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Nonintercepting ODR Diagnostics for Multi-GeV Electron Beams

Alex H. Lumpkin

ASD Diagnostics Group

Advanced Photon Source

Jefferson Lab CASA Seminar

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U.S. DEPARTMENT OF ENERGY

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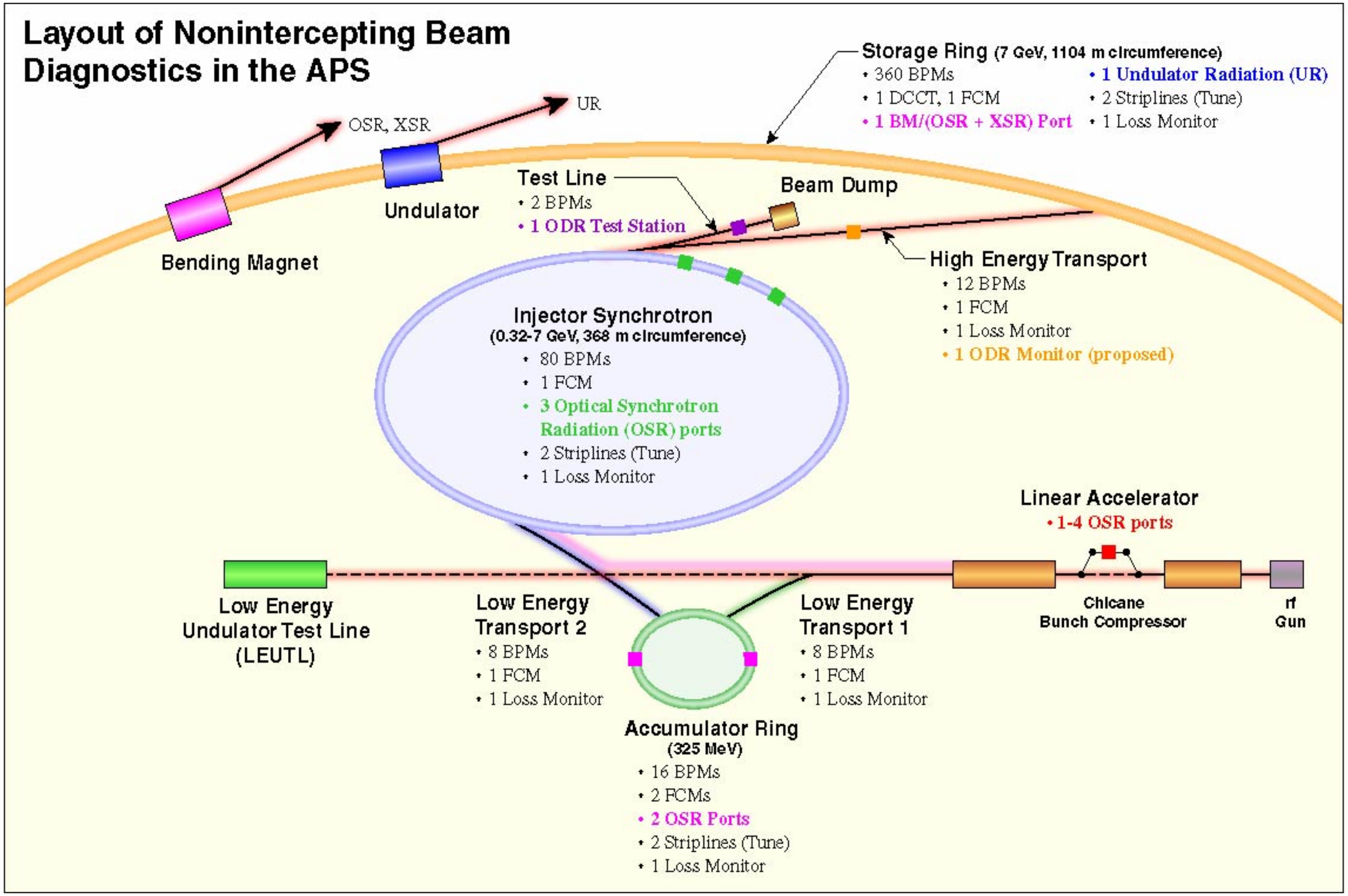
OUTLINE

- **Introduction**
- **Overview of the APS Nonintercepting (NI) Diagnostics**
- **Optical Diffraction Radiation (ODR) Background**
- **Optical Diffraction Radiation Experimental Results**
- **Potential Applications of ODR**
- **Summary**

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

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

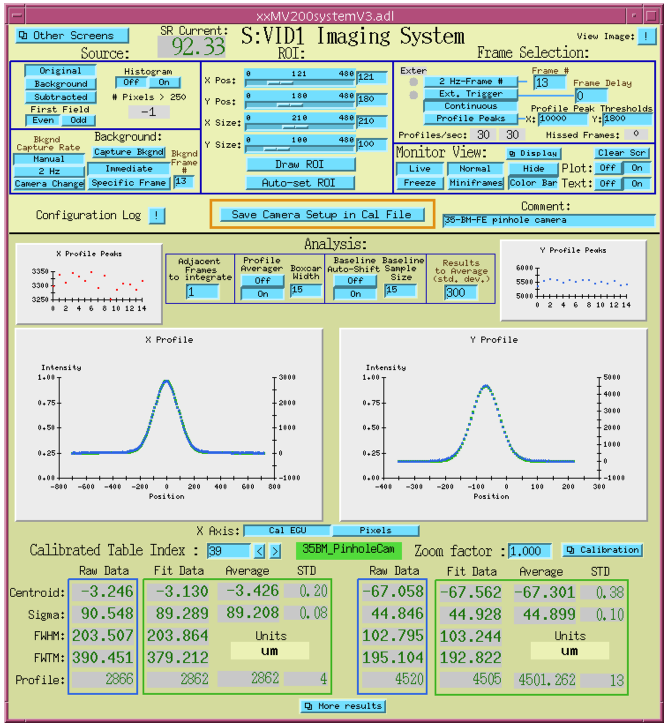


Development of Imaging Diagnostics for Multi-GeV Beams

- **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 facility 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), and laser wakefield accelerators (LWFAs) will be addressed.**
- **Relevance to CEBAF will be suggested.**

35-BM Pinhole Camera Serves All Users

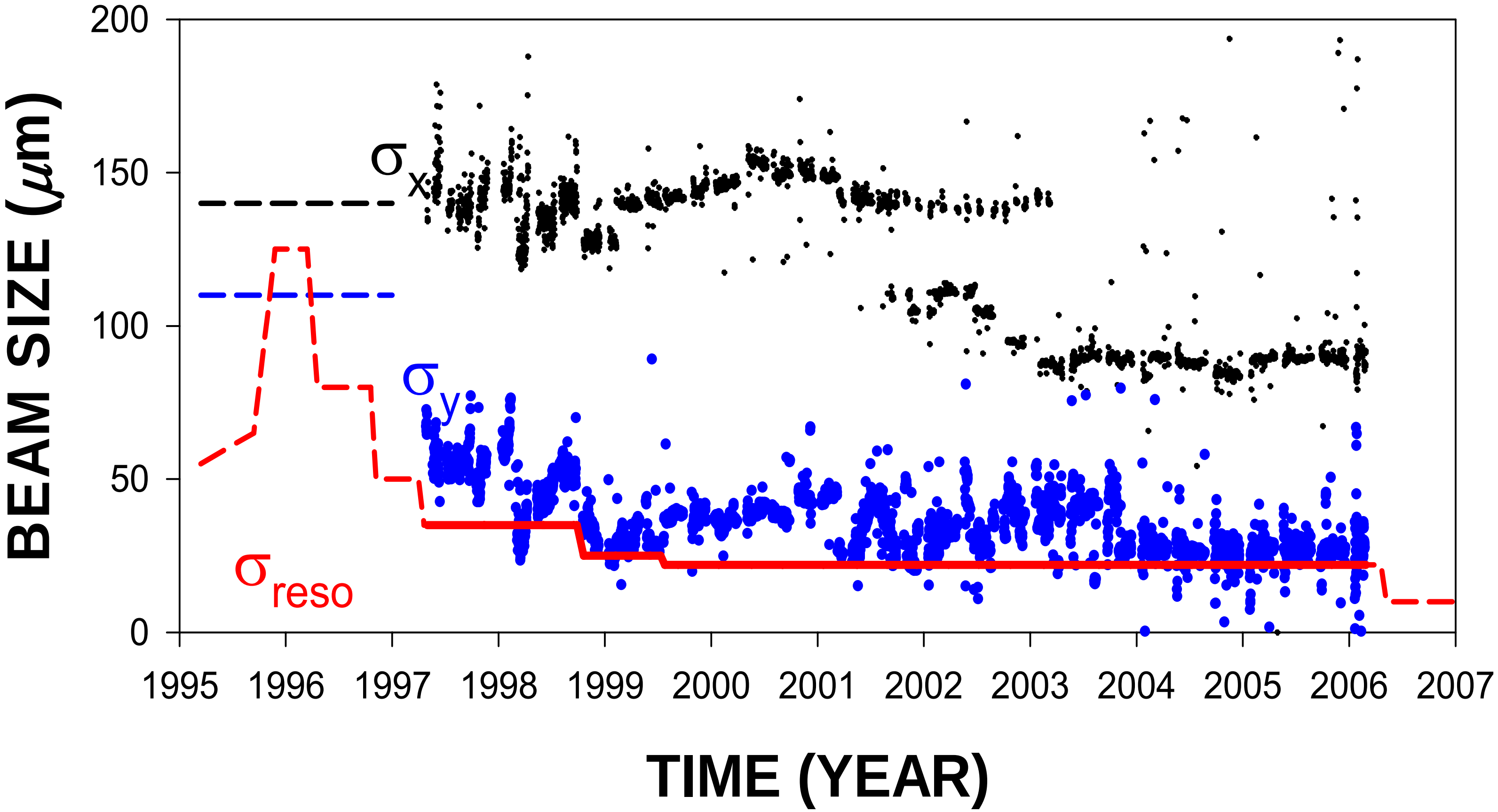
- Video image is available live in the APS CCTV network
- Video images are processed @ 30 Hz; beam size and centroid are available as process variables
- Beam size and centroid data are archived for future use



35-BM X-ray Pinhole Camera Data Archive

- Vertical beam size steadily decreases…

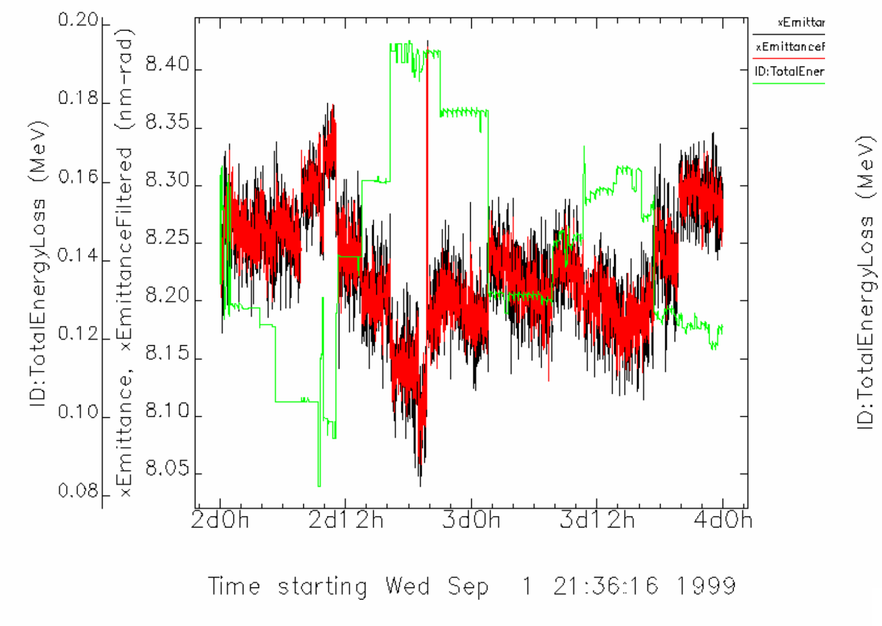
$\sigma_x = 90\ \mu\text{m},\ \sigma_y = 17-25\ \mu\text{m},\ \sigma_{reso} = 22\ \mu\text{m}$

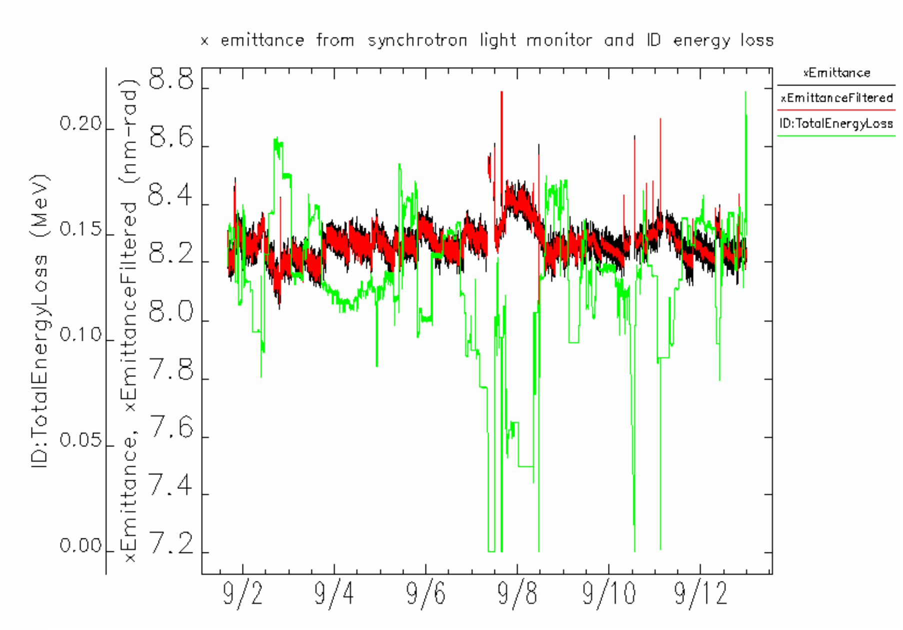


S35 Review: BXY

Beam Emittance Changed by Users' Activities

- During user runs, the beam size can vary up to 2.5 µm, largely due to ID gap changes by the user. The below data (2-week and 2-day tracking) show strong (anti)correlation of total energy loss by the APS insertion devices with emittance.

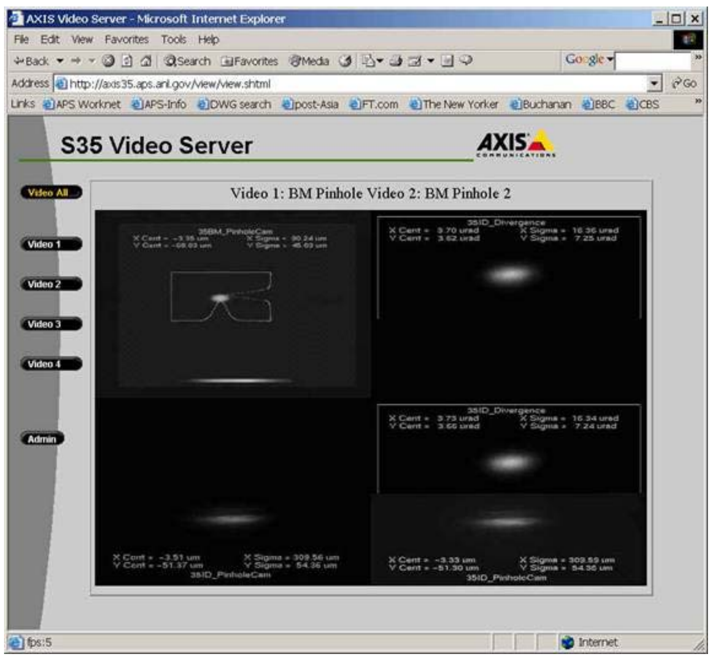


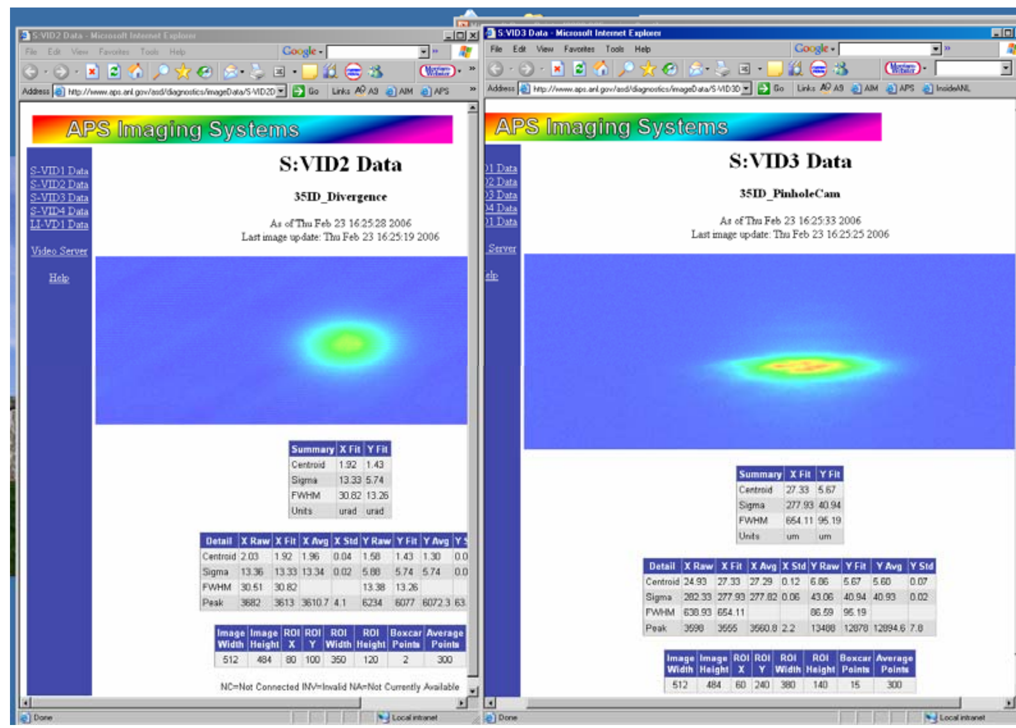


S35 Review: BXY

35-ID Divergence / Pinhole Images Serve All Users

- Web video is available at 5 frames/sec within the APS firewall. (http://axis35.aps.anl.gov)
- Beam image web page updated every minute outside the firewall. (http://www.aps.anl.gov/asd/diagnostics/imageData/S-VID2Data.html)





APS Topup Operations Need NI Beam Profile Monitor

- Techniques at KEK and elsewhere have been based on far-field detection of ODR angular distribution. Beam size effects are measurable **IF** divergence is very low by using the intensity minimum-to-maximum ratio.

  KEK used scanning mirror technique with 10-minute data record.
- More recently an intriguing use of the two conducting planes with a small relative tilt angle (dephased) has been shown to display beam-size effects. (PAC05 paper, UCLA, KEK)
- ODR near-field imaging technique offers a potential relative beam size monitor for the 7-GeV beam pulse with Q= 2-3 nC per pulse. This is a new paradigm based on looking at the ODR image profile along the single edge of a conducting plane and is also a single-shot method.
- ODR near-field also offers a complementary relative beam position monitor.
- Key scaling is that appreciable visible light emissions occur for impact parameters comparable to $\gamma\lambda/2\pi$. At 0.628 um and 7 GeV, this is 1.4 mm!
- Use OTR as a reference beam profile monitor at lower charge densities.

Strategy (Can we 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 are listed below:

- The charged-particle beam will transit thin metal foils to minimize beam scattering and Bremsstrahlung production.

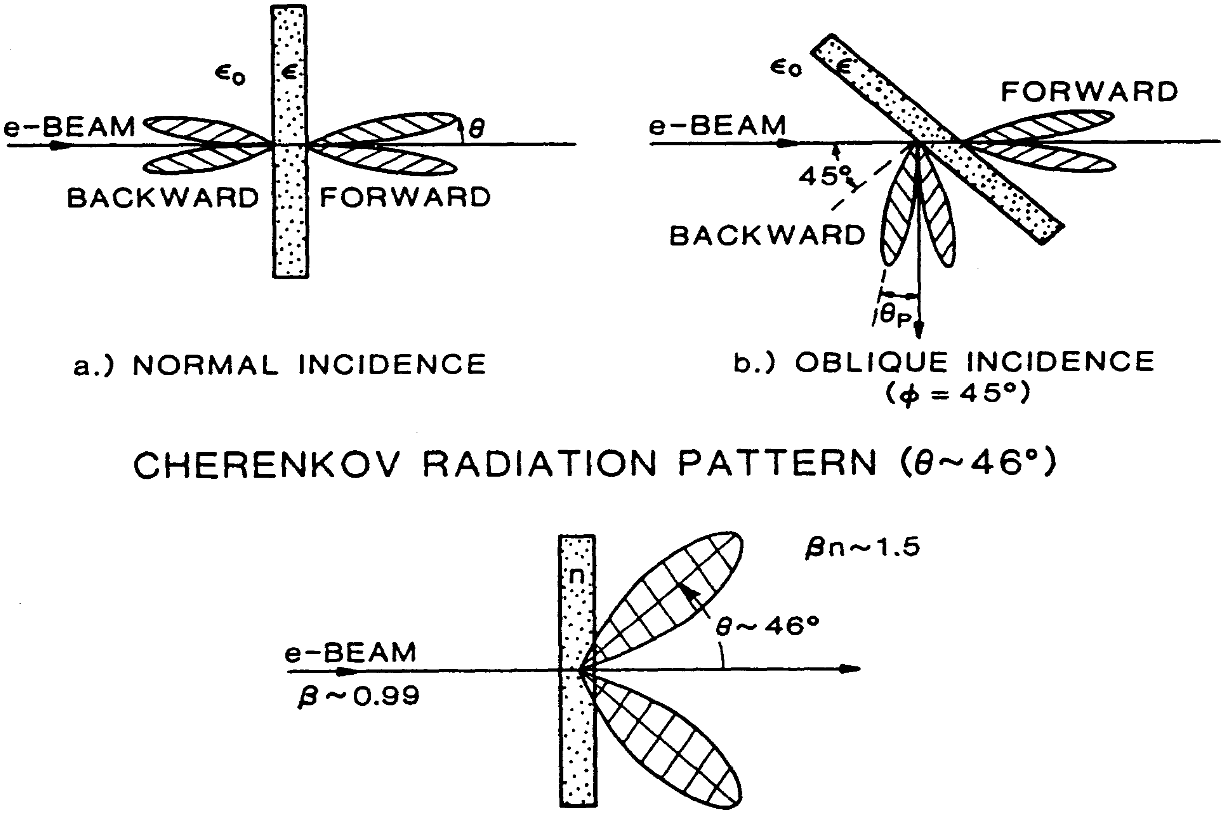
- These techniques provide information on
  - Transverse position
  - Transverse profile
  - Divergence and beam trajectory angle

Strategy (cont.)

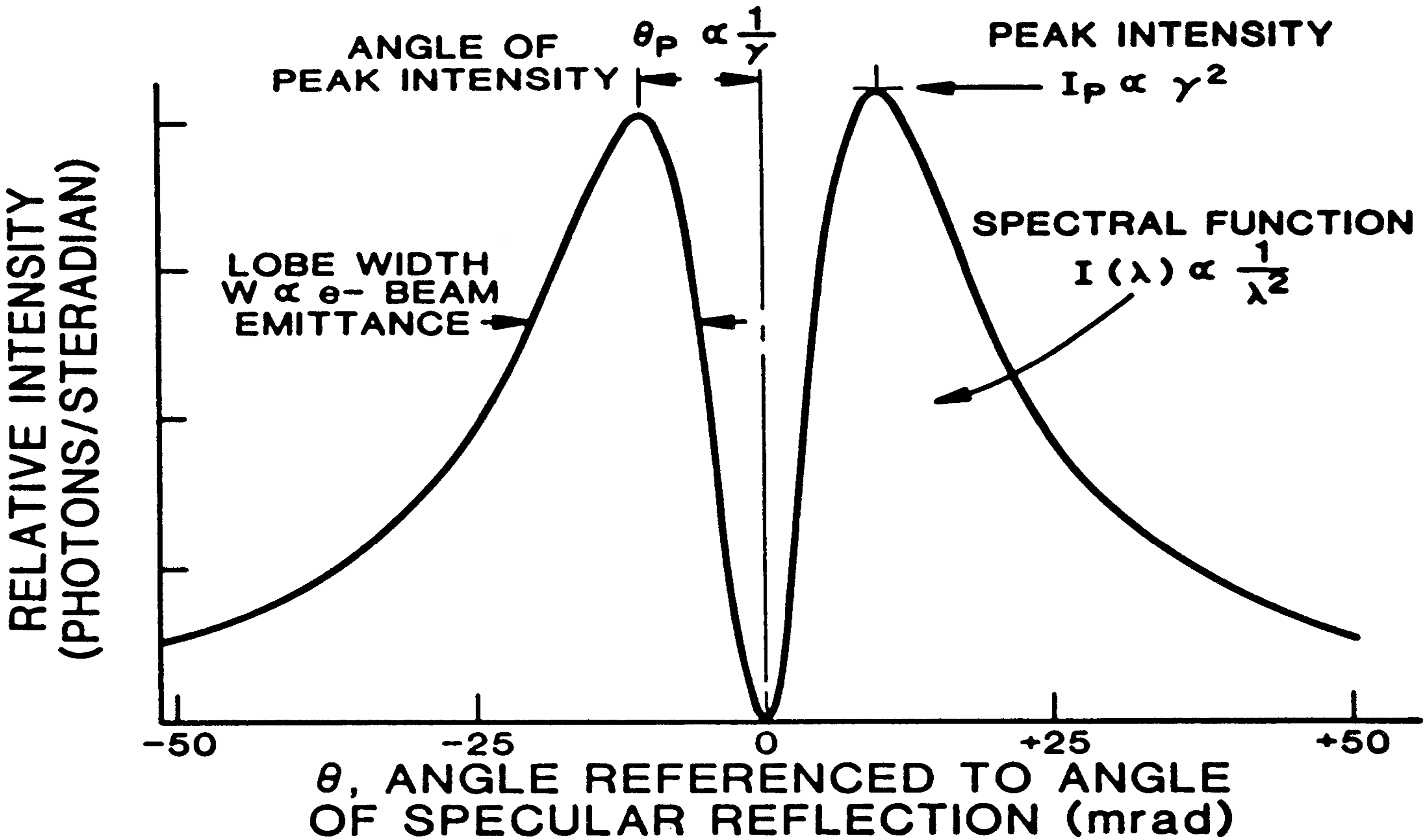
- Emittance
- Intensity (no saturation)
- Energy
- Bunch length and longitudinal profile (fs response time)

- Coherence factors involved for wavelengths longer than the bunch length or for micro-bunched beams (such as in a SASE FEL) at the fundamental. The latter provides a sensitive link of COTR to the FEL process.

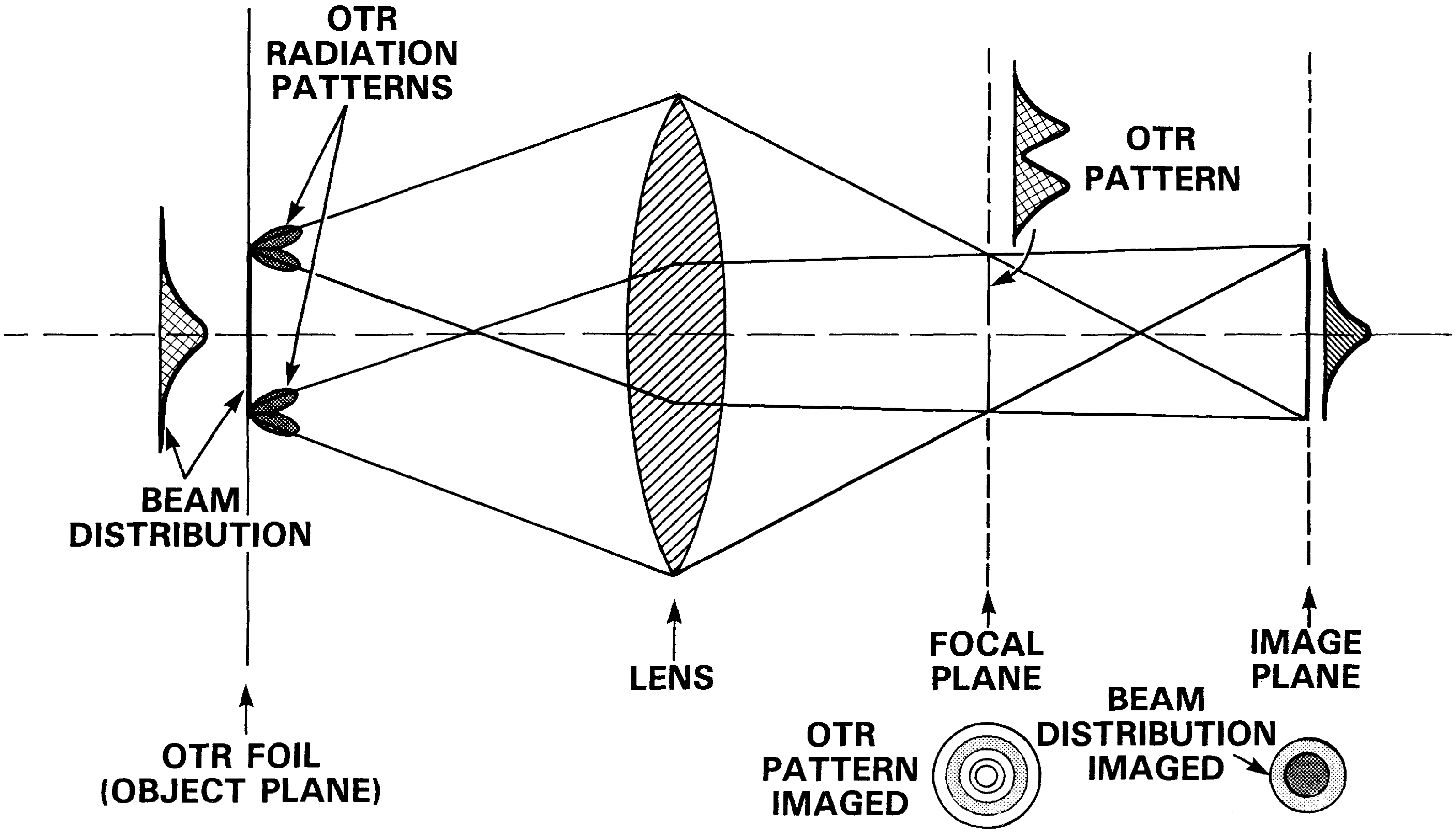
Optical Transition Radiation Patterns



Schematic OTR Intensity Profile



Optical Ray Diagram for OTR Imaging



Coherent Optical Transition Radiation Interferometry Calculations

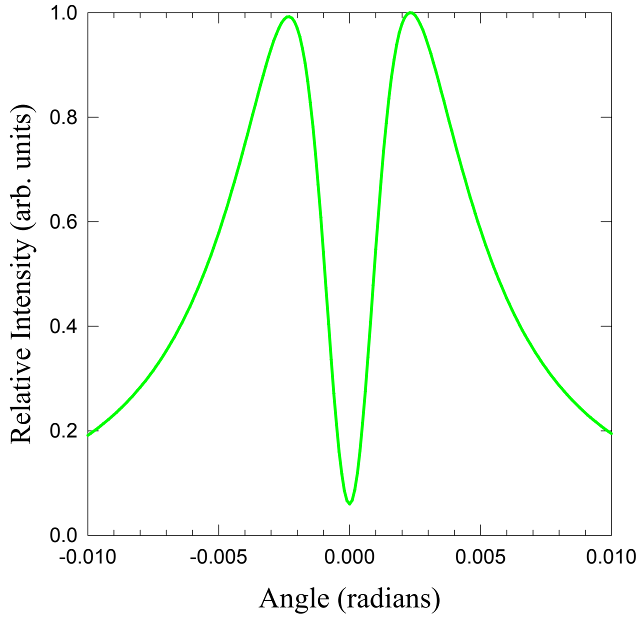
Coherent Spectral-Angular Distribution from a Macropulse,
Number of Photons per Unit Frequency and Solid Angle

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

Single Particle OTR Spectral-Angular Distribution

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

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



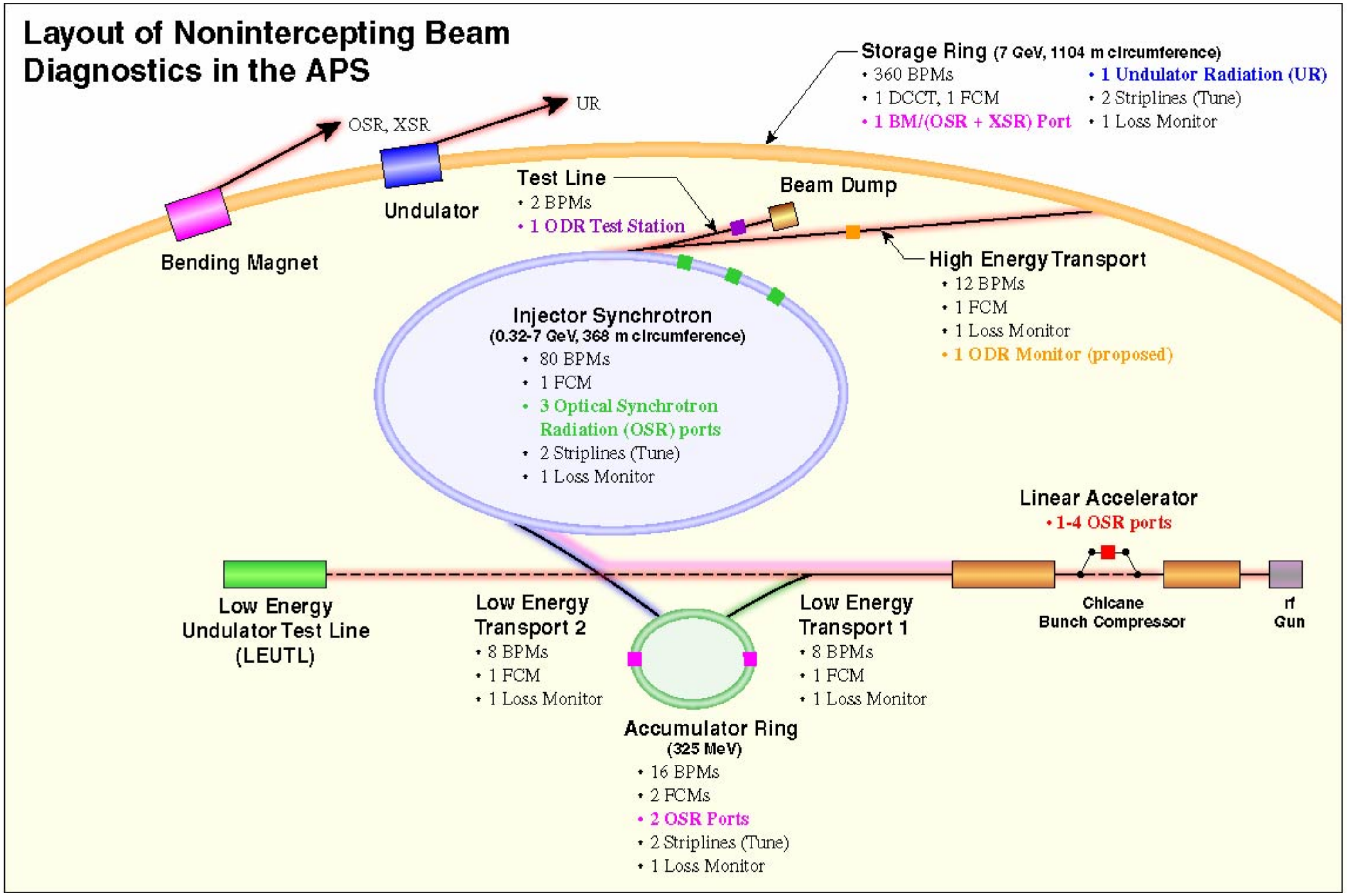
From D. Rule and A. Lumpkin, PAC'01

KEK Experiments Done at 1.3 GeV with a Far-Field Detection Technique: Reported in Dec. 2004

- The KEK accelerator test facility (ATF) was used to generate low emittance, 1.3-GeV beam.
- A single-edge screen was used for ODR generation and then an aperture.
- The angular distribution pattern was mapped with a scanning mirror over 10 minutes and signal tracked with a PMT.
- The very low divergence of the beam (1 μrad) resulted in beam-size effects being detectable at the 14-20 μm regime via the intensity minimum- to-maximum ratio of the ODR angular distribution.
- Impact parameters of ~40-100 μm used.
- P. Karataev et al., PRL 93, 244802 (2004).

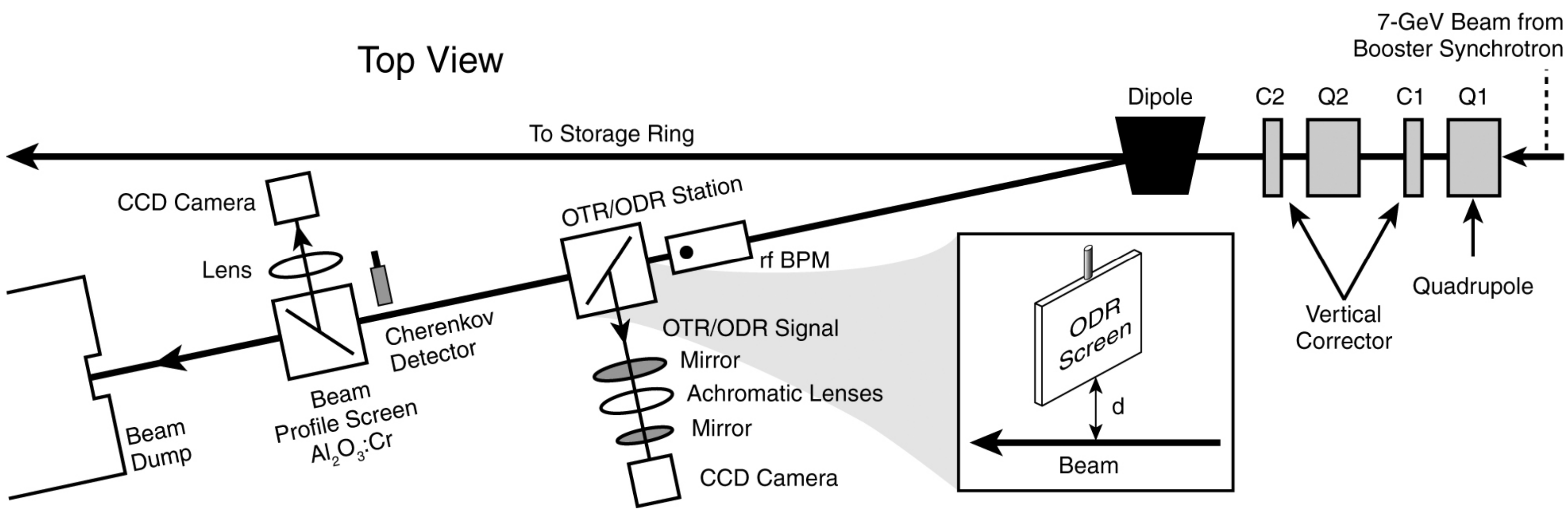
The APS Facility Has Provided Sources for Developing Time-Resolved, NI Diagnostics

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

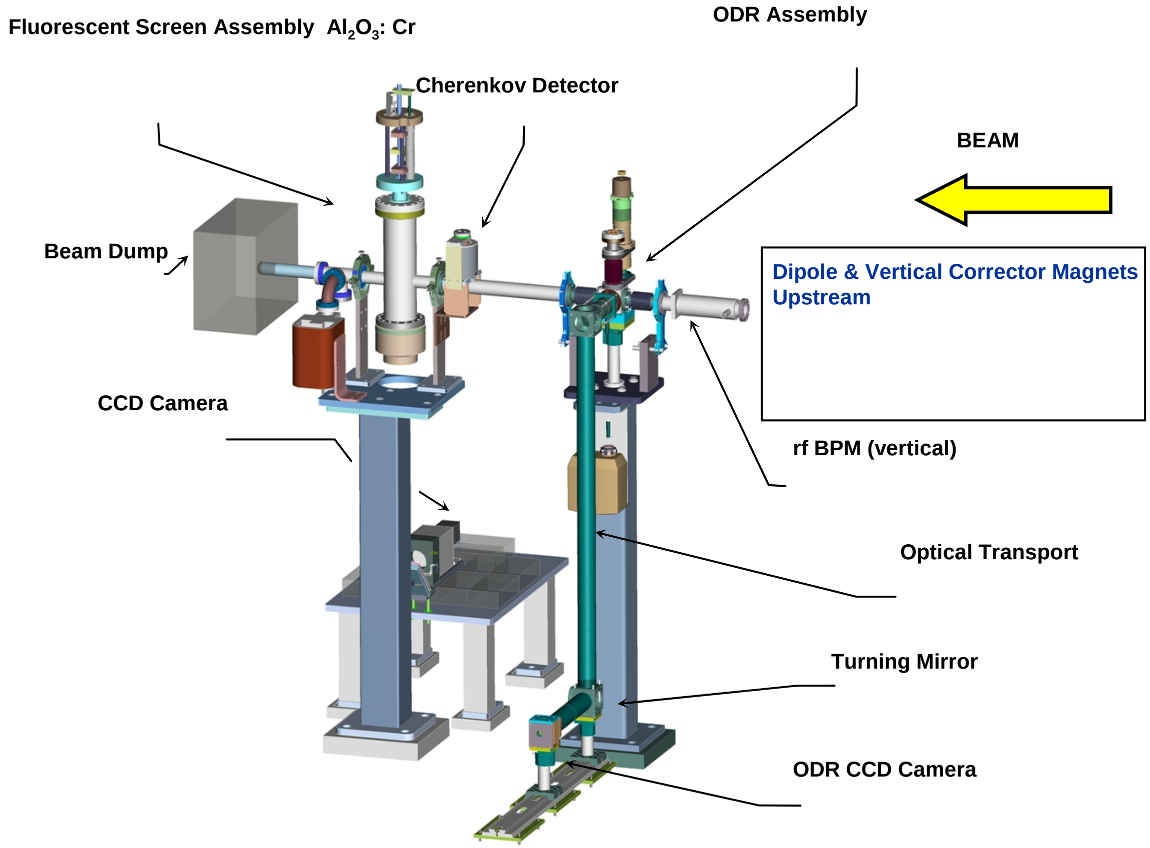


Schematic of the OTR/ODR Test Station on BTX Line at APS

- 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.

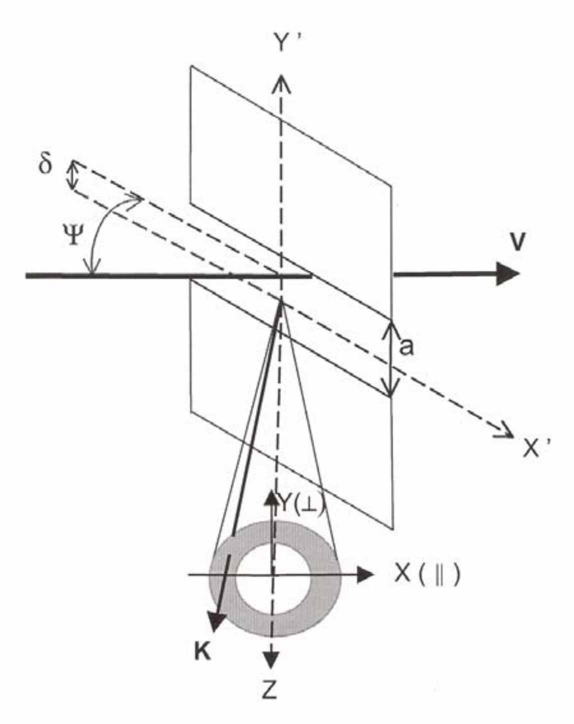


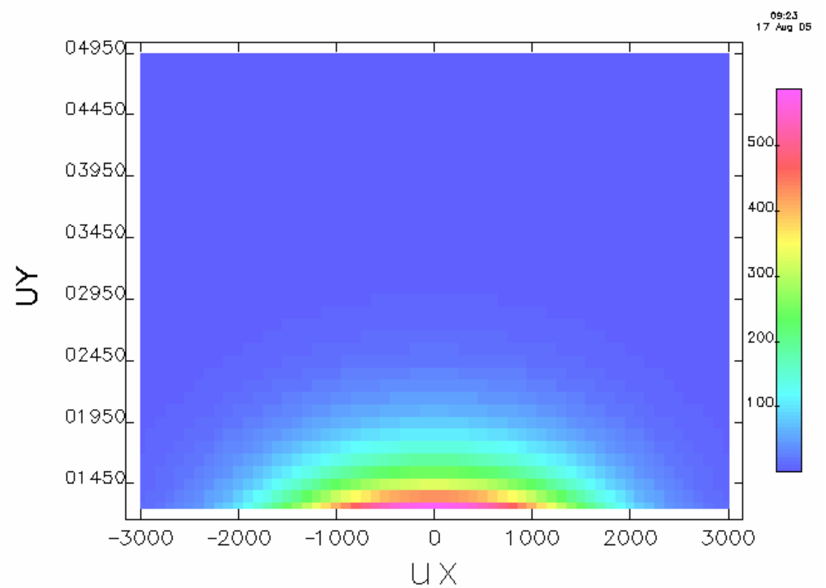
An OTR/ODR Test Station was Developed on the BTX Line for 7-GeV Beams



ODR is a Potential Nonintercepting Diagnostic for Multi-GeV Beams

- **At left, schematic of ODR generated from two vertical planes (based on Fig. 1 of Fiorito and Rule, NIM B 173, 67 (2001). We started with a single plane.**
- **At right, calculation of the ODR light generated by a 7-GeV beam for *d* =1.25 mm in the optical near field based on a new model (Rule and Lumpkin).**





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)

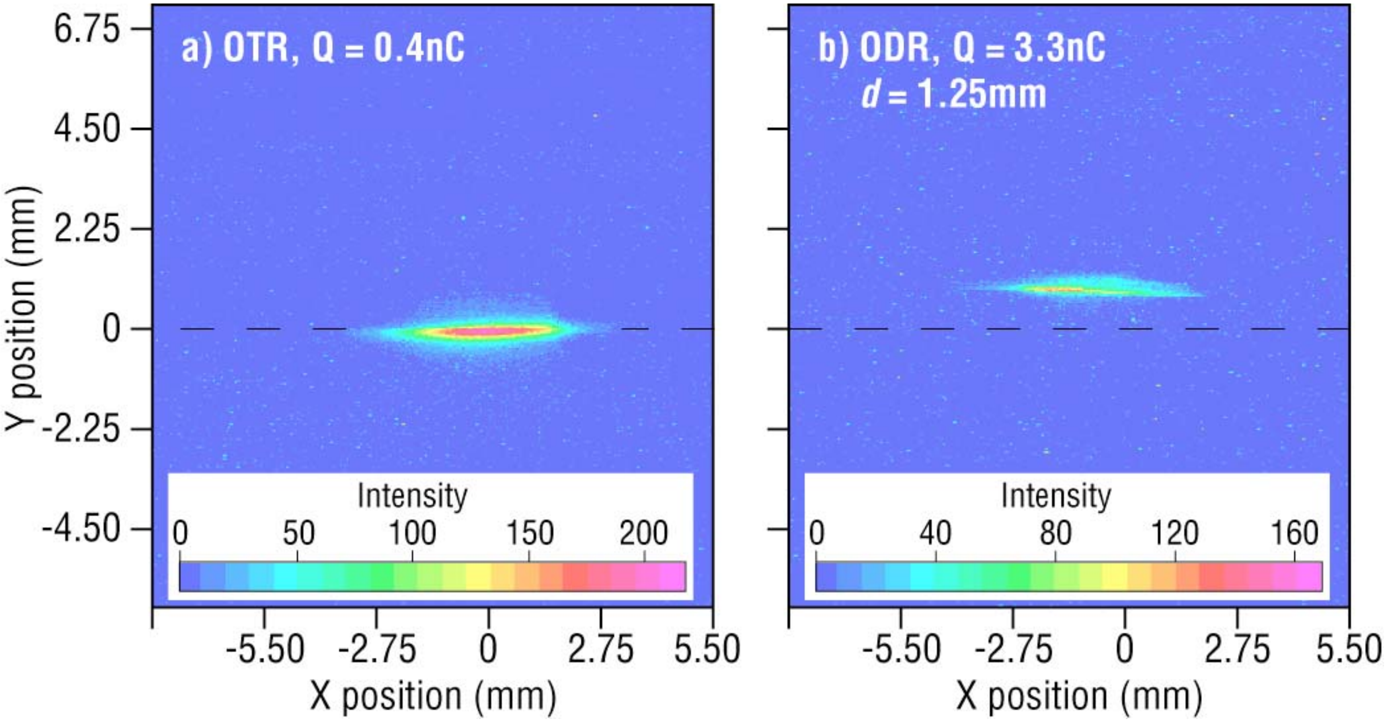
$$\frac{dI}{d\omega}(\boldsymbol{u},\omega) = \frac{1}{\pi^2}\frac{q^2}{c}\left(\frac{c}{\mathrm{v}}\right)^2 \alpha^2 N \frac{1}{\sqrt{2\pi\sigma_x{}^2}}\frac{1}{\sqrt{2\pi\sigma_y{}^2}} \times$$

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

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.

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

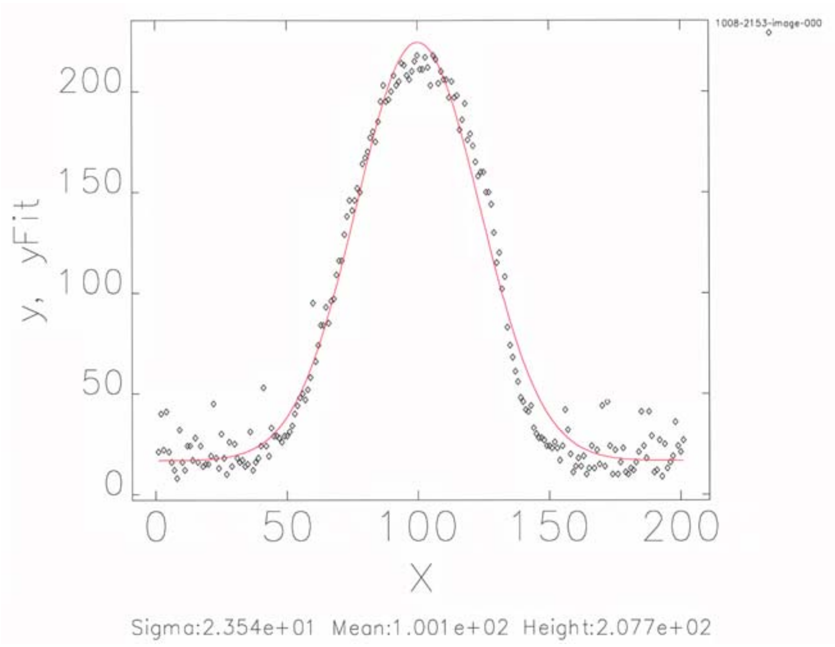


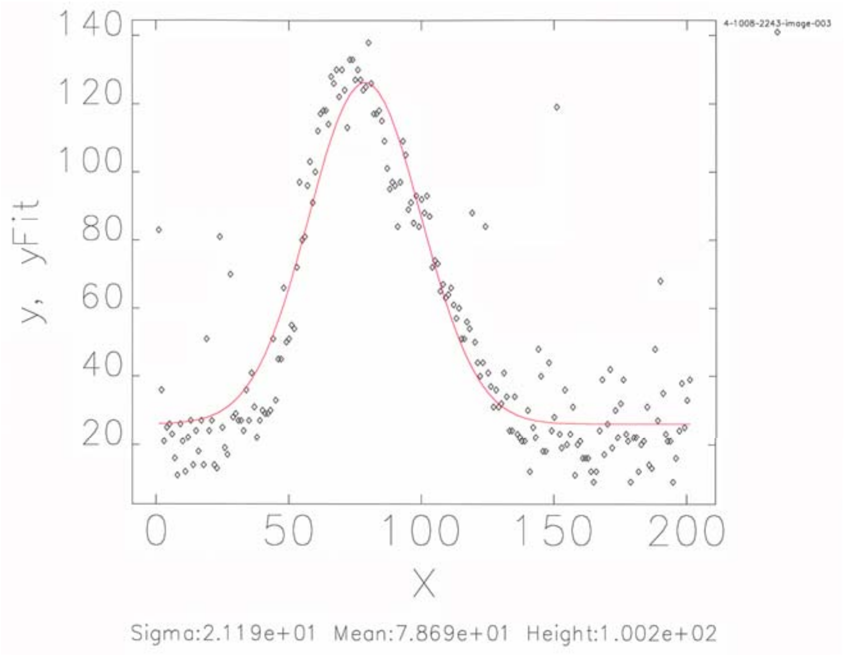
Submitted to Phys. Rev.

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

- OTR profile, Q=0.4nC

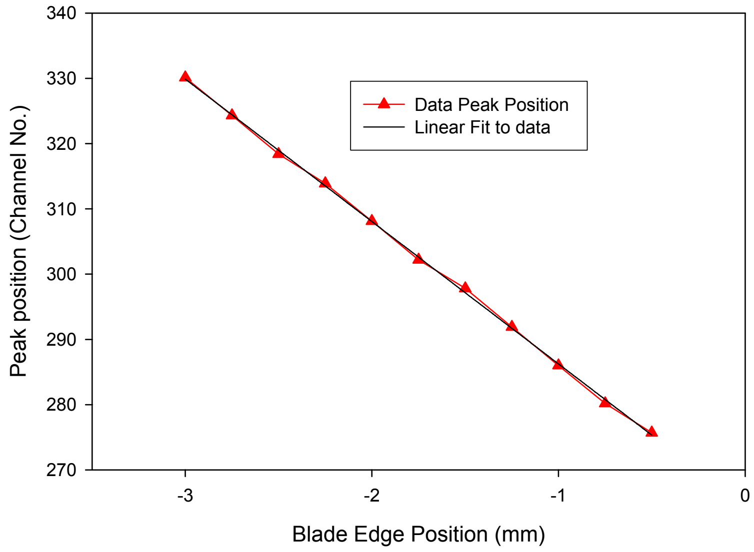
ODR profile, Q=3.2 nC
d=1.25 mm





Observed Signal Position and Intensity are Dependent on Impact Parameter Magnitude

Signal Peak Position versus Blade Edge Position
(10-08-04)



Signal Peak Intensity versus Blade Edge Position
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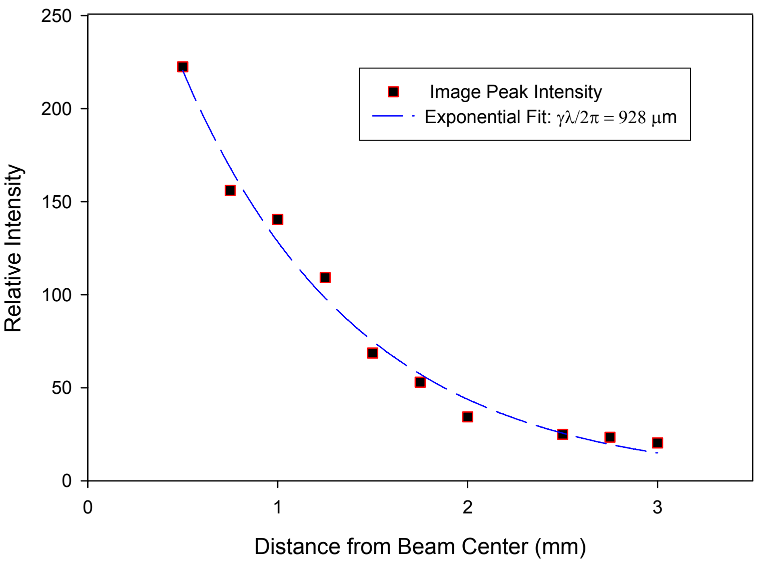
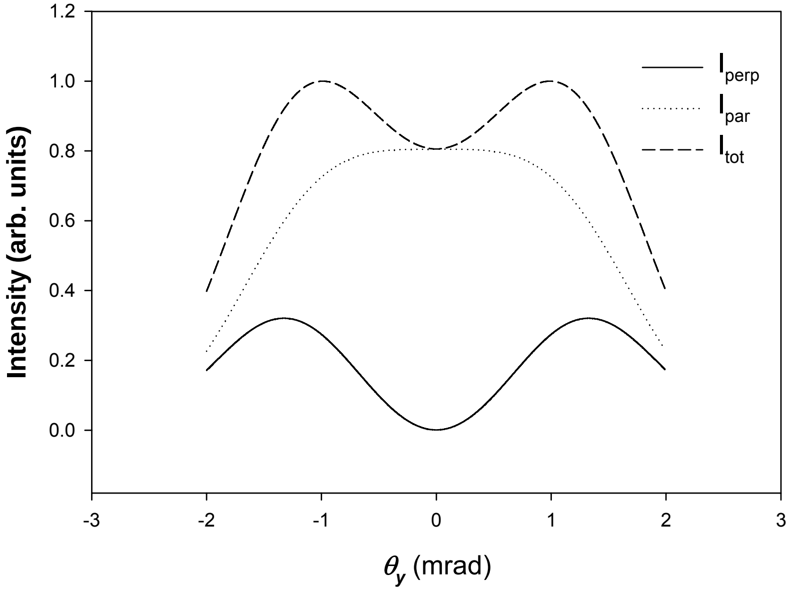


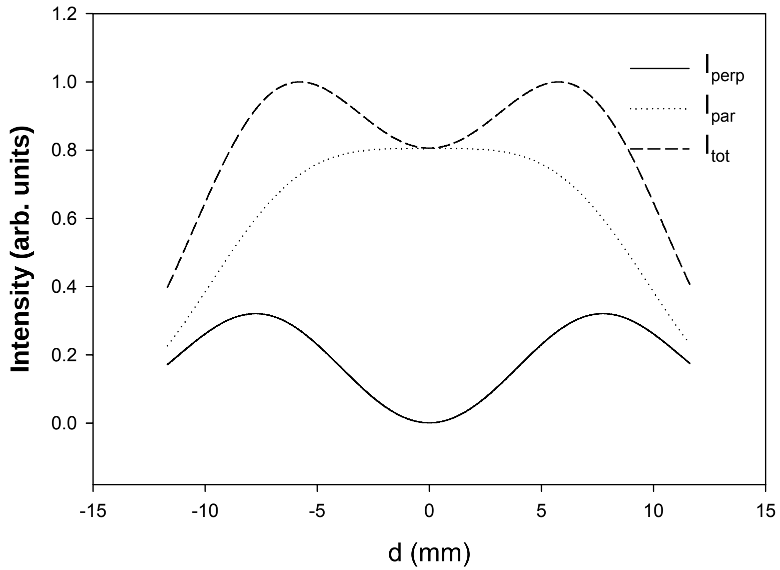
Upstream BTX Dipole Generates Low Intensity, Broad OSR Background in Visible Light Regime

- Horizontal bend gives only weak OSR signal out of the bend plane 5.8 m downstream with more intensity in parallel polarization component.

Synchrotron Radiation
λ=500 nm, E=7 GeV



Synchrotron Radiation
λ=500 nm, E=7 GeV
ρ=25 m, L=5.84 m

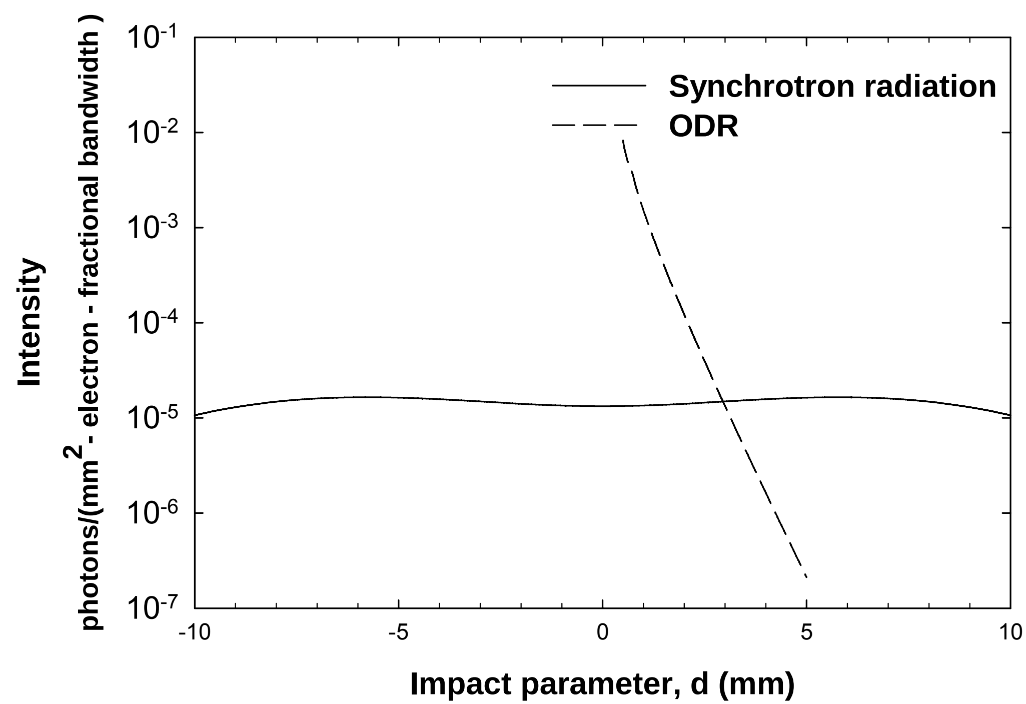


D.Rule and A.Lumpkin

Upstream BTX Dipole Generates Low Intensity, Broad OSR Background in Visible Light Regime

- Model indicates that ODR dominates the OSR in the 1-mm impact parameter range. ODR has exponential-like decay feature.

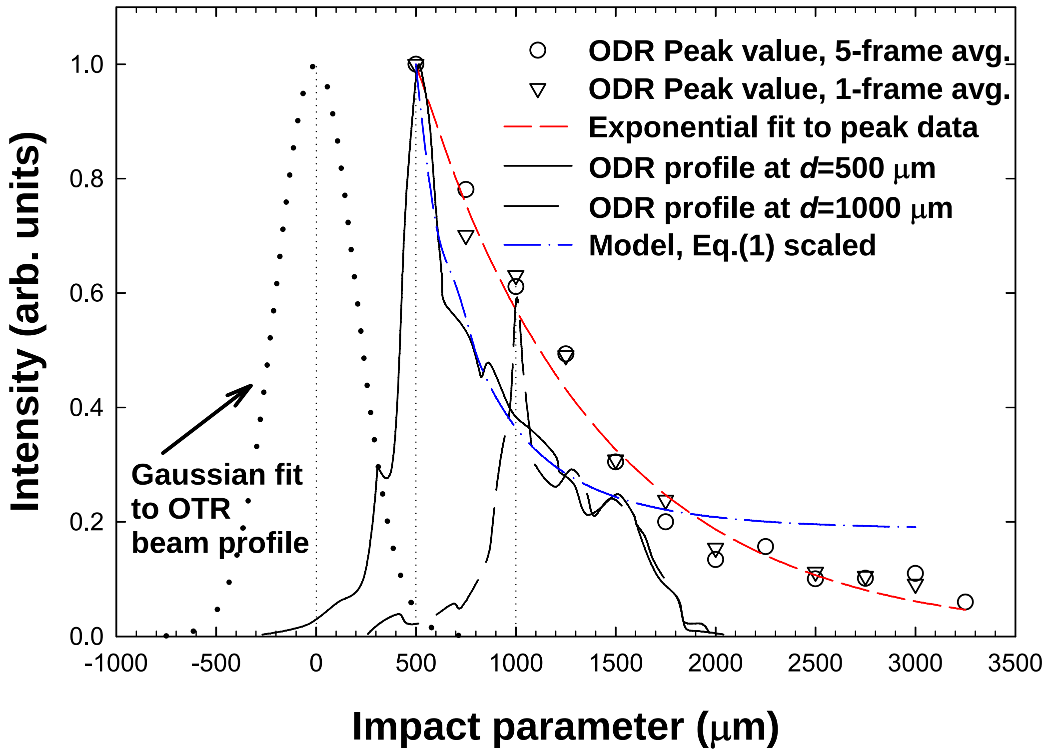
Synchrotron Radiation
and
ODR Convolved with a Gaussian Beam
λ=500 **nm, *E*=7 GeV**
ρ=25 **m, *L*=5.84 m**



D.Rule and A.Lumpkin

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

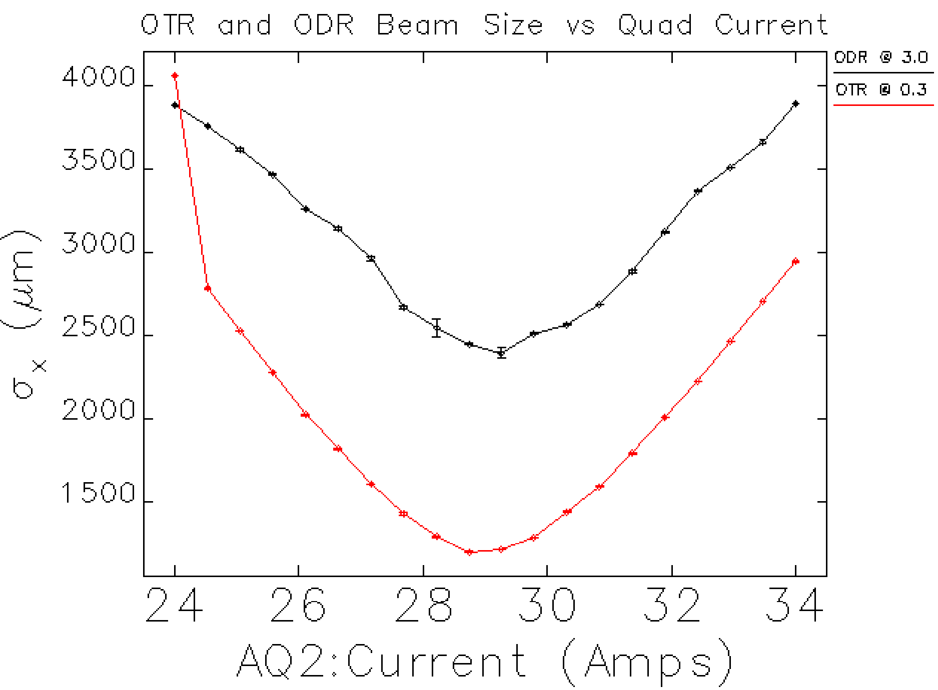
- Comparison of OTR beam profile and ODR vertical profile data. The ODR peak intensity has an exponential behavior with impact parameter while the total profile has the modified Bessel function effect.

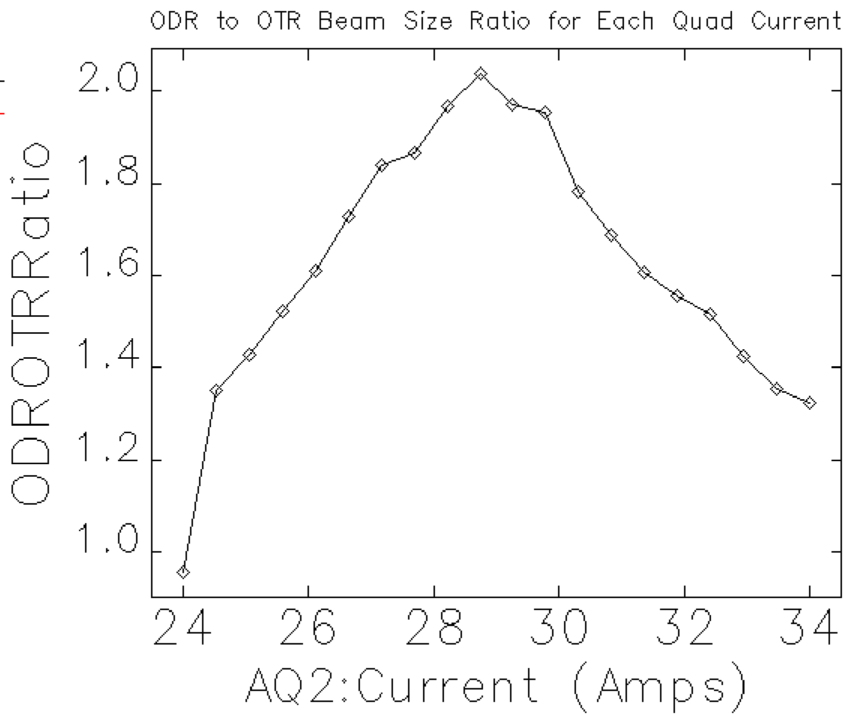


Submitted to Phys. Rev.

Relative Beam Size Monitor Concept Checked with Quad Scan

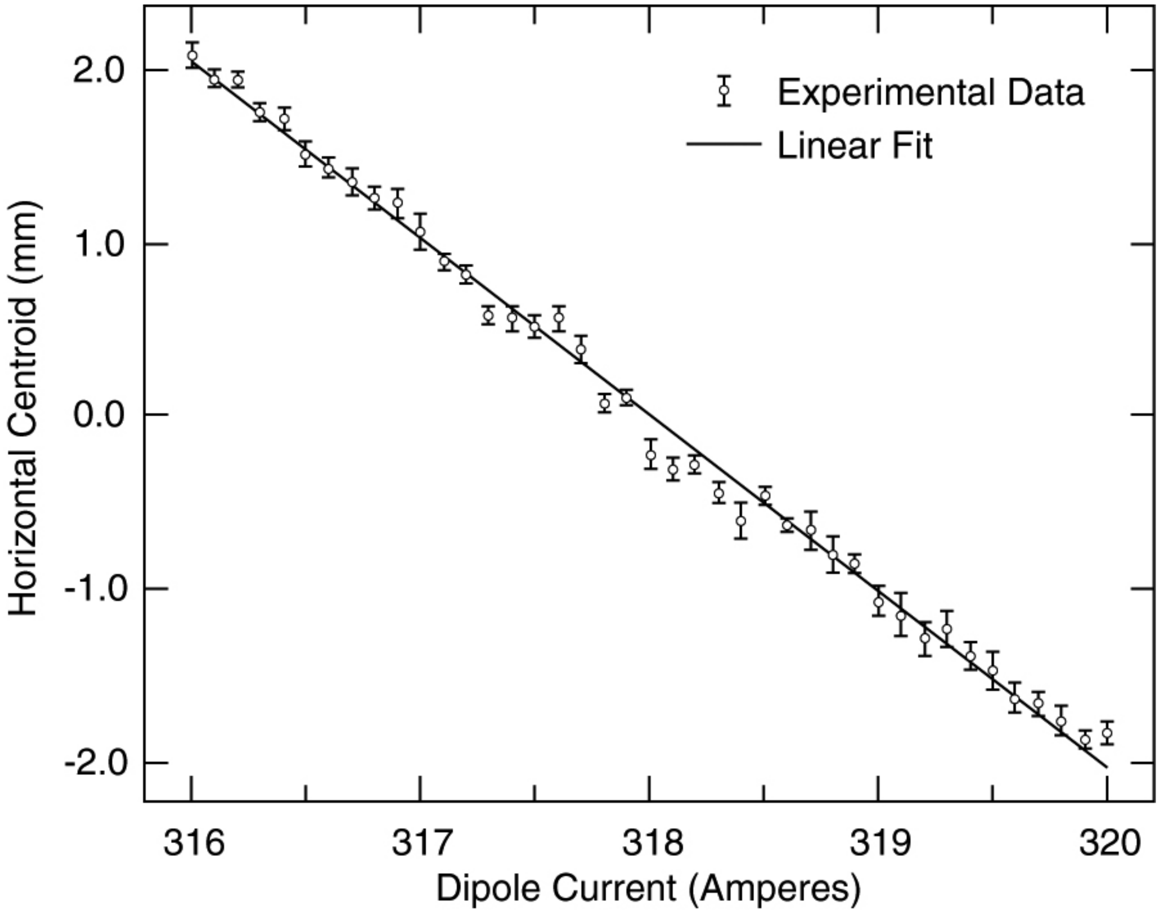
- No polarizer used for OTR or ODR images.





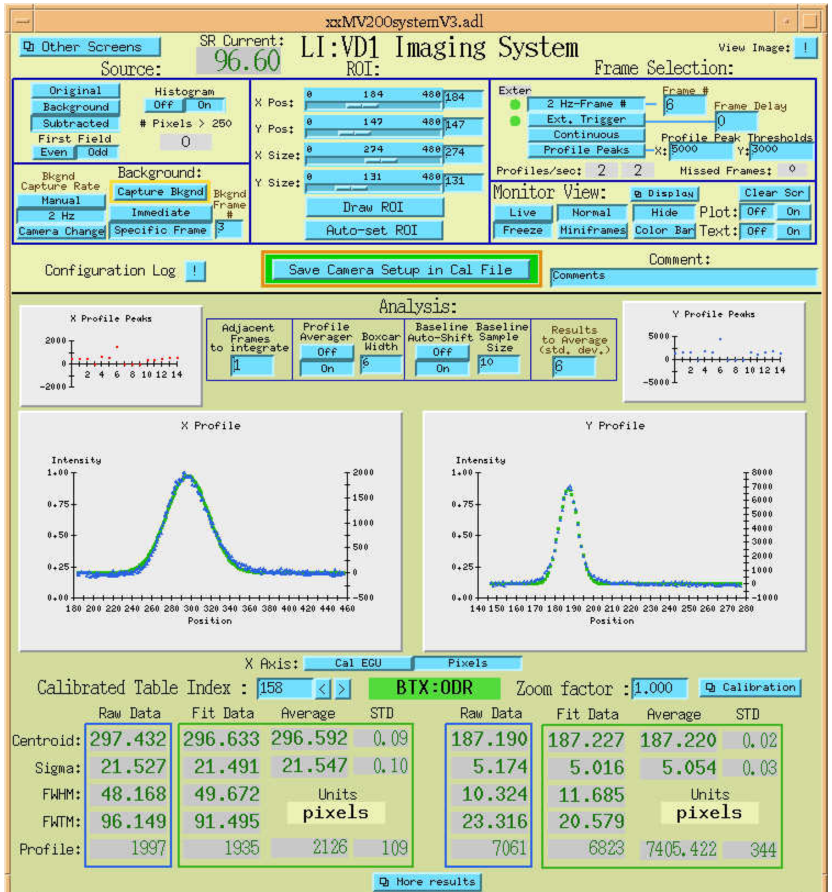
ODR Image Centroids Provide NI Relative Beam Position

- 7-GeV beam tracked in BTX line.

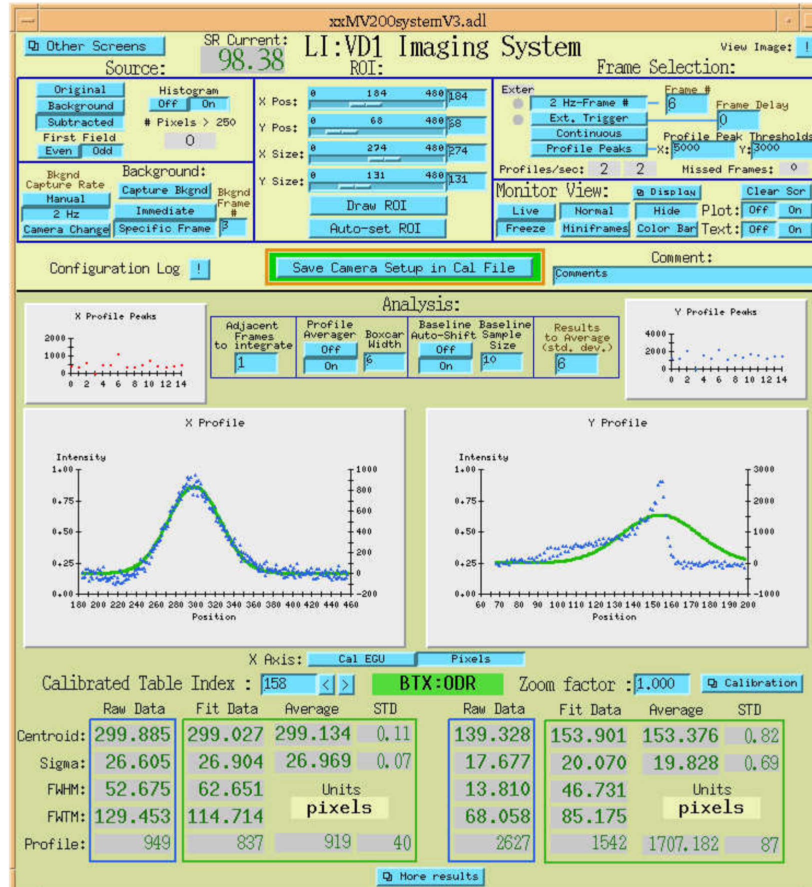


Online Image Processing Shows OTR and ODR Results

OTR Profiles

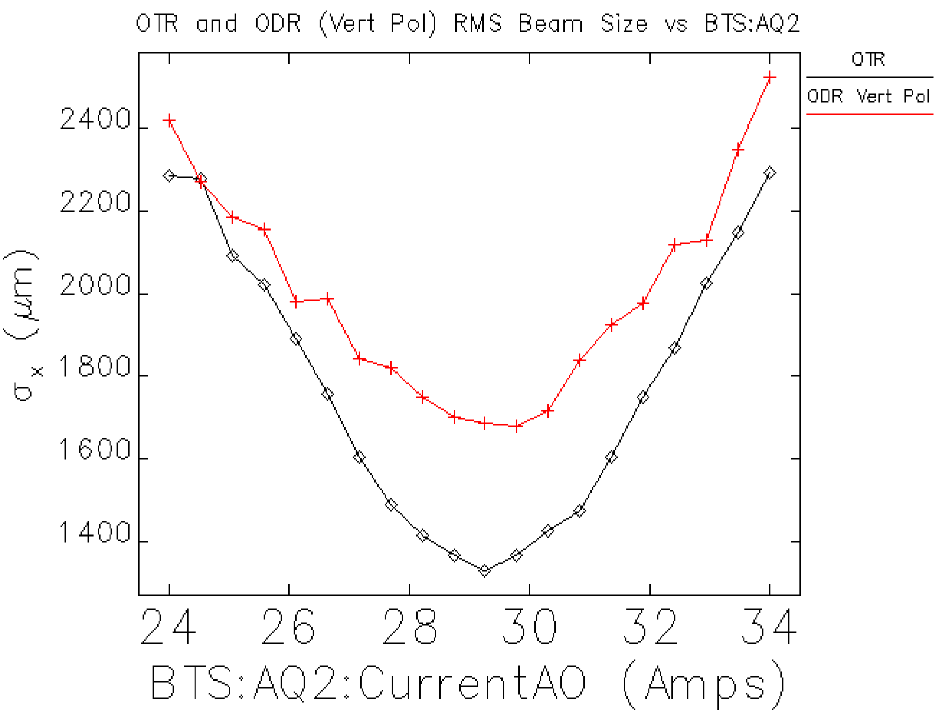


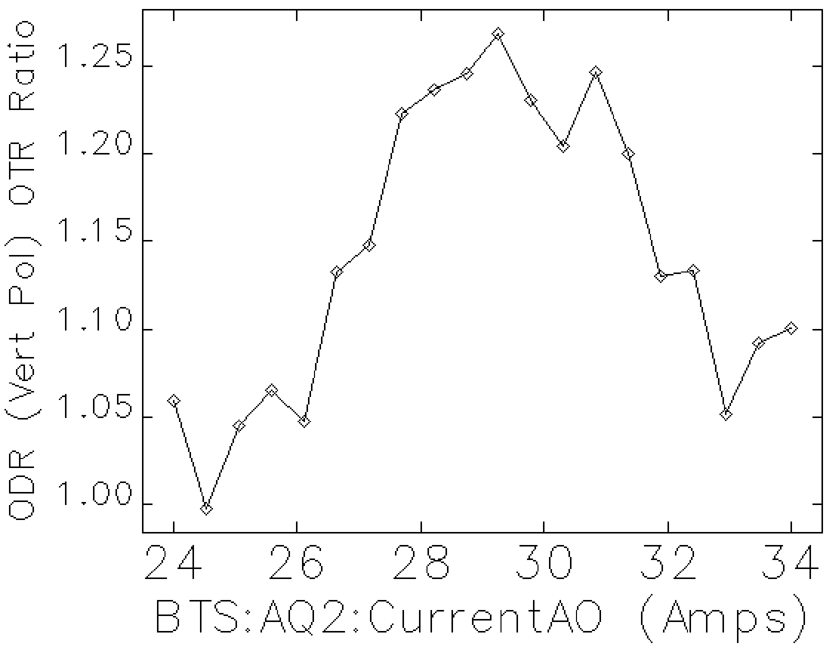
ODR Profiles (Vert. Pol.)



Orthogonal ODR Polarization Component (Vertical in this case) Useful for Horizontal Beam Size Measurement

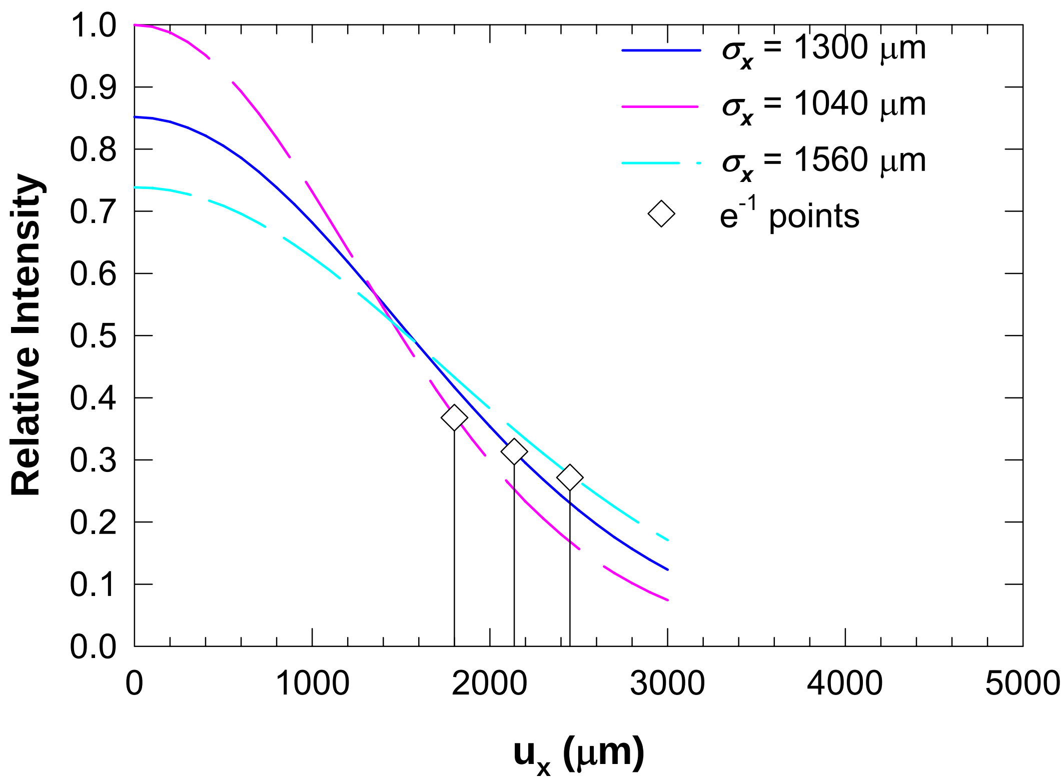
- Vertical Polarization component of ODR gives more direct representation of horizontal beam size than sum of ODR polarization components.





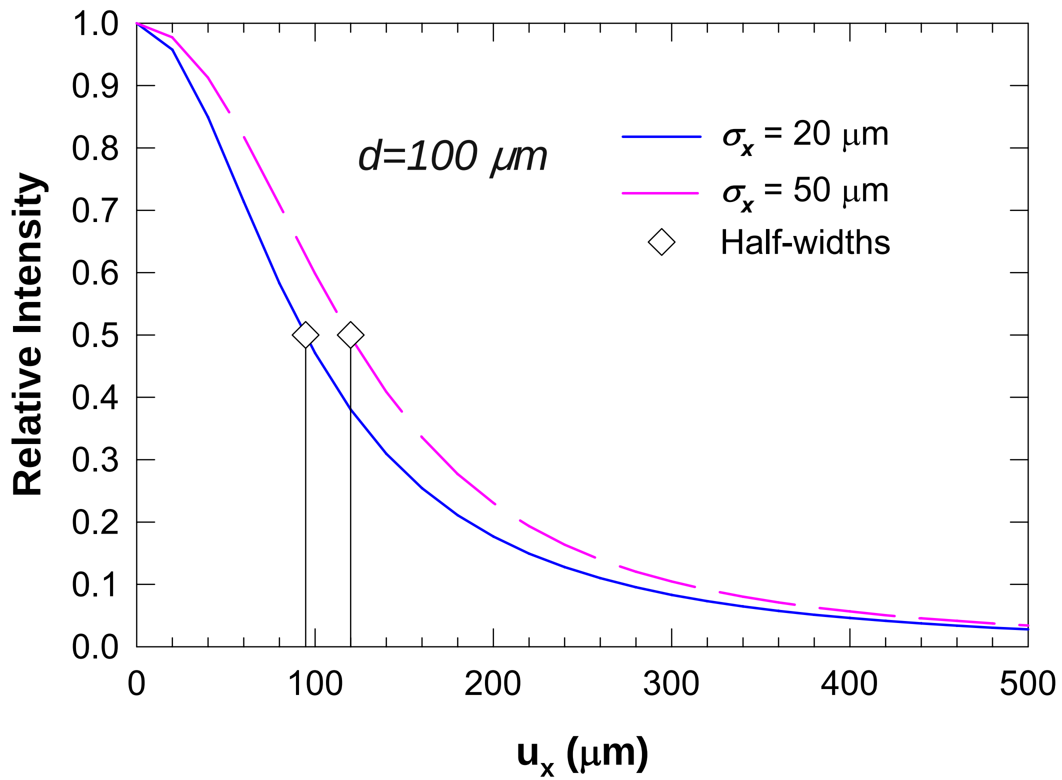
Analytical Model Indicates Beam-size Sensitivity on x Axis

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



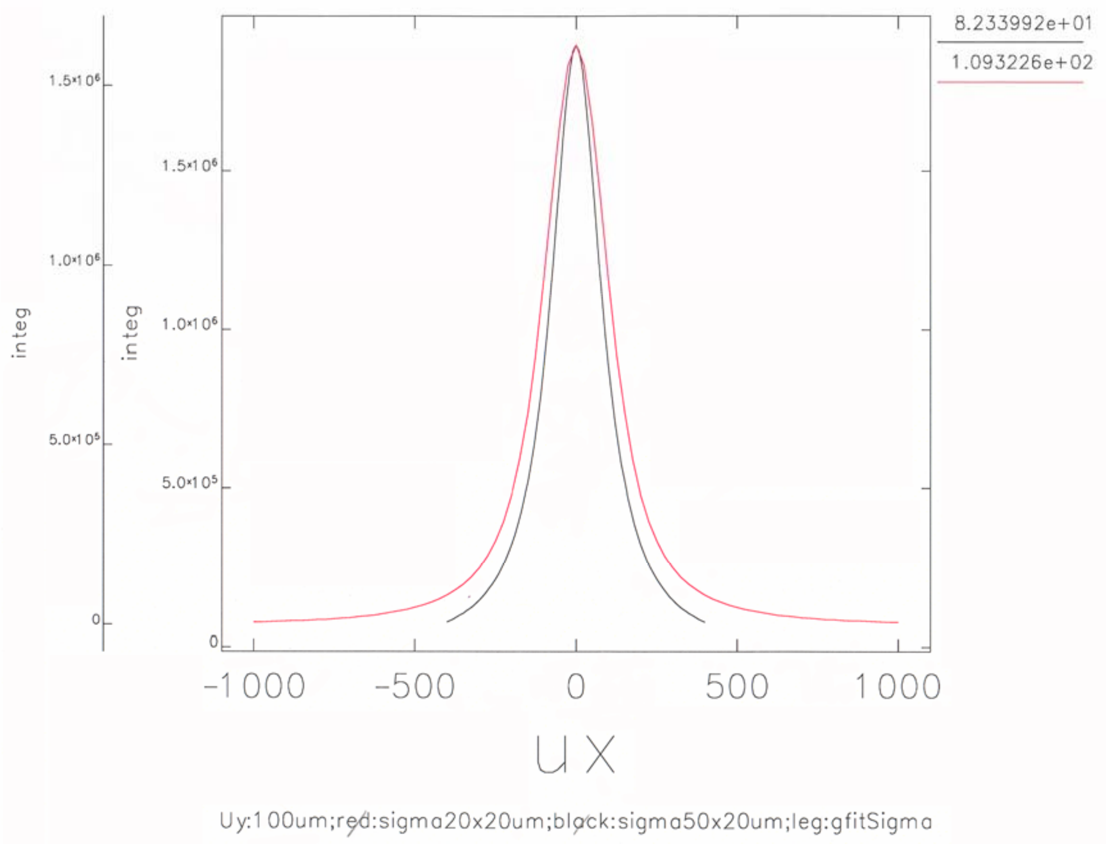
Analytical Model Indicates Beam-size Effect in New Regime at 20-50 μm for 7-GeV Beam (XFEL,ERL,ILC)

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



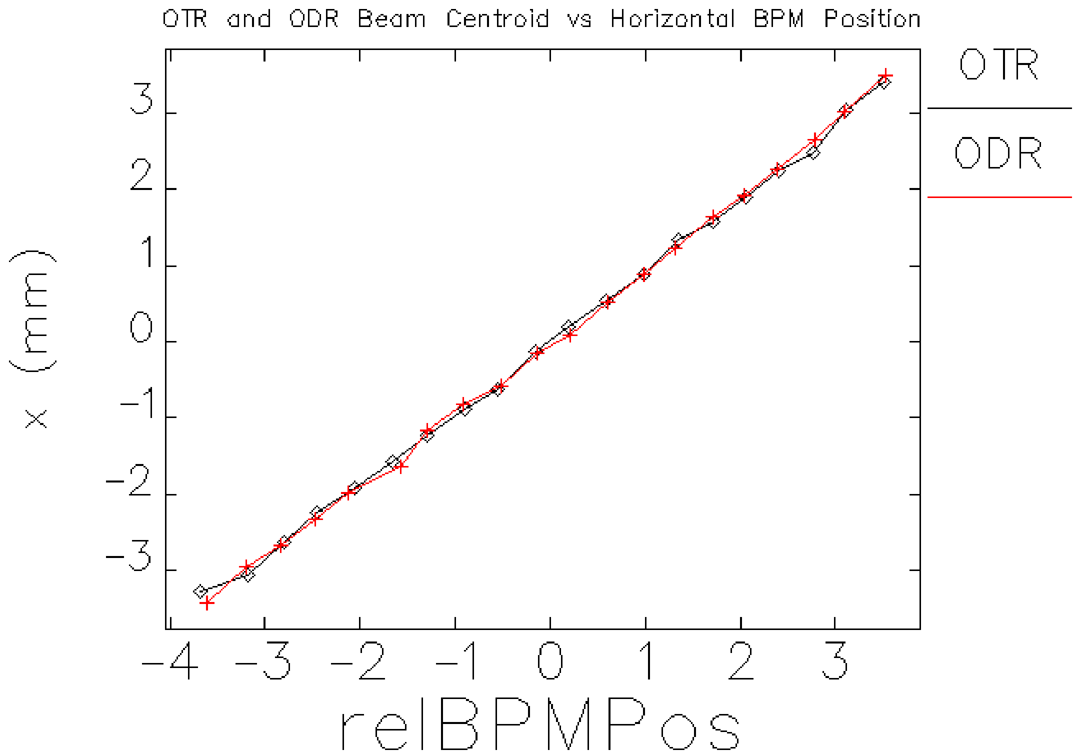
ODR Model Predicts Sensitivity to Beam Sizes at 20-50 μm Level for 7-GeV Beam (X-ray FELs, ILC, LWFA)

- ODR Image profile changes with horizontal beam size for fixed σ_y of 20 μm at *d*= 100 μm.



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

- OTR and ODR image centroids versus horizontal rf BPM values are linear.

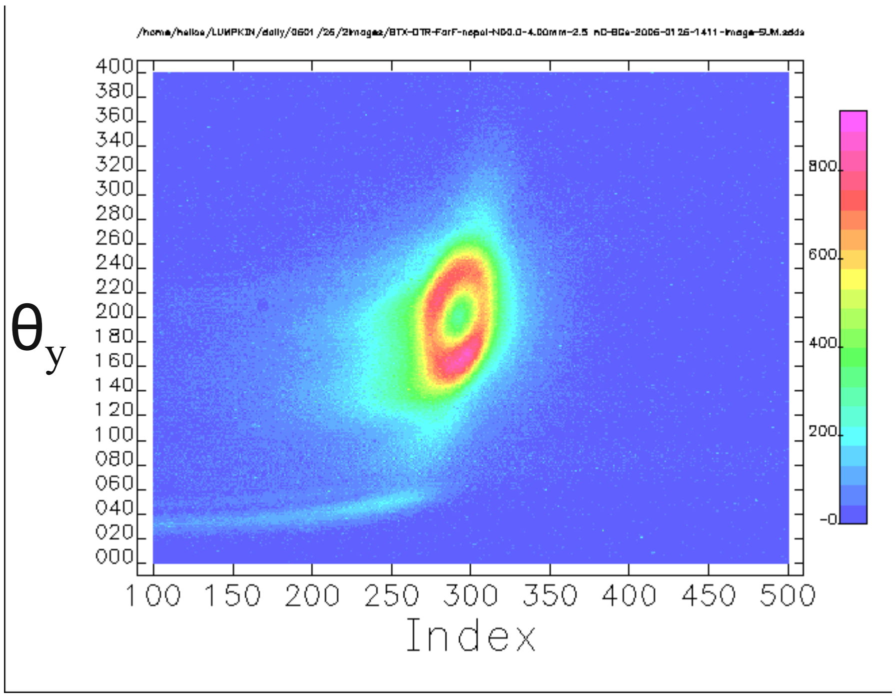


Far-field Imaging Provides Information about 7-GeV Beam's Divergence

- OTR image shows 70-μrad vertical opening angle. ODR shows single lobe structure expected from single metal plane.

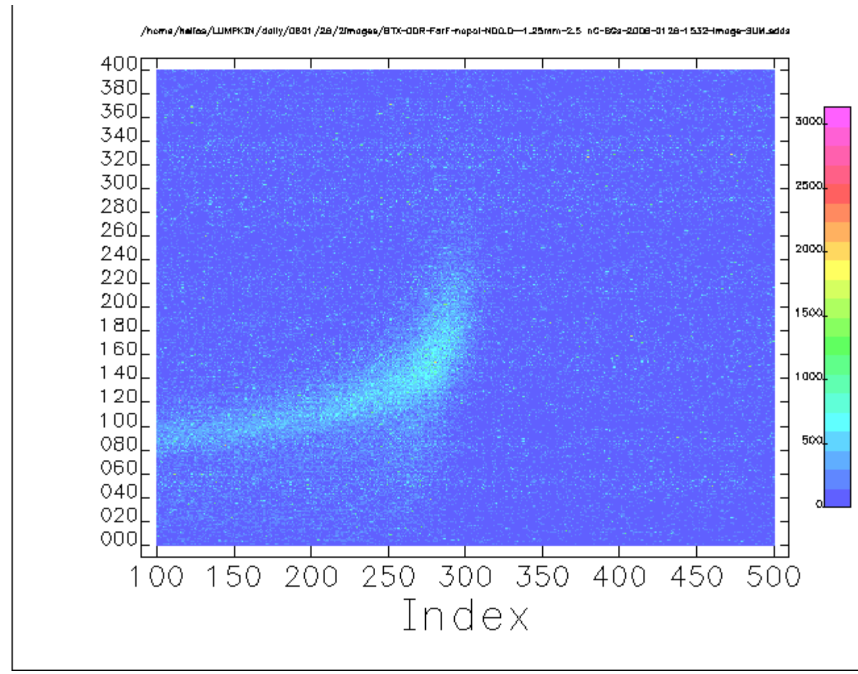
OTR

θ_y



θ_x

ODR

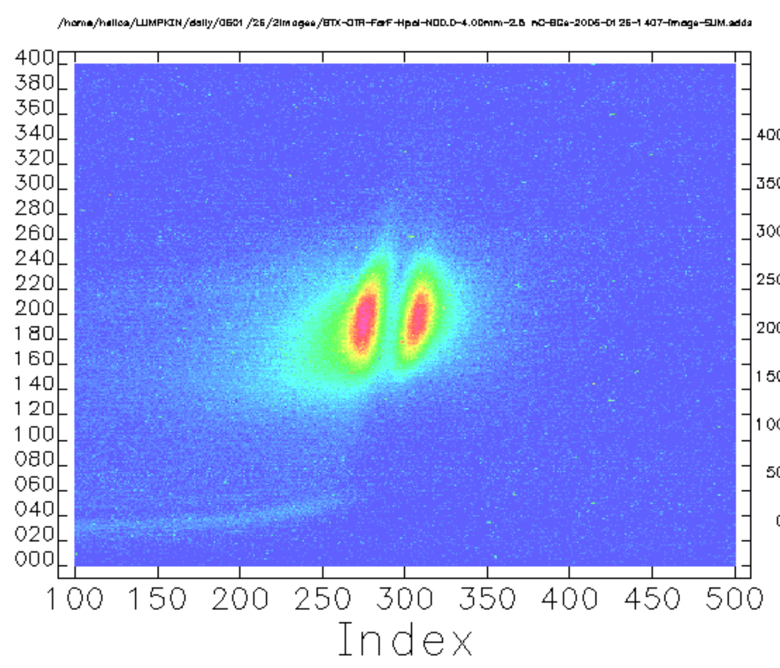


θ_x

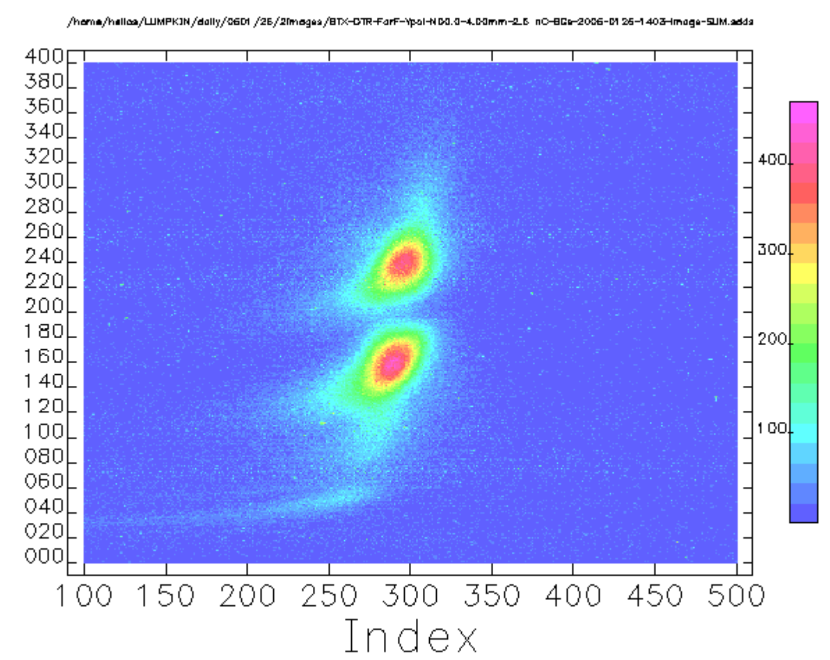
OTR Angular Distributions Show Polarization Effects as Expected

- Slight tilt of images is probably instrumental.

Horizontal



Vertical



θ_y

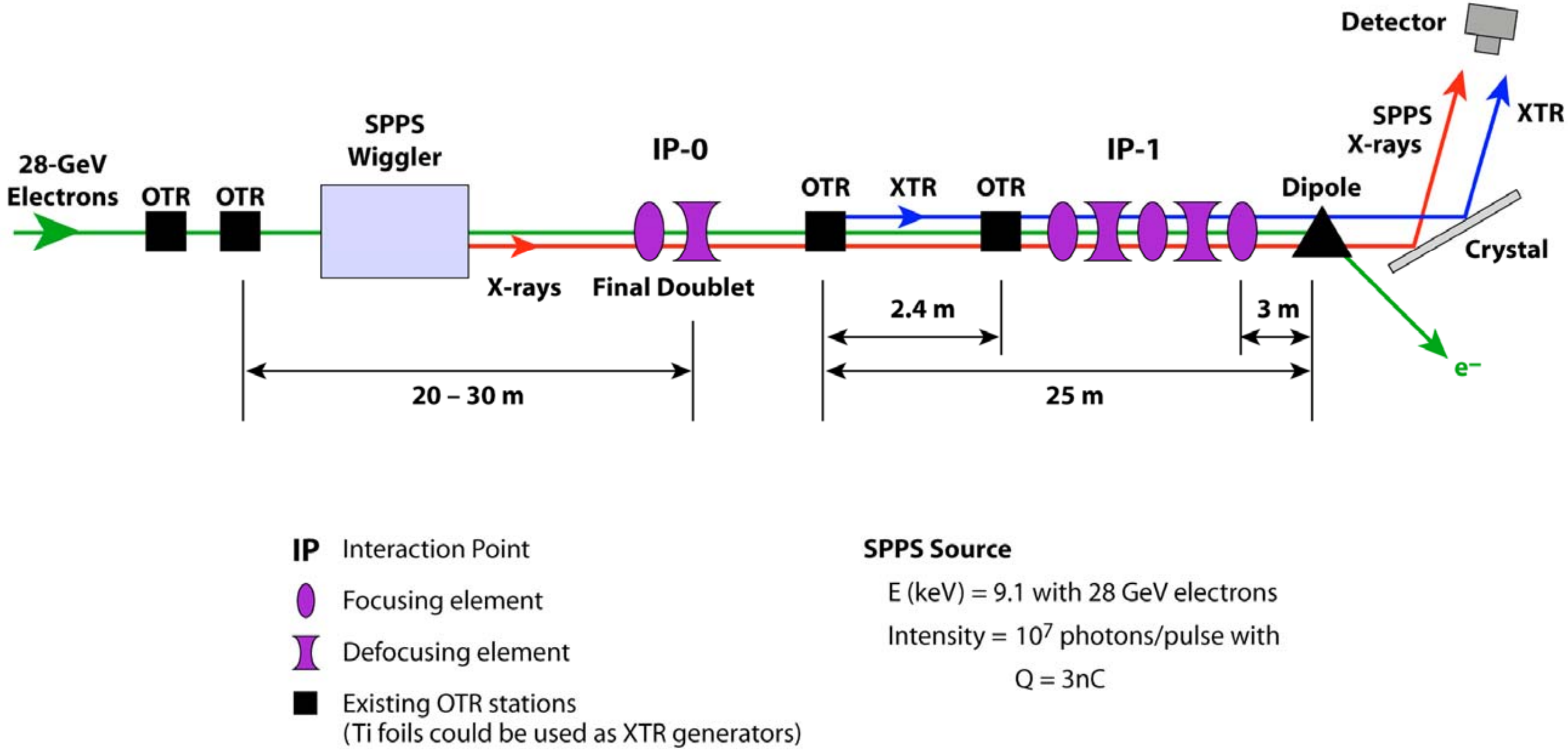
θ_x θ_x

ODR Near-field Techniques can Address the e-beam Parameters in Proposed Projects on X-ray FELs, ERLs, ILC, and Future LWFAs

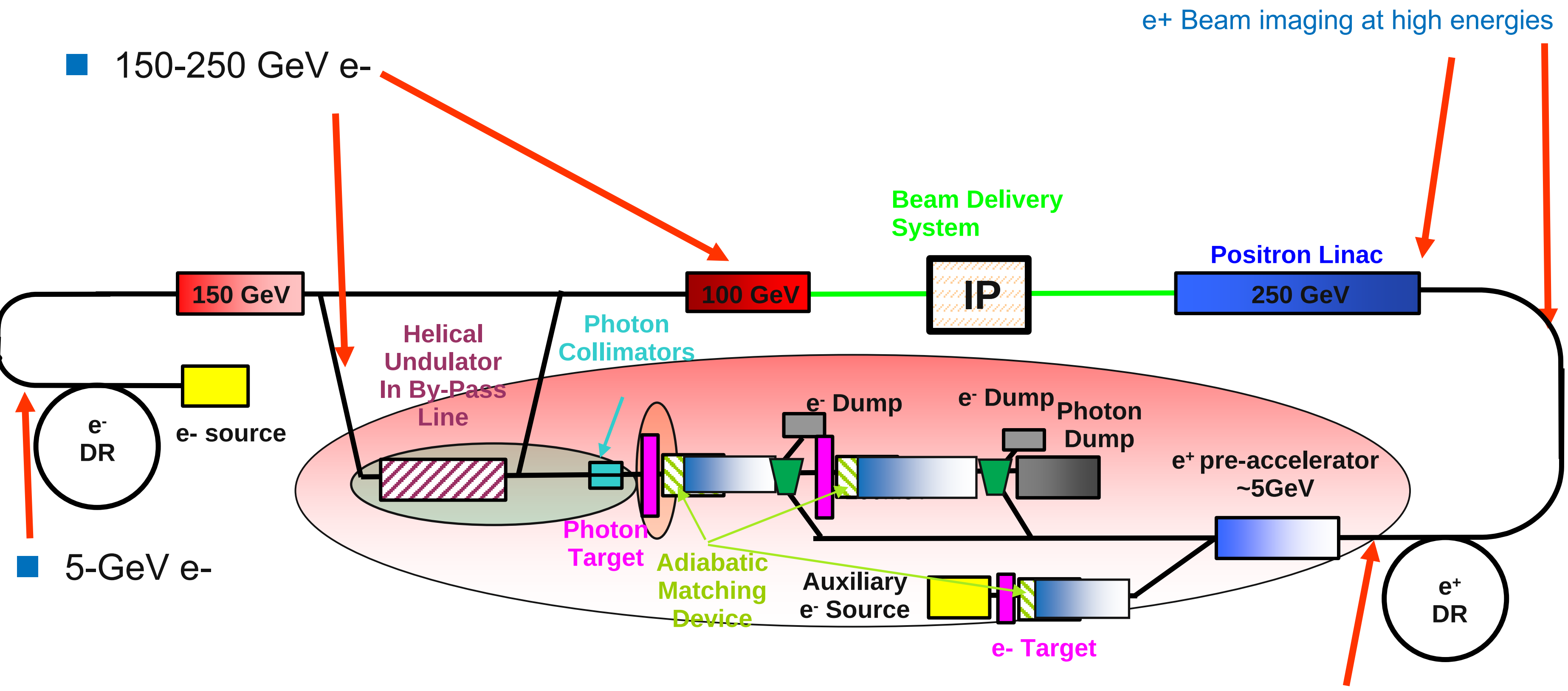
- Nominal beam sizes in LCLS undulator diagnostics locations are $\sigma_{x,y}$= 30 μm for 14 and 4.5 GeV beams. NI aspect of ODR relative beam size monitor is important to minimize beam scattering to protect permanent magnets. Could use the OTR station optics with sensitive camera.
- ERLs for light sources involve high average currents (100 mA) for 5-7 GeV beams (Cornell and APS Upgrade).
- The ILC beam after the damping ring is projected to be flat with σ_x= 50 μm and σ_y=5 μm at 5 GeV with high average current. Tests of ODR at higher energies would be useful for main linac application (SABER?).
- The beam sizes for ERLs , ILC, CEBAF, and LWFA are comparable to the LCLS undulator location. Use OTR for reference low-intensity beam size.
- Polarization aspects are very useful for beam-size tracking.
- Wakefield question should be checked, but the conducting screen/plane can be retractable and the impact parameter adjusted (CEBAF restarts).

Proposed Experiments at SLAC/SPPS at 28 GeV on ODR and XTR (Perhaps Move to SABER)

- The ODR would be generated by a Ti foil linked to a stepper motor drive for impact parameter adjustments.
- The XTR is generated by the same foils used for the OTR imaging experiments and would be selected at the 9-keV range by the crystal.



Schematic of ILC shows potential NI imaging applications to e- and e+ beams



Adapted from W. Gai and K.Kim VGs

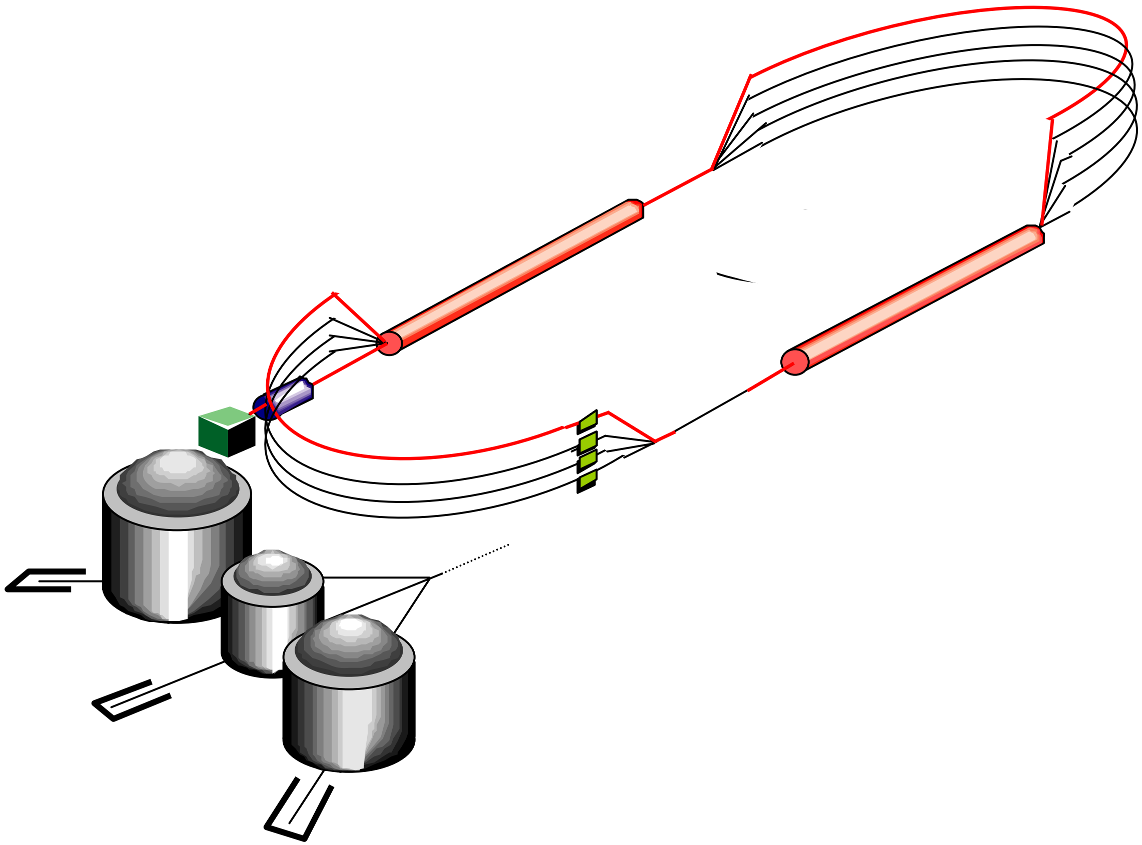
CEBAF Beam Offers Extended Parameter Space To Test and ODR Offers an NI Beam-size Monitor for Operations

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

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

CEBAF 5-GeV Recirculating Linac

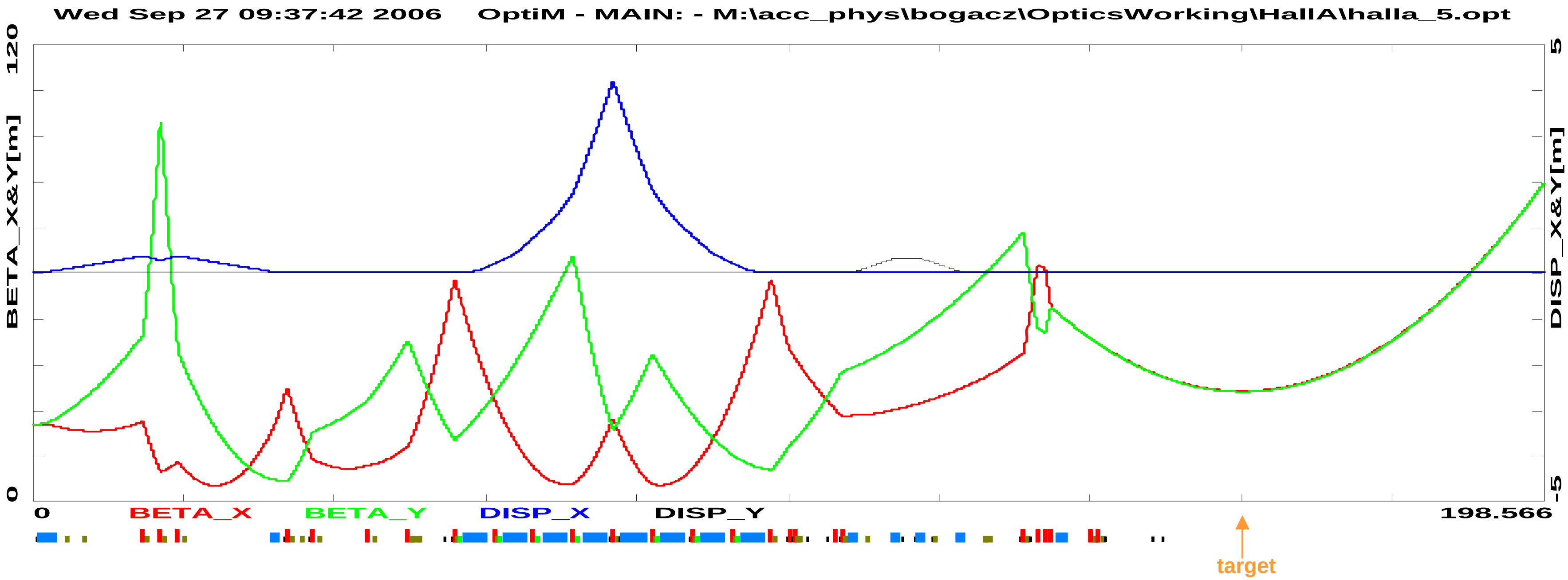
- 100 μAmps CW beam extracted at 1 GeV, 2, 3, 4, or 5 GeV.



Courtesy of Alex Bogacz, JLAB

Hall A – Lattice Parameters at 4 GeV

Twiss functions:

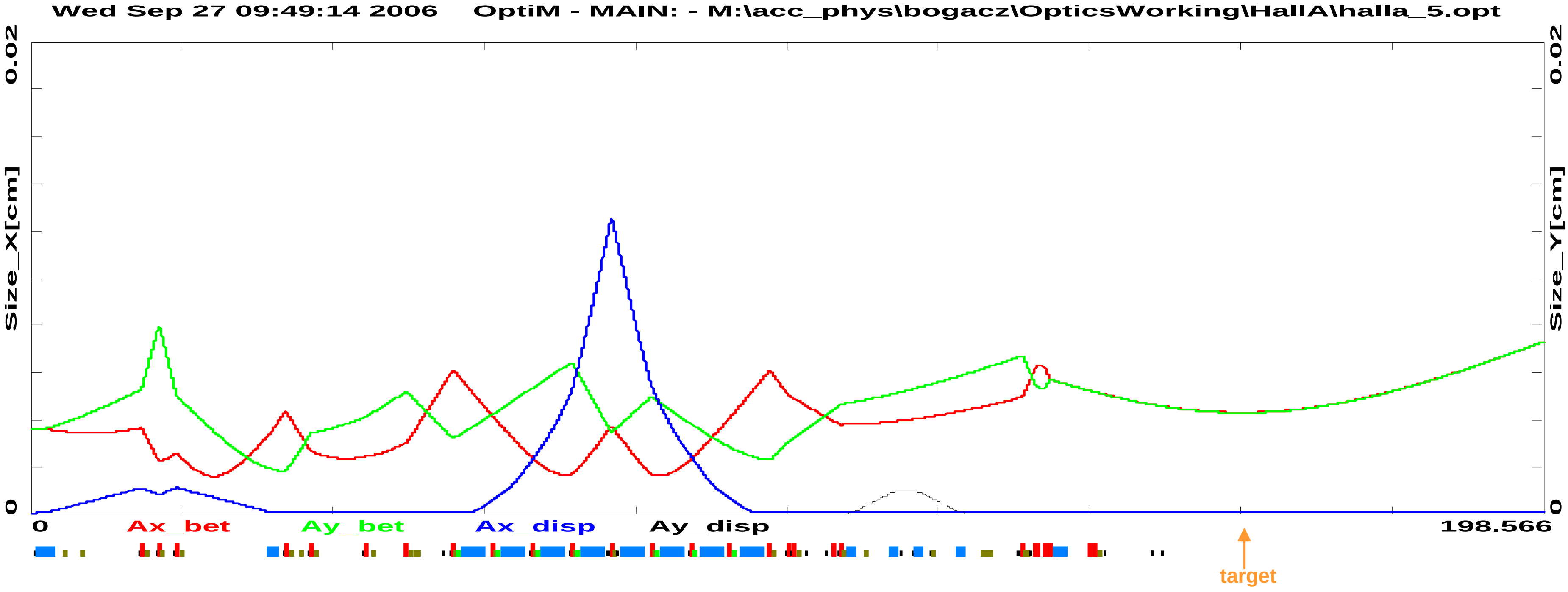


ε_N = **0.5 mm mrad** **$\Delta p/p = 3\times10^{-5}$**

Courtesy of Alex Bogacz, JLAB

Hall A – Beam Parameters at 4 GeV

Beam envelopes* : ε_N = 0.5 mm mrad $\Delta p/p = 3\times10^{-5}$



* all quantities are rms

Courtesy of Alex Bogacz, JLAB

APS Upgrade May Involve ERL as Injector at 7 GeV

- August 06 guidance from DOE/BES is to evaluate the ERL concept for the APS Upgrade.
- Maintain 100 mA with improved emittance and 100-fs bunch length.
- User beamlines maintained and upgraded. Avoid long shutdown for users for alternate SR lattice change.
- Time-resolved studies extended from rf crab cavity mode (1 ps) in APS.
- Inject at 7 GeV into present ring lattice with SC rf linac.
- Beam in ring for 1 turn, and then extracted for energy recovery pass in linac.
- Beam sizes of about 10 μm expected in both planes.
- ODR technique being evaluated for supporting the linac diagnostics.

SUMMARY

- ***A new NI relative beam size monitor based on ODR has been proposed to support APS top-up operations.***
- ***The ODR near-field imaging techniques also have relevance to x-ray FELs, ERLs, the proposed ILC, the APS upgrade, and emerging LWFAs.***
- ***The ODR techniques also appear applicable to NI monitoring of the CEBAF 5-GeV beam at 100*** μA ***before the experimental hall.***
- ***Discussions for CEBAF test and application to continue tomorrow.***

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, and FEL06.
- Previous publications by KEK on far-field imaging to deduce beam size in PRL (10-minute angle scan) and PAC05 (dephased planes).