ODR Imaging for Charged-Particle Beams

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Presented at Instrumentation Group Mtg

March 19, 2008

Batavia, Illinois

OUTLINE

- Introduction
- Optical Diffraction Radiation (ODR) as a nonintercepting (NI) beam-size monitor.
- Optical Diffraction Radiation Experimental Results (APS, CEBAF, FLASH)
- Potential applications of ODR to NML, ILC, Tevatron, XFEL, ERLS, etc.
- Summary

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), etc..

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

  - imaging sensor such as CCD or CID camera, with or without intensifier.

  - video digitizer.

  - image processing software.

Strategy (We can extend this to ODR.)

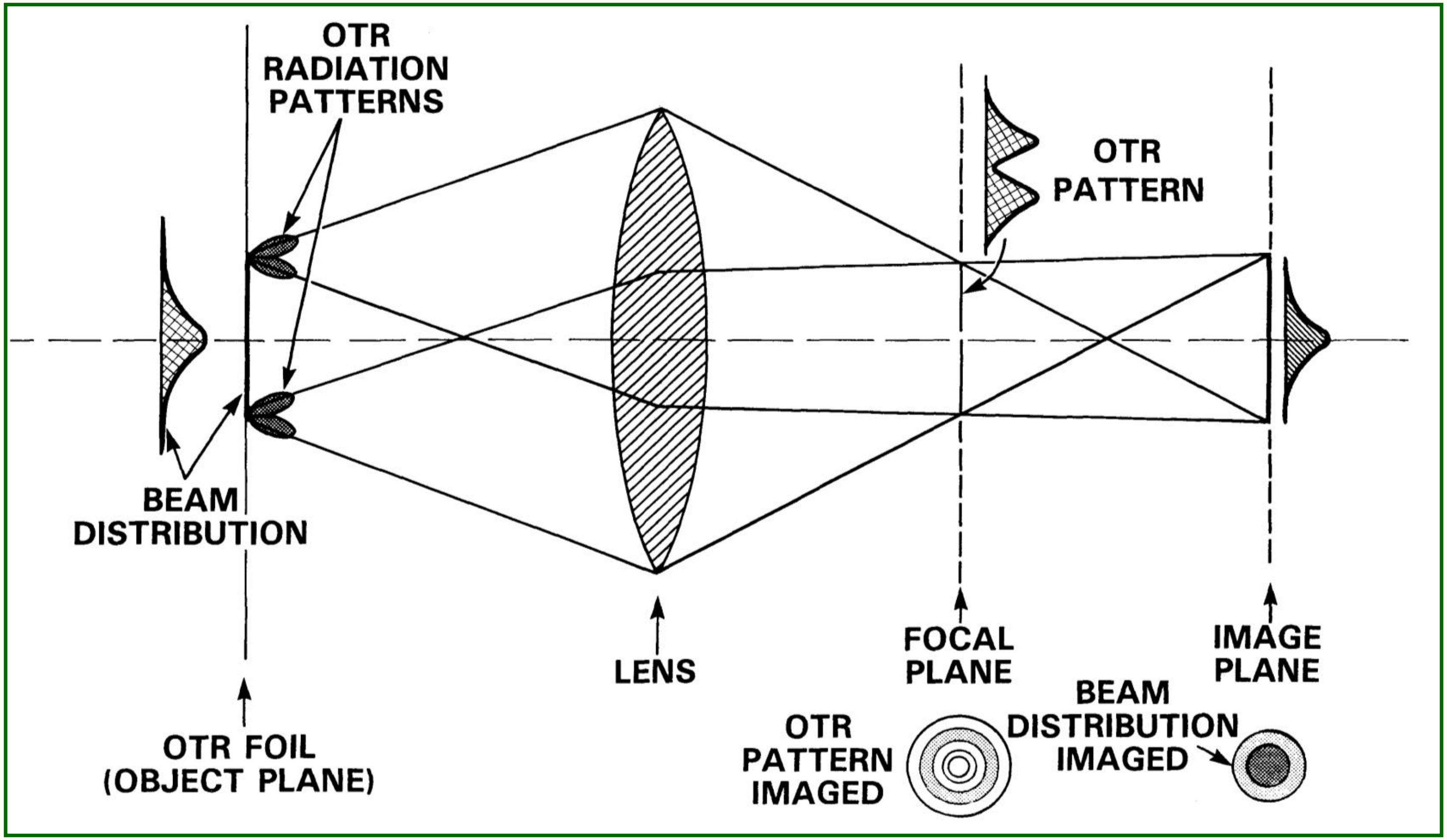
Convert particle-beam information to optical radiation and take advantage of imaging technology, video digitizers, and image processing programs. Some reasons for using OTR/ODR are listed below:

•The charged-particle beam will transit/pass nearby thin metal foils to minimize/eliminate beam scattering and Bremsstrahlung production.

•These techniques provide information on

- Transverse position
- Transverse profile
- Divergence and beam trajectory angle

Optical Ray Diagram for OTR/ODR Imaging



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)

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

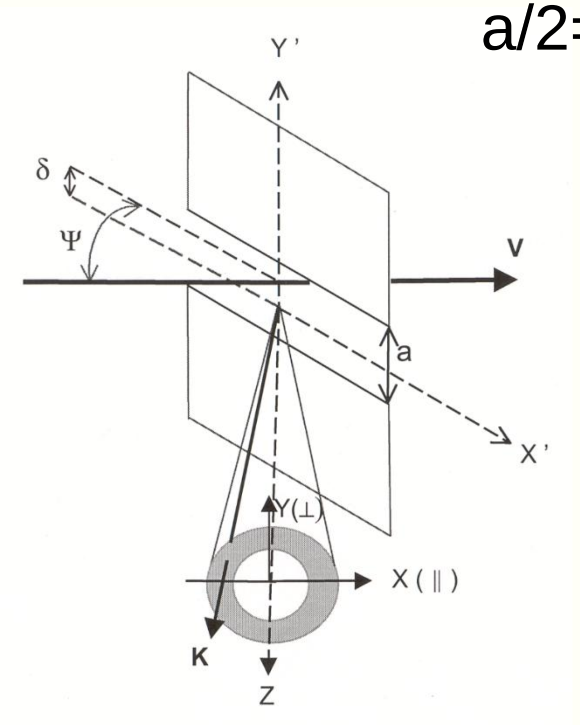
$$\iint dxdy\, K_1{}^2(\alpha b)\, e^{-\frac{x^2}{2\sigma_x{}^2}}\, e^{-\frac{y^2}{2\sigma_y{}^2}},$$

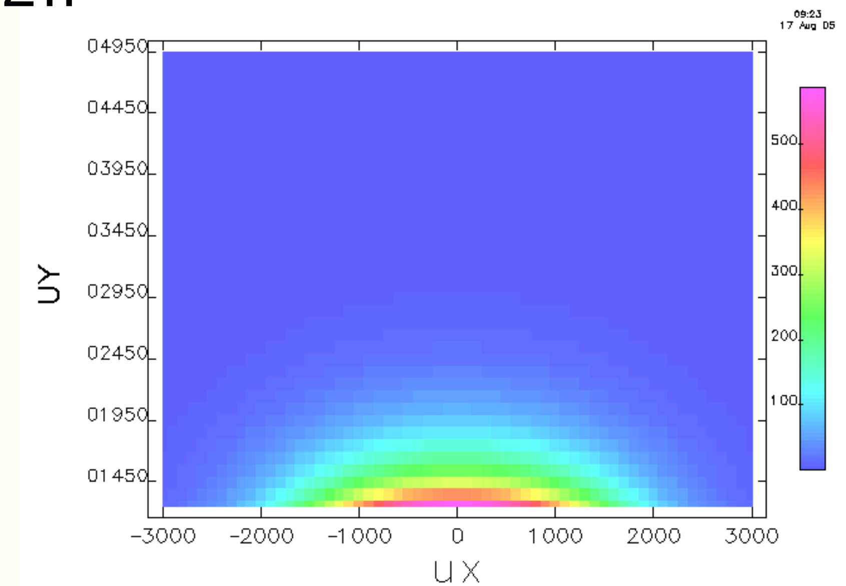
where ω = radiation frequency, v = electron velocity ≈ c = speed of light, q = electron charge, N is the particle number, $K_1(\alpha b)$ is a modified Bessel function with α= 2π/γλ and b is the impact parameter.

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).

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





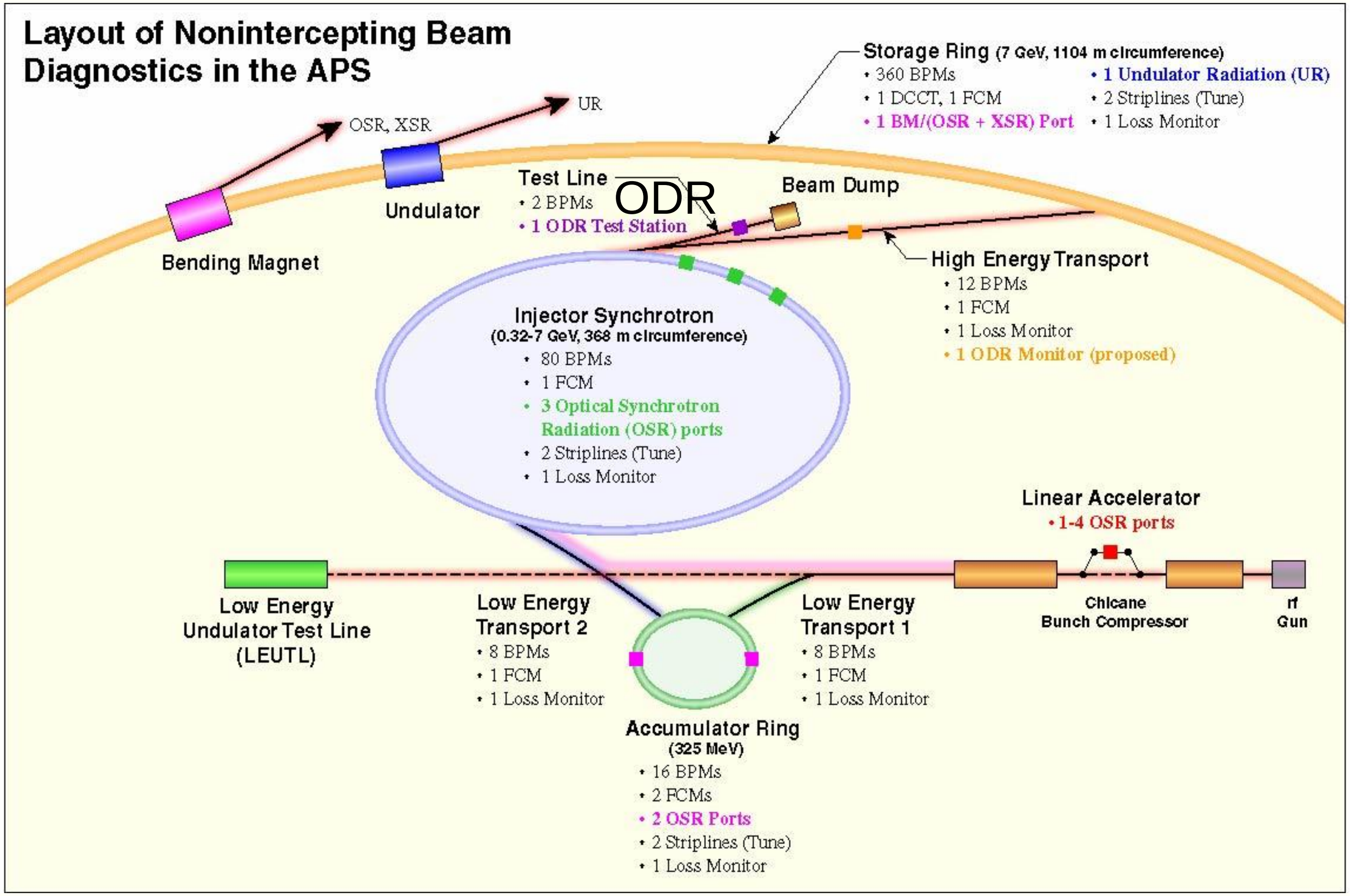
ODR intensity contour for 1375x200 um beam size

Development of Imaging Diagnostics for Multi-GeV Beams

- Diagnostics of bright beams continue to be a critical aspect of present and future accelerators.
- Beam size, divergence, emittance, and bunch length measurements are basic to any facilities involving bright beams.
- Nonintercepting (NI) characterizations of multi-GeV beam parameters are of particular interest in rings and high current applications. These can be addressed by optical and x-ray synchrotron radiation (OSR and XSR, respectively) in rings.
- The development of optical diffraction radiation (ODR) as a NI technique for relative beam size, position, and divergence measurements in linear transport lines has occurred in the last few years at KEK and APS.
- Results from the APS transport line for 7-GeV beam will be discussed.
- Relevance to new and proposed projects such as x-ray FELs, energy recovering linacs (ERLs), the International Linear Collider (ILC) will be addressed.
- Relevance to ILCTA will be suggested at sub-GeV energy, but high current.
- Sub-GeV lepton cases lead toward TeV-hadron cases (T. Sen PAC07 paper).

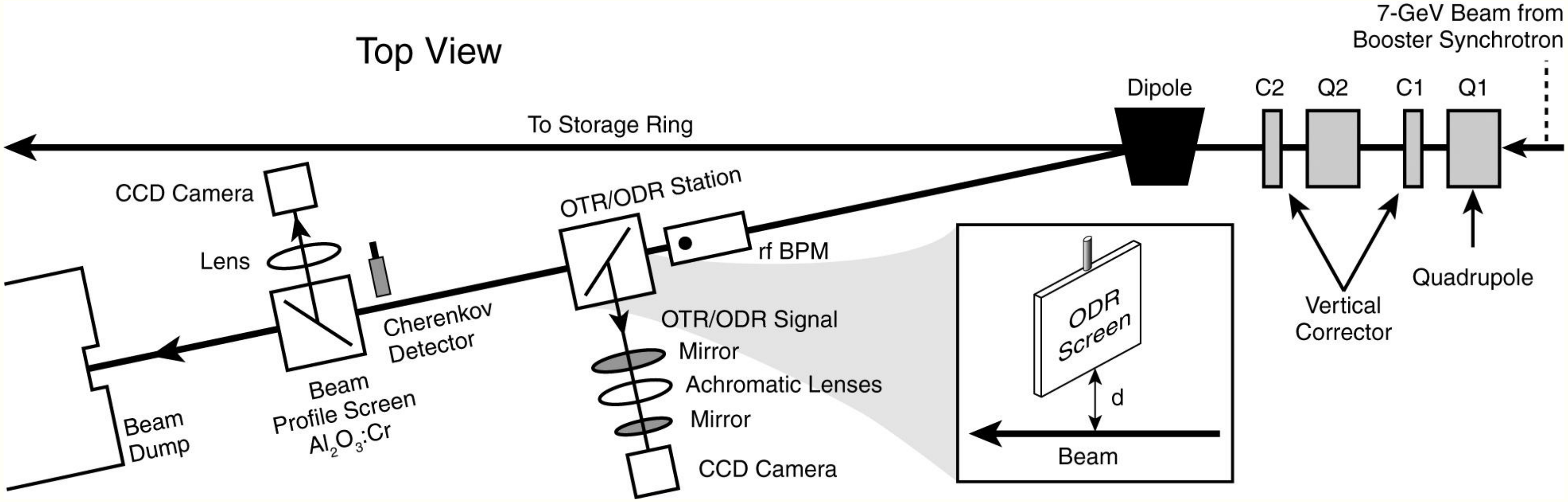
The APS Facility Has Provided Sources for Developing Time-Resolved, NI Diagnostics

- **Beam Energies from 50 MeV to 7 GeV are available for tests.**

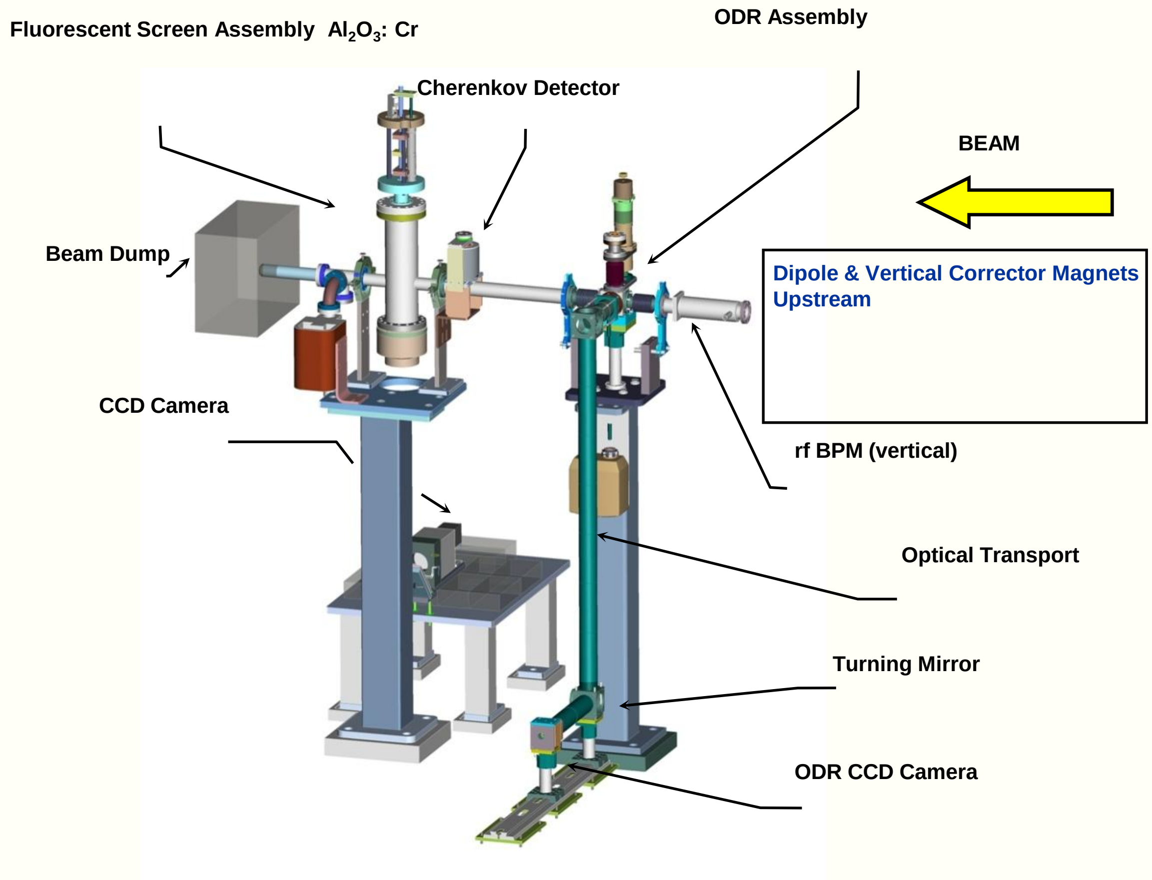


Schematic of the OTR/ODR Test Station on BTX Line at APS

- **Test station includes the rf BPM, metal blade with stepper motor control, imaging system, Cherenkov Detector, and downstream beam profile screen. The dipole is 5.8 m upstream of the ODR converter screen.**

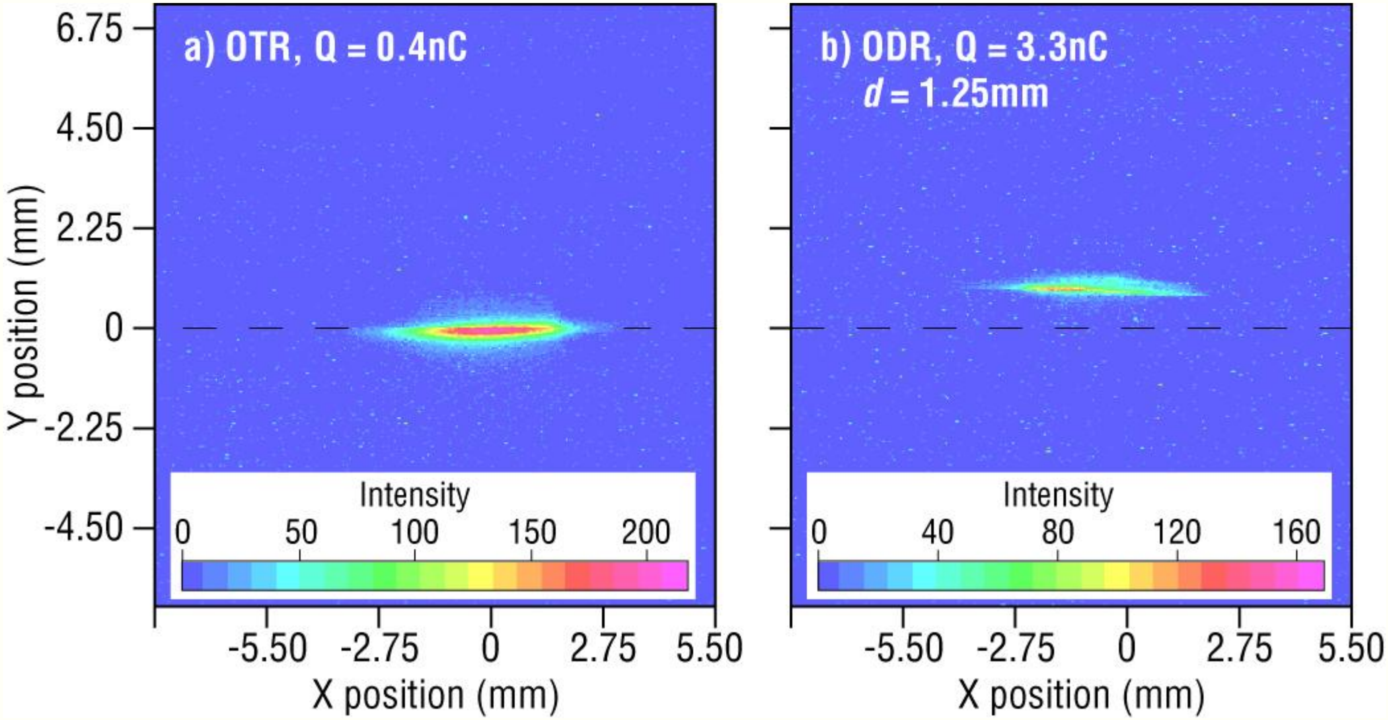


An OTR/ODR Test station was developed on the BTX line for 7-GeV beams



Investigations of Optical Diffraction Radiation on 7-GeV Beams at APS are Relevant to GeV Beams

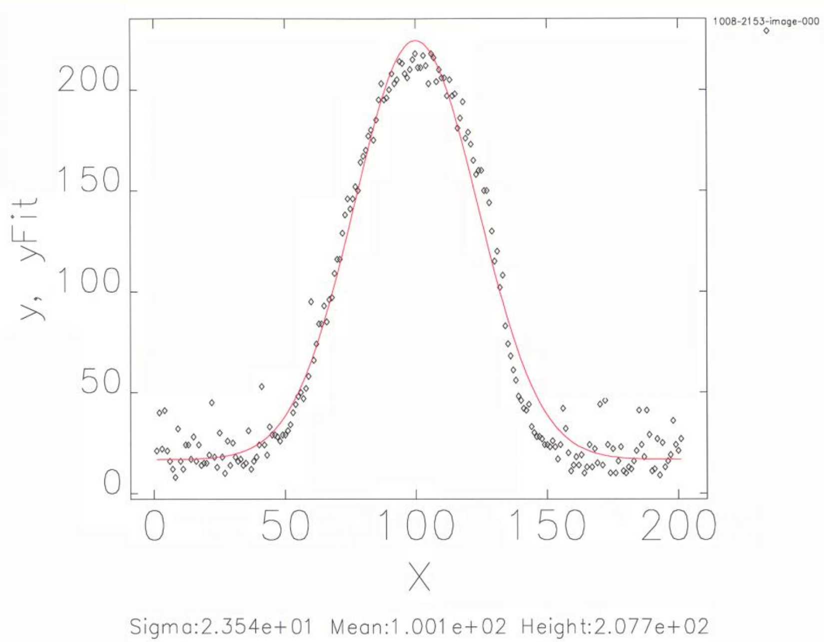
- **ODR offers the potential for nonintercepting, relative beam-size monitoring with near-field imaging. This is an alternate paradigm to far-field work at KEK.**

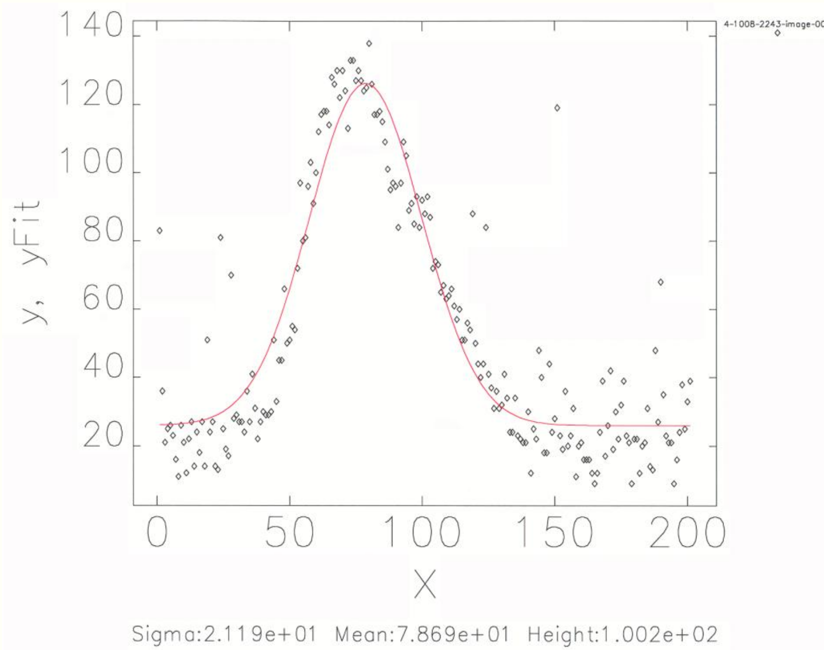


Lumpkin et al., Phys. Rev. ST-AB, Feb. 2007

OTR and ODR Images Recorded by On-line Video Digitizer and Processed

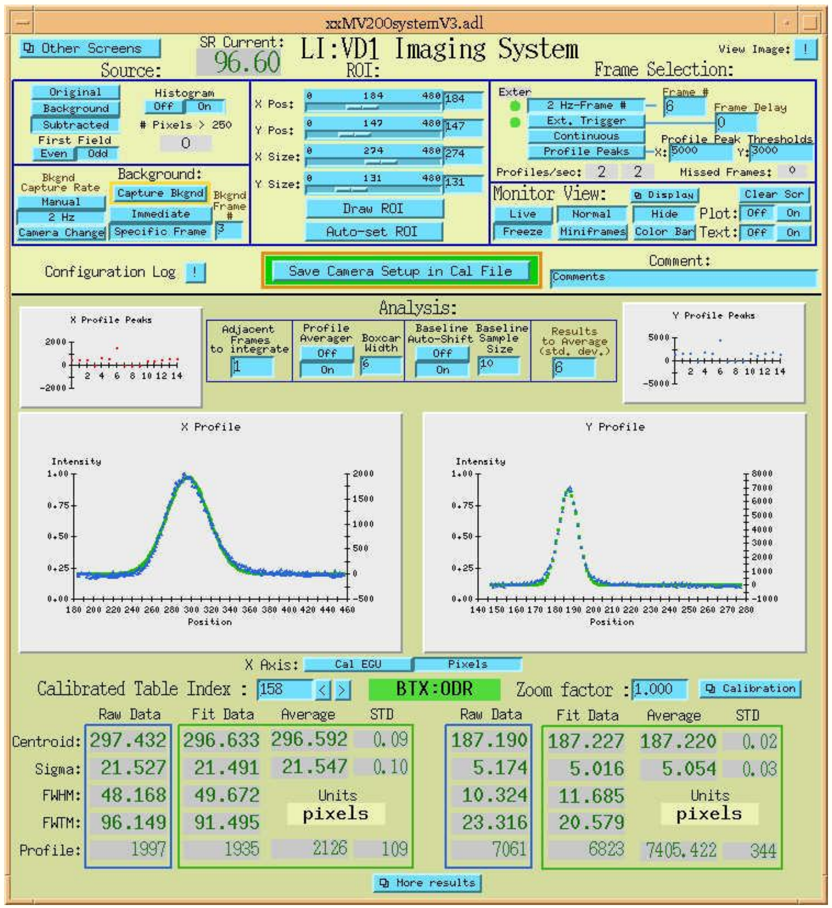
- OTR profile, Q=0.4nC — ODR profile, Q=3.2 nC, d=1.25 mm

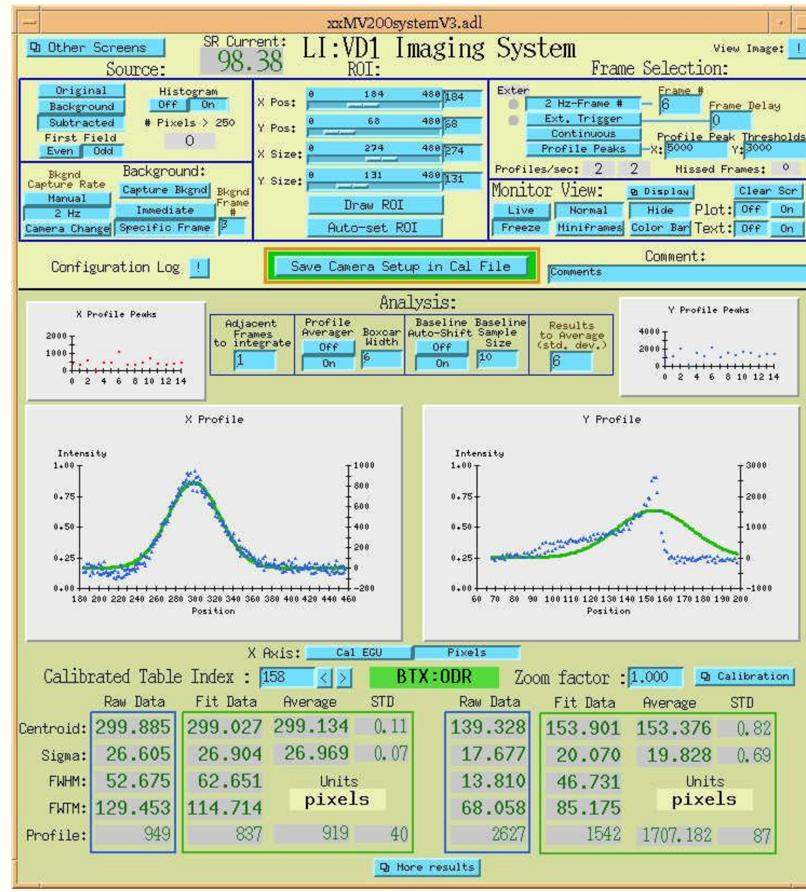




Online Image Processing Shows OTR and ODR Results

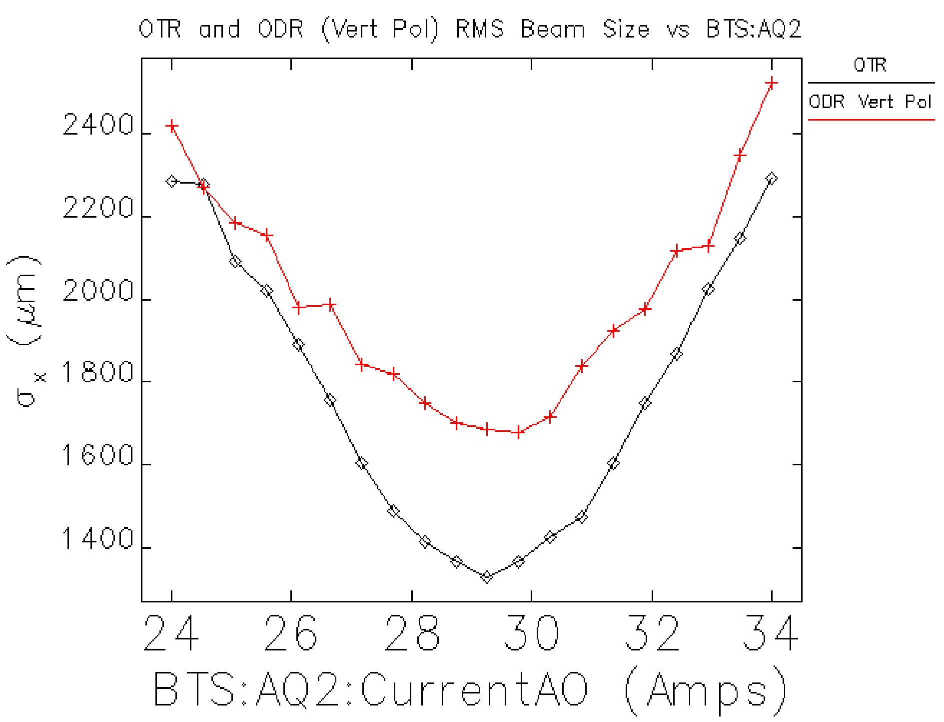
- **OTR Profiles** **ODR Profiles (VPol.)**

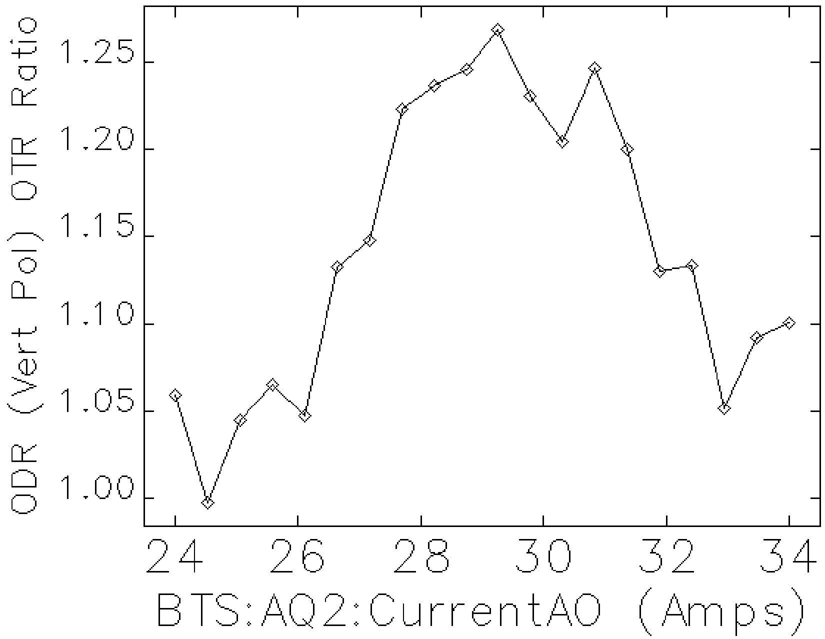




Perpendicular ODR Polarization Component Gives More Direct Representation of Beam Size.

- **Quadrupole current scan provides beam-size scan.**

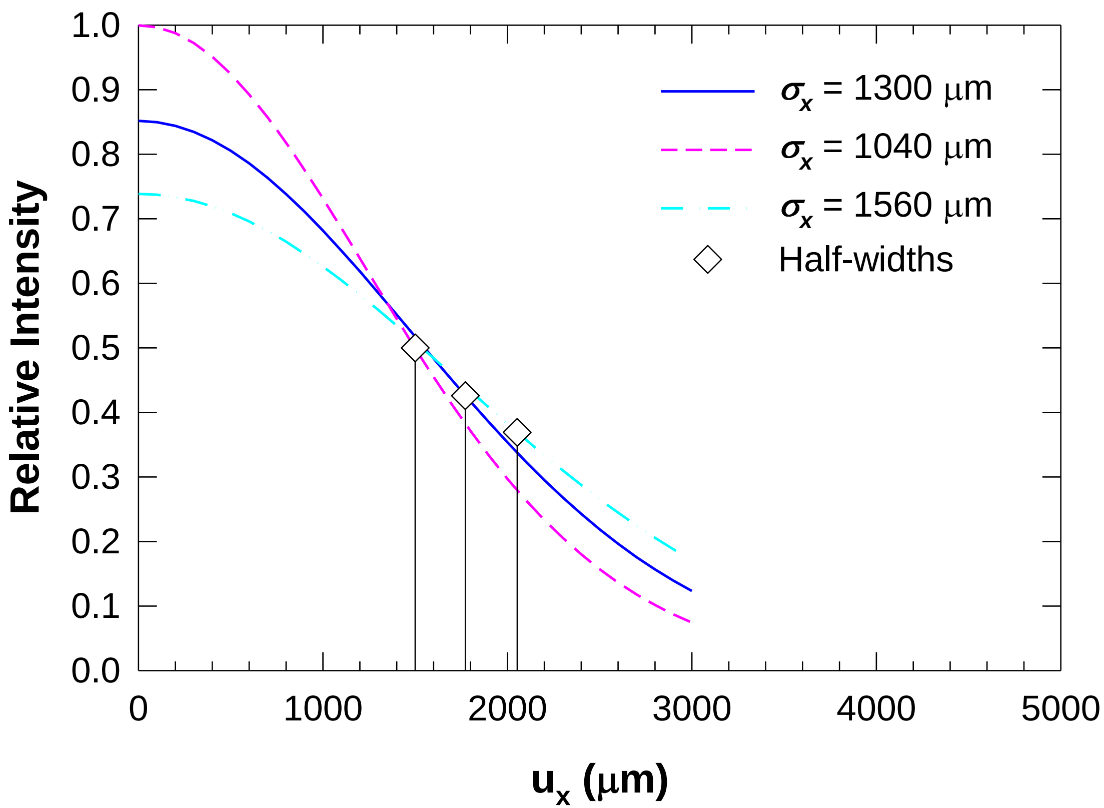




Lumpkin et al., Phys. Rev. ST-AB, Feb. 2007

Analytical Model Indicates Beam-size Sensitivity on x Axis (Parallel to Edge)

- Beam size varied +- 20% around 1300-μm value to show change in ODR profile detectable with *d*=1000 μm and σ_y=200 μm.



Analytical Model Indicates Beam-size Effect in New Regime at 20-50 μm for 7-GeV Beam (XFEL,ERL,ILC)

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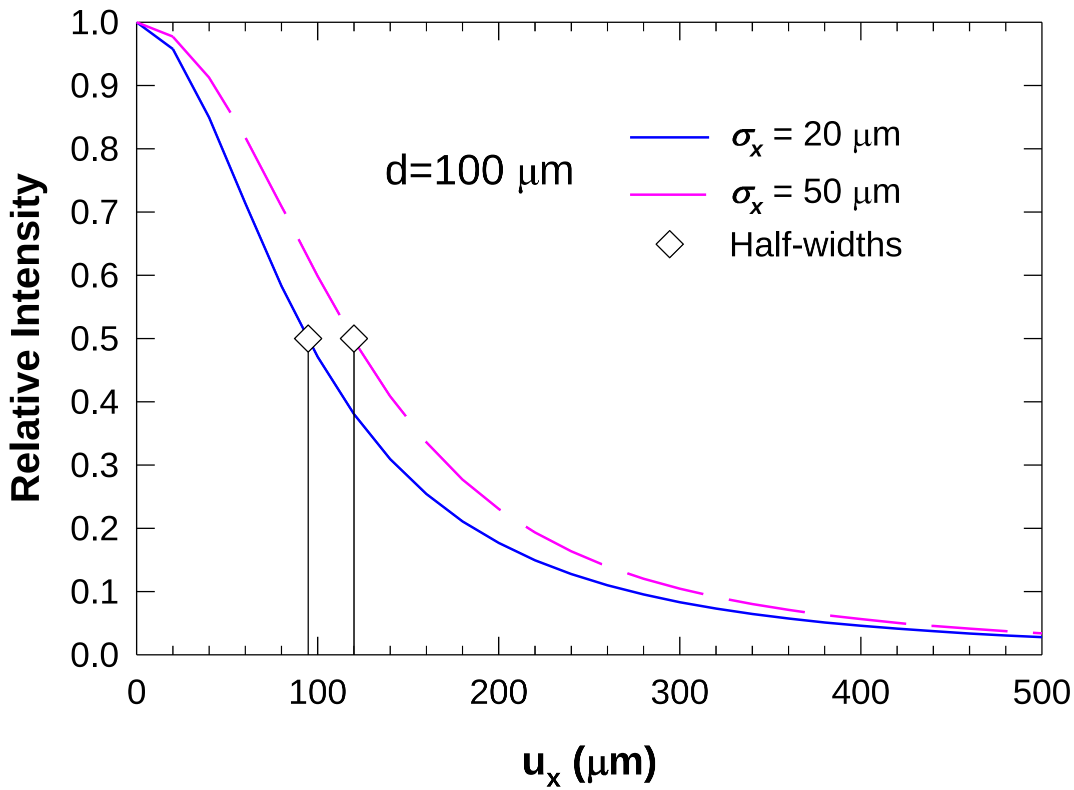
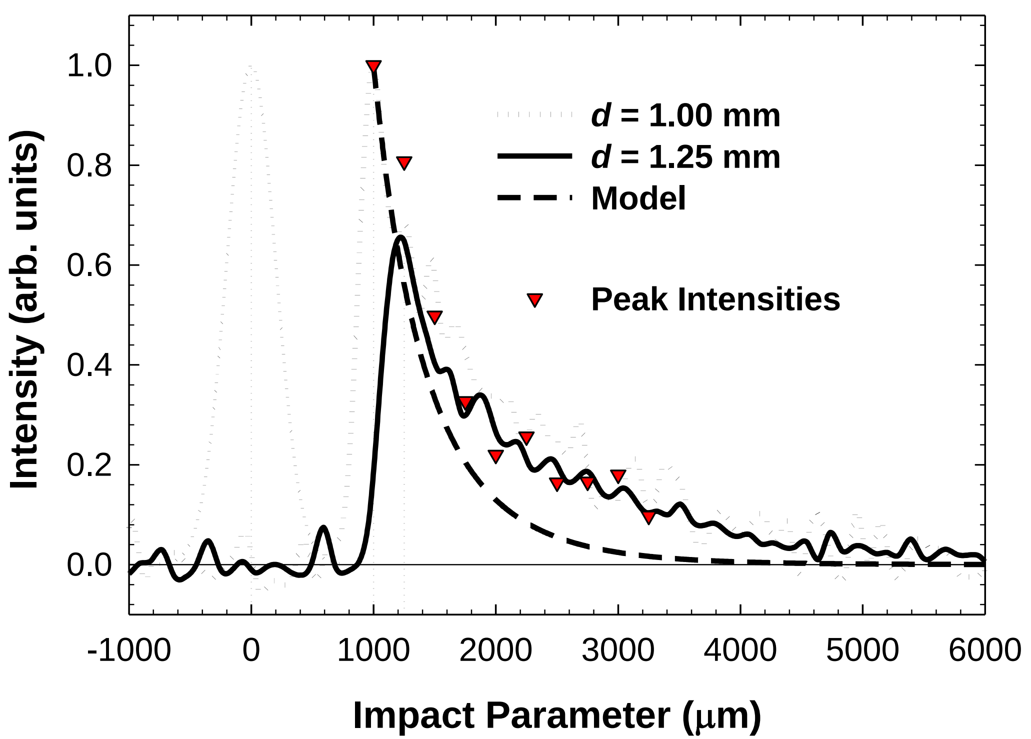
- Model shows new regime possible even without polarization selection for fixed σ_y = 20 μm.



Analytical Model Addresses Main Features of Vertical Profiles from ODR Near-field Images

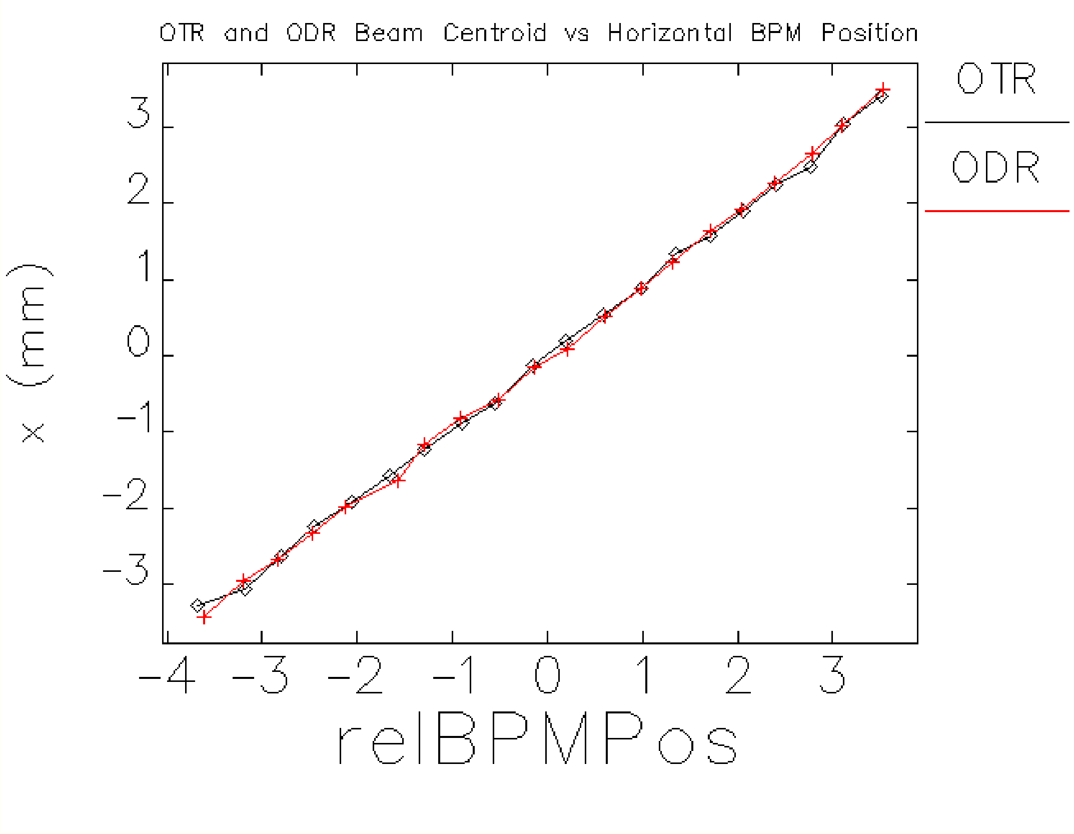
- Comparison of OTR beam profile and ODR vertical profile data. The peak intensity has an exponential behavior with impact parameter while the total profile has the modified Bessel function effect.



Phys. Rev. ST-AB 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.**



Further Studies Planned in FY08

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- Planning of the NML station at 550-750 MeV point.
- Baseline concept is to image at about 800 nm with a 16-bit camera and use the high charge of the macropulse to generate enough photons at this wavelength.
- Second concept is to image or detect in the MIR in the 3- to 10-μm regime, where there are more photons emitted. Possible detectors are pyroelectric arrays or cryo-cooled detectors (relevant to hadron issues).
- Collaboration with INFN on 900-MeV experiment at FLASH/ DESY. Studies possible in Jan.-Feb. 2008 with 16-bit camera.
- Collaboration at JLAB on CEBAF recirculating linac beam at location before nuclear physics target.

ODR Techniques for ILC

- **Most anticipated beam sizes addressed. Smallest beam sizes need studies.**

Energy (GeV)	X Beam size (μm)	Y Beam size (μm)
1	650	35
5	300	15
15	150	8
250	30	2

Multi-GeV values per M. Ross talk, July 27, 2007

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

Fermilab

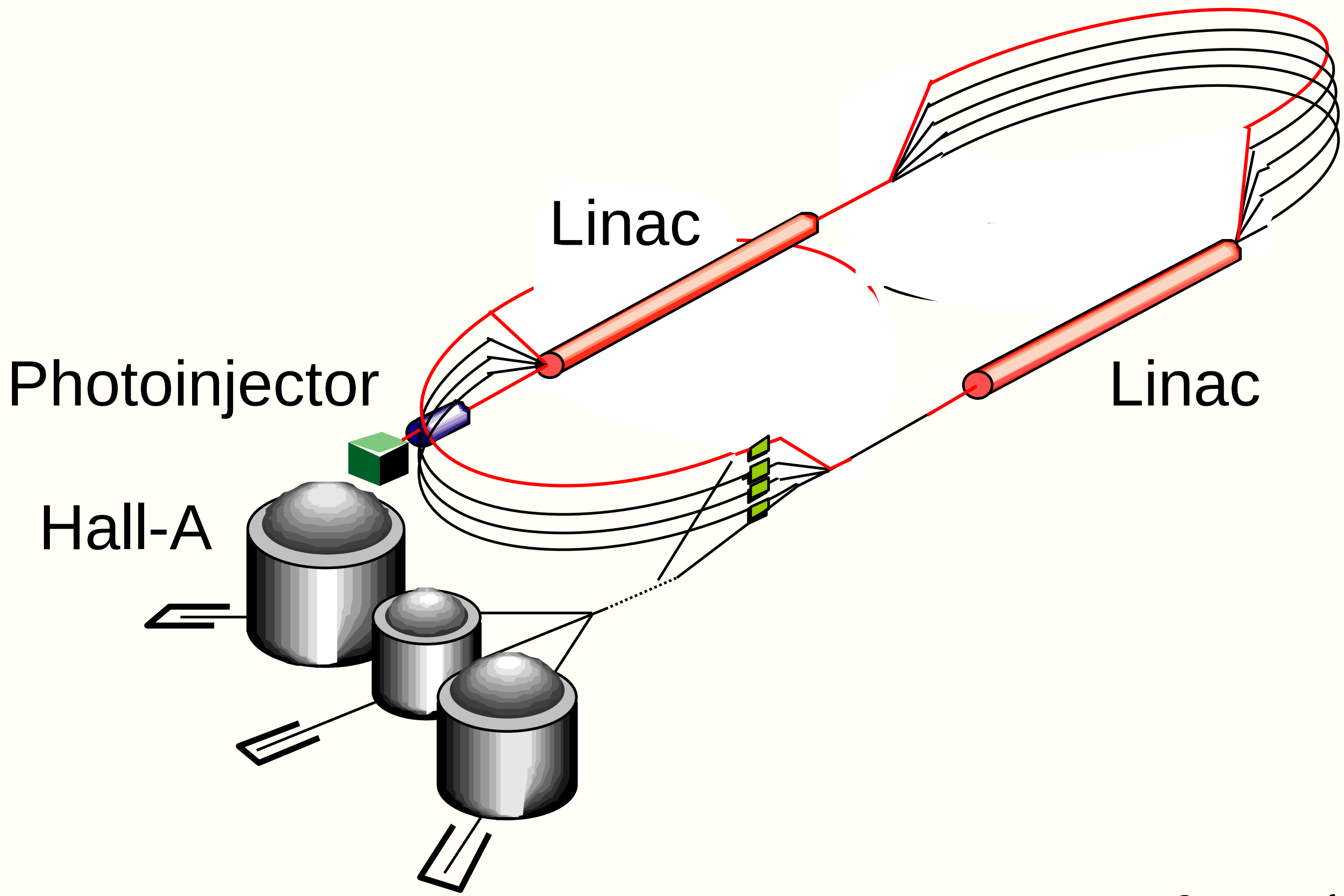
- **CEBAF beam size is 10 times smaller and the charge is 1000 times greater than APS case. What are background sources?**

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

A. Lumpkin et al., PAC07

CEBAF 5-GeV Recirculating Linac

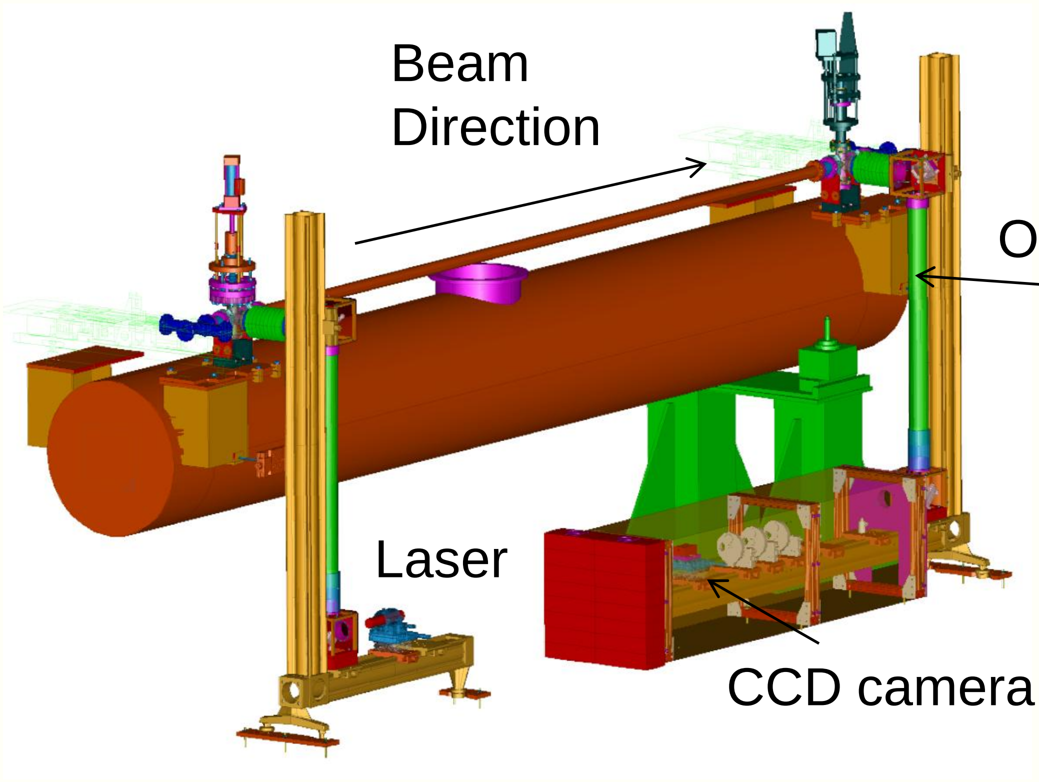
- **100 μAmps CW beam extracted at 1, 2, 3, 4 or 5 GeV**



Courtesy of Alex Bogaz, JLAB

Hall –A Transport Line

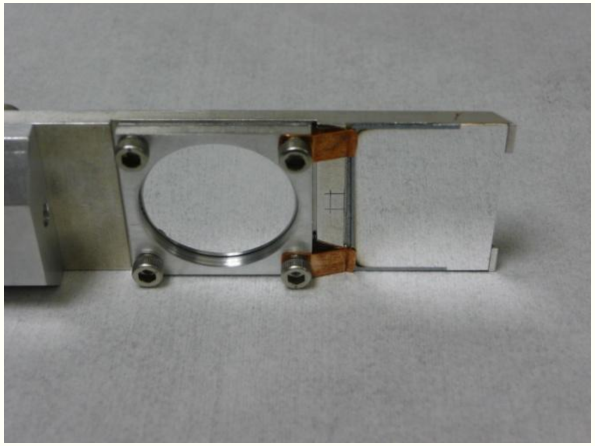
- **New OTR/ODR station installed next to flying wire station to allow comparison and cross-validation.**

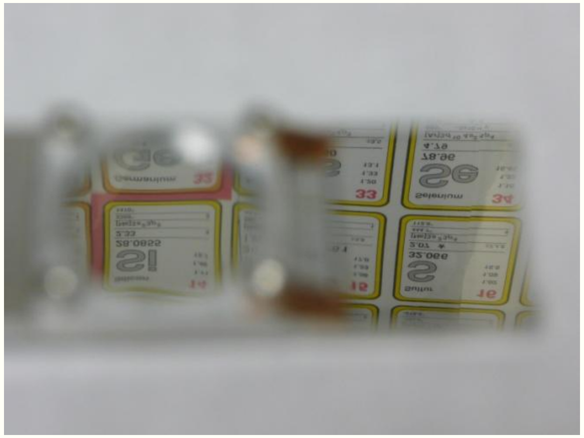


Courtesy of P. Evtushenko

OTR and ODR Converters Revised

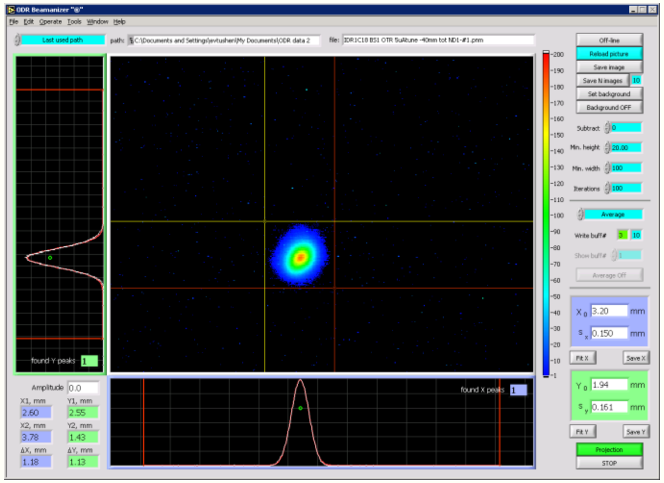
- New OTR converter using aluminized Kapton for the 20-mm aperture was prepared at Fermilab Thin Films lab by Eileen Hahn. About 1500 Angstroms of Al deposited by evaporation deposition method on a stretched 6-μm thick Kapton film.
- New ODR converter was prepared by sputtering a 600 Angstrom Al coating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



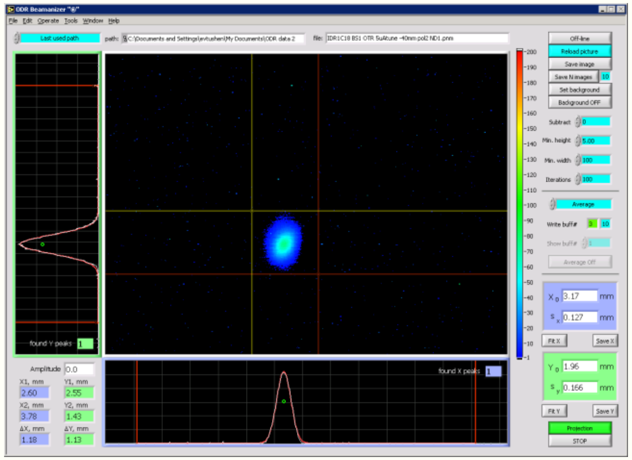


Initial OTR Images at 4.5 GeV

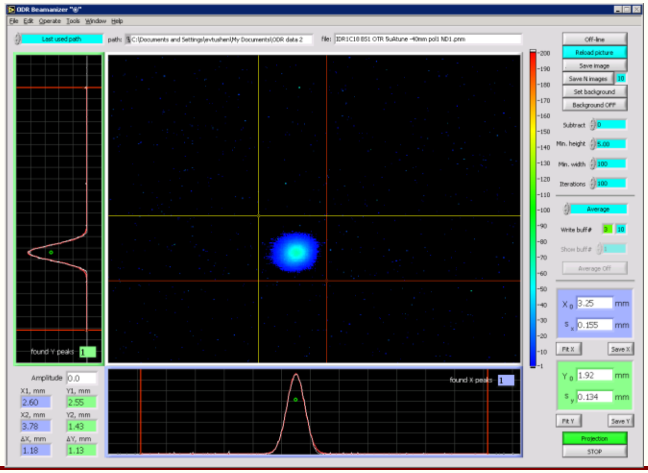
- **Newly installed Al-coated Si wafer used with 5-μA Tune beam (250 μs at 60 Hz). Polarization effects seen on $\sigma_{x,y}$.**



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



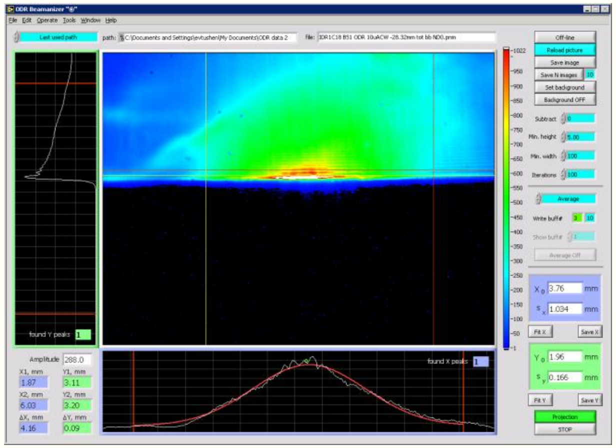
V-pol
σ_x:127 μm

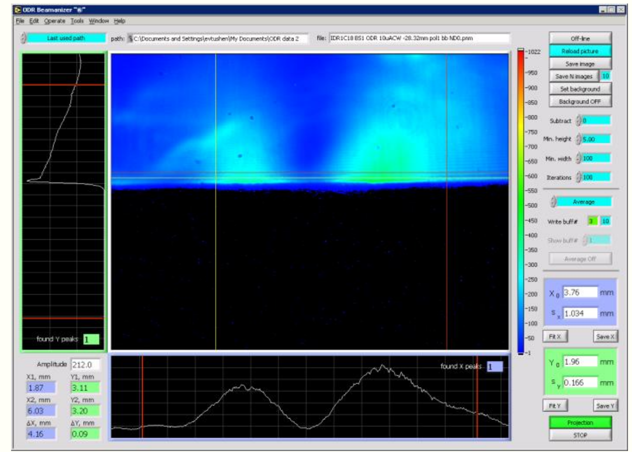


H-pol.
σ_y:134 μm

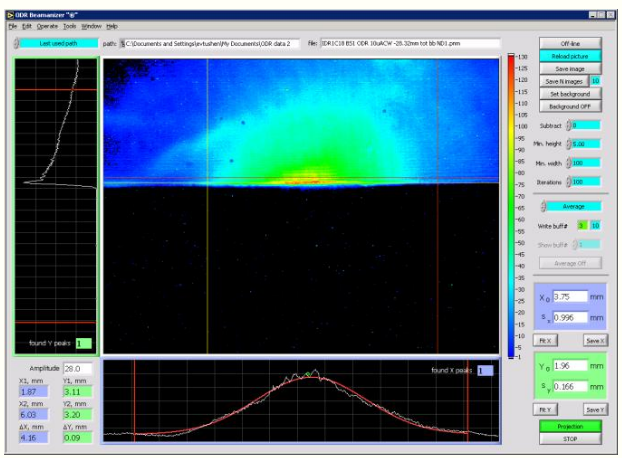
Basic ODR images at 10 μA CW

Polarization Component effects are clear.

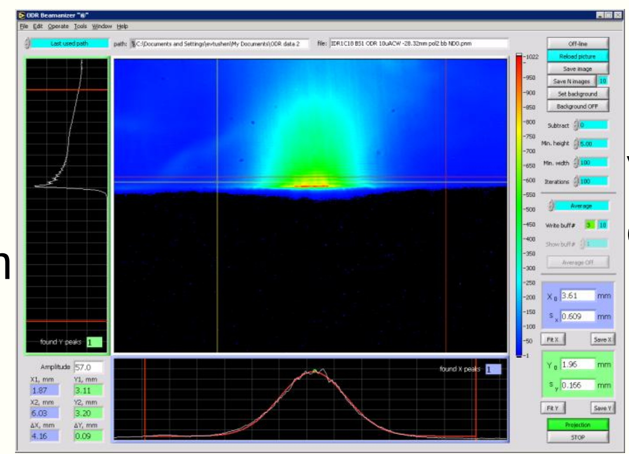




Hpol.:
Double
lobe



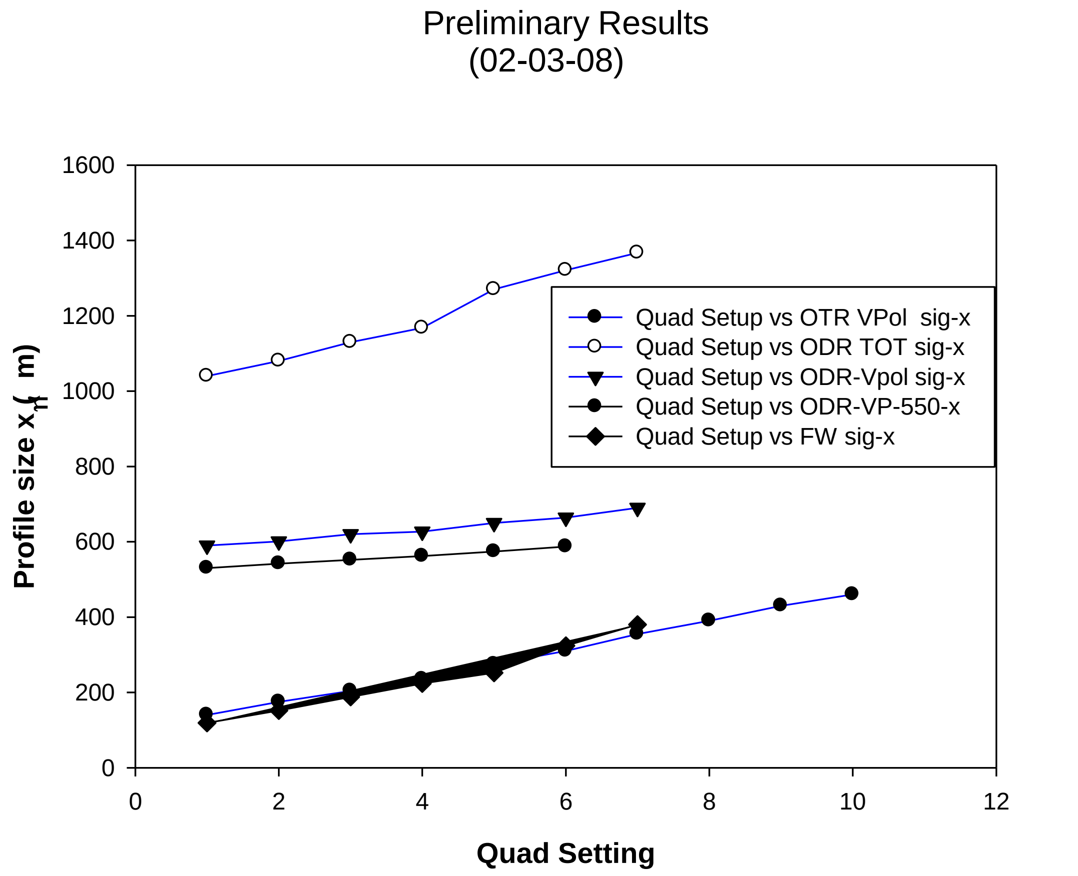
Total:
σ_x=996 μm



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.**



NML Beam Offers Extended Parameter Space To Test and ODR Offers an NI Beam-size Monitor for Operations.

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- **CEBAF beam size is 10 times smaller and the charge is 1000 times greater than APS case. NML beam sizes are nearly ILC prototypical.**

Parameter	APS	CEBAF	ILCTA	ILC
Energy (GeV)	7	1- 5	0.5-0.7	5, 250
Gamma (x1000)	14	2-10	1-1.4	10, 500
X Beam size (μm)	1300	50-80	200, 80	300, 30
Y Beam size (μm)	200	50-80	70, 30	15, 2
Current (nA)	6	100,000	50,000	50,000
Charge/ 33 ms (nC)	3	3,000	10,000	10,000

Sub-GeV e-Beam with 10 μC Should Give ODR Image

- NML beam sizes can provide prototypical test of ILC parameters.
- ODR image intensity scales in exponential argument as $-4\pi d/\gamma\lambda$.
- If energy reduced by 10 then can reduce *d* if beam is smaller and increase charge integrated in image by 3000 compared to APS case.
- Additionally, use 16-bit intensified/cooled camera to extend sensitivity range compared to standard CCD by about 1000.
- Can look at MIR/FIR, but imaging sensors limit resolution.
- Modeling should be extended to lower energies. Perpendicular polarization components should be evaluated.
- Both near-field and far-field imaging should be evaluated. Give beam size parallel and perpendicular to the plane/slit edge, respectively.
- These lower gammas are comparable to 1-TeV hadrons.

Possible Applications of ODR Monitoring to Hadrons?

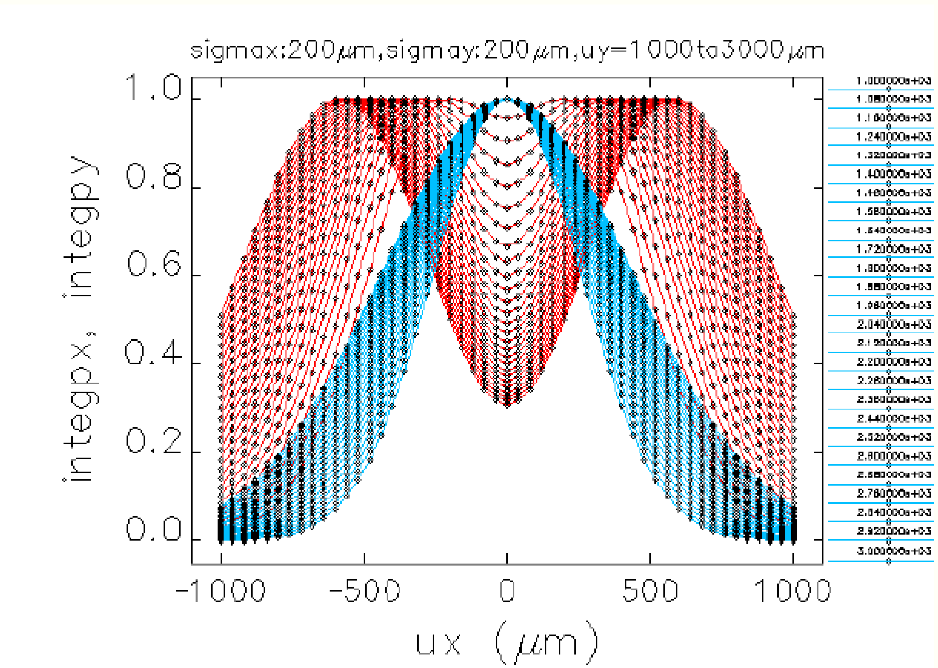
- **Relevant parameters if $\kappa = 2\pi b/\gamma\lambda = 1$ for far-field imaging and use of I_{min} to I_{max} ratio. (Synchrotron light background levels must be addressed in rings.)**

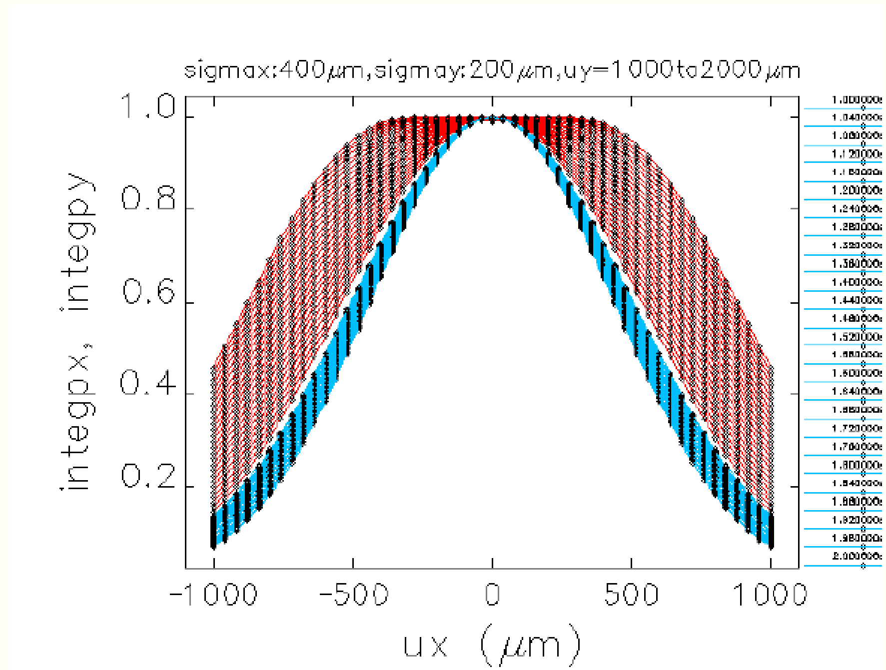
	Tevatron	RHIC	LHC
Energy [TeV]	0.98	0.25	7.0
Beta function at target [m]	50	82	1296
Beam size at target [μm]	399	1012	807
Target clearance N_c [σ]	12	12	12
Wavelength [μm]	14.4	143	4.1
Far-field distance [m]	2.5	1.6	36.1

T. Sen, V. Scarpine, R. Thurman-Keup, PAC07

ODR Example at NML

- **ODR x profile for perpendicular component changes by 1.5 for factor of 2 change in x beam size at 200 µm . Implies about 15% effect for a 20% beam size change.**

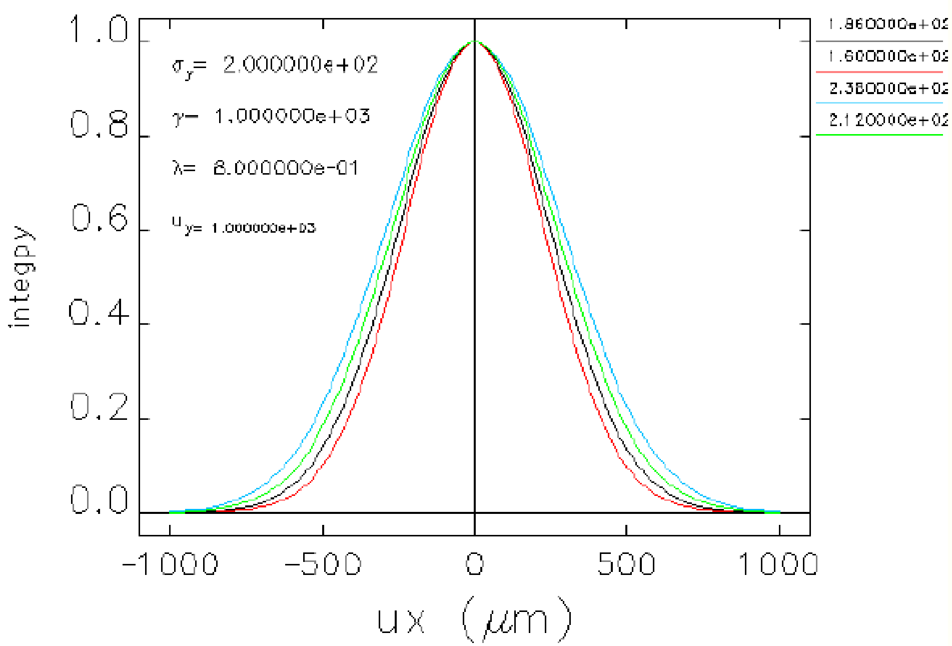


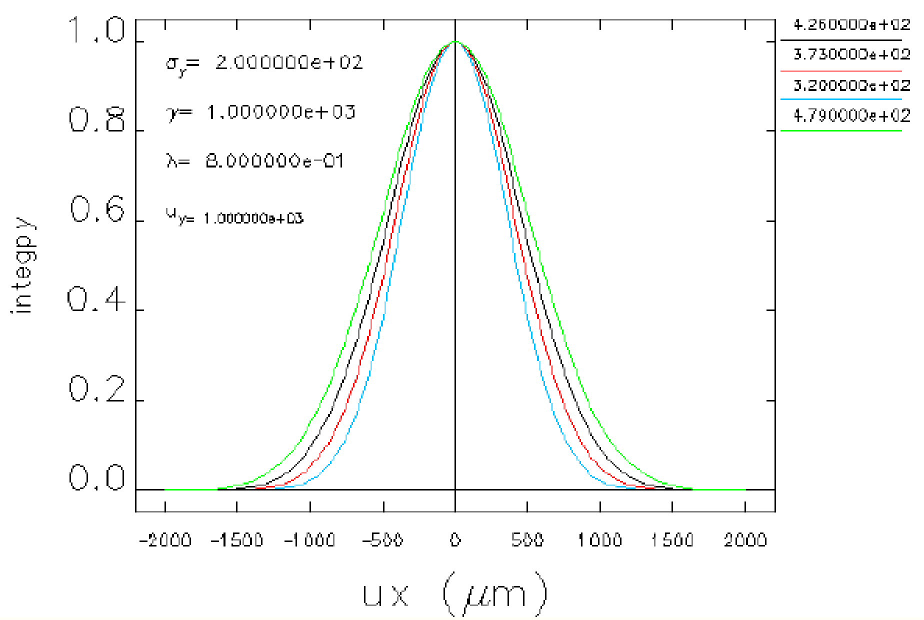


Courtesy of C.-Y. Yao, ANL

ODR Model Shows Beam-size Effects

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

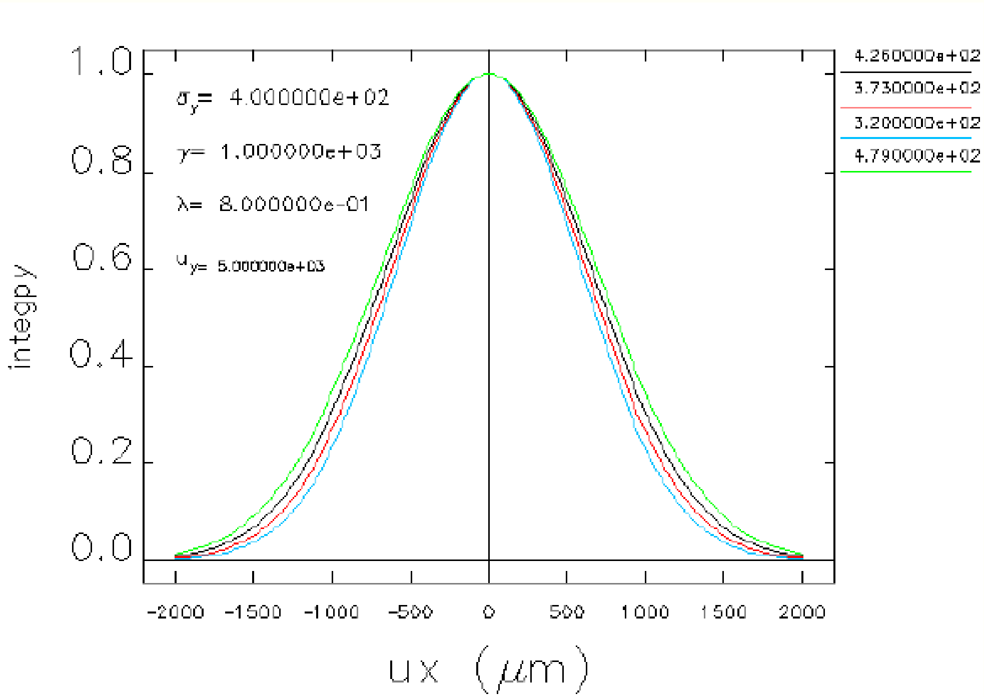


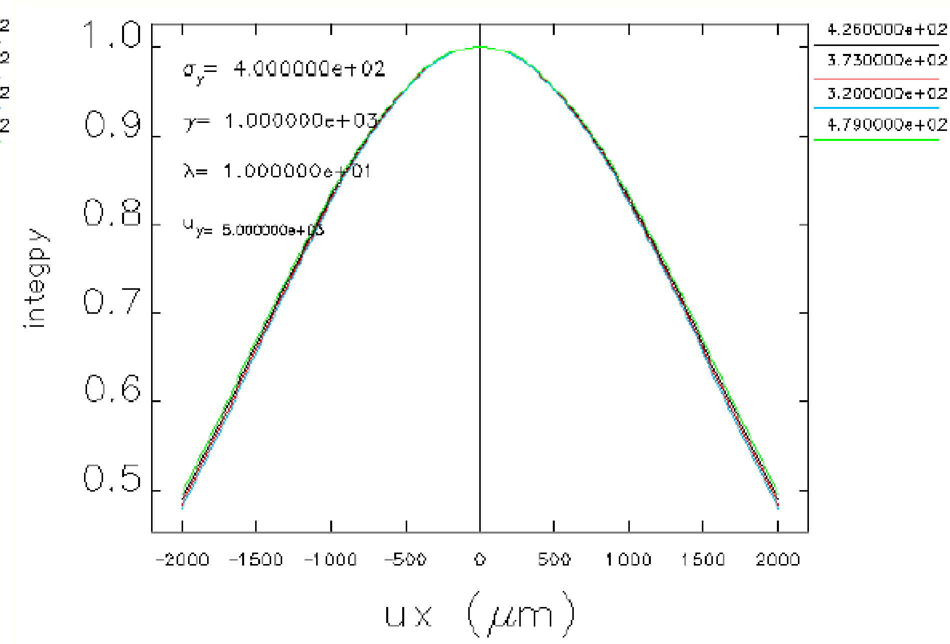


Courtesy of C.-Y. Yao, ANL

ODR Model Shows Wavelength Effect

- NML examples for beam-size monitor for σ_x=400 +- 20% μm with σ_y=400 μm, d = 12 σ_y , and γ=1000.

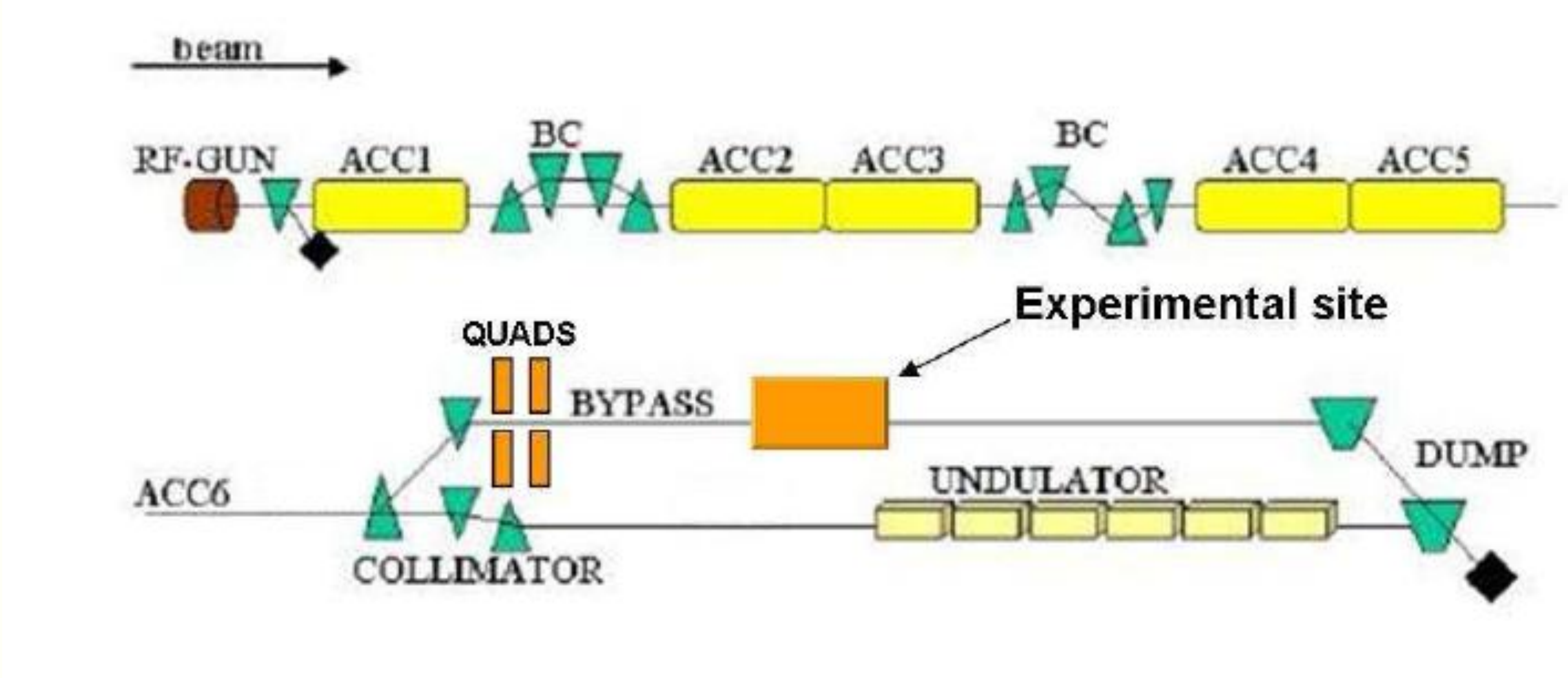




Courtesy of C.-Y. Yao , ANL

Experiments on ODR at DESY

- **FLASH facility used to provide 680-MeV beam with about 17 nC per macropulse for initial far-field ODR experiments.**



E.Chiadroni et al., INFN

Experiments on ODR at DESY

- **INFN group evaluated beam size (L) and divergence (R) effects on ODR angular distribution for a =1 mm, λ = 1.6 μm, γ~2000.**

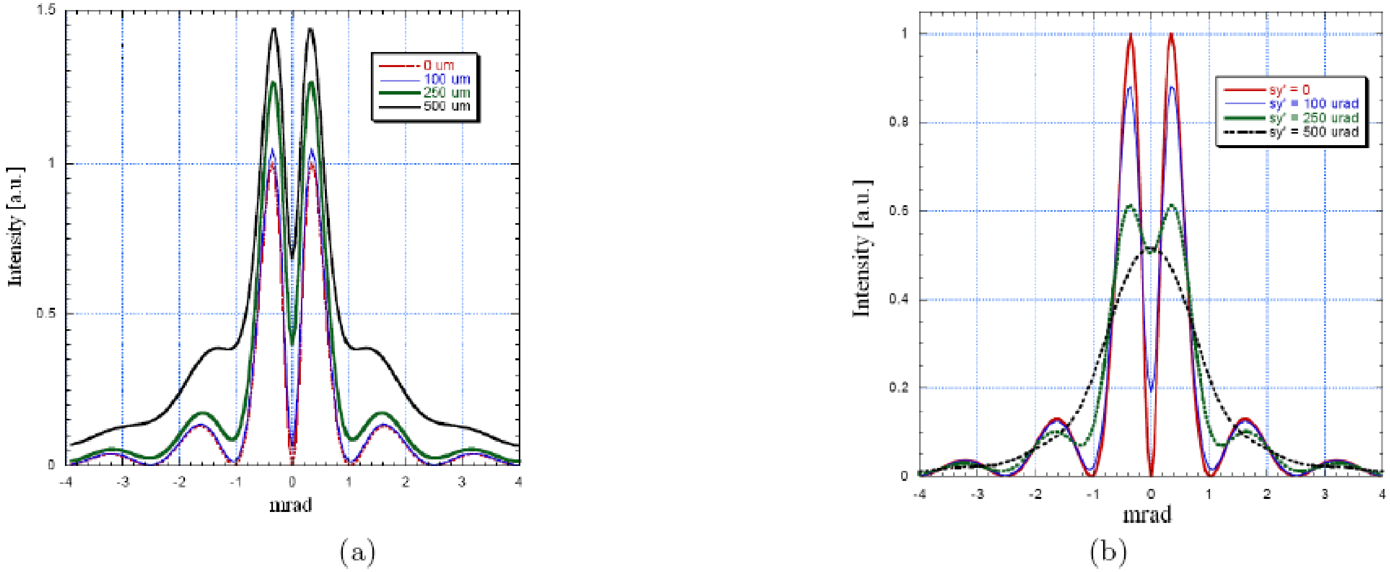


Figure 1. ODR angular distribution at 1 GeV for different beam sizes (a) and beam angular divergences (b).

E. Chiadroni et al.,INFN

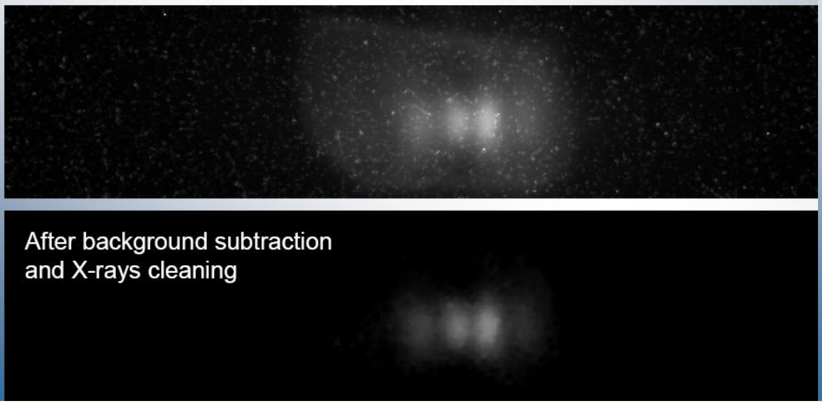
Experiments on ODR at DESY

- **Initial ODR angular distribution data using 16-bit CCD obtained at 680 MeV in Jan. 2007 reported at PAC07.**

ODR Evidences (1)

Beam transport optimization

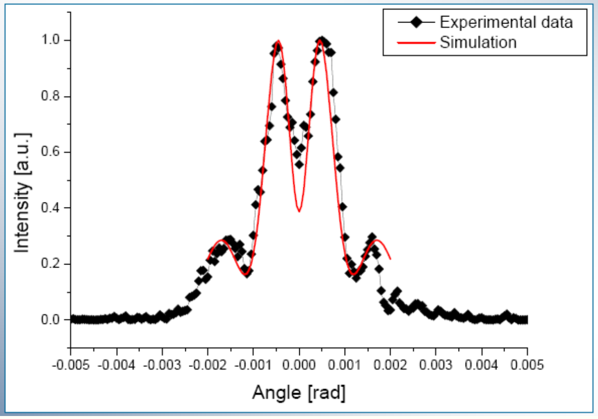
- *0.7 nC*
- 25 bunches
- *2 s* exposure time
- E_{beam} = *680 MeV*
- *800 nm* filter and polarizer in



ODR Evidences (2)

Simulation parameters:

- a = *0.5 mm*
- σ_y = *73 μm*
- σ'_y = *30 μrad*
- Both the angular divergence and the beam are assumed to be Gaussian distributed

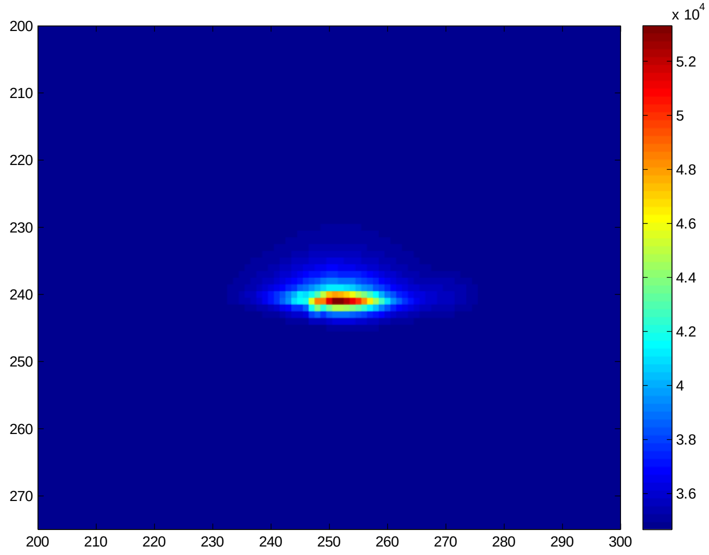


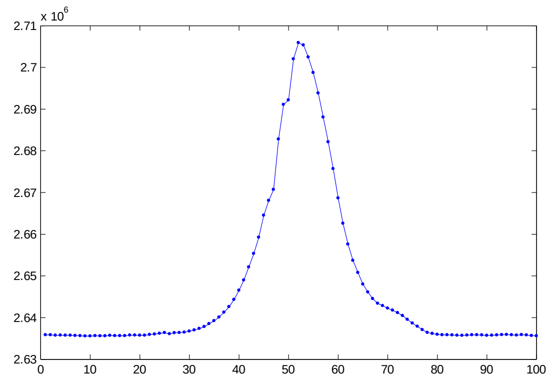
E. Chiadroni et al., PAC07

OTR at FLASH: 900-MeV Electrons

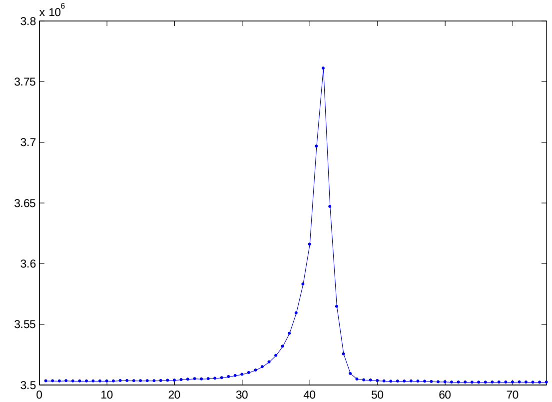
- **Near-field OTR Image obtained in collaboration with E. Chiadroni, et al. in January 2008 studies.**

3 image sum, 6nC per 6-bunch macropulse at 5 Hz.





X projection
$\sigma_x = 210\ \mu m$



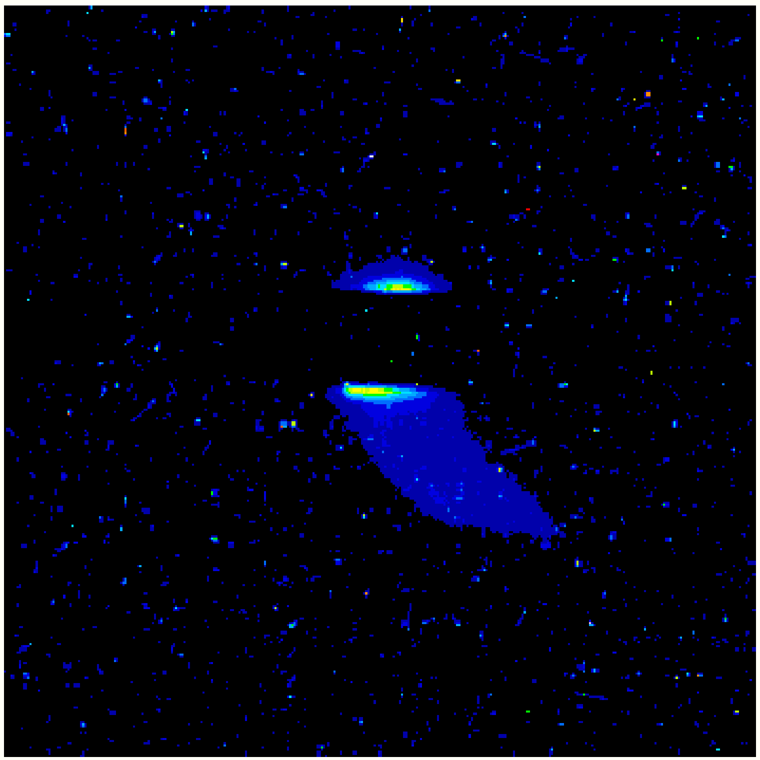
Y projection

Beam size: $\sigma_x = 210\ \mu m$
$\sigma_y = 100\ \mu m$

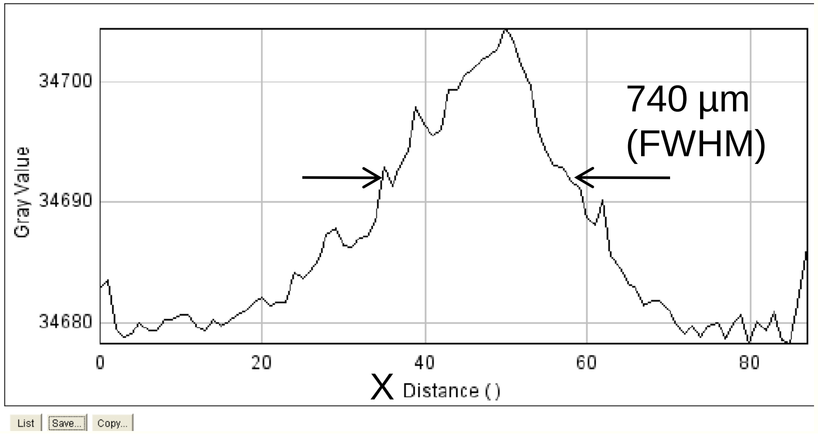
MATLAB by R.T-K

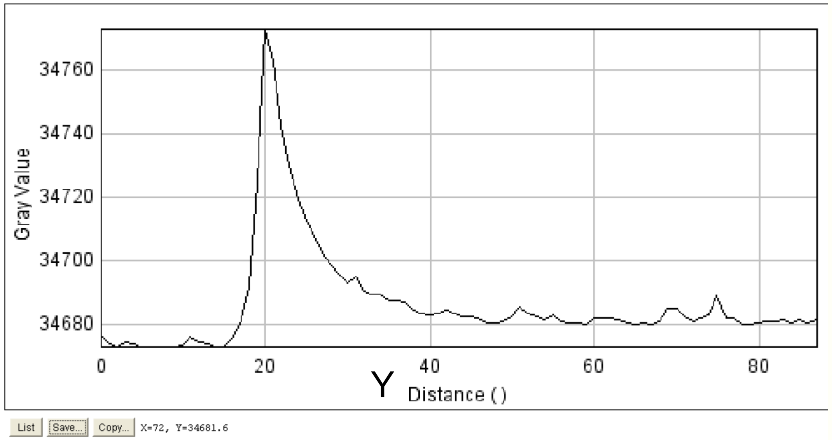
ODR at FLASH: 900-MeV Electrons

- **Near-field ODR Image obtained in collaboration with E. Chiadroni, et al. in January 2008 studies. b = 300, 700 μm.**



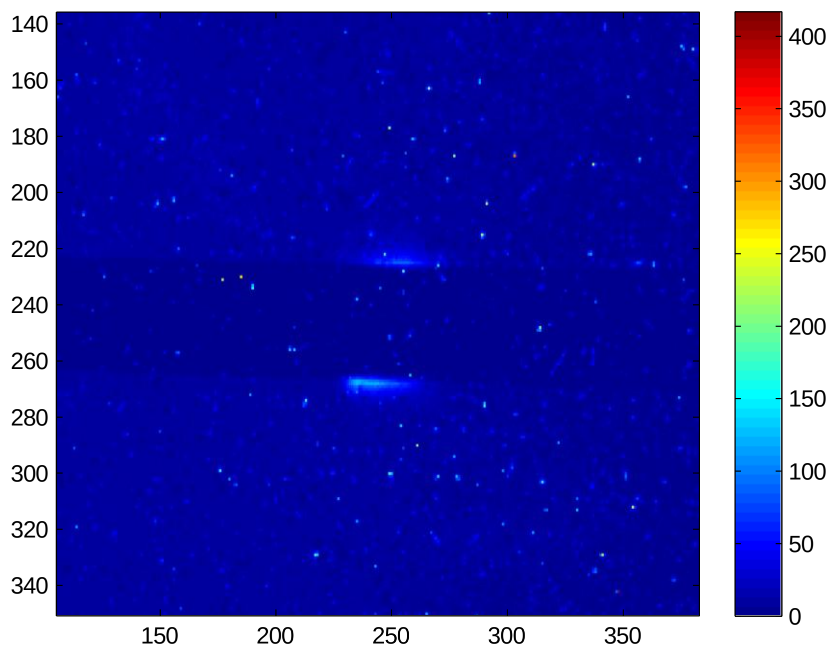
10 image sum, 6b/macro, 800 nm BP,0.5 s Exposure, 5Hz, 1-mm slit



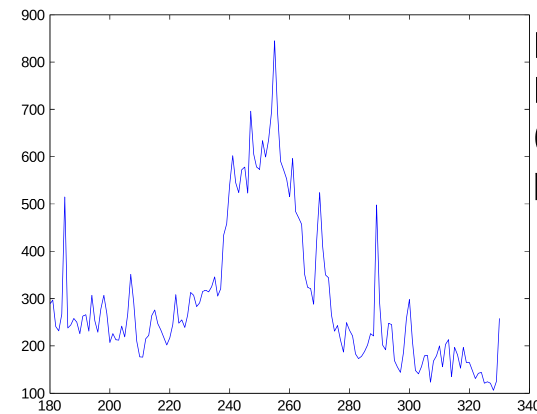


ODR at FLASH: 900-MeV Electrons

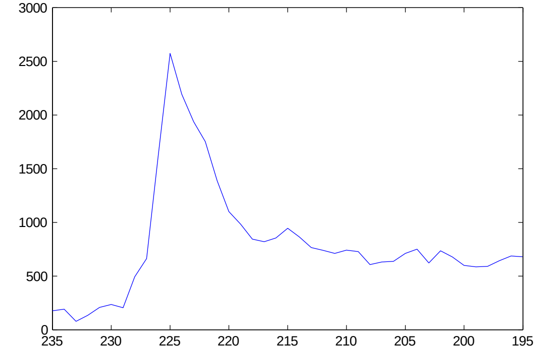
- **Near-field ODR Image obtained in collaboration with E. Chiadroni, et al. in January 2008 studies. b = 400,600 µm.**



10 image sum, 6b/macro, 800 nm BP,0.5 s Exposure, 5Hz, 1-mm slit, DC subtracted.



Projection to Horizontal plane (sum of vertical pixels 205-230)



Projection to vertical plane (sum of horizontal pixels 220-280)

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EXPERIMENT SUMMARY

- ODR experiments at CEBAF at 4.5 GeV done with 10 times smaller beams at 500 times more charge per image than the initial APS tests.
- The higher signal strength allowed combined bandpass filter and polarization effects to be explored.
- First observation of predicted double lobe in parallel polarization component. (02/08)
- Tests run at 80 μA CW beam with no/little signal in the downstream loss monitors for 1-mm impact parameter.
- Scaling calculations done for γ= 1000 beams at NML(e-) and the Tevatron (p).
- First near-field ODR imaging results from collaboration with Italian team using FLASH beam at 900 MeV.(01/08)

SUMMARY(2)

- ***A new NI relative beam size monitor based on ODR has been proposed to support APS top-up operations.***
- ***The ODR techniques also appear applicable to NI monitoring of the CEBAF 5-GeV beam at 100 μA before the experimental hall.***
- ***The ODR techniques appear applicable to NML for sub-GeV beam with high average current (like FLASH test) and for the multi-GeV beams of ILC.***
- ***The ODR technique may have relevance for intense proton beams of γ=1000 (Tevatron test in planning).***
- ***The ODR near-field imaging techniques also have relevance to x-ray FELs, ERLs, APS upgrade, emerging LWFAs, and Project-X (e-).***

ACKNOWLEDGMENTS

- Collaborators: W. Berg, N. Sereno,C.-Y. Yao, B.X. Yang ASD/APS/ANL; D.W. Rule, NSWC-Carderock Division.
- Previous publications on ODR near-field imaging results at APS in ERL05, PAC05, FEL05, BIW06, FEL06, and PRST-AB Feb. 2007.
- Previous publications by KEK on far-field imaging to deduce beam size in PRL (10-minute angle scan) and PAC05 (dephased planes).
- Discussions with S. Nagaitsev, M. Church, H. Edwards, and M. Wendt on ILCTA at NML and T. Sen on hadrons.
- CEBAF collaborations with P. Evtushenko, A.Freyberger, and C. Liu.
- INFN collaborations with M. Castellano, E. Chiadroni,et al.