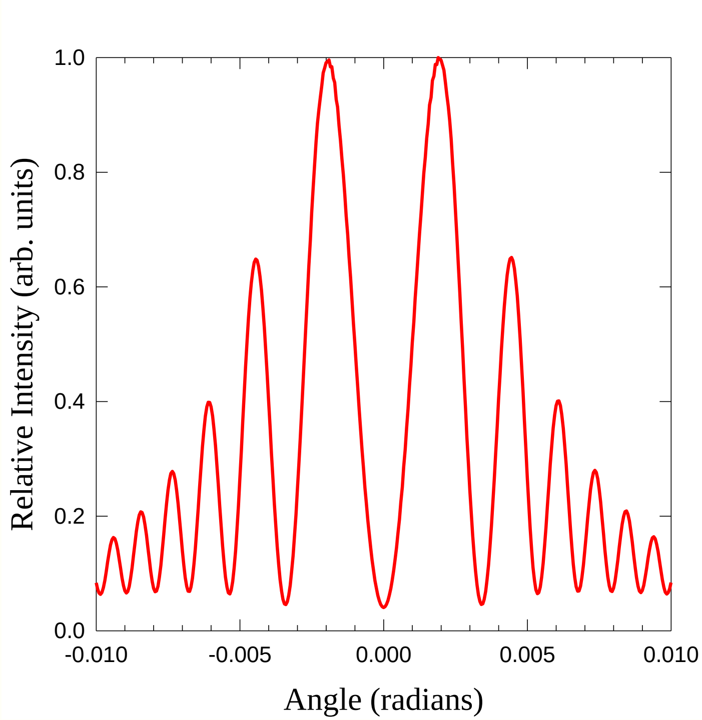
OTRI Calculations (cont.)

Wartski Interferometer Phase Term

E = 220 MeV, $\sigma_{x', y'}$ = 0.2 mrad

L= 6.3 cm, λ=537 nm

$$I(\mathbf{k}) = 4\sin^2\left[\frac{kL}{4}\left(\gamma^{-2} + \theta_x{}^2 + \theta_y^2\right)\right]$$



L = foil separation distance

$$k_x = k\sin\theta\cos\phi = k\sin\theta_x \approx k\theta_x$$

$$k_y = k\sin\theta\sin\phi = k\sin\theta_y \approx k\theta_y$$

$$k_z = k\cos\theta \approx k = \omega / c$$

$$\theta^2 = \theta_x^2 + \theta_y^2 << 1$$ **(relativistic case)**

From D. Rule and A. Lumpkin, PAC'01

OTRI Calculations (cont.)

Coherence Function

$$\Im(\mathbf{k}) = N + N_B(N_B - 1)|H(\mathbf{k})|^2$$

Fourier Transform of Charge Form Factors

$$H(\mathbf{k}) = \frac{\rho(\mathbf{k})}{Q} = g_x(k_x)g_y(k_y)F_z(k_z)$$

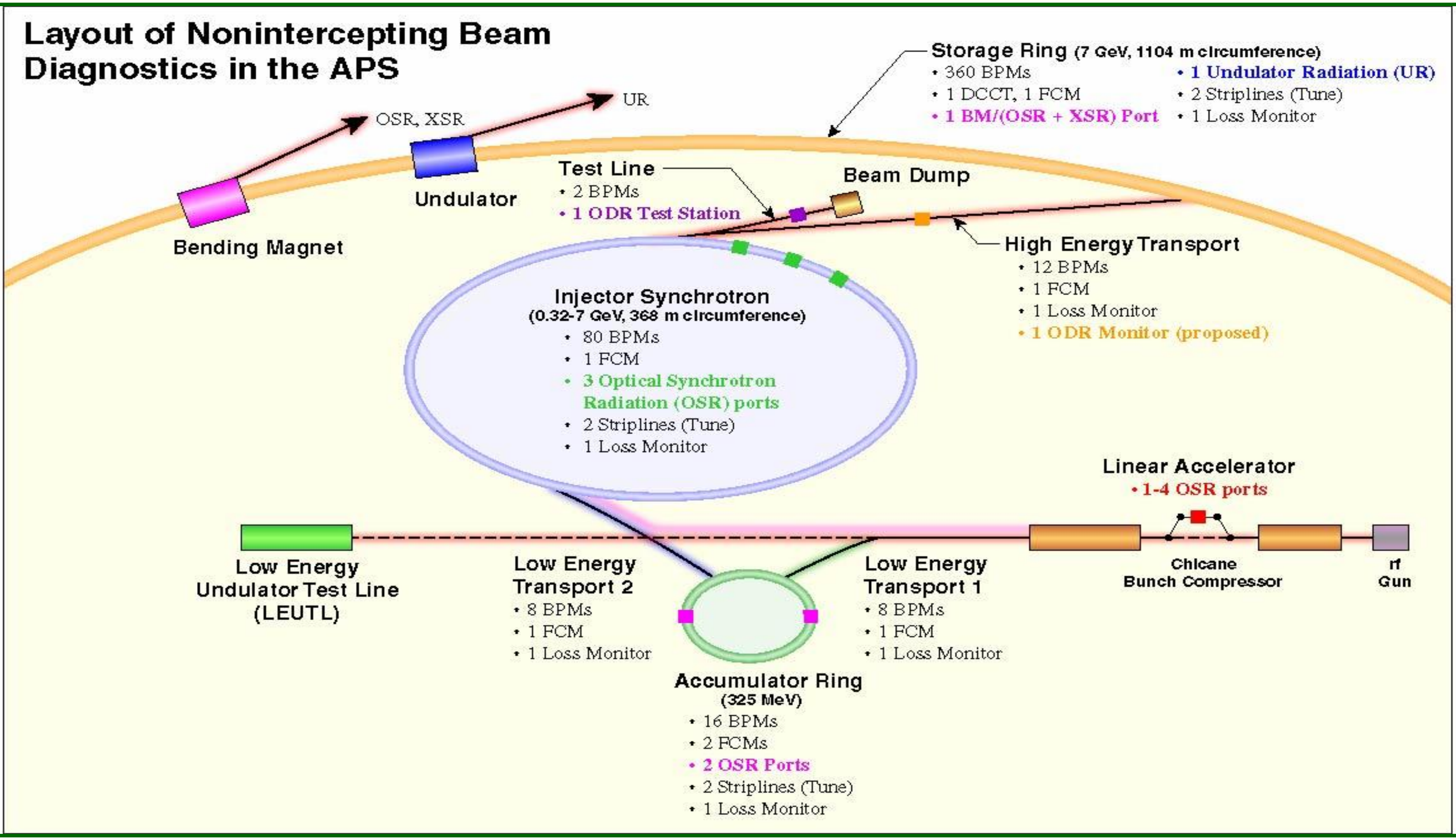
Q = total charge of macropulse

Bunching fraction = $f_B = N_B/N$

Note: The coherence function reduces to just the number of particles, *N* , when the number of microbunched particles, N_B *is zero.*

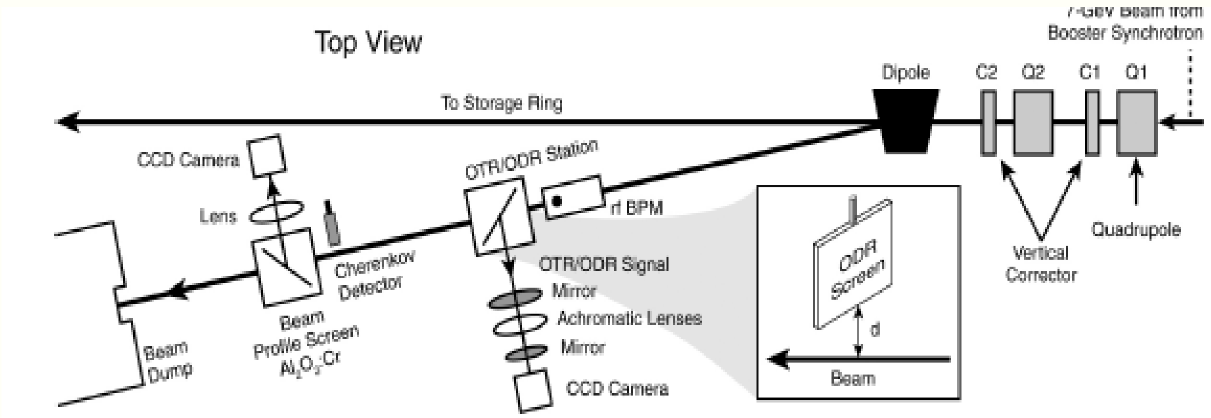
From D. Rule and A. Lumpkin, PAC'01

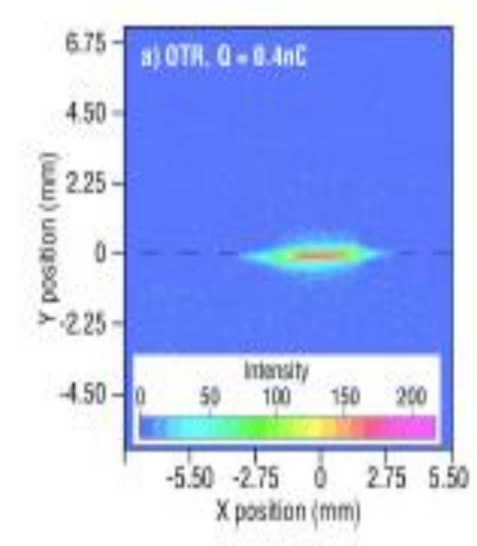
Schematic Layout for APS Accelerators



Layout of Nonintercepting Beam Diagnostics in the APS

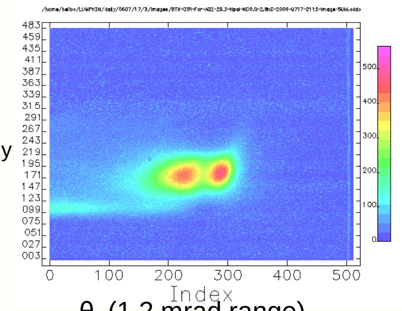
7-GeV Test with OTR at APS





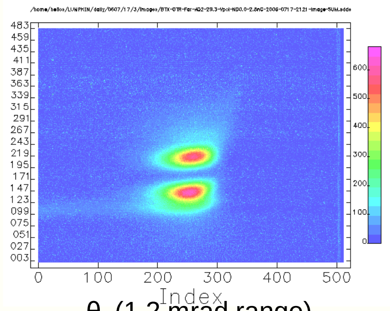
ε_x=1300 µm x 50 µrad = 65 nm rad.

θ_y

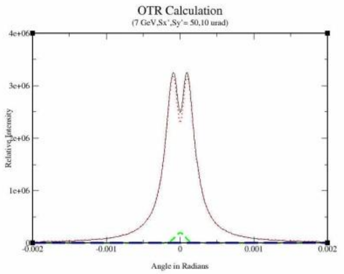


θ_x (1.2 mrad range)

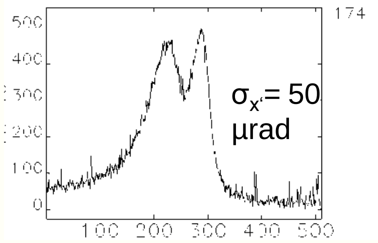
θ_y



θ_x (1.2 mrad range)



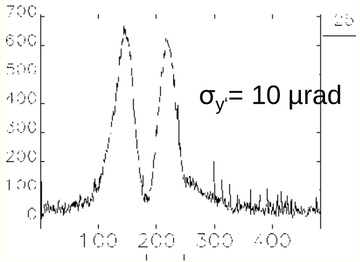
I



$\sigma_{x'}$= 50 µrad

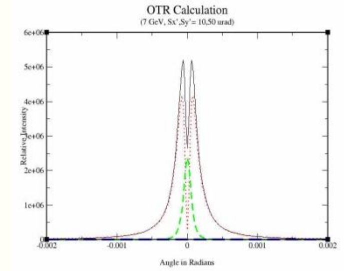
θ_x

I



$\sigma_{y'}$= 10 µrad

θ_y



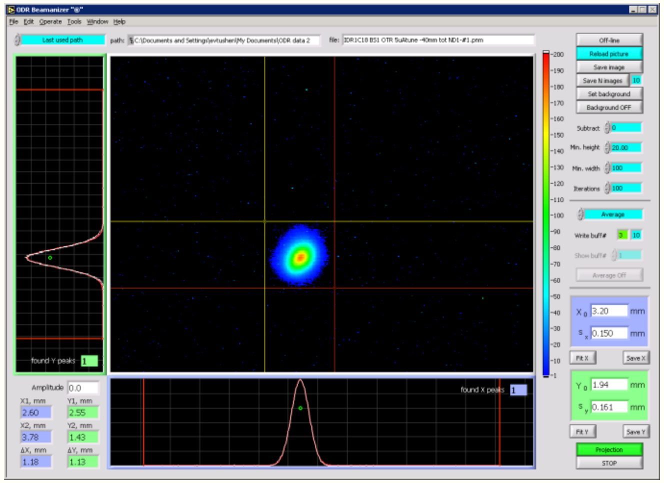
Lumpkin et al., PAC07

OTR polarization and PSF Background

- Lebedev evaluated OTR resolution in 1996 and Castellano et al. paper in 1998 points out an OTR PSF that has polarization feature. But they calc. about 12λ (FWHM) for total width and 0.1 rad collection angle.
- Polarization effects on beam image size observed in ODR and OTR in 2007 in collaboration with JLAB.
- Dao Xiang et al. in PRST-AB (2007) calc. PSF for OTR and ODR.
- OTR polarization effects reported for A0PI beam sizes at BIW10.
- KEK OTR experiment in 2005 did not use polarizer.
- KEK OTR experiment in IPAC10 does use polarizer and PSF structure.

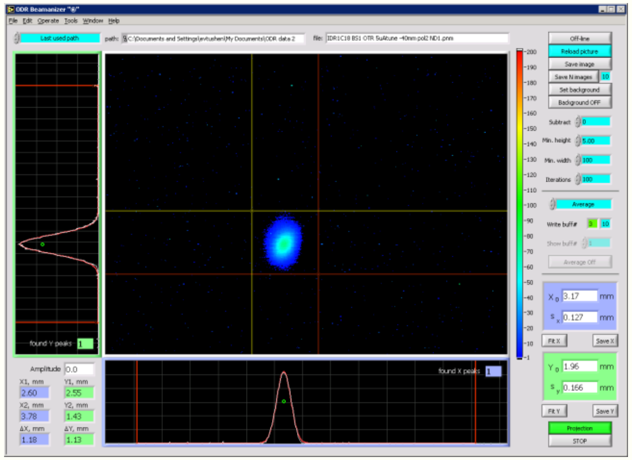
Initial OTR Images at 4.5 GeV

- Newly installed Al-coated Si wafer used with 5-μA Tune beam (250 μs at 60 Hz). Polarization effects seen on $\sigma_{x,y}$.



path: C:\Documents and Settings\evtushen\My Documents\ODR data 2
file: IDR1C18 BS1 OTR 5uAtune -40mm tot ND1-#1.pnm
Save N images 10
Subtract 0
Min. height 20.00
Min. width 100
Iterations 100
Write buff# 3 10
Show buff# 1
X_0 3.20 mm
s_x 0.150 mm
Y_0 1.94 mm
s_y 0.161 mm
found Y peaks 1
found X peaks 1
Amplitude 0.0
X1, mm 2.60
Y1, mm 2.55
X2, mm 3.78
Y2, mm 1.43
ΔX, mm 1.18
ΔY, mm 1.13

Total Intensity, ND1.0
σ_x:150 μm, σ_y:161 μm



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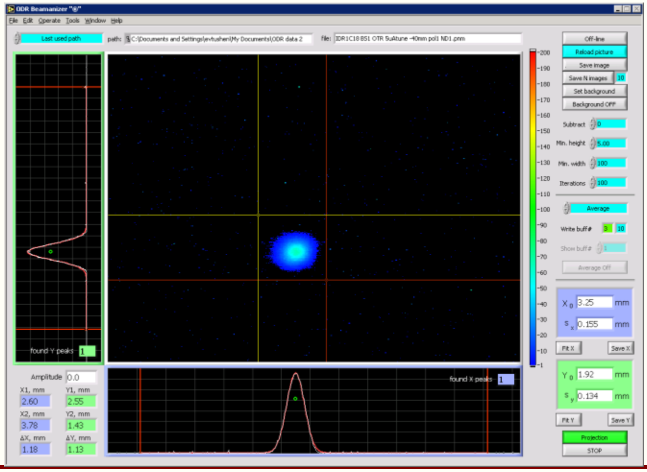
Save N images 10
Subtract 0
Min. height 5.00
Min. width 100
Iterations 100
Write buff# 3 10
Show buff# 1
X_0 3.17 mm
s_x 0.127 mm
Y_0 1.96 mm
s_y 0.166 mm
found Y peaks 1
found X peaks 1
Amplitude 0.0
X1, mm 2.60
Y1, mm 2.55
X2, mm 3.78
Y2, mm 1.43
ΔX, mm 1.18
ΔY, mm 1.13

V-pol
σ_x:127 μm
σ_y:166 μm



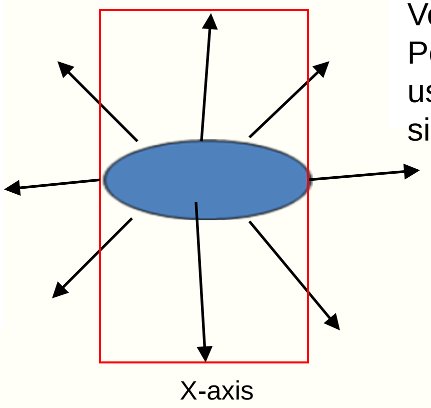
path: C:\Documents and Settings\evtushen\My Documents\ODR data 2
file: IDR1C18 BS1 OTR 5uAtune -40mm pol1 ND1.pnm
Save N images 10
Subtract 0
Min. height 5.00
Min. width 100
Iterations 100
Write buff# 3 10
Show buff# 1
X_0 3.25 mm
s_x 0.155 mm
Y_0 1.92 mm
s_y 0.134 mm
found Y peaks 1
found X peaks 1
Amplitude 0.0
X1, mm 2.60
Y1, mm 2.55
X2, mm 3.78
Y2, mm 1.43
ΔX, mm 1.18
ΔY, mm 1.13

H-pol.
σ_y:134 μm
σ_x:155 μm

- OTR image size sensitive to polarization via PSF or ?

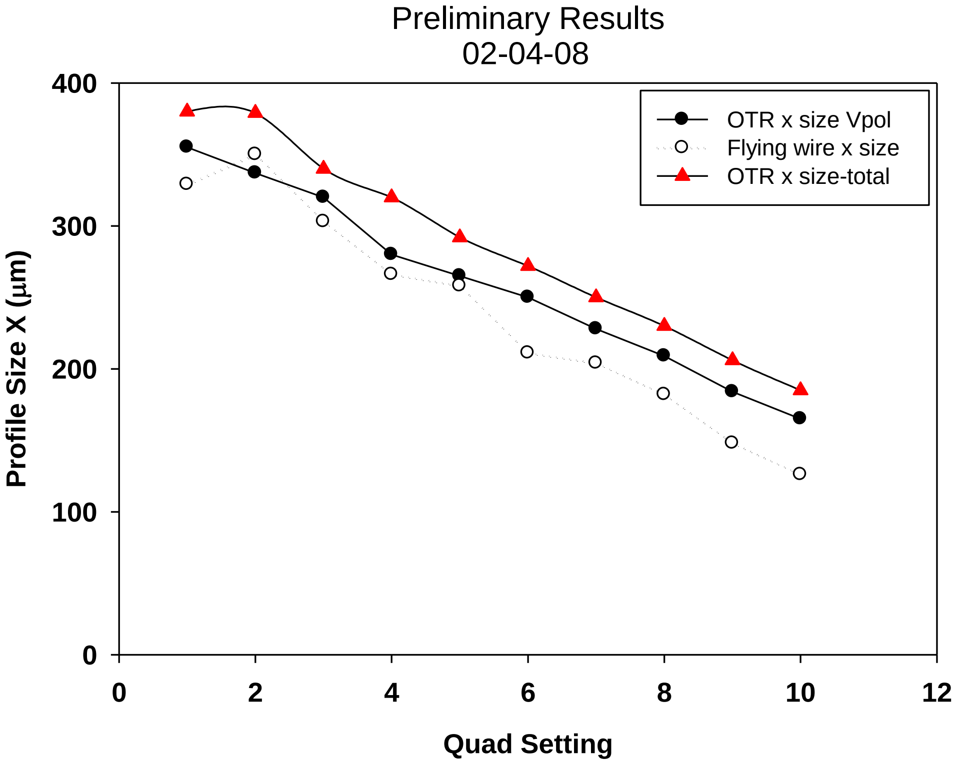
Polarized OTR Image Effects

- **Perpendicular OTR component has smaller image than total OTR image by about 20 µm at 150-350 µm sizes.**



Vertically Pol. OTR used for x size

Schematic of the induced currents that generate radially polarized OTR when a charge distribution strikes a metal surface.



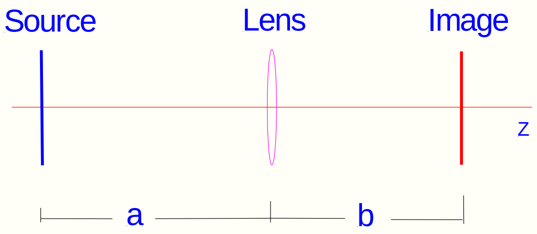
A. Lumpkin et al., BIW10

Resolution of near field imaging

--Point Spread Function

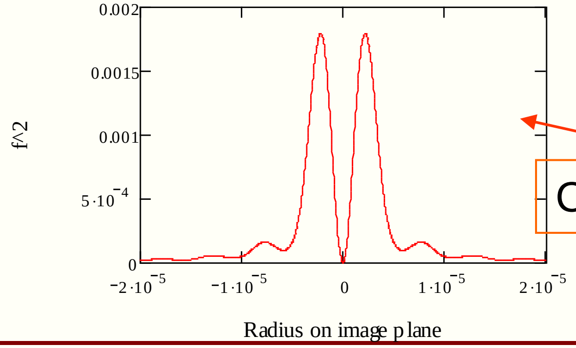
Because of diffraction, the image of point source is not a point but ring pattern which is determined by the OTR point spread function. For a simple model like below, the PSF would be proportional to:

$$f^2(\theta_m,\gamma,\varsigma)=[\int_0^{\theta_m}\frac{\theta^2}{\theta^2+\gamma^{-2}}J_1(\varsigma\theta)d\theta]^2$$

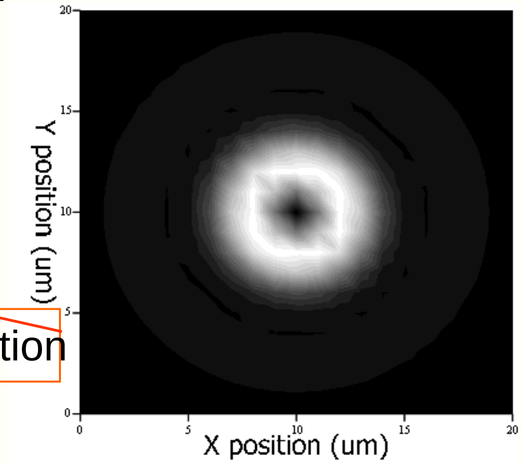


θ_m is the maximum acceptance angle of the lens, R$_l$ is the radius of the lens, θ= R$_l$/a, $\varsigma = kR_i / M$, $M = b/a$ is the magnification factor

With parameters M=1, $\theta_m = 0.1$ E=4GeV, λ=500nm, the image of a single electron is shown



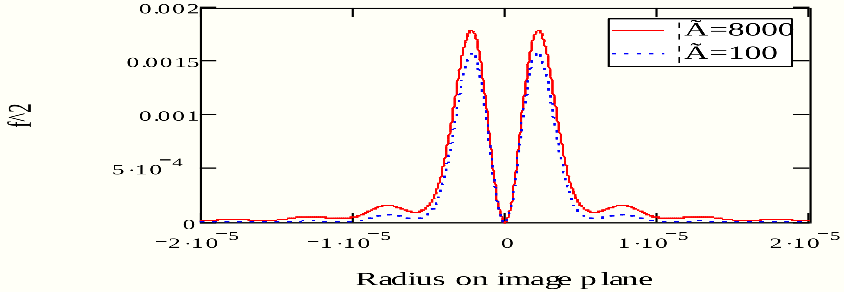
Cross section



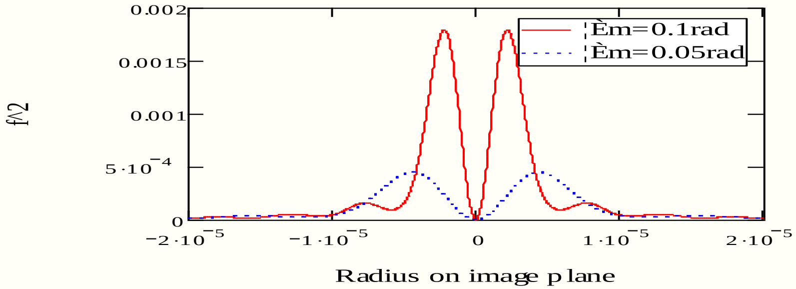
C. Liu et al., JLAB

A.H. Lumpkin et al. GSI Seminar February 16, 2011

Properties of PSF



PSF dependence on beam energy



PSF dependence on acceptance angle

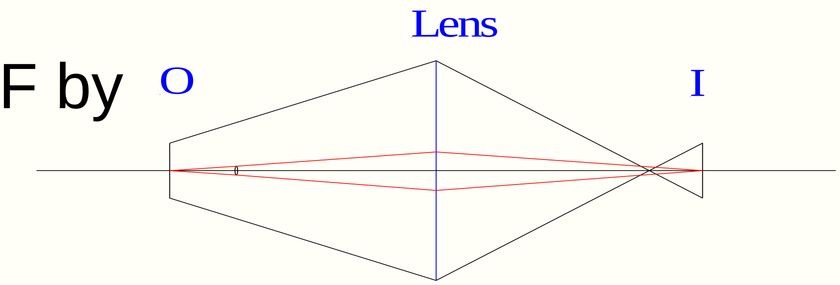
- Not sensitive to energy
- Sensitive to acceptance angle
- Horizontal polarizer reduce PSF by

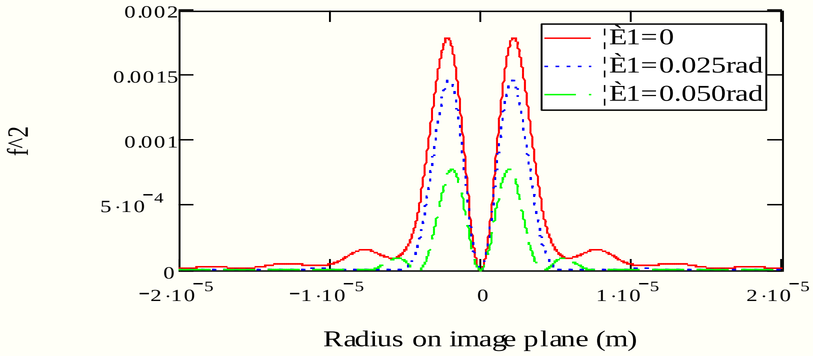
$y/\sqrt{x^2+y^2}$

With a mask blocking rays with angle smaller than θ1, PSF will be

$$f^2(\theta_m,\gamma,\varsigma)=[\int_{\theta_1}^{\theta_m}\frac{\theta^2}{\theta^2+\gamma^{-2}}J_1(\varsigma\theta)d\theta]^2$$

C. Liu et al., JLAB

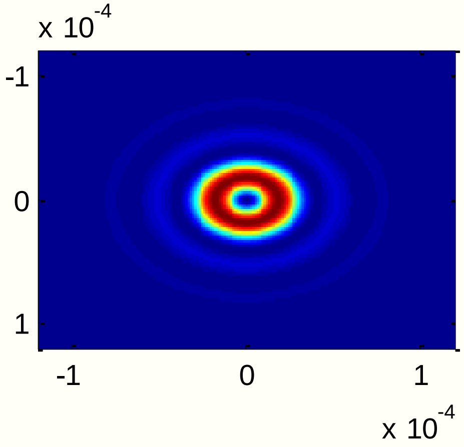


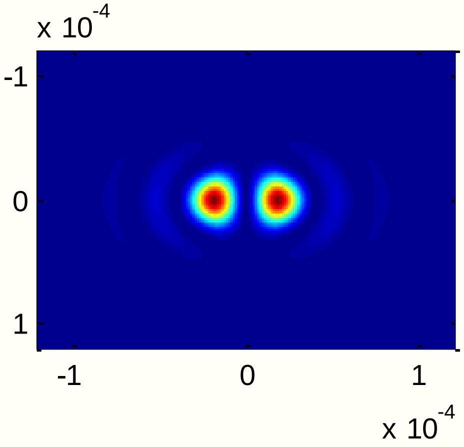


MATLAB OTR PSF Calculations

- **14.3 MeV, M=1, λ=500 nm, θ_{max}=0.010, sigma =25 μm**
- **This version with convolutions implemented at FNAL.**

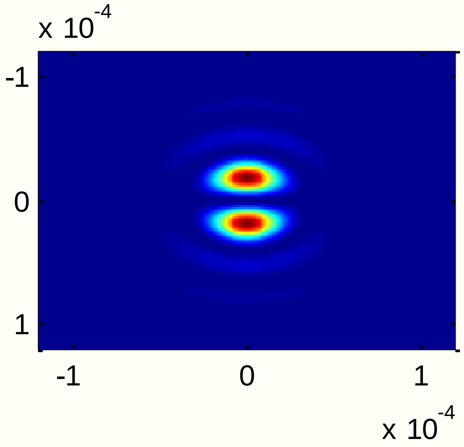
Total PSF

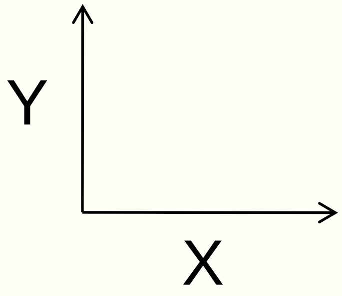




Hpol PSF

Vpol PSF

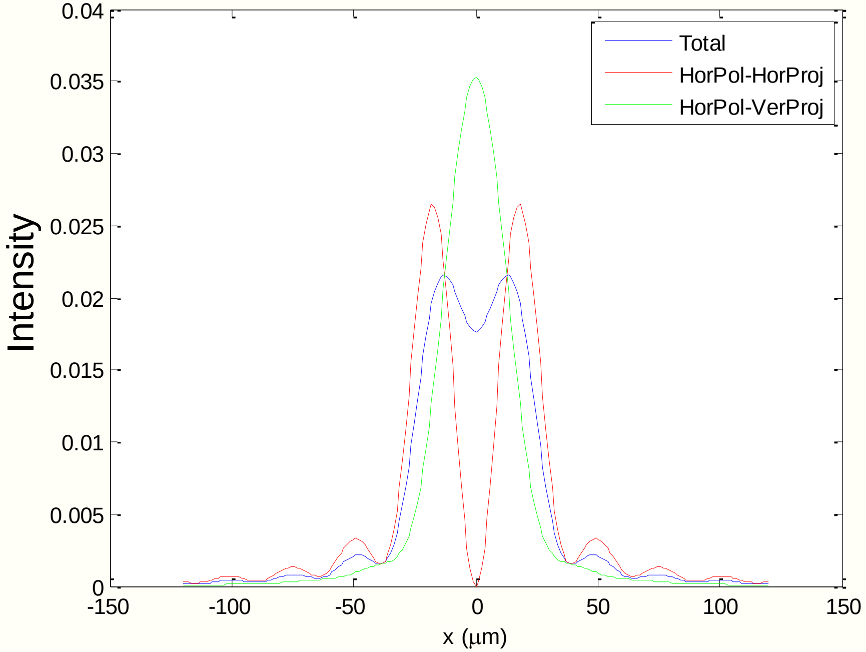


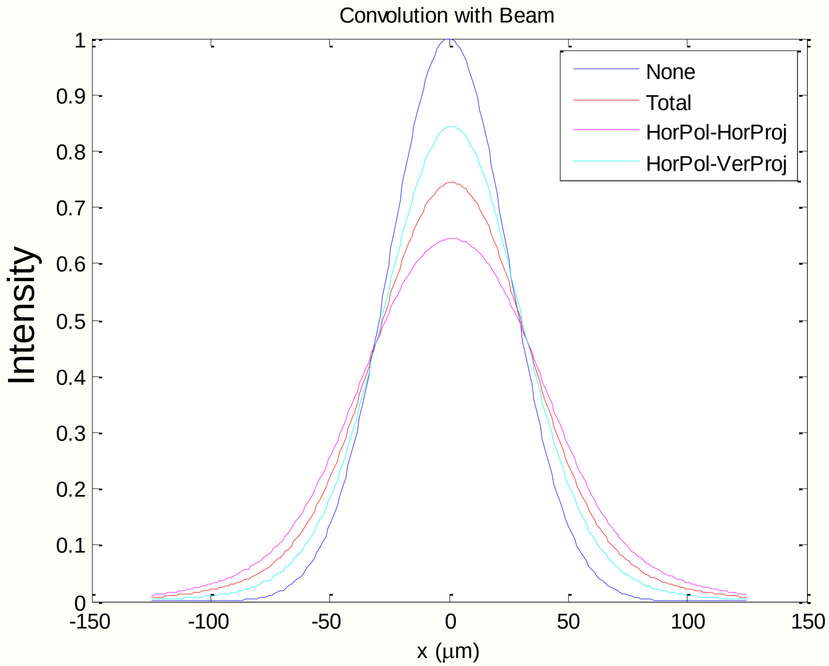


At Image plane

PSF Convolved

- **14.3 MeV, M=1, λ=500nm, θ_{max}=0.010, sigma =25 μm**

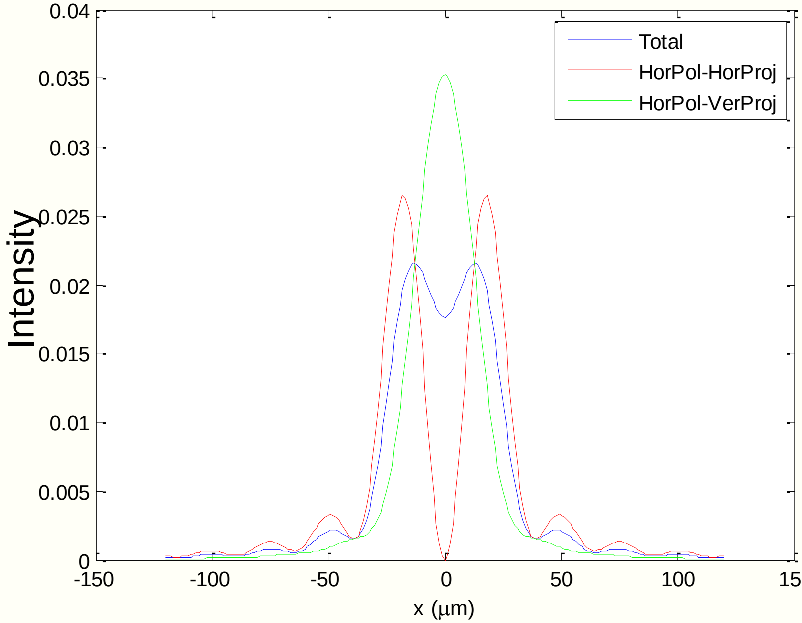


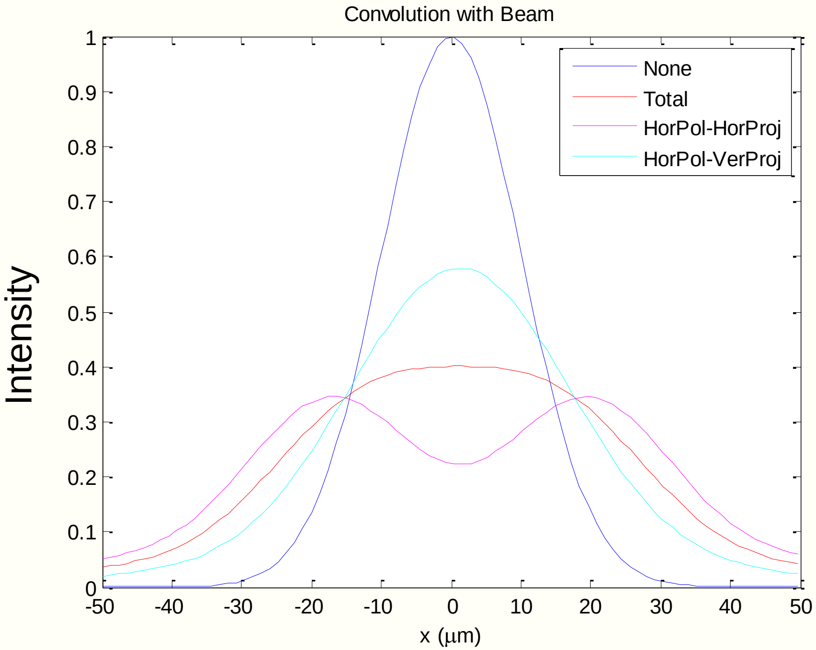


Original Sigma = 25
Total PSF Sigma = 33.1772
HorPol-HorProj PSF Sigma = 38.0076
HorPol-VerProj PSF Sigma = 29.3867

PSF Convolved

- **14.3 MeV, M=1, λ=500 nm, θ_{max}=.010, sigma = 10 μm**





Original Sigma = 10
Total PSF Sigma = 22.5904
HorPol-HorProj PSF Sigma = NA
HorPol-VerProj PSF Sigma = 16.627

KEK Experimental OTR PSF

- **KEK staff used vertical polarizer and small beam to observe PSF and suggested potential use of structure.**

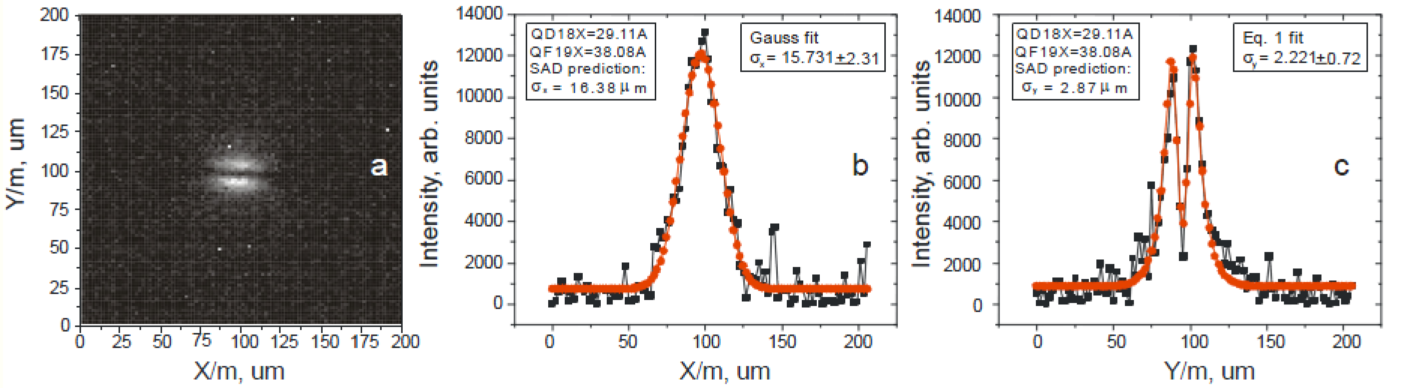


Figure 3: CCD image of the OTR taken with linear polarizer and 500 nm optical filter (a) and two image projections: horizontal (b) and vertical (c).

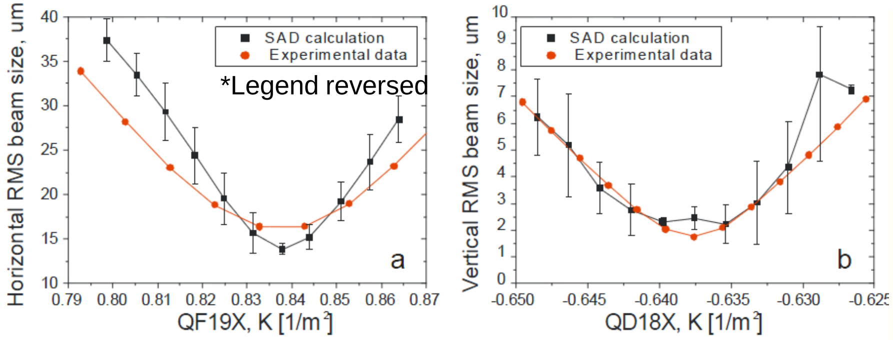


Figure 4: Horizontal RMS beam size as a function of the QF19X strength (a) and the dependence of the smoothing parameter σ (Eq. 1) versus QD18X quadrupole magnet strength. SAD predictions of the vertical beam size for the same magnet strengths are also shown in the picture.

$$f(x) = a + \frac{b}{1 + [c(x - \Delta x)]^4}\left[1 - e^{-2c^2\sigma^2}\cos[c(x - \Delta x)]\right] \quad (1)$$

where a, b, c, σ, and Δx are free parameters of the fit function, namely: a is the vertical offset of the distribution with respect to zero which included a constant background; b is the amplitude of the distribution; c is the distribution width; σ is the smoothing parameter dominantly defined by the beam size; and Δx is the horizontal offset of the distribution with respect to zero

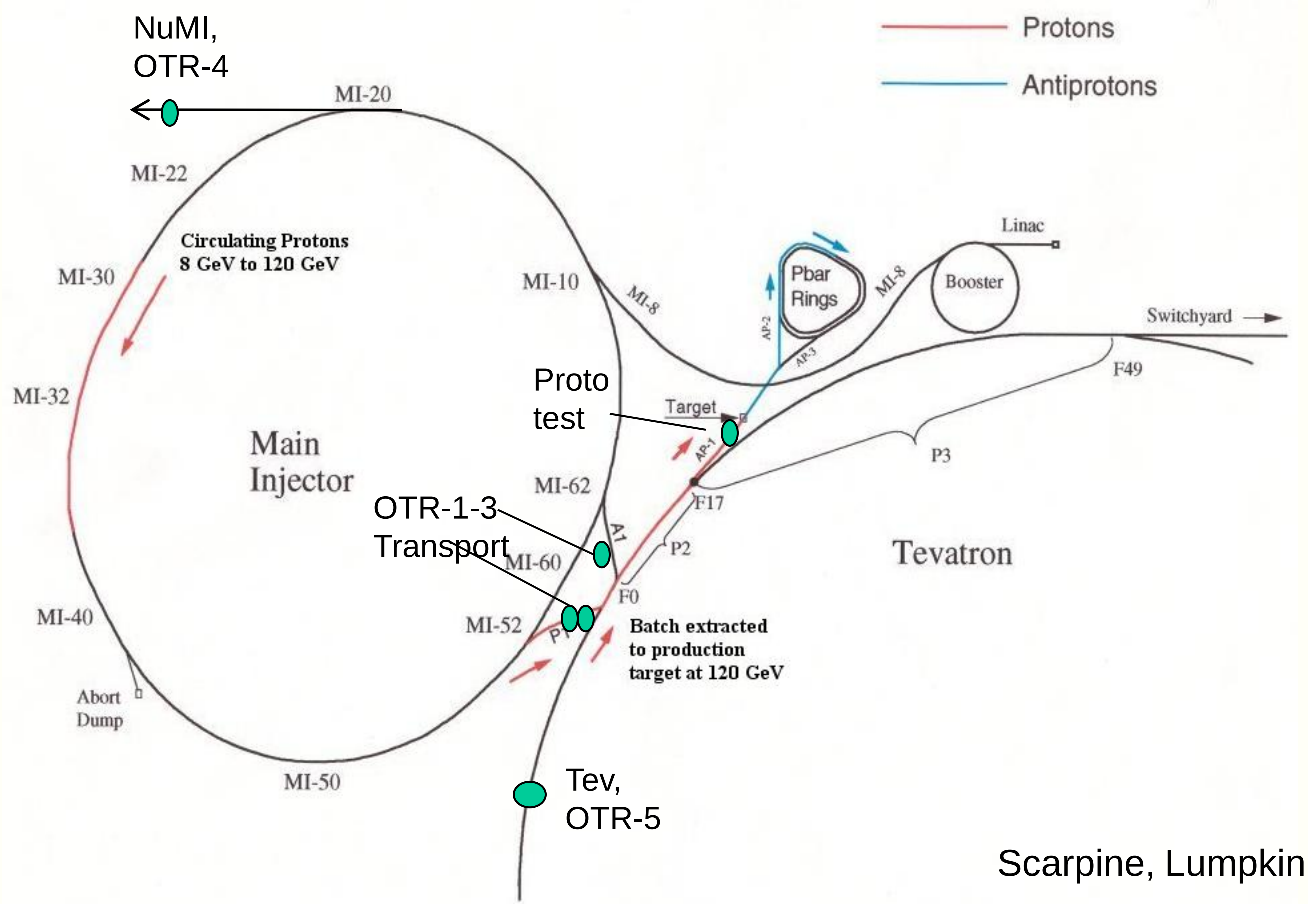
A. Aryshev et al., IPAC10

OTR PSF Observations

- It seems the OTR PSF polarization effect is a symmetric difference in image size around the total PSF size in the model, while the JLAB data are strongly asymmetric in effect magnitude.
- Postulate this anomalous aspect is due to the induced current distribution as revealed through polarized OTR.
- Such strong asymmetry also seen in the ODR data and simulations. Perpendicular component is better.
- The broken A.D. symmetry at low gamma should be in the PSF calc. model.

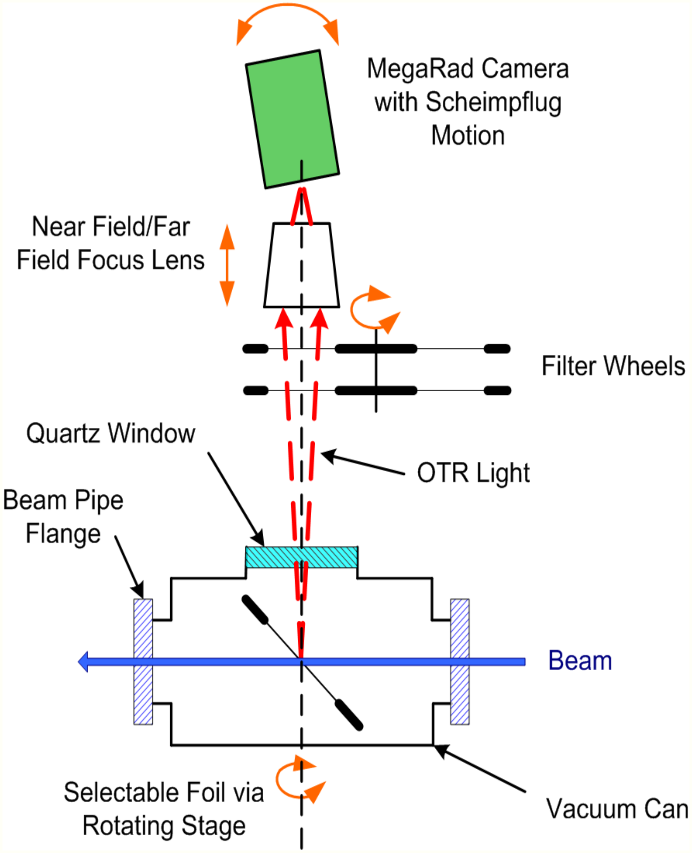
120-GeV Protons and Antiprotons

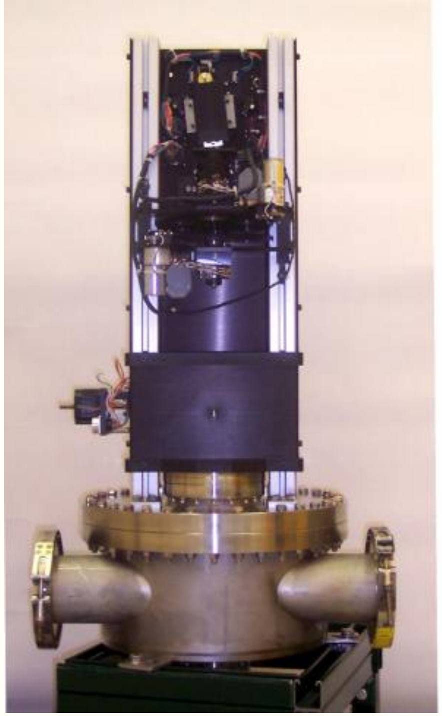
- **Five OTR stations in beamlines at Fermilab after feasibility evaluated by Lumpkin and Scarpine (PAC03).**

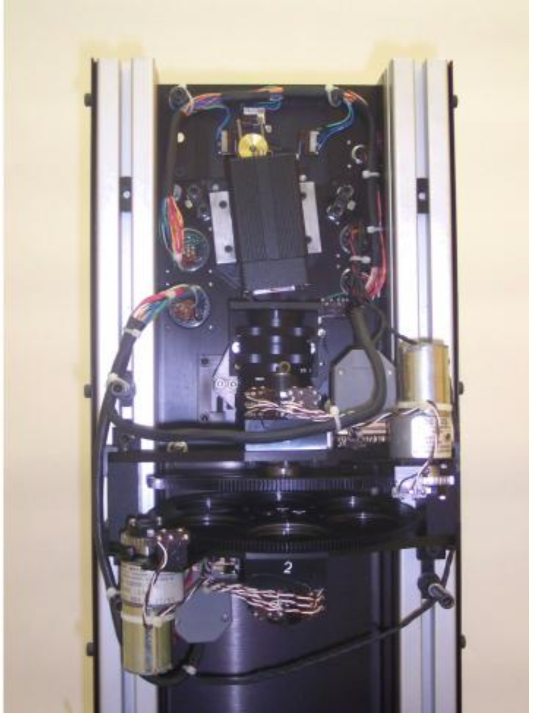


Scarpine, Lumpkin,Tassoto, PAC05,7

OTR Station at Fermilab



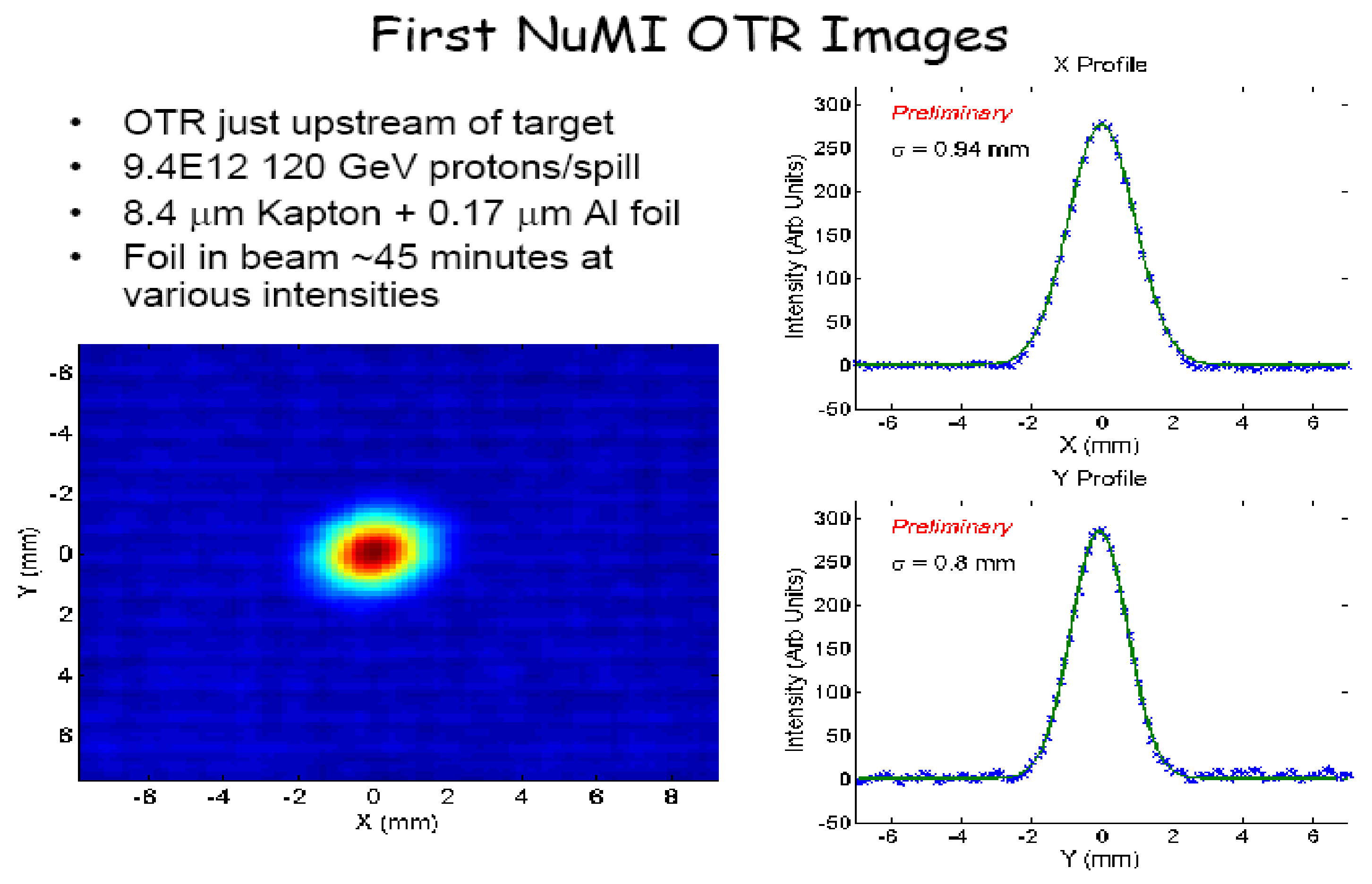




V.E. Scarpine and A. H. Lumpkin

Example with 120-GeV Protons

- **Intense beams imaged before the NUMI target.**



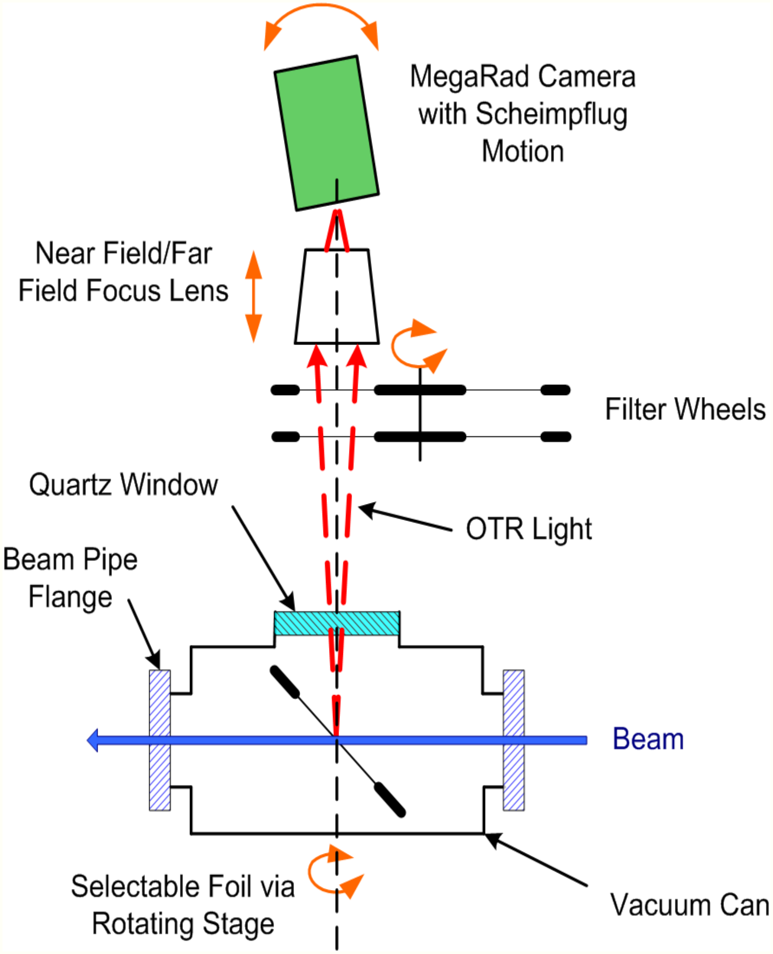
First NuMI OTR Images

- OTR just upstream of target
- 9.4E12 120 GeV protons/spill
- 8.4 μm Kapton + 0.17 μm Al foil
- Foil in beam ~45 minutes at various intensities

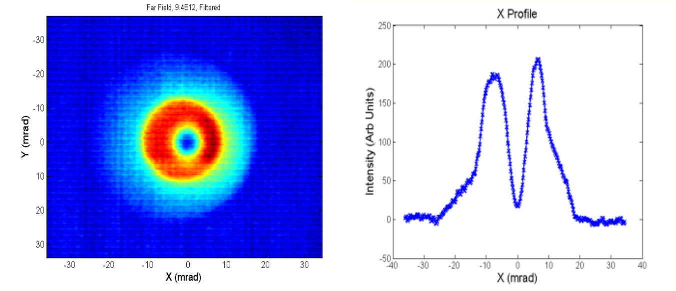
Courtesy of V. Scarpine

Far-field OTR for Protons

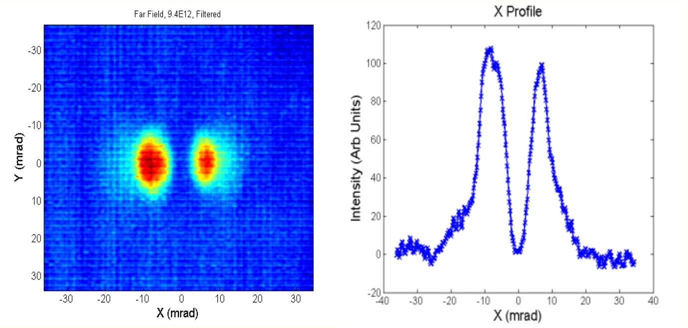
- **Initial success on imaging 120 GeV protons @10^{13} ppp.**



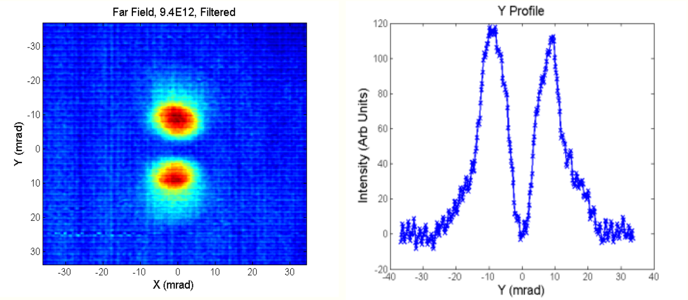
Total



Hpol



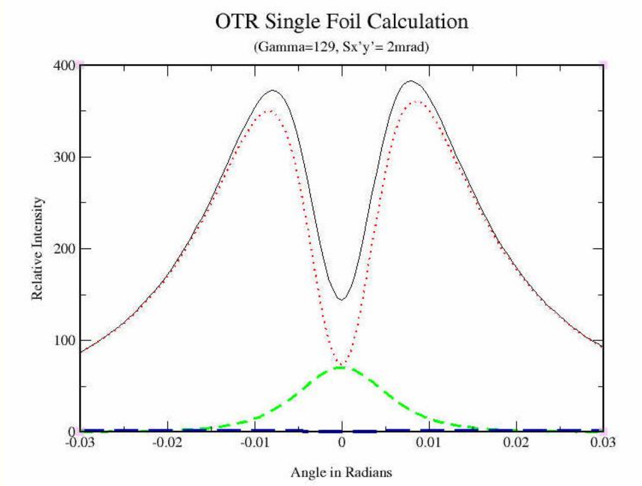
Vpol

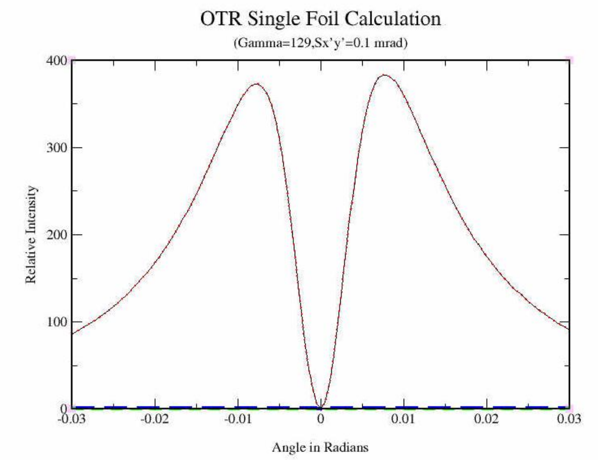


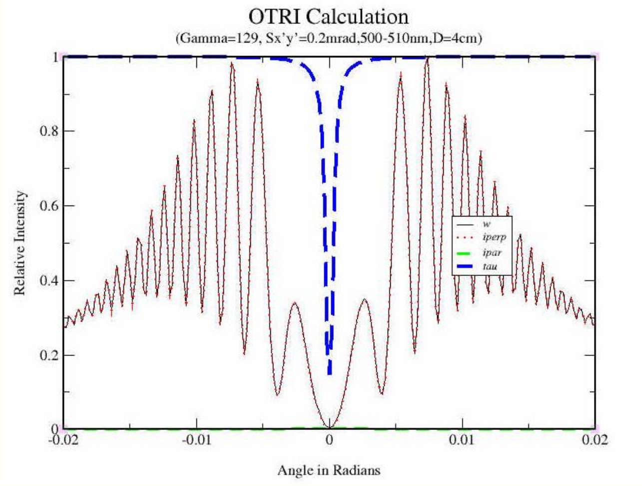
A. Lumpkin et al., PAC07

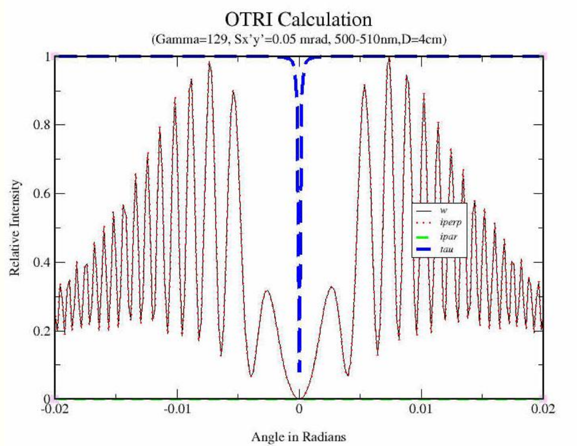
Model of OTR Divergence Effects

- **Both single-foil and two-foil effects considered.**


OTR Single Foil Calculation
(Gamma=129, Sx'y'= 2mrad)


OTR Single Foil Calculation
(Gamma=129,Sx'y'=0.1 mrad)

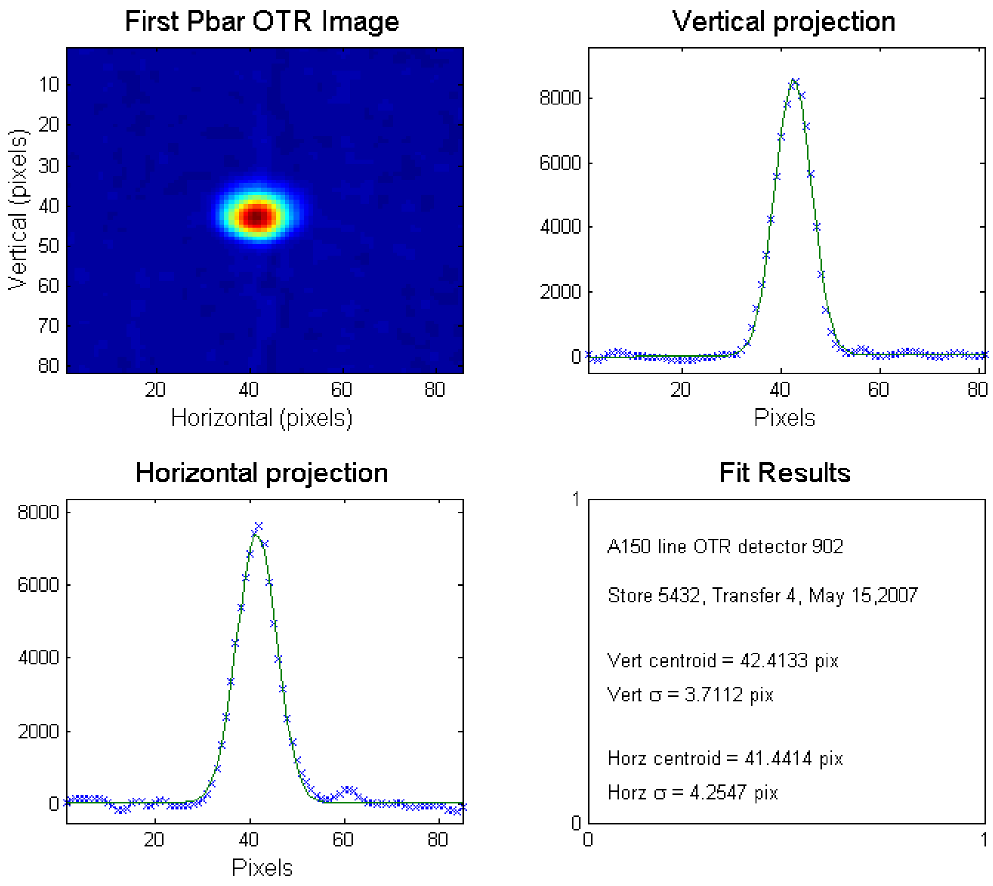

OTRI Calculation
(Gamma=129, Sx'y'=0.2mrad,500-510nm,D=4cm)


OTRI Calculation
(Gamma=129, Sx'y'=0.05 mrad, 500-510nm,D=4cm)

A. Lumpkin et al., PAC07

First 120-GeV Pbar Beam OTR Images Obtained 5-15-07 at FNAL

- Antiprotons (Pbars) were less intense than proton beams, but still can be imaged in a transport line.



A150 line OTR detector 902

Store 5432, Transfer 4, May 15,2007

Vert centroid = 42.4133 pix

Vert σ = 3.7112 pix

Horz centroid = 41.4414 pix

Horz σ = 4.2547 pix

V.E Scarpine, A.H. Lumpkin

OTR Works for Intense Relativistic Hadrons, What About Heavy Ions (HI)?

- Is there sufficient charge crossing the interface so OTR could be detectable? Use Q^2 and β^2 dependencies.
- Can the thin foil survive the areal charge density levels? (Beamline exit windows and stripper foils do).
- 120-GeV protons, up to 10^{13} in a 10-μs batch in 1mm x 1mm spot on aluminized Kapton (6 μm). Screen survived 6 months in beam at Fermilab.
- Look at lobe angle like 80-keV electrons? Or other.
- Use ICCD, cooled CCD, or CMOS cameras to boost sensitivity to low signals.
- Use Forward OTR; with annular mirror? Out of stripper foil?
- What beam intensity levels used at GSI (and LHC)?

Proposed OTR Application to Heavy Ions

- **Consider applying technologies and concepts for ions.**
- **Take advantage of charge state for OTR generation.**

For a non-relativistic charge Q, traveling with velocity v, the spectral energy density of transition radiation is,

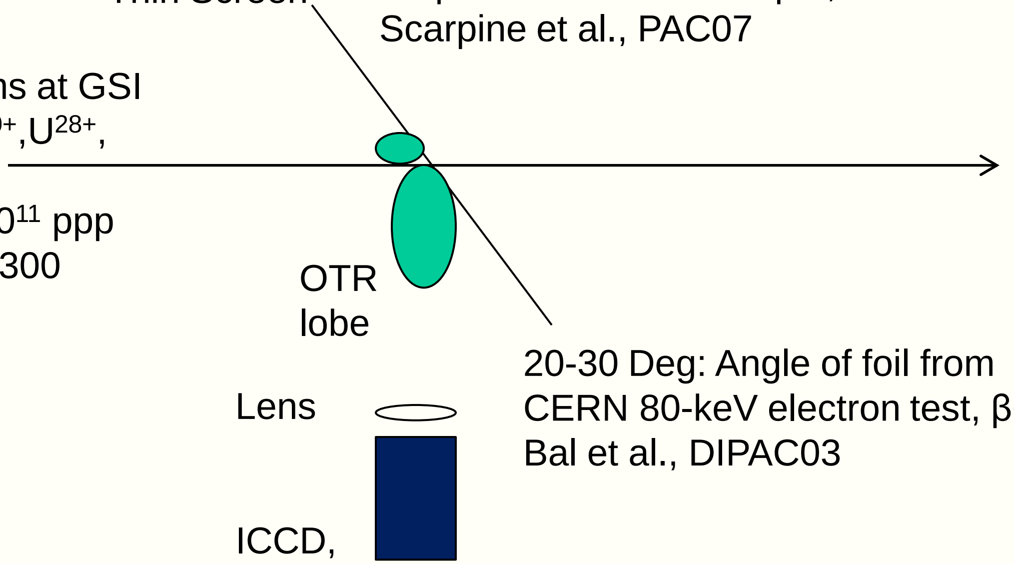
$W(\omega) = 4\, Q^2\, \beta^2/3\pi c$,

where $\beta = v/c$ and c is the speed of light.

Ginzburg and Tsyovich,(1984)

Hypothesize $Q^2 = (Ze)^2$ where Z is the ion charge state and e is the magnitude of electron charge.

More than a "gedanken" experiment!



Alum. Kapton at FNAL handled 10^{13} protons in 10 µs in 1-mm radius spot, Scarpine et al., PAC07

Thin Screen

HI beams at GSI e.g. Ar^{10+},U^{28+}, U^{73+}

10^9 to 10^{11} ppp

11.4 to 300 MeV/u

OTR lobe

20-30 Deg: Angle of foil from CERN 80-keV electron test, β~0.6, Bal et al., DIPAC03

Lens

ICCD, Images ~5×10^4 photons

OTR Cases Show Potential for Ions

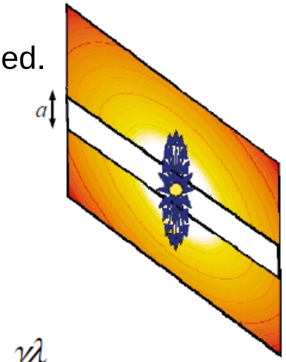
- **Table I. Comparison of various particle beam cases and estimated OTR photons generated for ions (Preliminary).**

Part.	E(MeV)	Q	β	γ	Y(ph/e)	N	Mult.	Photon #	CCD
e^-	.080	1	0.63	1.15	$2\text{x}10^{-6}$	$4\text{x}10^{11}$	1	$7\text{x}10^5$	*Int.
e^-	150	1	0.99	300	$2\text{x}10^{-3}$	$6\text{x}10^{9}$	-	$1\text{x}10^7$	yes
p^+	$120\text{x}10^3$	1	0.99	129	10^{-3}	10^{11}	-	10^8	CID
	MeV/u								
Ar^+	11.4	10	0.15	1.01	10^{-6}	10^{10}	5.3	$5\text{x}10^4$	*Int.
U^+	11.4	28	0.15	1.01	10^{-6}	10^{11}	42	$4\text{x}10^6$	*Int.
U^+	300	73	0.65	1.21	10^{-6}	10^{9}	5329	$5\text{x}10^6$	*Int.

***Use intensifier for gain and the gating feature. More discussions later today. Also the ion intensity increases projected for FAIR look even better for photon numbers. The Multiplier (Mult.) column is the estimated scaling with $Q^2\beta^2$.**

ODR Basics

- **Diffraction radiation is produced when a charge moving at constant velocity *passes nearby* a boundary between media with different dielectric constants.**



- DR is produced by the interaction between the EM fields of the traveling charge and the conducting screen

  *the image charge currents radiate, ODR is radially polarized.

- The extension of the electromagnetic field of a relativistic particle is a flat circle of diameter $\gamma\lambda/2\pi$,
- The radiation intensity is $I \propto e^{-\frac{2\pi a}{\gamma\lambda}}$
- DR impact parameter is $\frac{\gamma\lambda}{2\pi} \rightarrow$ if a

$$\begin{cases} >> \frac{\gamma\lambda}{2\pi} & \text{No radiation} \\ \cong \frac{\gamma\lambda}{2\pi} & \text{DR} \\ << \frac{\gamma\lambda}{2\pi} & \text{TR} \end{cases}$$

Enrica Chiadroni
LNF - INFN

Possible Beam Diagnostics

Diffraction Radiation Observables

- Near field (at or near target) intensity
- Far field angular distribution
- Polarization
- Frequency spectrum
- Interference between radiation from 2 sources

These can be combined to measure potentially

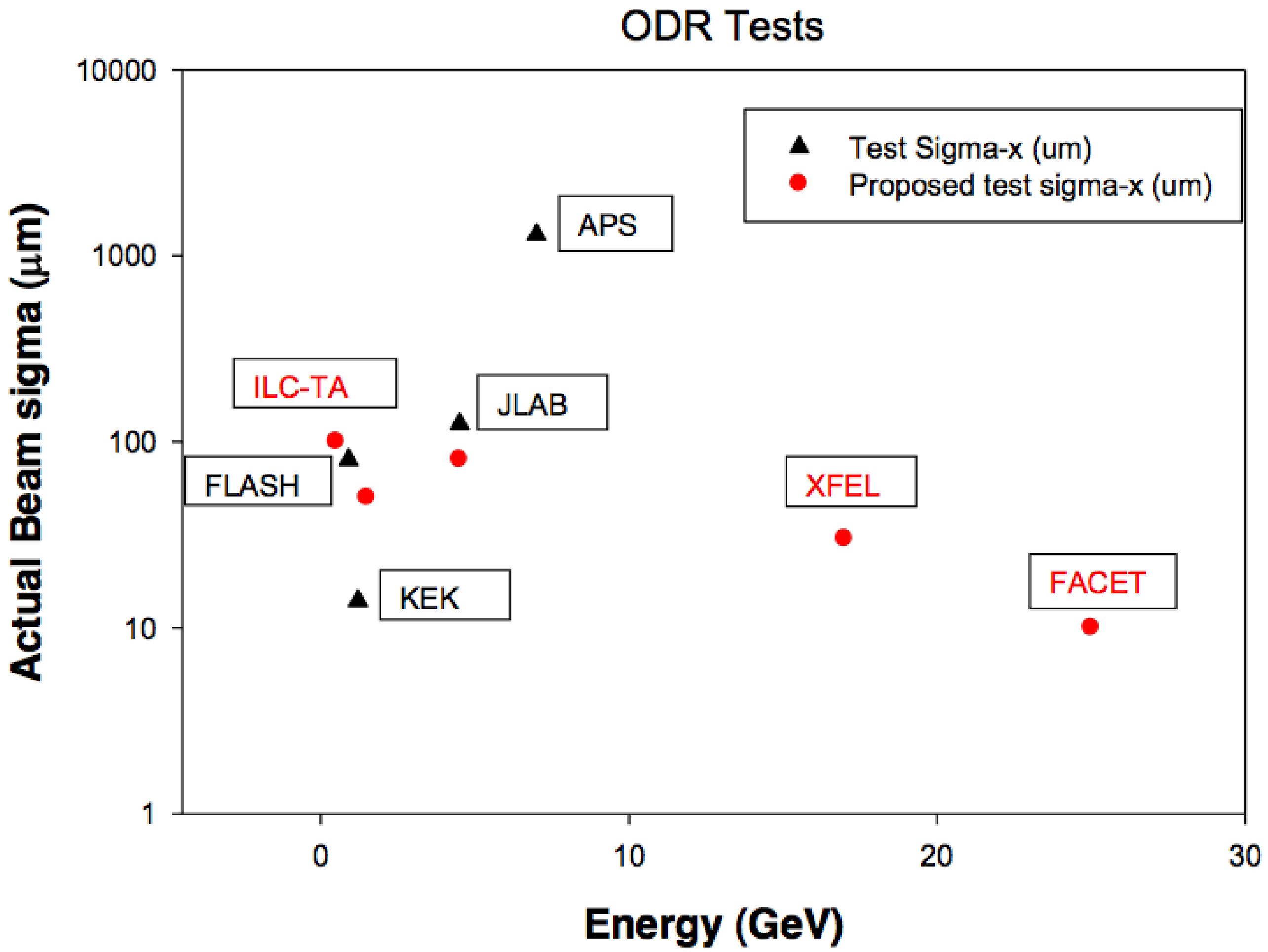
- Beam size
- Beam position
- Beam divergence
- Energy

Recent measurements at KEK, APS, FLASH,CEBAF

Interest at other labs: BNL

Further ODR Studies Proposed

- **Path to test near-field imaging on 10-μm size at 23 GeV.**

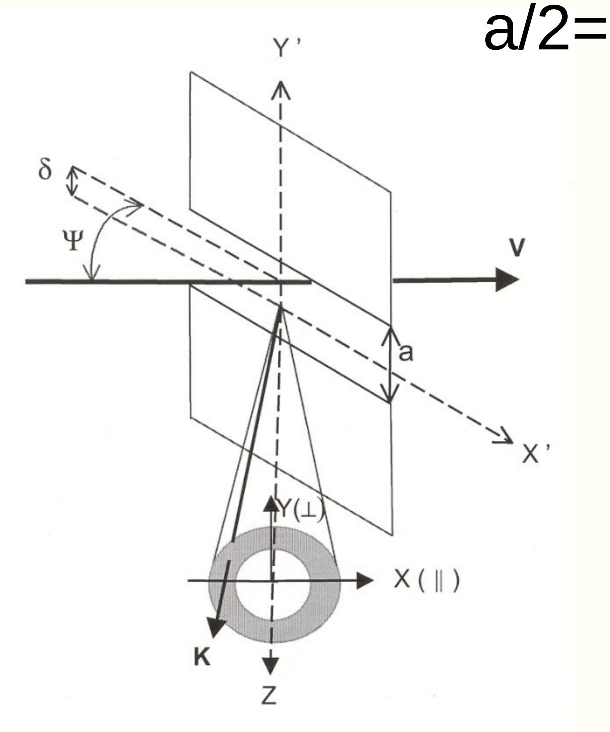


ODR Demonstrations

Tech-nique, Near or Far field	Beam Energy (GeV	Beam size (μm)	Charge	Detector	Div. (μrad)	Lab
Slit in plane,F	1.2	10-14	1 nC	PMT, scan	1.5	KEK
Slit in plane,F	0.68, 0.90	85**	30 nC	Cooled CCD	80	INFN/ FLASH
Single plane,N	7	1300	3 nC	CCD	70	APS/ ANL
Single plane,N	4.5	120	80 µC	CCD		FNAL/ CEBAF
Slit in plane,N	0.90	200	30 nC	Cooled CCD	80**	FNAL/ INFN
Two planes,F	0.90	89	30 nC**	Cooled CCD	150	INFN/ FLASH
Two-1/2 Planes	1.2, 0.9	10, 90		Cooled CCD		KEK, INFN

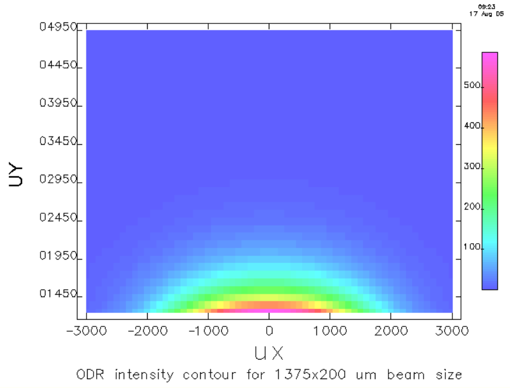
ODR is a Potential Nonintercepting Diagnostic for GeV Lepton Beams and TeV Hadron Beams

- At left, schematic of ODR generated from two vertical planes (based on Fig.1 of Fiorito and Rule, NIM B173, 67 (2001). We started with a single plane.
- At right, calculation of the ODR light generated by a 7-GeV electron beam for *d* =1.25 mm in the optical near field based on a new model (Rule and Lumpkin).

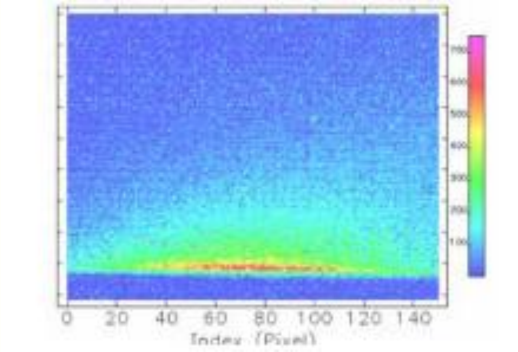


a/2=d~γλ/2π

Model



Data



An Analytical Model has been Developed by D. Rule for ODR Near-Field Distributions Based on the Method of Virtual Quanta

- We convolved the electron beam's Gaussian distribution of sizes σ_x and σ_y with the field expected from a single electron at point *P* in the metal plane (J.D. Jackson)

$$\frac{dI}{d\omega}(\mathbf{u},\omega)=\frac{1}{\pi^2}\frac{q^2}{c}\left(\frac{c}{v}\right)^2\alpha^2 N\frac{1}{\sqrt{2\pi\sigma_x^{\ 2}}}\frac{1}{\sqrt{2\pi\sigma_y^{\ 2}}}\times$$

$$\iint dxdy\ K_1^{\ 2}(\alpha b)e^{-\frac{x^2}{2\sigma_x^{\ 2}}}e^{-\frac{y^2}{2\sigma_y^{\ 2}}},$$

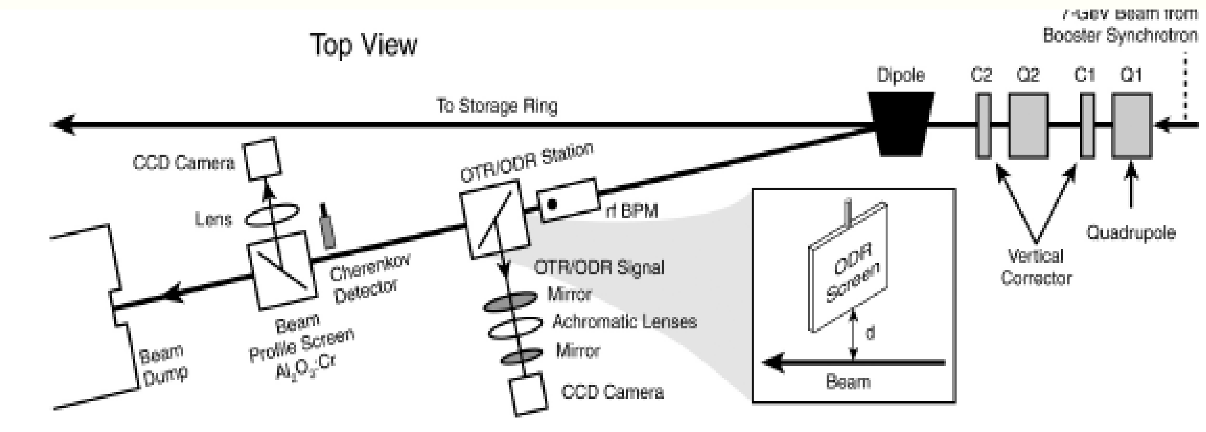
where ω = radiation frequency, v = electron velocity ≈ c = speed of light, q = electron charge, N is the particle number, $K_1(\alpha b)$ is a modified Bessel function with α= 2π/γλ and b is the impact parameter.

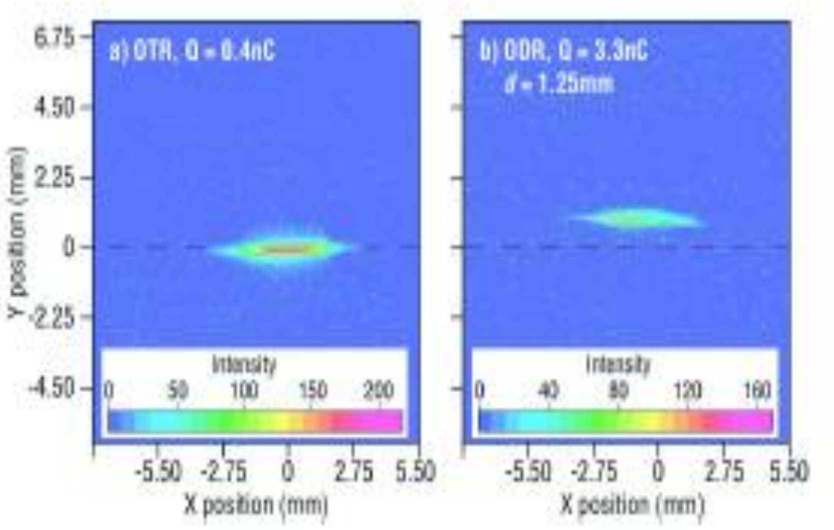
Lumpkin et al., Phys. Rev. ST-AB, Feb. 2007

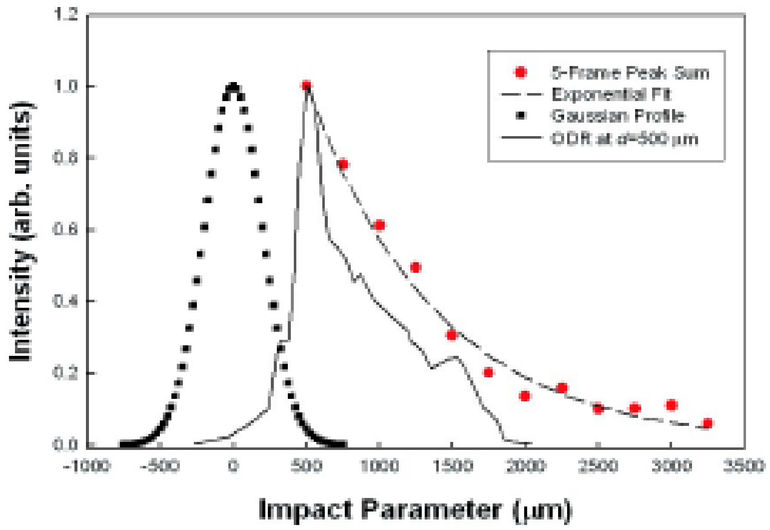
APS Test Summary

- Electron beam energy = 7GeV, γ= 13,699
- Bunch intensity ~ 1.9×10^{10} (3 nC)
- Beam sizes: σ_x = 1375 µm, σ_y = 200 µm
- Typical impact parameter ~ 5 σ_y
- Wavelength λ ~ 0.4-0.8 µm
- Sensitive to horizontal offsets of 50-100 µm
- Sensitive to beam size changes of 20%

7-GeV Test at APS



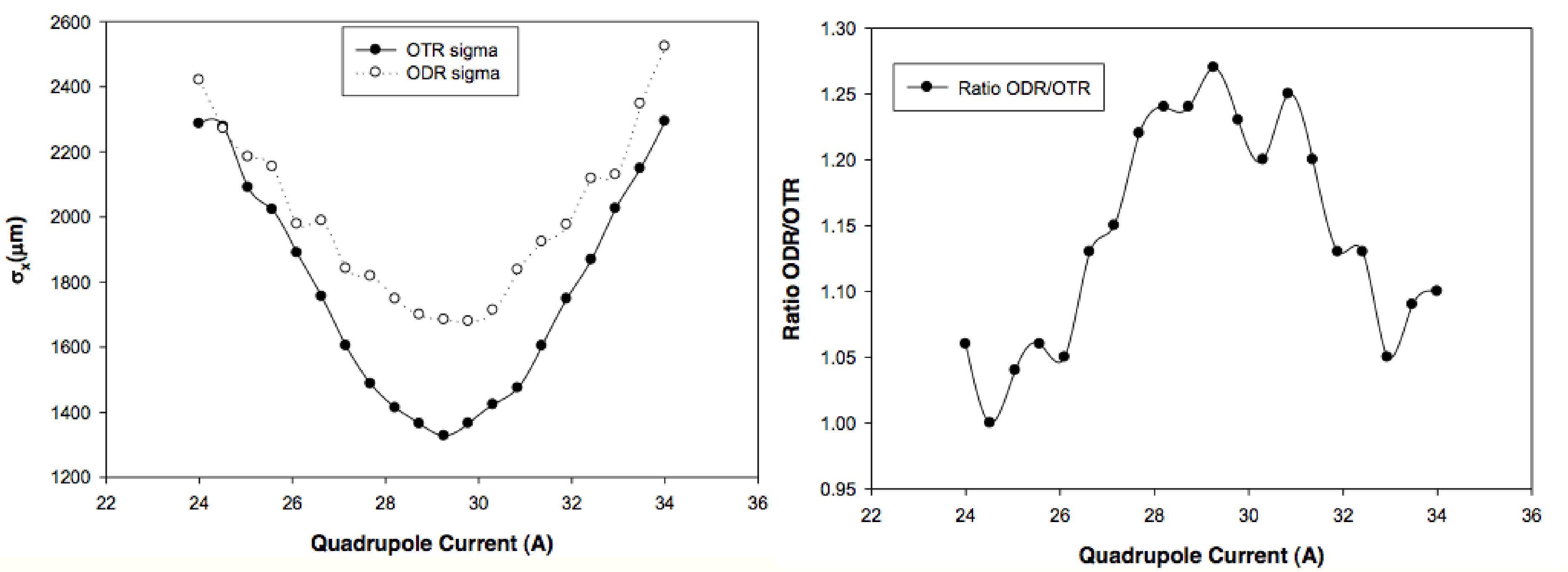




Lumpkin et al., PRST-AB (Feb. 2007)

Perpendicular ODR Polarization Component Gives More Direct Representation of Beam Size.

- Quadrupole current scan provides beam-size scan.

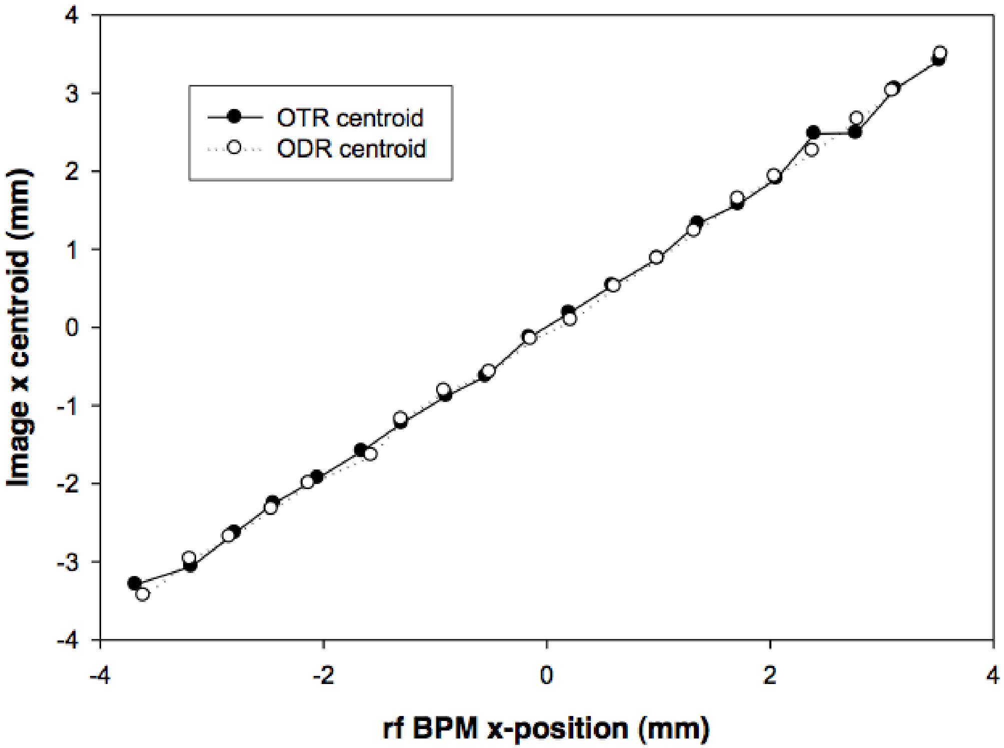


- ODR size tracks OTR or bunch real size
- ODR/OTR ratio function of ODR PSF

Lumpkin et al., Phys. Rev. ST-AB, Feb. 2007

ODR Also Has Good NI Beam-Position Sensitivity Using Orthogonal Polarization Component

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



- **ODR also BPM**

CEBAF Beam Offers Extended Parameter Space toTest an NI Beam-size Monitor for Operations.

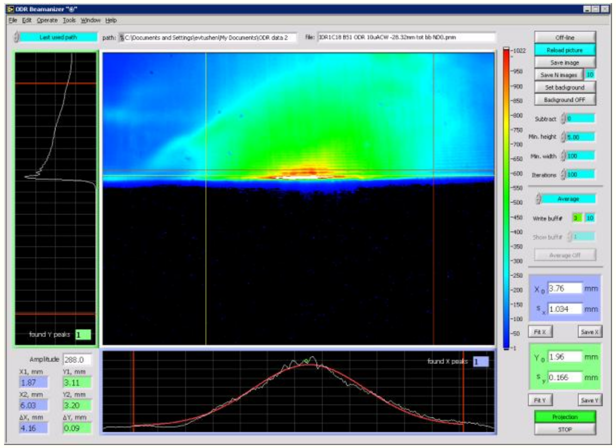
- **CEBAF beam size is 10 times smaller and the charge is 1000 times greater than APS case. What are background sources?**

Parameter	APS	CEBAF	ILC
Energy (GeV)	7	1- 5	5, 250
X Beam size (μm)	1300	100-150	300, 30
Y Beam size (μm)	200	100-150	15, 2
Current (nA)	6	100,000	50,000
Charge/ 33 ms (nC)	3	3,000	10,000

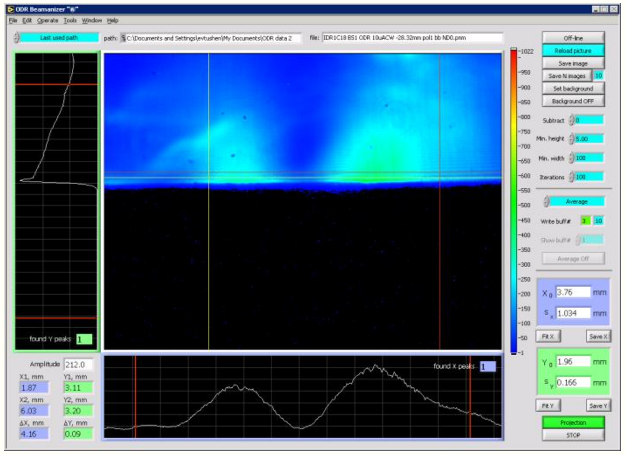
A. Lumpkin et al., PAC07

Basic ODR images at 10 µA CW

Polarization Component effects are very clear in ODR.

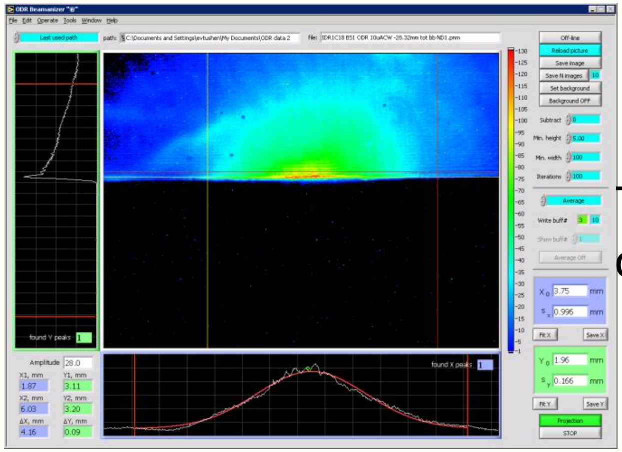


path: C:\Documents and Settings\evtushen\My Documents\ODR data 2
file: IDR1C18 BS1 ODR 10uACW -28.32mm tot bb ND0.pnm
Save N images: 10
Subtract: 0
Min. height: 5.00
Min. width: 100
Iterations: 100
Write buff#: 3 10
Show buff#: 1
X_0: 3.76 mm
s_x: 1.034 mm
Y_0: 1.96 mm
s_y: 0.166 mm
found Y peaks: 1
found X peaks: 1
Amplitude: 288.0
X1, mm: 1.87
Y1, mm: 3.11
X2, mm: 6.03
Y2, mm: 3.20
ΔX, mm: 4.16
ΔY, mm: 0.09



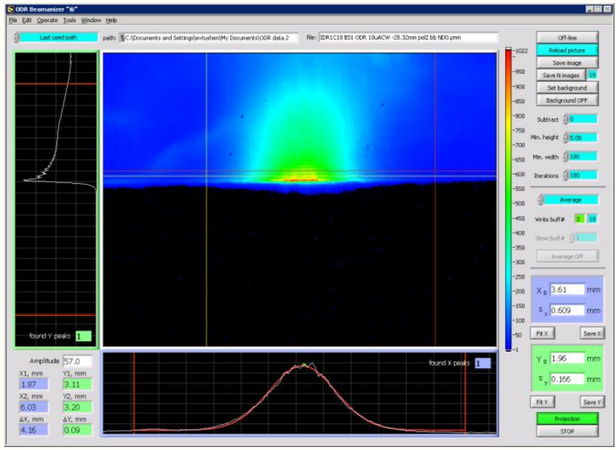
path: C:\Documents and Settings\evtushen\My Documents\ODR data 2
file: IDR1C18 BS1 ODR 10uACW -28.32mm pol1 bb ND0.pnm
Save N images: 10
Subtract: 0
Min. height: 5.00
Min. width: 100
Iterations: 100
Write buff#: 3 10
Show buff#: 1
X_0: 3.76 mm
s_x: 1.034 mm
Y_0: 1.96 mm
s_y: 0.166 mm
found Y peaks: 1
found X peaks: 1
Amplitude: 212.0
X1, mm: 1.87
Y1, mm: 3.11
X2, mm: 6.03
Y2, mm: 3.20
ΔX, mm: 4.16
ΔY, mm: 0.09

Hpol.:
Double
lobe



path: C:\Documents and Settings\evtushen\My Documents\ODR data 2
file: IDR1C18 BS1 ODR 10uACW -28.32mm tot bb ND1.pnm
Save N images: 10
Subtract: 0
Min. height: 5.00
Min. width: 100
Iterations: 100
Write buff#: 3 10
Show buff#: 1
X_0: 3.75 mm
s_x: 0.996 mm
Y_0: 1.96 mm
s_y: 0.166 mm
found Y peaks: 1
found X peaks: 1
Amplitude: 28.0
X1, mm: 1.87
Y1, mm: 3.11
X2, mm: 6.03
Y2, mm: 3.20
ΔX, mm: 4.16
ΔY, mm: 0.09

Total:
σ_x=996 µm

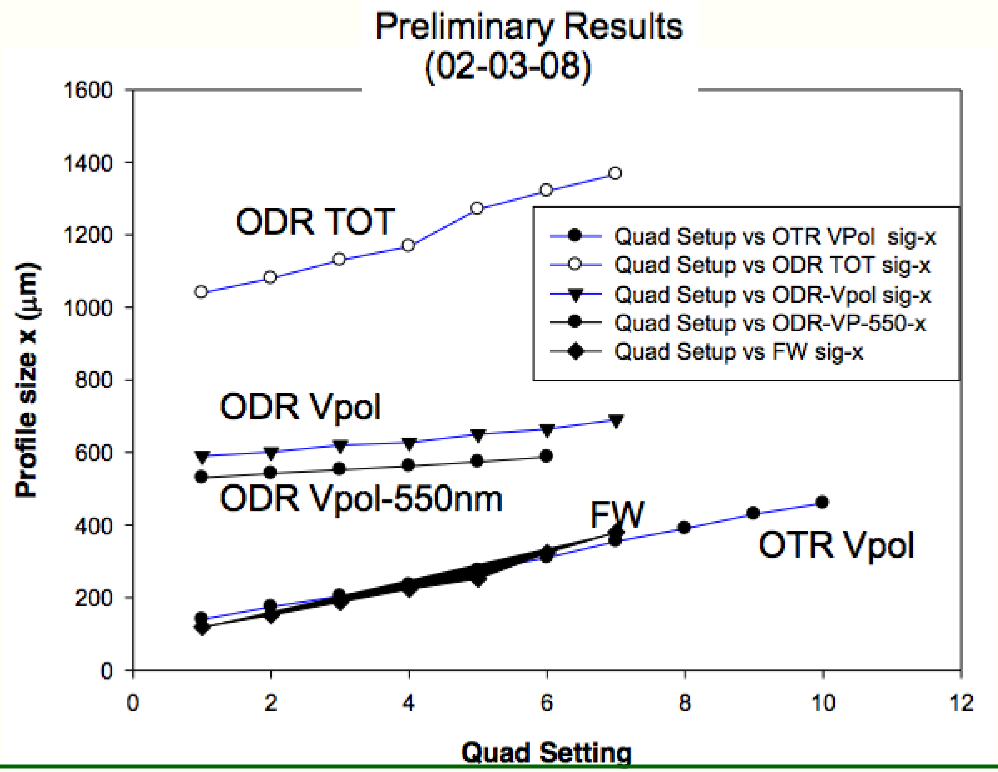


path: C:\Documents and Settings\evtushen\My Documents\ODR data 2
file: IDR1C18 BS1 ODR 10uACW -28.32mm pol2 bb ND0.pnm
Save N images: 10
Subtract: 0
Min. height: 5.00
Min. width: 100
Iterations: 100
Write buff#: 3 10
Show buff#: 1
X_0: 3.61 mm
s_x: 0.609 mm
Y_0: 1.96 mm
s_y: 0.166 mm
found Y peaks: 1
found X peaks: 1
Amplitude: 57.0
X1, mm: 1.87
Y1, mm: 3.11
X2, mm: 6.03
Y2, mm: 3.20
ΔX, mm: 4.16
ΔY, mm: 0.09

Vpol.;
σ_x=609 µm

OTR,Flying Wire, and ODR Comparison

- **Effects of vertical polarizer and 550x10 nm Bandpass filter on ODR profile size are shown.**

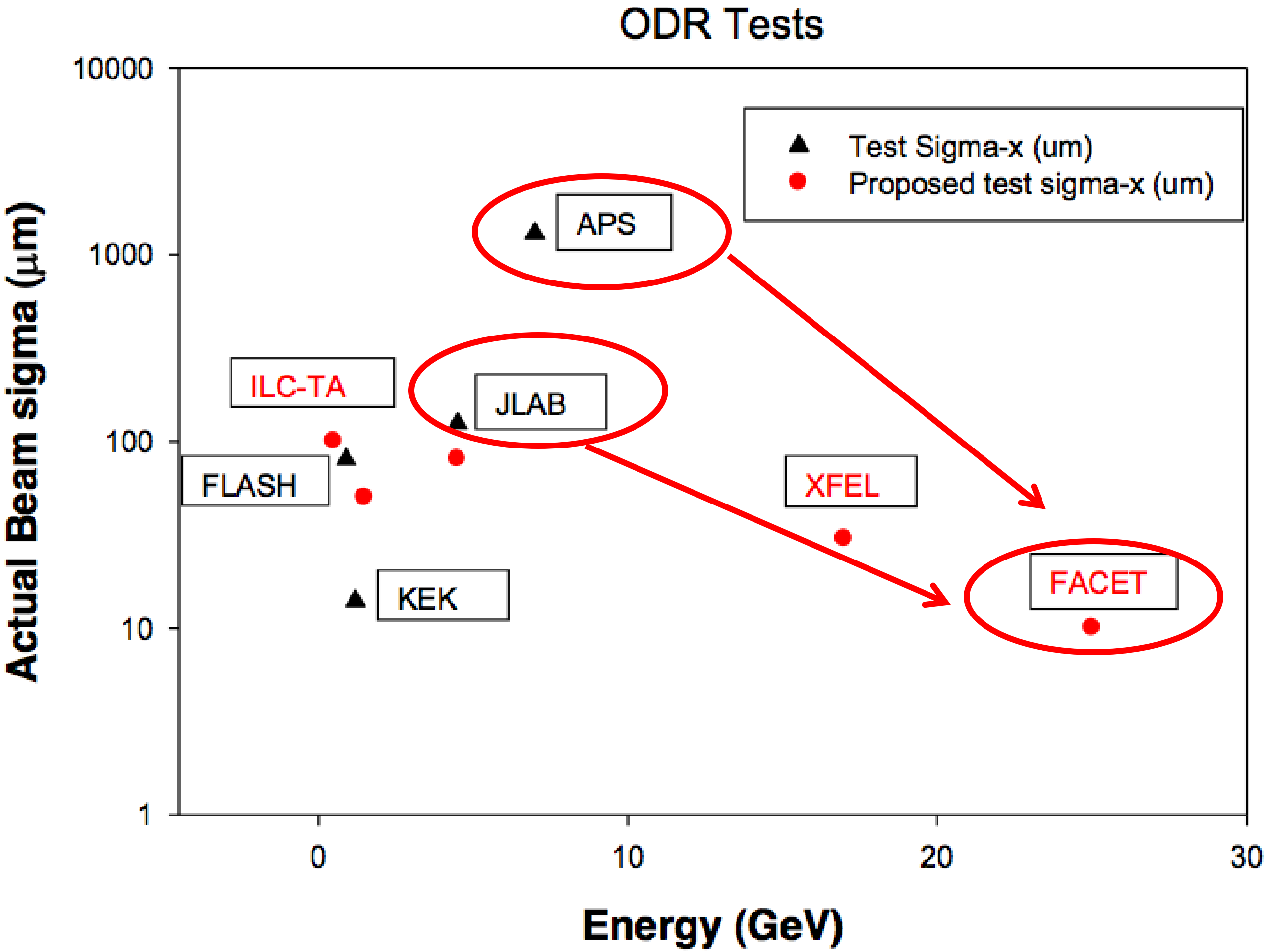


Preliminary Results
(02-03-08)

- **ODR size tracks OTR and flying wire (FW) size, better V-pol. and 550nm filter**

Further ODR Studies Proposed

- **Path to test near-field imaging on 10-µm size at 23 GeV.**



Proposed FACET test at 23 GeV

- **New parameter space for ODR tests provided at FACET.**

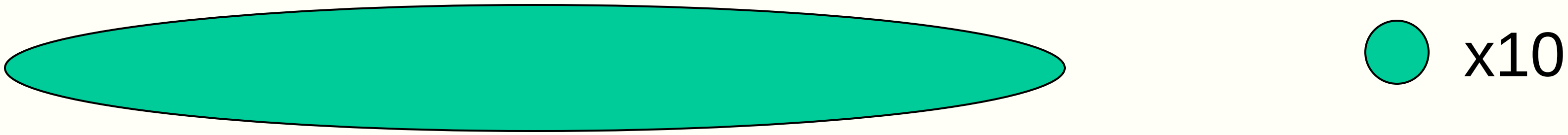
Parameter	APS	CEBAF	ILC	FACET
Energy (GeV)	7	1- 5	5,15,250	23
X Beam size (μm)	1300	80-100	300,150,30	10
Y Beam size (μm)	200	80-100	15,8,2	10
Current (nA)	6	100,000	50,000	30
Charge/ 33 ms (nC)	3	3,000	10,000	3

- **FACET parameters more similar to ILC parameter.**

FACET Tests

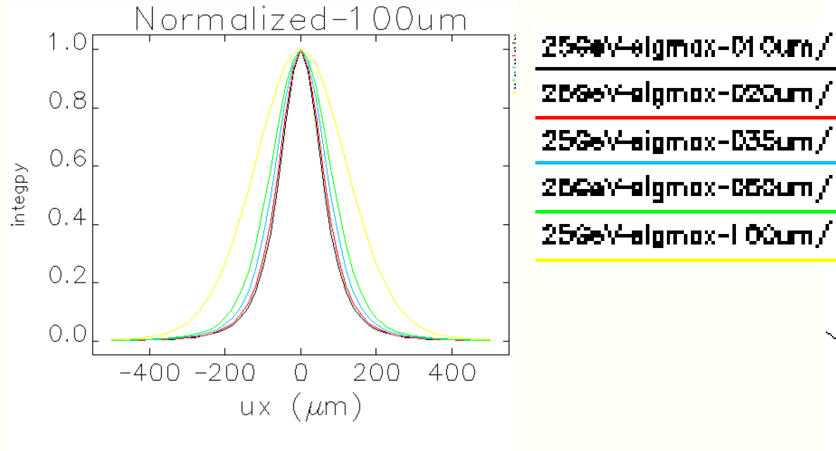
- **Scaling from APS test at 7 GeV indicates signals OK.**

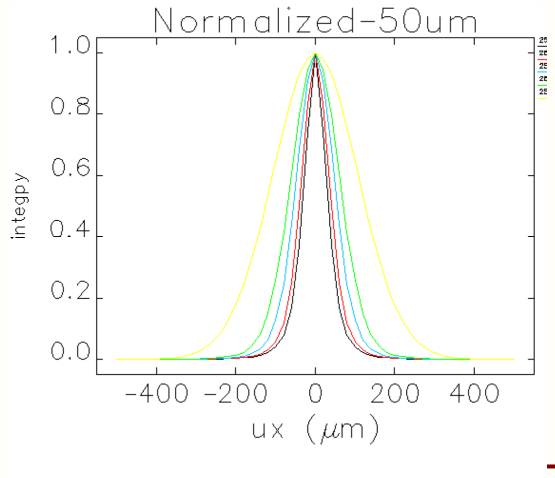
Parameter	APS	FACET
Charge (nC)	3	3
Rep, rate (Hz)	2	10
Energy (GeV)	7	23
Beam size (um)	1300 x 200	10 x 10
$\gamma\lambda/2\pi$ (mm)	1.4	4.6
5 sigma-y (mm)	1.0	0.05
CCD	8 bit	12 bit

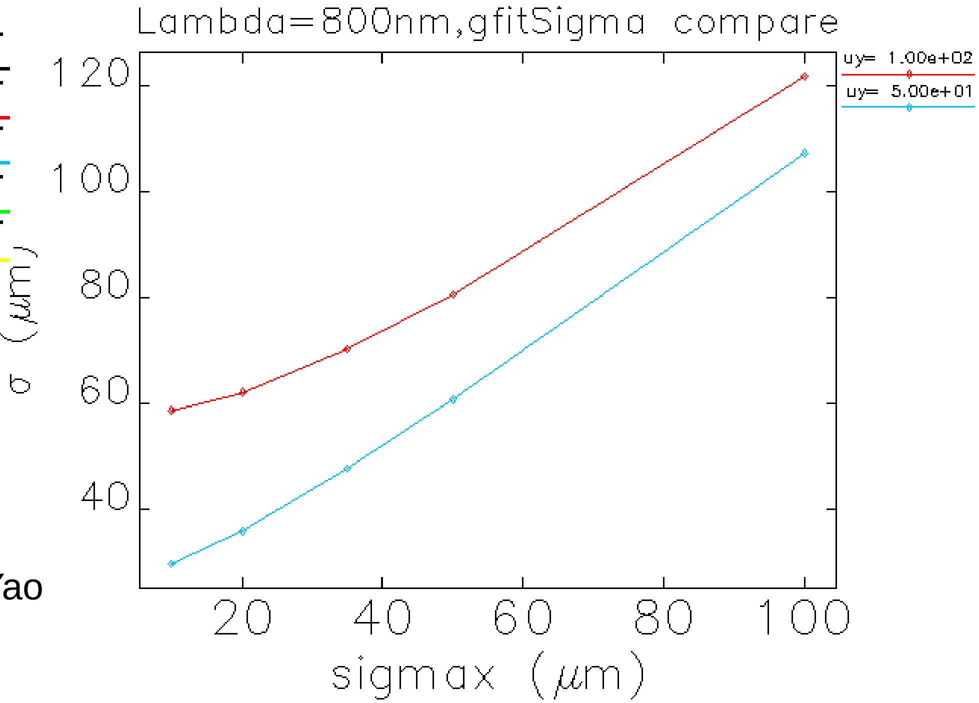


ODR model: FACET Case

- Vertical polarization component, lambda= 800 nm, IP= 100, 50 µm. Curves for 10, 20, 35, 50,100 µm.





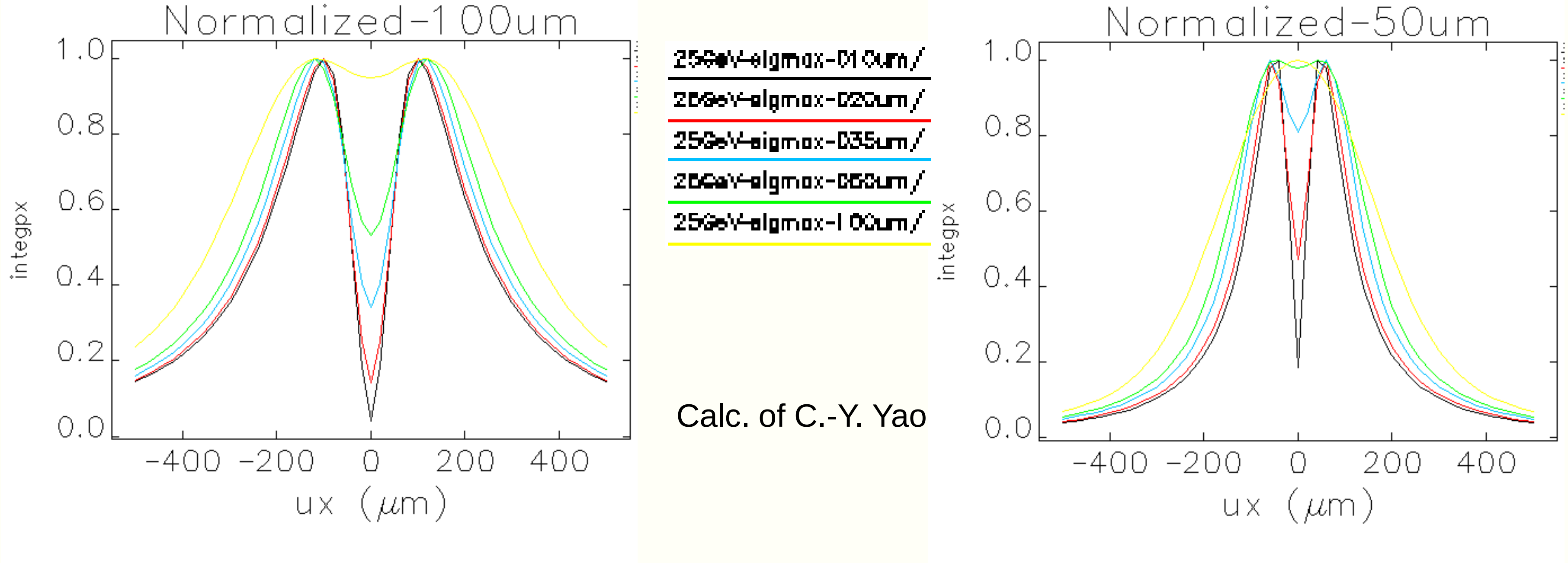


Calc. of C.-Y. Yao

- Better sensitivity predicted for IP=50µm (≈5σ_r)

ODR Model: FACET Case

- **Parallel polarization component shows beam-size effect at 10-µm regime. Curves for 10, 20, 35, 50,100 µm.**

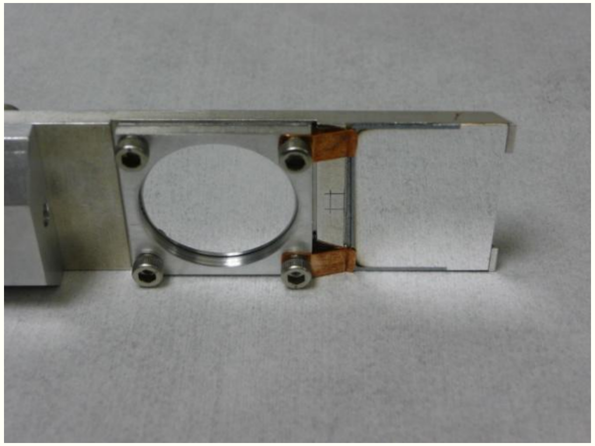


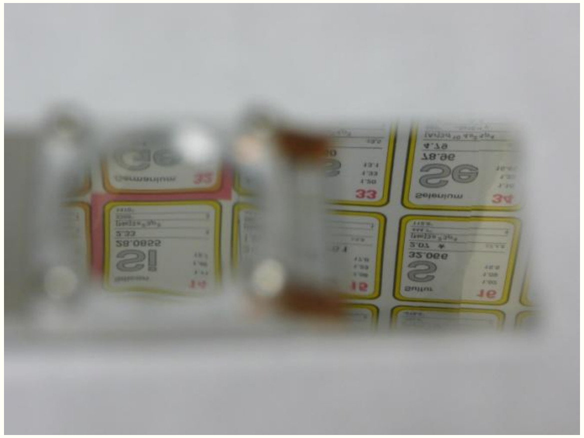
Calc. of C.-Y. Yao

- **H-Pol "valley" also sensitive to bunch size**
- **More sensitive with IP=50µm (small σ_x)**

OTR and ODR Converters

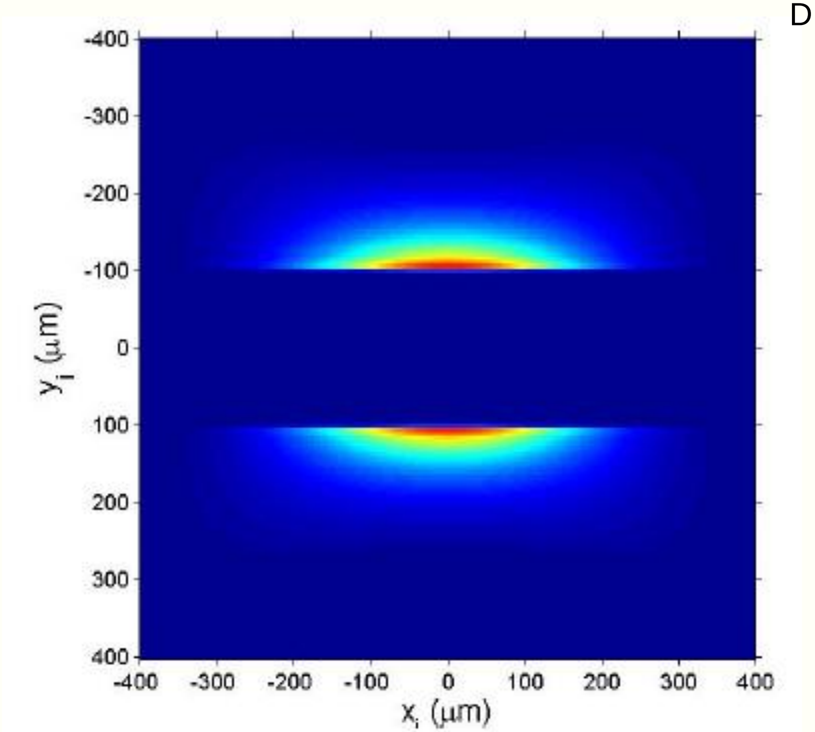
- New OTR converter using aluminized Kapton for the 20-mm aperture was prepared at Fermilab Thin Films lab by Eileen Hahn. About 1500 Angstroms of Al deposited by evaporation method on a stretched 6-µm thick Kapton film for CEBAF experiments. (possibly for GSI).
- New ODR converter was prepared by sputtering a 600 Angstrom Al coating on a 300-µm thick Si wafer cut for <100> plane. (Possibly use same type at FACET.)



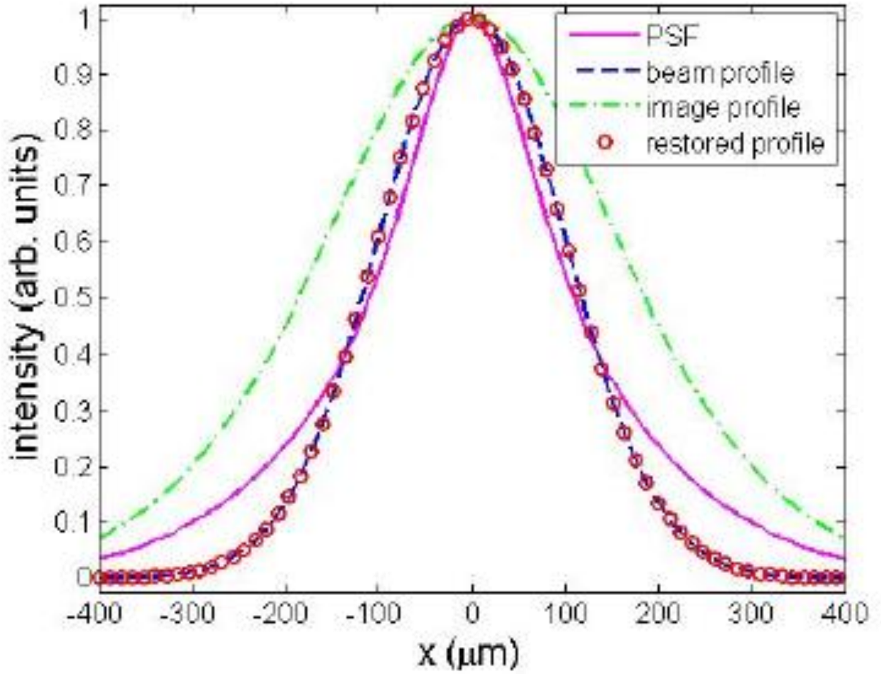


Deconvolution of Profile

- **ODR Point spread function (PSF) may be defined for optical system so can deconvolve from observed image.**



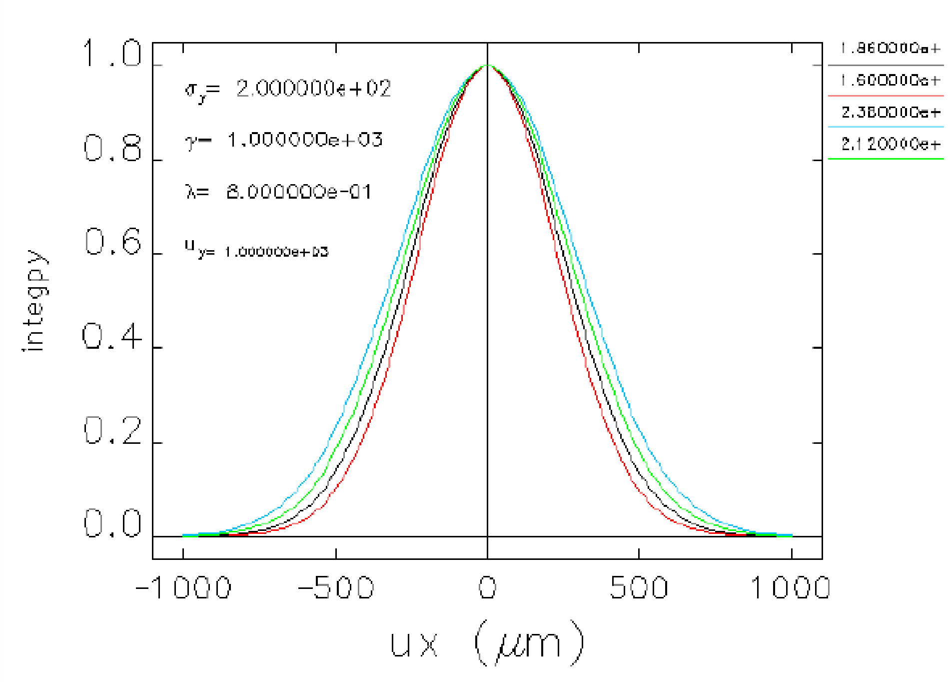
D. Xiang, Huang, Lin: PRST-AB (2007)

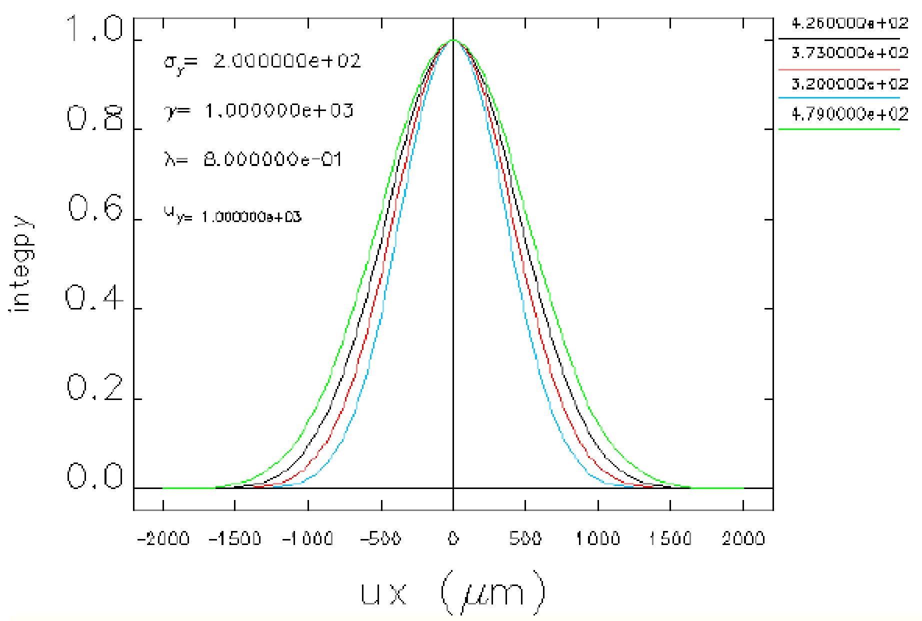


- **Beam profile and not only size and position can (potentially) be measured with NI ODR!!**

ODR Model Shows Beam-size Effects

- **NML examples for beam-size monitor for σ_x=200 μm (L) and 400 μm ± 20% (R) with σ_y=200 μm, *d* = 5 σ_y, and γ=1000.**

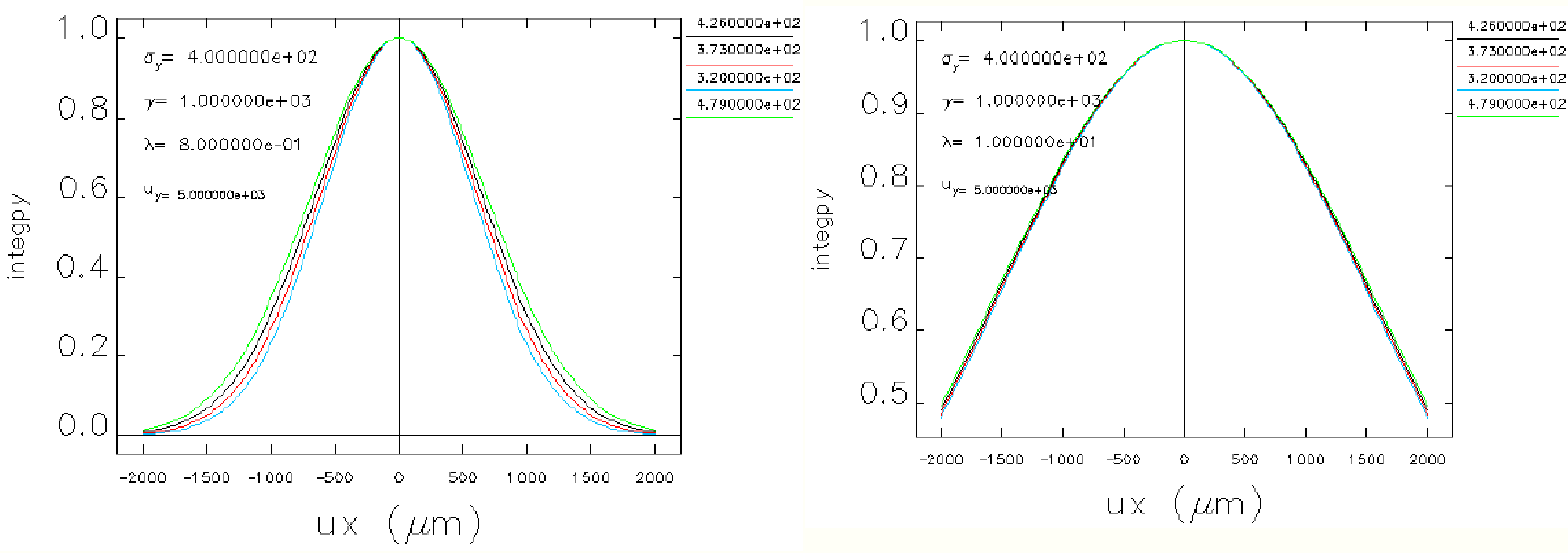




Courtesy of C.-Y. Yao, ANL

ODR Model Shows Wavelength Effect

- **Examples for beam-size monitor for σ_x=400 ±20% μm with σ_y=400 μm, *d* = 12 σ_y , and γ=1000. λ=0.8 μm (left) and 10 μm (right).**

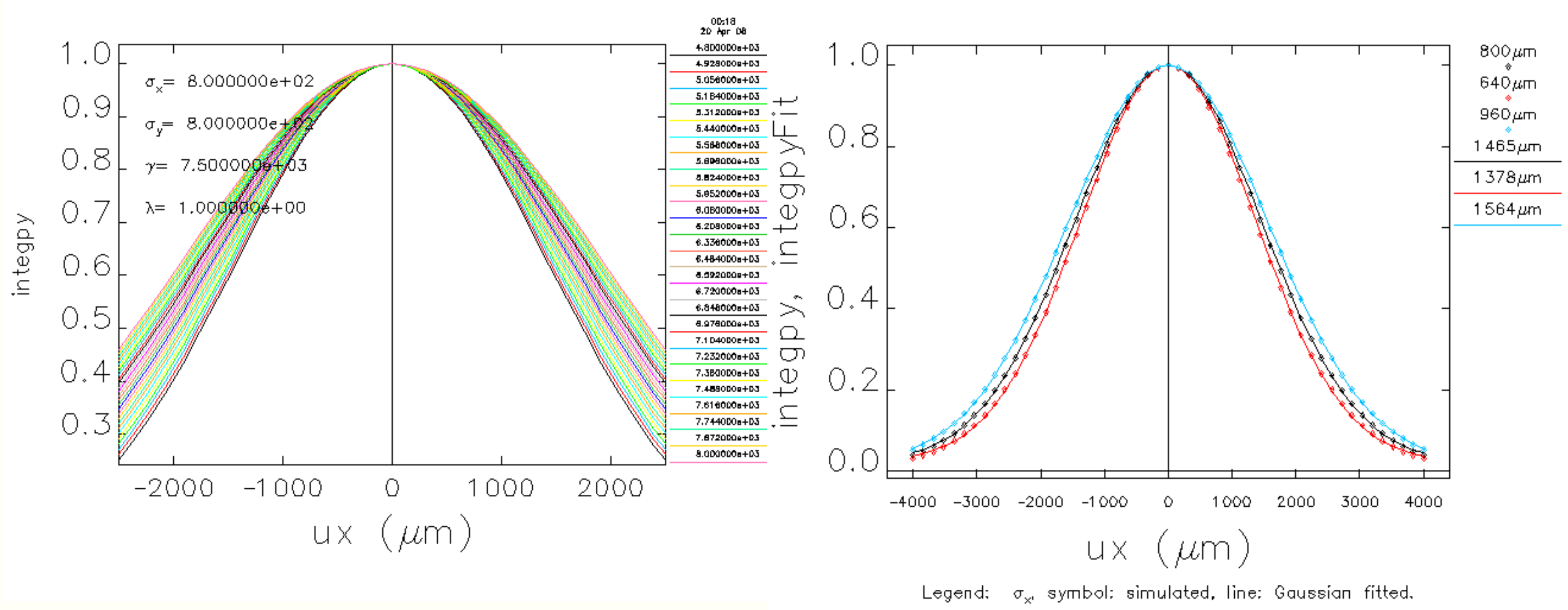


Perpendicular Polarization

Courtesy of C.-Y. Yao , ANL

ODR Model Shows Beam-size Effects

- LHC examples for beam-size monitor for σ_x=800 μm and varying *d* from 4.8-8 mm (L), and with σ_x=800 μm ± 20%, σ_y=800 μm, $d = 6\ \sigma_y$, λ=1.0 μm, and γ=7500 (R).



Perpendicular Polarization

Courtesy of C.-Y. Yao, ANL

SUMMARY

- Extensive experience with OTR imaging of relativistic leptons and some with hadrons provides base for diagnostic applications.
- OTR polarization effects need to be elucidated, and the microbunching instability COTR discussed Monday is a challenge for imaging bright beams. (Mitigation options).
- OTR imaging seems to have potential for intense, non-relativistic heavy ion beams in many GSI-FAIR cases. Follow-up needed.
- Demonstrations of ODR imaging for leptons done in several labs and parameter sets. Further tests at FACET and NML proposed.
- Modeling done for ODR imaging of hadrons in principle, but not very practical in rings, possibly in transport lines.
- The future still remains bright for imaging techniques for charged-particle beam diagnostics.

Acknowledgments

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