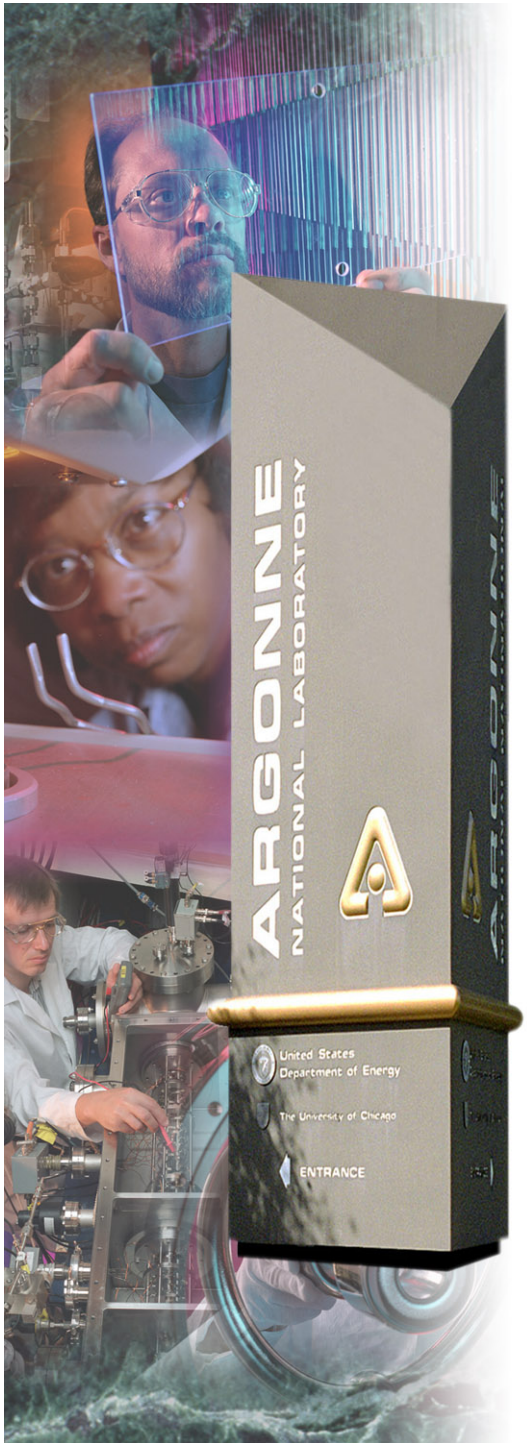

Nonintercepting Diagnostics for Transverse Beam Properties: from Rings to ERLs

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OUTLINE

- **Introduction**
- **Experimental Background**
- **Experimental results with APS electrons**
- **Applications to ERLs**
- **Summary**

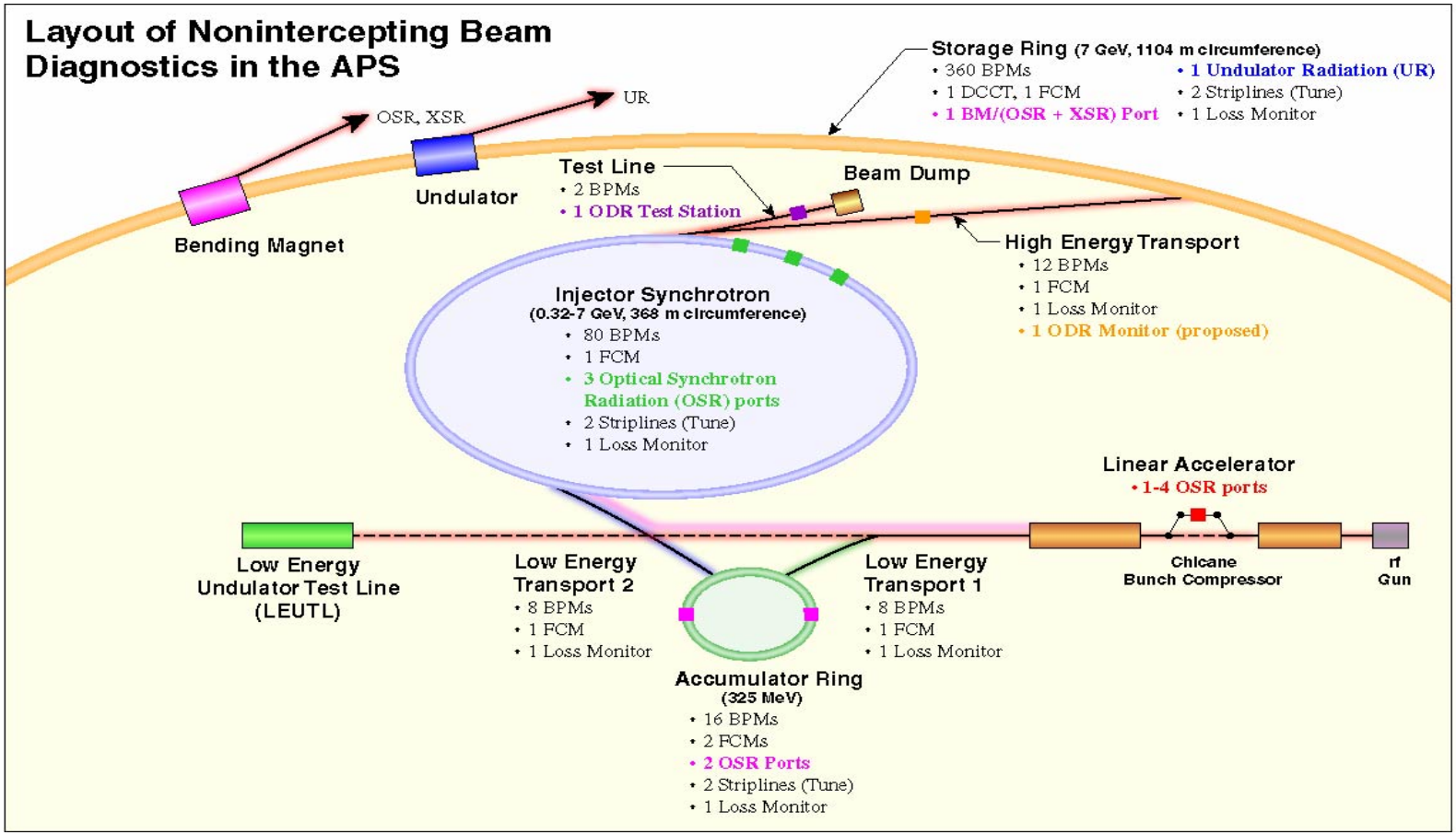
Introduction

- Characterization of particle-beam properties in accelerators and transport lines is often important to the experiment's success.
- Nonintercepting (NI) beam diagnostics are of growing interest. This is true of top-up operations for storage rings such as the Advanced Photon Source (APS) as well as energy recovering linacs (ERLs).
- Both beam position and beam profiles are needed in a NI technique. Rf BPMS generally address position only.
- Conversion of beam information to optical signals allows visualization of the beams and can be in a NI manner.
- Imaging technology is directly applicable to the optical signals.

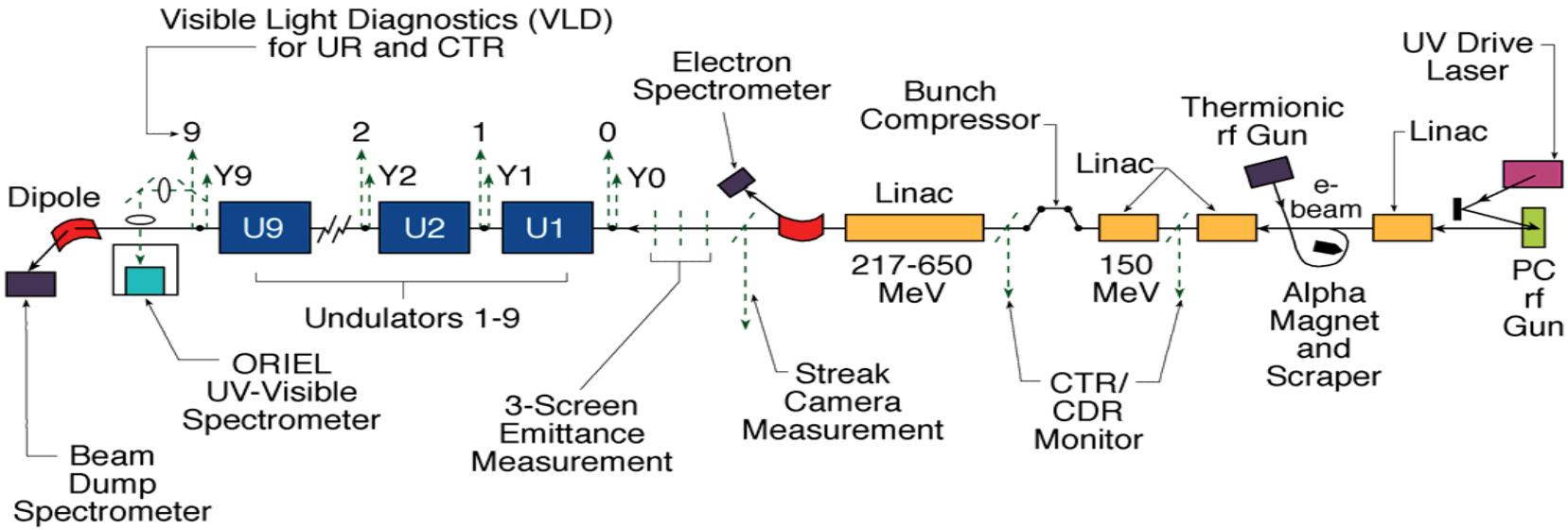
Experimental Background

- **Objective is to have minimally and nonintercepting diagnostics for beam position and profile.**
- **Rf beam position monitors (BPMs) are well-established: striplines, buttons, and cavities.**
- **Optical transition radiation (OTR) is generated when a charged–particle beam transits the interface of two media with different dielectric constants. (e.g. vacuum to metal).**
- **Optical diffraction radiation (ODR) is generated when a charged–particle beam passes near the interface of two media with different dielectric constants. (e.g. vacuum to metal).**
- **Optical synchrotron radiation (OSR) is generated when a charged–particle beam transits the magnetic field of a dipole magnet (bend and edge).**
- **Undulator radiation (UR) is enhanced synchrotron radiation with special properties in wavelength bandwidth, harmonics, intensity, etc.**

Schematic Layout for APS Accelerators



Schematic of APS SASE FEL Experiment



Beam Position routinely monitored with rf BPM technology in the APS machines

- **Top-up operations involve injection of one pulse every two minutes into the storage ring. Q=2.5-3.0 nC per shot from Synchrotron.**
- **Linac runs at 2856 MHz rf fundamental**
- **PAR has 9.77 MHz fundamental frequency and a 12th harmonic to aid damping.**
- **Injector Synchrotron has 352 MHz rf fundamental**
- **Storage ring has 352 MHz rf fundamental: beam current of 100 mA, button pickups with monopulse receivers and Bergoz electronics. Beam stability to a few microns with feedback.**

Universal BPM topology applied to the APS injector applications

Table 1. System Applications. **(Courtesy of R.Lill, BIW02)**

Location	Number of BPMs	Frequency (MHz)	Half Aperture (mm)	Stripline Sensitivity (dB/mm)	Normalized Position (μm/mV)
Linac	15	2856	17	2.0	13.6 x V_{out}
LEUTL	20	2856	17 and button type	2.0	13.6 x V_{out}
Linac to PAR	4	2856	17	2.0	13.6 x V_{out}
Booster to Storage Ring	8	352	25	1.4	20.0 x V_{out}

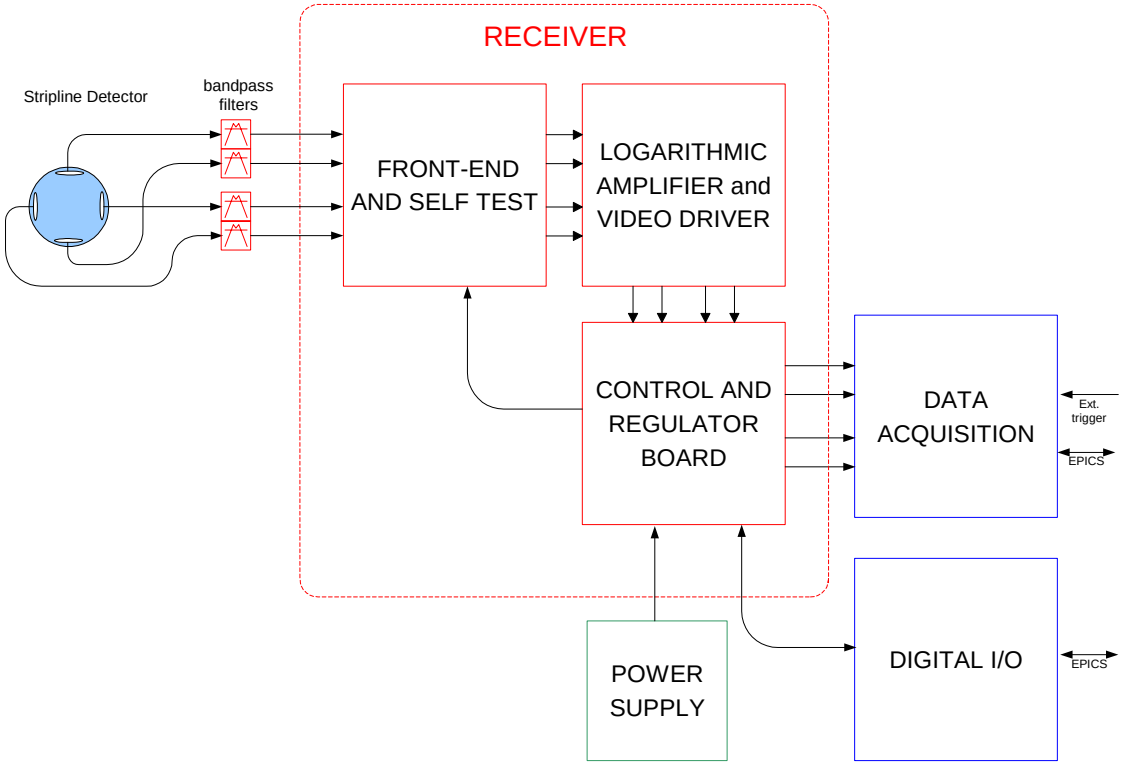
Design specifications meet top-up requirements

- **Table 2. Design Specifications (R.Lill, BIW02)**

Parameter	PC Gun	rf Thermionic Gun
Dynamic Range	0.1-2 nC (26dB)	0.1-10 nC (40 dB)
Single-Shot resolution	15 μm rms	100 μm rms
Drift	15 μm rms	100 μm rms
Accuracy,range	100 μm, +- 5 mm	100 μm, +- 5mm

Log-ratio system with subtraction in software addresses needs for APS injector top-up OPS

- **System block diagram (R.Lill et al. , BIW02 proceedings)**



Strategy

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.

- Basically, these comments apply to OSR and ODR as well except the beam needs to transit a dipole field or pass by a metal plane or through a slit, respectively.

OTR and OSR photon yields are comparable in the APS applications.

- **TABLE 1. Estimates of Total Visible Photons per 1-nC Charge in a Single Pass (λ = 400-700 nm).**

Accelerator	Beam Energy (GeV)	B – Field (T)	Angular Width	Integrated Flux
Linac OTR	0.20	Thin foil	2 π solid angle	10.6×10^7
Chicane	0.15	0.6	20 mrad	4.1×10^7
Accumulator Ring	0.375	1.2	10 mrad	3.1×10^7
Injector Synchrotron	7	0.7	8 mrad (16mm @ 2m)	8.4×10^7
Storage Ring	7	0.6	3 mrad (35mm @ 12m)	4.4×10^7

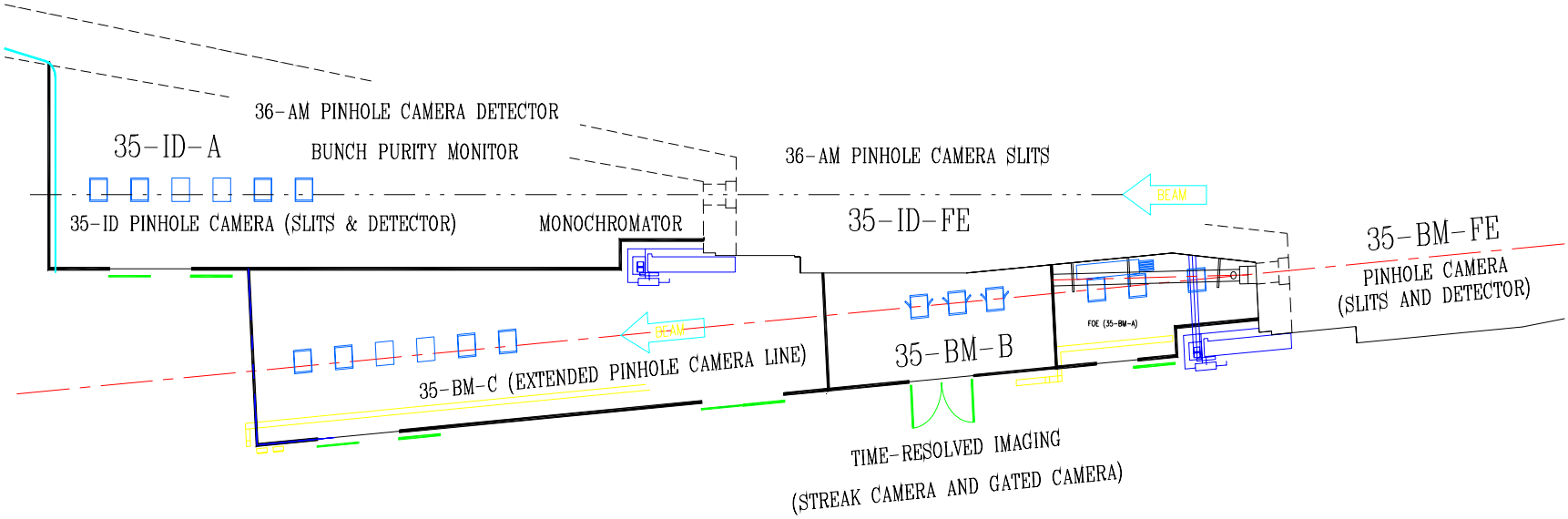
Lumpkin and Yang (BIW02)

OSR/XSR imaging can be used over wide range of energies

- **Calculations for 18-40 MeV at 200 mA in High power linac FEL: Greegor and Lumpkin (NIMA 1988)**
- **OSR Measurements at 23-38 MeV at LANL linac with intensified camera and Q = up to 10 μC in 100 µs. M.Wilke (BIW'94)**
- **Several cases at APS considered or implemented**
  - **Chicane dipoles at 150 MeV (proposed)**
  - **Particle Accumulator ring bends at 325 MeV**
  - **Booster Synchrotron bends at 325- 7000 MeV**
  - **Storage ring bends at 7000 MeV and 100 mA.**
  - **Diagnostics undulator, 1.8-cm period, L=3.4m**
- **Two-slit interferometer technique gives beam size info with better spatial resolution than direct visible light imaging.**
- **X-ray synchrotron radiation field is an option for better spatial resolution (σ_{res} = 22 µm with 15 µm slit)**

Extensive Nonintercepting OSR and XSR Beam Diagnostics available at APS Sector 35

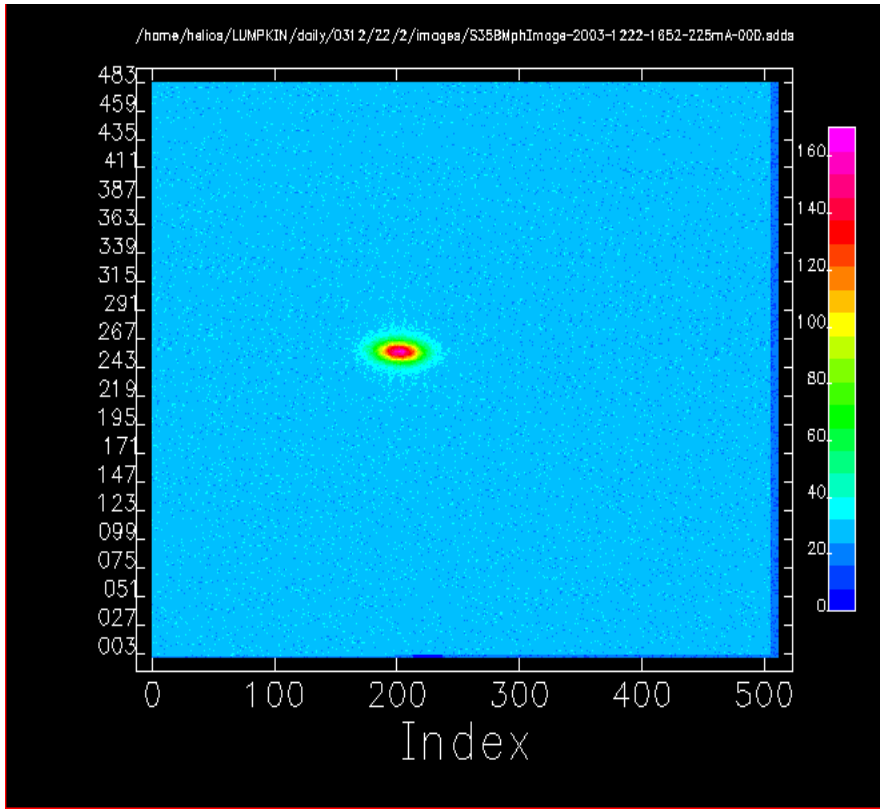
- **Sector 35 Layout**

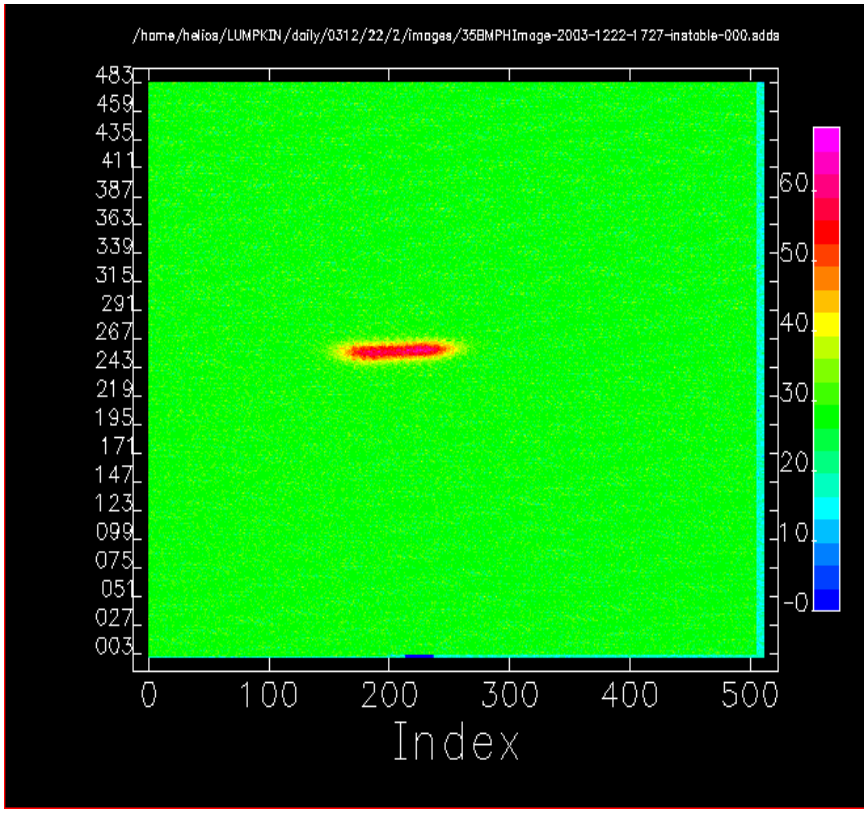


XSR Images used to identify longitudinal instability in Storage ring at 225 mA

S35 BM x-ray pinhole images for different HOM conditions.

a) stable **b) unstable**

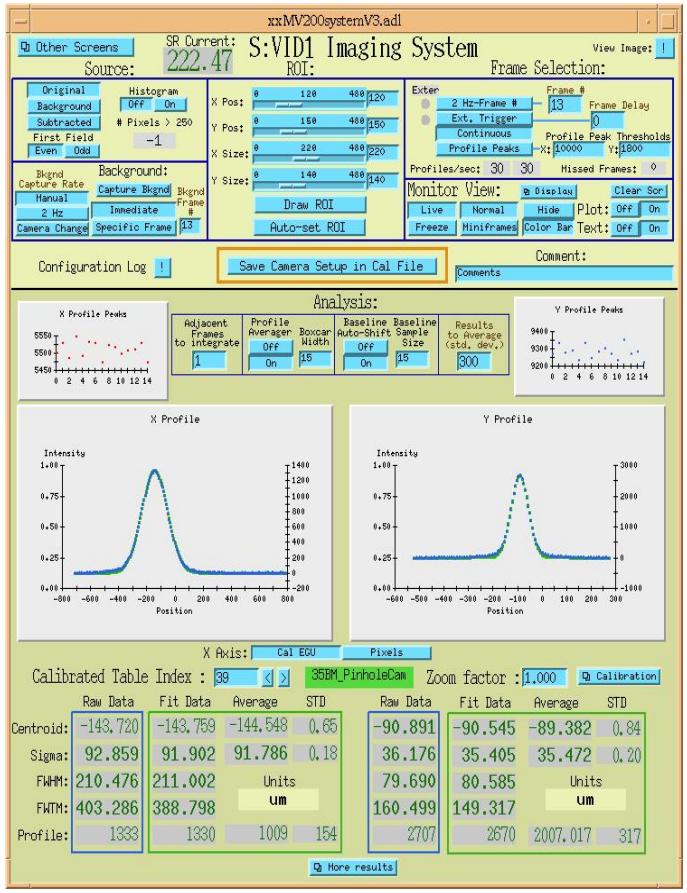




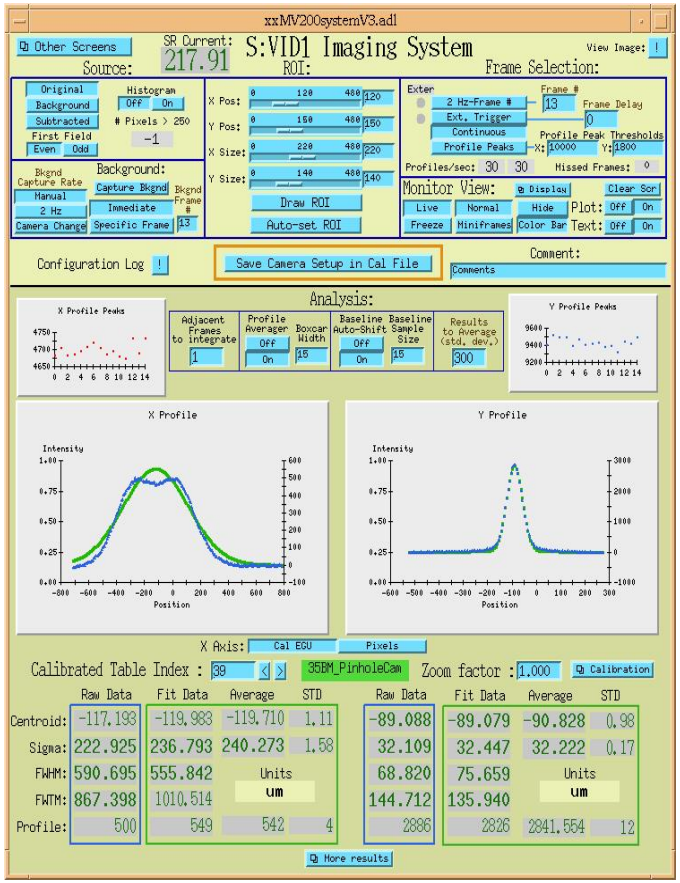
XSR Images used to identify longitudinal instability in Storage ring at 225 mA

Sample digitized profiles for different HOM conditions:

a) stable



b) unstable

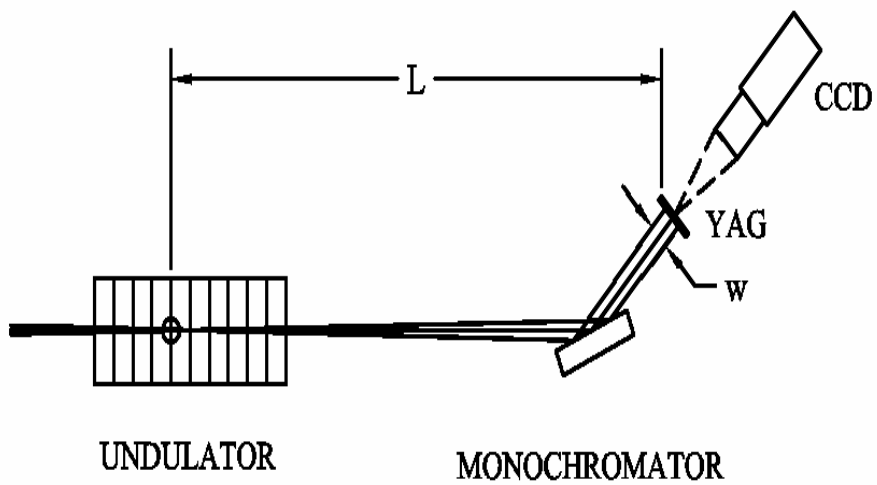


Beam Divergence measurements can be done to a few µrad at APS Sector 35

1. Divergence measurement with monochromatic undulator beam

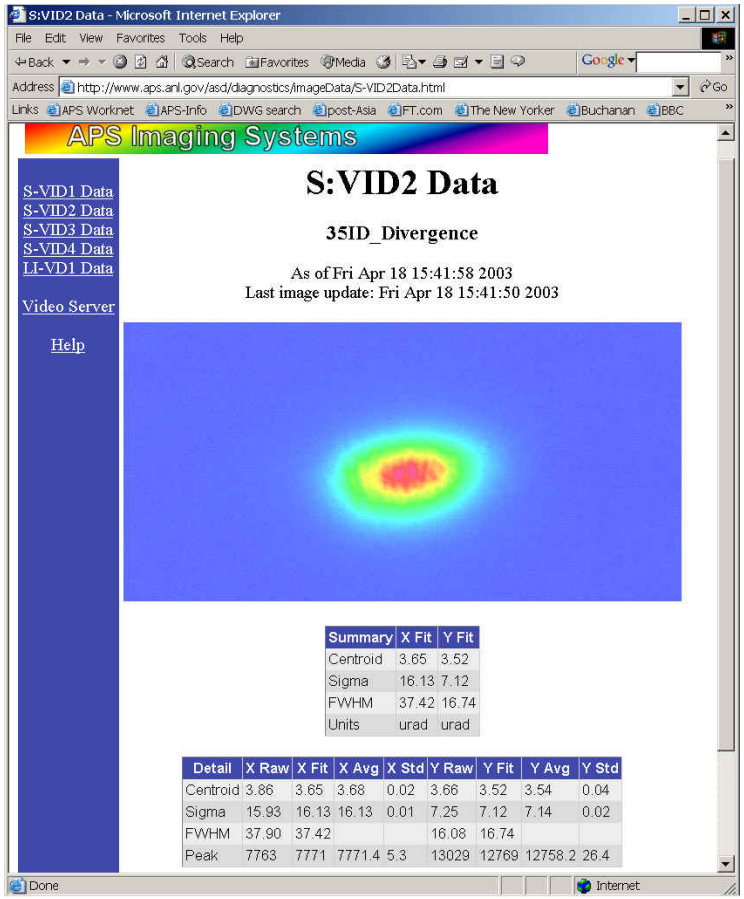
$$\text{Monochromator select photon energy: } \omega > \omega_1$$

$$\text{Effective beam divergence} = w/L$$



Stored beam divergence can be tracked using S35 ID, X-ray Monochromator, and Imaging

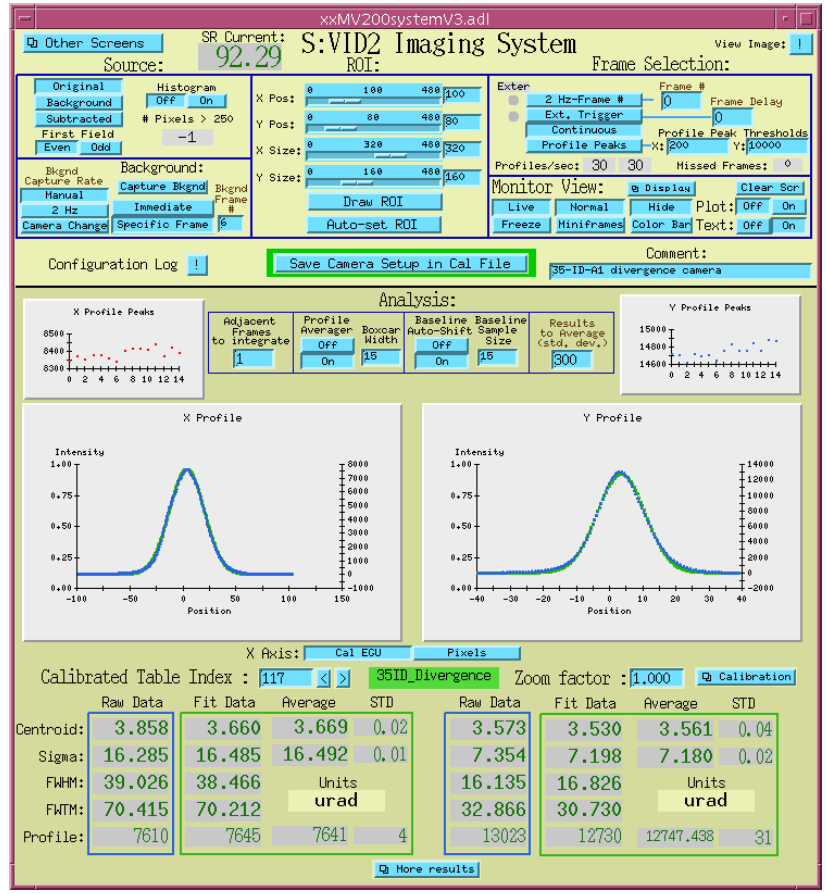
Observed UR Image



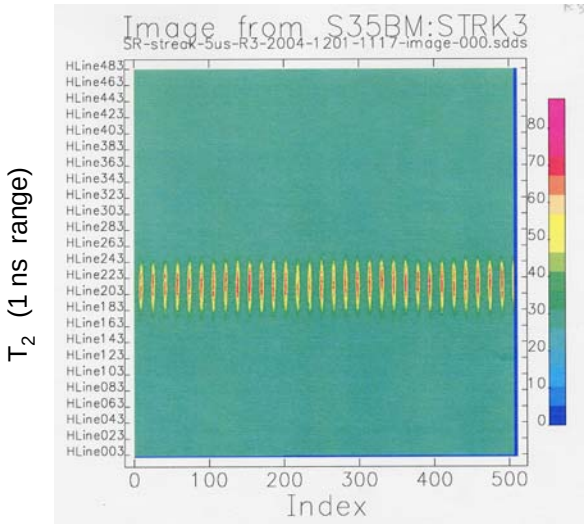
Summary	X Fit	Y Fit
Centroid	3.65	3.52
Sigma	16.13	7.12
FWHM	37.42	16.74
Units	urad	urad

Detail	X Raw	X Fit	X Avg	X Std	Y Raw	Y Fit	Y Avg	Y Std
Centroid	3.86	3.65	3.68	0.02	3.66	3.52	3.54	0.04
Sigma	15.93	16.13	16.13	0.01	7.25	7.12	7.14	0.02
FWHM	37.90	37.42			16.08	16.74		
Peak	7763	7771	7771.4	5.3	13029	12769	12758.2	26.4

Digitized Profiles

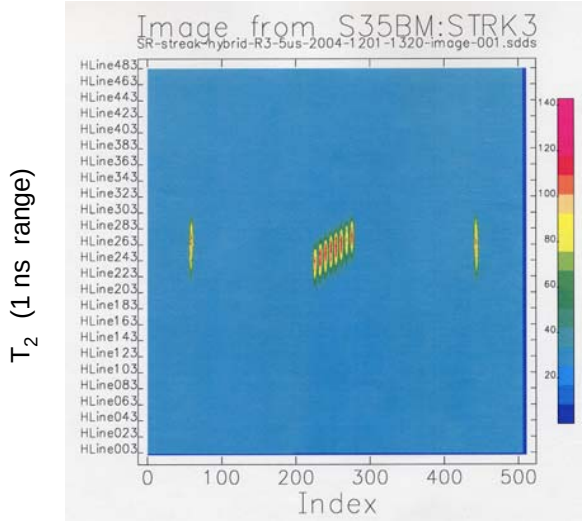


Bunch Lengths for Different APS Storage Ring Fill Patterns Revealed in Unique Dual-Sweep Streak Camera Images from Sector 35



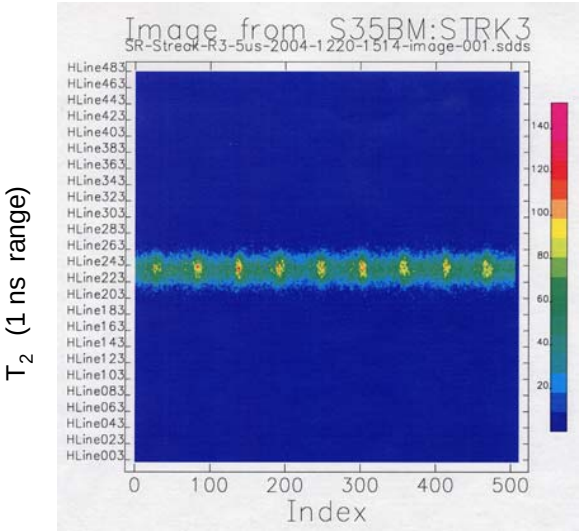
T_1 (5 µs range)

24-singlets



T_1 (5 µs range)

1+8*7



T_1 (5 µs range)

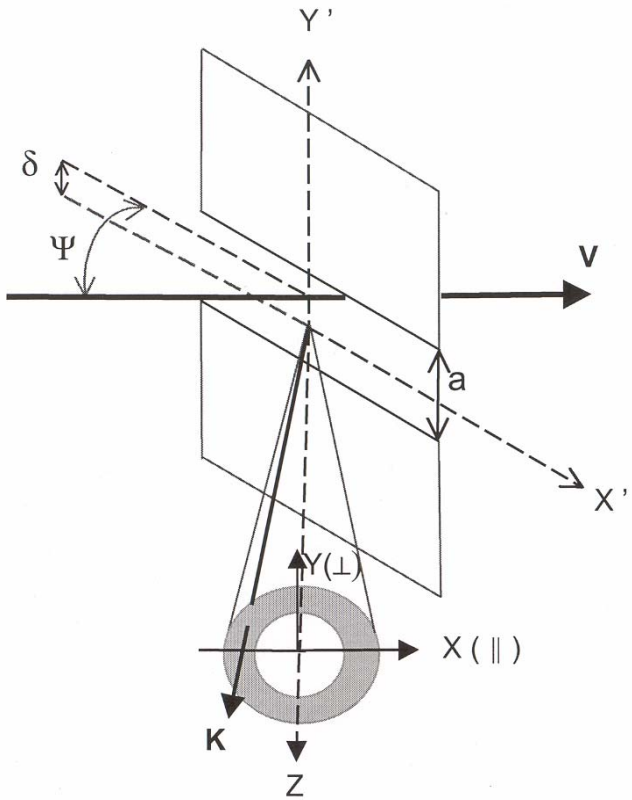
324-singlets

	24-singlets	**Hybrid: 1+8*7**	**324-singlets**
Bunch length (rms)	40 ps	Singlet: 50 ps Septuplet: 32 ps	25 ps

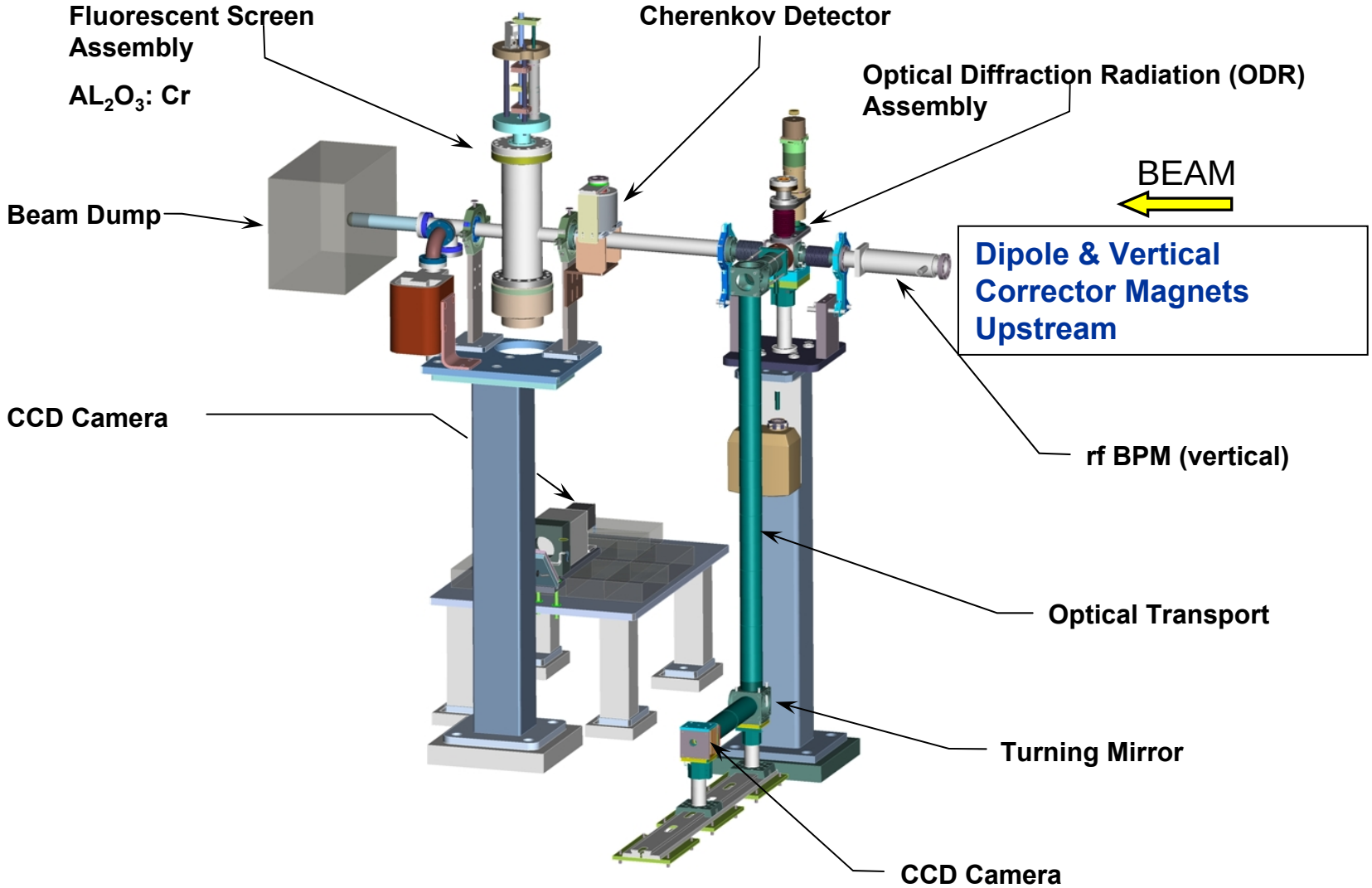
Courtesy of A. Lumpkin and B. Yang

Backward optical diffraction radiation emitted when a charged particle passes through a slit.

- **The conducting plates are at 45 degrees to the beam direction. Based on Fig.1 of Fiorito and Rule (NIM B173, 67 (2001))**



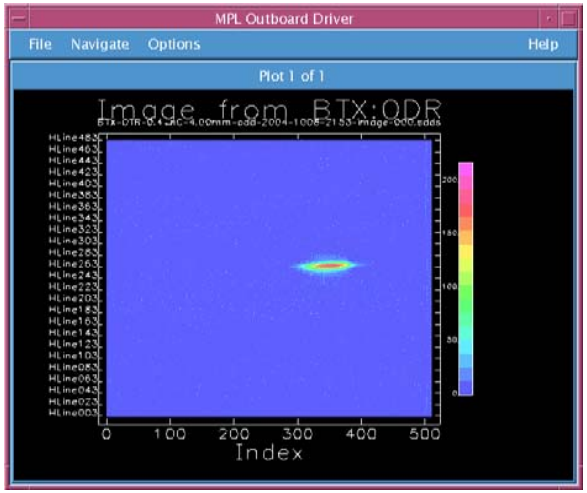
An OTR/ODR test station has been installed at the Booster to extraction line (BTX) at 7 GeV



First Near-Field Images of ODR Signal from a 7-GeV Beam Observed at APS (10-08-04)

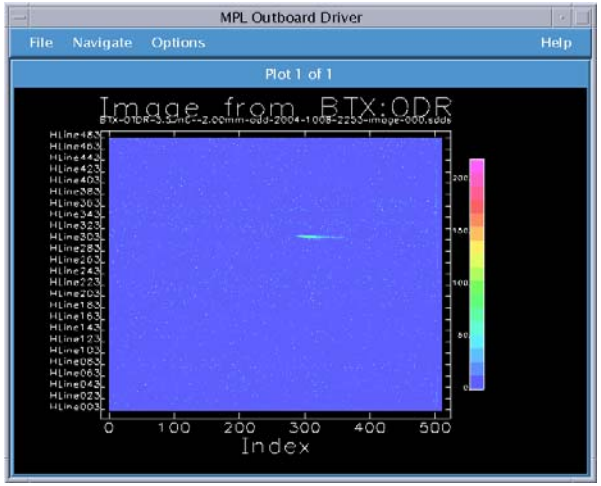
Y axis 2.2 mm range

OTR Image, 0.4 nC



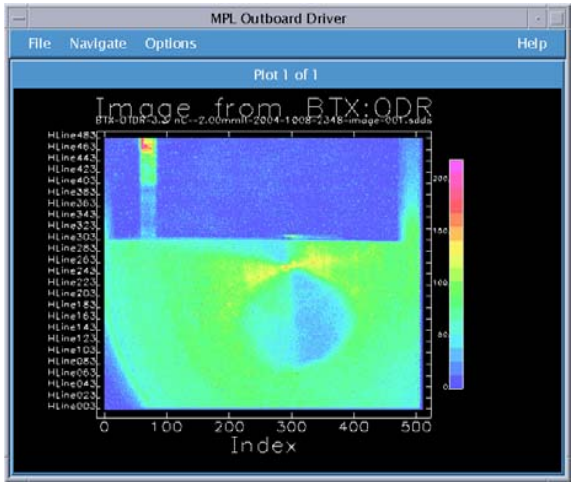
X axis 2.5 mm range
(Blade 4 mm below
beam center)

ODR Image, 3.2 nC



X axis 2.5 mm range
(Blade 2 mm above
beam center)

ODR Image,Light on



X axis 2.5 mm range
(Blade 2 mm above beam
center)

	OTR	ODR Signal	ODR/OTR rms ratio (a = 2 mm)
Image x Size (rms)	1375 um	990 um	0.72

Transverse Position and Profile information provided by imaging techniques: Low Power

- **Commissioning phase: Low average power (nA to microamps).**
- **Convert e-beam information to optical with YAG:Ce screens or OTR foils.**
- **Yag:Ce screens have saturation effect at threshhold areal charge density.**
- **Spatial resolution of 10 μm with appropriate optics and cameras should be obtainable.**
- **Time-resolved imaging with gated cameras and streak cameras possible for sub-macropulse effects.**

Transverse Position and Profile information provided by imaging techniques: High Power

- **High average power: Nonintercepting methods (mA-100's mA)**
- **OSR from bends, direct imaging and two-slit interferometer**
- **ODR from metal planes or apertures**
- **Undulator radiation from diagnostics undulator in light source**
- **XSR and UR generally converted to visible light by YAG:Ce for imaging.**
- **Time-resolved imaging with gated cameras and streak cameras are applicable.**
- **Laser wire and scanning wire techniques may be applicable.**

Summary

Electron-beam diagnostic techniques developed on the rings and transport lines of the APS have relevance to a number of ERL diagnostics issues.

- **Transverse position issues using rf BPMS are well in hand in general for single-shot and quasi-CW measurements.**
- **The architecture of ERLs has bends in the beam lines so the opportunity for synchrotron radiation imaging should be exploited. Both OSR and XSR should be considered depending on the beam energy and the resolution needed.**
- **A diagnostics undulator in a light-source ERL is a good candidate for NI measurements.**
- **Recent experiments at KEK, APS, and BNL on optical diffraction radiation show good promise for NI diagnostics for ERLs.**
- **Further details in the following talks and the WG4 discussions.**

Acknowledgements

- **The author acknowledges R.Lill for the input on the rf BPMs; B. Yang for input on the photon diagnostics; W. Berg, B. Rusthoven, and A. Barcikowski on the mechanical design for the ODR station; J. Xu and S.Shoaf for controls for the ODR station and Cherenkov detector; T. Pietryla for the Cherenkov detector; and N. Sereno and C.Yao for experiment support (all from APS). He also notes past and recent discussions on OTR/ODR with R.Fiorito and D. Rule, respectively.**