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Optical Transition Radiation (OTR) Detectors for Intense Proton and Antiproton Beams at FNAL

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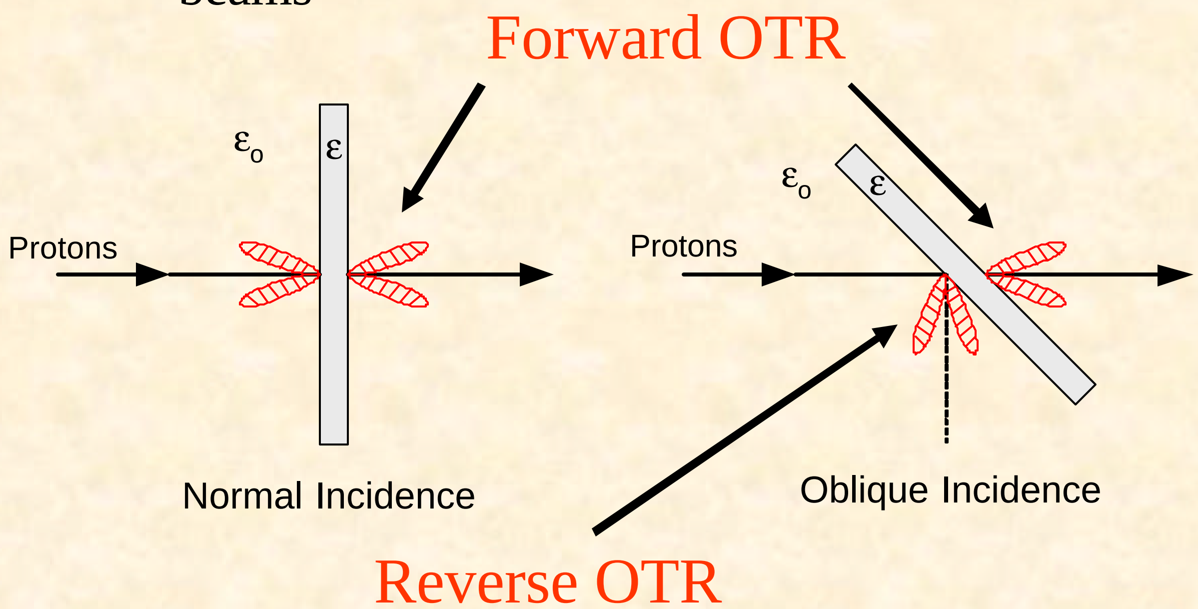
What is Optical Transition Radiation?

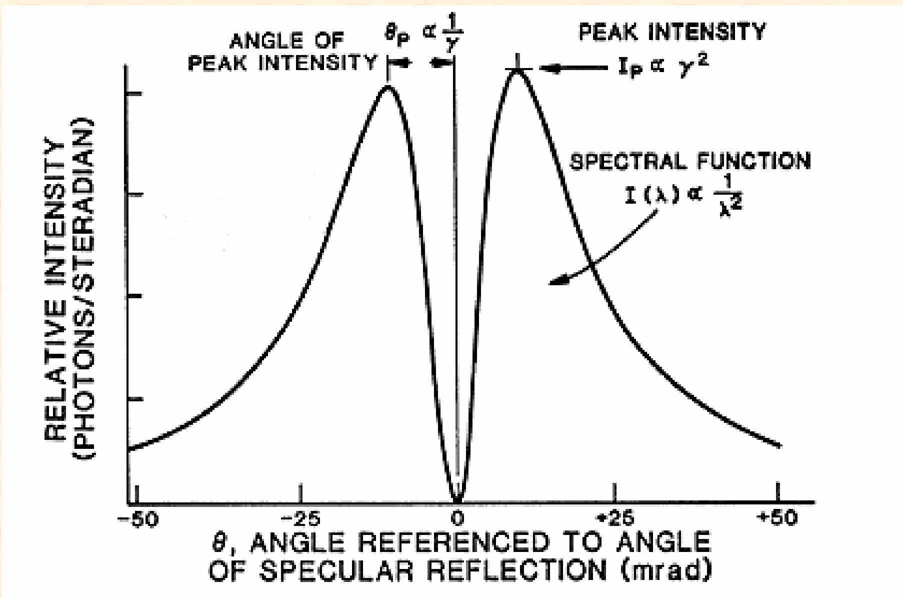
- Optical Transition Radiation (OTR) is generated when a charged-particle beam transits the interface of two media with different dielectric constants, for example, vacuum to metal
  - OTR detectors have been used with high energy and intensity electron beams



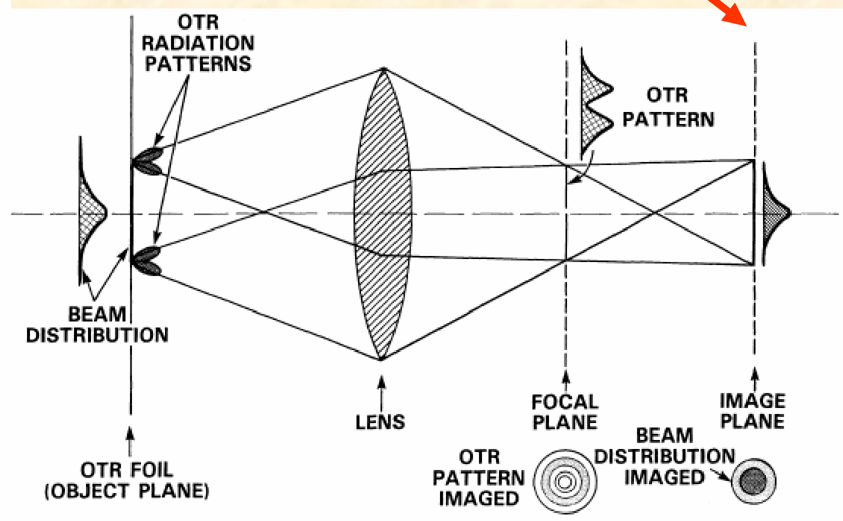
Quantity of light proportional to foil reflectivity for reverse OTR.
Emission spectrum is very broad and has adequate signal in visible region.

OTR Pattern and Imaging

OTR Emission Pattern



Near-field image plane sees beam distribution



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

Far-field image focal plane sees OTR emission pattern

OTR Detector Strategy

- Convert particle beam information to optical radiation and then use commercial imaging technology to acquire beam information
- Since OTR is a surface phenomena then can use thin foil to minimize proton/antiproton beam scattering
- OTR image can provide 2-D information on:
  - Transverse profile and shape (tilt) ← *primary objective for FNAL*
  - Transverse position
  - Emittance
  - Intensity
  - Divergence, energy, bunch length, longitudinal profile…

Motivation for High-Energy Protons/Antiprotons

- For low-energy beams (< 10 GeV) transverse size is relatively large so multiwire grids are adequate for profile measurements
- For high-energy beams, beam size (σ) ~ 1 mm so multiwires poorly sample profile
  - In addition, mutiwires give only 1-D profiles
- Can OTR detectors do better?
- Is there enough light for γ and beam size?

Will OTR Detectors Work for Fermilab Proton and Antiproton Beams?

Compare to Argonne APS electron machine to determine feasibility for FNAL

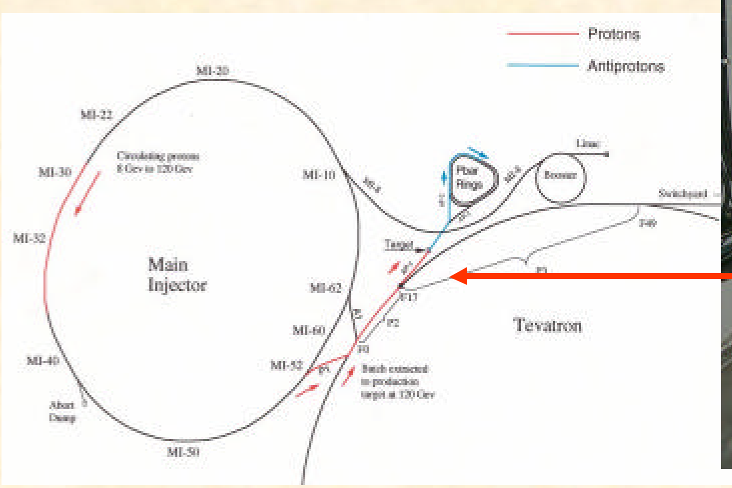
Feature	Electrons	Protons
Beam size (σ)	200 μm	1 mm
Macropulse	8-40 ns	10 μs
Q (nC)	0.3	10,000
Particle #	1.8×10^{9}	4×10^{13}
Gamma	100-14000	129
Theta peak	10-.07 mrad	8 mrad

Proton larger beam size and smaller γ dilutes OTR at camera but large number of particles should compensate. Focus on high-energy (γ > 100) protons and antiprotons to maximize OTR to camera.

Build prototype OTR detector to test and learn

Prototype OTR Location – AP1 Line

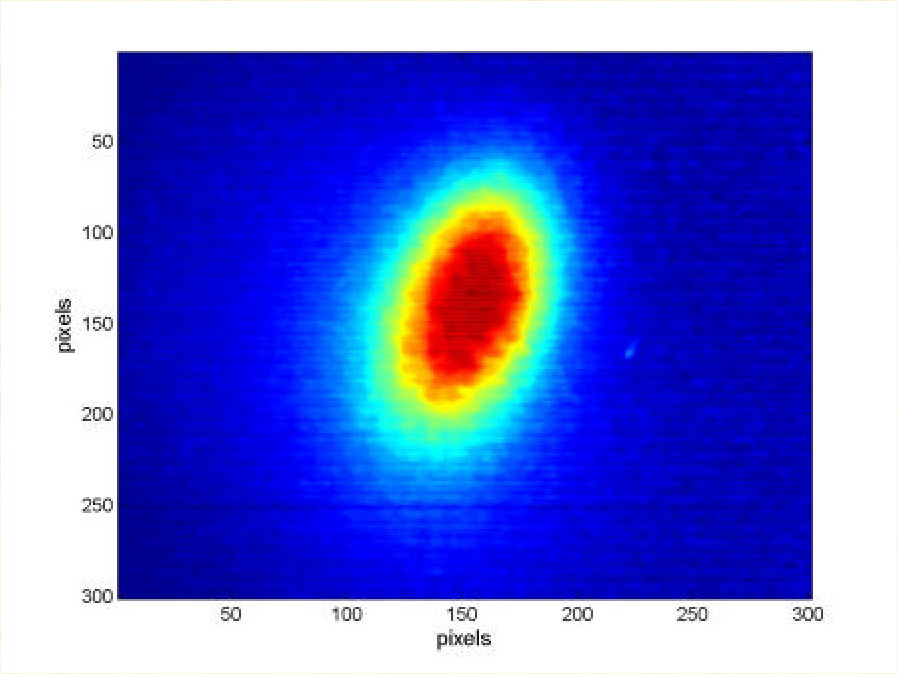
- High intensity – 4e12 protons/pulse
- Frequent beam - ~ 0.5 Hz pulse rate
- High energy – 120 GeV protons
  - 1/γ -> 8 milliradians
- Beam size of 1σ ~ 2-4 mm
- *High radiation environment?*
  - *~ 6 krad/wk at 1 meter*

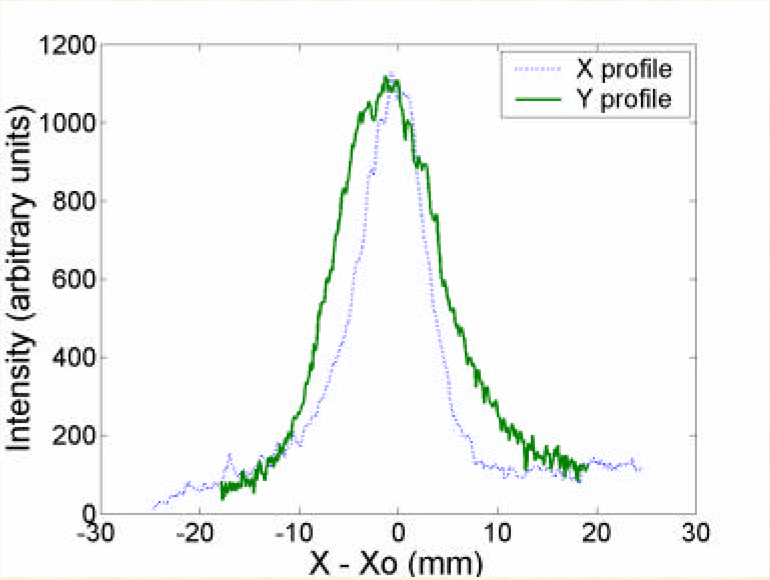


Foils in air
- 12 μm Ti foil
- 20 μm Al foil

Rad-hard CID camera

Prototype Images with 12 μm Titanium Foil

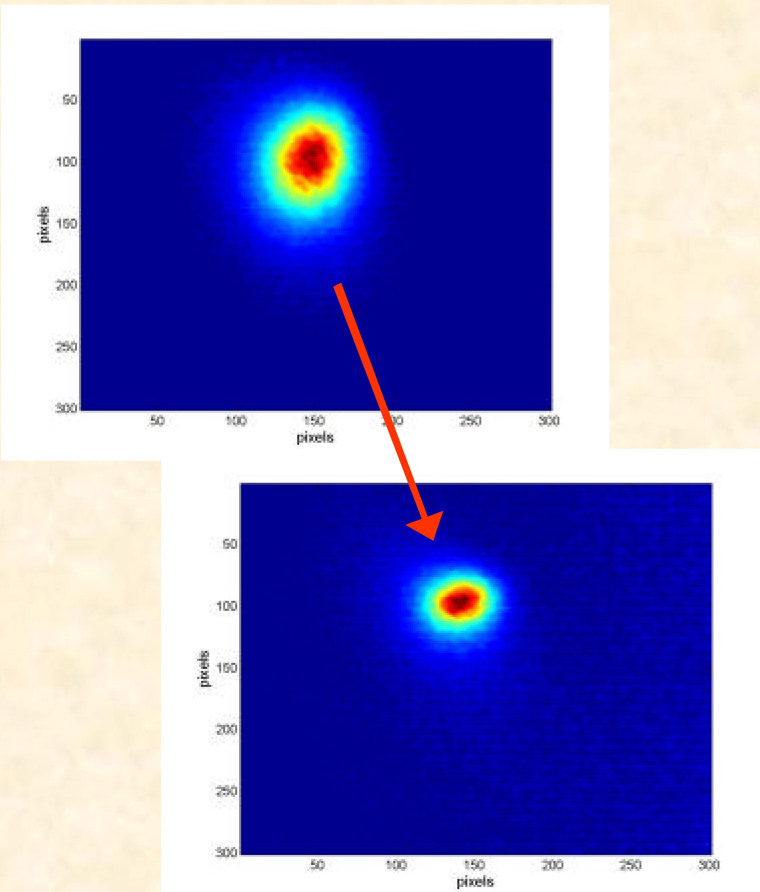




- Proton intensity ~4.5e12
- Using x0.005 light attenuator
- Imaging possible down to ~ 5e9 protons for same beam size and same γ

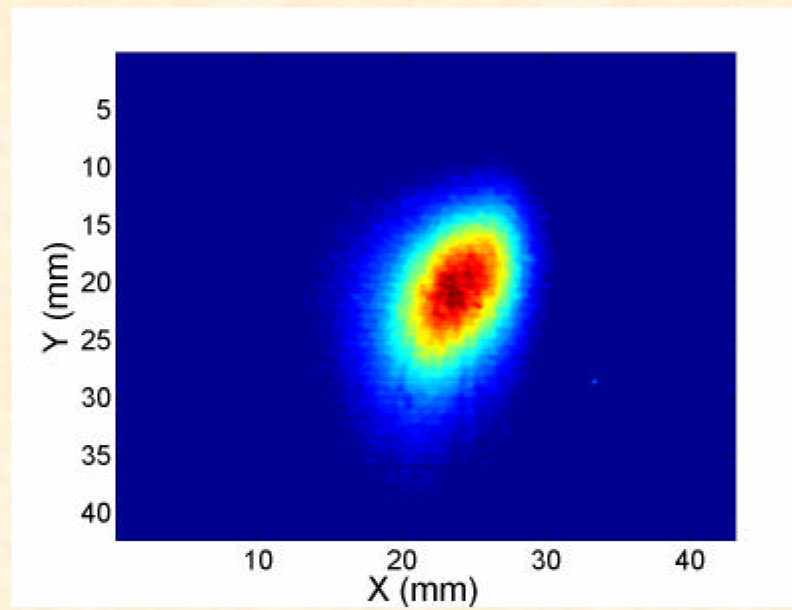
More Prototype Images

Vertical beam size reduced by x2



20 μm Al foil

- ~4.7e12 protons
- x0.001 light attenuation

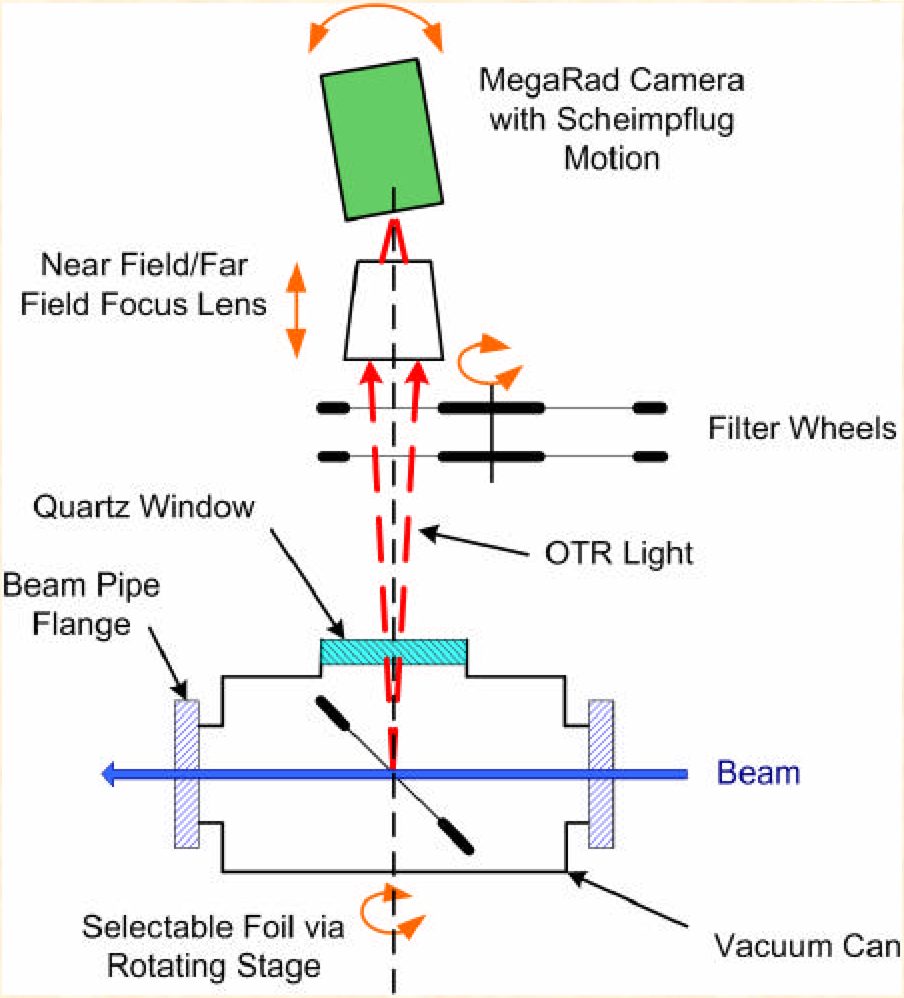


A Generic OTR Detector for Fermilab Proton and Antiproton Beamlines

Develop an OTR detector as part of the Run II upgrade program and as part of the NuMI primary beam line

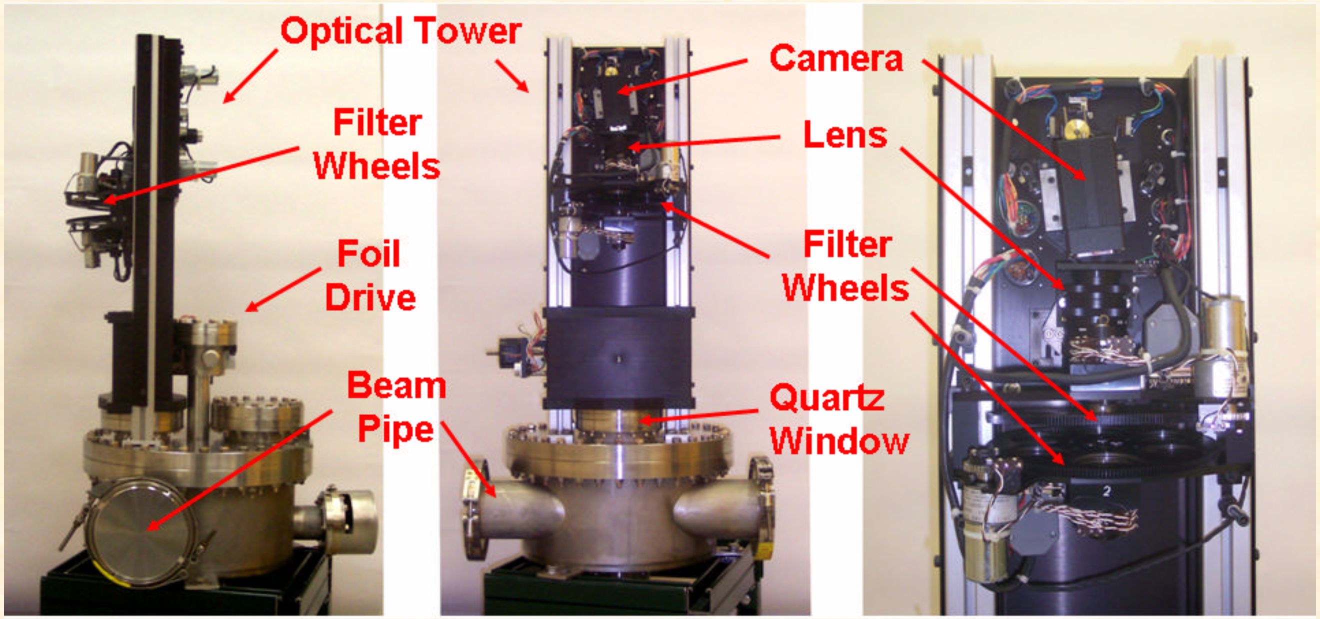
	A150 Line	Tevatron	NuMI Line	AP-1 Line	AP-2 Line
Beam Type	Proton/anti-proton	Proton/anti-proton	Proton	Proton	Mostly π's
Beam Energy (GeV)	150	150	120	120	8
Beam Intensity (E10)	~ 1 to 50	~ 1 to 50	~ 10 to 5000	~ 100 to 800	~ 0.1 to 0.5
Transverse Beam Size (σ in mm)	~ 1 to 2	~ 1.5	~ 1.0	~ 1 to 2	~ 10
Rep Rate	~ 20 transfers per day	Injection studies only	~ 0.5 Hz	~ 0.5 Hz	~ 0.5
Status	Installed - commissioning	Installed - commissioning	Installed - commissioning	Installed - commissioning	Not Installed

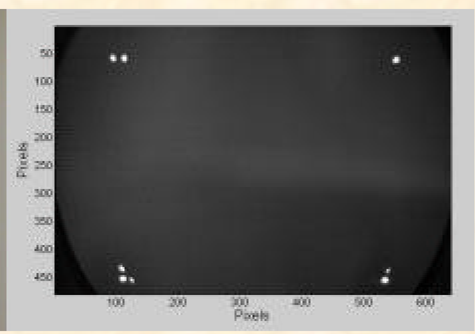
Diagram of Generic OTR Detector



- Radiation hardened CID camera
  - ~150 µm pixels at foil
- Near field/far field focusing
- Tiltable camera to maintain focus across foil (Scheimpflug)
- Neutral density filter wheels with polarizers
  - ~x1000 intensity range
- Bidirectional beam measurements with selectable foils
  - Foils replaceable in-situ
  - 85 mm clear aperture
- Vacuum certified to few 10-9

Constructed OTR Detector

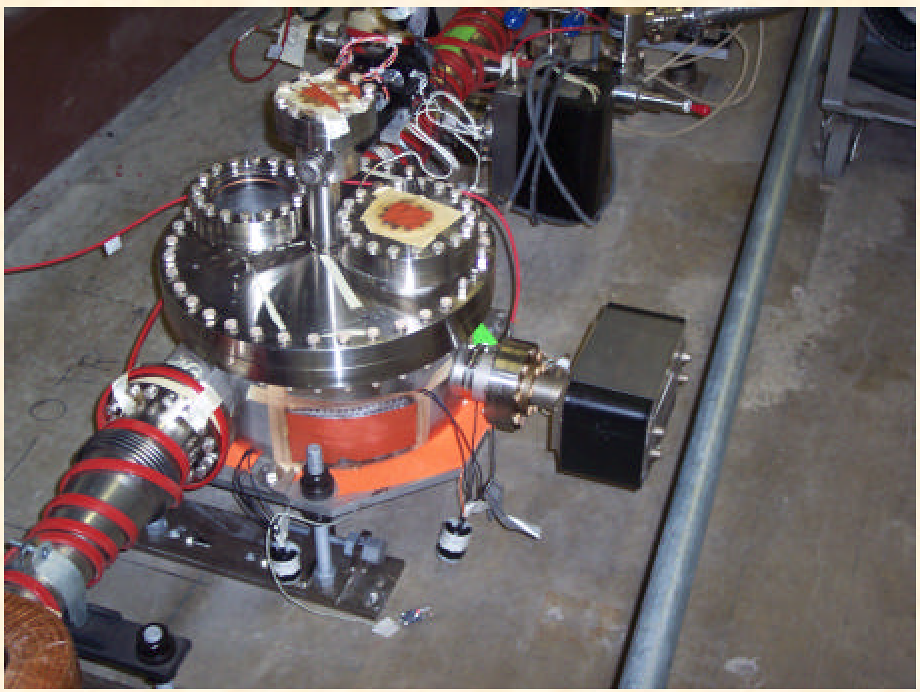


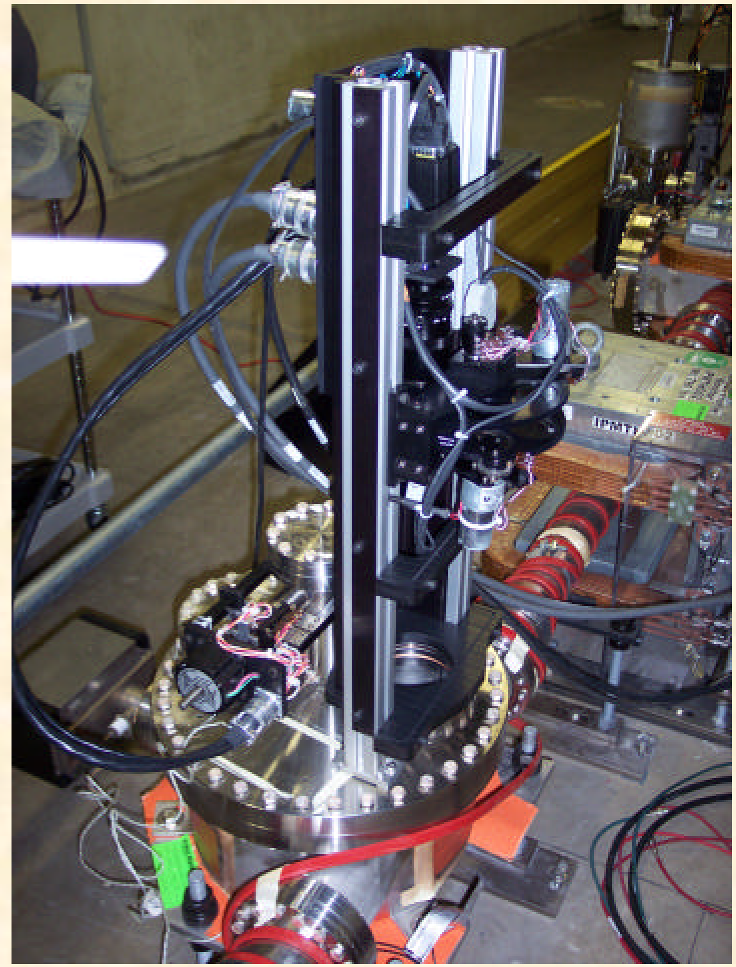


- 5 μm mylar or kapton with ~1200 angstroms Aluminum
  - replaceable foils
- Back illuminated fiducials for in-situ scale/orientation calibration

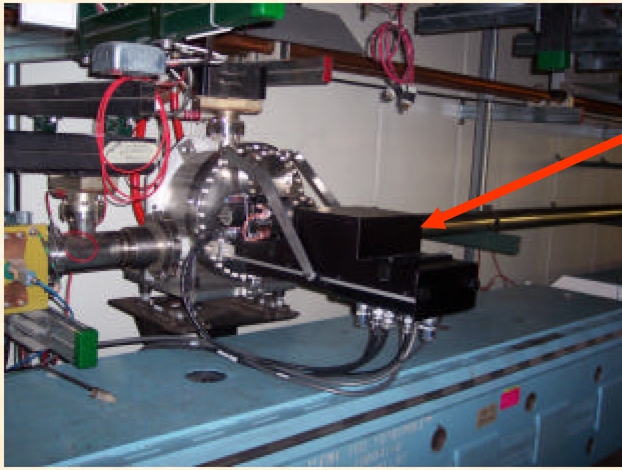
OTR Installed in Tevatron

- Installed at E0 next to new IPM
  - Cross-calibrate IPM to OTR and visa-versa
- Used for few turn injection studies
- Proton and pbar foils

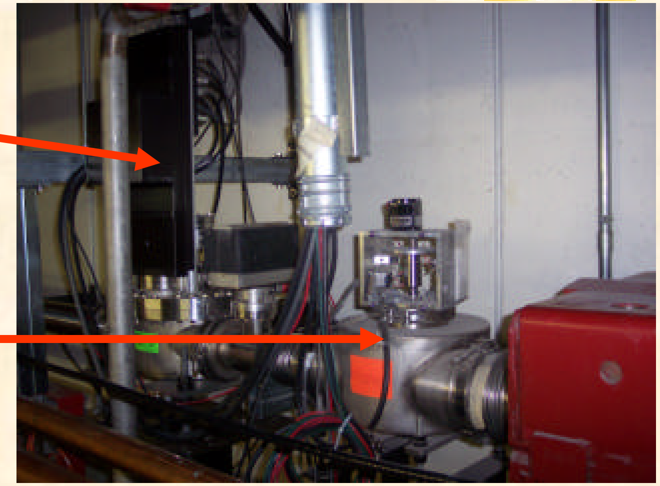




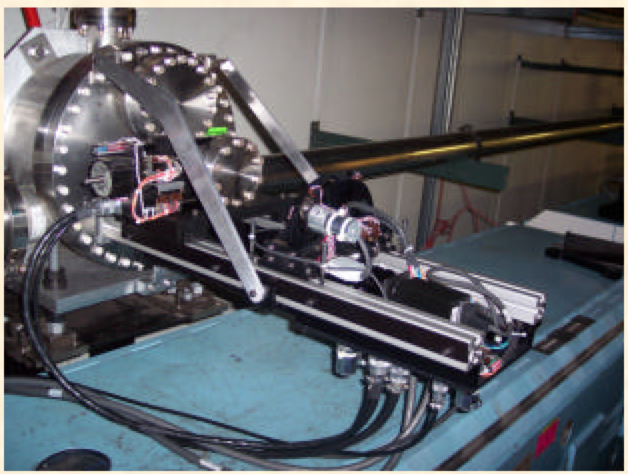
Two OTR Detectors Installed in A150 Line



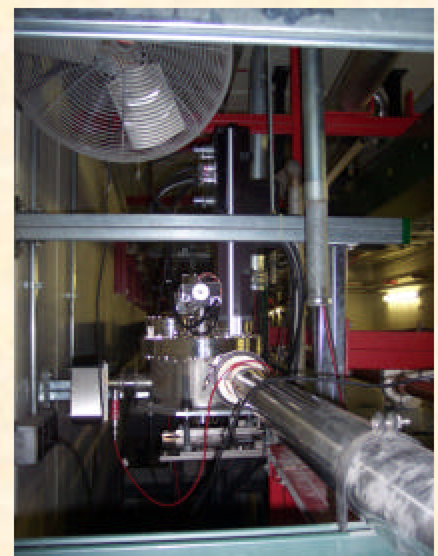
OTR detector



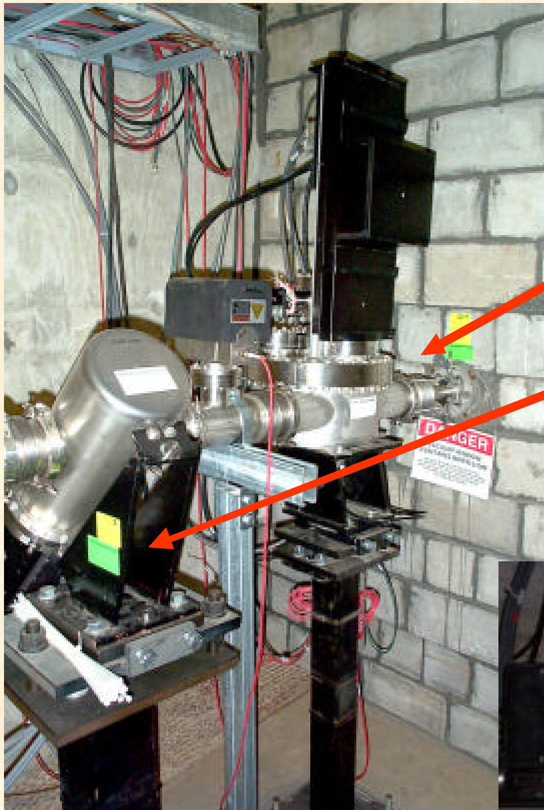
Multi-wire



- Two detectors in low dispersion region of A150 line
- Used for emittance measurements of antiproton injections into Tevatron
- Proton and pbar foils

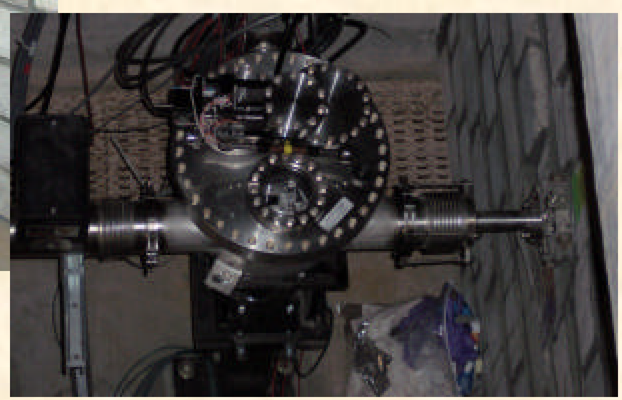


NuMI and AP-1 OTR Detectors



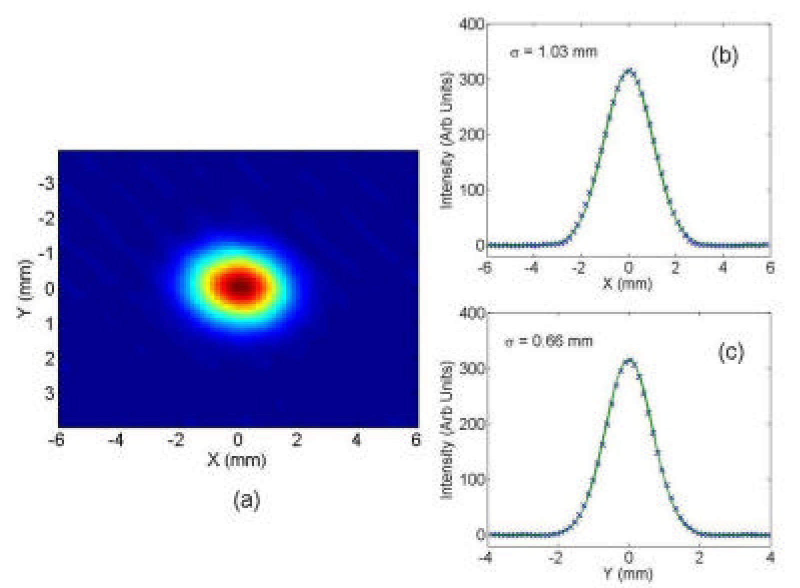
NuMI OTR Detector
- last detector before target
- multi-wire upstream to compare with

Top view without optics

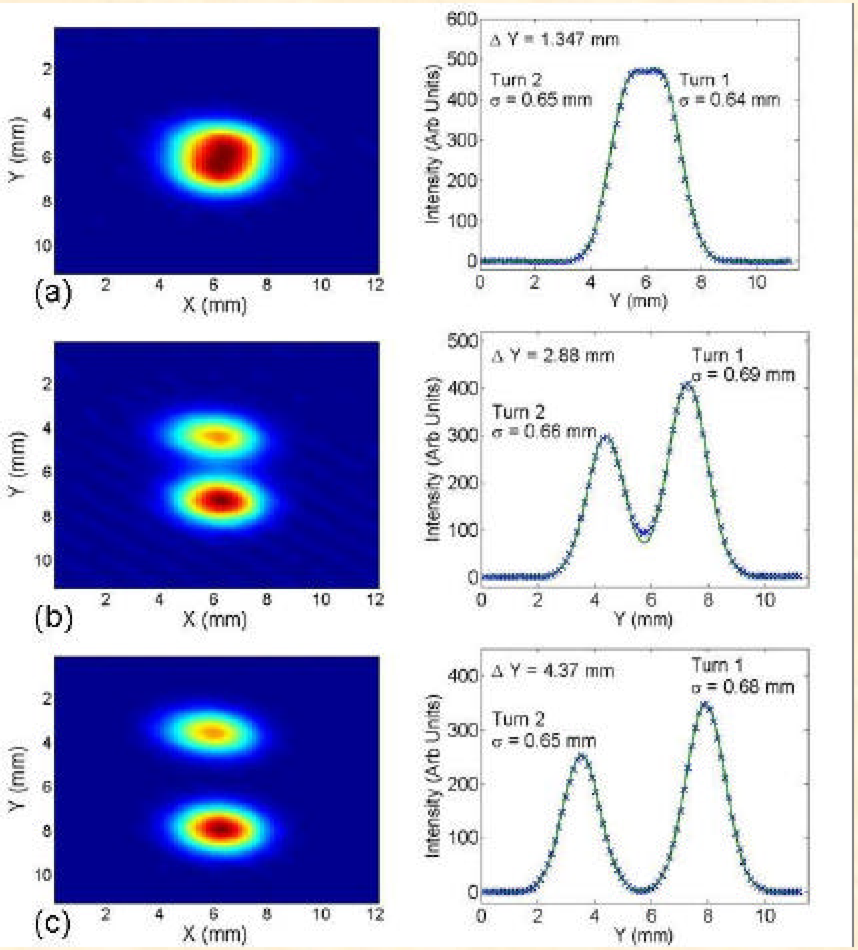


AP-1 OTR Detector
- mounted upside down
- high radiation area

Preliminary Tevatron Uncoalesced Proton Beam Measurements

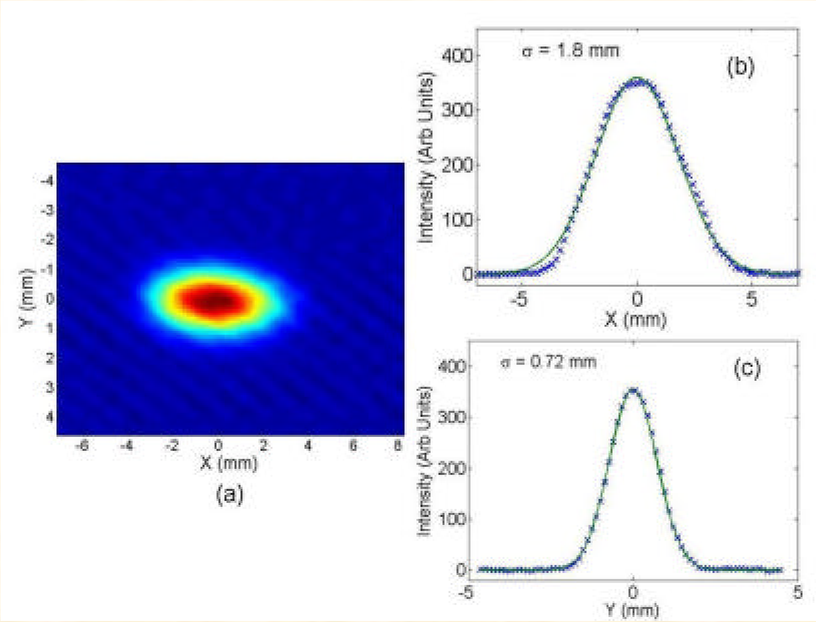


(a) Single-turn OTR image of 3e11 uncoalesced protons. (b) and (c) are X and Y beam profile data with fits, respectively.



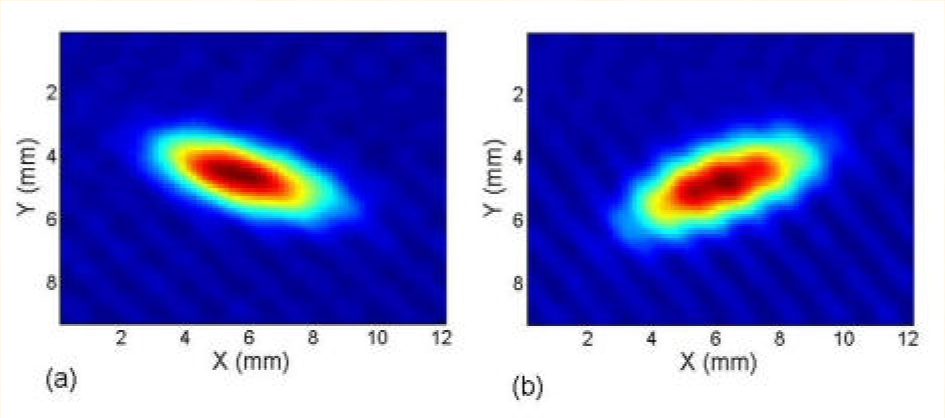
(a) Two-turn OTR image of 3e11 uncoalesced protons with double Gaussian fit of vertical profile. (b) and (c) Same as (a) but with increased vertical injection mismatch from the Main Injector into the Tevatron.

Preliminary Tevatron Coalesced Proton Beam Measurements



(a) Single-turn OTR image of 2.7e11 coalesced protons. (b) and (c) are X profile and Y profile data with fits, respectively.

(a) Single-turn OTR image of 2.7e11 coalesced protons with Tevatron skew quadrupole magnets increased by 20 amps and (b) decreased by 20 amps from nominal operating value.



Camera picking up interference background

OTR Production Issues

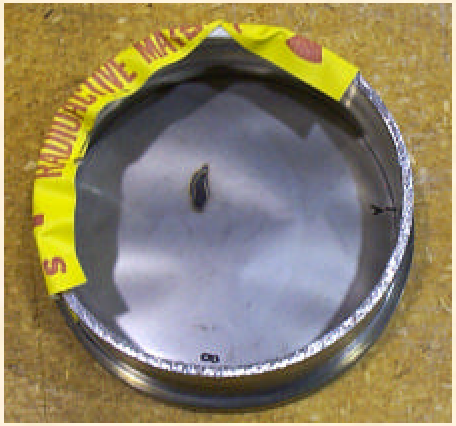
Prototype measurements of OTR indicate that the OTR generated for the Tevatron beam size, energy and intensity is from 20 to 50 times less than expected. Also, there appears to be a change in the measured OTR as a function of transverse position. Small errors in geometric alignment and OTR optical acceptance can produce a change in intensity across the field of view, but cannot explain the order of magnitude reduction in measured OTR.

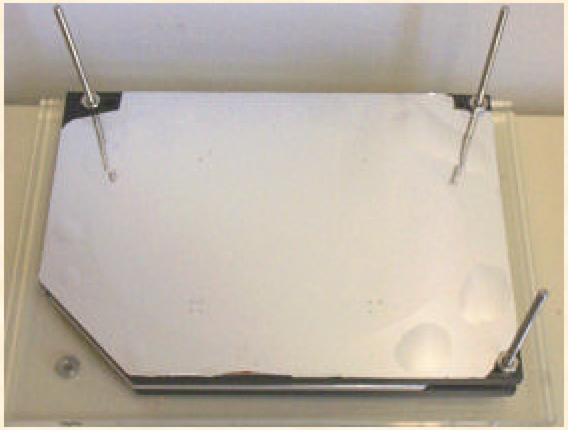
OTR is a surface phenomenon however, Jackson gives a formation depth for the generation of smooth intensity OTR

$$D = \gamma c/\omega_p$$

For 150 GeV protons and aluminum foils, D is of the order 1 μm. The present OTR detector foils have ~0.12 μm aluminum on 5 μm mylar. This would seem to indicate that the present aluminum thickness is too small and might explain the large reduction in OTR.

Foils Damage Under Intense Beams





Darkening of foil or distortion of foil shape changes OTR distribution and intensity

The left photograph is of a 3 mil thick titanium vacuum window exposed to over 10^{20} 120 GeV protons. The center photograph is a similar vacuum window exposed to ~$3x10^{18}$ 120 GeV protons but with a smaller beam spot size. The right photograph is of our prototype OTR 20 μm aluminum foil exposed to ~10^{19} 120 GeV protons with a larger beam spot size.

Titanium has higher melting point but seems to darken quicker that aluminum and has more scatter

Conclusion

- Fermilab has developed a generic OTR detector for high-energy, high-intensity proton and antiproton beam profile monitoring
- Initial prototype and Tevatron measurements indicate that OTR detectors can be power beam profiling monitors
- NuMI, A150 and AP-1 detectors are installed and commissioning has started
- OTR detector studies will investigate foil stability and OTR production
  - Change from Al kapton and mylar to straight Al, Ti, C, or Be?