Instrumentation

Vacuum system - mean free path, chamber background pressure

Ion sources - duoplasmatron, surface ionization,
liquid metal ion source (LMIS)
Ion optics - ion path simulations
Analyzers - magnetic sector, quadrupole, time of flight
Detectors - Faraday cup, electron multiplier.
channel plate/fluorescent screen

Mean Free Path in Air

Mean free path: average distance particle travels between collisions

P Pressure (Torr)	n Density (molecules/cm^3)	λ Mean Free Path (cm)
760	2.49×10^{19}	3.9×10^{-6} (40nm)
1	3.25×10^{16}	5.1×10^{-3}
10^{-3}	3.25×10^{13}	5.1
10^{-6}	3.25×10^{10}	5.1×10^{3} (51m)
10^{-9}	3.25×10^{7}	5.1×10^{6} (51km)
10^{-12}	3.25×10^{4}	5.1×10^{9}

SIMS secondary ion path length ~2m for IMS6F

Chamber Background Pressure

Time Available for Analysis

Deposition of gas molecules with sticking coefficient of one:

$1\text{x}10^{-6}$ torr 1 monolayer deposited/sec

$1\text{x}10^{-9}$ torr 1 monolayer deposited/1000 sec

Static SIMS limit is 10^{12} ions/cm^2 (surface is 10^{15} atoms/cm^2)

1 nA / (1000 µm x 1000 µm) = $5.25\text{x}10^{11}$ ions/cm^2-sec

< 10 sec to reach static limit

10 pA / (1000 µm x 1000 µm) = $5.25\text{x}10^{9}$ ions/cm^2-sec

> 800 sec to reach static limit

Dynamic SIMS may have 150 nA / (200 µm x 200 µm)

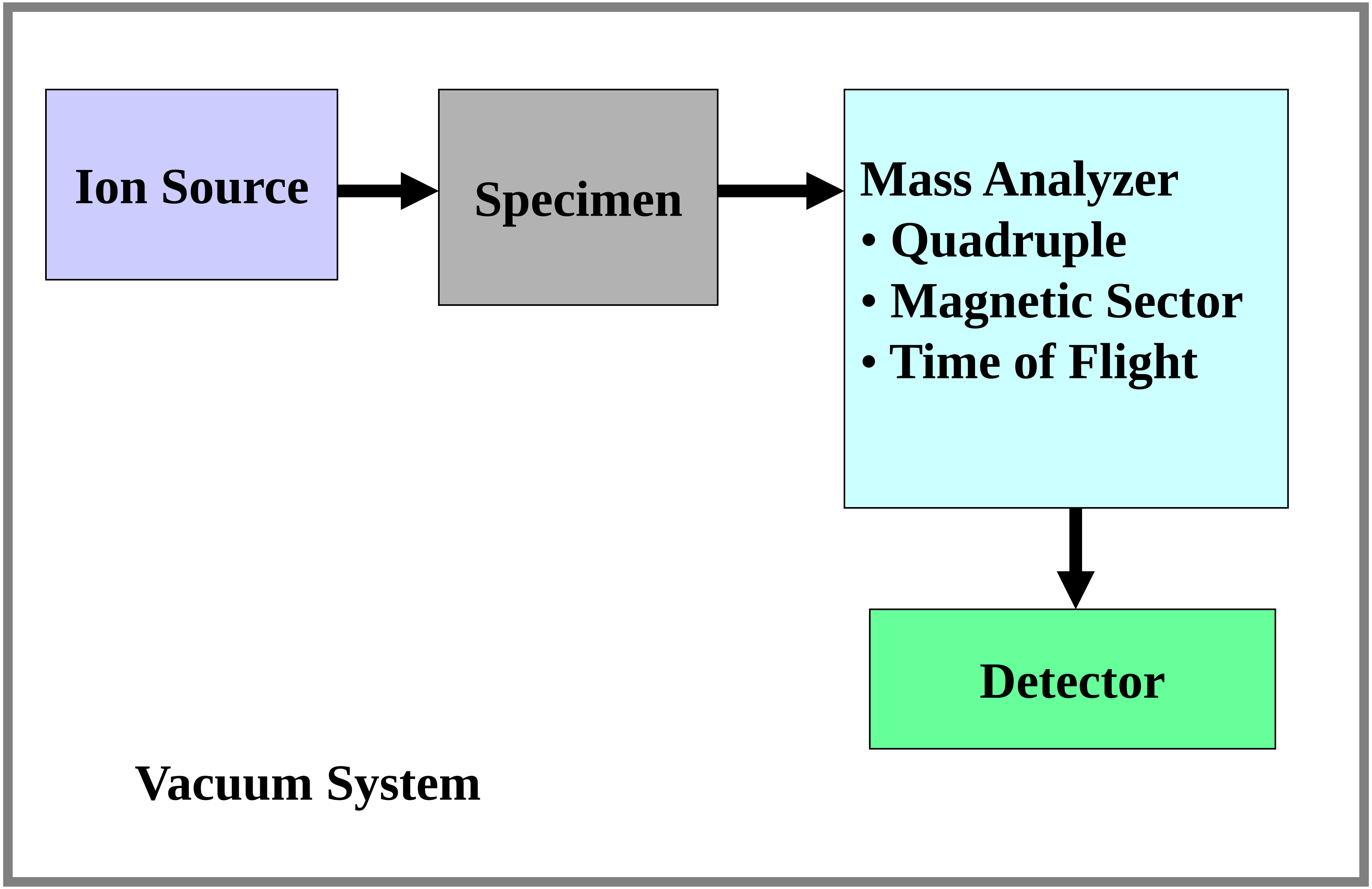
= $2.3\text{x}10^{15}$ ions/cm^2-sec

General Vacuum Practice

To maintain optimum vacuum level:

- Backfill with dry nitrogen and maintain nitrogen flow
- Wear gloves and use clean tools to prepare and load specimens
- Expose chamber to air for minimum time
- Avoid oil back streaming due to rough pumping too long without turbopump
- Delay sample insertion into analysis chamber until sample chamber pressure is sufficiently low
- Bake system when base pressure becomes elevated

SIMS Instrument Block Diagram



Ion Source

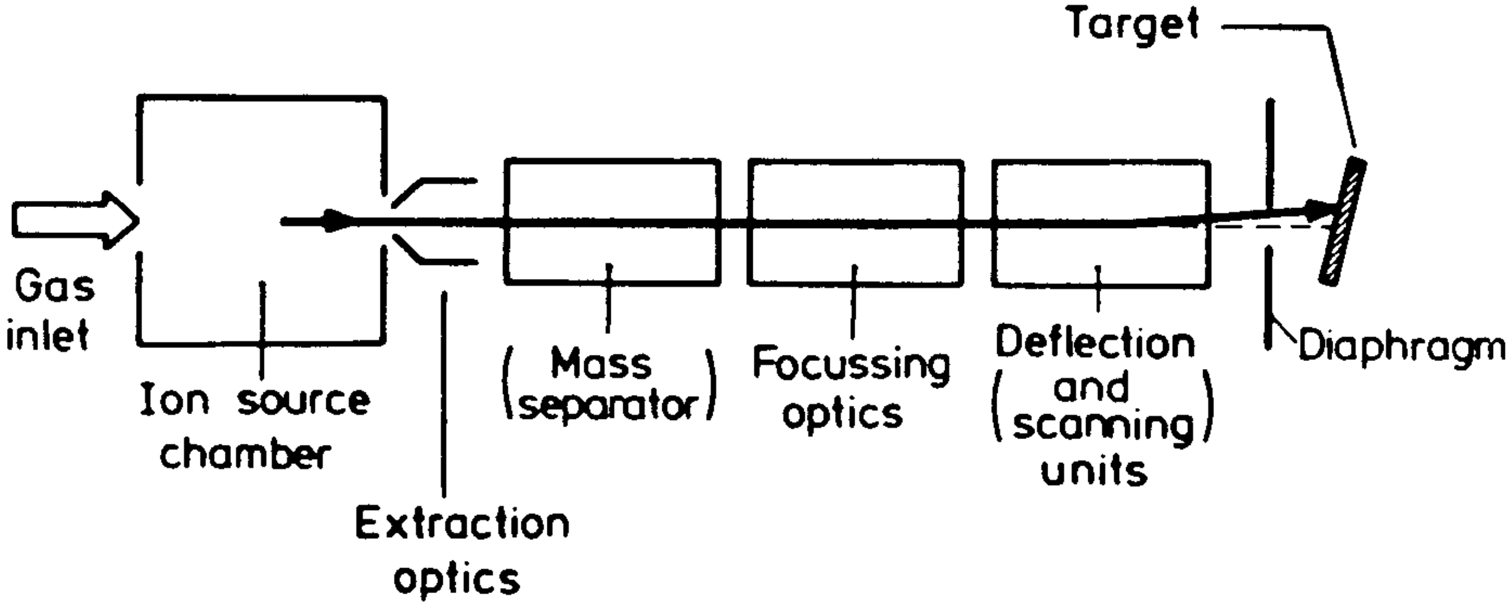
Specimen

Mass Analyzer
- **Quadruple**
- **Magnetic Sector**
- **Time of Flight**

Detector

Vacuum System

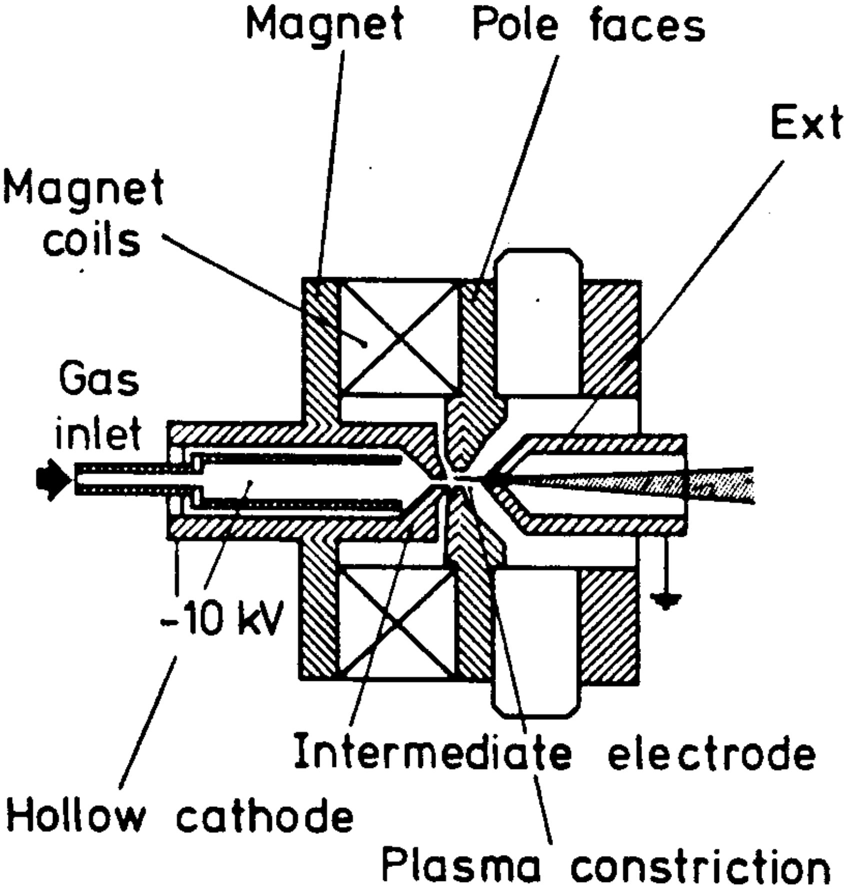
Block Diagram of Primary Ion Column



Typically duoplasmatron source for oxygen ions or surface ionization source for metal ions from liquid Cs. Extraction optics provide beam extraction, preliminary focusing, and acceleration to desired energy. Ions are mass separated, focused, and rastered.

SIMS, A. E. Morgan, in Characterization of Semiconductor Materials, Principles, and Methods, Vol. 1, G. E. McGuire, ed., Noyes Publications, Park Ridge, NJ (1989) 48

Duoplasmatron



Duoplasmatron with hollow cathode
~10^{-3} Torr during operation

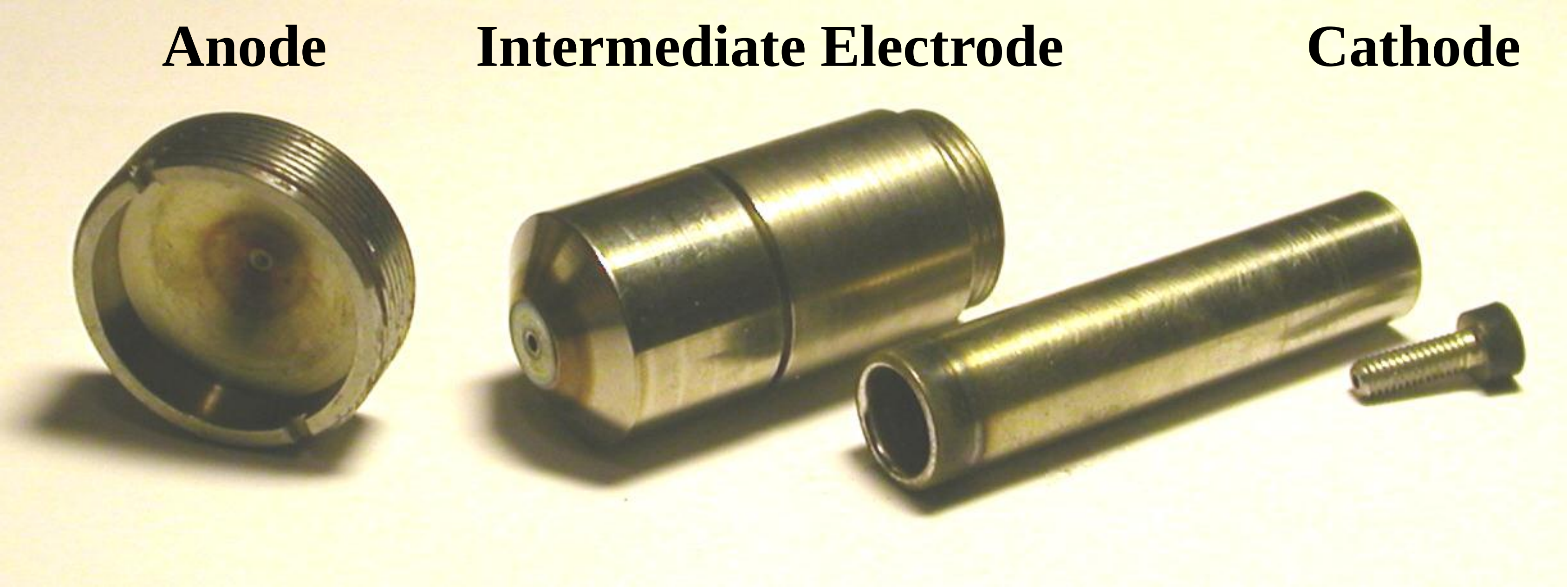
Beam constricted by shape of intermediate electrode and by inhomogeneous magnetic field near intermediate electrode.

Introduction to SIMS, H. W. Werner, in Electron and Ion Spectroscopy of Solids, L. Fiermans, et al., eds., Plenum Press, New York (1978) 342

Duoplasmatron

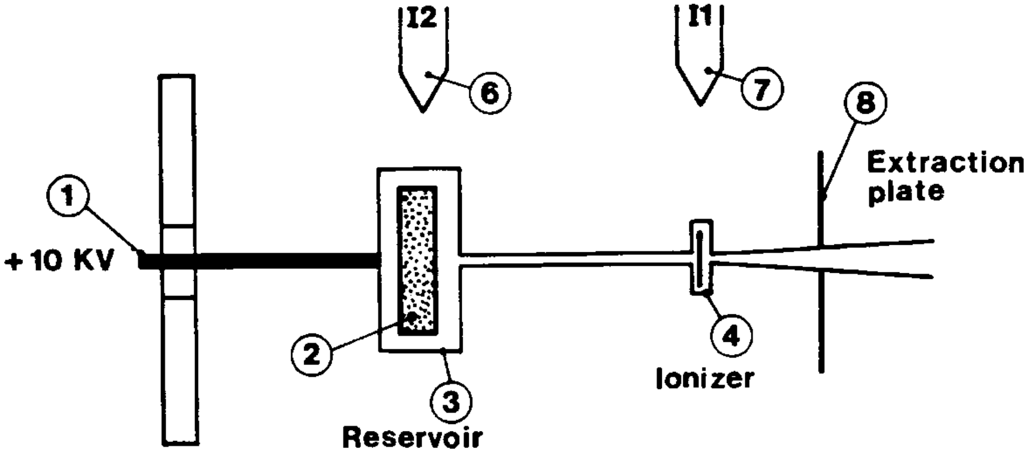
- Intermediate electrode and coil confine beam
- High ionization efficiency (> 80%)
- Low energy spread (tens of eV)
- High brightness (100 mA/cm^2)
- Various gaseous ion species possible

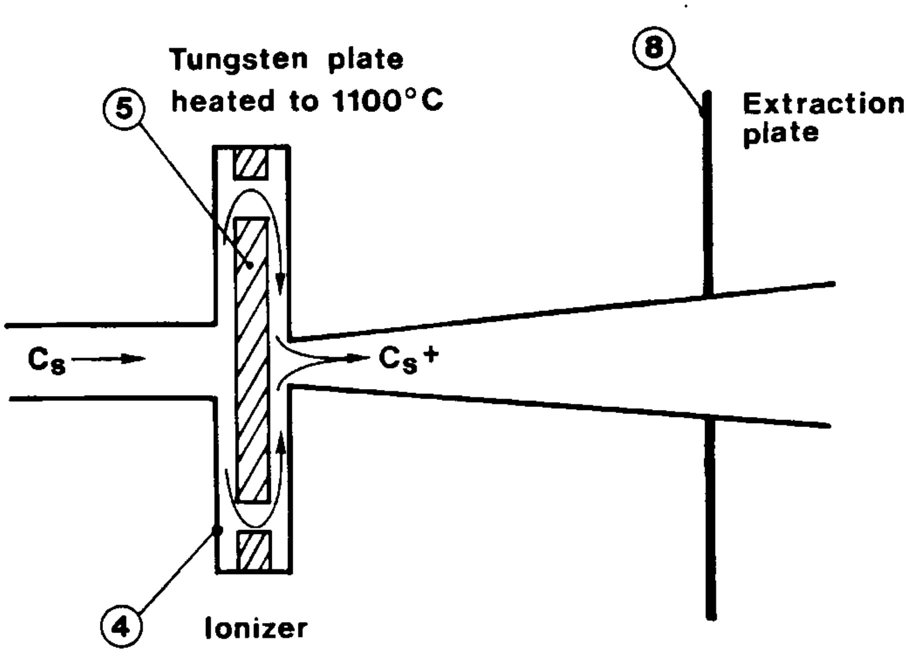
Duoplasmatron Parts



CAMECA IMS-f series instruments

Cesium Microbeam Source





1. High voltage input
2. Cs_2CO_3
3. Reservoir
4. Ionizer
5. Tungsten tablet
6. Reservoir filament
7. Ionizer filament
8. Extraction electrode

Cs from Cs_2CO_3 at 400°C

Cesium ionized on contact with tungsten at 1100°C

CAMECA Instruments

Cesium Source

- Cesium vapor strikes hot tungsten (> 1000° C)

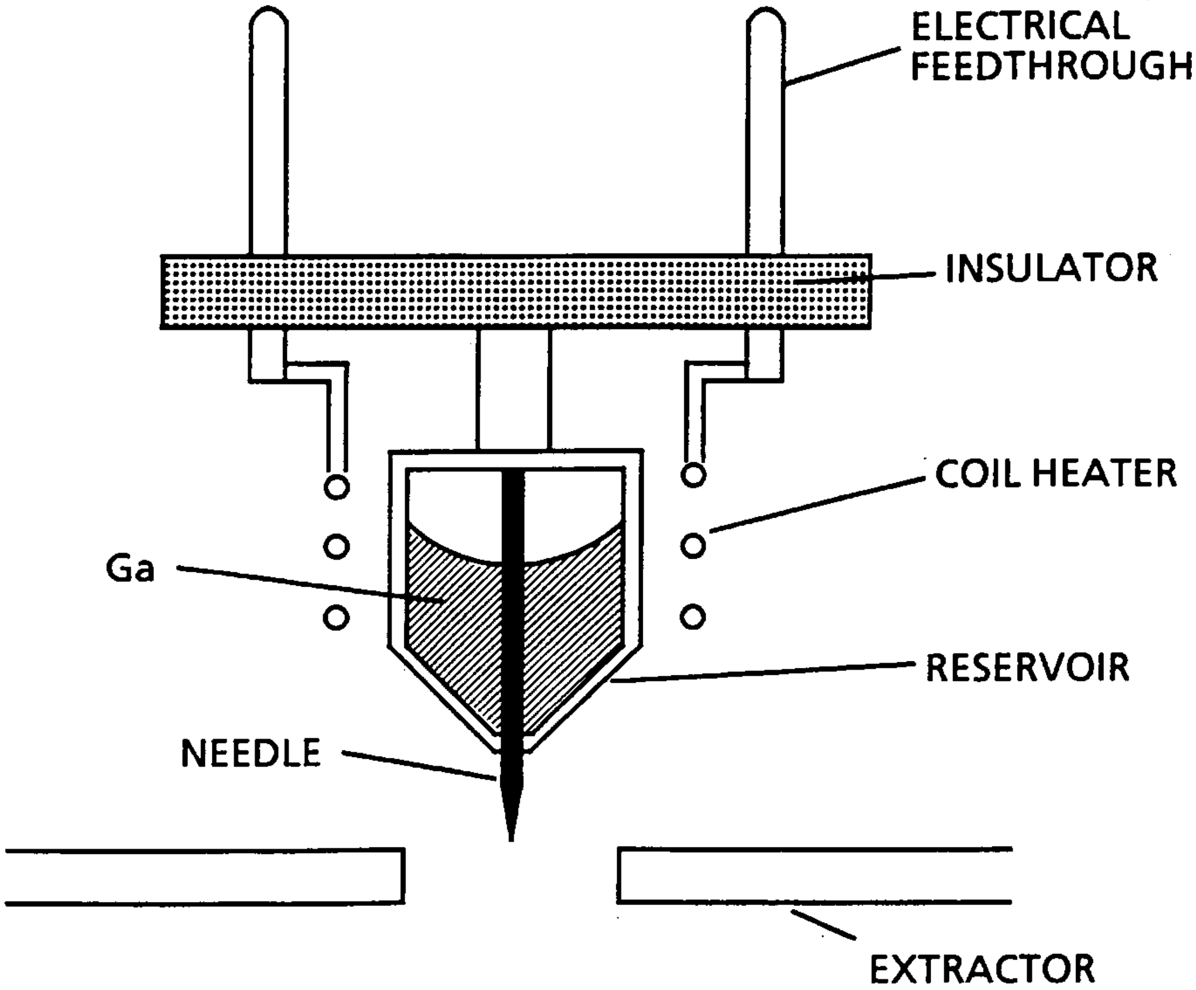
- Electron removed from cesium

- Cesium ion evaporates from tungsten due to high temperature

- 5 mA/cm^2

- Cs source material:
  Cs metal
  $CsCrO_4$
  Cs_2CO_3 now used on CAMECA microbeam source

Schematic Diagram of Liquid Metal Ion Source (LMIS)



Liquid Metal Ion Source (LMIS)

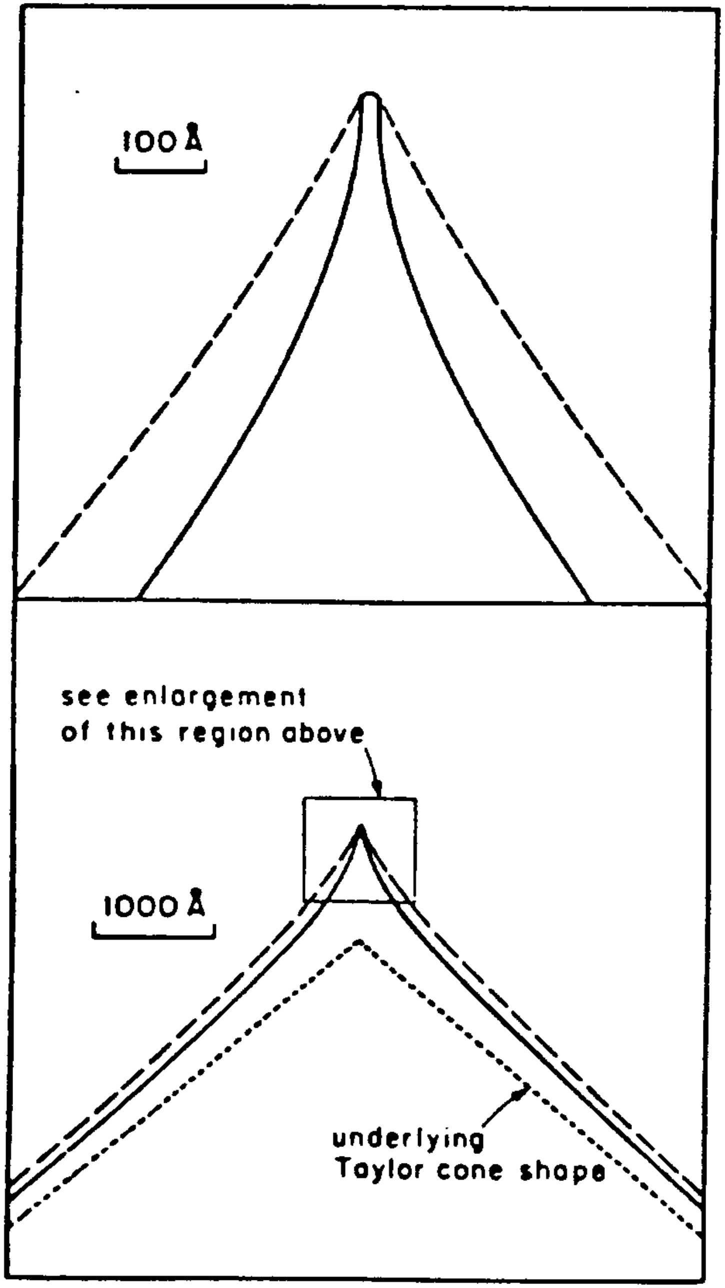
- Gallium wets tungsten needle

- High extraction voltage (10^8 volts/cm, 1 volt/Å) pulls gallium into Taylor cone

- 5-7 nm beam diameter columns commercially available

- Very high brightness (1 A/cm^2)

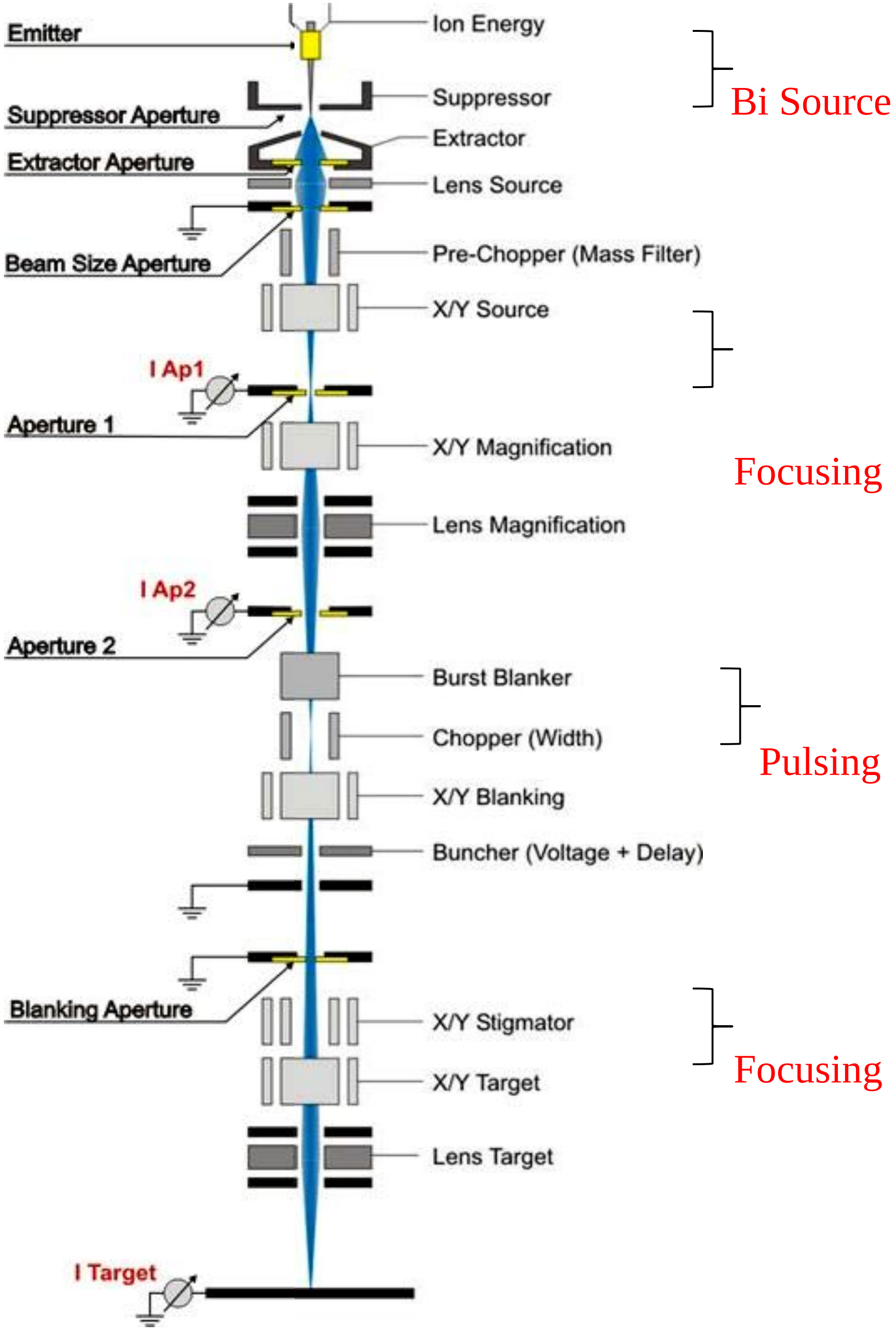
Calculated Shape of Liquid Gallium Emitter



“thin” (continuous line) and “fat” (dashed line) shapes correspond to different assumed shape factors

D. R. Kingham and L. W. Swanson, Appl. Phys. A34, 123 (1984)

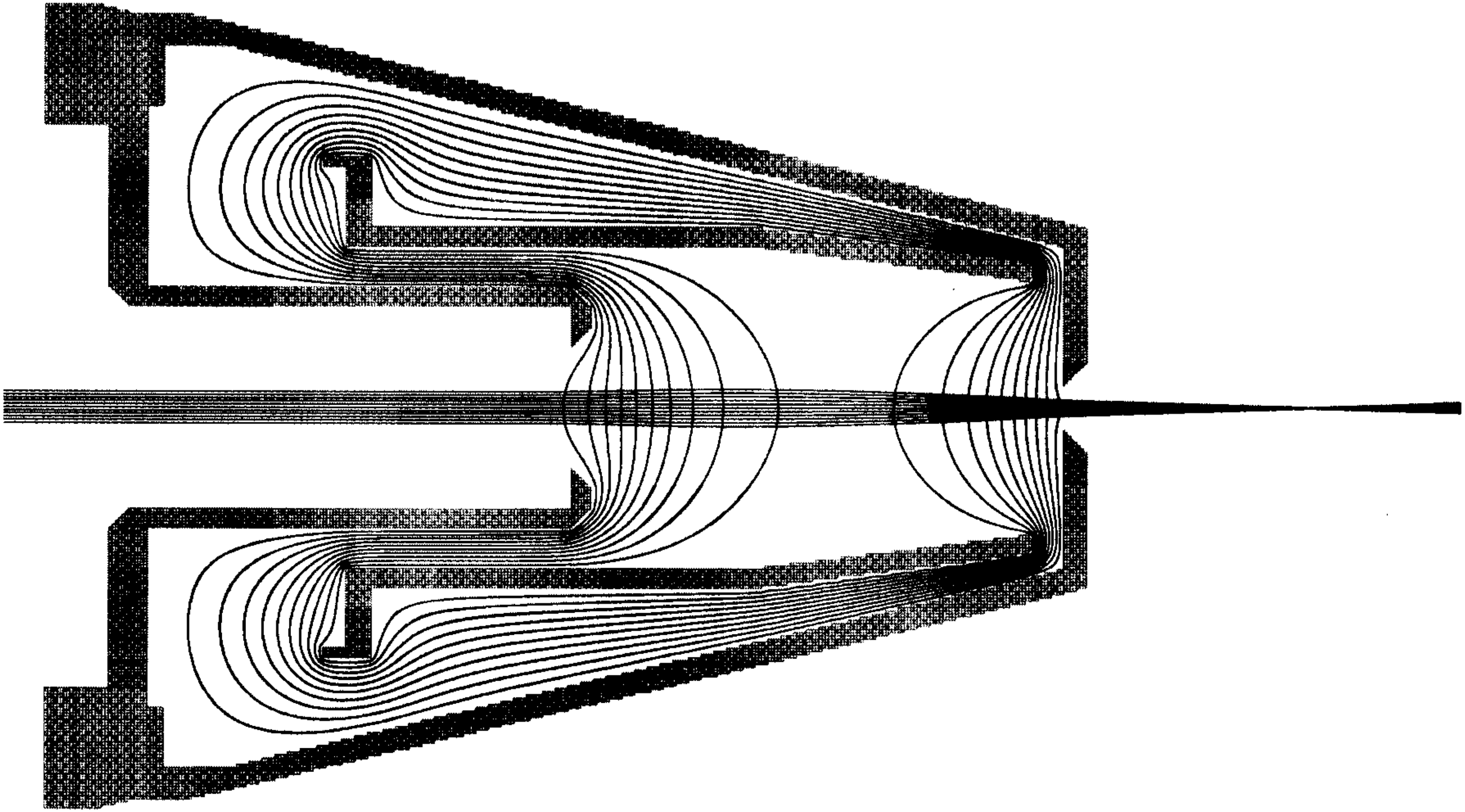
Primary Column



Bi^+ source

ION-TOFV

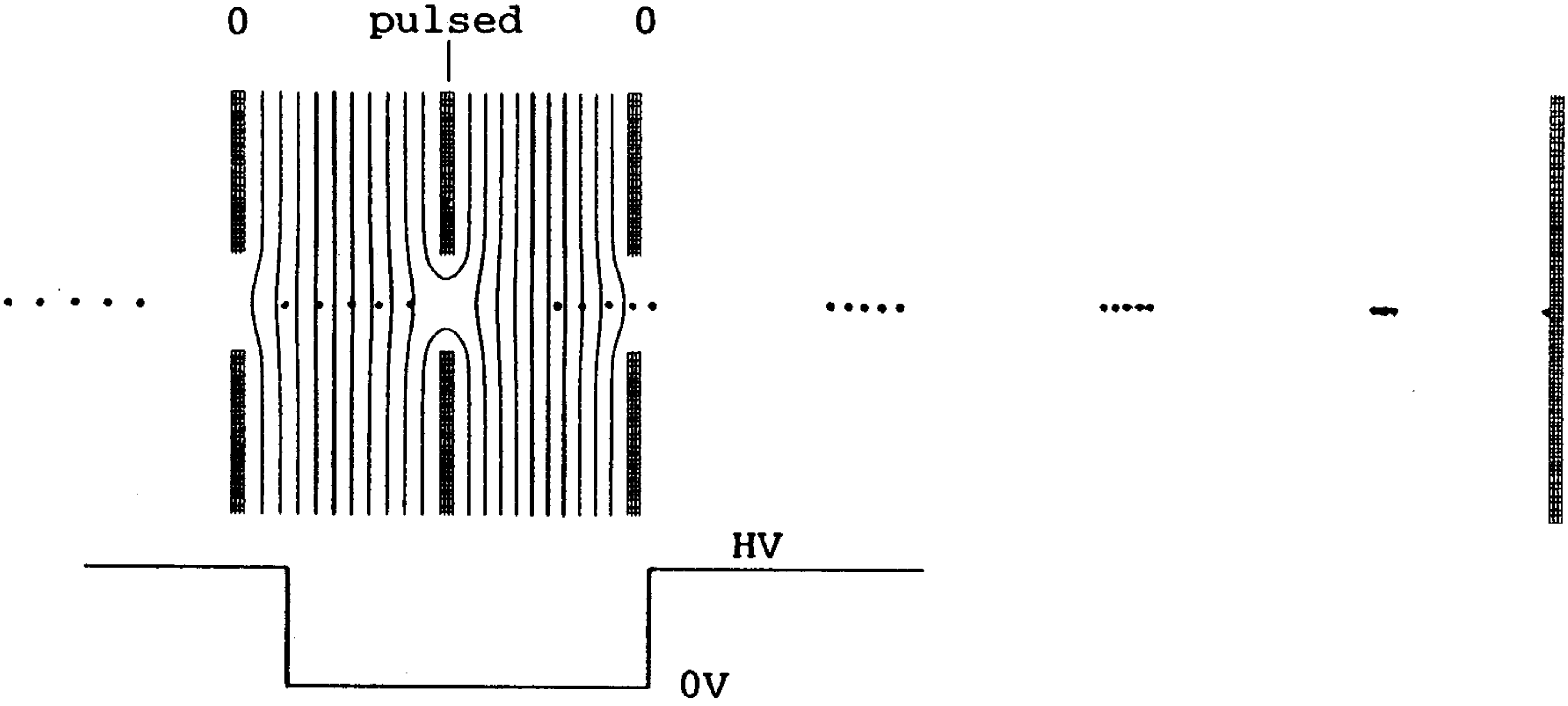
Simulation of Einzel Lens



Trajectories and equi-potential lines are shown.

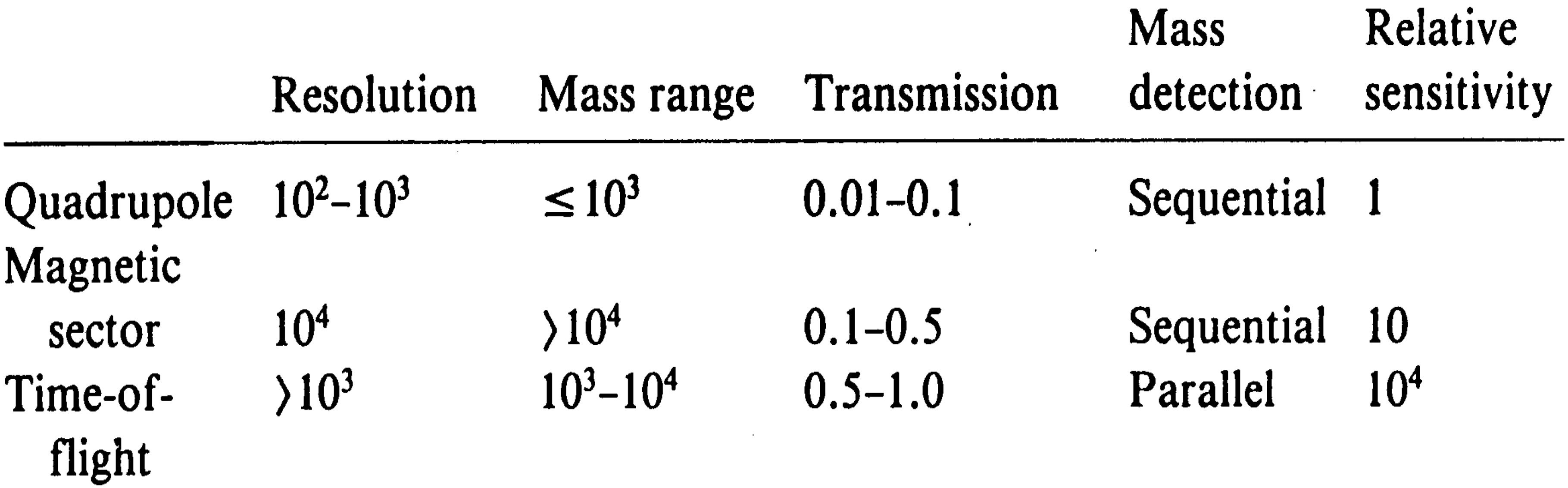
SIMION

Simulation of Electrodynamic Buncher



Used to bunch primary ions in time of flight source

Comparison of Mass Analyzer Types



	Resolution	Mass range	Transmission	Mass detection	Relative sensitivity
Quadrupole	10^2–10^3	$\leq 10^3$	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

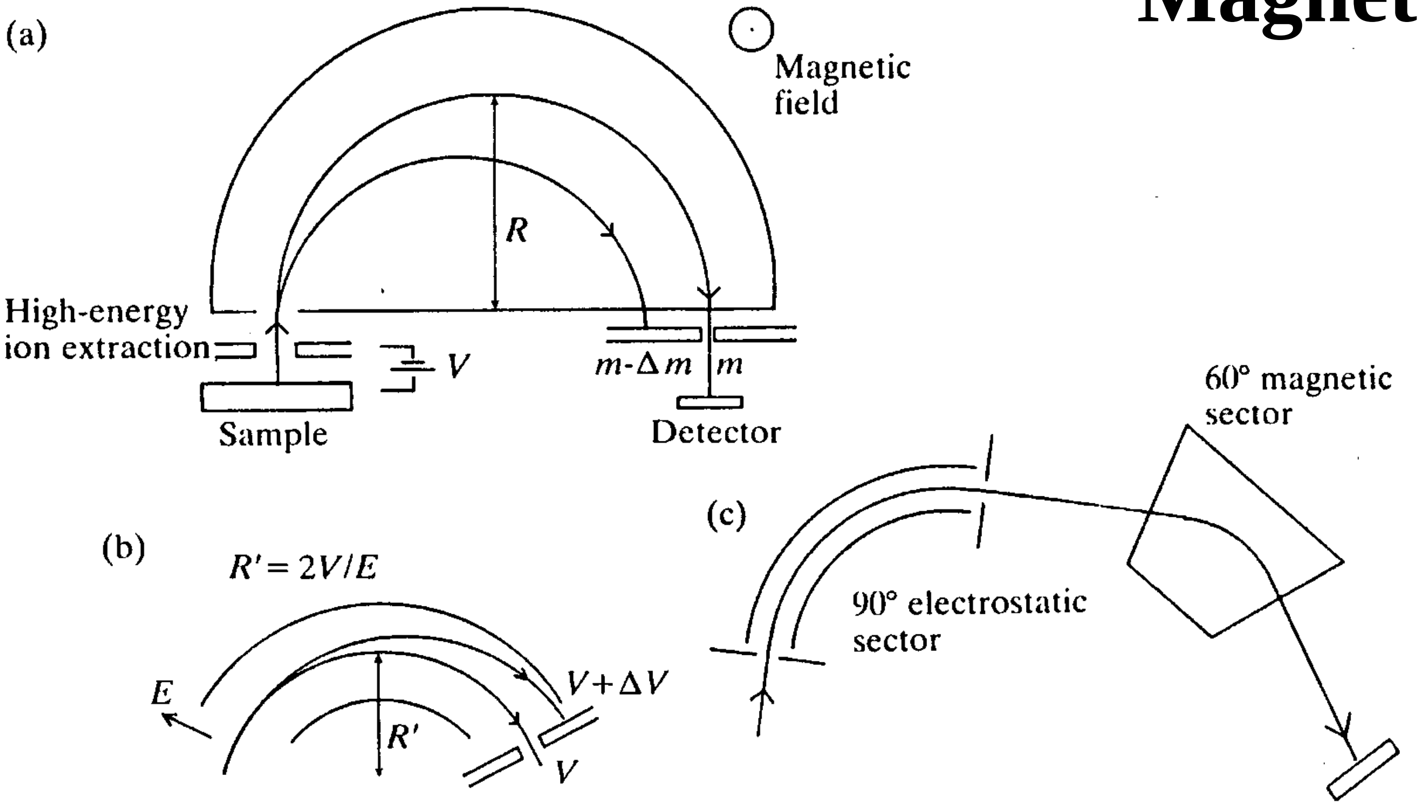
SIMS, J. C. Vickerman, A. Brown, and N. M. Reed, eds., Oxford University Press, Oxford (1989)

Magnetic Sector Analyzer

+ high mass resolution (10000 -25000)
  - resolves mass interferences
+ high transmission
  - best detection limits
+ wide energy bandpass (~ 150 eV)
+ optical gating possible
  - smaller craters

- large
- expensive
- high extraction field across small gap
- slow mass switching
- typically transmits one mass at a time
  - some instruments can transmit multiple isotopes
- ion molecule reactions significant for analyzer at 10^{-6} torr

Magnetic Sector



Operation of a magnetic sector mass analyser; (a) longitudinal cross-section of magnetic sector, showing mass dispersion; (b) longitudinal cross-section of electrostatic sector, showing energy dispersion; (c) double focusing mass spectrometer with spatial and energy focusing.

$$\begin{aligned} \tfrac{1}{2}\, mv^2 &= zV \\ BzV &= mv^2/R \end{aligned} \quad \Rightarrow R = \frac{1}{B}\left(\frac{2mV}{z}\right)^{1/2}.$$

SIMS, J. C. Vickerman, et al., eds., Oxford University Press, Oxford (1989)

Quadrupole Analyzer

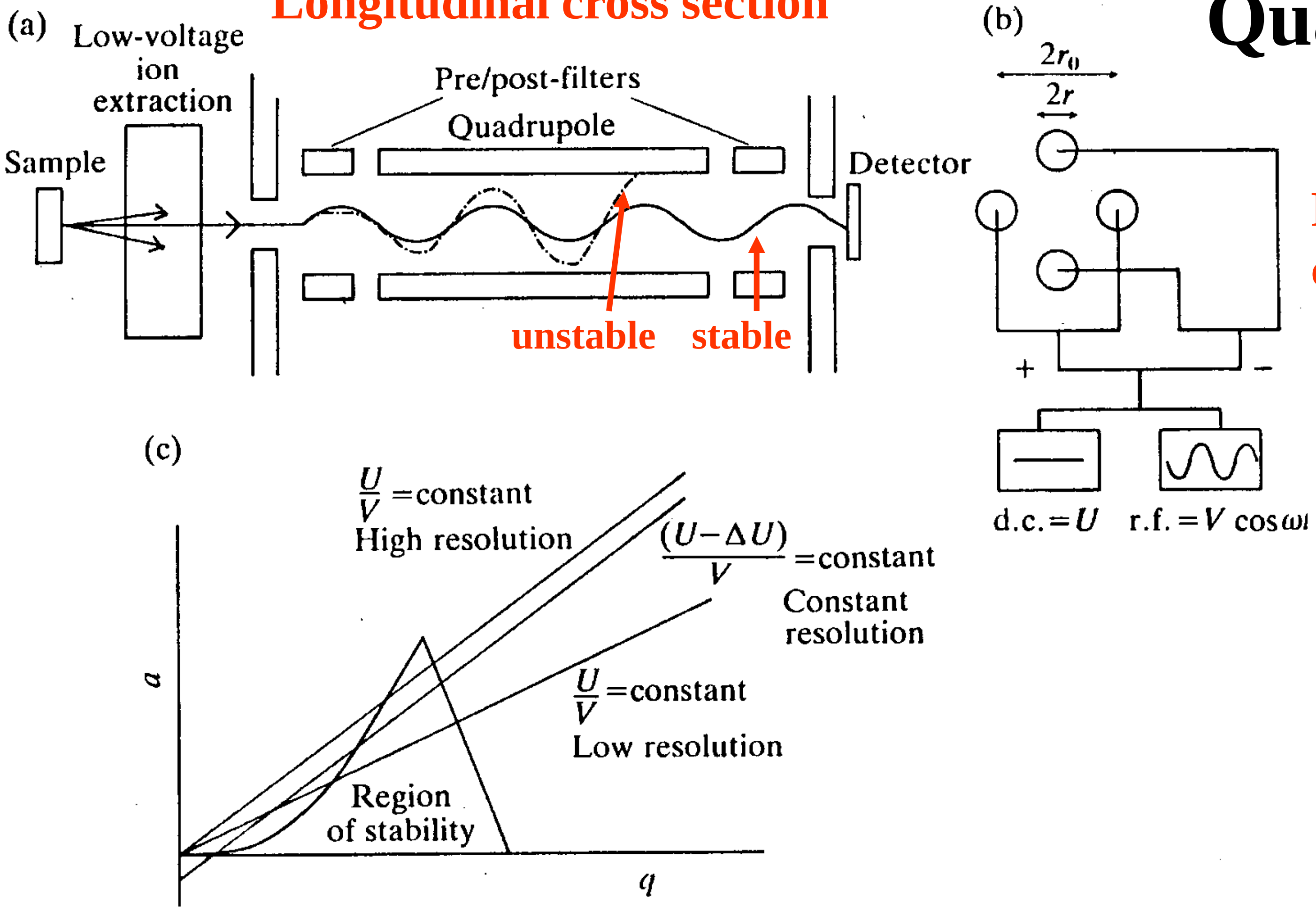
+ can be mounted in small area
+ less expensive
+ low sample extraction voltage
    low energy primary beam
    best depth resolution (ultra-shallow profiles)
+ large extraction area
    easy charge neutralization for insulators
+ fast mass switching
    mass spectra at interfaces

- low mass resolution
- low mass range
- narrow energy bandpass (10 - 20 eV)
- transmits one mass at a time

Quadrupole

Longitudinal cross section

Radial cross-section



Operation of a quadrupole mass filter: (a) longitudinal cross-section showing stable and unstable trajectories; (b) radial cross-section, showing applied voltages; (c) Ion trajectory stability diagram—ion trajectories are a function of the two dimensionless parameters $a = (8U/r_0^2\omega^2)(z/m)$; $q = (4V/r_0^2\omega^2)(z/m)$

SIMS, J. C. Vickerman, et al., Oxford University Press, Oxford (1989)

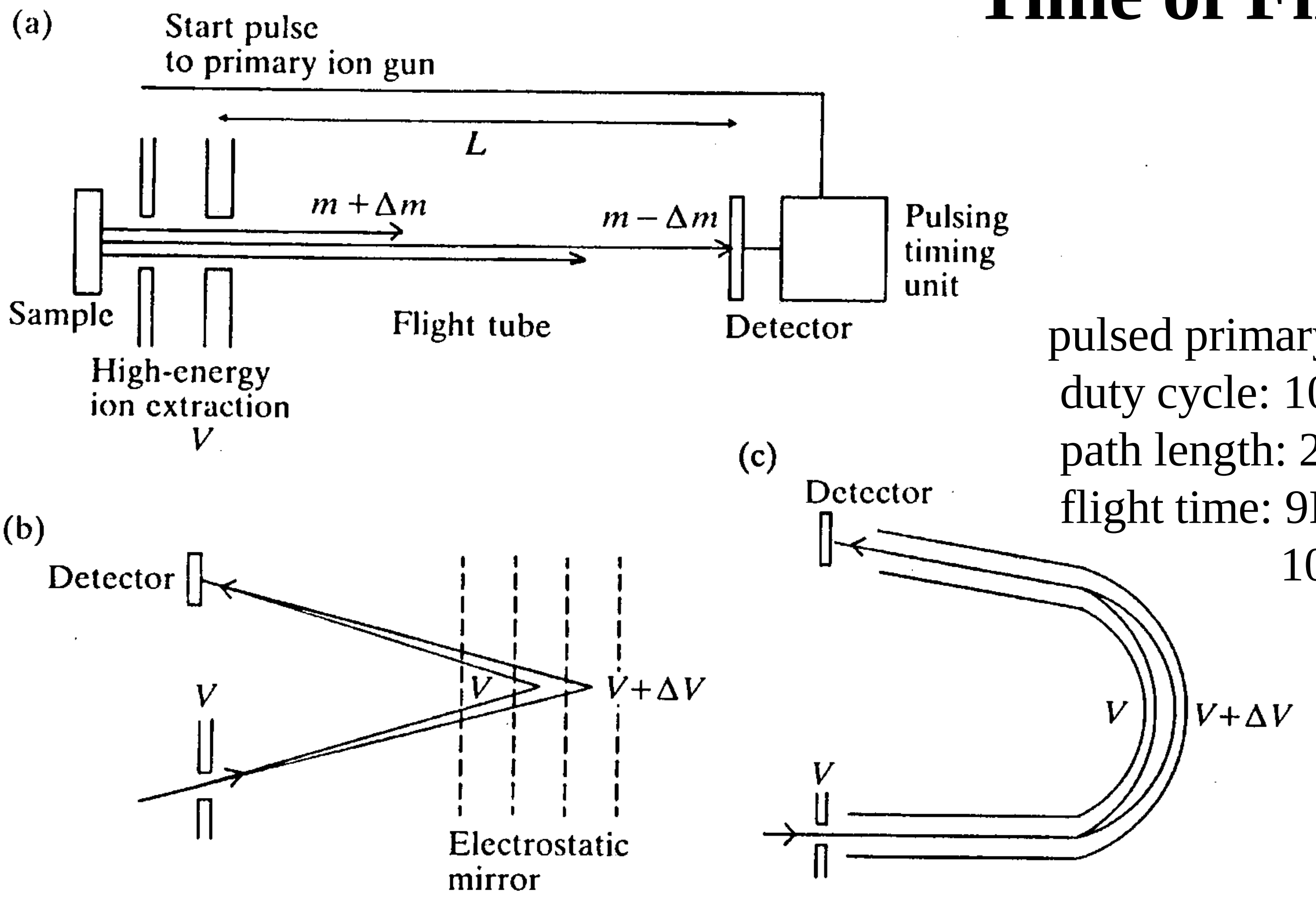
Time of Flight Analyzer

+ high mass resolution
+ high transmission (10-90%)
+ high mass range (theoretically unlimited)
+ parallel detection all masses
    best for static SIMS
+ easy mass calibration
+ short duty cycle
    neutralization easy

- pulsed primary beam
    limited dynamic range, limited profile depth
- high extraction field across small gap

S. J. Mullock, KORE Technology

Time of Flight

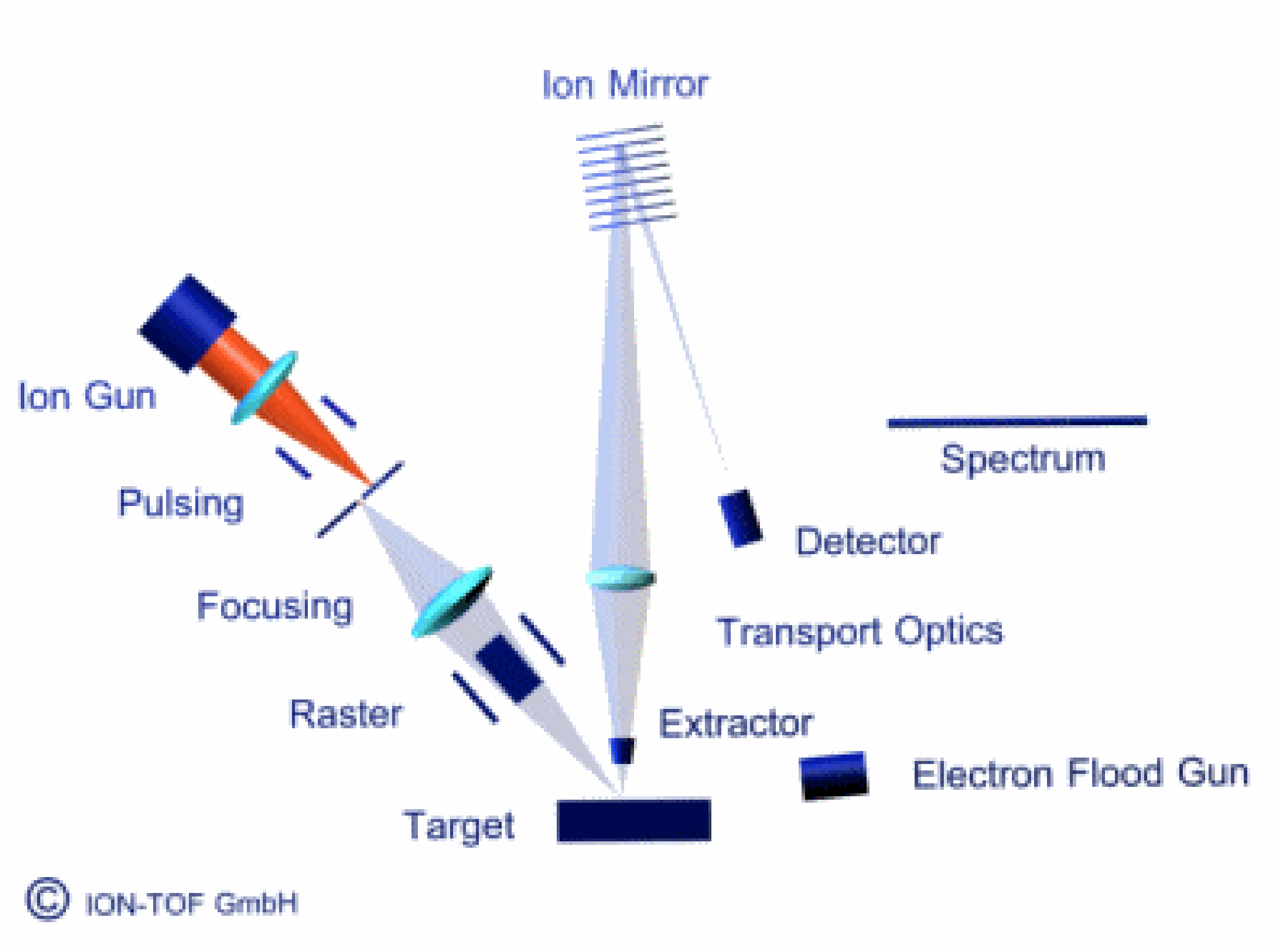


Operation of a mass analyser: (a) longitudinal cross-section of flight tube, showing time (mass) dispersion; (b) energy-compensating mirror design; (c) energy-compensating electrostatic sector design. $\frac{1}{2}mv^2=zV$; $t=L(m/2zV)^{1/2}$.

pulsed primary beam; 1-10 ns
duty cycle: 10-3 to 10-5
path length: 2 m typical
flight time: 9Be ~ 8 µs
1000 amu ~ 80 µs

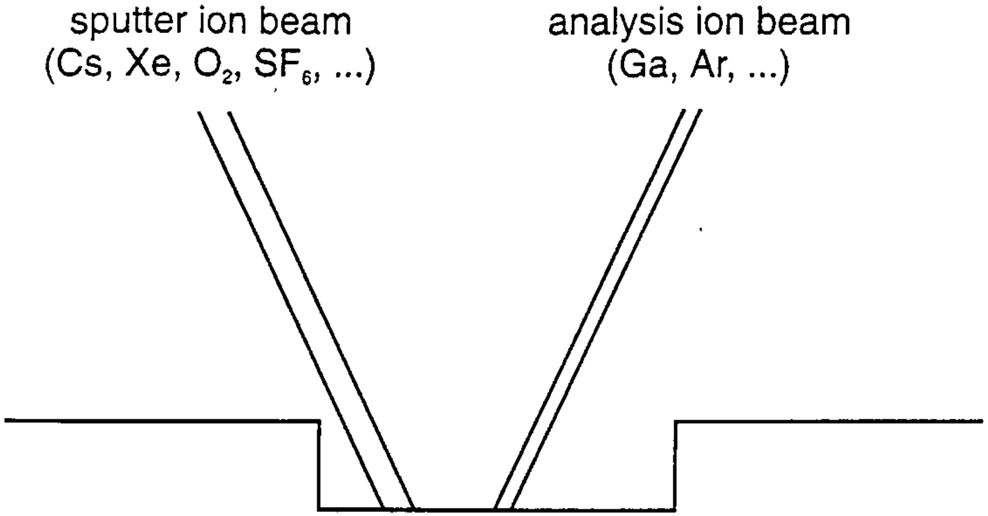
SIMS, J. C. Vickerman, et al., eds., Oxford university Press, Oxford (1989)

TOF-SIMS

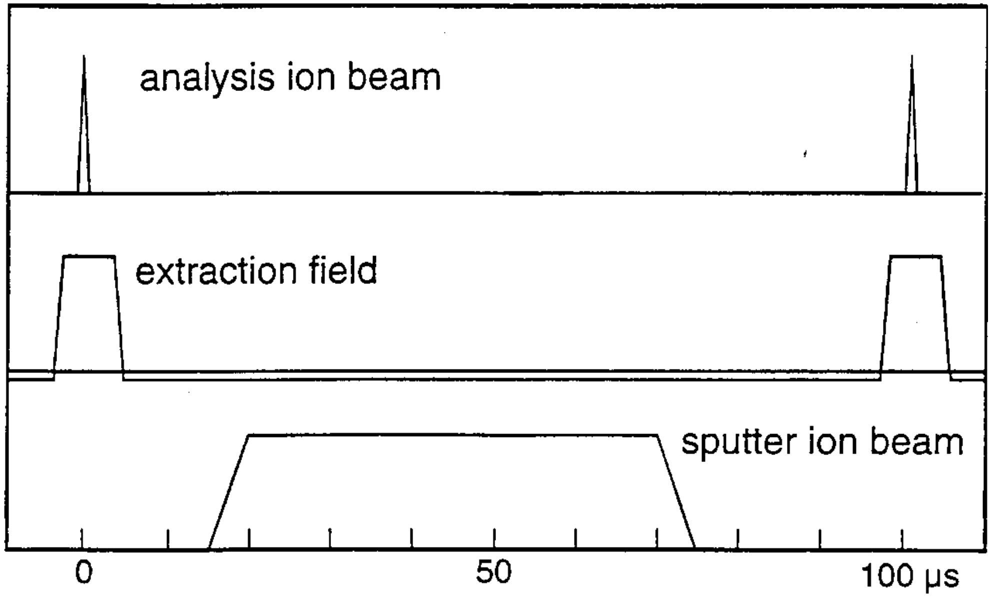


ION TOF V

Time of Flight



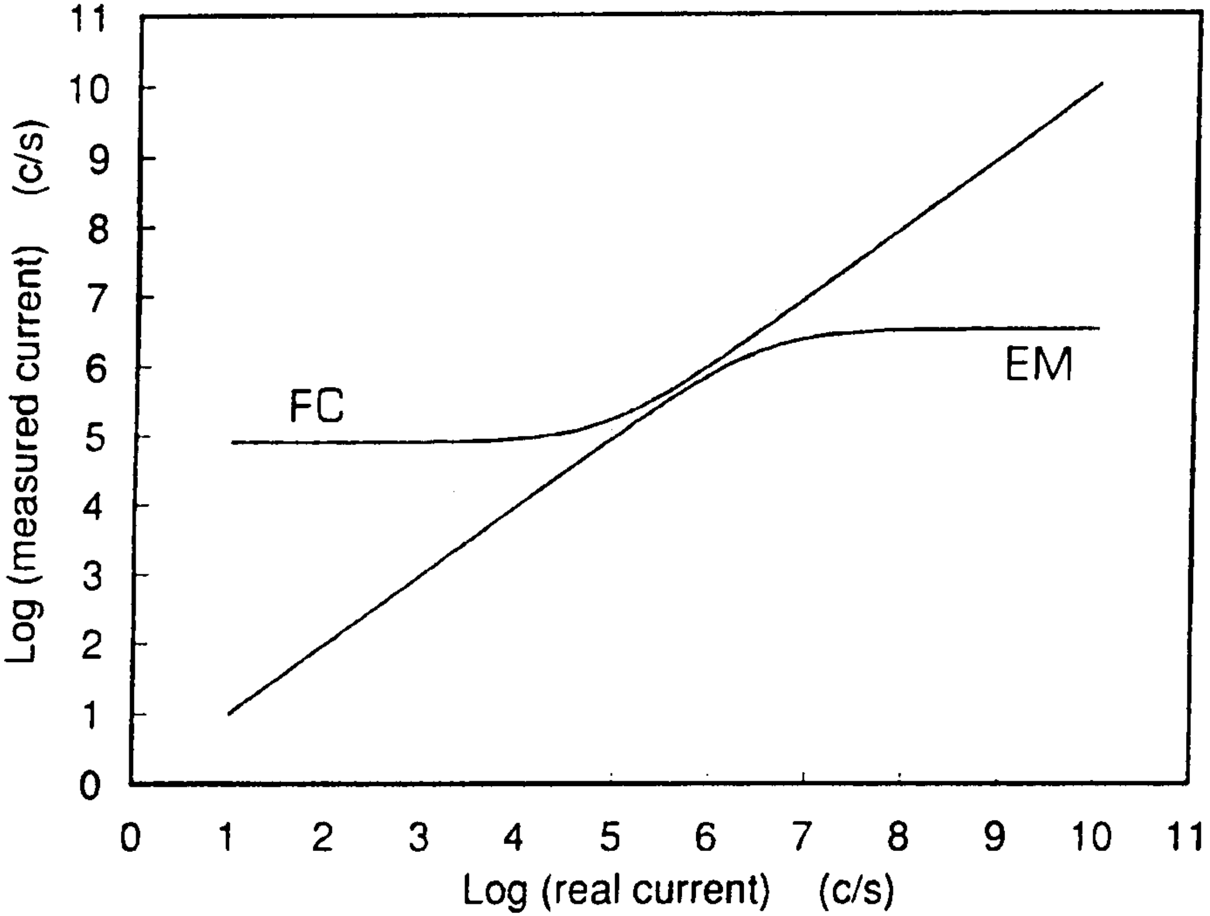
Ion beams for analysis and sputter



Timing diagram

K. Iltgen, C, Bendel, A. Benninghoven, and E. Niehuis, ION-TOF

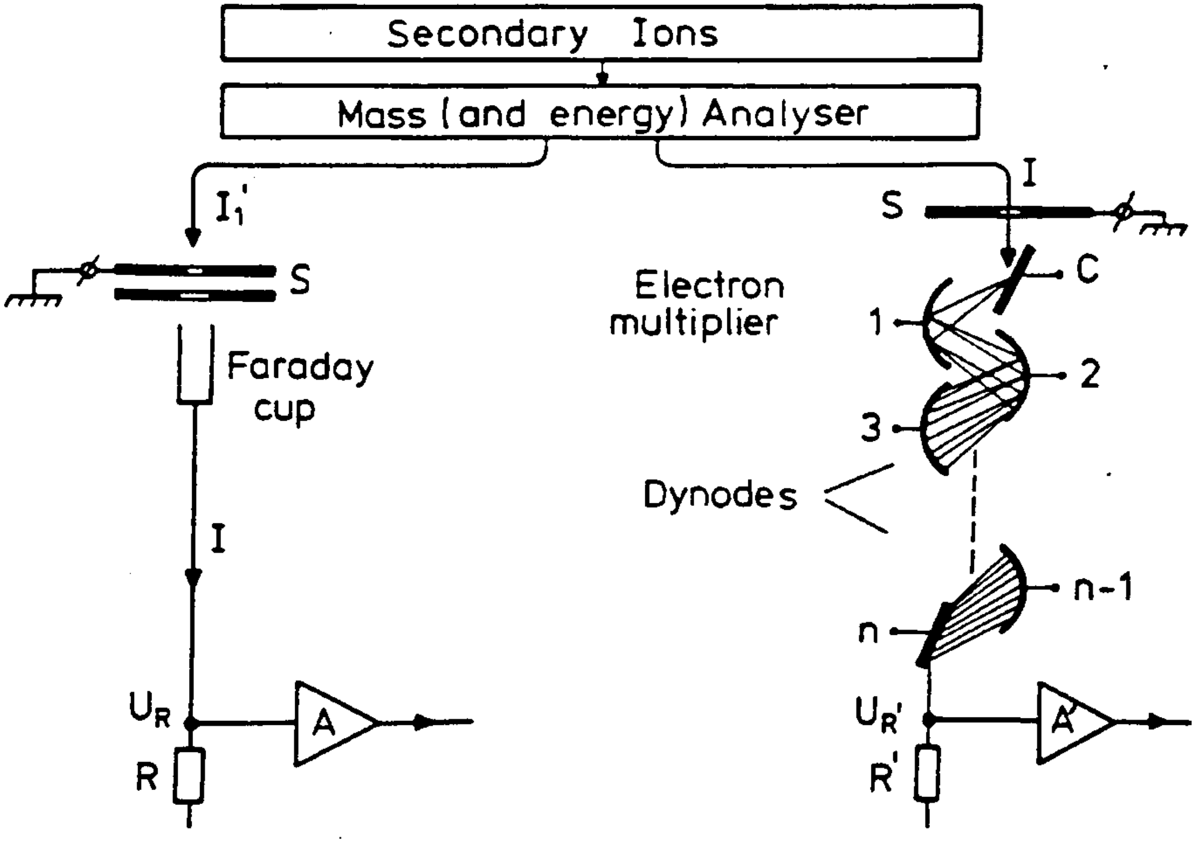
Faraday Cup and Electron Multiplier Responses



Use of Faraday cup (FC) and electron multiplier (EM) detectors covers large dynamic range.

Theoretical response of electron multiplier and Faraday cup detectors. Electron multiplier dead time assumed to be 300 ns and offset of Faraday cup detector equivalent to $8x10^4$ cts/sec.

Faraday Cup and Electron Multiplier



Multiplier gain ~10^8

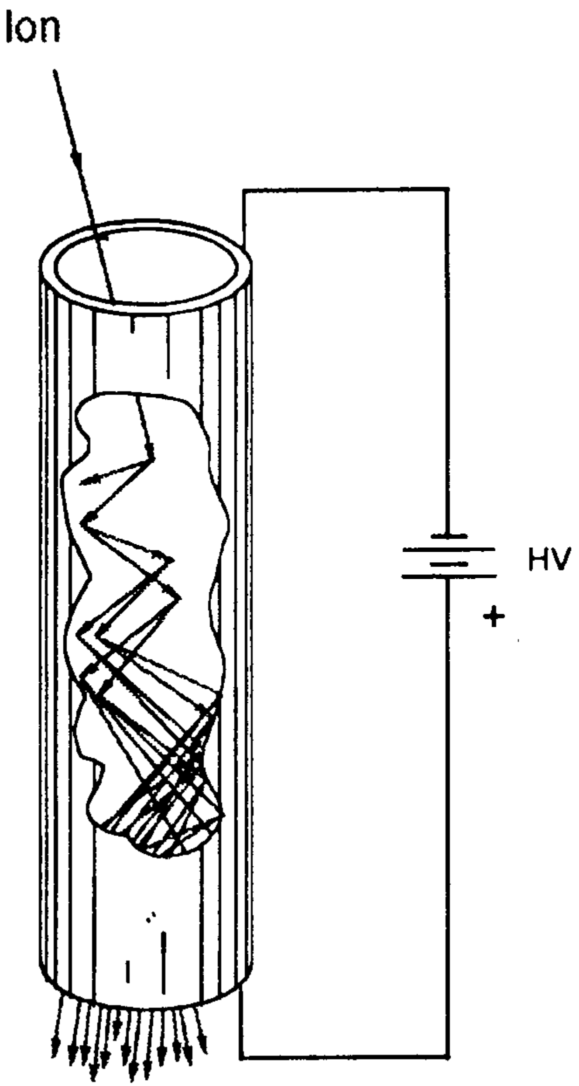
Schematic of ion detection with FC and EM. S is collector shielding slit on ground potential. Voltage across multiplier is divided equally among the dynodes.

Introduction to SIMS, H. W. Werner, in Electron and Ion Spectroscopy of Solids, L. Fiermans, et al., eds., Plenum Press, New York (1978) 324

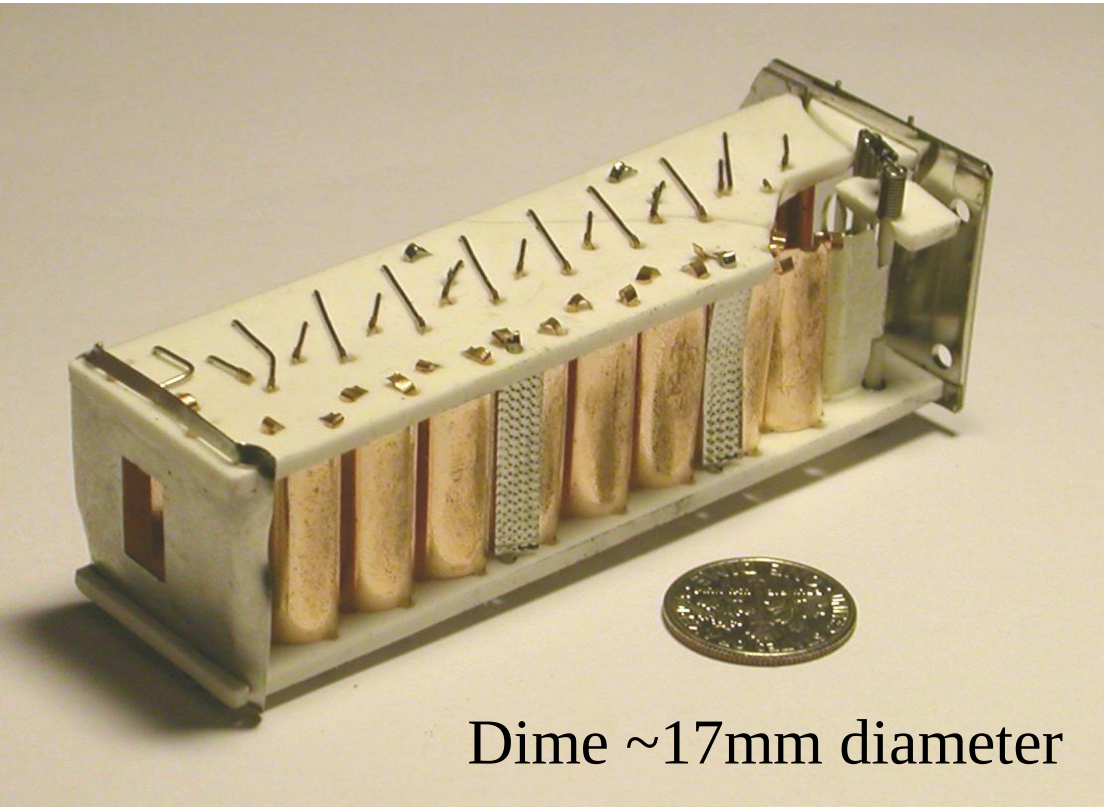
Electron Multiplier: Continuous Dynode

- First developed into a practical detector in the late 1950's
- SiO_2 emissive layer grown on the inside wall of a glass channel

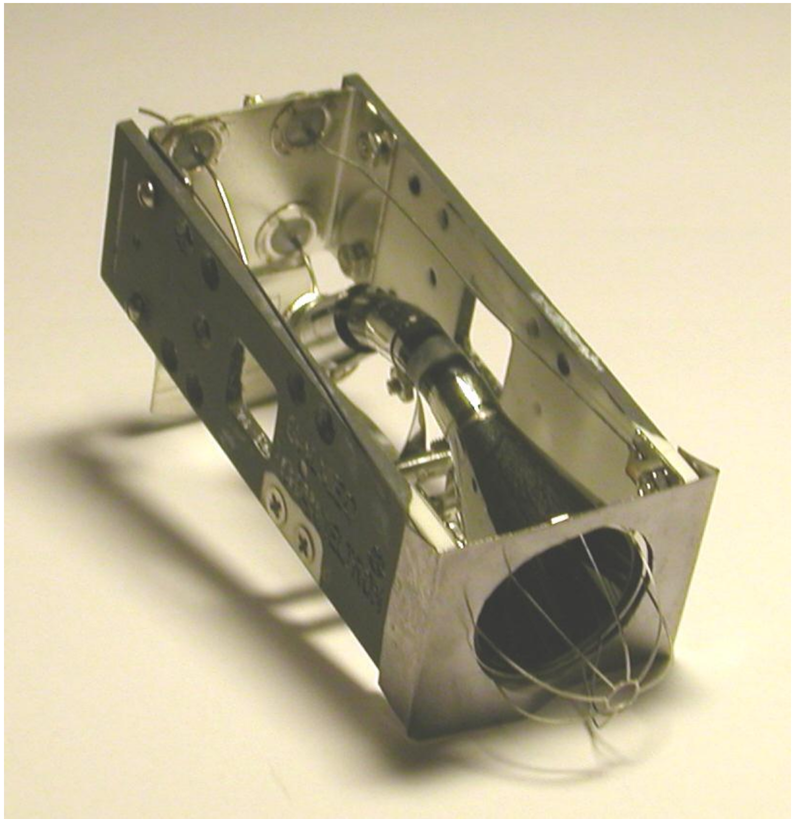
Stable in air	Yes
High gain (10^8)	Yes
Compact size	Yes
Linear at high outputs	No
Operating life	Shorter



Electron Multipliers

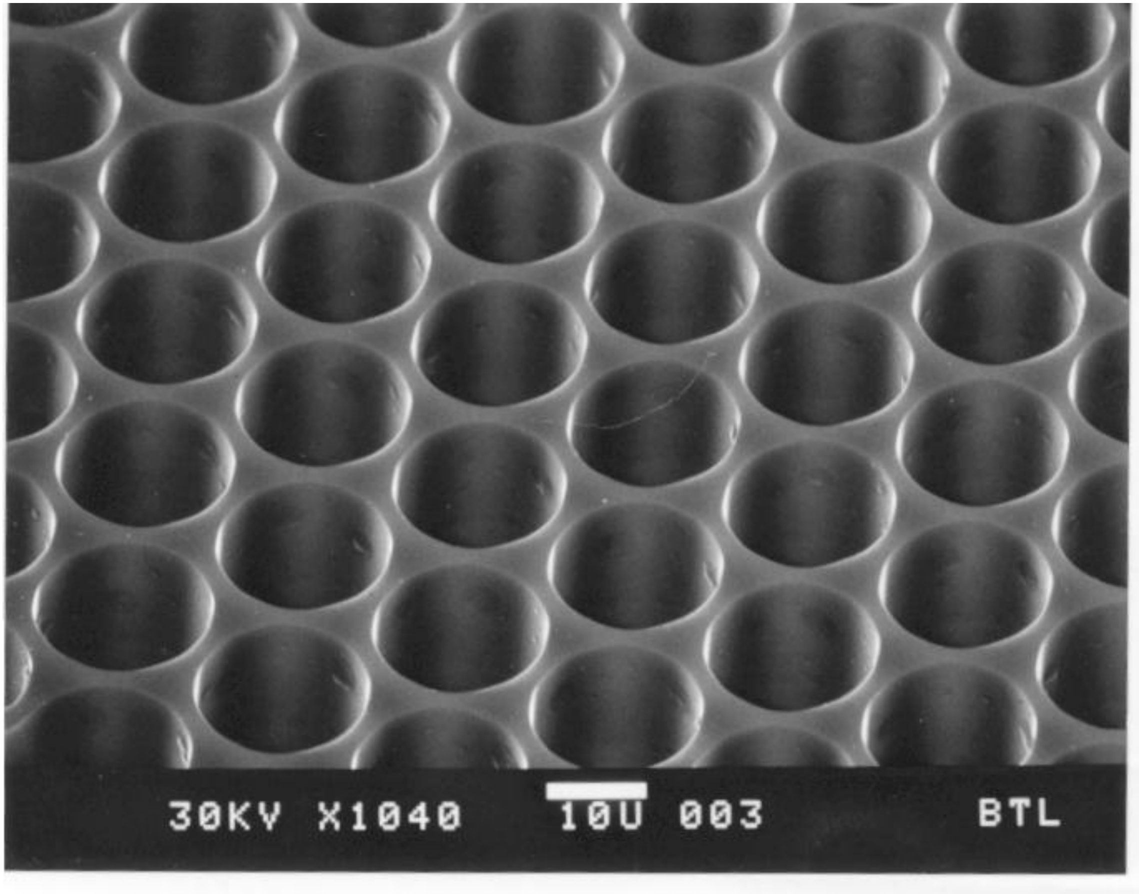

Dime ~17mm diameter

Discrete dynode



Continuous dynode (Channeltron)

Microchannel Plate



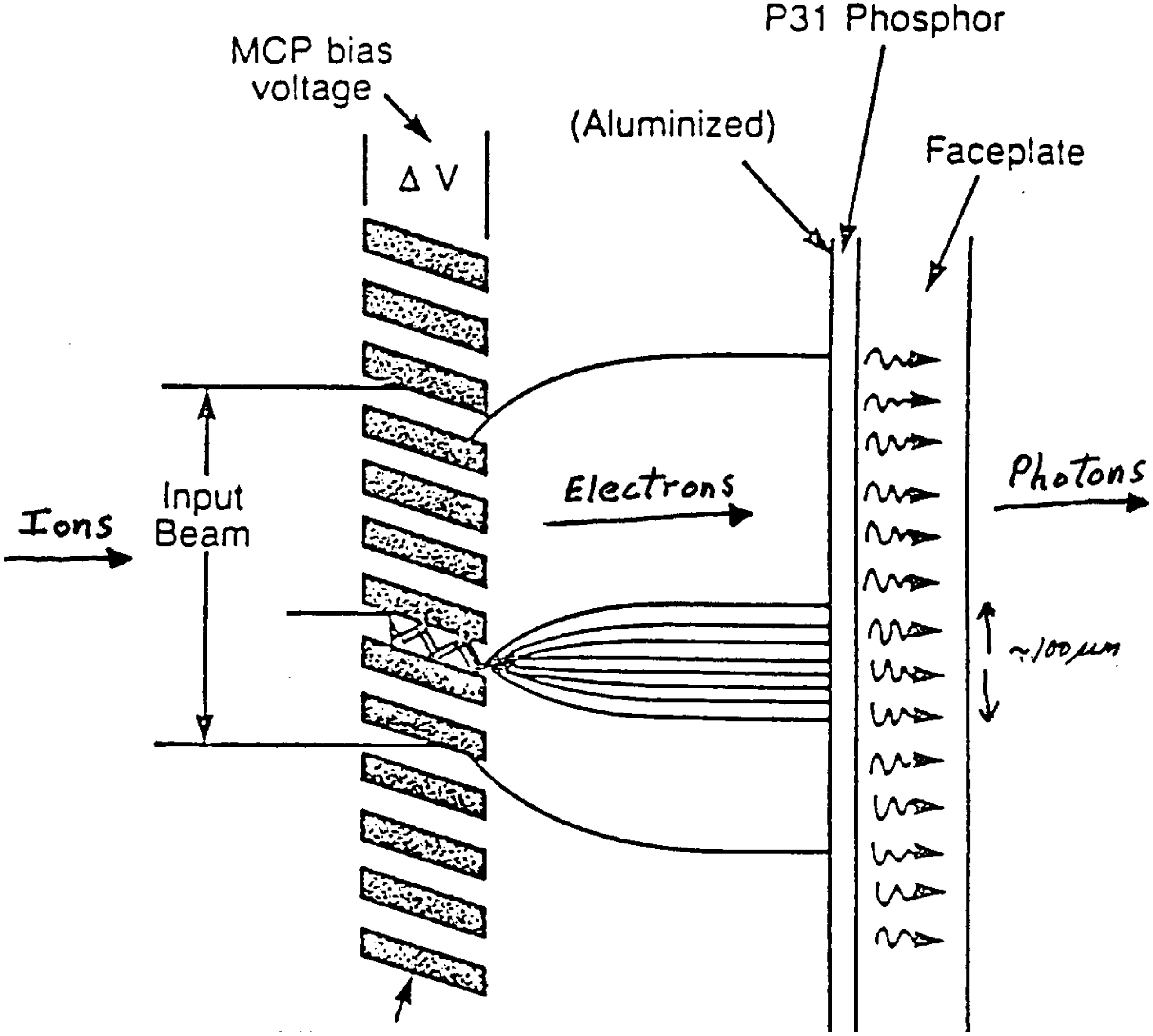
Array of 10^4 - 10^7 miniature electron multipliers oriented parallel to one another.

Multiplication factor
10^4 - 10^7

For 150 µm diameter imaged area, array of 17.5 µm diameter multipliers with 20 µm spacing over 2.5 cm diameter plate yields magnification of 160x and resolution of 0.1 µm.

J. L. Wiza, Nuclear Instruments and Methods 162, 587 (1979)

Microchannel Plate - Fluorescent Screen

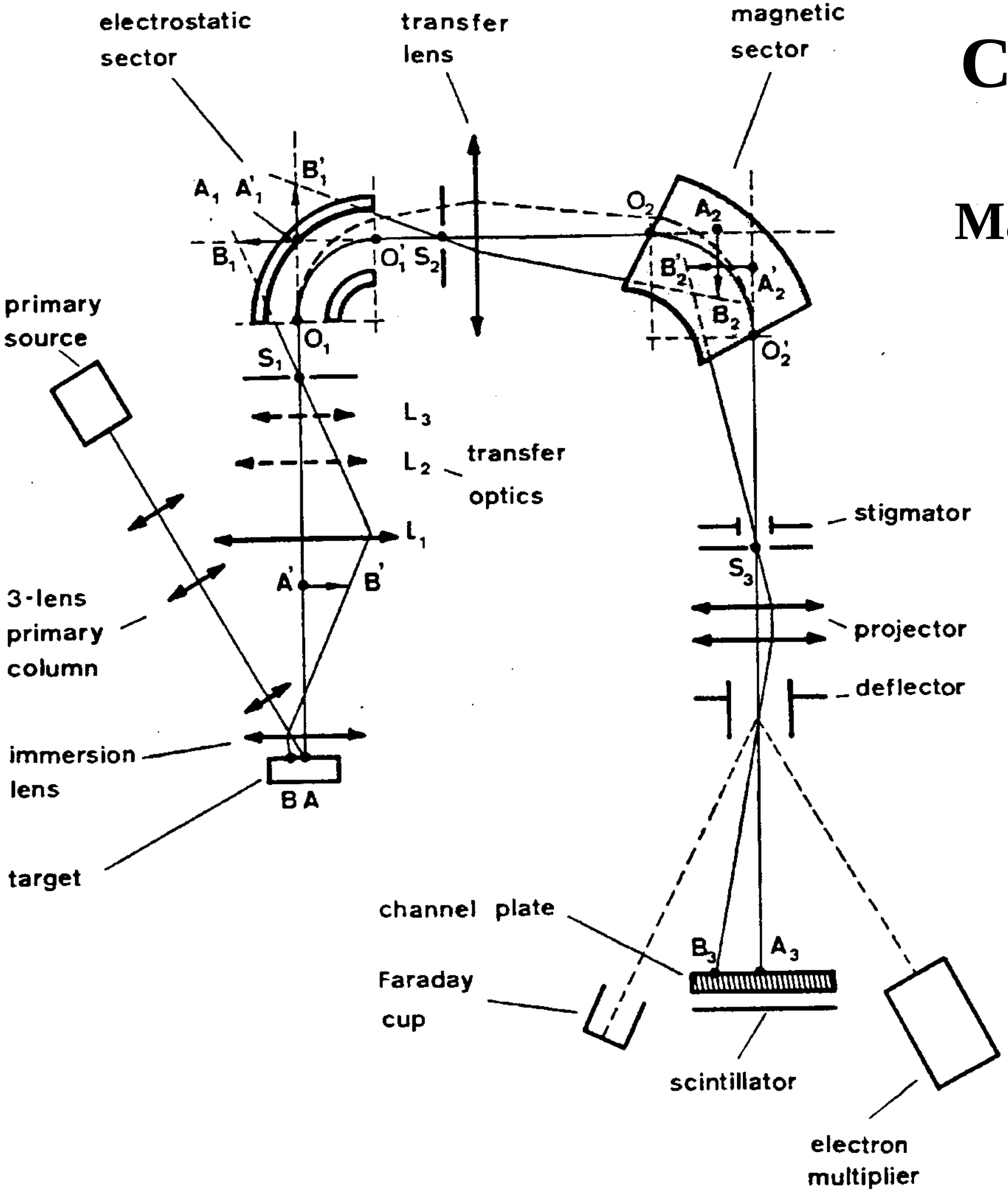


Microchannel Plate
16 µm, 8°, 300 - 1200 V

1.2 mm, 5 kV

CAMECA IMS-3f

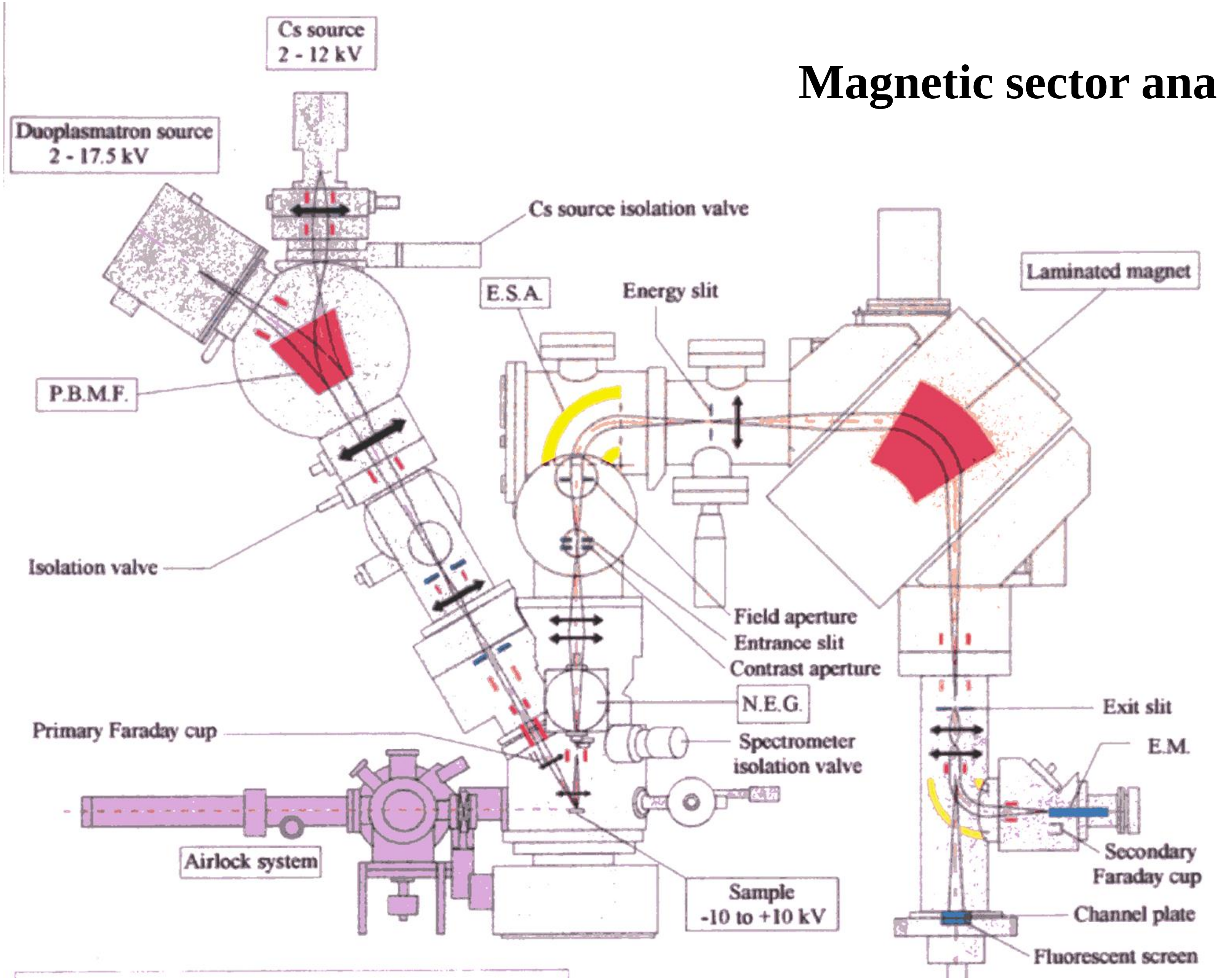
Magnetic sector analyzer



J. M. Gourgot, CAMECA News, No. 2, CAMECA S. A., Courbevoie, France (1977)

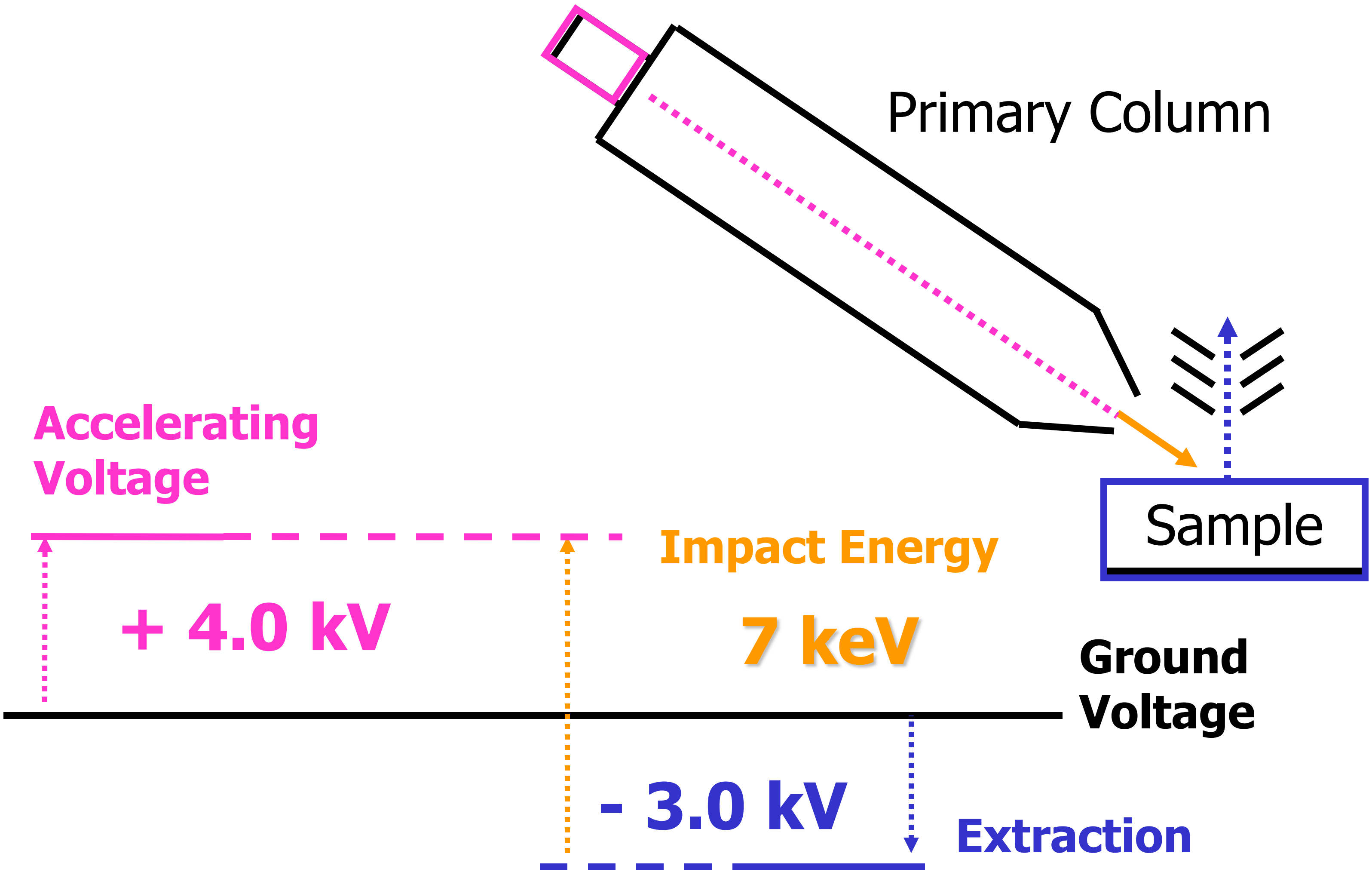
CAMECA IMS 6f

Magnetic sector analyzer



Primary Column: Impact Energy

Conventional magnetic sector SIMS



Primary Column

Sample

Accelerating Voltage

+ 4.0 kV

Impact Energy

7 keV

Ground Voltage

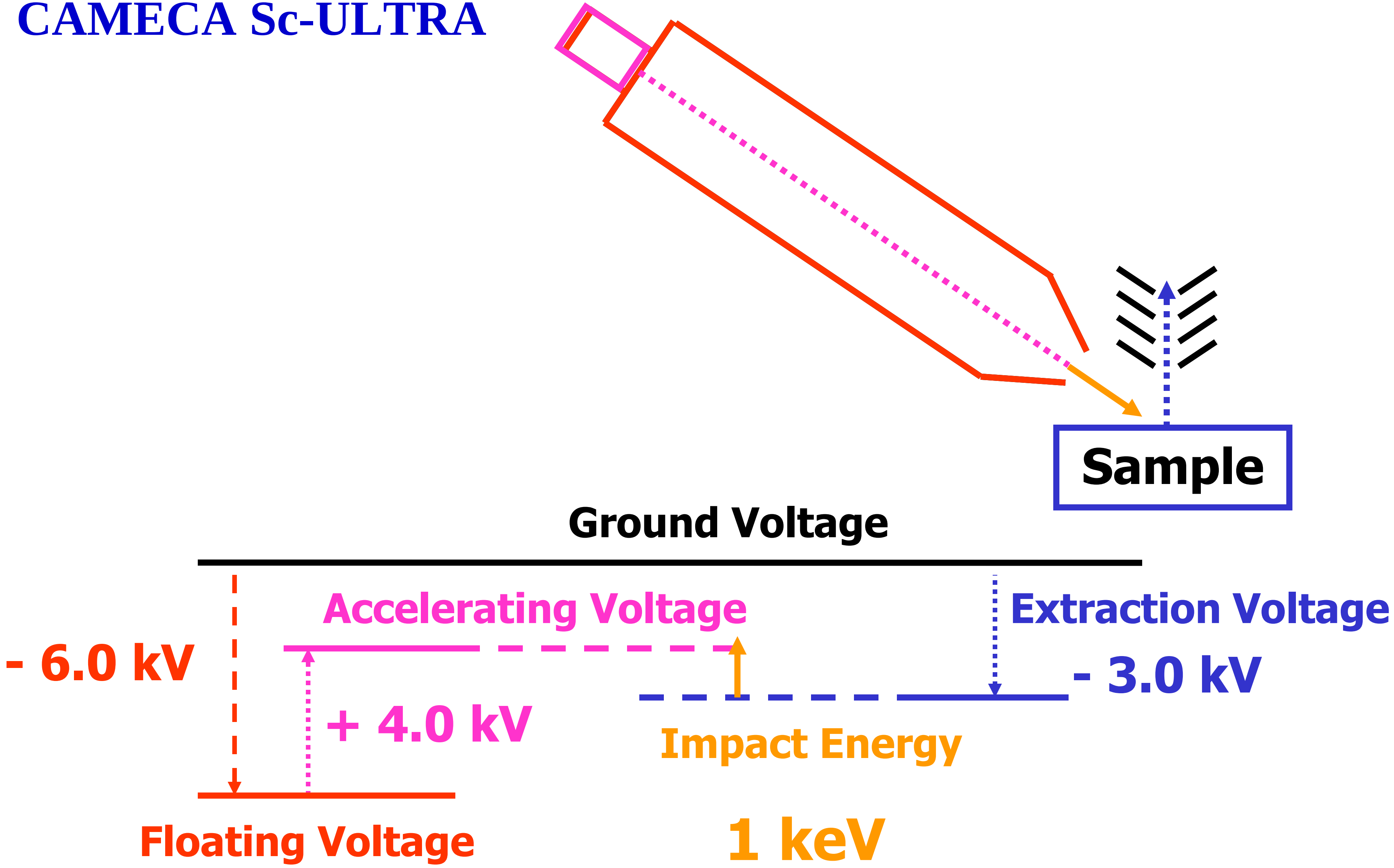
- 3.0 kV

Extraction Voltage

D. Giubertoni et al., FBK

Primary Column: Impact Energy

CAMECA Sc-ULTRA



Sample

Ground Voltage

Accelerating Voltage

Extraction Voltage

- 6.0 kV

+ 4.0 kV

- 3.0 kV

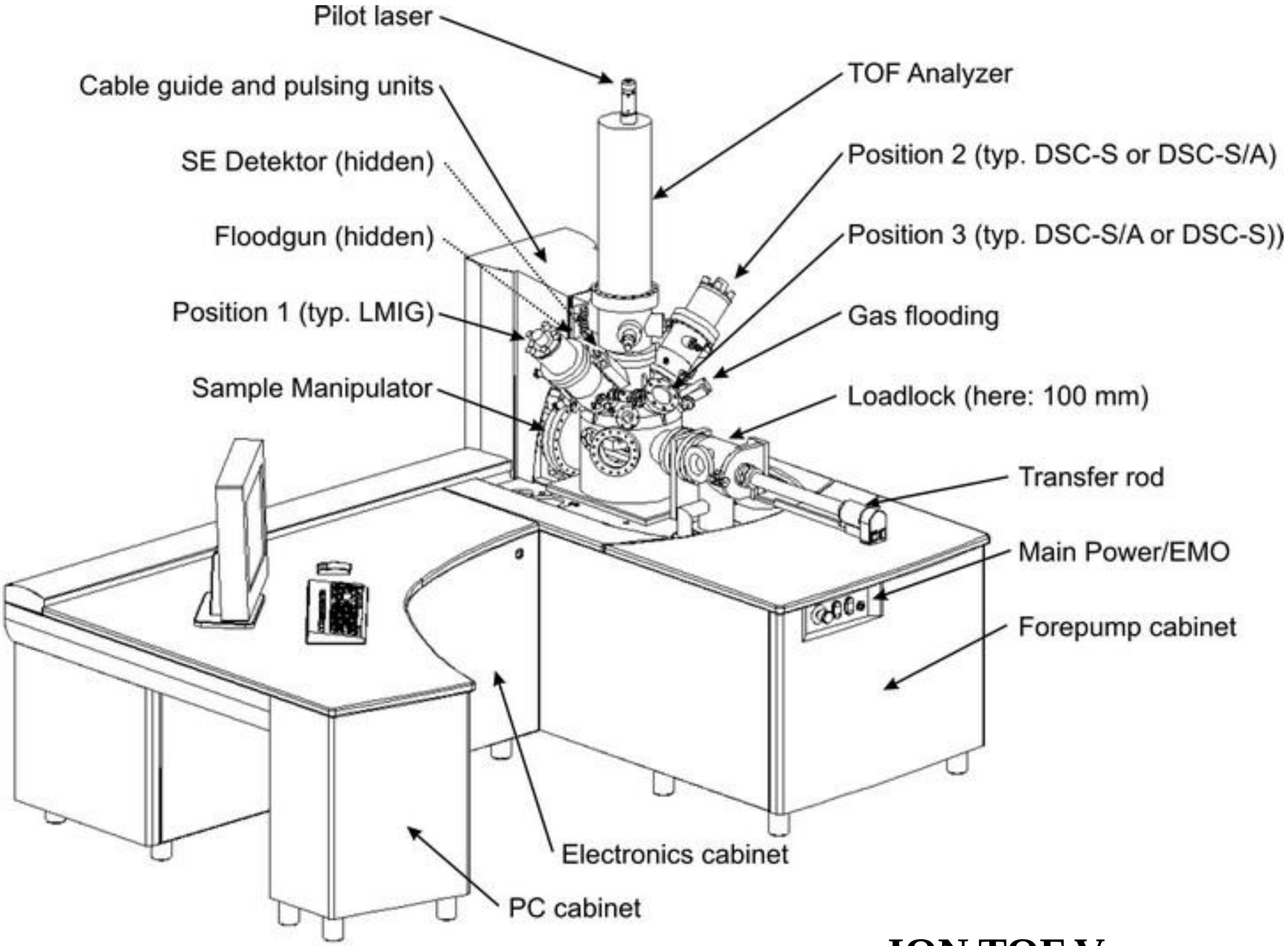
Impact Energy

Floating Voltage

1 keV

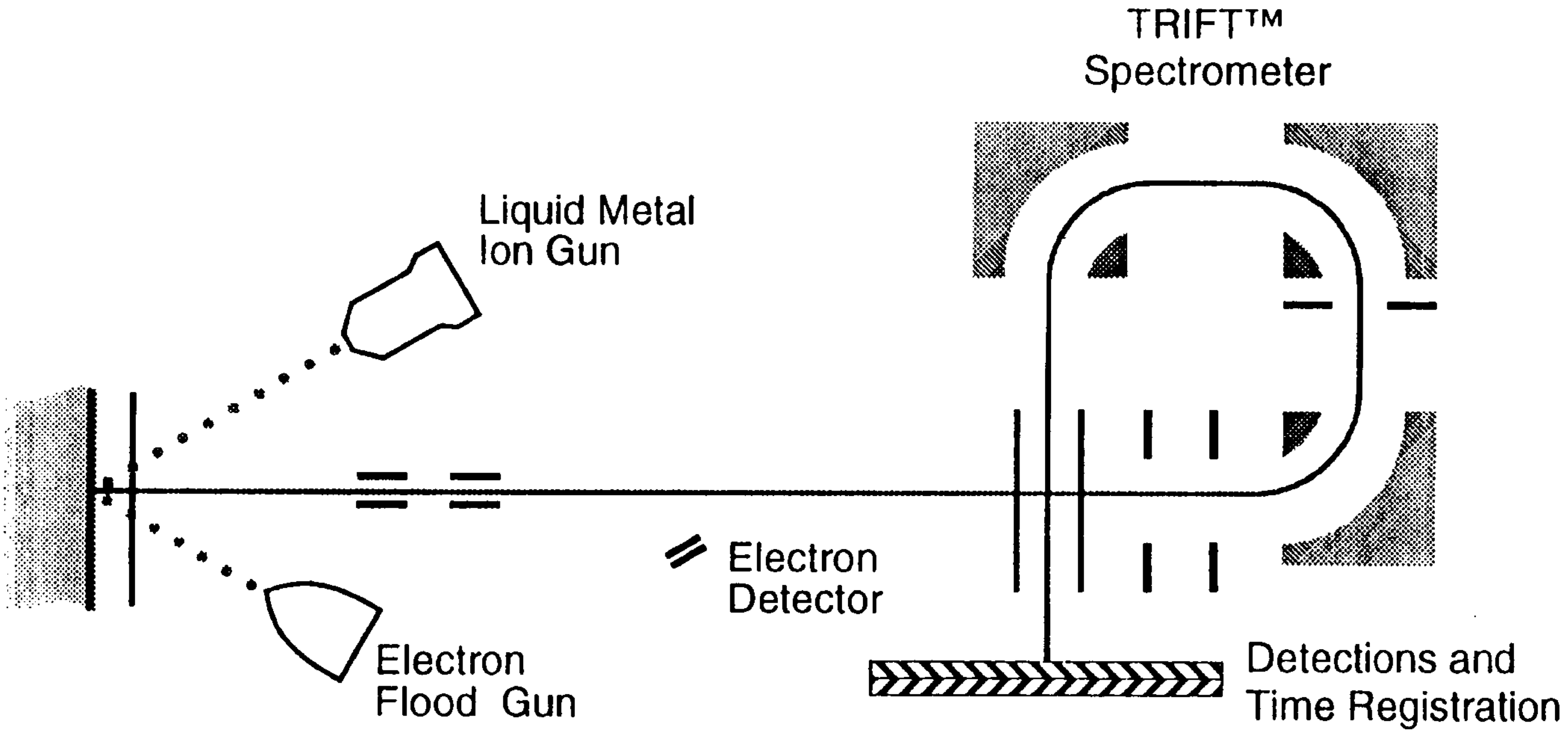
D. Giubertoni, et al., FBK

TOF-SIMS



ION TOF V

TOF-SIMS



Physical Electronics

Dynamic SIMS Primary Beam Calculations

Calculations for O_2^+ 10 kV,150 nA into 200 µm x 200 µm raster on Si using CAMECA IMS-3f. Sample potential 4500 V

O_2^+ velocity = $[2qV / m]^{0.5}$
= $[2 \times 1.6\text{x}10^{-19}$ coul x 10000 volts / $(32 \times 1.67\text{x}10^{-27}\text{kgm})]^{0.5}$
= $2.45\text{x}10^{5}$ m/sec
O_2^+ flight time = x / v = 1.12 m / $2.45\text{x}10^{5}$ m/sec = 4.6 µsec

O_2^+ current density = 150 nA / (200 µm x 200 µm)
= 0.38 mA/cm^2
O_2^+ flux = $0.38\text{x}10^{-3}$ coul/sec/cm^2 / $1.6\text{x}10^{-19}$ coul/ion
= $2.3\text{x}10^{15}$ ions/cm^2/sec
O_2^+ into 200 µm x 200 µm = $9.2\text{x}10^{11}$ ions/sec

Dynamic SIMS Analysis Calculations

150 nA primary current on Si, 10-20 nA total secondary ions before electrostatic analyzer (ESA) (CAMECA IMS-6F)

Si^+ velocity = 1.75×10^5 m/sec

Si^+ flight time = 1.72 m / 1.75×10^5 m/sec = 9.8 µsec

Material removed from 1 µm deep crater

volume = 4×10^{-8} cm^3

density of Si = 5×10^{22} atoms/cm^3 = 2.33 gm/cm^3

Si removed = density / volume = 2×10^{15} atoms = 93 ngm

Detected area = 60 µm diameter circle

volume = 2.83×10^{-9} cm^3

Si removed = 1.4×10^{14} atoms = 6.6 ngm

Ratio of detected volume to crater volume = 1 / 14