A Method for Real Time Monitoring of Charged Particle Beam Profile and Fluence

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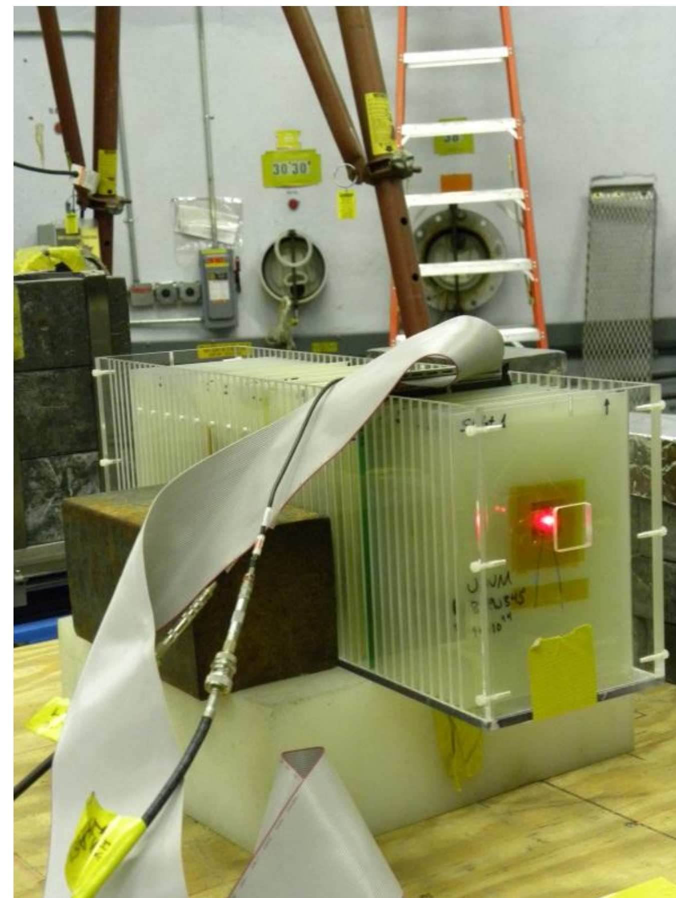
Outline

- Introduction and Motivation
- Hardware
- Software
- Hardware Calibration and Beam Profile Characterization
- Experimental Results

Motivation

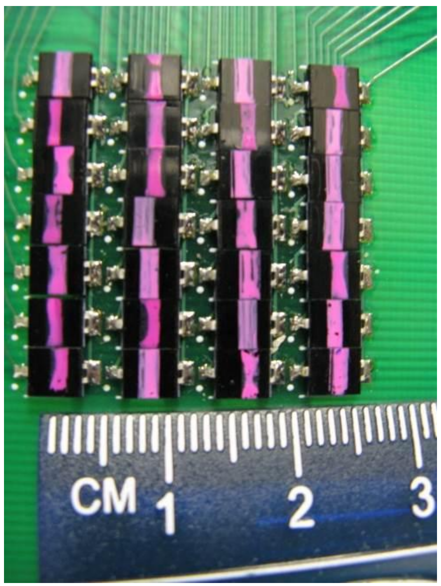
- Materials and equipment within a high radiation environment, such as those found at the LHC, undergo a loss of performance and accelerated aging as a consequence of the energy transferred by the radiation
- In order to develop instrumentation for these environments, it is necessary to understand the interactions between high-energy particles and materials
- To measure the radiation damage of the components of the detector systems, prototypes are irradiated at test beam facilities that can reproduce the radiation environment at the LHC



- The particle fluence and its profile in the test beam must be known; this is usually done with techniques such as thin metal foil activation and flying wires
- However, these techniques are often slow, have large uncertainties, and/or must be performed after the fact, i.e. when the beam is off
- We have developed a method of measuring both the beam profile and fluence of a charged particle beam in real time using a **matrix of forward-biased diodes**, by measuring the change of the voltage drop across each p-n junction as a function of fluence
- While the metal foil activation method provides the most precise measurement of fluence, the diode array can be used for **rapid, reliable, in-situ** estimates to a precision of under 11%
- This can be fed back to adjust beam properties as needed

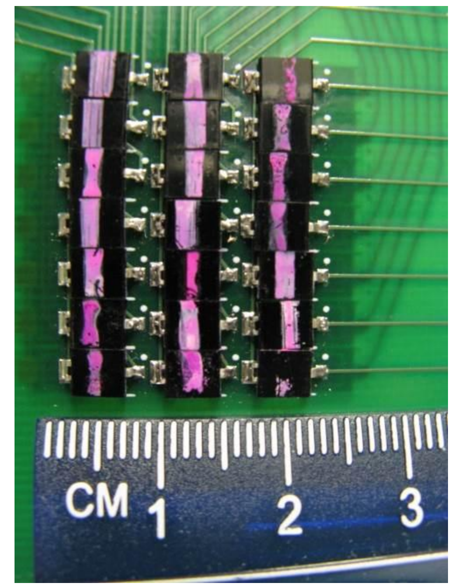
Hardware:
The Custom Diode Array

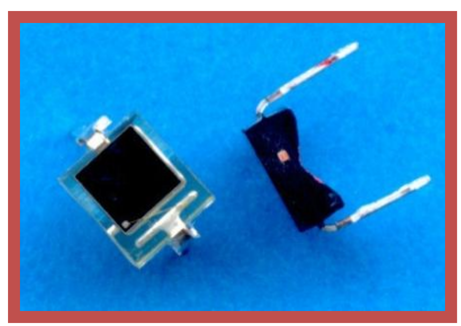
- The diode array consists of a 7x7 matrix of OSRAM BPW34F *p-i-n* diodes soldered to back-to-back metalized pads on both sides of a G10 board, with four columns on the front and three on the back



Front

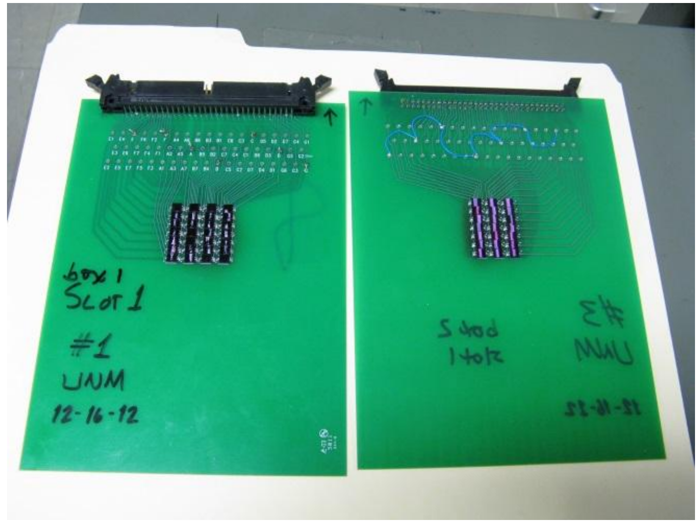
Back





- The array has an active area of 2.5 cm^2, with a diode pitch of 0.4 mm

Front



Back

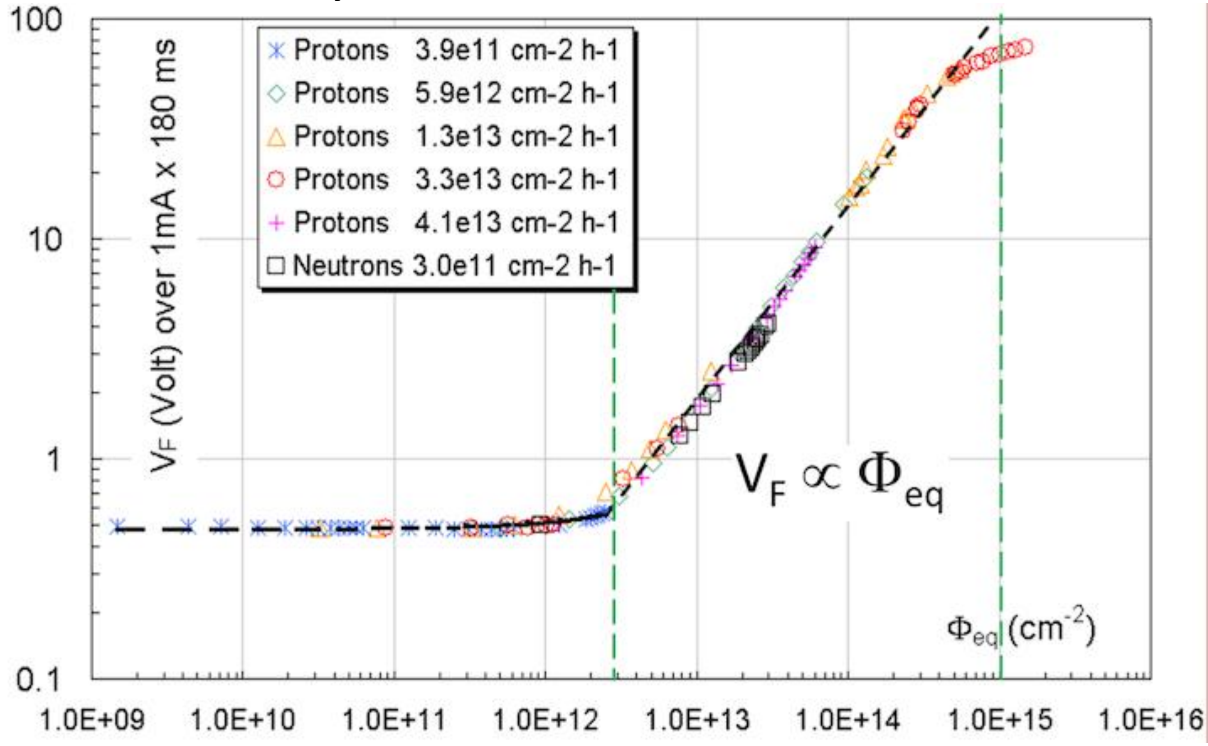
- When p-i-n diodes with high-resistivity silicon bases are operated under conditions of low injection, the concentration of carriers in the base region varies such that the resistivity changes, as a function of the charged particle fluence:

$$\rho = \rho_0 e^{\Phi / K_\rho}$$

where ρ_0 is the equilibrium resistivity before irradiation, Φ is the charged particle fluence, and the coefficient K_ρ has a value between 400 and 3000 cm^{-2}, depending on the type of silicon and the material properties of the diode

- According to a 2007 study by Federico Ravotti (CERN-THESIS-2007-013), with constant current, forward voltage across an OSRAM BPW34F *p-i-n* diode increases linearly with fluence

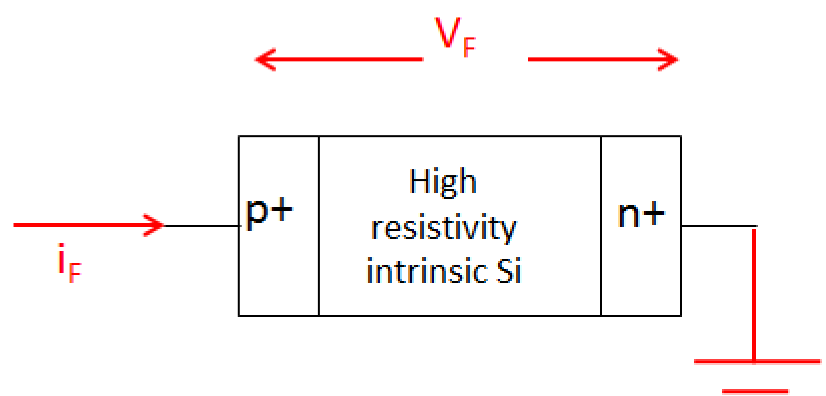
From Ravotti's calibration using 24 GeV protons from CERN's IRRAD1 facility, and the neutron environment at the IRRAD2 facility



- We use the OSRAM BPW34F *p-i-n* diodes to measure fluence because of ease of readout, high spatial resolution (useful for profile measurement), wide range of fluence response, dose rate independence, commercial availability, and low cost
- However, the *p-i-n* diode's forward voltage is temperature dependent; we minimize self-heating by sourcing the 1mA current in 130 ms pulses

Hardware: Diode Array Readout

- Readout of the diode array is performed by a custom LabVIEW program, which is able to scan all 49 channels quickly and remotely, without needing to stop the beam
- Our system makes use of a Keithley 2410 Sourcemeter, a Keithley 706 scanner, and a computer
- To scan a specific channel, the sourcemeter sources a 1 mA pulse of current and reads out the forward voltage across the *p-n* junction, with no special humidity requirements necessary

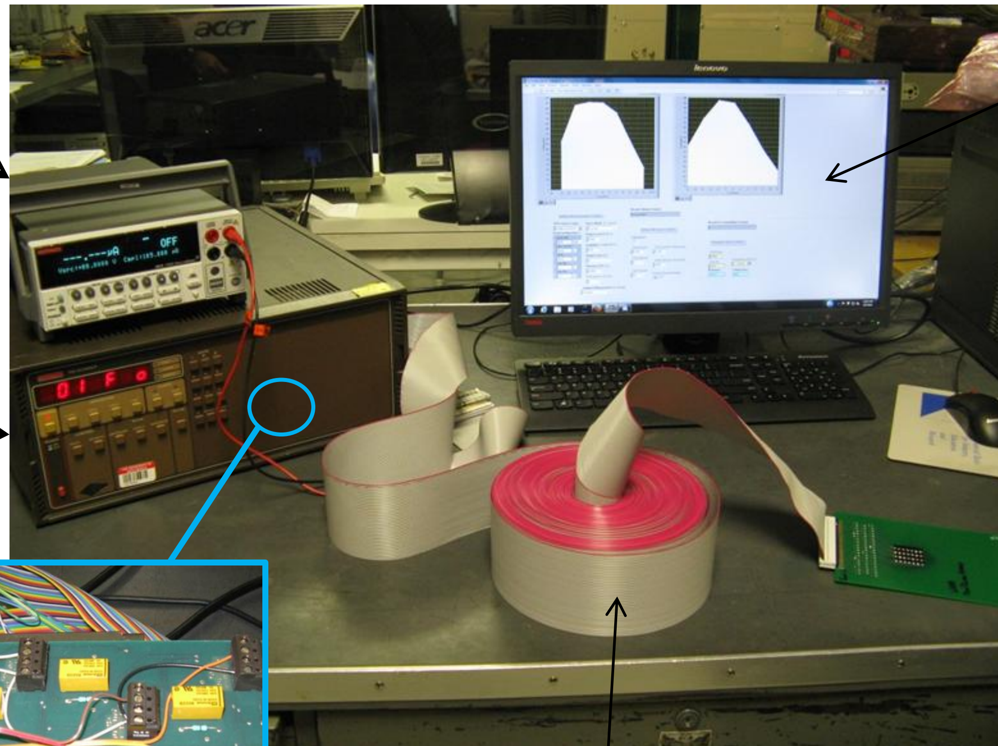


- A long cable (30+ m) connects the readout hardware in a radiation-safe zone to the array in the beam path

Readout Equipment

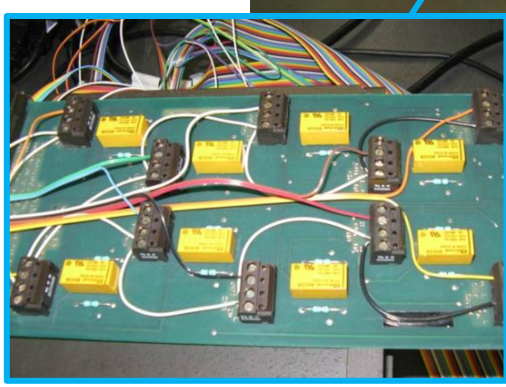
Keithley 2410 Sourcemeter

Custom LabView Software



Keithley 706 Switchboard Scanner

Diode Array

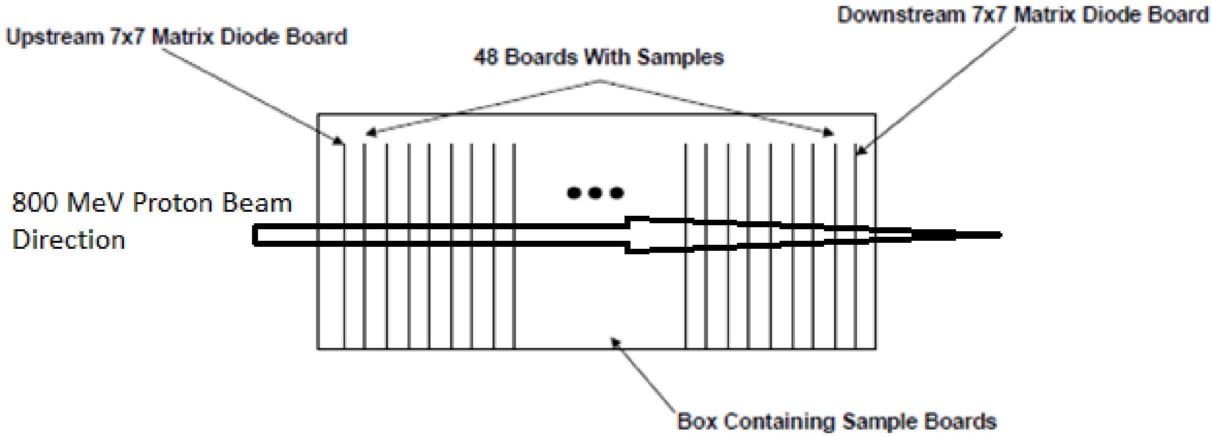


30m Ribbon Cable

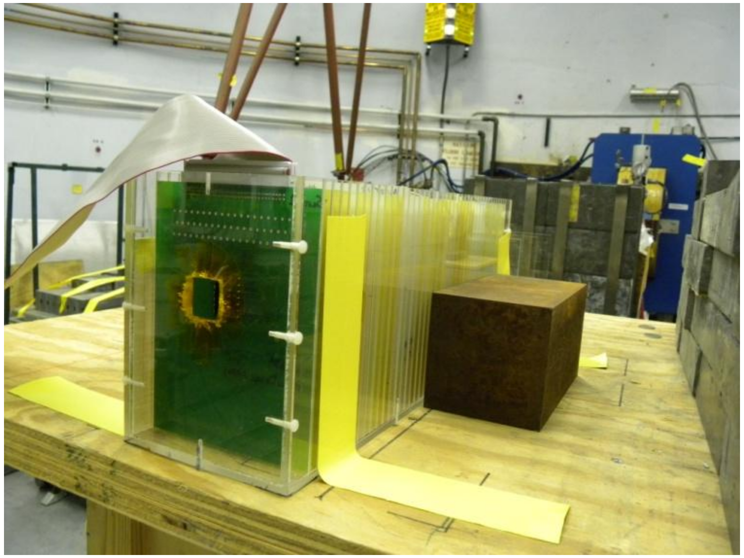
Switchboard

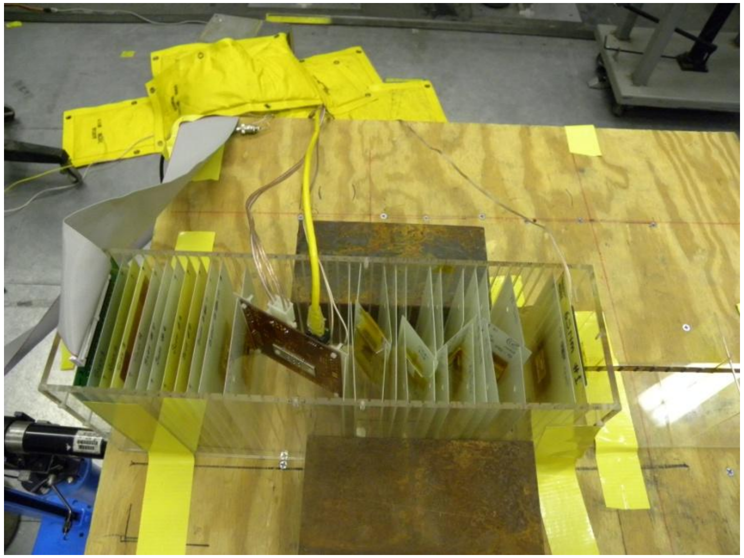
- We have two separate arrays, one upstream and one downstream of the beam path

- A diagram of the stack box:

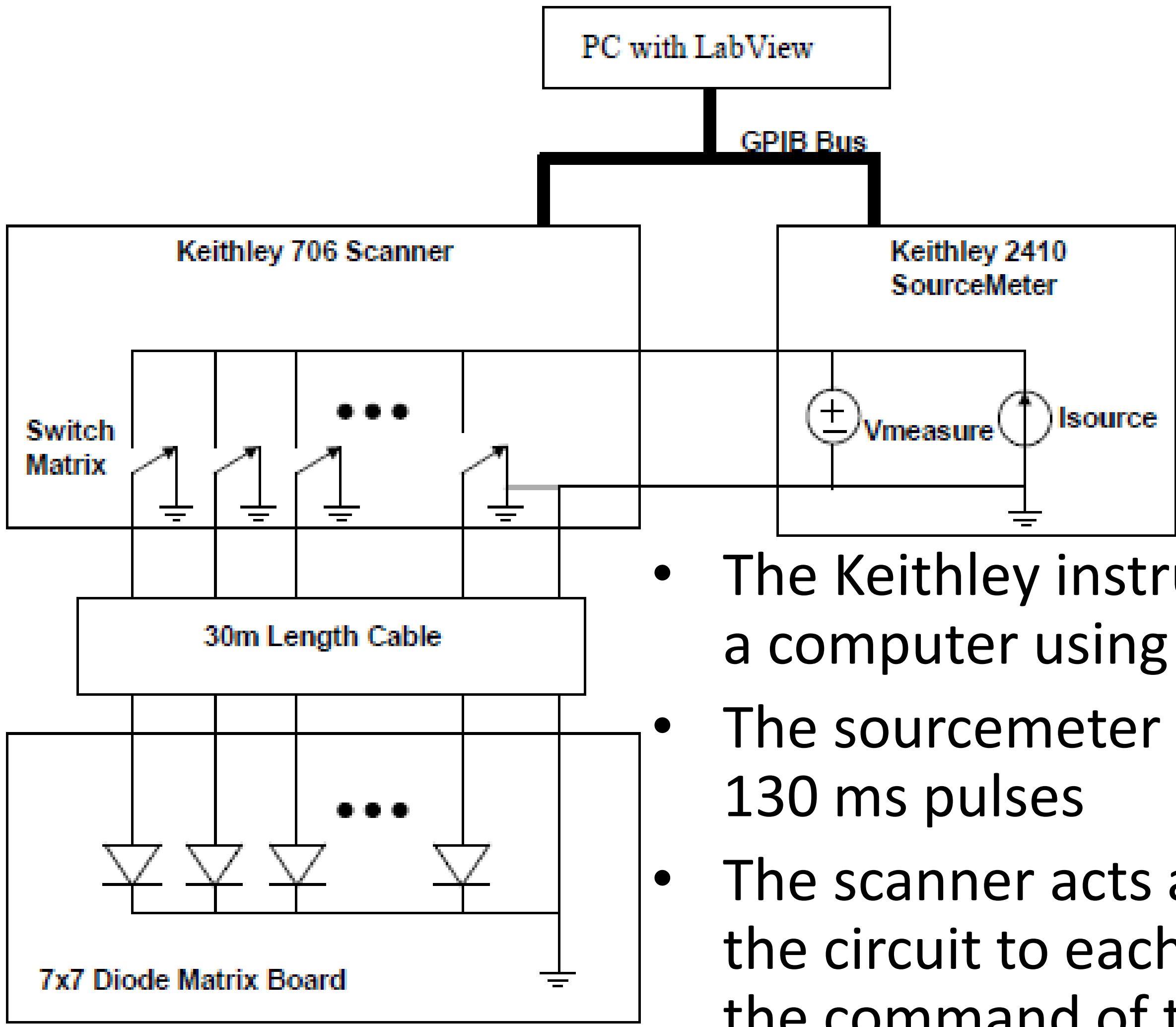


- In between are all the items to be irradiated, usually attached to a G10 board, as well as aluminum foils to get a more precise determination of the beam's fluence and profile after the irradiation





Readout Circuit diagram



- The Keithley instruments are controlled by a computer using LabVIEW
- The sourcemeter sources a 1 mA current in 130 ms pulses
- The scanner acts as a switch board, closing the circuit to each diode sequentially at the command of the LabView program
- A 30m ribbon cable connects the diode array to the scanner

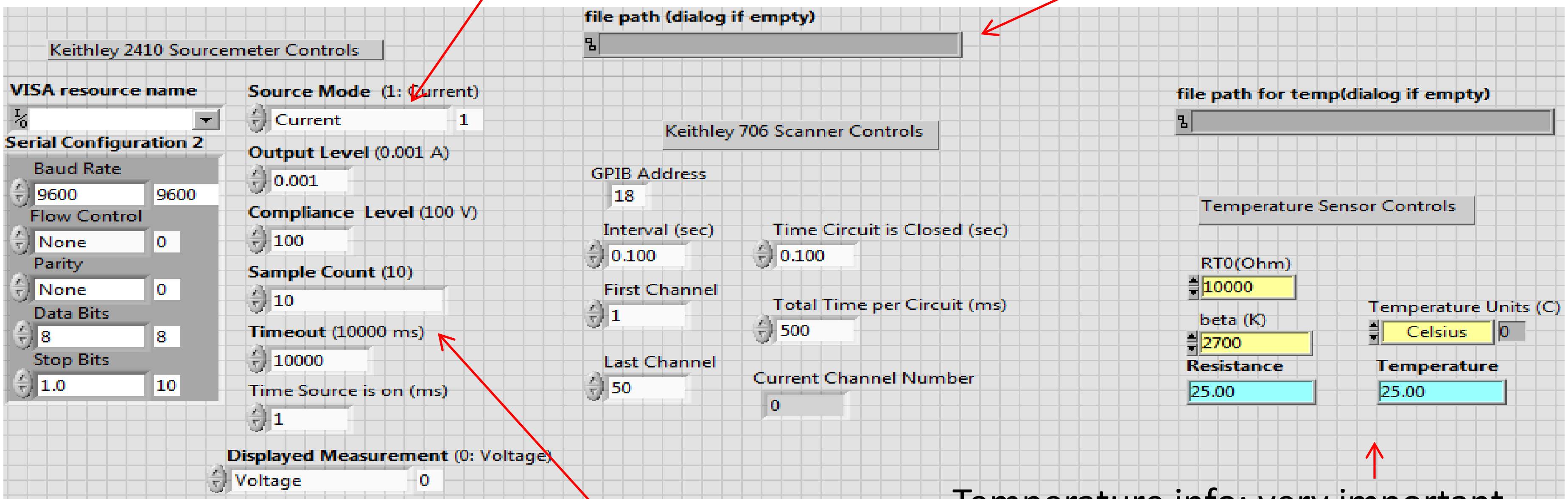
Software: LabVIEW

- Custom LabVIEW software is used to quickly and automatically scan all 49 diodes
- The program, in addition to the main .vi, includes some 24 sub .vi's, including drivers for the Keithley readout equipment
- This system is capable of scanning all diodes in the matrix in under a minute
- The software can also measure temperature, using the thermocouple on the board; due to the diodes' sensitivity to temperature, knowing the temperature is important for minimizing uncertainties

The LabVIEW Front Panel

Can Source Current or Voltage

File output



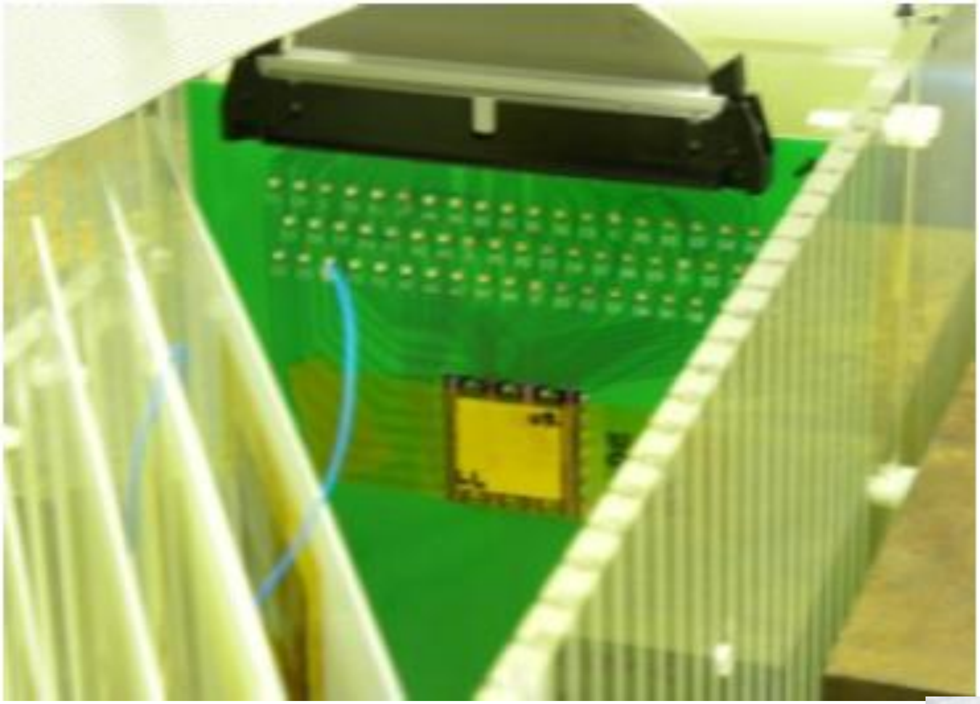
10 samples are taken per diode and averaged

Temperature info; very important, due to diodes' temperature sensitivity

- Design of program makes it possible to source either current or voltage
- The circuit to every channel is closed for 130 ms; 10 samples of the voltage are taken during that time and averaged
- The temperature of the diode array can also be monitored and used to correct the result

Hardware Calibration

- Aluminum foil activation was used to calibrate the fluence for the two diode arrays for the Los Alamos Neutron Science Center (LANSCE) 800 MeV proton beam
- The accelerator generates bunches of 5×10^{11} protons per pulse, at a current of 80 µA, with 90% of the protons specified to be in a ~2 cm diameter
- Foils were used measure fluence, with a 4x4 segmented foil attached directly to the upstream and downstream arrays
- At various points in the irradiation, a measurement was taken from the diode array and an unattached foil was removed, to be measured later
- The fluence was determined as normal for thin metal foil activation and compared to the diode data for calibration, with the segmented foil being used for profile characterization
- This calibration need be performed only once



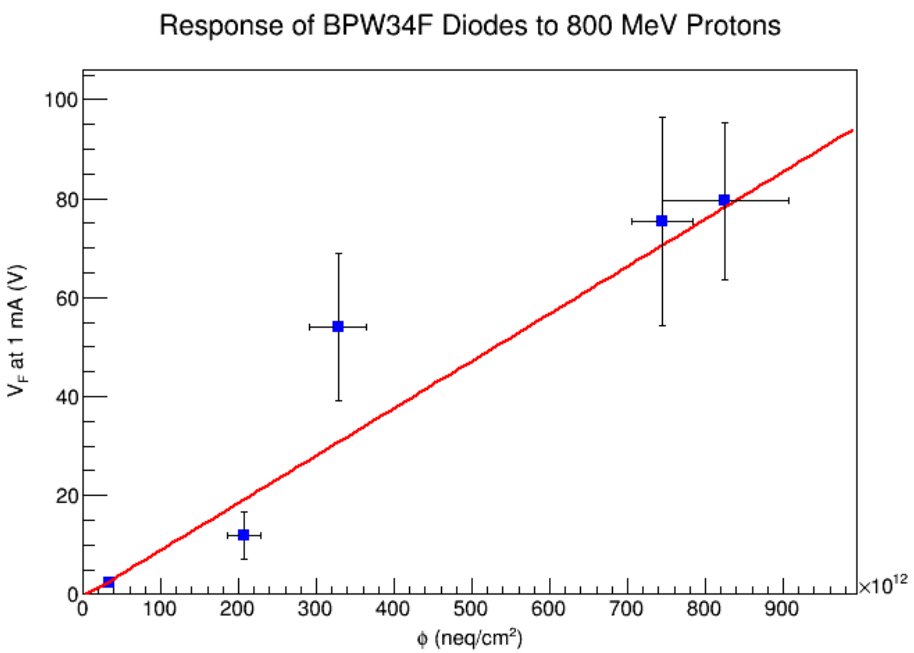
- Aluminum foil matrix attached directly to diode array

- Aluminum foil matrix close-up

- Measurements with the diode array are used as a real time check of the fluence, in order to be used as feedback to adjust the properties of the beam; however, as diodes can only measure fluence indirectly, the aluminum foil technique is used for full fluence measurement
- The fluence received by the diode is given by the equation

$$\Phi_{eq} = \frac{\Delta V_F}{c}$$

where Φ_{eq} is the 1 MeV neutron equivalent fluence, c is the linearity coefficient, and ΔV_F is the forward voltage



- For 800 MeV protons, we measured c= $(9.56 \pm 1.54) \times 10^{-14}$ V/cm^2
- Ravotti's 2007 study found that, for this type of diode, c=$(10.989 \pm 2.1978) \times 10^{-14}$ V/cm^2 when measured with 24 GeV protons

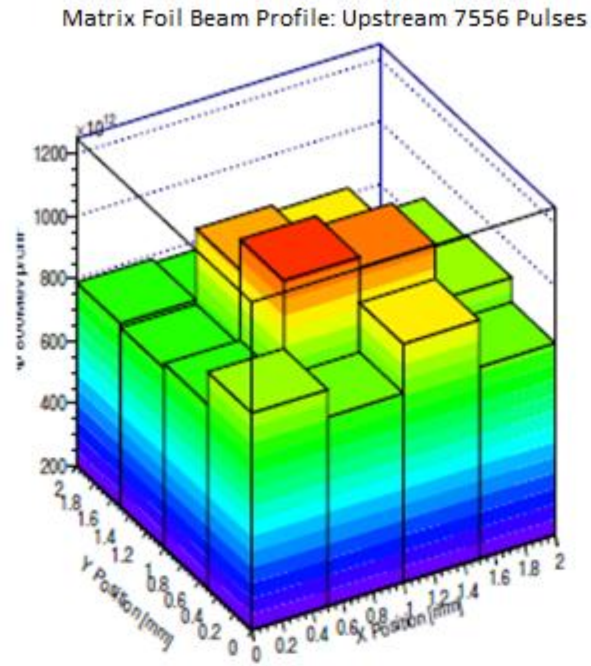
Beam Profile Characterization

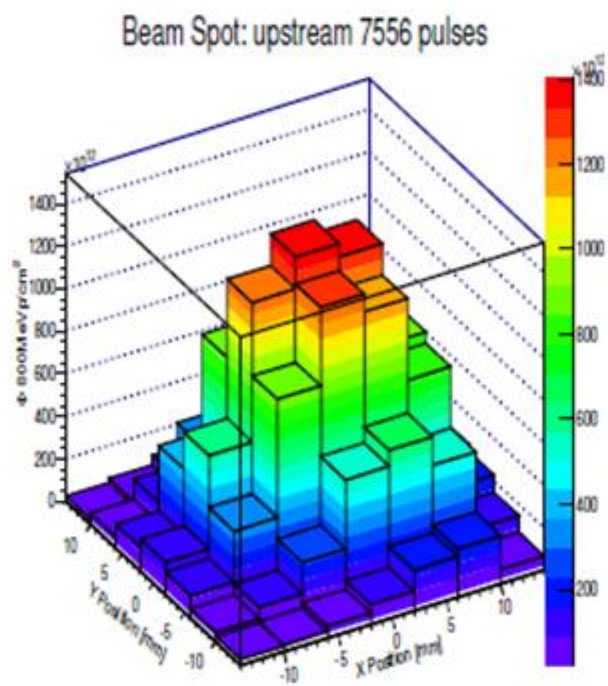
- Once the diode response to fluence has been calibrated, characterization of the beam profile can be performed
- Characterization is primarily a process of determining the intensity and spread of the beam, and can be done visually, once the data are gathered and displayed by the software
- The resolution of the charged particle beam profile measurements depends on the diode density; because the readout is digital, the resolution is given by $p/\sqrt{12}$, where “p” is the pitch, the distance between the centers of two adjacent diodes
- This gives us a resolution of 0.12 mm

Aluminum Foil Matrix

- The diode array data were taken on the spot in under a minute; the foils had to be manually removed and weren't measured until several days later

Diode Array





Example Measurement

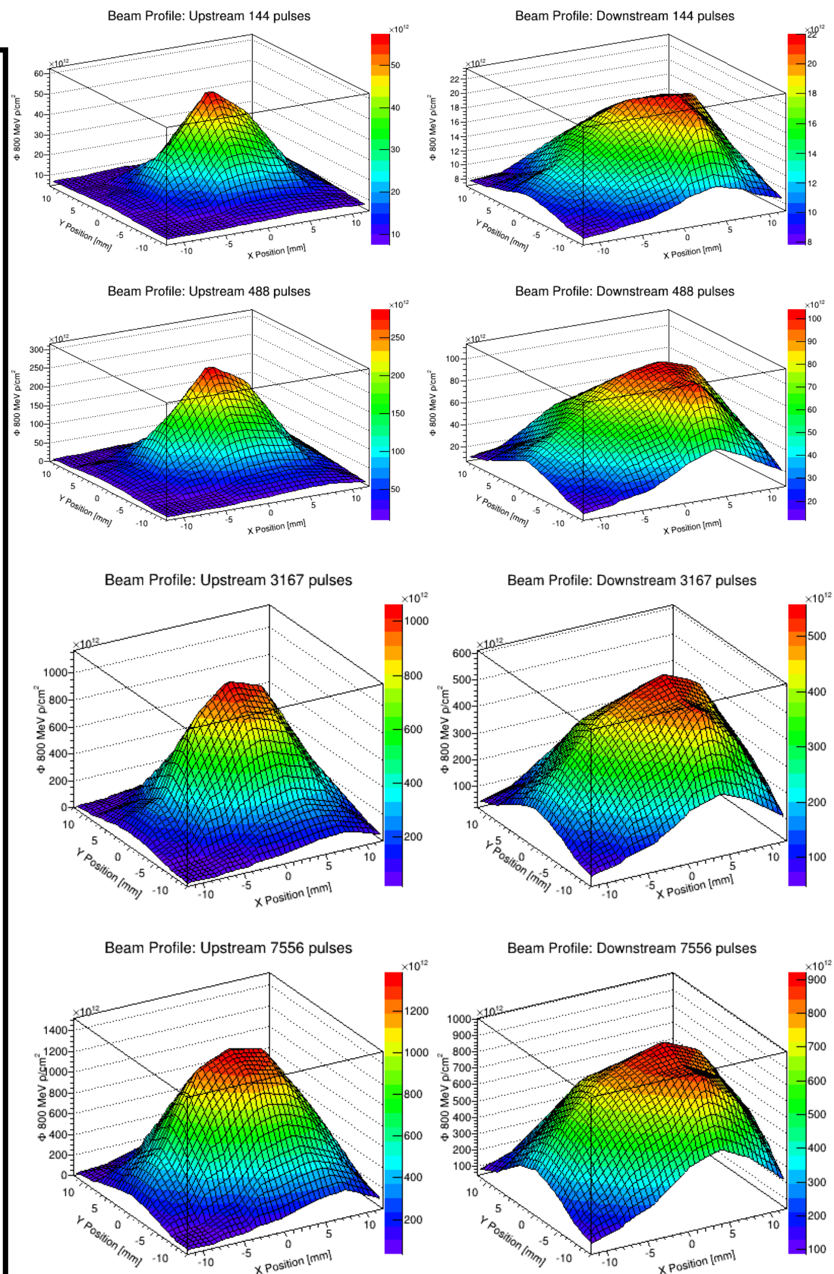
- Two diode arrays were irradiated at LANSCE in September 2012
- The arrays were placed in the first (upstream) and last (downstream) slots in the stack box, with about 40 300 μm silicon wafers between them
- By observing the spread and depletion of the beam as it passes through the stack, we can correct the beam's characteristics in order to ensure even exposure throughout the stack

~10^{13} protons

Increasing Fluence

~10^{15} protons

Upstream **Downstream**



Systematic Uncertainties

- Over a 130 ms pulse, there is heating in the diode, leading to an uncertainty in voltage of about 5%; however, this uncertainty can be made negligible for arbitrarily short pulses
- Using a 30m length cable produces an uncertainty of 9% in voltage measurement, due to noise and drop from the length of the cable; note that this can be reduced using a 4-wire sense measurement
- The Keithley 2410 Sourcemeter can measure voltages to a precision of 0.015% + 50 mV offset; however, as we are only interested in the change in voltage drop between the unirradiated and irradiated diode, the offset can be ignored
- The voltage uncertainty due to the temperature coefficient of the OSRAM BPW34F *p-i-n* diodes is about 2.6%
- The total uncertainty in the measurement of the voltage (fluence), determined by summing in quadrature, is ~11%

Conclusions

- By placing a diode array upstream and downstream on a charged particle beam, it can be used to rapidly and precisely determine both the beam's profile, and its fluence to a precision of ~11%
- This precision can be improved using a 4-wire measurement to compensate for the voltage drop in the cable, and shorter pulses to minimize self-heating of the diode
- This is comparable to the precision of the aluminum foil activation technique, which gives a precision of ~10% over an hour of measurement
- More importantly, the diode array technique can be used to determine fluence and profile in real time
- This means that if the beam needs adjustment, this can be known and corrected immediately
- This makes the array a significant time-saver, as it makes it possible for an experimenter to know about problems on-the-spot, rather than after the fact

Alternate Measurement Paradigms

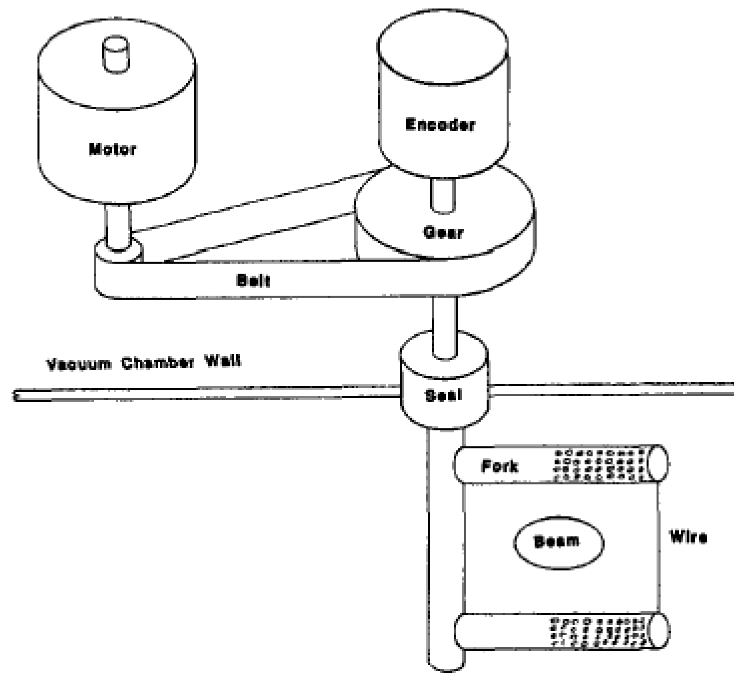
- Thin Metal Foil Activation
- Flying Wire
- Faraday Cups

Thin Metal Foil Activation

- Makes use of thin metal foils (often aluminum) placed in the path of a beam to determine fluence
- If the foil is segmented into a matrix, or radiographic image analysis is used, this technique can also be used to measure the beam’s profile
- While very precise, with a precision of 10% over an hour of measurement and increasing with time spent measuring, this technique can only be used after the fact

Flying Wire

- A system that measures transverse beam profile by moving a 25 µm carbon wire through the through the beam, which generates a spray of secondary particles with an intensity proportional to the number of beam particles present at the position of the wire
- By doing so, a computer can quickly create a picture of the beam profile, and can do so faster than the diode array (~3 s vs. ~50 s)
- Recent versions of this technique have attained a repeatability between 1-2% RMS
- However, this technique requires a significant amount of machinery, can have large uncertainties from heating, and can suffer from wire breakage, requiring the shutting down of the beam and replacement



Faraday Cups

- A conductive cup that is designed to catch charged particles in a vacuum; the resulting current can be measured to determine the number of ions or electrons hitting the cup
- While very accurate, due to the direct relationship between the number of charged particles that have hit the cup and the current, they are not very sensitive, with a current of only about 1 nA resulting from ~6 x 10^9 ions striking the cup

Ravotti's Measurement Protocol

- Previous papers found that injecting high current into a diode caused self-heating, increasing the voltage drop across the diode
- In irradiated diodes, this heating also lead to enhanced annealing
- By measuring several irradiated and control diodes with 1 mA current, Ravotti found that a current pulse of 50-700 ms helped to minimize the heating from the small current
- If the power dissipated in the base of the (unirradiated) diode is estimated as P = V*I, where V is the voltage drop and I the current, then the average power dissipated is 3mW
- From this value the energy deposition during readout can be calculated using the equation Q = P*t ~ 3 x 10^{-5} J
- Assuming a specific heat capacity of 0.7 $Jg^{-1}°C^{-1}$, and a mass of the diode of ~2.8mg, the change in temperature per 10 ms would be:

$\Delta T = \frac{Q}{c*m} = 0.015°C,$ increasing to 0.08 °C for an irradiated diode