First Tests of an Optical Transition Radiation Detector for High-Intensity Proton Beams at FNAL

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Introduction

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

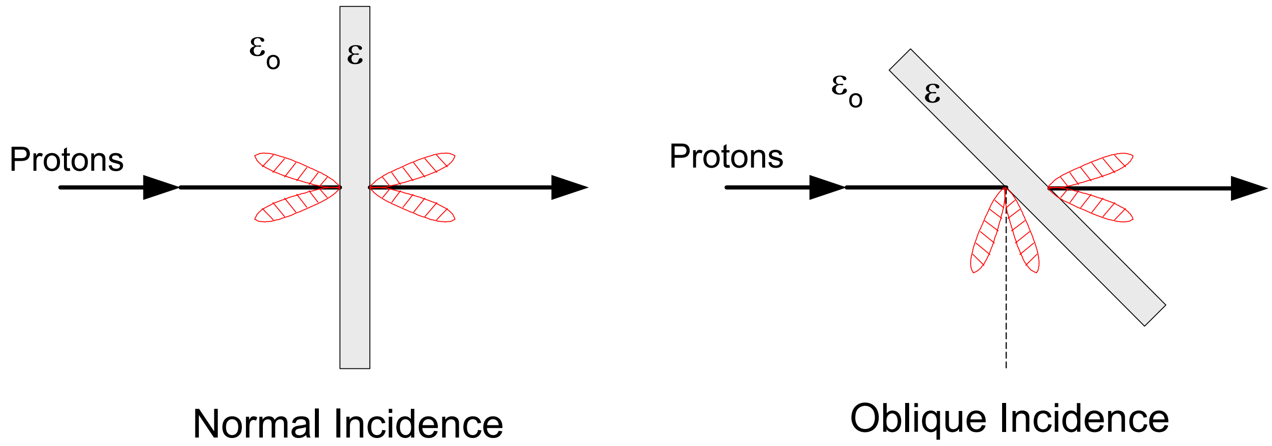
CERN has tested OTR detection with proton beams – major player for LHC

- Initial experiment at CERN-SPS in 1984

Objective

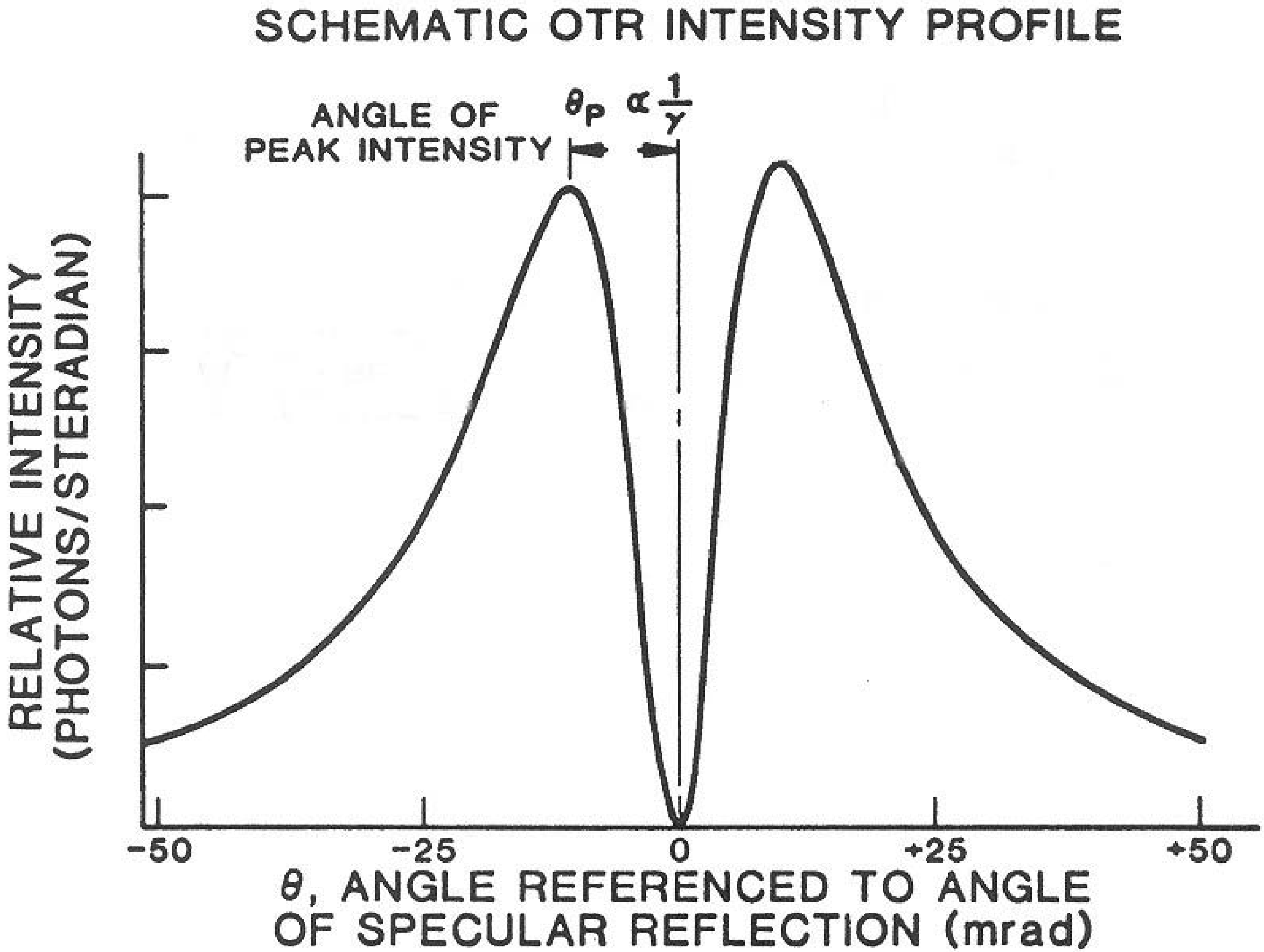
- Convert particle beam information to optical radiation and then use imaging technology to acquire beam information
- Use thin foil to minimize beam scattering
- Beam image provides 2D information on:
  - Transverse profile and shape (tilt)
  - Transverse position
  - Emittance
  - Intensity

OTR Distribution



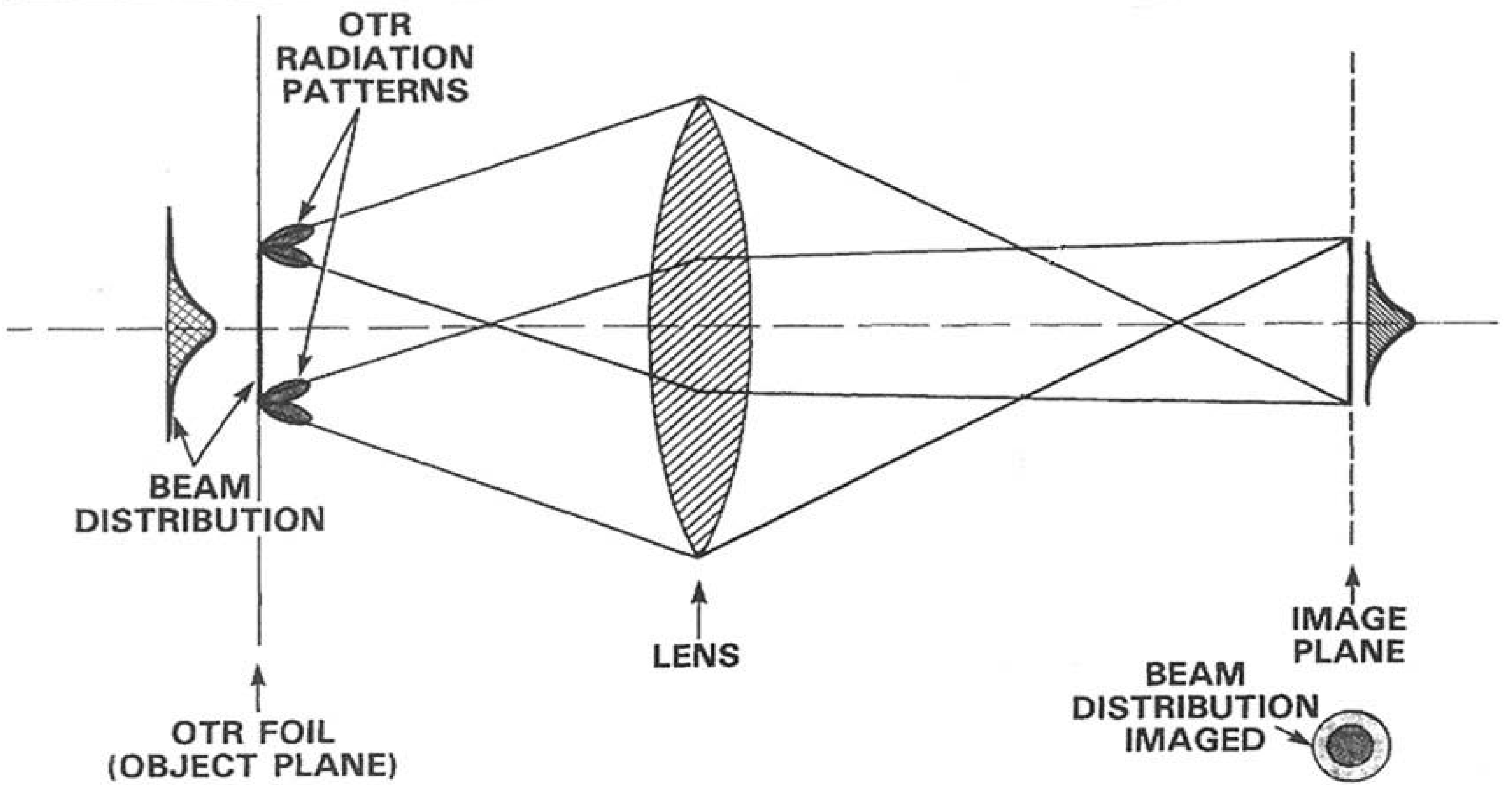
Quantity of light proportional to foil reflectivity

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



SCHEMATIC OTR INTENSITY PROFILE
ANGLE OF PEAK INTENSITY
θP α 1/γ
RELATIVE INTENSITY (PHOTONS/STERADIAN)
-50
-25
0
+25
+50
θ, ANGLE REFERENCED TO ANGLE OF SPECULAR REFLECTION (mrad)

OPTICAL RAY DIAGRAM FOR OTR IMAGING



Fermilab OTR Prototype Goals

- Learning tool for transfer line OTR detectors
- Identify physics and operational issues
- Test of materials
  - Foil types – Aluminum and Titanium
  - Lenses – singlets, compound and quartz
    - Study of radiation damage to lenses
- Test of imaging
  - Development of single frame acquisition
  - Image noise analysis
  - Beam position and shape analysis
    - Calibration techniques
- Test of radiation environment

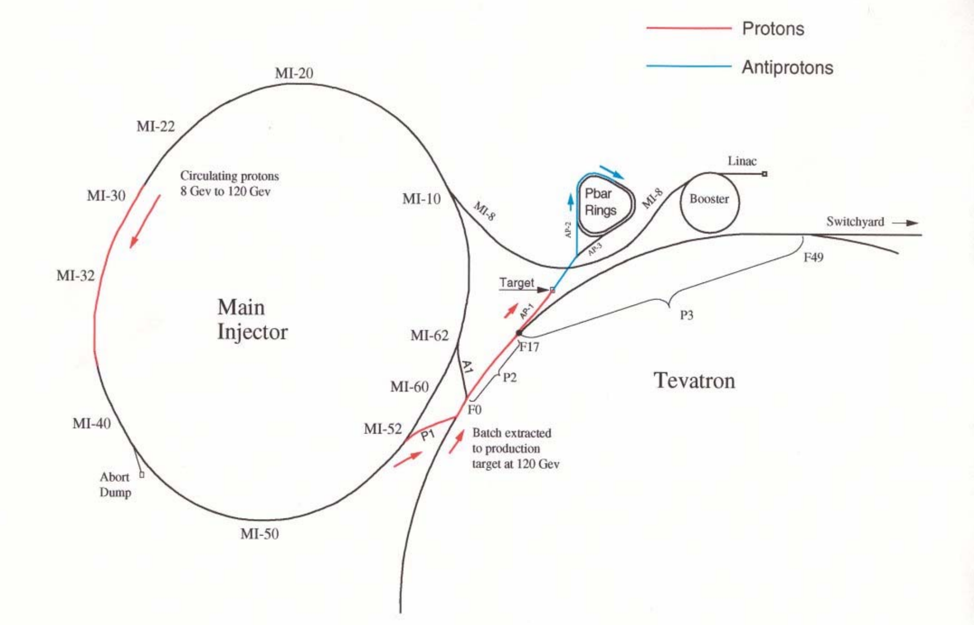
Location Requirements

1. Easy access
2. Location available early
3. High beam duty cycle
4. High energy beam – minimize OTR light cone
5. Large number of particles per batch/bunch
6. As low as possible radiation environment for camera and optics

Prototype OTR Location – Prevault AP1 Line

- Fairly frequent access to location
- Location immediately available
- Frequent beam- stacking
- High intensity – 4e12
- High energy – 120 GeV
  - 1/γ -> 8 milliradians
- Beam size of 1σ ~ 1 mm
- *High radiation environment?*

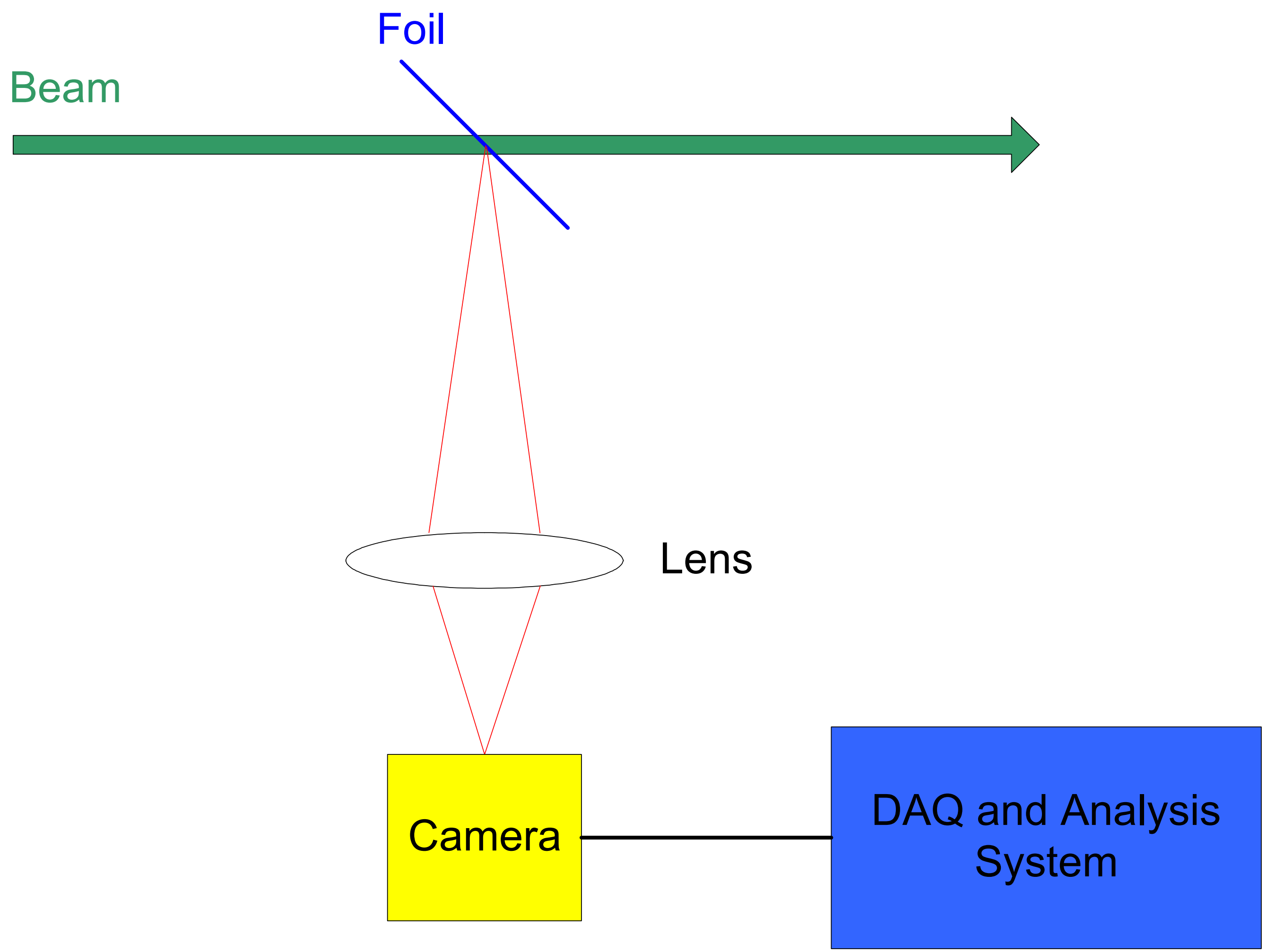
  ~ 6 krad/wk at 1 meter



Prevault

- OTR placed in 9” air gap
- Titanium windows up and down stream
  - OTR and radiation source

Simple OTR Detector



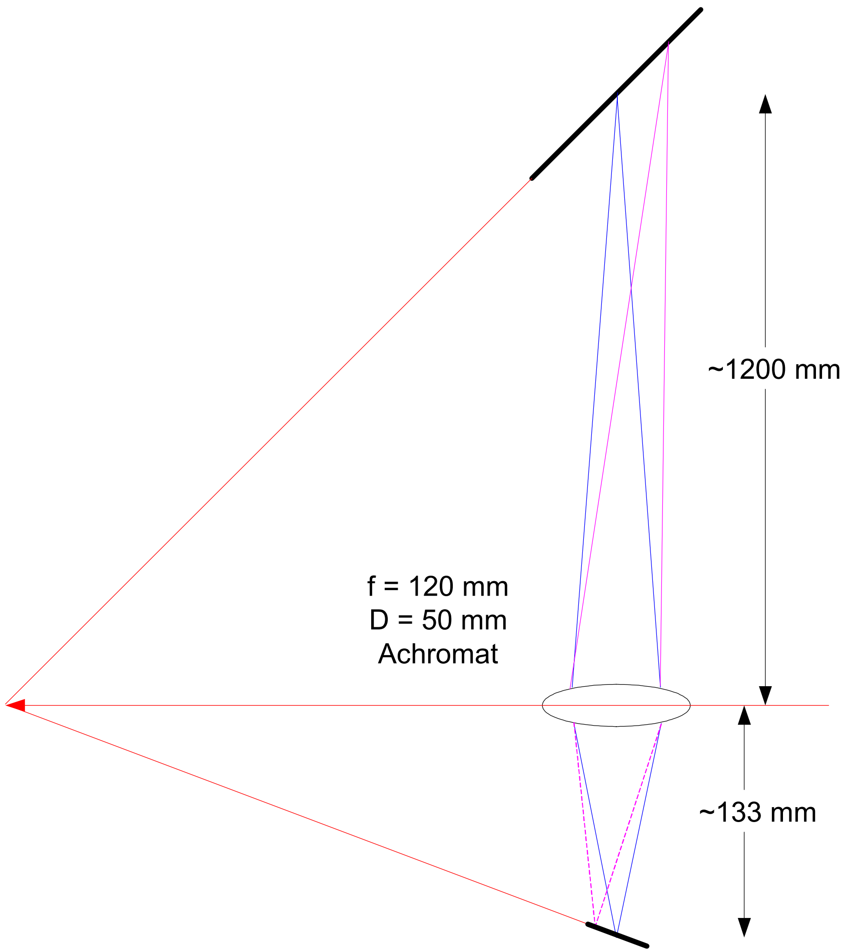
Foils

- 20 μ Aluminum and 12 μ Titanium
  - Thinner foils available
- Aluminum brighter than Titanium
- Titanium stronger; higher melting point
- Choice of foil dependent on particle flux
- Test both in prototype system
- Other possibilities?
  - Carbon

CID Camera

- Radiation hardened RS-170 format camera
  - 1e6 rads total dose (gamma)
  - 786 x 612 pixel format
  - 11.5 x 11.5 μ pixels
  - 30 frames per second
  - 47 db signal-to-noise ratio
  - ~35% quantum efficiency
  - Spectral response peak ~ 550 nm

Single Lens Optical Design

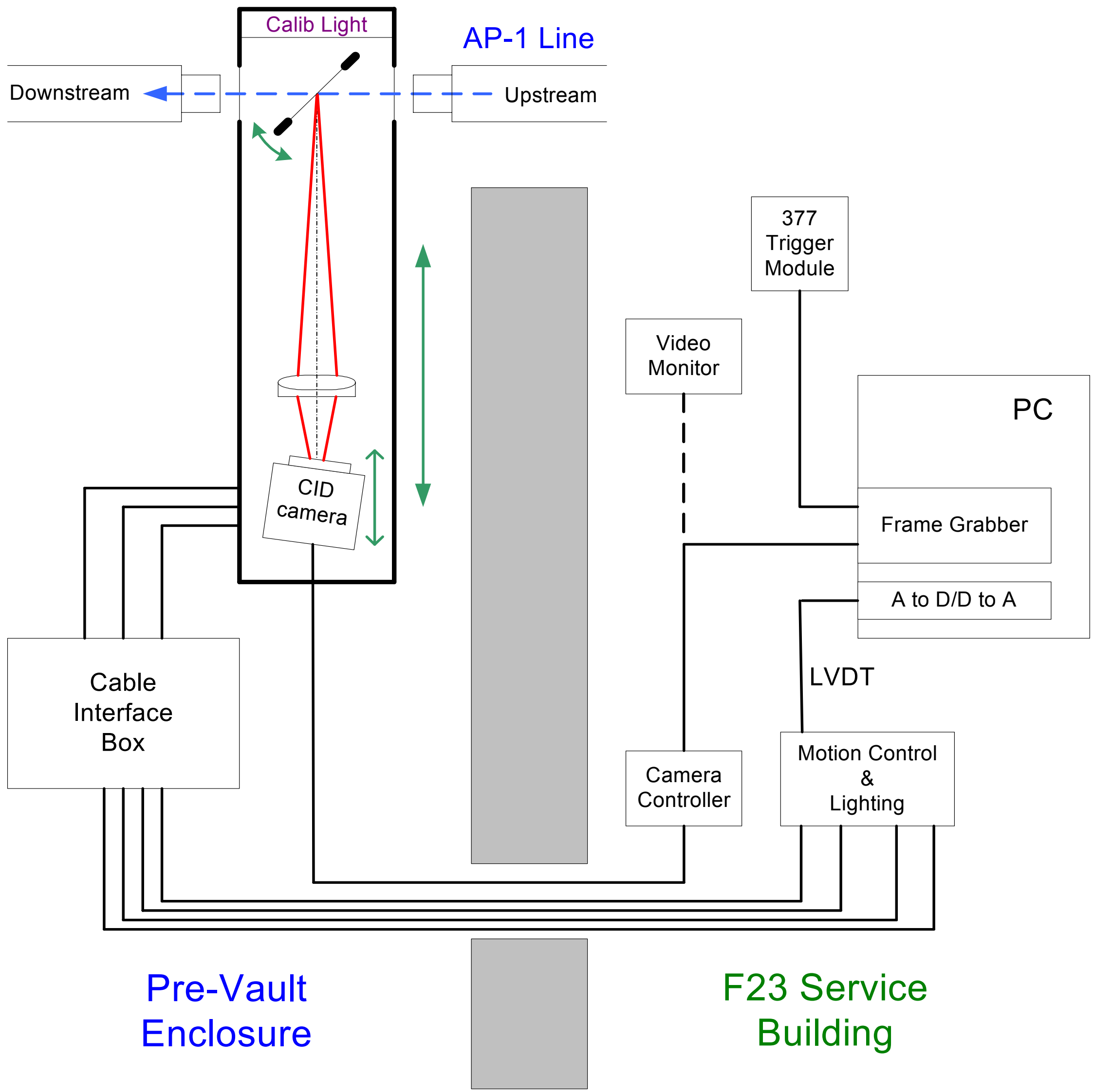


- Minimize radiation damage by placing camera/lenses far from radiation source
  - Distance to lens ~ OTR width ~ lens size
- Use achromatic doublet
  - Minimal glass
- Magnification = 1/9
- Field of view ~ 80 x 55 mm
  - ~ 100 micron per pixel
- OTR pattern ~ $4/\gamma$
  - 40 mm wide at lens (120 GeV protons)
- For best focus, place camera at Scheimpflug angle

Image Resolution

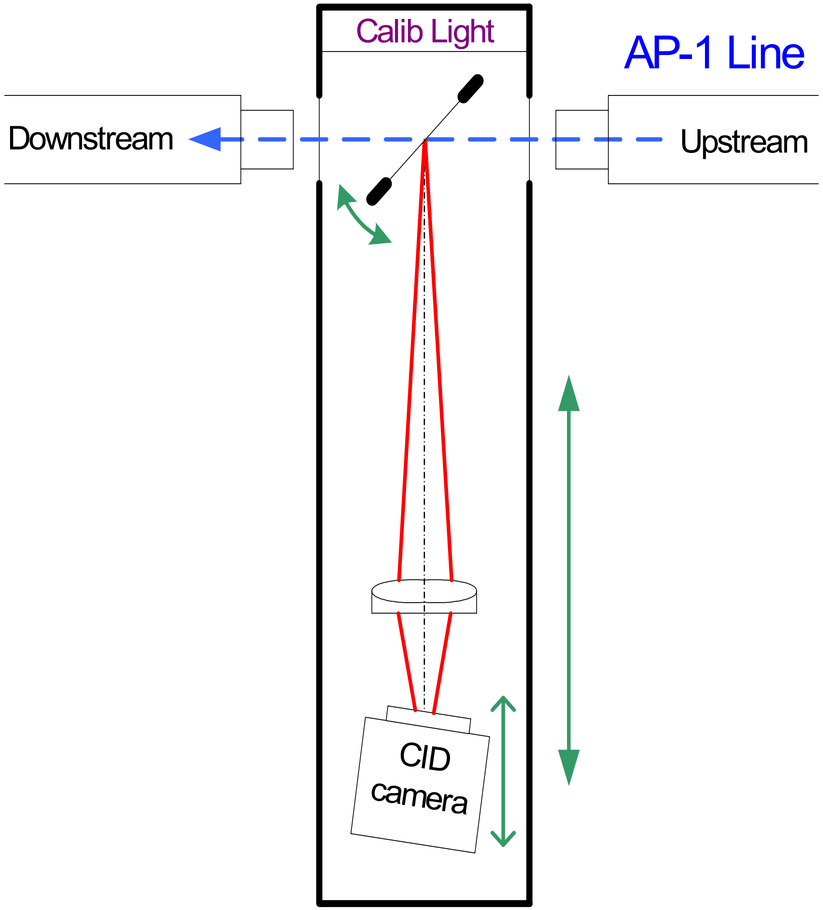
- Image standard USAF resolution target
- Point Spread Function appears to have $\sigma \sim 1.5$ pixels
- Can deconvolve PSF for sharper image
  - Needs further investigation
- Image lines are at 1 mm spacing

Prototype OTR Block Diagram

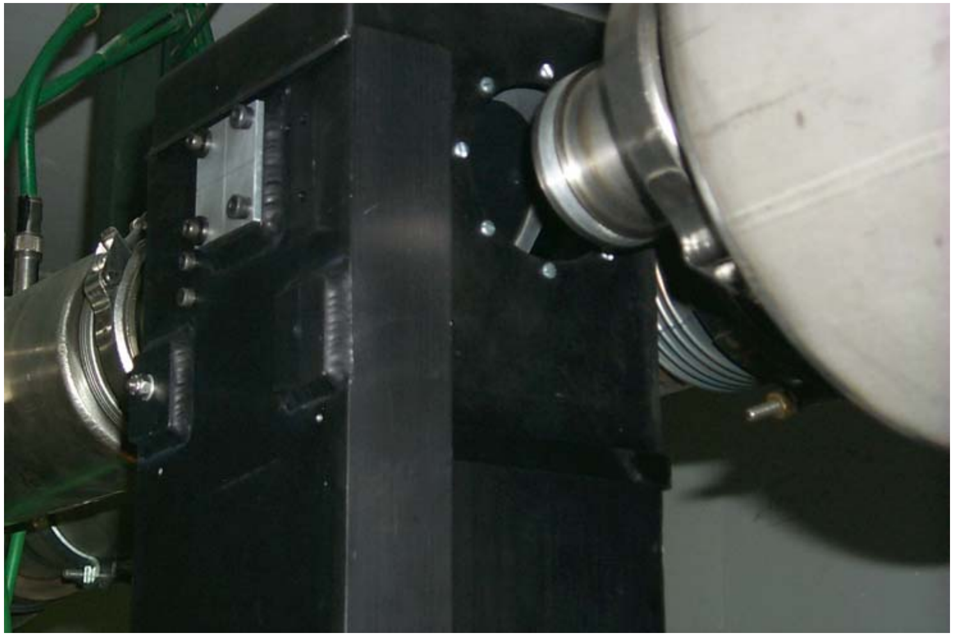


OTR Tube Mechanical Design

- Design by Carl Lindenmeyer
- Motion:
  - in/out of beam
  - $\theta - \phi$ tilt of foil (2 LVDTs)
  - camera focus (1 LVDT)
- Easy access to camera, lens and foil
  - tilt/no-tilt for camera (manual)
- Camera/lens position adjustable
- Neutral density filters
  - remote control
  - x0.5, x0.2, x0.01, x0.001



Prototype in Prevault



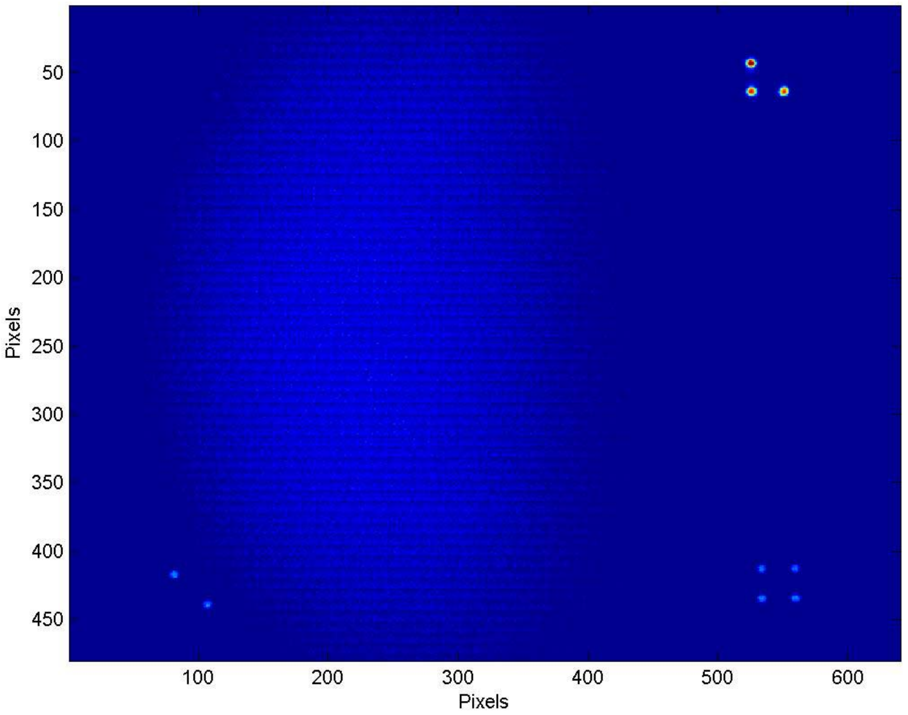
Images with 12 μ Titanium Foil

Scale Calibration

Calibrate image size by back illumination of fiducial holes

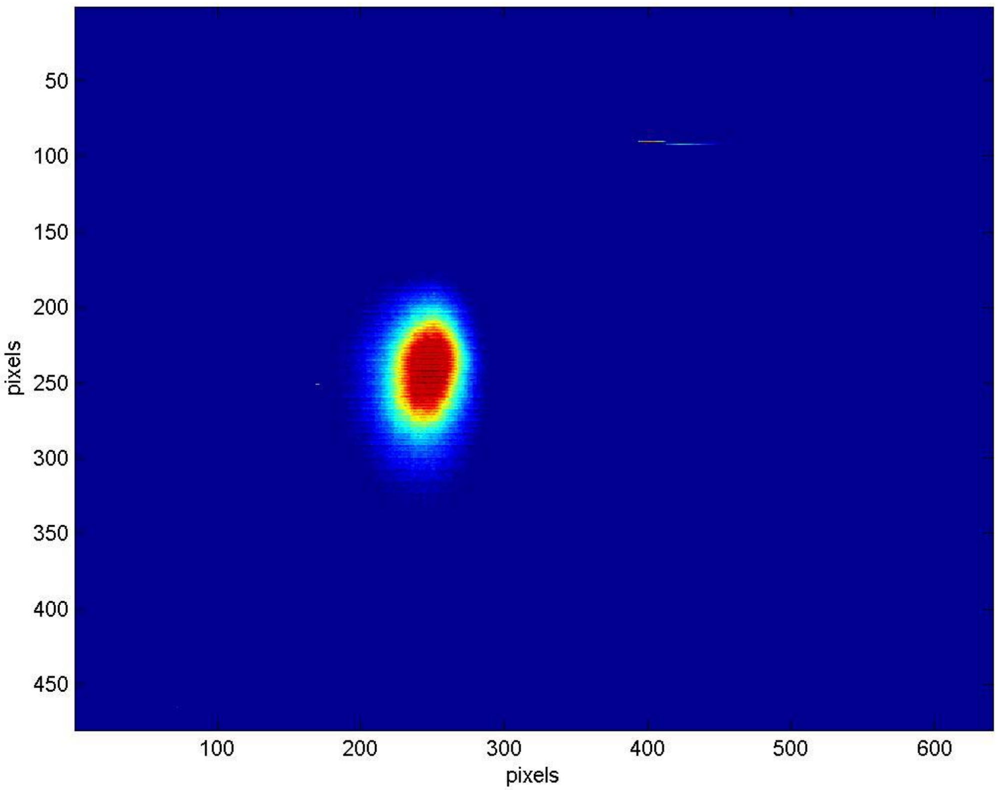
x: 1 pixel = 123 μ

y: 1 pixel = 106 μ

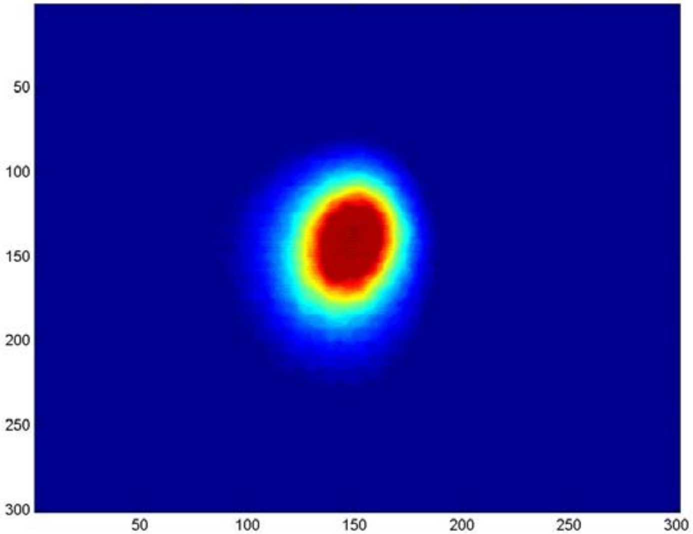


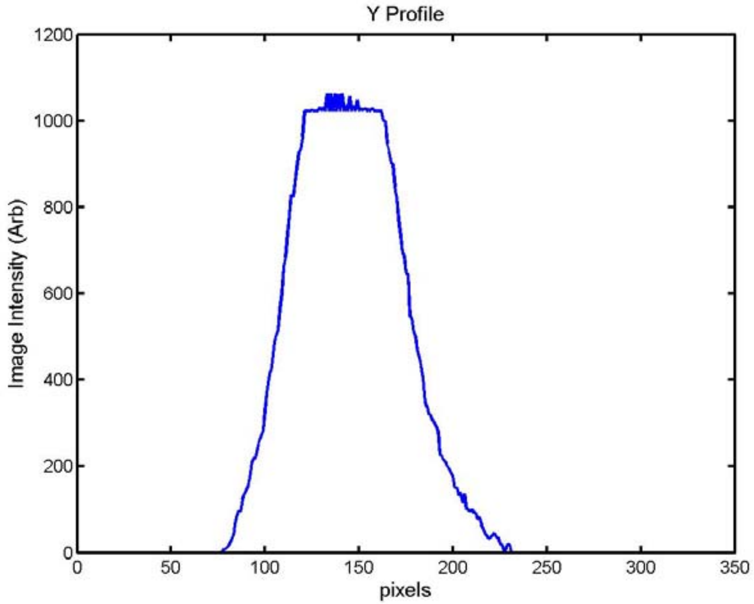
First Light, Aug 29, 2003

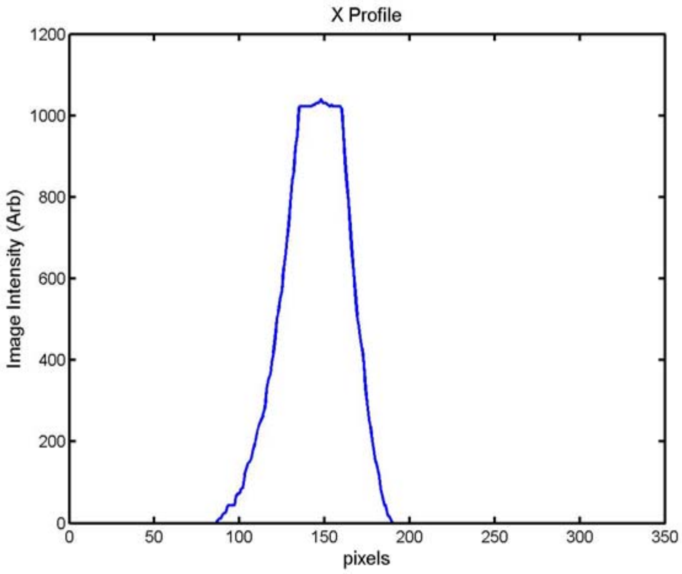
- One booster turn (~0.4e12 protons)
- Use x0.1 light attenuators



First Light Image Filtered

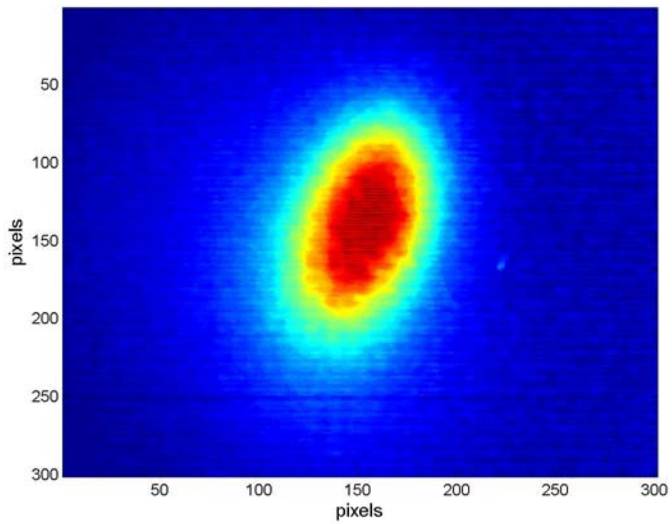


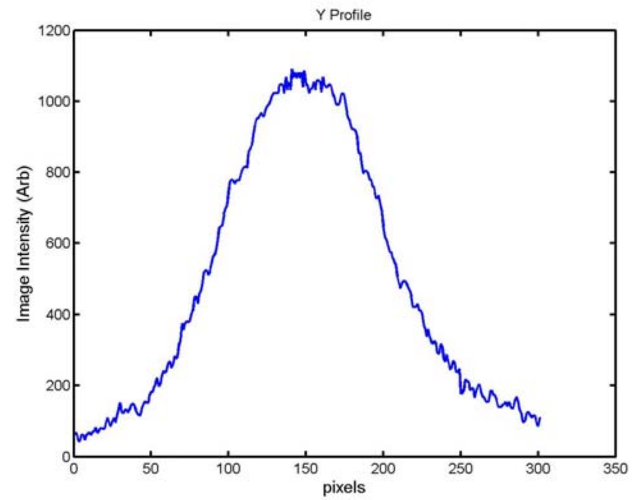


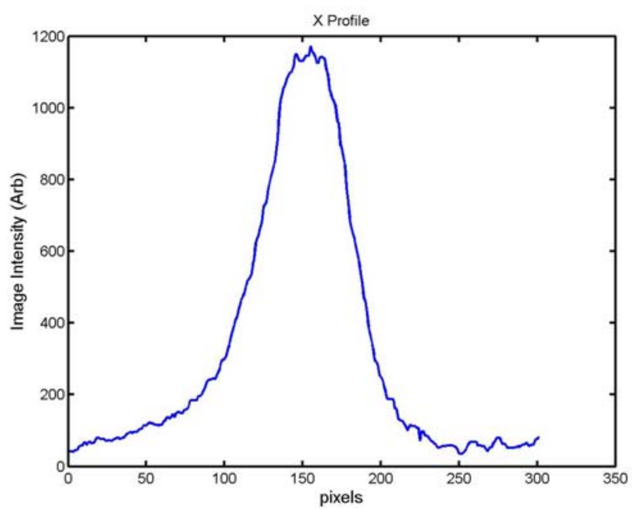


- Use 5x5 median filter
- Image saturated
- Beam tilt observed

Full Stacking Intensity (~4.5e12)

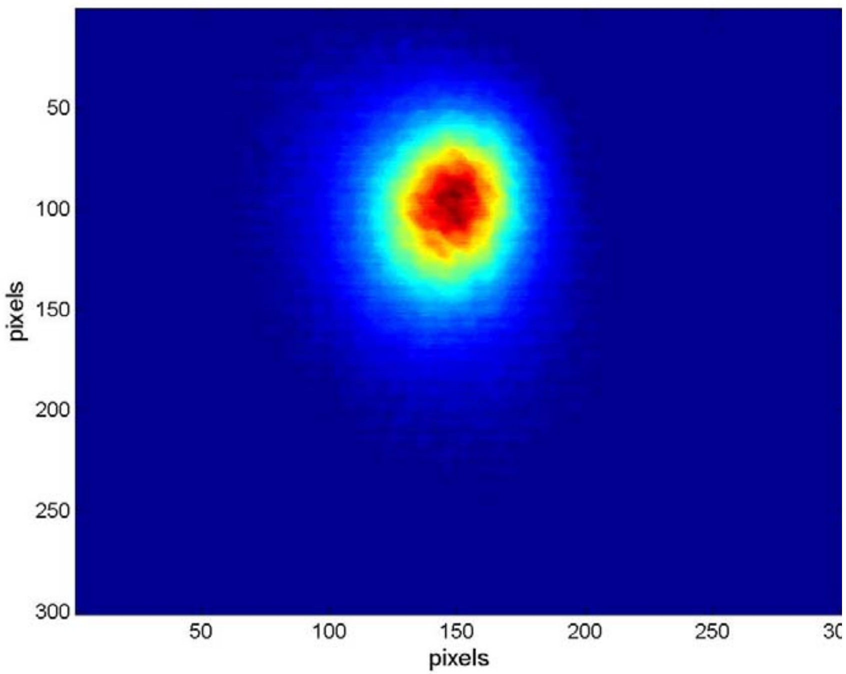


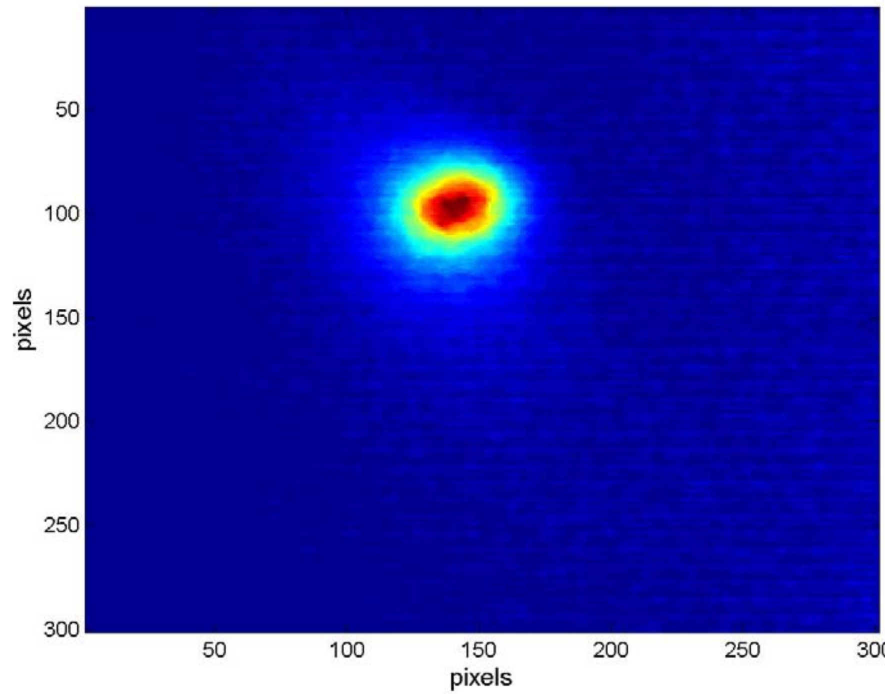




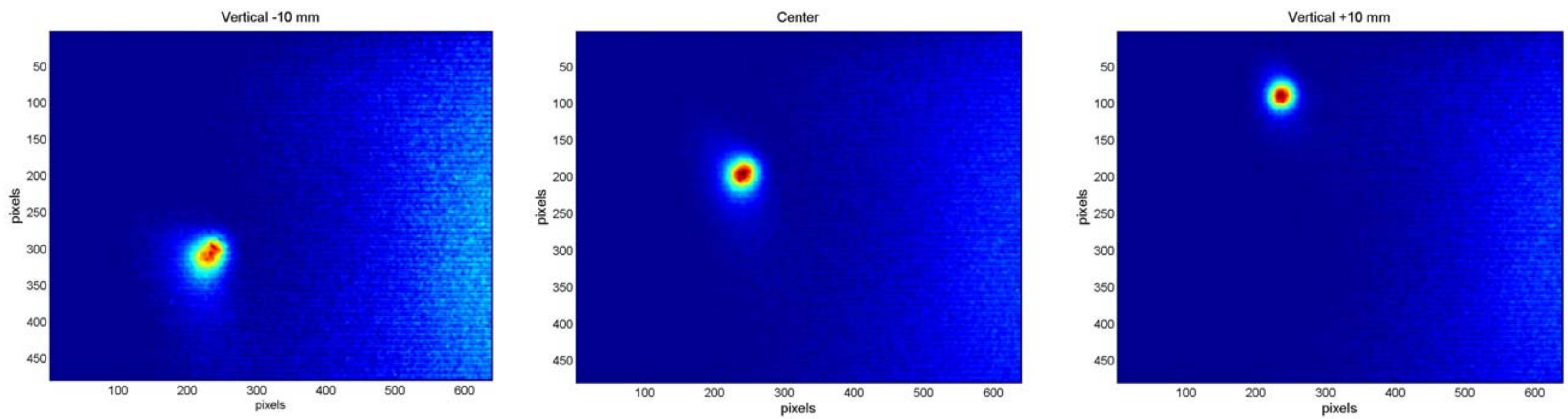
- Use x0.005 light attenuator
  - Many images still saturating
- Profiles in x-y not u-v

Reduce Vertical Beam Size





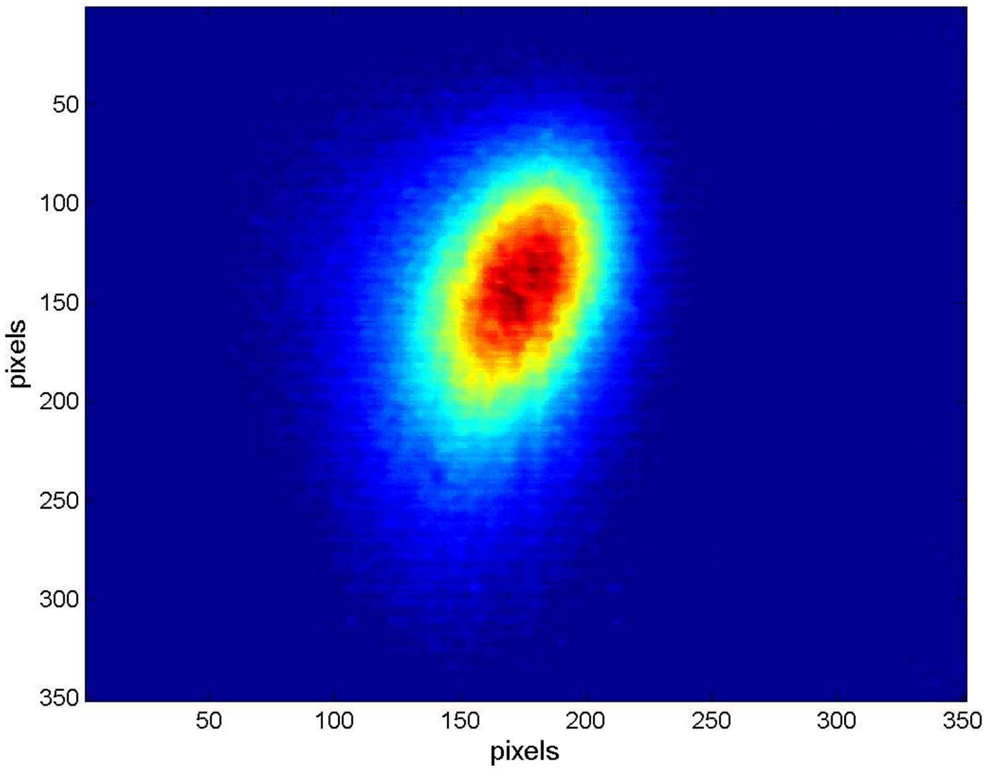
Vertical Beam Motion



- Move beam vertically by +9.7 mm
    - OTR measures 11.1 mm
- Move beam vertically by -9.9 mm
    - OTR measures -11.1 mm
- Scale needs to be understood

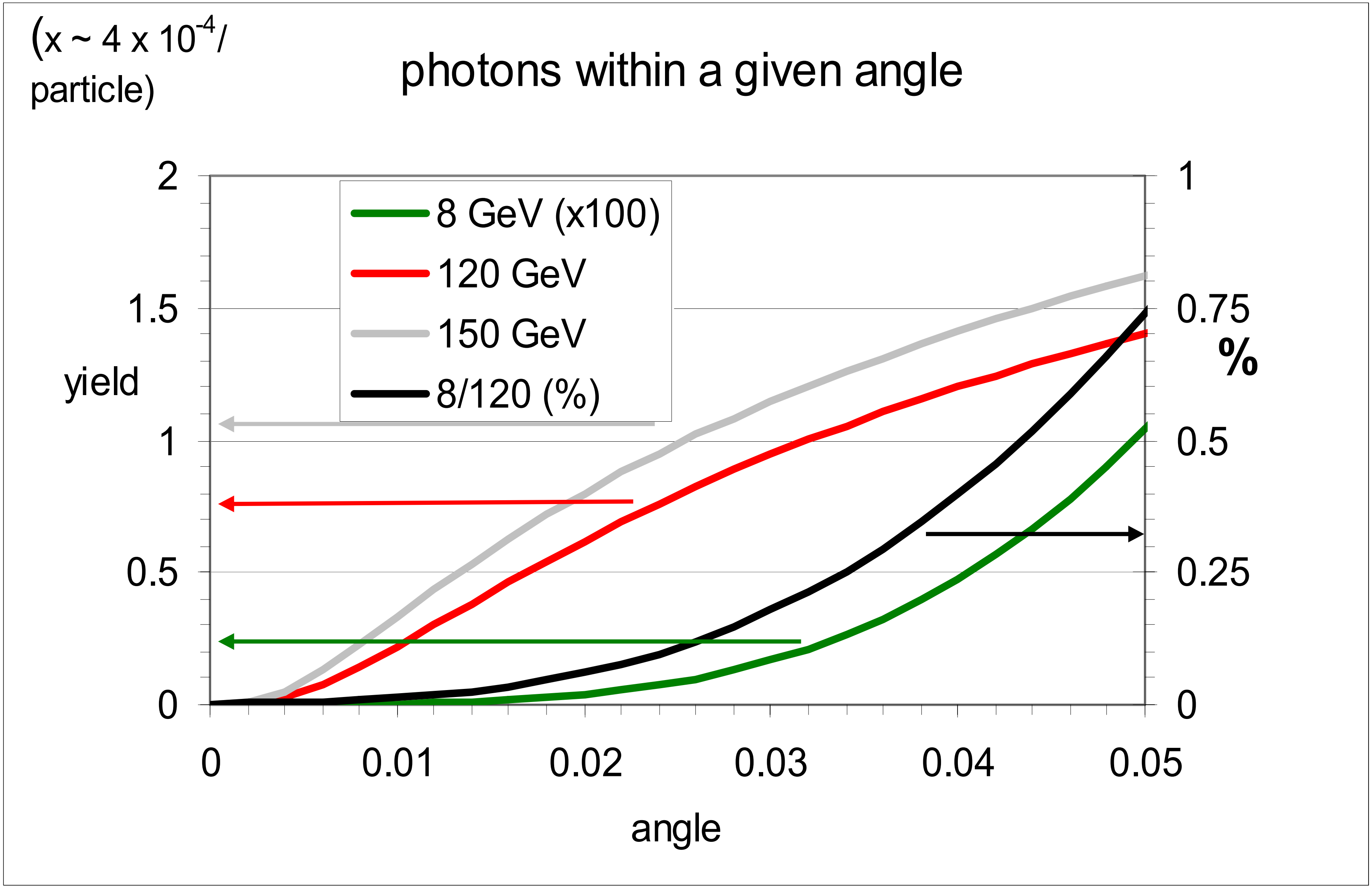
Image with 20 μ Aluminum Foil

- ~4.7e12 particles/batch
- x0.001 light attenuation
- Image show some structure but need to determine if it beam or foil induced



8 GeV Beam at Prevault

- We attempted to measure OTR from 8 GeV protons with the prevault detector with the aluminum foil
- We could no images even without light attenuators
  - Beam intensity up 5 booster turns of 30 bunches
- Two reasons for this:
  - 8 GeV Opening angle
  - 8 GeV beam area ($1\sigma \sim 9$ mm)


(x ~ 4 x 10^-4/ particle)
photons within a given angle
8 GeV (x100)
120 GeV
150 GeV
8/120 (%)
yield
%
angle
0
0.5
1
1.5
2
0.25
0.75
0.01
0.02
0.03
0.04
0.05

Possible OTR Applications at FNAL

- Measurements in A1 and P1 transport lines
  - May require modified camera if looking at individual bunches
- Beam profile measurements for NuMI
- Calibration tool for Tevatron IPM
  - Measure ~50 turns then extract

Conclusion

- We have developed and installed a prototype OTR detector and have taken first images
- We have taken images with 12 μ titanium and 20 μ aluminum foils
  - Foils show no artifacts after one week of beam
- Long-term radiation damage to foils is an unknown
  - Also for camera and optics

OTR Team

- Instrumentation - Warren Schappert, Gianni Tassotto, Eugene Lorman, Stephen Pordes
- OTR Consultant - Alex Lumpkin (ANL)
- Mechanical and Electrical - John Korienek, Carl Lindenmeyer, Ron Miksa
- Foils - Karen Kephart, Wanda Newby
- Pbar - Jim Morgan, Tony Leveling, Elvin Harms