Near-field ODR Imaging as a Potential Nonintercepting Beam-size Monitor for FLASH and XFEL

Alex H. Lumpkin, Fermilab

Presented at Accelerator Physics Seminar

September 4, 2009

Hamburg, Germany

OUTLINE

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

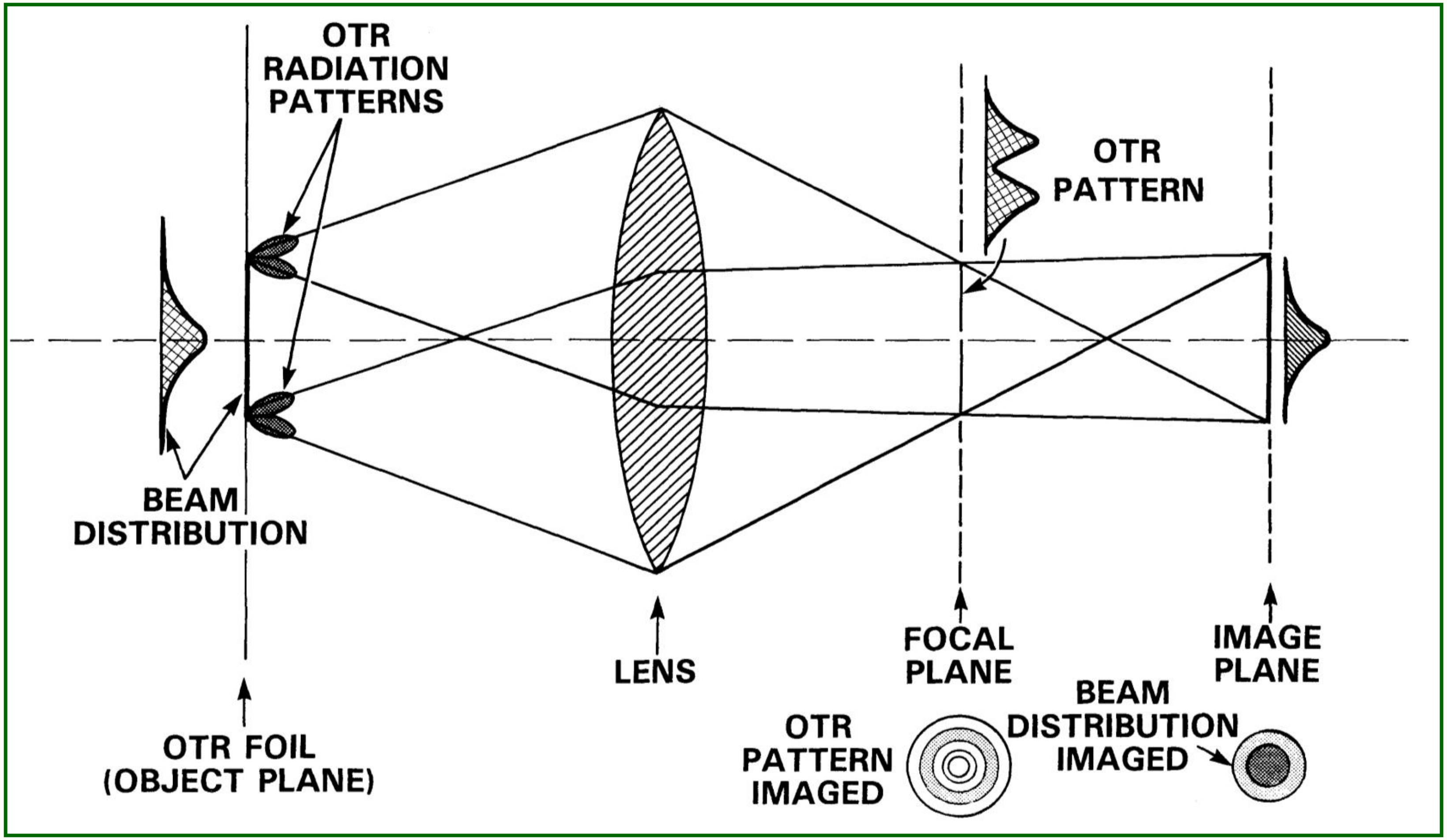
  - image processing software.

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)**

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

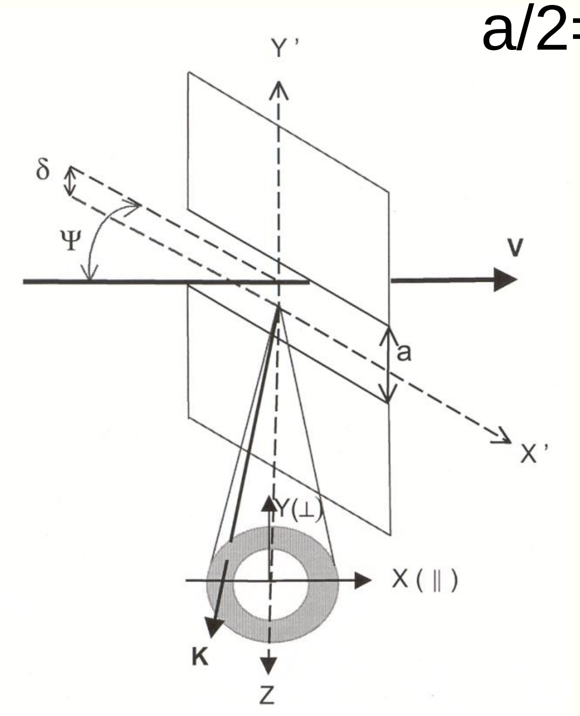
$$\iint dxdy\ K_1^{\ 2}(\alpha b)\, e^{-\frac{x^2}{2\sigma_x^{\ 2}}}\, e^{-\frac{y^2}{2\sigma_y^{\ 2}}},$$

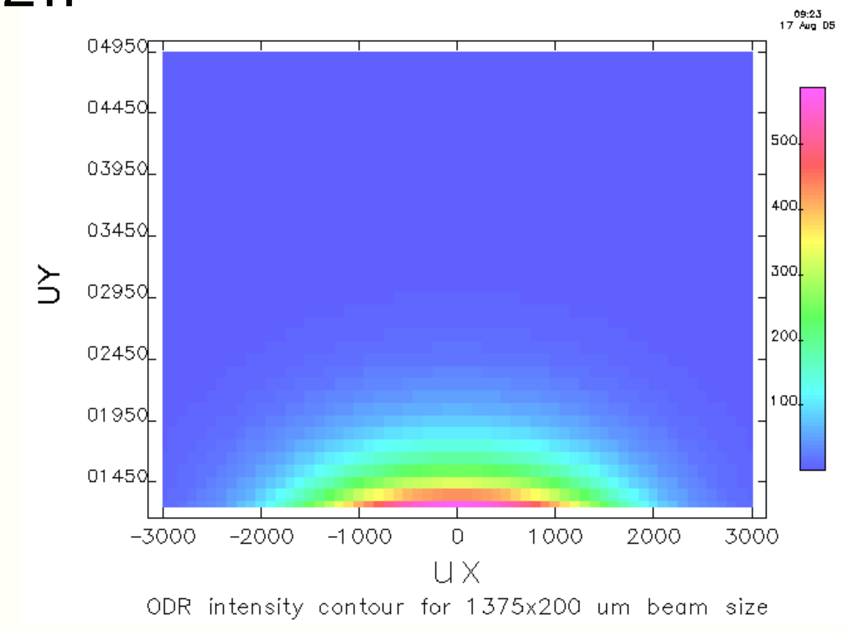
where ω = radiation frequency, v = electron velocity ≈ c = speed of light, q = electron charge, N is the particle number, $K_1(\alpha b)$ is a modified Bessel function with α= 2π/γλ and b is the impact parameter.

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).

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





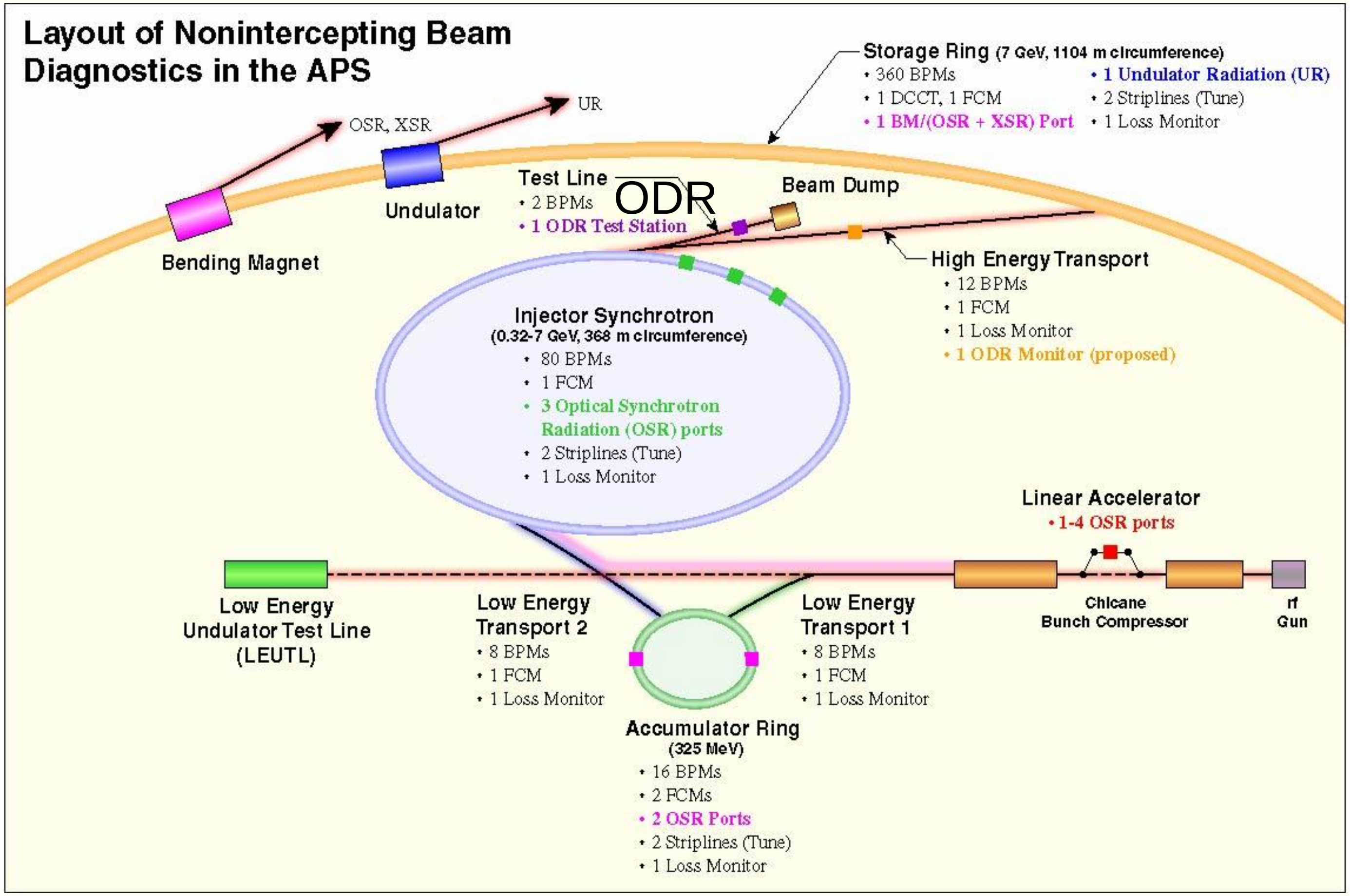
Development of Imaging Diagnostics for Multi-GeV Beams

Fermilab

- 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 ,INFN, 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).

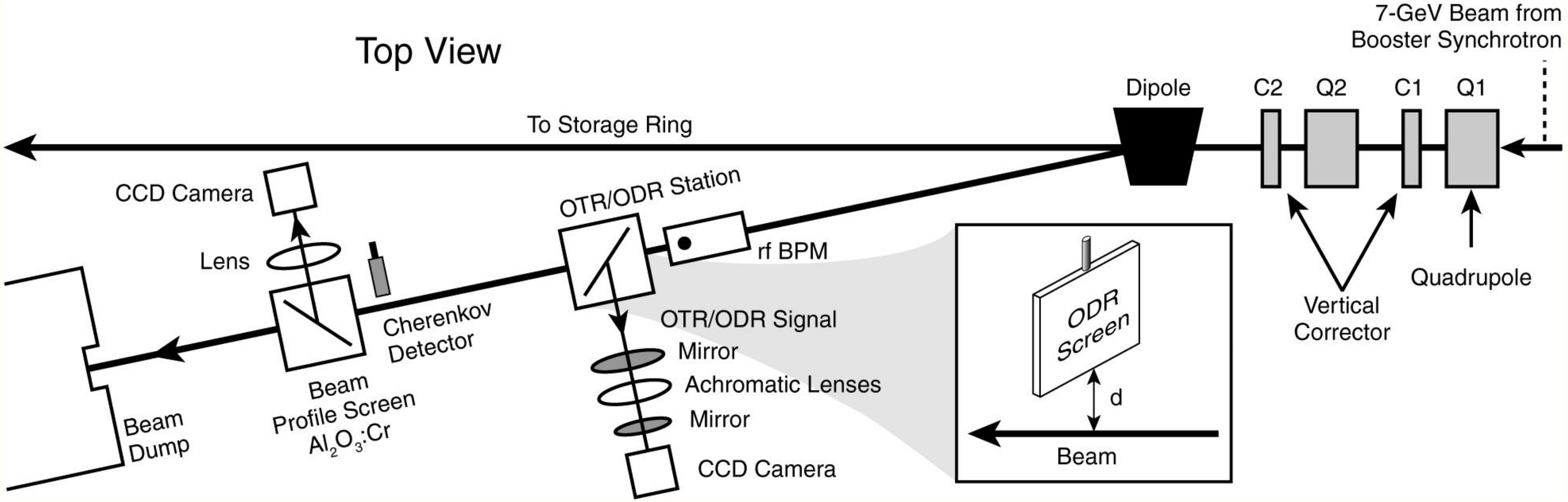
The APS Facility Has Provided Sources for Developing Time-Resolved, NI Diagnostics

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

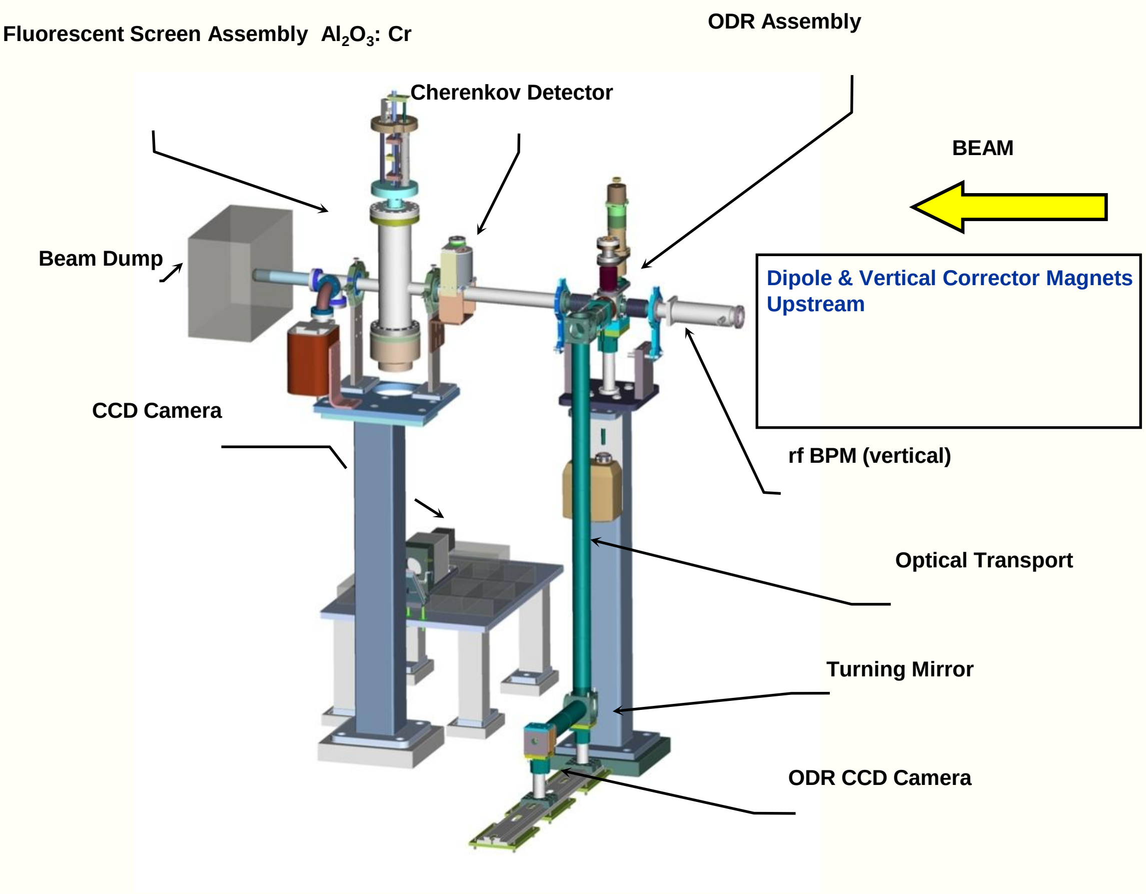


Schematic of the OTR/ODR Test Station on BTX Line at APS

- **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.**

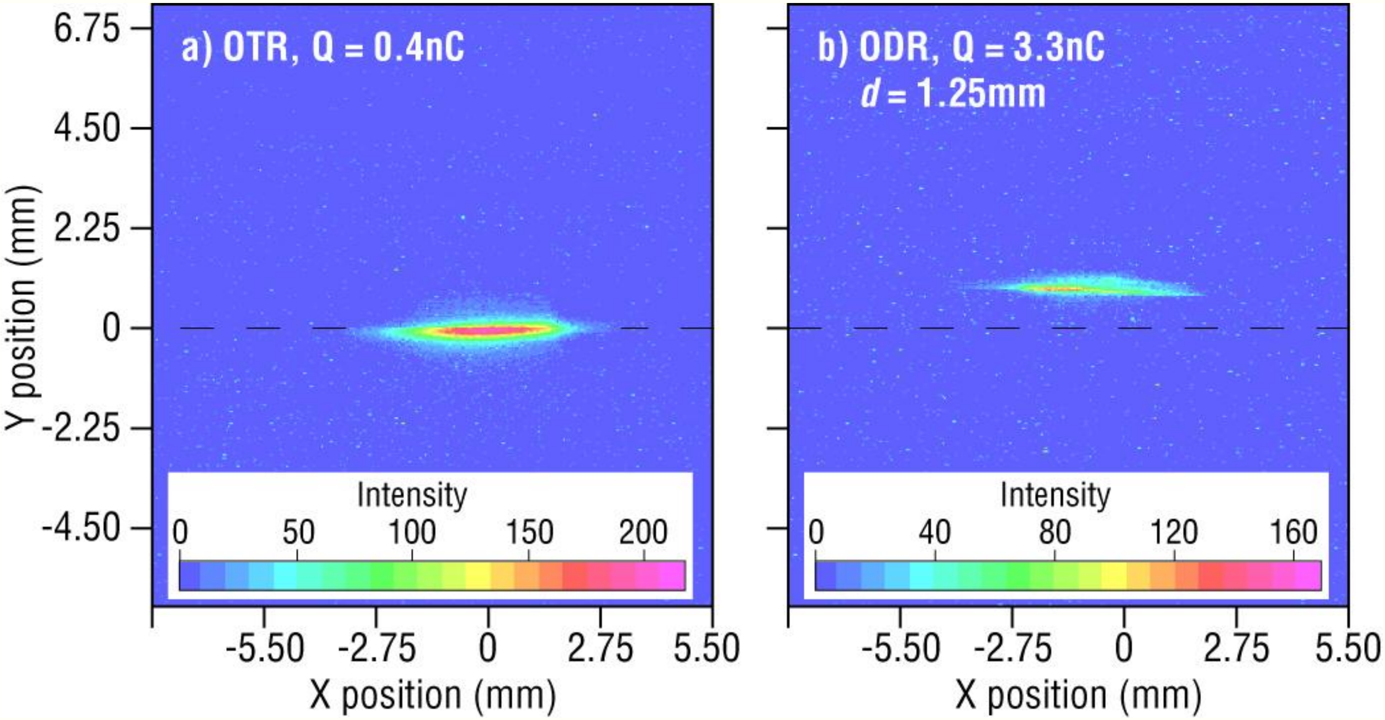


An OTR/ODR Test station was developed on the BTX line for 7-GeV beams



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

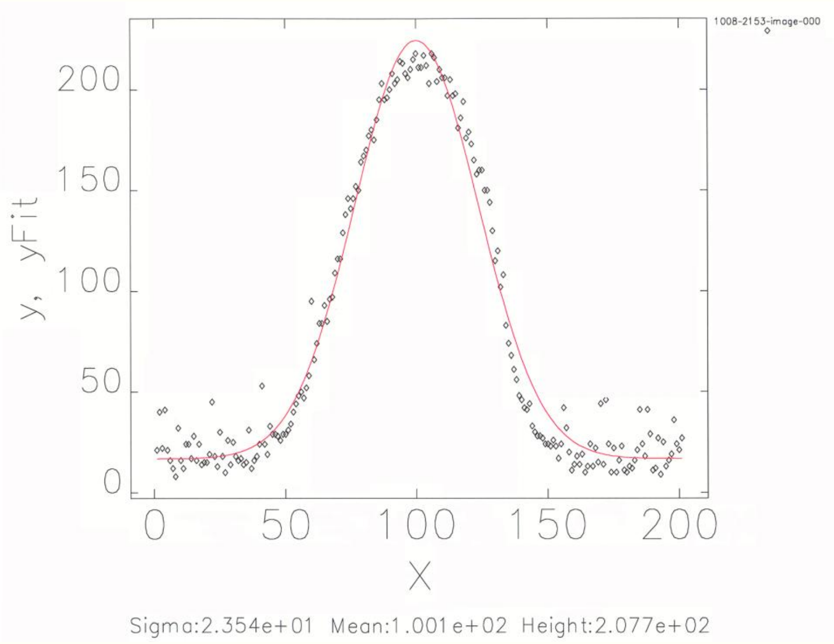
- **ODR offers the potential for nonintercepting, relative beam-size monitoring with near-field imaging. This is an alternate paradigm to far-field work at KEK and FLASH.**

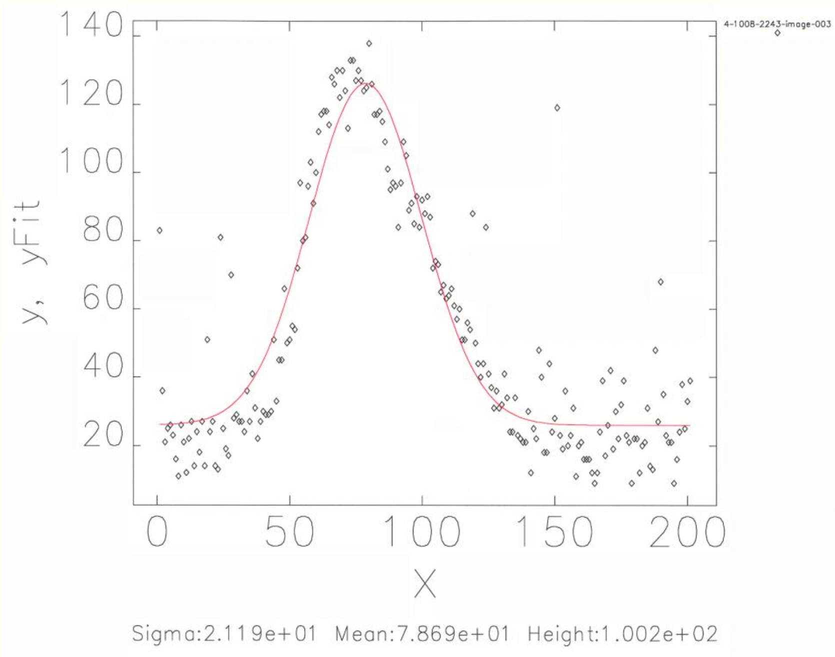


Lumpkin et al., Phys. Rev. ST-AB, Feb. 2007

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

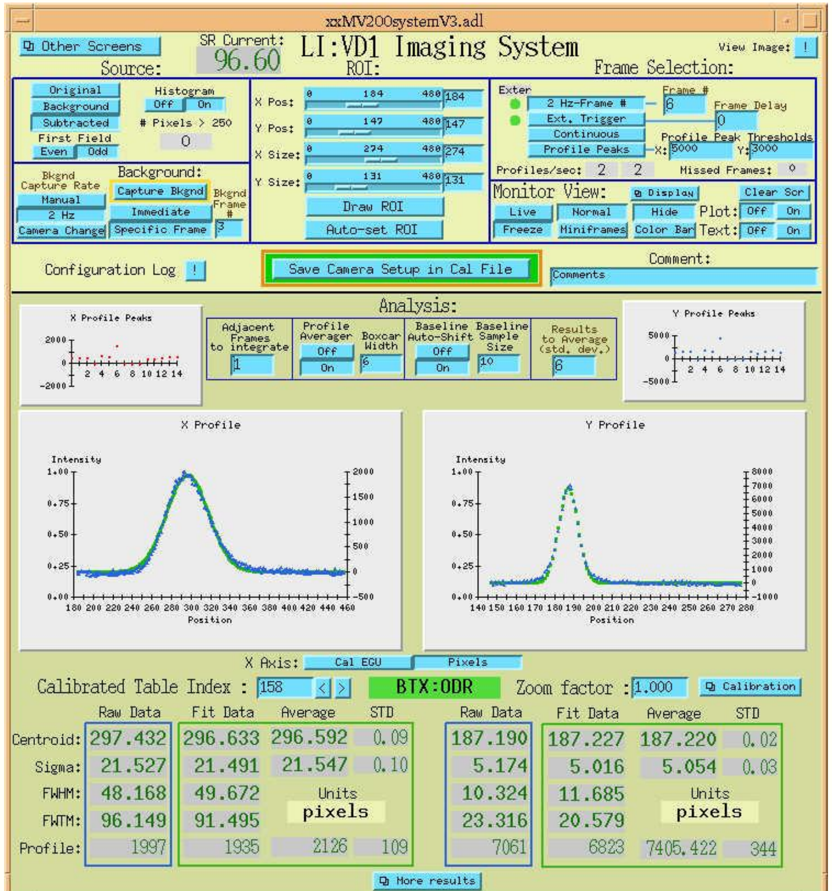
- OTR profile, Q=0.4nC ODR profile, Q=3.2 nC d=1.25 mm

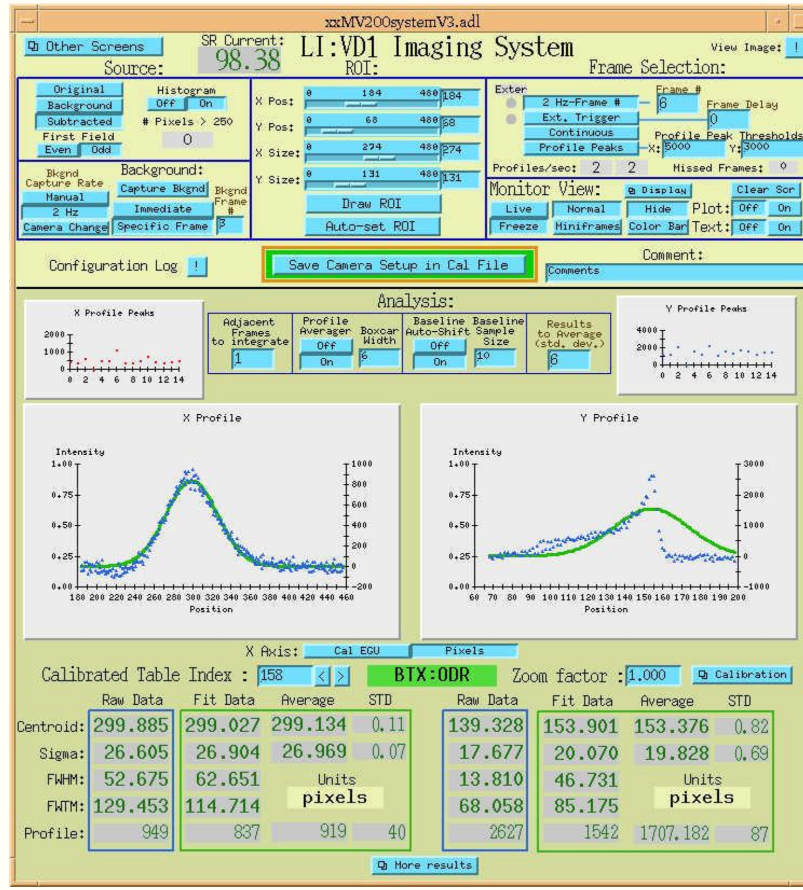




Online Image Processing Shows OTR and ODR Results

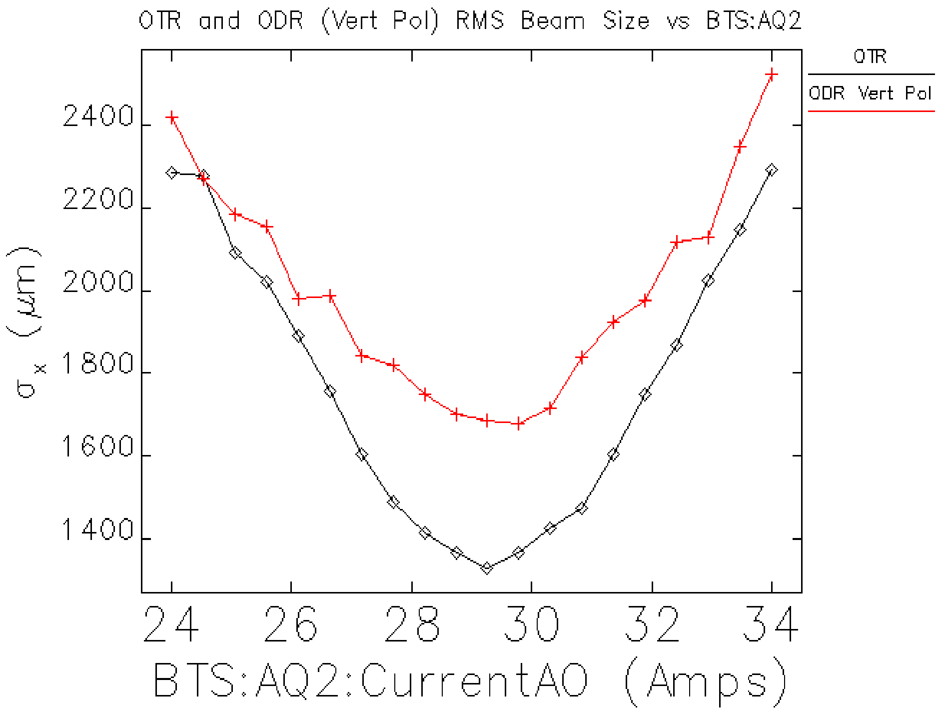
- OTR Profiles ODR Profiles (VPol.)

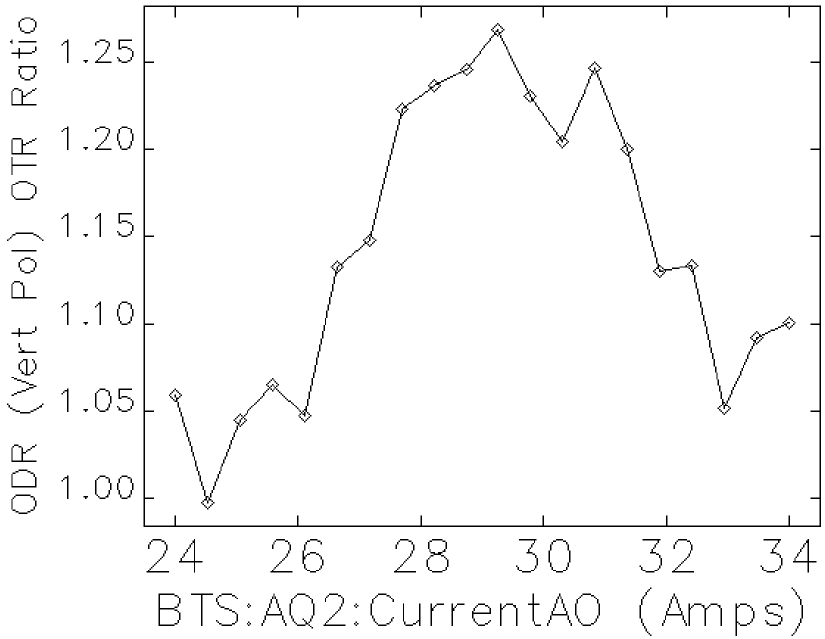




Perpendicular ODR Polarization Component Gives More Direct Representation of Beam Size.

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

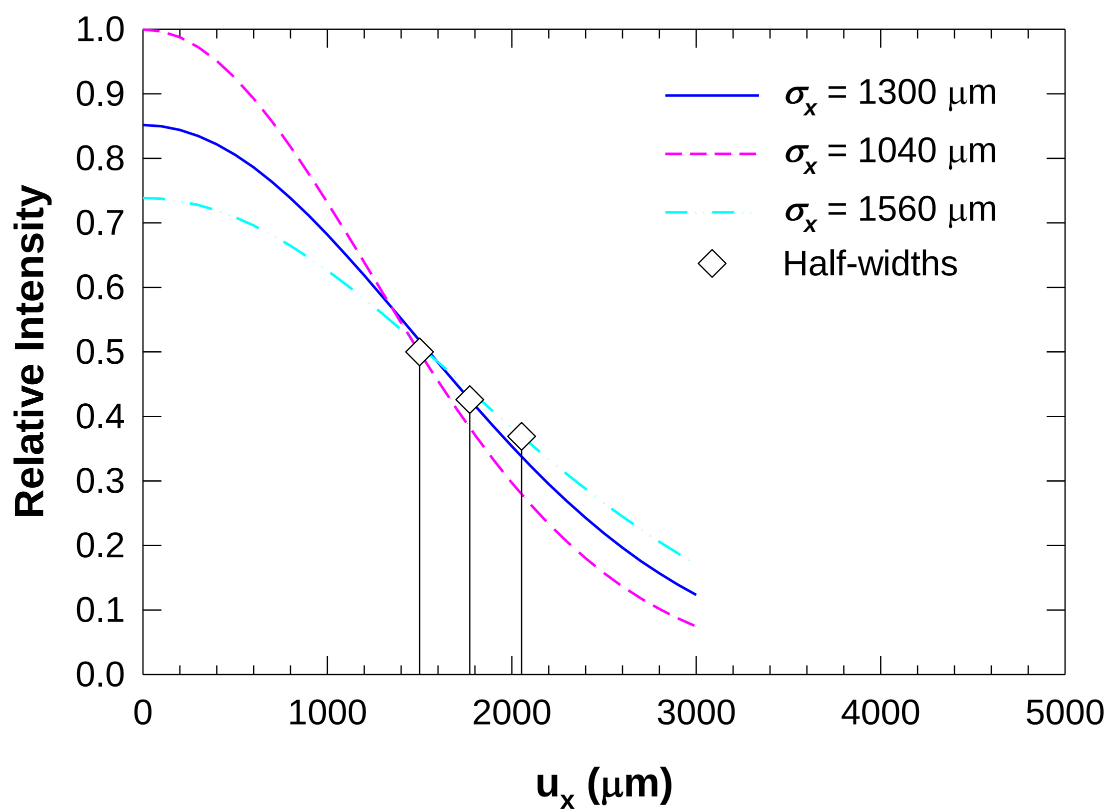




Lumpkin et al., Phys. Rev. ST-AB, Feb. 2007

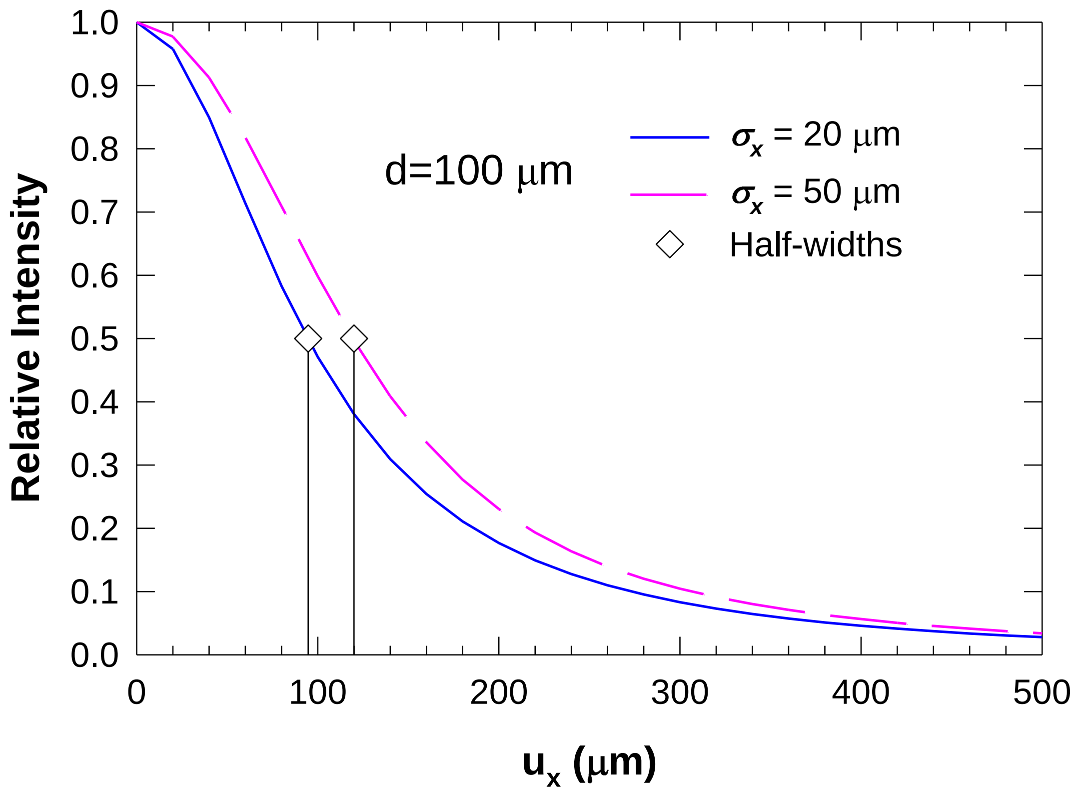
Analytical Model Indicates Beam-size Sensitivity on x Axis (Parallel to Edge)

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



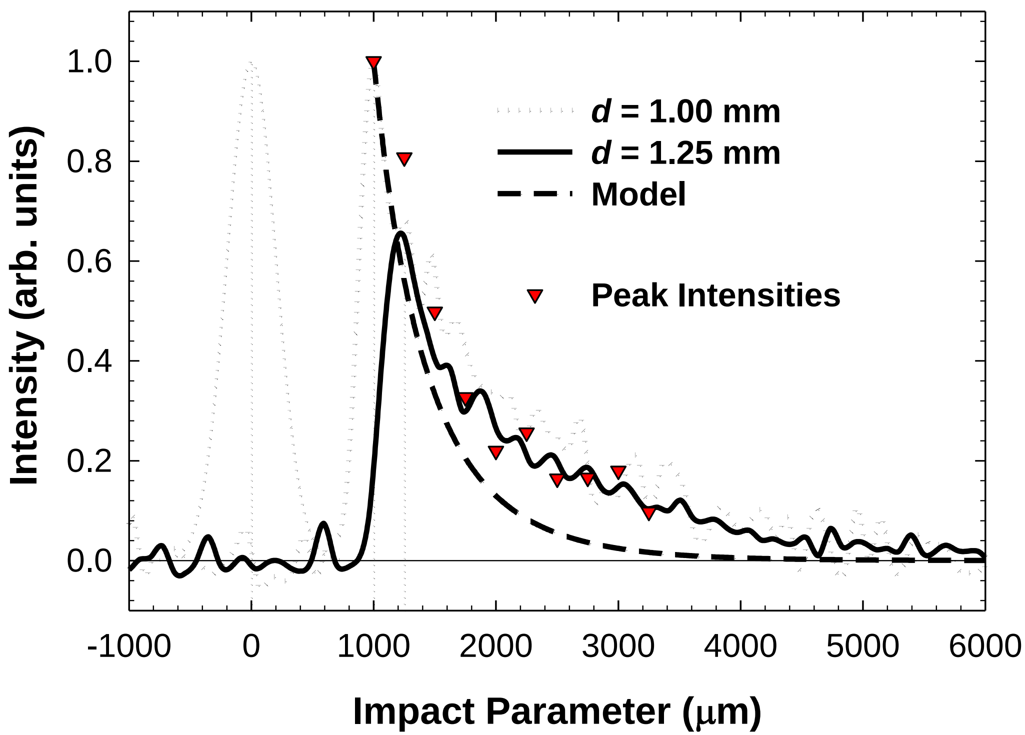
Analytical Model Indicates Beam-size Effect in New Regime at 20-50 μm for 7-GeV Beam (XFEL,ERL,ILC)

- **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

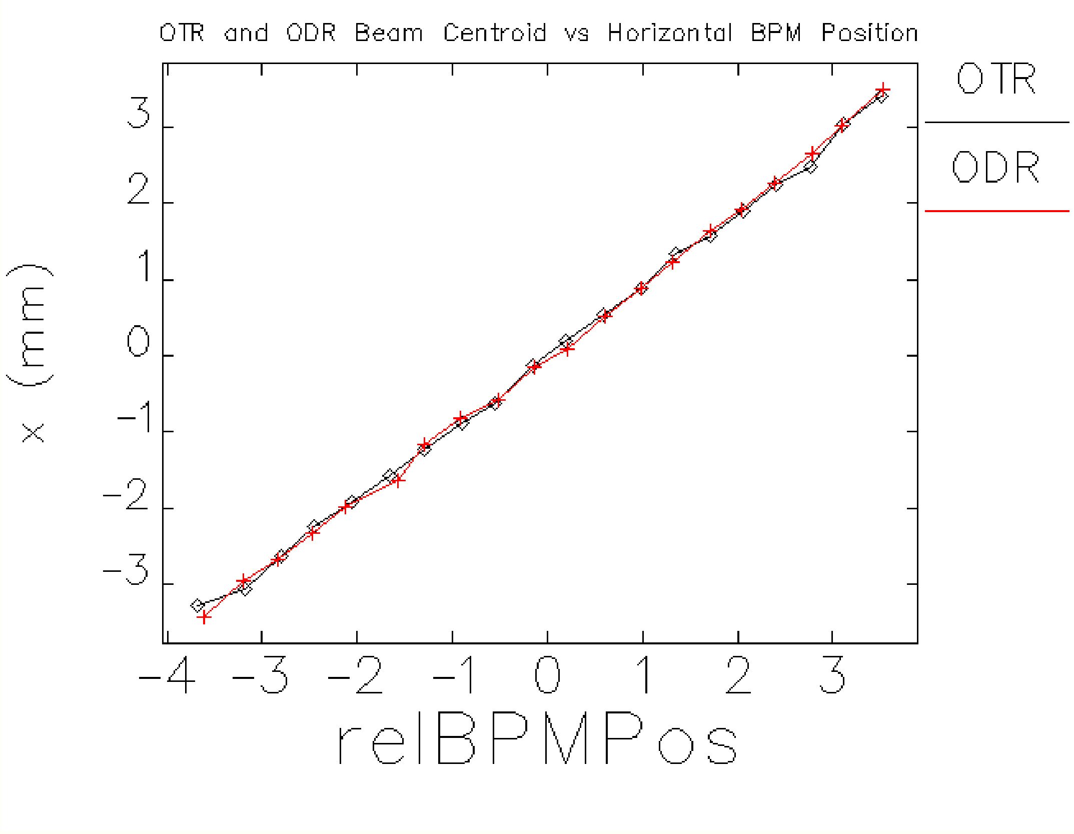
- **Comparison of OTR beam profile and ODR vertical profile data. The peak intensity has an exponential behavior with impact parameter while the total profile has the modified Bessel function effect.**



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 in FY08

- 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 done 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.

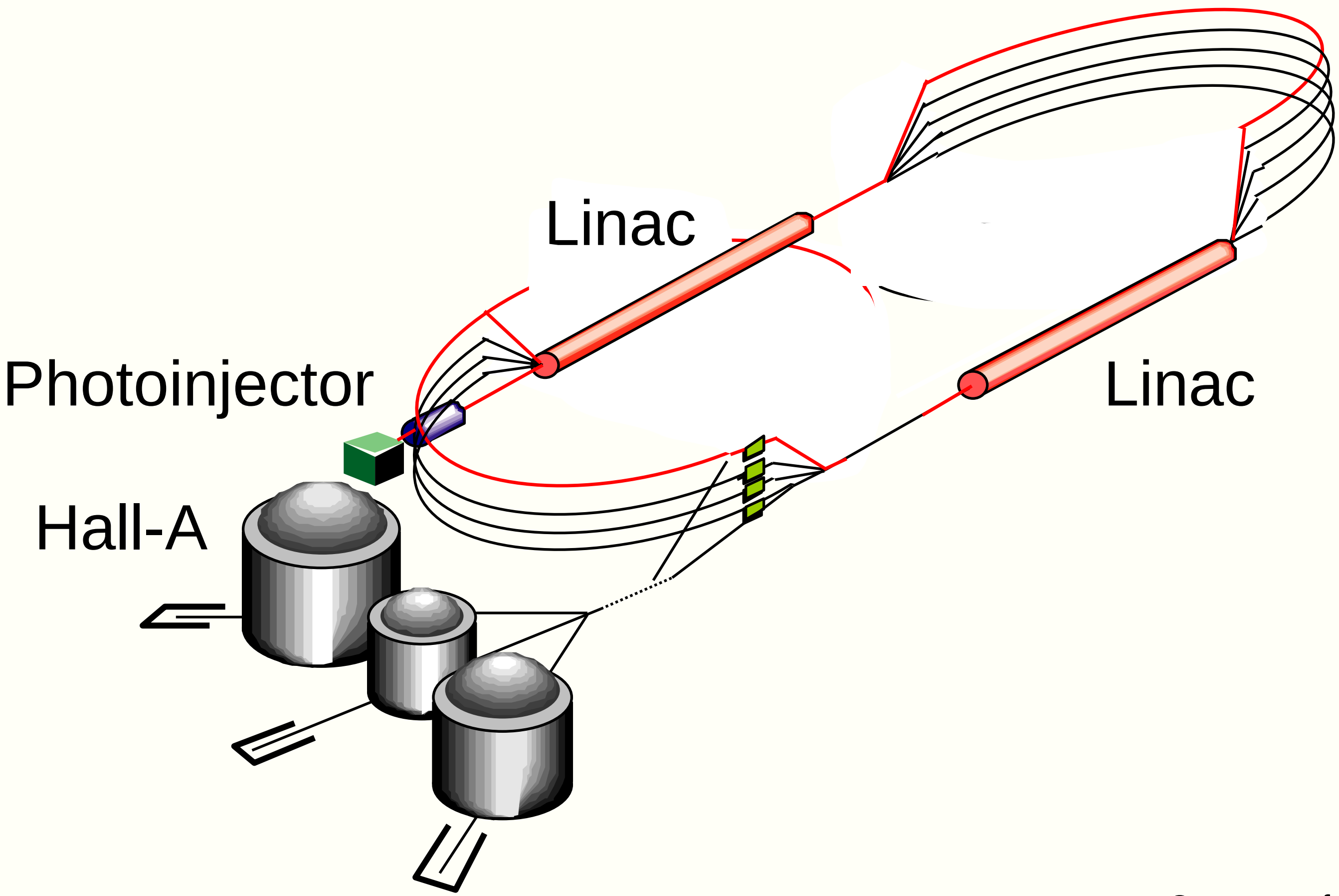
- **CEBAF beam size is 10 times smaller and the charge is 1000 times greater than APS case. What are background sources?**

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

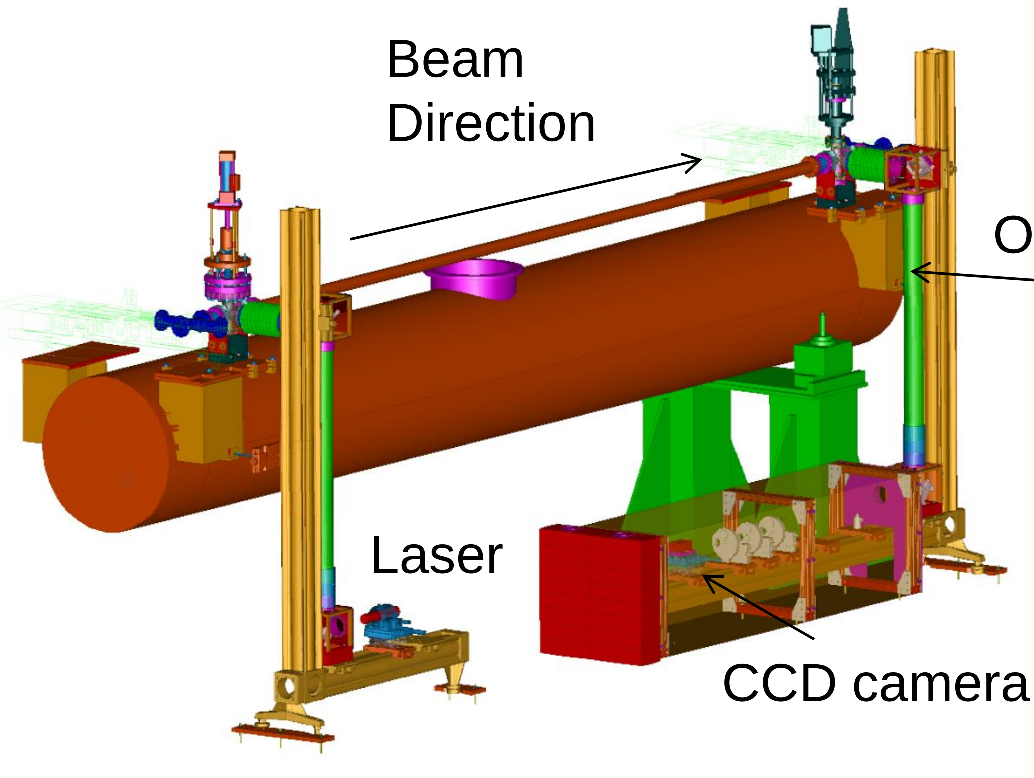
- **100 μAmps CW beam extracted at 1, 2, 3, 4 or 5 GeV**



Courtesy of Alex Bogaz, JLAB

Hall –A Transport Line

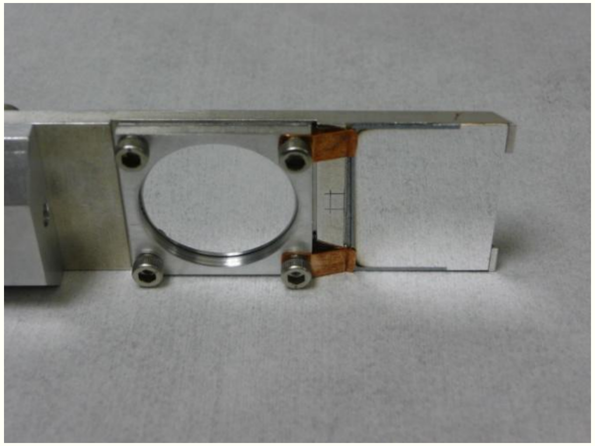
- **New OTR/ODR station installed next to flying wire station to allow comparison and cross-validation.**

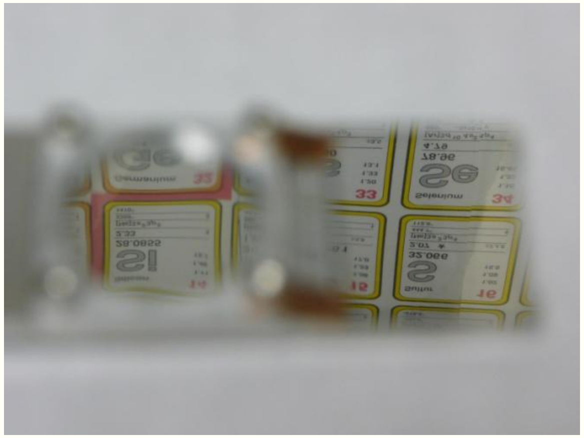


Courtesy of P. Evtushenko

OTR and ODR Converters Revised

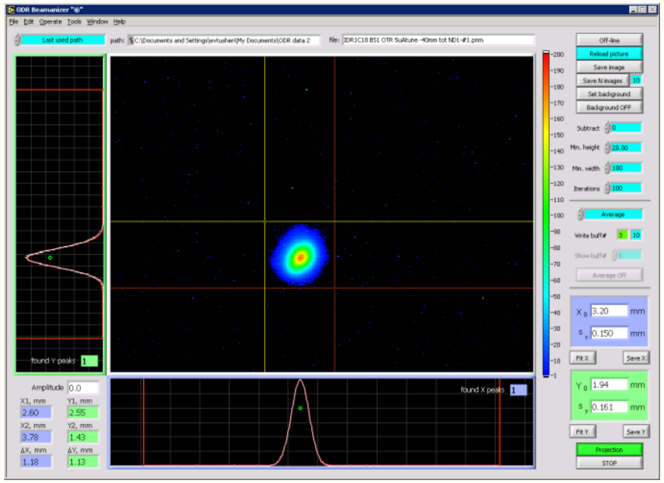
- **New OTR converter using aluminized Kapton for the 20-mm aperture was prepared at Fermilab Thin Films lab by Eileen Hahn. About 1500 Angstroms of Al deposited by evaporation deposition method on a stretched 6-µm thick Kapton film.**
- **New ODR converter was prepared by sputtering a 600 Angstrom Al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



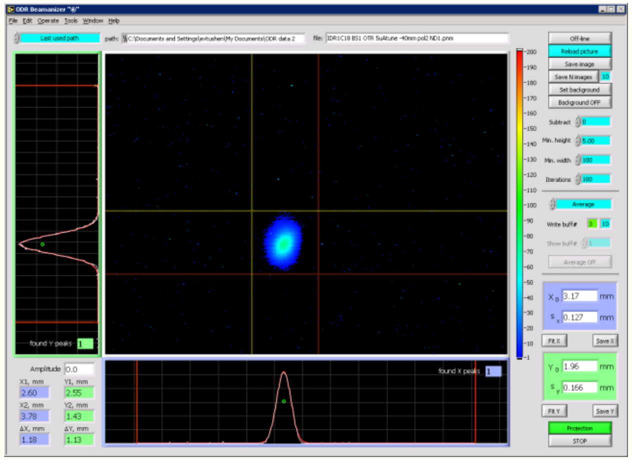


Initial OTR Images at 4.5 GeV

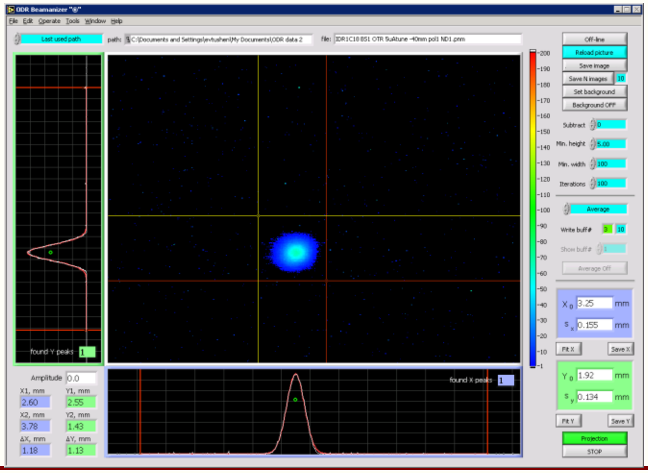
- **Newly installed Al-coated Si wafer used with 5-μA Tune beam (250 μs at 60 Hz). Polarization effects seen on $\sigma_{x,y}$.**



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



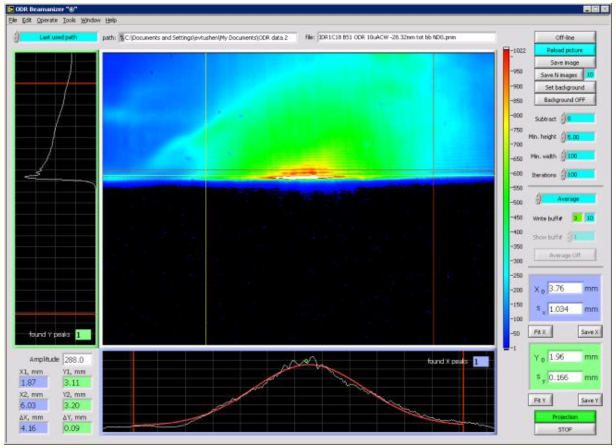
V-pol
σ_x:127 μm

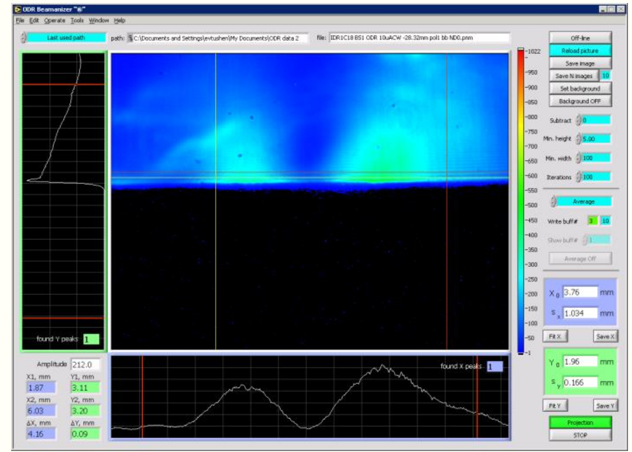


H-pol.
σ_y:134 μm

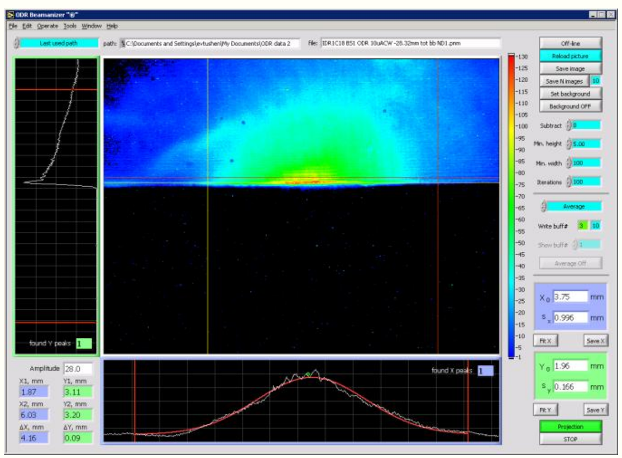
Basic ODR images at 10 μA CW

Polarization Component effects are clear.

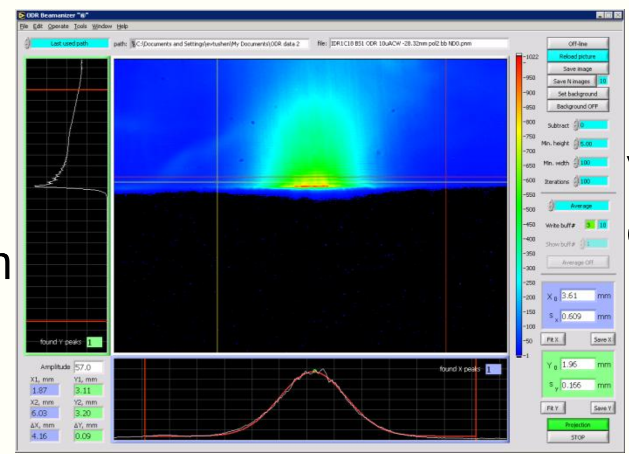




Hpol.: Double lobe



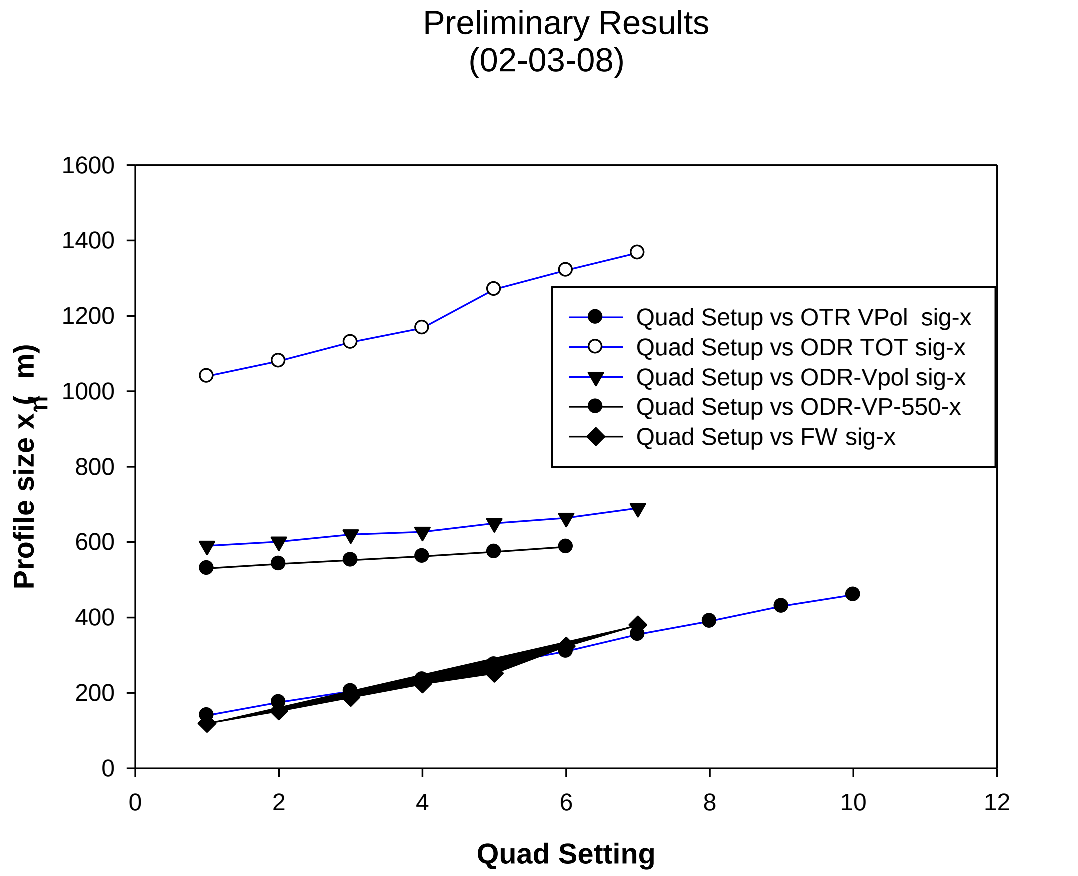
Total: σ_x=996 μm



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.

- **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

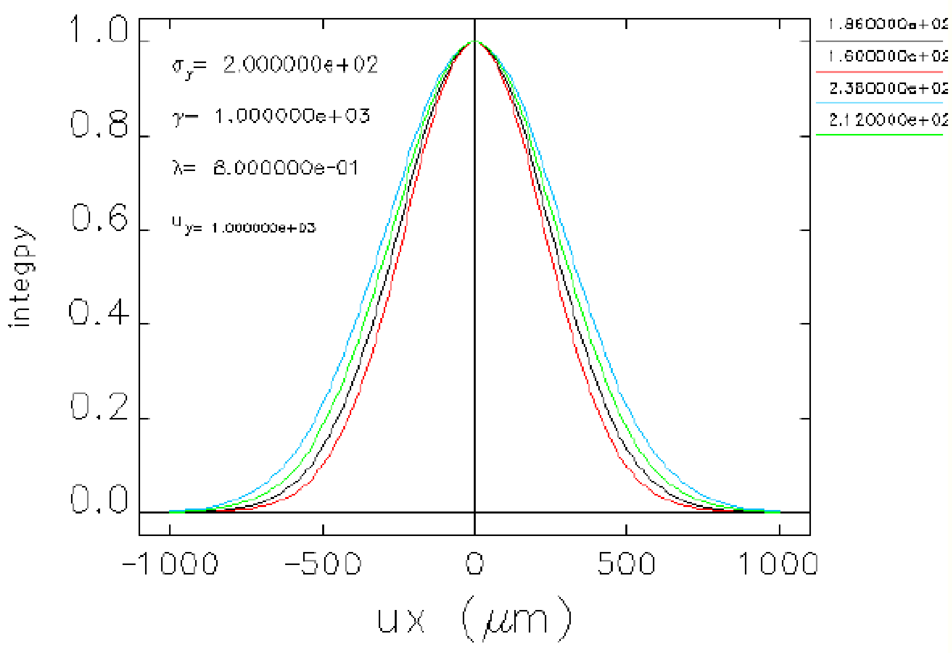
Sub-GeV e-Beam with 10 μC Should Give ODR Image

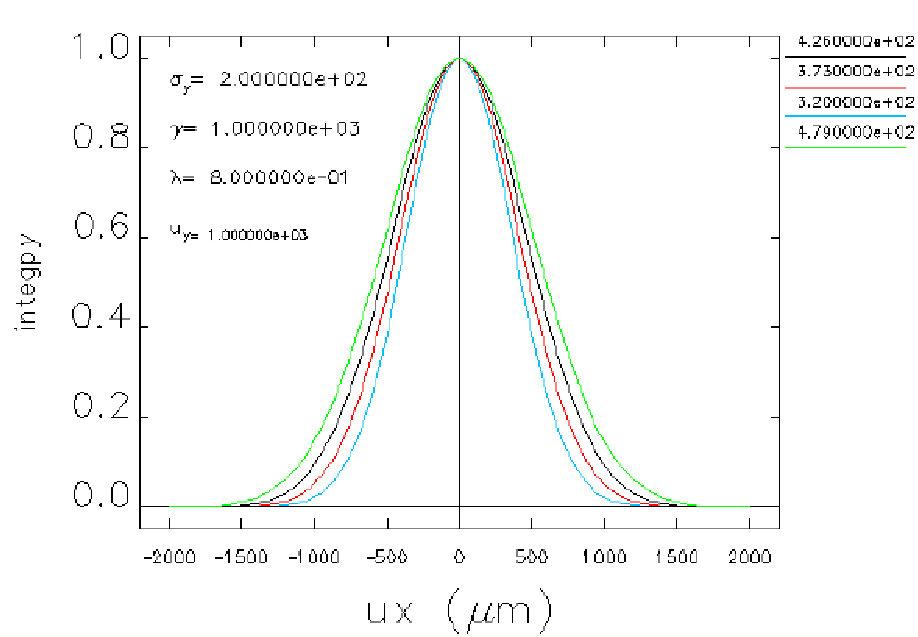
- NML beam sizes can provide prototypical test of ILC parameters.
- ODR image intensity scales in exponential argument as $-4\pi d/\gamma\lambda$.
- If energy reduced by 10 then can reduce *d* if beam is smaller and increase charge integrated in image by 3000 compared to APS case.
- Additionally, use 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.

ODR Model Shows Beam-size Effects

Fermilab

- **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.**

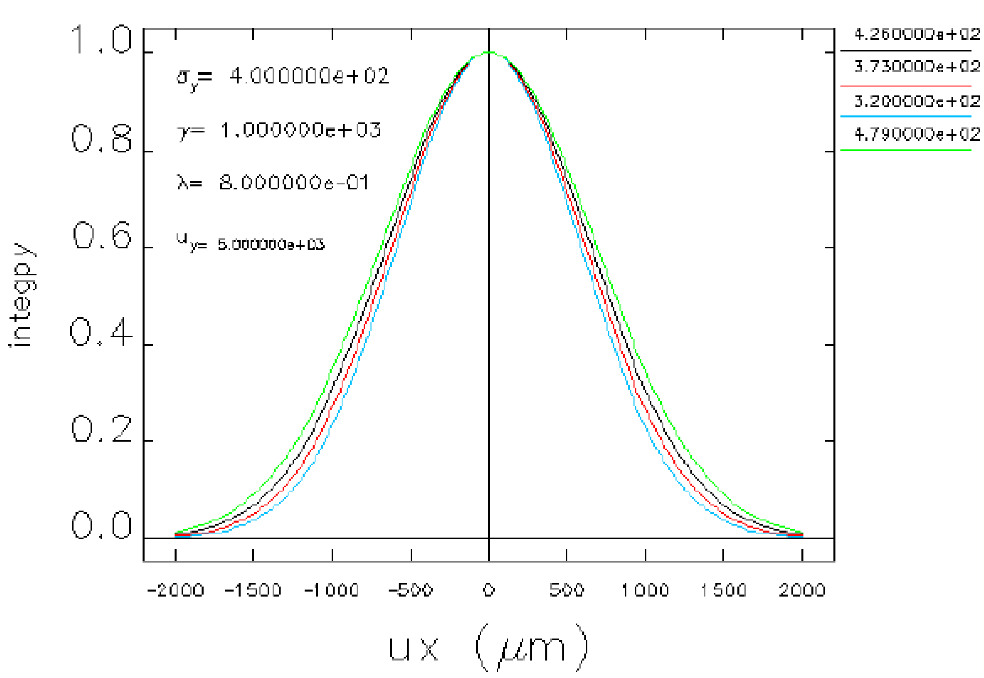


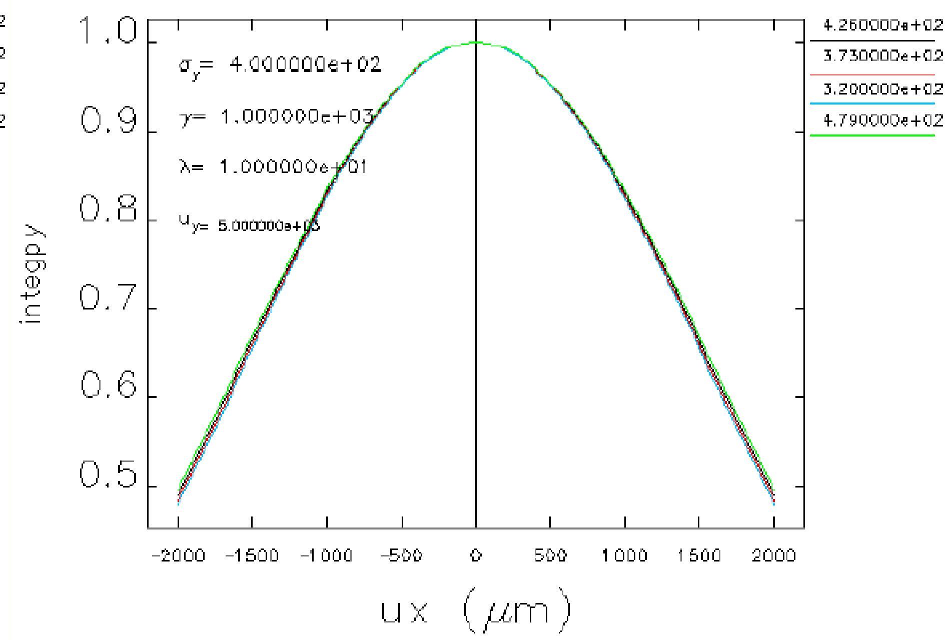


Courtesy of C.-Y. Yao, ANL

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.**

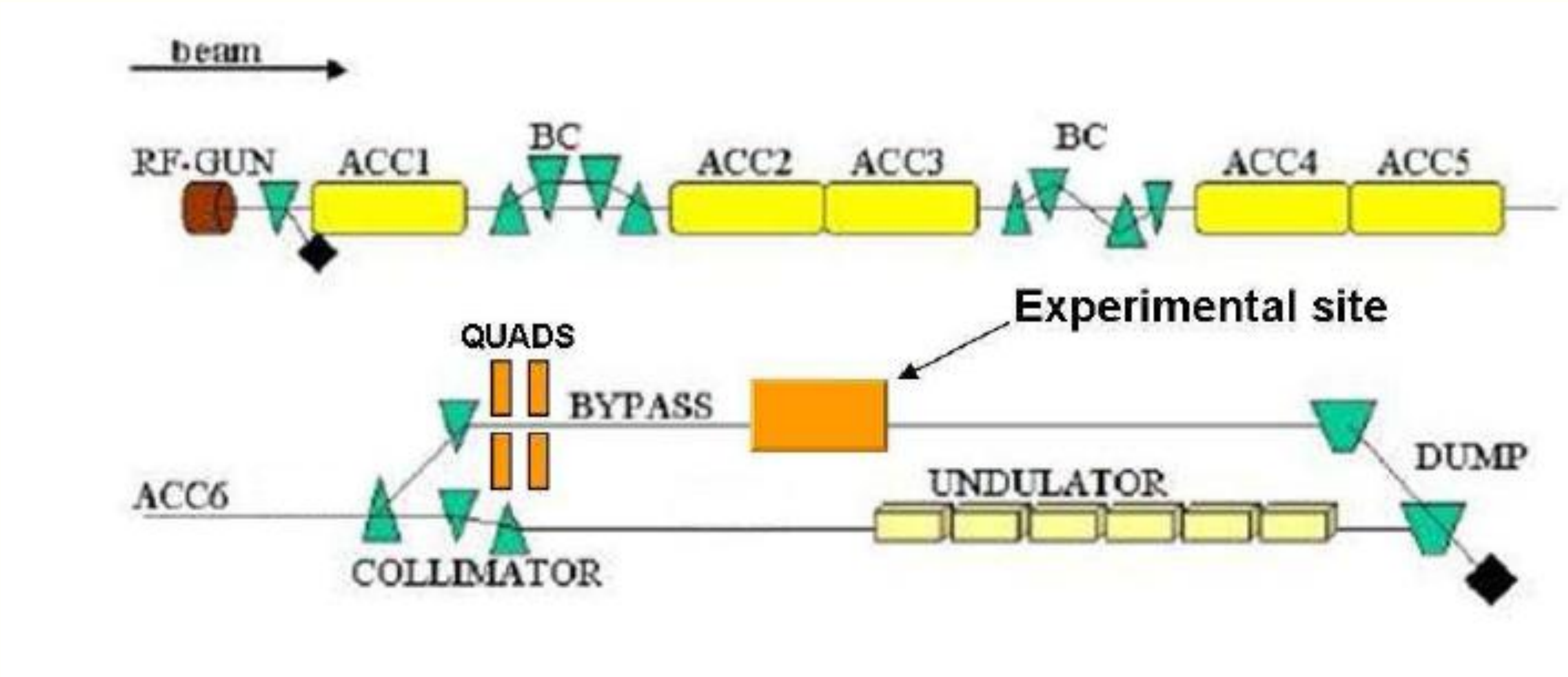




Courtesy of C.-Y. Yao , ANL

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.**

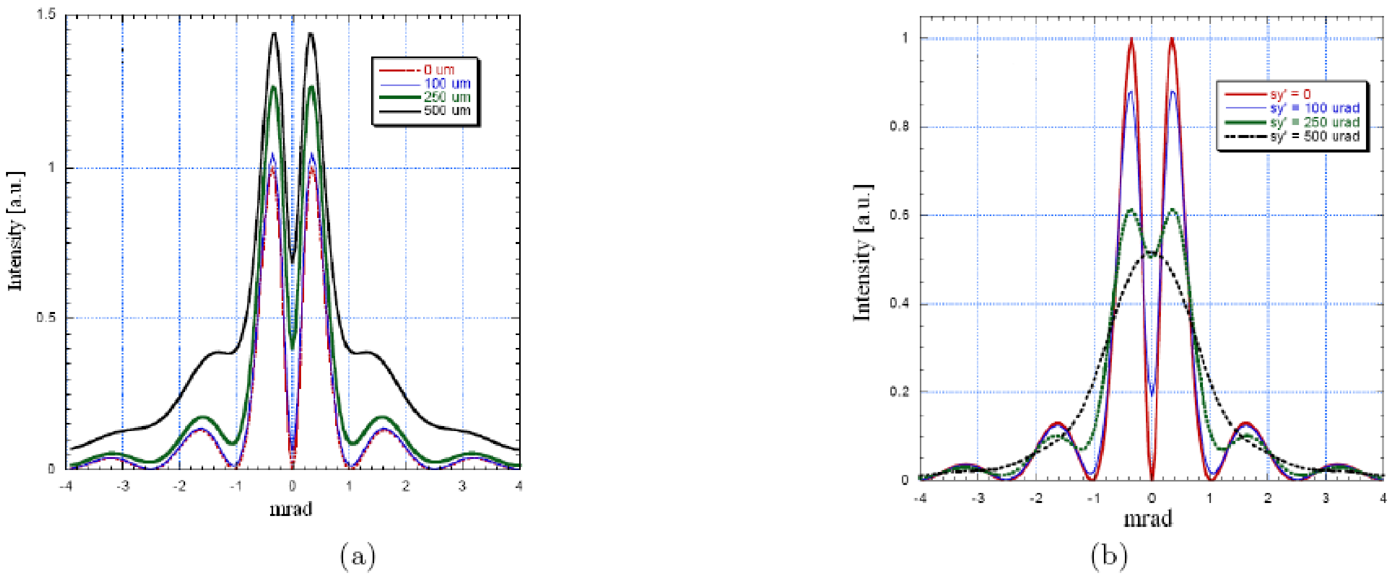


Figure 1. ODR angular distribution at 1 GeV for different beam sizes (a) and beam angular divergences (b).

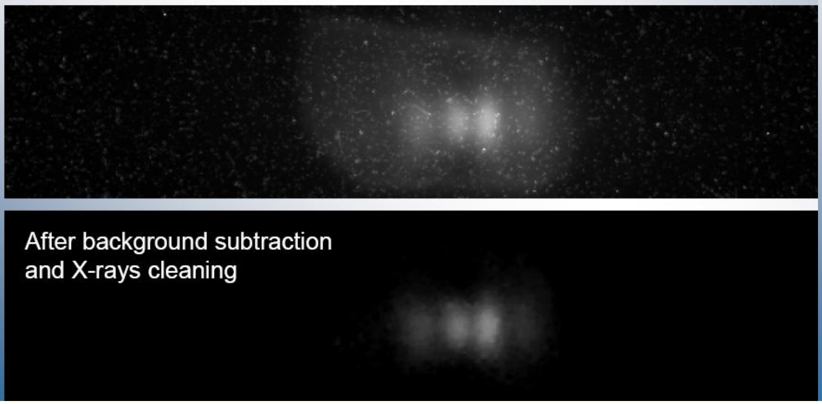
E. Chiadroni et al.,INFN

- **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

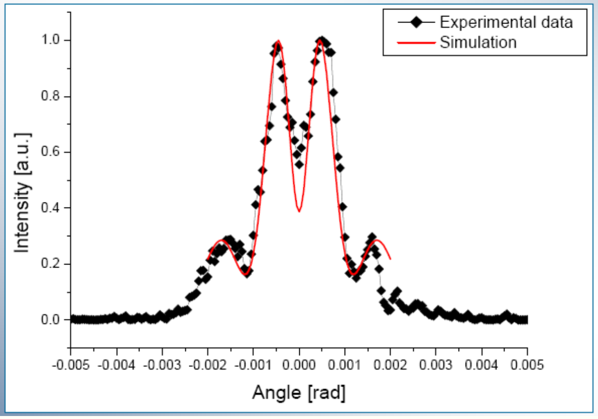
- *0.7 nC*
- 25 bunches
- *2 s* exposure time
- E_{beam} = *680 MeV*
- *800 nm* filter and polarizer in



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

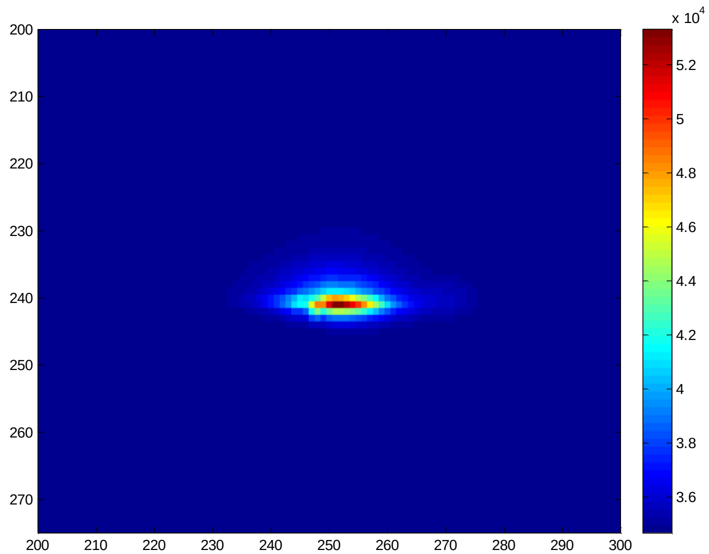


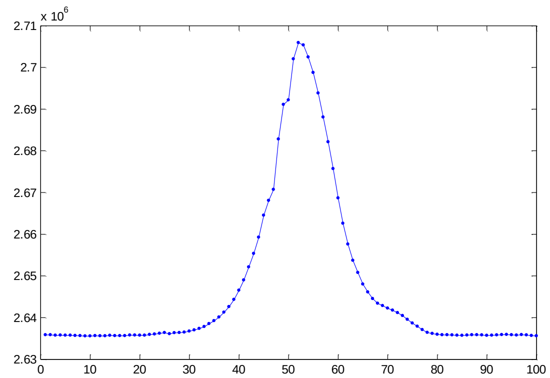
E. Chiadroni et al., PAC07

OTR at FLASH: 900-MeV Electrons

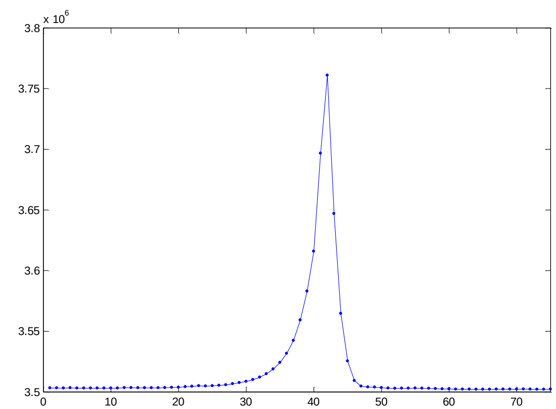
- **Near-field OTR Image obtained in collaboration with E. Chiadroni, et al. in January 2008 studies.**

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





X projection
σ_x = 210 μm



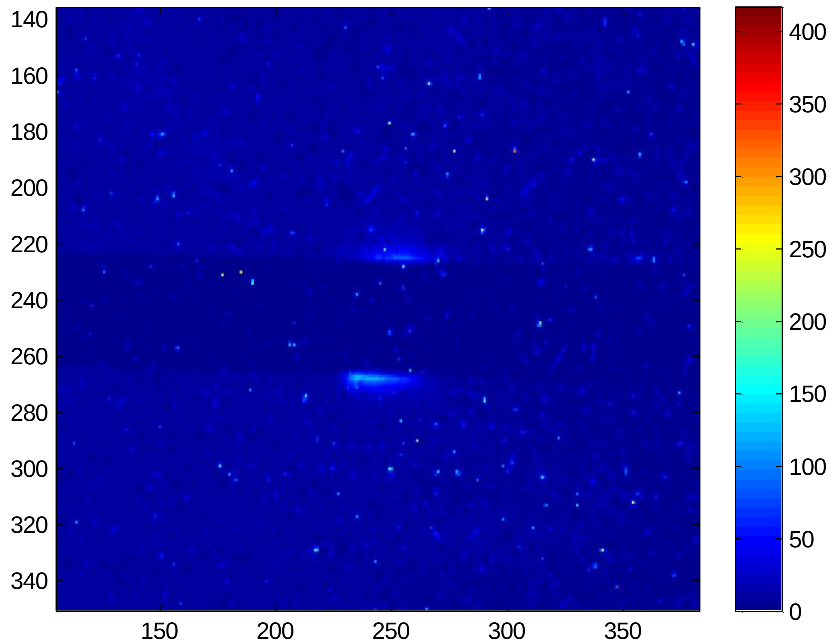
Y projection

Beam size: σ_x = 210 μm
σ_y = 100 μm

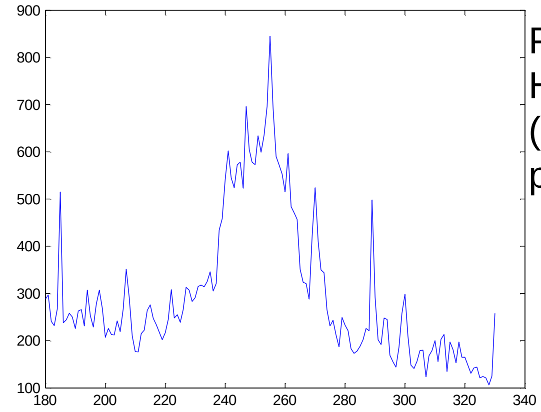
MATLAB by R.T-K

ODR at FLASH: 900-MeV Electrons

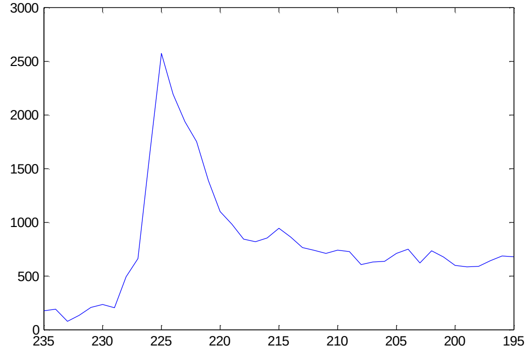
- **Near-field ODR Image obtained in collaboration with E. Chiadroni, et al. in January 2008 studies. b = 400,600 μm.**



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)

MATLAB by R.T-K

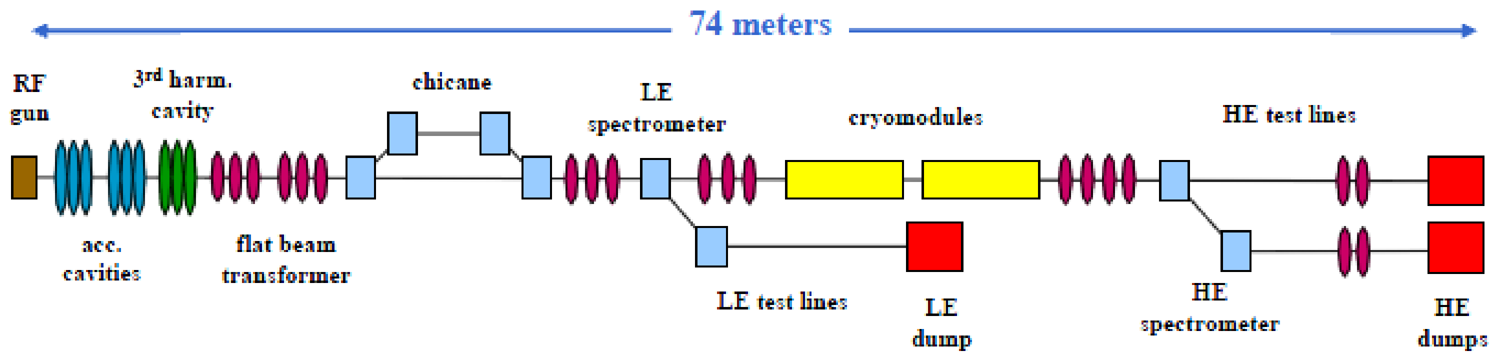
EXPERIMENT SUMMARY

- 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)

Move to New Muon Lab (NML)

- A0PI will be moved to NML in FY11; A0 group will be integrated into NML commissioning, operation, and experiments
- Purpose of NML is two-fold: test RF cryomodules; support AARD

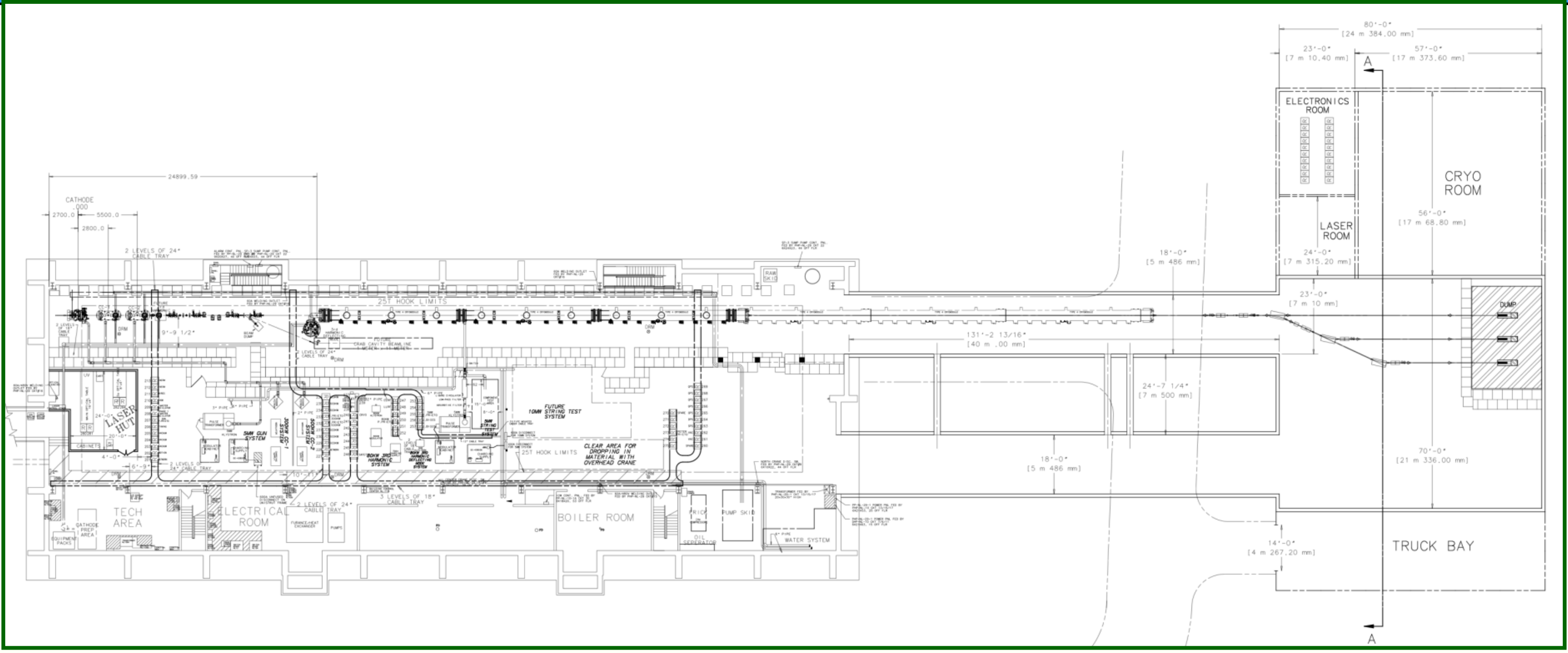
Preliminary Schematic of NML



- Injection energy >40 MeV, 2 RF cryomodules, high energy of >500 MeV
- Low energy beamline space available for AARD
- High energy beamline space available for AARD
- Operation at >3 nC, 3 MHz bunch trains 1 msec long, 5 Hz repetition rate
- Possibility of future building expansion for higher energy energy and more extensive area for AARD

M.Church

NML Conventional Facility Building Extension



- Design of NML Extension with CF&S Group (FESS)
- Room for 6 Cryomodules (2 RF Units)
- Expanded Diagnostic and AARD Test Area
- Cryoplant (300W)
- Possible 2-Tunnel Design to Mock-up ILC Design

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.***
- ***The ODR near-field imaging techniques also have relevance to x-ray FELs, ERLs, APS upgrade, and Project-X (if e- source also).***

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.