Ion-matter interactions and applications

Bhas Bapat
MOL-PH Seminar
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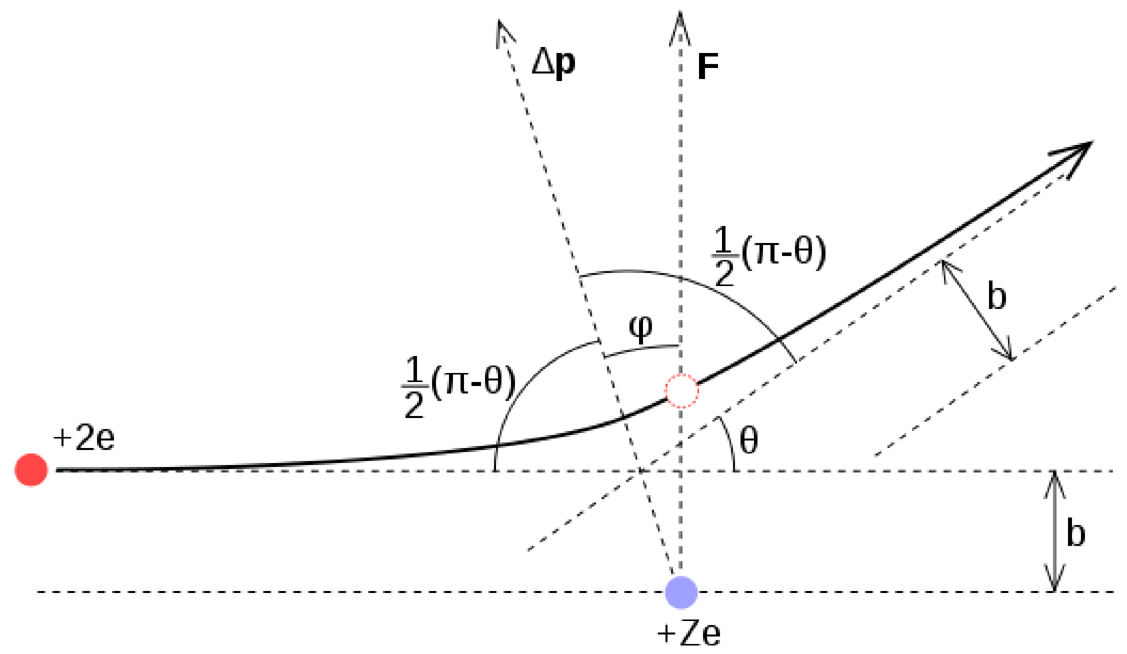
Outline

- Ion-atom collisions
- Energy loss in matter
- Applications
  - Atmospheric Science
  - Astrophysics
  - Material science
  - Medicine
  - Geology

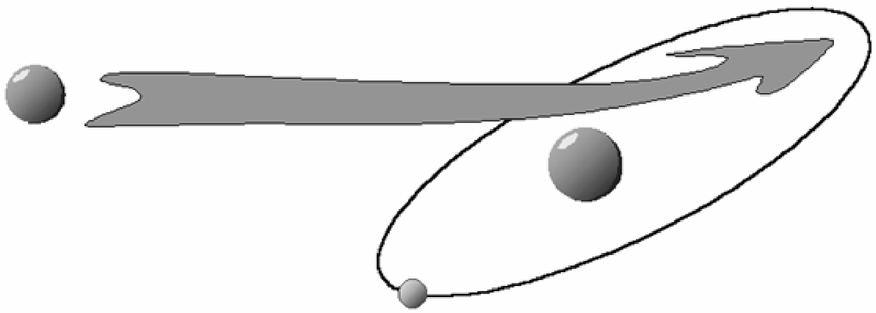
Ion-atom collisions – Basics

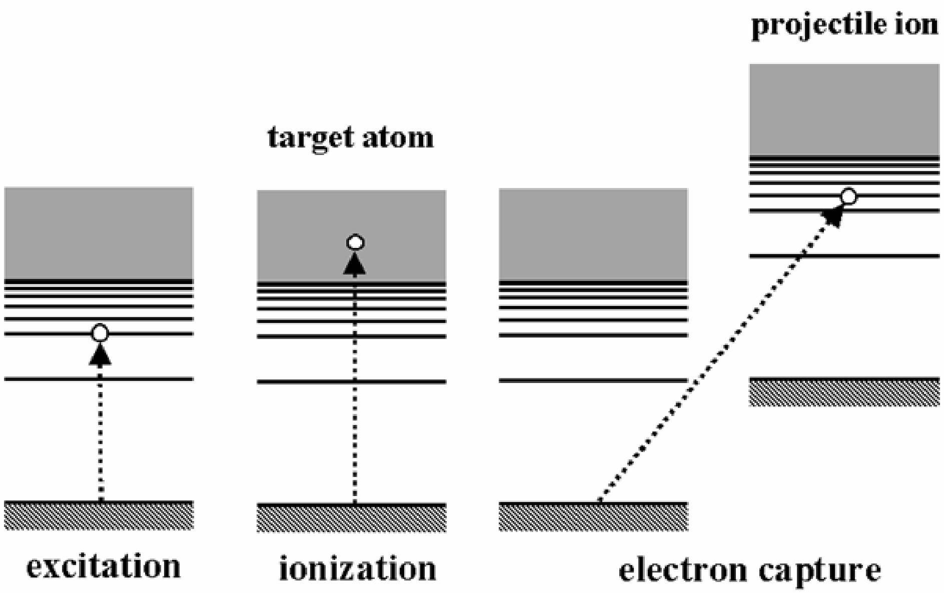
- Coulomb repulsion/attraction (electrons/nucleus)
- Scattering/deflection of the projectile (Rutherford)
- Net energy conserved, but the projectile itself may gain or loose energy



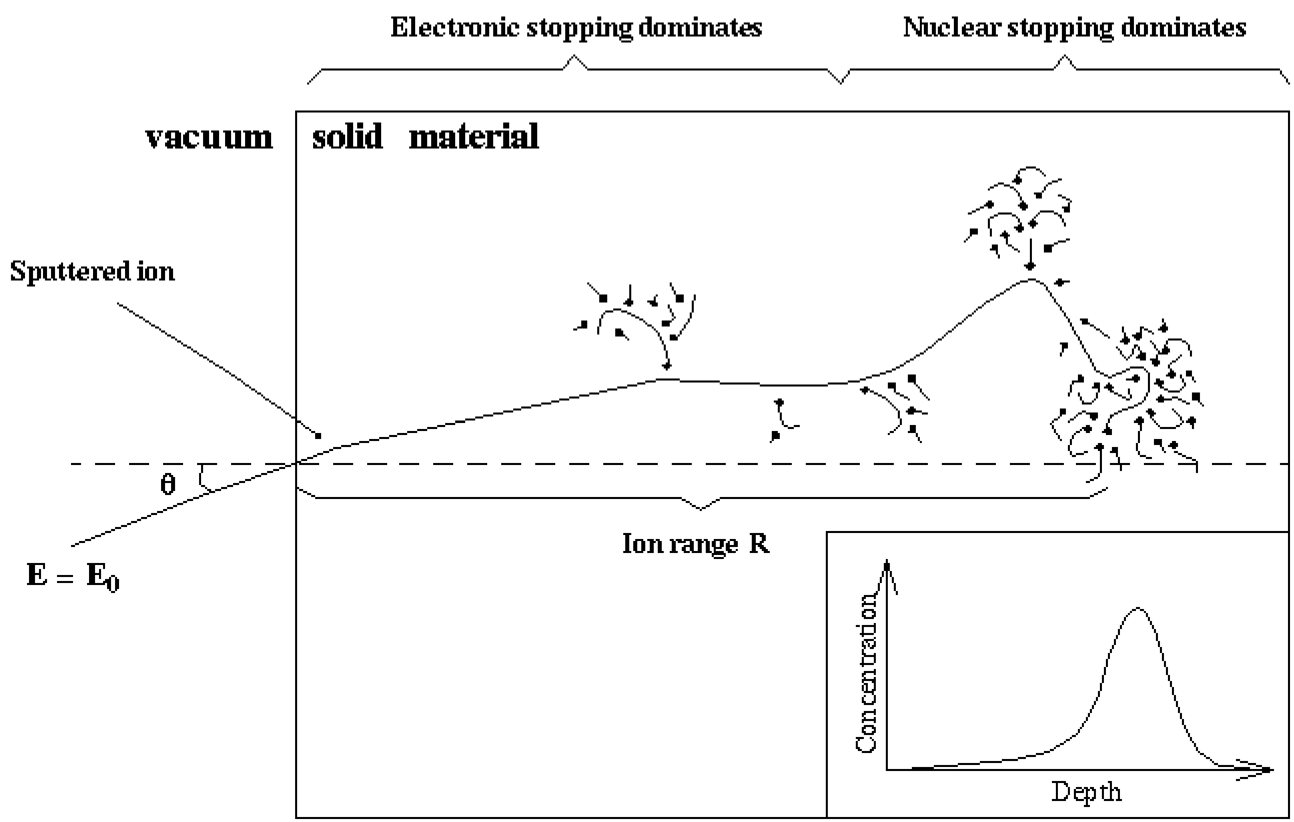
Ion-atom collisions – Basics

- Ion impact on an atom leads to many processes
  - Ionisation
  - Excitation
  - Electron loss
  - Electron capture





Energy Loss in matter



- Energy loss occurs due to
  - Interaction of projectile electrons with target electrons
  - interaction of the nuclei (coulomb repulsion)

Energy Loss in matter

- Loss pattern depends on the projectile charge, mass and velocity

for fast ions of charge ze, mass m and velocity v incident on a medium of number density N and average atomic number Z

$$\frac{dE}{dx} = \frac{4\pi e^4 z^2}{mv^2} NB$$

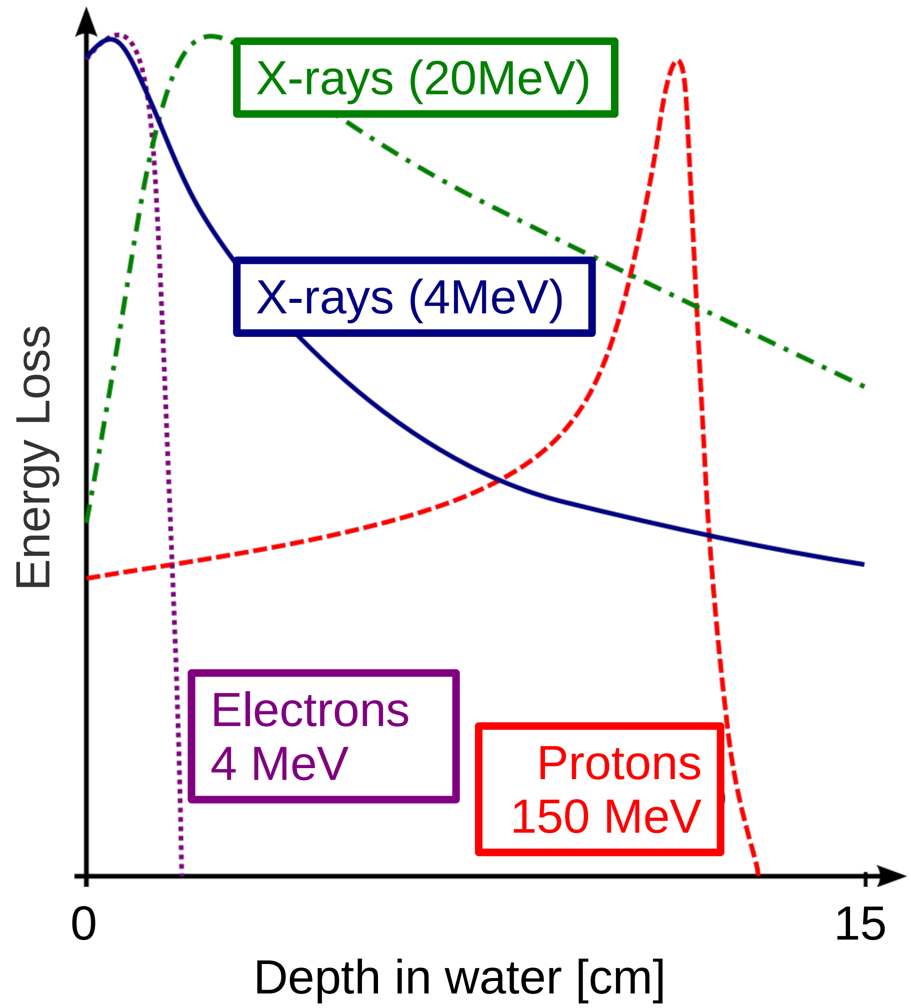
$$B = Z\left[\ln\left(\frac{2mv^2}{I}\right) - \ln\left(1 - \frac{v^2}{c^2}\right) - \frac{v^2}{c^2}\right]$$

- As the ion passes through the medium loss continues to rise (mainly $1/v^2$ factor), eventually slowing down and capturing electrons until it is neutralised ($z = 0$).
- Several low energy electrons are formed at the 'tail'
- It is this (final) slowing down is the key to many applications

Energy Loss : photons and electrons

Electrons and photons behave differently to ions.

The energy loss patterns of photons, electrons and protons are different and are the key to their usefulness in various applications



Applications

- Material Processing
  - Semiconductor Industry, IC fabrication
  - Doping/Material modifications
- Medical Applications
  - Tumor therapy
- Geology/Archaeology
  - Accelerator Mass Spectrometry

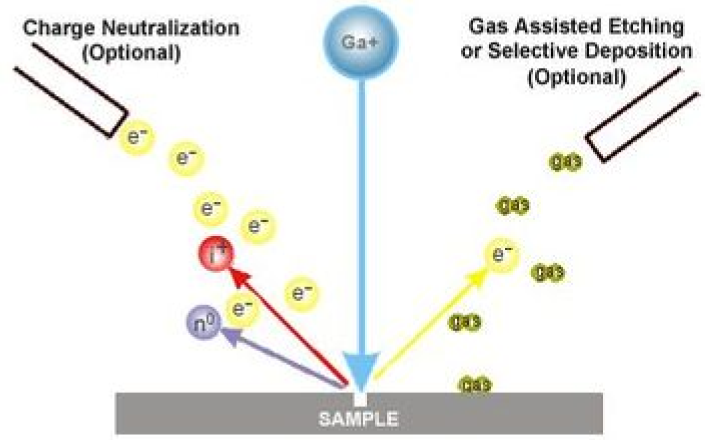
Material Processing

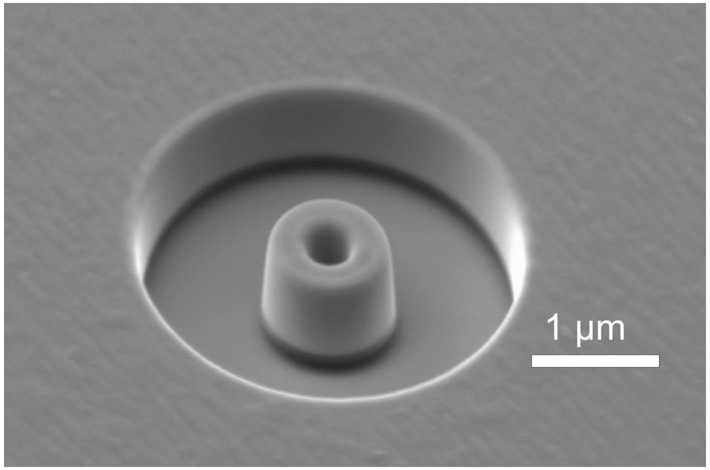
Material Processing

- Doping done commonly by CVD, MBE, IB
- Ion bombardment invented in 1954, commercial application in 1970
- Doping concentration 10^{14}–10^{15} cm^{-3}
- Beam spots 10 μm, currents 10 μA Ions: usually Al^+ P^+ As^+ In^+ B^+, energy 100 keV to MeV
- Precise control needed since slight doping variation leads to huge changes in semiconductor properties
- High process repeatability
- ICs solely possible due to IB technique!

Material Processing

- Ion-beam milling uses a focused beam of MeV protons or ions to pattern materials at nanodimensions.
- Ions travel in an almost straight path, so fabrication of 3-D, high aspect ratio structures possible with accuracy
- Negligible secondary electrons effects, especially with proton beams
- Due to the Bragg peak, increased localized damage at the end of range
- Ions are stopped in the solid, so substitution defects can be created





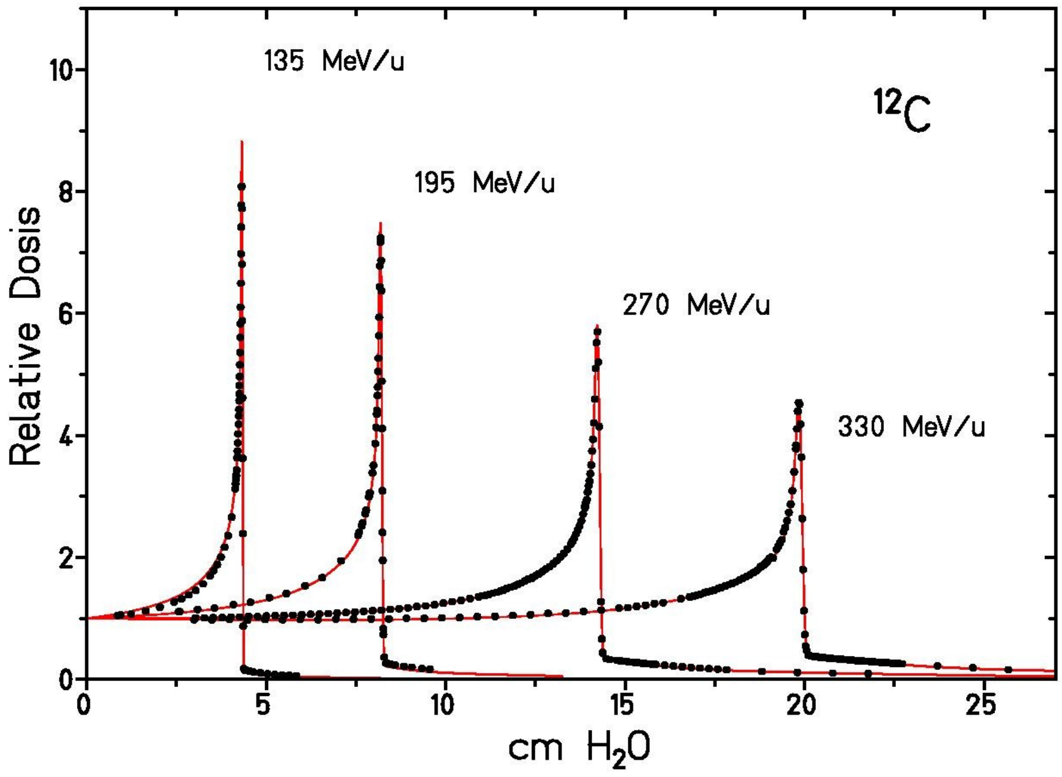
Tumor Therapy

Tumor Therapy

- Traditional tumor therapy
  - Chemo
  - Radiation (x-ray)
- Disadvantage
  - Large dose required for deep-seated tumors
  - Undesired, heavy damage along the access path
  - Straggling/scattering leads to widespread loss of healthy tissue

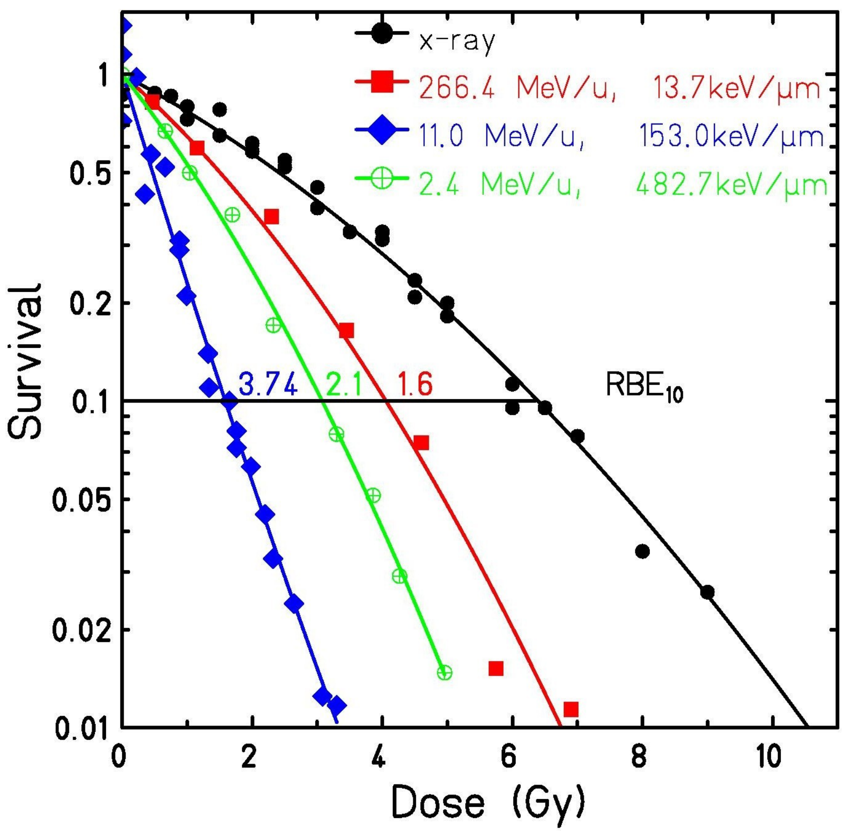
Tumor Therapy using ion beams

- Depth profiling possible
- Very little damage to healthy tissue on the path
- Buildup of secondary fragments is localised
- Dose tail is short
- Lateral dose is small



Tumor Therapy using ion beams

- Therapy using ion beams
  - Very low straggling compared to x-rays
  - Very high damage at specific depth at low doses



Well-controlled tissue destruction in the case of ion therapy, as compared to gamma rays

Low survival probability even at low dose for ions

Tumor Therapy using ion beams

- Disadvantages
  - Needs high energy beams
  - Needs energy tuning
  - Elaborate accelerator facility
- Successes
  - High individual success rates
  - Dedicated medical accelerators in Europe, US, Japan

Rev. Mod. Phys. 82, 383–425 (2010)

Heavy-ion tumor therapy : Physical and radiobiological benefits

Dieter Schardt, Thilo Elsässer, Daniela Schulz-Ertner

Accelerator Mass Spectrometry

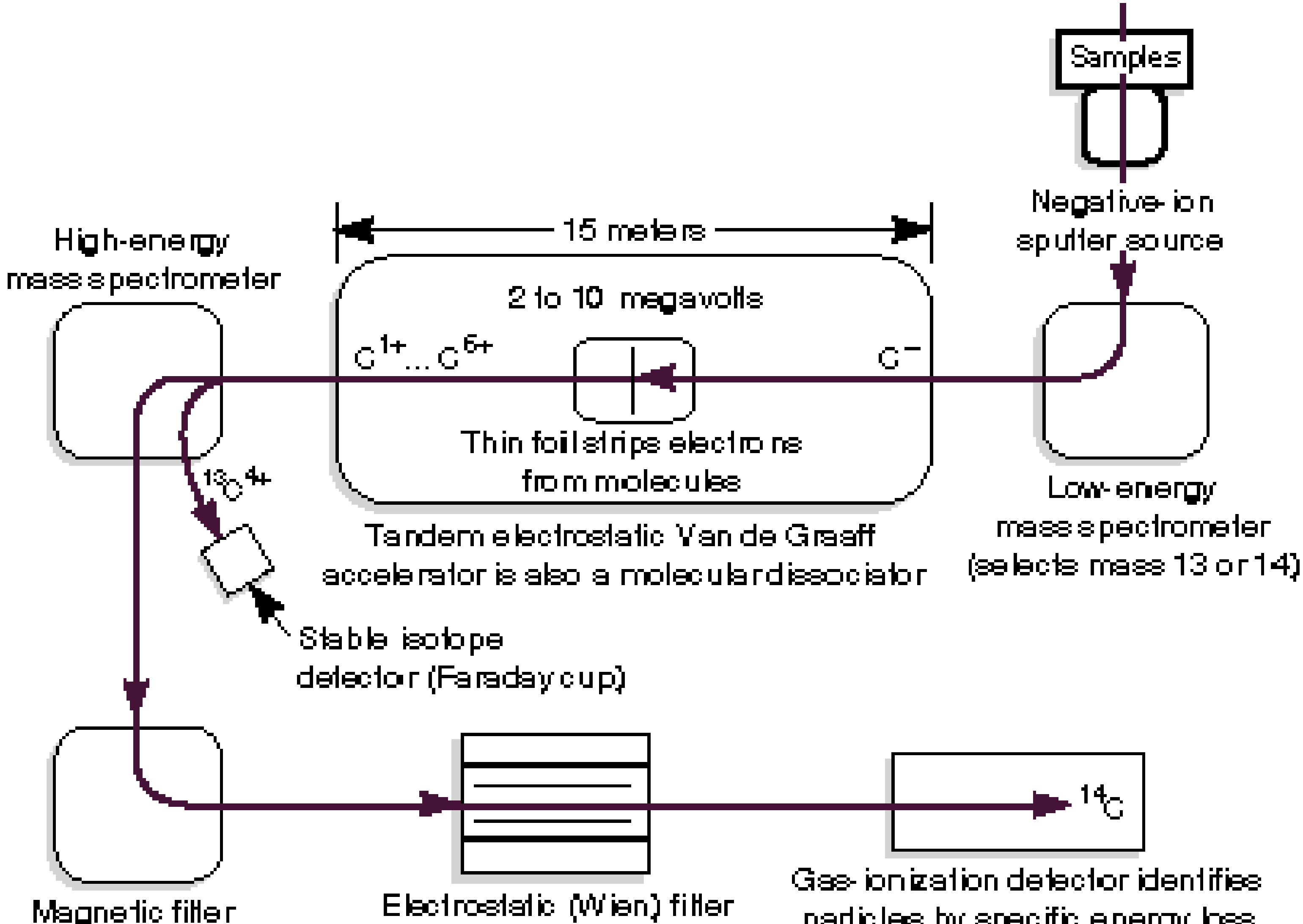
AMS : Background

- Radiocarbon dating
  - Determine the amount of radiocarbon in a sample by β counting and from the count rate estimate the age of the sample based on known ^{14}C half life.
  - Abundance of ^{14}C (relative to ^{12}C) is negligible and half-life is long
  - Makes counting tedious and inefficient
- Better Method (*Muller 1977*)
  - Separate ^{14}C from ^{12}C by based on velocity filtering of accelerated (high energy) ion beams
  - normal mass spectrometers not suitable due to molecular isobaric background

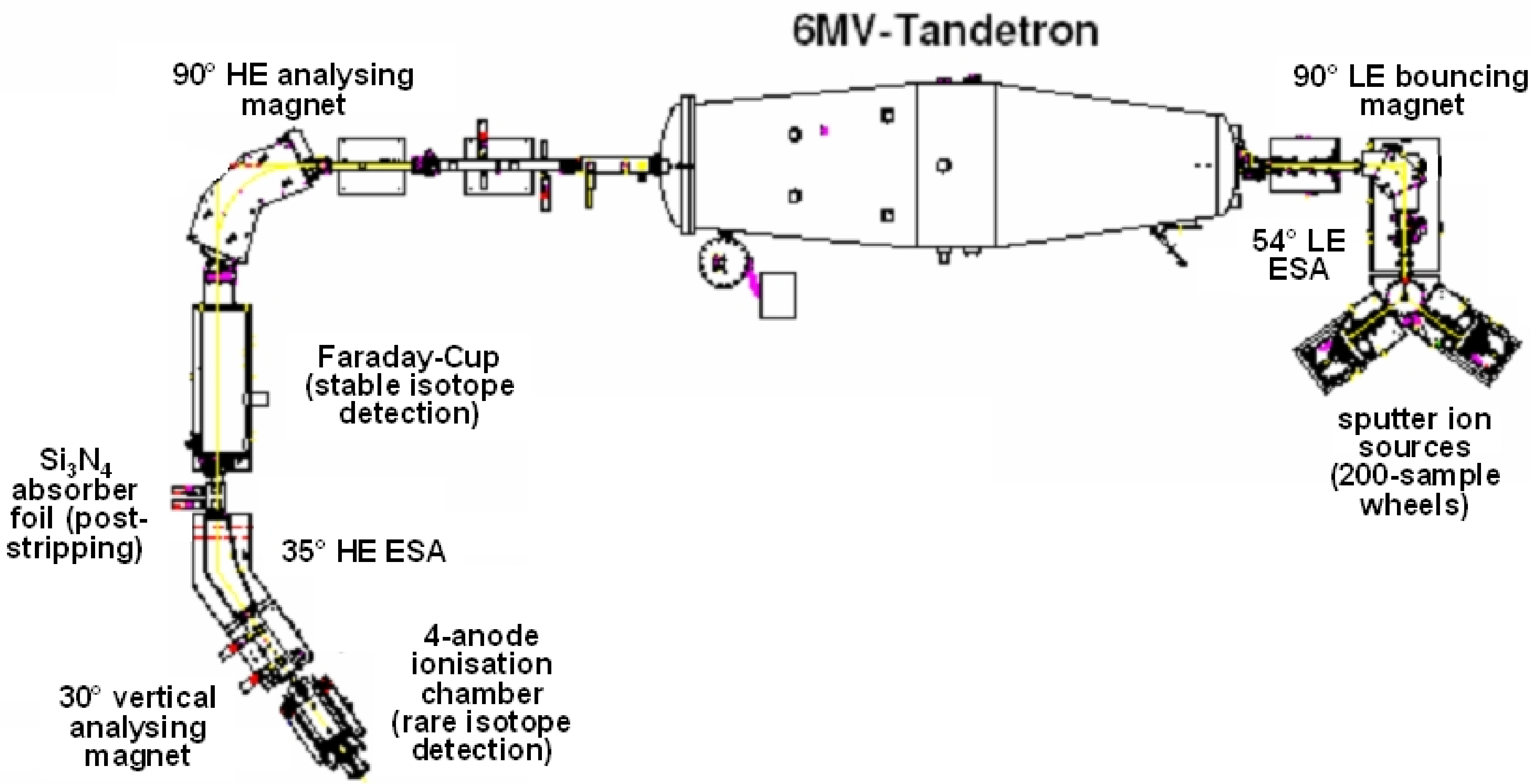
AMS : Principle

- Create ions of samples (usually mix of species)
- Accelerate them to (several) MeV
- Separate atomic (ionic) species after acceleration by a combination of m/q separation using an Analysing Magnet, velocity filtering by means of a Wien filter (crossed E, B) fields and Energy telescope (energy loss in a gas cell)
- The two "tricks" that make AMS work are the molecular dissociation process that occurs in the accelerator and the charge detection at the end.
- Can even separate isobars due to difference in atomic numbers, even though the masses are identical (eg ^{36}Cl, ^{36}S) based on the Bragg Curve

AMS : Technique



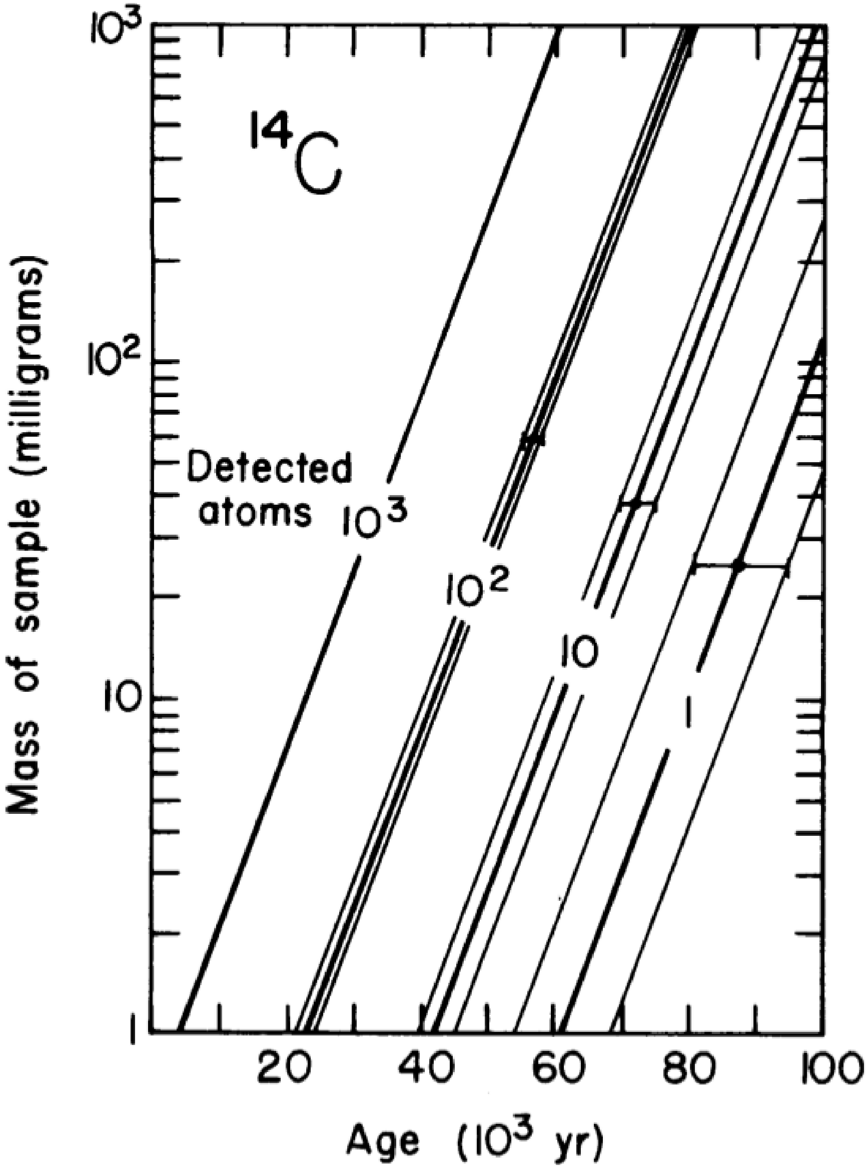
AMS : Technique



A typical AMS for geology applications

AMS : Abundance Sensitivity

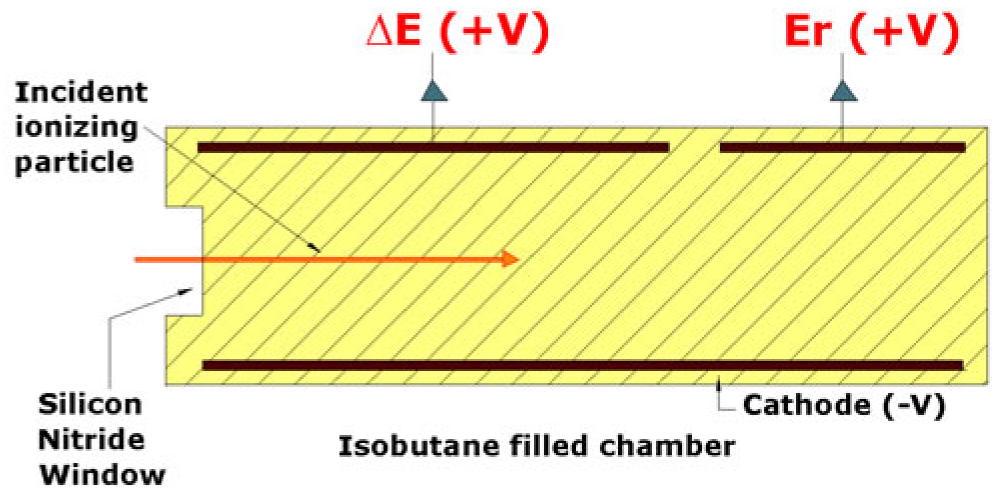
- Strength: power to separate a rare isotope from an abundant neighboring mass ("abundance sensitivity", e.g. ^{14}C from ^{12}C).
- Permits detection of naturally occurring, long-lived radio-isotopes such as ^{10}Be, ^{36}Cl, ^{26}Al and ^{14}C. Their typical isotopic abundance ranges from 10^{-12} to 10^{-18}.
- AMS can outperform the competing technique of decay counting for all isotopes where the half-life is long enough.

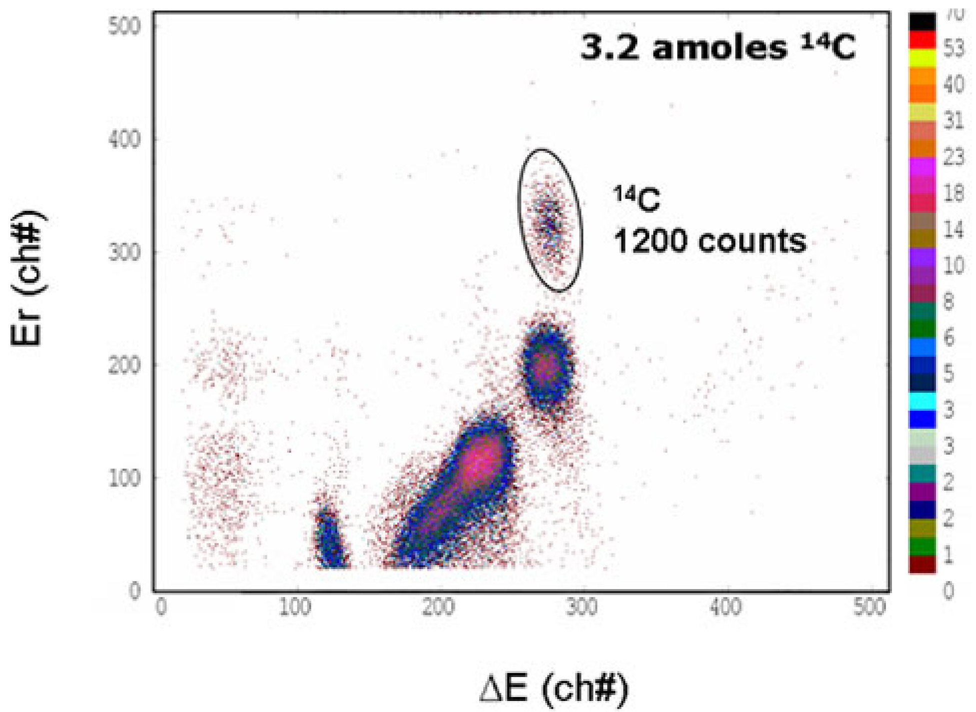


AMS : isobar separation

Recall: Energy loss is a function of both z and m especially at the tail of the stopping curve

Hence isobars can be separated in an energy loss (E-ΔE) detector (also called an energy telescope)





AMS : Uses

- Dating and Tracers
  - Determination of ^{14}C concentration
  - ^{26}Be, ^{26}Al, and ^{36}Cl are used for surface exposure dating in geology/meteor studies.
  - ^{3}H, ^{14}C, ^{36}Cl, and ^{129}I are used as hydrological tracers.
- Medical Applications
  - ^{41}Ca has been used to measure bone resorption

Summary

- Fundamental research in Ion-Atom collisions have played a significant role in shaping today's applications
  - Material processing
  - Medical Applications
  - Geology
- Other Atomic Molecular Physics Applications
  - Lasers, Optical communication
  - Semiconductors and other wonder materials
  - Various analytical/diagnostic techniques, forensics, security . . .
- Cannot afford to ignore this important branch of fundamental research!