Nuclei in the Cosmos School 2025

# BEAMS, TARGETS & DETECTORS
# Part I

Faïrouz Hammache
IJCLab Orsay, France

NASA/Space Telescope Science Institute

# Layout of the lectures

## Lecture I

### I. Brief Introduction

### II. Beams for Nuclear astrophysics

1. Requirements
2. How to accelerate an ion
   - Accelerator types & purpose of each type
3. Radioactive beams
   - production methods
   - examples

### III. Targets for nuclear astrophysics

1. Requirements
2. Solid targets
   - Production
   - Characterization
3. Gas targets

## Lecture II

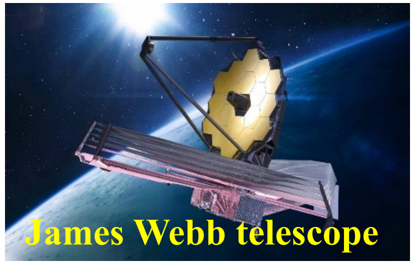
### IV. Detectors for nuclear astrophysics

1. Some general characteristics of detectors
2. Requirements
3. Detection systems for charged particles
   - i) Silicons detectors
   - ii) Magnetic spectrometers
   - iii) Gas detectors
   - iv) Active Gas targets

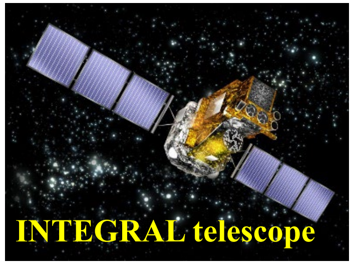
   } -Functioning principle -What is measured -Examples
4. Detection systems for gamma-rays
5. Recoils Separators for Heavy recoils detection

# From nuclear physics to abundances

**Observations**
(on earth, meteorites, telescopes, satellites,…) → **Observed abundances**








**Astrophysics Modelling**
(BBN & stellar evolution , nucleosynthesis) → **Predicted abundances for each species**

**Determine the amount of energy released by nuclear reactions**

**Reaction Network**

Set of differential equations to follow **the time evolution of isotopic abundances :**

$$\frac{dY_i}{dt} = \sum_i N^i_j \lambda_j Y_j + \sum_{j,k} N^i_{j,k} \rho N_A \langle \sigma v \rangle Y_j Y_k$$

**β decay rates, Half-lifes**

**Reaction rates**

$$\langle \sigma v \rangle = \left( \frac{8}{\pi \mu} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) E e^{-E/kT} dE$$

**Reaction cross sections**

# Cross-section measurements

- Number of reactions /s:

$$N_{reac} = \sigma \times (n_1 \times \Delta x) \times N_2$$

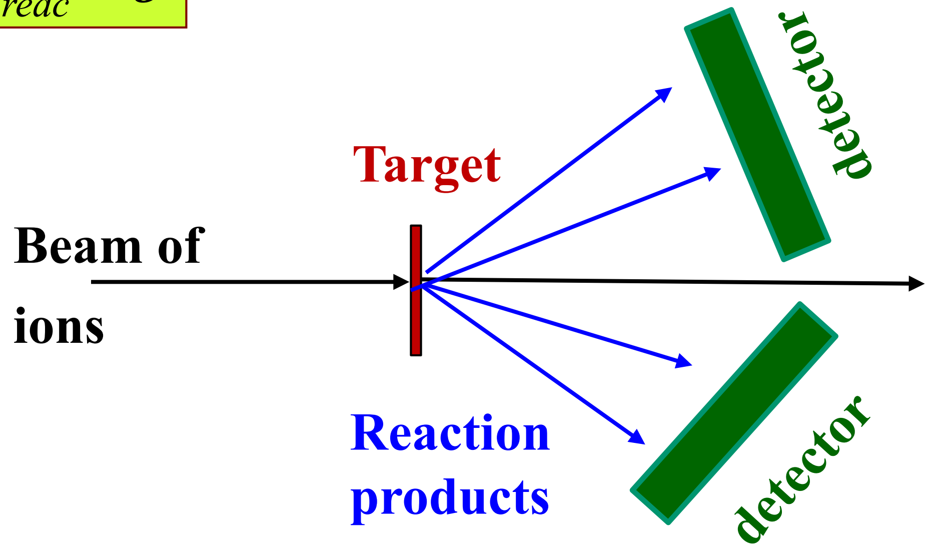
where $n_1$ is the number of target atoms per $cm^{-3}$,

$\Delta x$ (cm) the (thin) target thickness, $N_2$ the number of projectiles per s and $\sigma$ the desired cross-section

- Number of detected events /s:

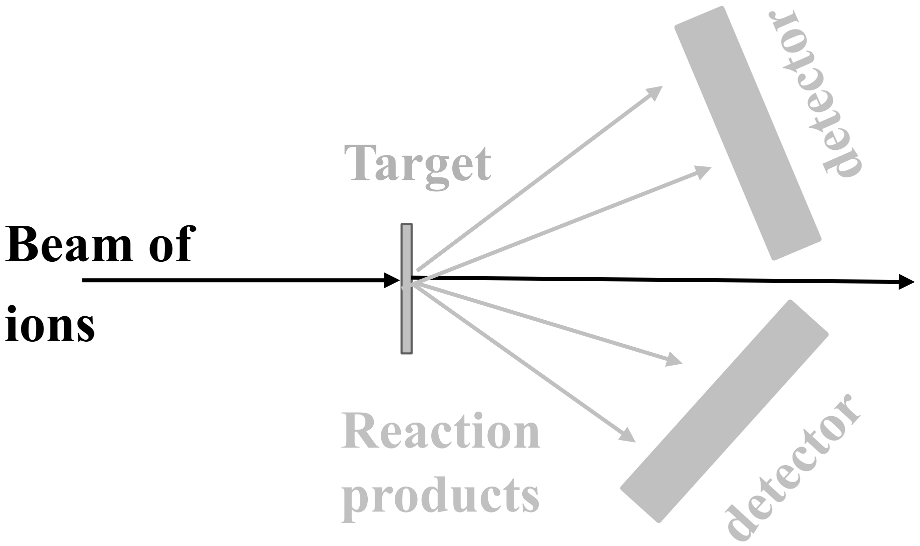
$$N_{det} = N_{reac} \times \varepsilon$$

where ε is the detection efficiency

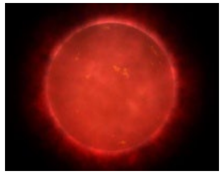


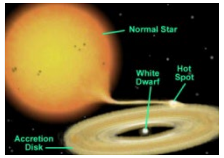

To measure a cross-section, you need **beam**, **target** and **detectors**

# Beams for Nuclear Astrophysics



# Beam requirements for Nuclear Astrophysics (NA)






- **Which beams?**

→ stable beams for direct XS measurements of reactions in quiscent burning sites
→ radioactive beams for reactions in explosive burning environements for direct XS measurements
→ radioactive or stable beams for reactions in explosive burning environements for indirect XS measurements

- **Which beam energies ?**

→ Go to the lower energy possible towards the Gamow peak for direct XS measurements (few tens of keV to ~ MeV)
→ Energies at and above the Coulomb barrier for indirect XS measurements (few tens of MeV to hundreds of MeV)

- **Which beam accelerators ?**

❑ **Electrostatic accelerators**:

**Stable ions**
- Cockcroft–Walton accelerator (eg: @ LUNA-400 kV)
- Van de Graaff (single ended machine)
- Tandem Van de Graaff (eg. @ ALTO-Orsay)

❑ **Electrodynamic (electromagnetic) accelerators**:

- Cyclotrons (eg: @ GANIL, FRIB)
- Linear accelerators, LINAC (eg: ISAC @ TRIUMF, CERN, FRIB)

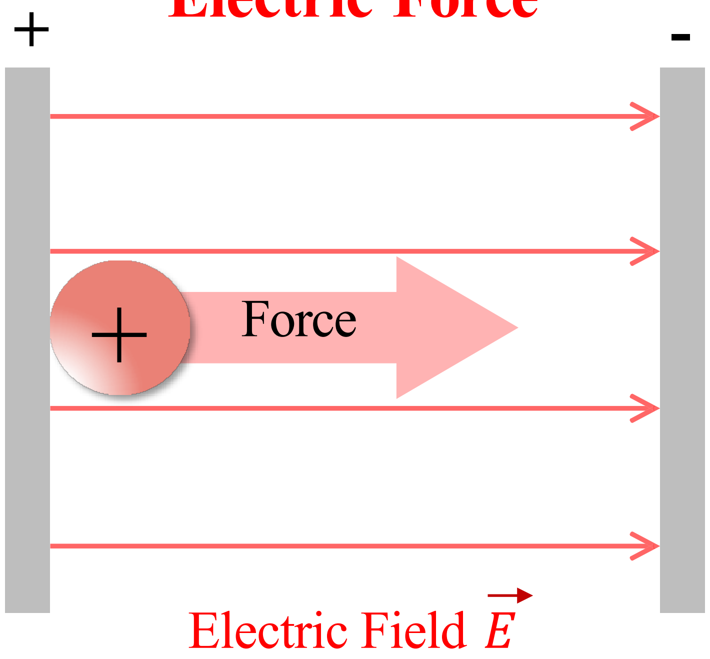
**Stable & radioactive beams**

# How to accelerate an ion?

The basic equation that describes the acceleration/bending/focusing processes is the **Lorentz Force**.

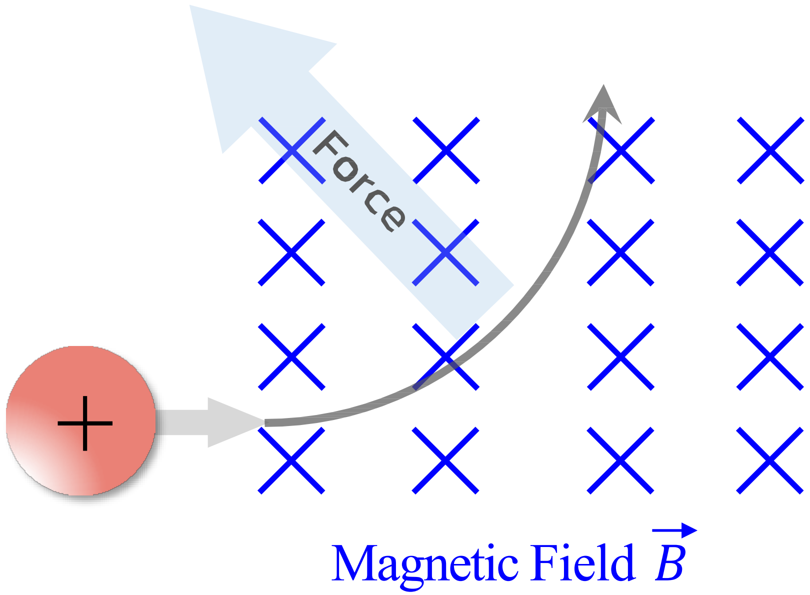
$$\vec{F} = q\,(\vec{E} + \vec{v} \times \vec{B})$$

## Electric Force




Give energy to particles by using "Electric field"
Speed increase → Gain energy → "Accelerate"

## Magnetic Force




Change direction (bend or focus)

"Control direction"

→ You may use static electric field or varying electric field

# Electrostatic accelerators: Basic principles

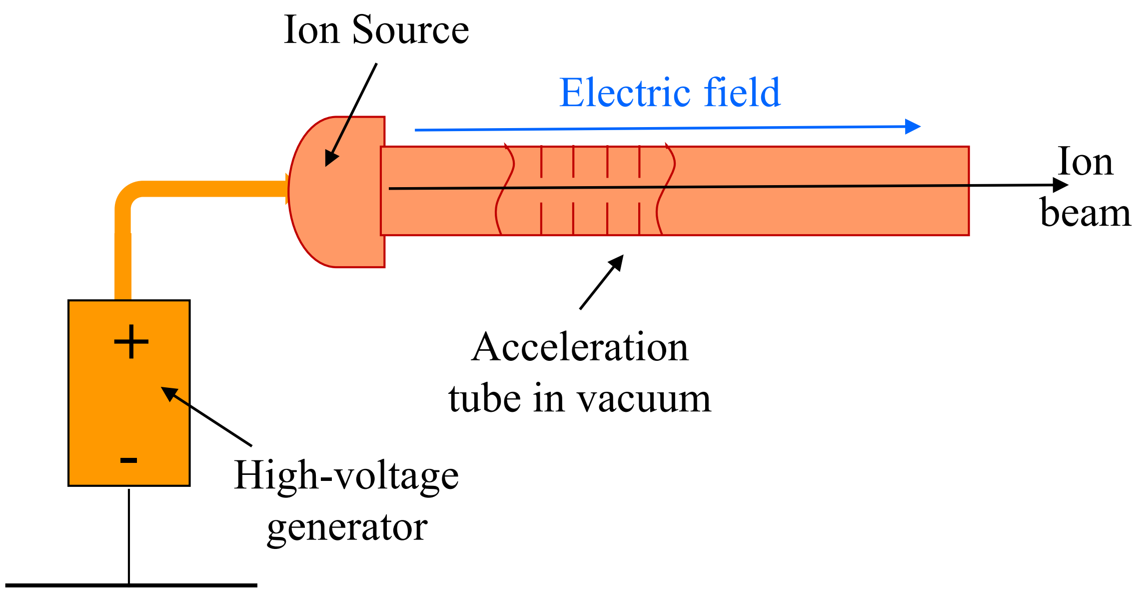
- A high-voltage generator supplies power to the connected accelerating tube where the particles are accelerated. The drift tube incorporates a number of electrodes along its axis to ensure a uniform static electric field distribution for acceleration.

- The charged particle is accelerated through a constant potential difference. If a particle has a charge **qe** and mass **m** and moves through a potential difference of **V** then it will gain a kinetic energy, $\mathbf{E_{kinetic}}$, of: $\mathbf{E=mv^2/2= qeV}$

E.g: A $^{7}Li^{3+}$ (q=3) at V= 7 MV → E= 3×7=21 MeV

- Beam energy range goes from **tens keV** to **tens MeV**

- **Accelerator types:**
  - Cockcroft-Walton: 200 kV- 4 MV
  - Van de Graaff: 1-5 MV
  - Tandem Van de Graaff: 3-25 MV
  - …



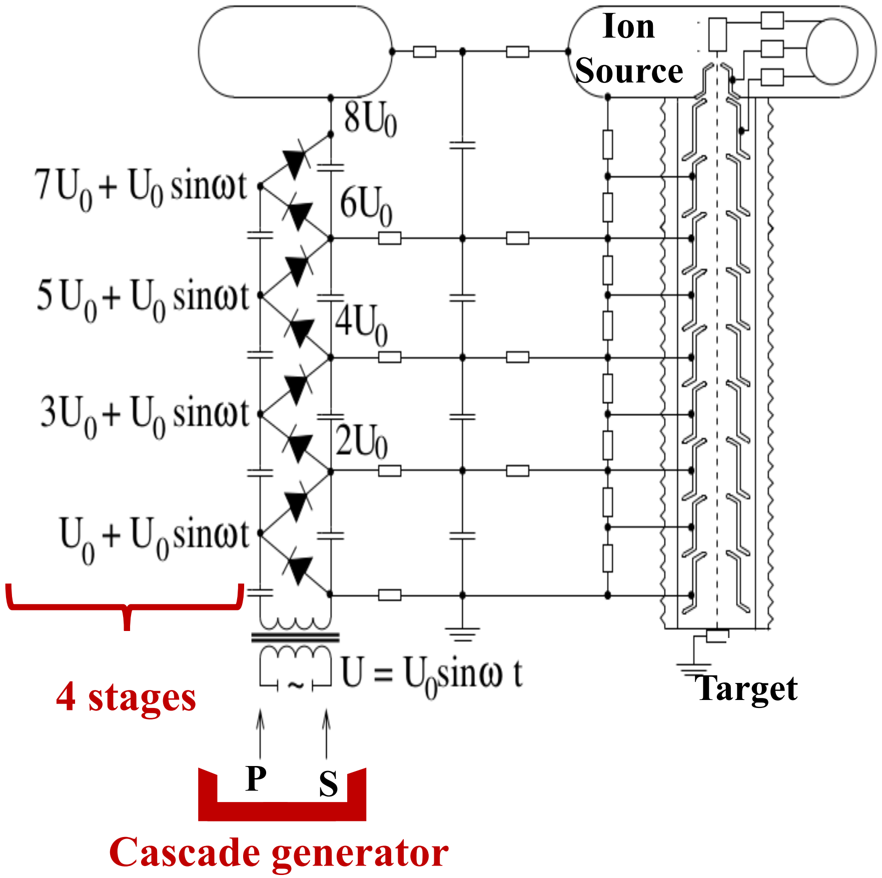
# Electrostatic accelerators: Cockcroft Walton Accelerator

- The first accelerator was built in 1932 by J.D. Cockcroft and E.T. Walton.
- A high voltage of about 700 kV was reached
- First sudy of nuclear reactions: $^{7}Li+p \rightarrow {}^{4}He+{}^{4}He$, $^{7}Li+p \rightarrow {}^{7}Be+n$ @ 400 keV
- The HV generator : cascade generator or voltage multiplier circuit

Sir John D. Cockcroft

"Noble Prize in Physics in 1951"

Ernest T.S. Walton




- Multi-step voltage divider which accelerates ions linearly via constant voltage step
- Maximum voltage reached depends on several factors:
  - number of stages in the multiplier
  - the physical design (isolation, corona effects,…)
- Voltages can reach:
  - **100 – 700 kV** (small generators)
  - **1 MV to 5 MV** (large-scale accelerators)
- Main limiting factors :
  - electrical discharges (corona effect, arcing)
- Stability becomes harder to maintain at very high voltages

➔ Energy range suitable for direct measurements of cross-sections of astrophysical interest

# Cockcroft Walton Accelerators: LUNA-400 KV

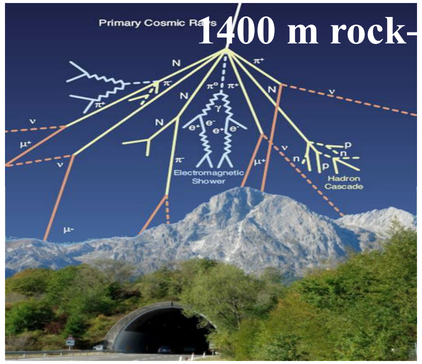
➔ The 400 kV accelerator used by the **LUNA** (Laboratory Underground for Nuclear Astrophysics) collaboration at Gran Sasso is a Cockcroft Walton type but single-stage design.

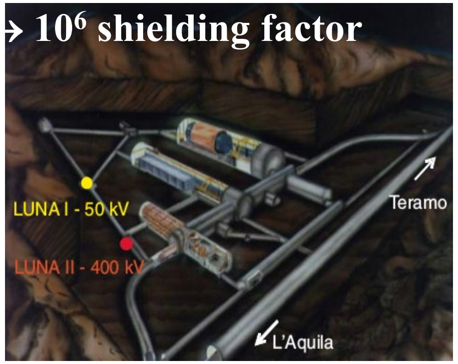
**LUNA-400kV (2002-up to now)**

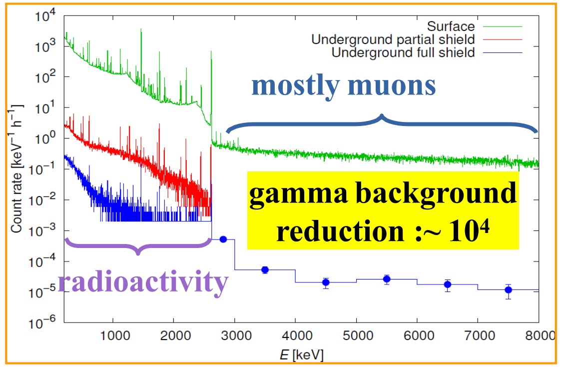
Voltage range : **50 - 400 kV**

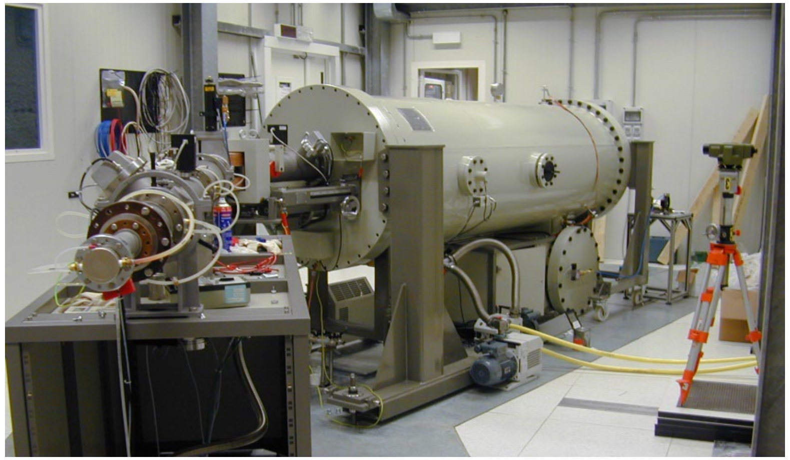
**1 mA hydrogen & 500 μA $He^+$ → High beam intensities**

**Stability: 5 eV/h**



Very well known resonances of $^{25,26}Mg(p,\gamma)$ & $^{23}Na(p,\gamma)$ were measured from 300 to 400 keV → energy calibration

→ Precise determination of the beam energy $E_B$

→ **Beam energy spread $\Delta E_B \leq$ 100 eV**

Extremely important for measurements at very low energies (ie. < 100 keV) due to the exponential drop of σ(E) when E↘

Ex: $^{14}N(p,\gamma)^{15}O$

An error of 1.5 keV in $E_B$ at $E_p$=100 keV → ~20% error in σ(E)

With an error of 300 eV in $E_B$ at $E_p$=100 keV → 5% error in σ(E)

➢ Many key reactions of astrophysical interest were studied in the last 23 years:

→ $^{14}N(p,\gamma)^{15}O$ for CNO solar neutrino/globular cluster age

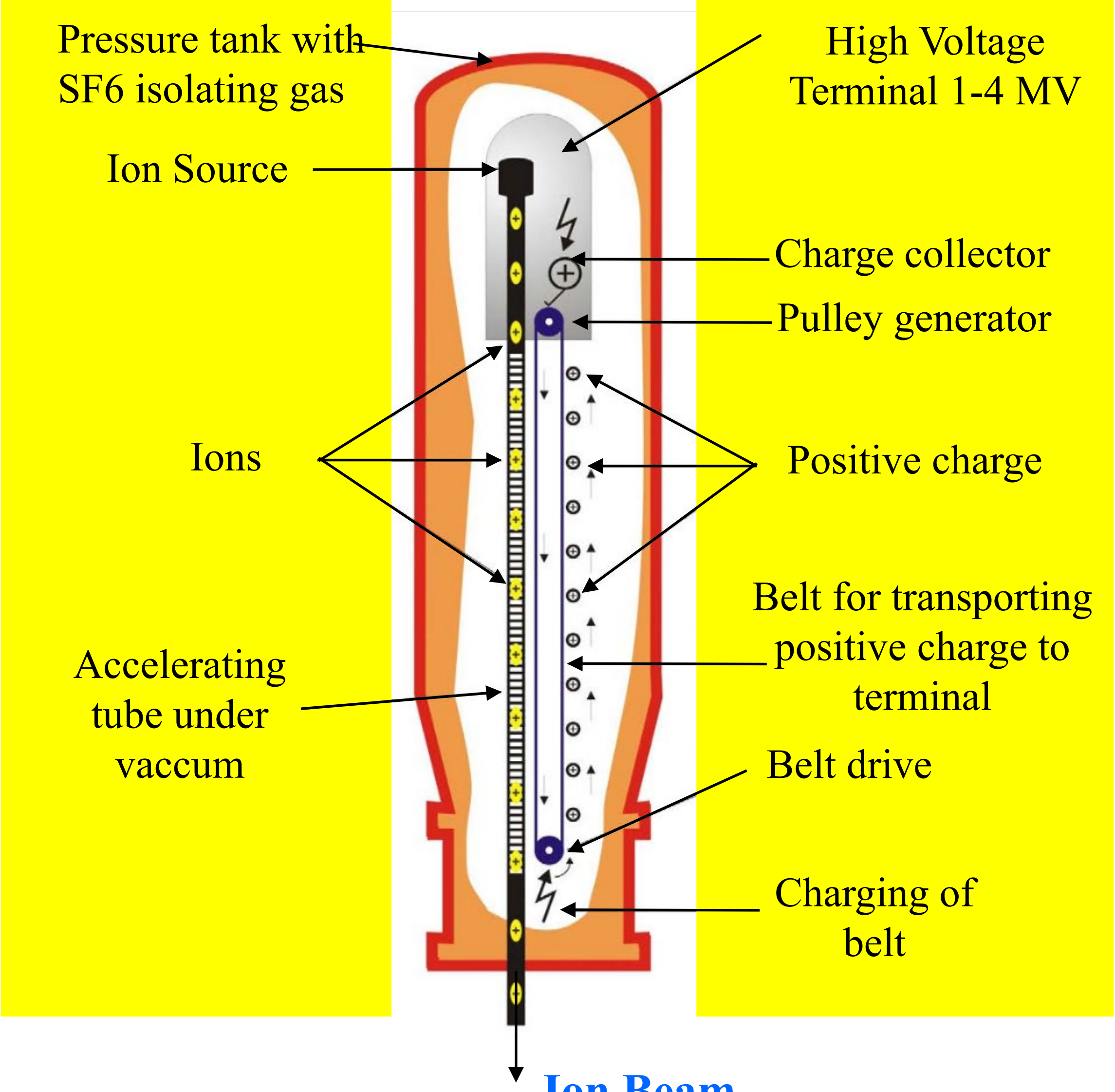
→ $^{13}C(\alpha,n)^{16}O$ (neutrons for s-process)

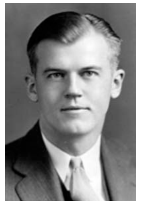
→ $D(p,\gamma)^3He$, $^3He(^4He,\gamma)^7Be$ (BBN)

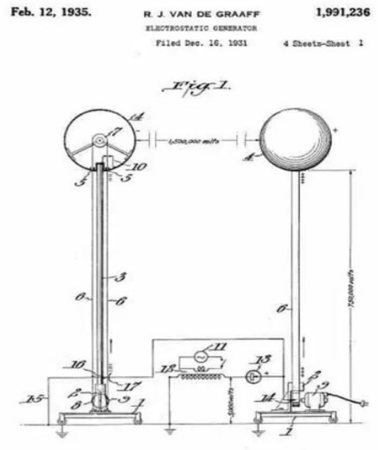
…

# Electrostatic accelerators: Van de Graaff accelerator

- Robert Van de Graaff developed the 1st high-voltage electrostatic accelerator with voltage of 1.5 MV in 1929-1931





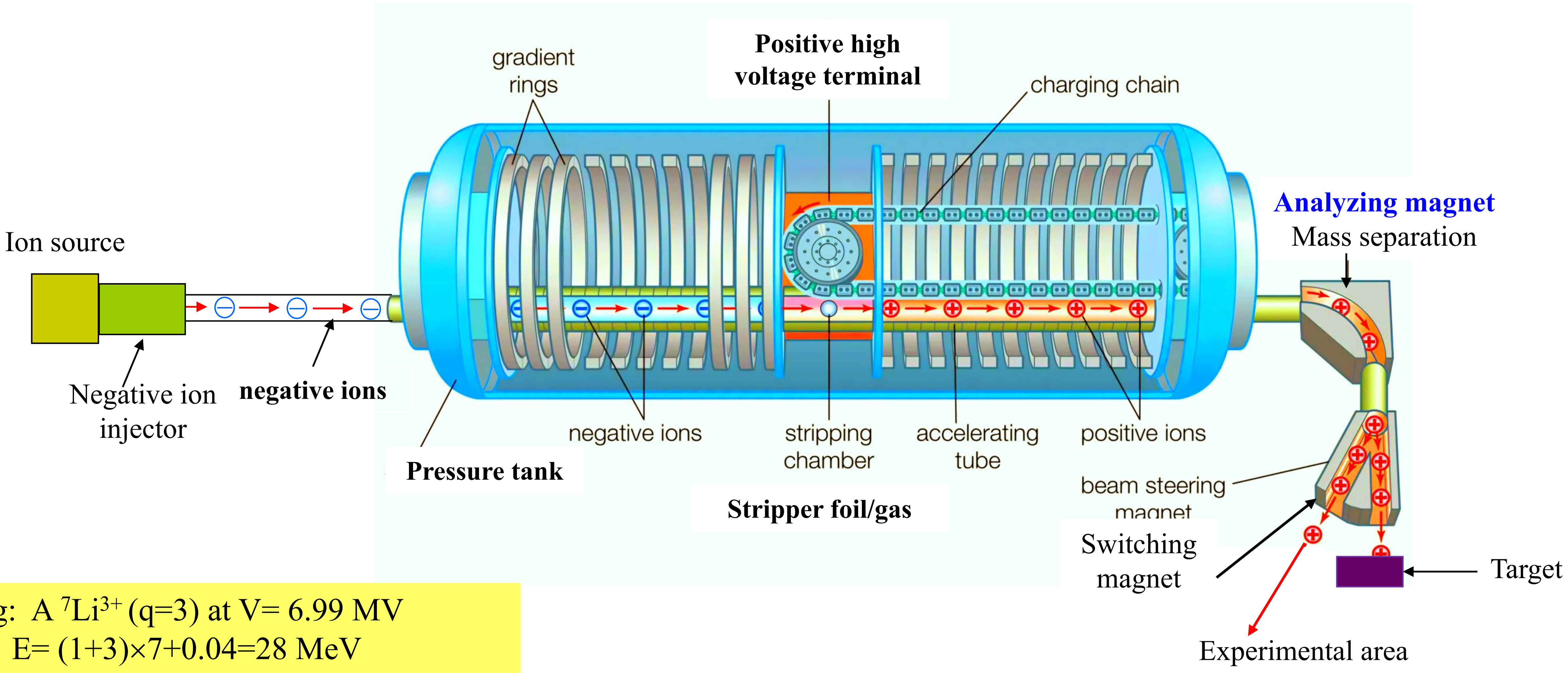

- Charge is sprayed on an insulating belt (field emission)
- Circulating belt:
  → transports charge to the high voltage terminal
  → creates high electric potential

- Pressure tank for protection against flashover
- Good vacuum in the accelerator tube to prevent flashovers due to residual gas (also minimizes particle losses)

- Single-step acceleration of ion particles → **$E = qeV$**
- Old VdGs → V can go up to 10 MV
- Energies more suitable for direct measurements of XS

# Electrostatic accelerators: Tandem VdG accelerator

- Two-step accelerations of ion particles with one high voltage terminal → $E=(1+q)eV+V_{extraction}$
- Most of the tandems used for NA have a voltage going from 10 to 15 MV — $V_{extraction}$: very small ~30-40 kV
- Delivered energies more suitable for transfer, inelastic and charge exchange reaction measurements (see Richard's talk)




E.g: A $^{7}Li^{3+}$ (q=3) at V= 6.99 MV
→ E= (1+3)×7+0.04=28 MeV

# Tandem VdG accelerator: Tandem@ALTO


- High Voltage: goes up to 14.8 MV
- Accelerate of a wide range of ion species from light species, H, to heavy ones such as gold
- Charging Mechanism: It employs a laddertron system for charge transport
- Beam Pulsing Capabilities: It can produce pulsed beams with standard periods of 100, 200, and 400 ns, and pulse widths typically around 2 ns.
- Voltage stability: ~0.01%–0.1%
- Energy spread (after analyzing magnet): ~0.01% typical

The light beams delivered such as $^{1,2}H$, $^{3,4}He$, $^{6,7}Li$ are often used for indirect studies of key nuclear astrophysics reactions:

- (p,p') inelastic reactions
- **($^3$He,d) proton transfer** reaction to study **(p,γ)** reactions
- **($^6$Li,d), ($^7$Li,t) α-transfer reactions** to study **(α,n)** & **(α,γ)** reactions
- ($^3$He,t) charge exchange reactions

$^{39}$K(p,γ)$^{40}$Ca (TUNL) **Fox+PRL24**
$^{12}$C(α,γ)$^{16}$O (ALTO) **Oulebsir+PRC12**
$^{13}$C(α,n)$^{16}$O (ALTO) **Pellegriti+PRC08**

# Electrodynamic accelerators: Basic principles

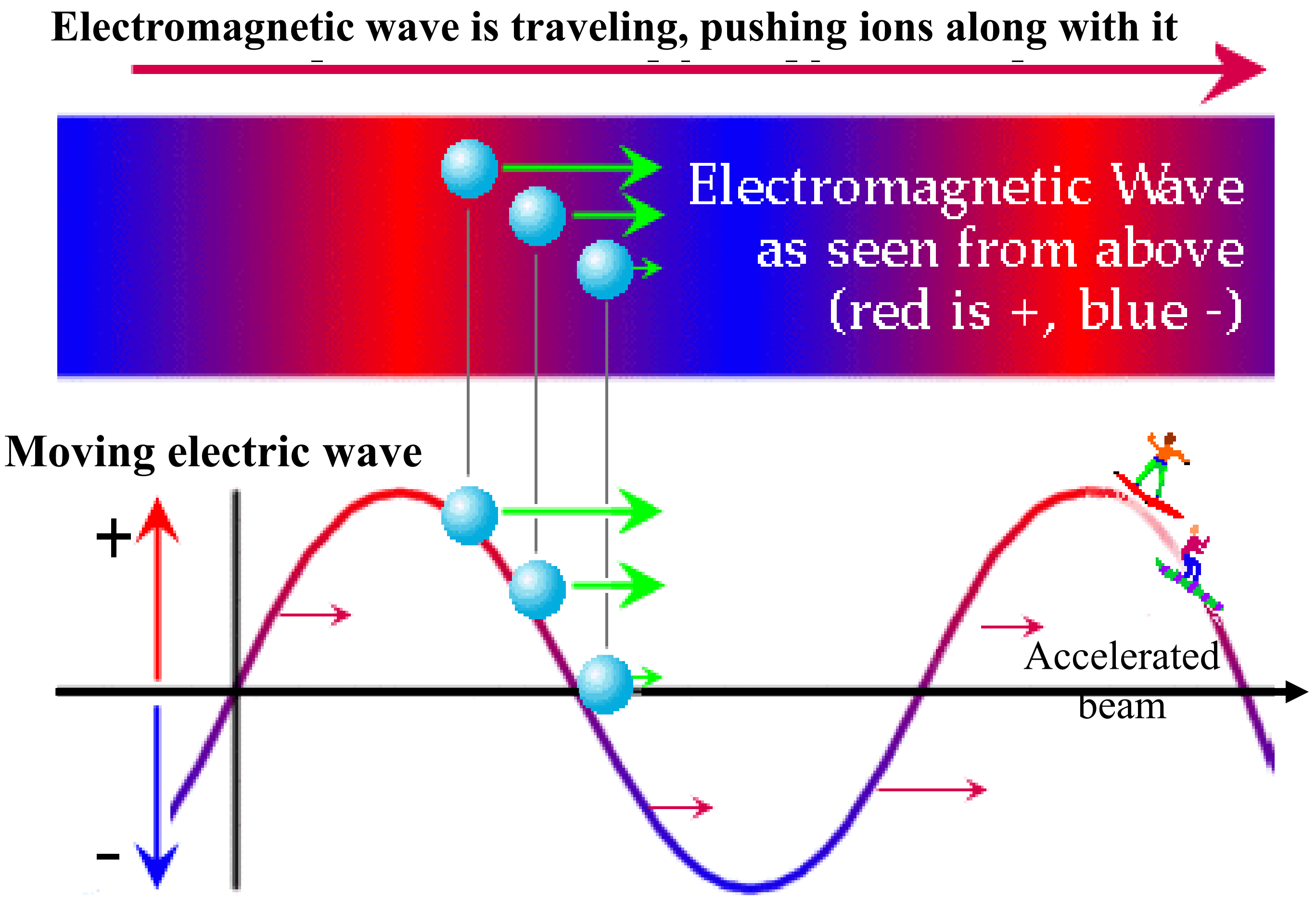
→ use changing electromagnetic fields (either magnetic induction or oscillating radio frequency fields) to accelerate particles.

→ The particles can pass through the same accelerating field multiple times ⇒ Beam energy is not limited by the strength of the acceleration field, hence it can reach TeV (e.g: CERN)

→ They can be linear, with particles accelerating in a straight line, or circular, using magnetic fields to bend particles

→ Basis of most of the modern large-scale accelerators (GANIL, RIKEN, FRIB, CERN,…)

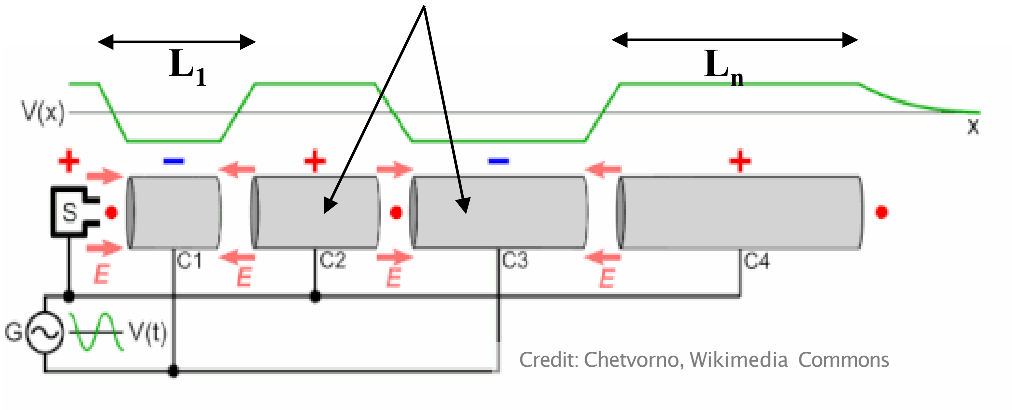
→ Often used to accelerate primary stable beams to produce radioactive beams or to post-accelerate radioactive beams



# Electrodynamic accelerators: Linear accelerator (LINAC)

- Increases the velocity of ions by subjecting them to a series of oscillating electric potentials along a linear beamline (idea of Ising (1924))
- **Wideröe (1927**) implemented the idea by applying a sine-wave voltage to a series of drift tubes → Wideröe Linac: First RF Linac for protons & ions

- Drift Tube LINAC (DTL)
  - Beam passes through a series of tubes called drift tubes. connected to an RF power source.
  - The RF field alternates rapidly
  - Particles are accelerated in the gaps between tubes and must reach each gap when the RF field is in the right phase to accelerate them
  - As particles gain speed, they spend less time in each tube. To keep timing with the RF field, drift tubes are made longer to ensure they reach each gap at the right moment for acceleration



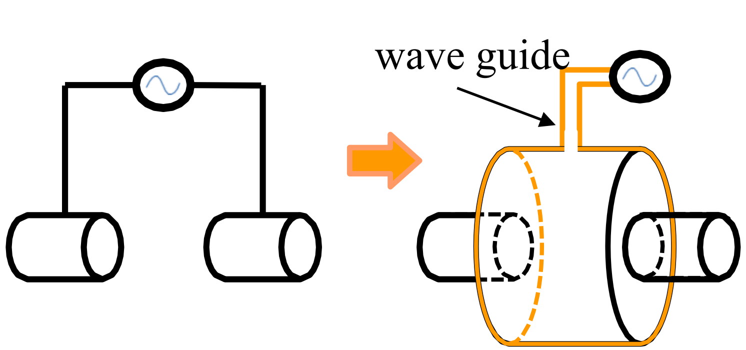

Advantage: you can continuously accelerate the beam without voltage breakdown.

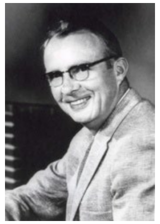
BUT: As particles gain more energy, the drift tubes get longer and harder to manage. And to achieve higher acceleration, higher RF frequencies are needed, which can increase beam losses ⇒ DTLs work best for acceleration up to ~10s MeV

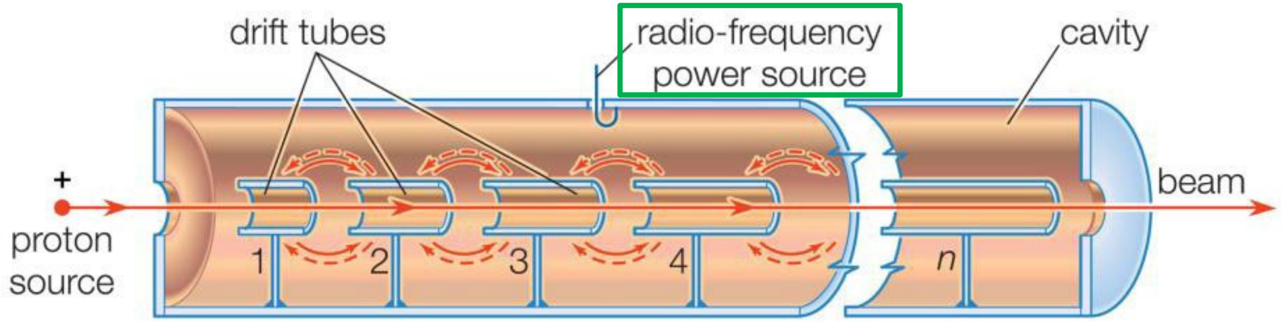
# Electrodynamic accelerators: LINACS

- The solution consists of enclosing the system in a cavity which resonant frequency matches the RF generator frequency (**Luis Alvarez 1947**).

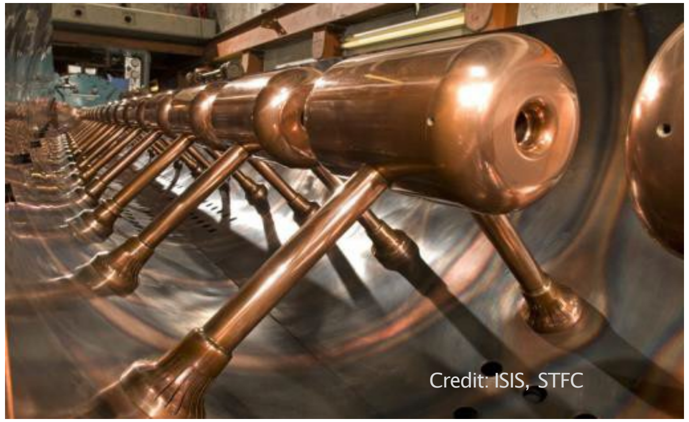
⇒ High frequency RF accelerating fields are confined in **Cavities**






© 2012 Encyclopædia Britannica, Inc.

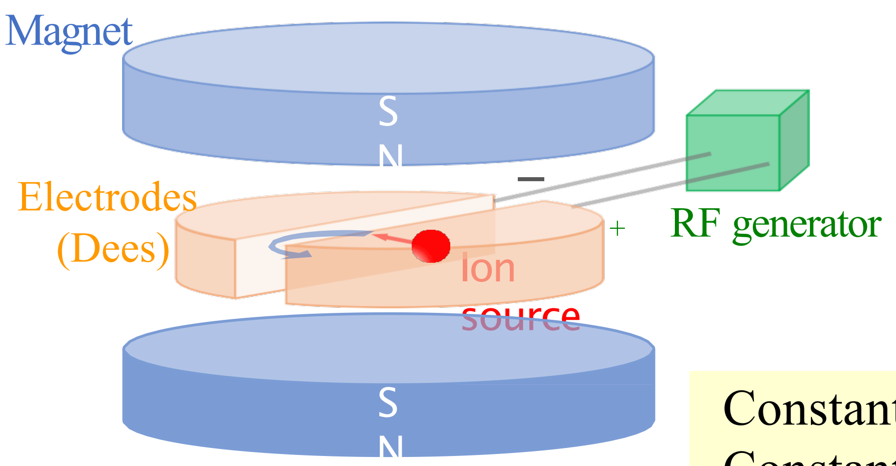



→ Beam energies can go from tens of MeV to few GeV

- Can be used to accelerate stable beams at very high energy with high beam current
  - **NFS/GANIL**: p & d up to 33 & 40 MeV (I=5 mA) to produce neutrons for science via (p,n) & (d,n) reactions
  - **FRIB Superconducting LINAC:** all stable ions with energies up to **200 A MeV** used to produce radioactive beams

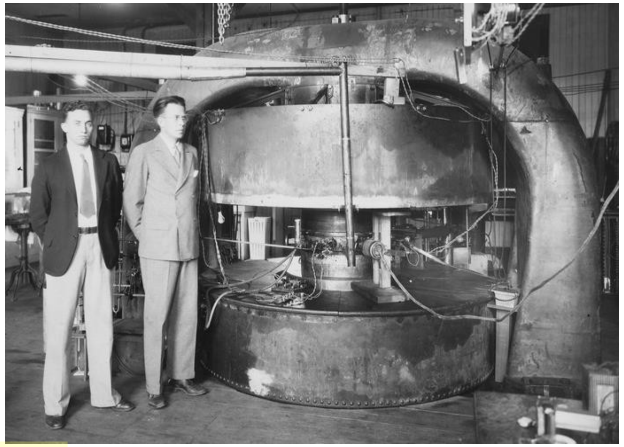
- Can be used to post-accelerate radioactive beams. E.g: **ISAC I & ISAC II** @ TRIUMF

# Electrodynamic accelerators: Cyclotrons



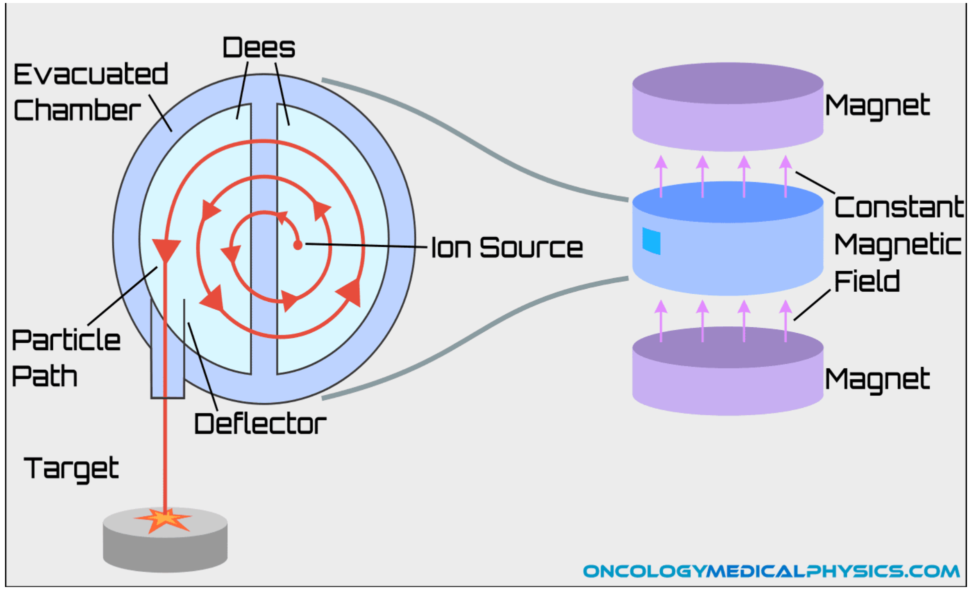

Ernest O. Lawrence

Nobel Prize in Physics in 1939 for the invention and development of the cyclotron and for results obtained with it



Credit: U.S. National Archives and Records Administration

Constant strong magnetic field
Constant RF frequency to generate oscillating electric field




- Suitable for protons and ions
- Magnetic field *B* is fixed, then need larger magnet for higher energy
- Beam energy ~ 100s MeV

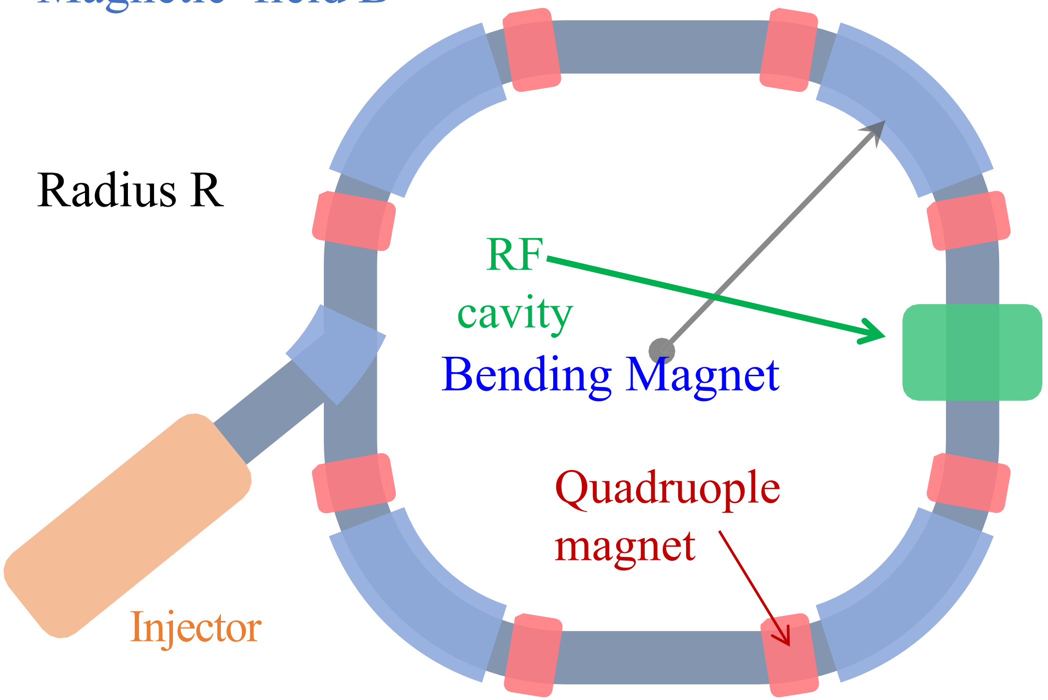
- E.g: - **Cyclotron at iThemba LABS** : stable ions up to 200 MeV
- K500 and K510 Cyclotrons of Texas AM: accelerate stable beams & post accelerate radioactive beams
- CIME @ GANIL: post-accelerate radioactive beams
- …

# Electrodynamic accelerators: Synchrotrons

Descendant of the cyclotron

- Increase beam energy
- Particles travel in closed path like racetrack

→ Use multiple local magnets → Synchronize between
- Beam energy
- Magnetic field
- RF frequency (non-relativistic)




$$BR = \frac{p}{e}$$

Momentum p

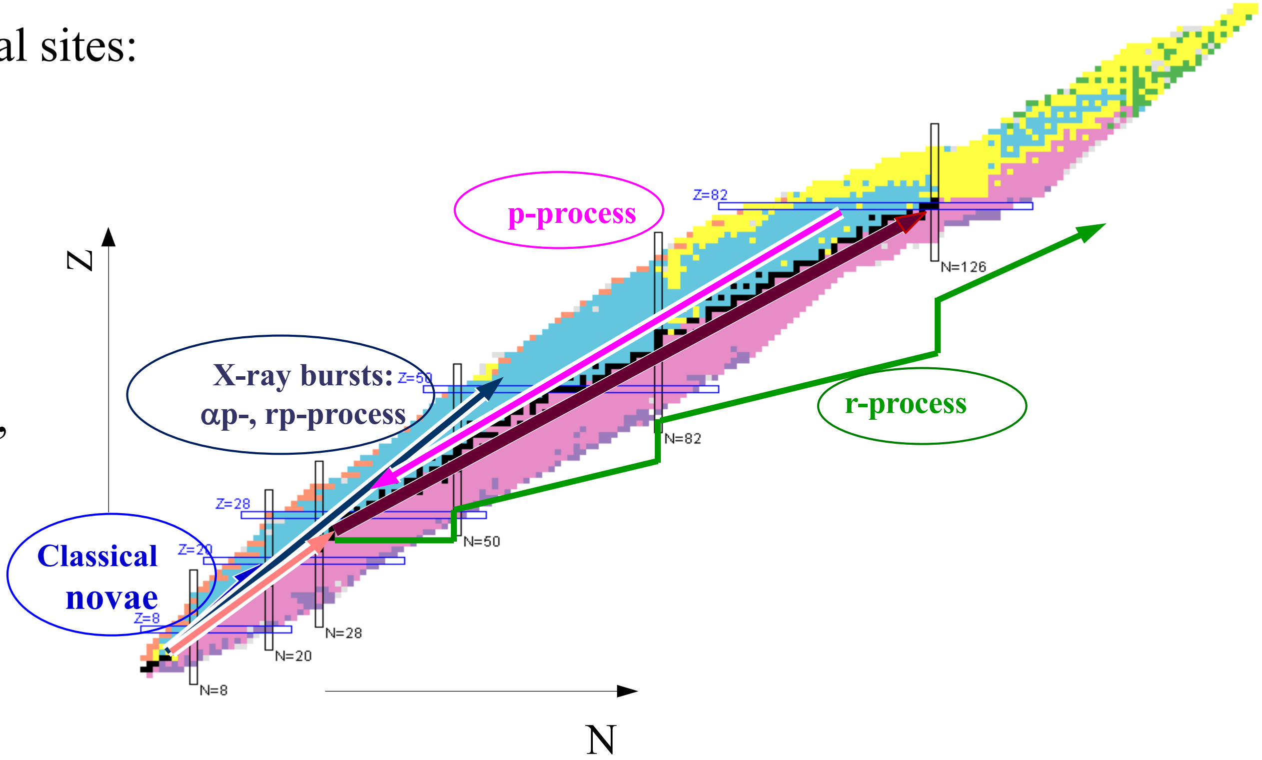
- Can accelerate ions, protons and electrons
- Basis of modern large-scale particle accelerators
- Beam energy can go to 10s TeV (**CERN**)

# What about radioactive beams?

- Needed to study reactions occuring in explosive astrophysical sites:

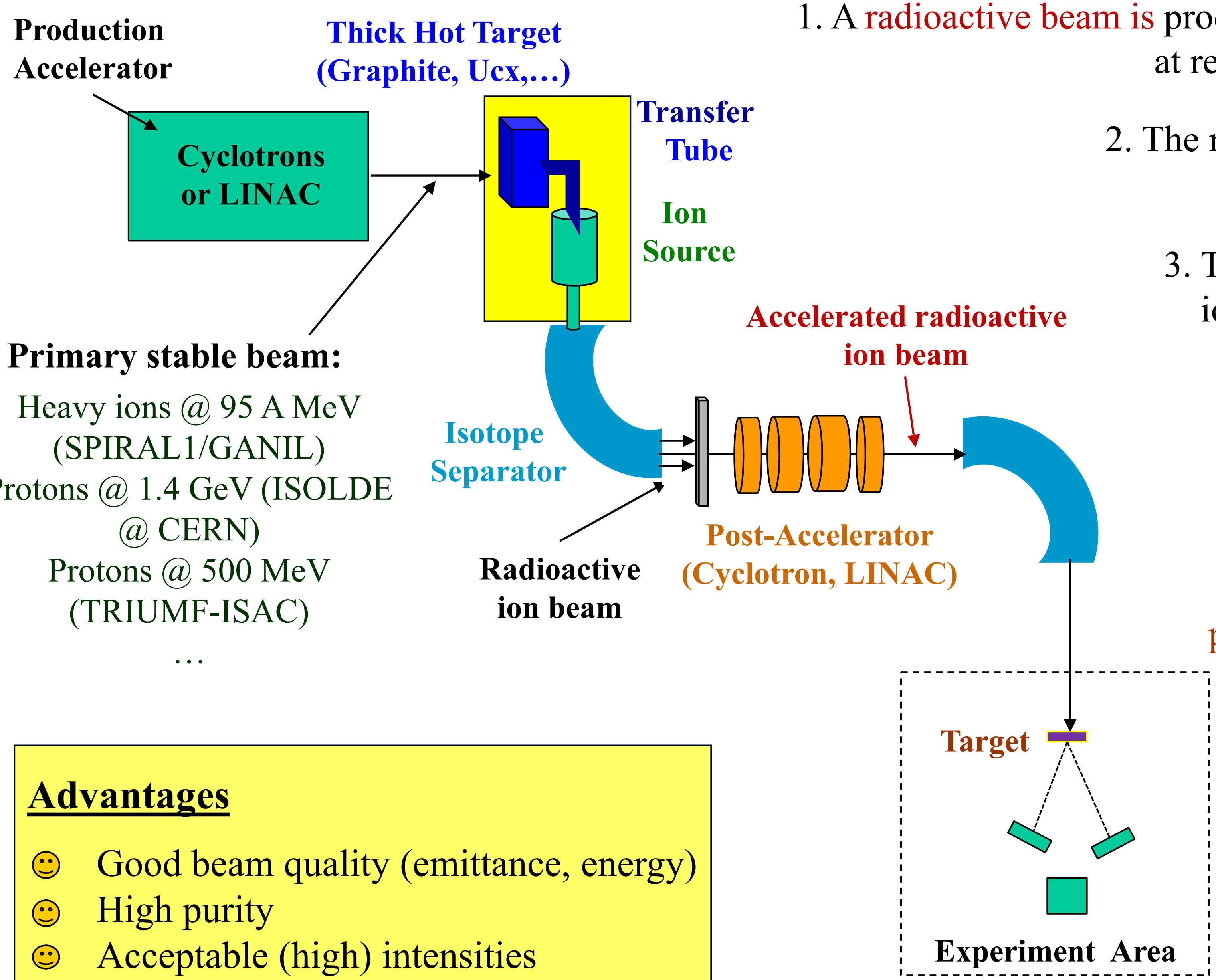
→ Under **extreme stellar conditions of T & ρ** (**Classical Novae**, **X-ray bursts**, **CCSNe**, **Kilonova**), the nuclear flow goes through a series of **light particle captures** forming nuclides far from stability: loosely bound, short β-decay lives ⇒ **radioactive nuclei**

→ Energies $\mathbf{E_0}$ **~ hundreds of keV to few MeV**




- Produced by several techniques: ISOL Method, In Flight Method (Fragmentation), …
- Low beam intensities → 5-8 orders of magnitude lower than intensity of stable beams
- Possible beam contamination
- Beam induced background

# Radioactive beam production: Isotope Separation On Line (ISOL) Method




1. A radioactive beam is produced via spallation, fission or fragmentation nearly at rest in a thick target bombarded with a primary beam.

2. The reaction products are transported to an ion source by diffusion through an transfer tube

3. They are ionized and continuously extracted from the ion-source by few tens kV acceleration voltages then mass separated from other isotopes

4. The selected isotopes are either sent to an experiment area for β-decay and/or mass measurements
or
post-accelerated to the desired energy and sent to the experimental area to induce the reaction of interest

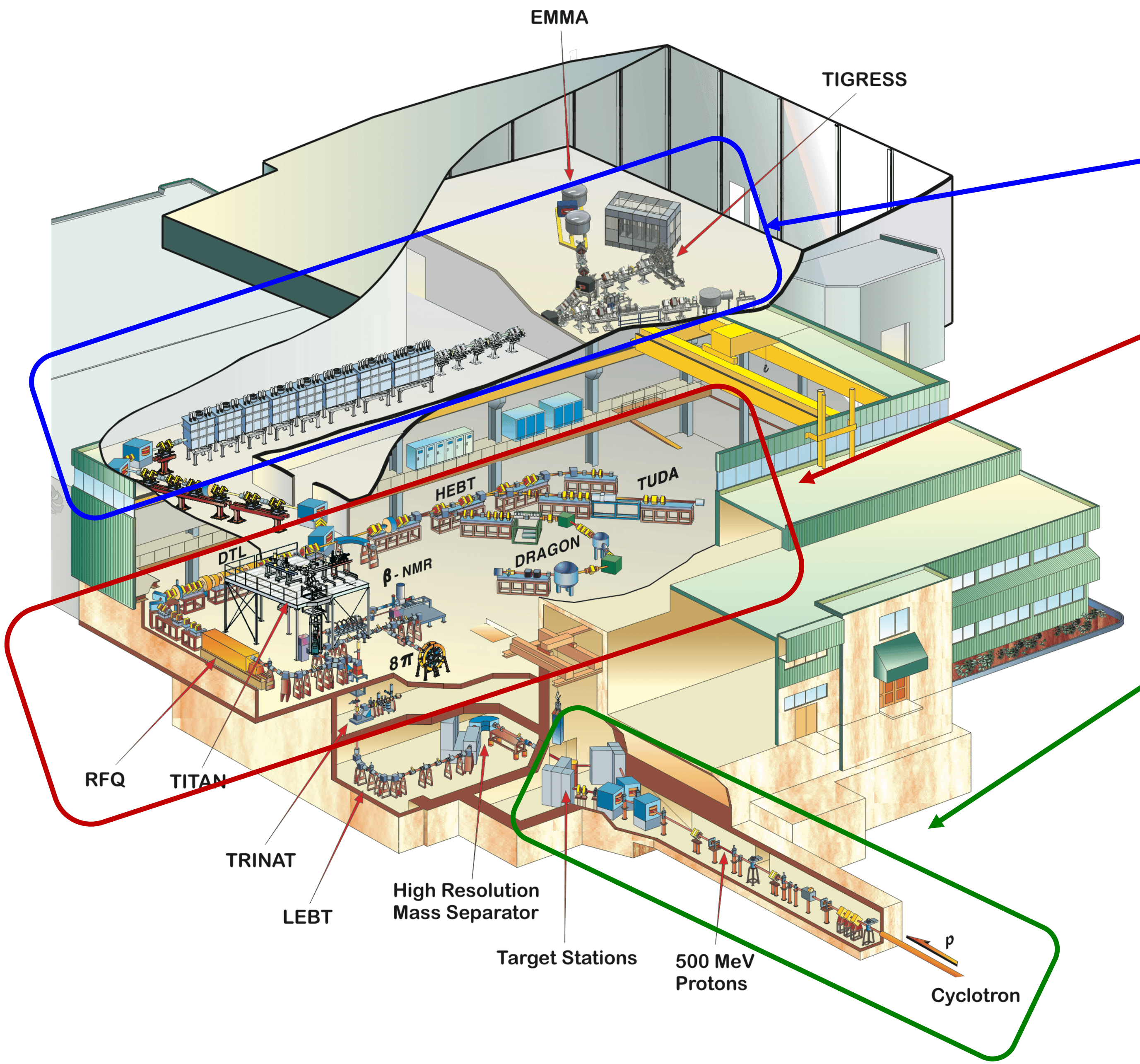
## Advantages

- ☺ Good beam quality (emittance, energy)
- ☺ High purity
- ☺ Acceptable (high) intensities

## Drawbacks

- ☹ Limited number of species
  - ↳ depend on chemical properties
  - ↳ limited to nuclei with $t_{1/2} \geq 1$ s

# Radioactive Ions Beam ISOL facility: Isotope Separation & Acceleration ISAC I & II @ TRIUMF




ISAC-II: Superconducting-linac
high energy → 5-15 MeV/u

Isotope Separator and Accelerator facility - ISAC
Isotope Separator Online (ISOL) facility
ISAC-I: Normal conducting-linac, low & medium energy → 0.15-1.5 MeV/u

Primary beam driver:
Cyclotron, 500 MeV, $H^-$
Produces rare isotopes, neutrons

Direct measurements of key astrophyics reactions:

$^{7}Be(\alpha,\gamma)^{11}C$ **Psaltis+PRL2022**

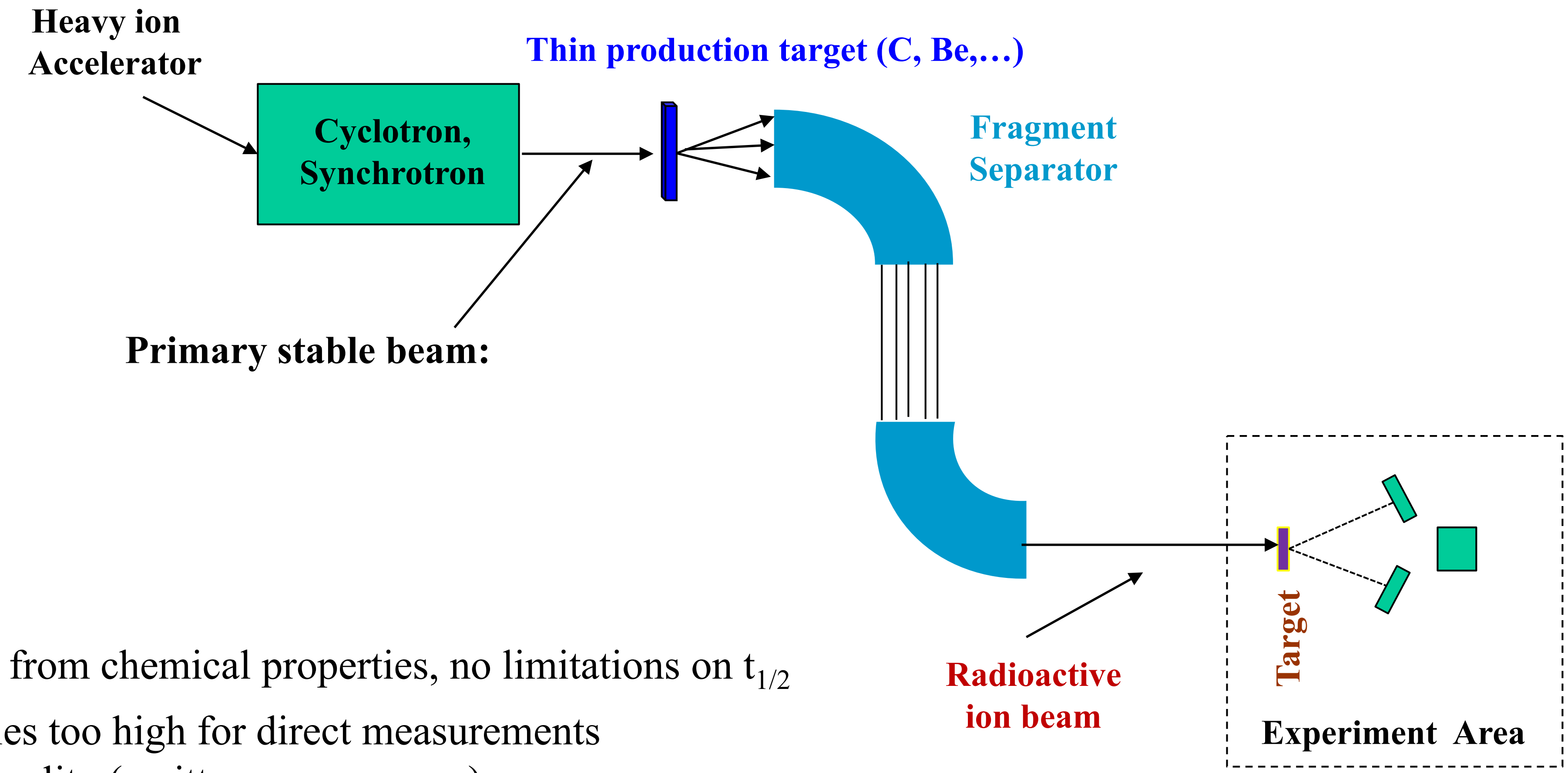
$^{26}Al^{m}(p,\gamma)^{27}Si$ **Lotay+PRL2022**

$^{23}Na(\alpha,p)^{26}Mg$ **Tomlinson+PRL2015**

$^{18}F(p,\alpha)^{15}O$ **Beer+ PRC2011, …**

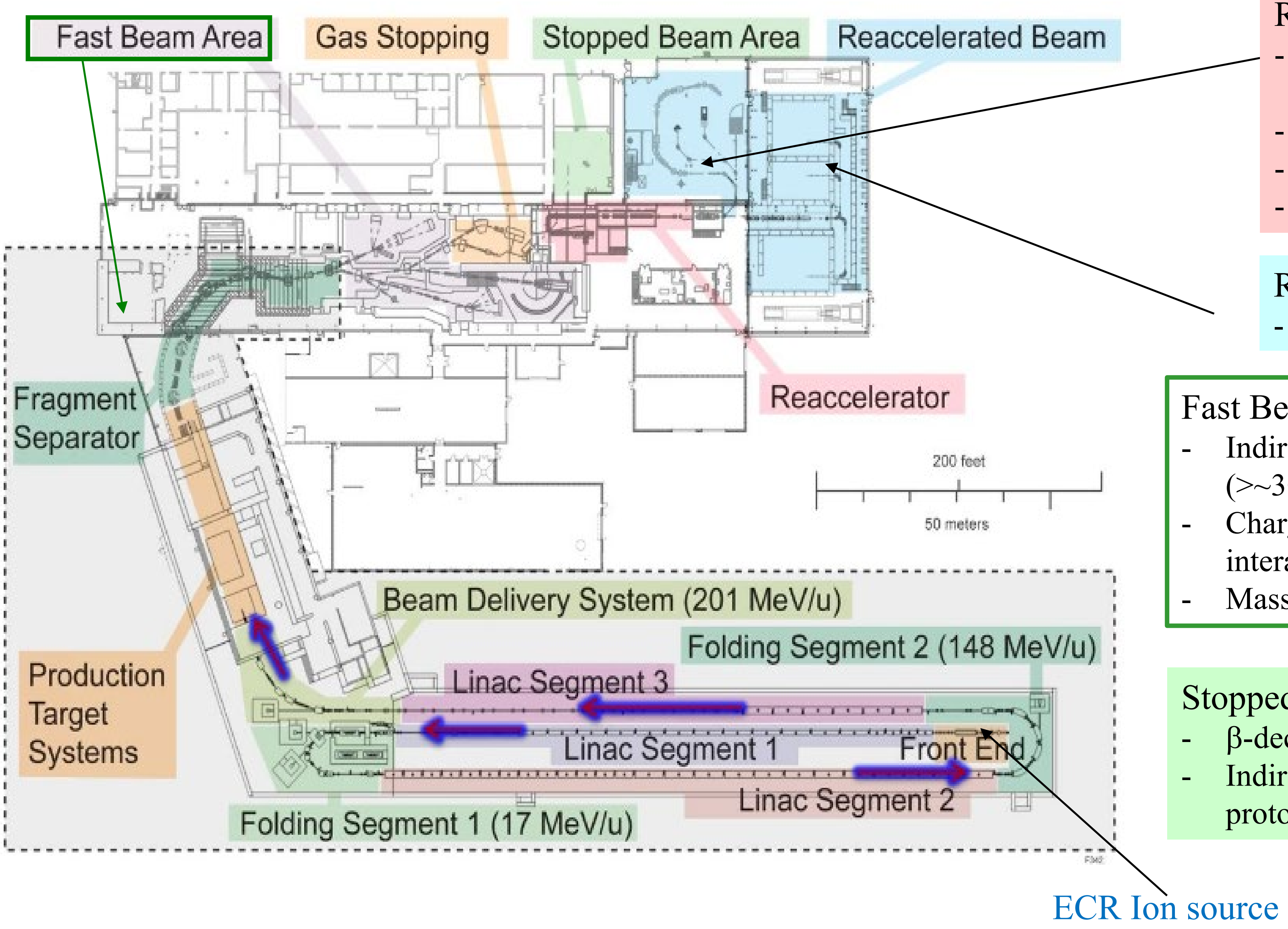
# Radioactive beam production: In-flight Method

- A very high energy beam is fragmented in a low Z thin target. From the many reaction products produced @ high energy , the desired one is selected in mass, charge and momentum via a fragment separator, slowed down using a degrader and transported to the experimental area. **GANIL, GSI, RIKEN, FRIB**




- ☺ Independent from chemical properties, no limitations on $t_{1/2}$
- ☹ Beam energies too high for direct measurements
- ☹ Poor beam quality (emittance, energy,…)
- ☹ Beam contamination

# RIB fragmentation facilities: FRIB @MSU




**ReA3 Reaccelerated Beams:**

- Direct measurements of key astrophysical reactions (<~ 3MeV/u)
- Transfer reaction @ low energies
- Standalone: stable beams, batch mode
- Ion source for long lived RIBs

**ReA6 Beams:**

- Transfer reactions @ ~ 3-6 AMeV

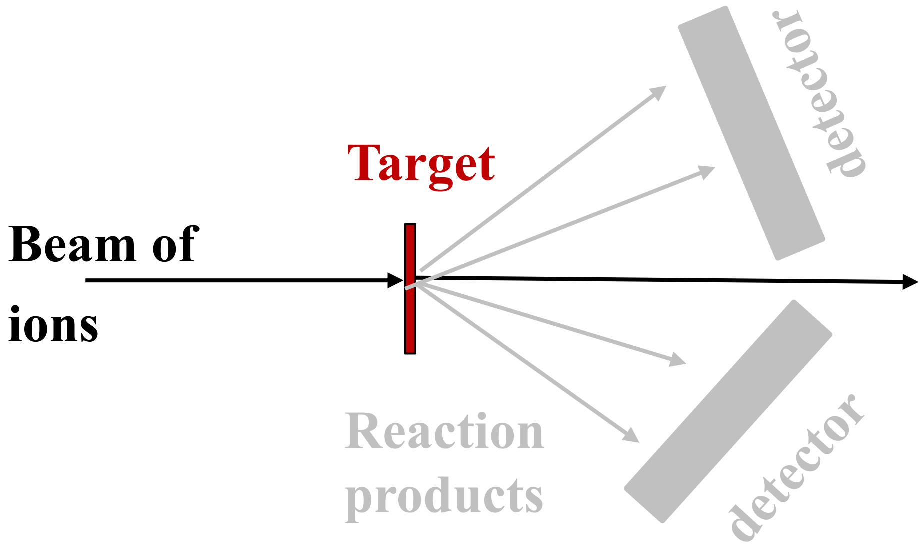
**Fast Beams:**

- Indirect astrophysical reaction measurements (>~30 A MeV)
- Charge exchange reactions to probe weak interactions
- Mass measurements using ToF techniques

**Stopped Beams:**

- β-decay, βn-decay, masses for astrophysics
- Indirect reactions βγ for n-capture, βp for proton capture

# Targets for Nuclear Astrophysics



# Target requirements: when using stable beams

- **Purity** – impurities can cause background reactions.
- **Thickness** – must balance between high enough reaction yield and low energy loss.
- **Isotopic enrichment** – many reactions involve rare isotopes (e.g., $^{15}N$, $^{25}Mg$, $^{22}Ne$), requiring use of enriched material.

→ Direct & indirect measurements

- **Thermal conductivity** – targets must dissipate heat effectively under intense beam.

→ Direct measurements

Making **targets** is a delicat task. They must be pure, and able to withstand intense beam irradiation without degrading (direct measurements).

→ When possible, targets should be made without backing to avoid contamination (self supporting targets).

→ Thin layer of active material on a stable backing (e.g., carbon, tantalum).

→ Targets should be cooled to reduce sputtering and target degradation under high beam intensity

# Thin solid targets for reactions with stable beams: Few manufacturing techniques

## Physical Vapor Deposition Techniques:

• **Evaporation:** Material is heated (resistively or via electron beam) in a vacuum until it evaporates. The vapor condenses on a cooled substrate forming a thin film. Common for low-melting-point metals and compounds.


a) Vapor source

b) Movable shutter: used to collect initial vapour with potential impurities and to stop the deposition at any moment

c) The substrate holder on which the vapour condenses

d) the sensor head of the quartz thickness monitor

e) Water cooled electrodes

**Sputtering:** Argon or another inert gas is ionized and accelerated toward a target material. Atoms ejected from the target deposit on the substrate. Good for refractory materials and allows for precise control over thickness.

## Chemical Techniques:

**Electrodeposition:** Uses an electric current to deposit the desired ions from a solution onto a conductive substrate. Ideal for controlling over thickness. Useful for creating layered or enriched targets (e.g., with isotopically enriched materials. e.g $^{17}$O) or for the preparation of radioactive targets (e.g: $^{7}$Be)

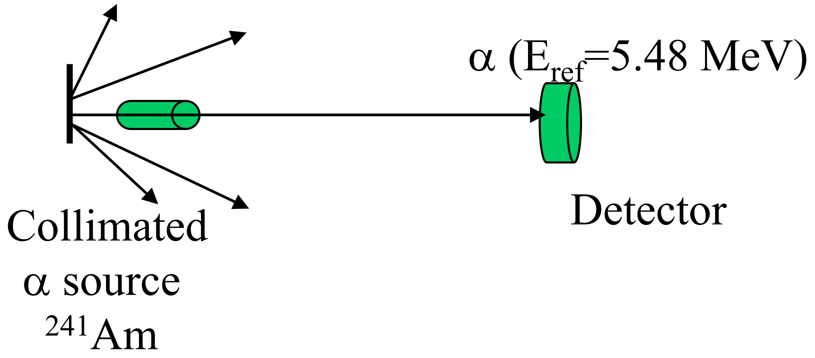
## Implantation Technique:

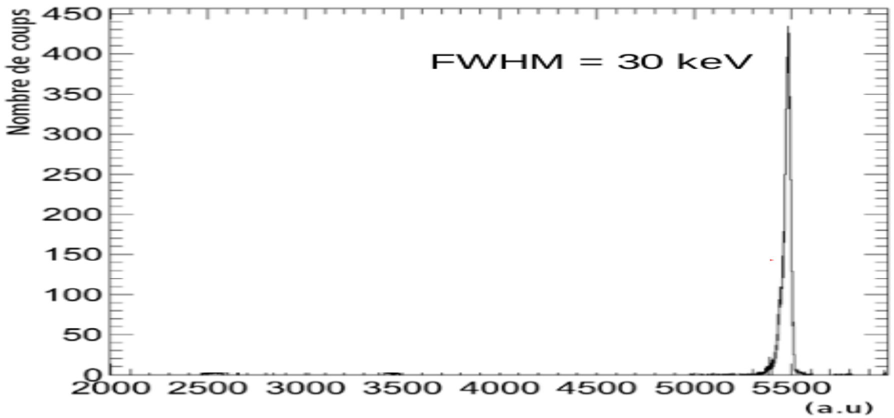
Implant ions of the desired element into a substrate (e.g.,$^{14,15}$N into tantalum) by using an electromagnetic isotope separator. Used when the target material is reactive, gaseous or in trace quantities. Can produce targets with well-controlled stoichiometry.

# Solid Targets Characterization

Most important characteristics of a target are: thickness, homogeneïty and impurities content

- α particle energy loss for **thickness** & homogeneity of relatively thin foils:

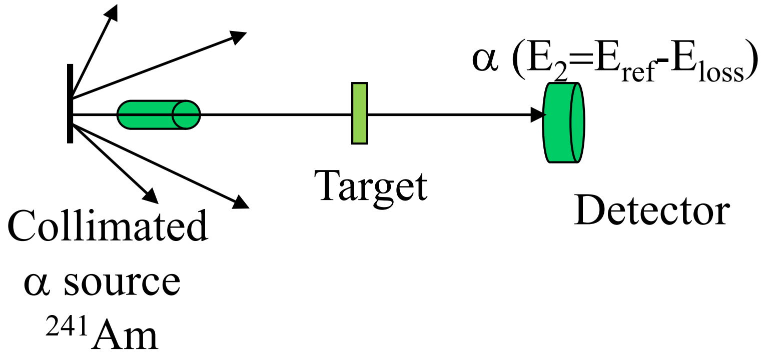


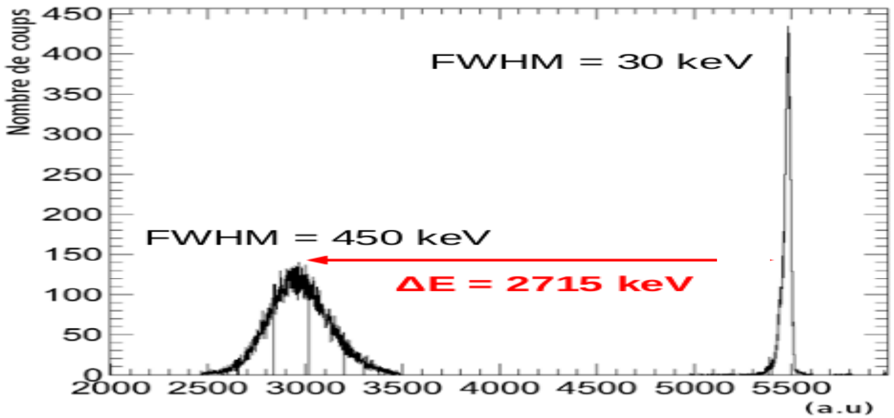



# Solid Targets Characterization

Most important characteristics of a target are: thickness, homogeneïty and impurities content

- α particle energy loss for **thickness** & homogeneity of relatively thin foils:



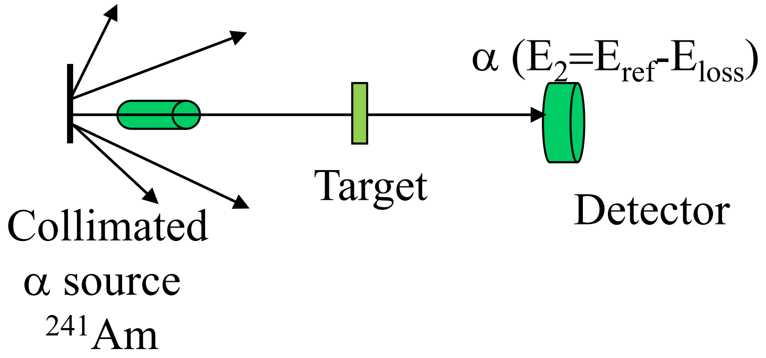



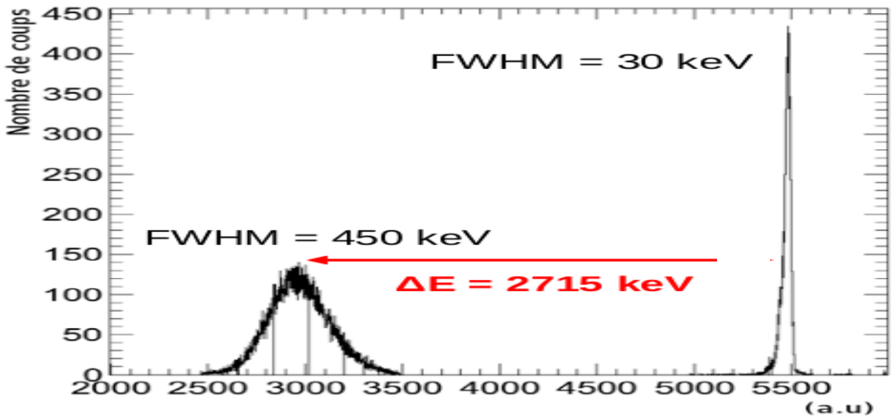

- ΔE measurement + α energy loss table (**Ziegler+77**) in the target ⇒ Target thickness
- Measurement @ various positions on target⇒ homogeneïty

# Solid Targets Characterization

Most important characteristics of a target are: thickness, homogeneïty and impurities content

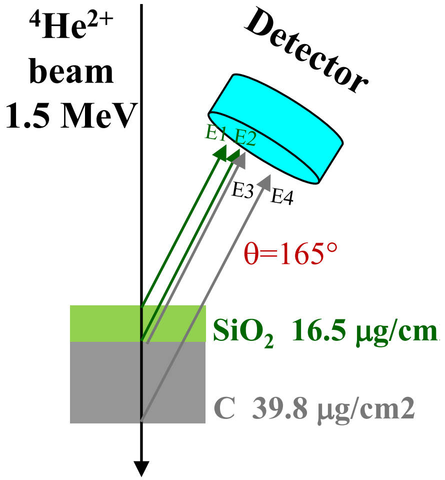
- α particle energy loss for **thickness** & homogeneity of relatively thin foils:

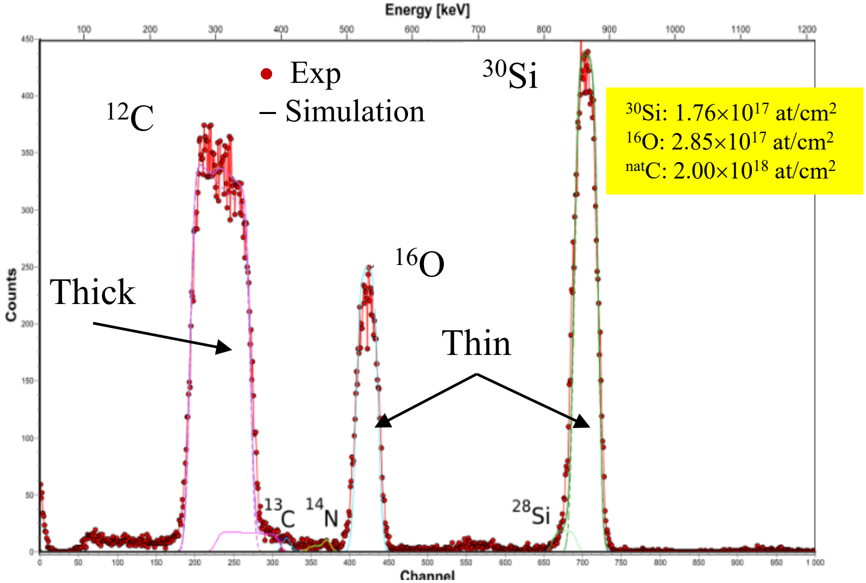



- ΔE measurement + α energy loss table (**Ziegler+77**) in the target ⇒ Target thickness
- Measurement @ various positions on target⇒ homogeneïty

- **Rutherford BackScattering (RBS) method for impurity and content analyses:** Target is bombarded with particles (p, alpha,...) with E ~ few MeV. The backscattered projectiles are detected at various angles.




- Backscattering energy depends on mass element
- Peak area for each element ∝ element concentration
- Shape & width → depth profiling: thickness of the layer where the element in present

# Gas targets

**Gas targets** are important in nuclear astrophysics, especially for reactions involving gaseous elements (like **He**, **Ne**) and when using **inverse kinematics**.

**Windowed Gas Cells:** Chambers filled with gas, separated from the vacuum using thin entrance and exit windows made of thin foils (e.g., Havar, Mylar, Kapton, or titanium), usually a few micrometers thick.
Typical pressures of a few mbar to several hundred mbar.

☺ Simple design.
☺ Easy to control gas pressure and target thickness.
☹ Window degradation under heavy beam irradiation.
☹ Energy loss and straggling in window foils
☹ Background reactions from the windows

**Windowless Gas Targets:** Use differential pumping systems to isolate a high-pressure gas region from the vacuum beamline
- gas is injected as a narrow jet into the beamline.
- Extended gas cells – longer regions with gas

☺ No energy loss from window foils.
☹ Require complex differential pumping.
☹ Beam energy loss and spread in gas must be carefully characterized.
☹ Target thickness may vary along the beam path.

**Recirculating Gas Systems:** used especially for expensive isotopically enriched gases like $^{15}N$, $^{22}Ne$, $^{3}He$, etc.
The Gas is continuously recirculated through the target and purification system. Used with windowless or closed gas cells.

☺ Saves rare/expensive gas.
☺ Maintains constant pressure
☹ Adds complexity (seals, valves, purifiers).