Measurements of Intense Proton Beams using Optical Transition Radiation

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Transverse Beam Profile Methods for Protons

Invasive:

1. Wires
   - Single scanning wire – multi-pulse profiling
   - Multi-wire – Single pulse profiling but more beam loss
   - Survival?

Non-invasive:

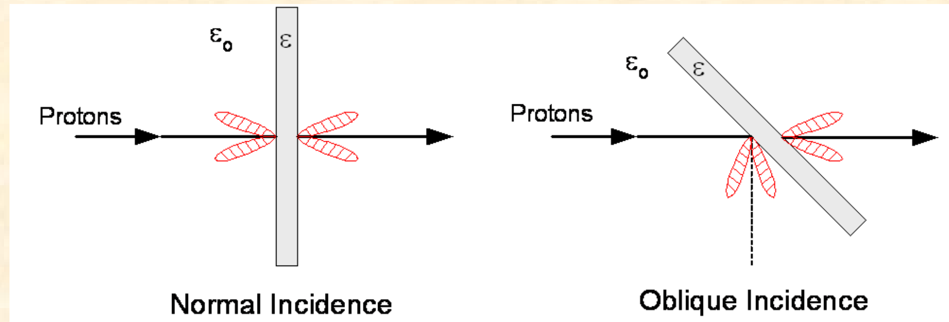
1. IPM – Ionization Profile Monitor – can be single pulse; expensive
2. Electron Wire – can be single pulse; expensive
3. Beam Fluorescence – similar to IPM but usually multi-pulse

Another possible invasive method is Optical Transition Radiation (OTR)

- ***Why consider it?***

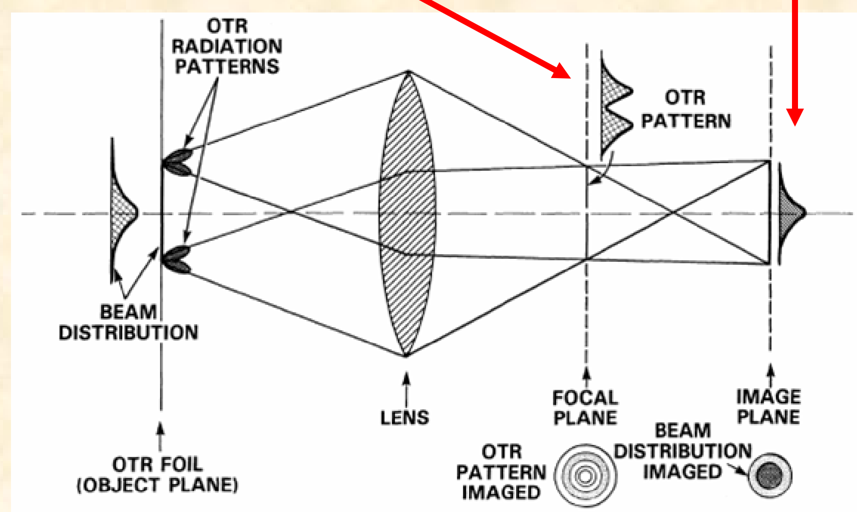
Optical Transition Radiation

- OTR is generated when a charged-particle beam transits the interface of two media with different dielectric constants
  - *Surface phenomena*
- OTR detectors are primary beam instruments for electron machines
  - *Far-field and Near-field imaging*
- A number of labs using OTR for proton profiling
  - CERN, JPARC
- Fermilab has developed a generic OTR detector for proton and antiproton beams



Far-field imaging

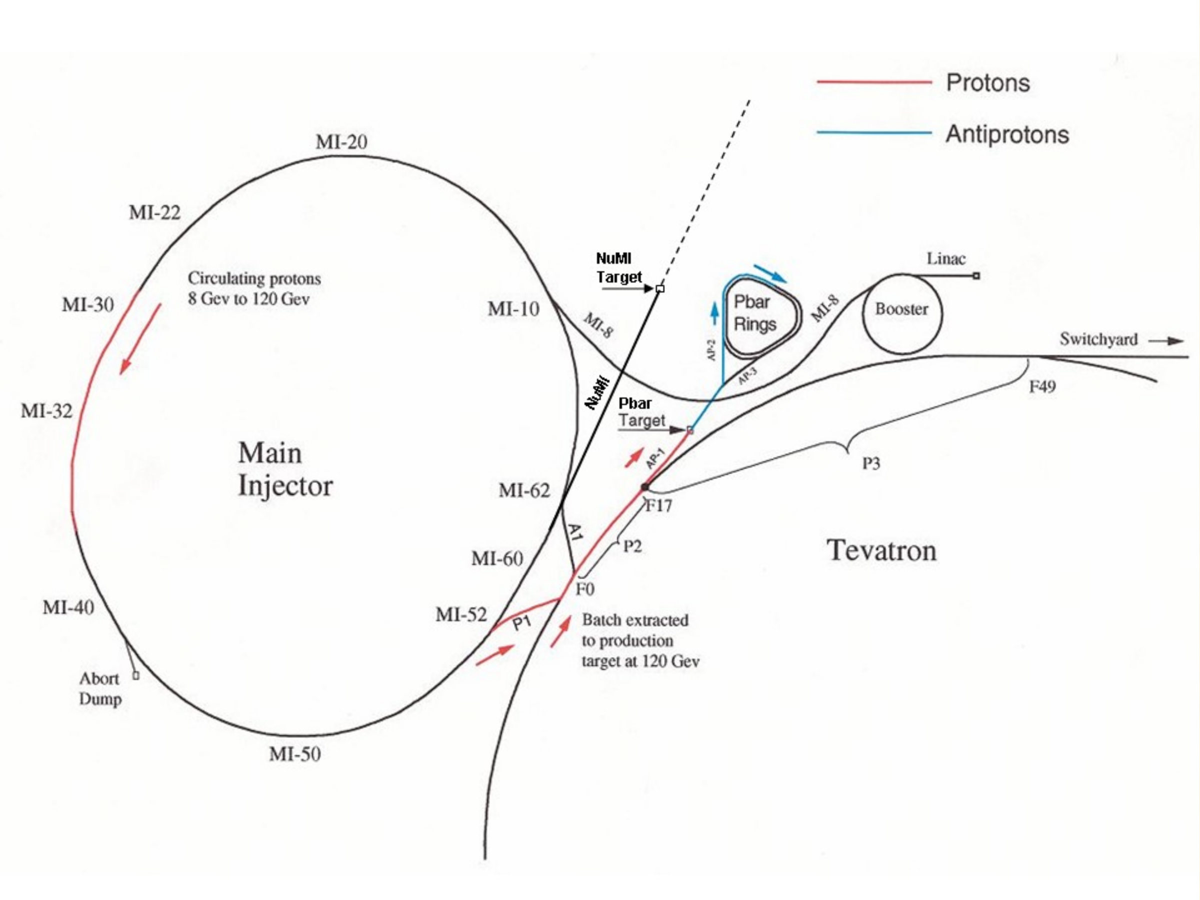
Near-field imaging



Proton/Pbar OTR Detectors at FNAL

Fermilab Accelerator Complex

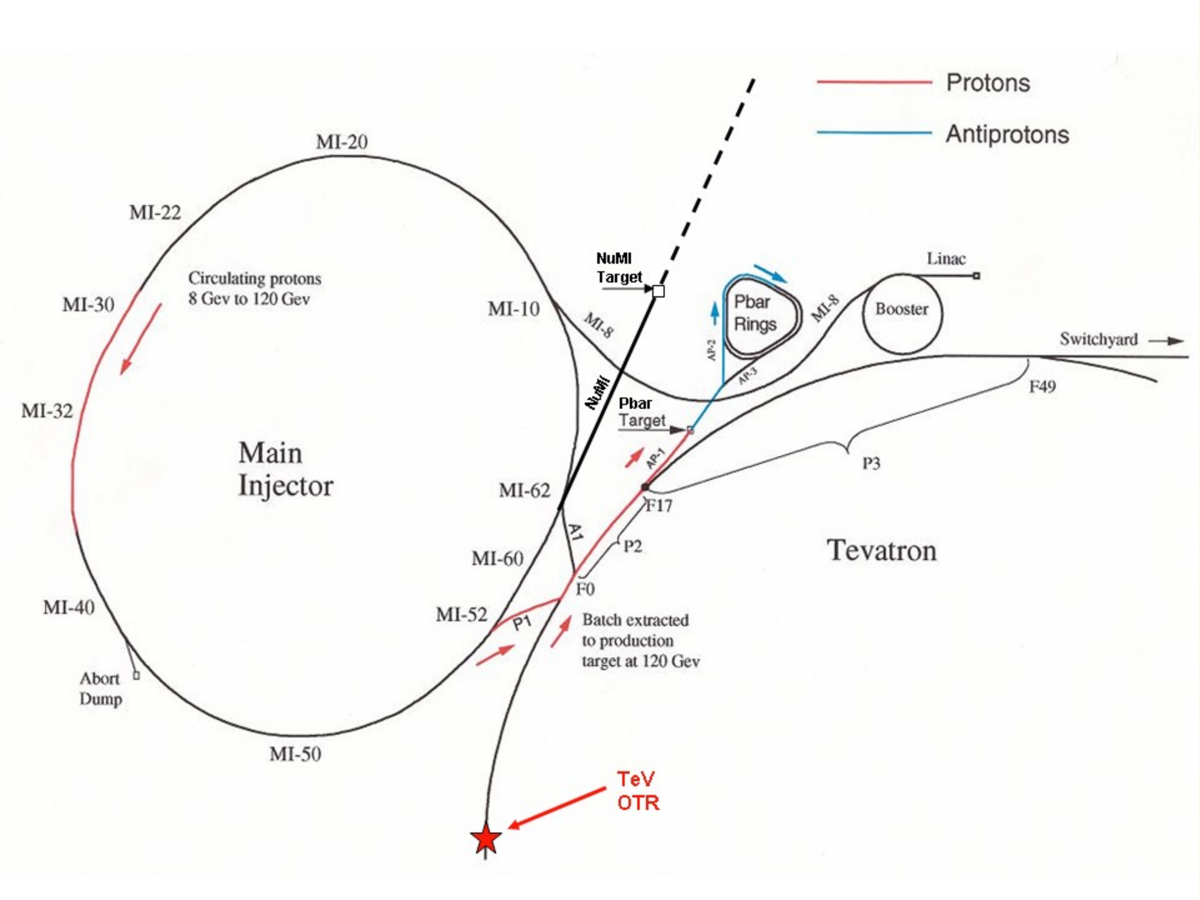
- Linac
- Booster
- Main Injector
- Tevatron
- Pbar Production
- NuMI



Proton/Pbar OTR Detectors at FNAL

TeV OTR

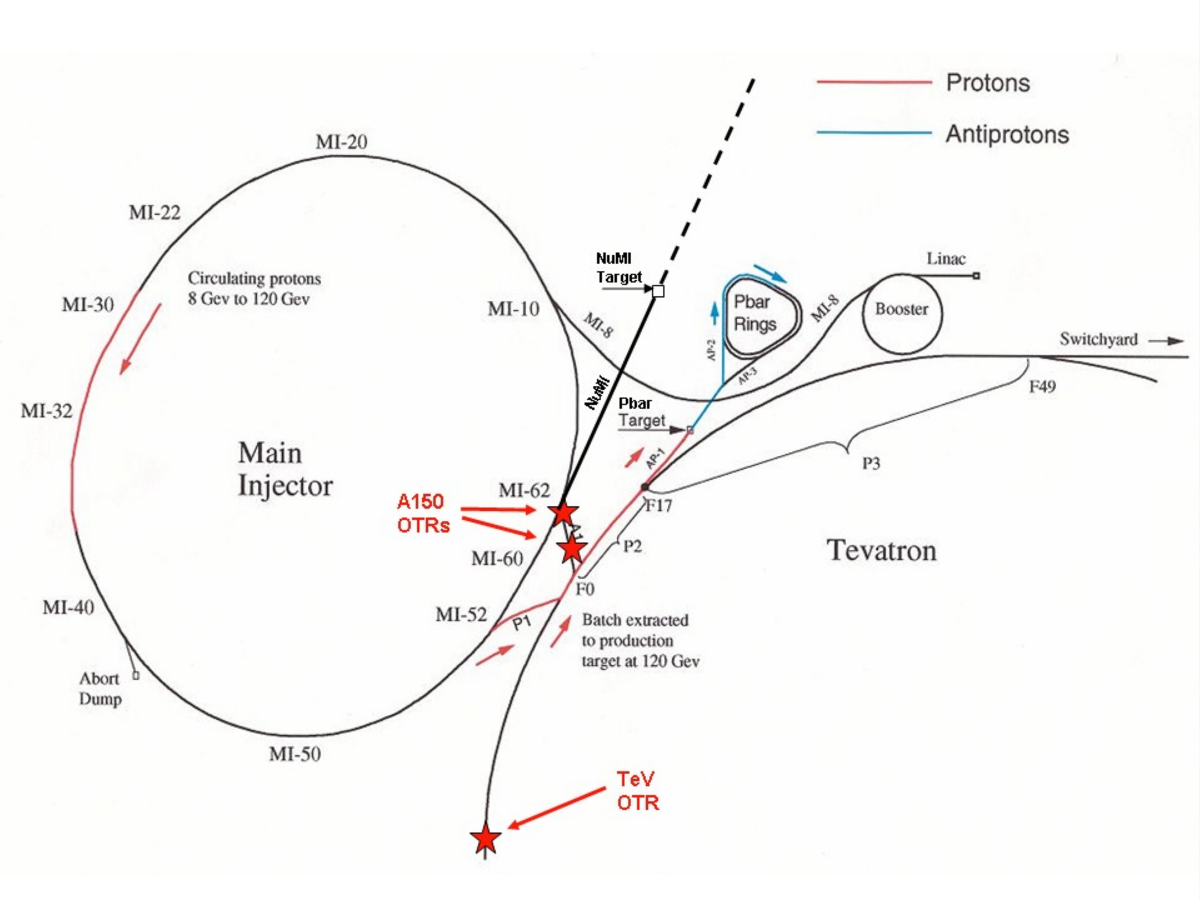
- Next to IPM
- 150 GeV Proton & Pbar Injections



Proton/Pbar OTR Detectors at FNAL

TeV OTR
- Next to IPM
- 150 GeV Proton & Pbar Injections

A150 OTR
- 150 GeV Pbars
- Emittance

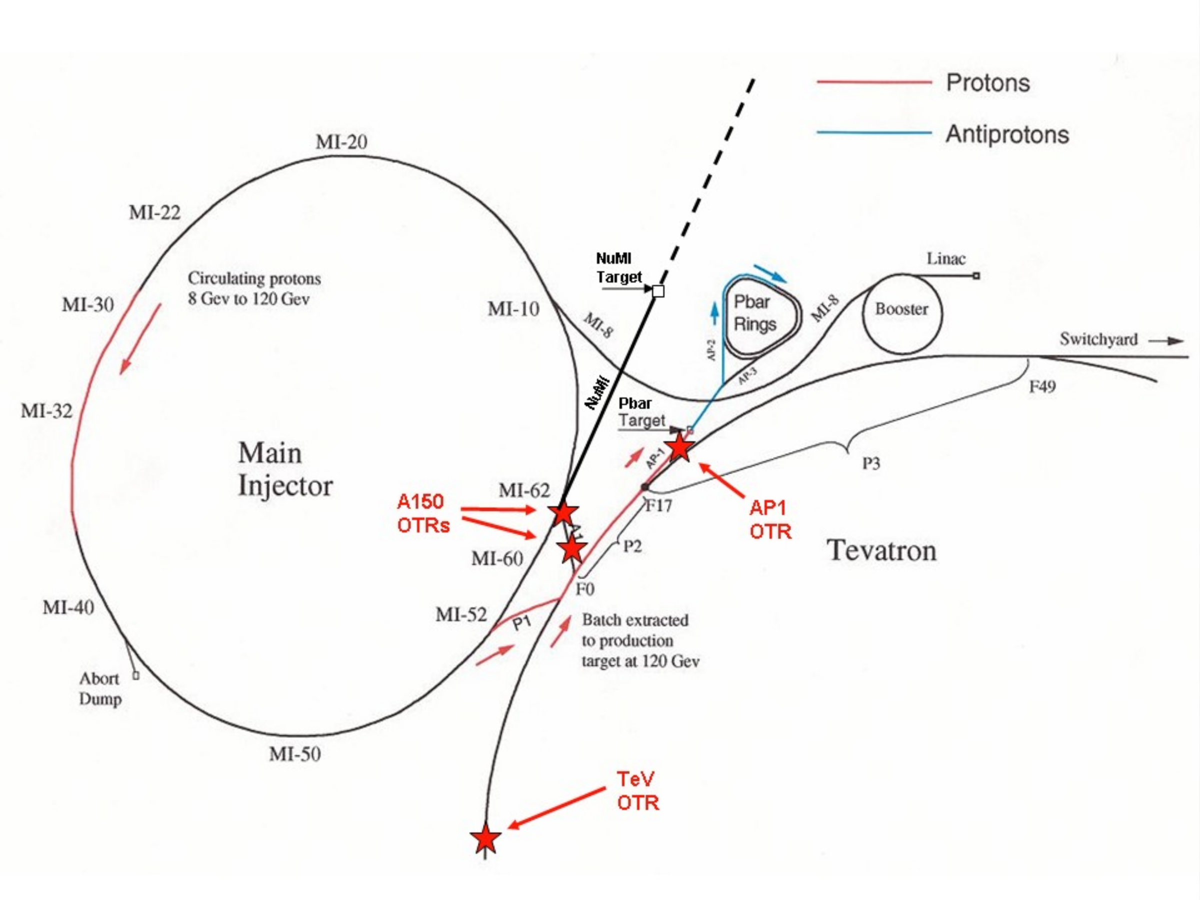


Proton/Pbar OTR Detectors at FNAL

TeV OTR
- Next to IPM
- 150 GeV Proton & Pbar Injections

A150 OTR
- 150 GeV Pbars
- Emittance

AP1 OTR
- Up to 8e12 120 GeV protons at ~0.5 Hz



Proton/Pbar OTR Detectors at FNAL

- TeV OTR
  - Next to IPM
  - 150 GeV Proton & Pbar Injections
- A150 OTR
  - 150 GeV Pbars
  - Emittance
- AP1 OTR
  - Up to 8e12 120 GeV protons at ~0.5 Hz
- **NuMI OTR**
  - Up to ~4e13 120 GeV protons at ~0.5 Hz

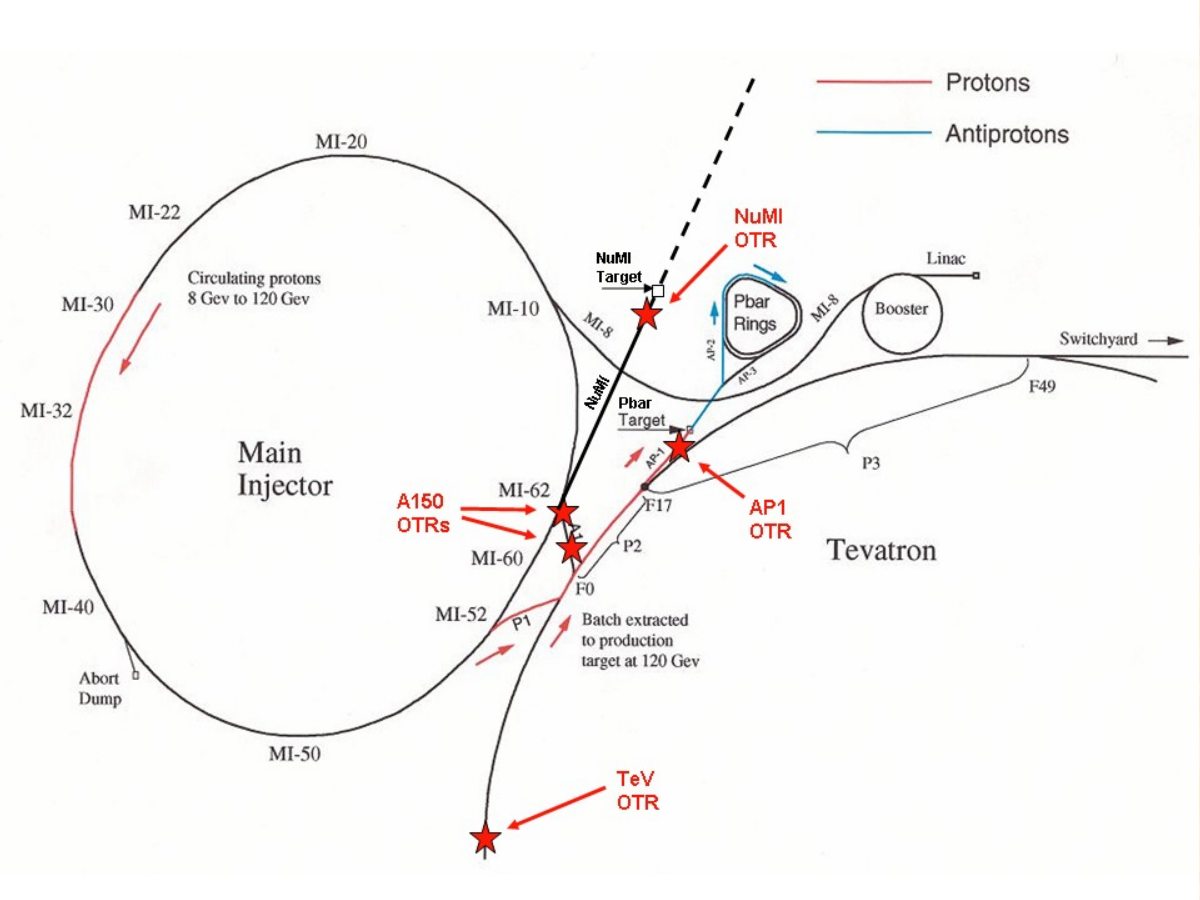
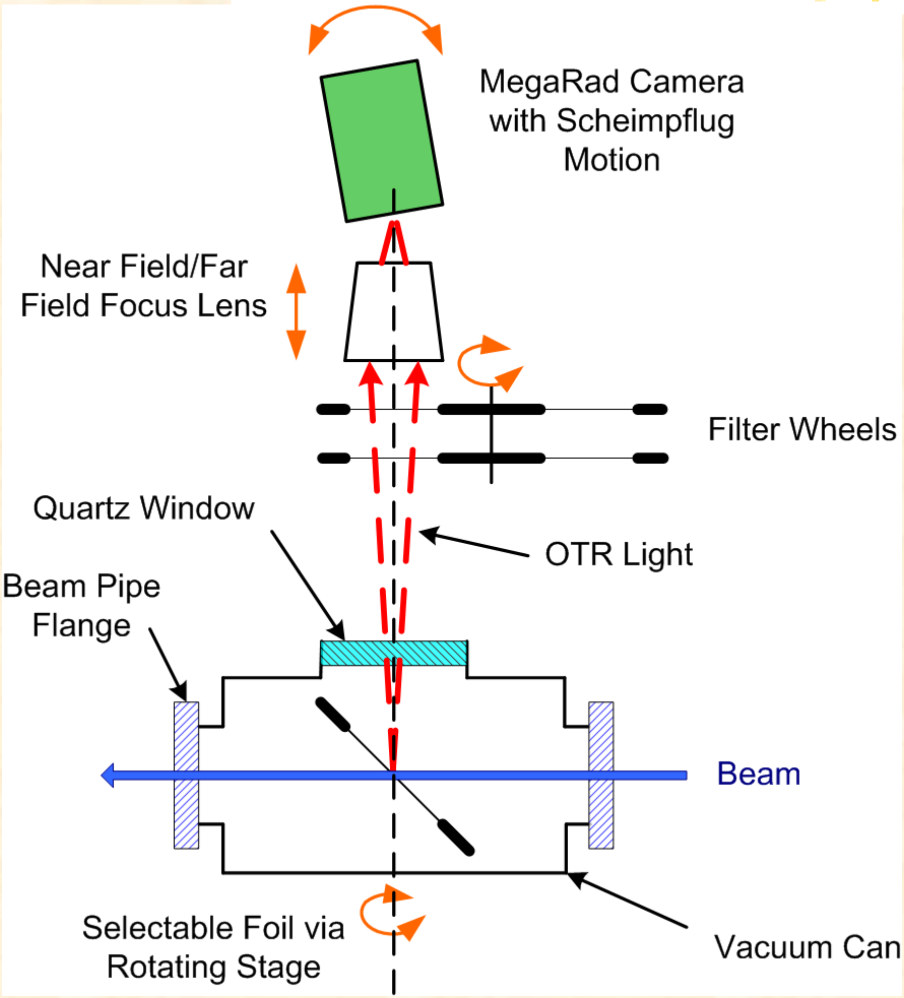


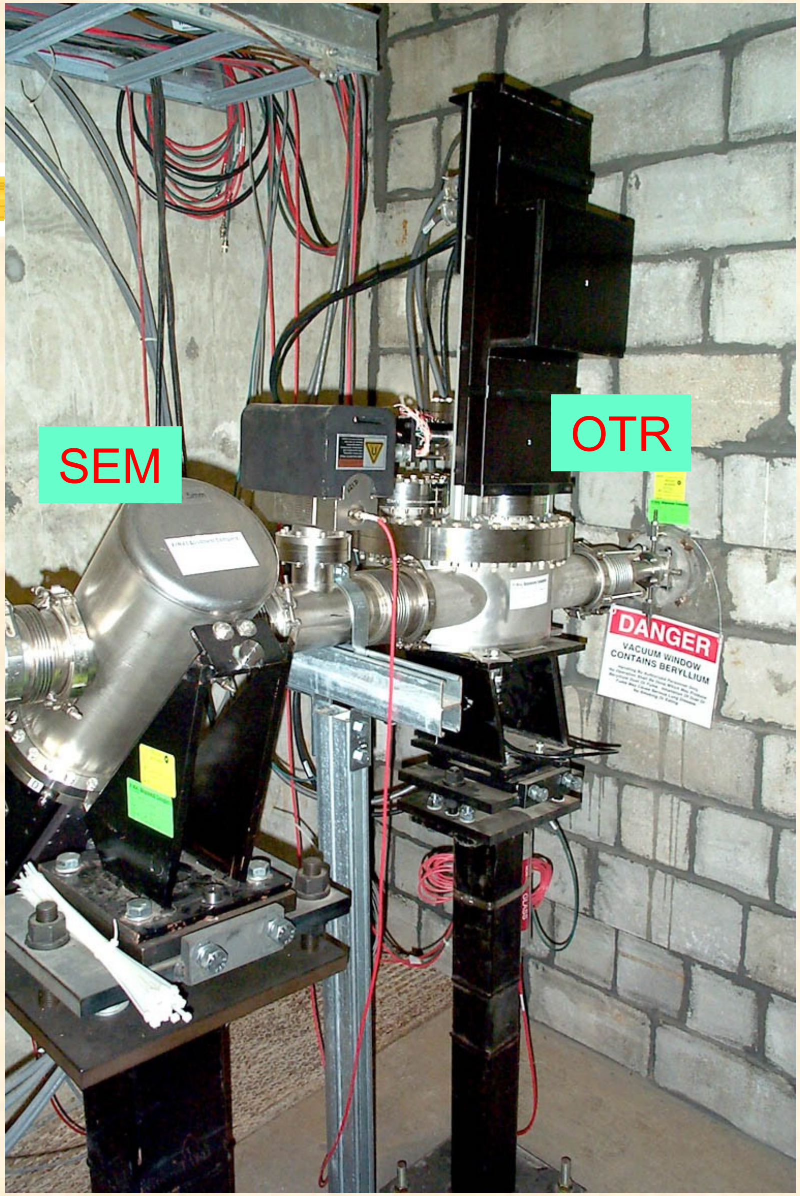
Diagram of Generic OTR Detector



- Radiation hardened CID camera
  - ~130 μm pixels at foil
- Near field/far field focusing
- Tiltable camera to maintain focus across foil (Scheimpflug condition)
- Neutral density filter wheels with polarizers
  - ~x1000 intensity range
- Bidirectional beam measurements with selectable foils
  - 5 to 6 μm aluminized Mylar or Kapton foils
  - Foils replaceable in-situ
  - 85 mm clear aperture
- Vacuum certified to few 10-9

NuMI OTR Detector

- OTR detector just in front of shield wall
  - Next to target SEM profile monitor
- 6 µm aluminized Kapton
  - ~1200 angstroms of aluminum
- Two foil design
  - Primary and Secondary foils
- ***Primary foil : ~6.5e19 protons***
- Near-field and far-field imaging
- Measure beam shape for every pulse
- **Operating at ~2e13 to 4e13 120 GeV protons per pulse at ~0.5 Hz**
  - **Beam size σ ~ 1 mm**
  - **Up to 350 kW beam power**



NuMI OTR Commissioning

- Real-time pulse-by-pulse OTR data analysis
- Gaussian fits to profiles -> centroid, sigma, intensity, 2D tilt, ellipticity
- Auto-saving every 1000[th] beam OTR image -> tracking foil lifetime

Front-End Controls Display

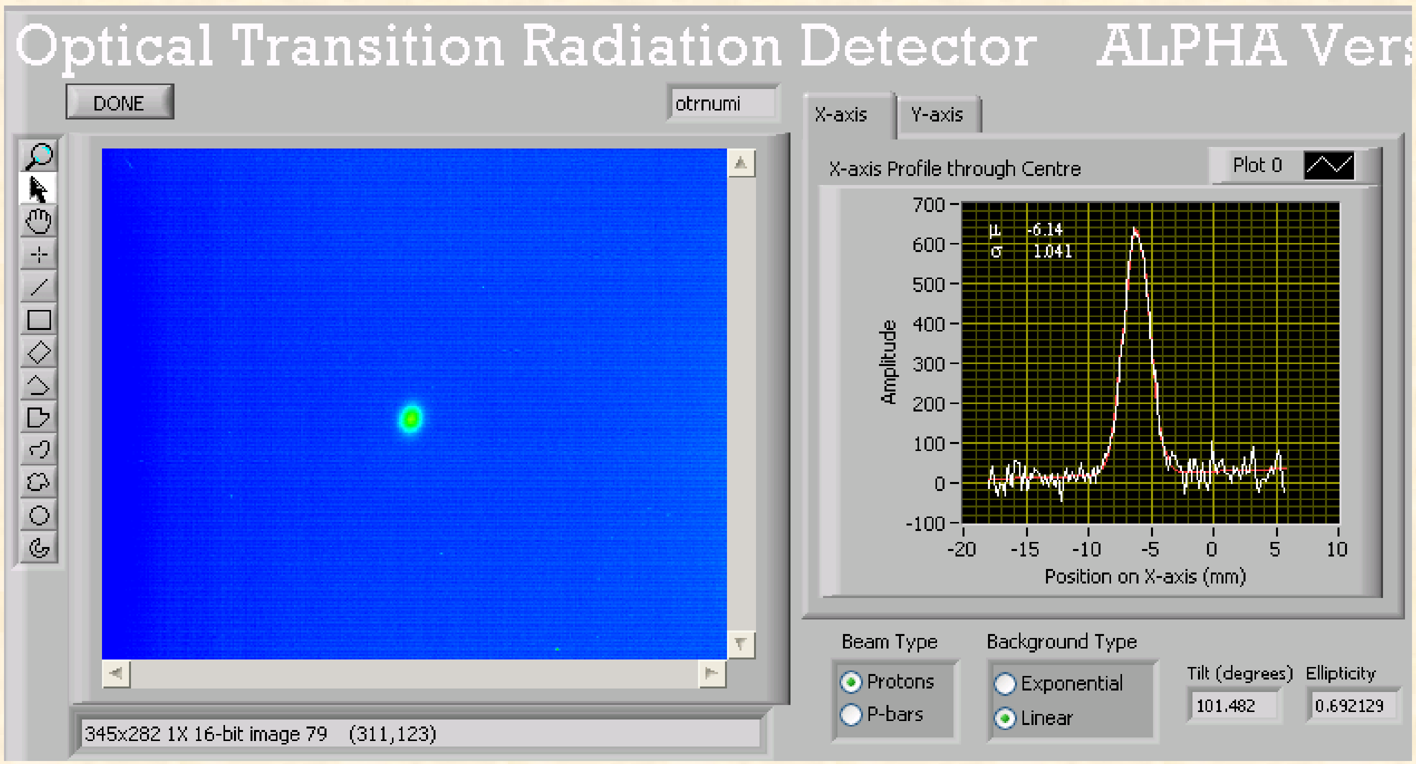


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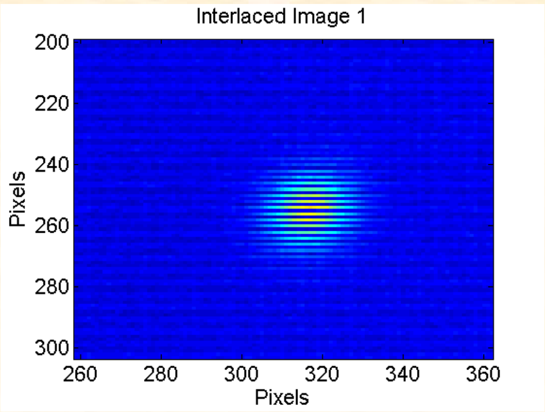
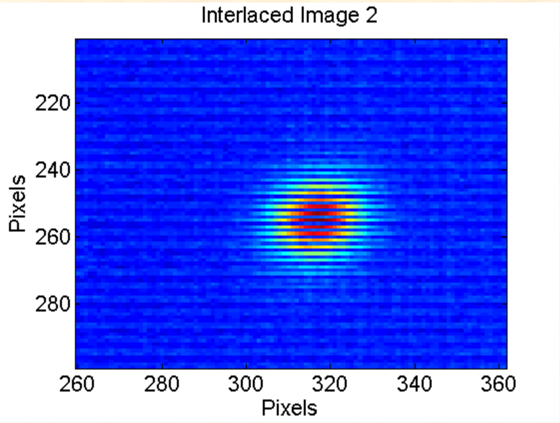
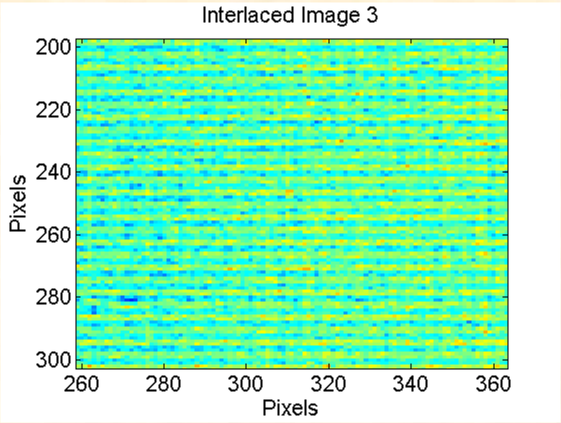
Image Processing

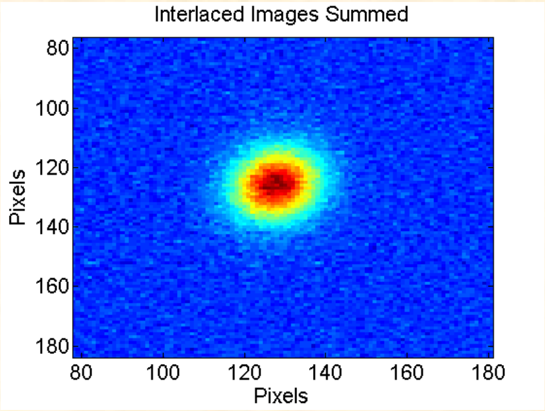
Three interlaced images





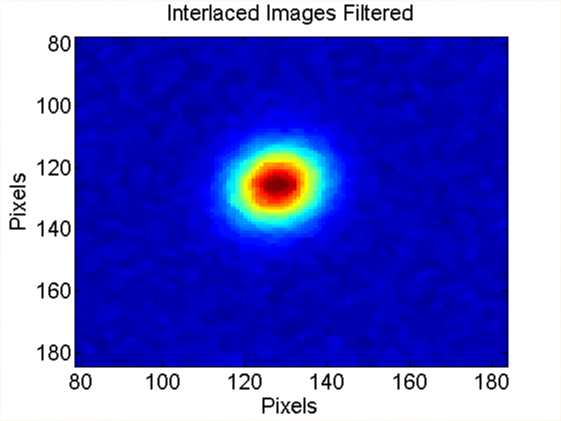


Sum = I1 + I2 – 2*I3

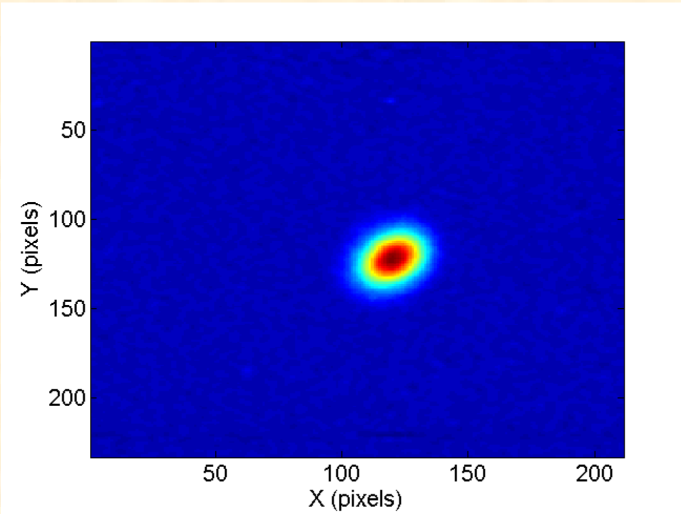


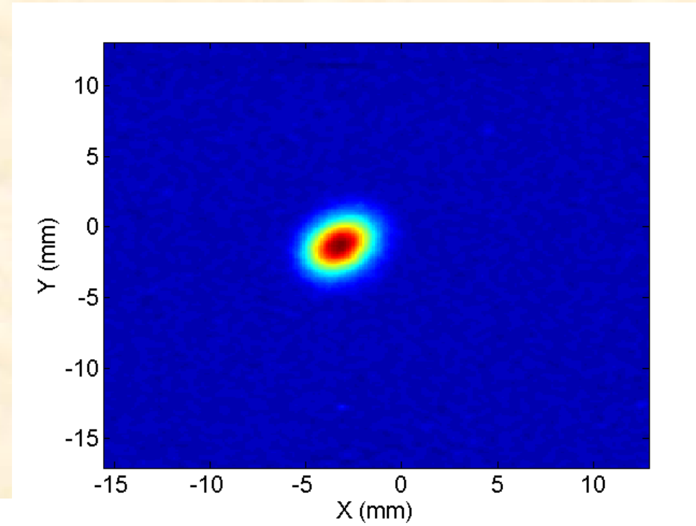
- Camera is asynchronous to beam arrival
- Use three images to reconstruct beam image
- Filter image to remove noise

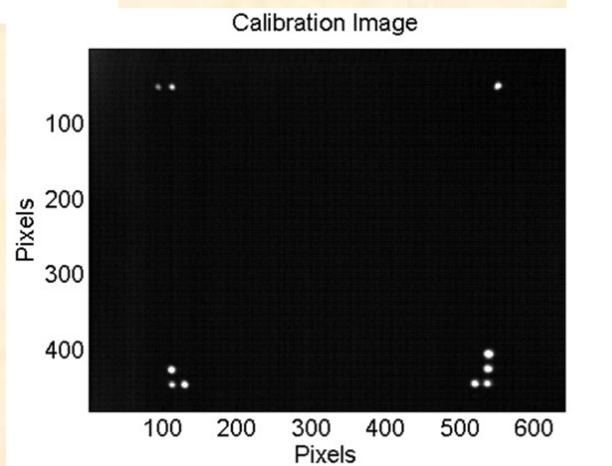
Filtered Image



Apply Image Calibration







Fiducial holes in foil give:

- Scale
- Orientation
- Perspective correction

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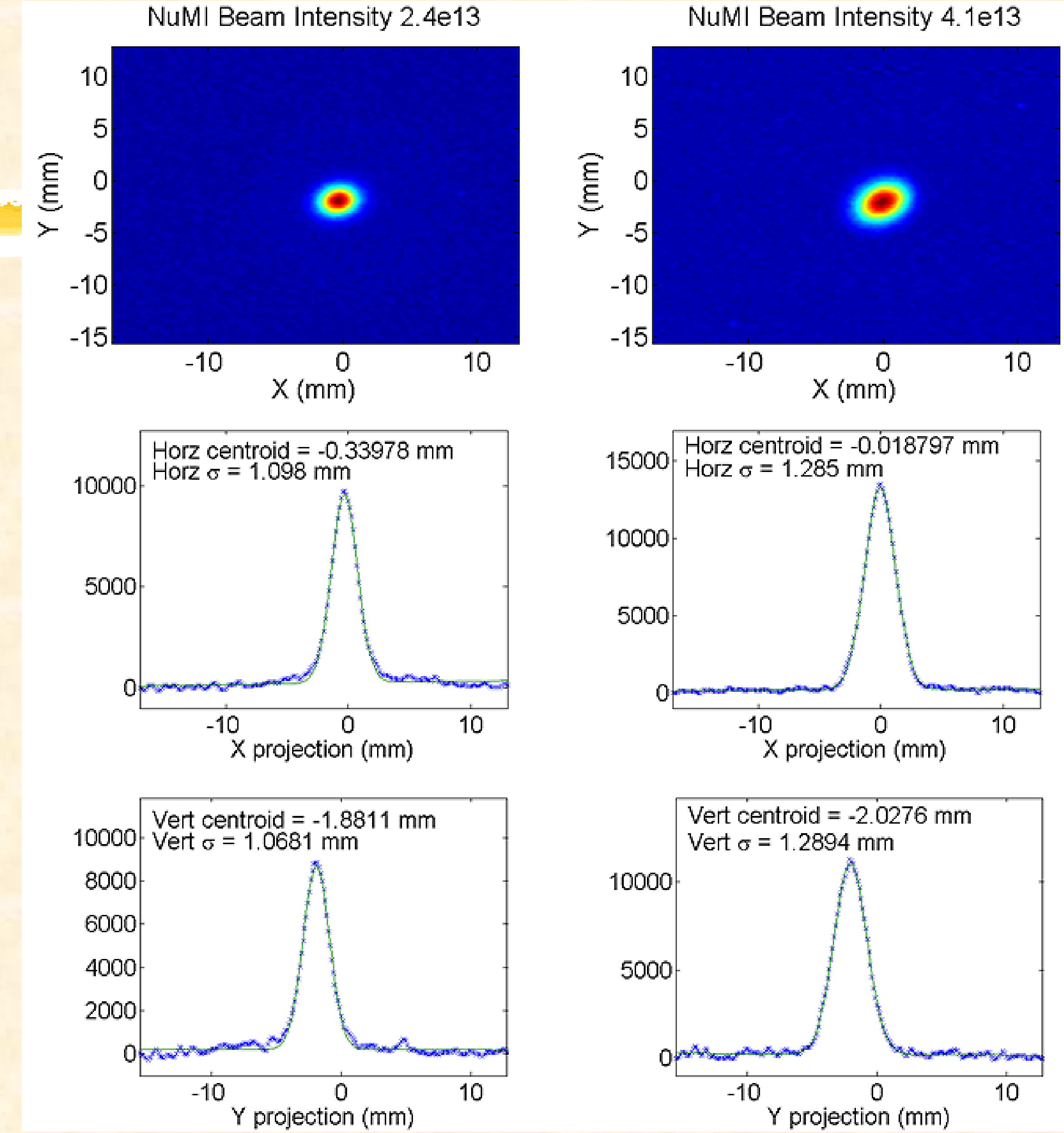
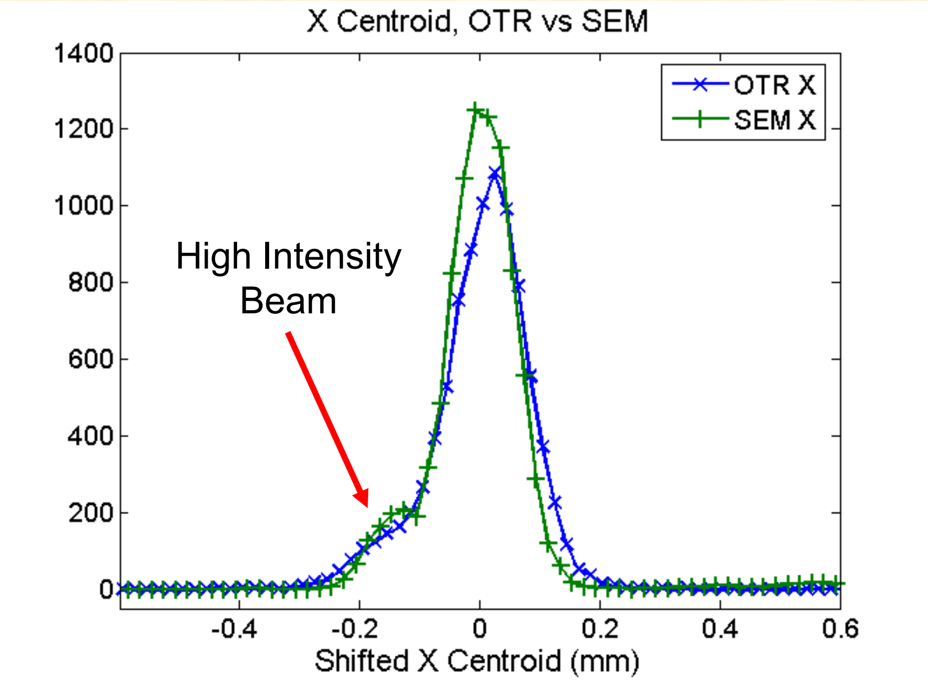
Images Over Intensity

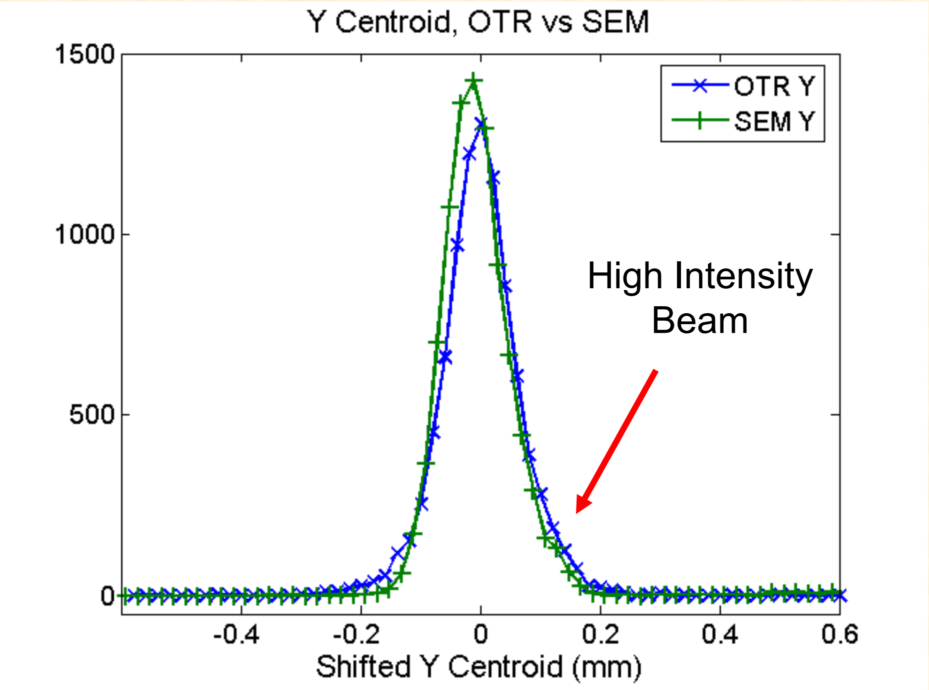


- Beam intensities of 2.4e13 and 4.1e13
- Gaussian fits to beam projections
- Higher intensity beam has larger ellipticity and beam tilt
- ***This show an advantage of a 2-D imaging device over 1-D profile monitors***

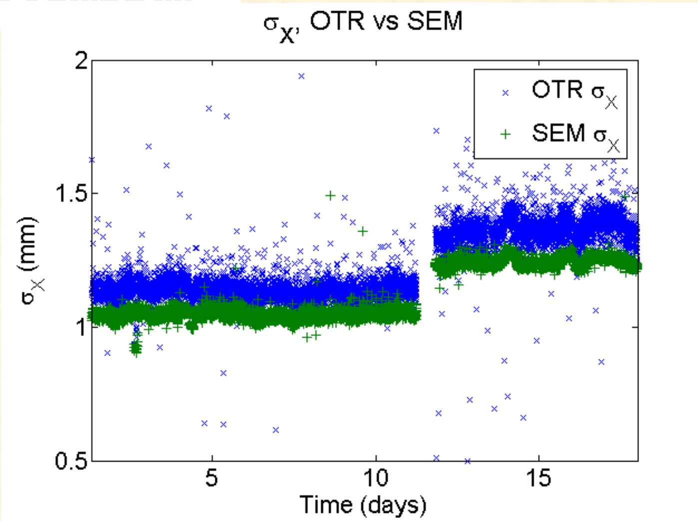
Beam Centroids, OTR vs SEM

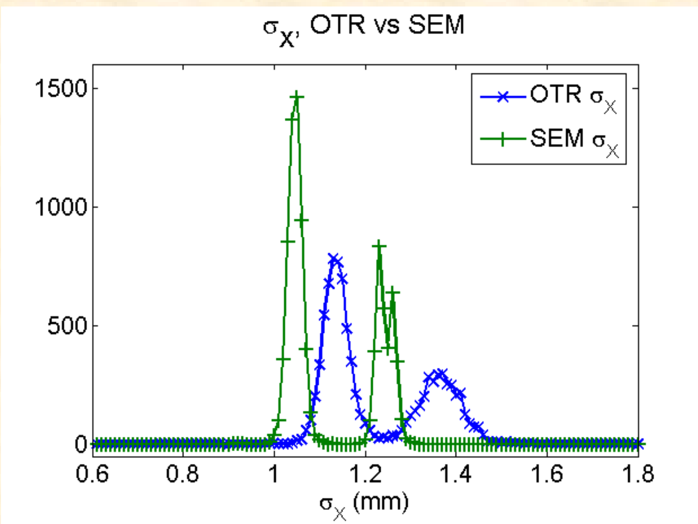
- Monitor OTR and SEM over many days
- Compare X and Y beam centroid shapes
- OTR and SEM give similar beam centroid positions





Beam σ, OTR vs SEM



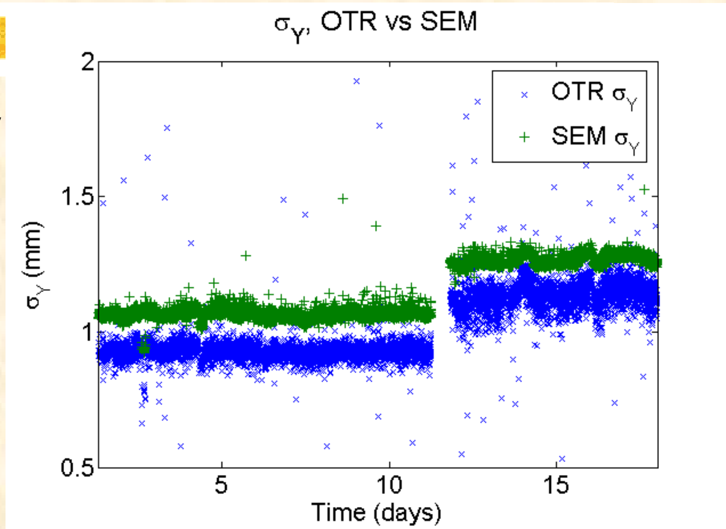


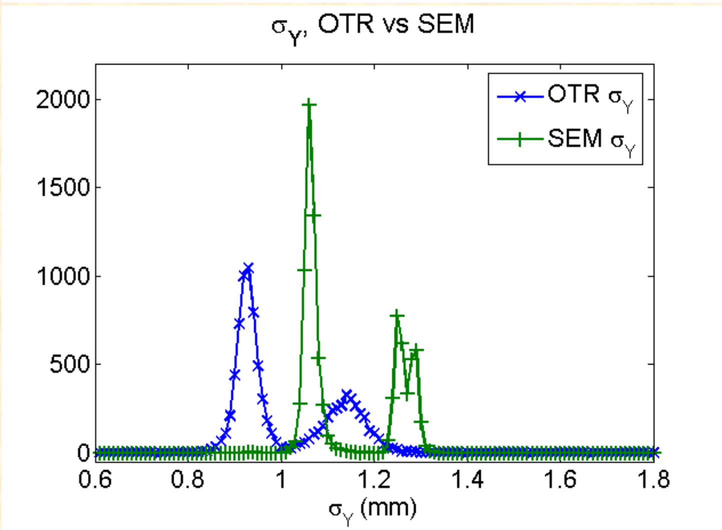
σ_x σ_y

Detectors track each other

but…

- *calibration error?*
- *aging foil?*





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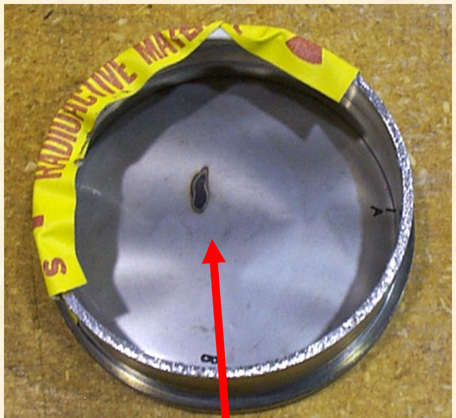
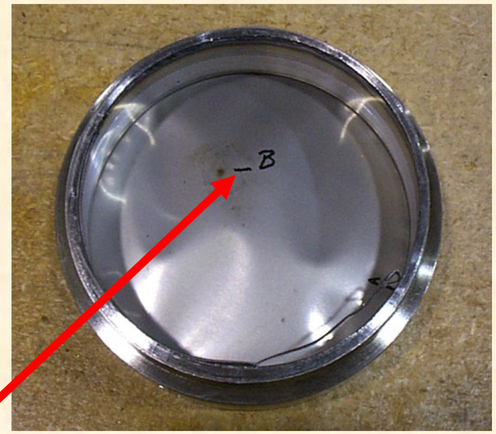
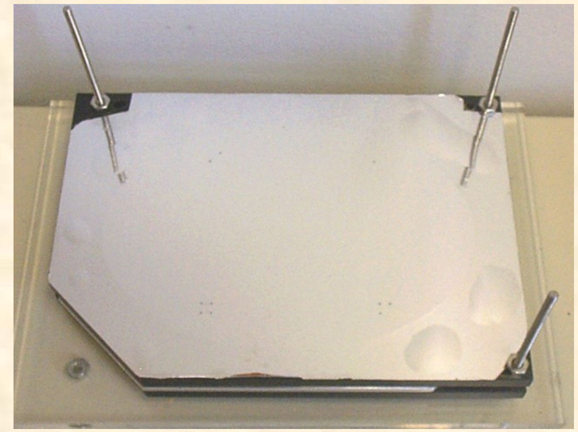
Foils Damage Under Intense Beams

Vacuum Windows





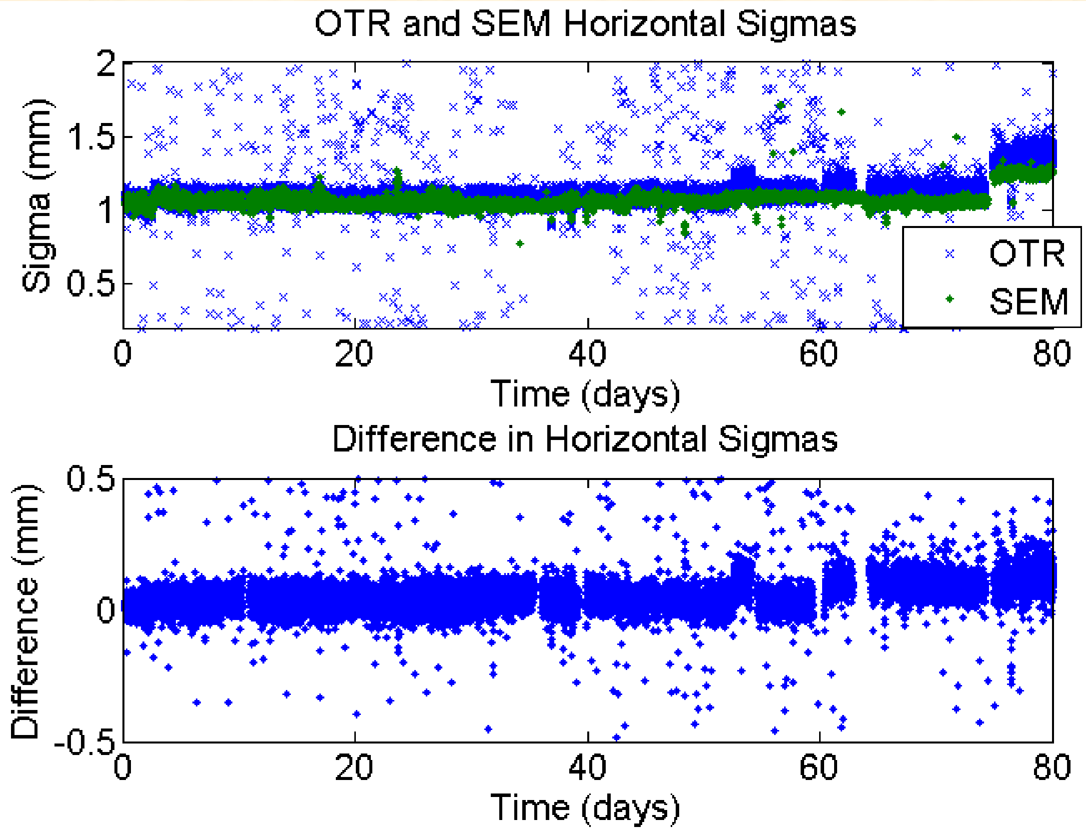
OTR Foil



Any darkening of foil or distortion of foil shape changes OTR distribution and intensity and hence the measurement of beam shape

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.

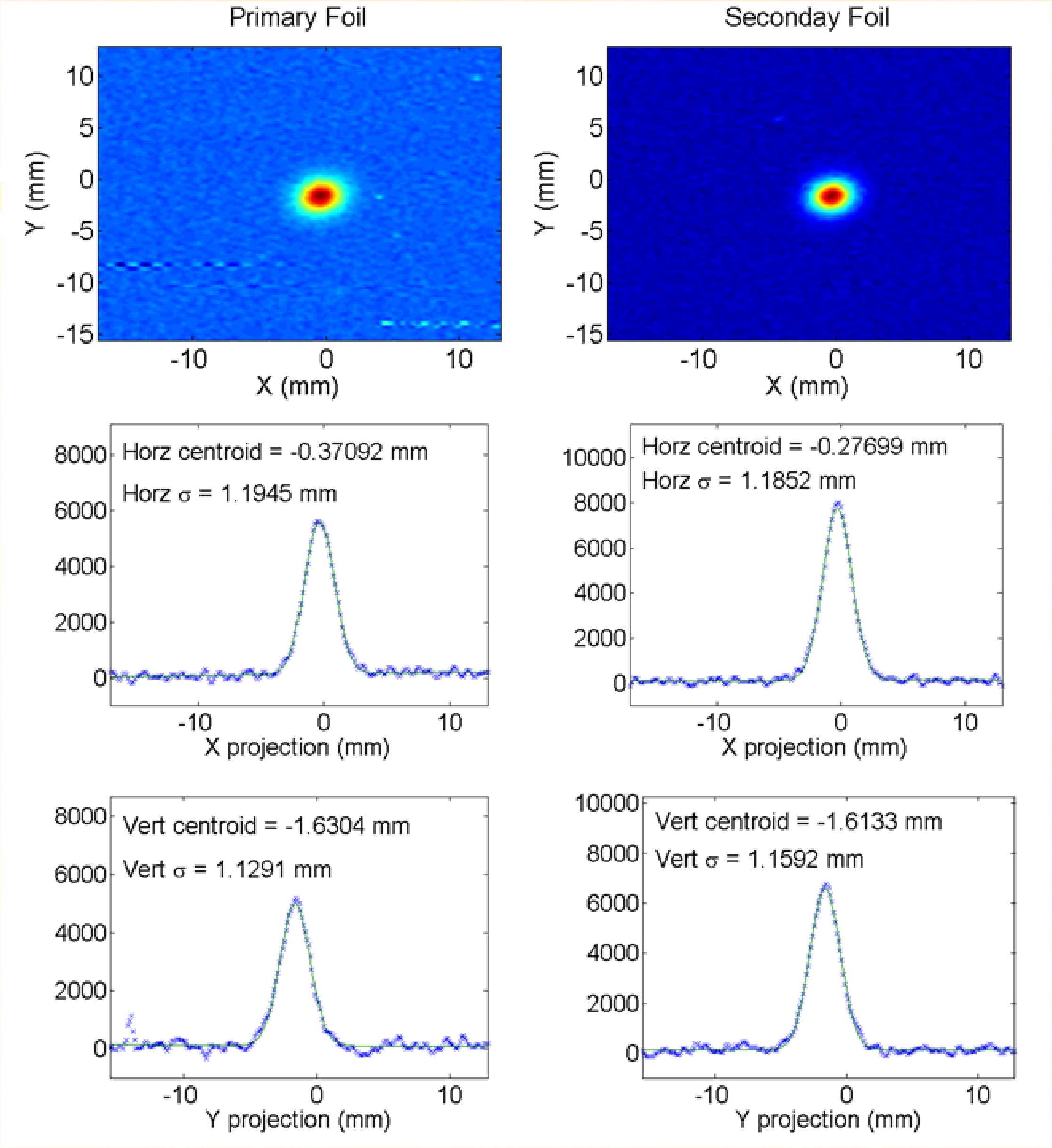
Is NuMI Foil Changing with Time?



- Compare horizontal values of σ from OTR and SEM over ~80 day time period from primary foil
- OTR σ appears to be slowly drifting away from SEM σ value
- Is the OTR primary foil aging?

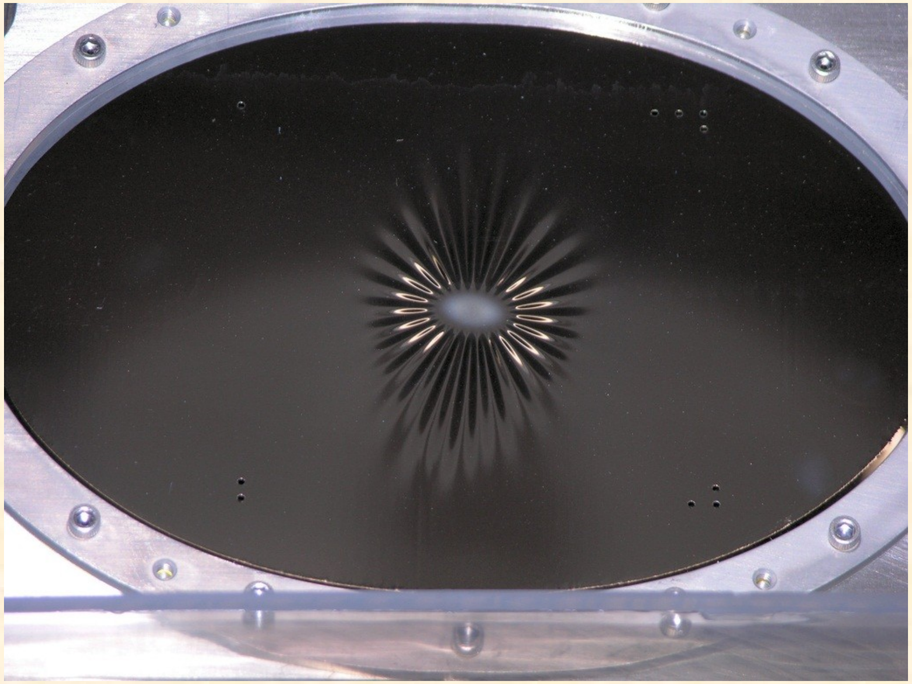
Primary Foil Aging?

- Operate primary foil ~3 months of continuous beam
  - ~6.5e19 protons
- Insert secondary foil under similar beam conditions
- Secondary foil generating ~25% more OTR
- ***Is aluminized Kapton sputtering away?***

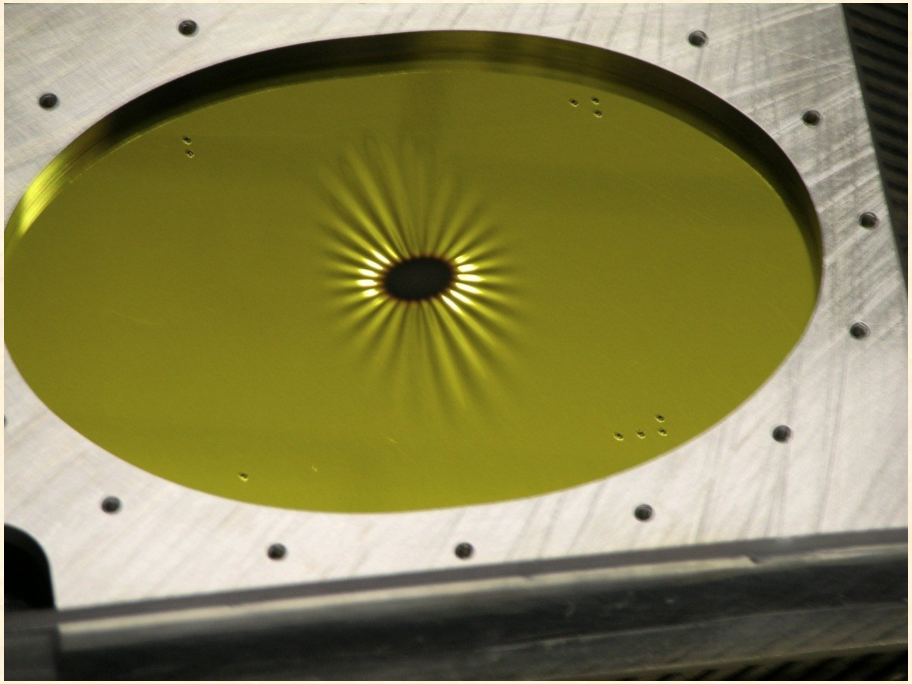


Damage to NuMI Aluminized Kapton Foil

Aluminum Side



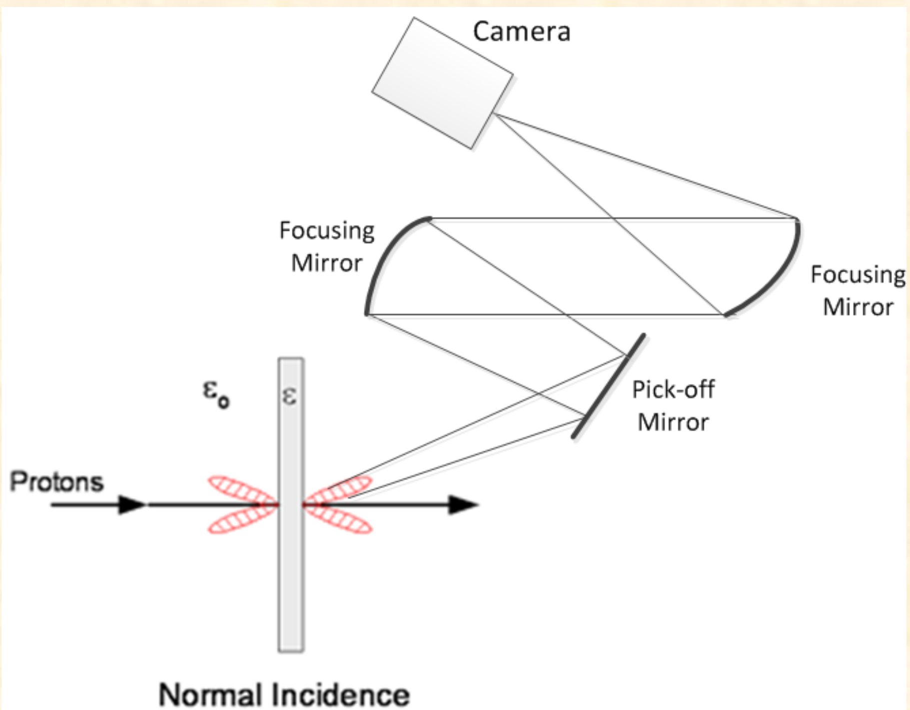
Kapton Side

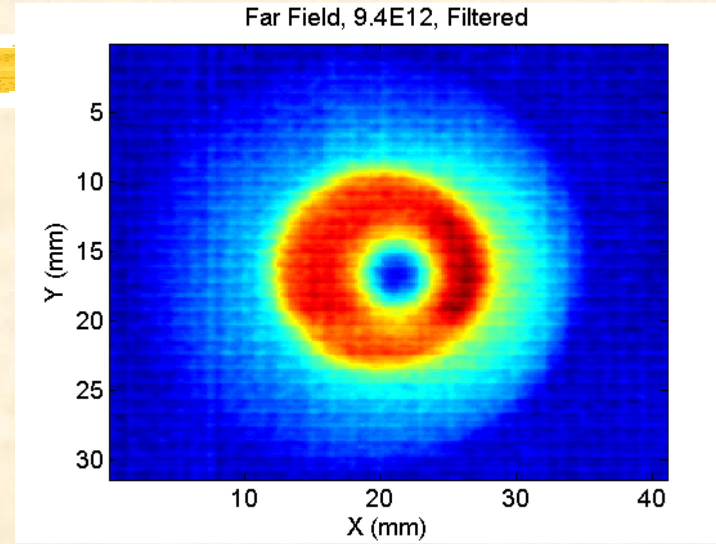


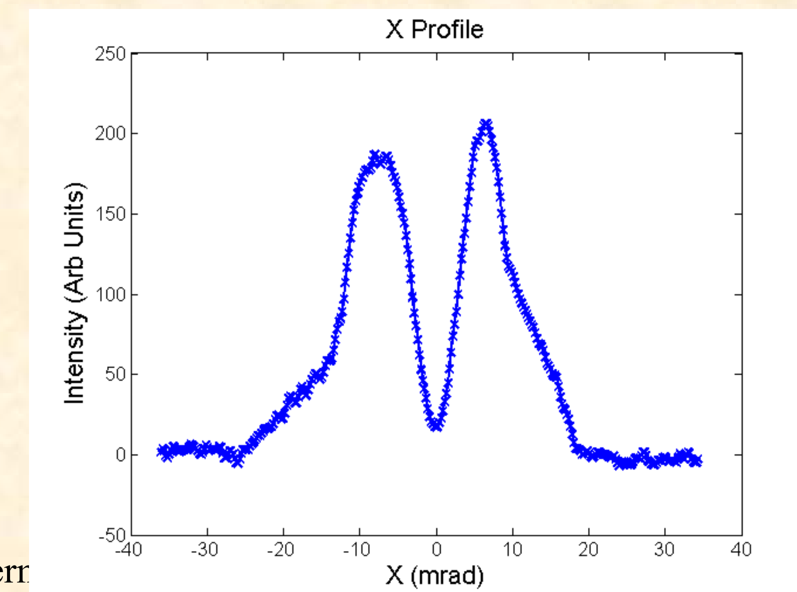
~ 6.5e19 120 GeV protons

Forward OTR Detector

- Utilize target vacuum window as OTR generator
  - Eliminate reflection of material
- Less light collected than reverse OTR
  - Compensate with amplified camera

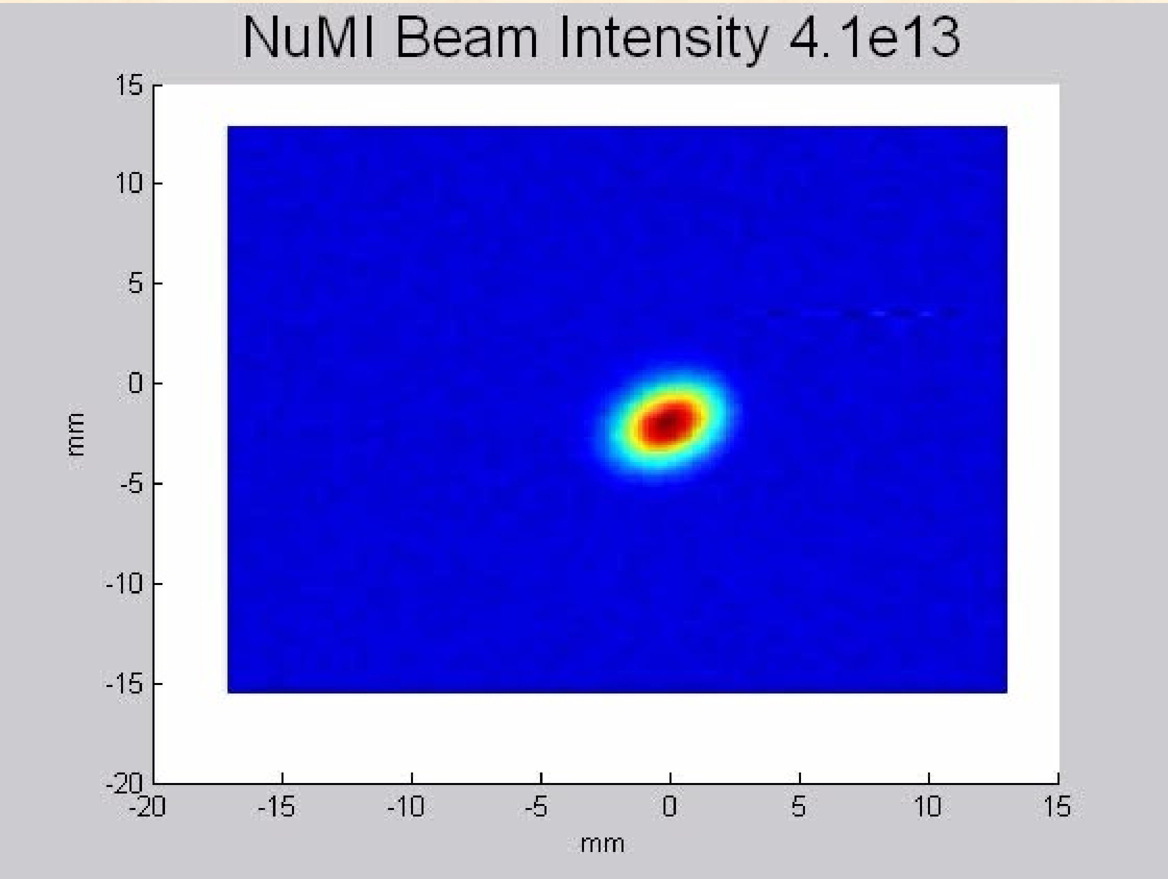






Conclusion

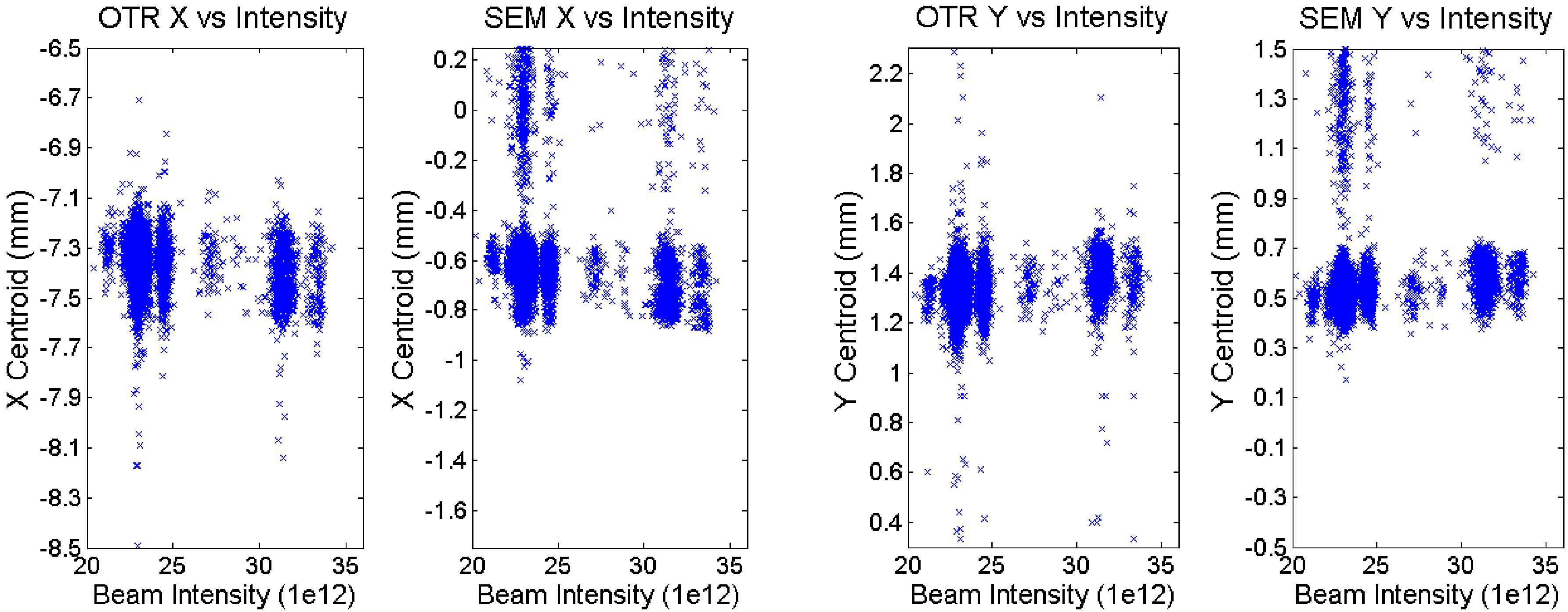
- NuMI OTR has operated for ~6.5e19 protons
- Beam position and σ measured for every pulse
- Primary 6 μm aluminized Kapton foil shows aging
  - Data shows aging effects
  - Foil show reflection changes and mechanical distortion
- Switch to forward OTR detection
  - Utilize vacuum window as OTR generator
  - Eliminate reflection effect
  - Limited light collection



extra

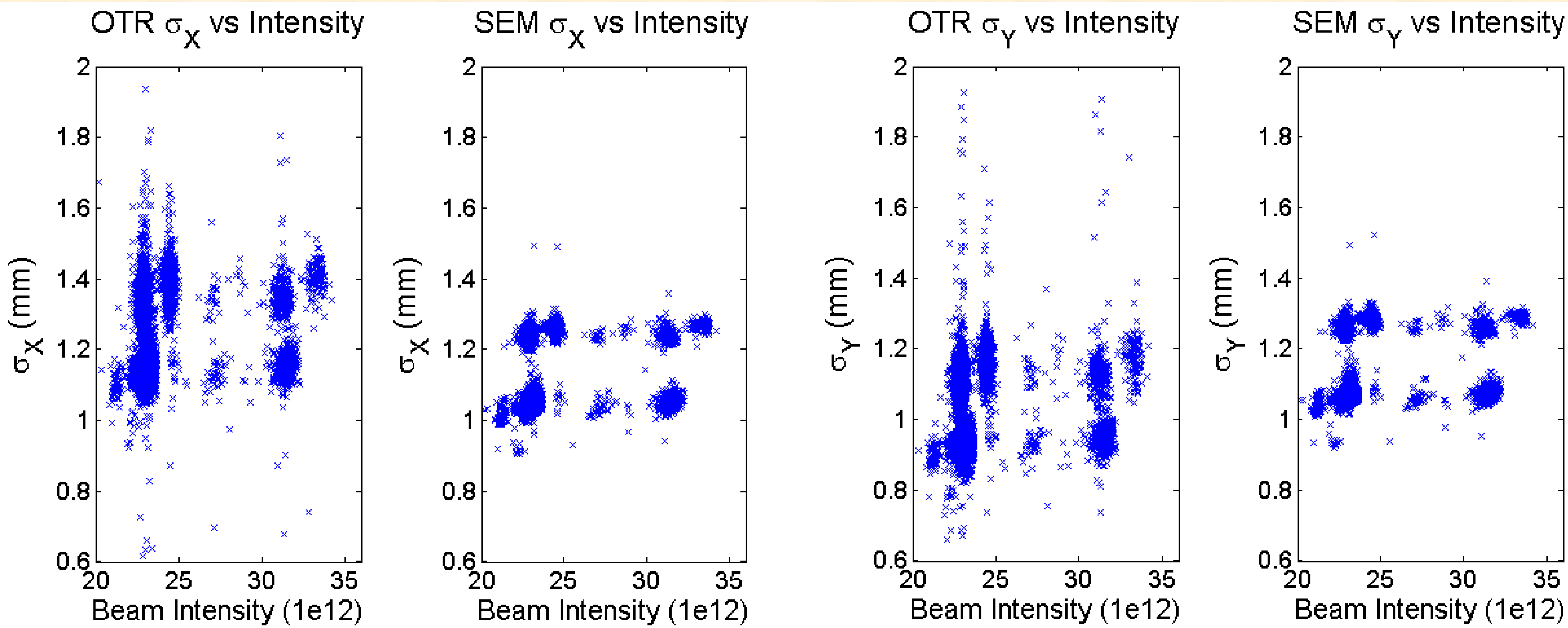
Beam Centroid vs Intensity

X and Y beam centroid changes slightly with beam intensity



Note: difference in OTR and SEM mean position due to difference in (0,0) reference points.

Beam σ vs Intensity



OTR and SEM track each other with intensity but OTR has more scatter. Improvements in image processing may reduce scatter.