Nuclear Physics at the ISOLDE-facility at CERN

Lecture 2: the CERN-ISOLDE facility

Gerda Neyens
CERN, EP-SME-IS and KU Leuven University, Belgium

gerda.neyens@cern.ch

on behalf of the CERN ISOLDE team
www.cern.ch/isolde

Small quiz

- Who are the two VIP’s in this photo, visiting the ISOLDE facility ?

Note: all ladies in this photo are ISOLDE physicists!

Outline

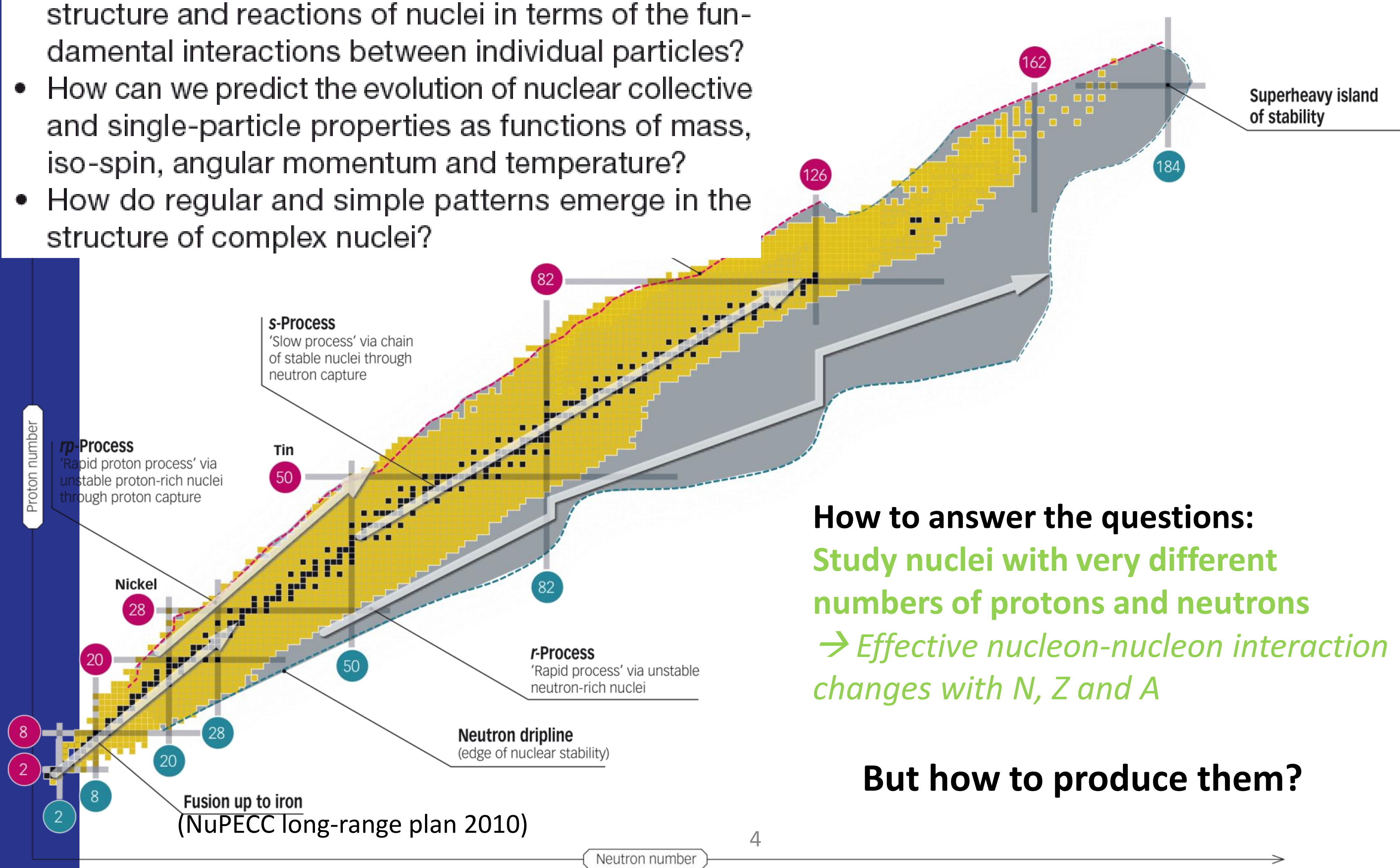
Aimed at both physics and non-physics students

- Lecture 1: Introduction to nuclear physics
- **This lecture**: CERN-ISOLDE facility
  - How to produce exotic isotopes ?
  - Types of radioactive ion beam (RIB) facilities
  - ISOLDE within CERN
  - RIB beam production at ISOLDE
- Lecture 3: Nuclear Physics and Applications at ISOLDE

Open questions in nuclear physics

- How can we describe the rich variety of low-energy structure and reactions of nuclei in terms of the fundamental interactions between individual particles?
- How can we predict the evolution of nuclear collective and single-particle properties as functions of mass, iso-spin, angular momentum and temperature?
- How do regular and simple patterns emerge in the structure of complex nuclei?

2 kinds of interacting fermions



(NuPECC long-range plan 2010)

How to answer the questions:

Study nuclei with very different numbers of protons and neutrons

→ Effective nucleon-nucleon interaction changes with N, Z and A

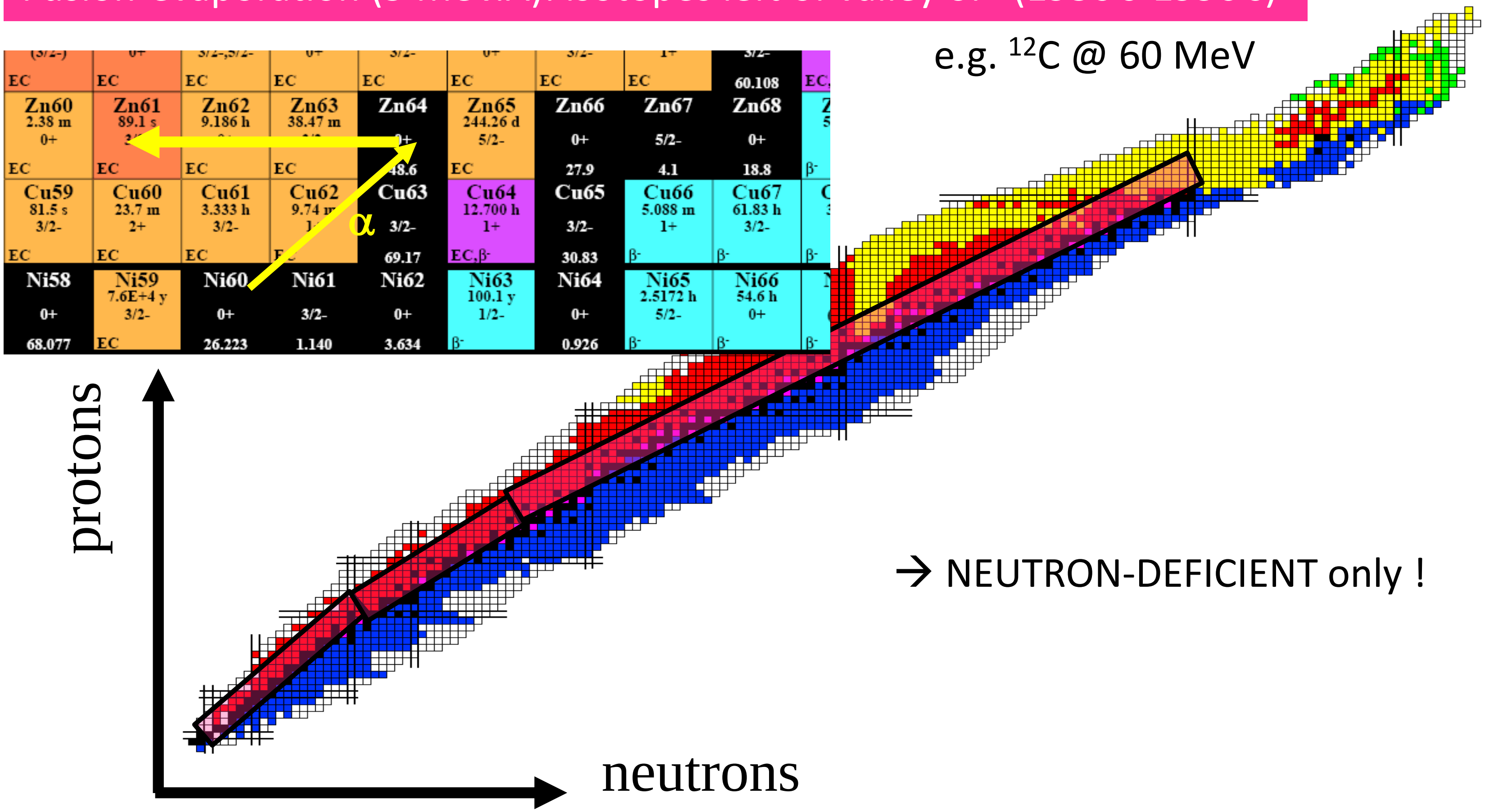
But how to produce them?

Production of exotic nuclei

Until 2001: accelerate a STABLE isotope to make a NUCLEAR REACTION

Fusion-evaporation (5 MeV.A): isotopes left of valley of (1950's-1990's)

e.g. ^{12}C @ 60 MeV



→ NEUTRON-DEFICIENT only !

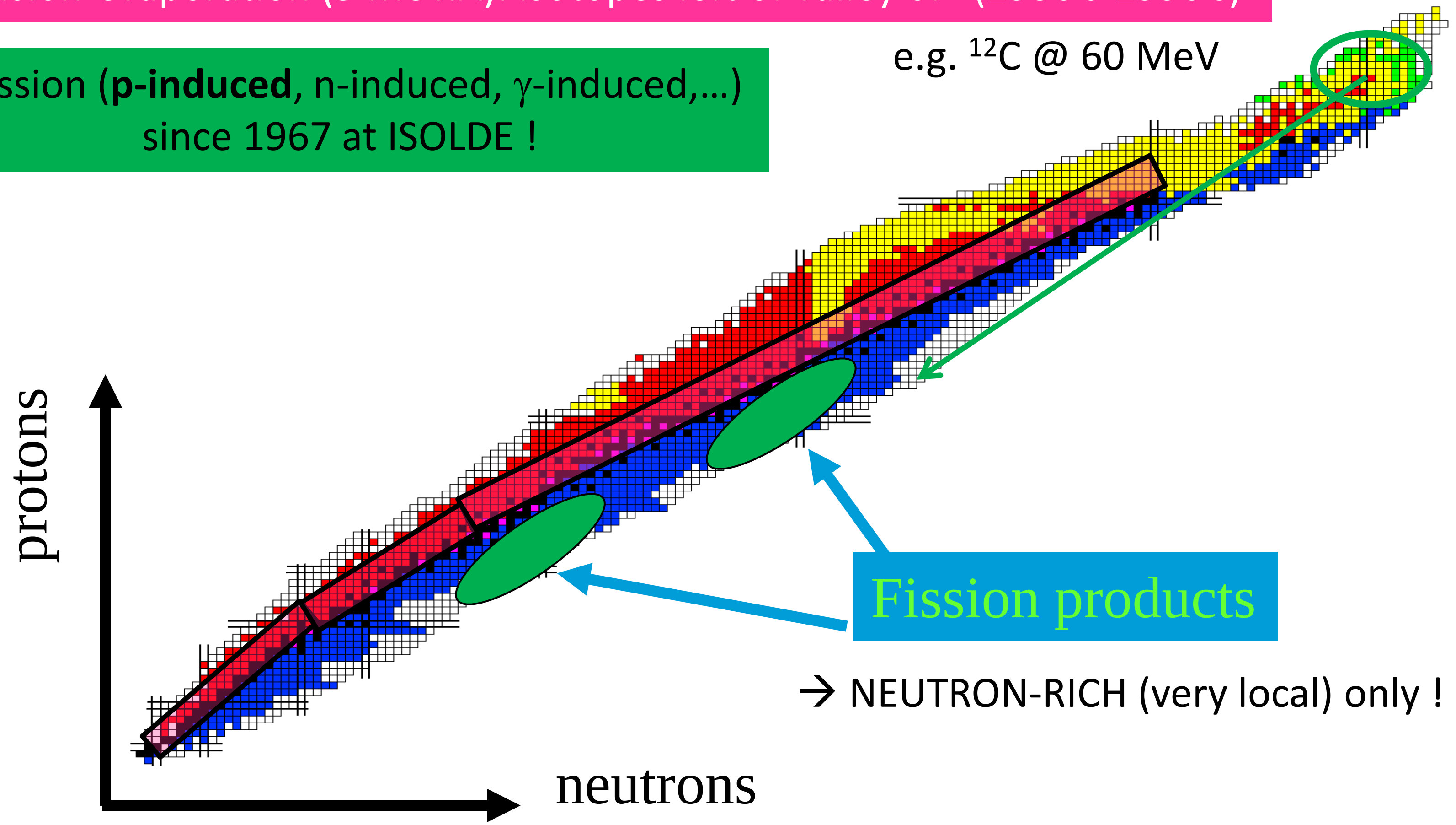
Production of exotic nuclei

Until 2001: accelerate a STABLE isotope to make a NUCLEAR REACTION

Fusion-evaporation (5 MeV.A): isotopes left of valley of (1950's-1990's)

Fission (**p-induced**, n-induced, γ-induced,...) since 1967 at ISOLDE !

e.g. ^{12}C @ 60 MeV

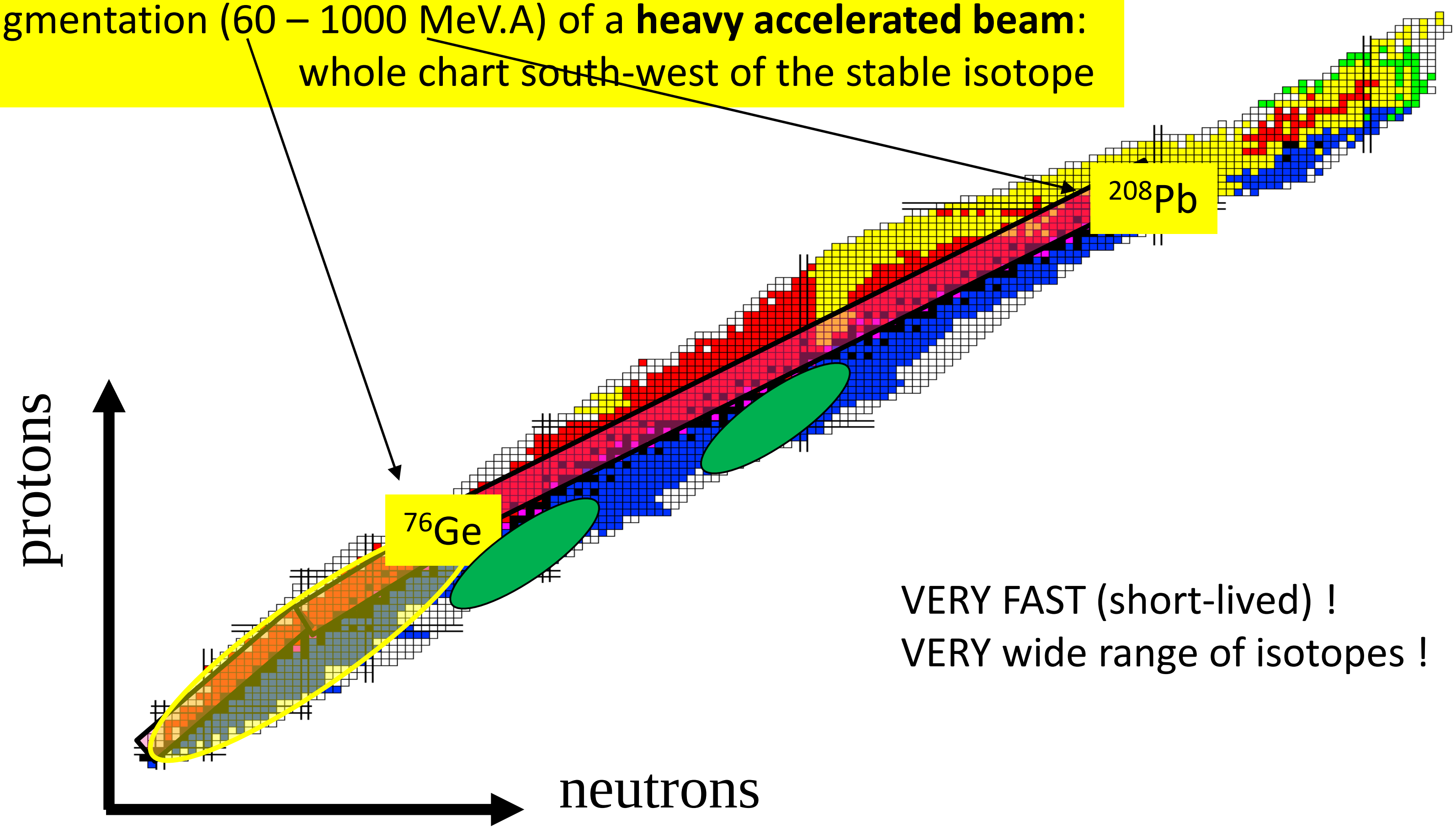


→ NEUTRON-RICH (very local) only !

Production of exotic nuclei

Until 2001: accelerate a STABLE isotope to make a NUCLEAR REACTION

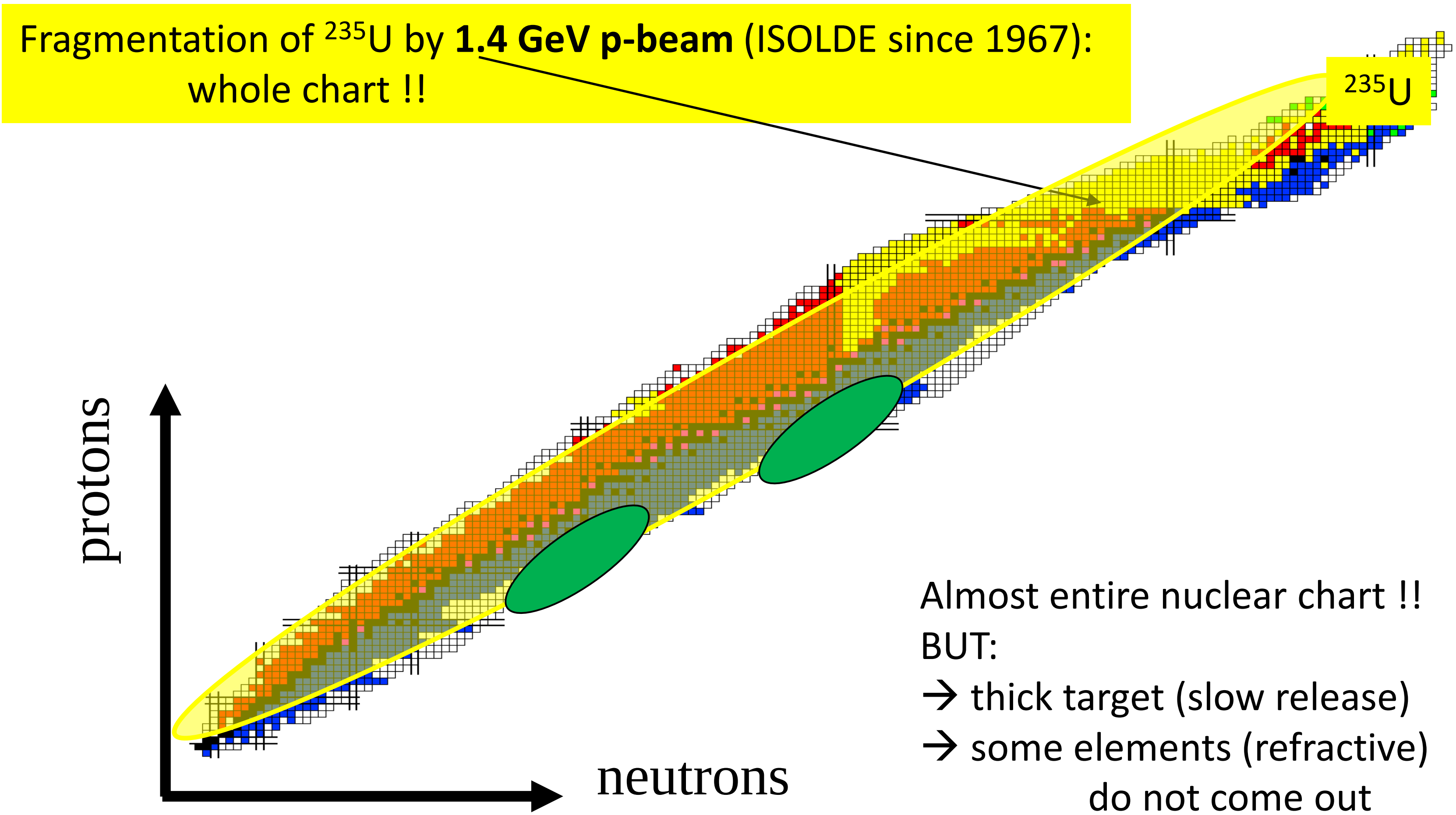
Fragmentation (60 – 1000 MeV.A) of a **heavy accelerated beam**:
whole chart south-west of the stable isotope



VERY FAST (short-lived) !
VERY wide range of isotopes !

Production of exotic nuclei

Until 2001: accelerate a STABLE isotope to make a NUCLEAR REACTION

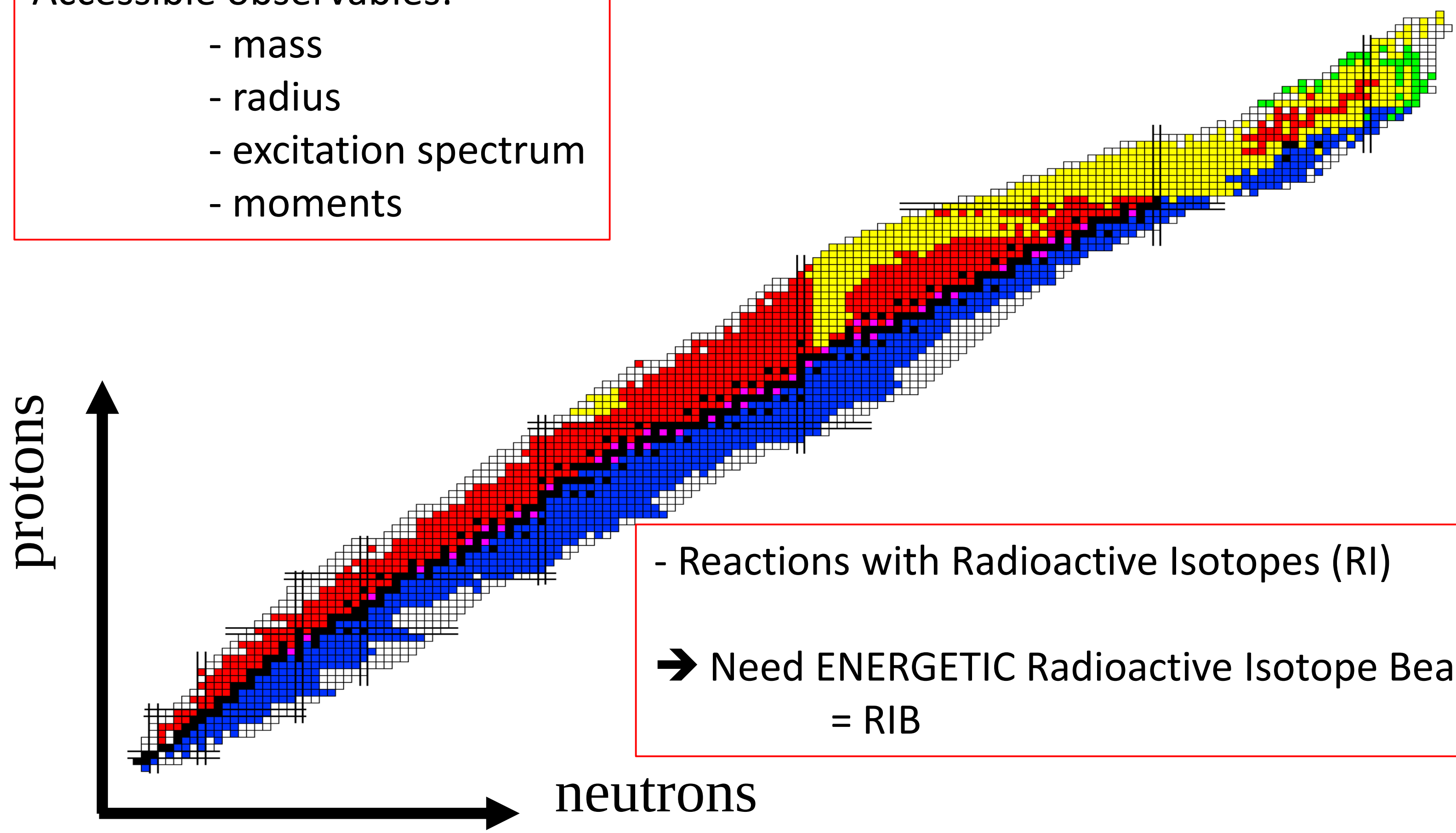


Almost entire nuclear chart !!
BUT:
→ thick target (slow release)
→ some elements (refractive) do not come out

Production of exotic nuclei

Until 2001: accelerate a STABLE isotope to make a NUCLEAR REACTION

Accessible observables:
- mass
- radius
- excitation spectrum
- moments



- Reactions with Radioactive Isotopes (RI)

➔ Need ENERGETIC Radioactive Isotope Beam = RIB

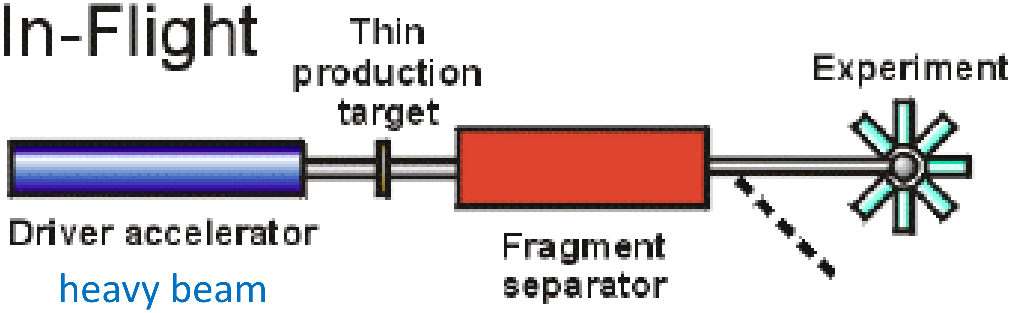
RIB facilities

RIB:
Radioactive Ion Beam
Rare Isotope Beam

- **Two complementary RIB facilities:**
  - In-Flight and ISOL-based

Fast RIB beams from **fragment** separators since around 1985 (LISE@GANIL)

In-Flight



heavy beam

50-1000 MeV.A

e.g. ^{208}Pb @ 200 GeV

+
Pure exotic beam (>80% purity)
All elements and isotopes (below mass 208)

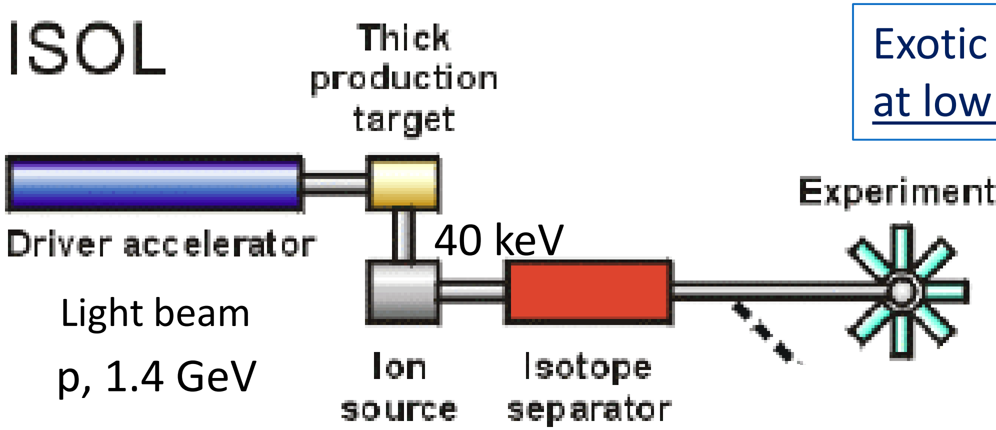
-
Very high energy: 50-500 MeV.A
Very large beam spot (cm^2)

RIB facilities

RIB:
Radioactive Ion Beam
Rare Isotope Beam

- Two main types of (complementary) RIB facilities:
  - In-Flight and ISOL-based

Exotic isotopes at ISOLDE-CERN since 1967
at low energy: no reactions with RIB possible



Light beam
p, 1.4 GeV

Purity of the exotic beam not very good
(element selective laser ionization)

Low energy: 40 keV
Very small beam spot (mm^2)

Ideal for ground state properties !

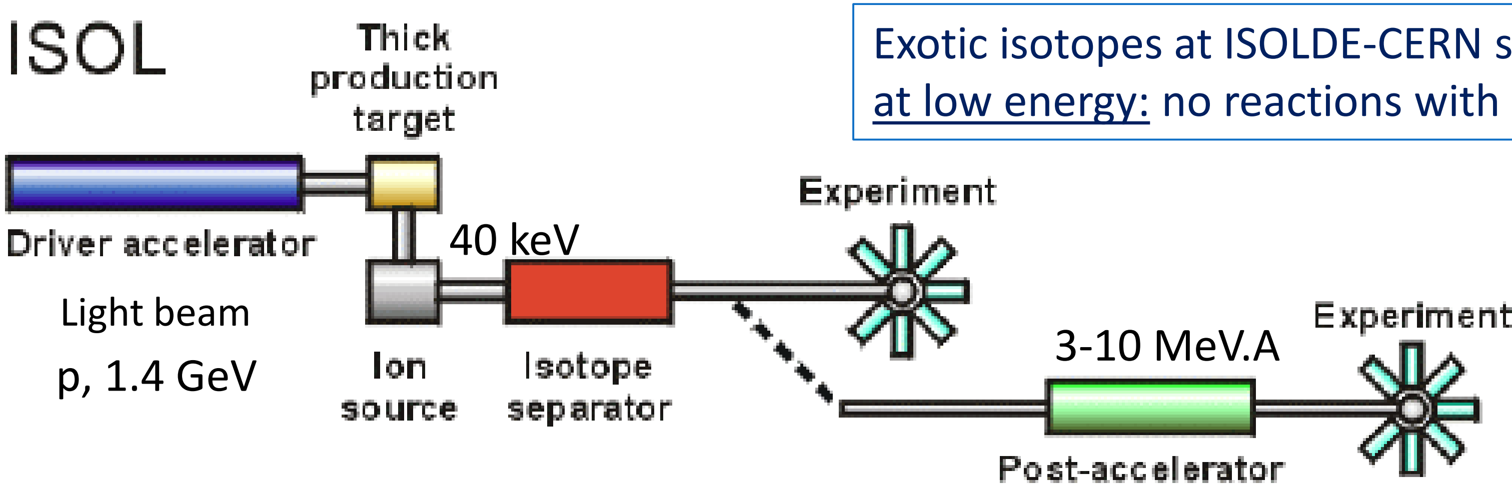
Isotope Separation On-Line Device (ISOLDE)

2017: CELEBRATING 50 YEARS of ISOLDE !

RIB facilities

RIB:
Radioactive Ion Beam
Rare Isotope Beam

- Two main types of (complementary) RIB facilities:
  - In-Flight and ISOL-based



Exotic isotopes at ISOLDE-CERN since 1967
<u>at low energy:</u> no reactions with RIB possible

<u>Post-accelerated RIBs</u> since 2001
(pioneered at LLN-Belgium, 1991)

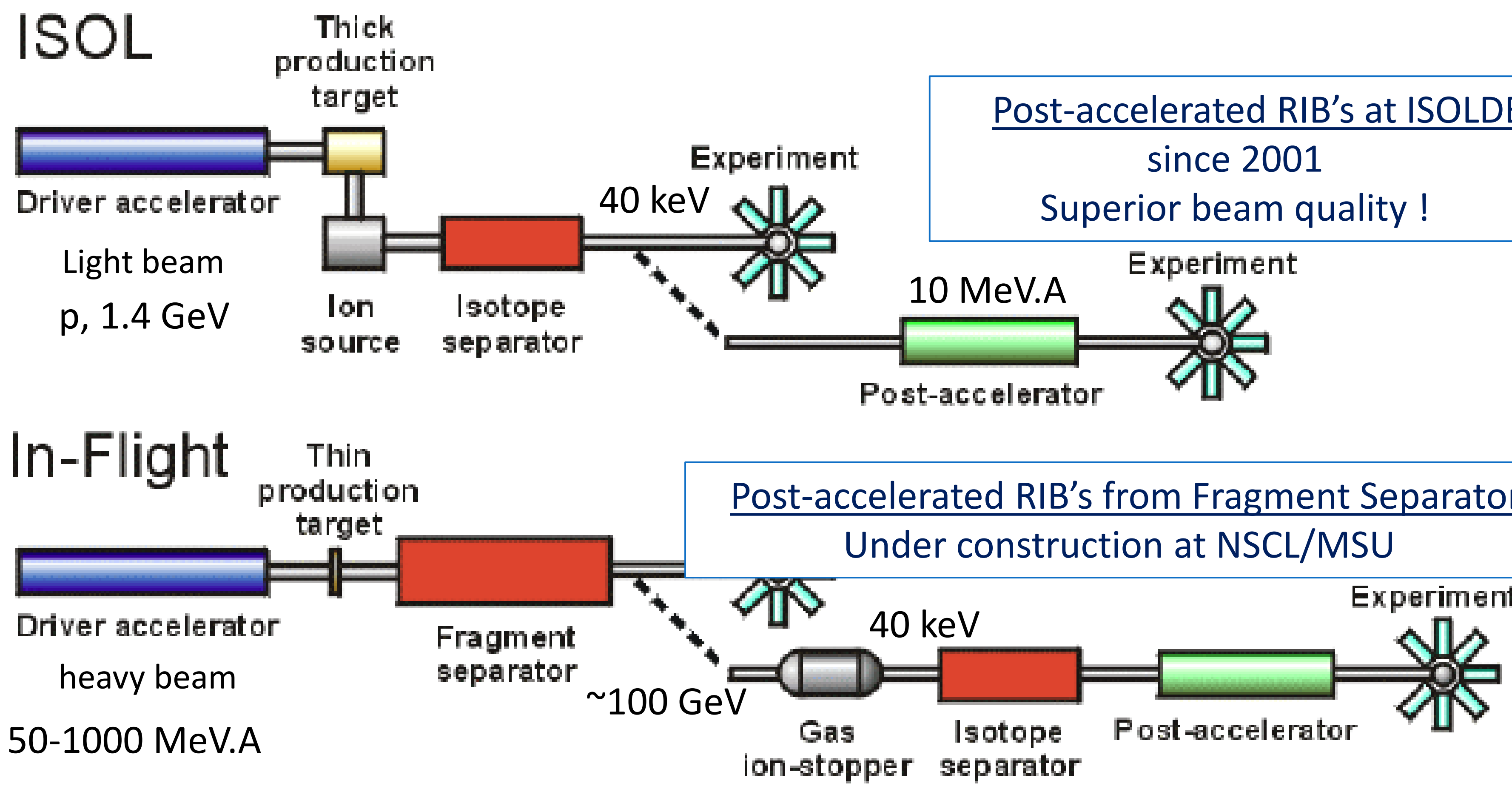
Post-accelerated RIB's have superior quality (beam spot, beam energy, beam intensity) over in-flight produced RIB's for nuclear structure research using Coulomb Excitation and Transfer reactions

RIB facilities

RIB:
Radioactive Ion Beam
Rare Isotope Beam

SINCE ~ 2001

- Two main types of (complementary) RIB facilities:
  - ISOL (Isotope Separation On-Line) and In-Flight



Post-accelerated RIB's at ISOLDE
since 2001
Superior beam quality !

Post-accelerated RIB's from Fragment Separators
Under construction at NSCL/MSU

Complementary (different) isotopes can be produced in ISOL en In-Flight

RIB facilities comparison

	ISOL+reacceleration	In-Flight
Projectile	light	heavy
Target	thick	thin
Ion beam energy	low	high
Beam intensity	high	low
Variety of nuclides	smaller	large
Release from target	Slow and element dependent	Fast and universal
Beam quality	good	poor
Examples	ISOLDE@CERN ISAAC@TRIUMF SPIRAL@GANIL FRIB@NSCL/MSU	GSI LISE@GANIL RIKEN NSCL/MSU

ISOLDE – short history

ISOLDE = Isotope Separator OnLine DEvice

CERN facility for production and studies of RIBs

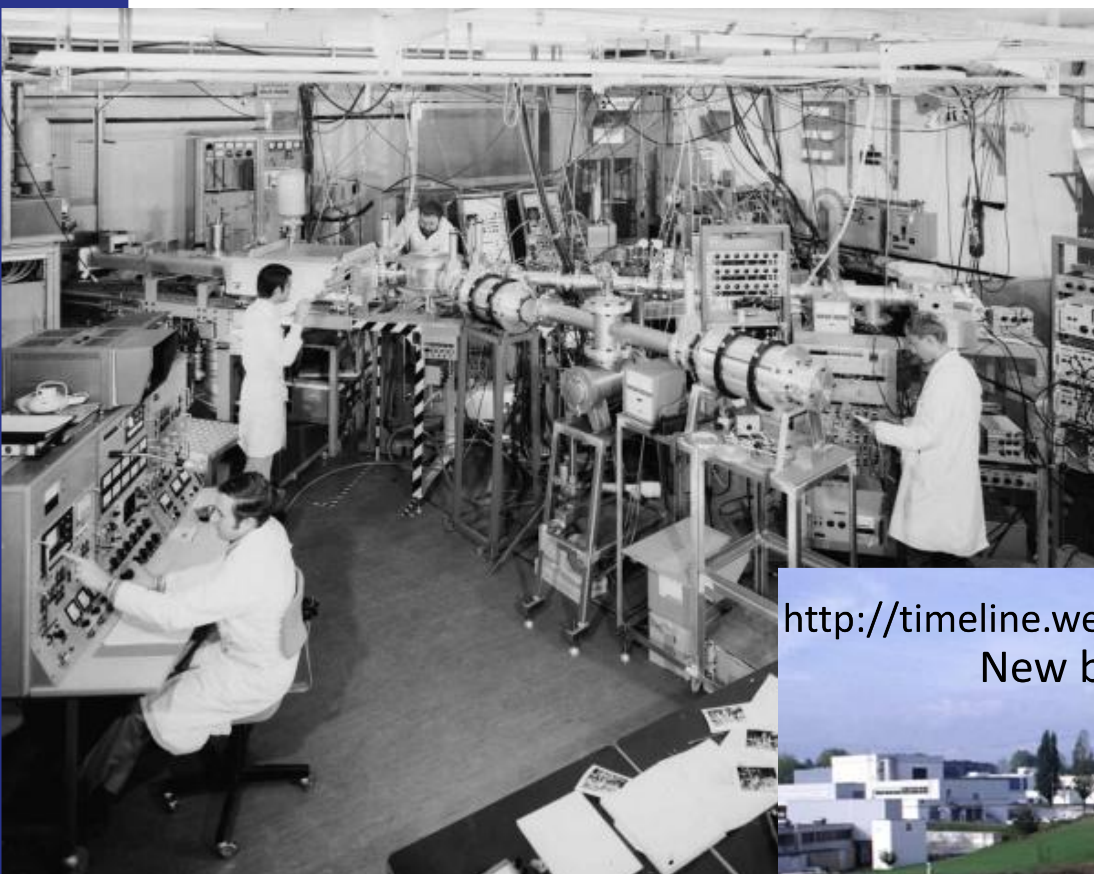
Accepted: December 1964
First beam: October 1967
Upgrades: 1974 and 1988

New building: 1992

First post-accelerated RIB 2001 (3 MeV/u)

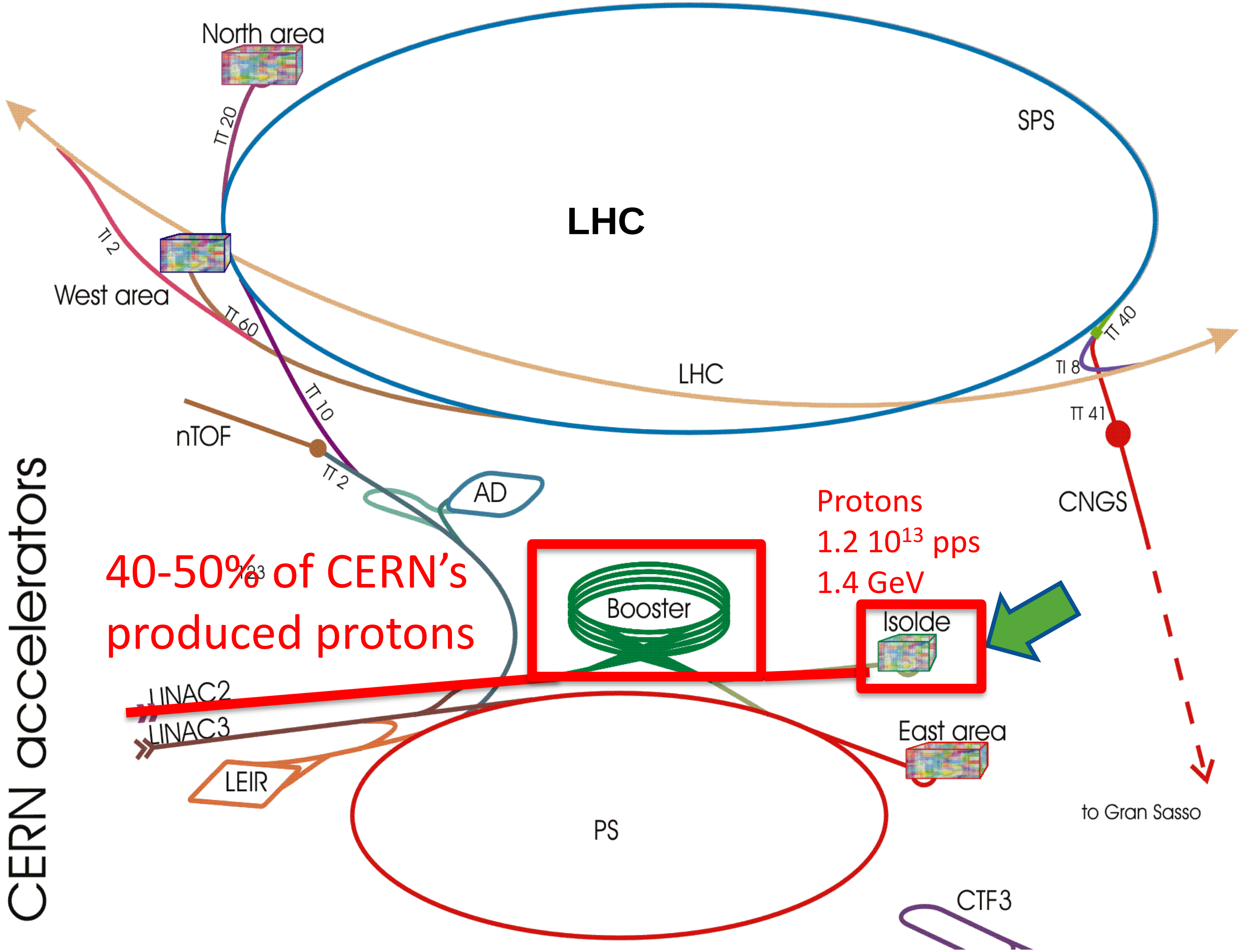
Hall extension during LS1 → longer post-accelerator (10 MeV/u)

HIE-ISOLDE: October 2015-2018

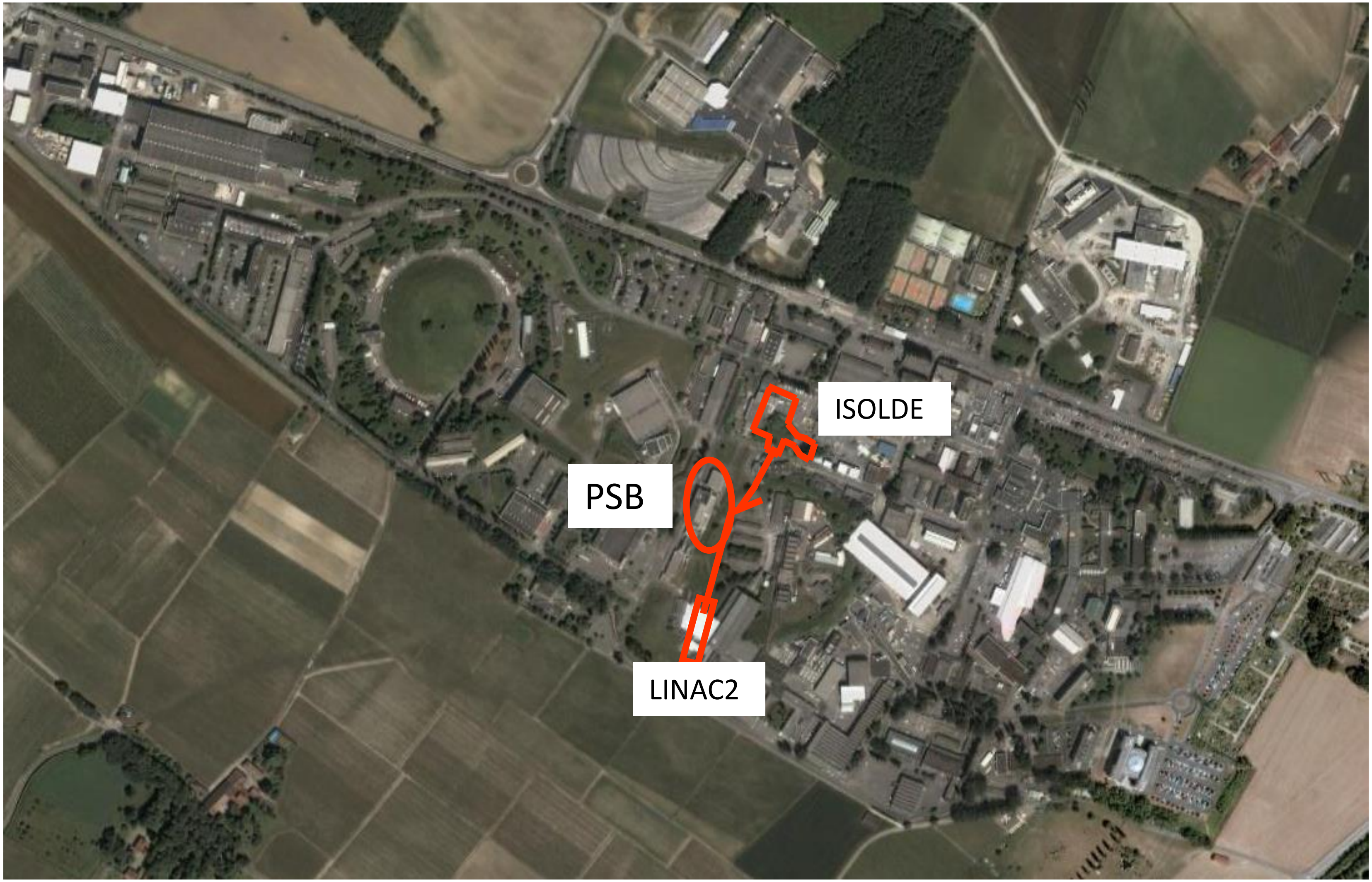


http://timeline.web.cern.ch/timelines/ISOLDE
New building 1992

ISOLDE at CERN

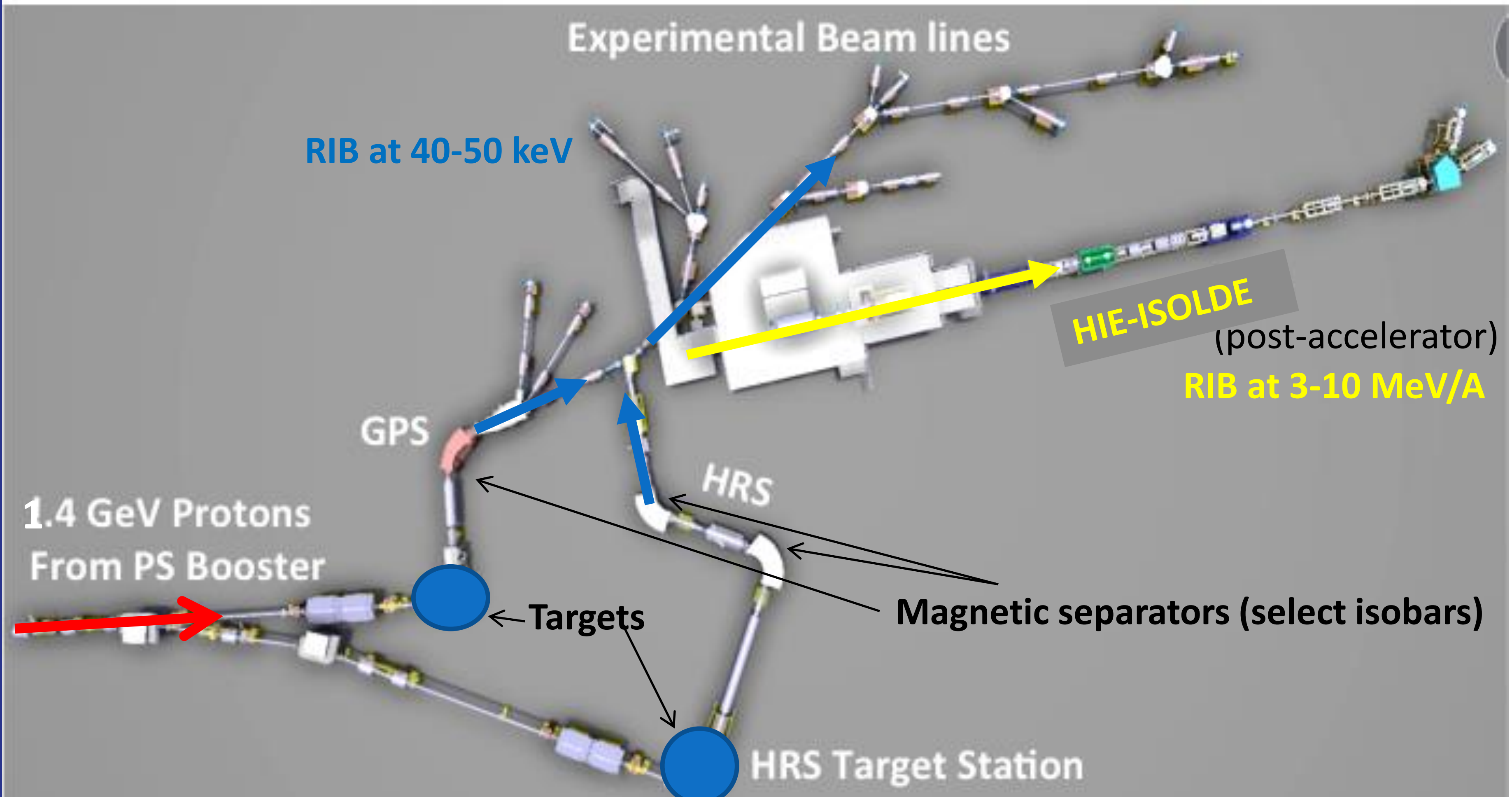


ISOLDE within CERN accelerators



ISOLDE beam production stations

Isotope production via reactions of light beam with thick and heavy target

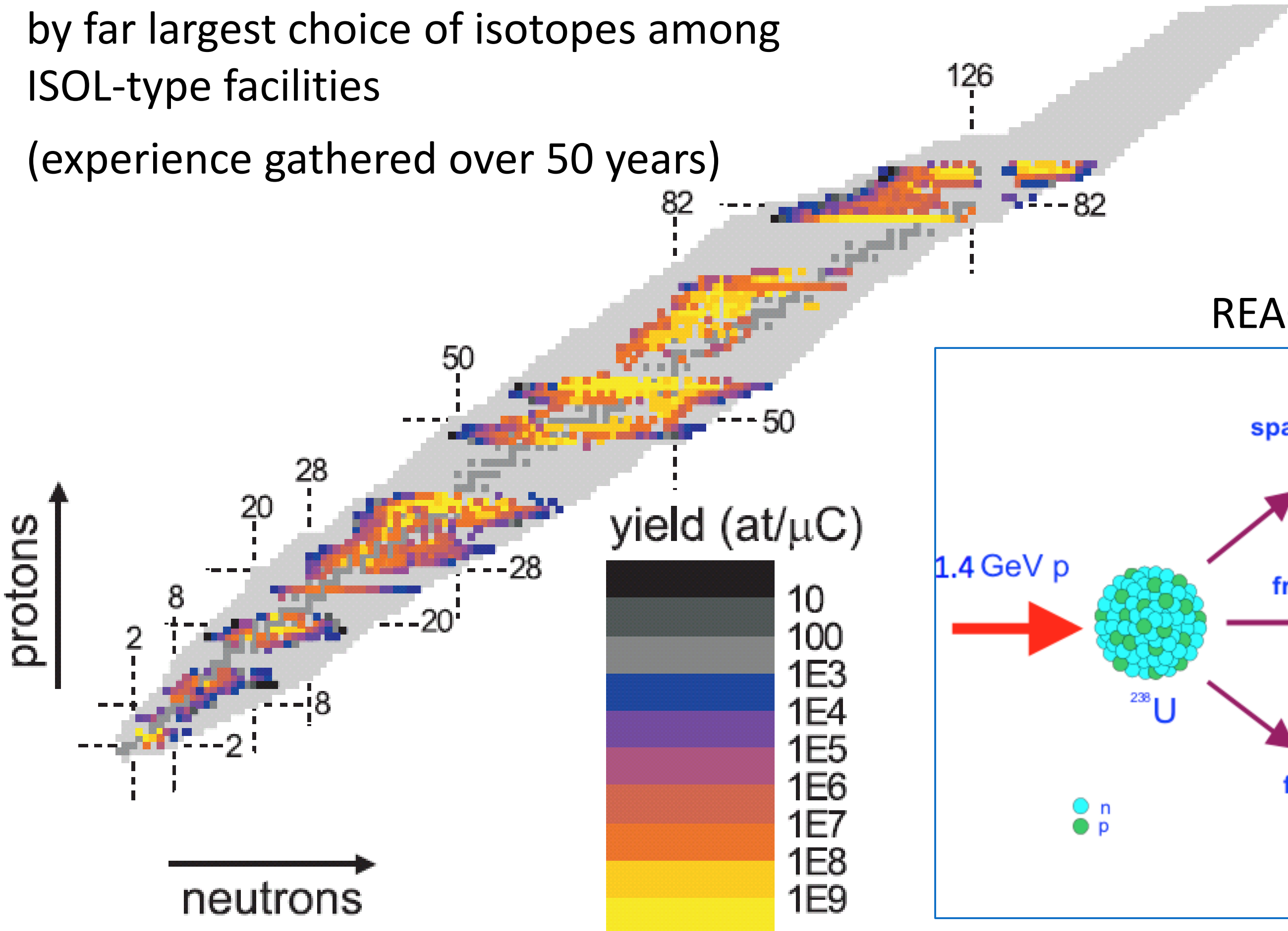


Production – ionization – separation

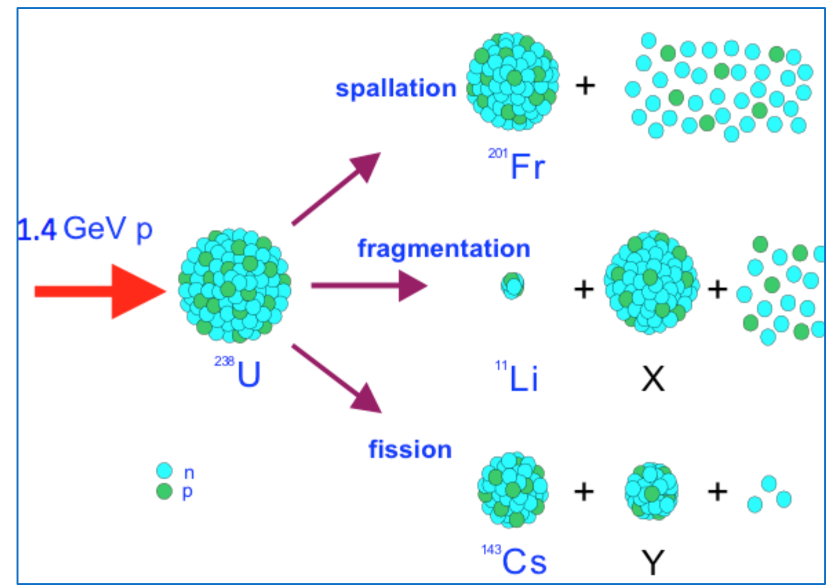
Produced isotopes at ISOLDE

by far largest choice of isotopes among
ISOL-type facilities

(experience gathered over 50 years)



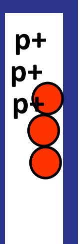
REACTIONS

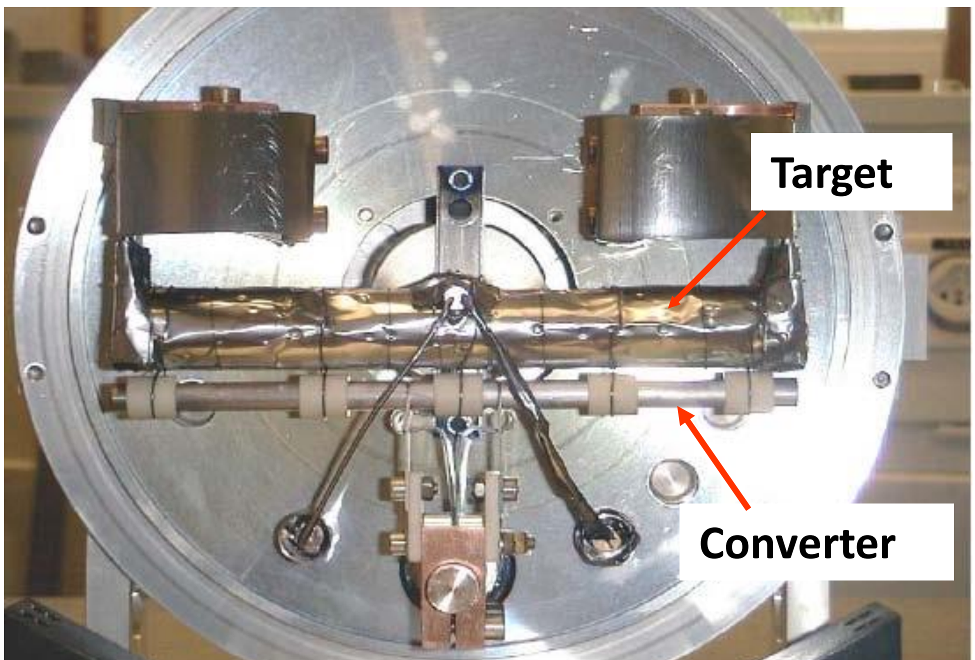


So far ~ 1000 radioactive isotopes of > 70 elements @ 50 keV
> 100 accelerated isotopes (till now up to 5.5 MeV/u)

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 degrees
- Operated by robots due to radiation



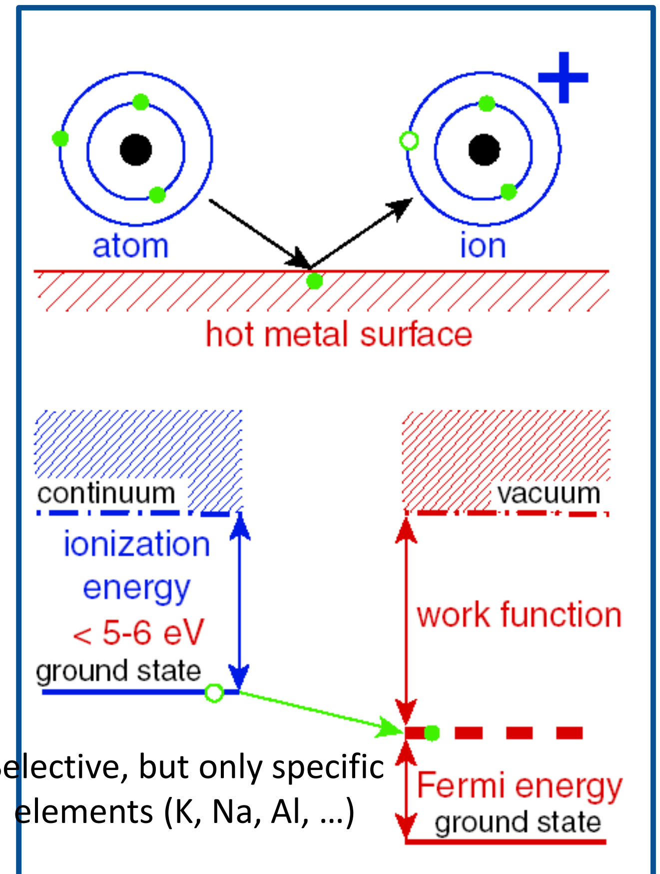


Converter Target

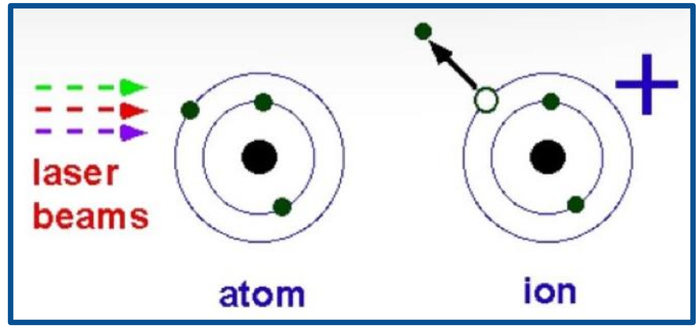
Standard

Ionization

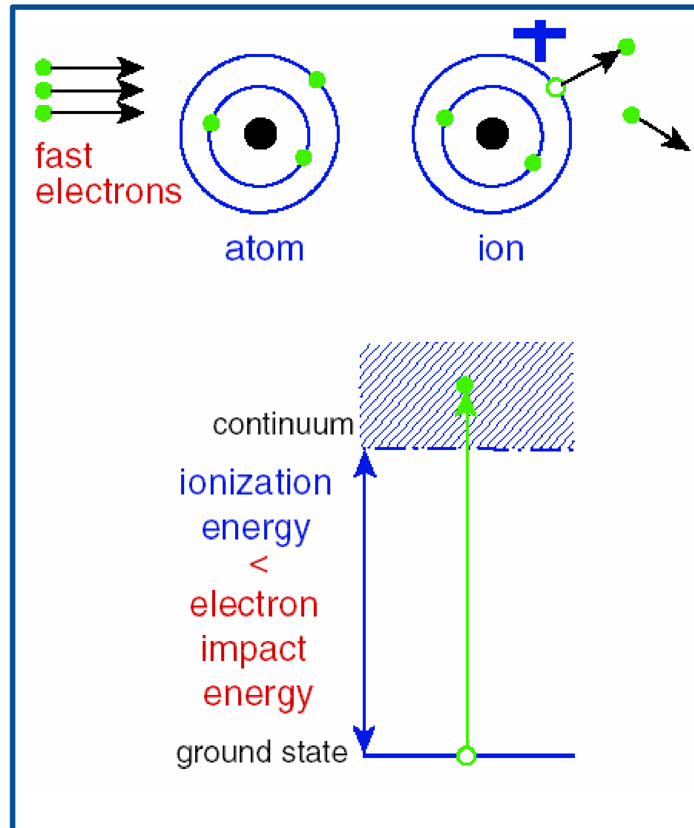
- Surface
- Plasma
- Lasers (RILIS)



Selective, but only specific elements (K, Na, Al, ...)



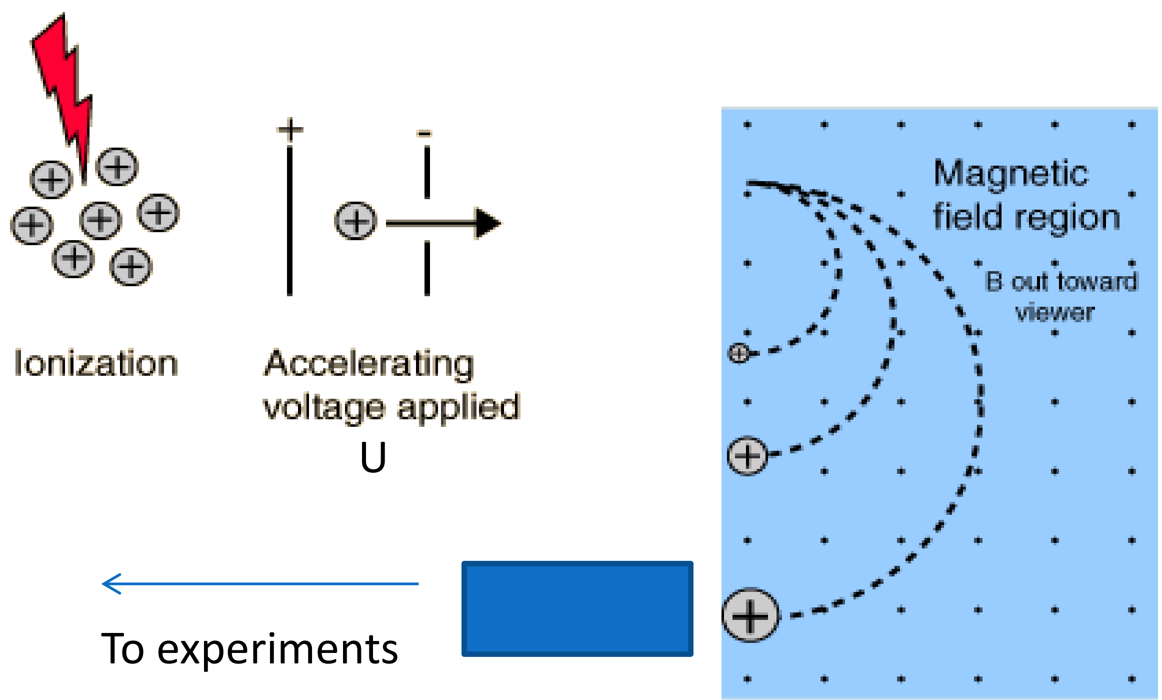
100% element selective !!



After U. Koester

Beam extraction and separation

- All produced ions are extracted by electrostatic field (up to 50-60kV)
- The interesting nuclei are mass selected via magnetic field
  - **Lorentz force**: curvature depends on velocity (fixed), **mass** and charge (1^+)
  - Select isotopes with a specific mass (defined by the atomic number A - isobars)
  - m/dm <5000, so many unwanted isobars also get to experiments

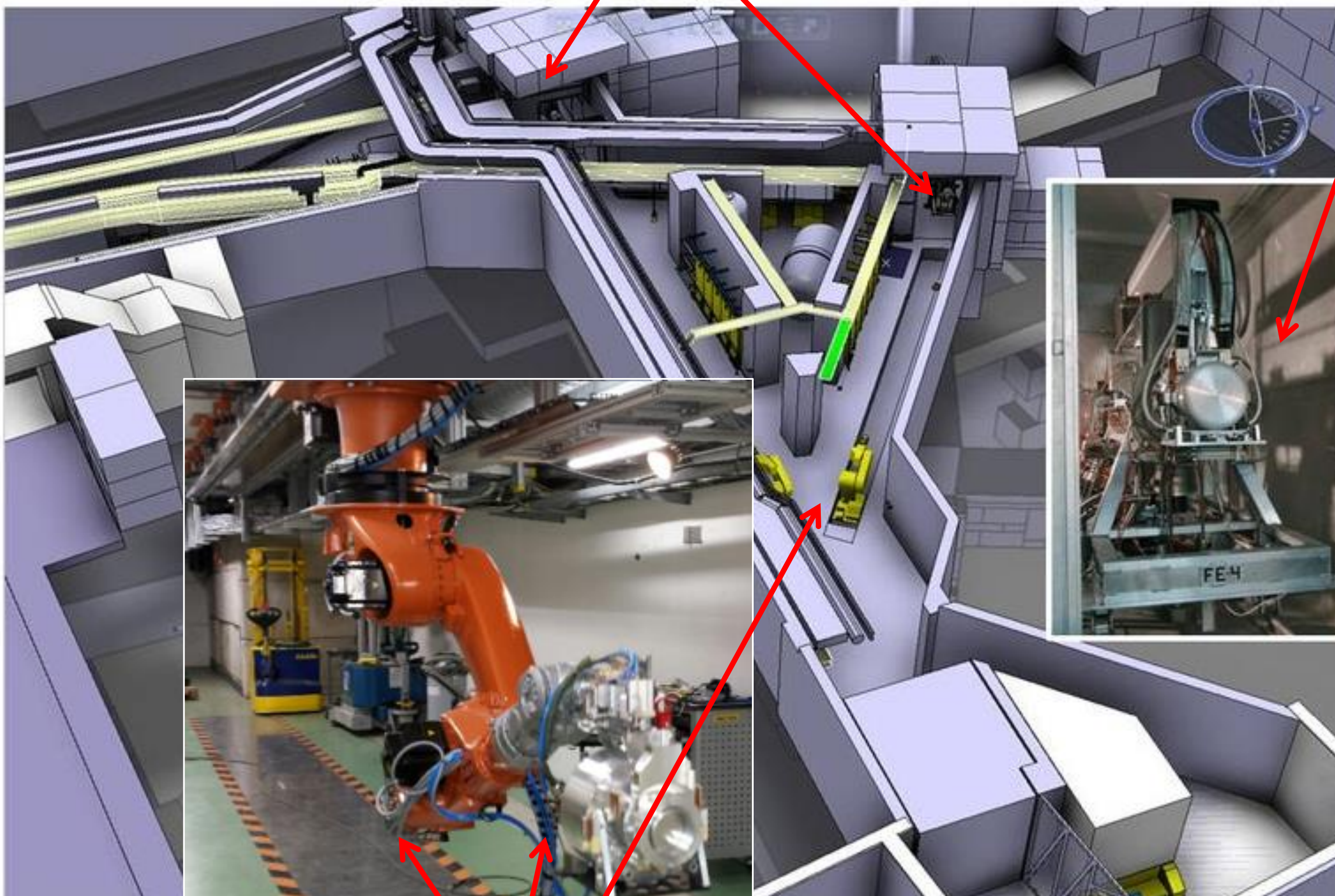


$$r = \frac{mv}{qB} = \sqrt{2mU}/(qB)$$

Production, ionization, extraction

target

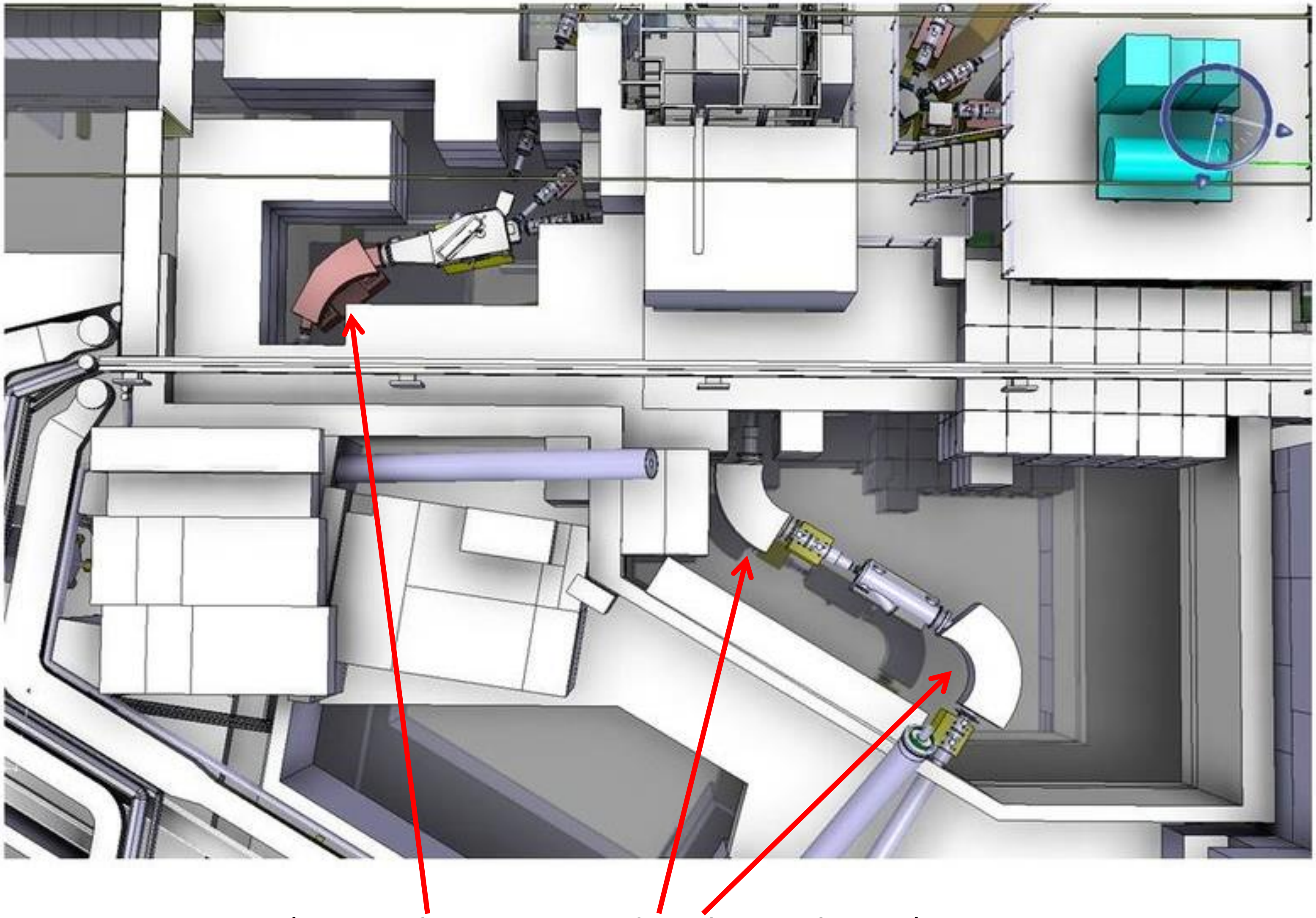
Target+ vacuum+ extraction



robots

Ion energy: 30-60keV

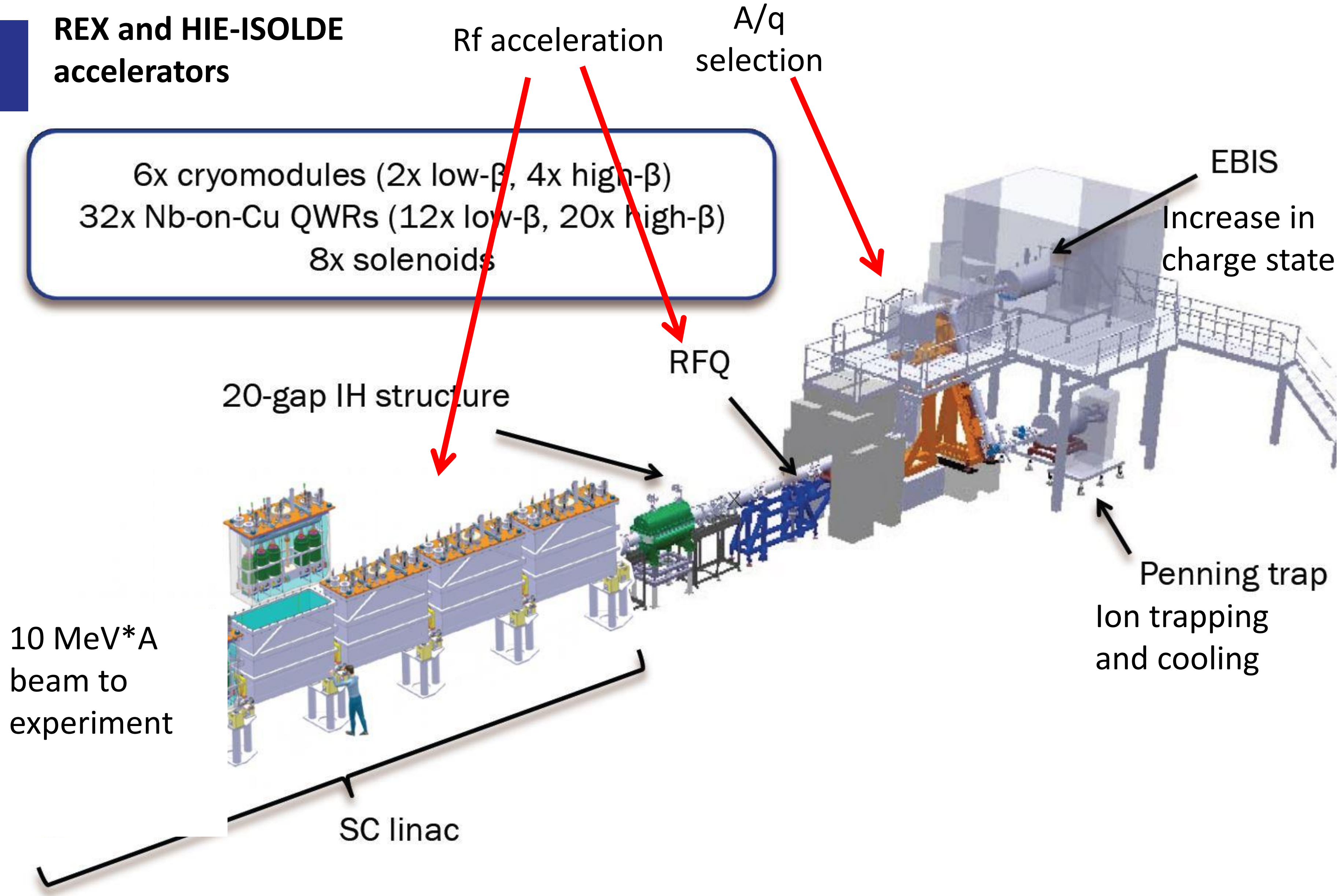
Separation



Magnet separators (General Purpose and High Resolution)

Post-acceleration

REX and HIE-ISOLDE accelerators

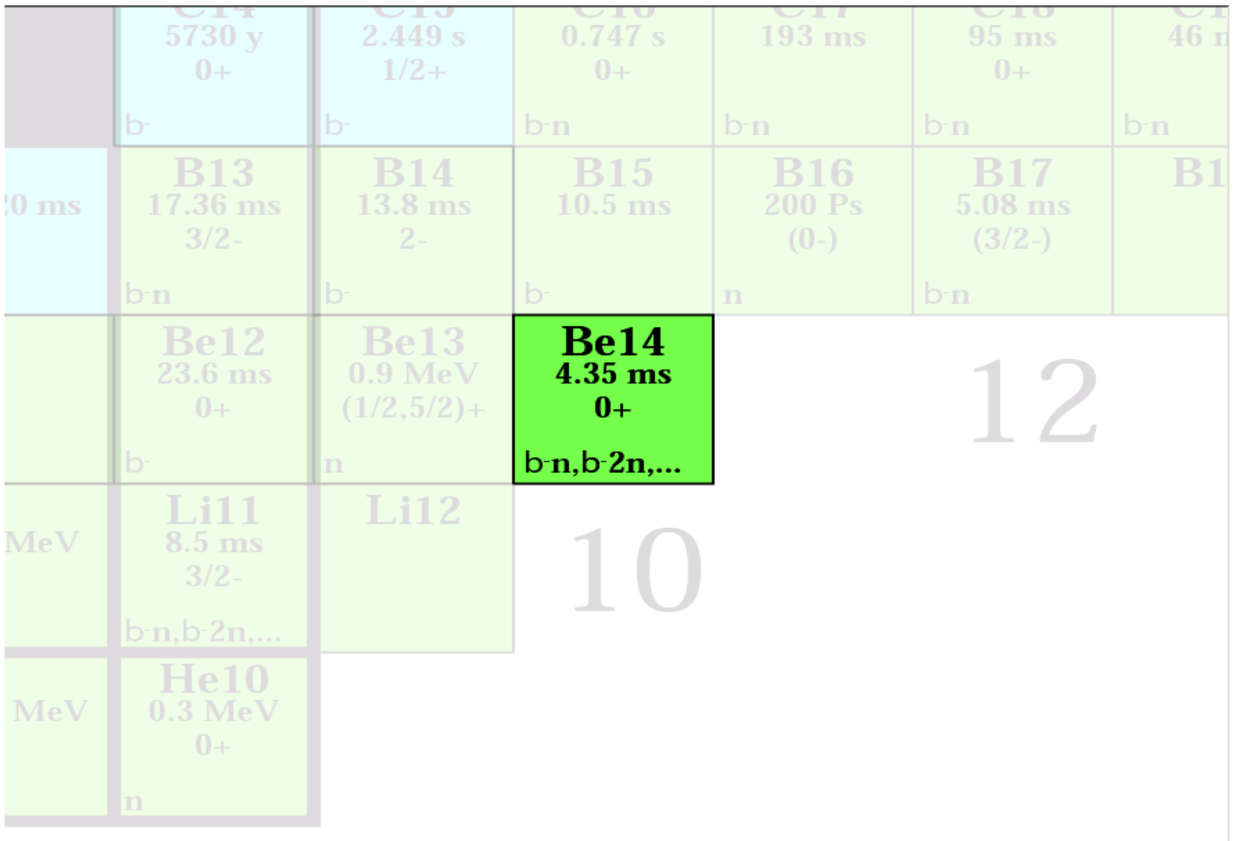


Post-acceleration current situation

3th cryomodule installed (out of 4) in winter shutdown
➔ up to 7 MeV.A acceleration possible
➔ first beam this week !

Production and selection - example

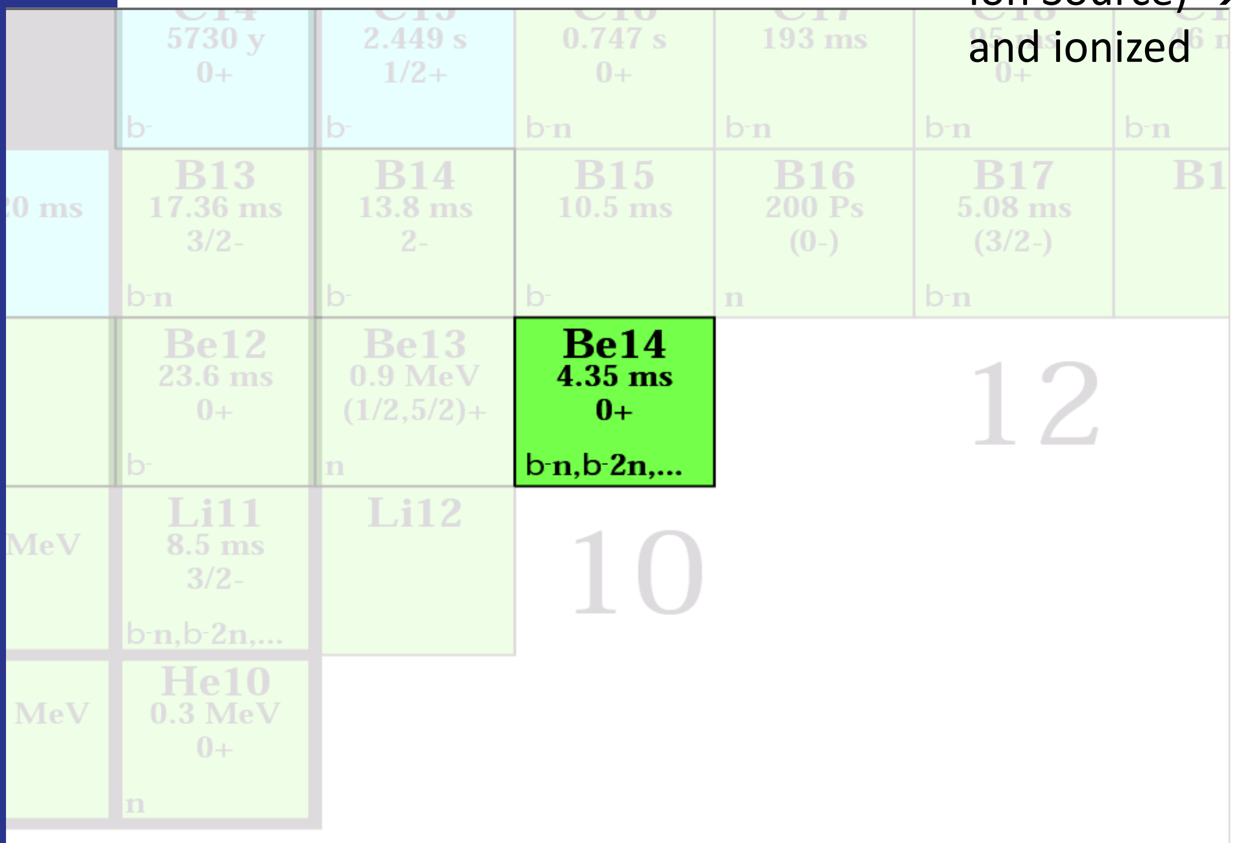
- How produce a pure beam of 14Be – the most exotic Be isotope (4 ms !)

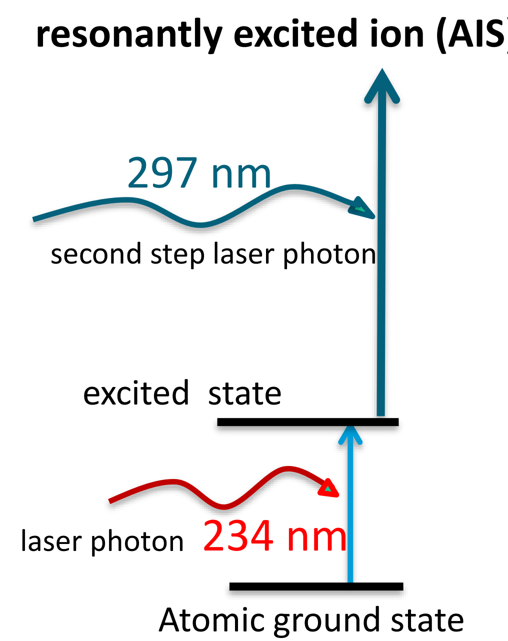


Production and selection - example

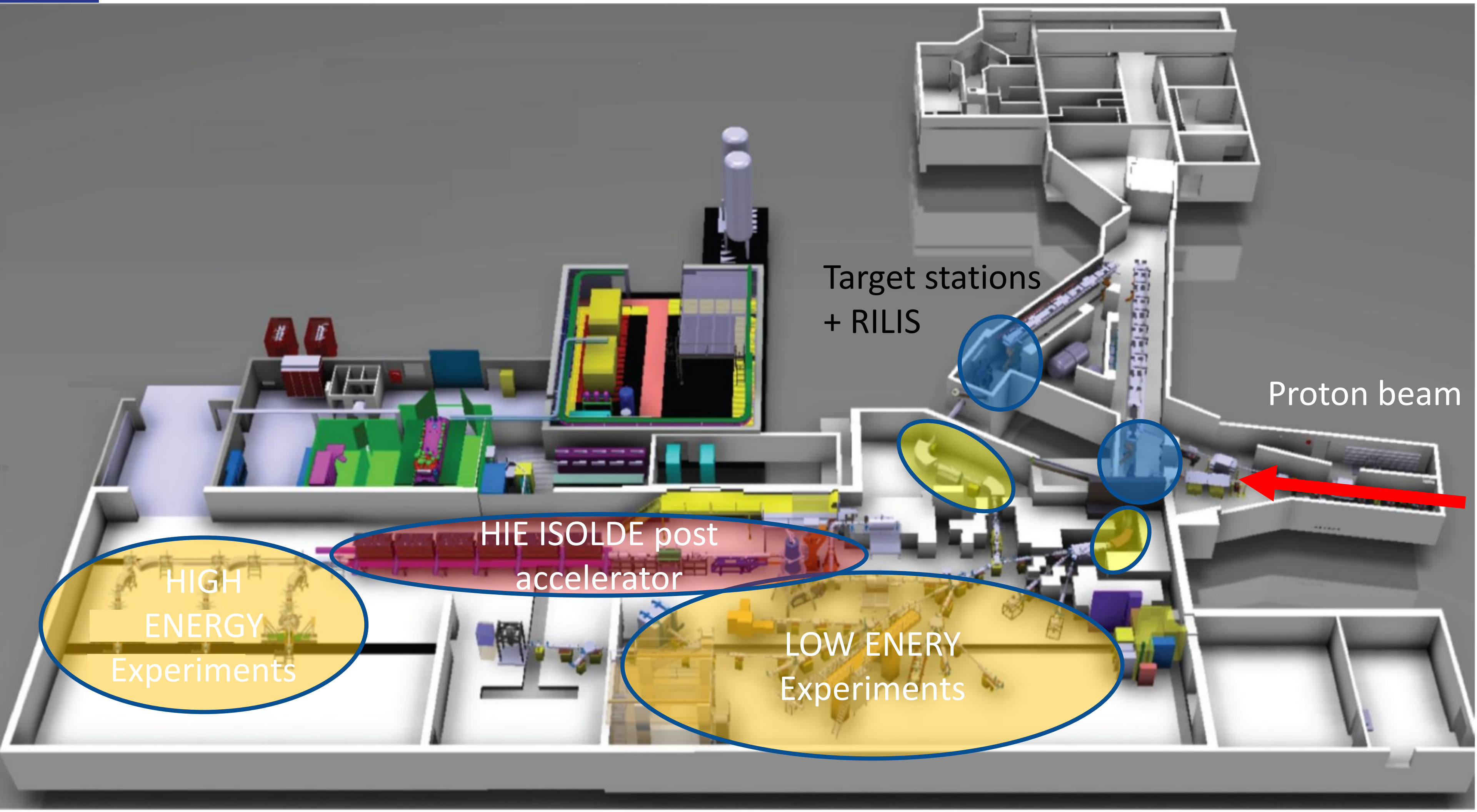
Mass 14 isobars are selected using HRS

Element selectivity (Be only) is obtained by using the RILIS (= Resonant Ionization Laser Ion Source) → only Be is resonantly excited and ionized



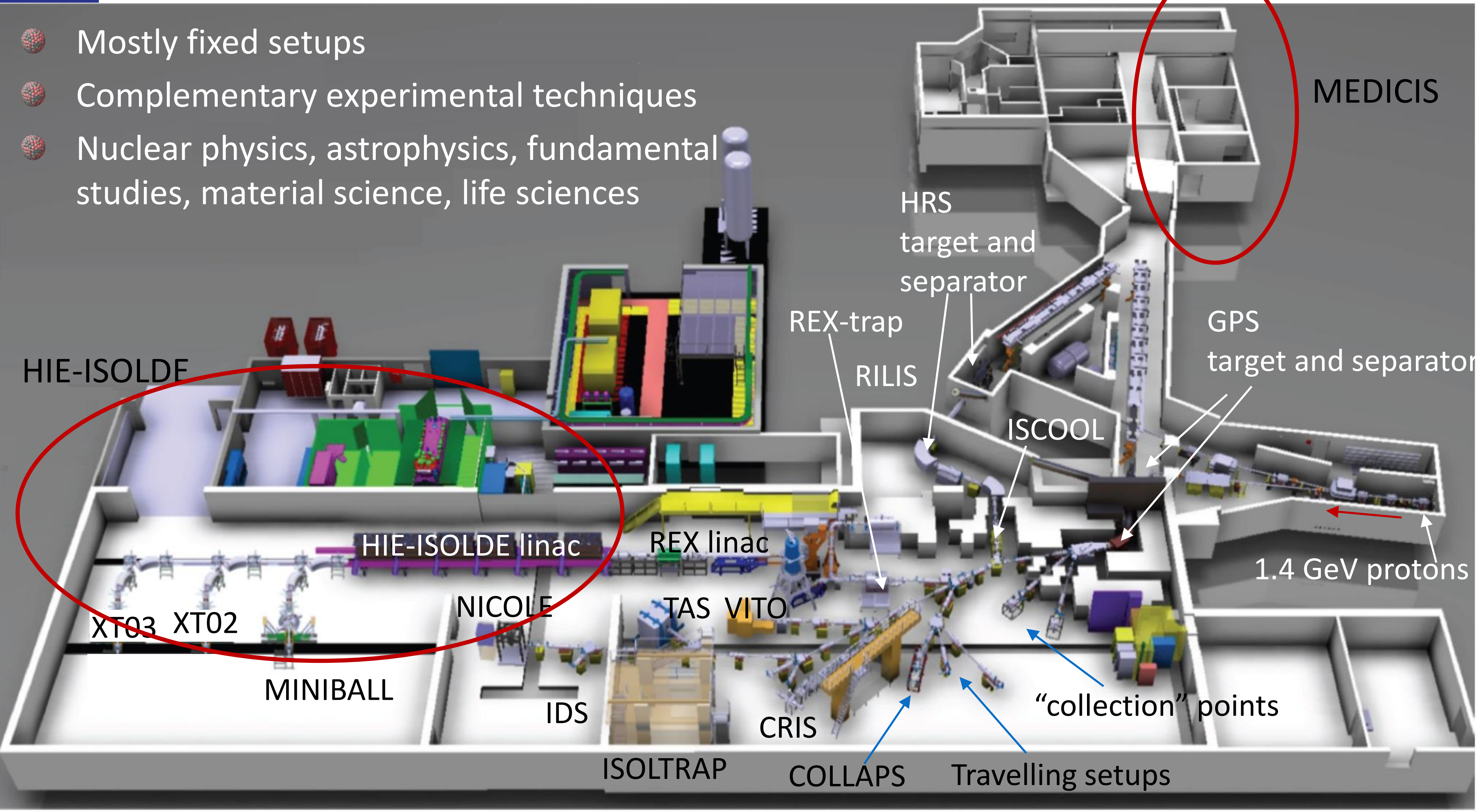


ISOLDE present layout

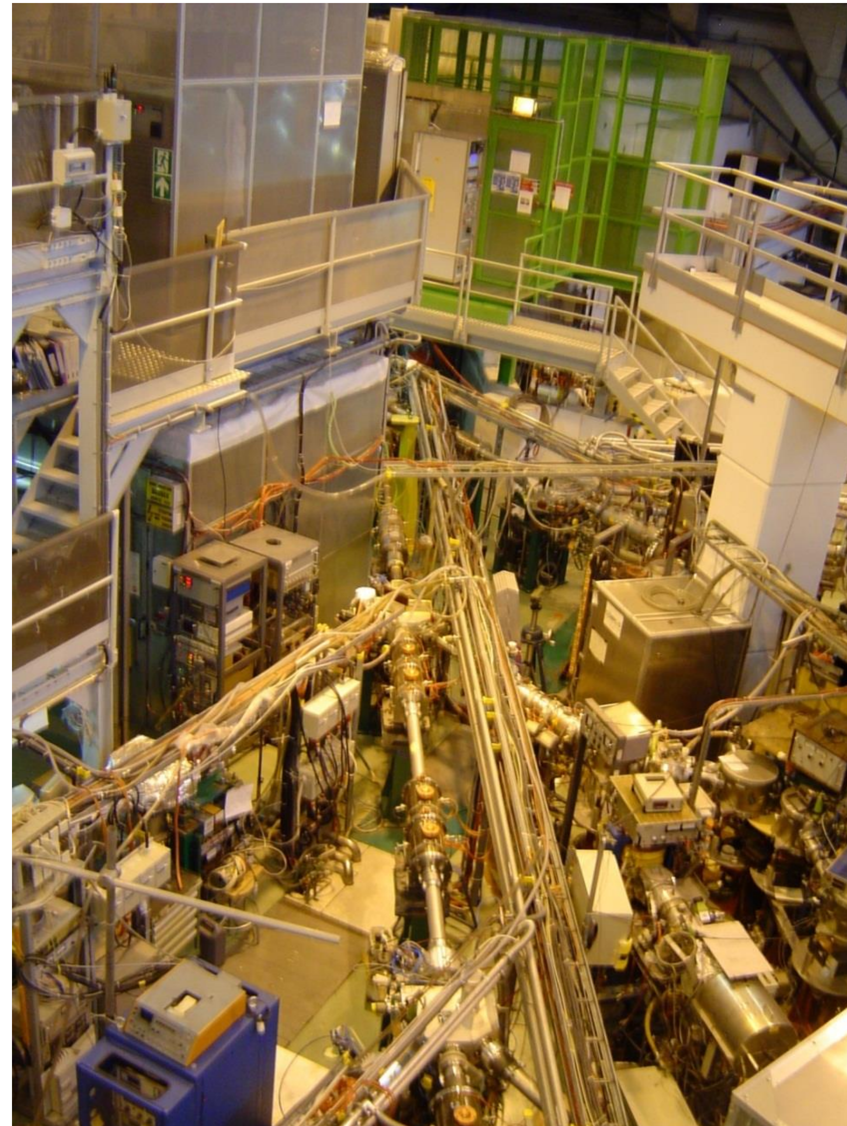


ISOLDE present layout

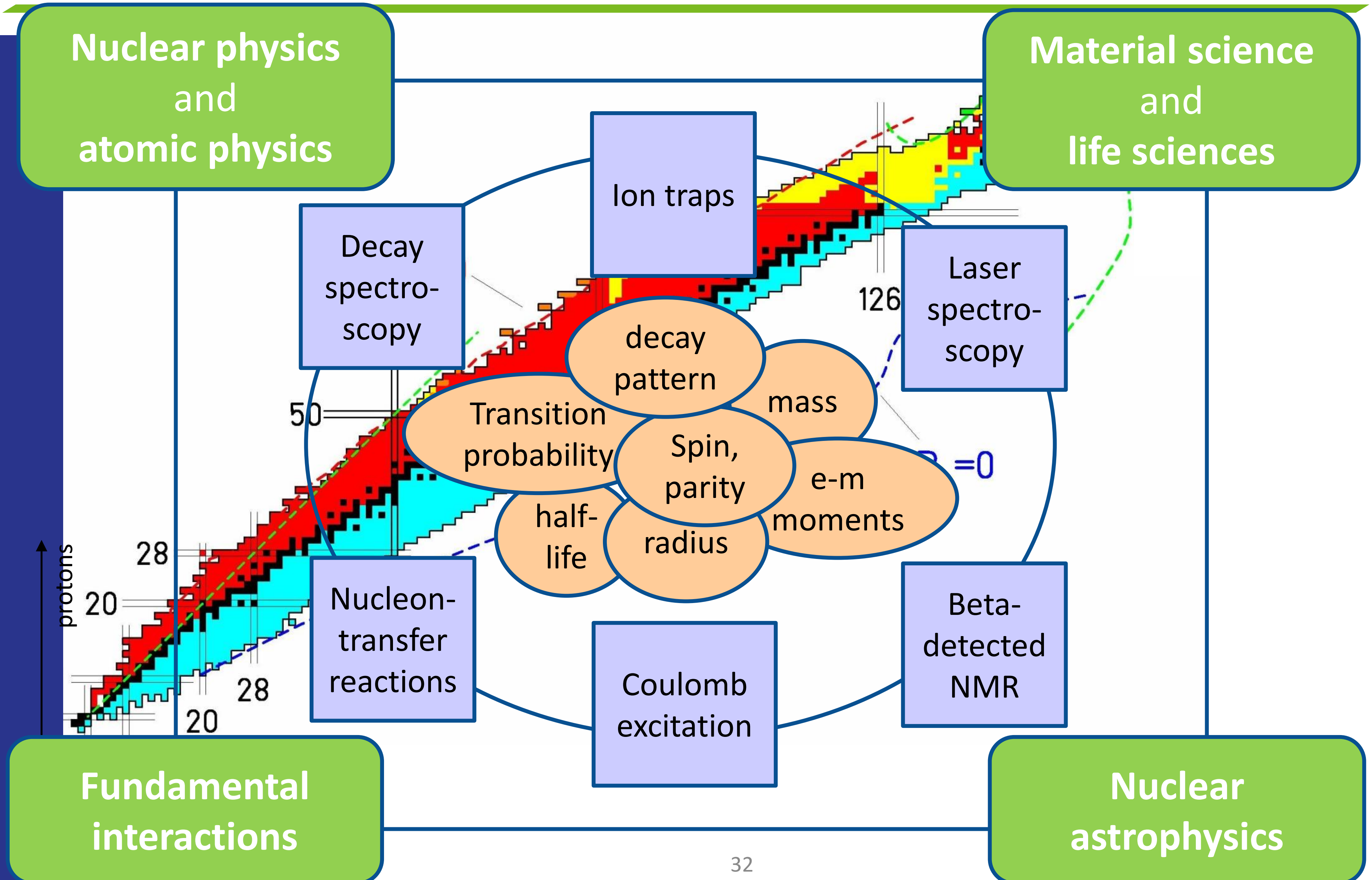
- Mostly fixed setups
- Complementary experimental techniques
- Nuclear physics, astrophysics, fundamental studies, material science, life sciences



Experimental beamlines



ISOLDE techniques and physics topics



Summary

- Two complementary types of RIB facilities
  - ISOL and in-flight
  - Several dozen facilities worldwide and new ones coming

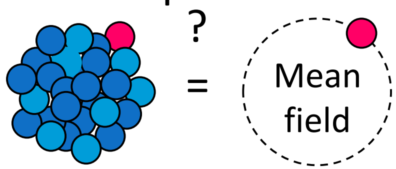
- ISOLDE at CERN
  - ISOL-type facility which uses protons from PSB
  - Elements: production target, ionization, extraction, separation, (post-acceleration)
  - Largest variety of beams worldwide
  - Upgrade project: HIE-ISOLDE post-accelerate beams to 10 MeV/nucleon
- ISOLDE research topics:
  - Nuclear physics
  - Atomic physics
  - Nuclear astrophysics
  - Fundamental studies
  - Applications
  - **=> Lecture 3**

Research with radionuclides

Nuclear physics

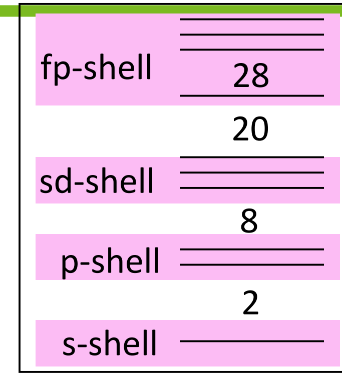
Strong interaction in many-nucleon systems

Nuclear driplines



34Ne:
10 protons + 24 neutrons

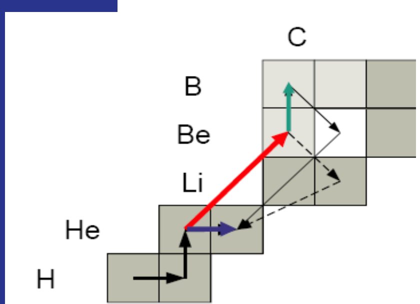
Does it exist?

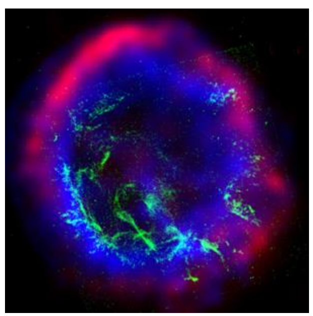


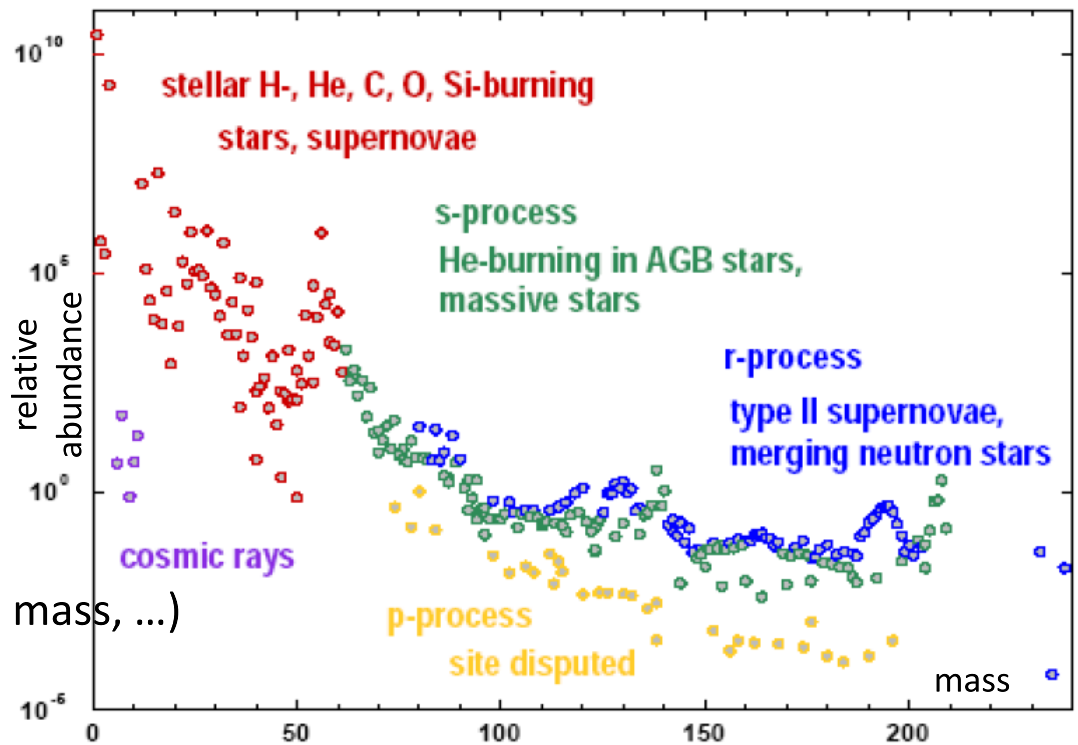
Astrophysics

Nucleo-synthesis, star evolution

Abundances of elements







Fundamental studies

Beyond standard model (neutrino mass, …)

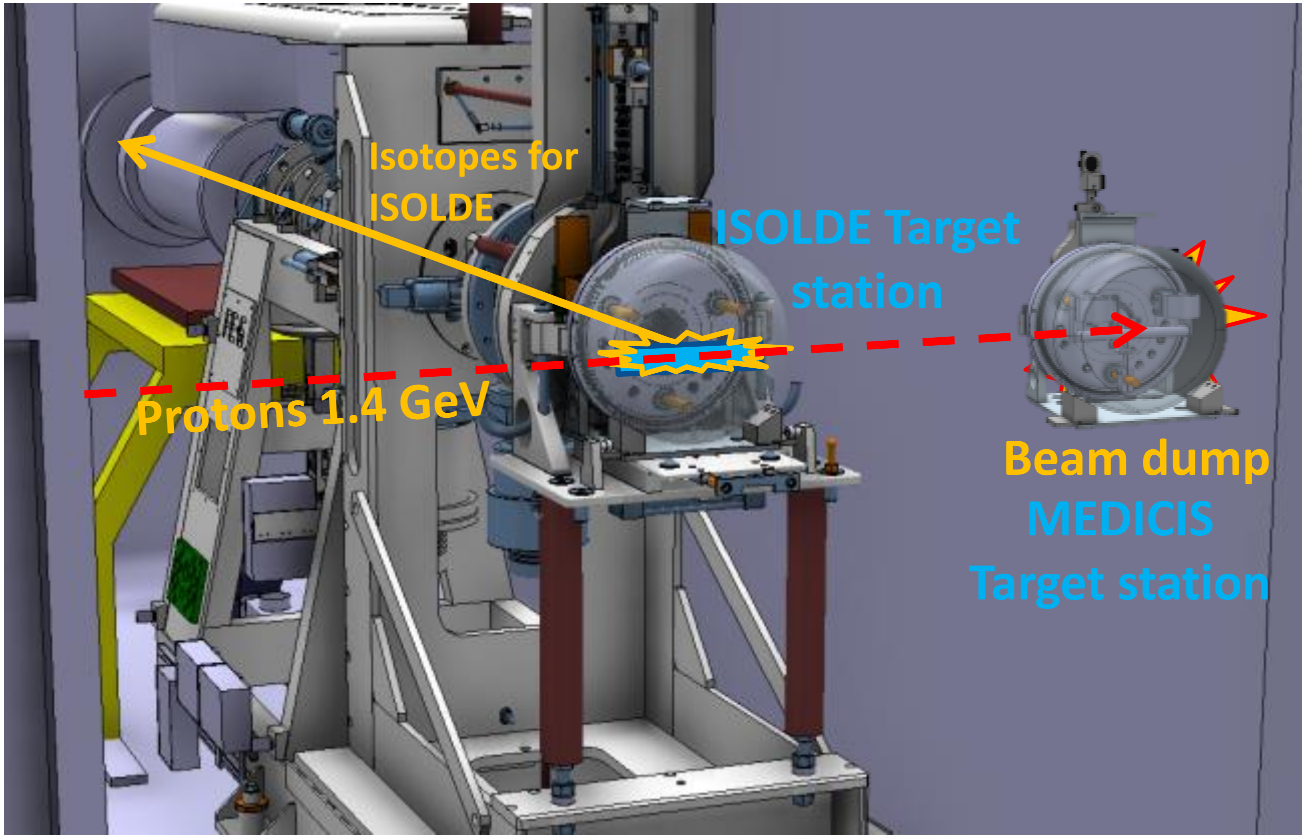
Applications, ***e.g.***

Solid state physics, life sciences

Applications: MEDICIS at ISOLDE

Production of medical isotopes for trials (not commercial use) via ISOLDE "dump" protons

-> little ISOLDE + chemical preparation



Use protons (~90%) normally lost into the **Beam Dump**

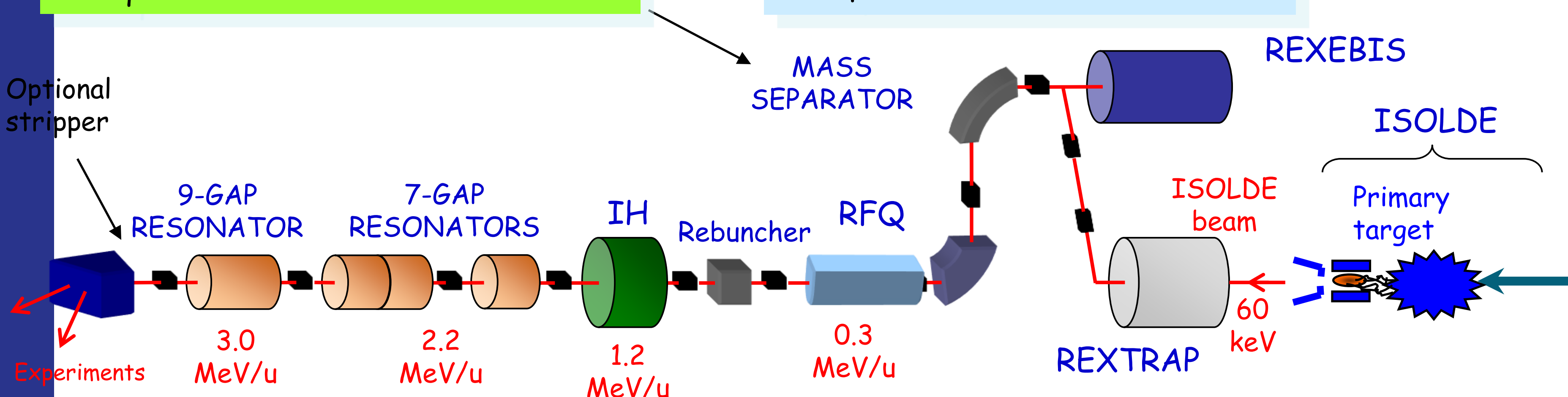
REX post-accelerator

Nier-spectrometer

- Select the correct A/q and separate the radioactive ions from the residual gases.
- A/q resolution ~150

EBIS

- Super conducting solenoid, 2 T
- Electron beam < 0.4A 3-6 keV
- Breeding time 3 to >200 ms
- Total capacity $6 \cdot 10^{10}$ charges
- A/q < 4.5



Linac

Length	11 m
Freq.	101MHz (202MHz for the 9GP)
Duty cycle	1ms 100Hz (10%)
Energy	300keV/u, 1.2-3MeV/u
A/q max.	4.5 (2.2MeV/u), 3.5 (3MeV/u)

REX-trap

- Cooling (10-20 ms)
  Buffer gas + RF
- (He), Li,…,U
- 10^8 ions/pulse

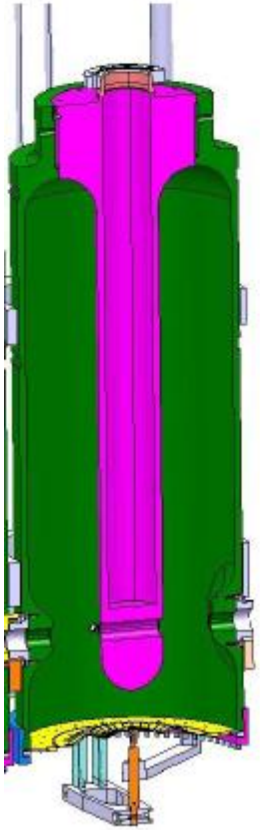
(Space charge effects $>10^5$)

Total efficiency : 1 -10 %

HIE-ISOLDE

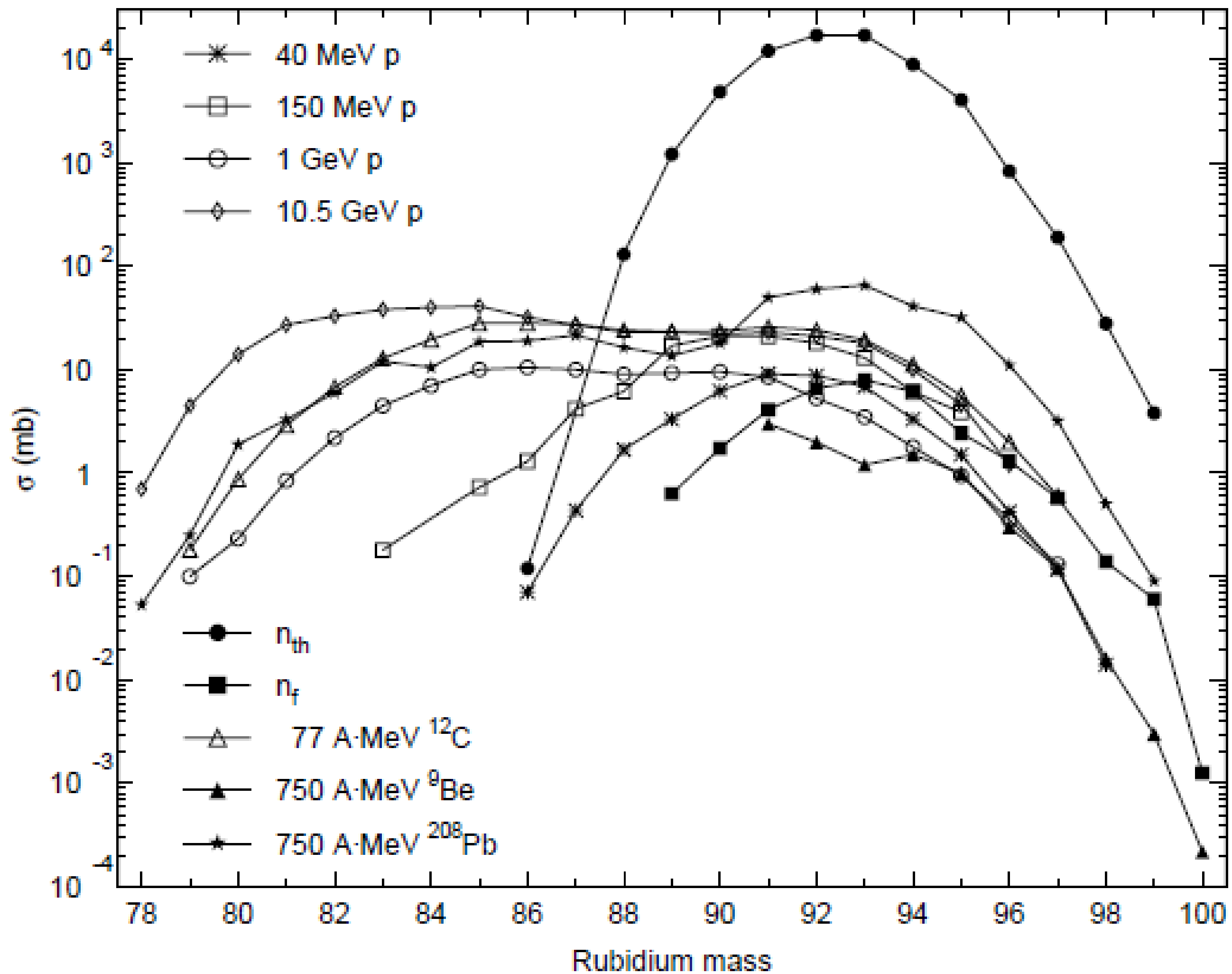
Quarter-wave resonators
(Nb sputtered)

- SC-linac between 1.2 and 10 MeV/u
- 32 SC QWR (20 @ β_0=10.3% and 12@ β_0=6.3%)
- Energy fully variable; energy spread and bunch length are tunable. Average synchronous phase fs= -20 deg
- 2.5<A/q<4.5 limited by the room temperature cavity
- 16.02 m length (without matching section)
- No ad-hoc longitudinal matching section (incorporated in the lattice)
- New beam transfer line to the experimental stations

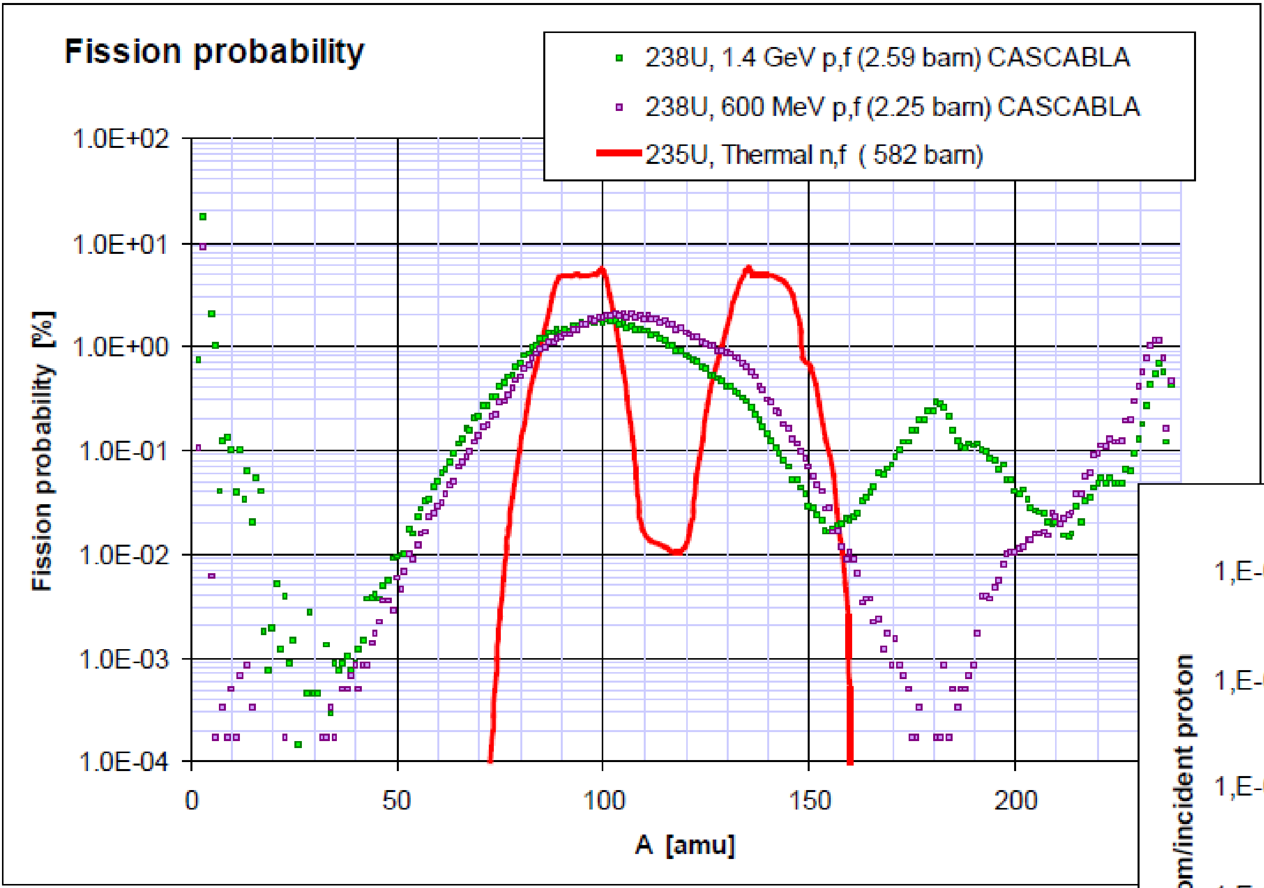


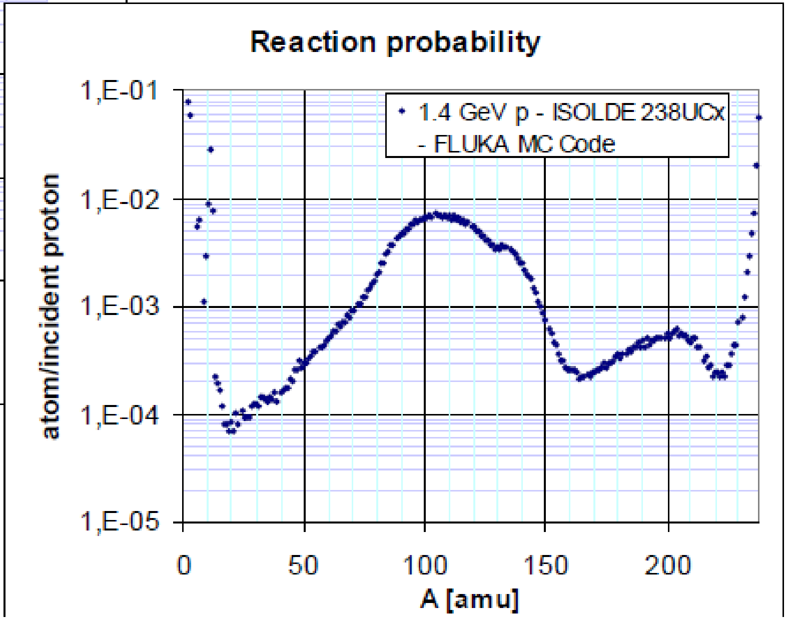
Reaction probability

- Primary beam type and energy are important



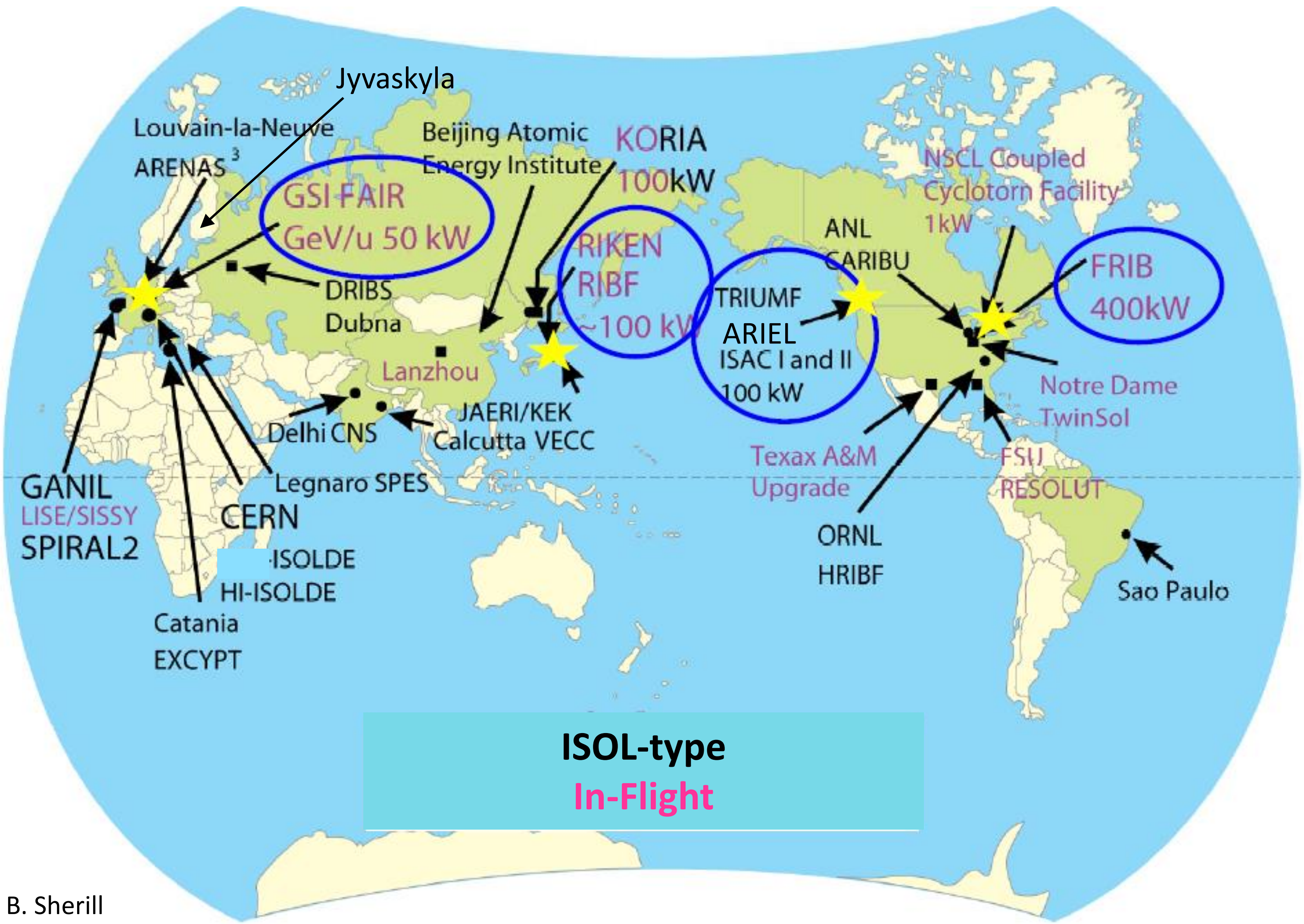
Reaction probability





RIB facilities worldwide

- Existing and in preparation



After B. Sherill