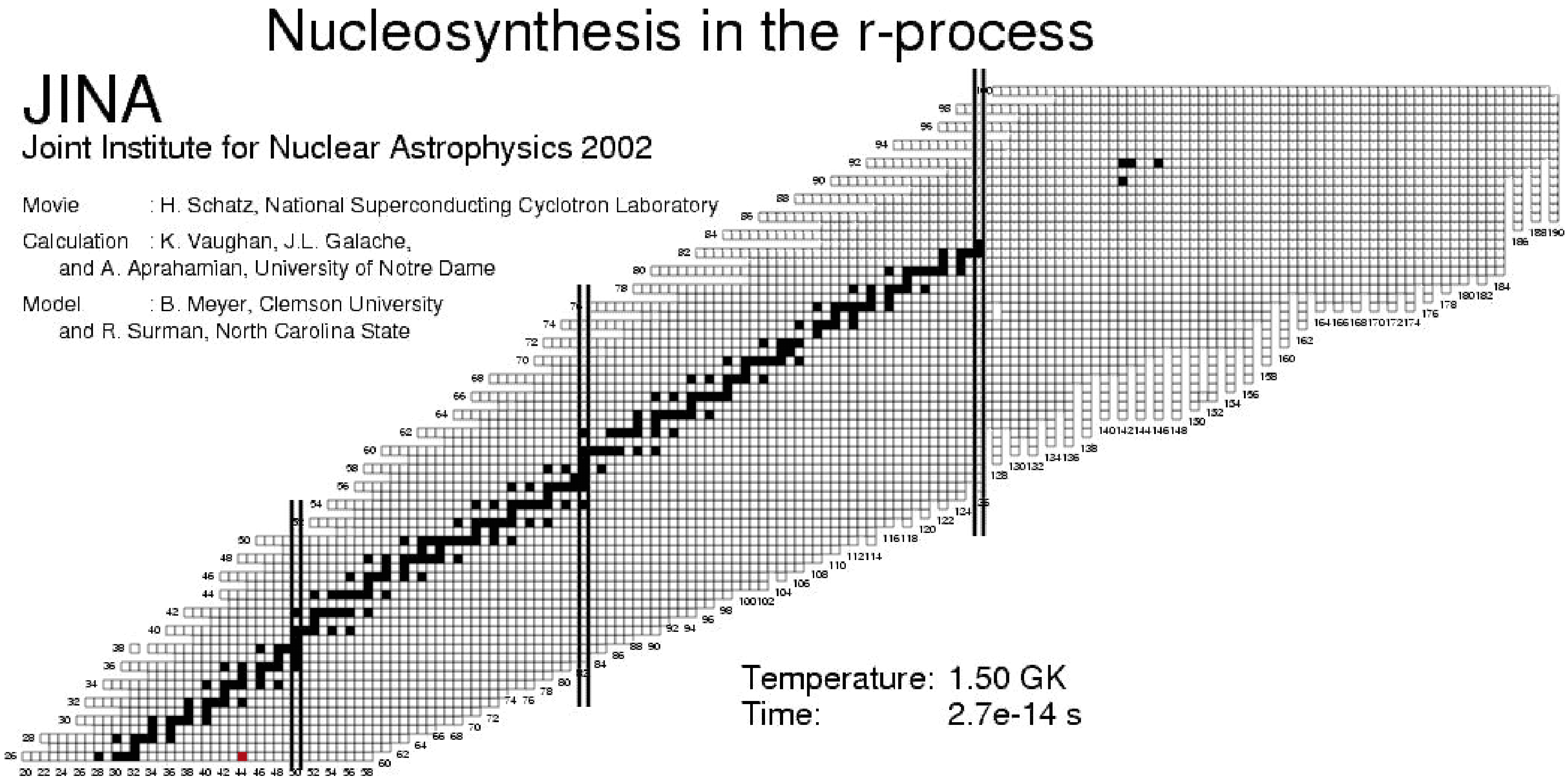
Radioactive Ion Beams



Nucleosynthesis in the r-process

JINA

Joint Institute for Nuclear Astrophysics 2002

Movie : H. Schatz, National Superconducting Cyclotron Laboratory

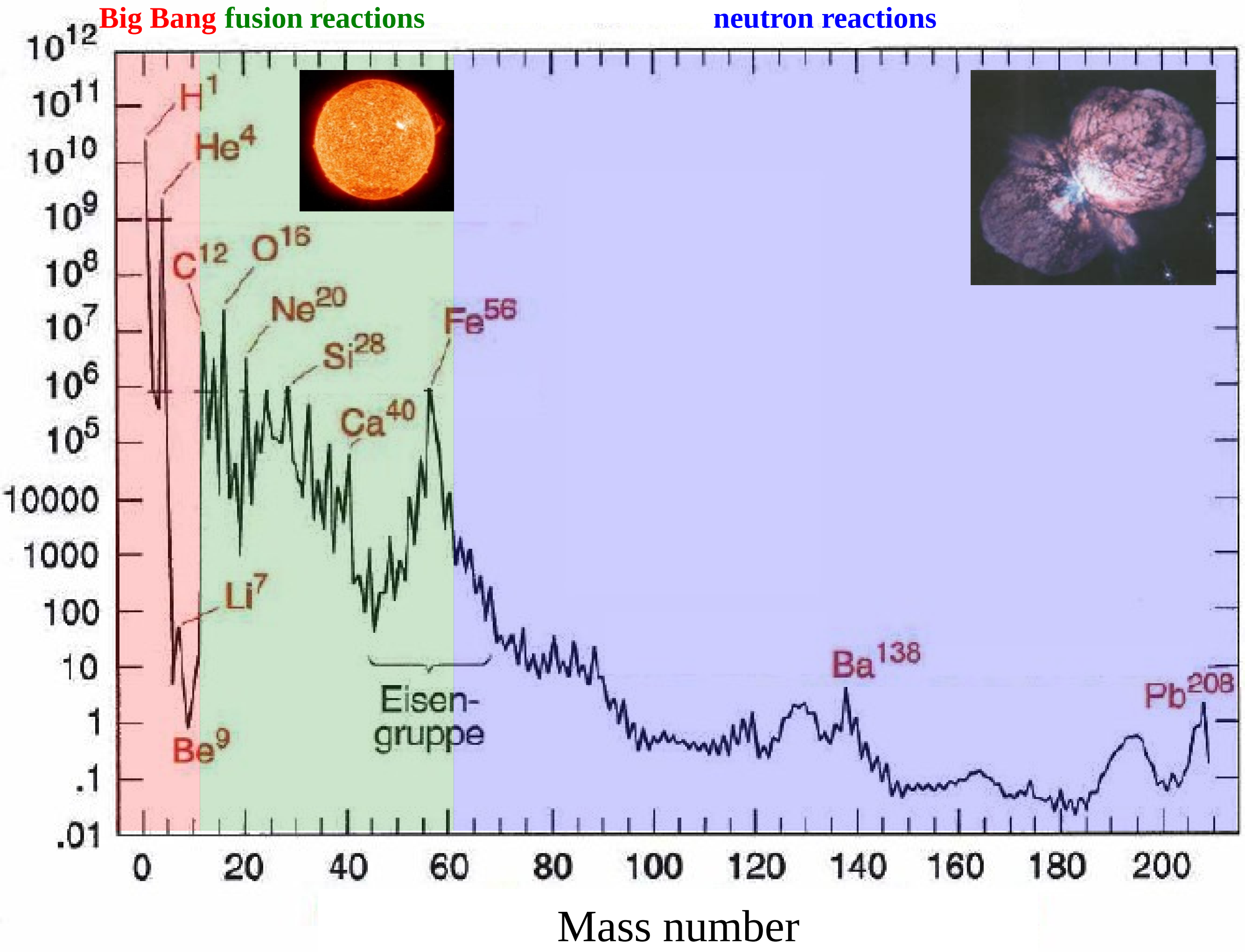
Calculation : K. Vaughan, J.L. Galache,
and A. Aprahamian, University of Notre Dame

Model : B. Meyer, Clemson University
and R. Surman, North Carolina State

Temperature: 1.50 GK
Time: 2.7e-14 s

Solar abundances of elements

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

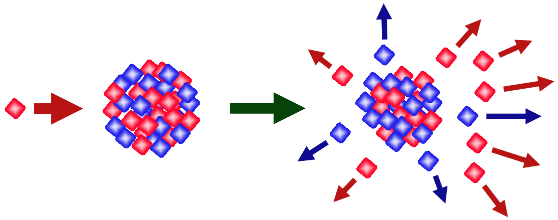


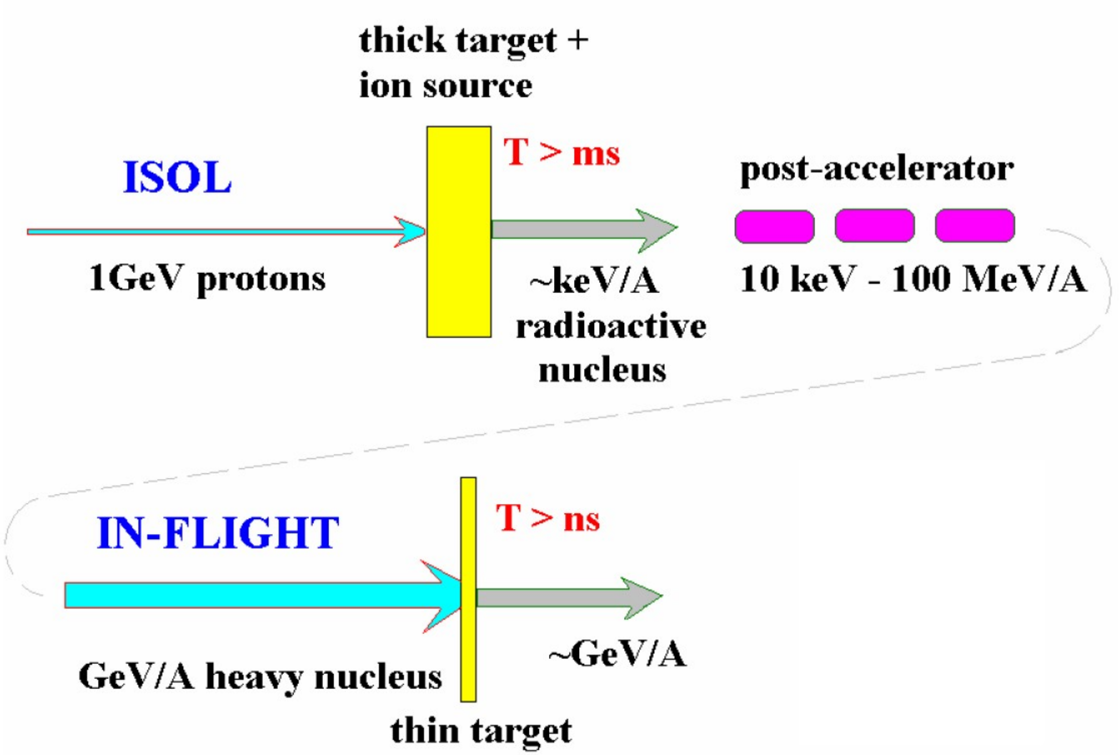
open questions:

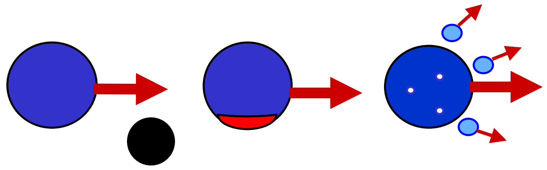
- Why is Fe more common than Au ?
- Why do the heavy elements exist and how are they produced?
- Can we explain the solar abundances of the elements?

Spallation & Projectile Fragmentation Reactions

Spallation







Fragmentation

High-energy proton-induced nuclear reactions

Some early high-energy proton accelerators:

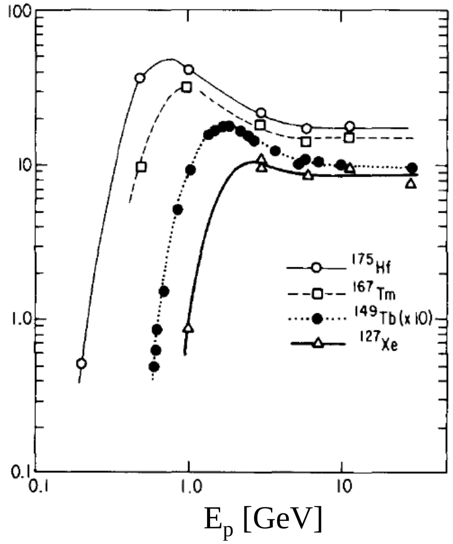
Facility	Energy	from year
Bevatron (Berkeley)	6 GeV	1954.....
AGS (Brookhaven)	11 GeV	1960.....
Fermilab (Chicago)	>300 GeV	1967.....

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

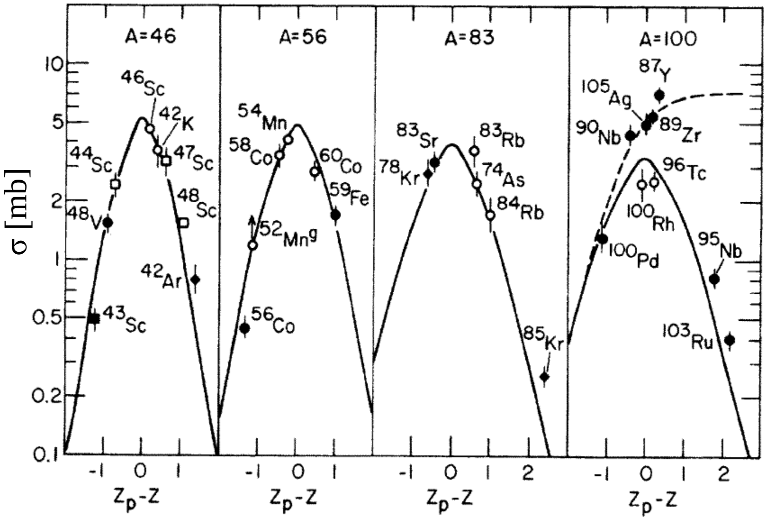
⇒ **Production cross sections and (some) kinematics for suitable radioactive isotopes**

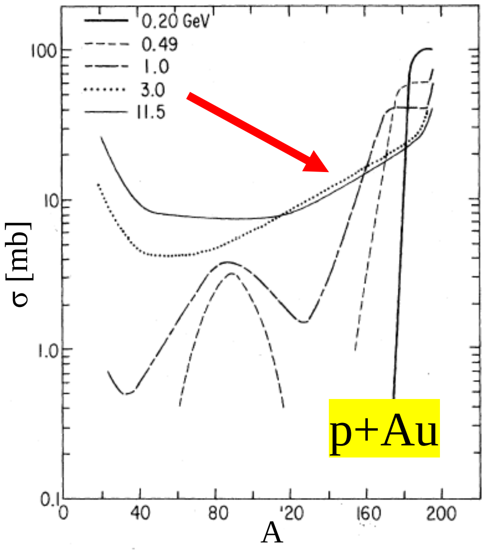
High-energy proton-induced nuclear reactions



Important findings:

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





- Mass yields: exponential slope

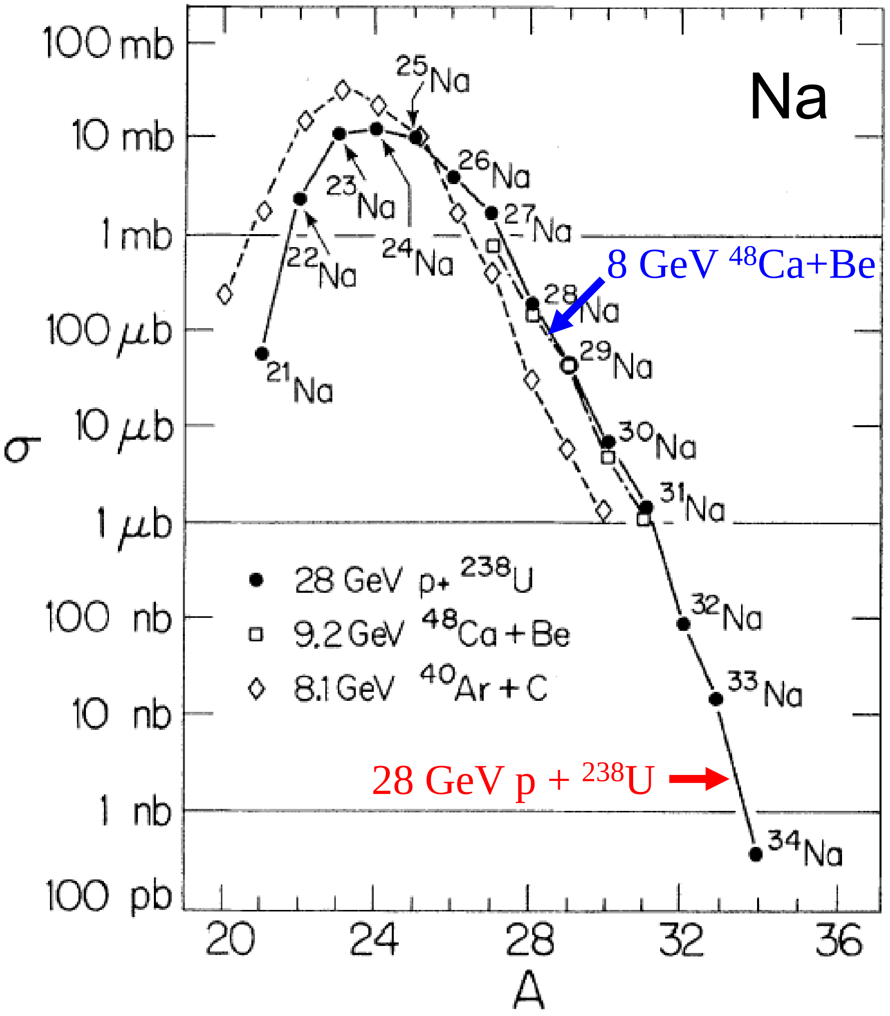
Proton- vs. heavy-ion induced reactions

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

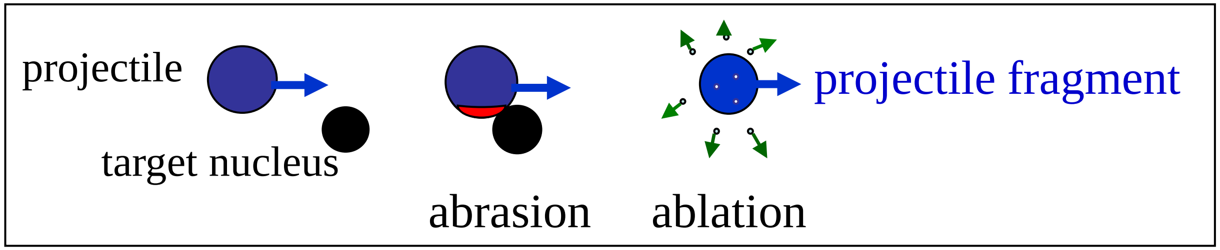
Target fragmentation: $\text{GeV } p + A_{target} \rightarrow A$

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

are equivalent



Projectile fragmentation reactions



At GeV energies nucleons can be regarded as a classical particles

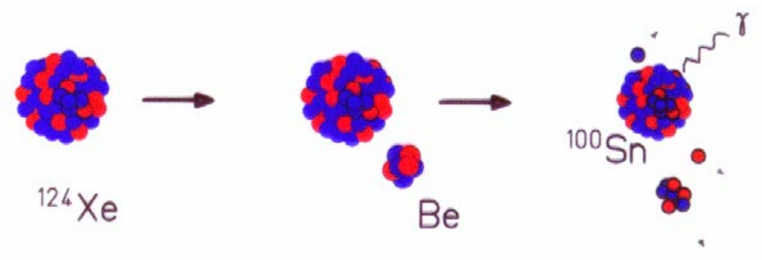
- Nucleon-nucleon collisions can be treated classically using measured free nucleon-nucleon cross sections (intra-nuclear cascade).
- In these collisions very *little transfer momentum* is exchanged.
- After the cascade the residual nucleus is *highly excited*.
- Heavy-ion projectiles can be treated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

Physical models: Two-step approach

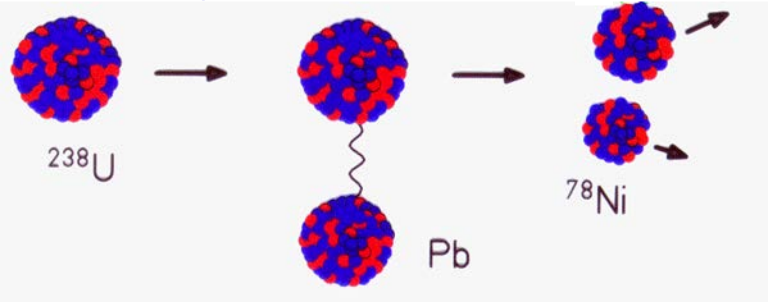
Step 1: **Intranuclear-cascade** models or **Abrasion** models
Step 2: **Evaporation** calculation

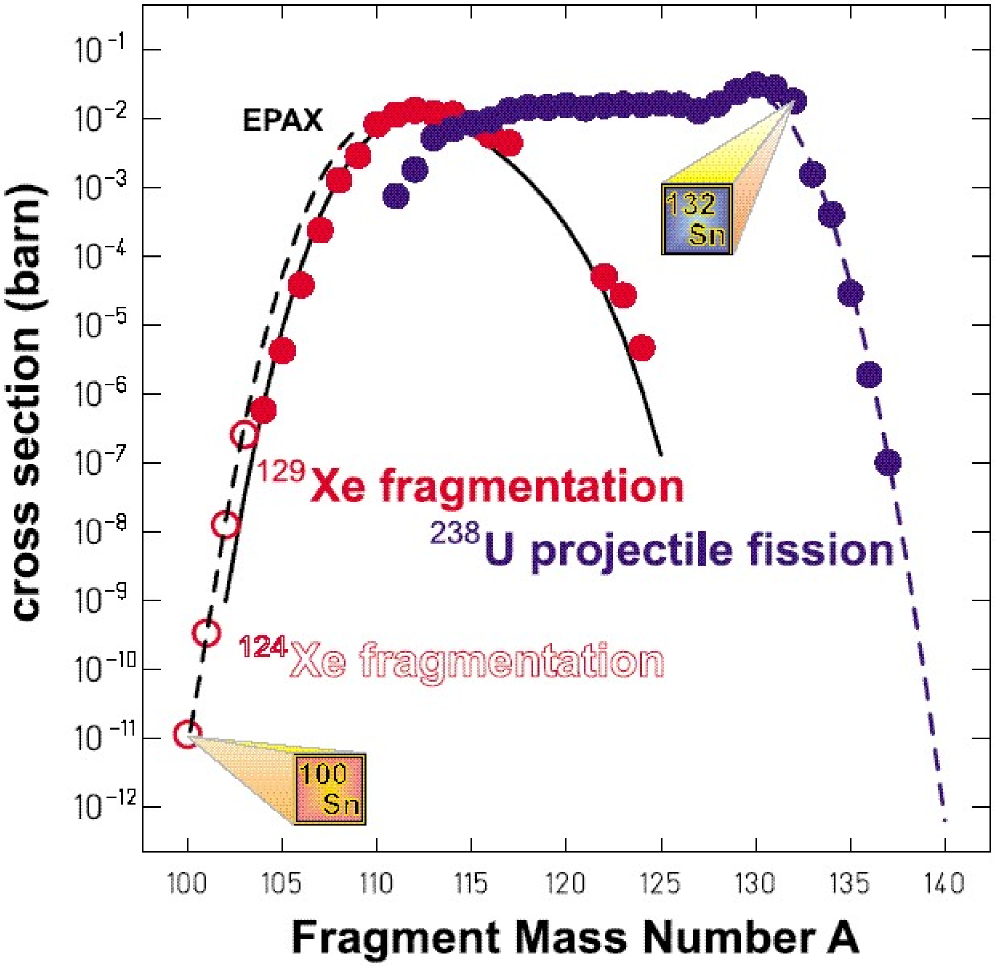
Projectile fragmentation reactions

Projectile Fragmentation

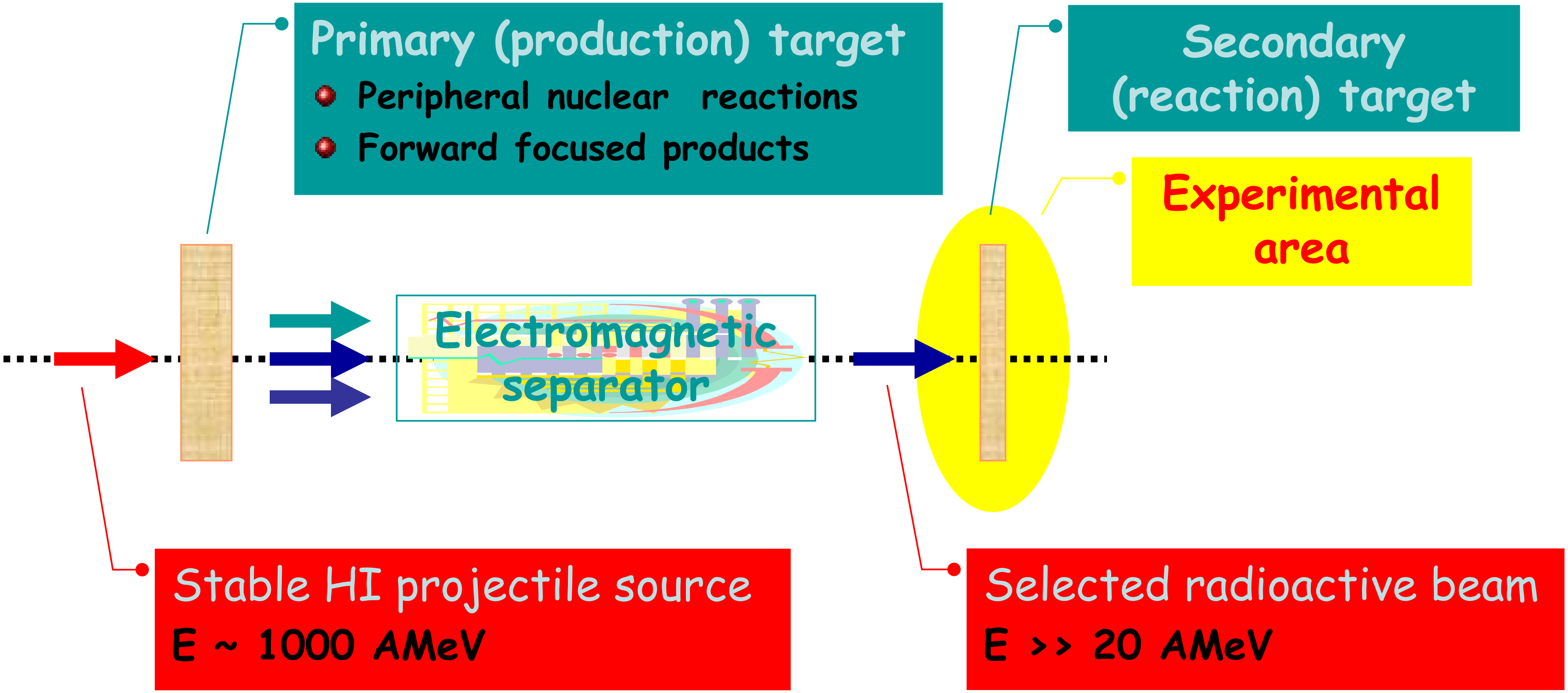


Projectile Fission





In-Flight Separation of Radioactive Ion Beams



Primary (production) target

- Peripheral nuclear reactions
- Forward focused products

Secondary (reaction) target

Experimental area

Electromagnetic separator

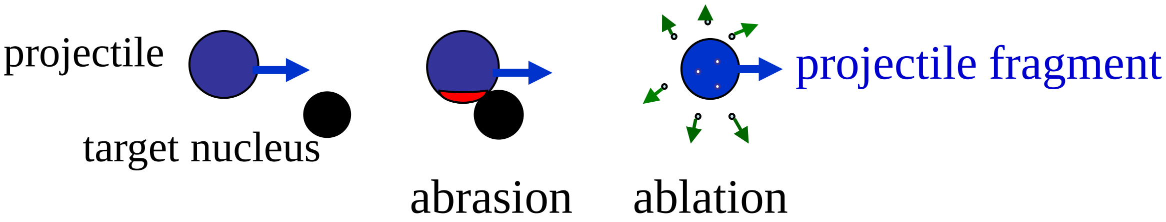
Stable HI projectile source

E ~ 1000 AMeV

Selected radioactive beam

E >> 20 AMeV

Fragmentation at Relativistic Energies



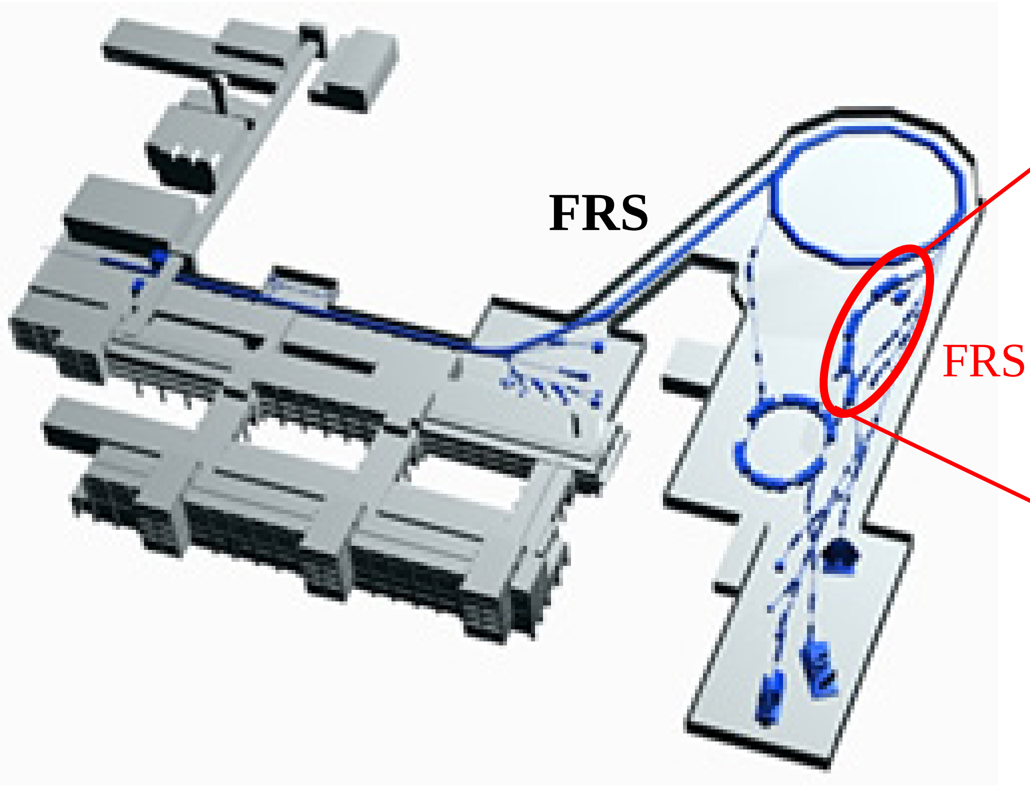
projectile

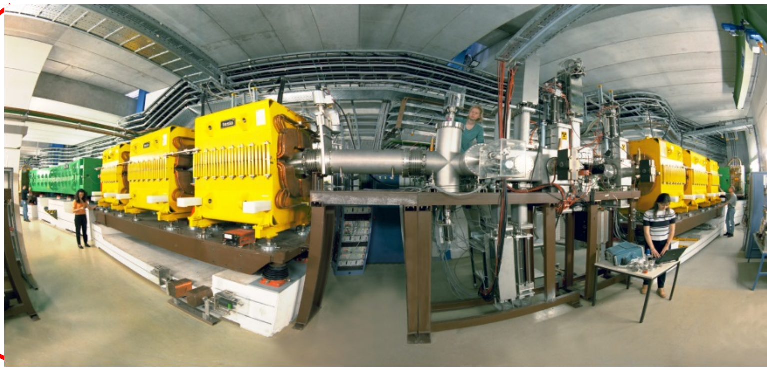
target nucleus

abrasion

ablation

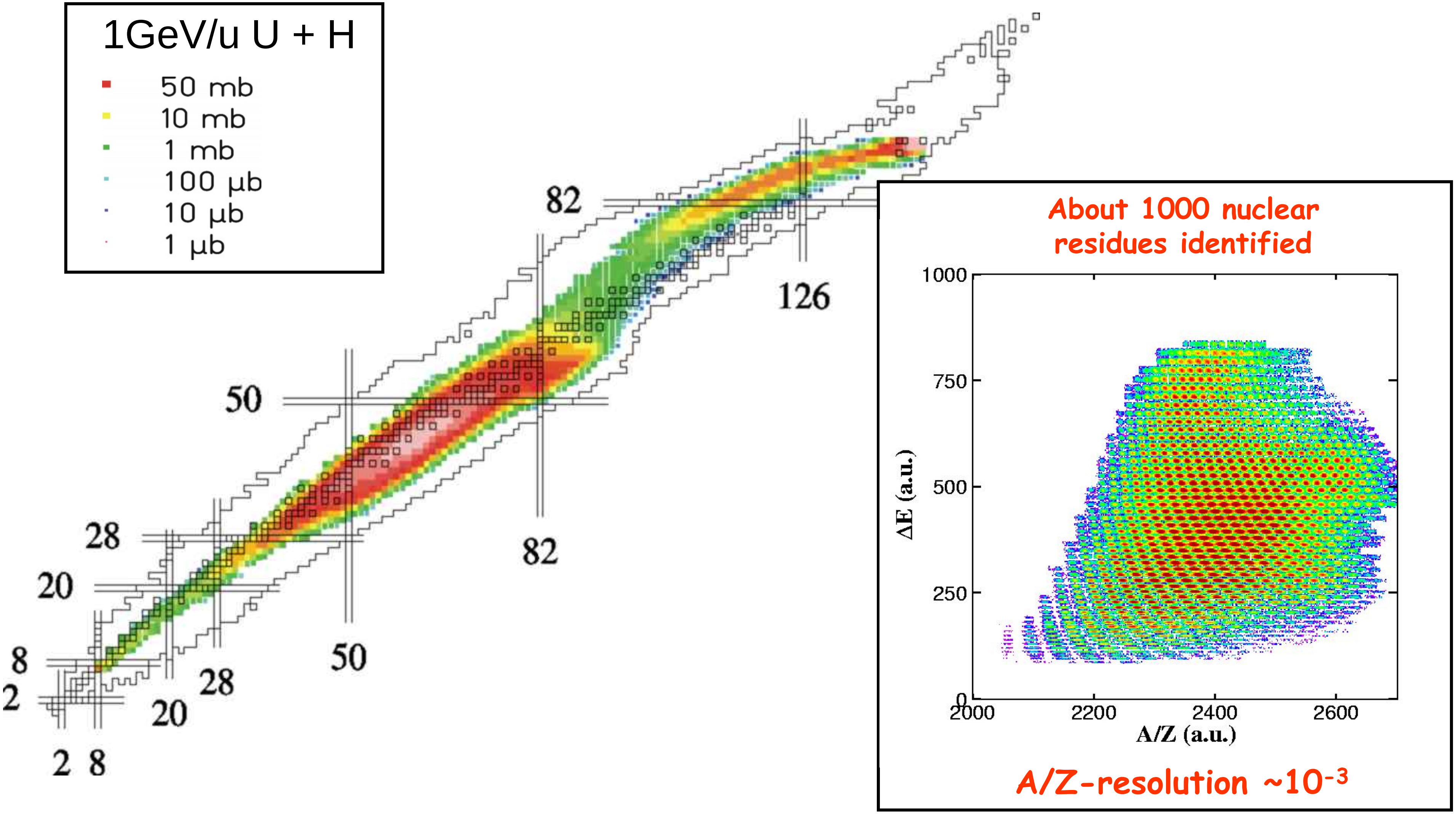
projectile fragment





FRagment **S**eparator

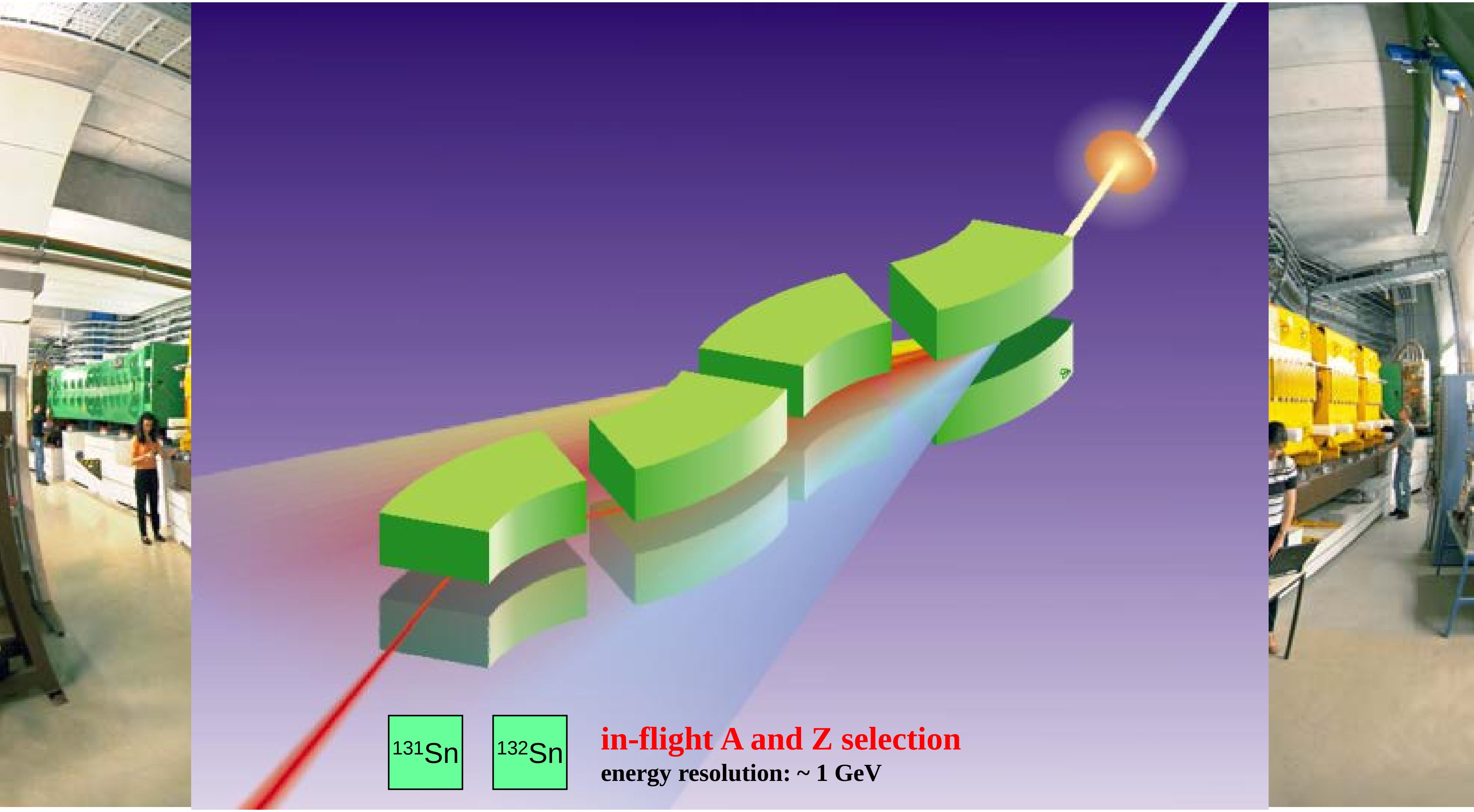
Radioactive Ion Beams at GSI



About 1000 nuclear residues identified

A/Z-resolution ~10^{-3}

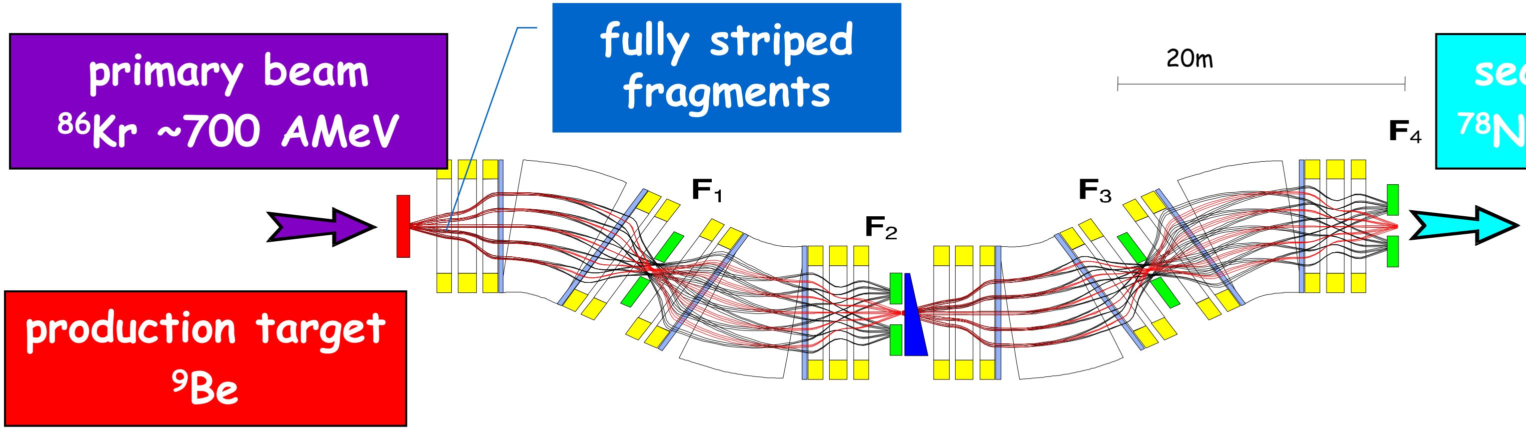
FRagment Separator at GSI



in-flight A and Z selection

energy resolution: ~ 1 GeV

Rare Isotope Selection at FRS: Bρ-ΔE-Bρ Selection

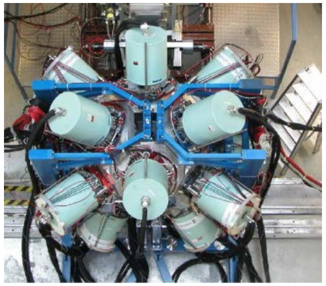


primary beam
^{86}Kr ~700 AMeV

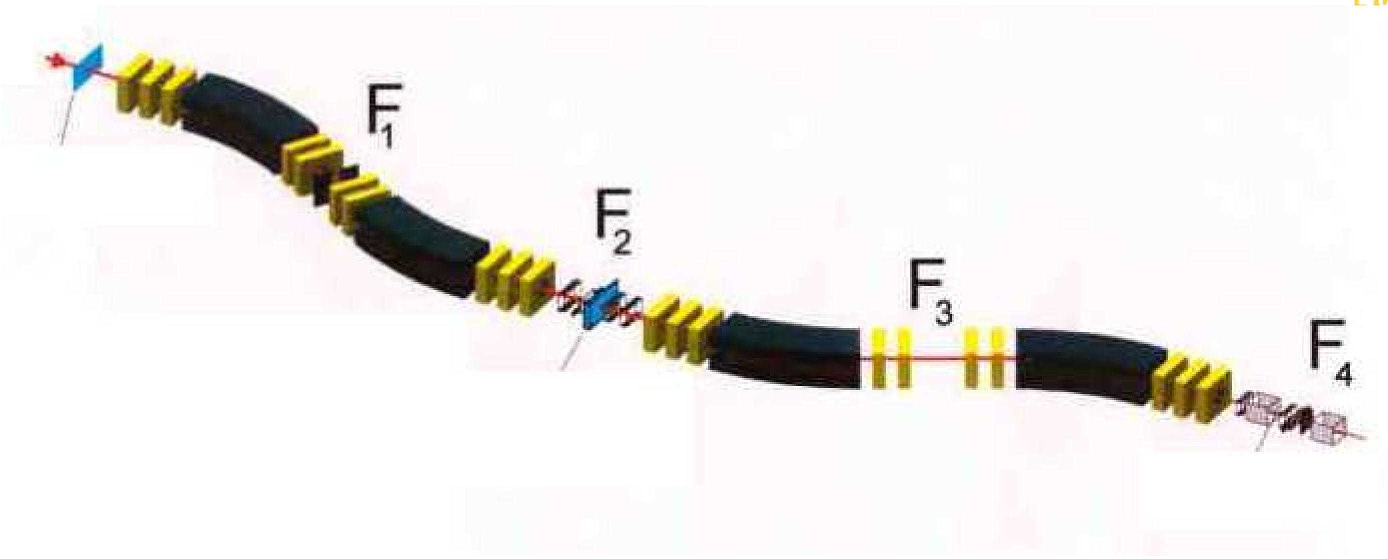
fully striped fragments

production target
^{9}Be

secondary beam
^{78}Ni ~ 100 AMeV



ISING



Rare Isotope Selection at FRS: Bρ-ΔE-Bρ Selection

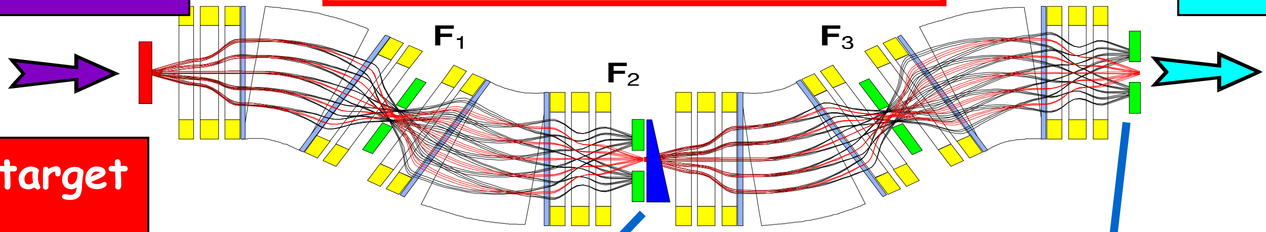
Transmission :

- 20-70 % for fragmentation
- < 2 % for fission

primary beam
^{86}Kr ~700 AMeV

production target
^{9}Be

secondary beam
^{78}Ni ~ 100 AMeV



magnetic dipoles

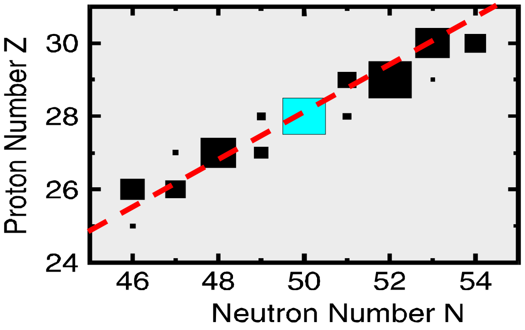
$B\rho \propto \beta\gamma A/Z$

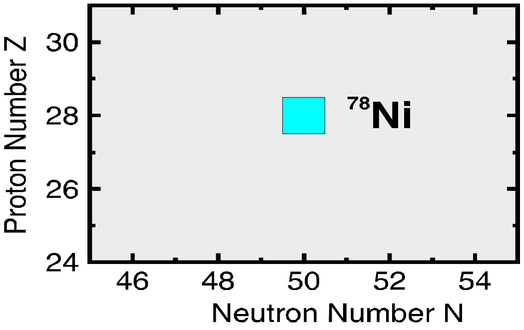
degrader

$\Delta E \propto Z^2 f(\beta)$

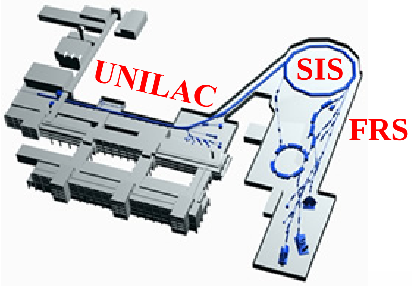
magnetic dipoles

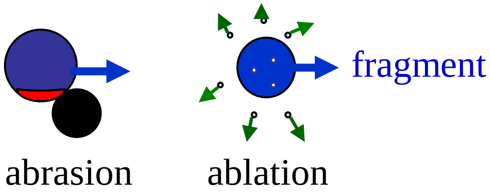
$B\rho \propto \beta\gamma A/Z$

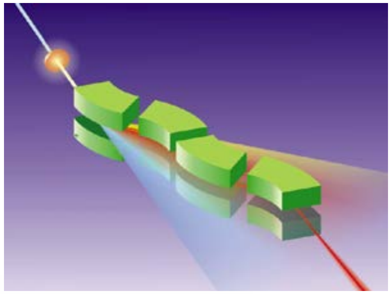




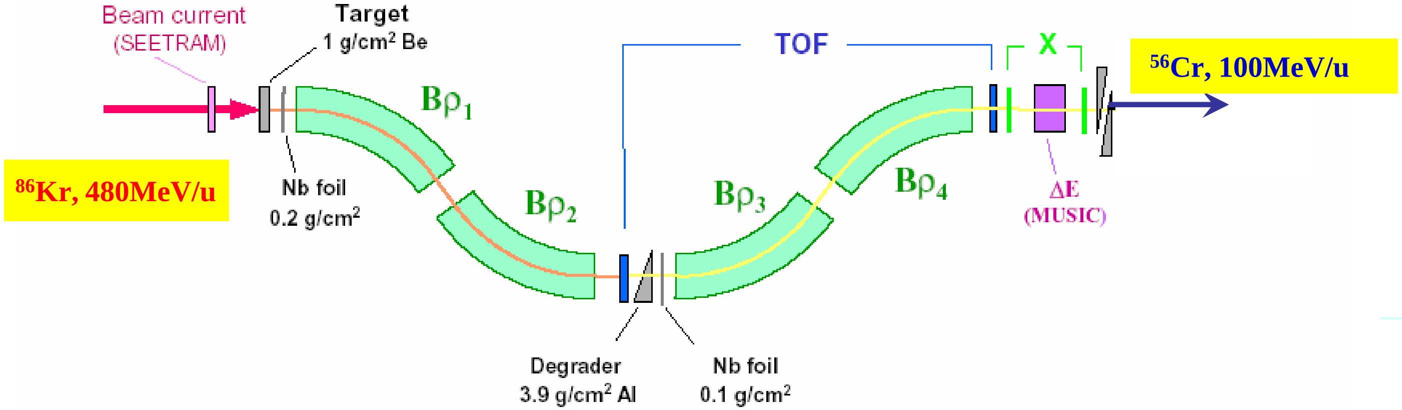
Production, Separation, Identification





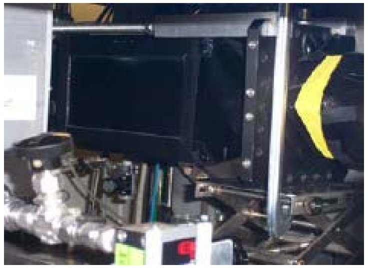


FRagment
Separator

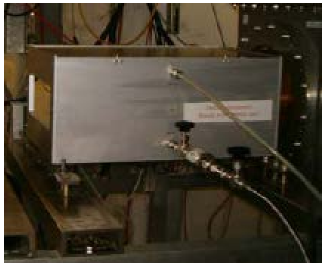


Standard FRS detectors

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

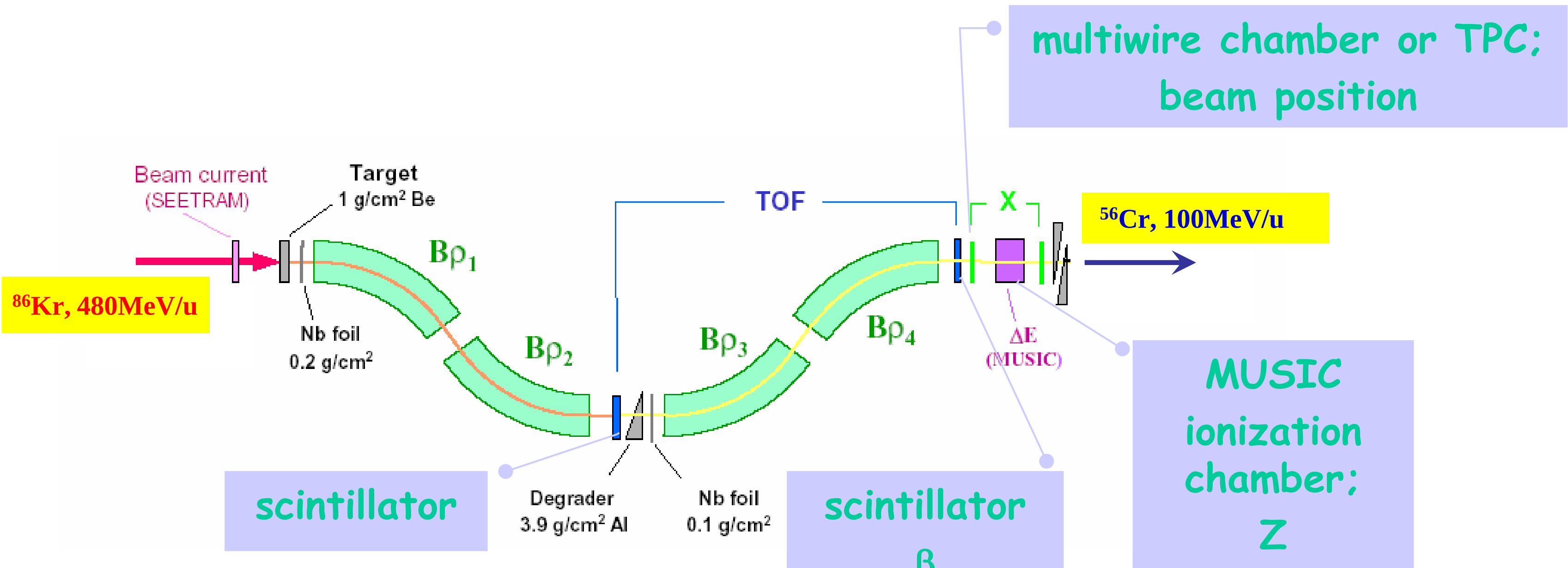


Plastic
scintillator
(**TOF**)
@ S4



MUSIC
(**ΔE**)
@ S4

Production, Separation, Identification

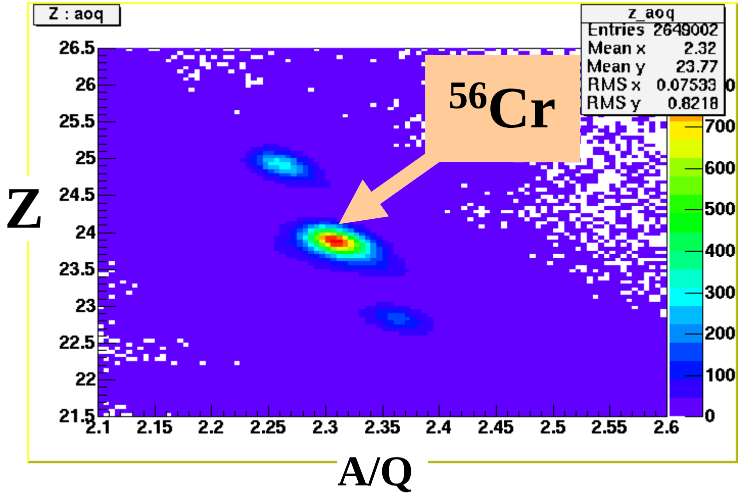


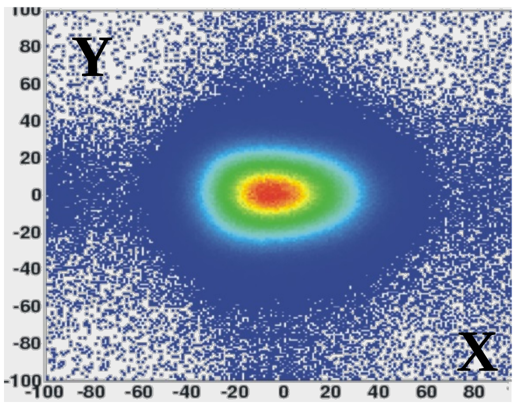
multiwire chamber or TPC;
beam position

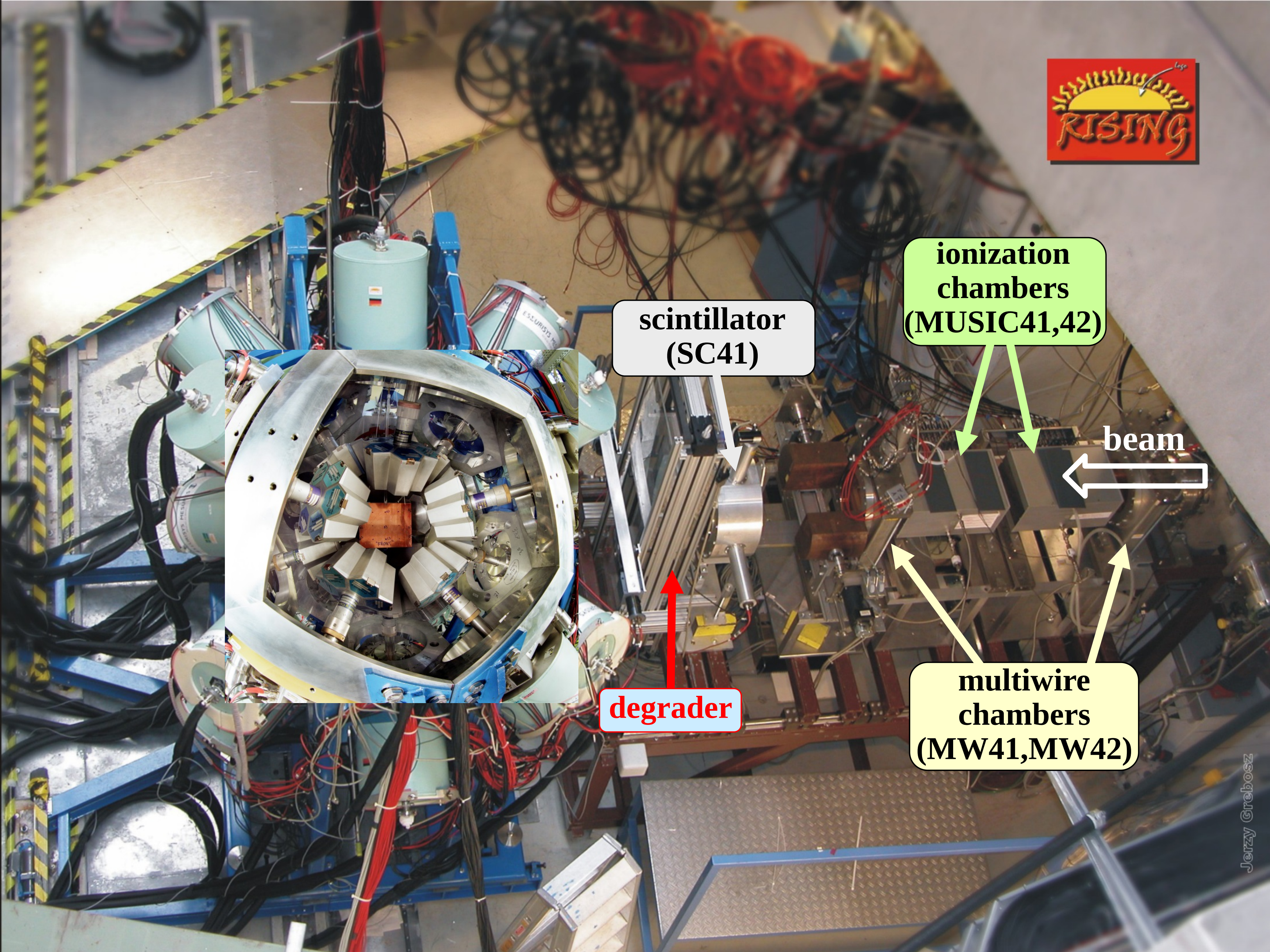
scintillator

scintillator
β

MUSIC
ionization
chamber;
Z







scintillator (SC41)

ionization chambers (MUSIC41,42)

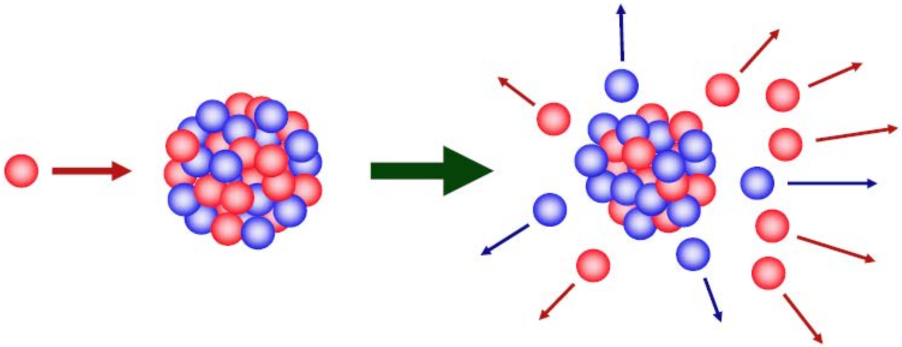
beam

multiwire chambers (MW41,MW42)

degrader

Jerzy Grebosz

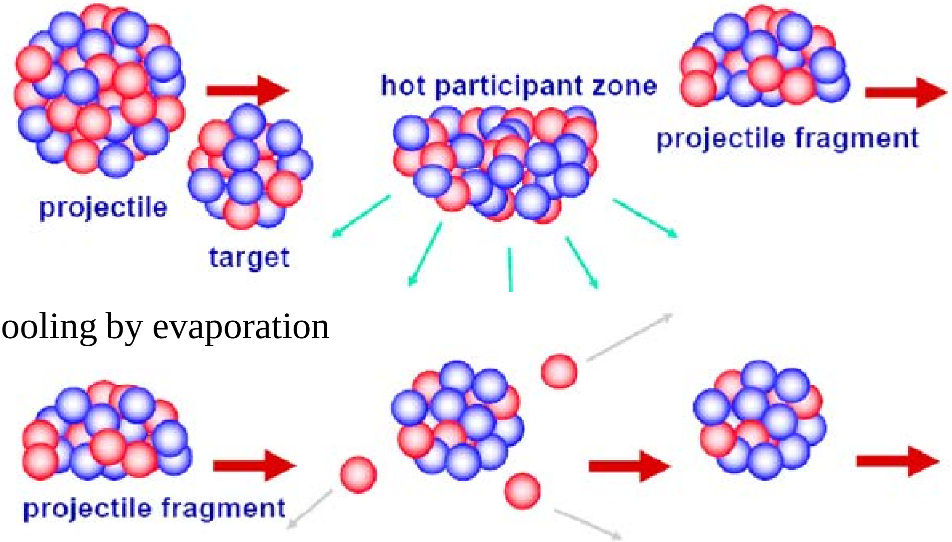
Production of radioactive ion beams



Target fragmentation

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

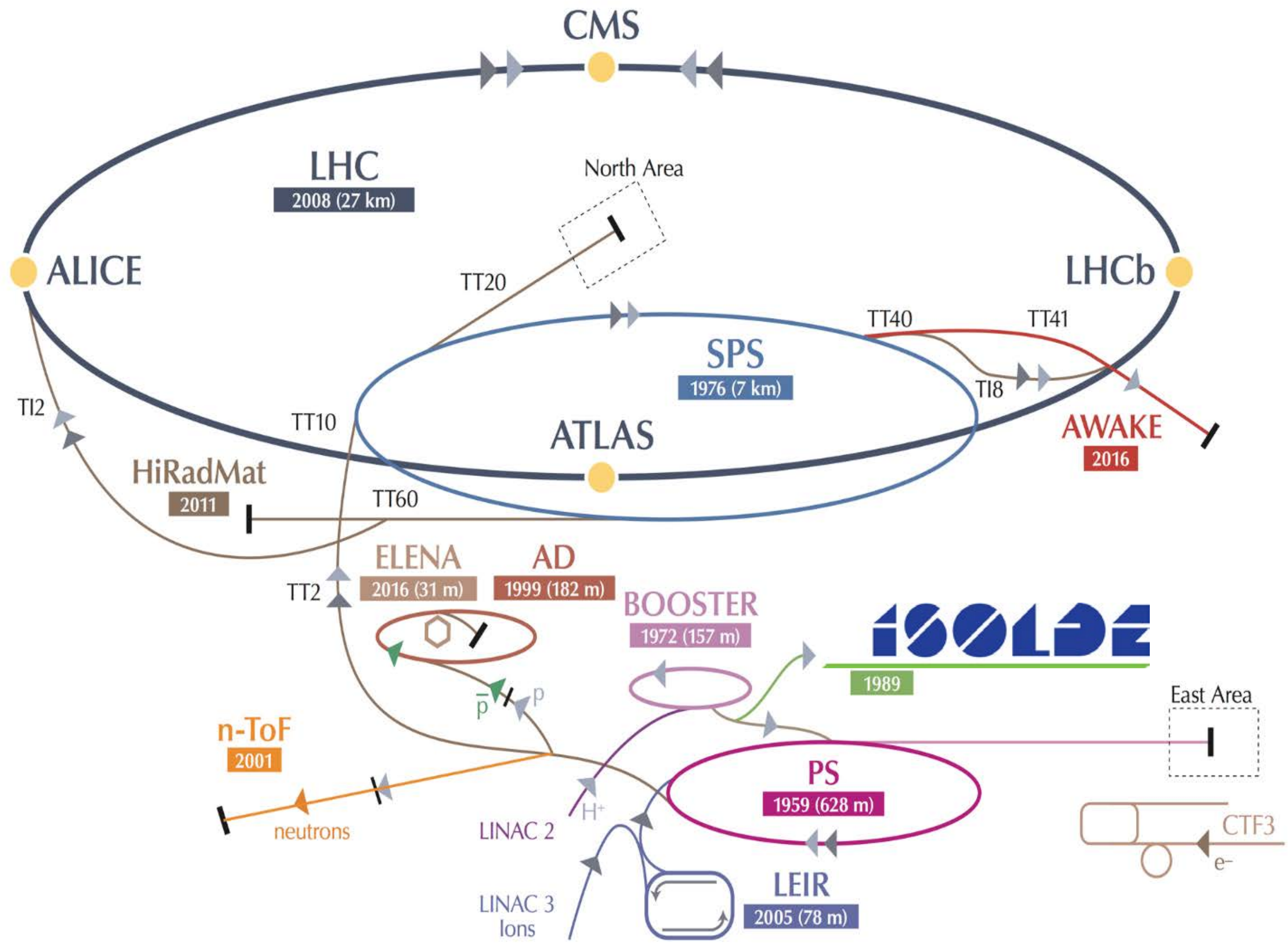
Projectile fragmentation



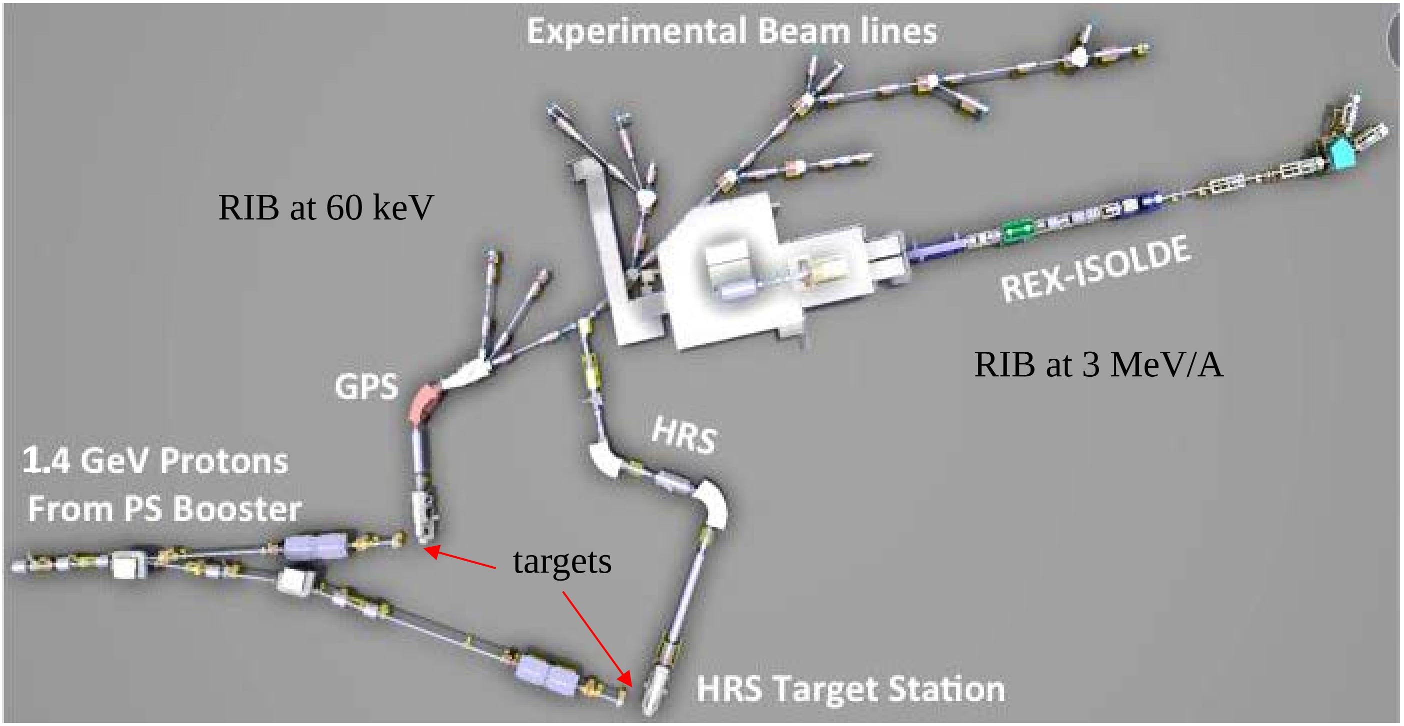
cooling by evaporation

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

ISOLDE at CERN

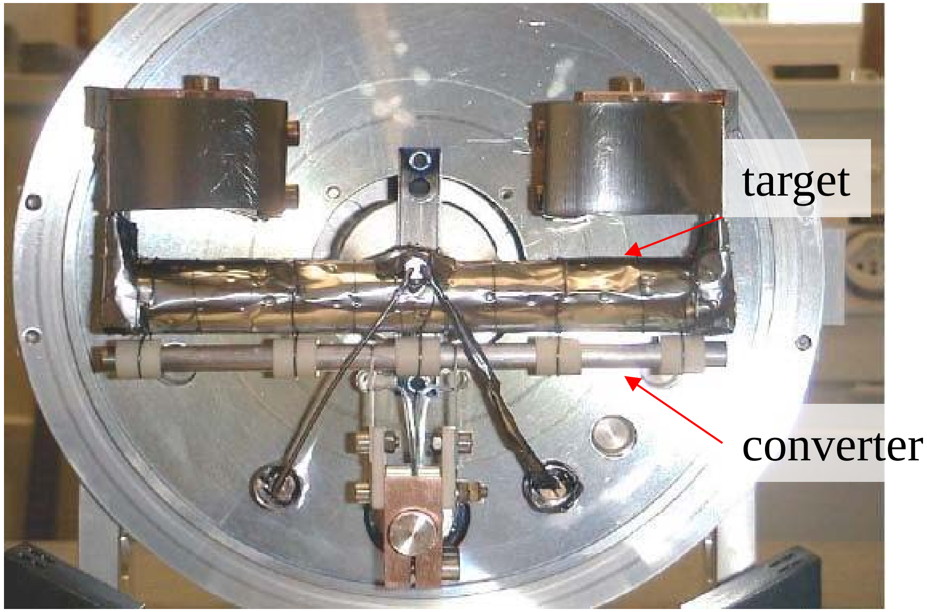


ISOLDE at CERN



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 – 2000^0 C
- Operated by robots due to radiation

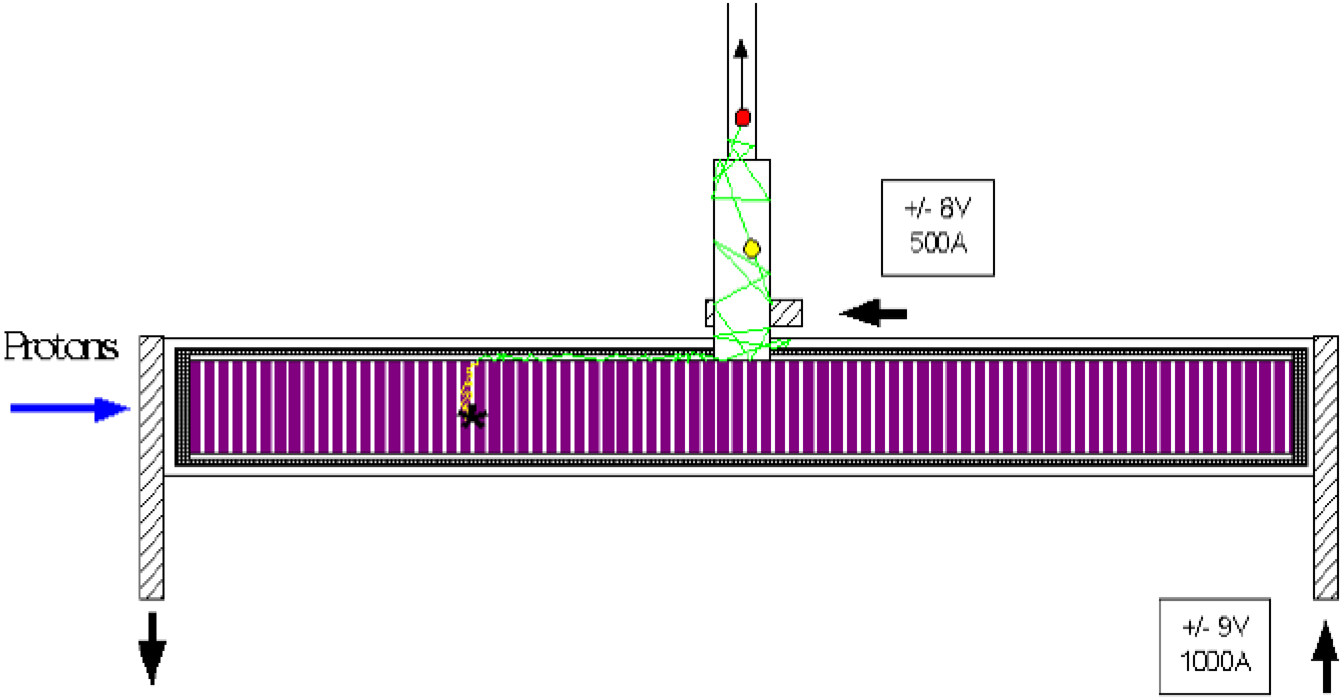


converter target

standard target

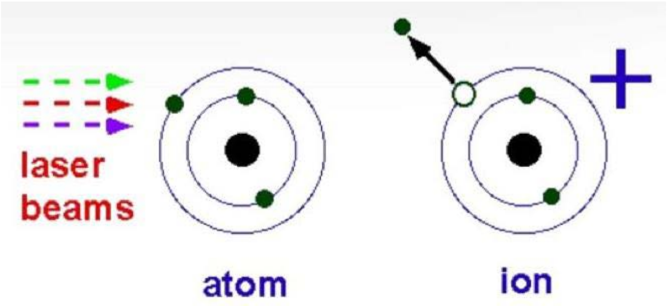
Inside a standard target

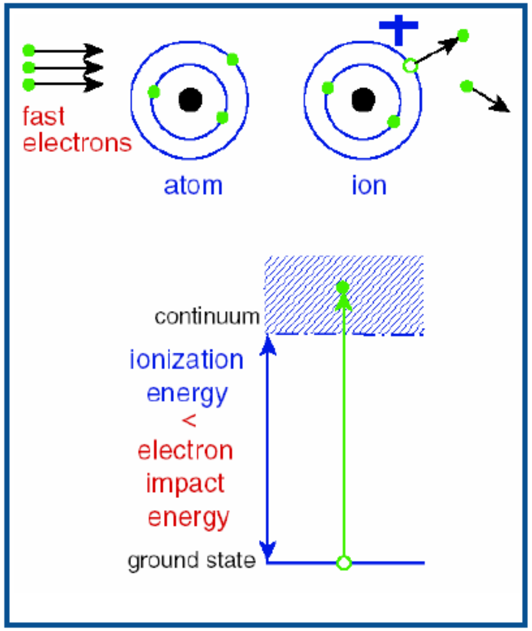
In the early Copenhagen experiments a ten kilo target consisting of a mixture of baking powder [essentially $(NH_4)_2CO_3$] and uranium oxide was used. Fast neutrons from an internal beryllium target in the cyclotron were used to irradiate the external target, and the radioactive isotopes were produced 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.

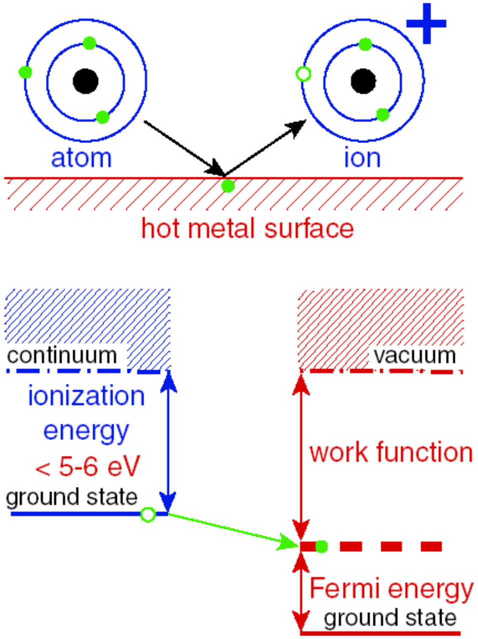


Ionization

- Lasers
- Plasma
- Surface

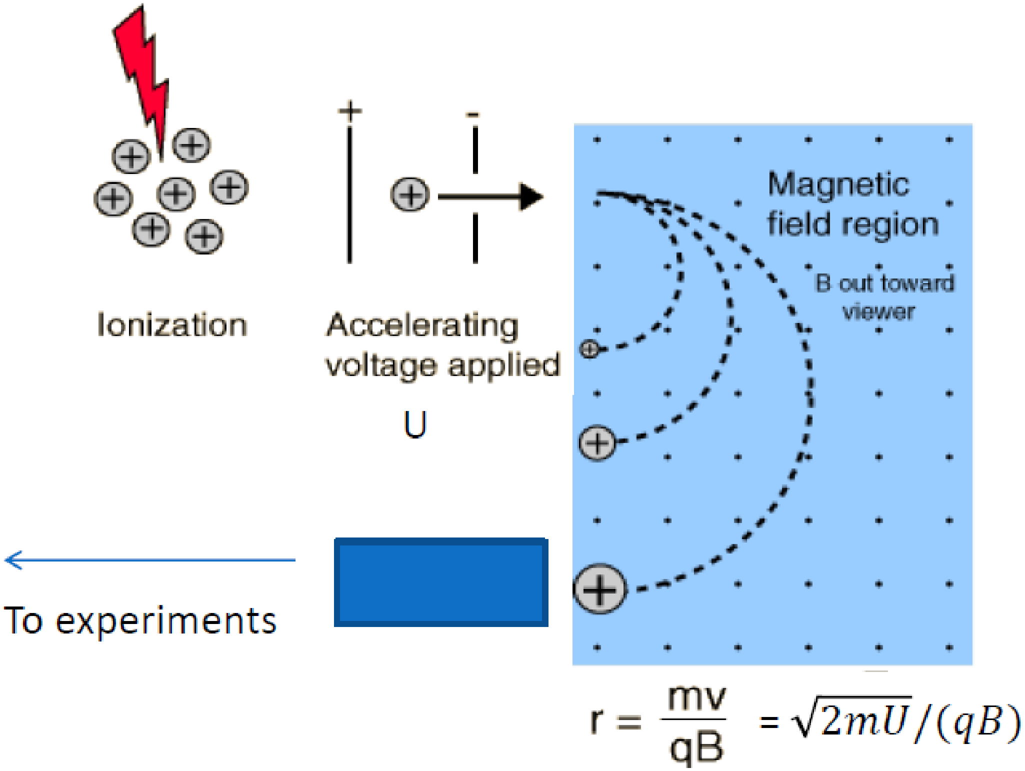






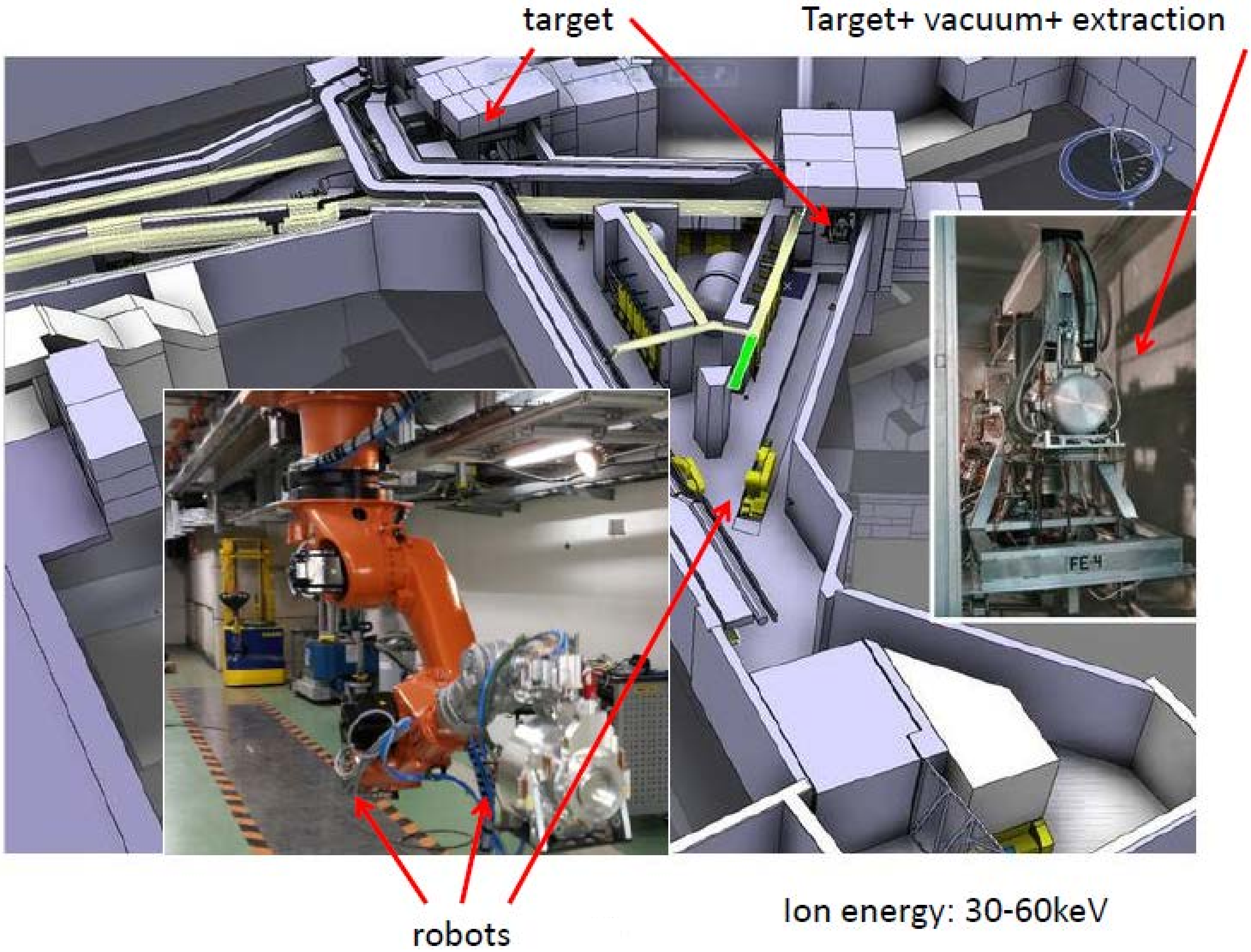
Beam extraction and separation

- 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



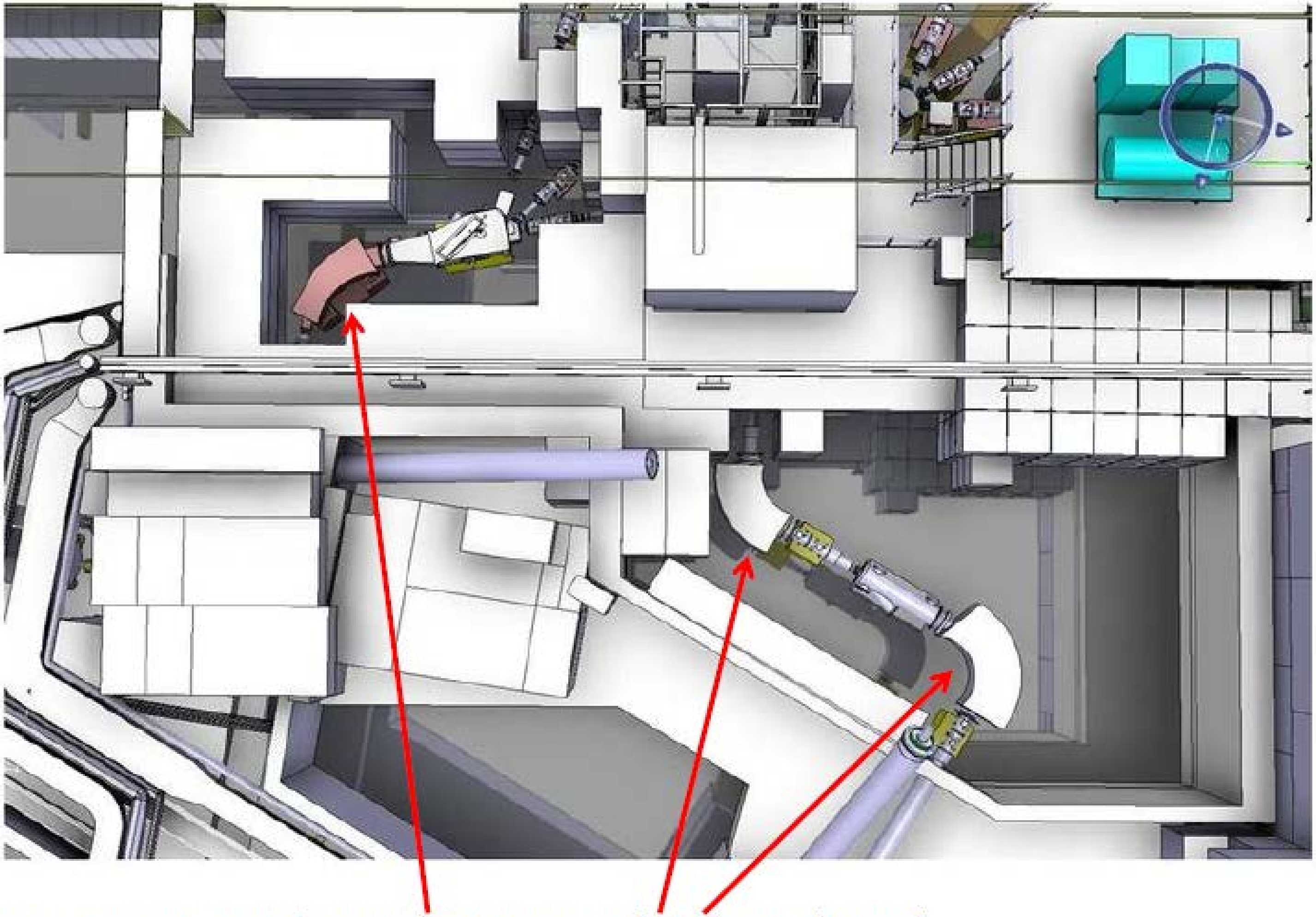
$$r = \frac{mv}{qB} = \sqrt{2mU}/(qB)$$

Production, ionization, extraction



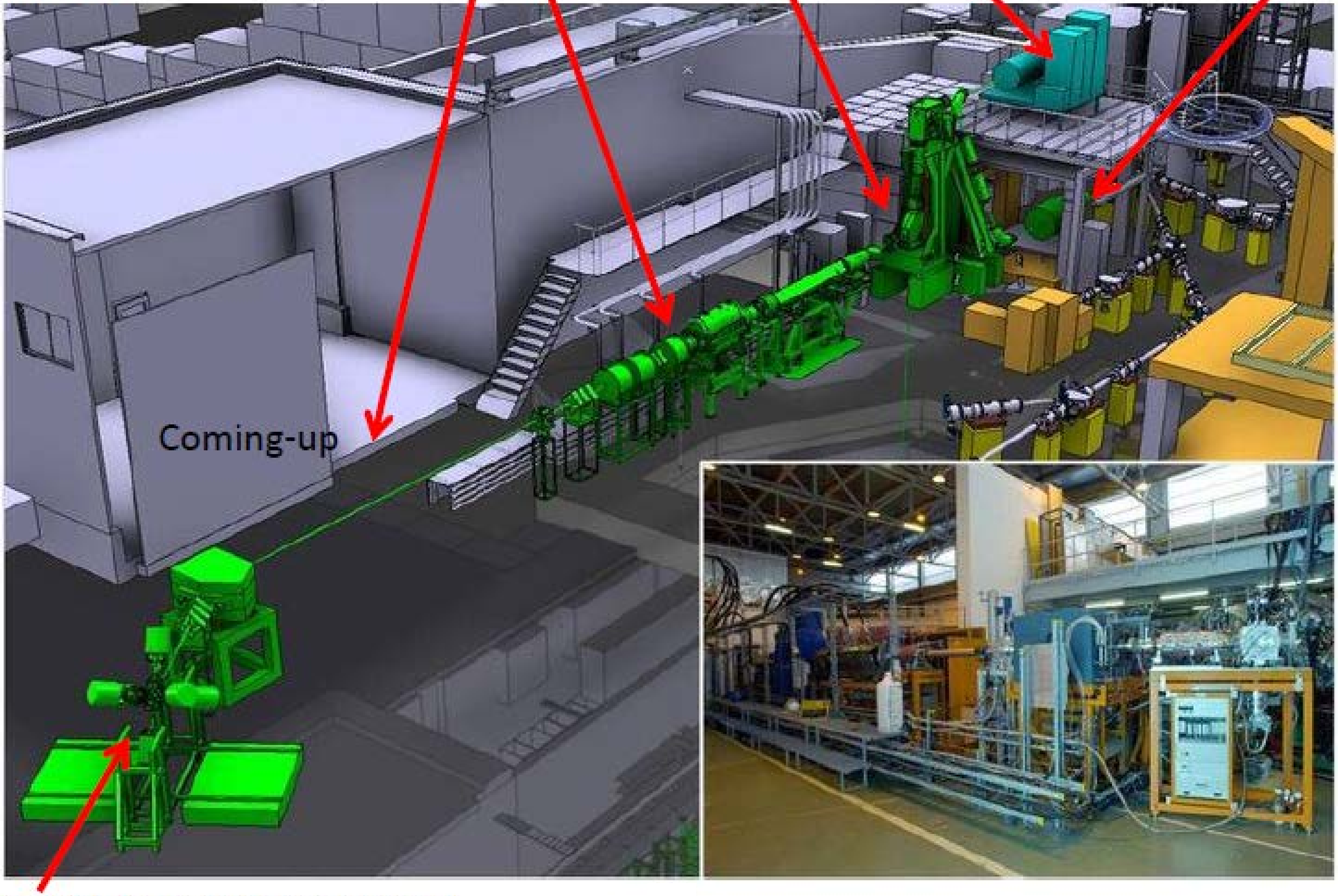
Ion energy: 30-60keV

Separation



Magnet separators (General Purpose and High Resolution)

Post-acceleration



REX and HIE-ISOLDE accelerators

Rf acceleration

A/q selection

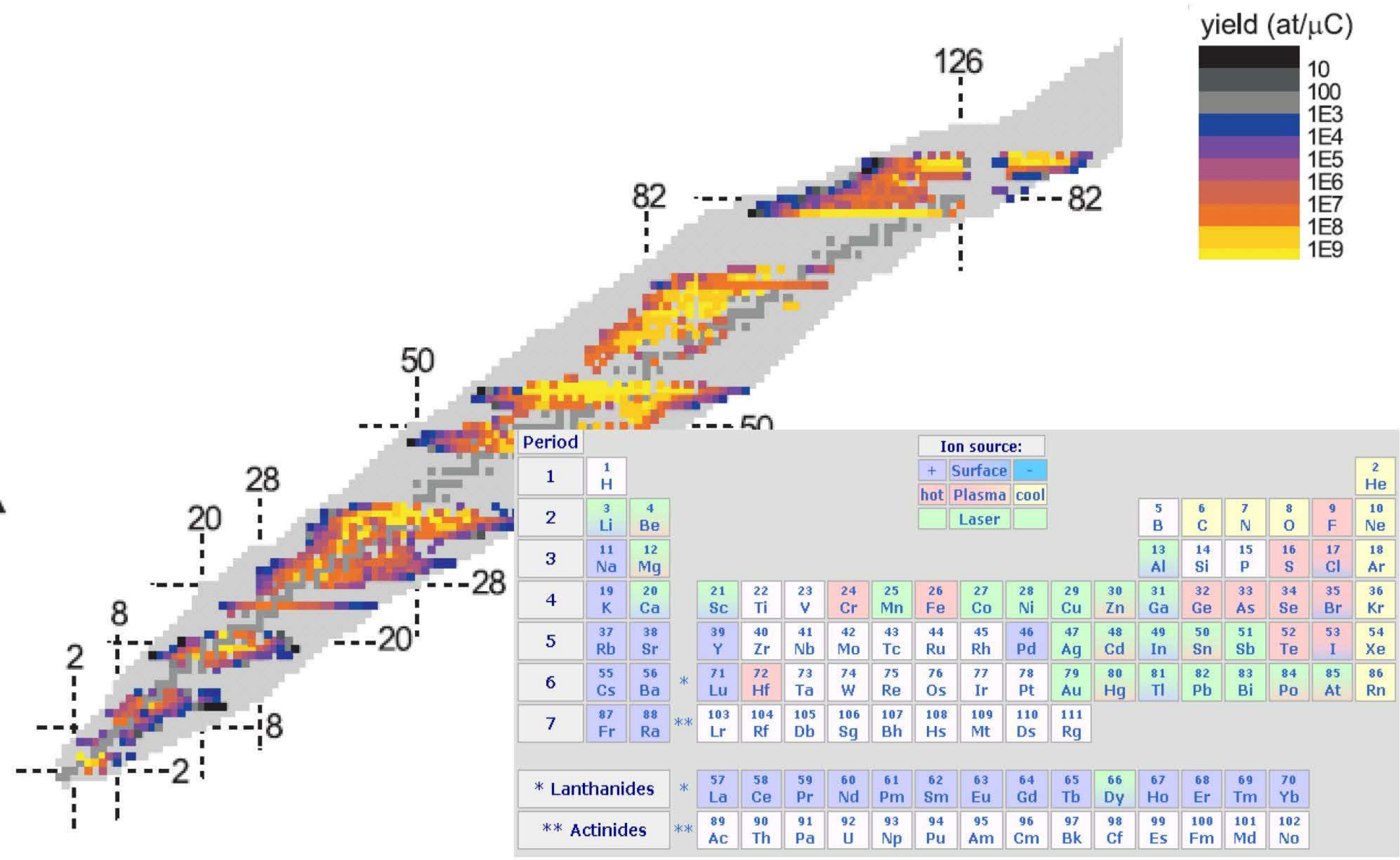
Increase in charge state

Ion trapping and cooling

Coming-up

3MeV*A beam to experiment

Extracted nuclides

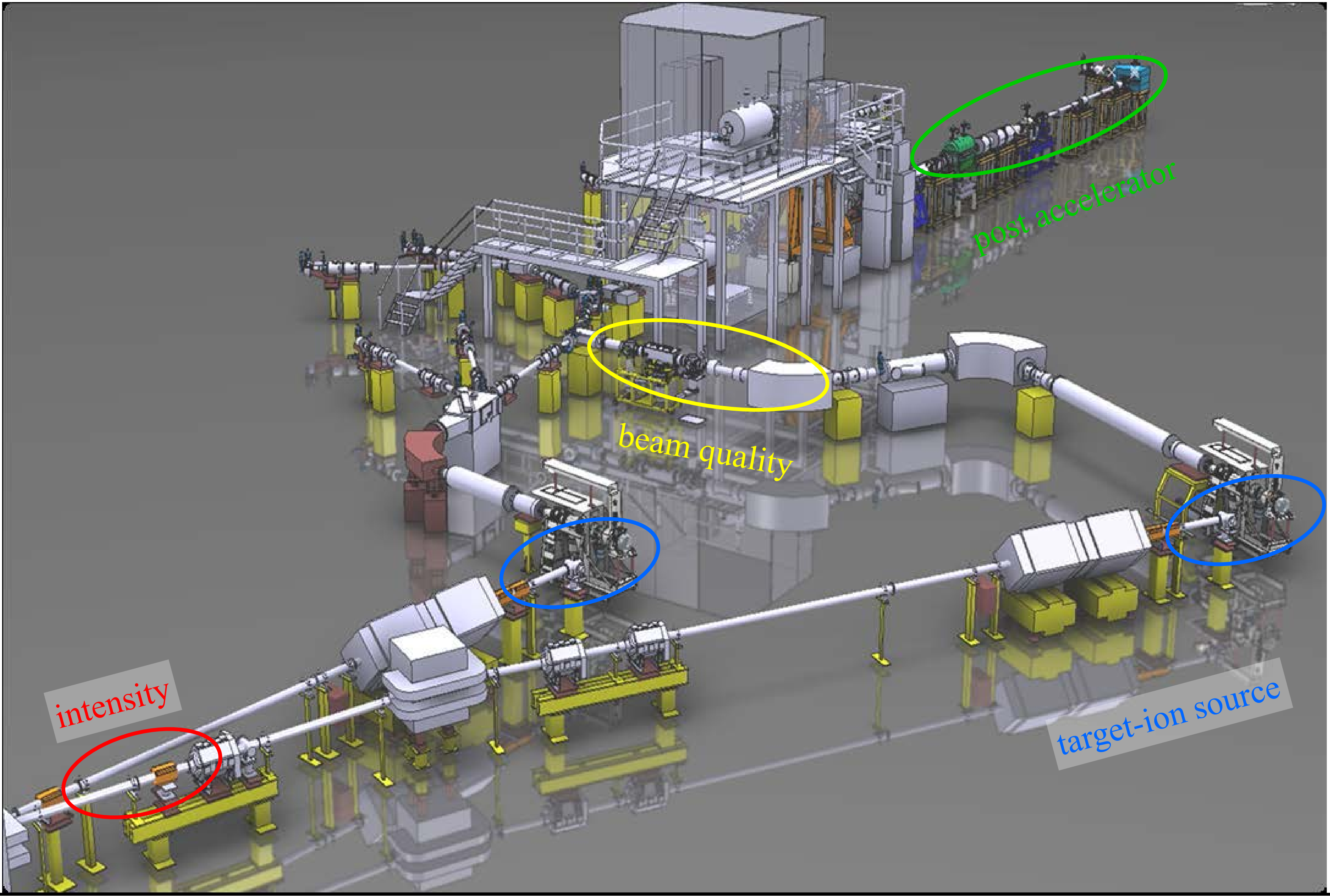


Ion source:

+	Surface	-
hot	Plasma	cool
	Laser	

Period																			
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg							
* Lanthanides			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
** Actinides			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

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

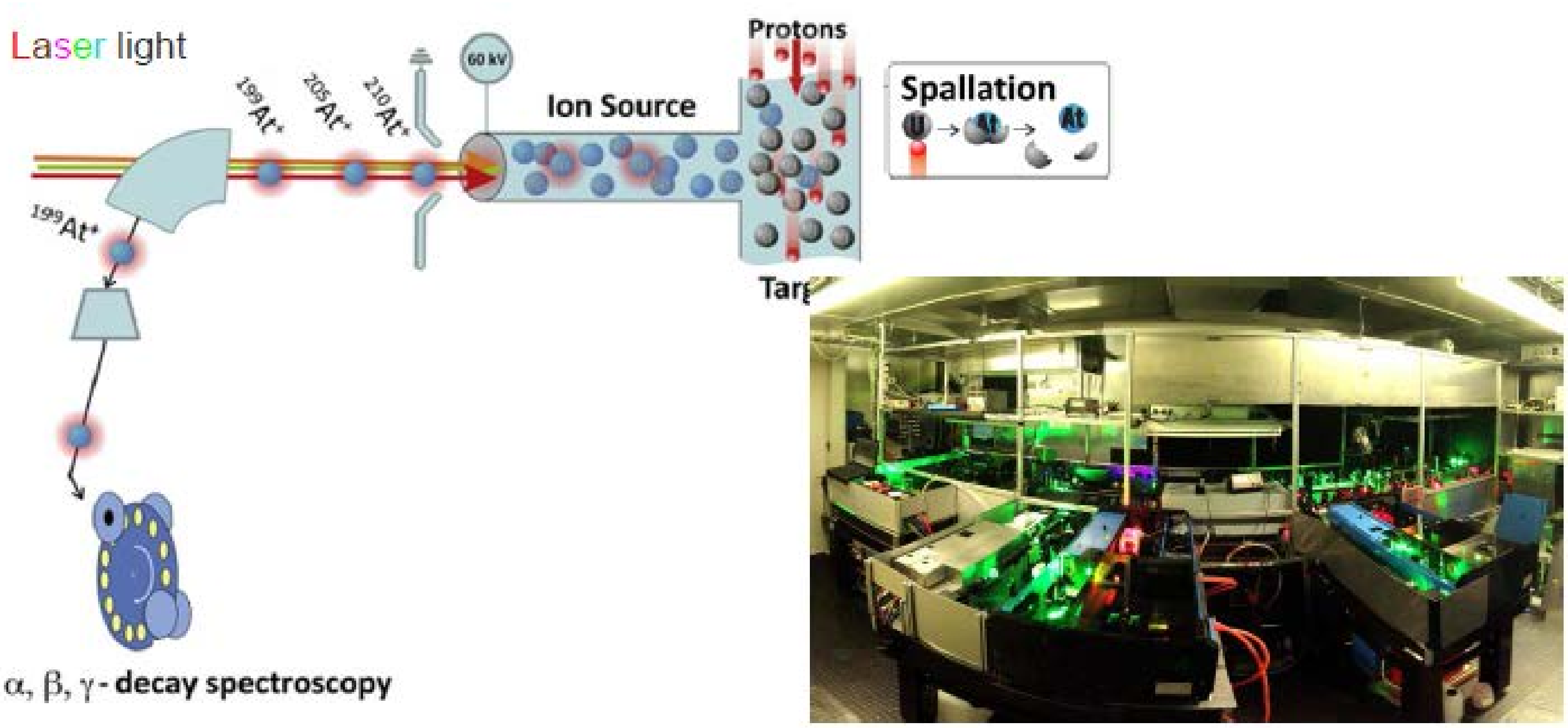


An example: Selective production of Astatine

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

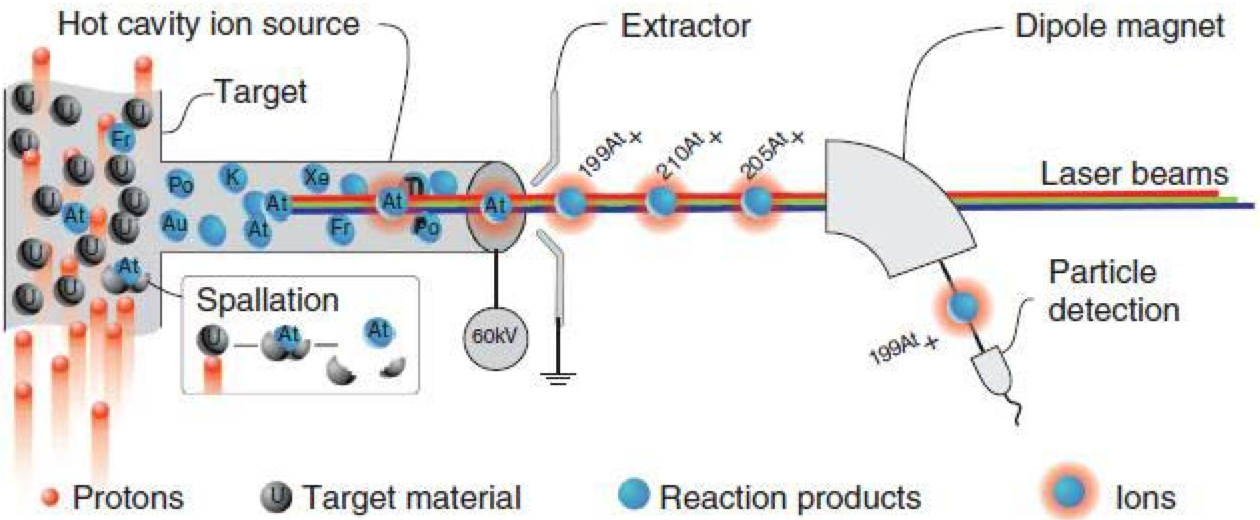
⇒ Ionization potential not experimentally deduced

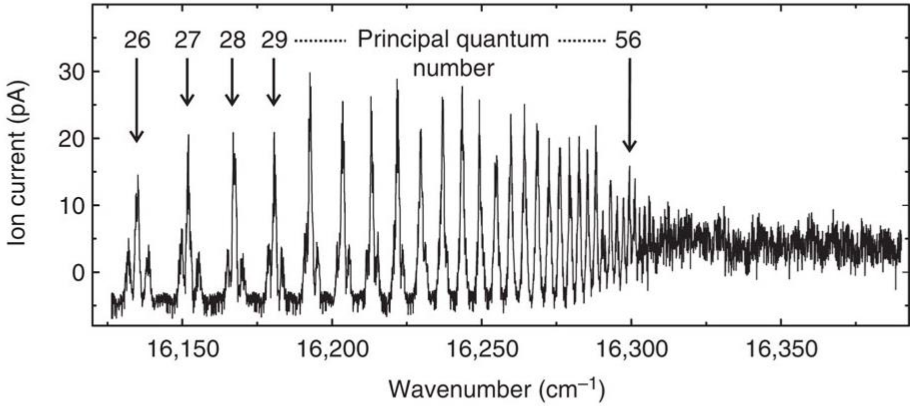
⇒ Only two atomic transitions were known



Example: Astatine isotopes

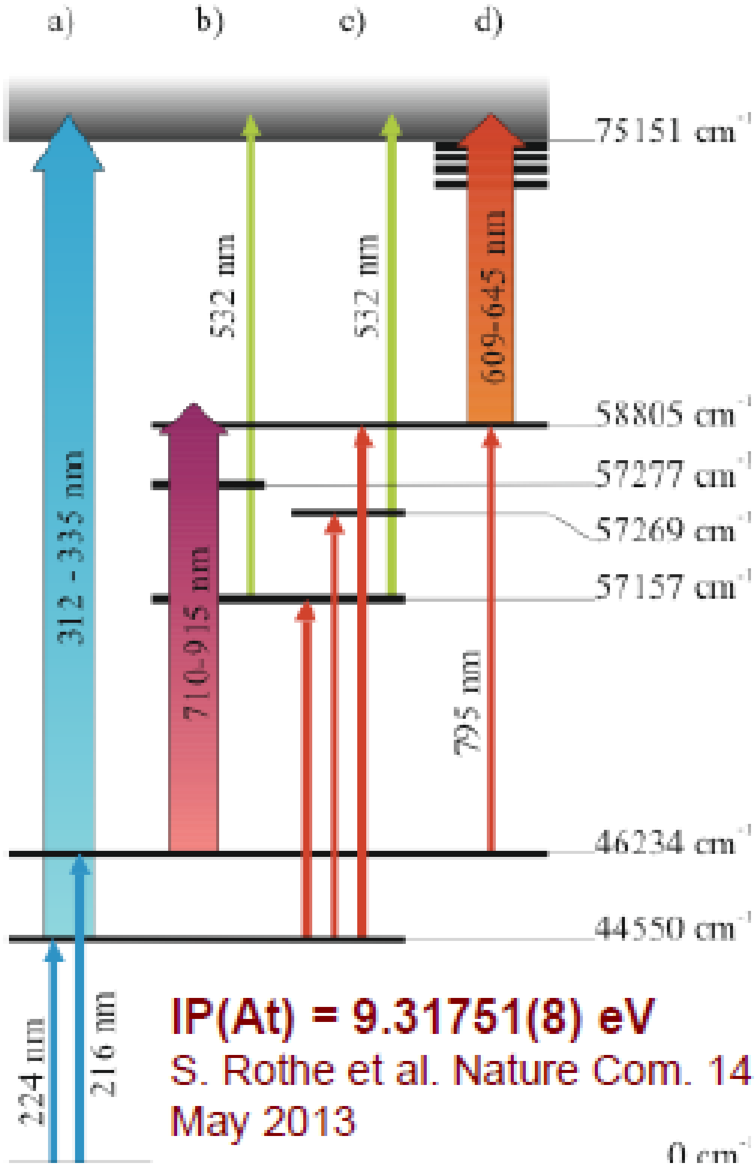
- How to produce pure beams of **At** isotopes (all are radioactive)?
  - Use laser to ionize them
  - Determine for the first time the At ionization potential





S. Rothe et al.; Nature Communications 4 (2013), 1835

Determination of the atomic properties of Astatine

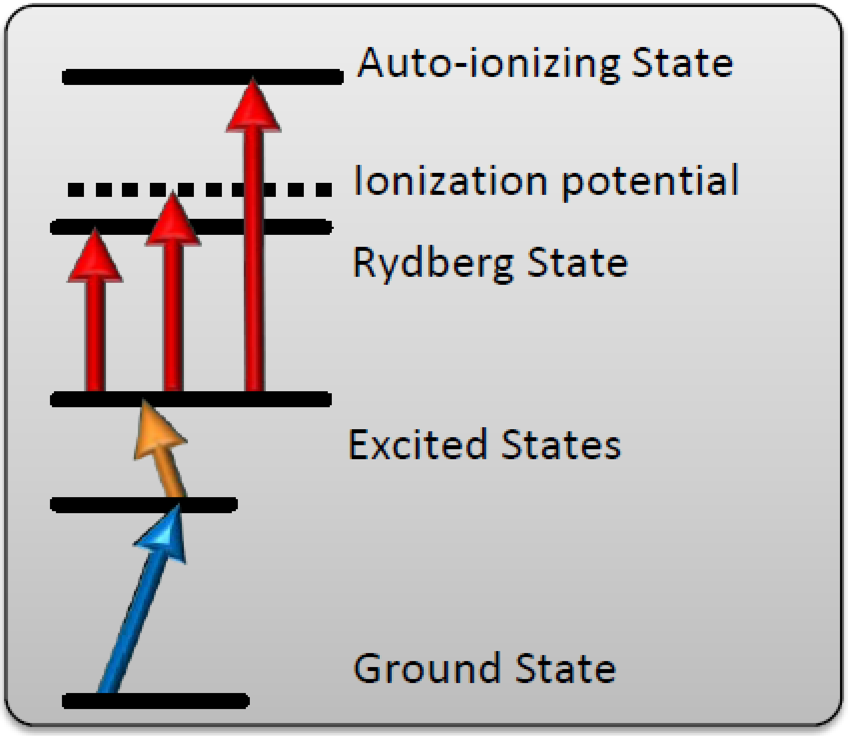


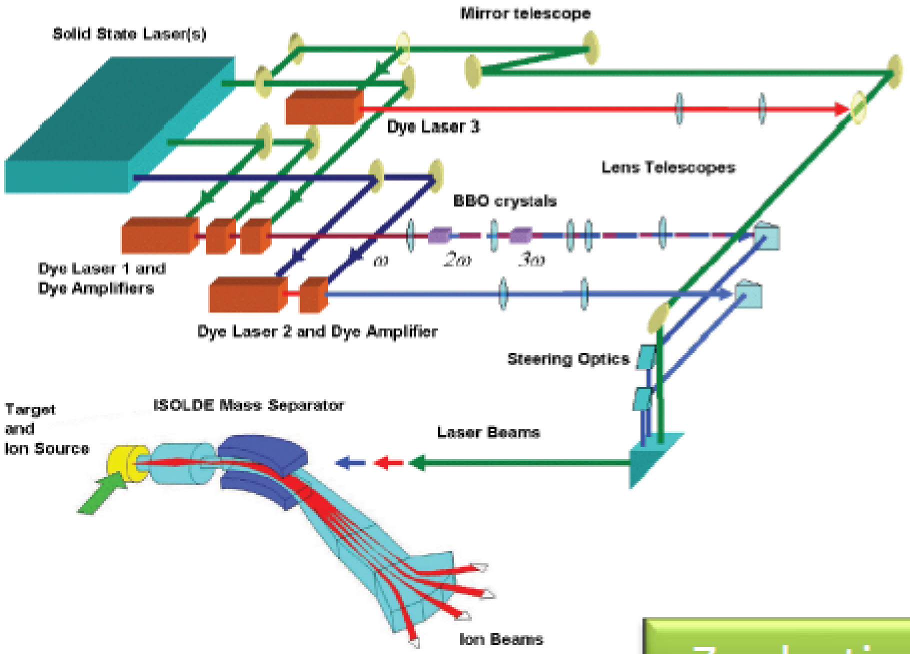
IP(At) = 9.31751(8) eV

S. Rothe et al. Nature Com. 14 May 2013

- 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

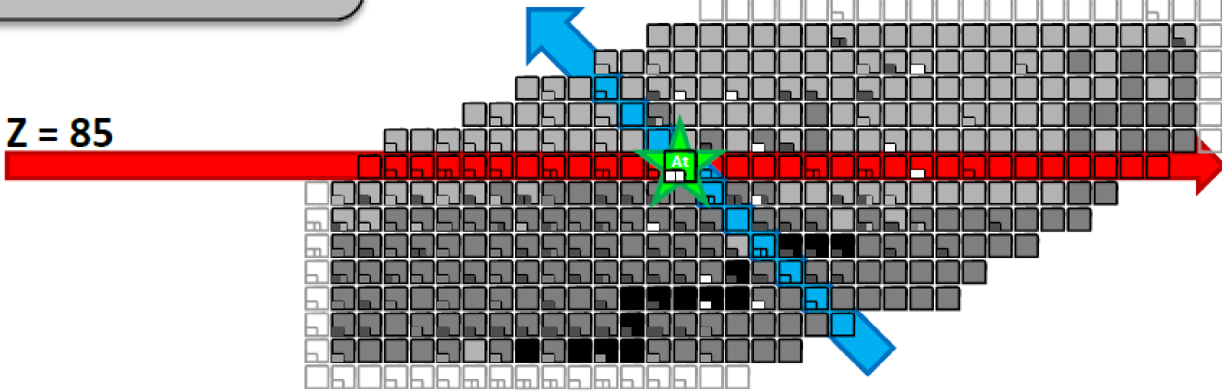
The resonance ionization laser ion source (RILIS)

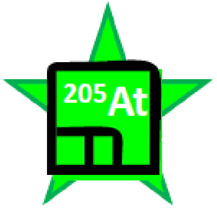




Z selective

Laser tuned to Z = 85



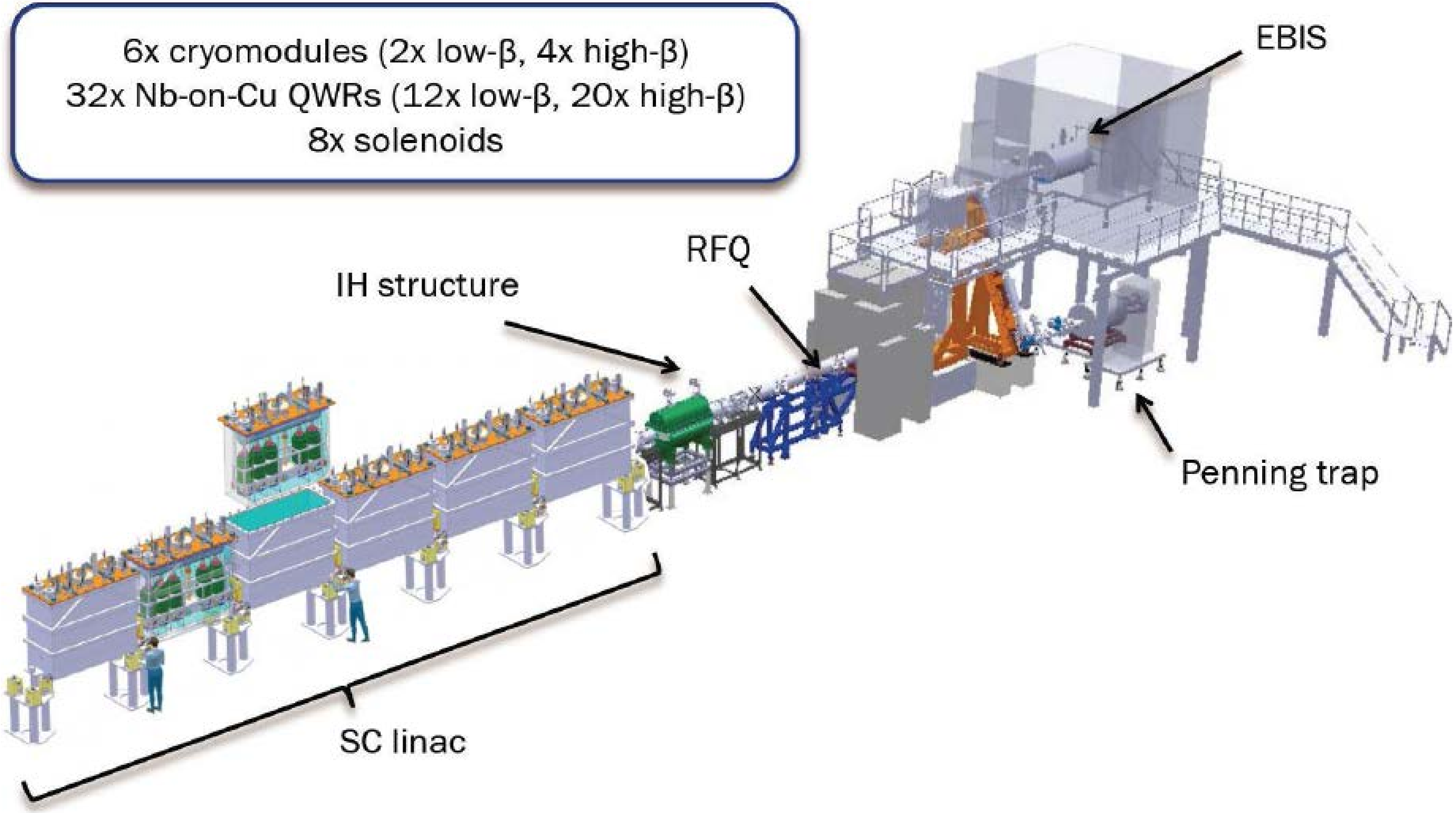


Magnet set to A = 205

Courtesy RILIS team

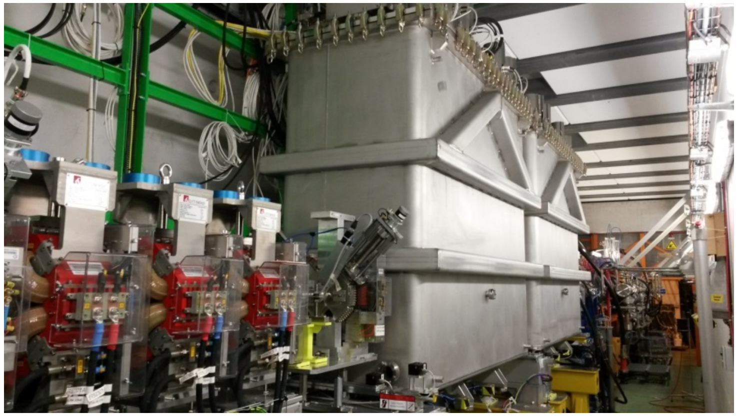
40 MV post-accelerator

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



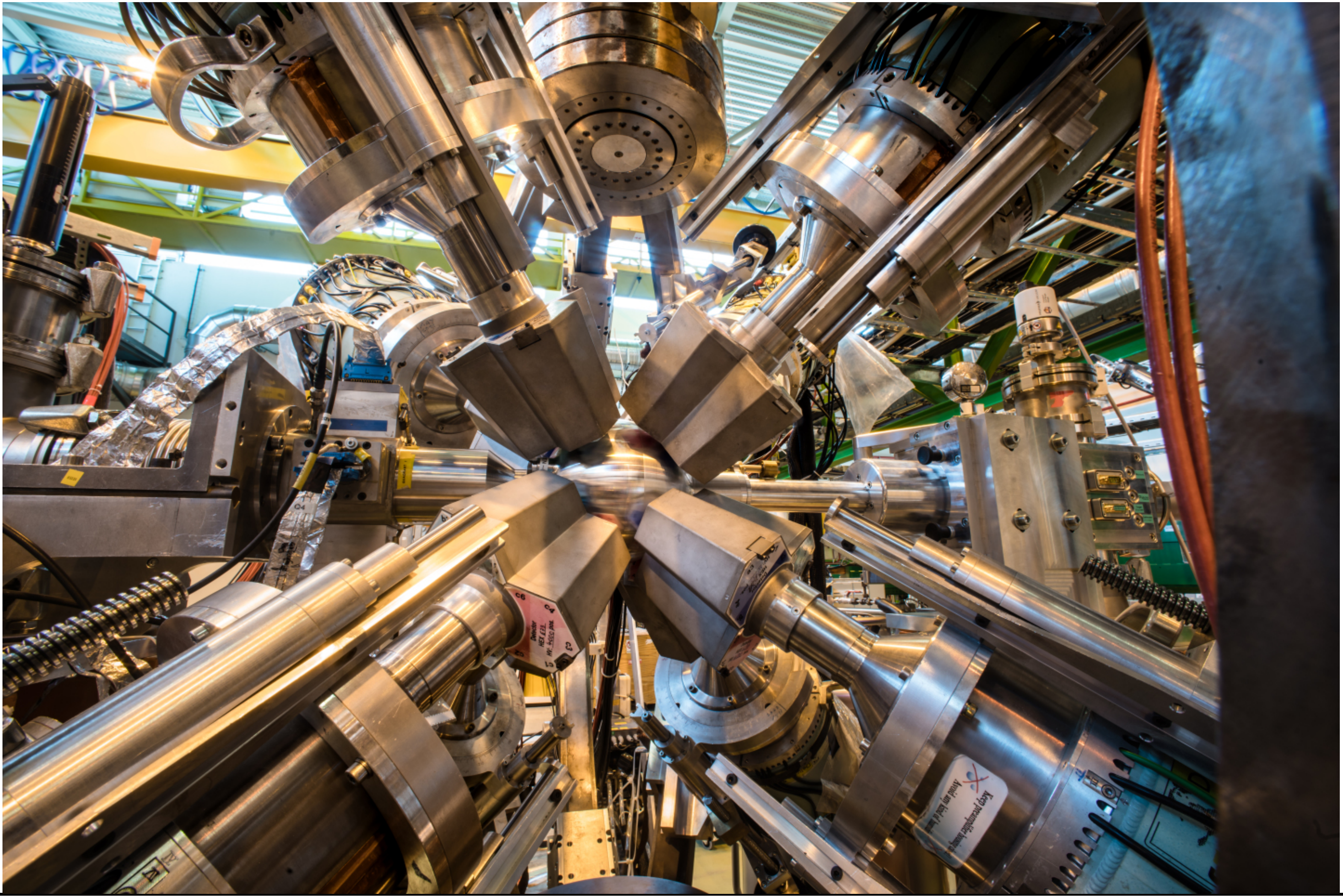
40 MV post-accelerator

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)

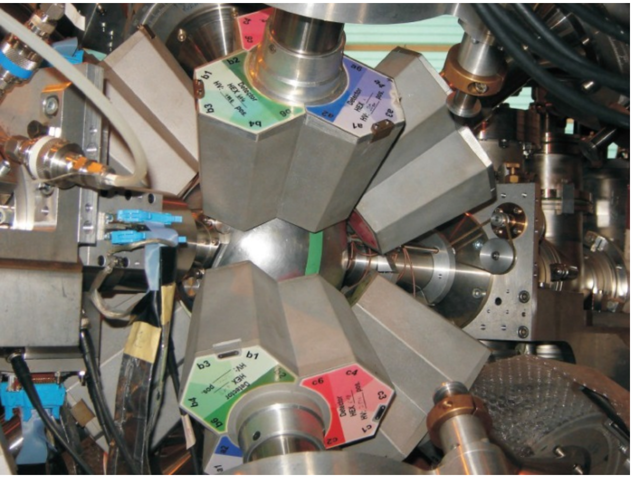


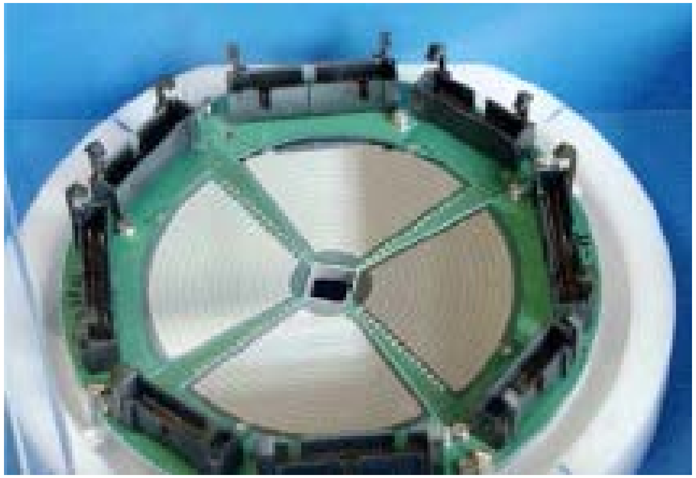
The new linac had to fit into just 16 m of space. “We had to develop a very compact linac. That’s what makes it unique. In other facilities, every cavity has its own cryostat but if we had to do that it would be far too long, so we had to squeeze all of them into one cryomodule. We had to have the solenoids 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)

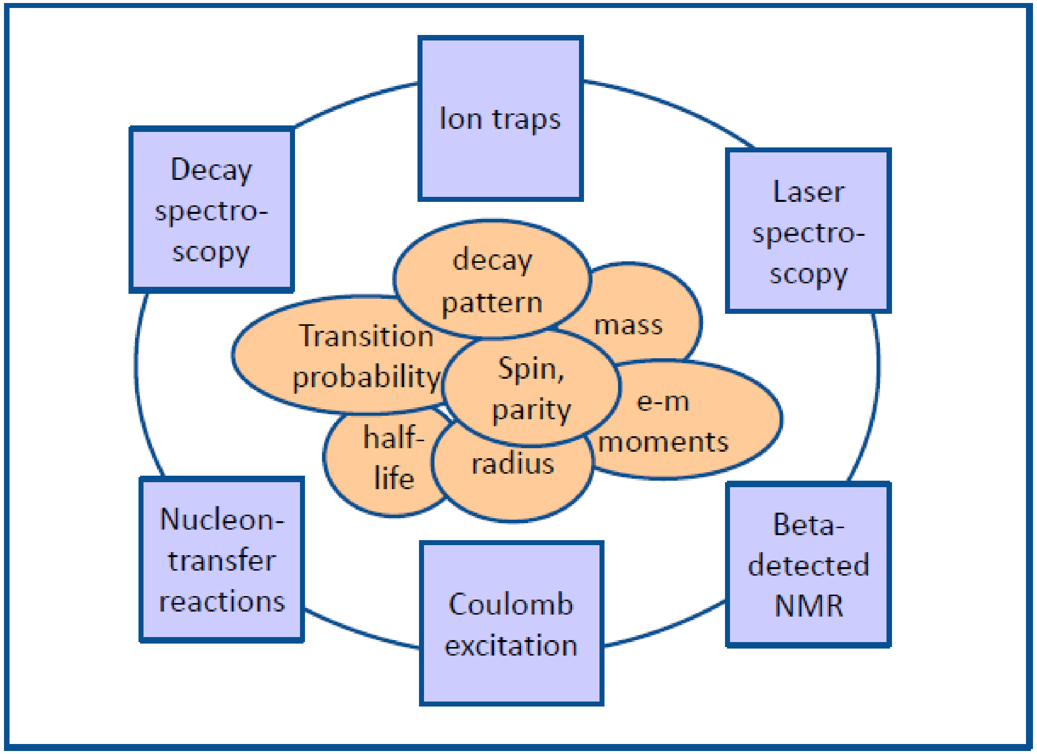
The Minibal Germanium Array



Coulomb excitation experiments at REX-Isolde







Ion traps

Decay spectroscopy

Laser spectroscopy

decay pattern

mass

Transition probability

Spin, parity

e-m moments

half-life

radius

Nucleon-transfer reactions

Coulomb excitation

Beta-detected NMR