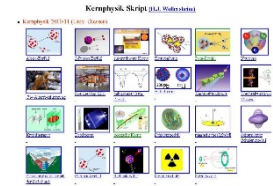


Outline: Accelerator for exotic beams

Lecturer: Hans-Jürgen Wollersheim

e-mail: h.j.wollersheim@gsi.de

web-page: <https://web-docs.gsi.de/~wolle/> and click on



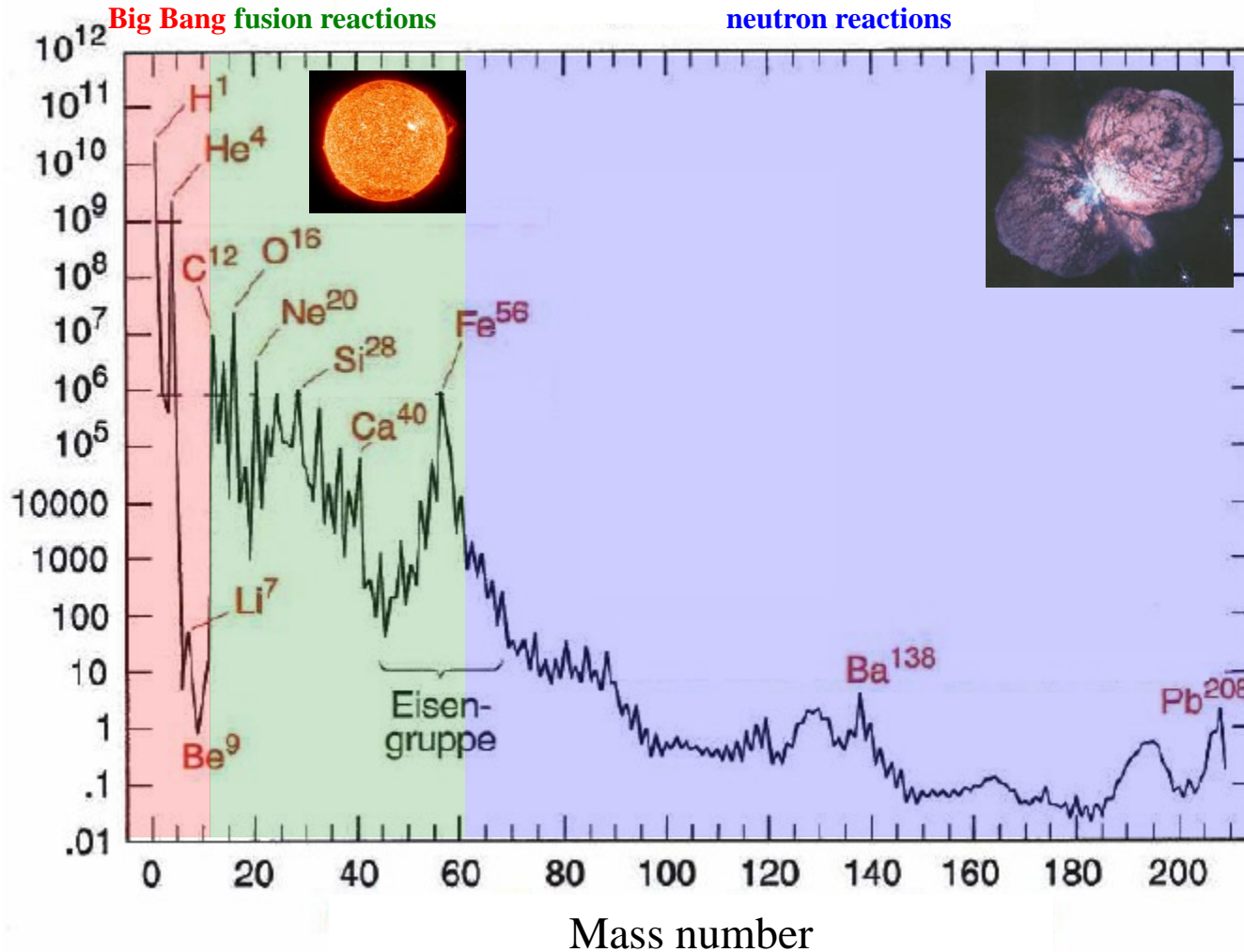
1. nucleosynthesis in the r-process
2. fragmentation reactions
3. production, separation, identification
4. Isolde at CERN

Radioactive ion beams



Solar abundances of elements

Solar abundance ($\text{Si}^{28} = 10^6$)

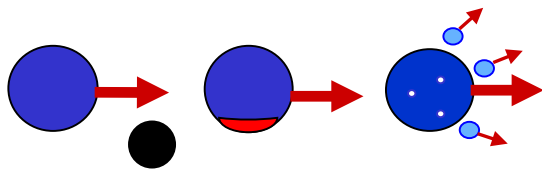
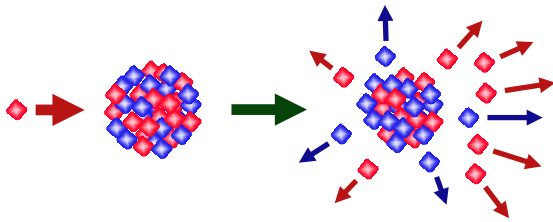


open questions:

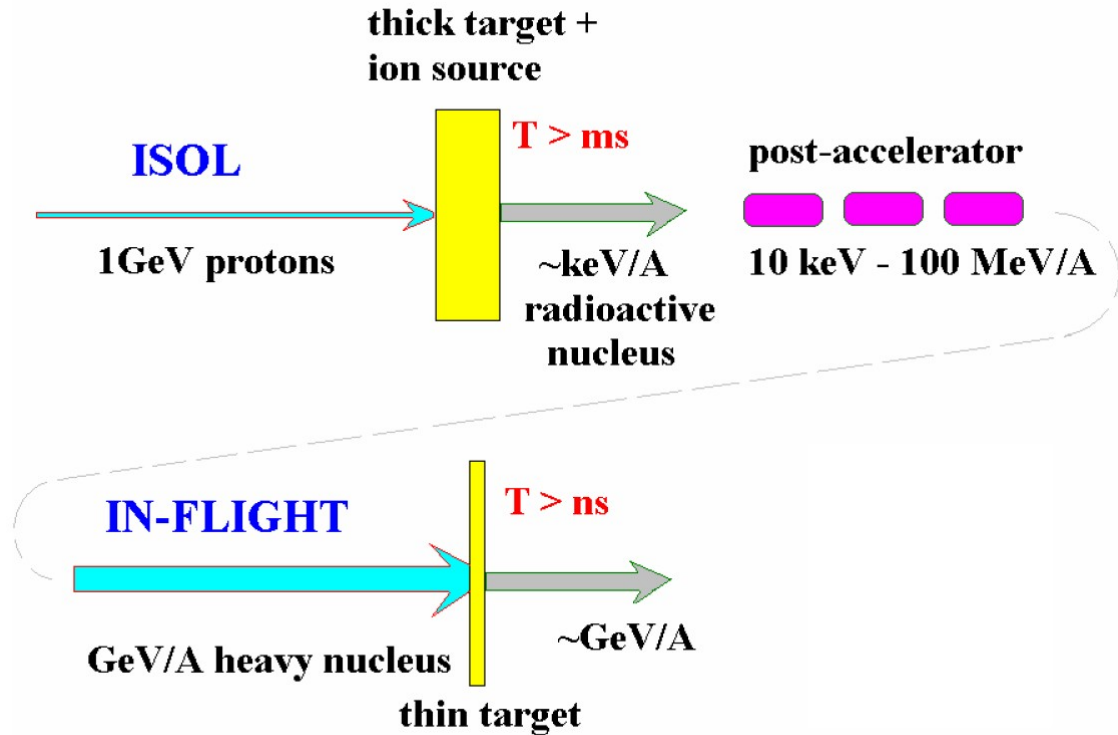
- Why is Fe more common than Au ?
- Why do the heavy elements exist and how are they produced?
- Can we explain the solar abundances of the elements?

Spallation & Projectile Fragmentation Reactions

Spallation



Fragmentation



High-energy proton-induced nuclear reactions

Some early high-energy proton accelerators:

Facility	Energy	from year
Bevatron (Berkeley)	6 GeV	1954.....
AGS (Brookhaven)	11 GeV	1960.....
Fermilab (Chicago)	>300 GeV	1967.....



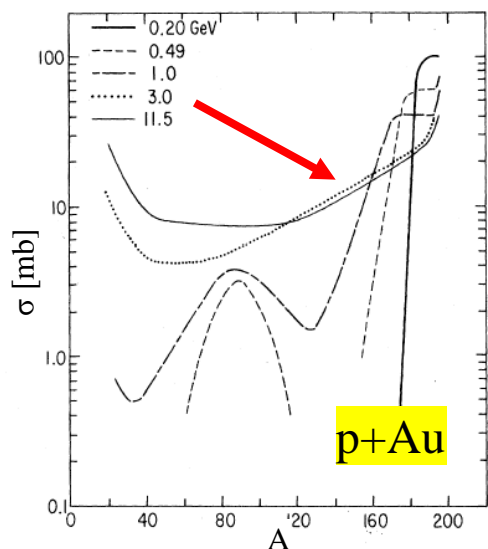
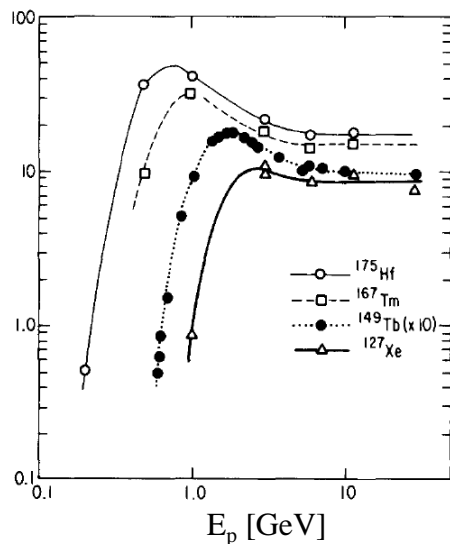
Bevatron (Berkeley)

They were also used to bombard various stable target materials.

These targets were analyzed with radiochemical methods, i.e. γ -spectroscopy with or without chemical separators

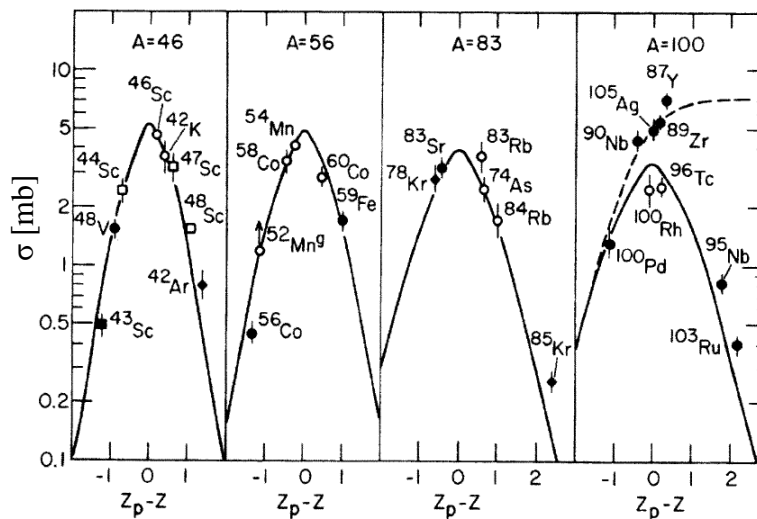
➔ Production cross sections and (some) kinematics for suitable radioactive isotopes

High-energy proton-induced nuclear reactions



Important findings:

- ❖ Energy-independence of cross sections
- ❖ Bell-shaped Z-distribution for constant A



- ❖ Mass yields: exponential slope

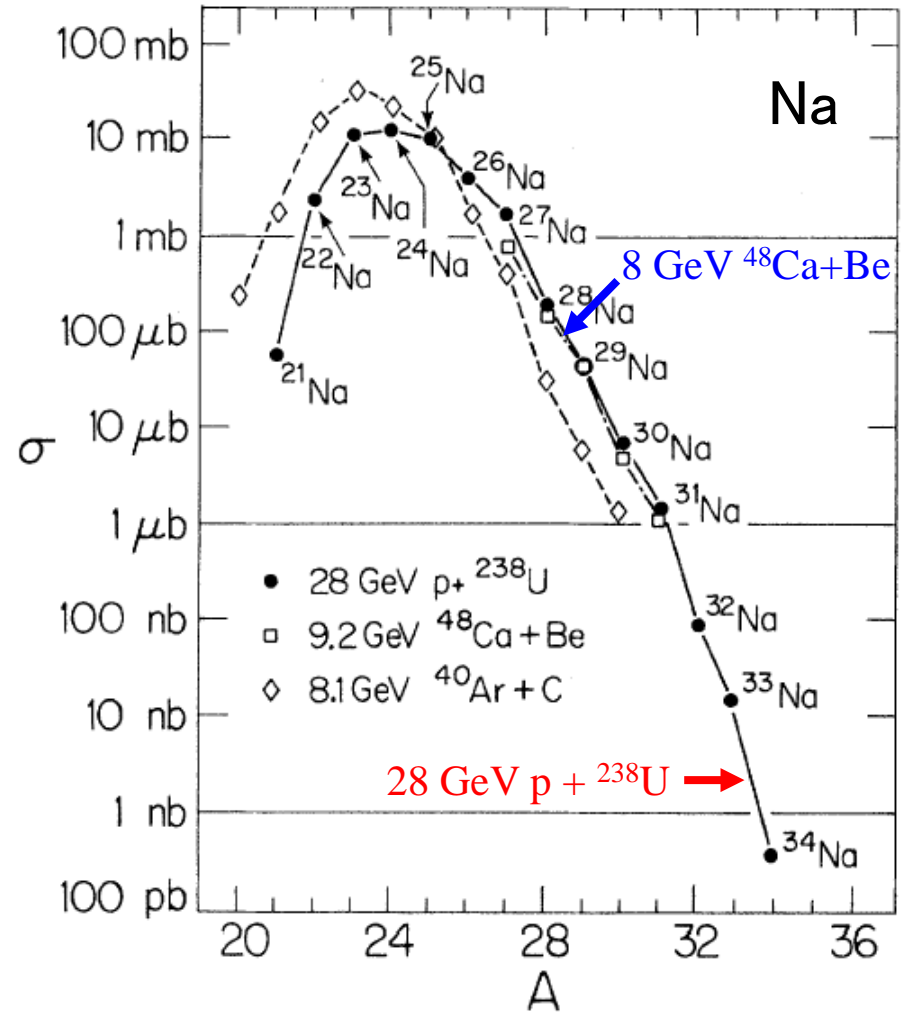
Proton- vs. heavy-ion induced reactions

Proton- and heavy-ion induced reactions give very similar isotope distribution:

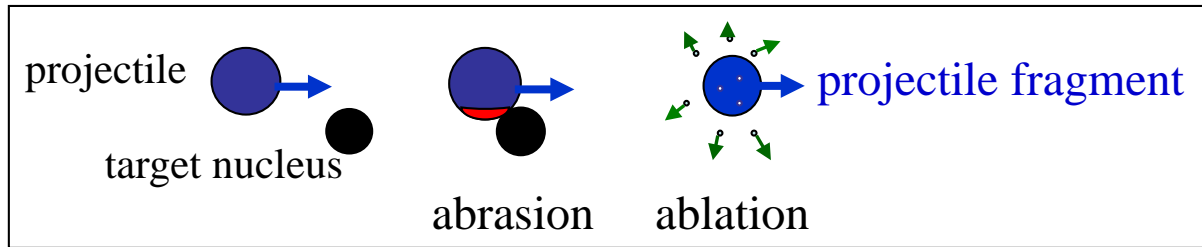
Target fragmentation: $\text{GeV } p + A_{\text{target}} \rightarrow A$

Projectile fragmentation: $\text{GeV/u } A_{\text{proj}} + p \rightarrow A$

are equivalent



Projectile fragmentation reactions



At GeV energies nucleons can be regarded as a classical particles

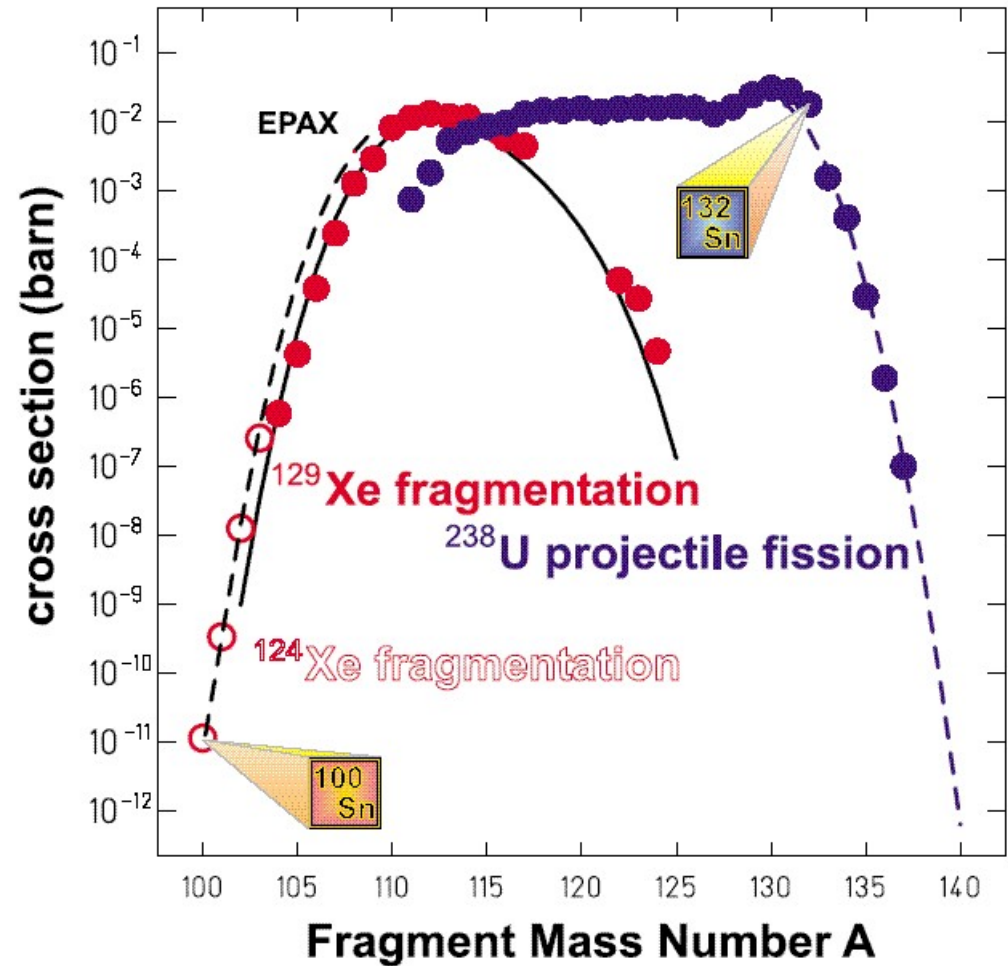
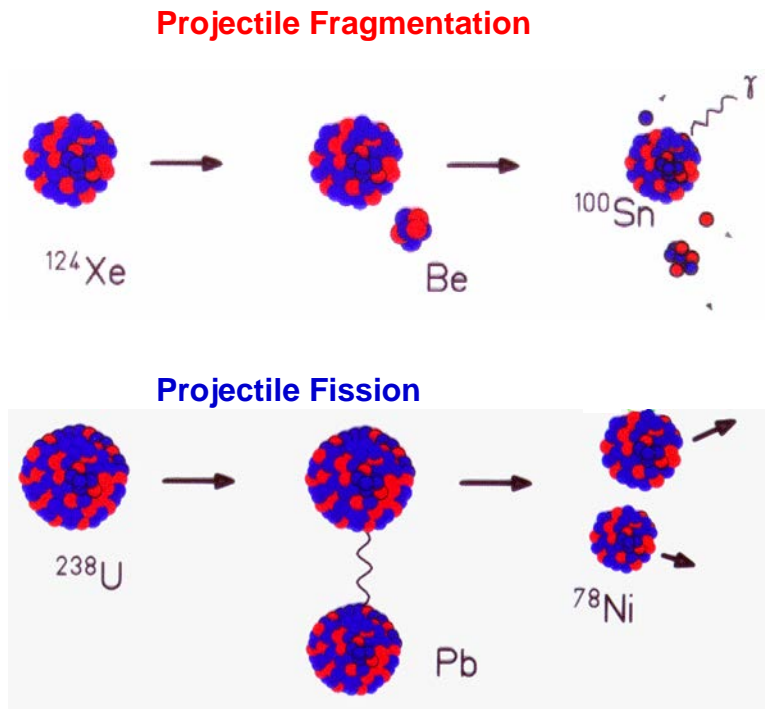
- Nucleon-nucleon collisions can be treated classically using measured free nucleon-nucleon cross sections (intra-nuclear cascade).
- In these collisions very *little transfer momentum* is exchanged.
- After the cascade the residual nucleus is *highly excited*.
- Heavy-ion projectiles can be treated as a bag of individual nucleons.

Physical models: Two-step approach

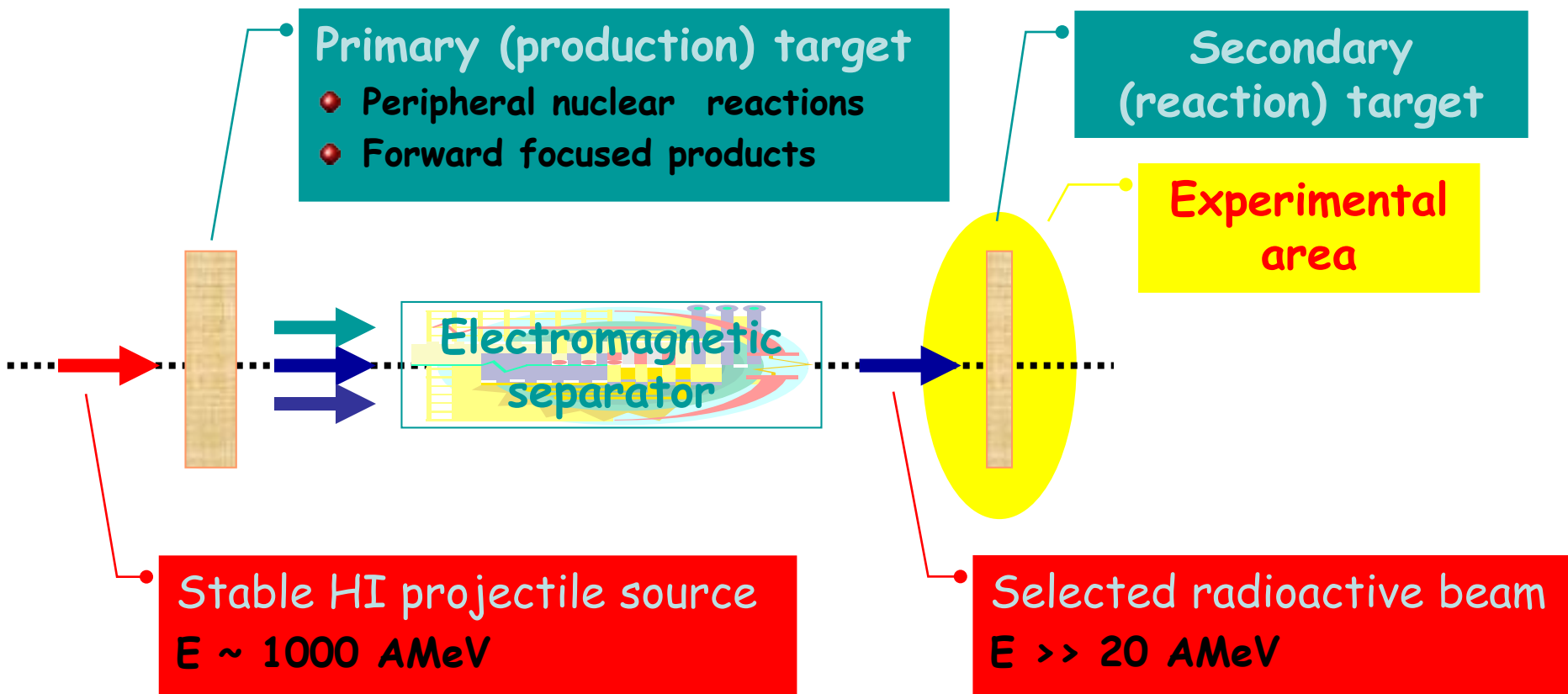
Step 1: **Intranuclear-cascade** models or **Abrasion** models

Step 2: **Evaporation** calculation

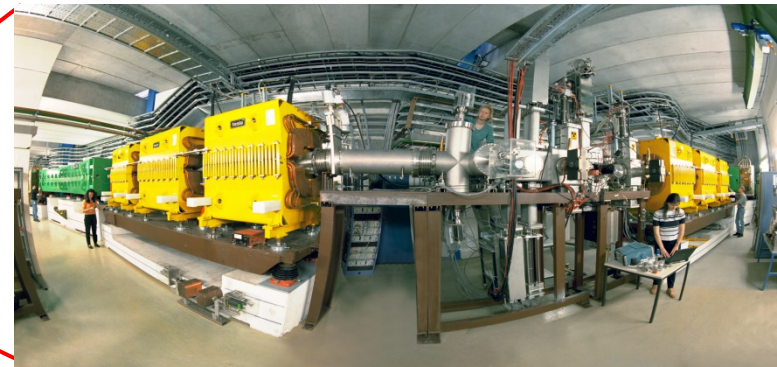
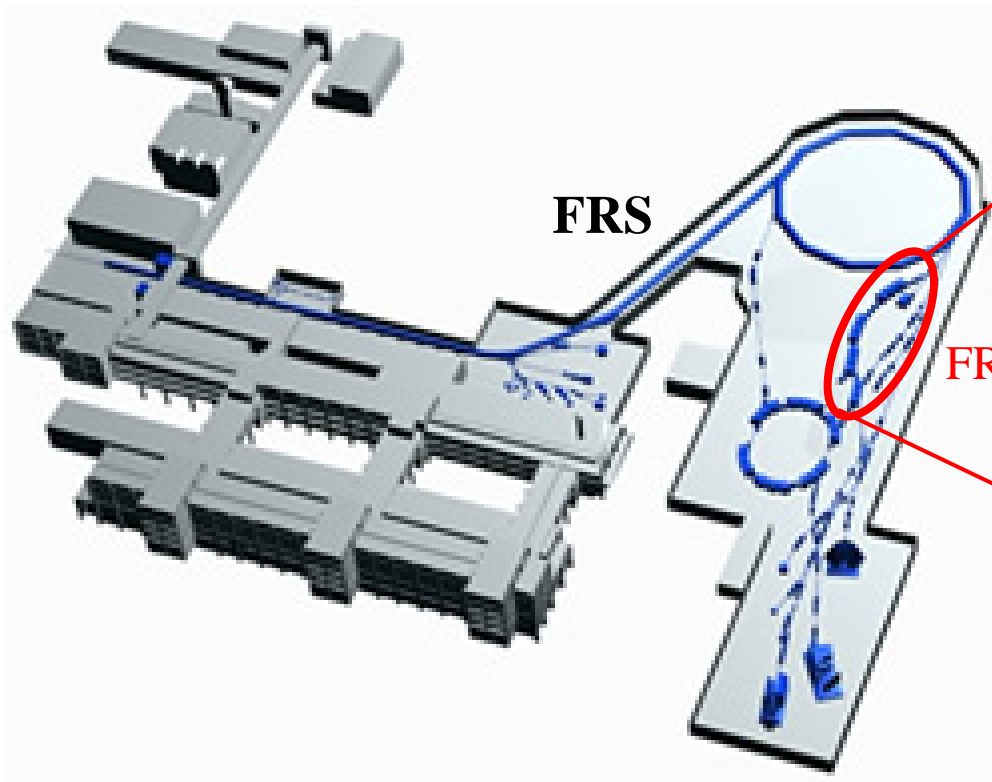
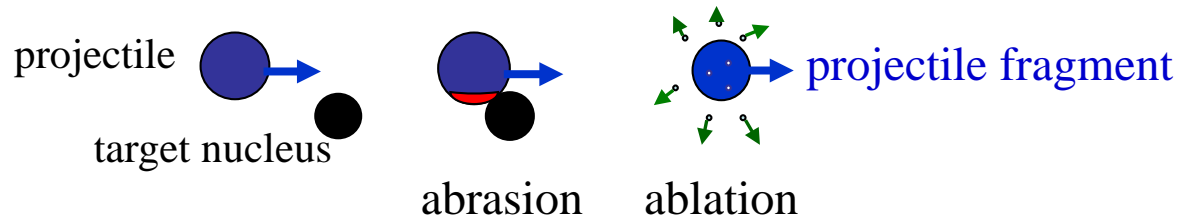
Projectile fragmentation reactions



In-Flight Separation of Radioactive Ion Beams

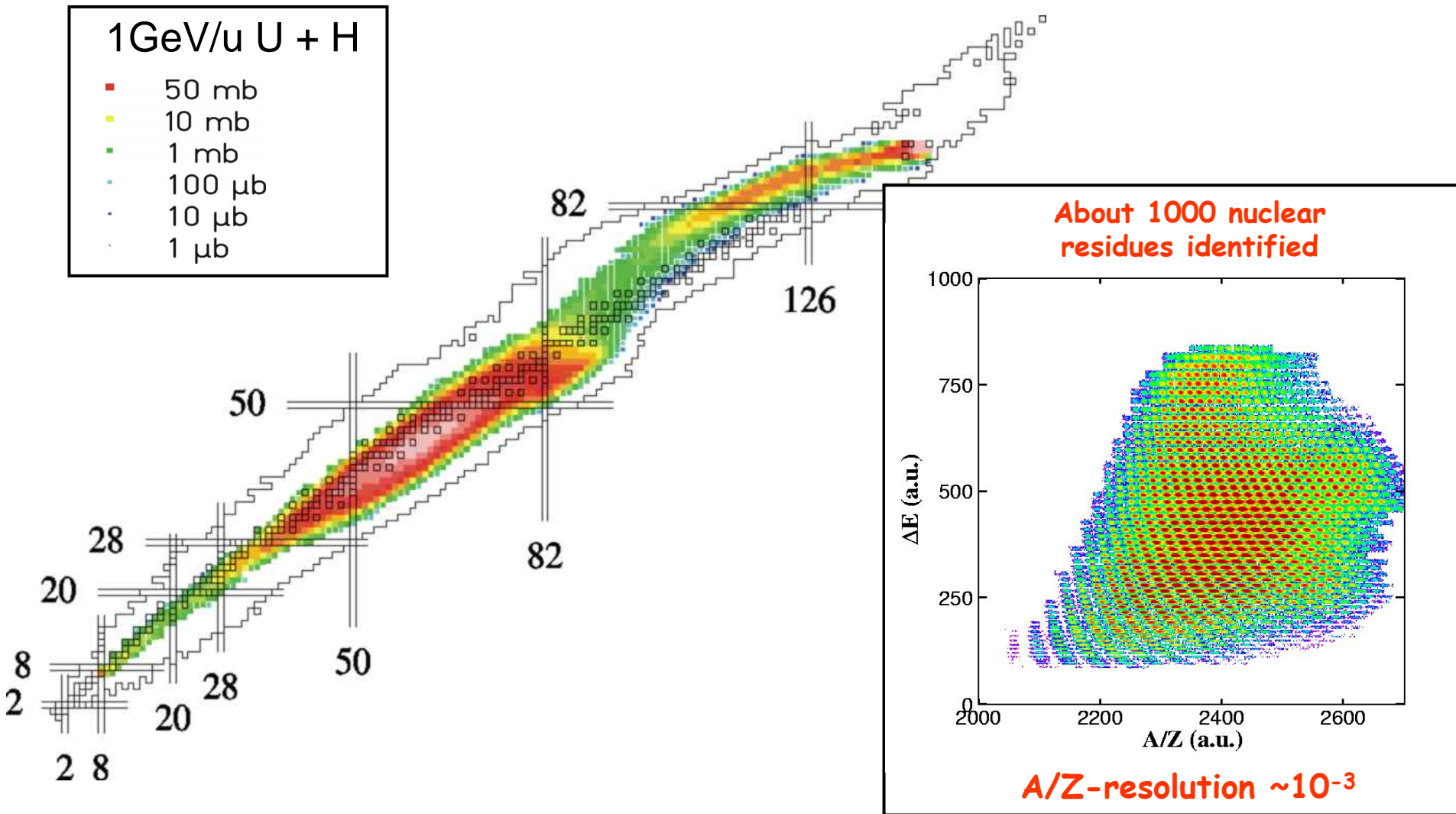


Fragmentation at Relativistic Energies

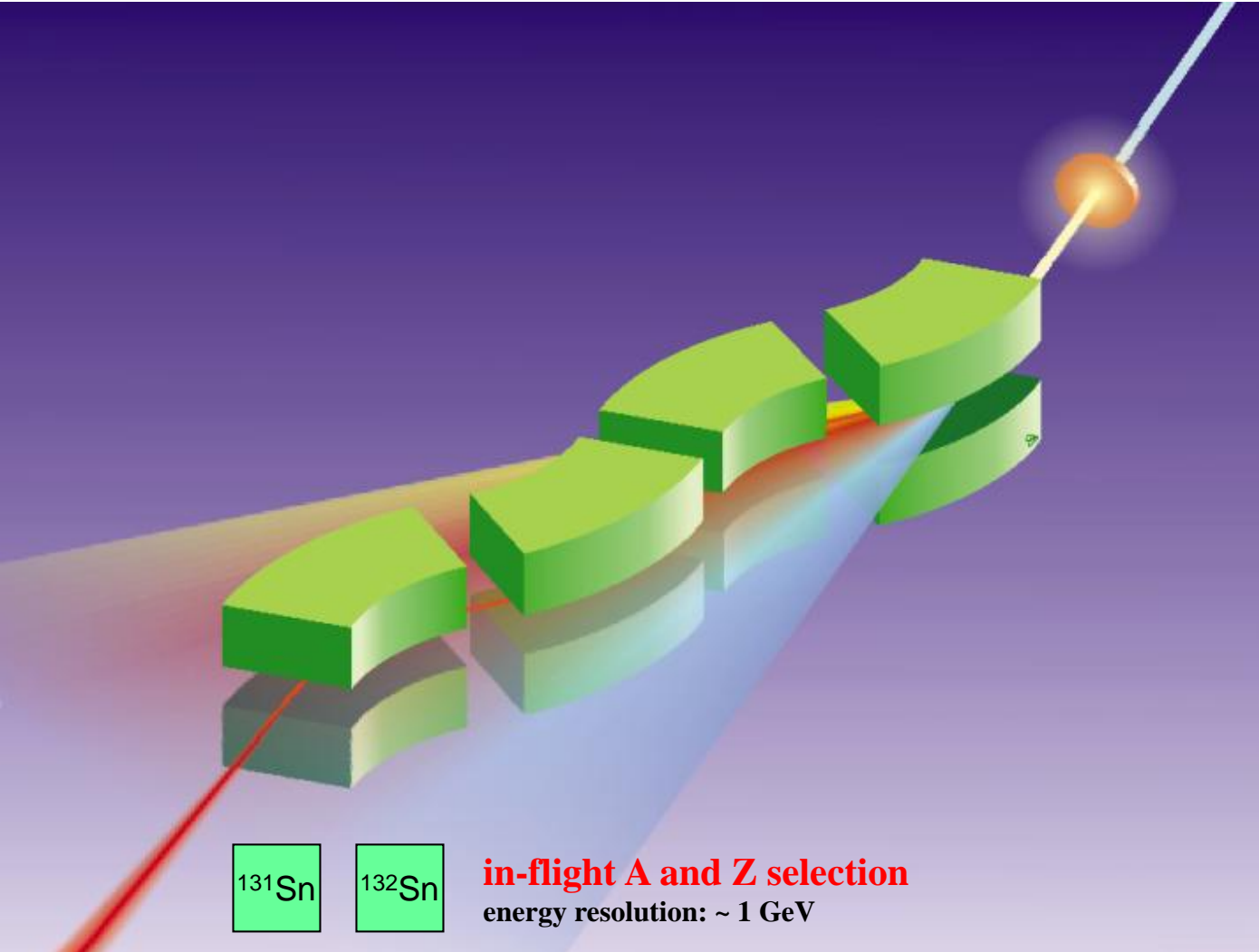


FRagment **S**eparator

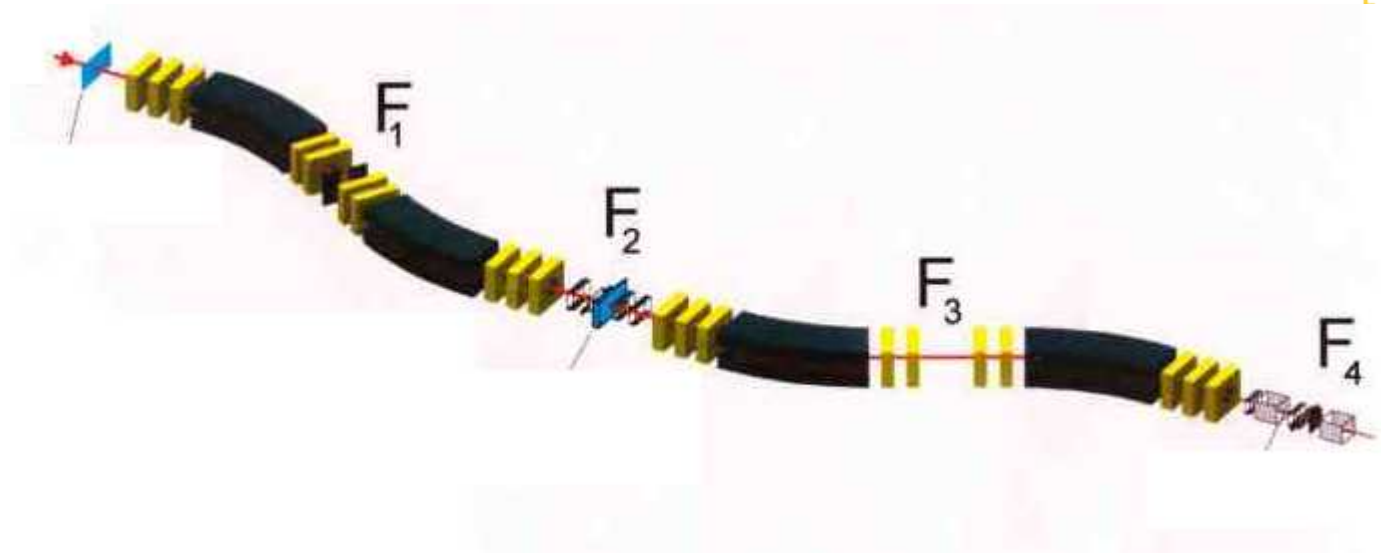
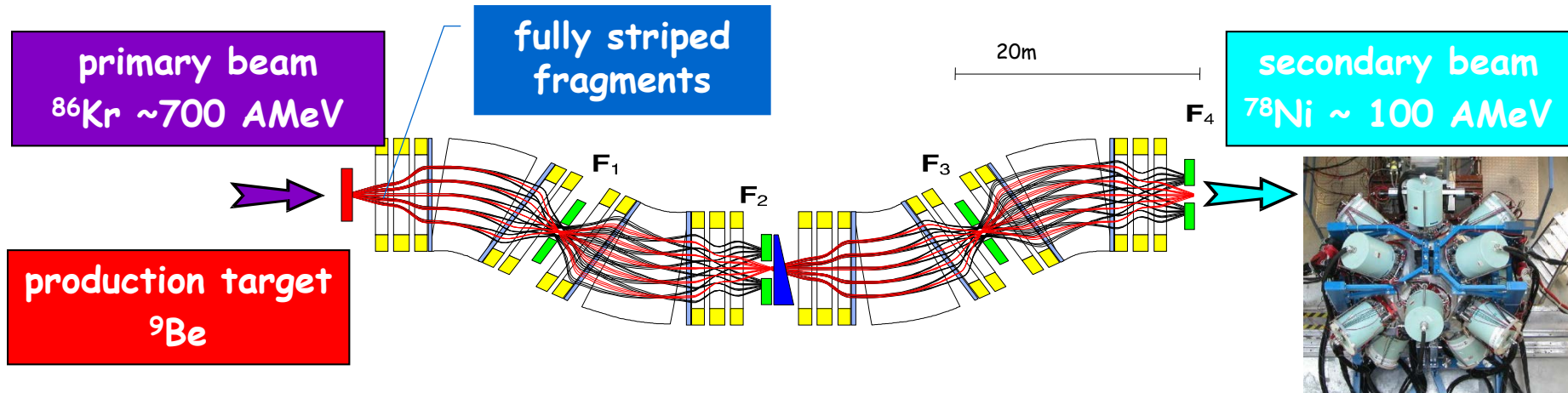
Radioactive Ion Beams at GSI



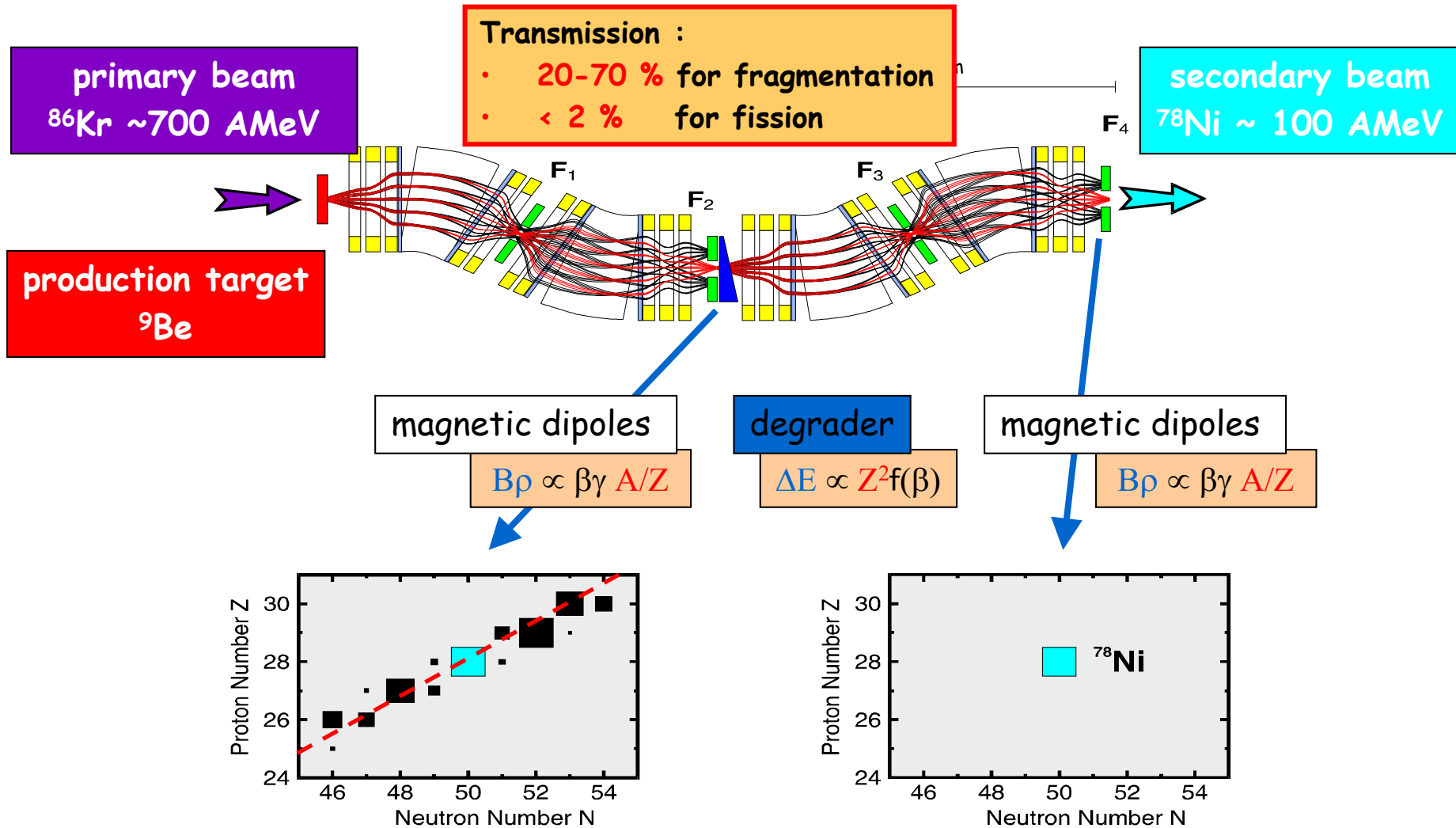
FRagment Separator at GSI



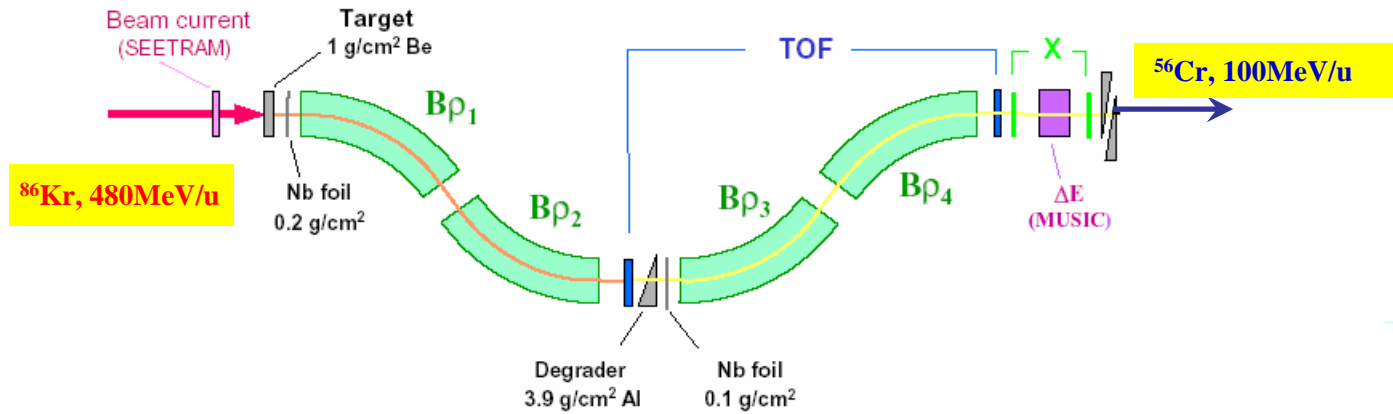
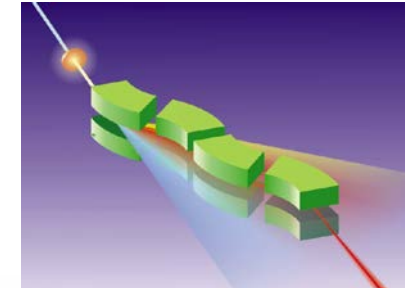
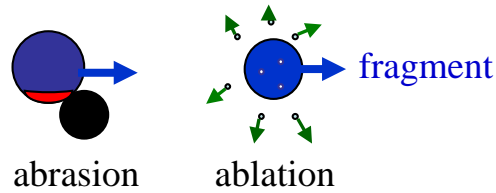
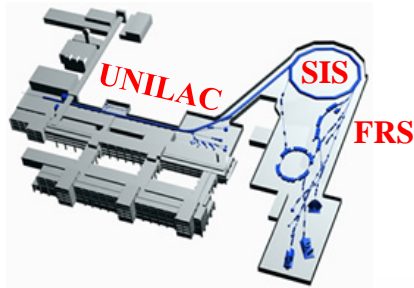
Rare Isotope Selection at FRS: $B\rho$ - ΔE - $B\rho$ Selection



Rare Isotope Selection at FRS: $B\rho$ - ΔE - $B\rho$ Selection



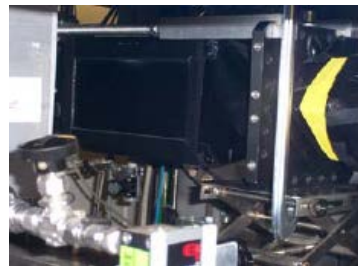
Production, Separation, Identification



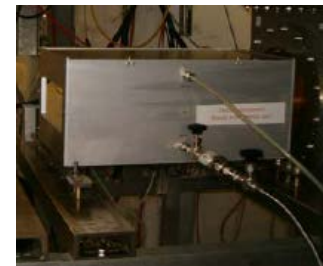
Standard FRS detectors



TPC-**x,y**
position
@ S2,S4

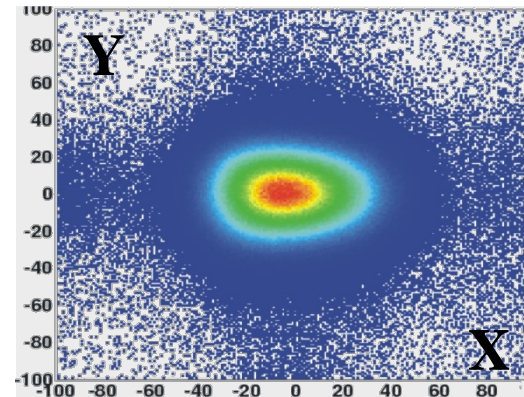
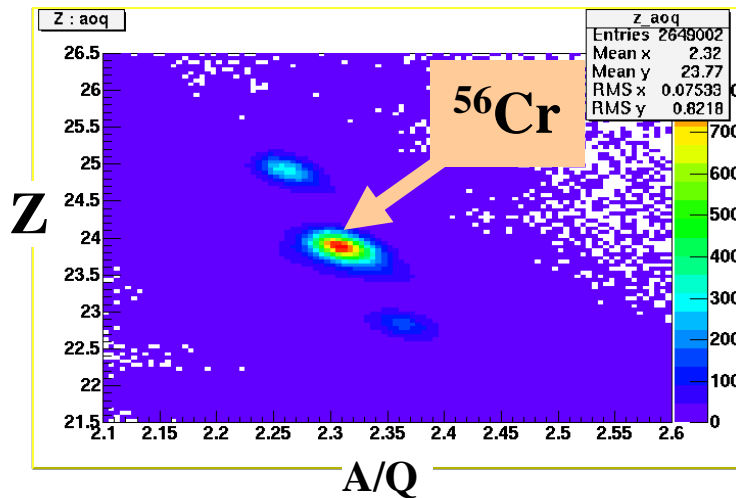
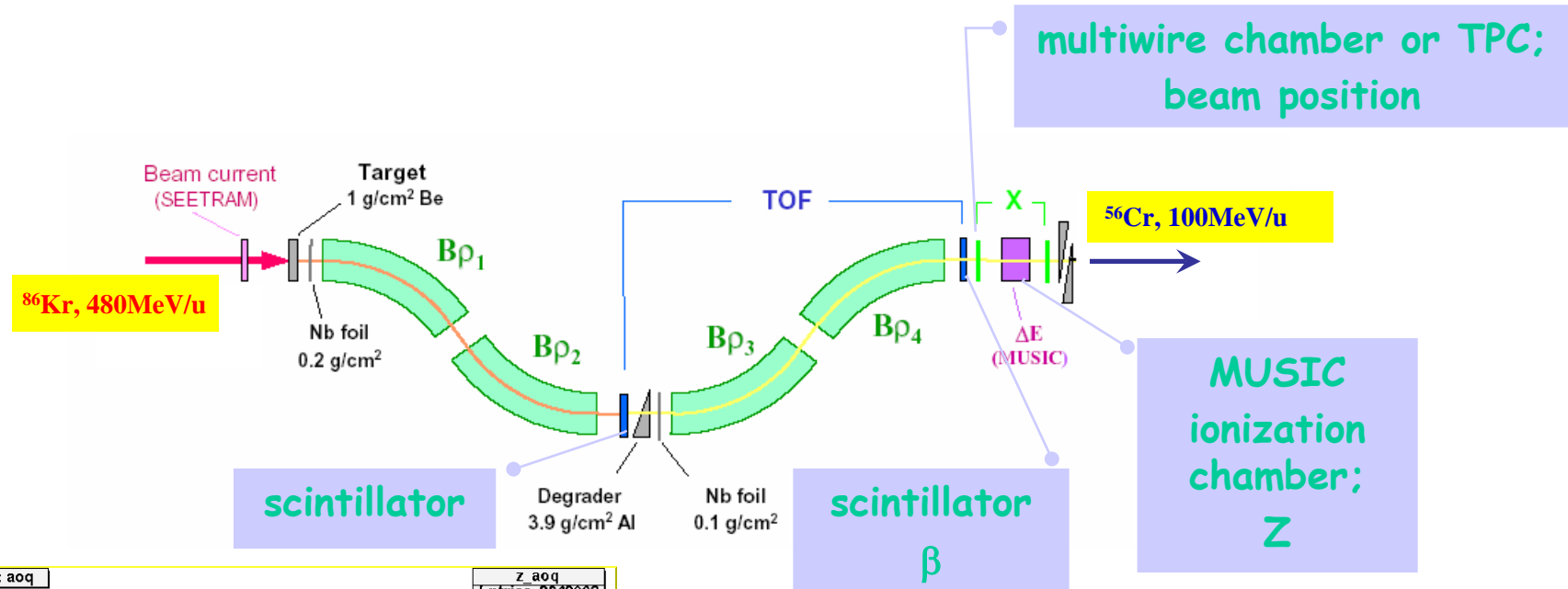


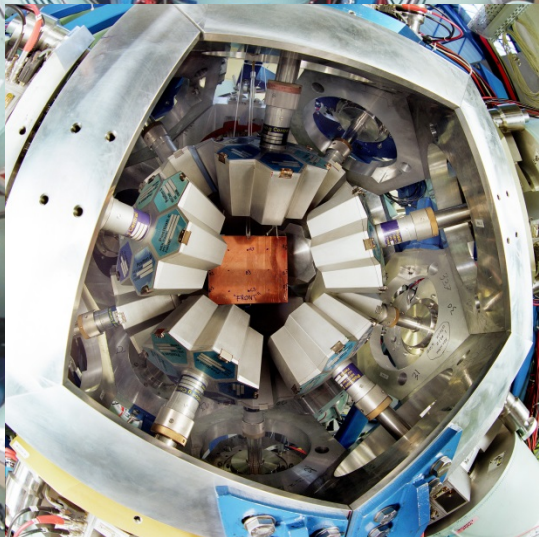
Plastic
scintillator
(**TOF**)
@ S4



MUSIC
(**ΔE**)
@ S4

Production, Separation, Identification





scintillator
(SC41)

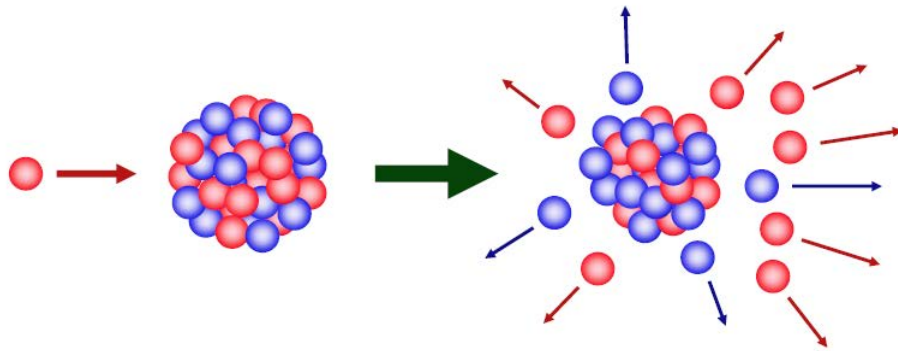
ionization
chambers
(MUSIC41,42)

beam
←

degrader

multiwire
chambers
(MW41,MW42)

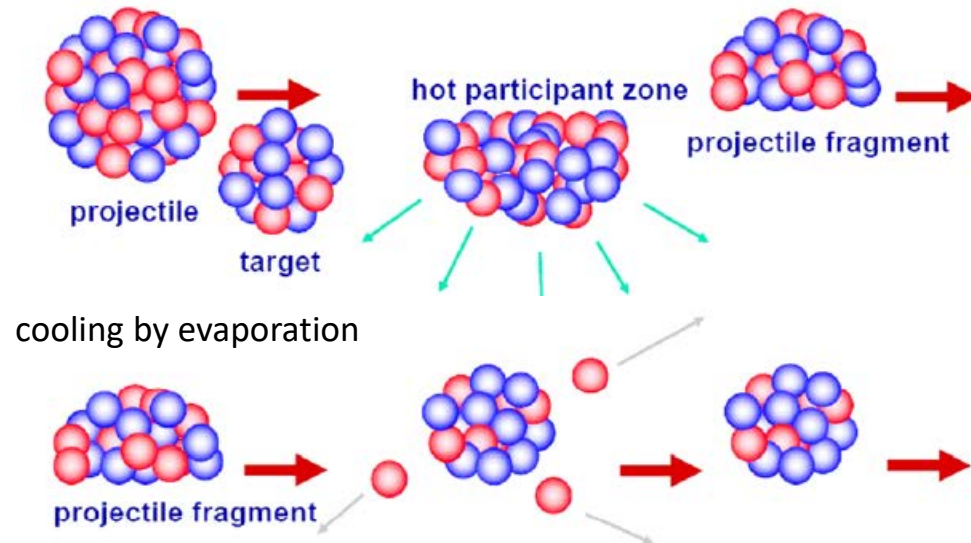
Production of radioactive ion beams



Target fragmentation

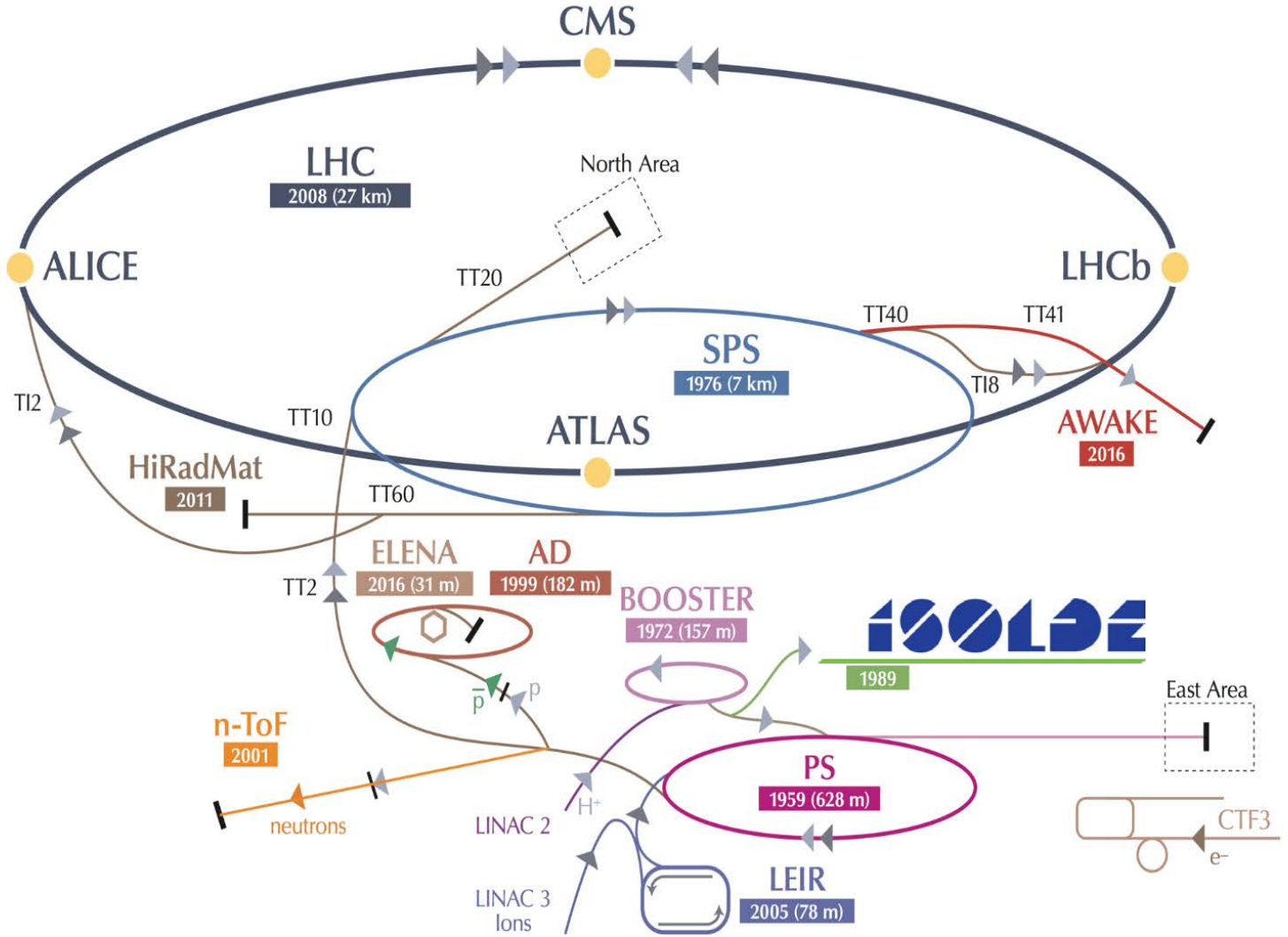
Random removal of protons and neutrons from heavy target nuclei by energetic light projectiles

Projectile fragmentation

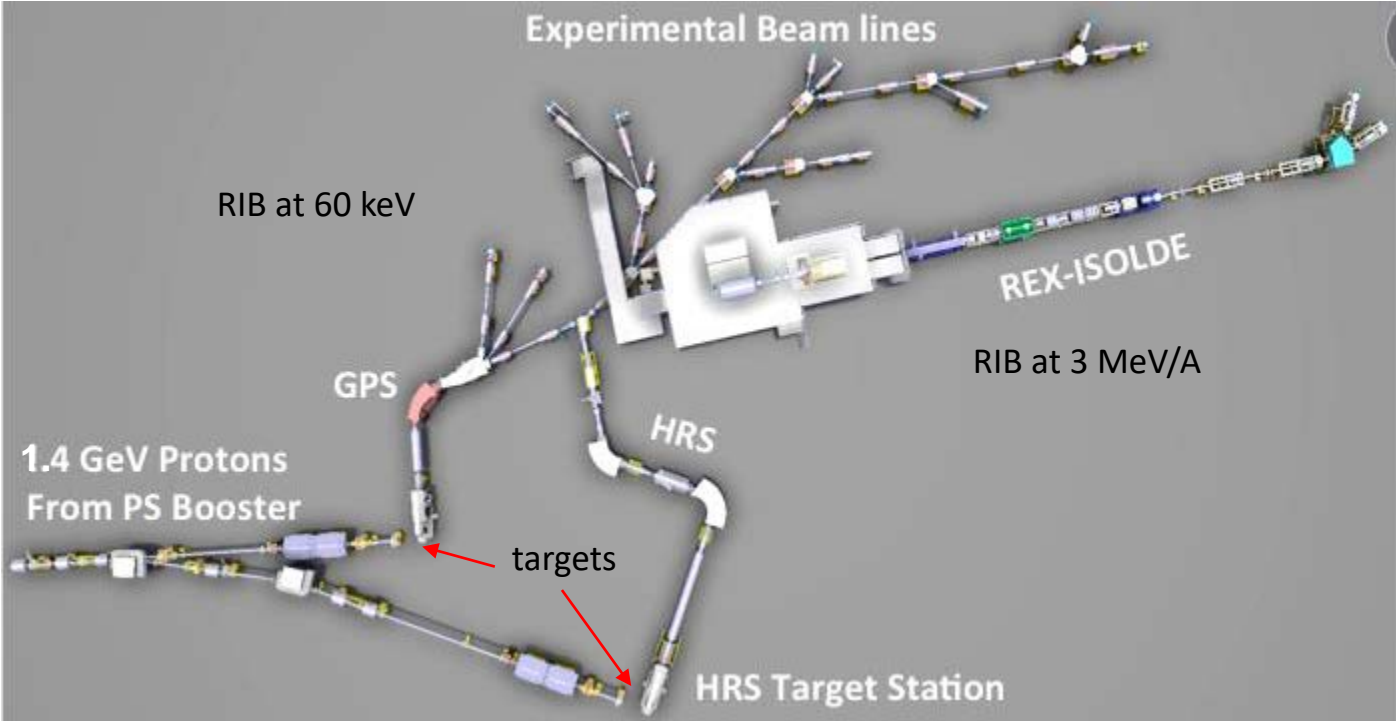


Random removal of protons and neutrons from heavy projectile in peripheral collisions

ISOLDE at CERN

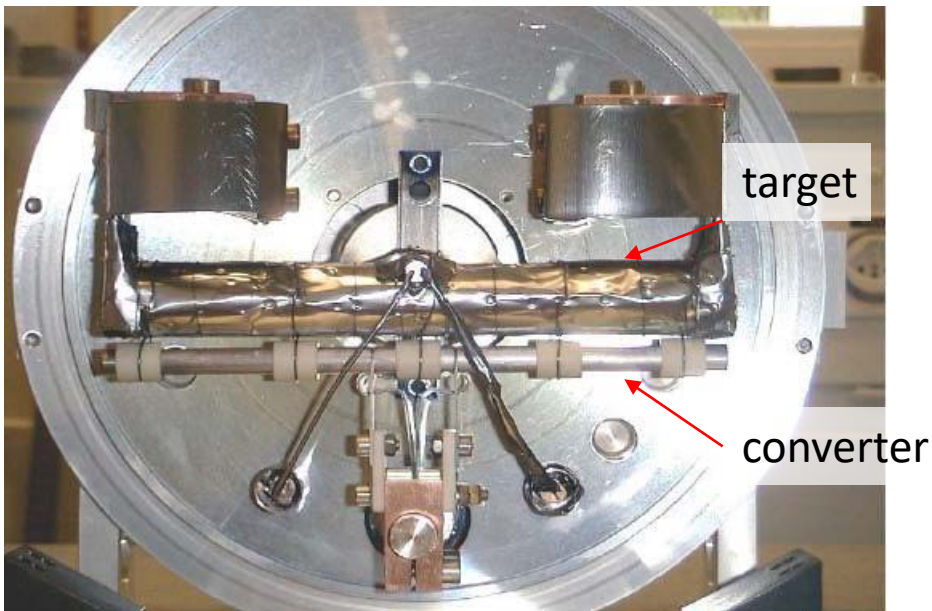


ISOLDE at CERN



Production targets

- Over 20 target materials and ionizers, depending on beam of interest
- U, Ta, Zr, Y, Ti, Si, ...
- Target material and transfer tube heated to 1500 – 2000^o C
- Operated by robots due to radiation



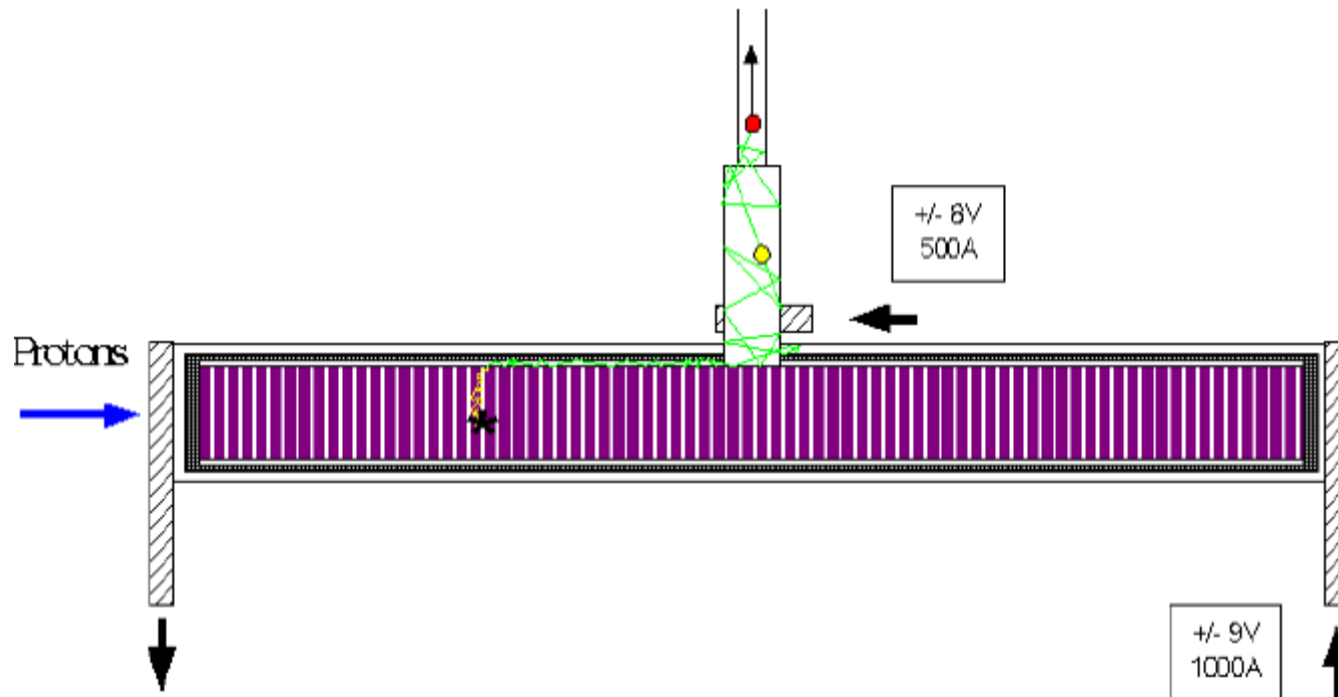
converter target



standard target

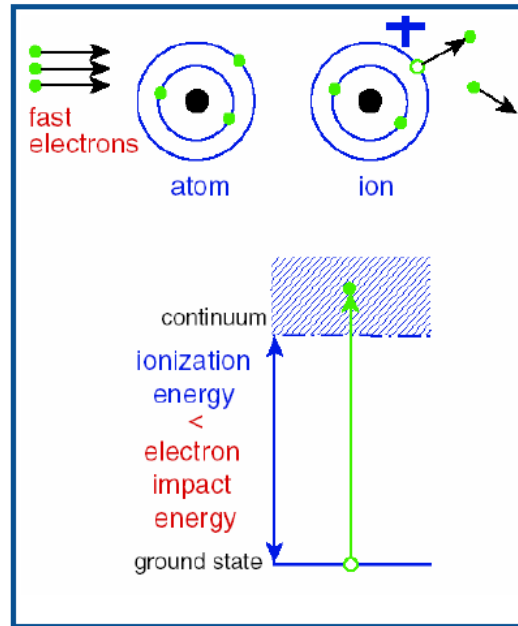
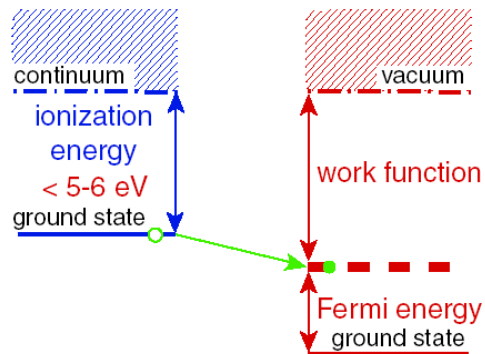
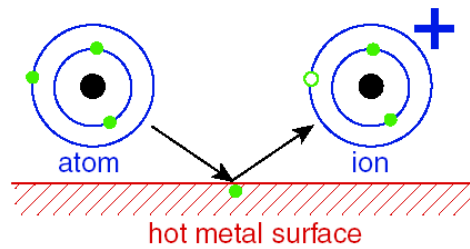
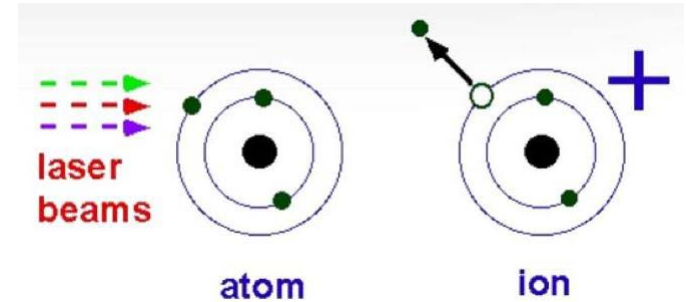
Inside a standard target

In the early Copenhagen experiments a ten kilo target consisting of a mixture of baking powder [essentially $(\text{NH}_4)_2\text{CO}_3$] and uranium oxide was used. Fast neutrons from an internal beryllium target in the cyclotron were used to irradiate the external target, and the radioactive isotopes were produced by fission reactions in the uranium. The radioactive noble gases were then diffused out of the target and swept into the ion source of the isotope separator.



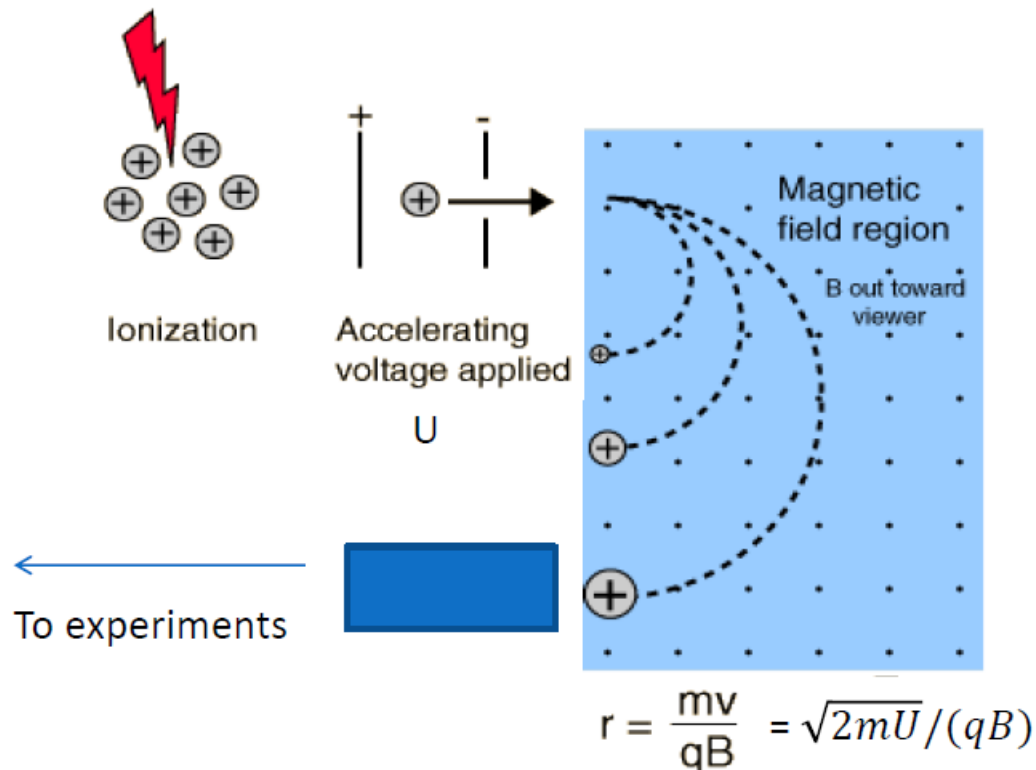
Ionization

- Lasers
- Plasma
- Surface

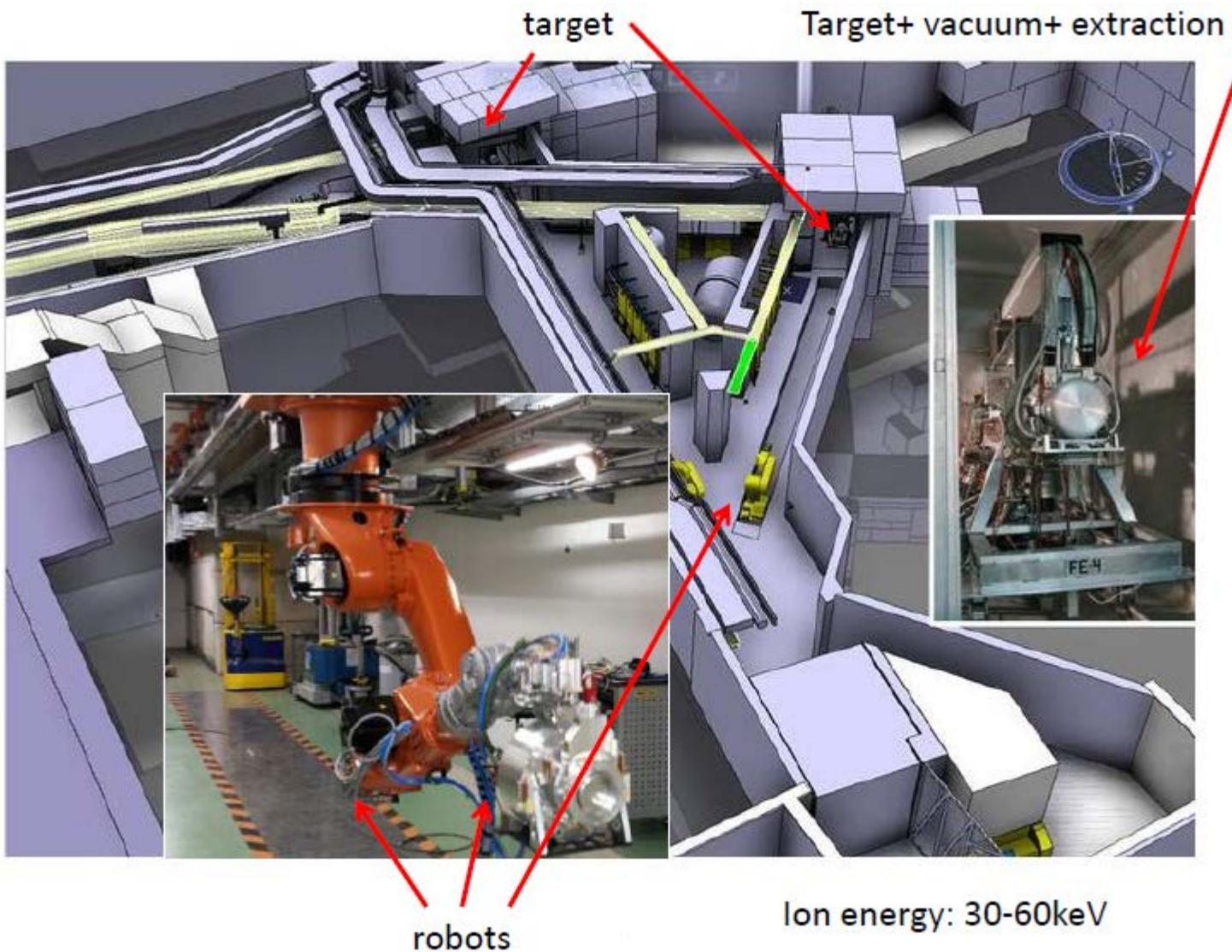


Beam extraction and separation

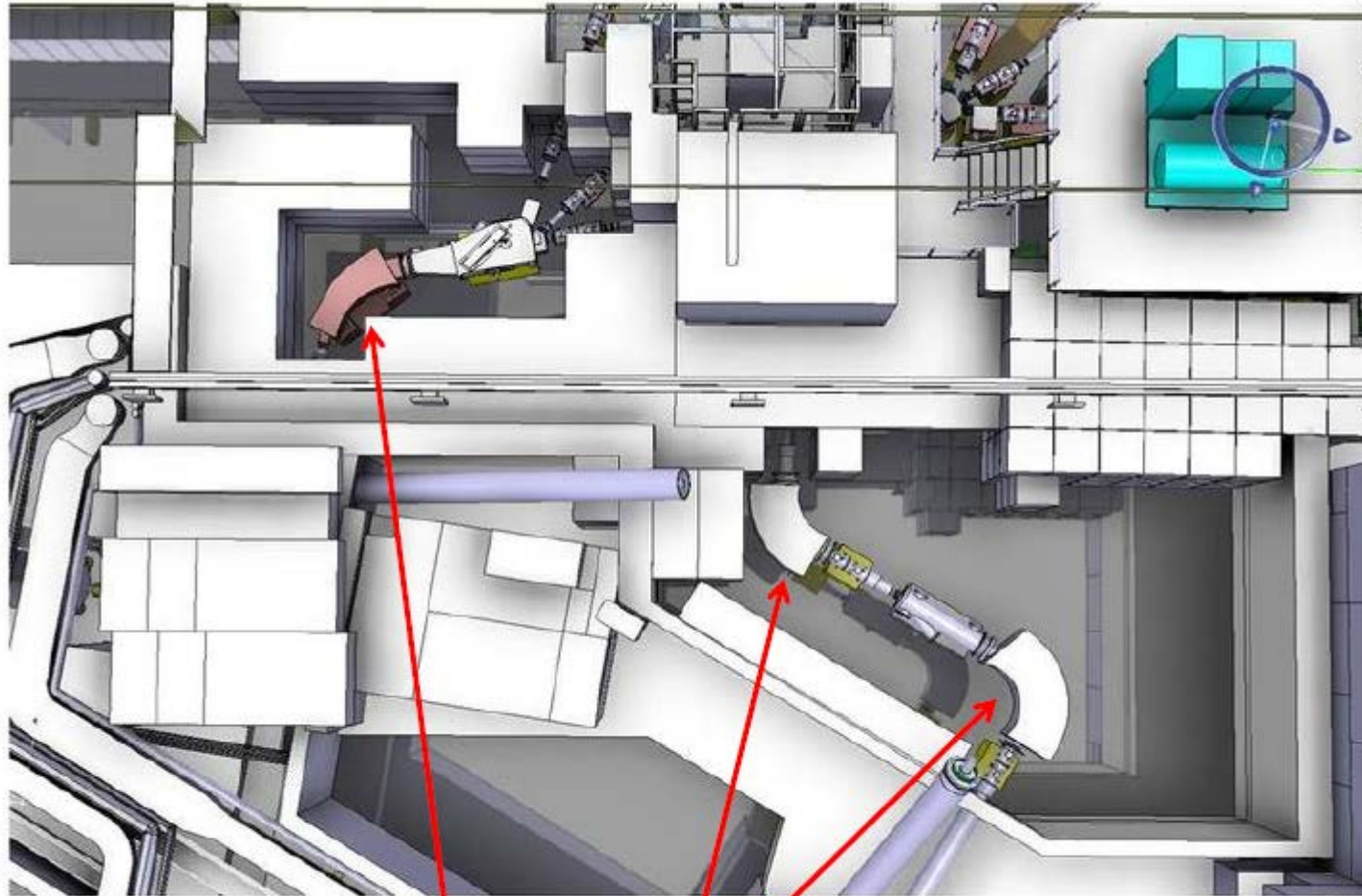
- All produced ions are extracted by electrostatic field (up to 60 kV)
- The interesting nuclei are mass selected via magnetic field
 - Lorentz force depends on velocity and mass
 - $m/\Delta m < 5000$, so many unwanted isobars also get to experiments



Production, ionization, extraction



Separation



Magnet separators (General Purpose and High Resolution)

Post-acceleration

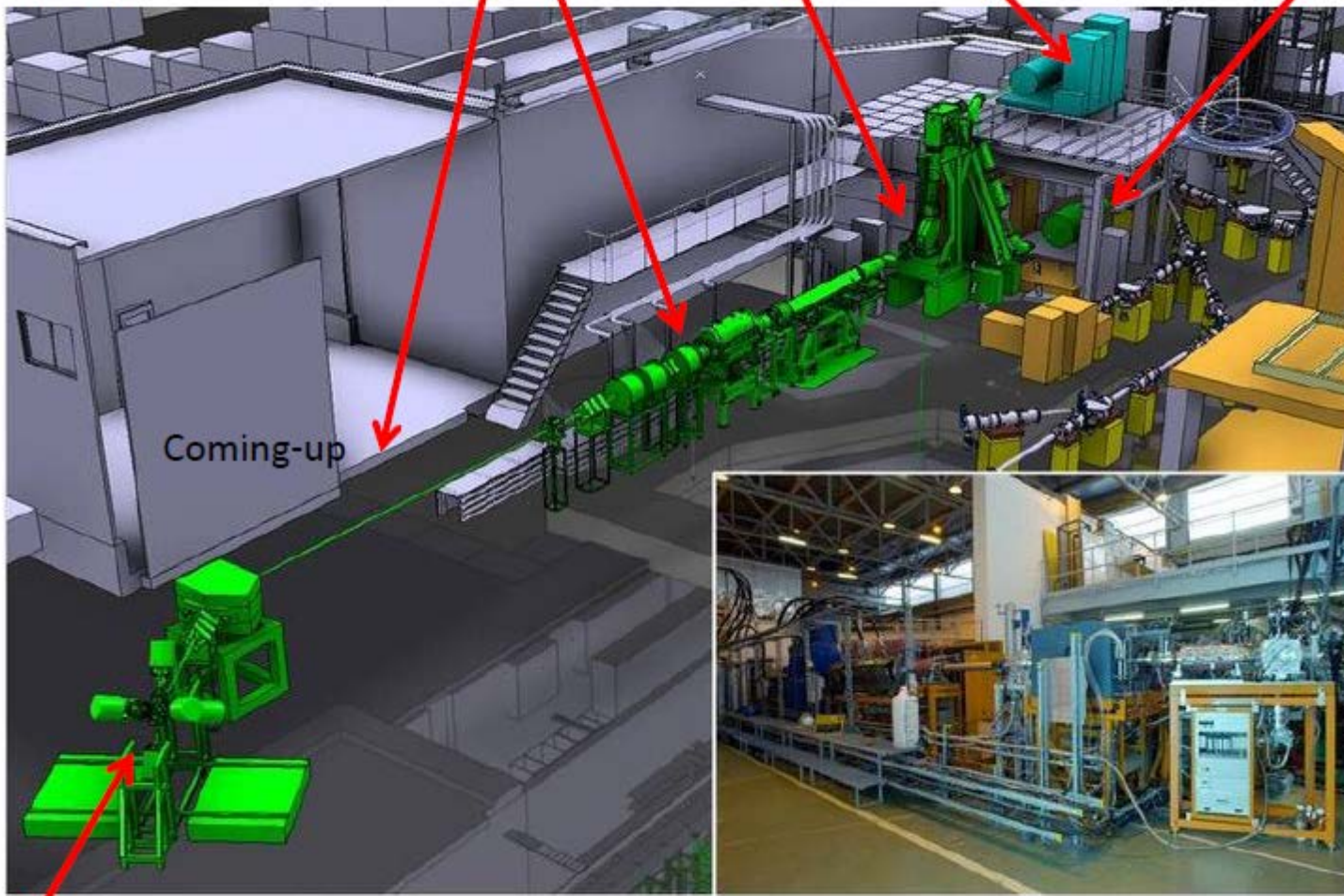
REX and HIE-ISOLDE accelerators

Rf acceleration

A/q selection

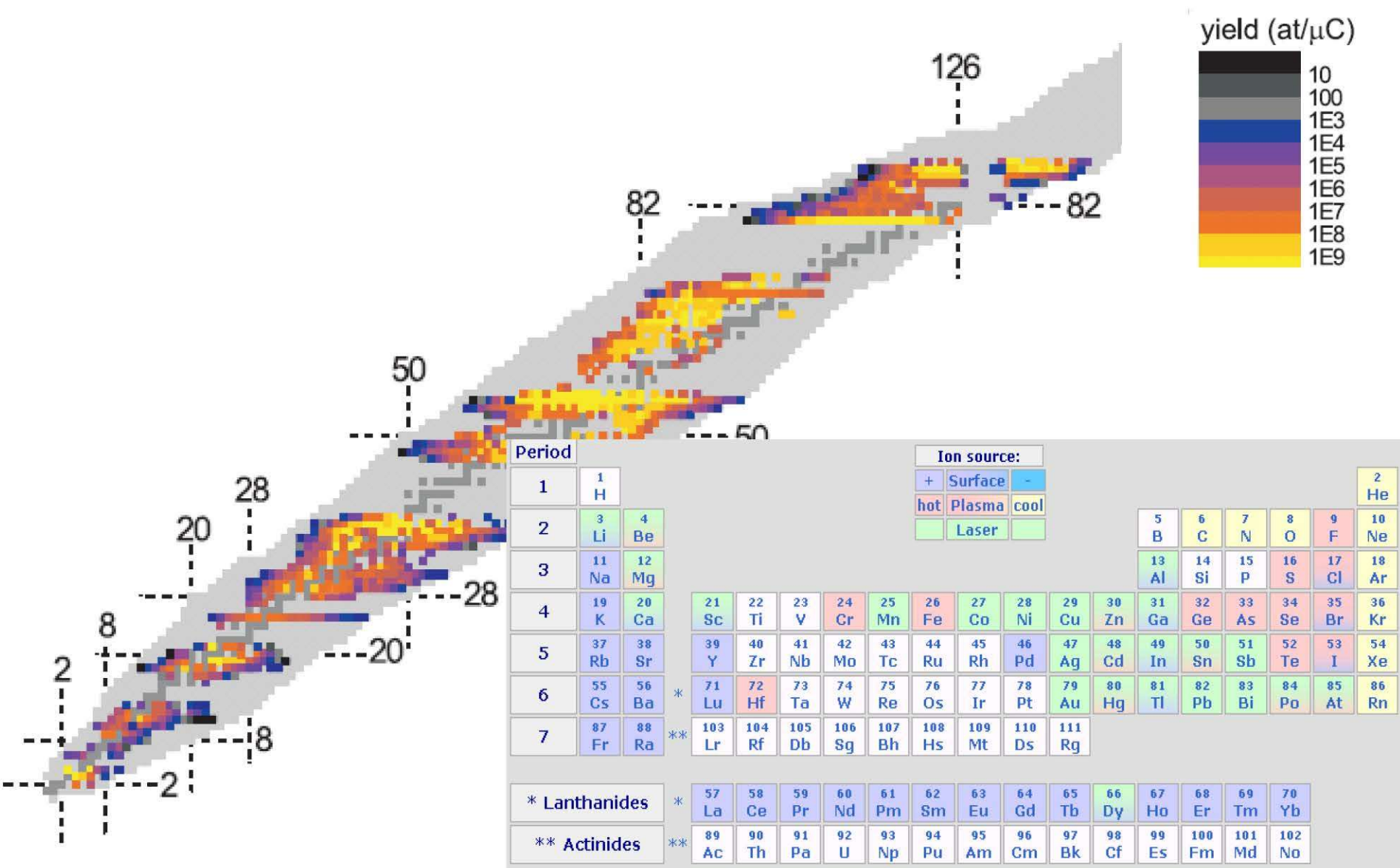
Increase in charge state

Ion trapping and cooling

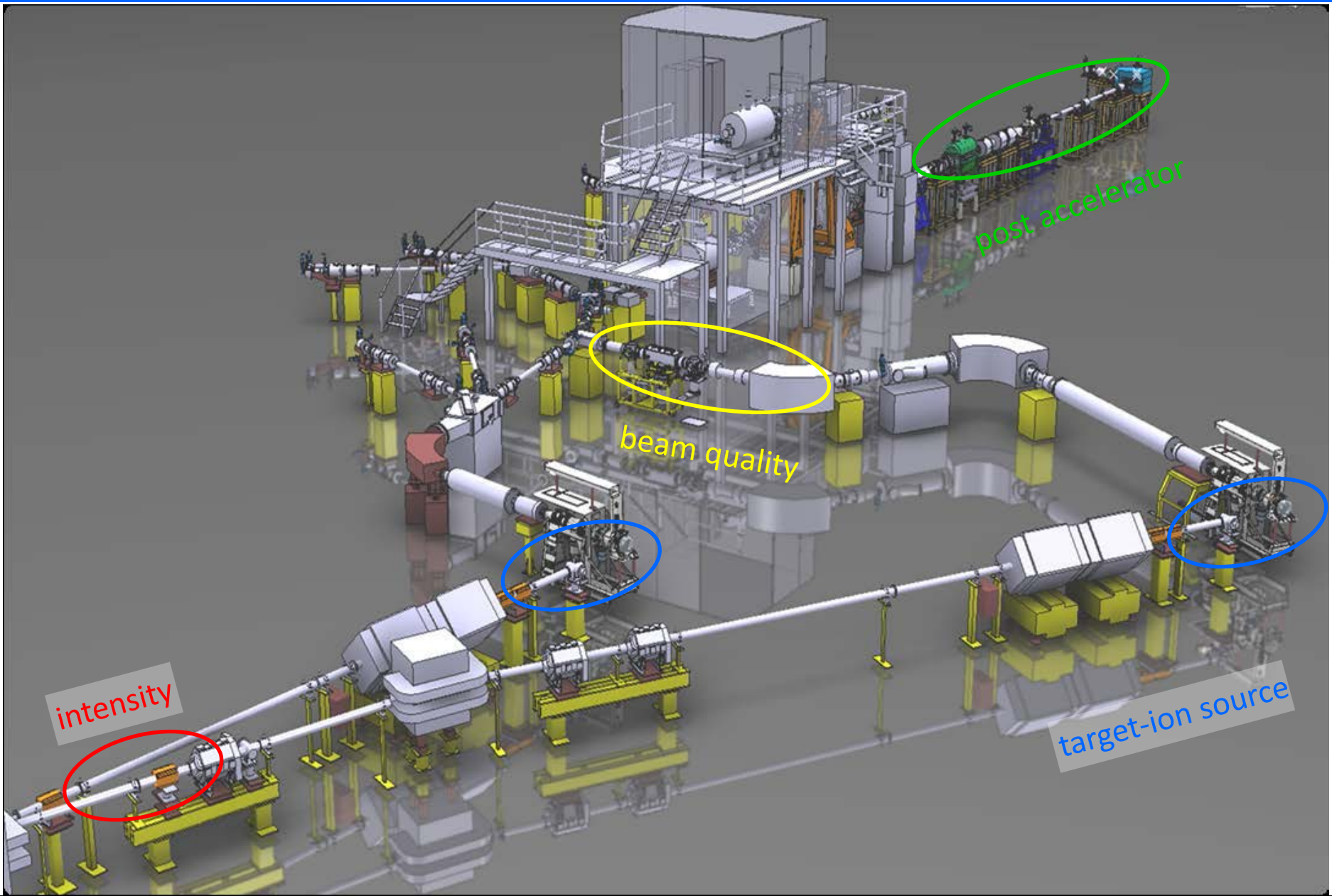


3MeV*A beam to experiment

Extracted nuclides



High-Intensity and Energy upgrade of Isolde (HIE-Isolde)

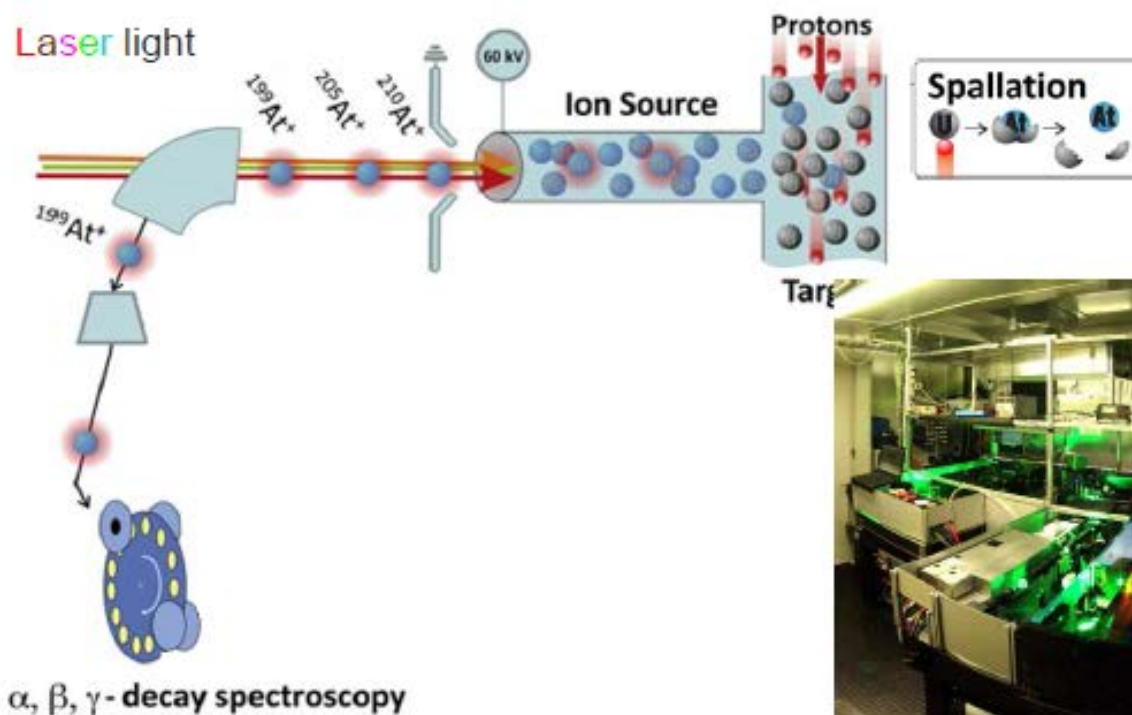


An example: Selective production of Astatine

Guinness World Records has dubbed this element the rarest on Earth, stating: “Only around 25g of the element astatine occurring naturally”

⇒ Ionization potential not experimentally deduced

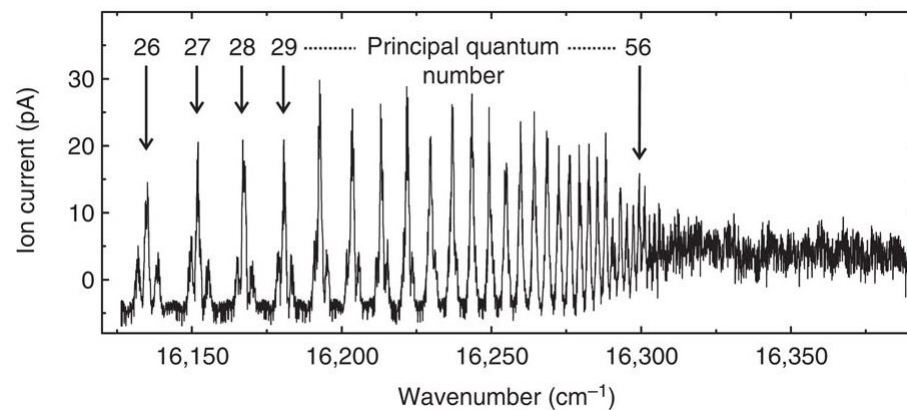
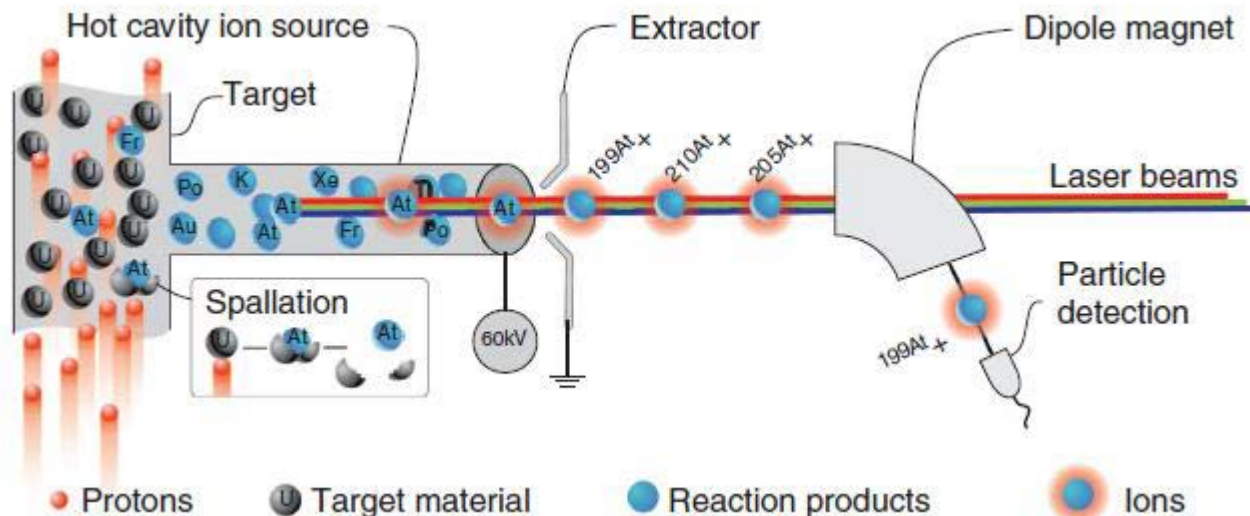
⇒ Only two atomic transitions were known



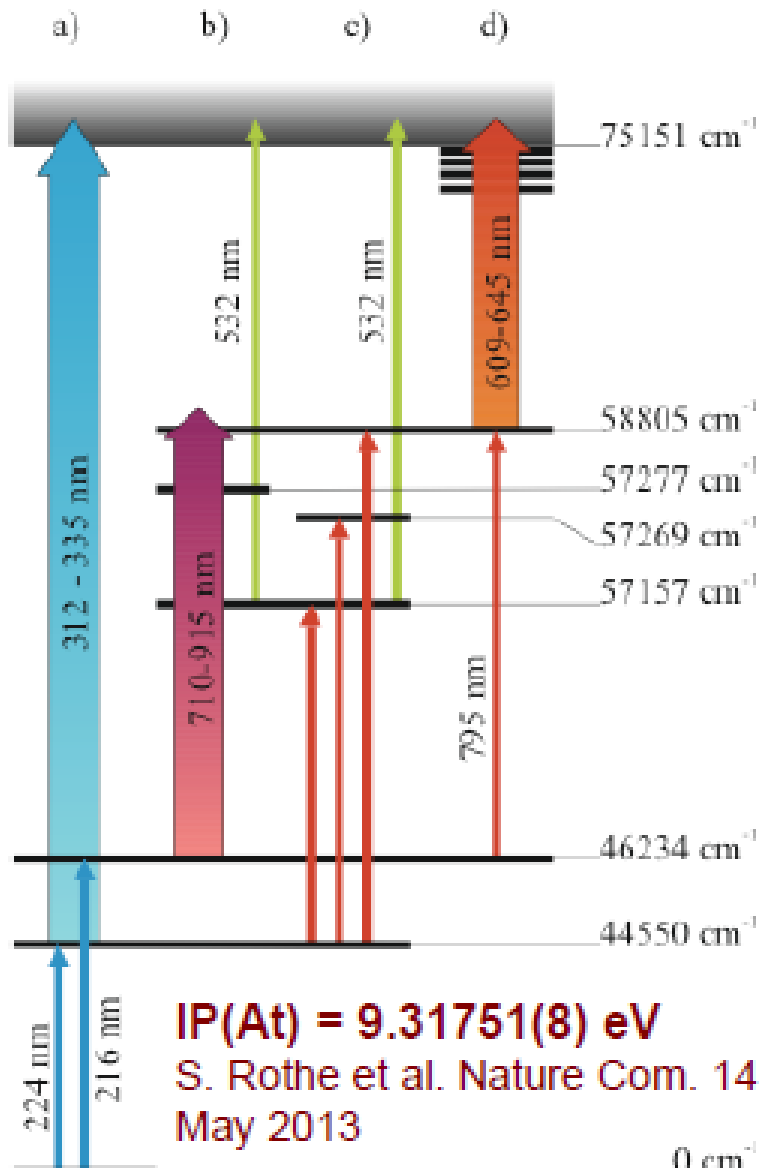
Example: Astatine isotopes

❖ How to produce pure beams of **At** isotopes (all are radioactive)?

- Use laser to ionize them
- Determine for the first time the At ionization potential

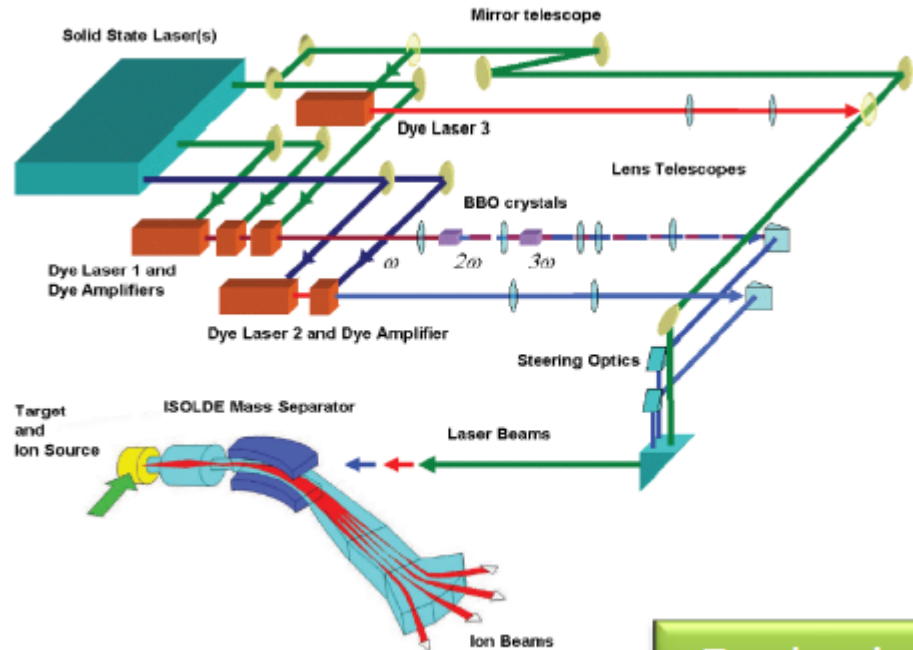
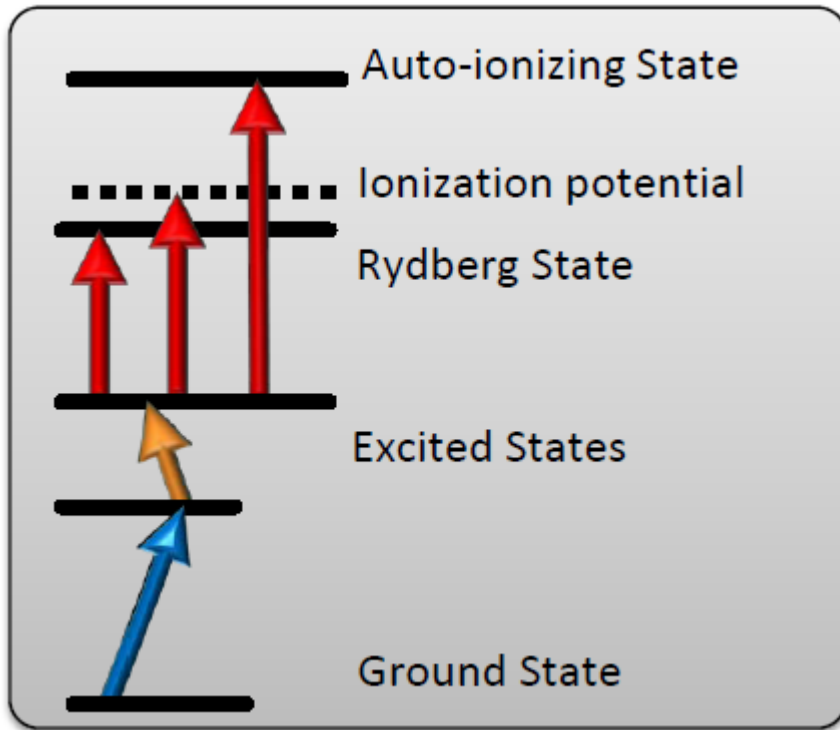


Determination of the atomic properties of Astatine



- ❖ Determination of ionizing potential
- ❖ Identification of new atomic transitions
- ❖ Comparison with atomic theory
- ❖ Scan of ionizing laser: converging Rydberg levels allow precise determination of the IP
- ❖ laser spectroscopy
- ❖ Test of atomic theory and quantum chemistry
- ❖ Properties of chemical homologue $Z = 117$
- ❖ New beams / exotic decay modes: β -fission
- ❖ Potential development of ^{211}At as a medical radioisotope

The resonance ionization laser ion source (RILIS)

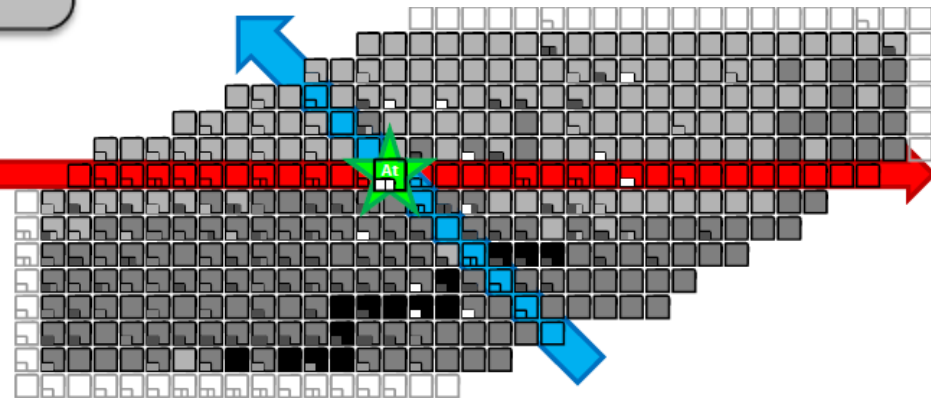


Z selective

Laser tuned to $Z = 85$



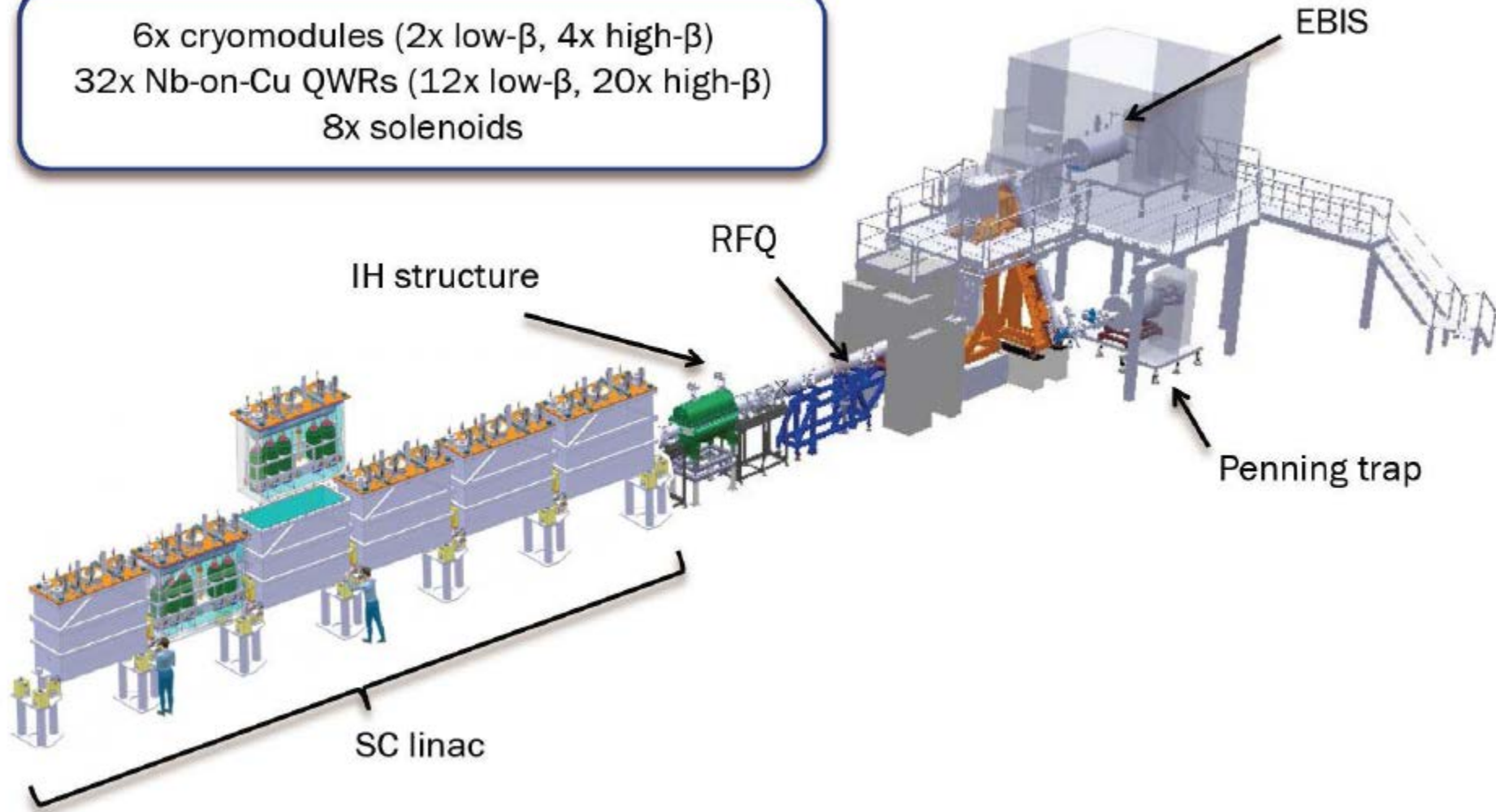
Courtesy RILIS team



Magnet set to $A = 205$

40 MV post-accelerator

6x cryomodules (2x low- β , 4x high- β)
32x Nb-on-Cu QWRs (12x low- β , 20x high- β)
8x solenoids



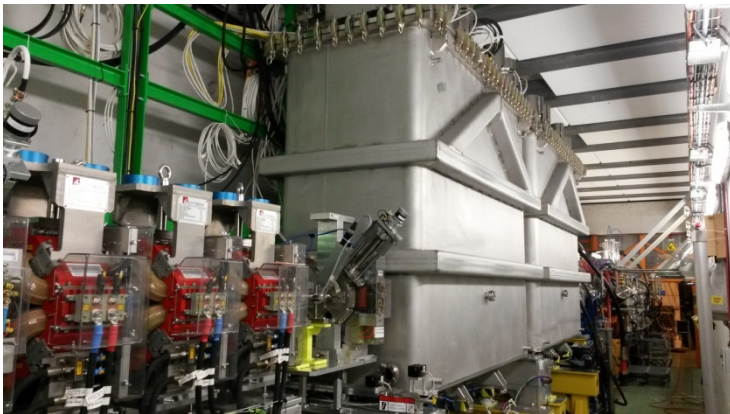
40 MV post-accelerator



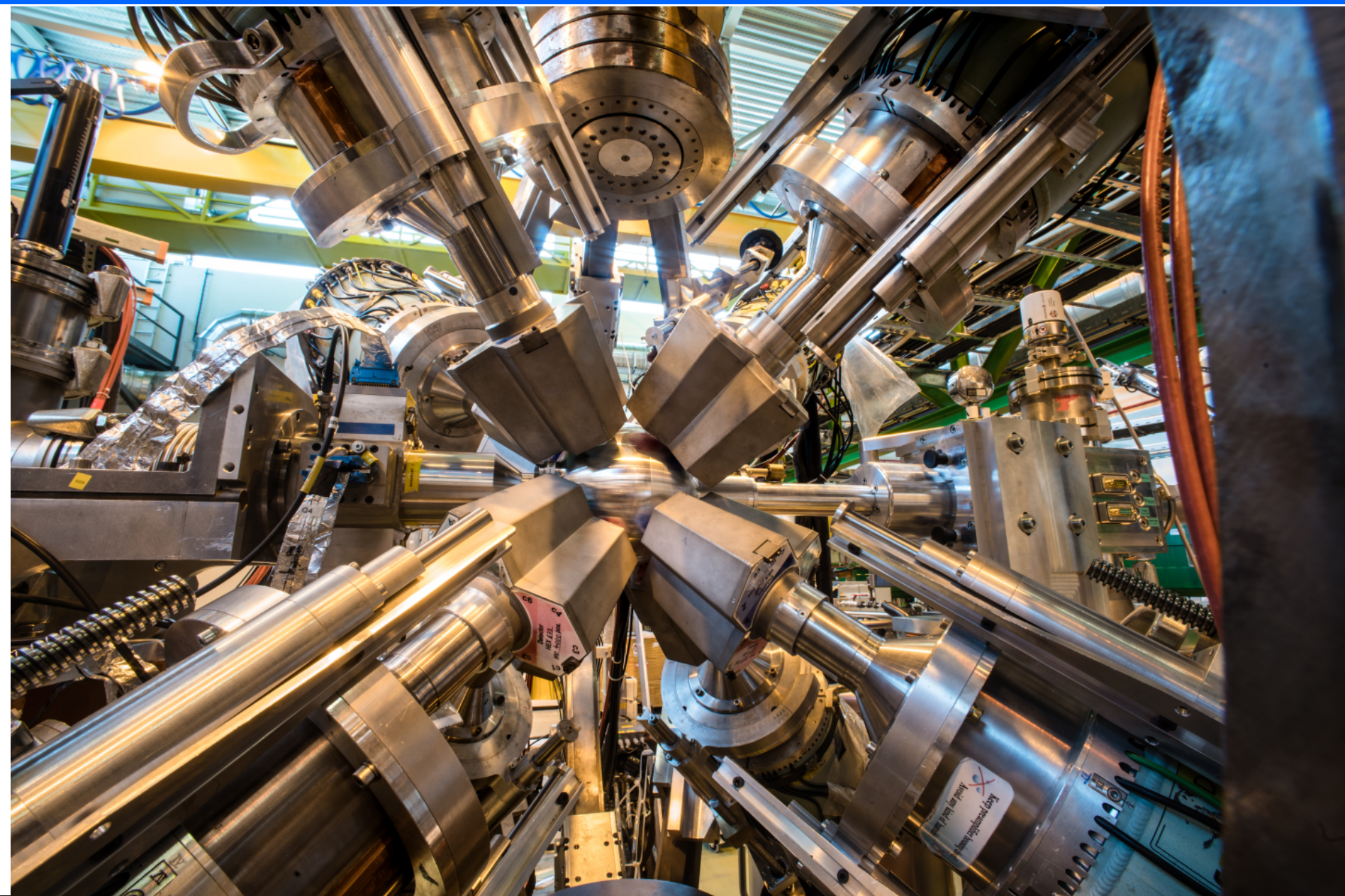
HIE-ISOLDE has innovated many new ideas, particularly in space-saving solutions. One way the engineers kept the system compact was to build cryomodules that each contain five cavities, not just one (Image: Maximilien Brice/ CERN)



The new linac had to fit into just 16 m of space. “We had to develop a very compact linac. That’s what makes it unique. In other facilities, every cavity has its own cryostat but if we had to do that it would be far too long, so we had to squeeze all of them into one cryomodule. We had to have the solenoids fitted too, they’re almost the same length as a cavity, so we had to do lots of design, research and development. The biggest challenge was to design in spaces with clearances of just 1 mm,” explains Yacine Kadi, project leader for HIE-ISOLDE. (Image: Maximilien Brice/CERN)



The Miniball Germanium Array



Coulomb excitation experiments at REX-Isolde

