Electron Beam Profile Monitor for High Intensity Proton Beams

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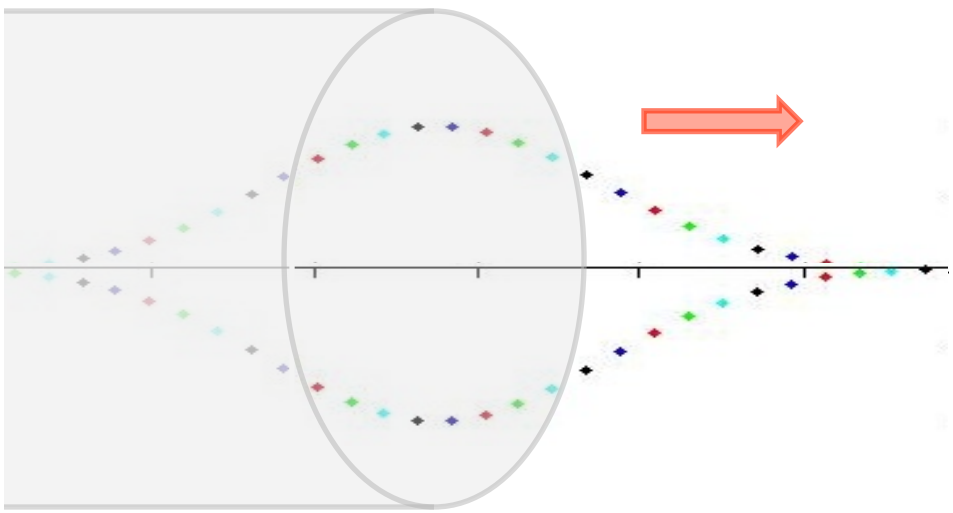
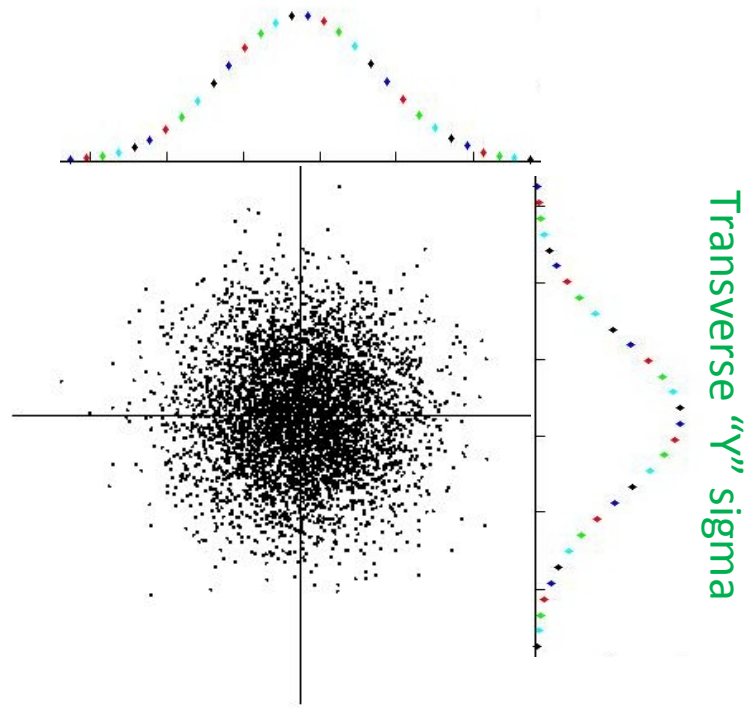
Beam Profile Monitors

- What are we trying to measure?
  - Longitudinal and transverse "sigmas"

Longitudinal "Z" sigma



Transverse "X" sigma



Transverse "Y" sigma

"Gaussian" or "Normal" distribution (aka "Bell Curve")

Beam Profile Monitors [1]

- Destructive vs. nondestructive techniques
  - Secondary Emission Monitors (SEM)
    - [destructive: causes significant beam loss]
  - "Flying Wire"
    - [destructive: destroyed at high intensity]
  - Optical Transition Radiation (OTR)
    - [destructive: degrades at high intensity]
  - Ionization Profile Monitor (IPM)
    - [nondestructive: (possible vacuum considerations)]

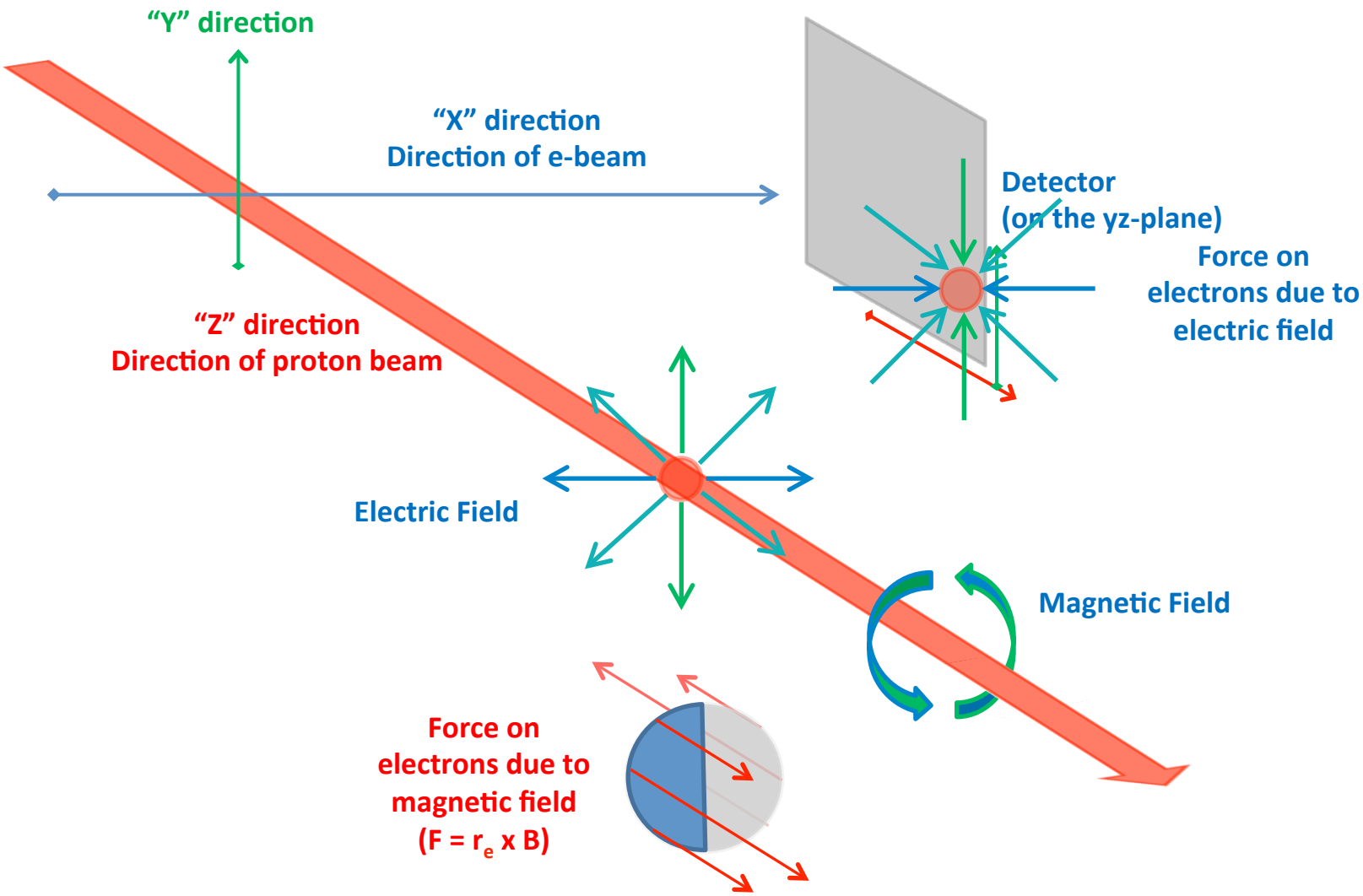
[1] Beam Instrumentation for Future High Intense Hadron Accelerators at Fermilab
M. Wendt, M. Hu, G. Tassotto, R. Thurman-Keup, V. Scarpine, S. Shin, J. Zagel, Fermilab, Batavia, IL 60510, U.S.A.

Electron Beam Profile Monitor

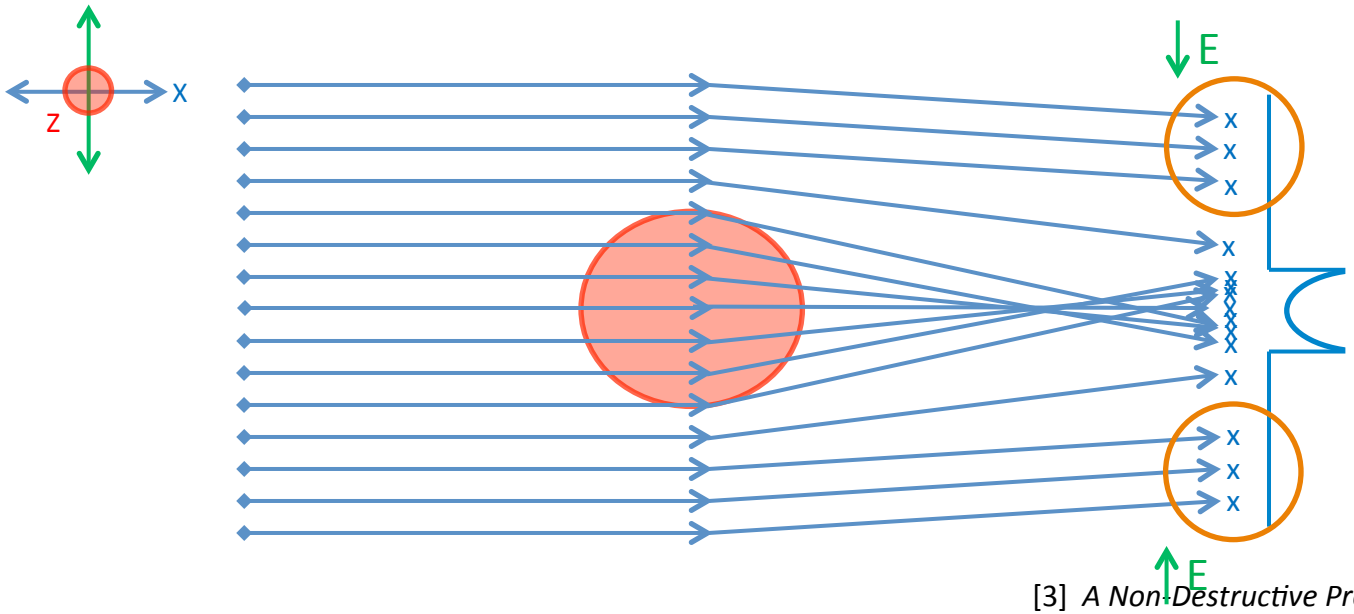
- Nondestructive
- Can survive high-intensity hadron beam.
- Idea has been around since at least 1970 [2].
- Technique already in use in accumulator ring of the Spallation Neutron Source at Oak Ridge National Laboratory
- BUT . . . Fermilab has unique requirements.
  - Different proton beam stats: shape, frequency, bunch size, intensity, etc.
  - Different logistics: equipment, facilities
  - Different experimental goals

[2] Collisionless Sheath: An Experimental Investigation
Paul D. Goldan, Aeronomy Laboratory, Environmental Science Services Administration, Boulder, CO

Orientation Diagram



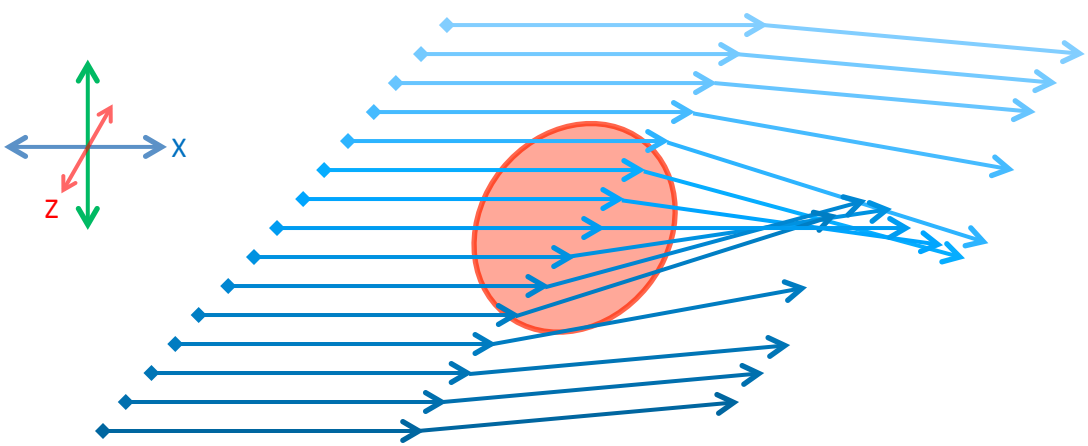
Theory

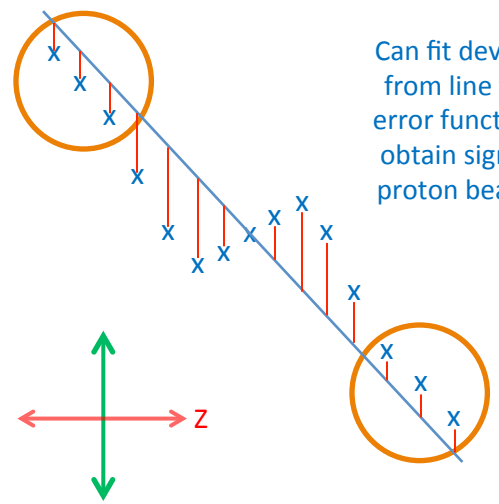


Can analyze for density distribution to approximate sigma of proton beam*

As distance from the proton beam increases, the deflection angle no longer changes significantly, causing a leveling off, or "tail." Sufficient "tail" is critical to achieving an accurate fit to the error function!

[3] *A Non-Destructive Profile Monitor for High Intensity Beams*
W. Blokland and S. Cousineau, ORNL, TN 37831, U.S.A.



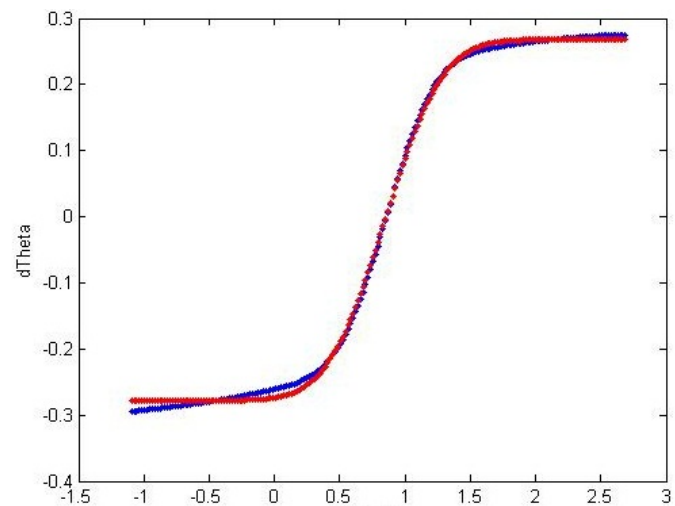


Can fit deviation from line to an error function to obtain sigma of proton beam*…

Theory

- The derivative of the electron beam deflection angle with respect to the impact parameter (offset from center of proton beam) gives the transverse beam profile. [4]

- By fitting the graph of the deflection angle vs. the impact parameter to an error function (erf), the transverse "sigma" of the proton beam can be determined.



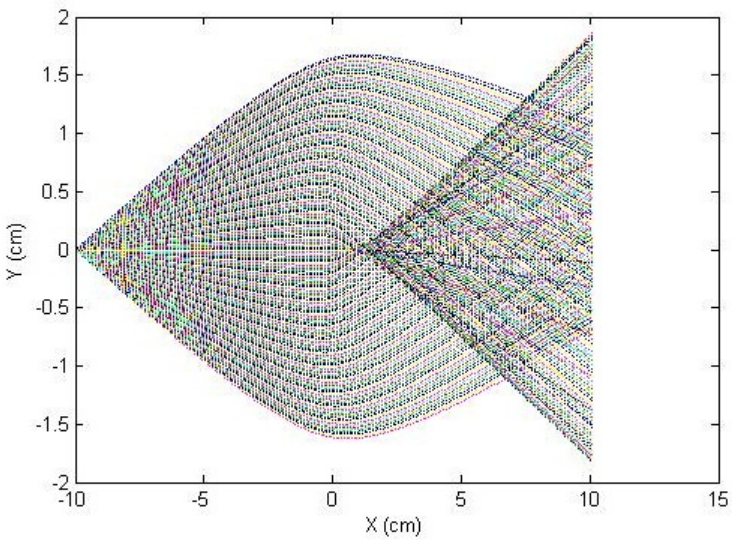
[4] Feasibility Study of Using an Electron Beam for Profile Measurements in the SNS Accumulator Ring
A. Aleksandrov, S. Assadi, S. Cousineau, V. Danilov, S. Henderson, M. Plum, Spallation Neutron Source, Oak Ridge National Laboratory, Oak Ridge, TN 37831, U.S.A.
P. Logatchov, A. Starostenko, Budker Institute of Nuclear Physics, Novosibirsk, Russia

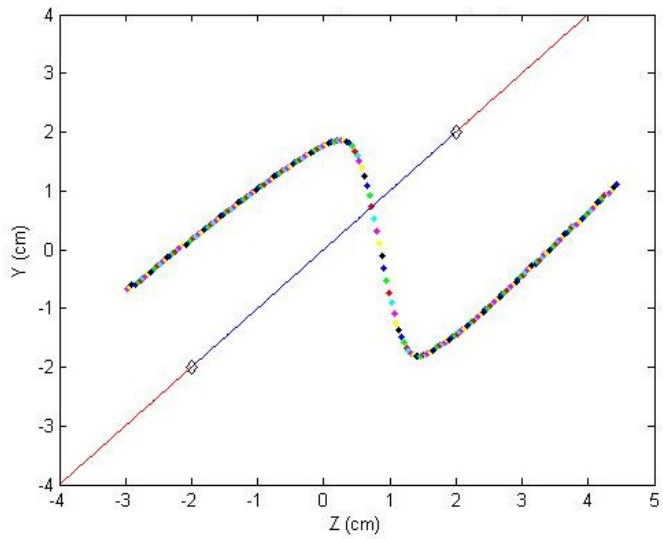
Simulation

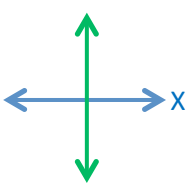
- Purpose:
  - Simulate the electron trajectories and use the final data points to reconstruct the proton beam sigma.
- Initial parameters:
  - Electron beam energy: 60 keV
  - Proton bunch intensity: 4e11 protons per bunch
  - Proton bunch transverse sigma: 1 mm – 5 mm
  - Proton bunch longitudinal sigma: 1 ns – 2 ns
- Two techniques:
  - Fast deflector
  - Slow deflector

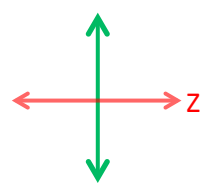
“Fast Deflector”

- Use electrostatic deflection to aim stationary e-beam source towards various vertical points along proton beam:





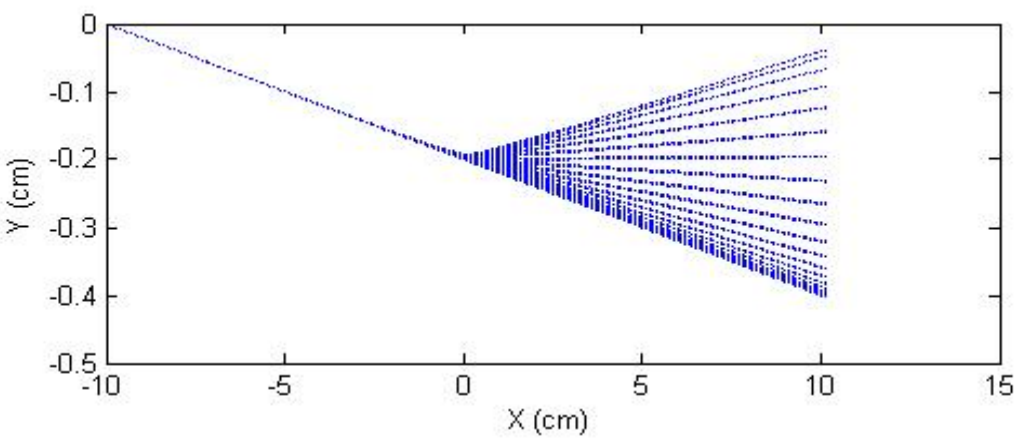


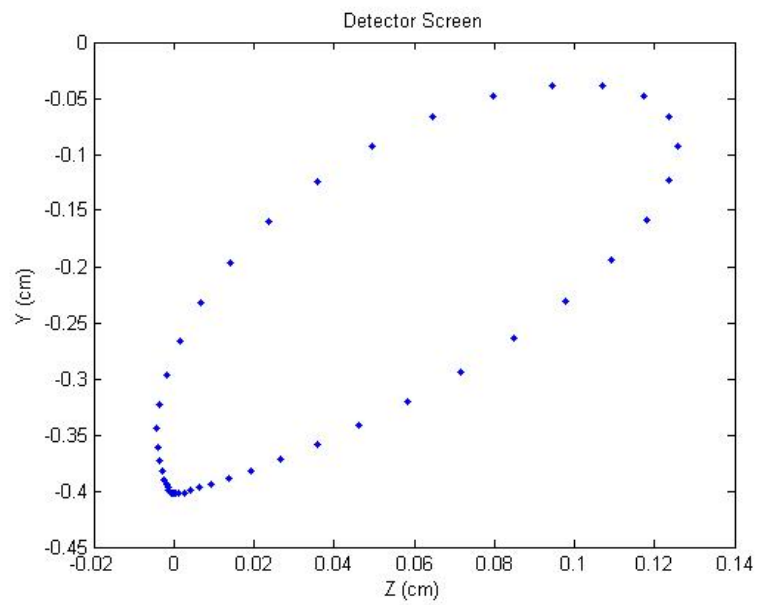


0.1 mm x 0.1 mm x 2 ns proton beam, 200 electrons

“Slow Deflector”

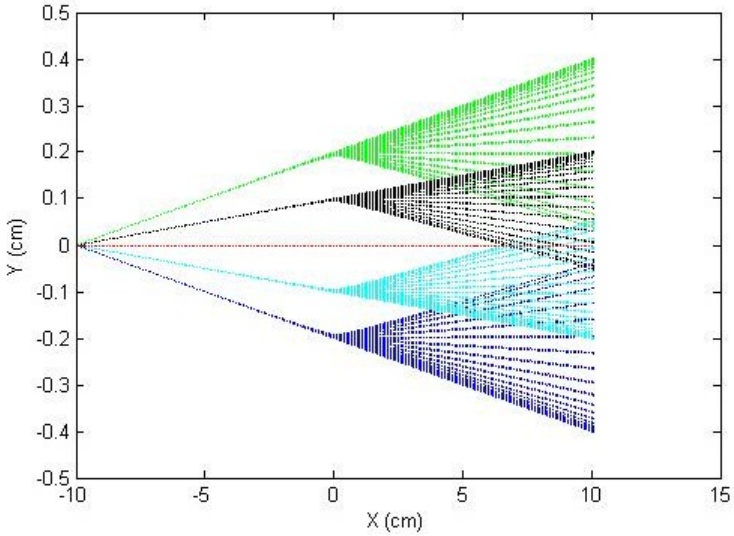
- E-beam is aimed at an angle but instead of sweeping as the proton beam passes, it remains stationary.
- The detector measures the deflection from this single angle as the entire proton bunch passes.





“Slow Deflector”

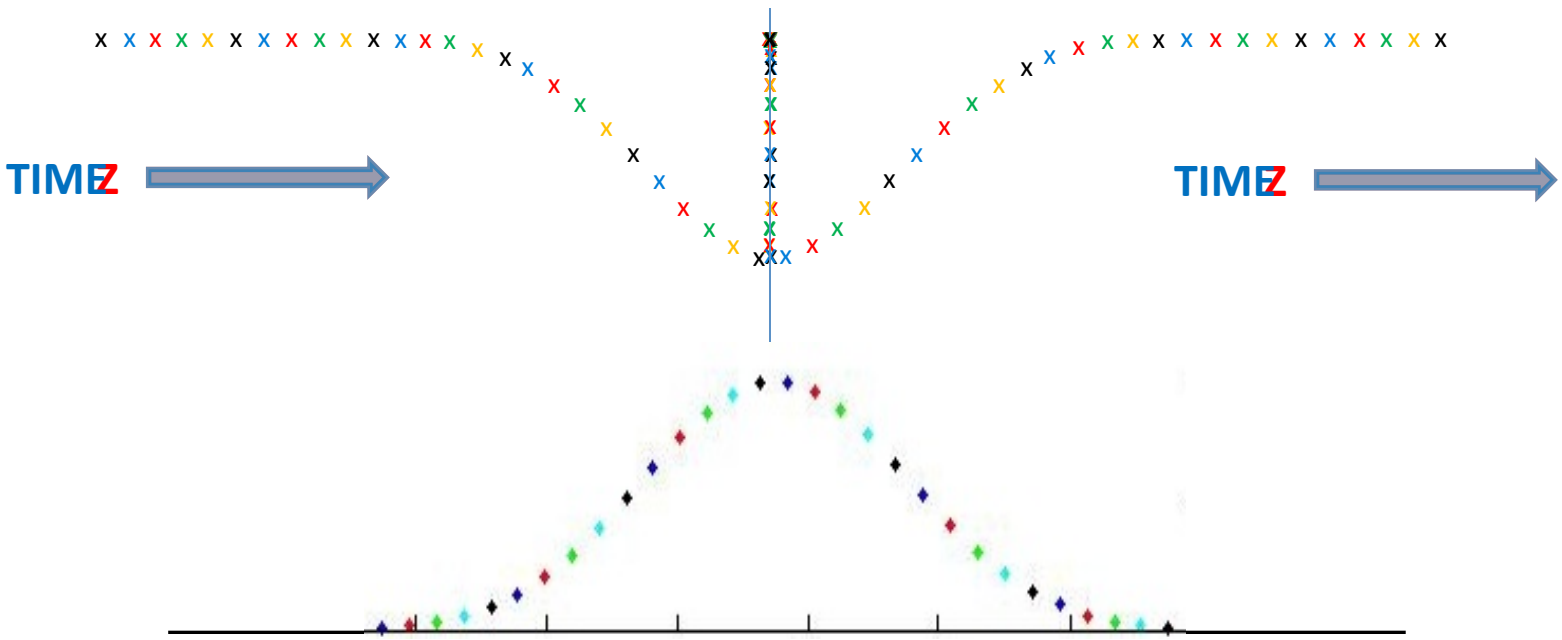
- After the bunch has passed, the e-beam is aimed at a slightly different angle, and the process is repeated until the angles have passed through the entire transverse range of the proton beam.
  - The max y-deflections from each angle are collected and analyzed as though they were a single sweep to reconstruct the transverse sigma.



“Slow Deflector”

When ordered by time stamp, data points reconstruct the longitudinal sigma

Constant stamp, deflects as proton beam passes.



“Fast” vs. “Slow”

- “Fast”
  - ☆ – Obtains transverse sigma in a single sweep
  - ✗ – No capacity to measure longitudinal sigma
- “Slow”
  - ☆ – Can use conductive strips instead of camera.
  - ☆ – Less expensive/simpler to build
  - ☆ – Timing less critical
  - ☆ – Adds ability to measure longitudinal sigma
  - ✗ – Must take hundreds of measurements to obtain accurate transverse sigma.

Simulation Attempts: "Fast Deflector"

- **Results:** Obtained transverse sigma within 5% of true transverse sigma value.
  - 60 keV e-beam:
    - Within 5% at 4e11
    - Within 9% at 6e11
    - Within 15% at 1e12
  - 100 keV e-beam:
    - Within 5% at 6e11
    - Within 10% at 1e12
    - Within 15% at 4e12
  - *200 keV e-beam:*
    - *Within 11% at 2e12*
  - *400 keV e-beam:*
    - *Within 12% at 4e12*
  - *1 MeV e-beam:*
    - *Within 5% at 4e12*
  - *10 MeV e-beam:*
    - *Within 10% at 4e13*
  - *100 MeV e-beam:*
    - *Within 5% at 4e13*

Simulation Attempts: "Slow Deflector"

- Longitudinal sigma obtained within 3% accuracy (4e11)
- Transverse sigma obtained within 5% accuracy when at least 150 angles used (4e11)
- Similar degradation in accuracy at higher proton bunch intensities

Simulation Attempts: Conclusions

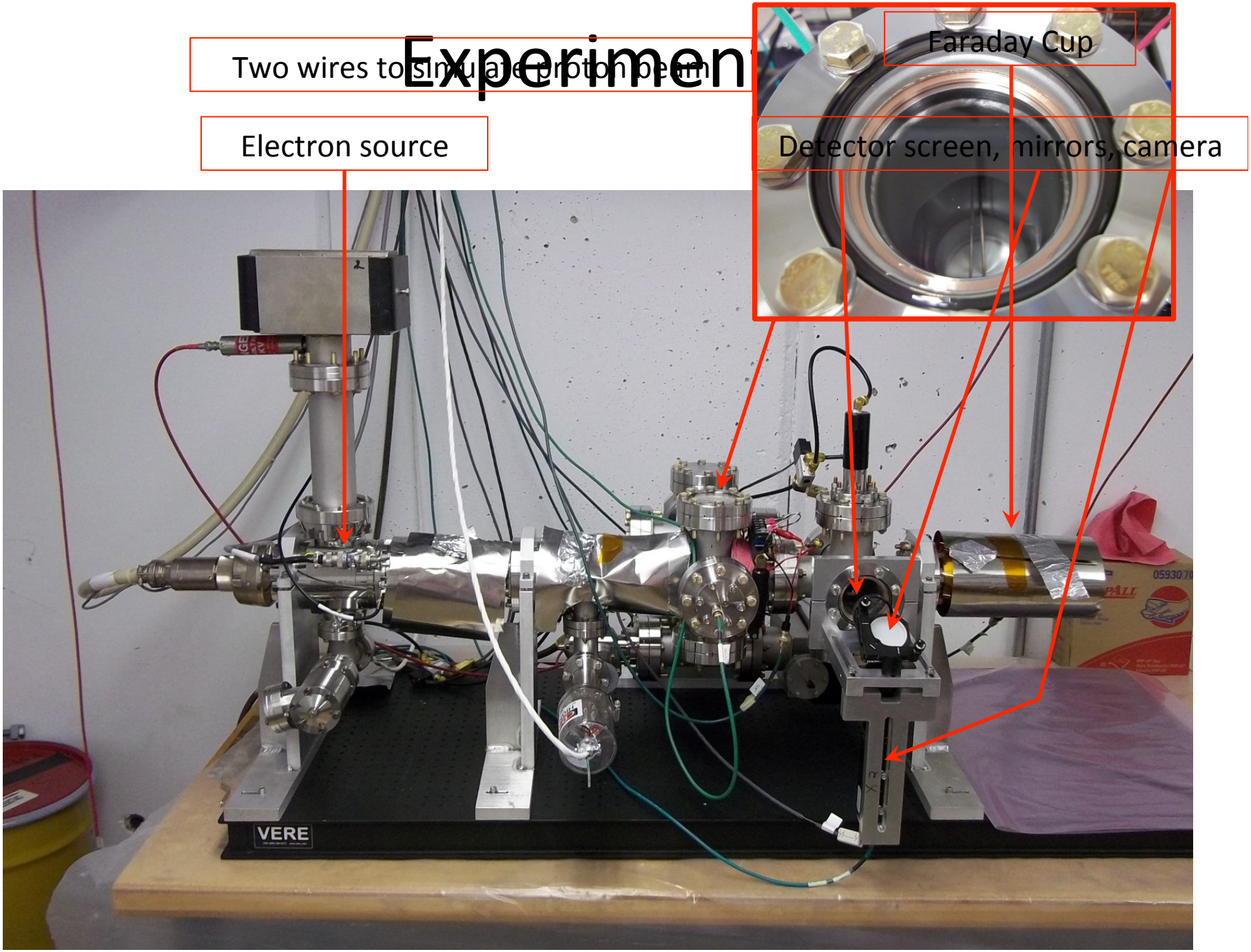
- Calculated sigmas within 5% of true sigma values can be obtained for proton bunch energies of up to 4e11 with a 60 keV electron beam.
- Sigma values begin to degrade if proton bunch intensity increases beyond 4e11.
  - This may be somewhat mitigated by using a higher energy electron beam. (A 100-keV version is also commercially available.)

Experiment

- Obtained commercially available electron beam source to conduct initial feasibility testing for the electron beam profile monitor proposal.
- Initial characterization of electron beam itself conducted prior to June 2011 [5]

[5] Initial Characterization of a Commercial Electron Gun for Profiling High Intensity Proton Beams in Project X
R. Thurman-Keup, A.S. Johnson, A.H. Lumpkin, J.C.T. Thangaraj, D. Zhang, FNAL, Batavia, IL 60510, U.S.A.
W. Blokland, ORNL, Oak Ridge, TN 37831

Experiment


Two wires to simulate proton beam
Electron source
Faraday Cup
Detector screen, mirrors, camera
VERE

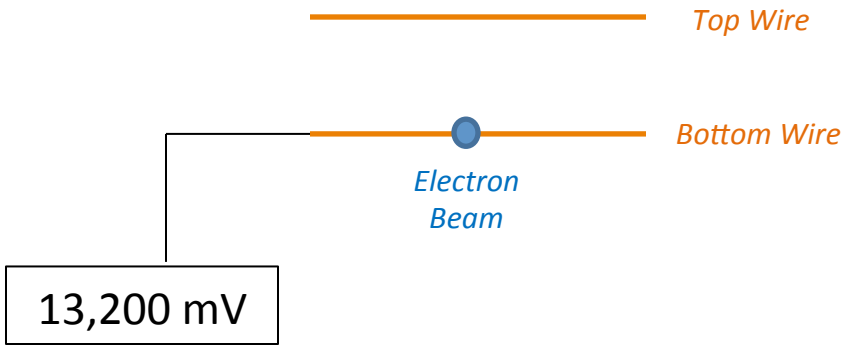
Experiment

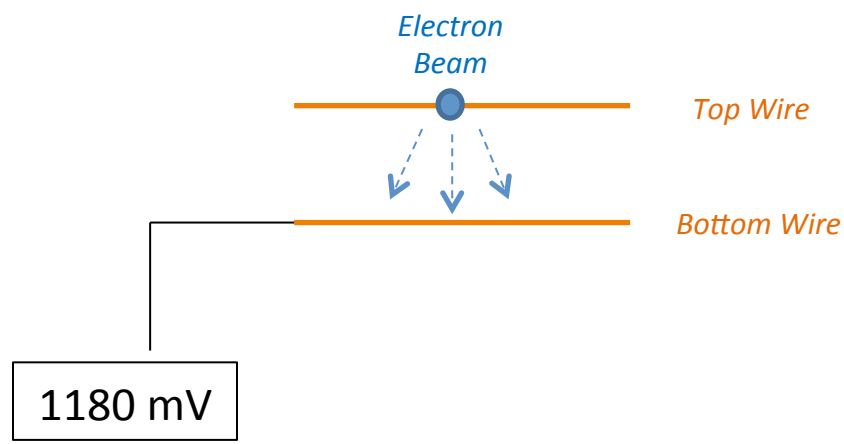
- Unexpected complications:
  - As we swept the electron beam downward (or upward), it would suddenly deflect in the opposite direction and then disappear altogether.
  - The electron beam would disappear longer than expected if blocked by the wire, and in fact never reappeared until the beam was steered back up (down) from the unknown obstacle.
  - ➢ Electron beam "charged" wire even with no applied current/voltage.
  - ➢ Negatively charged wire would then interact with the negatively charged beam.

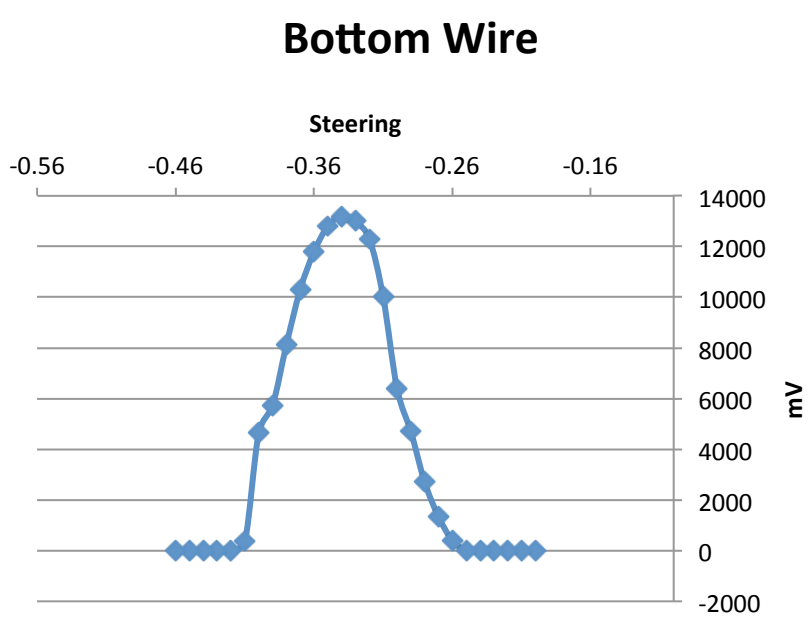
Experiment

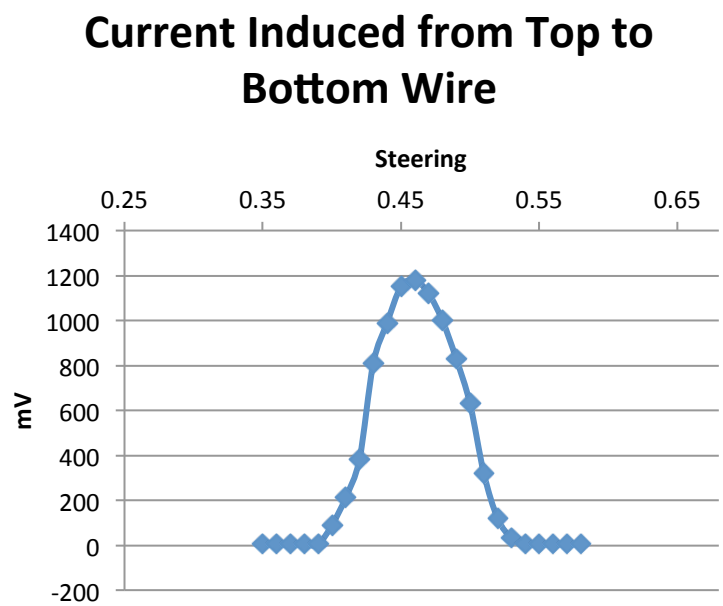
- Solution:
  - "Find" the *unpowered* wire by passing the e-beam across it and recording the induced voltage that returns to the instruments.
    - When the voltage is non-zero, the beam is close enough to charge the wire.
    - When the voltage is at a maximum, beam is directly on the wire.
    - Max voltage recorded corresponded very well to estimated size of wire on screen.
  - Still unable to get the electron beam close to the wires, limiting our experimental abilities.

Experiment


Top Wire
Bottom Wire
Electron Beam
13,200 mV


Electron Beam
Top Wire
Bottom Wire
1180 mV

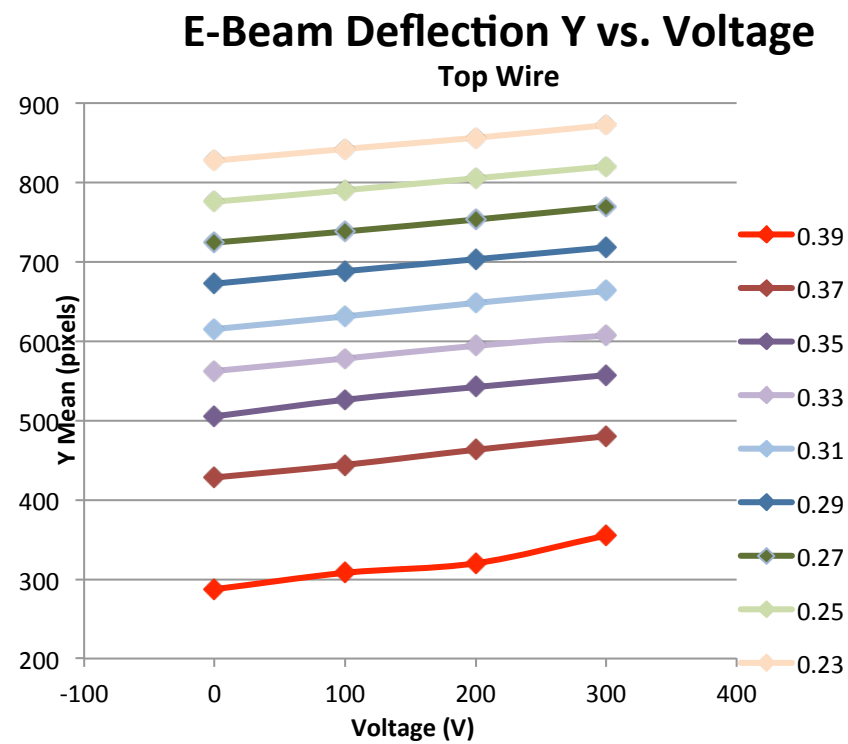

Bottom Wire
Steering
-0.56
-0.46
-0.36
-0.26
-0.16
14000
12000
10000
8000
6000
4000
2000
0
-2000
mV


Current Induced from Top to Bottom Wire
Steering
0.25
0.35
0.45
0.55
0.65
1400
1200
1000
800
600
400
200
0
-200
mV

Experiment

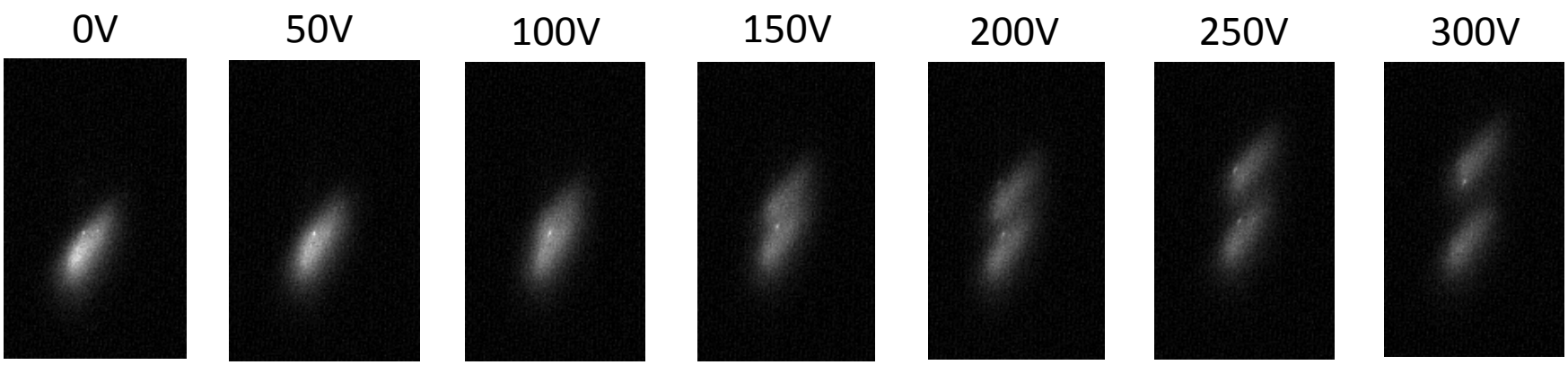
- Deflection measurements

Steering	0V	100V	200V	300V	Max Y Deflection
0.39	287	308	320	355	68
0.37	428	444	463	480	52
0.35	505	526	542	557	52
0.33	562	578	594	607	45
0.31	615	631	648	663	48
0.29	672	688	703	718	46
0.27	724	738	753	769	45
0.25	775	790	805	820	45
0.23	827	842	856	872	45



Experiment

- Pulsed beam
  - E-beam image pulsed at 40 microseconds.
  - Pulsed voltage at 20 microseconds
  - Half of image shows electrons deflecting due to the pulse; half shows electrons with no deflection.



Experimental Conclusions

- The effect appears to agree qualitatively with theory but exact replication is difficult without using an actual proton beam for more testing.

End of Summer Conclusions

- Conclusions:
  - “Fast” deflector can capture reasonably accurate transverse sigma in a single sweep within the parameters proposed for Project X.
  - “Slow” deflector can capture reasonably accurate transverse and longitudinal sigmas using at least 150 measurements.
  - Initial experiments confirm the validity of using an electron beam profile monitor for future experiments such as Project X.

End of Summer Conclusions

- Future research:
  - Need to develop and test a fast and/or slow deflector.
  - Experiments with an actual proton beam should be done to ensure effects match simulation/theory, and to validate analysis techniques.
  - More simulation data should be collected with each varying parameter:
    - Effects at higher intensities/lower energies need more data.
  - Better analysis techniques may be developed with more simulated and experimental trials.

Questions?

Acknowledgements

This work was supported by Fermi National Accelerator Laboratory and the U.S. Department of Energy, Office of Science. I would like to thank my mentors, Manfred Wendt and Randy Thurman-Keup. I would also like to thank Amber Johnson for her assistance.

References

[1] M. Wendt, et al., "Beam Instrumentation for Future High Intense Hadron Accelerators at Fermilab," 42nd ICFA Advanced Beam Dynamics Workshop on High-Intensity, High-Brightness Hadron Beams (HB 2008), August 2008.

[2] Paul D. Goldan, "Collisionless Sheath: An Experimental Investigation," *Physics of Fluids,* Vol. 13, pp. 1055-1059, April 1970.

[3] W. Blokland and S. Cousineau, "A Non-Destructive Profile Monitor for High Intensity Beams," 2011 Particle Accelerator Conference, March 2011.

[4] A. Aleksandrov, et al., "Feasibility Study of Using an Electron Beam for Profile Measurements in the SNS Accumulator Ring," 2005 Particle Accelerator Conference, p. 2588, May 2005.

[5] R. Thurman-Keup, et al., "Initial Characterization of a Commercial Electron Gun for Profiling High Intensity Proton Beams in Project X," 2011 Particle Accelerator Conference, March 2011.