Physics 100 – Module 1

Materials Science and Materials Analysis using a Particle Accelerator

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By Appointment

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My Background:

In the department for 22 years

15th 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 490/491/492 (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

The Union College Ion Beam Analysis Laboratory

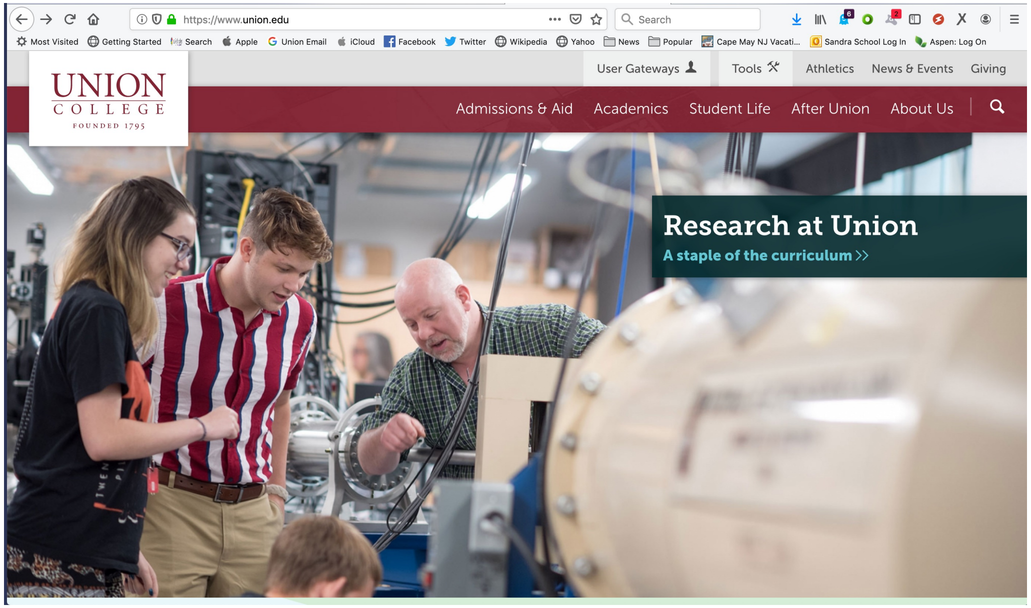
Katie (a former member of Union's women's hockey team) is a 2022 graduate who worked on detecting and measuring fluorine from PFAS chemicals from fire-foams.

Morgan graduated in August 2023 with her PhD from UNC Chapel Hill. She worked on an environmental project the analysis of artificial turf.

Chalise is a recent graduate who worked on an environmental project on the distribution of Pb from the Hell Gate Bridge in Queens NY, works for an environmental consulting firm in Texas.

Skye is a recent graduate who is working on an environmental project the analysis of artificial turf and is a medical physicist

Mia & Colin (2022 graduates and former phy100 students), and Jake (a 1st year graduate student at WPI) worked on PIXE and PIGE projects in environmental physics as part of their summer research projects and made Union's homepage.



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

Hell Gate Bridge in Astoria Queens. Photo: SM LaBrake

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

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

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

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

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.

The Pelletron Particle Accelerator

The Pelletron Particle Accelerator

- Built by the National Electrostatics Corporation
- Acquired in 1991
- Replaced 450 kV Van-de-Graff accelerator
- Always looking for ways and money (btw it's about ~1.5 million dollars for a new accelerator) to upgrade the accelerator.
- Our current accelerator has 4 main components

    Ion production

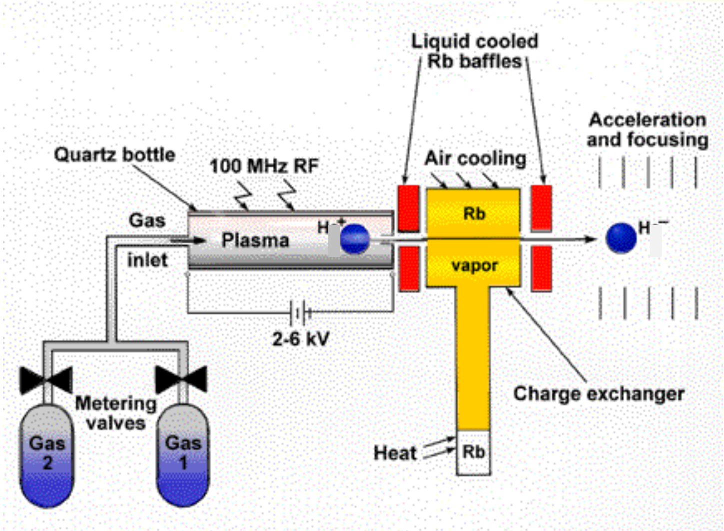
    Two-Stage (tandem) acceleration of ions

    Steering of ions

    Scattering chamber

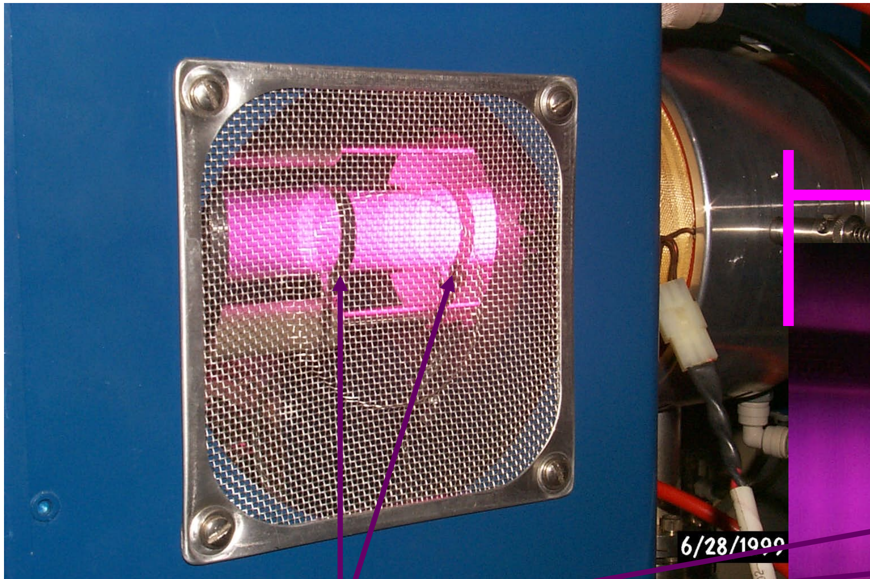
The Source: Ion Production

- 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.
- The H^+ or He^+ charges pass through a low-density Rubidium (Rb) vapor and through charge-exchange collisions pick up extra negative charges. H^+ gains $2e^-$ to become H^- and He^{+2} gains $3e^-$ to become He^-.
- The H^- or He^- charges continue into the accelerator.
- Of course, there are other ions that are also accelerated (N^-, O^-, ...) but we ignore these.

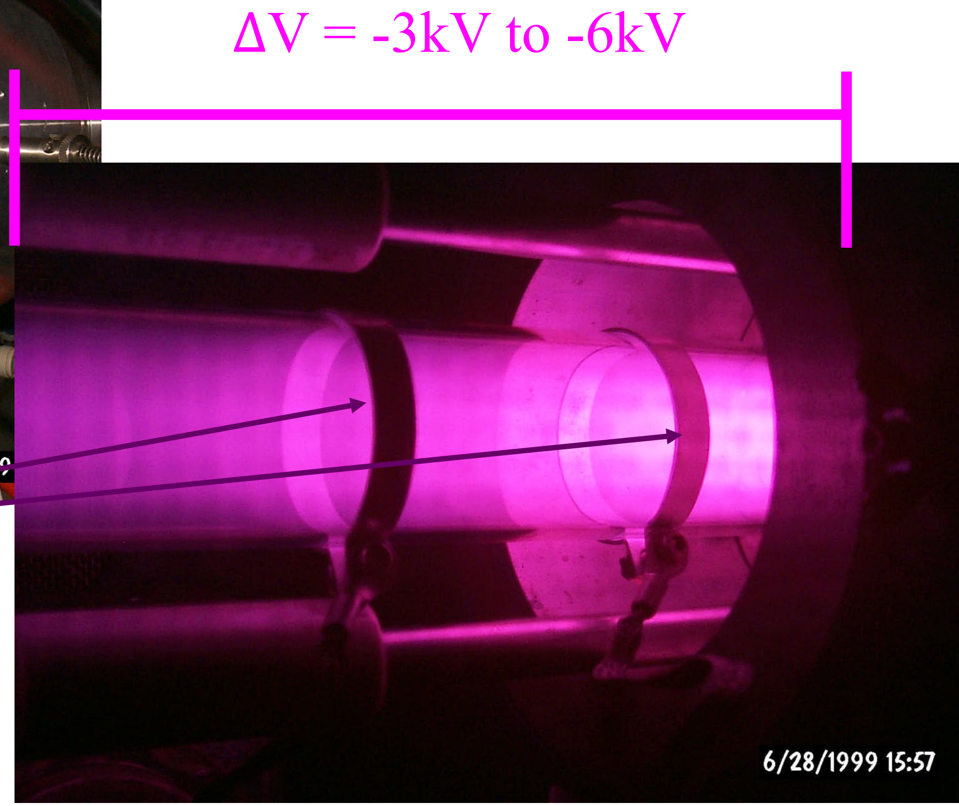


http://www.pelletron.com

Ion Production and Plasma Source



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



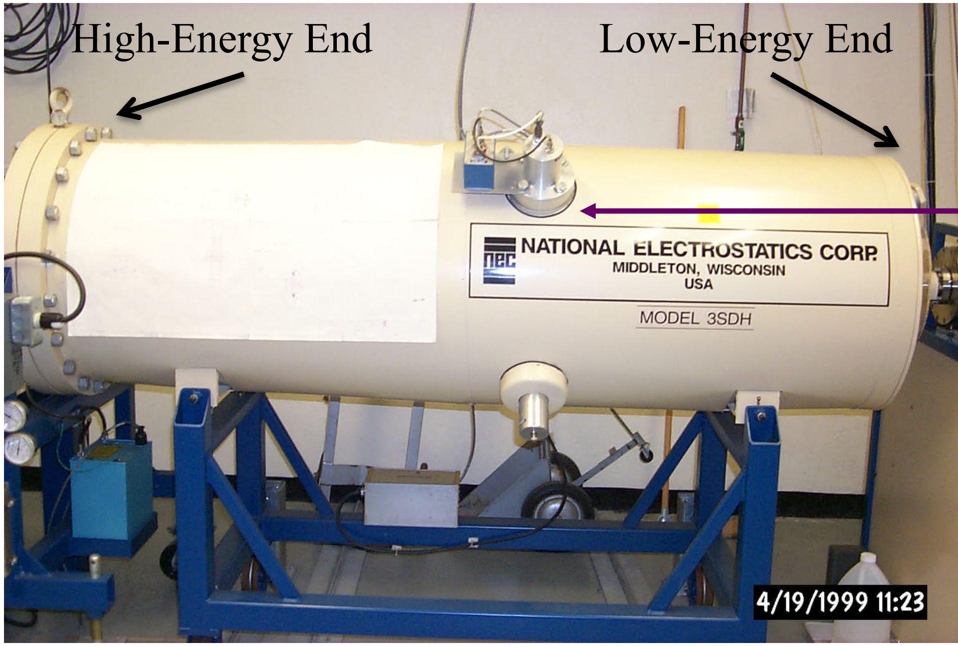
Characteristic glow of a hydrogen plasma.

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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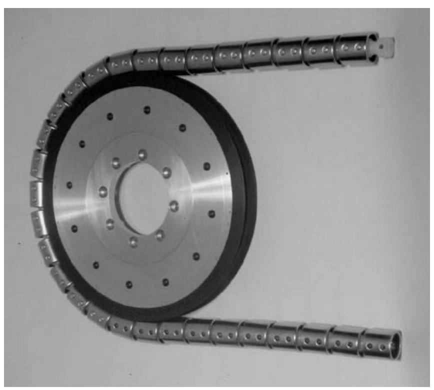
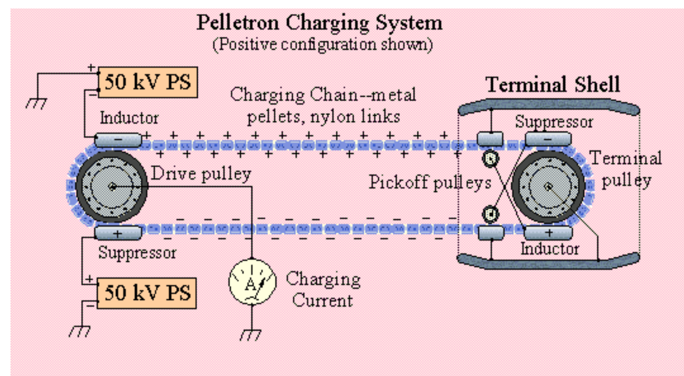
Tandem acceleration of ions

- 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

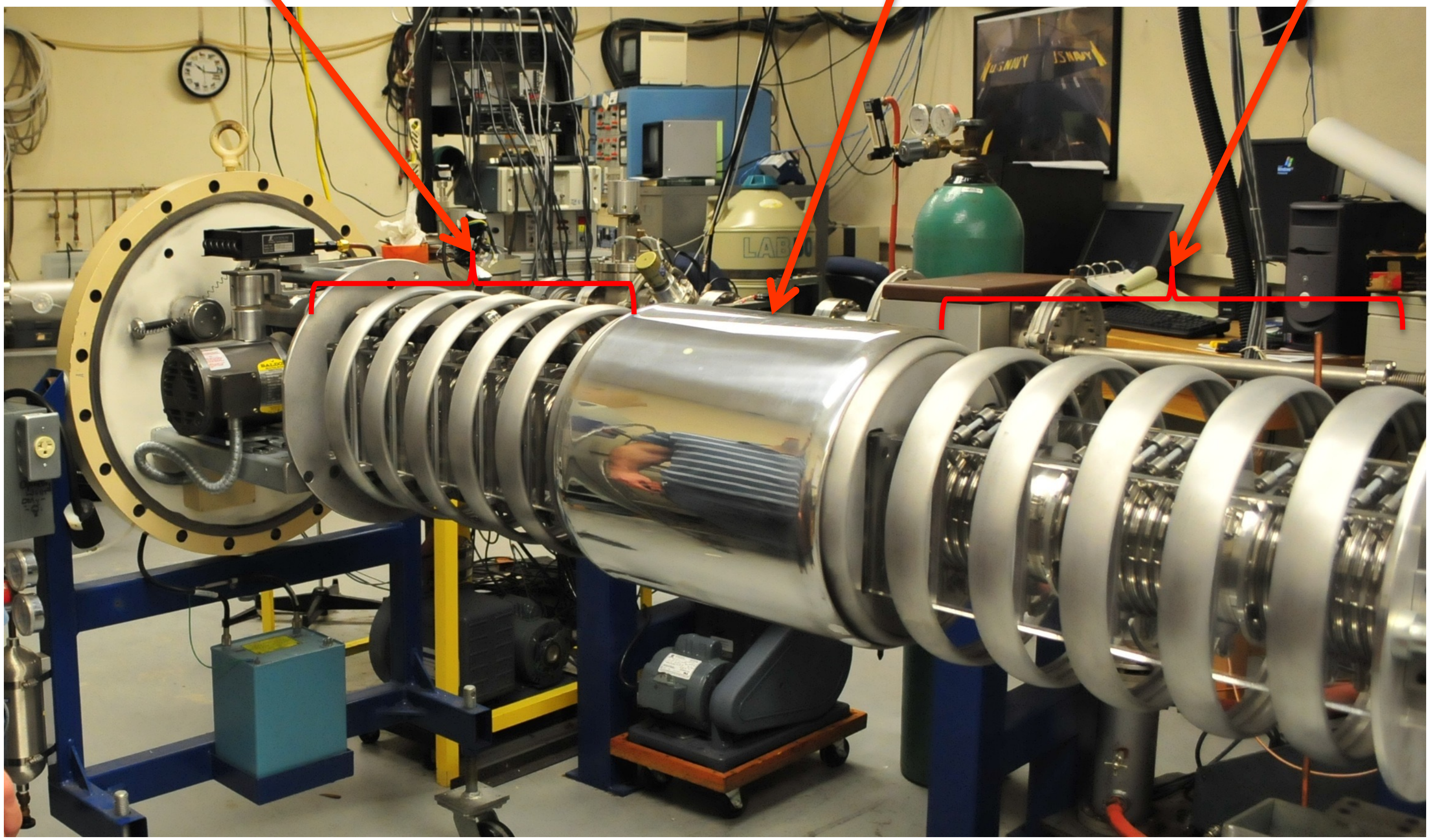


Pelletron Charging System by NEC

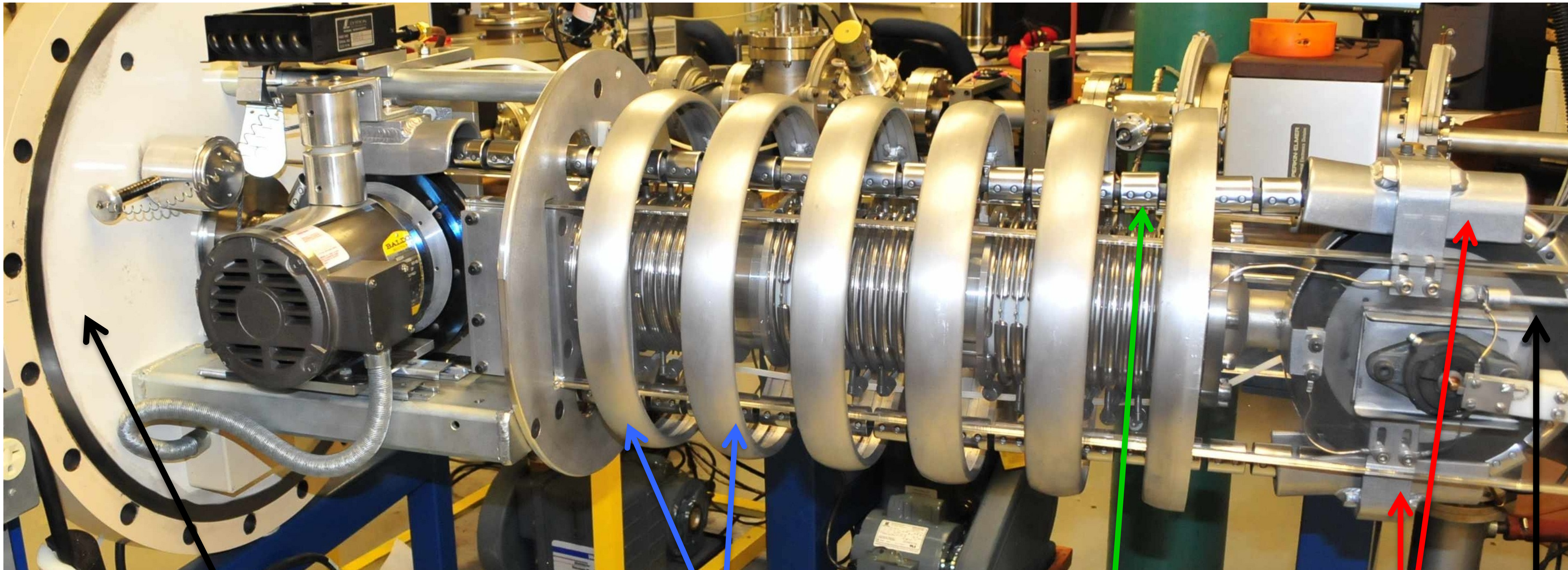
http://www.pelletron.com/charging.htm

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

Work and Electron-Volt Units:

- **We want to calculate the net work accelerating the proton through the accelerator.**
- **We'll do this in three stages.**

Stage 1: The work to get the positively charged proton out of the quartz bottle into the rubidium.

Stage 2: The work to get the negatively charged proton through the low energy end of the accelerator.

Stage 3: The work to get the positively charged proton through the high energy end of the accelerator.

- **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*.**
- **Work is the product of a force times a displacement and the total work done gives rise to a change in the energy of motion of the proton. We call this change in energy of motion the kinetic energy.**

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Work and Electron-Volt Units:

- **Electric work is defined as:**

$$W = -q\Delta V$$

- **where, *q* is the charge (in Coulombs or elementary charges) that's being accelerated through the potential difference, Δ*V***
- **And Δ*V* is the potential difference in volts.**
- **If *q* is in Coulombs, then the work done is in Joules. If *q* is in elementary charges, then the work done is in electron volts (eV).**
- **Suppose you have one elementary charge ($q = 1e = 1.6\times10^{-19}C$) accelerated through a potential difference of one volt ($\Delta V = -1V$), the work done is:**

$$W = -q\Delta V = -(1e)\times(-1V) = 1eV$$

$$W = \left(1e\times\frac{1.6\times10^{-19}C}{1e}\right)\times1V = 1.6\times10^{-19}J$$

$$1eV = 1.6\times10^{-19}J$$

Work, Kinetic Energy & Speed:

- **The work done on the charge is related by the work-kinetic energy theorem, to the speed of the charge.**

$$W = \Delta K = K_f - K_i$$

- **where, K_f is the final kinetic energy of the charge in Joules and K_i is the initial kinetic energy of the charge (also in Joules).**
- **The kinetic energy (or the energy due to the motion of the charge) is defined as:**

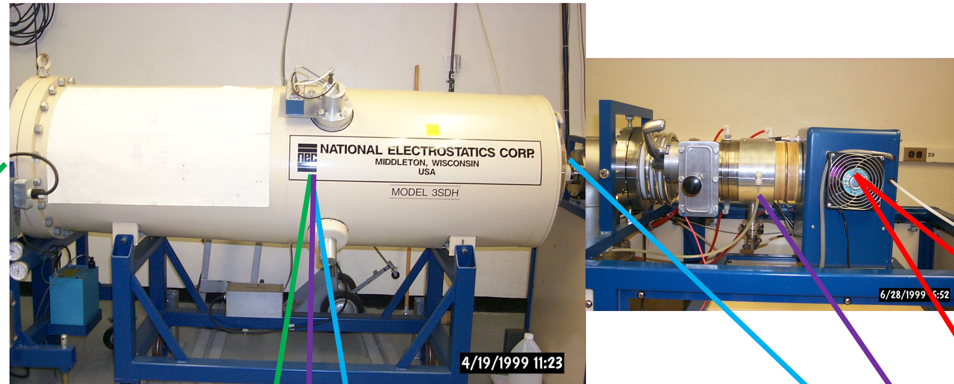
$$K = \frac{1}{2}mv^2$$

- **so that the work done is:**

$$W = \Delta K = K_f - K_i = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2 \sim \frac{1}{2}mv_f^2$$

- **assuming that the initial speed of the charge is approximately zero ($v_i \sim 0$).**

Work, Kinetic Energy & Speed:



High-energy end (HEE)	Nitrogen charge exchanger	Low-energy end (LEE)	Rubidium charge exchanger	Ion-source (IS)
H^+		H^-		H^+
$0V$ … $1.1\times10^6 V$		$1.1\times10^6 V$ … $0V$		$0V$ … $3600V$

These are the same spot and in the nitrogen charge exchanger

$$H^- - 2e^- \rightarrow H^+$$

These are the same spot and in the rubidium charge exchanger

$$H^+ + 2e^- \rightarrow H^-$$

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A Couple of Quick Calculations

What is the kinetic energy of the proton after it leaves the accelerator in electron volts and joules?

$$W_{IS} = -q\Delta V_{IS} = -(+e)[0V - 3800V] = 3800eV$$

$$W_{LEE} = -q\Delta V_{LEE} = -(-1e)[1.1\times10^{6}V - 0V] = 1.1\times10^{6}eV$$

$$W_{HEE} = -q\Delta V_{HEE} = -(+e)[0V - 1.1\times10^{6}V] = 1.1\times10^{6}VeV$$

$$W_{net} = K_f = W_{is} + W_{lee} + W_{lee} = 2.2038\times10^{6}eV \sim 2.2MeV$$

$$W_{net} = K_f = 2.2038\times10^{6}eV\times\frac{1.6\times10^{-19}J}{1eV} = 3.52\times10^{-13}J$$

What is the speed (in m/s) of the proton after it leaves the accelerator?

$$K_f = \tfrac{1}{2}mv_f^2 \rightarrow v_f = \sqrt{\frac{2K_f}{m}} = \sqrt{\frac{2\times3.52\times10^{-13}J}{1.67\times10^{-27}kg}} = 2.1\times10^{7}\frac{m}{s}$$

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?

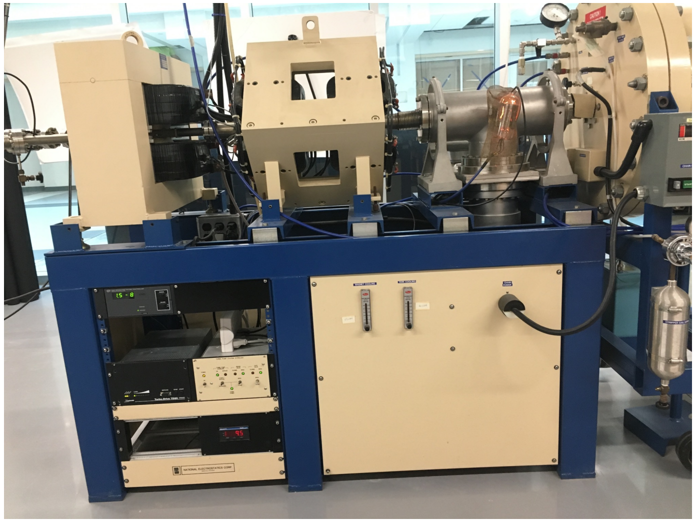
- In other words, does the measured speed of the proton equal the theoretical speed of the proton?

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 $2.05\text{x}10^7$ 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 $\vec{F} = q\vec{v} \times \vec{B}$



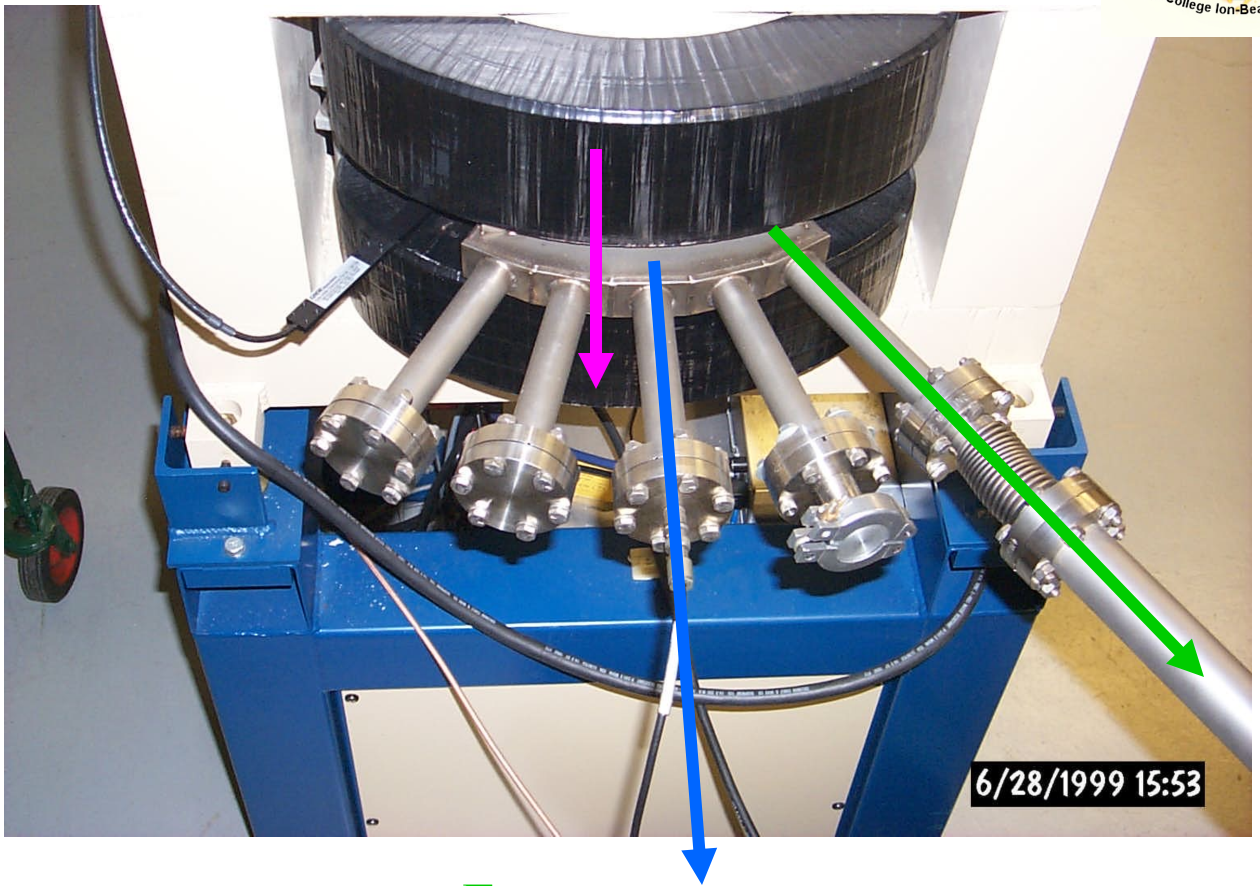
Side view of steering and quadrapole magnets

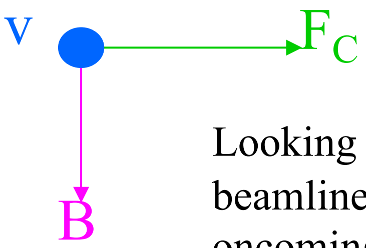
Steering of Ions

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

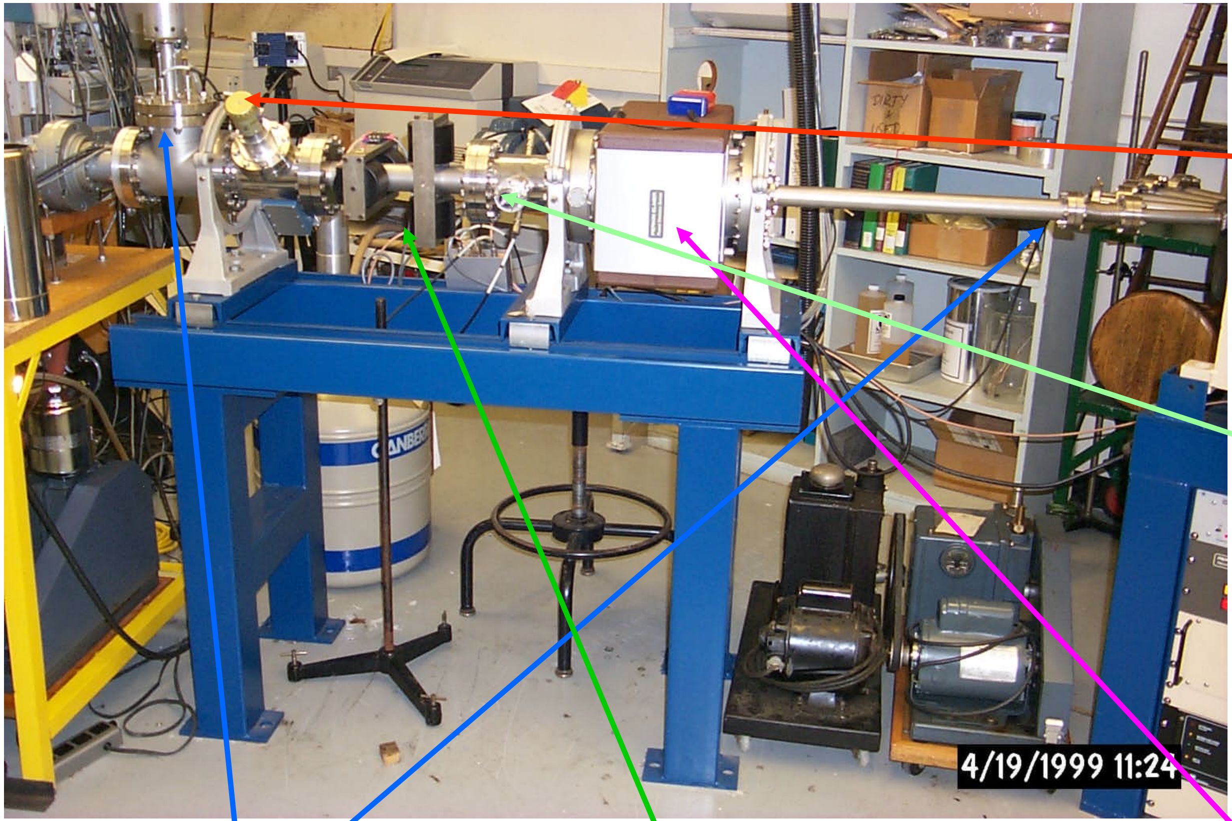
- So, we've accelerated the proton and calculated its energy and speed.
- Now can we steer it in the magnetic field? If so, what is its orbital trajectory, or radius?
- The proton feels a force given by $\vec{F} = q\vec{v} \times \vec{B}$.
- This makes the particle travel in a circle of radius *r* due to the centripetal force it feels.

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

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

- 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

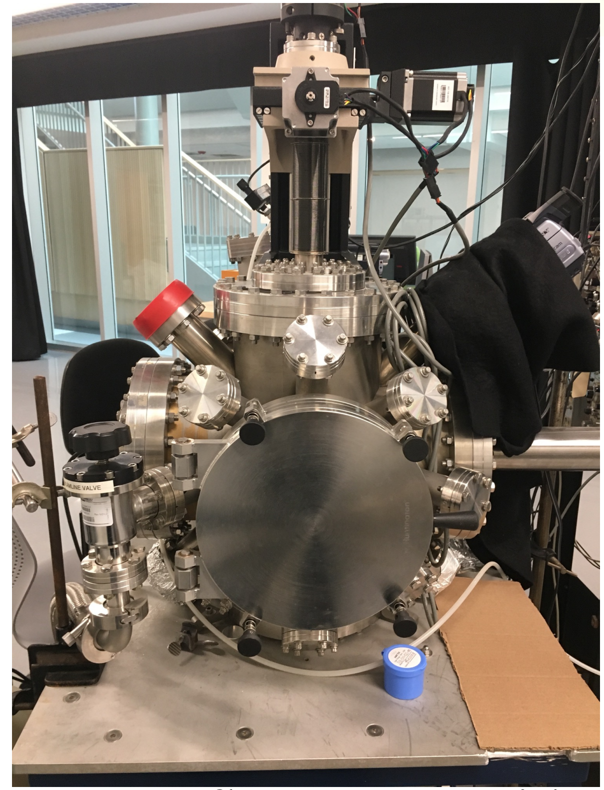
Faraday cups

Horizontal and Vertical steering magnets

Ion pump (not in use)

The scattering chamber

This is where the experiments are done.

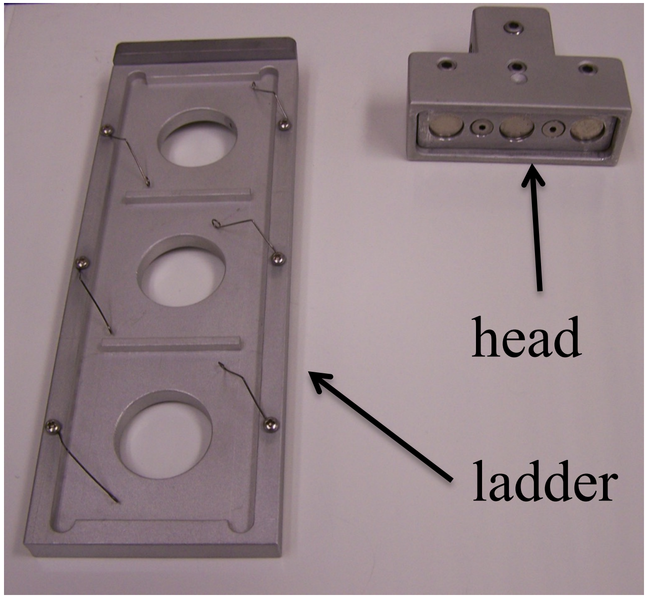


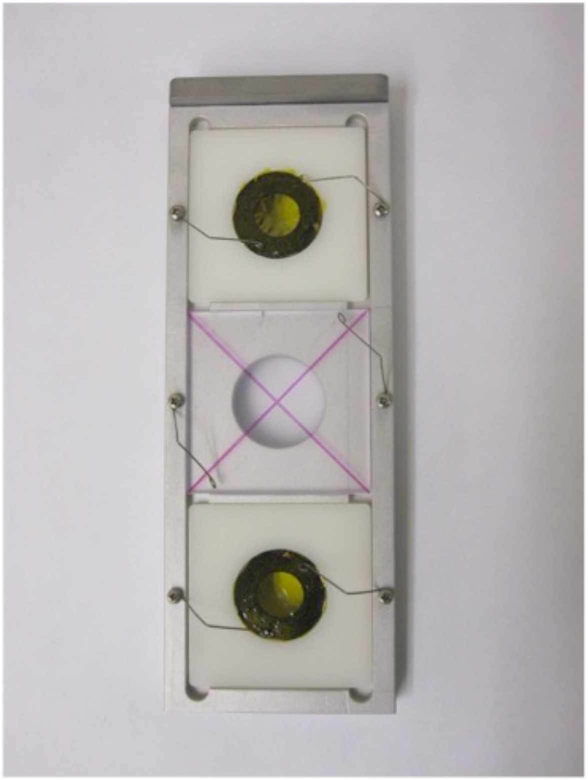
- The scattering chamber is a 10” multi-port Conflat system with a 3-axis target manipulator mounted on top.

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

Colin has his PhD in physics and is a lecturer in Astrophysics at LSU while Rob is a nuclear engineer at Cornell.

Target Ladder Assembly



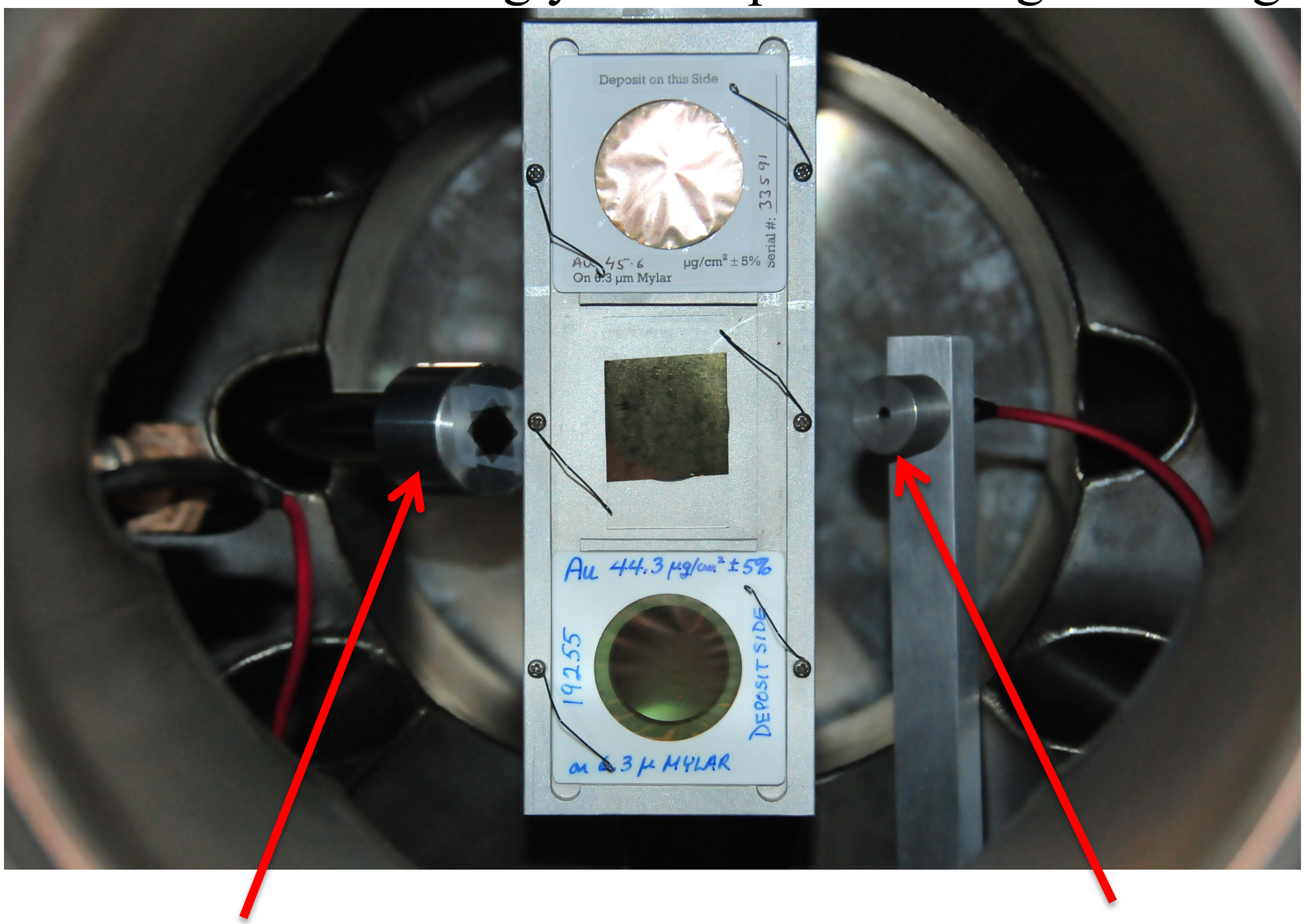


- Inside of the scattering chamber is the target ladder assembly. It is attached to the target manipulator by a "head" by a shaft (not shown) and the ladder is magnetically coupled to the head.

- 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

Consumer products

Environmental Samples

Mass spectrometry

Nuclear reactions

Nuclear structure

Medicine

Nuclear Medicine

Biochemistry

Paleontology

Forensic science.

Art restoration and archeometry