Physics 100 – Module 1

Materials Science and Materials Analysis using a Particle Accelerator

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My Background:

In the department for 17 years

9th time teaching Physics 100.

Teach primarily

- Physics 110/111 (Physics for the Life Sciences)
- Physics 120/121 (Physics for Majors and Engineers)
- Physics 210 (Medical Physics)
- Physics 220 (Introduction to Quantum Mechanics)
- Physics 300 (Modern Experimental Techniques)
- Physics 490/491 (Senior Thesis)

Background continued…

- I am trained as a theoretical physicist in waveguide theory.

  Production, propagation, and diffraction of x-rays (a type of electromagnetic wave) through glass capillary fibers.

  Includes surface roughness and x-ray attenuation effects.

- I am also an experimental physicist who runs the particle accelerator.

  Environmental pollution studies with artificial turf athletic fields

  Environmental pollution studies with aerosols/liquids

  Environmental pollution near airports – Pb pollution from small aircraft

  Medical and Health Physics issues – Hg in Fish/metal distribution in tissues

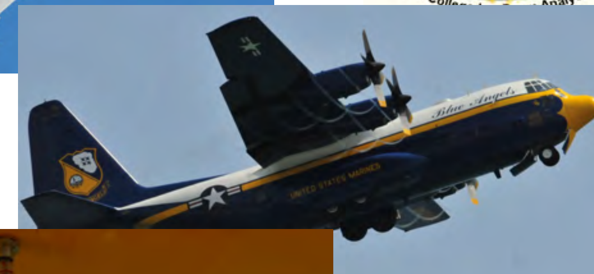
  Soil contamination – Heavy Metals in soils and sediments

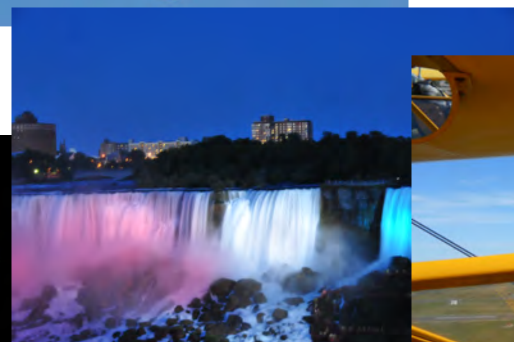
  Art/Archeometry – dating artifacts by diffusion processes into a sample

My physics hobbies…

Fluid Mechanics
Aerodynamics
Flight and Flight Mechanics
Aircraft Photography







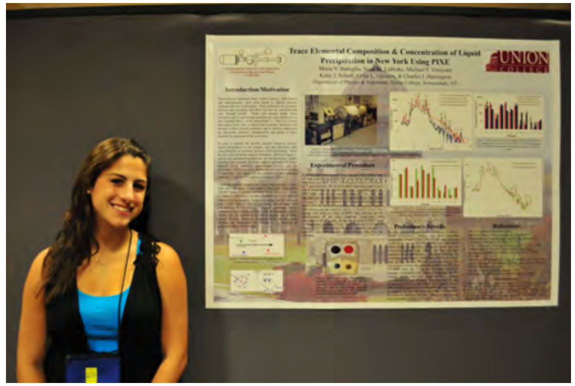
Motion and Gravity



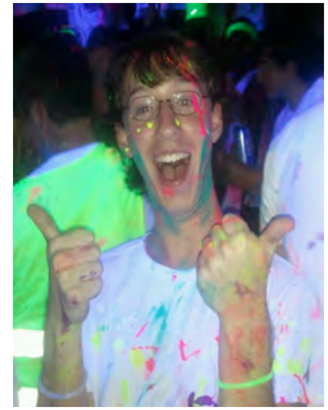

*The **U**nion **C**ollege **I**on **B**eam **A**nalysis **L**aboratory*

The UCIBAL
Union College Ion-Beam Analysis Lab

Chad & Colin are now graduate students (at SUNY Buffalo and University of South Carolina), who worked on the analysis of atmospheric aerosols by PIXE/PIGE/RBS/PESA.



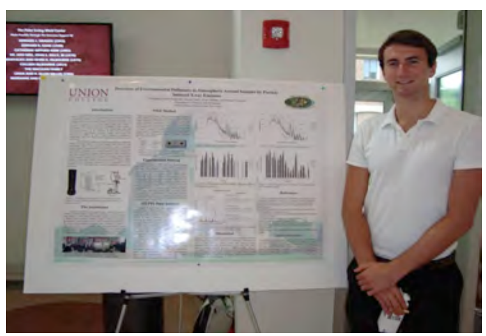
Maria is a Resident Pediatrician on Long Island who worked on liquid precipitation samples and on the development of a procedure for looking at the distribution of metals in animal (skate) tissues. Here she is at CAARI, an international accelerator conference in Fort Worth Texas



Jeremy is 3rd year graduate student a Uconn (and former PHY100 student) who worked on his senior thesis on the accelerator studying lead emissions from small airplanes at Schenectady airport.

Morgan is a first year graduate student at UNC Chapel Hill. She worked on an environmental project the analysis of artificial turf.

Colin is a 5th year graduate student at Penn State who worked on the analysis of atmospheric aerosols by RBS/PESA.



Ben who is looking at ERDA, now works on Wall Street in NYC.

Chalise is a junior who is working on an environmental project on the distribution of Pb from the Hell Gate Bridge in Queens NY.

Skye is a senior who is working on an environmental project the analysis of artificial turf.

Some past and present research students

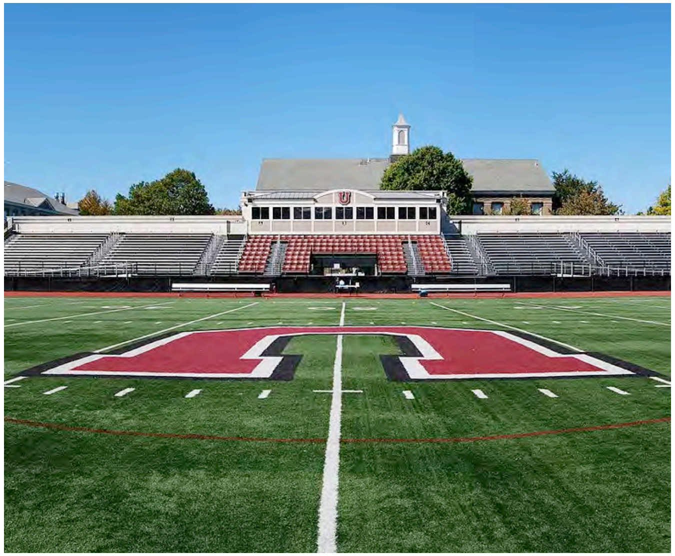
What does the *UCIBAL* study?

Applications of Nuclear Physics to Environmental Problems

Solids – soils, trees, tissues
Liquids – water, wines, blood
Gas – atmospheric aerosols

http://www.offthehoof.co.uk/2013/03/how-to-avoid-environmental-pollution/

http://www.conserve-energy-future.com/wp-content/uploads/2013/04/Smoke_from_airplane.jpg



https://www.pinterest.com/explore/union-college/

http://ocean.nationalgeographic.com/ocean/critical-issues-marine-pollution/

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Game Plan….

•We're going to use a what?

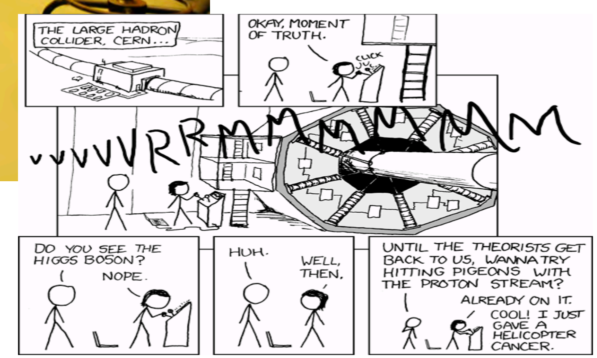
•Accelerator – What it is, What it does. Energy and velocity calculations.

•*PIXE* – Basics, Theory and Sample calculations.

•Modifications to the *PIXE* Theory.

•Materials Analysis of a sample using *PIXE* and the accelerator.

We're going to use a what?
A 1.1MV tandem electrostatic particle accelerator!



http://sciencegeekgirl.com/files/2008/12/large_hadron_collider1.png?w=300

The Pelletron Particle Accelerator

- Built by the National Electrostatics Corporation
- Acquired in 1991
- Replaced 450 kV Van-de-Graff accelerator
- In the process of writing a grant proposal for ~1.5 million dollars for a new accelerator which if funded would be installed in 2020.
- Our current accelerator has 4 main components

  Ion production

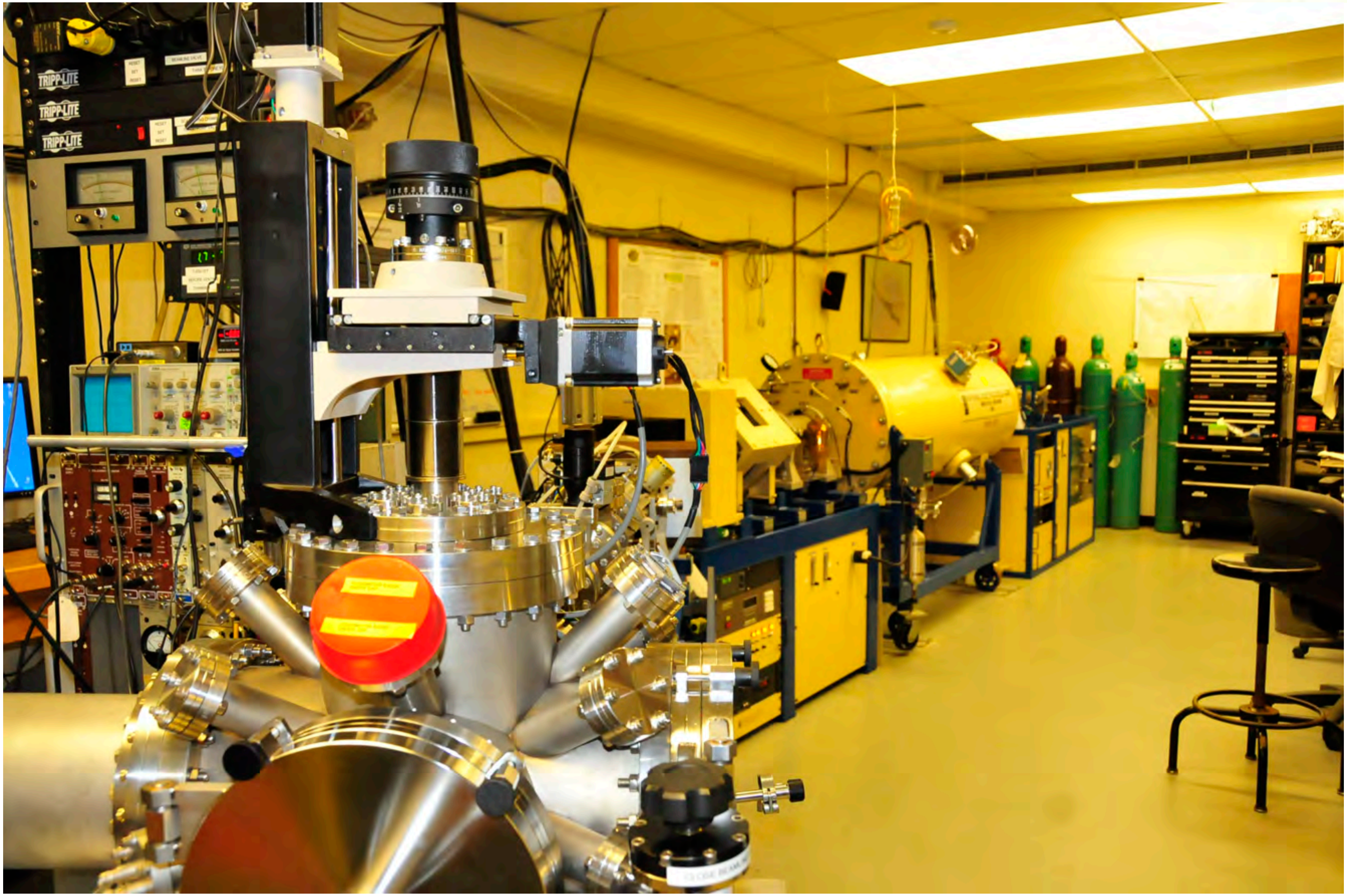
  Two-Stage (tandem) acceleration of ions

  Steering of ions

  Scattering chamber

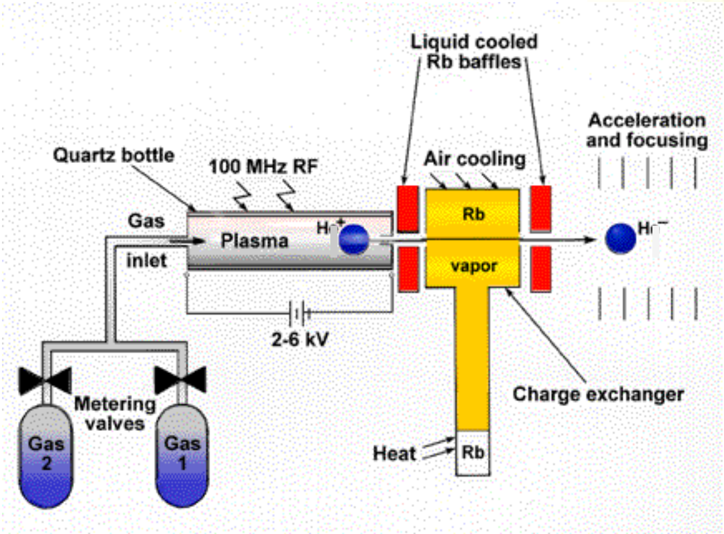
The Pelletron Particle Accelerator

The UCIBAL
Union College Ion-Beam Analysis Lab



The Source: Ion Production

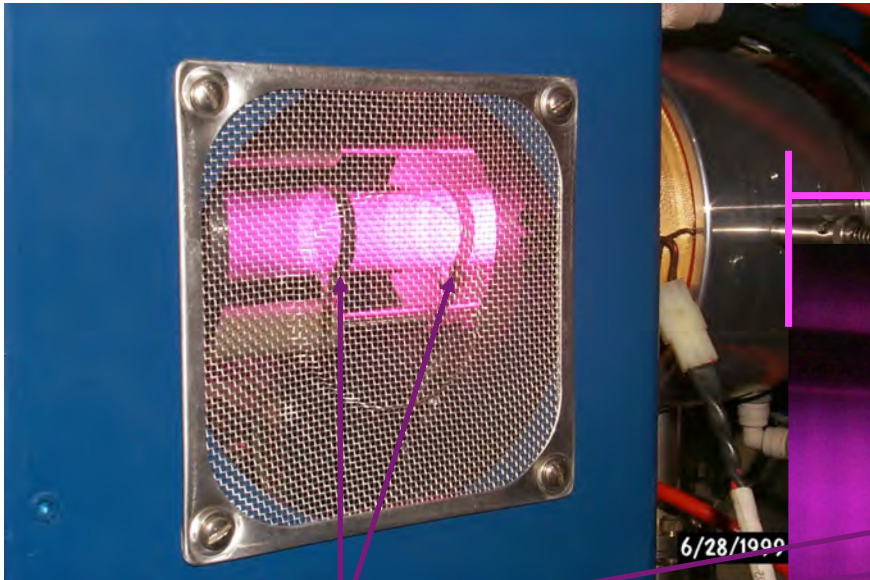
- H or He gas is bled into the gas inlet.
- 100MHz Radio Frequency (RF) electromagnetic energy is dumped into the quartz bottle which produces H^+, He^+, He^{++} and other ions.
- A potential difference of about 3.6kV for H or He is applied across the bottle.
- This accelerates the ions out into the charge exchanger.



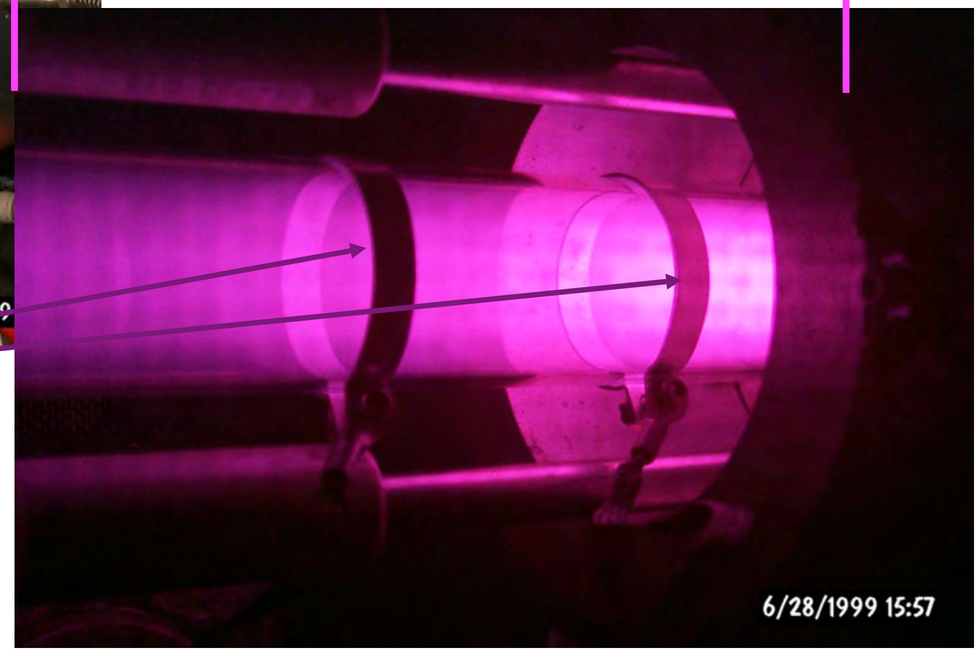
http://www.pelletron.com

- The H^+ or He^+ charges pass through a low density Rubidium (Rb) vapor and through charge-exchange collisions pick up extra negative charges.
- The H^- or He^- charges continue on into the accelerator.
- Of course there are other ions that are also accelerated (N^-, O^-, ...)

Ion Production and Plasma Source



DV = 3kV to 6kV



Looking into the back end bottle. The metal bands are what couples the RF source to the bottle.

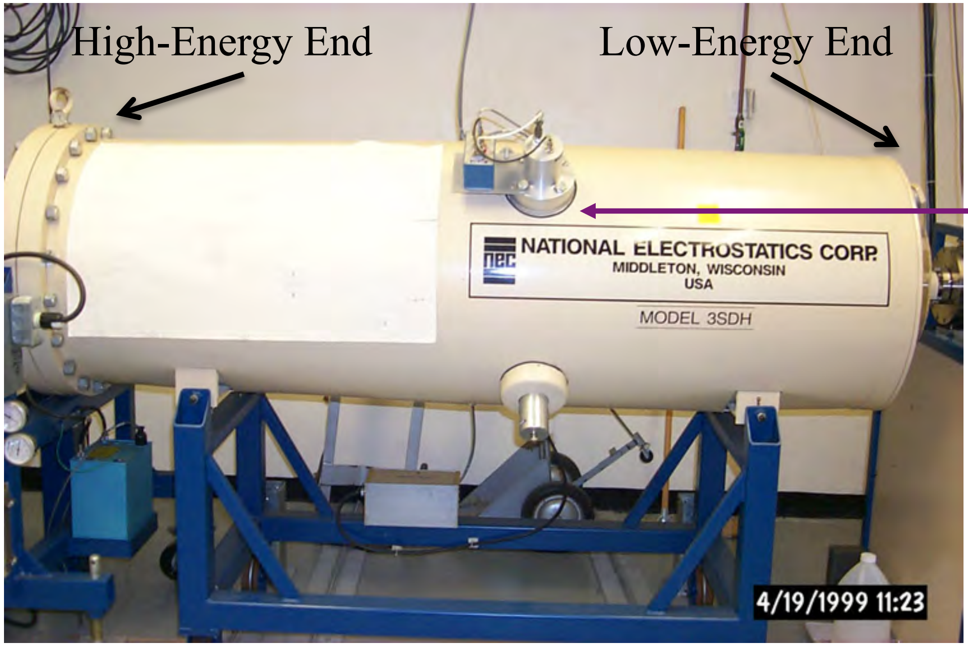
Characteristic glow of a hydrogen plasma.

The Low Energy End of the Accelerator

Ion Source or Low-Energy end of the accelerator showing the Rubidium furnace and cooling system. The H^+ plasma is the faint pink glow.

Wide view of ion source. This also has a *Faraday cup* in view. The faraday cup is designed to count the number of charges and determine the beam current.

The Accelerator



- The chain is housed inside of this tank.
- The terminal is in the center.
- From right edge of the photo (the low-energy end) to the terminal a *1.1MV* is applied.
- From the terminal to the high-energy end there is another *1.1MV* difference in potential.
- Nitrogen gas is bled from the left end of the photo to the terminal to pull off the added negative charges through anther charge-exchange collision.
- The resultant positive particle is accelerated away from the terminal back down *1.1MV* towards the left edge and thus produces a tandem acceleration of the ion species.

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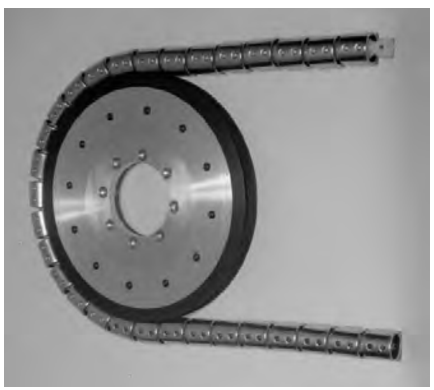
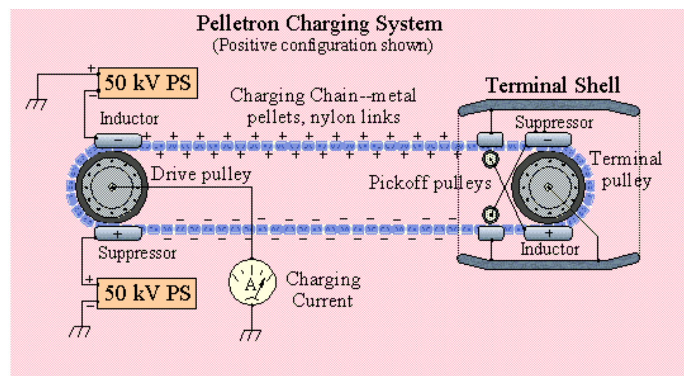
Tandem acceleration of ions

- The negative ions are accelerated toward the center of the pressure tank by a 1.1 MV difference in potential between the low-energy end and the terminal.
- The center of the pressure tank (the terminal) is made positive with respect to the charge exchanger.
- The potential difference is developed by the Pelletron Charging system, which consists of metal pellets and insulating connectors.
- The terminal is charged by induction and is a very stable and reliable system.



Pelletron Chains

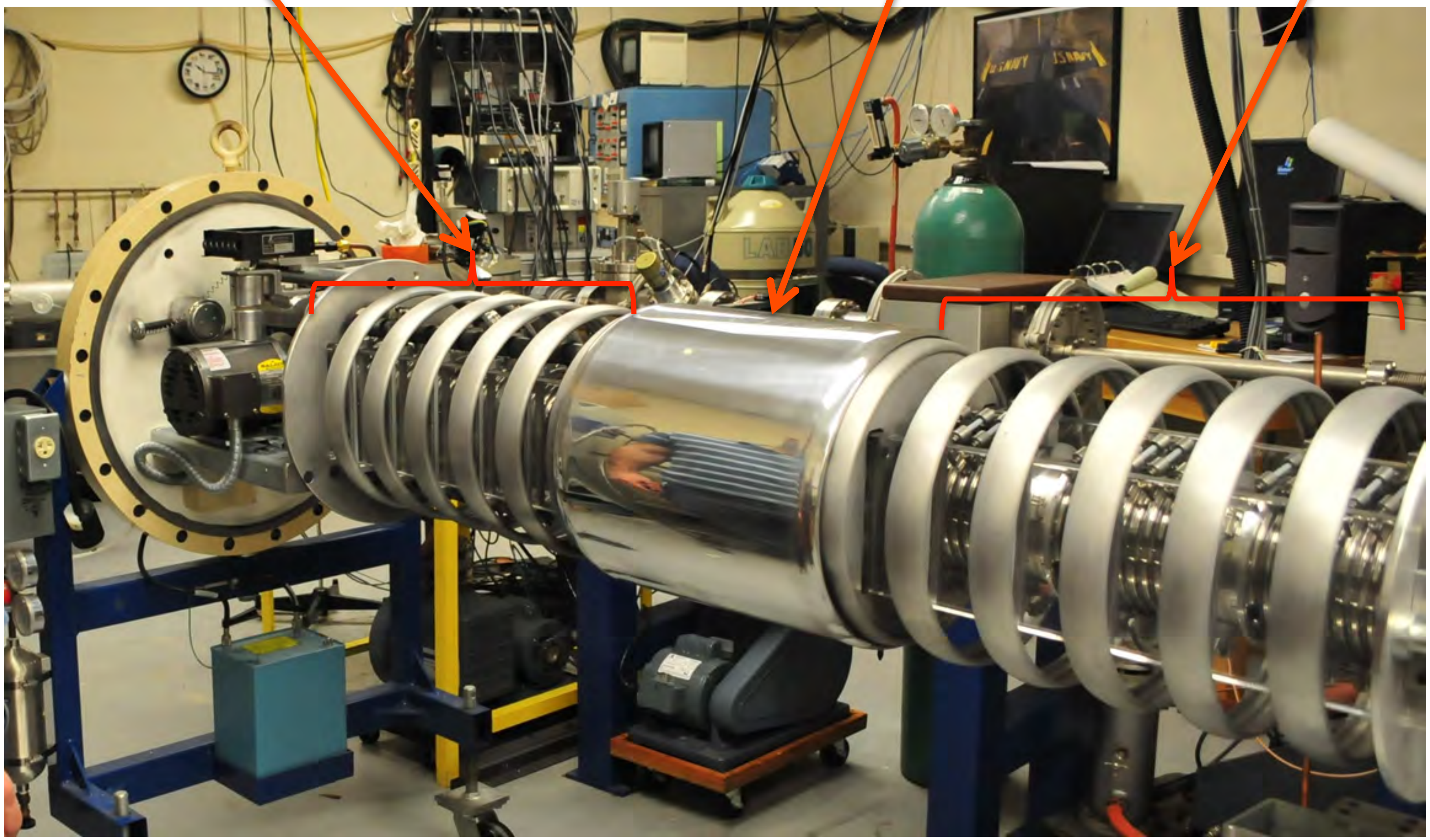
http://www.pelletron.com/charging.htm



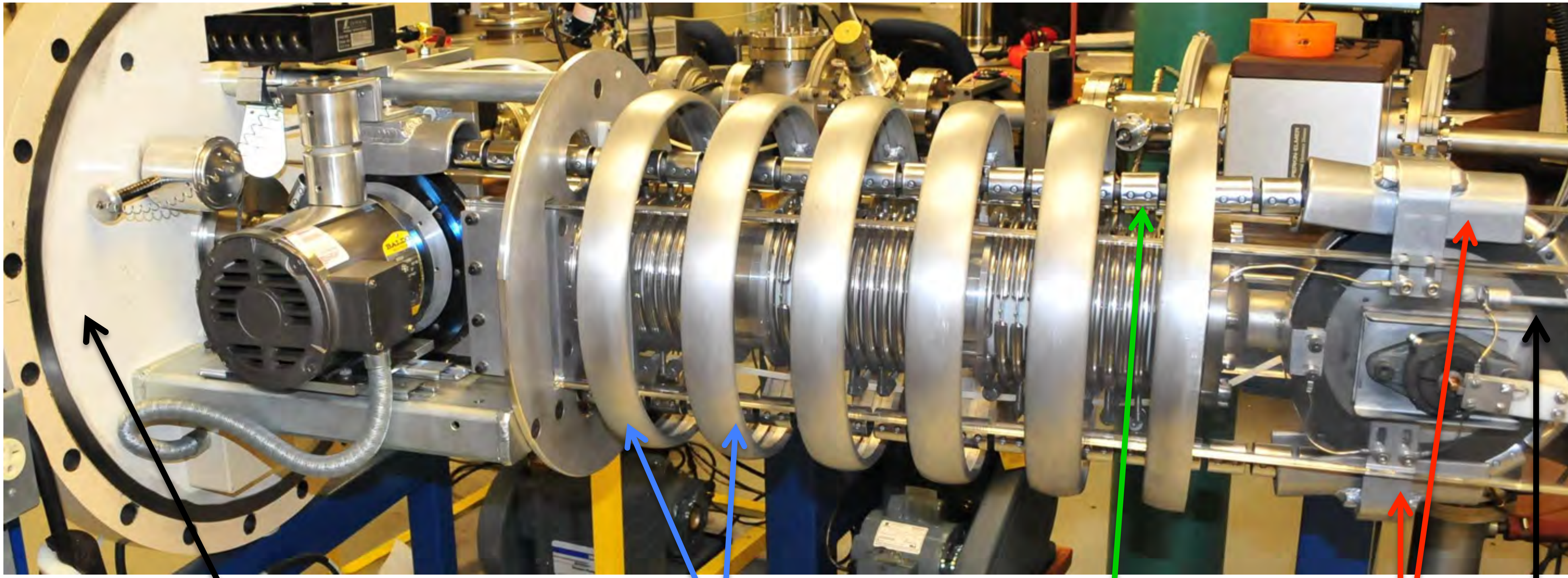
Pelletron Charging System by NEC

The Accelerator – What's inside the tank…

High Energy Column Terminal Shell Low Energy Column



The Accelerator – What's inside the tank…



High-energy end of accelerator

Accelerating Rings

A Pellet

Inductors

Terminal Shell

Units:

Typically work is expressed in units of kiloelectron volts (keV) or Megaelectron volts (MeV). What are these?

- **First let's consider accelerating a charged particle from rest to some speed *v*.**
- **The work done is a product of the charge and the accelerating potential that the charge passes though.**
- **It is like a ball rolling down a hill. There is a conversion of *potential energy* at the top of the hill to *kinetic energy* at the bottom of the hill. The ball starts from rest and at the bottom of the hill has a speed *v* and thus a *kinetic energy* associated with its motion. So too does the charge.**
- **It is repelled away from a like charge at the top of the potential hill and attracted to an opposite charge at the bottom of the potential hill**

$$\text{Work} = W = \left|q\Delta V\right| = \left(1e^{-}\right)\times\left(1\text{Volt}\right) = 1\text{electron}\times\text{Volt} = 1eV$$

Units:

- **Each elementary charge has *1.6x10^{-19} Coulombs* worth of charge. Therefore the work done can also be written as:**

$$\text{Work} = W = q\Delta V_{\text{accelerating}} = 1eV = 1e \times \frac{1.6 \times 10^{-19}\,\text{Coulombs}}{1e} \times 1\text{Volt} = 1.6 \times 10^{-19}\,\text{Joules}$$

- **An electron-volt is a unit of energy**
- **And our conversion is that *1eV = 1.6x10^{-19} J.***
- **By the work-kinetic energy theorem, the work done accelerating the charge changes the kinetic energy from zero (the charge is initially at assumed to be at rest) to some speed *v* given by**

$$\text{Work} = \Delta\text{Kinetic Energy} = \Delta KE = \frac{1}{2} m_{ion} v_{ion}^2$$

A Couple of Quick Calculations

How fast is the proton traveling when it leaves the ion source?

$$W_i = -q\Delta V = -\left(1e \times \left(0kV - 3.6kV\right)\right) = 3.6keV$$

$$W_i = \Delta KE$$

$$W_i = 3.6keV \times \frac{1.6\times10^{-19}J}{1eV} = 5.76\times10^{-16}J = KE_f - KE_i = KE_f$$

$$5.76\times10^{-16}J = \frac{1}{2}m_p v_p^2$$

$$\therefore v_p = \sqrt{\frac{2\times5.76\times10^{-16}J}{1.67\times10^{-27}kg}} = 8.31\times10^5 \tfrac{m}{s}$$

A Couple of Quick Calculations

What is the kinetic energy of the proton after it leaves the accelerator?

$$W_{total} = \sum_{j=1}^{N} w_j = -\sum q\Delta V = w_{source} + w_{low-energy} + w_{high-energy}$$

$$W_{total} = -\left\{1e^{+} \times (0kV - 3.6kV) + (-1e^{-}) \times (1.1MV - 0MV) + 1e^{+} \times (0MV - 1.1MV)\right\}$$

$$W_{total} = KE_f = 3.6keV + 1.1MeV + 1.1MeV = 2.2036MeV \approx 2.2MeV$$

$$\therefore KE_f = 2.2MeV \times \frac{1.6 \times 10^{-19} J}{1eV} = 3.52 \times 10^{-13} J$$

What is the speed of the proton after it leaves the accelerator?

$$KE_f = \frac{1}{2} m_p v_p^2 \rightarrow v_p = \sqrt{\frac{2KE_f}{m_p}} = \sqrt{\frac{2 \times 3.52 \times 10^{-13} J}{1.67 \times 10^{-27} kg}} = 2.05 \times 10^7 \tfrac{m}{s}$$

A Couple of Quick Calculations

Comment:

Generally one needs to worry about the speeds of these particles and how they compare to the speed of light.

- Need to include Relativistic effects?

- In other words does the measured speed of the proton equal the theoretical speed of the proton?

This is hard to do… so, we set a limit… and we define a relativistic limit to be when the velocity of the object is less than *one-tenth* the speed of light ($c \sim 3x10^8$ *m/s*) then we do not have to worry about relativistic effects.

Here the velocity is $2.05x10^7$ m/s which is *0.069* times the speed of light, less than the limit, so no relativistic effects.

Steering of Ions

- The steering magnets are a momentum filter (or here, a really crude mass spectrometer.)
- A momentum filter is a device which separates charged particles based on their momentum (or kinetic energy, which is proportional to their momentum).
- When a charged particle passes through a magnetic field with a component of its velocity perpendicular to the magnetic field, the charge will feel a force and it will move in the direction of the applied force.
- The magnetic force is given by $\vec{F} = q\vec{v} \times \vec{B}$

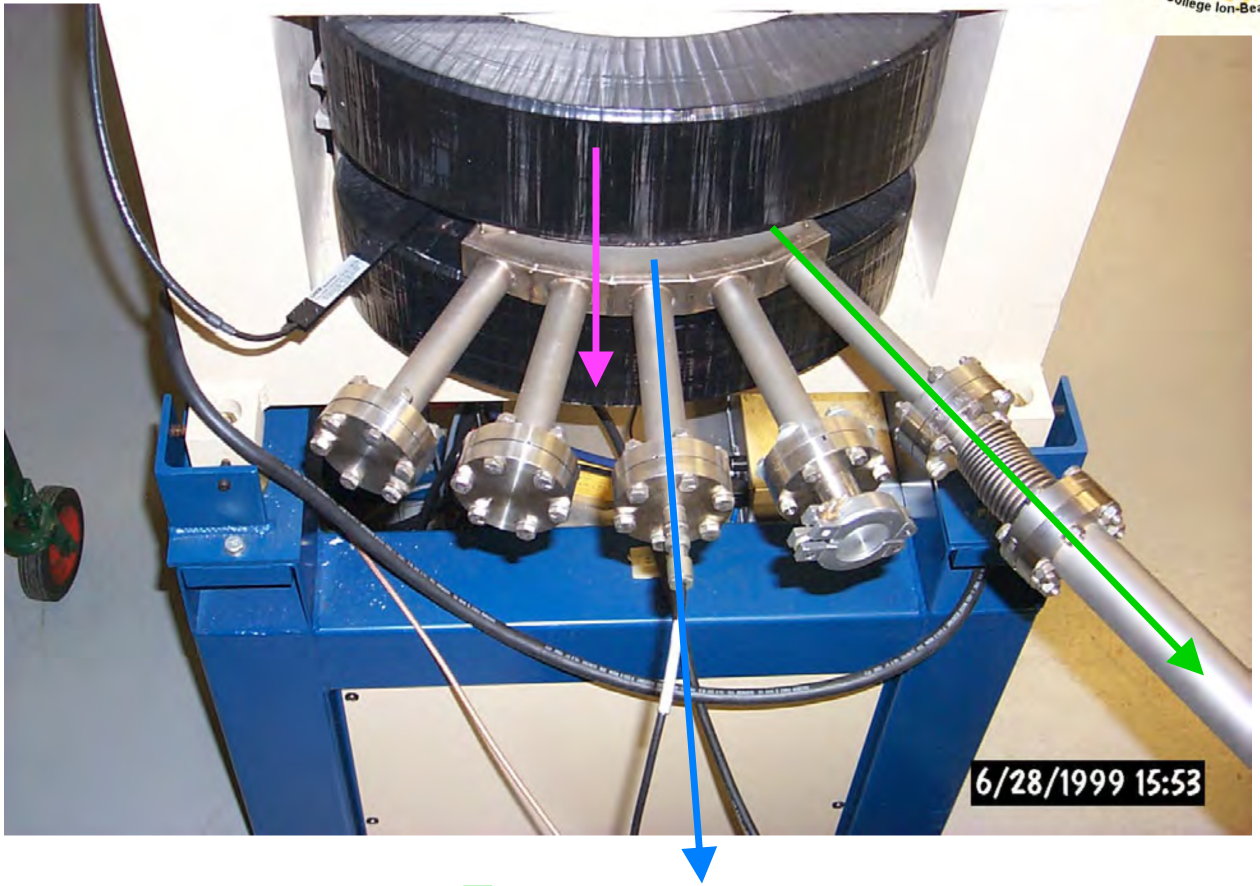
Side view of steering and quadrapole magnets

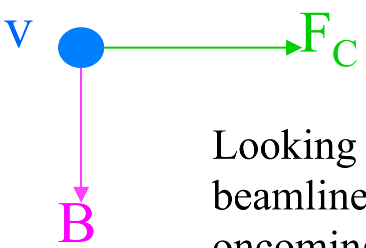
Steering of Ions

B points straight down to the floor from the upper to the lower magnet.

The velocity vector of the charges is coming out of the machine at you. This is called the zero-degree beamline.

Choosing the field appropriately (to match the particle's energy bends the charges to your right and down the 30º beamline.





Looking down the beamline at the oncoming charge

A Couple of Quick Calculations

- So, we've accelerated the proton and calculated its energy and speed.

- Now can we steer it in the magnetic field? If so, what is its orbital trajectory, or radius?

- The proton feels a force given by $\vec{F} = q\vec{v}\times\vec{B}$.

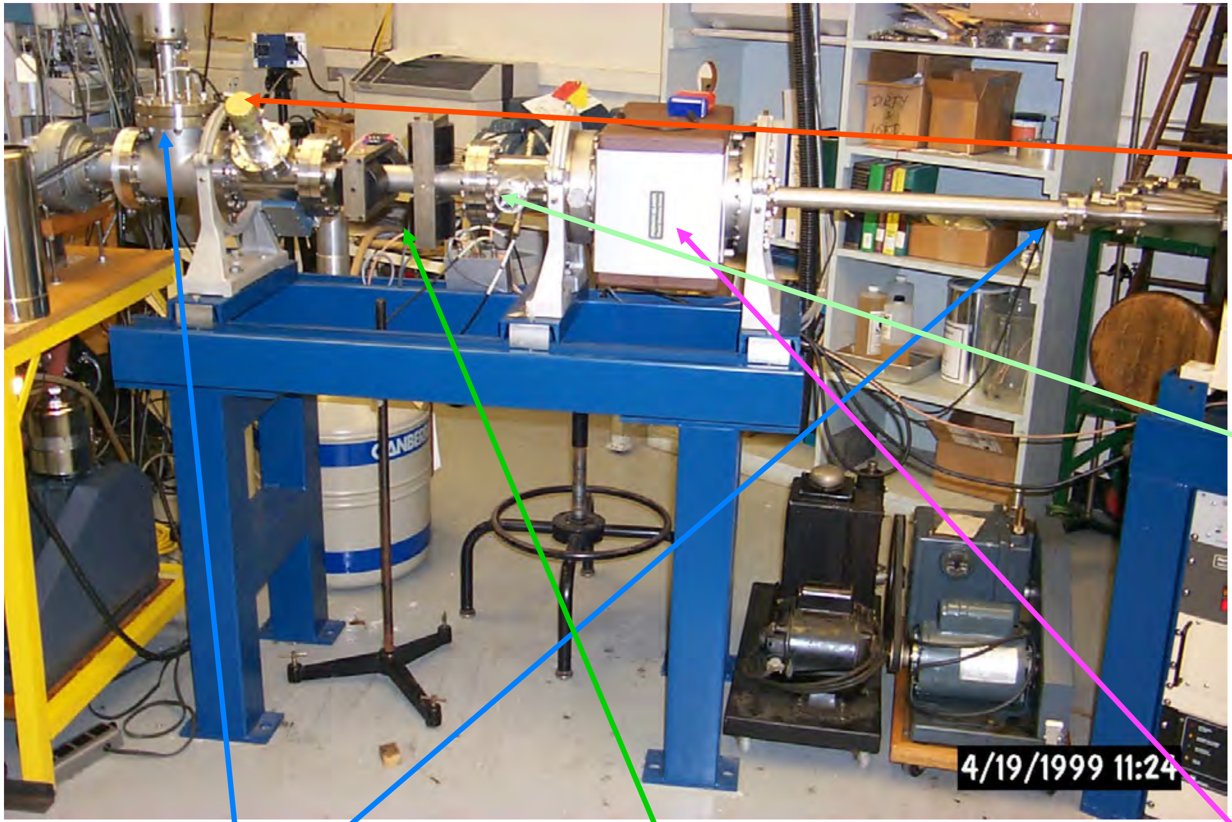
- This makes the particle travel in a circle of radius r due to the centripetal force it feels.

$$F_B = F_C \rightarrow qv_pB = \frac{m_pv_p^2}{r}$$

$$r = \frac{m_pv_p}{qB} = \frac{1.67\times10^{-27}kg\times2.05\times10^{7}\,\frac{m}{s}}{1.6\times10^{-19}C\times0.6214T} = 0.344m = 34.4cm$$

- Once the charges leave the magnetic field the force vanishes and they continue in a straight line toward the scattering chamber.

A few odds and ends on the way to the scattering chamber….



Beam profile monitor

Energy controller

Faraday cups

Horizontal and Vertical steering magnets

Ion pump (not in use)

The scattering chamber

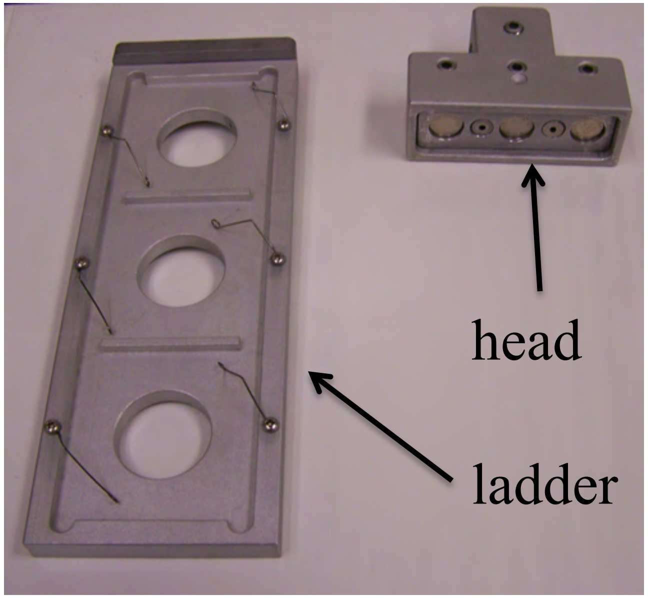
The UCIBAL
Union College Ion-Beam Analysis Lab

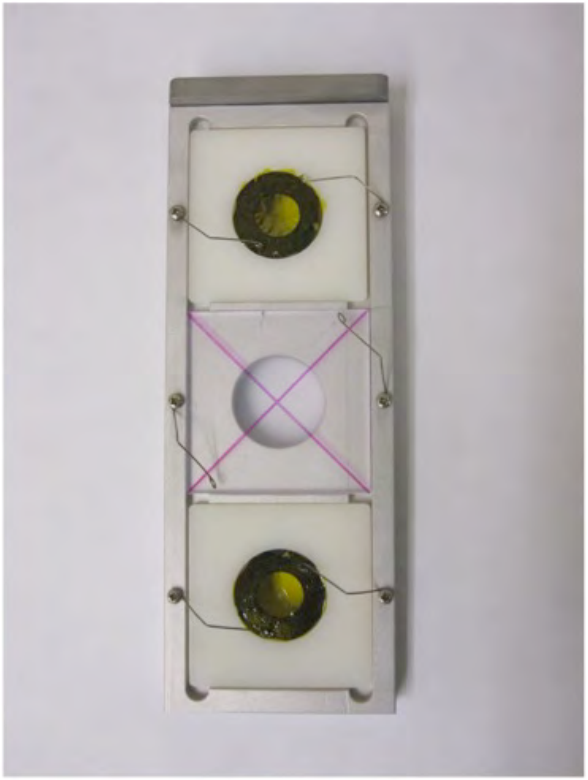
This is where the experiments are done.

- The scattering chamber is a 10" multi-port Conflat system with a 3-axis target manipulator mounted on top.

- Samples are placed inside and can be moved horizontally in a plane, vertically, and rotated about a central axis.

Target Ladder Assembly



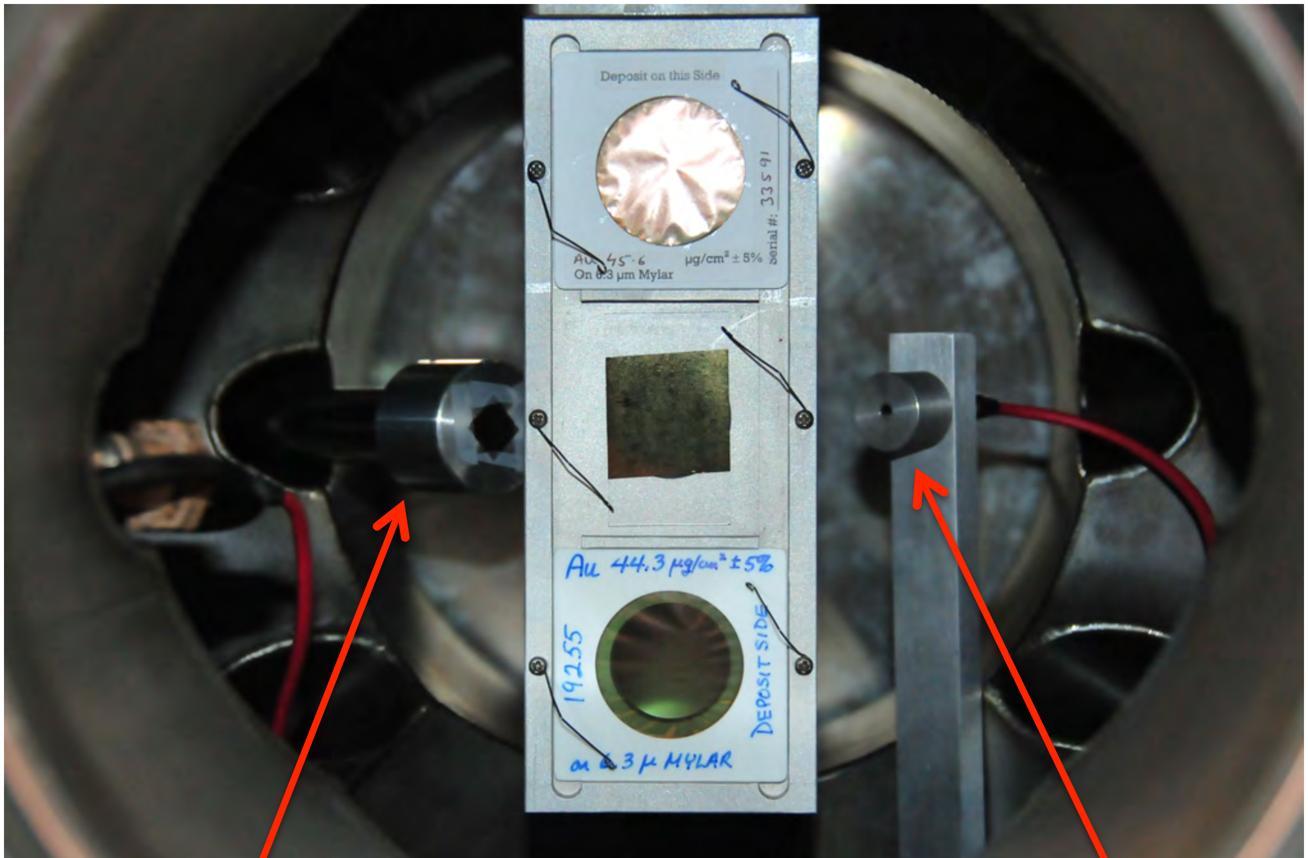


- Inside of the scattering chamber is the target ladder assembly. It is attached to the target manipulator by a "head" by a shaft (not shown) and the ladder is magnetically coupled to the head.

- Three targets at a time may be analyzed using the ion beam.

Inside the scattering chamber

The ion beam enters facing you and passes thought the targets



X-ray detector (for *PIXE*)

Si surface barrier detector (for *RBS & ERDA*)

Uses of a particle accelerator

Materials Analysis

Environmental Samples

Mass spectrometry

Nuclear reactions

Nuclear structure

Medicine

Nuclear Medicine

Biochemistry

Paleontology

Forensic science.

Art restoration and archeometry