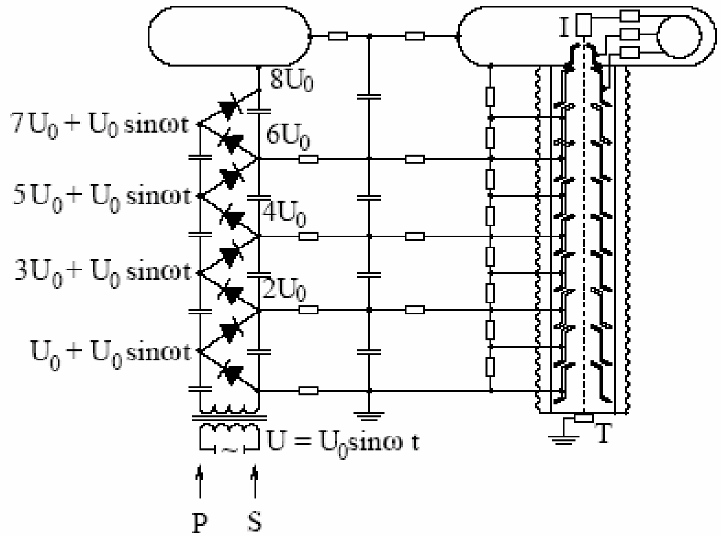
ELECTROSTATIC ACCELERATORS

1. Cockcroft Walton Accelerator
2. Van de Graaff Accelerator
3. Pelletron and Laddertron Accelerator
4. Dynamitron Accelerator
5. Tandem Accelerator
6. Ion Optics, Acceleration Tube
7. Voltage Measurement and Control
8. Beam Properties and Applications
9. Progress in Electrostatic Accelerator Development

Cockcroft Walton Accelerator

High Voltage Cascade Generator

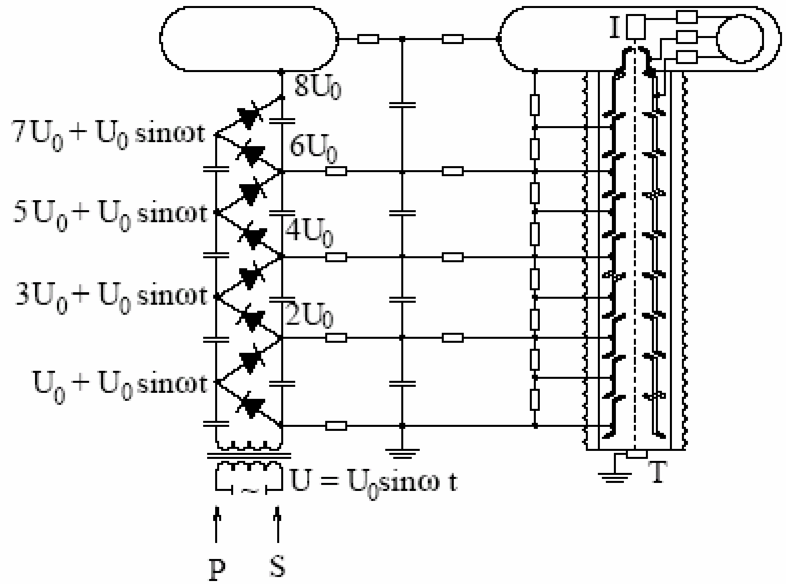


High Voltage U, Voltage Drop ΔU, Ripple δU:

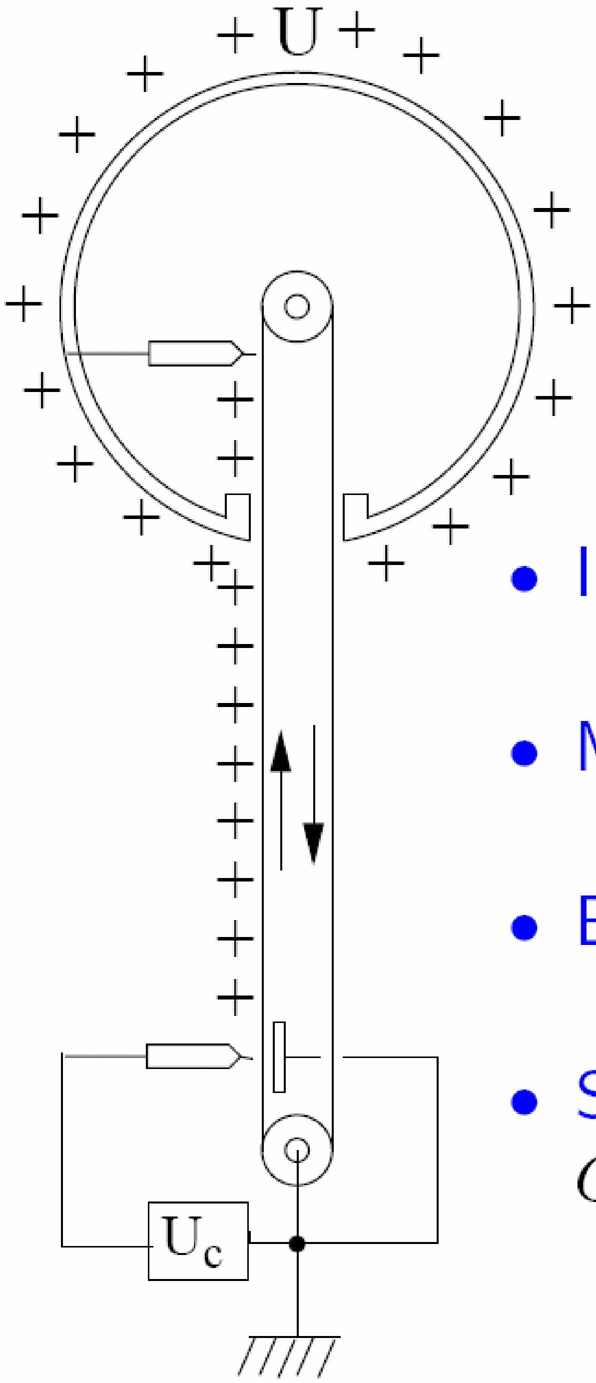
$$
\begin{aligned}
U &= 2nU_0 - \Delta U \pm \delta U \, , \\
\Delta U &= \frac{I}{fC}\left(\frac{2}{3}n^3 + \frac{3}{4}n^2 + \frac{1}{12}n\right) \, , \\
\delta U &= \frac{I}{fC}\frac{n(n+1)}{2} .
\end{aligned}
\tag{1}
$$

$f = 0.5 - 10$ kHz, $C = 1 - 10$ nF, $n = 3 - 5$,
$U = 400 - 800$ kV

Cockcroft Walton Accelerator



- Rounded Terminal Electrodes! $|\vec{E}| = \frac{U}{r}$
- Open Air Machines: $|\vec{E}| < 3\,\mathrm{MV/m}, \quad U < 1.5\,\mathrm{MV}$
- Accelerating tubes in evacuated ceramic insolator
- High Voltage distributed among several tubes: $|\vec{E}| < 100$ kV/cm
- Accelerating Tubes: rounded and overlapping

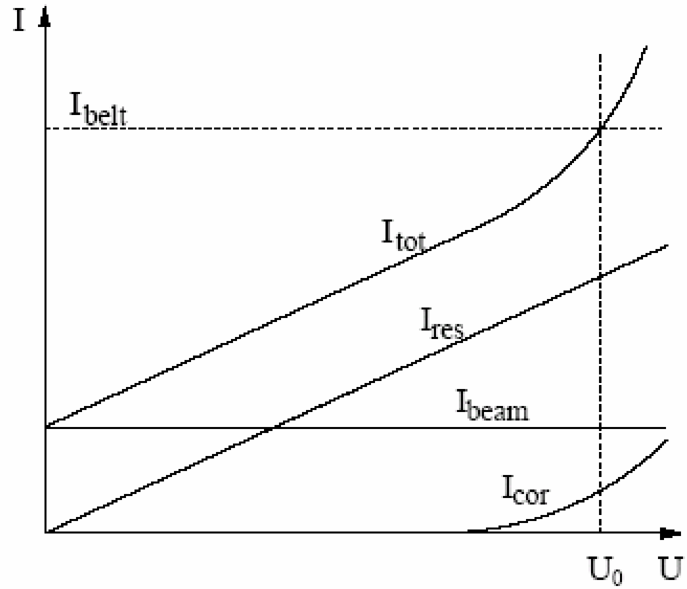


Van de Graaff Accelerator

- Insulating support column
- Motor-driven insulating belt
- Electric charge carried to HV terminal
- Spherical HV terminal electrode: $U = Q/C$
  $C = 4\pi\epsilon\epsilon_0 r = (1.11 \cdot 10^{-10}\ \mathrm{F/m})$

Typical current-versus-voltage functions in a Van de Graaff accelerator

Equilibrium Voltage U_0



Equilibrium Voltage U_0 depends on charging current I_{belt}

$$\frac{\mathrm{d}U}{\mathrm{d}t} = \frac{1}{C}\frac{\mathrm{d}Q}{\mathrm{d}t} = \frac{1}{C}(I_{belt} - I_{beam} - I_{res} - I_{cor}).$$

$$\frac{\mathrm{d}U}{\mathrm{d}t} = \frac{1}{C}\left(I_{belt} - I_{beam} - \frac{U}{R}\right).$$

$$U(t) = U_0 + [U(0) - U_0]\mathrm{e}^{-t/\tau}, \quad \tau = RC$$

Breakdown Potential

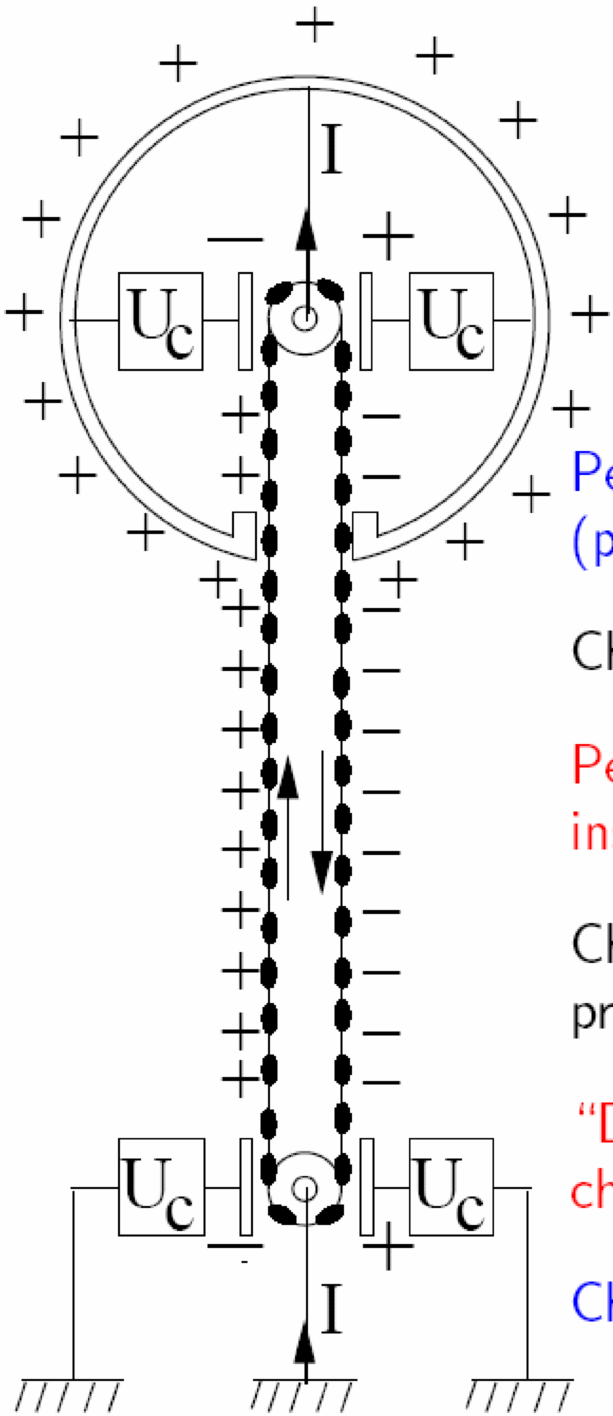
Discharging by sparks depends on:

1. Radius of curvature, area and smoothness of terminal
2. Electrode material and surface contaminations
3. Composition and pressure of the gas
4. Shape, material and surface conditions of insulating supports
5. Potential distribution along the insulator and accelerating tube

High pressure up to 20 bar.

Dry and purified hexafluoride (SF_6) gas or mixtures of nitrogen and carbon dioxide (80 % N_2 and 20 % CO_2)

Large radii of curvature, clean polished surfaces, smooth potential distribution



Pelletron and Laddertron Generator

Pelletron (Laddertron) chains made of metal pellets (plates) connected by insulating nylon links

Charging by influence in an electrical field

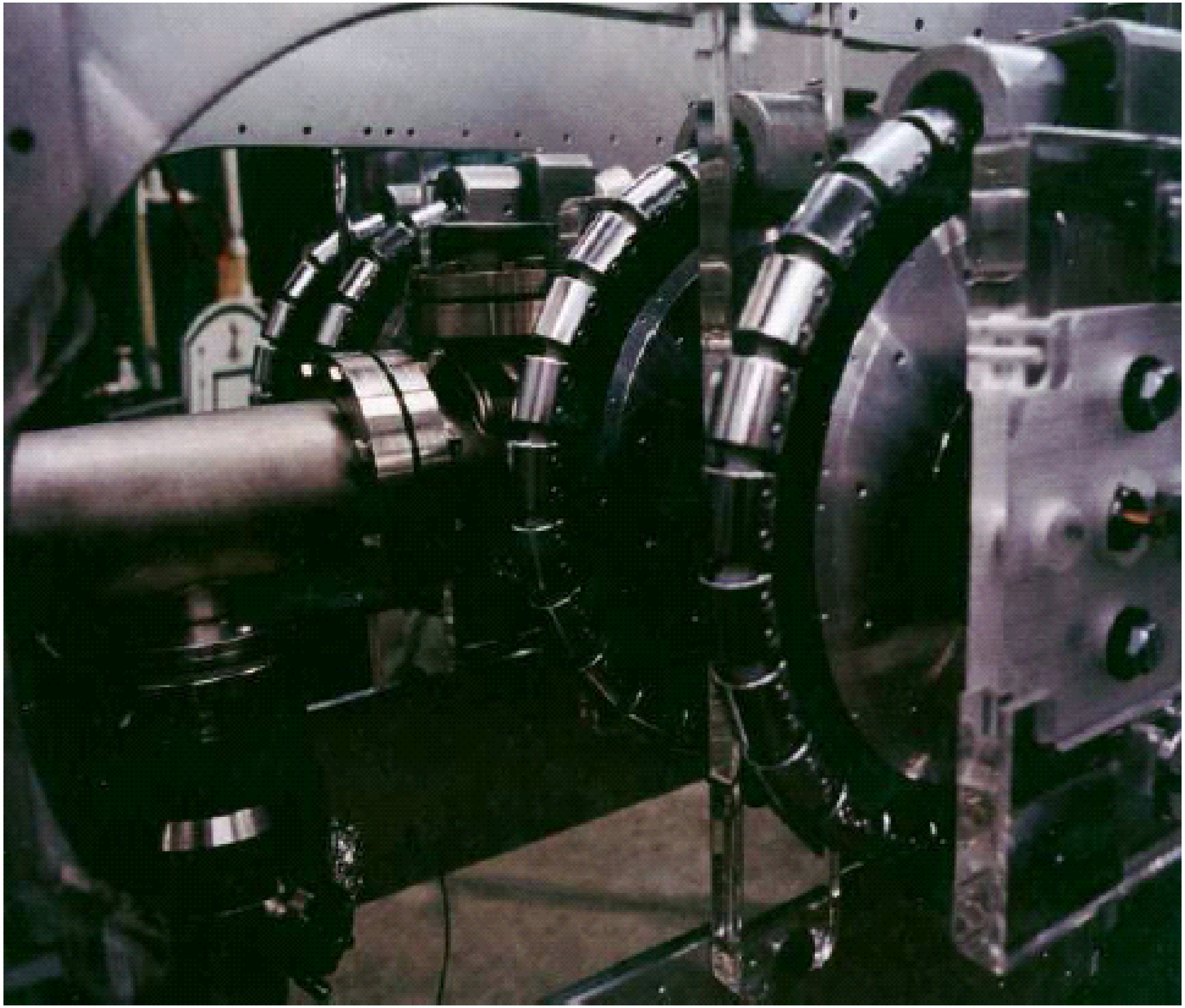
Pellets are charged as they leave the grounded pulley inside the electric field

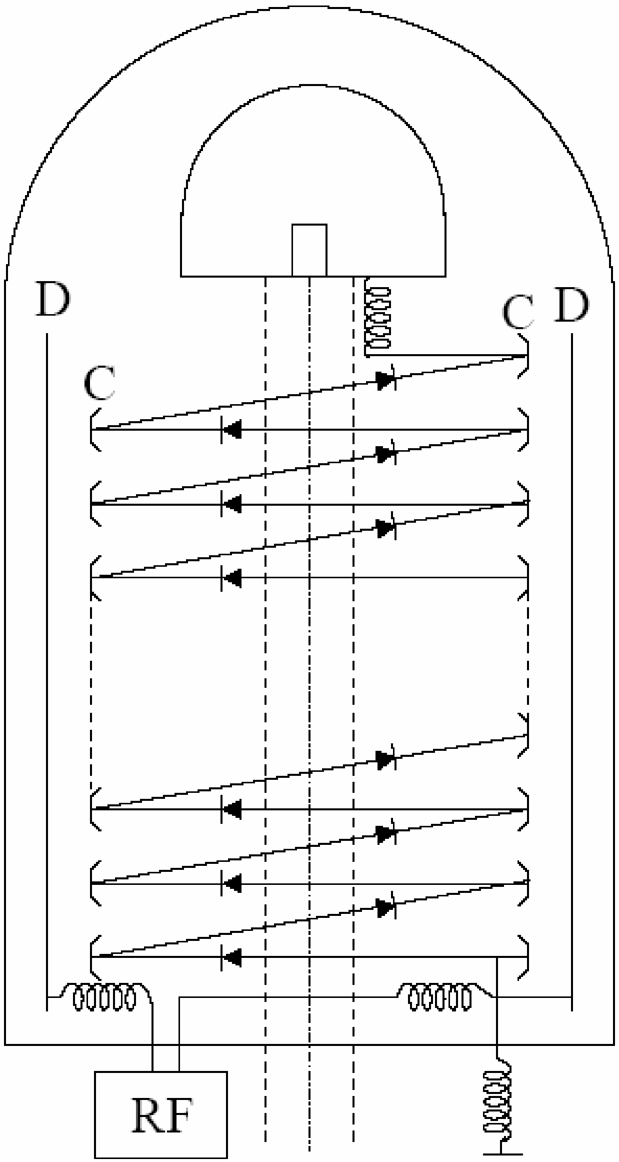
Chain transports charge to the terminal where the reverse process occurs

“Down-charging” works as “up-charging” $\Longrightarrow$ double charging capacity

Charging currents about 100 – 300 μA, HV up to 25 MV

Pelletron Chain from NEC





Dynamitron Generator

RF oscillator: $f = 30 - 300$ kHz, U_0 up to 100 kV

Capacitive coupling between driver (D) and coupling (C) electrodes

Cockcroft-Walton like cascade generates DC voltage

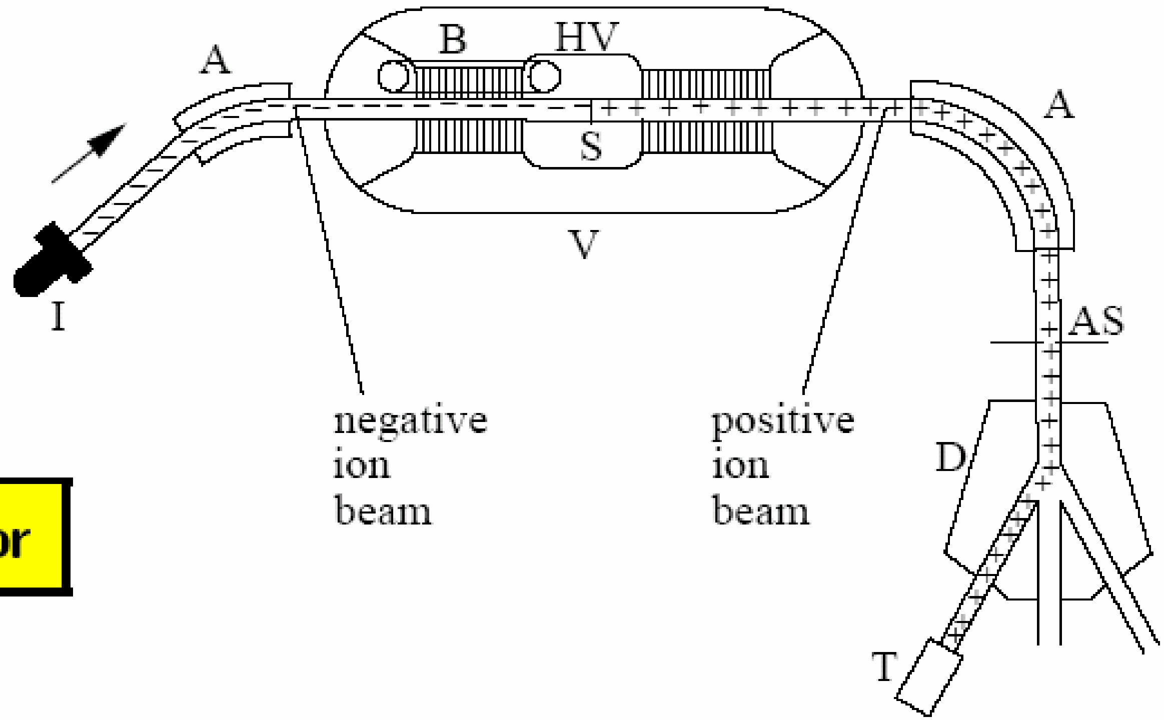
High voltage proportional to number n of rectifier stages

$$U = 2nf_cU_0$$

Advantages: No moving parts inside the pressure vessel. Sparkovers harmless due to low capacitance of the system. High currents e.g. 10 mA. Low voltage drop ΔU and ripple δU due to high frequency. Highly stable terminal voltages (level 10^{-5})

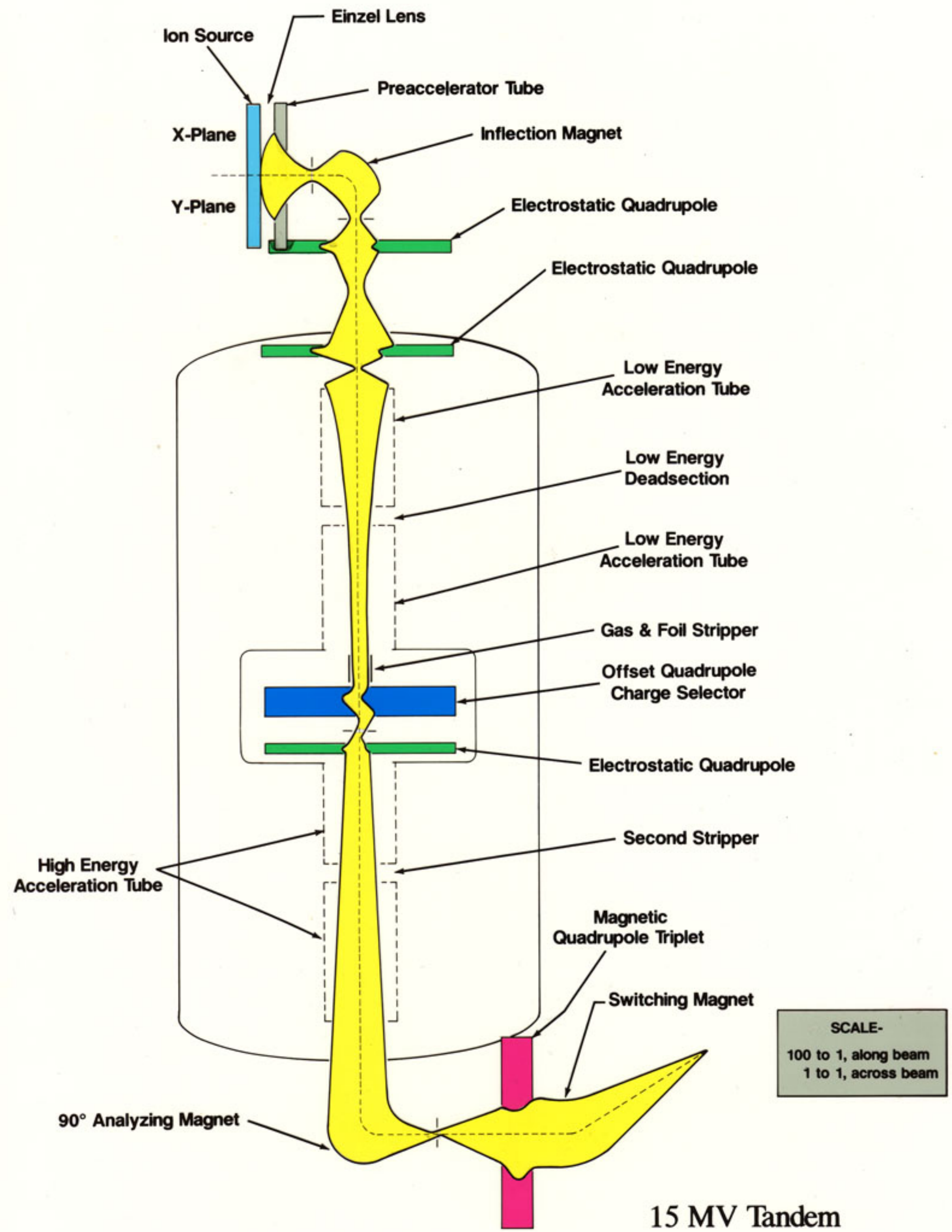
Scheme of Tandem Accelerator

Tandem Accelerator



Kinetic Energies T $\quad T = eU + qU = (e+q)U.$

$$\begin{aligned} \mathrm{p,\ d} \quad &: \quad T = 2\,eU\,, \\ {}^{3}\mathrm{He}^{2+},\ {}^{4}\mathrm{He}^{2+} \quad &: \quad T = 3\,eU\,, \\ {}^{32}\mathrm{S}^{16+} \quad &: \quad T = 17\,eU\,. \end{aligned}$$

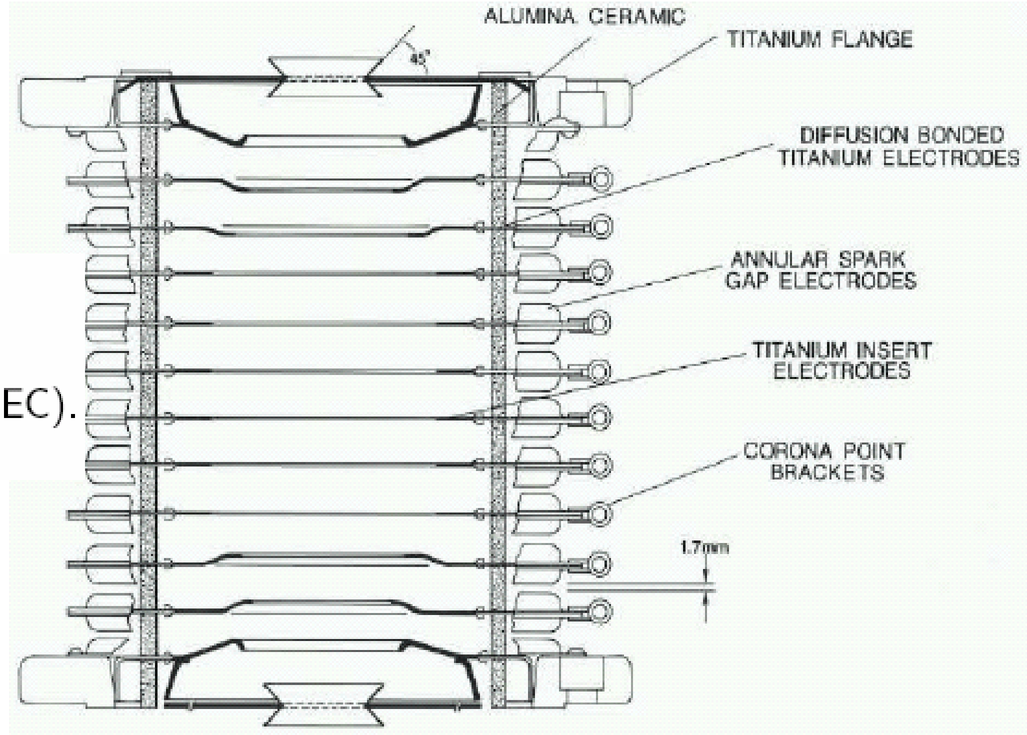


Einzel Lens
Ion Source
Preaccelerator Tube
X-Plane
Inflection Magnet
Y-Plane
Electrostatic Quadrupole
Electrostatic Quadrupole
Low Energy
Acceleration Tube
Low Energy
Deadsection
Low Energy
Acceleration Tube
Gas & Foil Stripper
Offset Quadrupole
Charge Selector
Electrostatic Quadrupole
Second Stripper
High Energy
Acceleration Tube
Magnetic
Quadrupole Triplet
Switching Magnet
SCALE-
100 to 1, along beam
1 to 1, across beam
90° Analyzing Magnet

15 MV Tandem

Acceleration Tube

Acceleration Tube Segment (courtesy of NEC). L=20 cm, I.D.=10 cm, U=330 kV



Modular acceleration tube elements

Electrodes connected to equipotential rings

"Uniform field" tube: high voltage gradient

Electrodes bonded to alumina ceramic

Electron suppression: high vacuum, limiting apertures, external magnetic fields

VOLTAGE MEASUREMENT AND CONTROL

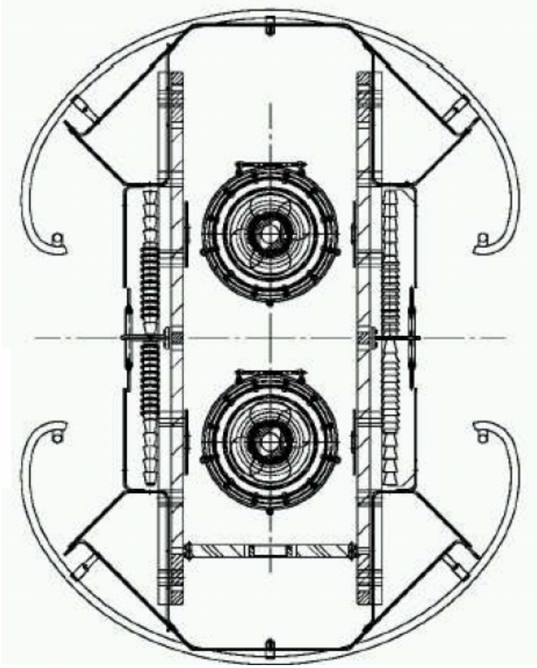
1. Current in calibrated resistor chain (10 GΩ per 1 MV)

2. Generating Voltmeter

3. Magnetic deflection in 90° analyzing magnet: Accuracy: 10^{-4}-10^{-5}

4. Cross-calibration: Sharp nuclear resonances

5. Two acceleration tubes: Magnetic analysis of reference beam



Two acceleration tubes in a coaxial HV power supply (courtesy of HVEE)

Beam Properties

Cockcroft Walton Accelerator:

- Electrons, protons, light and heavy ions up to uranium
- Low voltages ($\approx$200 – 800 kV), low beam energies
- Beam currents up to several 10 mA, DC and pulsed beams

Beam Properties

Van de Graaff and Tandem Van de Graaff:

- Electrons, protons, light and heavy ions up to uranium
- Voltages between 1 and 25 MV, beam energies up to several 100 MeV
- Excellent beam quality, energy resolution up to 10 000
- Easy energy variation: energy scans in fine energy steps
- Beam currents between 10 nA and several 10 mA, DC and pulsed beams.

Application of Electrostatic Accelerators

Cockcroft Walton Accelerators

- Preaccelerator for large accelerator facilities
- Neutron generator: $\mathrm{d} + \mathrm{d} \rightarrow \mathrm{n} +^{3}\mathrm{He}$ and $\mathrm{d} + \mathrm{t} \rightarrow \mathrm{n} +^{4}\mathrm{He}$
  about 2 and 14 MeV neutrons, DC or pulsed
- Ion beam modification of materials
- Ion beam analysis
- Experiments in atomic, nuclear and astro physics

Application of Electrostatic Accelerators

Van de Graaff and Tandem Van de Graaff Accelerators:

- Ion implantation and ion beam mixing
- Accelerator mass spectrometry (AMS)
- Ion microprobe beam applications ($> 1\ \mu$m-beam)
- Ion beam analysis
  - Rutherford backscattering spectroscopy (RBS)
  - Particle induced X-ray emission (PIXE)
  - Particle induced gamma ray emission (PIGE)
  - Nuclear reaction analysis (NRA)
  - Elastic recoil detection (ERD)
  - Resonance scattering analysis (RSA)

Application of Electrostatic Accelerators

High Power Electron Accelerators:

- Production of X-rays
- Sterilization of medical products
- Food irradiation
- Purification of gases
- Treatment of waste water and toxic wastes
- Wire and cable crosslinking
- Thin films polymer crosslinking
- Heat shrinkable tubing and plastics
- Polymer tube crosslinking

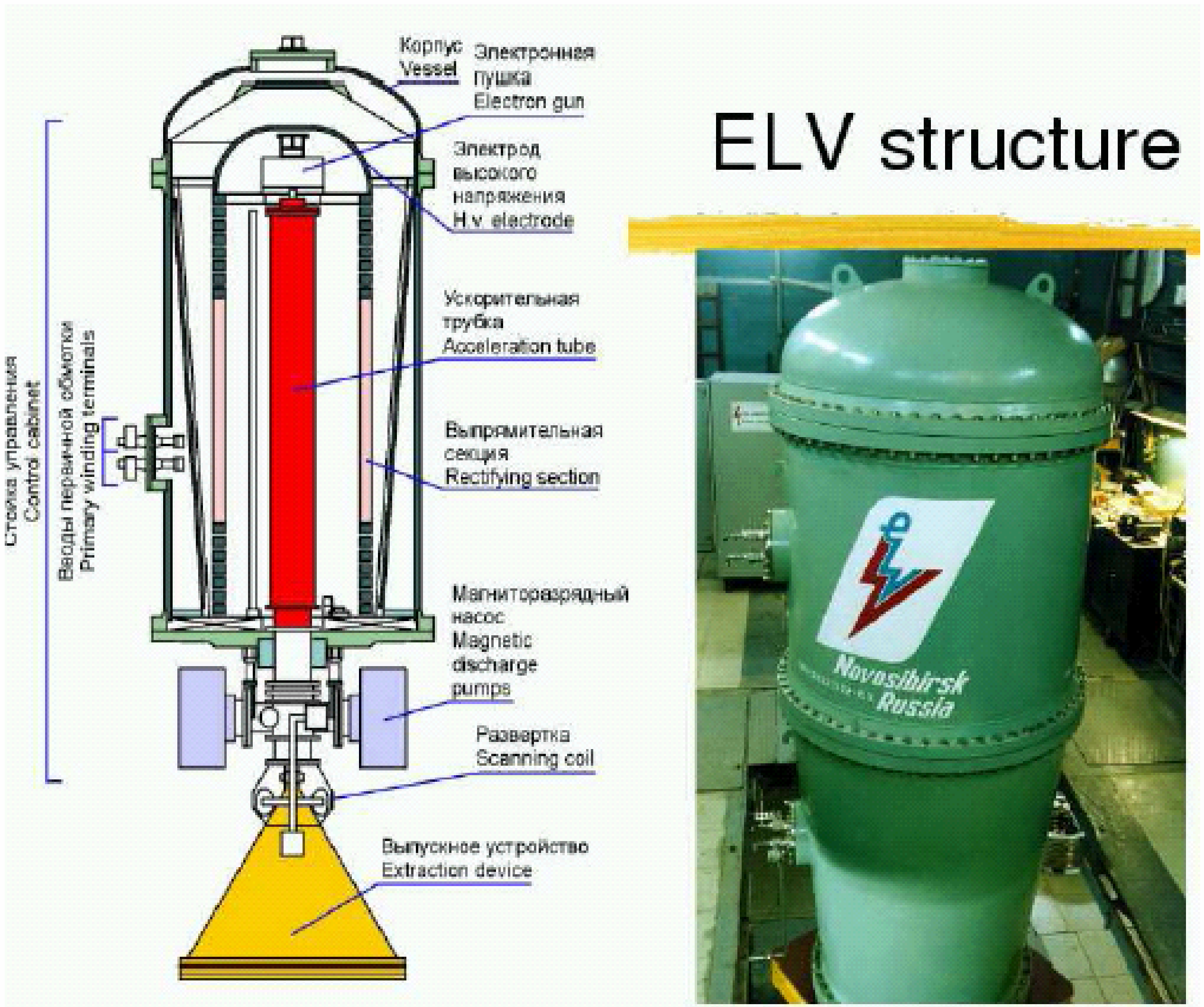
Progress in Electrostatic Accelerator Development

- Big Tandem Accelerators with terminal voltages up to about 25 MV
- Compact and customized electrostatic accelerators
- Complete turnkey systems for applications in medicine, biology and industry

- Bakeable, metal/ceramic, organic-free acceleration tubes
- Rugged, high stability charging systems
- Long lived ion sources, light and heavy ions from hydrogen to uranium
- Computer control

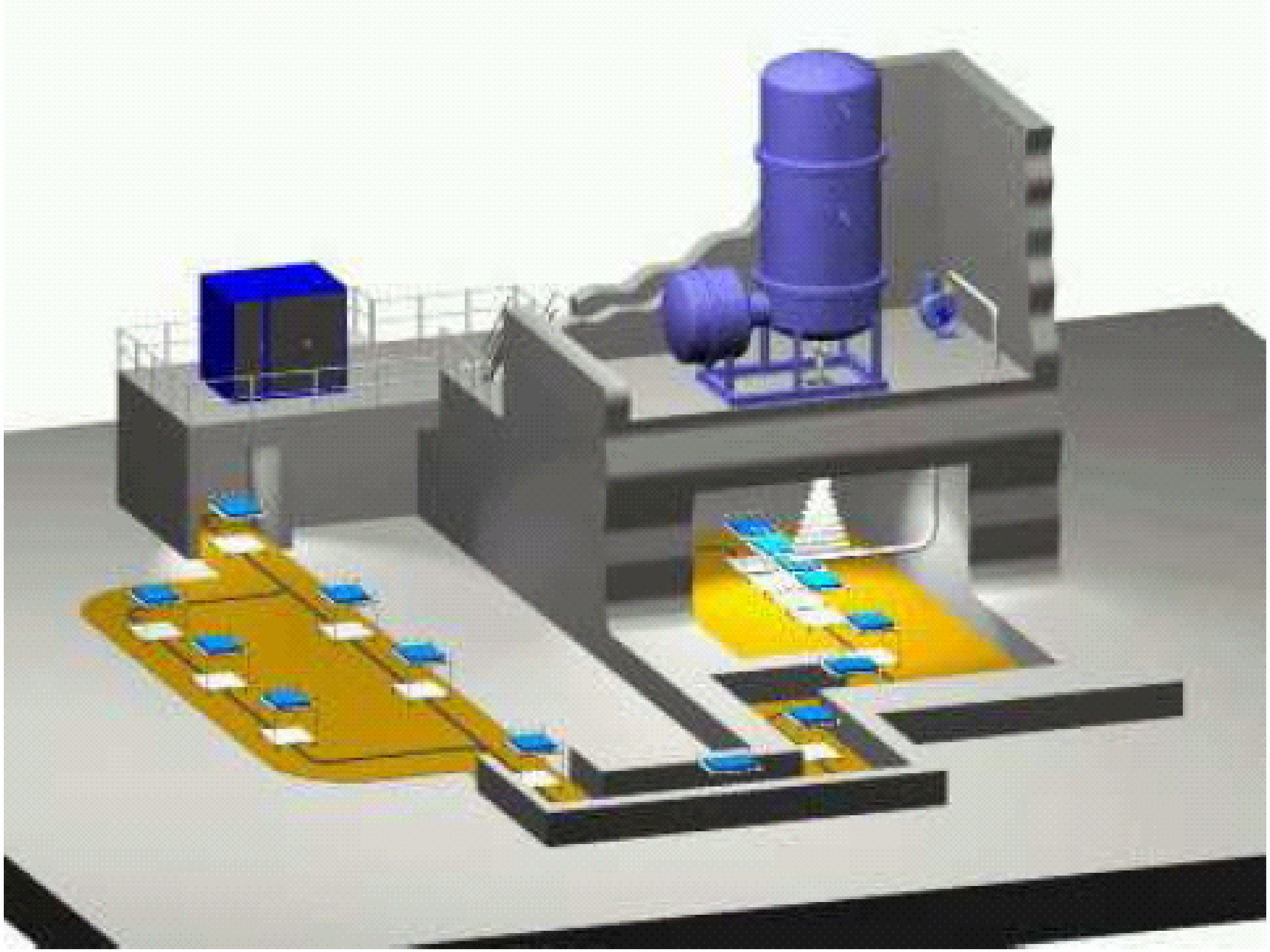
Electron Accelerator ELV

ELV-8: 1.0 – 2.5 MeV, 50 mA, 90 kW
ELV-12: 0.6 – 1.0 MeV, 400 mA, 400 kW

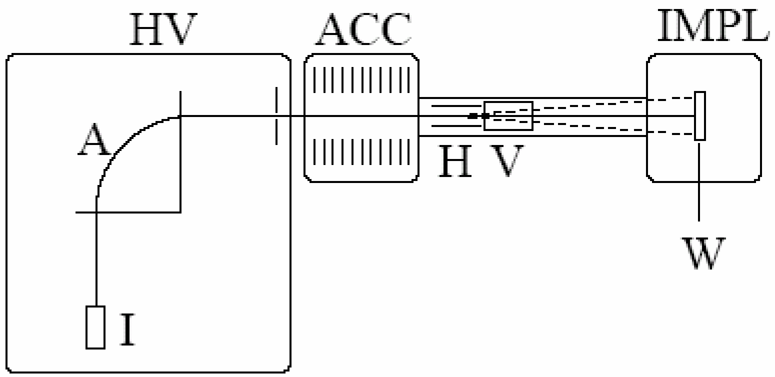


5 MV Dynamitron Facility Layout

5 MV Dynamitron from IBA, electron current up to 34 mA, 170 kW



Scheme of Ion Implanter



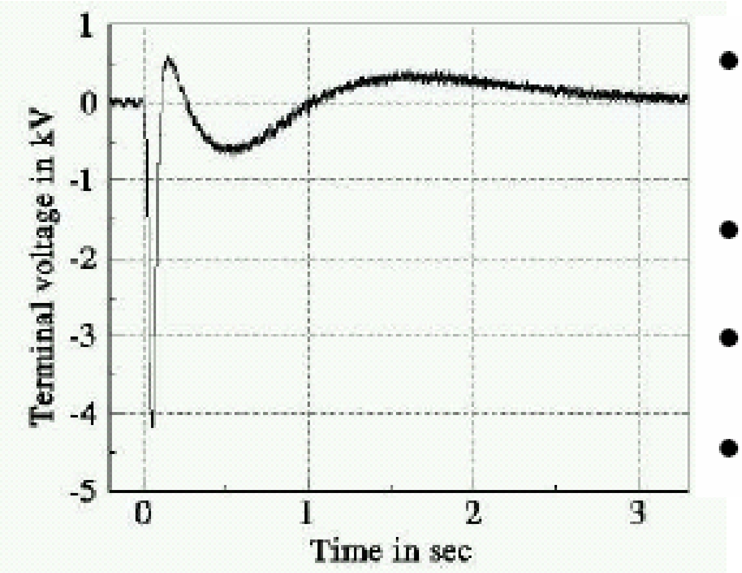
- Beams: B^+, P^+, As^+,...
  1 – 2 mA, 5 – 200 keV
- H,V electrostatic raster scanning
- Dose uniformity <0.5 %
- Automated material handling systems
- 200 mm wafer: throughput 250 per hour

Ion Implanter

Ion implantation for doping processes in silicon integrated circuits:

- High current implanter: 30 mA, 1 keV – 200 keV
- Medium current implanter: 1 μA – 5 mA, 2 keV – 900 keV
- High energy implanter: 1 μA – 1 mA, variable energy up to 5 MeV

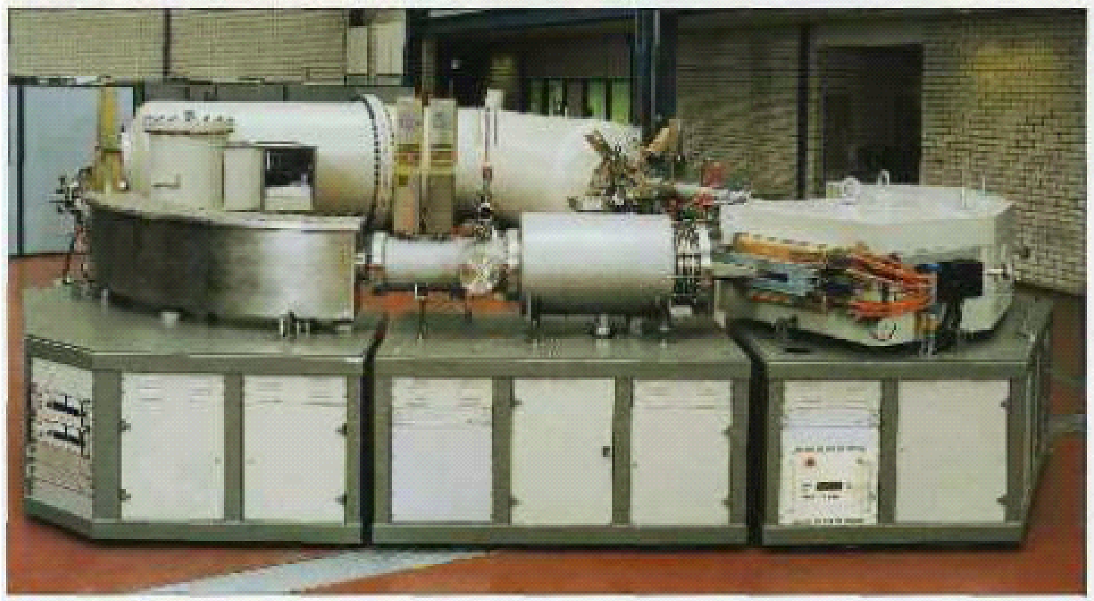
5 MV Tandetron from HVEE



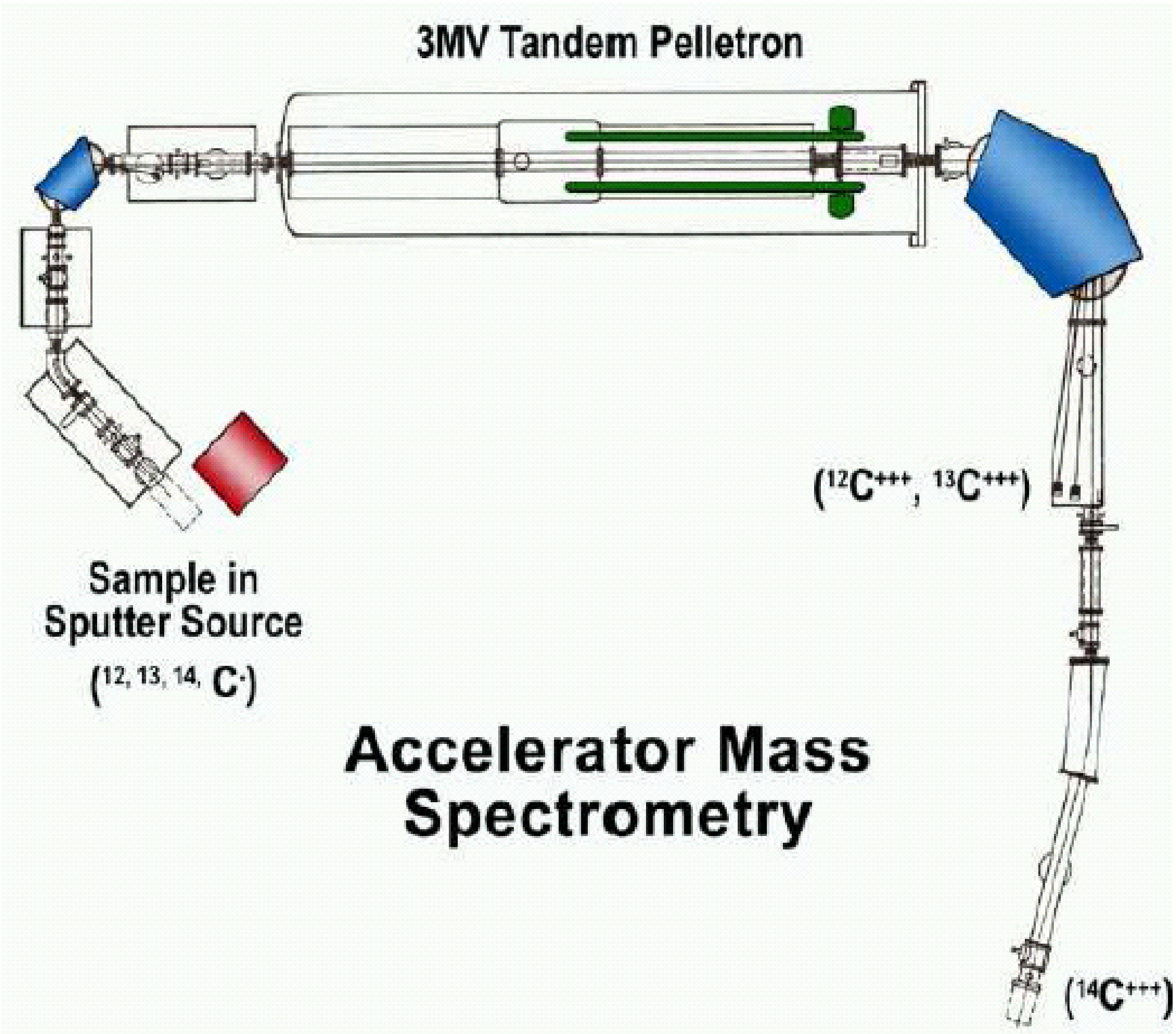
- Prompt Si^- beam injection at 3 MV, beam load >1 kW
- Maximal undershoot 4.2 kV, $1.4 \cdot 10^{-3}$
- Recovery within 50 ms to $3 \cdot 10^{-4}$
- Final rms stability about $1 \cdot 10^{-5}$

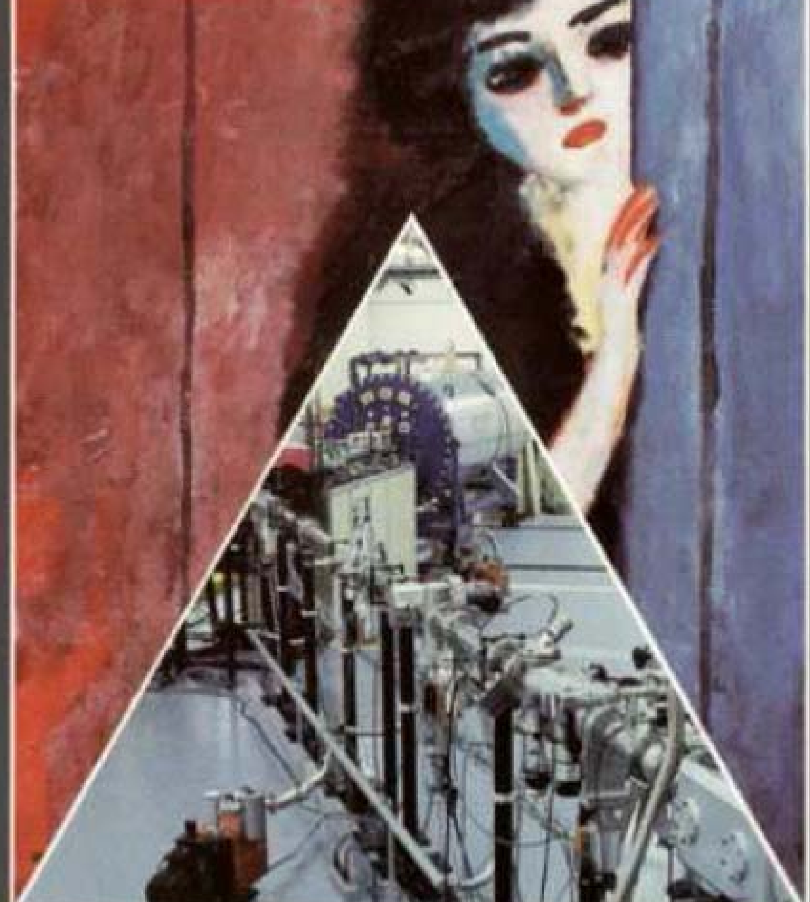
Accelerator Mass Spectrometry from HVEE

^{3}H, ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, ^{41}Ca, ^{129}I, ^{236}U



Accelerator Mass Spectrometry from NEC





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Summary

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