PC 3242 Part II

Topic	Text Book (Zhen Cui '05)	Lectures
Optical lithography	Chapter 2	1, 2 & 3
Electron Beam Lithography	Chapter 3	4 & 5
Focused Ion Beam Technology	Chapter 4	
Low Energetic Ions (keV)		6, 7 & 8
SIMS	Extra material provided	
FIB in Lithography	Chapter 4	
High Energetic Ions (MeV)	Extra material provided	8
RBS	Extra material provided	9
Light ions in lithography	Extra material provided	10
Etching	Chapter 7	10, 11
Nano Imprint Lithography	Chapter 6	12
3DP Three Dimensional Printing	Extra material provided	13

JA van Kan 2024

FIB/SIMS

Primary ion beam sources

- **Electron bombardment**
  - using a high current density of electrons to ionize the gas (e.g. Ar, Xe)
  - mainly used in SIMS instruments

- **Plasma**
  - higher gas pressure, higher electron density, plasma is formed (e.g. duoplasmatron, RF and hollow cathode source for O_2, Ar)
  - mainly used for high energy accelerators

- **Surface ionization**
  - ion emission thermally stimulated by warming an adsorbed layer of Cs on a high work function metal (Ir) (Only Cs is used due to the enhancement of negative secondary ion yields)

- **Field ionization**
  - stripping electrons off source atoms near a high local electric field (tip); liquid metal (typically Ga) on W tip; liquid metal ion sources.
  - field ion microscope to study atomic structure of material & FIB.

SIMS

Liquid Metal Ion Source LMIS

The apex of a LMIS is typically 5 nm in size!

The energy spread is normally about 15 eV

➔ Large energy spread will cause chromatic aberrations.

At low currents (<10 uA) the beam is almost completely singly charged

➔ Higher currents come with higher charge states which is detrimental to FIB applications for lithography.

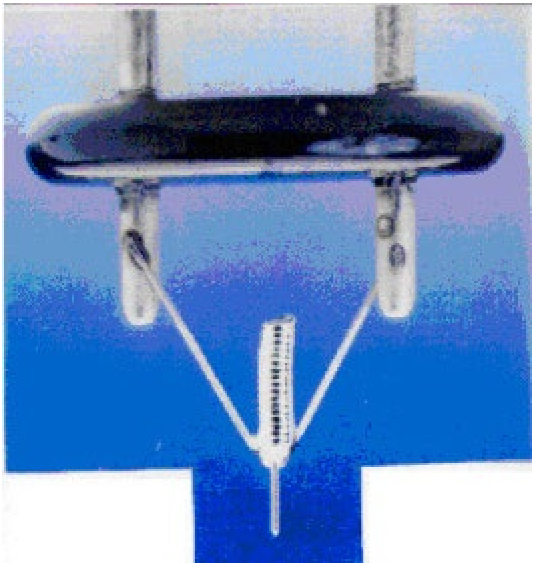
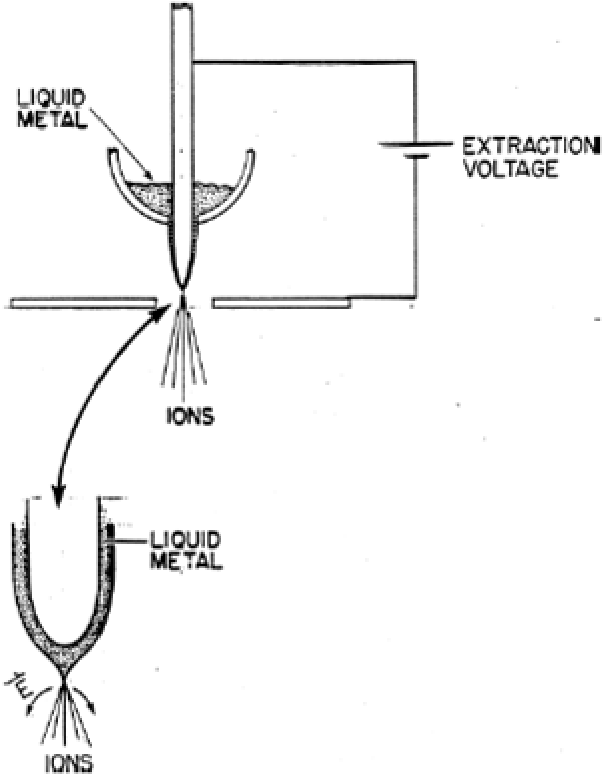


Photo of a LMIS



Schematic diagram of a LMIS

FIB/SIMS

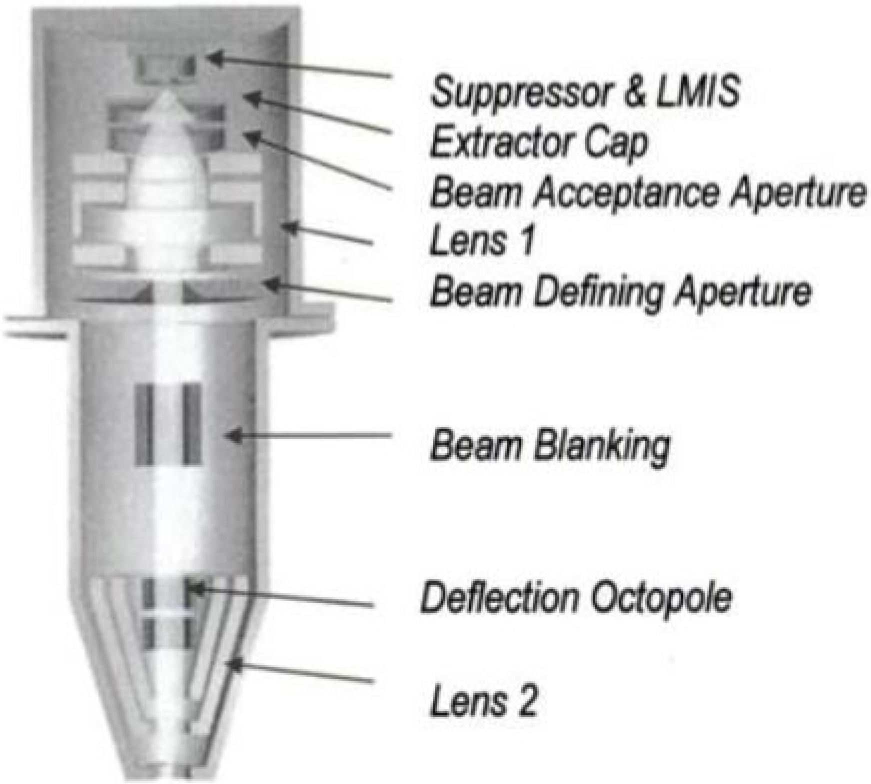
Column

Best resolution performance 5 nm in Ga,
New systems are being developed!

Mass filter ExB

Typical **lithographic** systems are dual beam systems;
- Material deposition FIB;
  C, Pt, W, SiO_2
- Sputtering of Si, SiO_2, Cr

- SEM is used for localization of markers.
- SEM 100 eV – 30 keV; 3 nm at 30 keV
- FIB Ga 1 keV – 30 keV;
  1 pA – 20 nA; 4-5 nm
- 2” Substrates



Schematic diagram of a FIB Column courtesy of FEI

SIMS / FIB

Focused ion beam systems are similar to electron beam systems. They have a source, lens system, work stage, vacuum and control system. Governing physics:

Force on a charged particle in an Electric field: $F_e = qE$

Force on a charged particle in a magnetic field: $F_m = qv \times B,$

Here v is the velocity and V is the acceleration voltage.

$$v = \sqrt{\frac{2qV}{m}}$$

In a FIB system electrostatic lenses are used as magnetic lenses would result in different focal planes for different Masses!

Some of the energy spread is caused by space charge

Coulomb repulsion between particles of the same charge is roughly inversely propositional to the speed of the particles

$$F_{rep} \sim \frac{1}{v}$$

SIMS / FIB

Electrons in e-beam writing are much faster than ions in FIB, but similar in speed compared to proton in proton beam writing.

$$\frac{F_{rep}^{FIB}}{F_{rep}^{e-beam}} = \frac{v_e}{v_{ion}} = \sqrt{\frac{V_e\, m_{ion}}{V_{ion}\, m_e}} \approx 350$$

$$V_{ion} = V_e = 20keV$$

$$q = 1 \qquad m_{ion} = 66au$$

This space charge leads to energy spread and therefore larger beam spot size

➔ Here chromatic aberrations are more important than spherical aberrations

Better performance at lower currents 2nA-2uA.
ΔE ~ 5 eV this gets worse at higher currents (chromatic aberrations).

Basic SIMS Formula

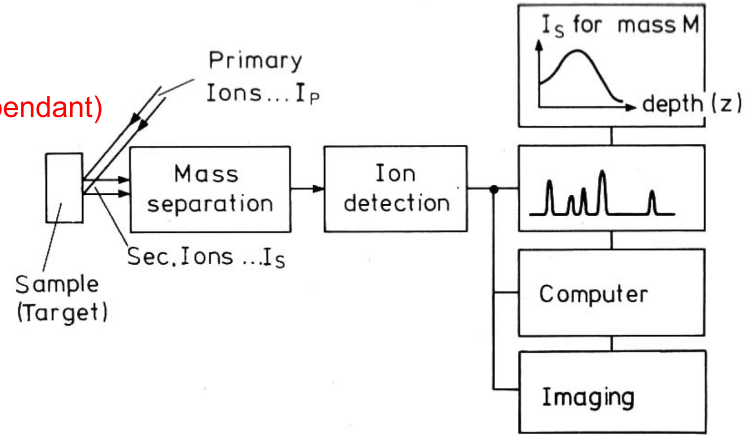
$$I(A\,q) = I_p \cdot F_{sims} \cdot c(A) \cdot T \qquad F_{sims} = Y \cdot \alpha$$

$$I(A^q) = I_p \cdot Y(E,q) \cdot \alpha(A^q) \cdot c(A) \cdot T$$

Secondary ion current of species A detected (or sputtered) (cps):

In SIMS all are needed, in FIB only I_p, $Y(E,q)$ and $c(A)$ are needed

q = Charged state (e.g. + or -)
I_p = Primary current density (ions/sec)
$Y(E,q)$ = Total sputtered yield (matrix dependant)
$\alpha(A^q)$ = Ionization probability to charge state q (matrix dependant)
$c(A)$ = Fractional concentration of A in matrix
T = Instrumental transmission function



SIMS

Difficulties in Quantification

$$I(A^q) = I_p Y \alpha(A^q) c(A) T$$

- Y_{total} depends moderately on $c(A)$, incident angle and beam energy
- $\alpha(A^q)$ depends strongly on $c(A)$

$I(A^q)$ not linearly proportional to $c(A)$

=> Matrix Effects

SIMS

Sputter yield in FIB

Redeposition will reduce sputter yield. Especially in deep holes!
➔
Fast scanning can increase the sputter yield.

Chemically active gases (eg Cl, Br) can enhance the sputter yield.

A combination between sputtering and chemical gas phase etching can increase the sputter yield up to 10x. At the same time it will reduce the redeposition,

SIMS

Depth Resolution or FIB depth control

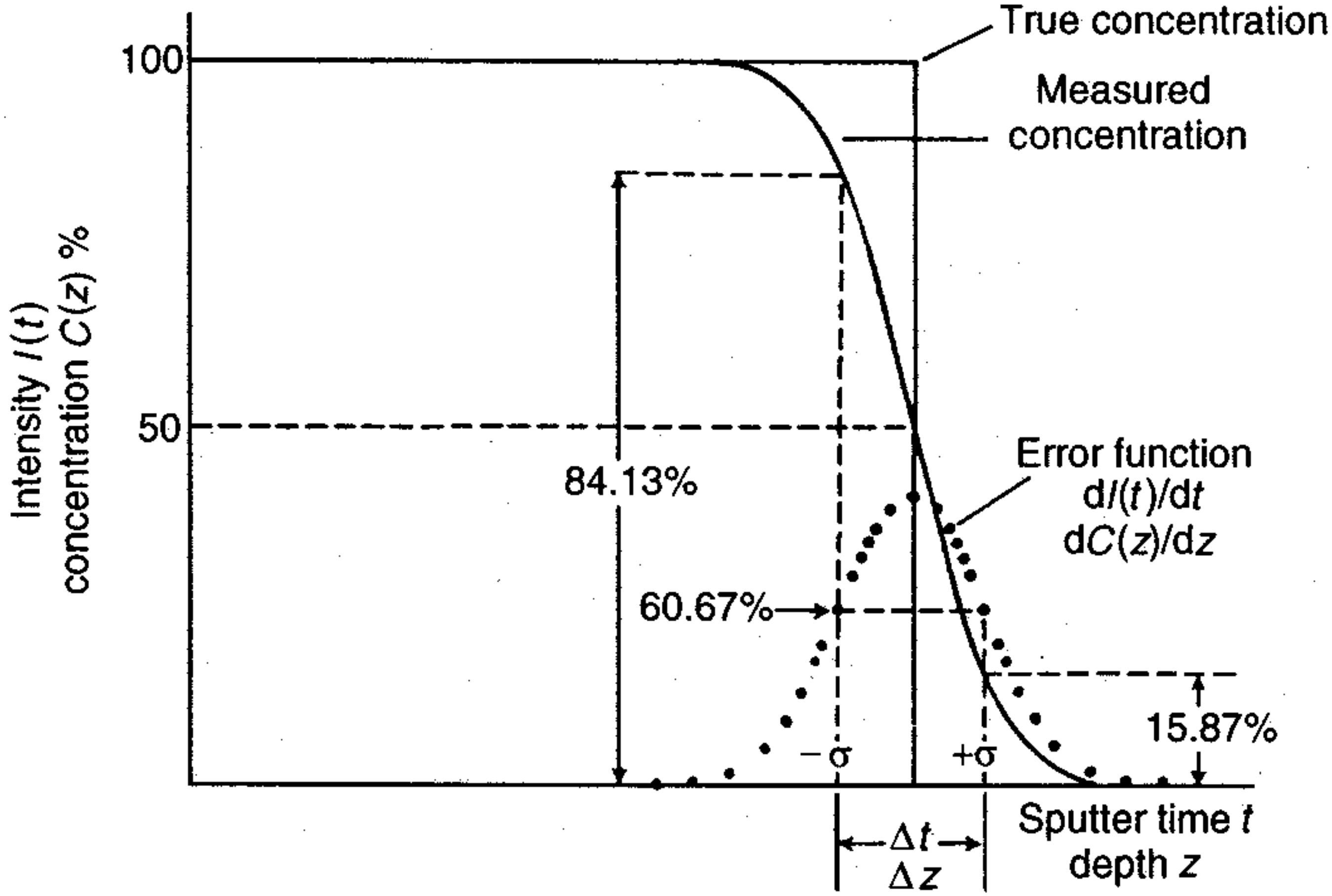


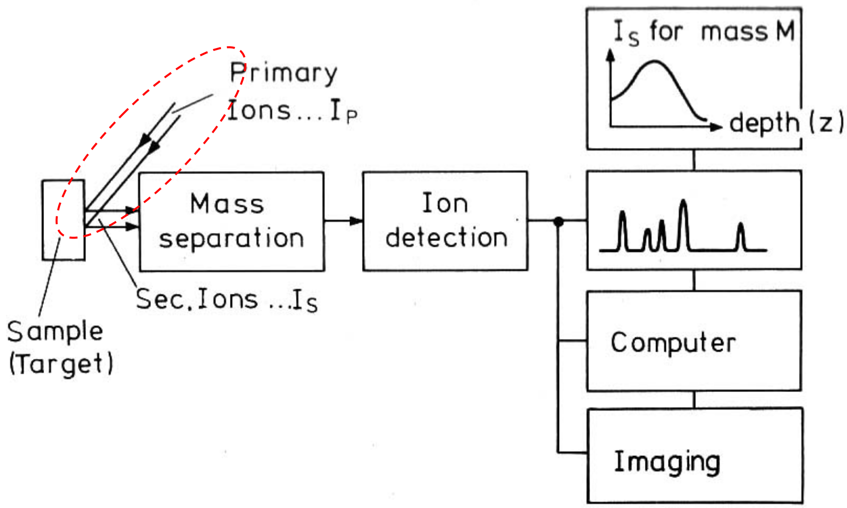
Figure 5.32. The definition of depth resolution

- Beam induced broadening
- Chemical effects (segregation)
- Development of (micro) topography
- Surface charging
- Instrumental drift

➔ Skilled interpretation of the data is required

SIMS

To avoid edge effects:
Rastering & Gating is used



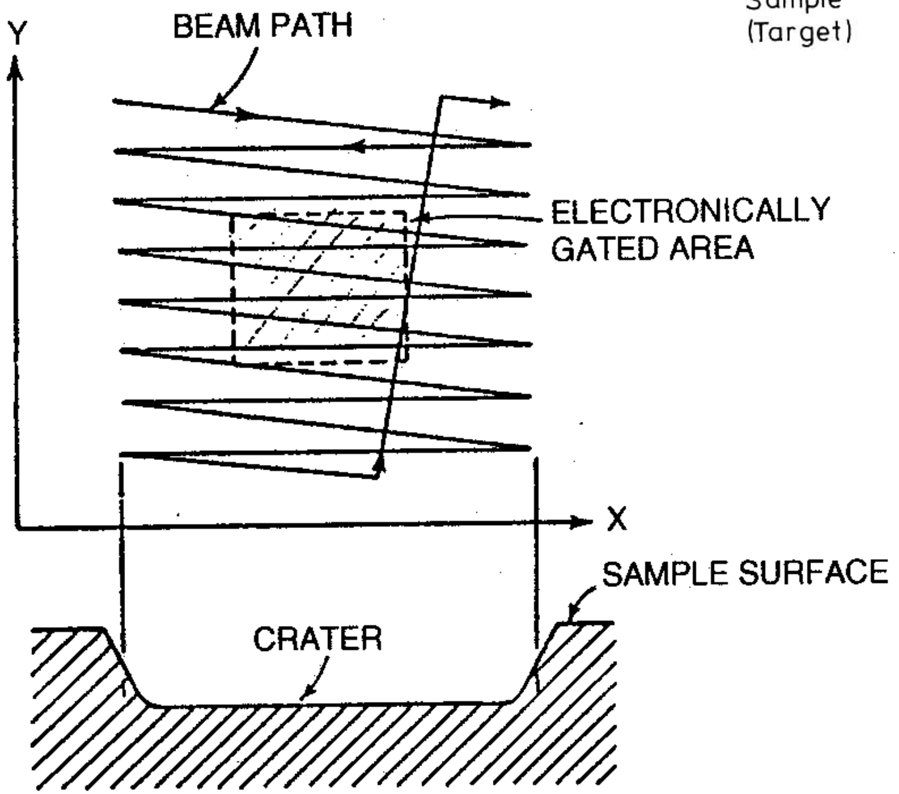


Figure 5.29. A schematic representation of the method for sputter etching a crater by rastering an ion beam of a material surface

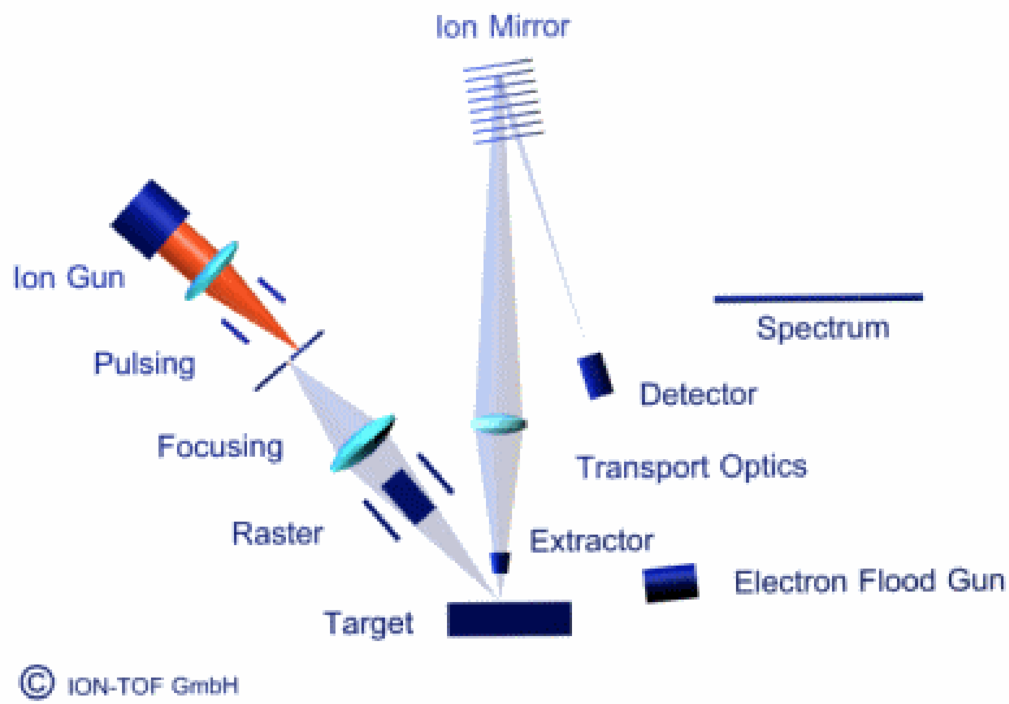
SIMS

Time-of-Flight Mass Spectrometer (TOF-MS)

In a more sophisticated design, the TOF analyser corrects for small differences in initial energy and angle in order to achieve high mass resolution. Combinations of linear drift paths and electrostatic sectors or ion mirrors are used.

Mass resolutions, M/dM, above 10,000 can be achieved.

<u>Major advantages</u> of this approach over quadrupole and magnetic sector type analysers are the extremely **<u>high transmission</u>**, the parallel detection of all masses and the **<u>unlimited mass range</u>**.

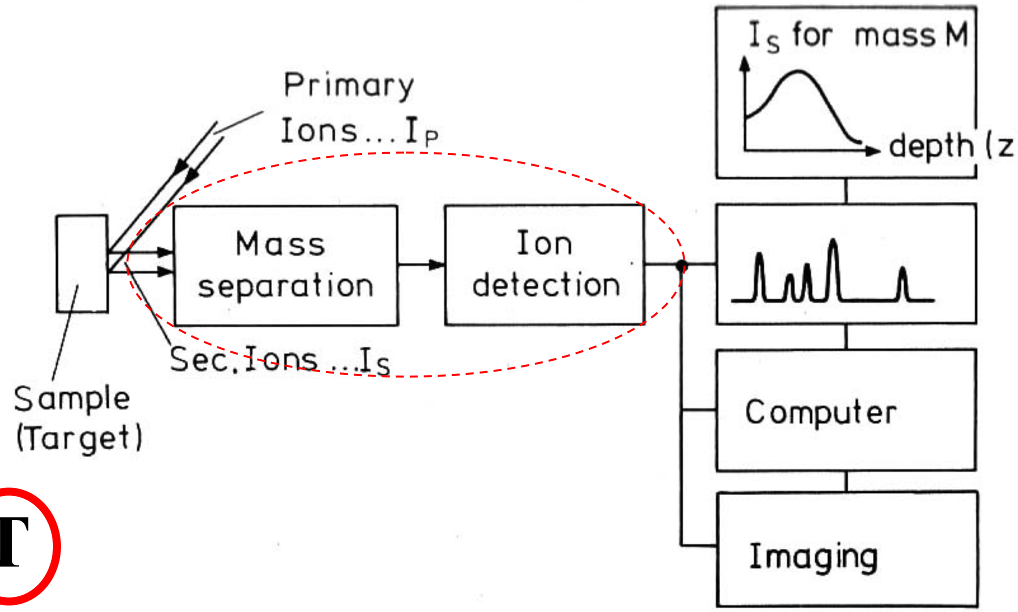


http://www.ion-tof.com/html/time_of_flight.html

SIMS

Mass Analysers

- Quadrupole
- Magnetic sector
- Time-of-Flight



$$I(A^q) = I_p . Y . \alpha(A^q) . c(A) . T$$

Table 5.3. Comparison of mass analysers for SIMS

Type	Resolution	Mass range	Transmission	Mass detection	Relative sensitivity
Quadrupole	10^2-10^3	$<10^3$	0.01–0.1	Sequential	1
Magnetic sector	10^4	$>10^4$	0.1–0.5	Sequential	10
Time-of-flight	$>10^3$	10^3-10^4	0.5–1.0	Parallel	10^4

MeV Ions

MeV ION BEAM ANALYSIS TECHNIQUES: PIXE & RBS

MeV Ions

HANDBOOK OF MODERN ION BEAM MATERIALS ANALYSIS

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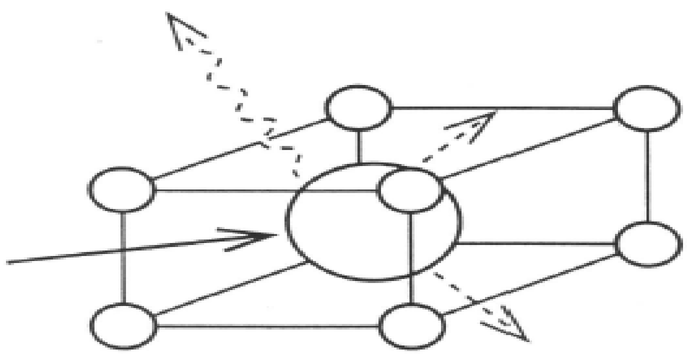


MRS

MATERIALS RESEARCH SOCIETY
Pittsburgh, Pennsylvania

1995

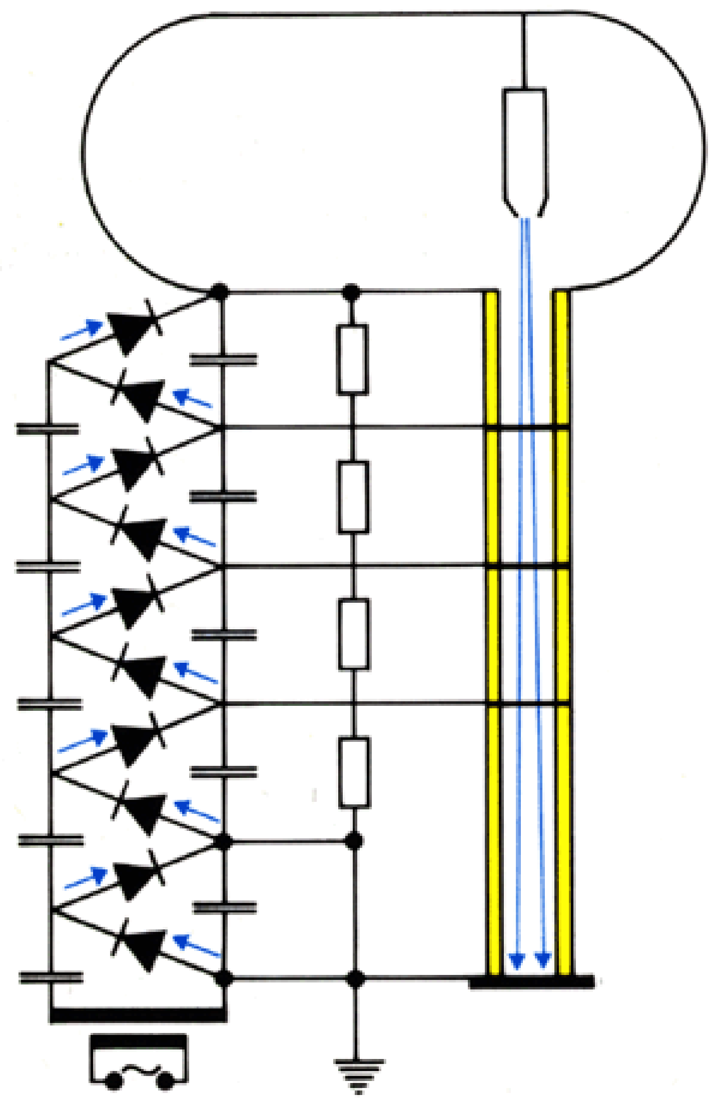
MeV Ions

Generating High Voltages

Earliest accelerator (built 1932): Cockroft-Walton High Voltage Generator: ion source is gradually charged up through the diode-capacitor combination

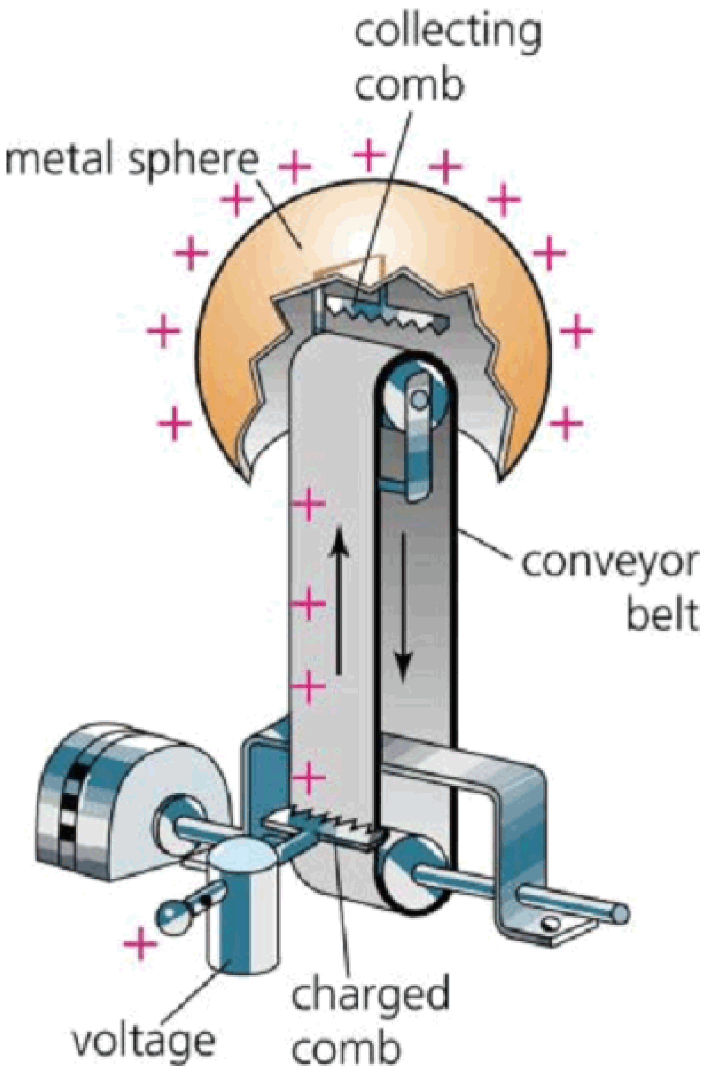
In those days the accelerators operated in air therefore the voltages were limited to ~400 kV

High stability in energy (~10V/MV) is possible in modern machines
➔ Low chromatic aberrations



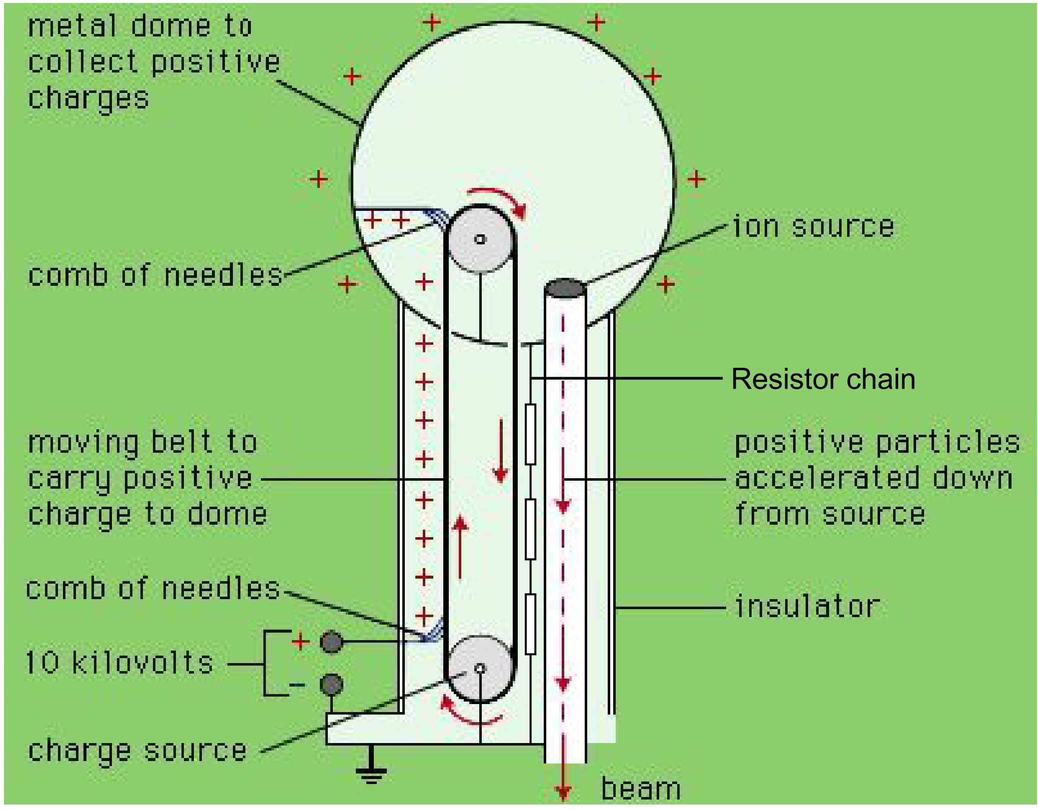
MeV Ions
van de Graaff accelerators

- Charge is 'sprayed' on insulating belt and moved to inside of sphere
- Charge is 'scraped off' and moves to the outside of the 'high voltage terminal'
- Ion source floating at high voltage.
- Electrical isolation of the MV potential by insulating gas



Not very stable in energy (Δ~1000V/MV)

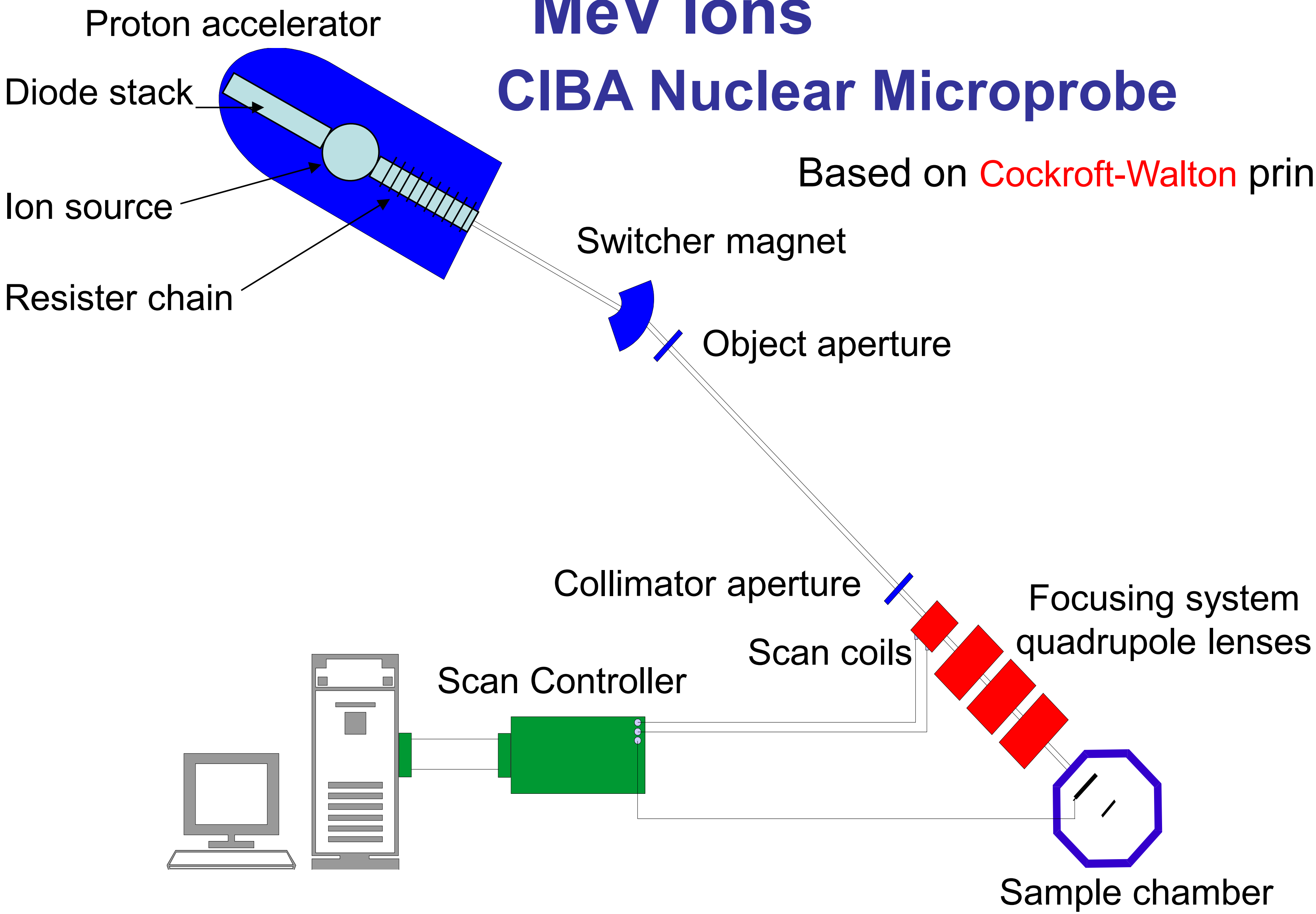
➔ High chromatic aberrations



MeV Ions

CIBA Nuclear Microprobe

Based on Cockroft-Walton principle



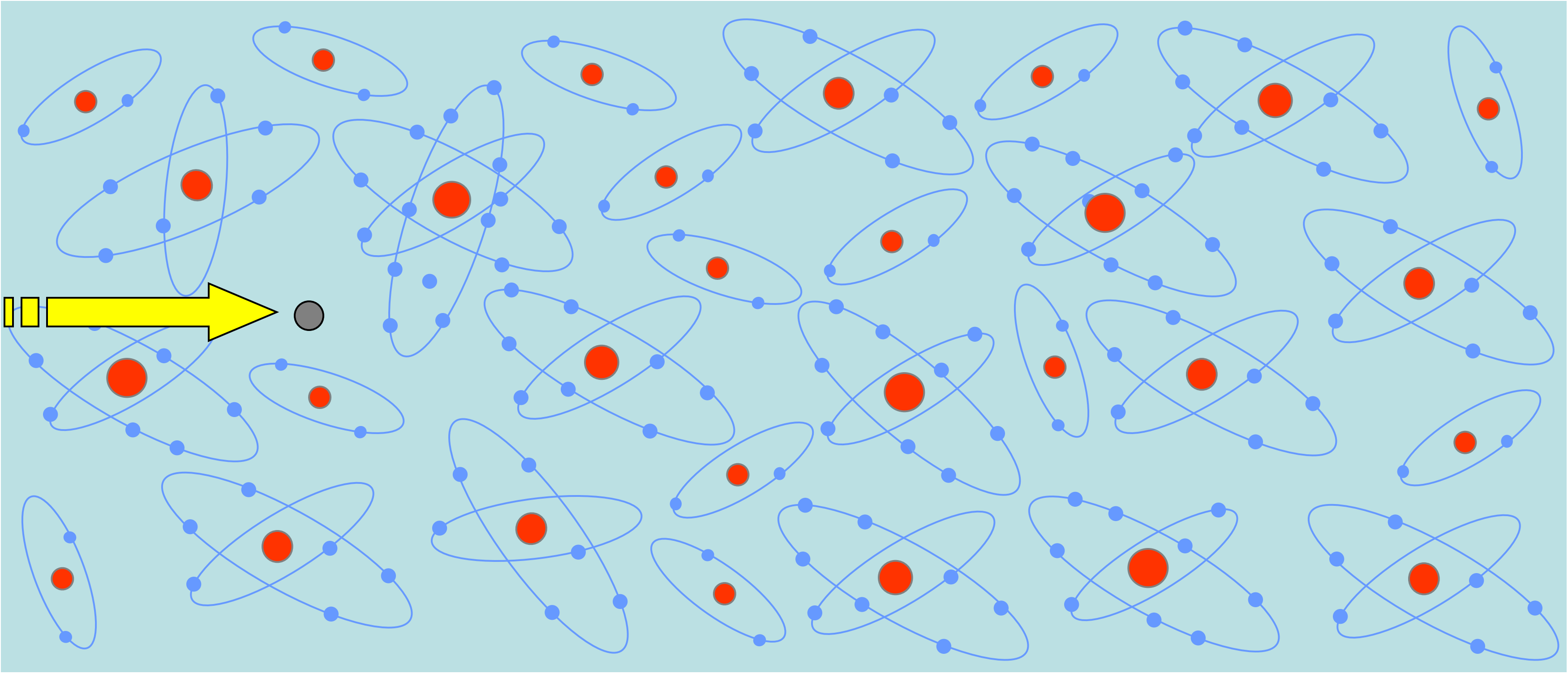
MeV Ions

In its passage through matter, an ion may interact with

- **THE ATOMIC ELECTRONS**

  and/or

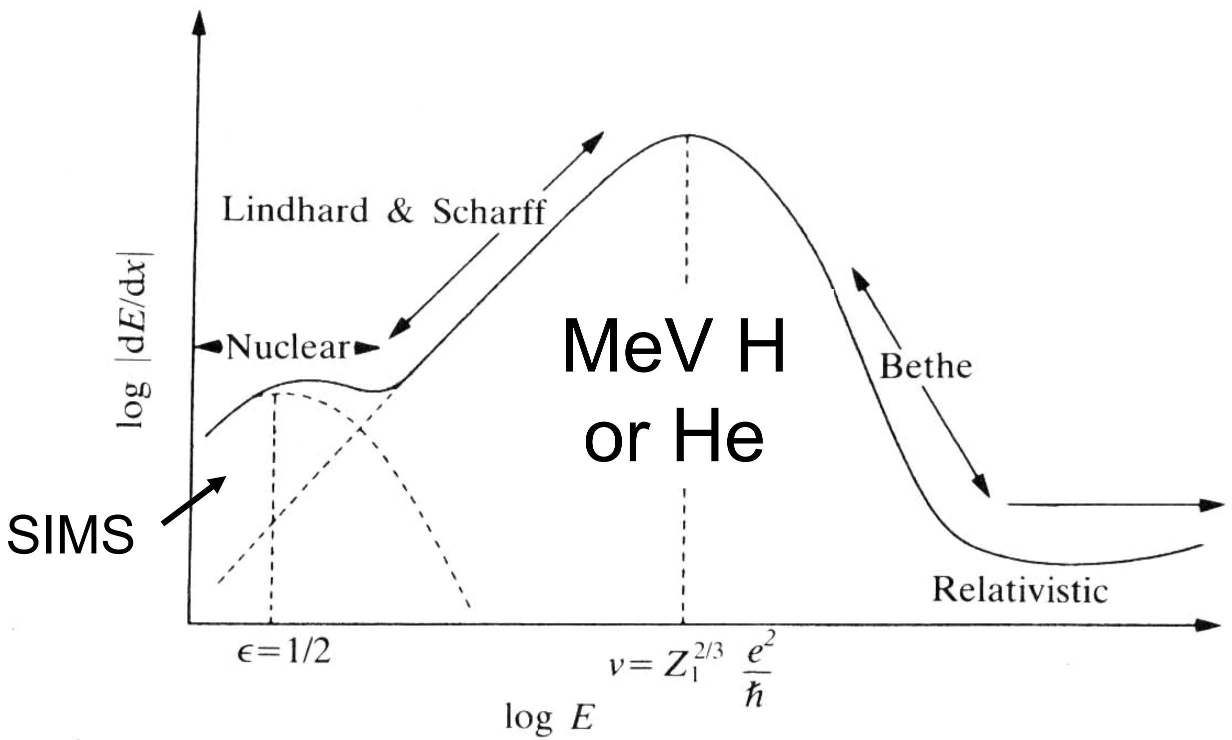
- **THE ATOMIC NUCLEI**



MeV Ions

Stopping

Nuclear ⬄ Electronic



$$\varepsilon = \frac{aEM_2}{Z_1Z_2e^2(M_1+M_2)}$$

a; Thomas Fermi screening radius

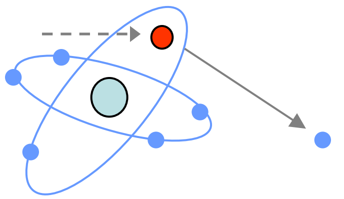
FIG 3.6. Schematic diagram of the stopping power of an ion as a function of energy. At low velocities nuclear stopping dominates for medium and heavy ions. At higher velocities electronic stopping takes over and the projectile is preferably neutral. Beyond the stopping-power maximum the Bethe regime is approached where the projectile is preferably stripped. Reproduced with permission from Ref.1.

MeV Ions

The interaction of an ion with an atomic electron is purely Coulomb (i.e. interaction governed by the Coulomb's law).

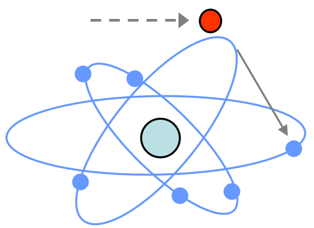
Such interaction will result in:

- **IONIZATION – the electron is ejected from its atomic orbit**



or

- **ATOMIC EXCITATION – the electron is raised to an outer orbit**



An ionized/excited atom will eventually return to its ground state, accompanied by the emission of one or more x-rays/photons.

MeV Ions

SECONDARY ELECTRONS & BREMSSTRAHLUNG

Brake Radiation

- **An electron ejected from its atomic orbit is called a *secondary electron or δ-ray*. It may further ionize or excite another atom, resulting in the emission of more x-rays/photons, these δ-rays have short range.**

- **A secondary electron may also be decelerated by the coulomb field of a nucleus, losing part or all its energy in form of *bremsstrahlung* (braking radiation).**

MeV Ions

Magnetic Rigidity

A measure of how difficult it is to bend charged particle beams depends on the particle mass m, energy E and charge q

$$\left.\begin{aligned} F_{cir} &= \frac{mv^2}{R} \\ F_L &= qv \times B \end{aligned}\right\} \quad B = \frac{mv}{Rq} = \frac{\sqrt{2m\,E}}{Rq}$$

Take R constant, then we get

$$B \sim \frac{\sqrt{mE}}{q}$$

Ions

Electrons

$$\frac{B_i}{B_e} = \frac{\sqrt{m_i E_i}}{\sqrt{m_e E_e}}$$

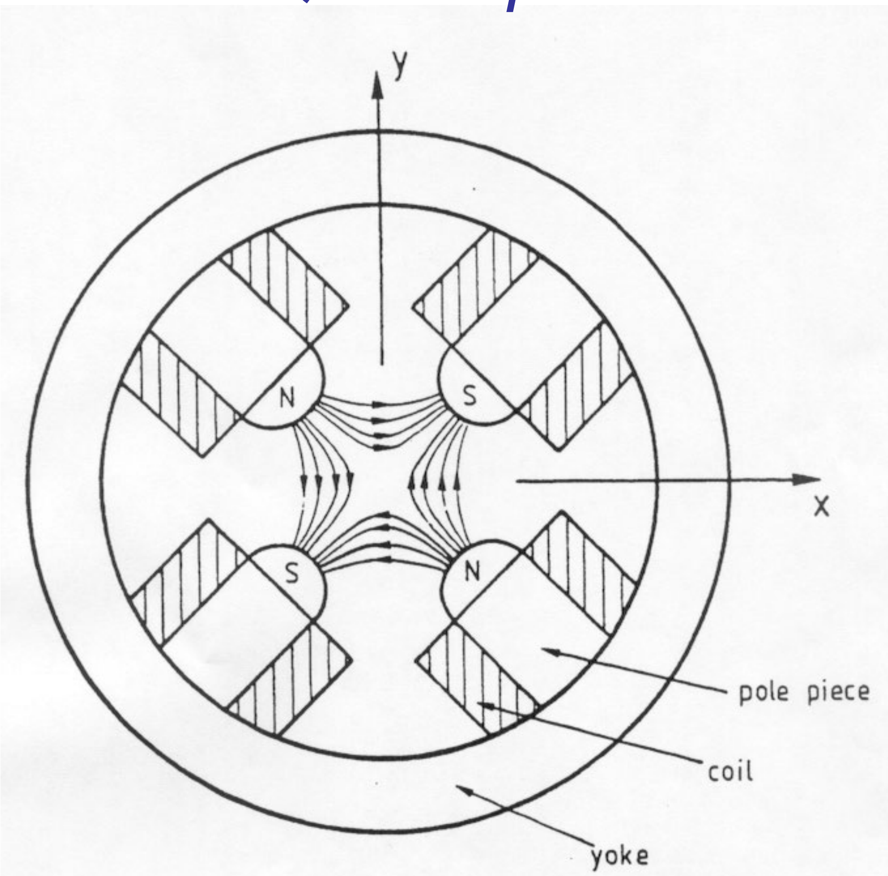
(singly charged)

*Proton mass is 1836 greater than electron mass. So a 2 MeV proton requires a magnetic field strength of **430 times** that needed to focus a 20 keV electron!*

$\Rightarrow$ To focus MeV protons we need to apply a very high B field!
$\Rightarrow$ Very difficult to focus using magnetic solenoid lenses, so use a magnetic quadrupole lens focusing system.

MeV Ions

Quadrupole Lenses



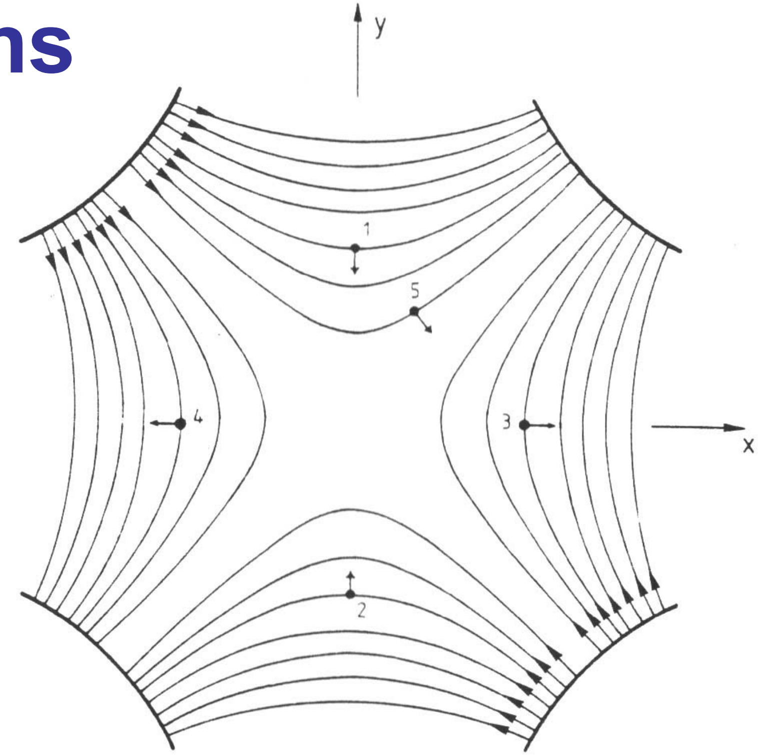
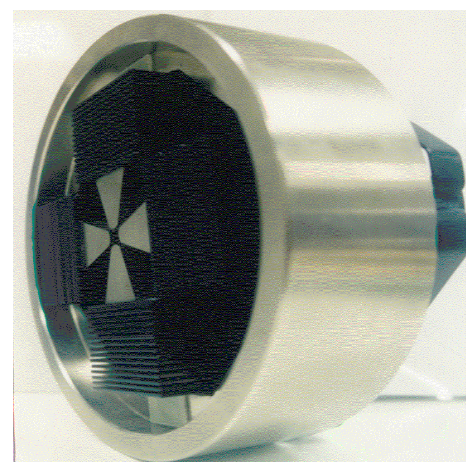


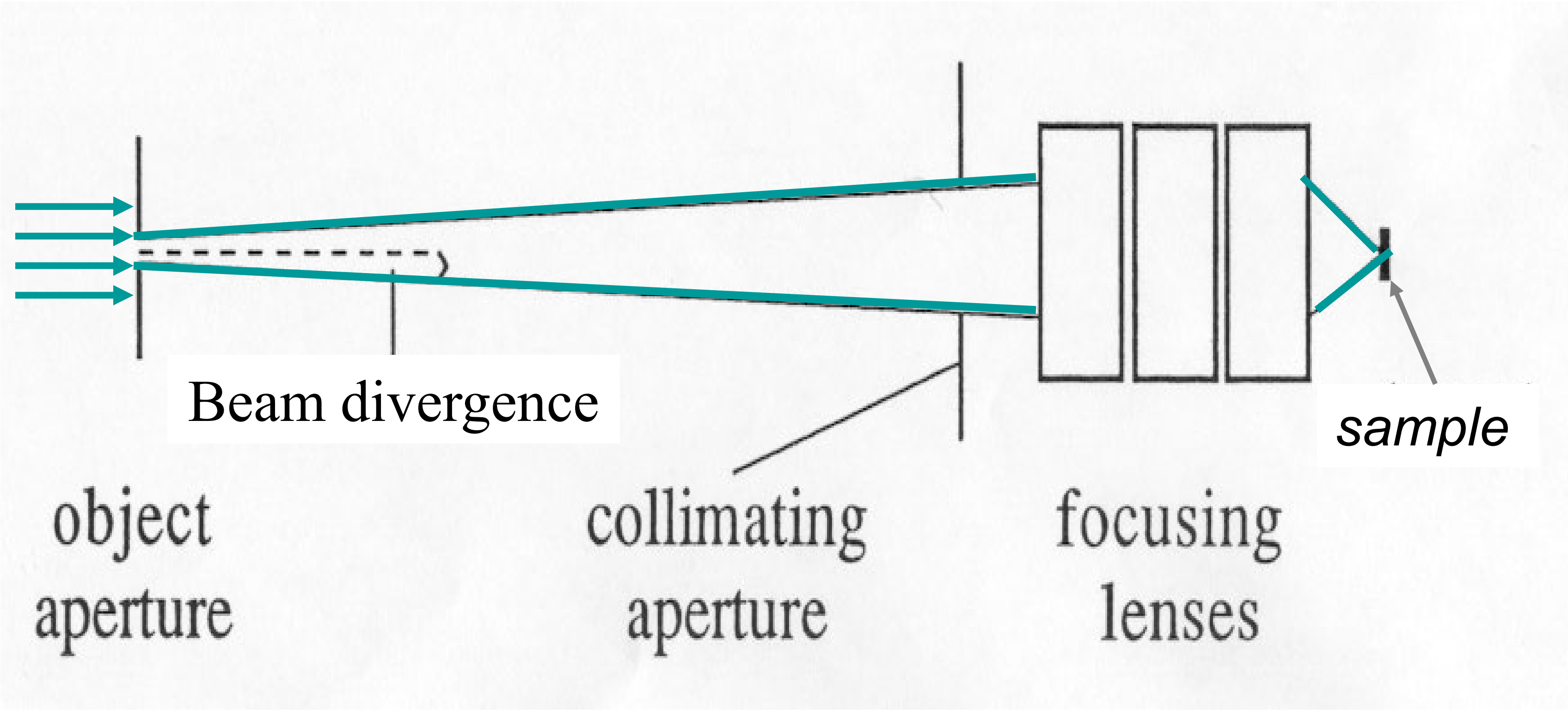
Figure 1.14 The action of the quadrupole field on a charged particle. The arrows represent the direction of the magnetic field force on a charged particle passing down into the lens for various positions in the cross section plane.



Lorentz Force: F = q $\underline{\mathbf{v}} \times \underline{\mathbf{B}}$
i.e. quadrupole lens gives a focusing force because ***v*** *and* ***B*** *are perpendicular*

MeV Ions

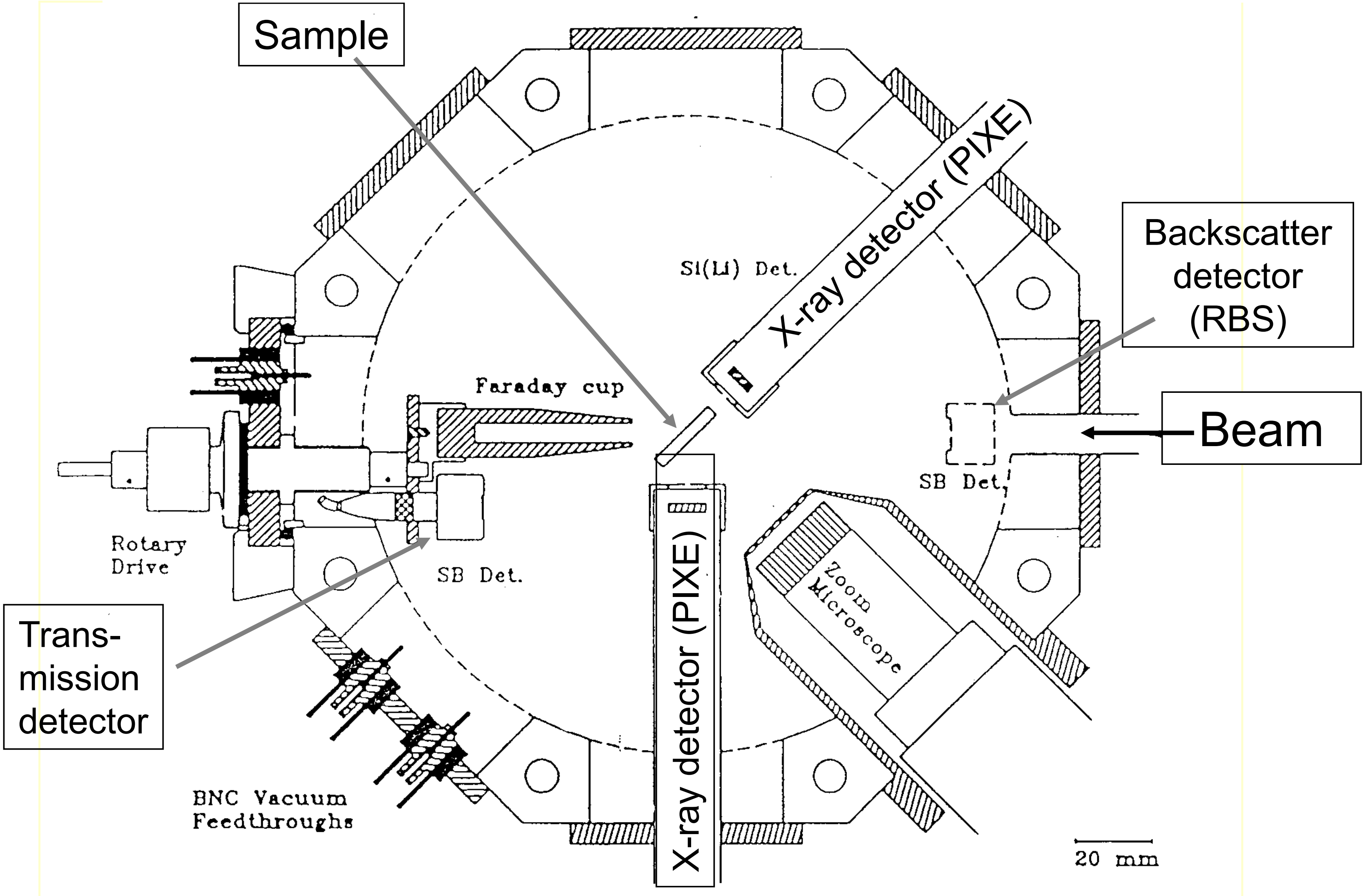
Nuclear Microprobe Layout



- MeV ion beam from particle accelerator is focused onto the sample (target)
- Focused beam spot size is 10 nm to 1 μm, depending on the amount of beam current used
- Focused beam is scanned over sample surface and the (x,y) position and relevant detector signal is measured

MeV Ions

Schematic of microprobe chamber



MeV Ions
Analysis Techniques

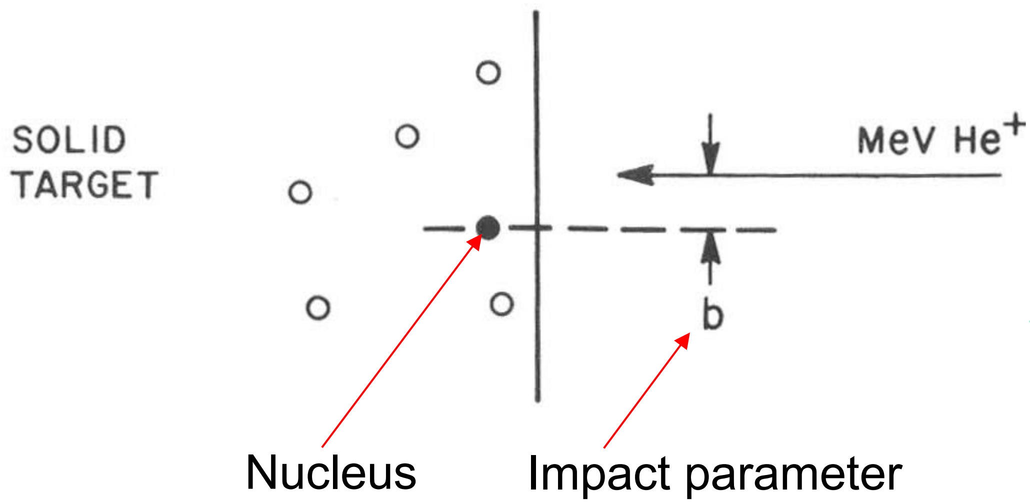
TECHNIQUE	ACRONYM	ENERGY (MeV)	PARTICLE/RADIATION MEASURED REMARK
Particle-Induced X-ray Emission	PIXE	1 - 4	Characteristic x-rays Maximum sensitivity in atomic ranges $10<Z<35$ and $75<Z<85$
Rutherford Backscattering Spectrometry	RBS	≤ 2	Elastically scattered ions in backward angles Non-Rutherford scattering becomes significant for energy >2 MeV
Scanning Transmission ion Microscopy	STIM	1-4	Transmitted ion energy loss measured Density mapping
Proton Induced Electron Emission	-	1-4	δ-rays (or secondary electrons) Fast mapping; used in beam focusing
Elastic Recoil Detection Analysis	ERDA	2 - 40	Recoiled target nuclei Mass of incident ion must be greater than that of target nucleus. $^{3}He+$ and $^{4}He+$ are used only for the measurement of H.
Nuclear Reaction Analysis	NRA	0.4 - 4	Prompt product particles or gamma-rays (PIGE) Reactions used include (p,γ) $(p,p'\gamma)$, $(p,\alpha\gamma)$, (d,p), $(d,p\gamma)$ Deuterons eg $^{12}C(d,p)^{13}C$ and $^{14}N(d,p)^{15}N$.

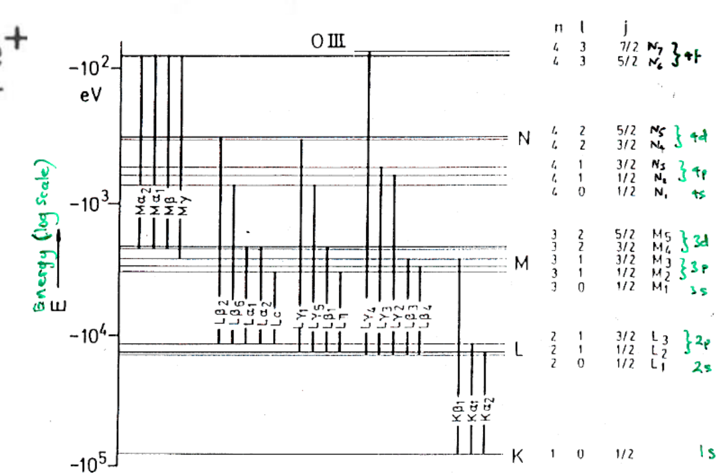
Often two or more of these techniques are carried out simultaneously in order to obtain complementary information.

MeV Ions

Impact Parameter – Energy Transfer

	Impact parameter (b)	Energy transfer (T)
• Coulomb elastic scattering	> 1 Å	-
• Coulomb inelastic collision of valence electrons	~ 1Å	T_e ~ 10 eV
• Coulomb excitation L-Shell	~ 10^{-1} Å	T_e ~ 100 eV
K-Shell	~ 10^{-2} Å	T_e ~ 1 keV
• Nuclear inelastic scattering	~ 10^{-4} Å	T_{nuc} ~ 100 keV
• Nuclear Transformation	~ 10^{-4} Å	Depends on reaction





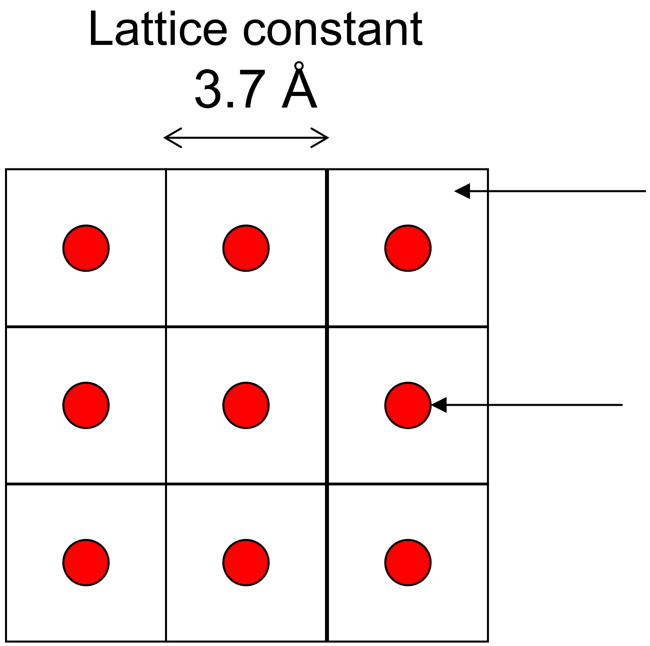
MeV Ions

Impact Parameter – Energy Transfer

Assume a nearest neighbour distance of 3.7 Å

↓

~90 % of energy transfer: b $\geq$ 0.64 Å is just a few 10s eV!



Very small energy deposition (< 10s eV)
Total area of a unit cell: 13.7 Å^2. This corresponds to 90% of the interaction area! (White – Red area)

Larger energy deposition (> 10s eV)
For b < 0.66 Å the total area is 1.29 Å^2 or 10% of the interaction area!

At b = 0.64 Å
Area ~ 1.29 Å^2 for ●

MeV Ions

Electron/Ion scattering and proximity effect

Fast ions

In ion - electron interaction the energy transfer is very small. Why?

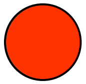
Hint Ions are much heavier than electrons,

Fast electrons

In electron - electron scattering the masses are the same and therefore we can expect about 50% energy transfer.

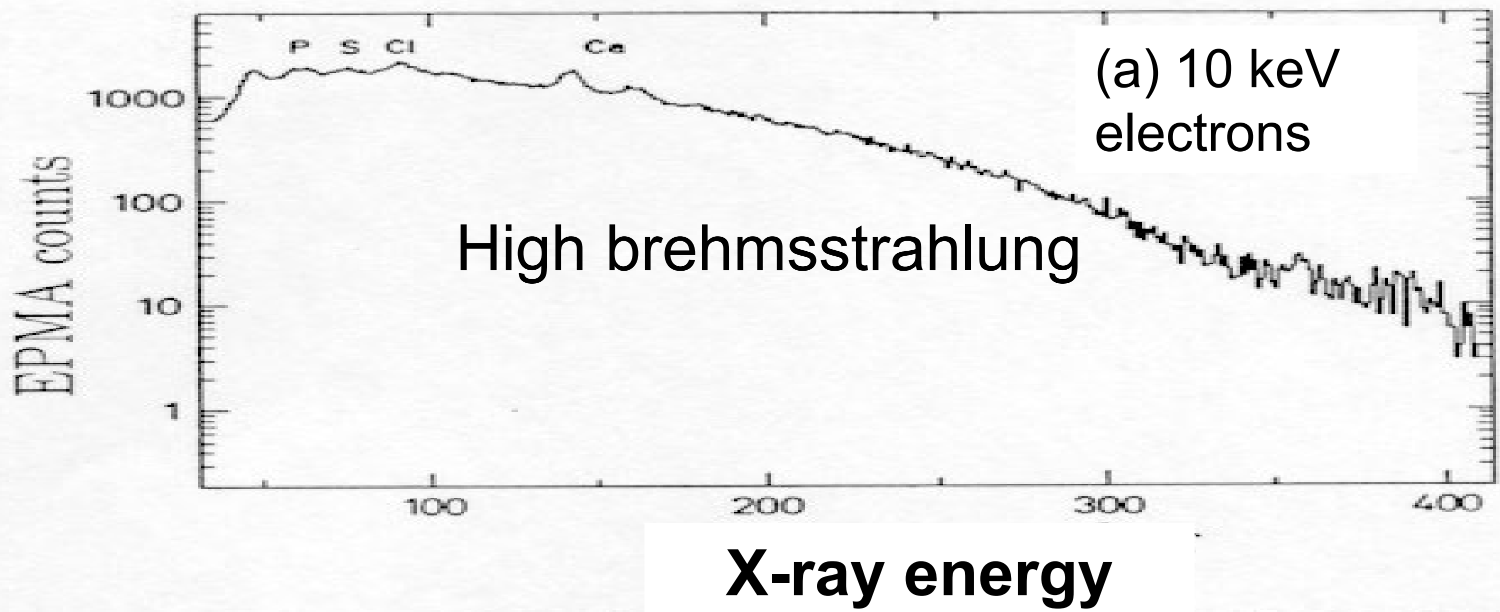
Imagine a cannon ball moving through feathers what will happen?

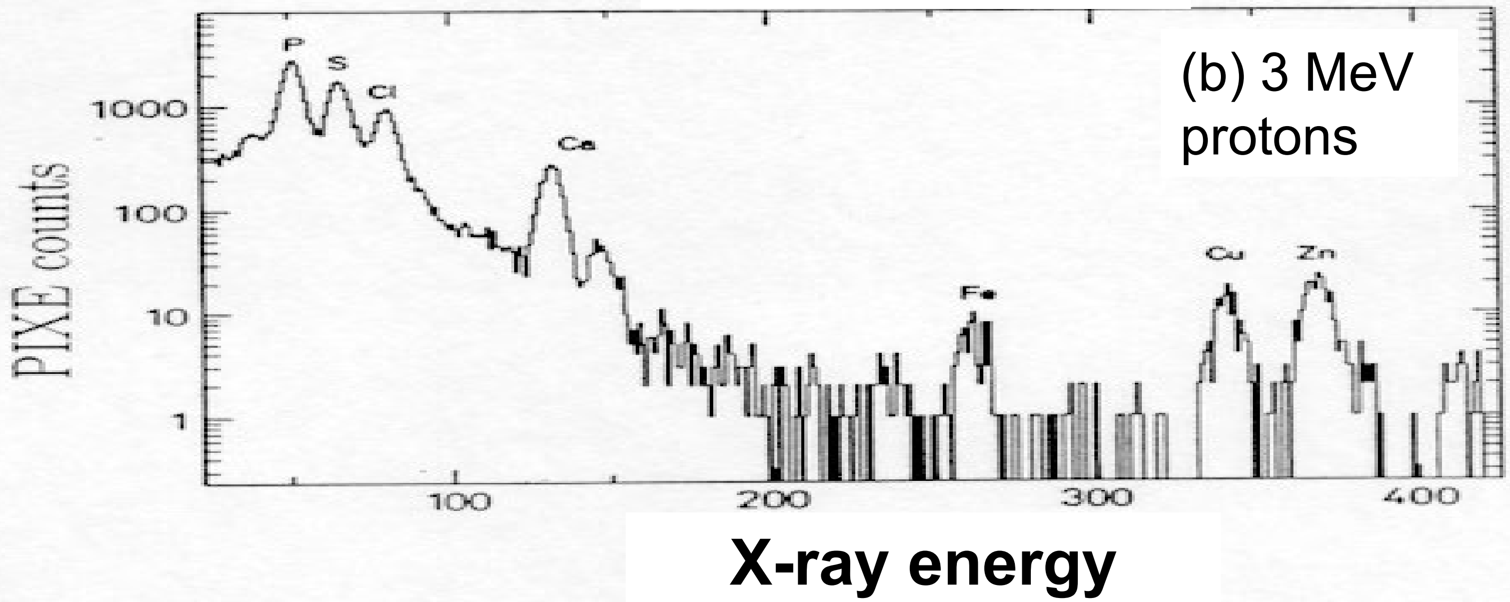
Imaging a snooker ball hitting other snooker balls what will happen?



MeV Ions

X-ray spectra generated by Electrons and Ions





MeV Ions

Nuclear microprobe STIM and PIXE elemental maps from a scan over an artery section form a rabbit