Long Island Consultants Network

Ionization Profile Monitors for Particle Accelerators

POEM Technology

Arnold Stillman

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Outline

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Acceleration of charged particles

- **Electric Field Acceleration**
  Accelerators boost the motion of charged particles by means of oscillatory electric fields at RF frequencies.
- **Drift Tubes**
  The voltages on adjacent hollow electrodes, called drift tubes, are 180 degrees out of phase with each other. A charged particle traveling through the center of the drift tube is shielded from the electrode's field until it exits the tube.
- **Drift Tube Geometry**
  As the particle gains energy and inertia, the distance between ”kicks” lengthens and the drift tubes get longer

Linear Accelerator Drift Tubes

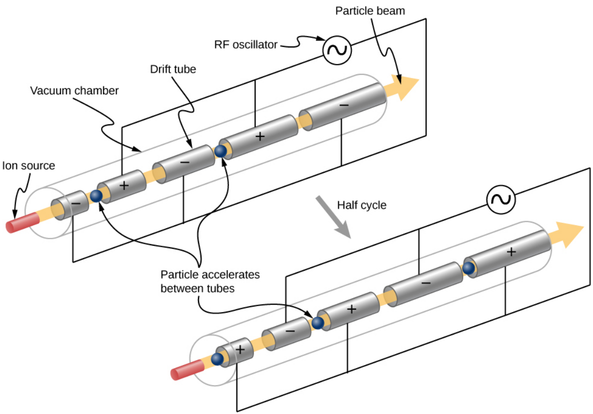


Figure 1: The alternating RF phase of the drift tube potentials accelerates particles in a series of electric kicks. Each tube is longer than the preceding tube because the particle is moving faster as it accelerates.

Linear Accelerator Drift Tubes

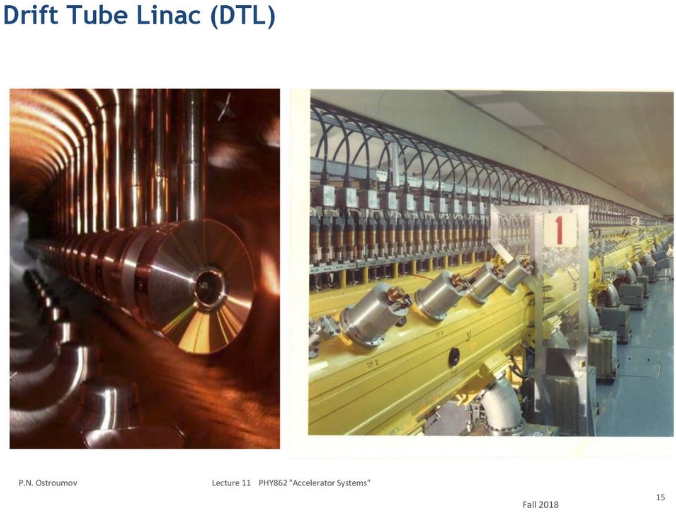


Figure 2: Examples of Drift Tubes and a LINAC

Bunching of Particle Beams

- **RF Acceleration**
  It is impossible to accelerate a uniform distribution of charged particles. As the RF frequency rises to accelerate the beam, some of the particles are in phase with the field but some are lagging, not having reached the peak electric field yet.
- **Bunching**
  This bunching pertains until all the beam is captured in RF ”buckets”. It is exactly the inverse of bunching at a traffic light, which induces the bunching by enforcing deceleration.

Vacuum Requirements

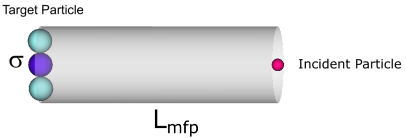
All accelerators operate with a significant vacuum in the beam pipe. The vacuum eliminates unwanted scattering, or ”blowing up” of the beam due to collisions with remnant gas particles.

The AGS Booster Vacuum

In the AGS Booster, after heating and pumping for several days, the remaining gas in the beam pipe is carbon dioxide, at a pressure of $\approx 10^{-10} - 10^{-11}$ Torr. This pressure corresponds to a gas density of about $10^{-5}\mathrm{CO}_2$ molecules cm^{-3}, almost the vacuum of space near Earth.

Mean Free Path

Ideally, one
wants an unimpeded beam path to eliminate particles scattering off gas molecules and out of the beam.



The distance between
collisions is the mean free path for interactions.
An approximation to the mean free path is;

$$L_{mfp} = \frac{1}{\rho\sigma},$$

where ρ is the gas density and σ is the cross-sectional area for interaction.

Mean Free Path

Mean Free Path

With this density and a cross section of about three times the area of a carbon dioxide molecule, the mean free path is over 10^5 kilometers in the AGS Booster. The low density of gas molecules will determine the weak input signal to any detection element.

Accelerator Magnets:Quadrupoles

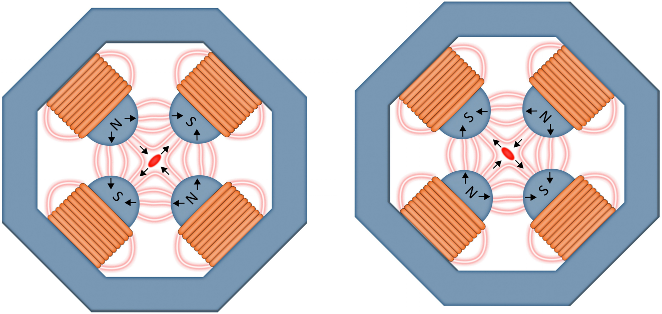


Figure 3: Only quadrupole or higher even-moment magnetic fields allow for focusing the beam to small dimensions. Since a quadrupole only focuses in one plane but defocuses in the other, two are necessary to focus in the x and y planes.

Accelerator Magnets:Quadrupoles

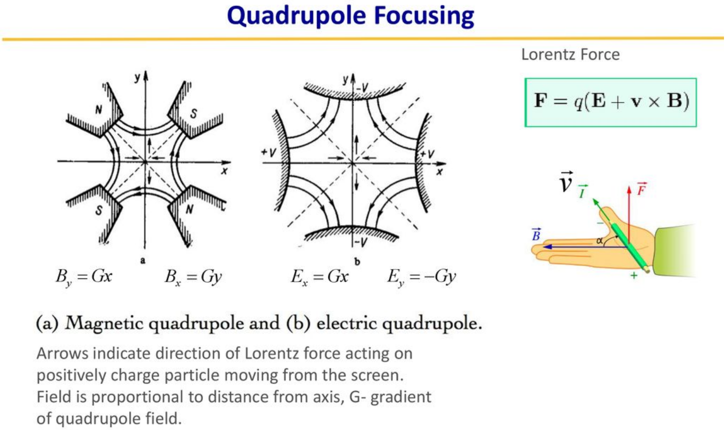


Figure 4: How Quadrupoles Focus[1]

Accelerator Magnets:Sextupoles

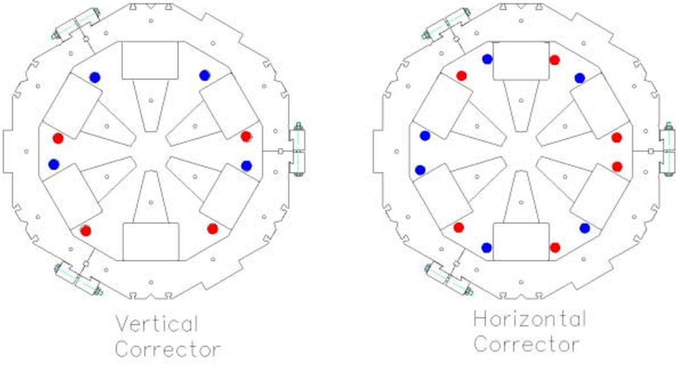


Figure 5: Sextupole magnets control chromatic aberrations caused by the inherent velocity distribution of the beam particles.

Circular Accelerator Magnets:Dipoles

Dipole magnets bend the beam into a circular path and also determine the maximum energy a beam will reach.

$$\frac{mv^2}{R} = \frac{q}{c}|\vec{v} \times \vec{B}|$$

or

$$R = \frac{mvc}{qB} = \frac{mc^2 v}{qBc} = \frac{v}{c}\frac{mc^2}{qB} = \frac{\gamma mc^2}{qB} = \frac{E}{qB}.$$

So finally,

$$R = \frac{E}{qB}.$$

Circular Accelerator Magnets:Dipoles

The Maximum Energy

The maximum energy of an accelerator particle, ignoring radiative losses, is

$$E = qBR.$$

For a proton energies in GeV, $BR = 300\,\mathrm{T\,km}$.
The largest accelerator magnets have $B \approx 8\mathrm{T}$.

The Accelerator Lattice

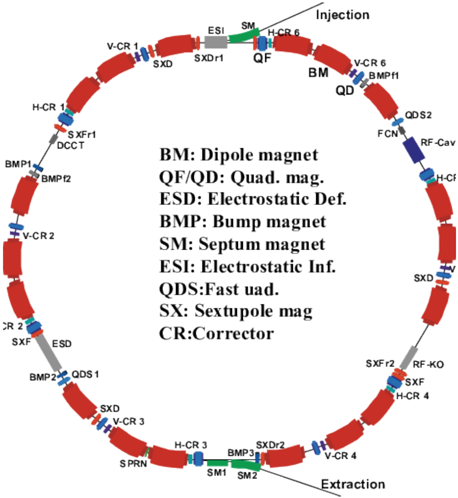


Figure 6: In a circular accelerator,

Basic Synchrotron and Beam Properties

- **Beam Temperature/Emittance**
  - **Bunching**
    The particles in a beam are arranged in bunches throughout the accelerator. In the frame of reference of the bunch, the particles have a distribution of velocities, a temperature.

Basic Synchrotron and Beam Properties

- **Emittance**
  For experimental purposes, a tightly focused beam is necessary and the mean thermal energy should be minimized. A measure of this mean thermal energy is known as emittance.

Basic Synchrotron and Beam Properties

- **Phase Space**
  Equivalently, it is also the area of the momentum/position phase space occupied by the bunch particles.

Basic Synchrotron and Beam Properties

- **Beam Position**
  - **Radial Forces**
    As the energy of the particle increases, the magnetic confining field must ramp up to keep it from crashing into the beam pipe and being lost.
  - **The Radial Position**
    The interplay of magnetic ramp and accelerating force keeps the particle in its radial position.
  - **Feedback by Monitoring**
    Knowing this radial position is one of the goals of a profile monitor.

Basic Synchrotron and Beam Properties

- **Beam Momentum**
  - **Particle Momentum and Radial Position**
    As the particle energy increases, so does its longitudinal momentum.
  - **Transverse Momentum**
    To conserve phase space area, or emittance, the transverse momentum must shrink.

Basic Synchrotron and Beam Properties

- **Tune**
  - **The Field Lattice**
    The acceleration fields and magnetic fields occur at discrete positions in the ring.
  - **Betatron Oscillations**
    The fields induce kicks to the particle, leading to transverse and longitudinal oscillations of position, known as betatron oscillations.

Basic Synchrotron and Beam Properties

- **Betatron Resonance**
  If the betatron frequency happens to share a resonance with the rotational frequency of the particle orbit, the beam will again be lost as the resonance amplitude causes it to crash into the beam pipe.
- **Tune**
  The ratio of betatron frequency to revolution frequency is the synchrotron *tune*.

Basic Synchrotron and Beam Properties

- **Chromaticity** Chromaticity is the ratio of specific tune variation to specific momentum variation of the particles,

$$\xi = \frac{\Delta\nu/\nu}{\Delta p/p}$$

where ν is the tune and p is the momentum of the beam. The dispersion,

$$D = \frac{\Delta x}{\Delta p/p}$$

is the change in beam centroid position per specific momentum variation. It transforms the chromaticity to a function of position;

$$\xi = D\frac{\Delta\nu/\nu}{\Delta x}$$

Basic Synchrotron and Beam Properties

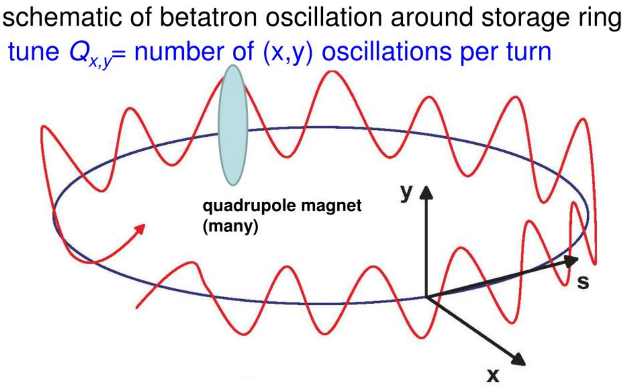


Figure 7: Betatron Oscillations [2]

IPM Theory of Operation

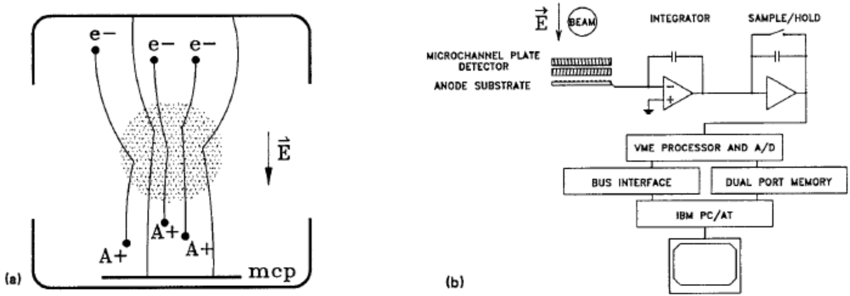


Figure 8: a. The creation of ion pairs and their drift to a micro-channel plate detector. b. Signal processing and display. The VME processor is the interface to the AGS Controls system.

IPM Theory of Operation

- **Ionization Signal**
  Residual gas ionization chambers generate a signal by collecting ions that are created by the collision of beam particles with any gas molecules present.
- **Ion Collection**
  The ions so created then travel to collecting anodes under the influence of guiding fields.
- **The AGS Booster IPM**
  The AGS Booster ionization profile monitor is unique for its use of an electric field to collect ionization signals rather than a magnetic field[3].

IPM Theory of Operation

- **The Electrodes**
  The collection volume of the ionization profile monitor (IPM) is formed by pairs of electrodes that create uniform electric fields.
  - **The Signal Collection Electrodes**
    There is one pair for horizontal profiles and one pair for vertical profiles.
  - **The Correction Electrodes**
    There is a third electrode pair to reverse any kick to the particles from collection electrodes.

IPM Theory of Operation

To create ion pairs, particles must be minimum ionizing particles. The Bethe-Bloch equation,

$$\frac{dE}{dx} = 0.3071 \frac{z^2 Z}{A\beta^2} \ln\left(\frac{2m_e c^2 \beta^2 \gamma^2}{I} - \beta^2 - \frac{\delta}{2}\right)$$

describes the energy loss of an ionizing particle with charge *ze* passing through matter with atomic number *Z* and atomic weight *A*.

- **Tabular Values**
  In practice, one uses tabulated values for the energy deposition in matter.
- **The Tabular Values for Gases**
  For gases, the table in Sauli[4] provides the energy loss in units of MeV cm^{-2}.

IPM Theory of Operation

Table 1

Properties of several gases used in proportional counters (from different sources, see the bibliography for this section). Energy loss and ion pairs per unit length are given at atmospheric pressure for minimum ionizing particles

Gas	Z	A	δ (g/cm³)	E_{ex} (eV)	E_i (eV)	I_0 (eV)	W_i	dE/dx (MeV/g cm⁻²)	dE/dx (keV/cm)	n_p (i.p./cm) a)	n_T (i.p./cm) a)
H_2	2	2	8.38×10^{-5}	10.8	15.9	15.4	37	4.03	0.34	5.2	9.2
He	2	4	1.66×10^{-4}	19.8	24.5	24.6	41	1.94	0.32	5.9	7.8
N_2	14	28	1.17×10^{-3}	8.1	16.7	15.5	35	1.68	1.96	(10)	56
O_2	16	32	1.33×10^{-3}	7.9	12.8	12.2	31	1.69	2.26	22	73
Ne	10	20.2	8.39×10^{-4}	16.6	21.5	21.6	36	1.68	1.41	12	39
Ar	18	39.9	1.66×10^{-3}	11.6	15.7	15.8	26	1.47	2.44	29.4	94
Kr	36	83.8	3.49×10^{-3}	10.0	13.9	14.0	24	1.32	4.60	(22)	192
Xe	54	131.3	5.49×10^{-3}	8.4	12.1	12.1	22	1.23	6.76	44	307
CO_2	22	44	1.86×10^{-3}	5.2	13.7	13.7	33	1.62	3.01	(34)	91
CH_4	10	16	6.70×10^{-4}		15.2	13.1	28	2.21	1.48	16	53
C_4H_{10}	34	58	2.42×10^{-3}		10.6	10.8	23	1.86	4.50	(46)	195

a) i.p. = ion pairs

Figure 9: dE/dx for various gases. Of interest for the IPM design is the number of primary electrons, n_p.

IPM Theory of Operation

The number of electrons created in Fig.9 is for gases at atmospheric pressure. The vacuum in the AGS Booster is nominally 10^{-11}Torr, so the number of ion/electron pairs created is diminished by that factor.
Using the nominal design numbers for protons in the Booster (the Booster also accelerates heavy ions), the expected current for generating a profile will be,

$$i_{signal} = (3 \times 10^{-9} Necl/(2\pi R_B),$$

where N is the number of particles in the beam, e is the elementary charge,c is the speed of light, R_B is the Booster radius and l is the length of the collection volume,

IPM Theory of Operation

- **The Signal**
  For a presumed 10^{12} protons per beam pulse and a collection length of 75mm, the estimated signal is about 5nA over the complete profile.
- **Channels**
  For reasonable sampling, there are 64 channels of position input.
- **The Tail of the Gaussian**
  By design, the profile should be Gaussian in shape horizontally and vertically. The tails will have an input current created by countably few ions, so a dual micro-channel plate provides a gain of up to 10^7.

Electrode Design

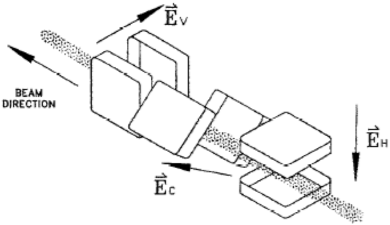
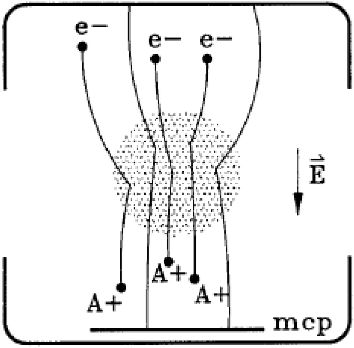


Figure 10: AGS Booster IPM Electrodes:The E_H and E_V capture horizontal and vertical profiles respectively. The E_C electrode provides the negative vector sum of the collection electrodes to correct any beam displacements.

Electrode Design

The electrodes generate an electric field intense enough to cause the ion trajectory to remain within the anode pitch.

- **Electric Field** $\approx 340\text{kV}/\text{m}$.
- **Electrode Spacing** 20.32cm, The voltage is 75kV.
- **Corrector Electrode Voltage** The correction voltage is 100kV.



Electrode Design

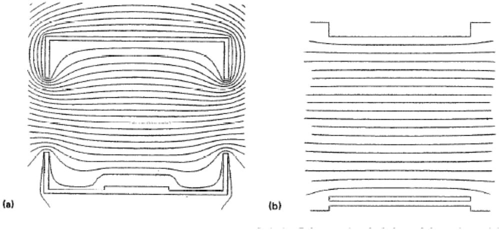


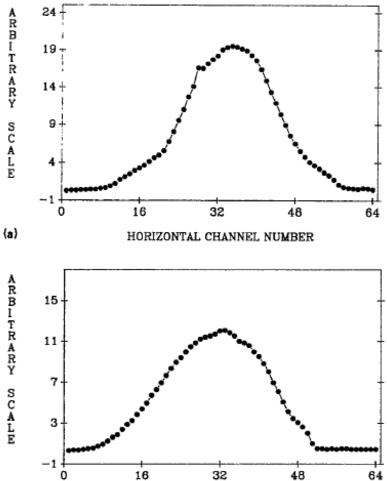
Figure 11: The Electric Field of Electrodes:Simulations show that the E-field between the electrodes is flattest when the electrodes are U-shaped. The short arms of the electrodes are one-quarter the width of the electrode.**a.**The E-field and fringe fields. **b.**The E-field between the electrodes. The rectangle near the lower electrode surface models the micro-channel plate.

The Anodes

Since the IPM sits in an ultra-high vacuum, the anodes at the exit of the micro-channel plates must be printed on a ceramic substrate to eliminate outgassing. The spacing of the anodes, 1.4mm, spans the nominal width of the design profile for proton and heavy ion operations.

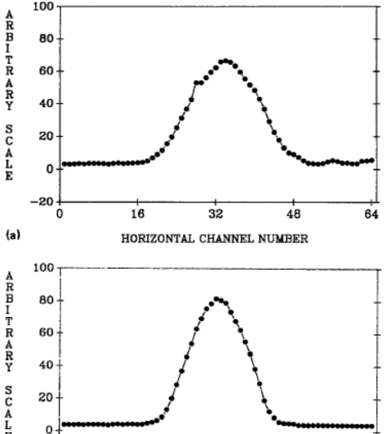
Calibration

UV calibration. There are a few unresponsive vertical channels and channel 28 in the horizontal is bad.



First Proton Results

The first profiles taken are of a proton run.



Control System Integration

To eliminate background noise, the control system takes advantage of the existence of an acceleration cycle which contains no beam to grab profile data for null subtraction. Fig.12 shows the before and after.
The live data is then acquired during the next four beam acceleration cycles. The profiles in Fig. 13 are typical.[5]

Control System Integration

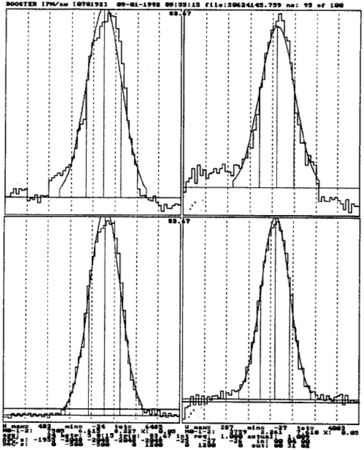


Figure 12: Background Subtraction:Horizontal is on the left and vertical is on the right. The solid lines represent the centroid and 1σ positions.

Control System Integration

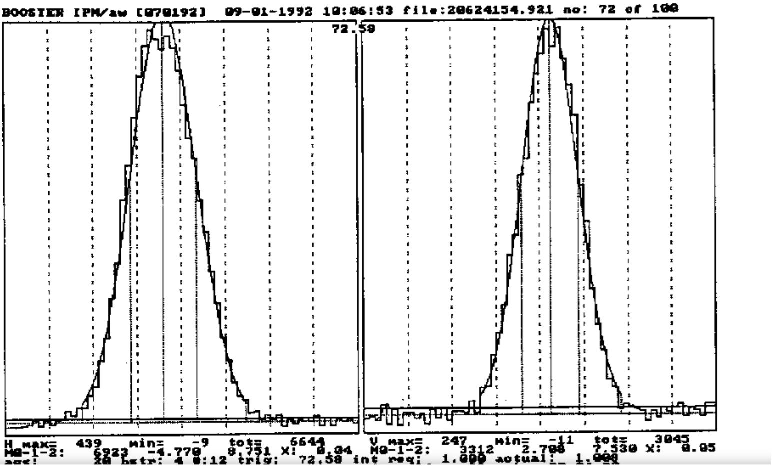


Figure 13: The IPM Profiles:The AGS Control Room view

Control System Integration

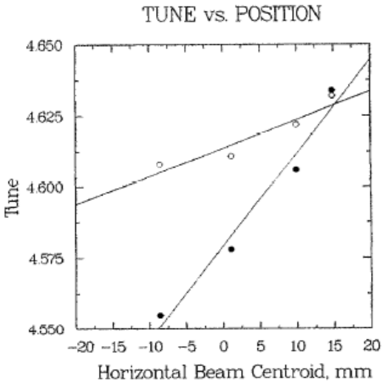


Figure 14: A Chromaticity Measurement: Filled circles are horizontal tune measurements and open circles are vertical tune measurements.

Control System Integration

Centroid positions can give the Booster chromaticity. Recall the chromaticity is,

$$\xi = D\frac{\Delta\nu/\nu}{\Delta x} \quad \text{or} \quad \xi = D\frac{T}{\Delta x},$$

where T is the tune corresponding to the beam centroid position. In the figure, the slope of the tune measurements gives the chromaticity as:

$$\xi_H = 1.54 \pm 0.07 \quad \text{and} \quad \xi_V = 0.46 \pm 0.03.$$

These values are in good agreement with the values of $\xi_H = 1.38 \pm 0.03$ and $\xi_V = 0.46 \pm 0.03$ taken using frequency measurements.

Conclusion

The unique design of the AGS Booster ionization profile monitor incorporates two elements specific to this particular instrument:

- **Gain**
  A dual micro-channel plate provides the gain necessary to amplify a countable few ions created by the passage of the beam into a current that integrating electronics can present as real data. Typical gain is one the order of 10^6.
- **Ion Collection**
  Shaped electrostatic electrodes replace the magnets universally in use for residual gas profile monitors.

Conclusion

Final notes:

- **The Vacuum**
  The signal current calculation makes use of the Bethe-Bloch equation for the passage of charged particles in matter. Given the ultra-high vacuum in the AGS Booster, it was unclear whether the equation even applied at these gas densities.
- **Mean Free Path**
  The data acquired for any profile include the total counts in the profile, *e.g* the area under the Gaussian. Since the beam density of particles and the gas density of particles are know quantities, the total number of counts in the profile would seem to be able to yield the cross-section for interaction of a beam particle with a gas molecule.

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