Imaging Techniques for Transverse Profile/Size Monitors

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Outline

I. Introduction

II. Beam profiling with YAG:Ce scintillation

- Scintillator resolution
- Depth-of-focus issue

III. Optical Transition Radiation (OTR)

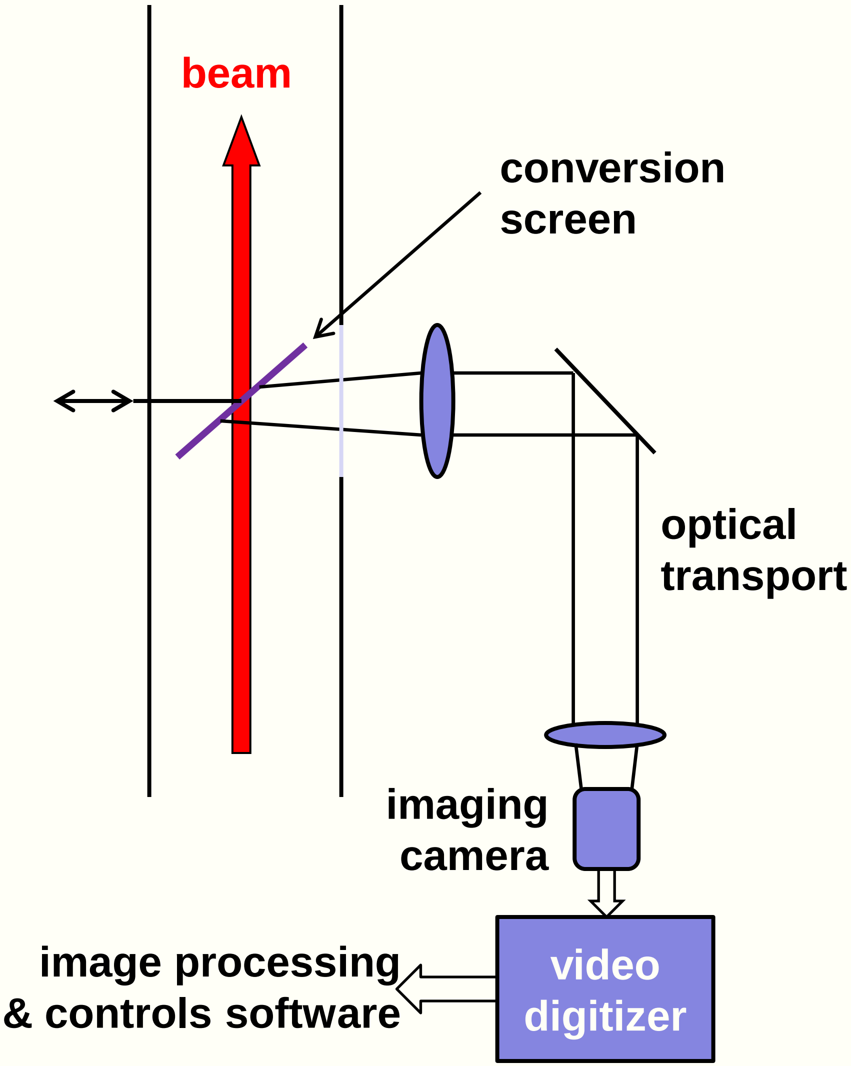
- OTR basics
- OTR point-spread-function (PSF) aspects
- Microbunching instability and coherent OTR (COTR)
- Nonrelativistic beams

IV. Future tests

V. 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, e.g. transverse emittance.
- 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



Identify Corrections to Consider

- System related
  - YAG:Ce powder and crystal screen spatial resolution.
  - Camera resolution and depth of focus.
  - OTR polarization effects and OTR point spread function.
  - Camera calibration factor.
  - Finite slit size (if applicable) .
- Accelerator / beam related
  - Beta star term in spectrometers.
  - Macropulse blurring effects on energy spread , beam size, and beam divergence in OTR images.
  - Most of the examples will be for electrons.

Observed vs Actual Slit Image Size

- **Uncorrelated terms are treated as a quadrature sum to actual image size *Act* (see *Lyons'* textbook [a]).**
  - **Observed image size *Obs***
  - **YAG screen effects *YAG***
  - **Camera resolution *Cam***
  - **Finite slit width *Slit***
- **In addition there can be macropulse effects and OTR polarization effects.**

$$Obs^2 = Act^2 + YAG^2 + Cam^2 + Slit^2$$

and solving for the actual beam size we have,

$$Act = \sqrt{Obs^2 - YAG^2 - Cam^2 - Slit^2}$$

[a]*Louis Lyons*, Statistics for Nuclear and Particle Physicists (1986)

Converter Screen Properties

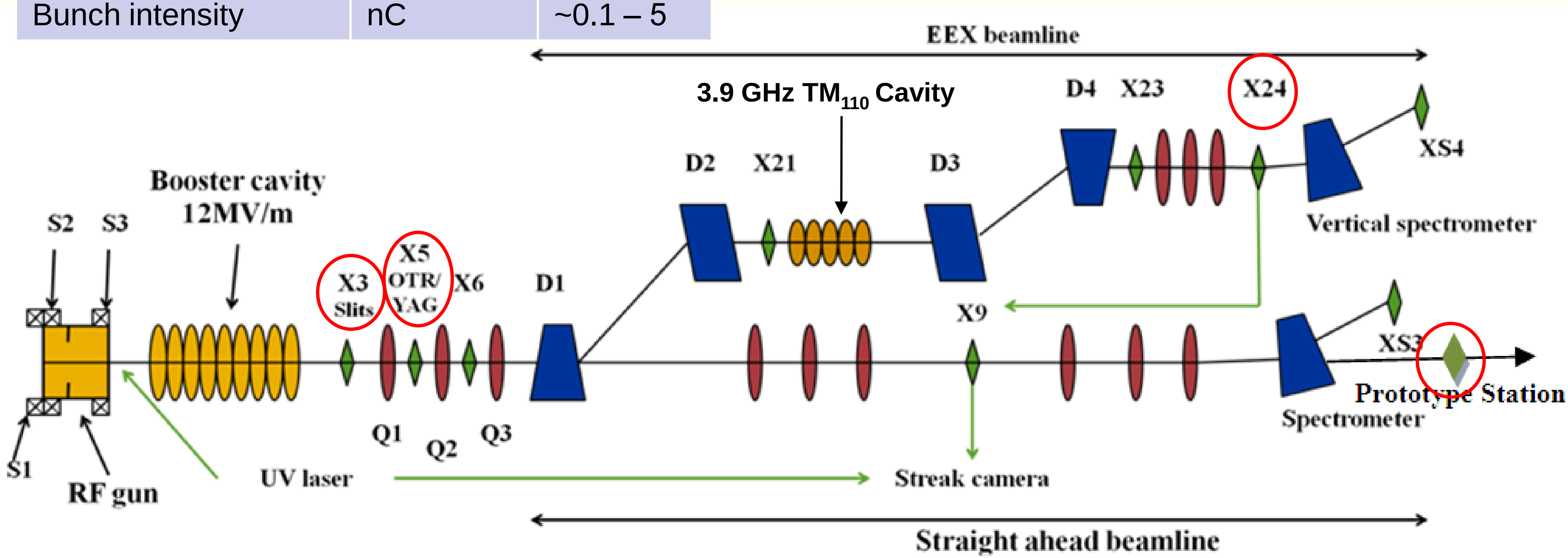
	YAG:Ce (Cerium doped) powder or single crystal	OTR screen, e.g. Al or aluminized Si
Efficiency	~100x	1x
Spatial resolution	Volume effect, grain size	EM surface phenomenon
Spectral content	Narrow band (~20 nm)	Broad band
Saturation, non-linearities	at high beam intensities	no
Response time	~50 – 100 nsec	~10 fsec (skin depth)
Screen geometry: normal / angular (45^0)	depth of focus, scattering, effective thickness, system simplicity, etc.	
Screen thickness, energy deposition, beam scattering	100 μm range	minimum: 1 μm (fragile!) maximum: some 100 μm
Light scattering	Halo effects through scintillating volume	None

YAG:Ce Powder Scintillator Screens

- **YAG:Ce screens, used at the A0 Photoinjector:**
  - **The screens have nominally a 5-μm grain size and are coated at 50-μm thickness on various metal substrates.**
  - **Substrates are Al or SS and 1 mm thick.**
  - **In the A0PI arrangement the scintillator was on the front surface of the substrate, and oriented at 45^0 to the beam direction.**
  - **Powder screens are kindly provided by *Klaus Floettmann* (DESY).**
- **Observed Characteristics**
  - **The response time is about 80 ns FWHM.**
  - **There have been reports of saturation of the mechanism for incident electron beam areal charge densities ~10 fC/μm^2.**
    - **This effect can cause a charge dependence of the observed image size in addition to the low-charge, screen resolution limit.**

Beamline and diagnostics support for EEX applications

Parameter	Units	Value
Energy	MeV	15
Energy spread	keV	10 – 15
transverse emittance	mm mrad	2.6±0.3
Bunch length	ps	3.1±0.3
Bunch intensity	nC	~0.1 – 5



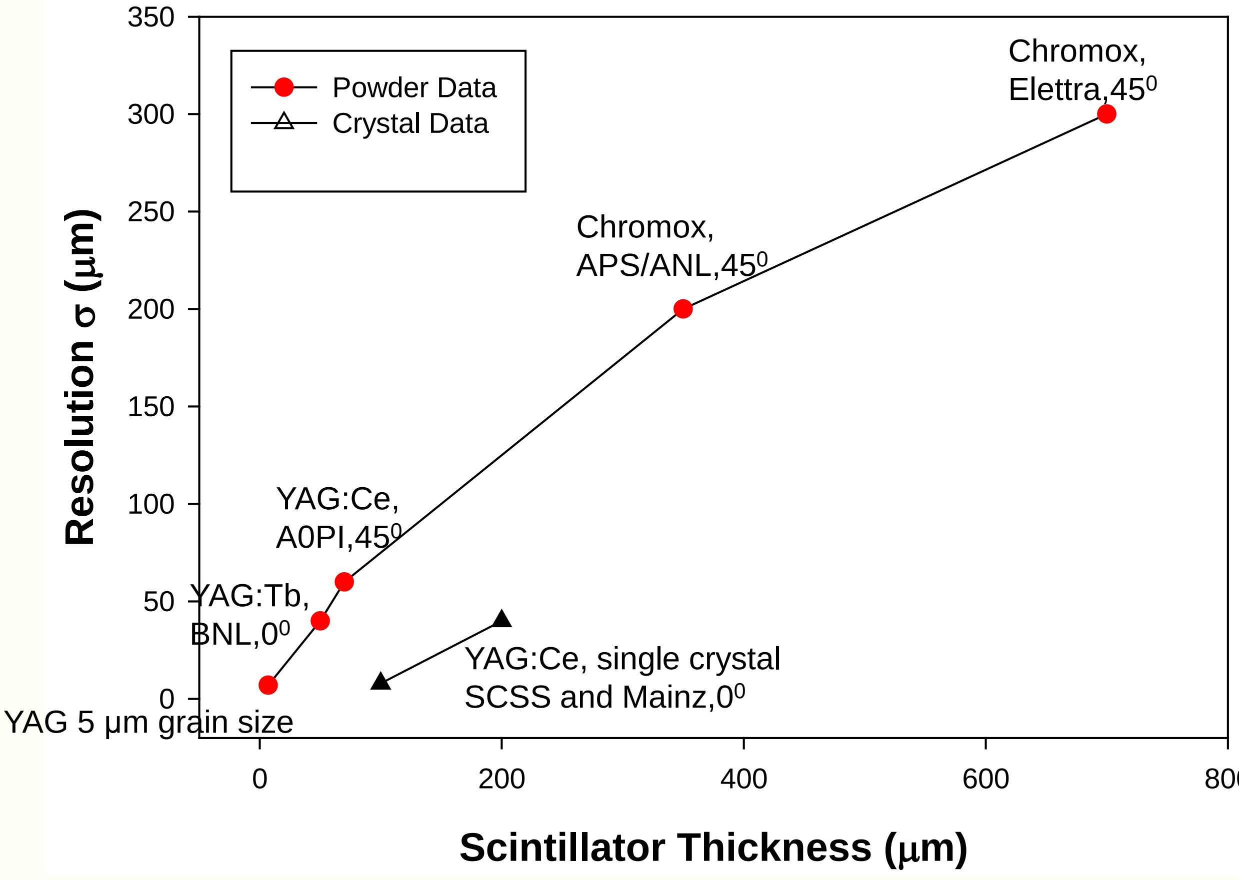
YAG:Ce Powder vs OTR Screen

	# of bunches	X5 linear polarization	Fit σ (pixel)	X Size (μm)
OTR	10	none	5.49 ± 0.05	124.5
		vertical	4.47 ± 0.09	101.0
YAG:Ce	1	none	5.67 ± 0.05	128.7
		vertical	5.71 ± 0.04	129.6

- **Both screen surfaces at 45^0 to the beam direction.**
- **Gaussian fits to the projected beam profiles of 10 images.**
- **Deduced YAG resolution term (page 6): 80 ± 20 μm**
- **Other data sets averaged for YAG term: 60 ± 20 μm**

Screen Resolution vs. Thickness

- **Scintillator screen resolution vs. thickness after applying corrections discussed on page 6.**



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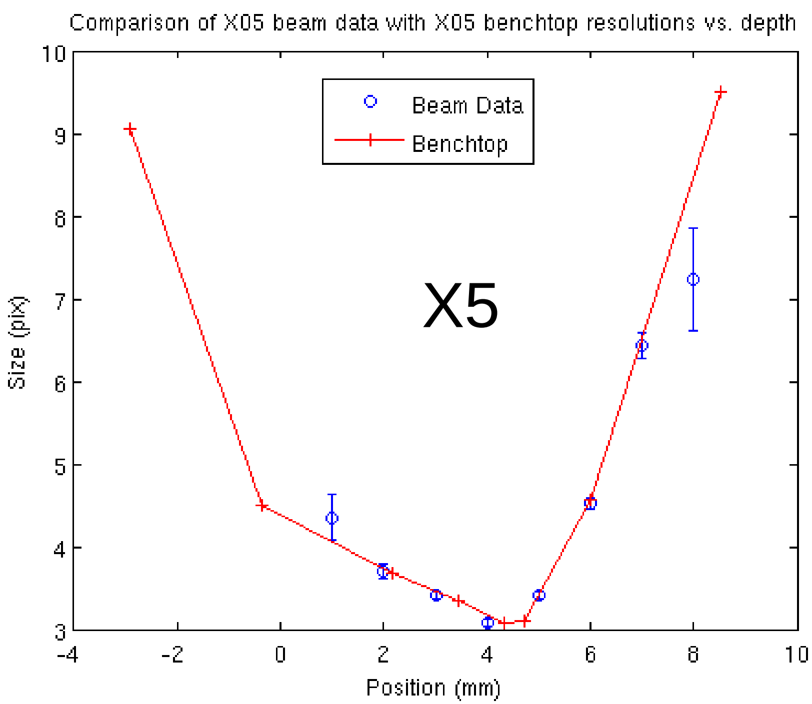
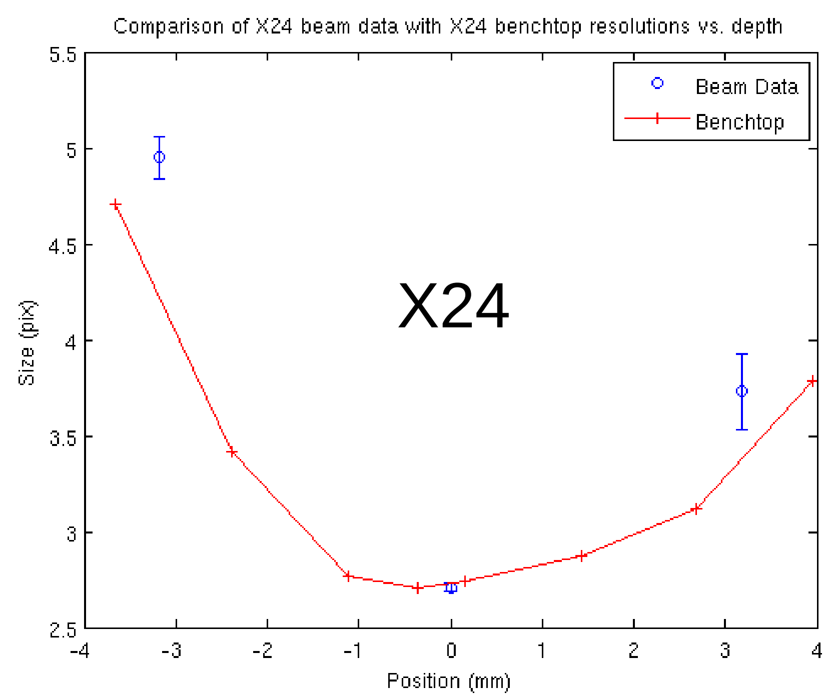
  - Most data examples will be for electrons except one hadron case and one heavy-ion case.

Depth-of-Focus Issues

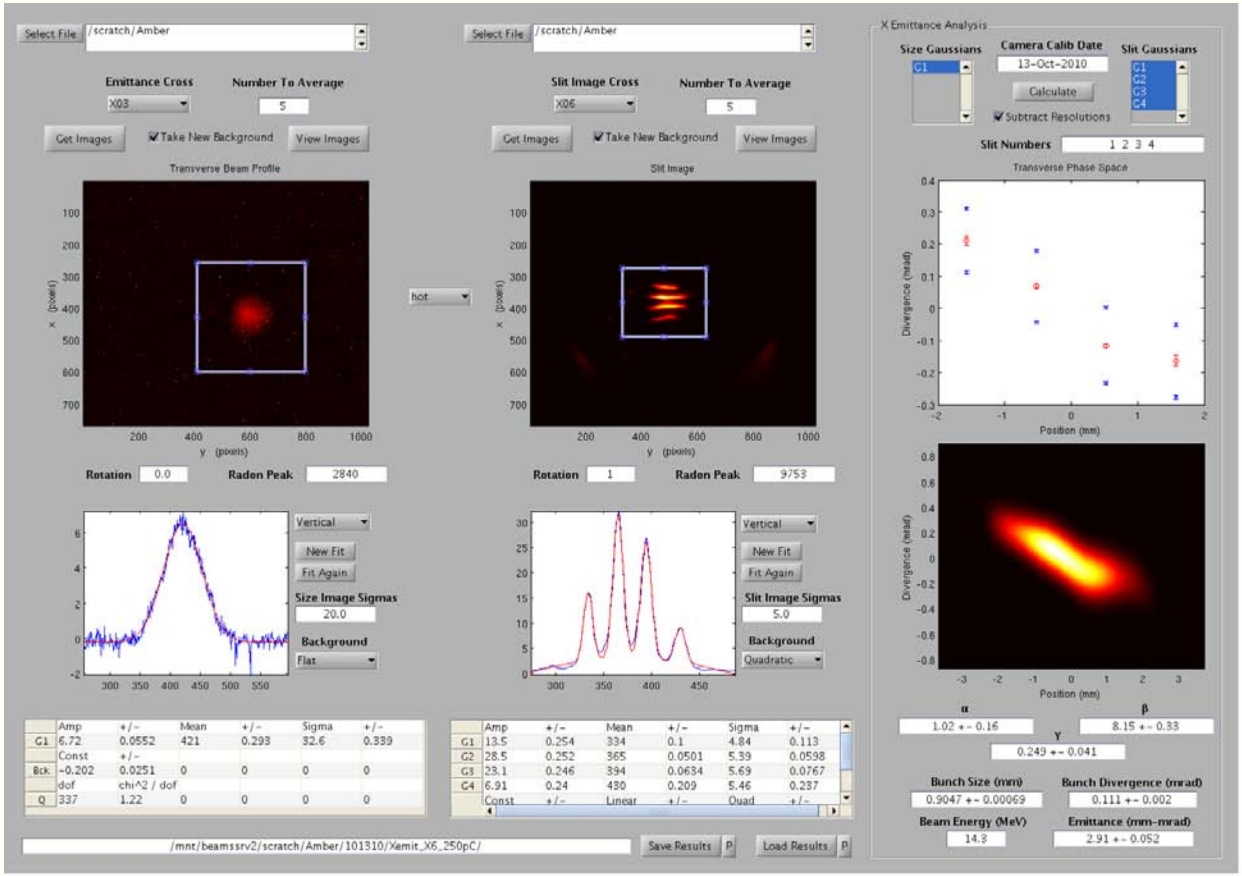
- **1 mm (X5) / 4 mm (X24) spaced slits, 50 µm wide**
  - **Camera calibration ~30 µm / pixel.**
- **Depth-of-focus issues in extended field of view for 45^0 arrangement of the YAG:Ce scintillator screen**





MATLAB Emittance Code

- **Application tool provides online emittance and C-S parameter calculations to facilitate operations.**



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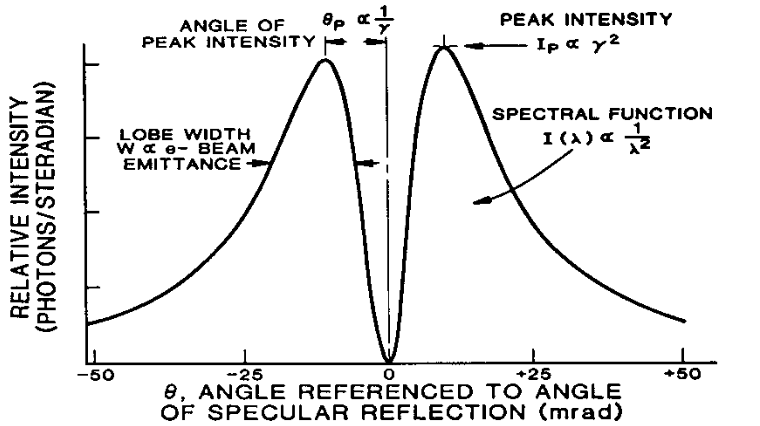
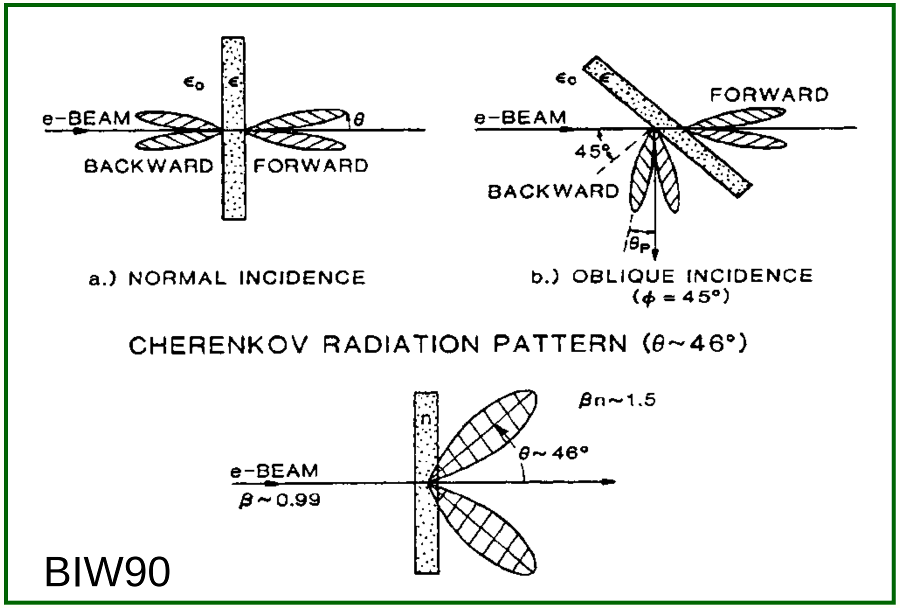
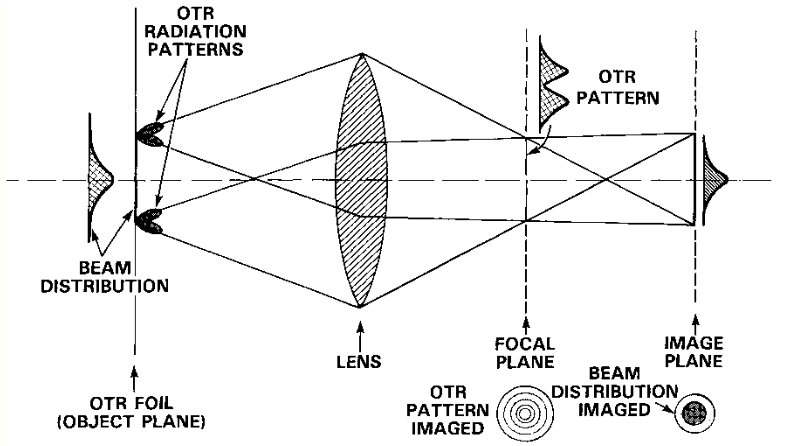
Optical Transition Radiation (OTR)

- **OTR can be used for beam**
  - **profile / size**
  - **position**
  - **divergence**
  - **energy,**
  - **relative intensity**
  - **bunch length**
- **Charged particle passing a media boundary (EM dipole).**

OTR angular intensity distribution of a single charged particle







OTR Calculation

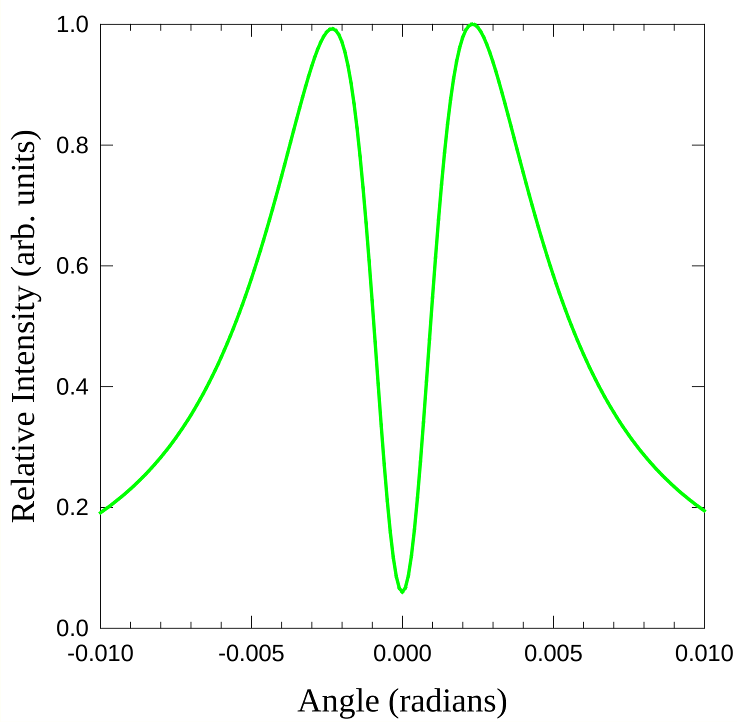
- **OTR single particle spectral-angular distribution:**

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

  - ***Ω* spatial angle**
  - ***ω* angular frequency**
  - ***N_1* # of photons**
  - ***$\Theta_{x,y}$* radiation angle**
  - ***e, ħ, c, π* constants**

***E* = 220 MeV**

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



- **Coherent spectral-angular distribution from a macropulse**

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

  - ***N* # of photons from per unit frequency and solid angle (typ. 1 e -> 0.001 photons)**
  - ***r* reflection coefficient**
  - ***I* interference function (double foil)**
  - ***F* coherence function (can be non-linear)**

OTR 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 = $f_B = N_B/N$

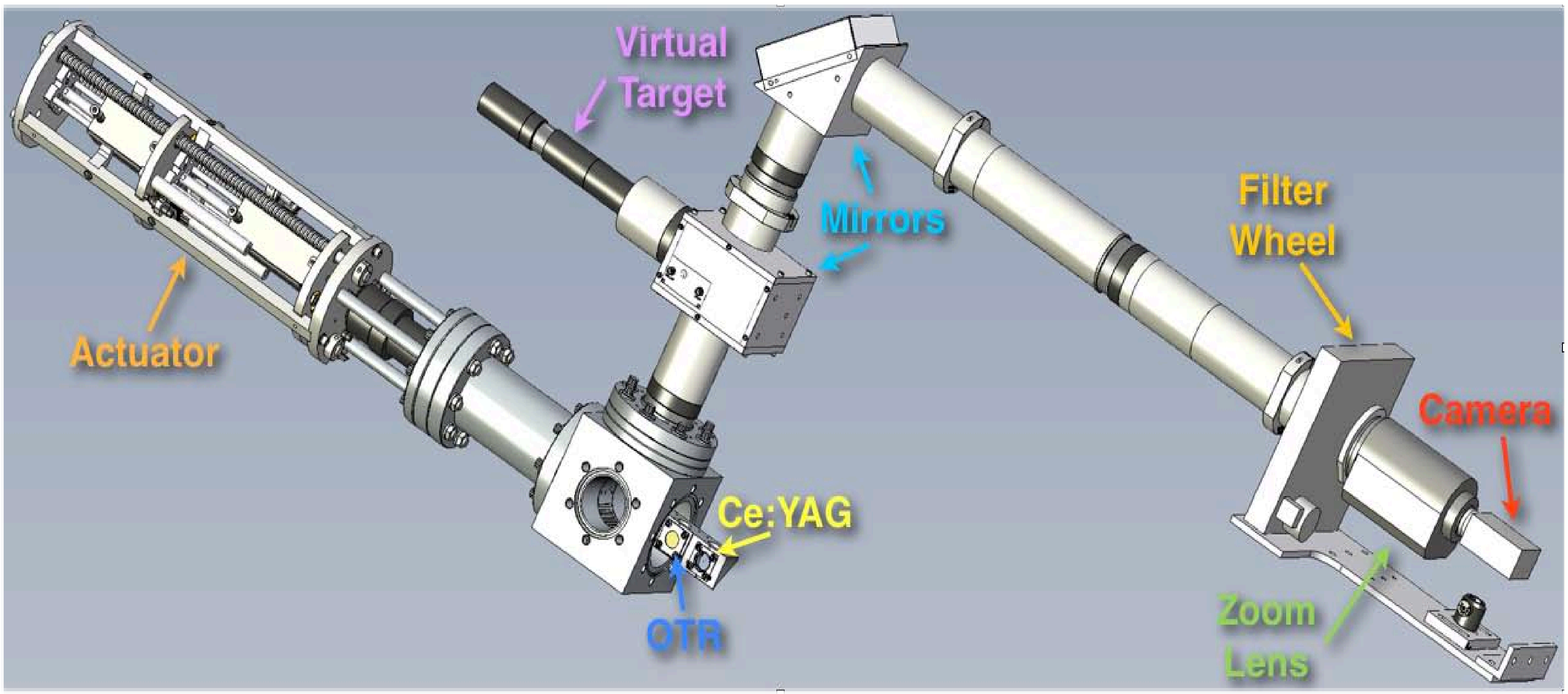
For the broadband microbunching instability, enhancements can occur at visible wavelengths,COTR.

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

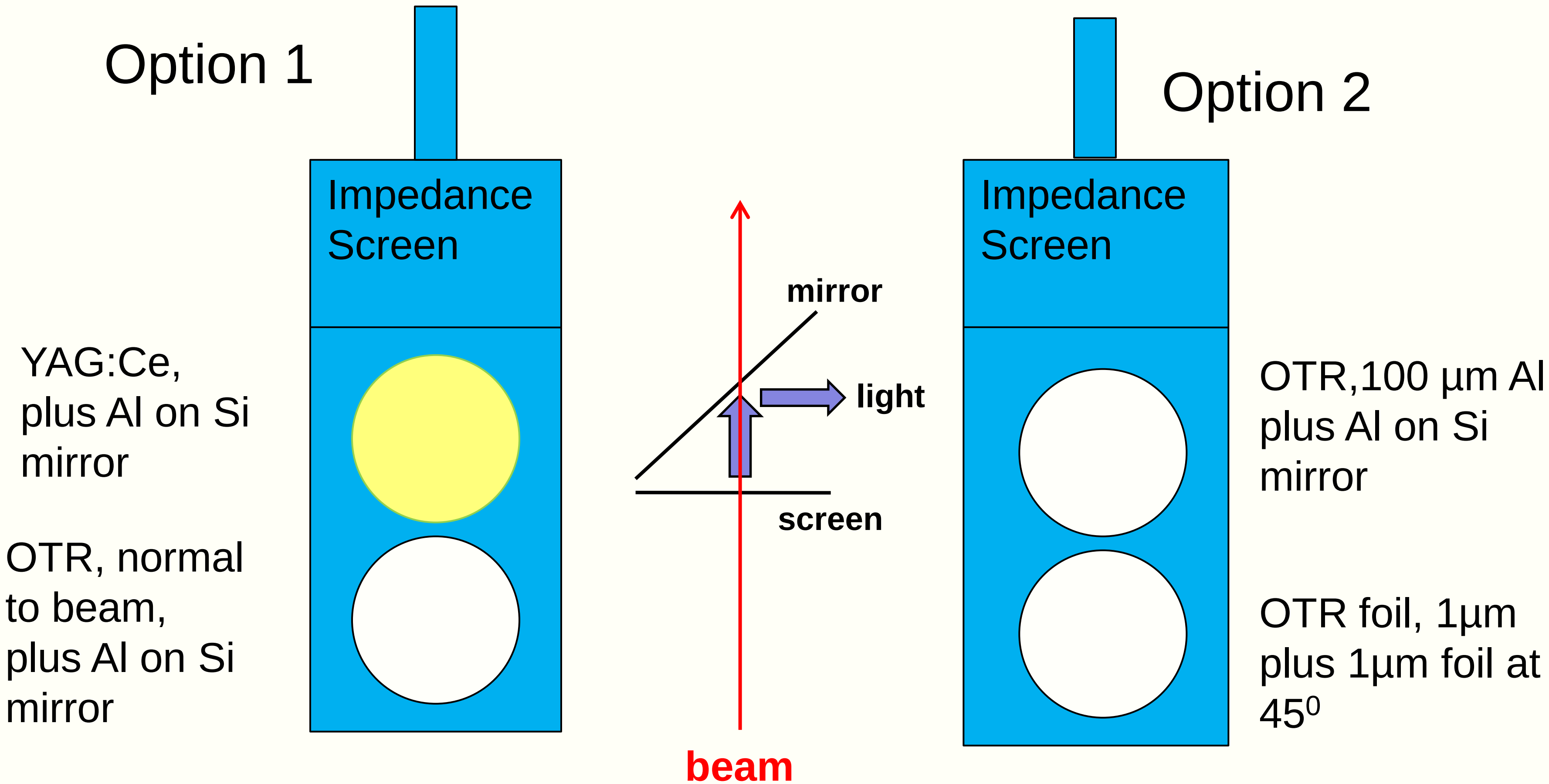
Prototype Imaging Station

- **New developed imaging station in collaboration with RadiaBeam, Inc.**



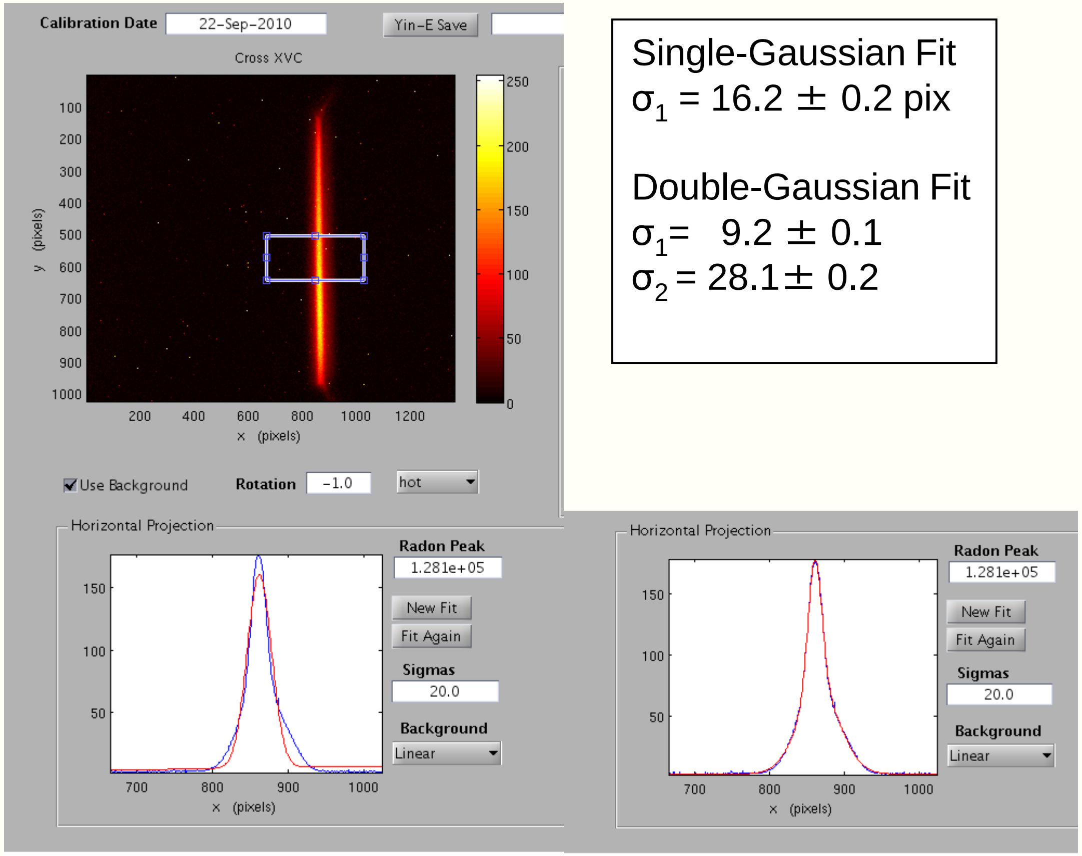
OTR / YAG Configurations

- **Switchable assemblies to compare options.**
  - **Still tweaking!**



Test of OTR Normal to Beam

- **Optics focused on crystal location:**
  - **gives superposition of focused OTR and defocused OTR source from mirror.**



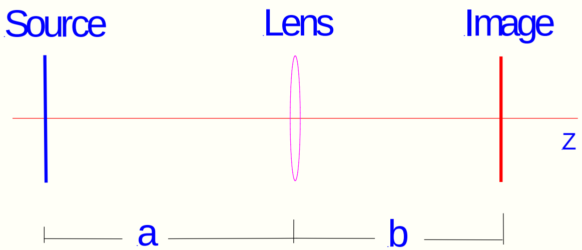
Single-Gaussian Fit
$\sigma_1 = 16.2 \pm 0.2$ pix

Double-Gaussian Fit
$\sigma_1 = 9.2 \pm 0.1$
$\sigma_2 = 28.1 \pm 0.2$

Point Spread Function (PSF)

Fermilab

- **At the diffraction limit $\Delta x \approx \lambda/\Delta\theta$ the image of a point source radiates a ring pattern defined by the OTR point spread function (PSF):**



PSF: convolution integral of

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

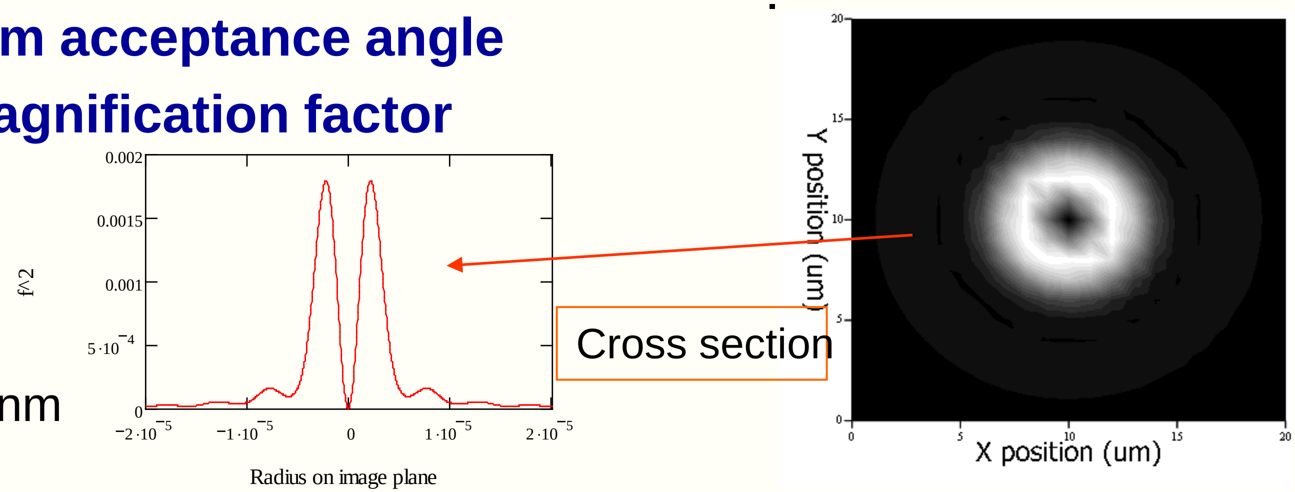
OTR response

Point charge diffraction stimulus function

$$\theta = R_i/a \qquad \varsigma = kR_i/M$$

- θ_m **maximum acceptance angle**
- $M = b/a$ **magnification factor**
- R_i **radius of the lens**

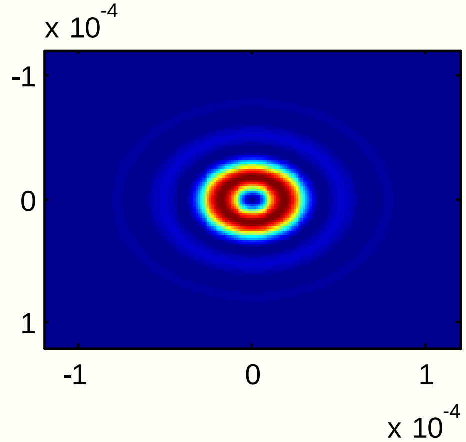
Example:
M=1, E=4GeV, λ=500nm
courtesy *C. Liu (BNL)*



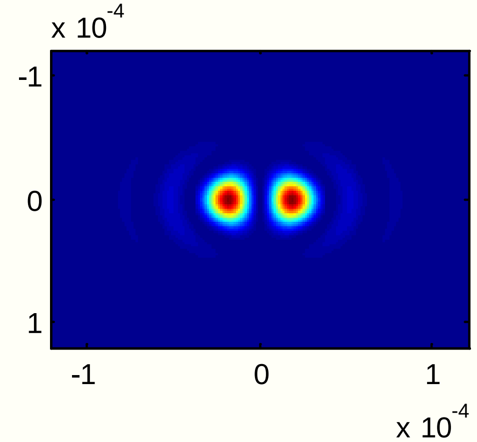
OTR PSF Calculations (MATLAB)

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

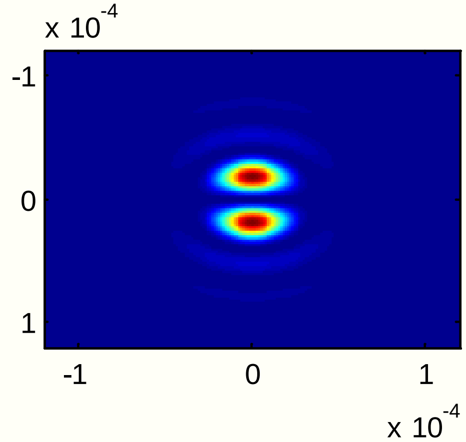
Total PSF

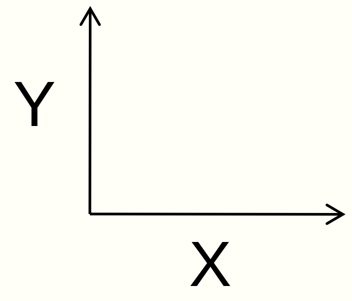


Hpol PSF



Vpol PSF

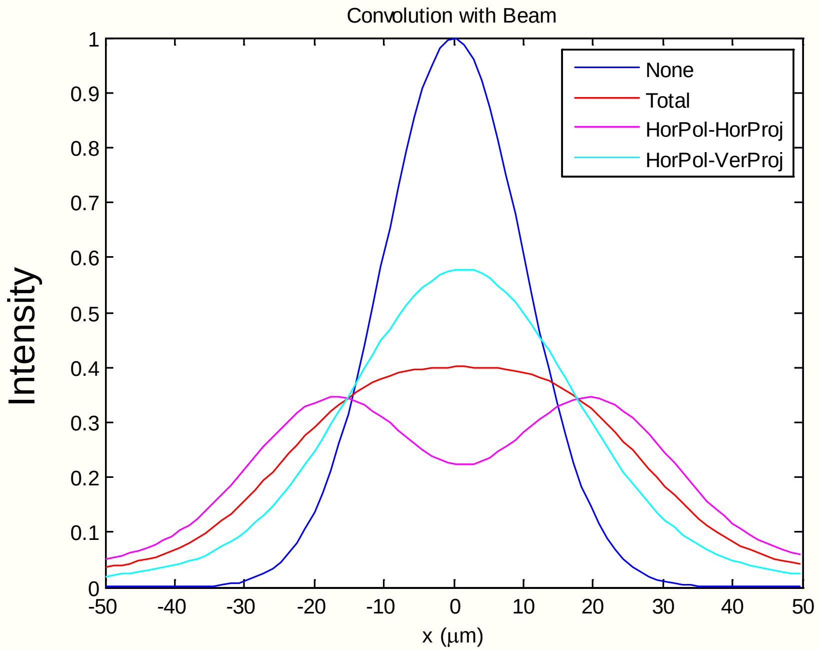


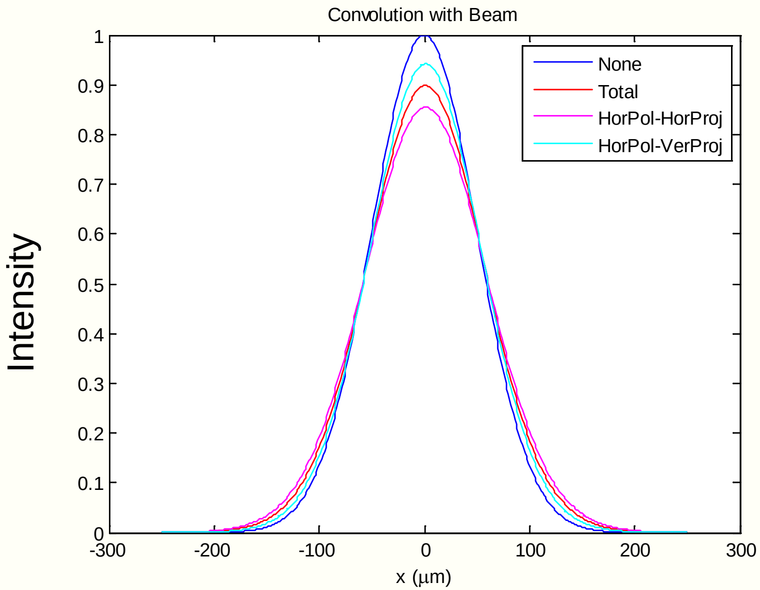


At Image plane

PSF Polarization Convolved (cont.)

- **14.3 MeV, M = 1, λ = 500nm, θ_{max} = 0.010, σ = 10 & 50 μm**





Original Sigma = 10 μm
Total PSF Sigma = 22.59 μm
HorPol-HorProj PSF Sigma = NA
HorPol-VerProj PSF Sigma = 16.63 μm

Original Sigma = 50 μm
Total PSF Sigma = 55.63 μm
HorPol-HorProj PSF Sigma = 58.49 μm
HorPol-VerProj PSF Sigma = 53.05 μm

Polarized Beam Images at XUR

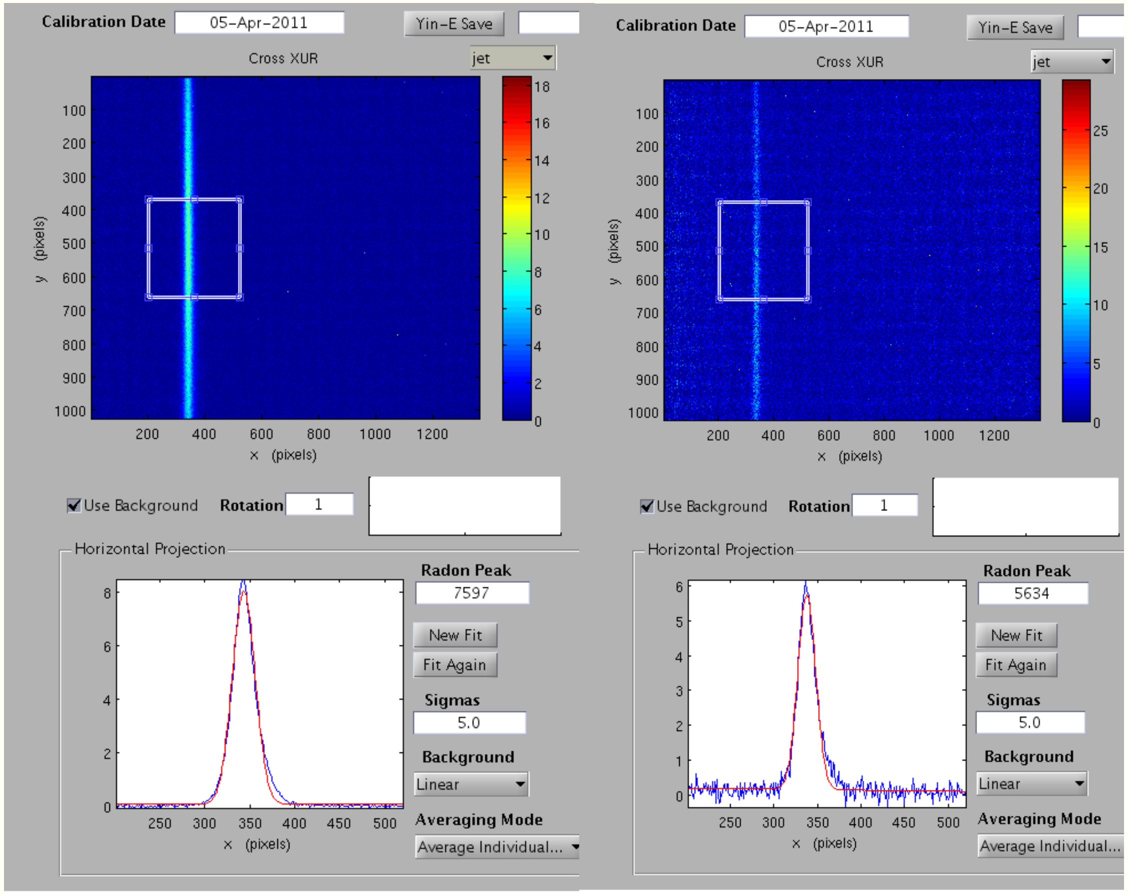
- **OTR Perpendicular component has 15 % smaller profile.**
  - **Beam measurements with a vertical stripe, ~50 μm wide.**

Total Pol.: Left
Single-Gaussian Fit
σ_1 = 66.8 ± 0.3 μm

Vert. Pol.: Right
Single-Gaussian Fit
σ_1 = 55.1 ± 1.1 μm

12μm effect @ 55 μm

(Cal.: 5.3 μm/pixel)



KEK Experimental OTR PSF

- **KEK staff used vertical polarizer and small beam to observe PSF and suggested potential use of structure.**
  - **Use PSF valley for profile measurements at the PSF limit.**

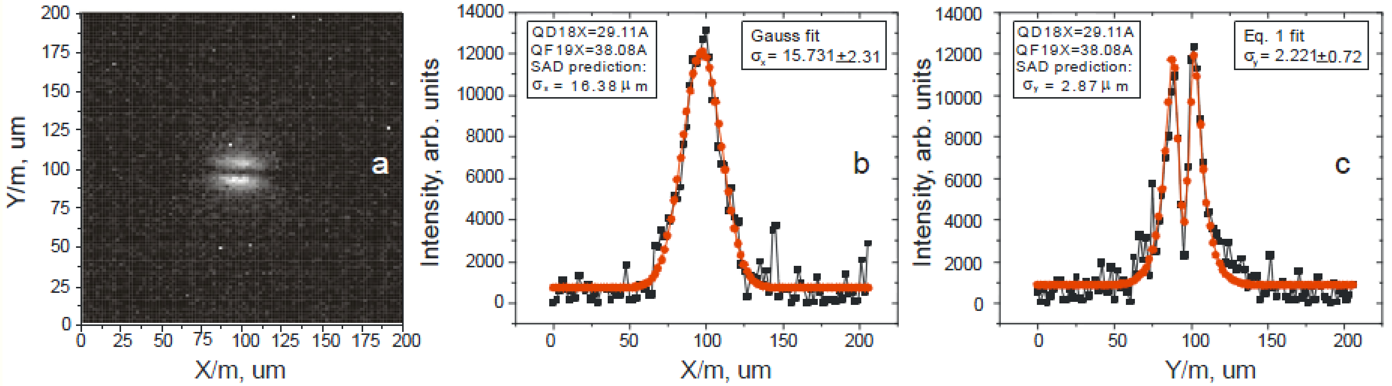


Figure 3: CCD image of the OTR taken with linear polarizer and 500 nm optical filter (a) and two image projections: horizontal (b) and vertical (c).

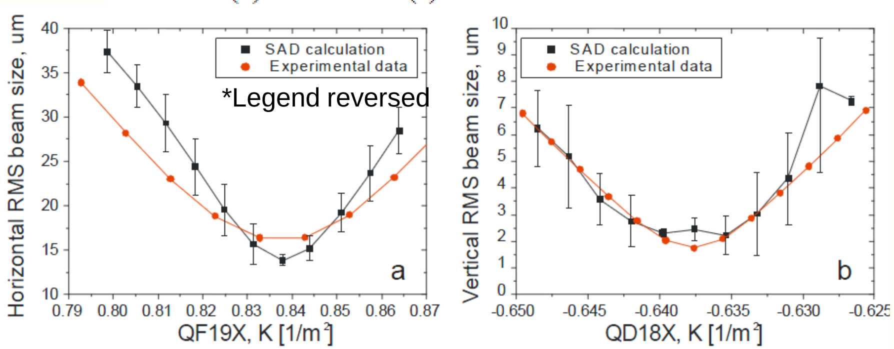


Figure 4: Horizontal RMS beam size as a function of the QF19X strength (a) and the dependence of the smoothing parameter σ (Eq. 1) versus QD18X quadrupole magnet strength. SAD predictions of the vertical beam size for the same magnet strengths are also shown in the picture.

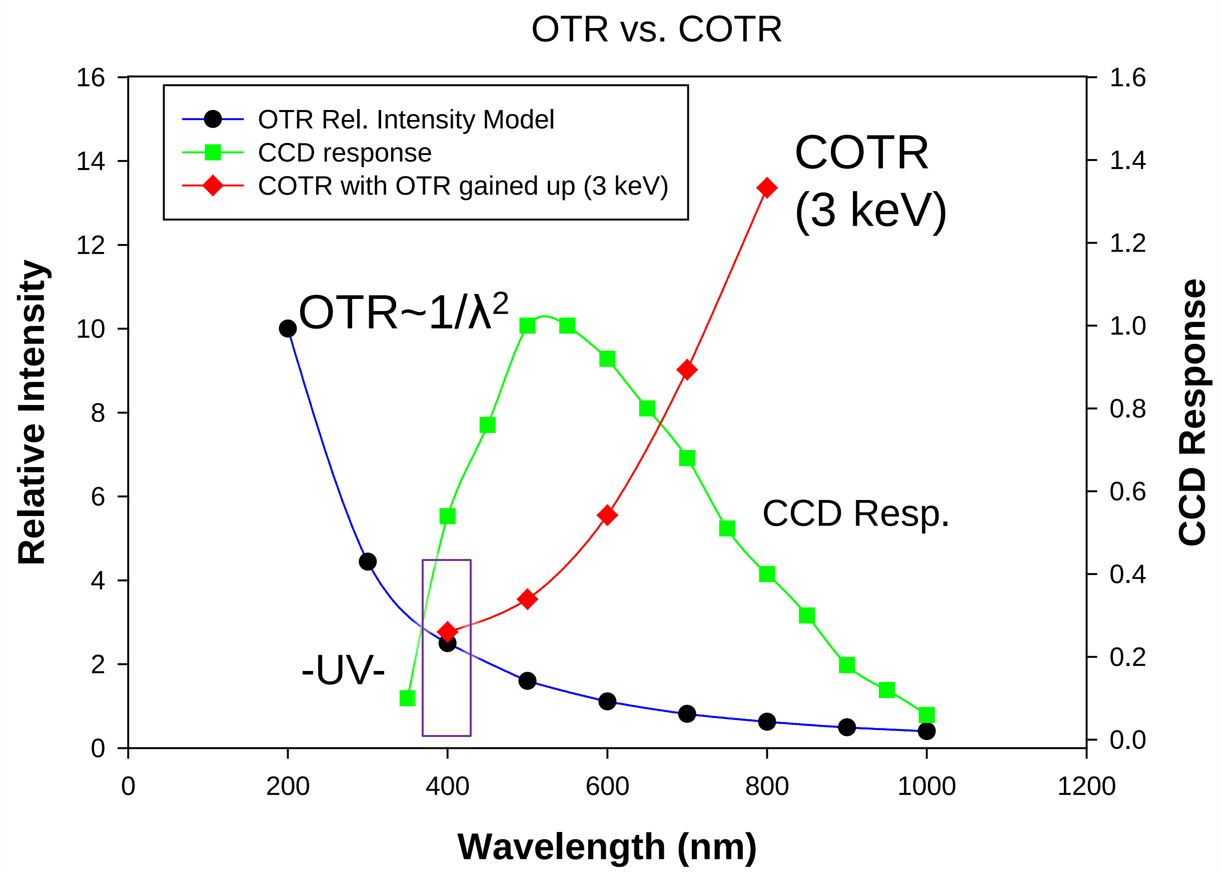
$$f(x) = a + \frac{b}{1+\left[c(x-\Delta x)\right]^4}\left[1 - e^{-2c^2\sigma^2}\cos\left[c(x-\Delta x)\right]\right] \quad (1)$$

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

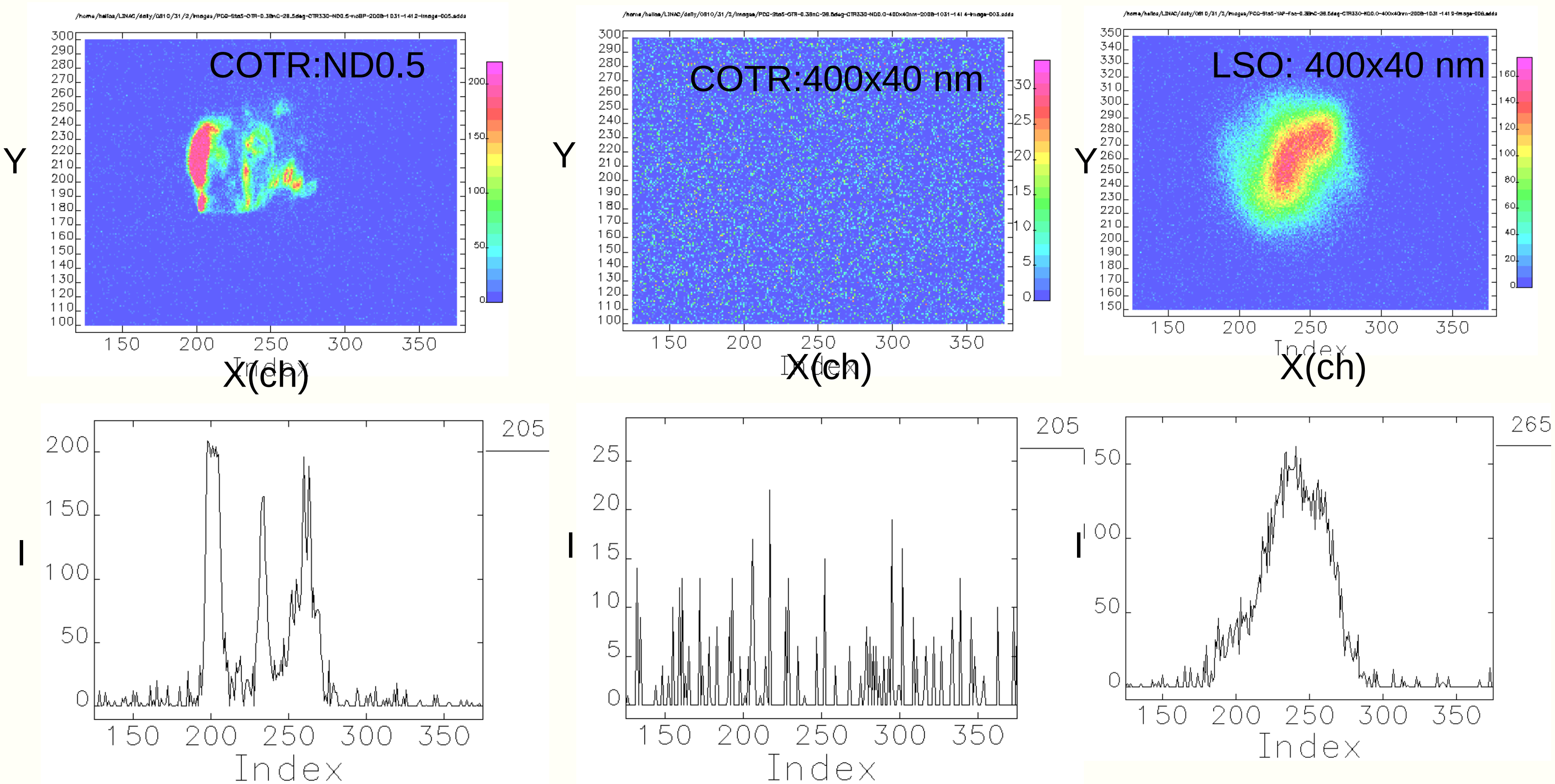
COTR Case at 250 MeV

- **Estimation of OTR/COTR spectral effect for LCLS case.**



COTR Mitigation Test at St-5/ANL

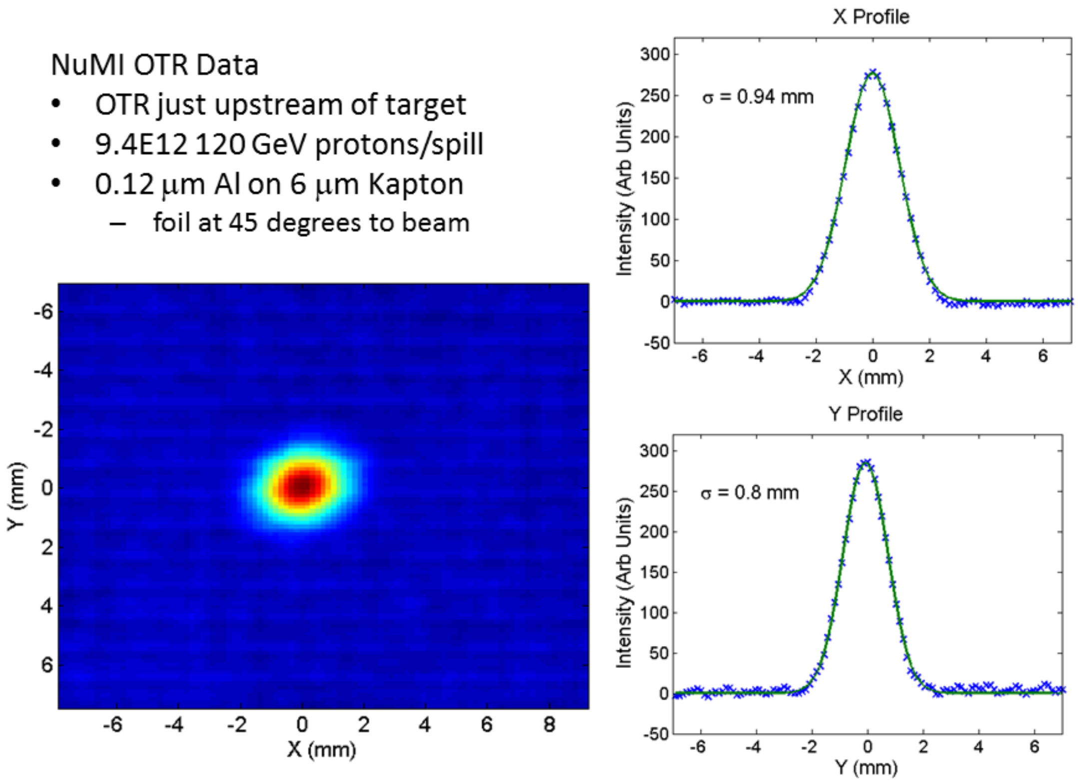
- **Reduction of COTR effects with 400x40 nm BPF, but need more sensitive camera than 40dB analog CCD to see remaining OTR.**



120-GeV Proton Beam OTR Images Obtained at FNAL (2007)

- Proton beams for the neutrinos with the main injector (NuMI) target can be imaged in the transport line.

NuMI OTR Data
- OTR just upstream of target
- 9.4E12 120 GeV protons/spill
- 0.12 μm Al on 6 μm Kapton
  - foil at 45 degrees to beam



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 batch in 1mm x 1mm spot on aluminized Kapton (7 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, LHC, RHIC?

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,

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

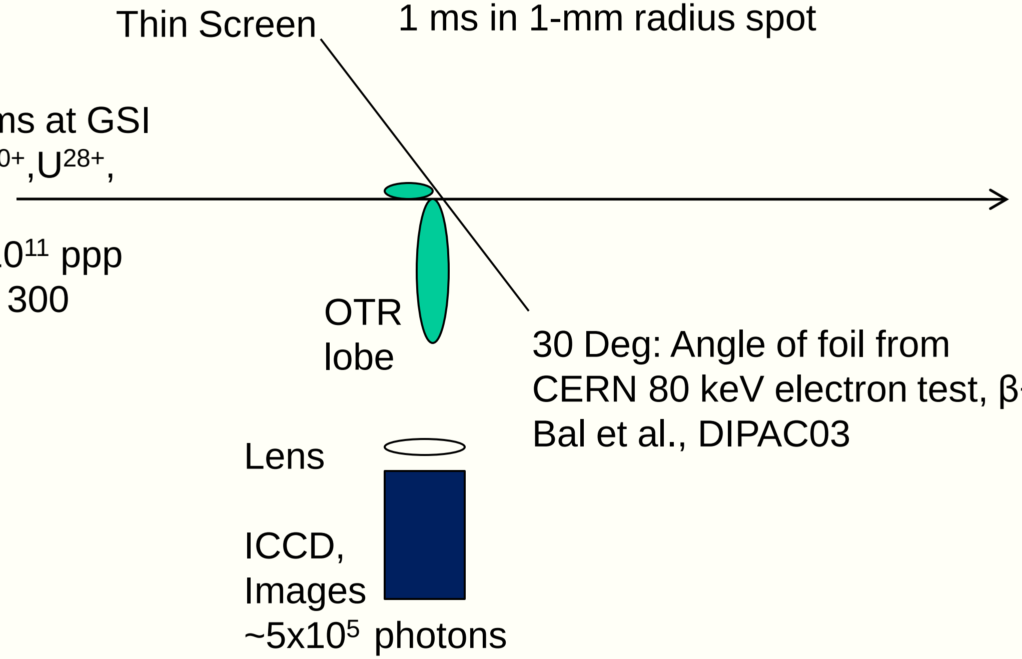
where $\beta = v/c$ and c is the speed of light.

Ginzburg and Tsyovich,(1984)

More than a “gedanken” experiment!

Alum. Kapton at FNAL handled 10^{13} protons in 1 ms in 1-mm radius spot

HI beams at GSI e.g. Ar^{10+}, U^{28+}, U^{73+}
10^9 to 10^{11} ppp
11.4 to 300 MeV/u



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

OTR Cases Show Potential for Ions

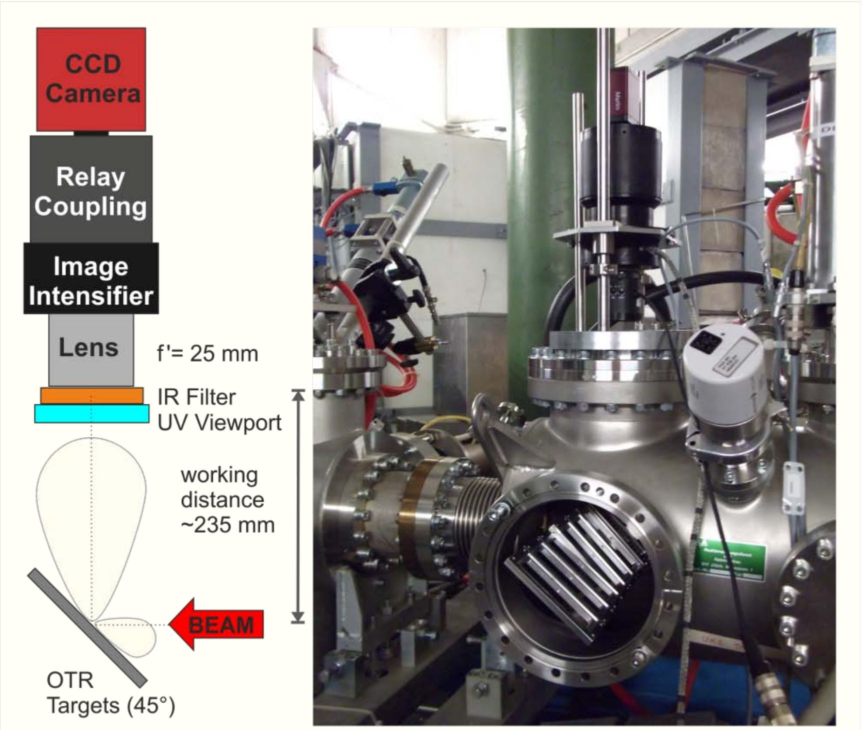
- **Table I. Comparison of various particle beam cases and estimated OTR photons generated (Preliminary).**

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

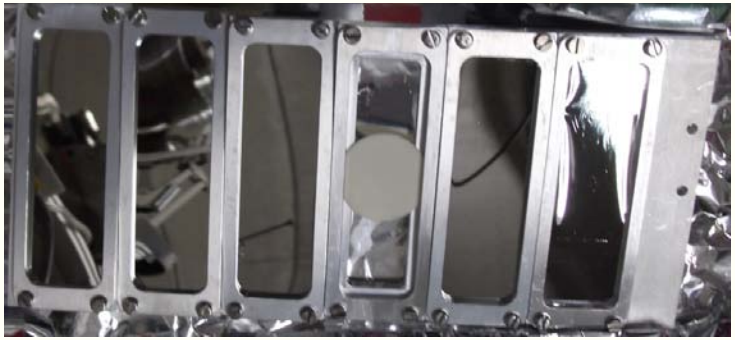
***Use intensifier for gain and the gating feature. More discussions later today. Also the ion intensity increases projected for FAIR look even better for photon numbers. The Multiplier (Mult.) column is the scaling with $Q^2\beta^2$.**

Experimental Setup at GSI

Experimental setup consists of an OTR target ladder (6 targets on one ladder) and image-intensified CCD camera system (ICCD) from PROXITRONIC.



Target ladder before high current irradiation



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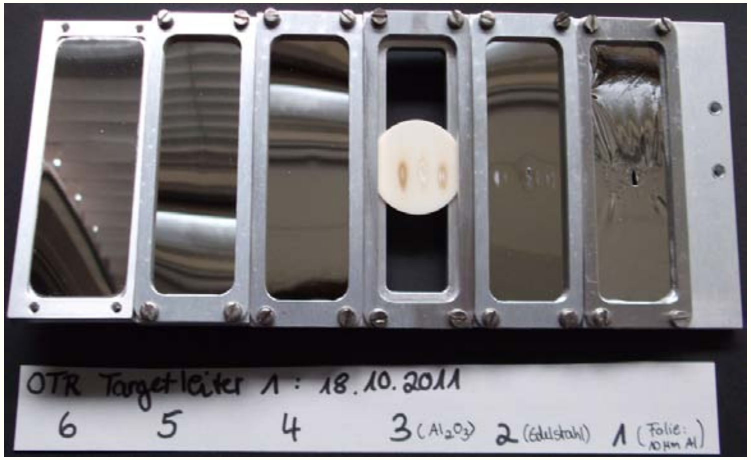


For future investigations we reduced beam current!

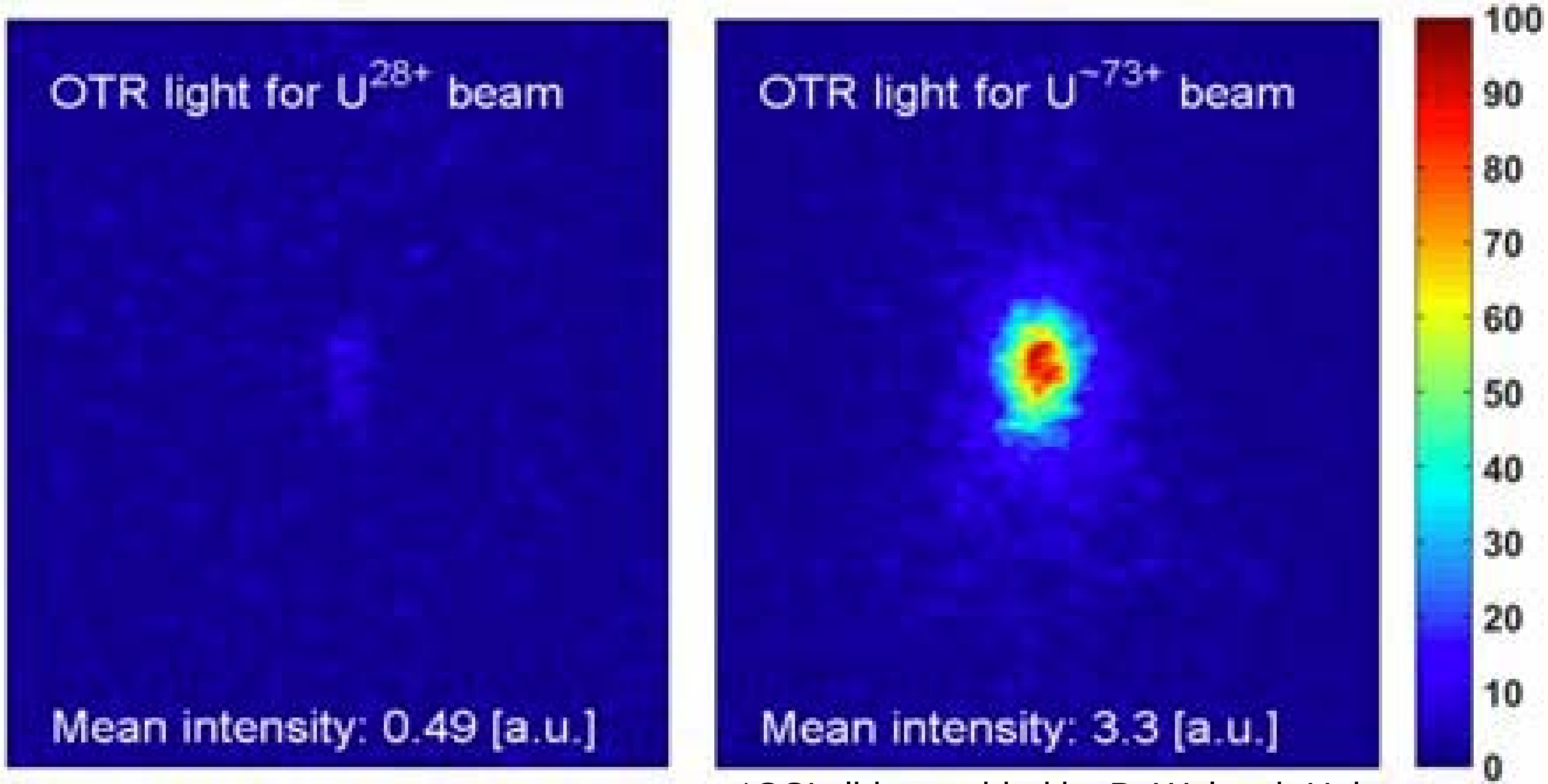
- the exact ICCD gating feature (down to 10 µs) was used to select preferentially the prompt OTR signal versus any background sources in the scene.

*GSI slides provided by B. Walasek-Hohne

First HI OTR Results: Q^2

Q^2 dependence

- Figure compares raw data of beam distributions for both charge states, but same ion number of ~$7 \cdot 10^8$. The ratio of the integral ICCD intensities roughly supports the predicted Q^2 dependence: $3.3/0.49 \sim 73^2/28^2$ for chosen ROI.

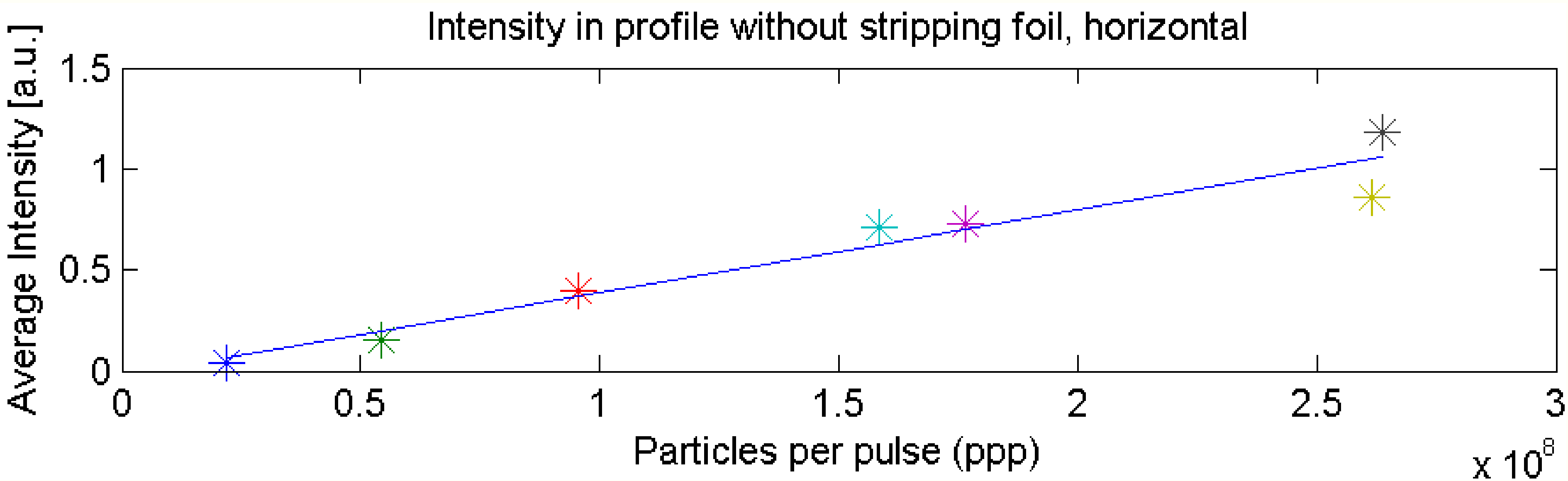


*GSI slide provided by B. Walasek-Hohne

First OTR Results at GSI:Linearity

Light yield versus particles per pulse

- OTR light yield scales linearly with particle number



*GSI slide provided by B. Walasek-Hohne

Proposed FACET test at 23 GeV

- **New parameter space for OTR/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

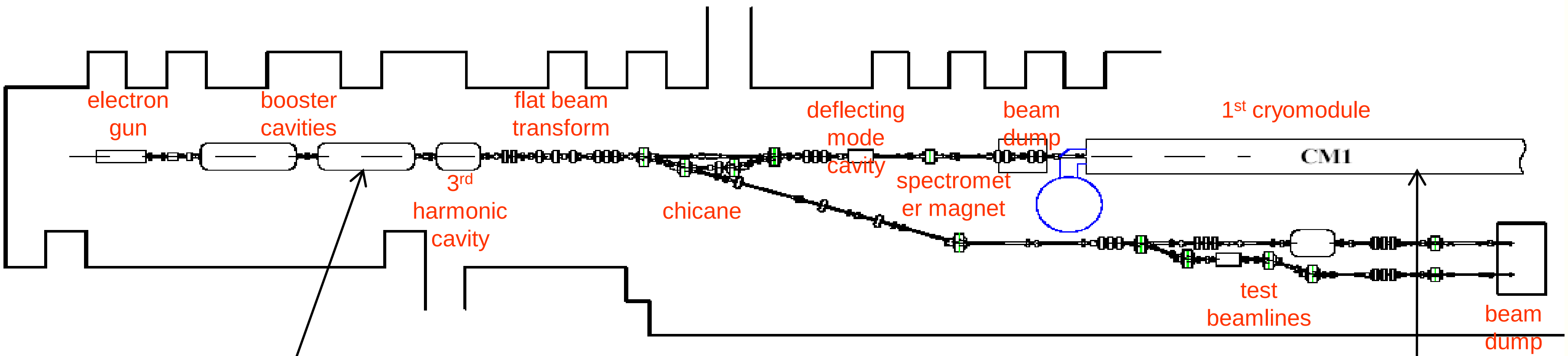
- **FACET parameters closer to ILC parameters.**

40-MeV Injector for ASTA/FNAL

Fermilab

- **Injector being installed with First beam expected in 2012.**

40-MeV Injector



Booster cavity 2 (from DESY and Saclay) installed in NML

Courtesy of *M. Church*

First cryomodule (from DESY) installed at NML.

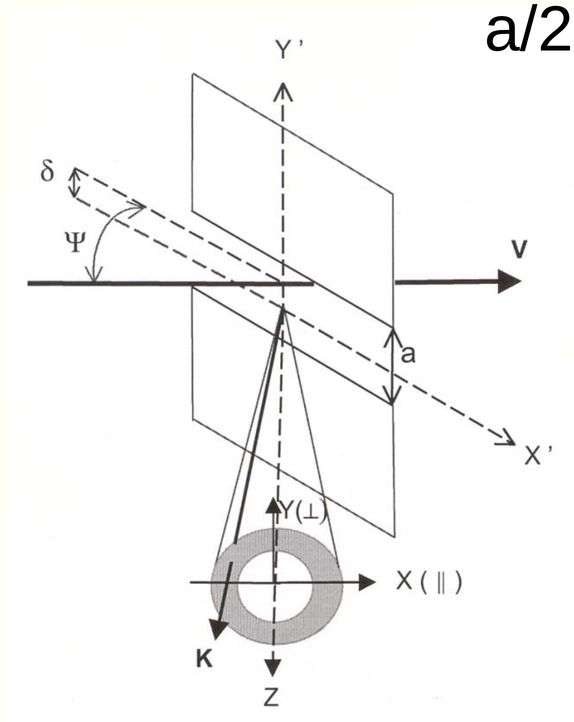
Summary

- Scintillator resolution terms should be characterized,
  - Use normal incidence of beam as preferred geometry to minimize depth-of-focus issues in beam images.
- OTR polarization effects need to be elucidated
  - Plan to optimize OTR PSF and optical resolution.
  - Plan to use linear polarizers with OTR imaging for the perpendicular profile components at ASTA.
- Mitigate microbunching instability effects for profiling of bright beams.
  - Plan to use 400x40 nm band pass filters and LYSO:Ce crystals after bunch compression at ASTA to suppress expected diagnostics complications due to COTR.
- New paradigm for heavy-ion beam imaging with OTR.
- The future remains bright for imaging techniques.

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

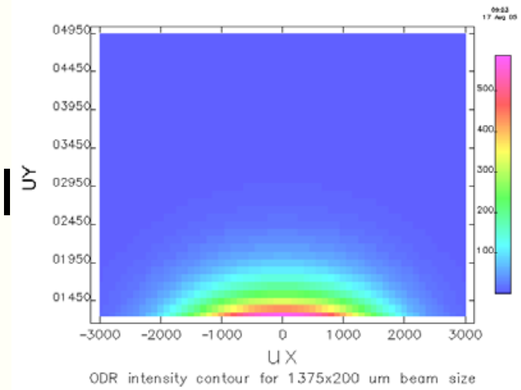
Fermilab

- **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 model (Rule and Lumpkin).**

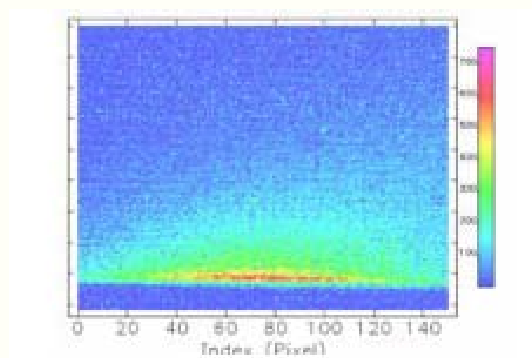


$a/2=d\sim\gamma\lambda/2\pi$

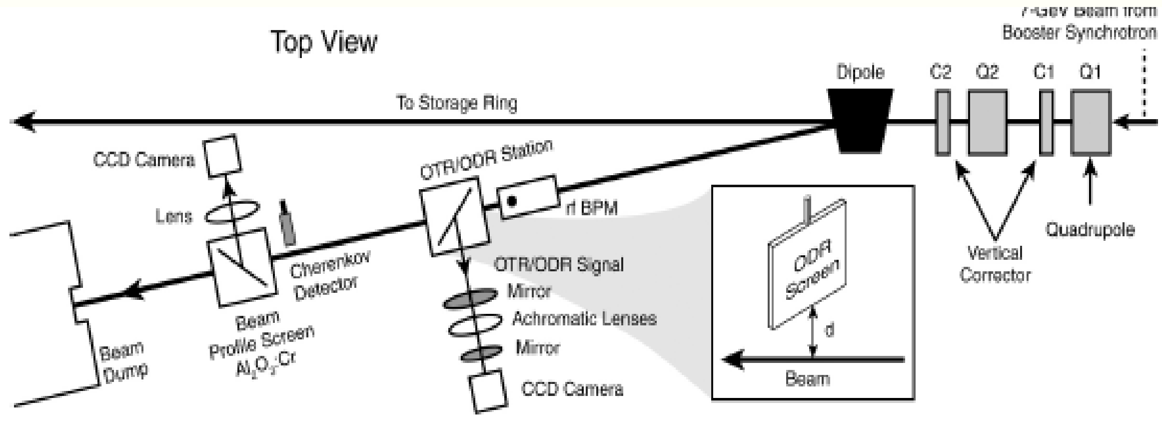
Model

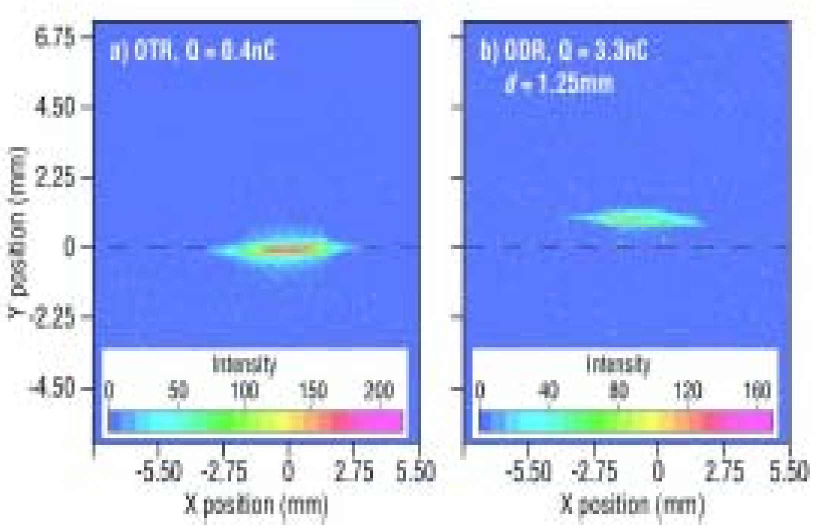


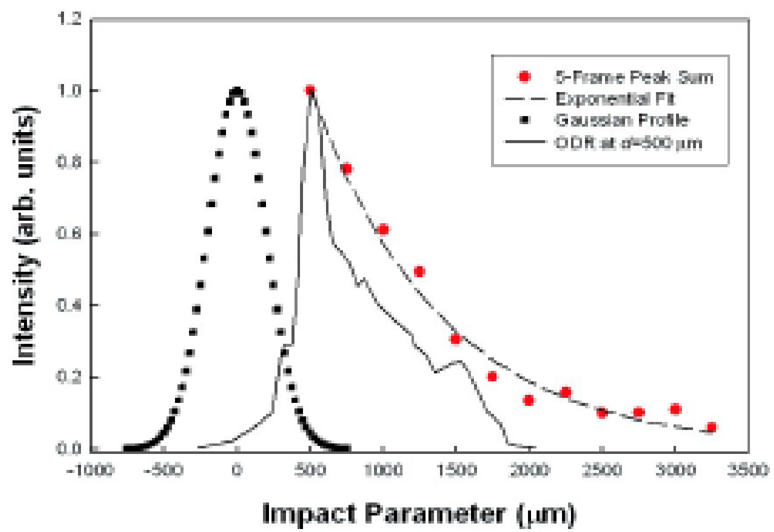
Data



7-GeV Test at APS



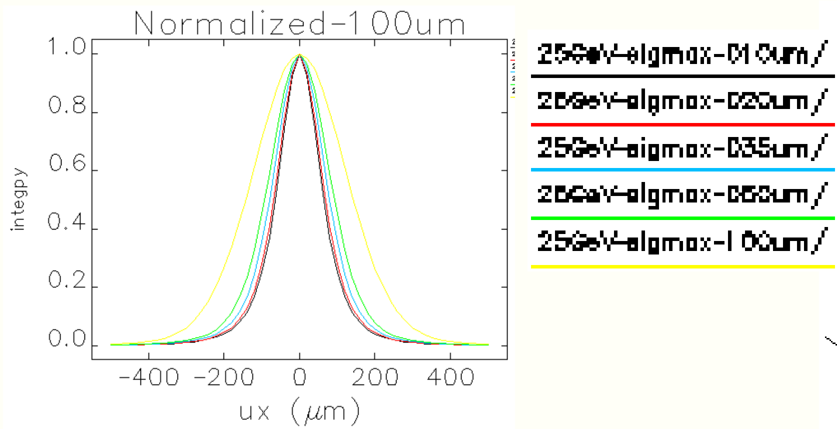


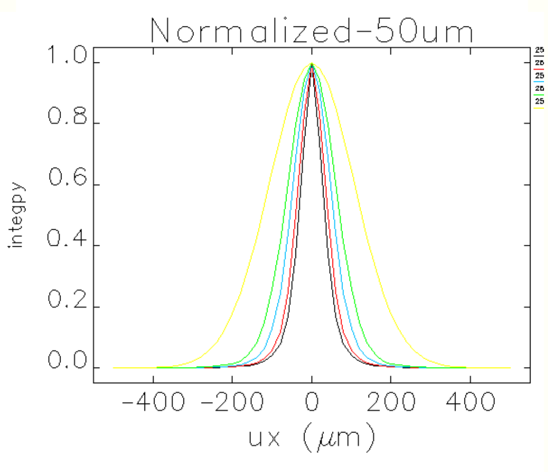


Lumpkin et al., PRST-AB (Feb. 2007)

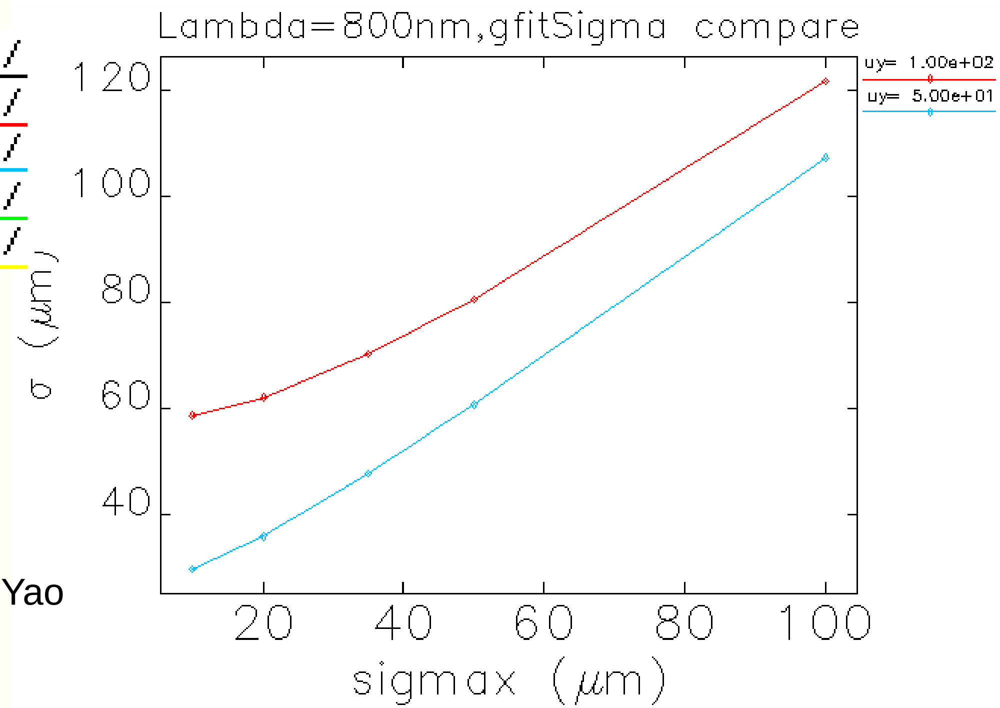
ODR model: FACET Case

- **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)**

Further ODR Studies Proposed

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