(Nuclear) Physics at the ISOLDE-CERN facility (1/2)

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CERN, TRIUMF, and University of Toronto

on behalf of the ISOLDE-CERN group
http://isolde.web.cern.ch

(Lecture 1 based on slides by Hanne Heylen)

Outline

- **Lecture 1**: ISOLDE-CERN: radioactive ion beam production
- Lecture 2: Nuclear Physics and Applications at ISOLDE

Who am I?

Stephan Malbrunot-Ettenauer
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- 2007 – '12: PhD in experimental nuclear physics,
  University of British Columbia & TRIUMF, Vancouver, Canada

- Since 2012 based at CERN
  - 2012-'14 Postdoctoral Researcher at Harvard, stationed at the AD@CERN
  - 2014-'16 CERN Research Fellow at ISOLDE
  - 2017-'22 CERN Research Physicist at ISOLDE
  - 2022- now Research Physicist at TRIUMF, Vancouver
    Adjunct Professor at the University of Toronto,

- Research Interest
  - low energy, high precision measurements at accelerator facility
  - ion traps, laser spectroscopy, exotic atoms, …

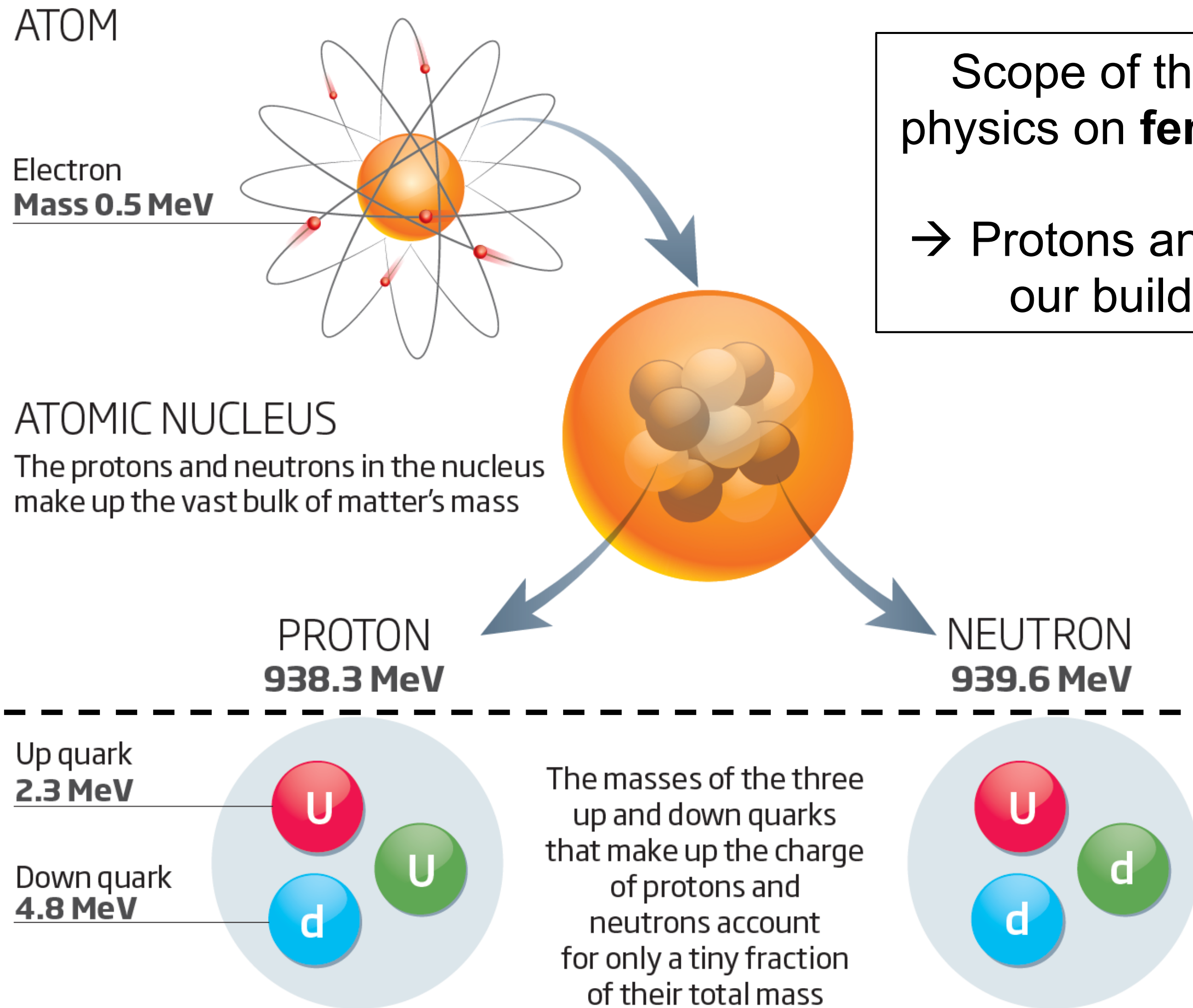
1. Introduction

Atomic nuclei: the heart of matter

10^{-10} m

10^{-14} m

10^{-15} m



Scope of these lectures:
physics on **femto**meter scale

→ Protons and neutrons are our building blocks

NewScientist, vol 226, issue 3024, June 2015

Chart of isotopes

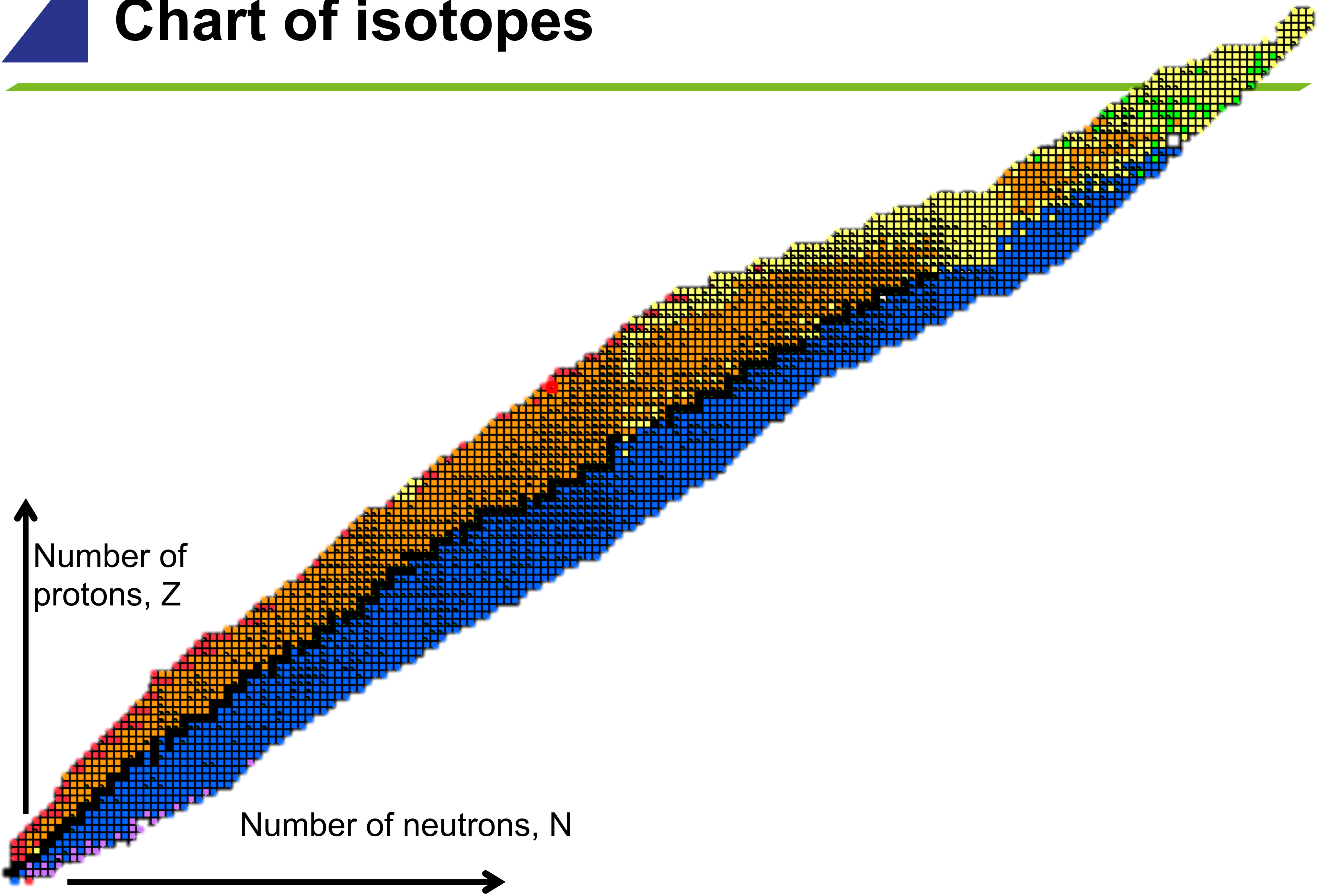
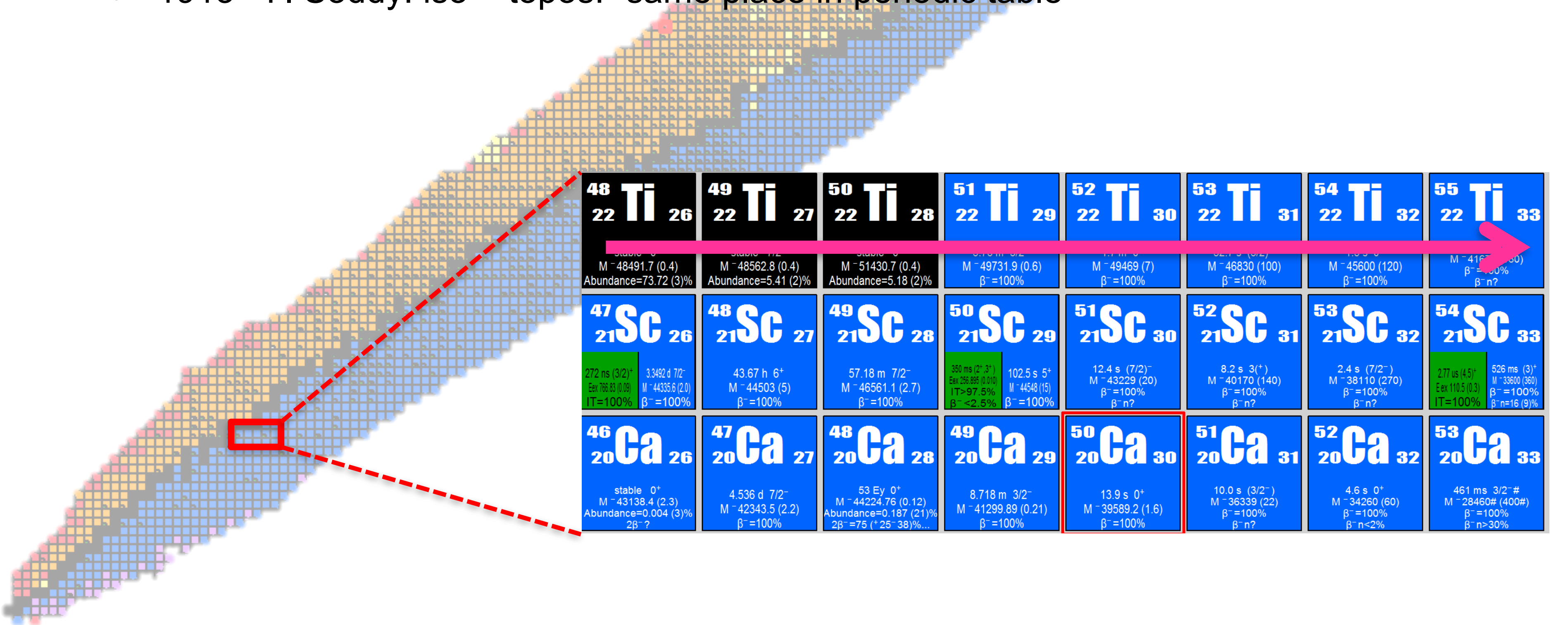


Chart of isotopes

- Nucleus/Isotope: $^{A}_{Z}X_{N}$
  - Z protons → element X
  - N neutrons
  - Atomic number A = N+Z
- Nucleons = protons and neutrons
- **Isotopes** = nuclei with the **same number of protons**, but not neutrons
  - 1913 - F. Soddy: iso + topos: “same place in periodic table”



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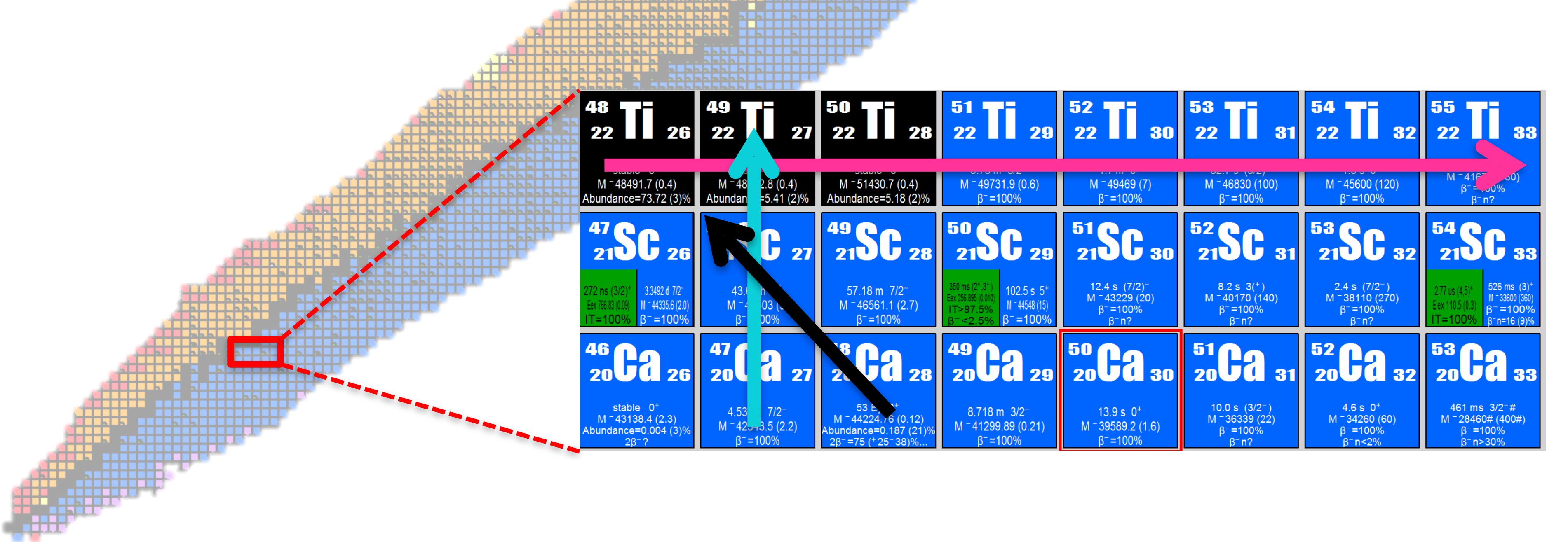
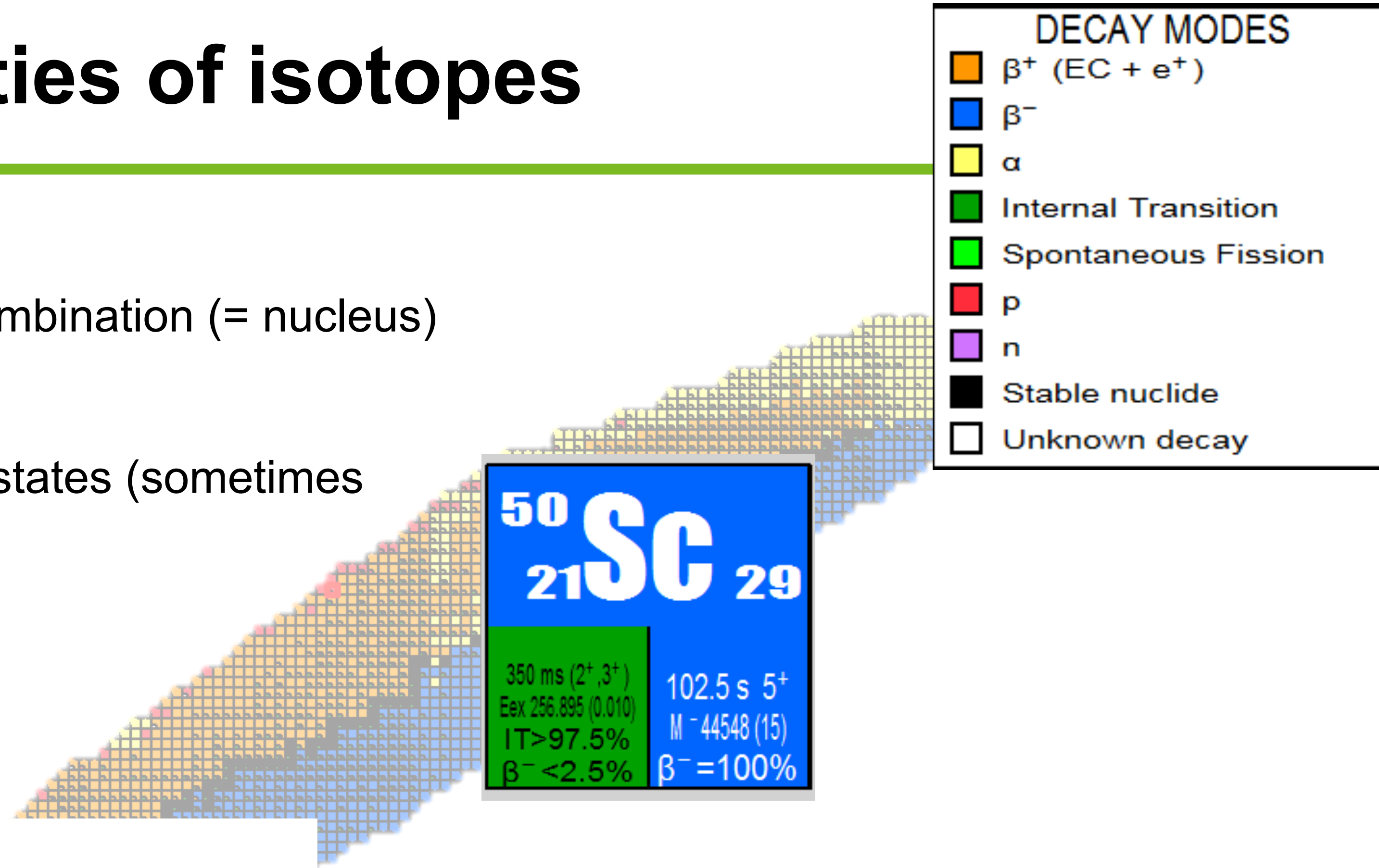
- **Isotopes** = nuclei with the **same number of protons**, but not neutrons
- **Isotones** = nuclei with the **same number of neutrons**, but not protons
- **Isobars** = nuclei with the **same number of nucleons A** (but different Z and N)

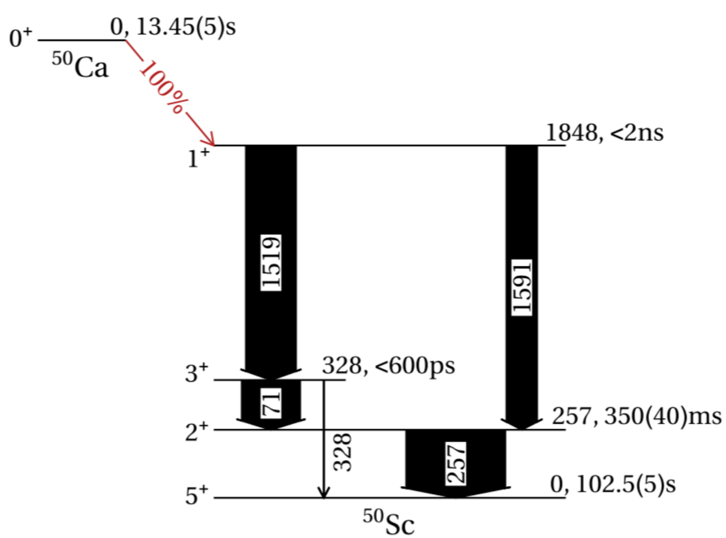


Properties of isotopes



A specific (Z, N)-combination (= nucleus) has different states

- Ground state
- Several excited states (sometimes **isomers**)



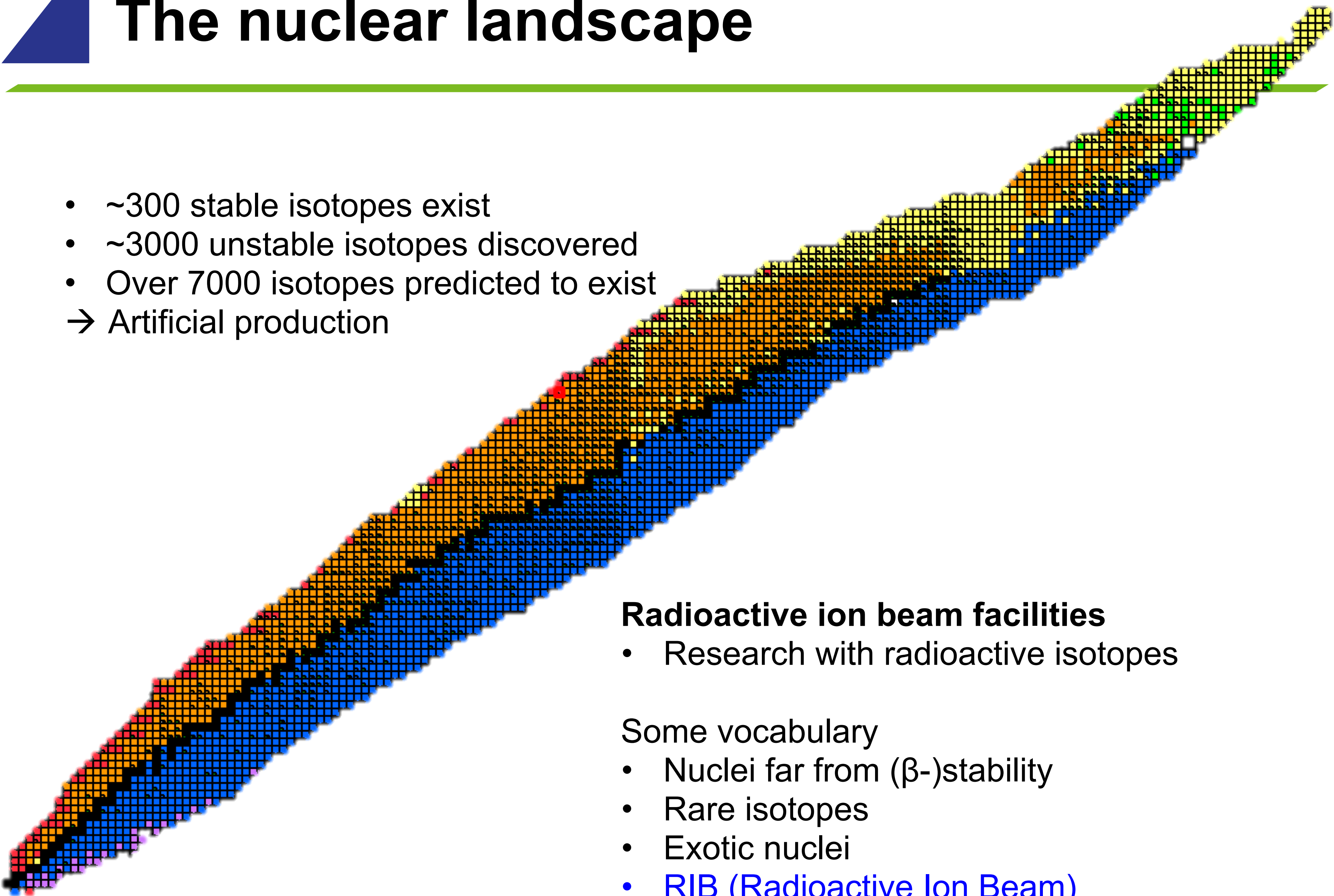
Basic properties of a nuclear state:

- Half-life
- Decay mode and probability
  - γ-decay (within a nucleus)
- Binding energy/excitation energy
- Nuclear spin and parity I^{π}
- ... (see next lecture)

The nuclear landscape

- ~300 stable isotopes exist
- ~3000 unstable isotopes discovered
- Over 7000 isotopes predicted to exist

→ Artificial production



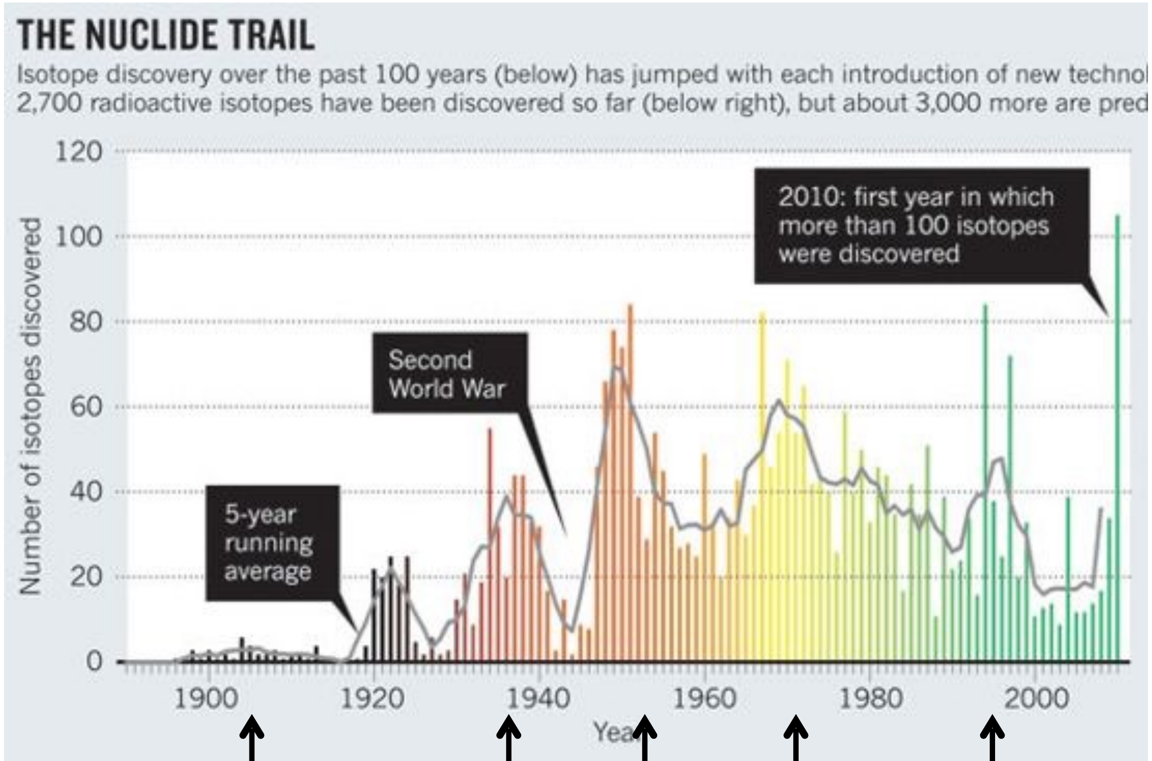
Radioactive ion beam facilities

- Research with radioactive isotopes

Some vocabulary

- Nuclei far from (β-)stability
- Rare isotopes
- Exotic nuclei
- RIB (Radioactive Ion Beam)

Thoennessen and Sherrill, Nature 473, 25 (2011)



Radioactivity

First accelerators

Reactors

Fusion-evaporation

Fragmentation

2. Production of radioactive isotopes

Radioactive ion beam production

Experimentalists dreams

- Pure beams of 1 isotopic species
- Intense beams
- Good ion optical quality (low energy spread, low angular distribution)

↕

Challenges

- Low production cross section
- Overwhelming production of unwanted species in the same nuclear reaction
- Short half-lives

More info: Y Blumenfeld et al., Phys. Scr. 014023 (2013)

Radioactive ion beam production

General steps

1) Production
2) Beam purification and preparation
3) Transport to experimental set-up
4) Do measurement

} Within a few half-lives (ms)

Key words

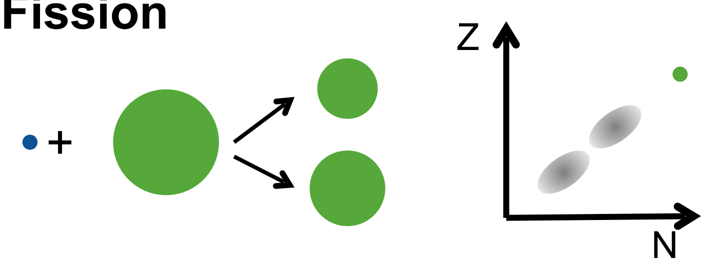
- Efficient
- Selective
- Fast

Homework
What are the factors that determine the final ion beam intensity in your set-up?
→ Focus on ISOLDE

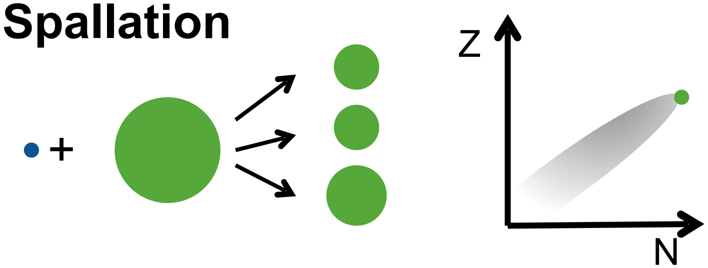
More info: Y Blumenfeld et al., Phys. Scr. 014023 (2013)

Production: nuclear reactions

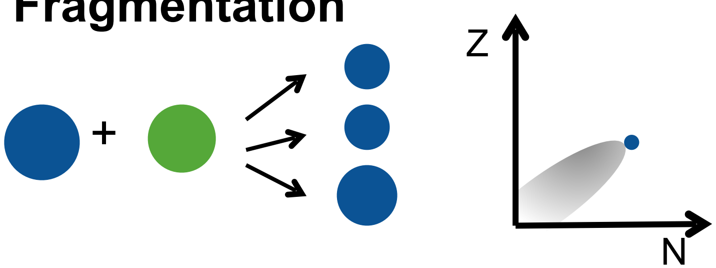
Fission



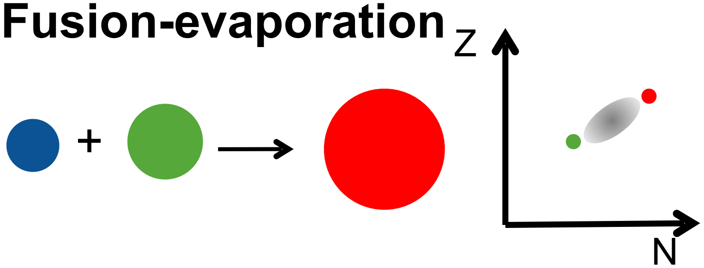
Spallation



Fragmentation



Fusion-evaporation



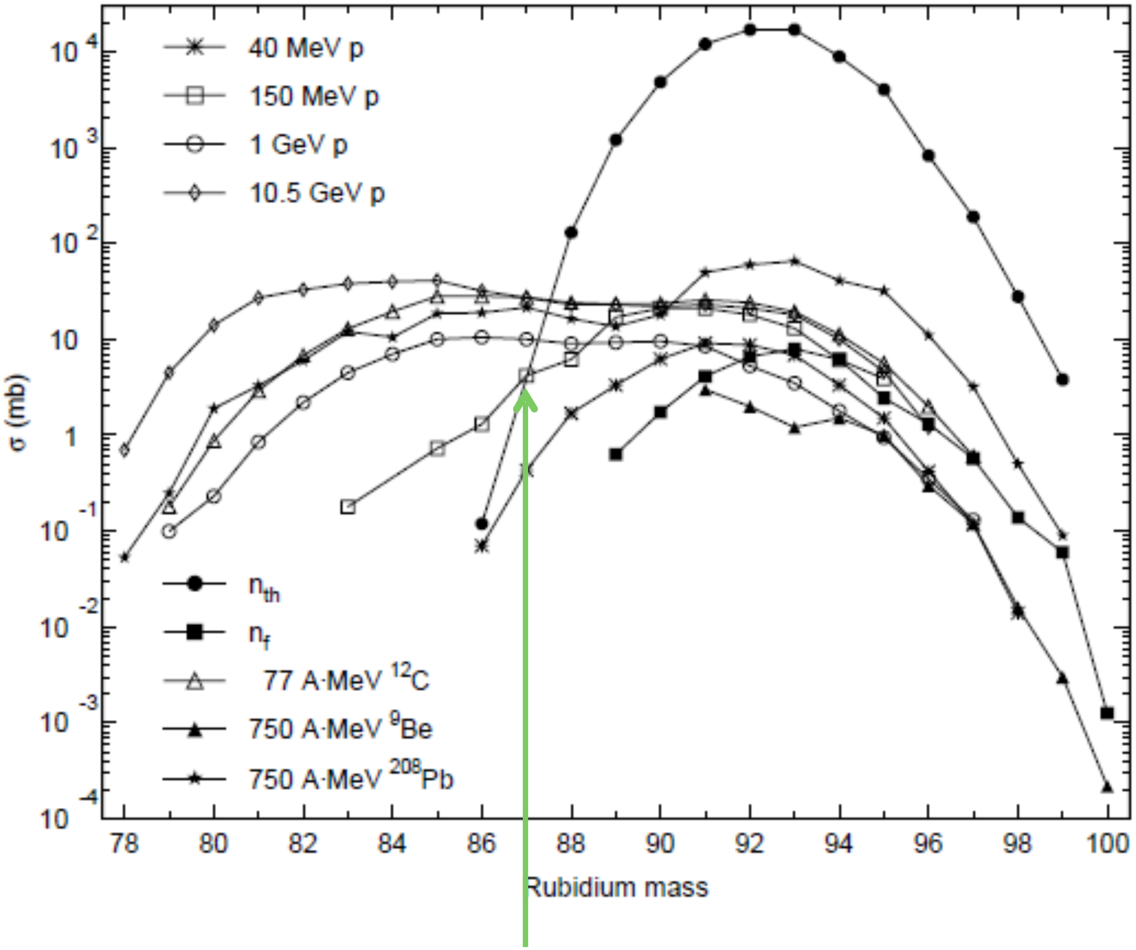
Accelerated primary beam (projectile)

- Proton, neutrons, alpha-particles, heavy ions

Target

- Heavy nuclei

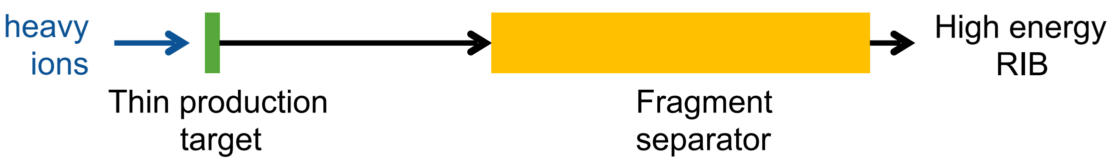
Production: nuclear reactions



Primary beam type and energy are important!

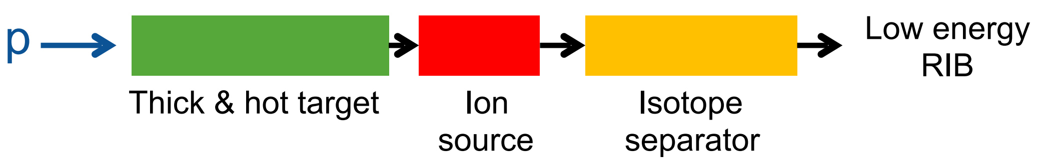
RIB production methods

In-flight



- Chemistry independent
- Fast
- Poor beam quality
- Discovery of new isotopes

ISOL

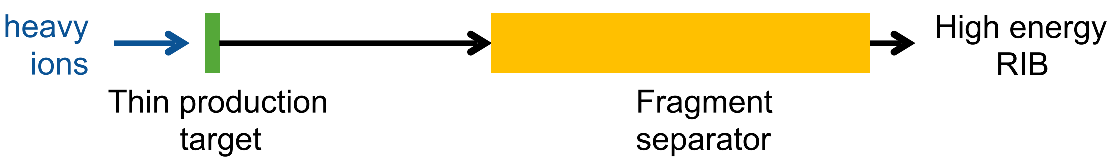


- Chemistry dependent
- Slow release from target
- Good beam quality

- 2 complementary approaches
- Extensions, adaptations, mixtures of components of the two schemes are possible as well

RIB production methods

In-flight



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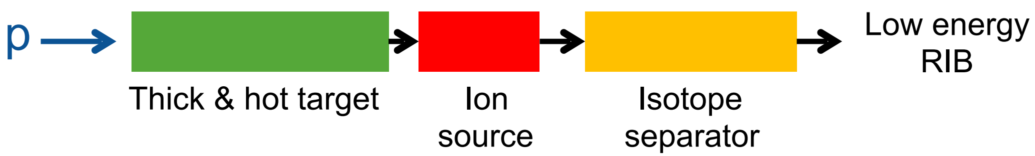
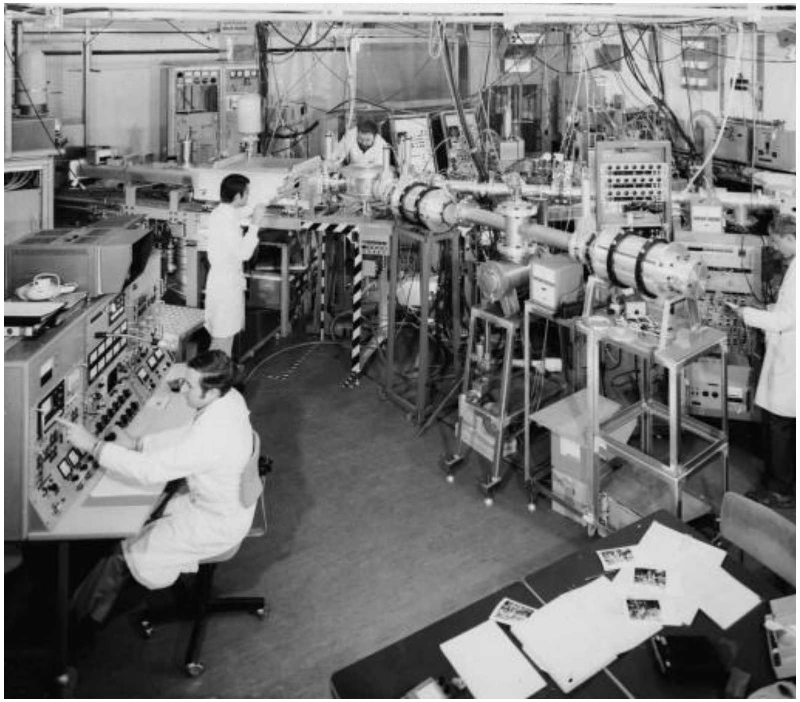
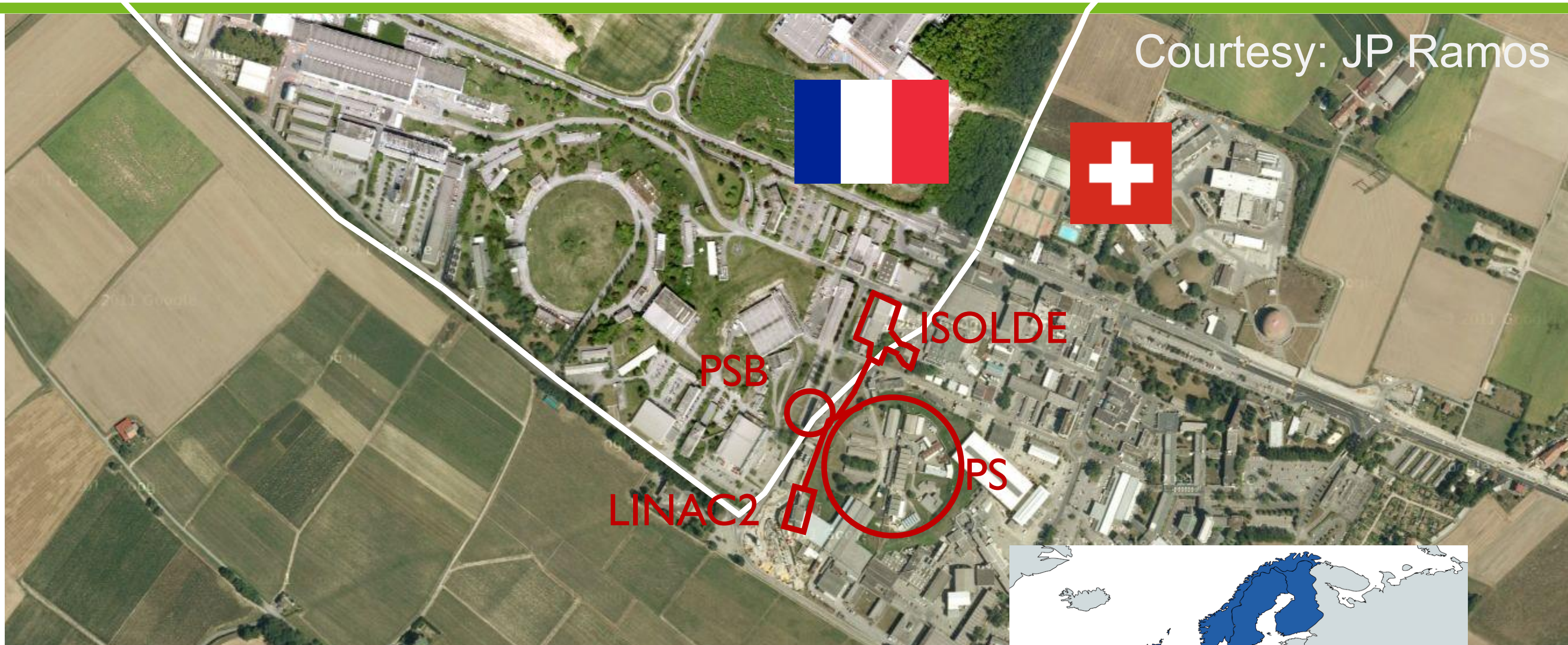
ISOL

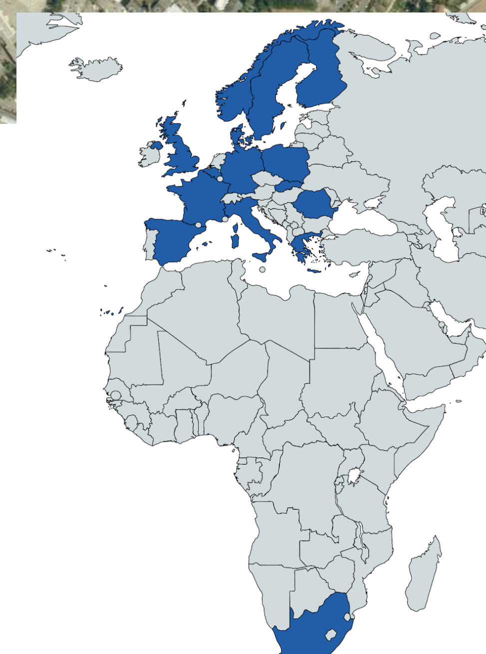




3. ISOLDE-CERN

ISOLDE at CERN



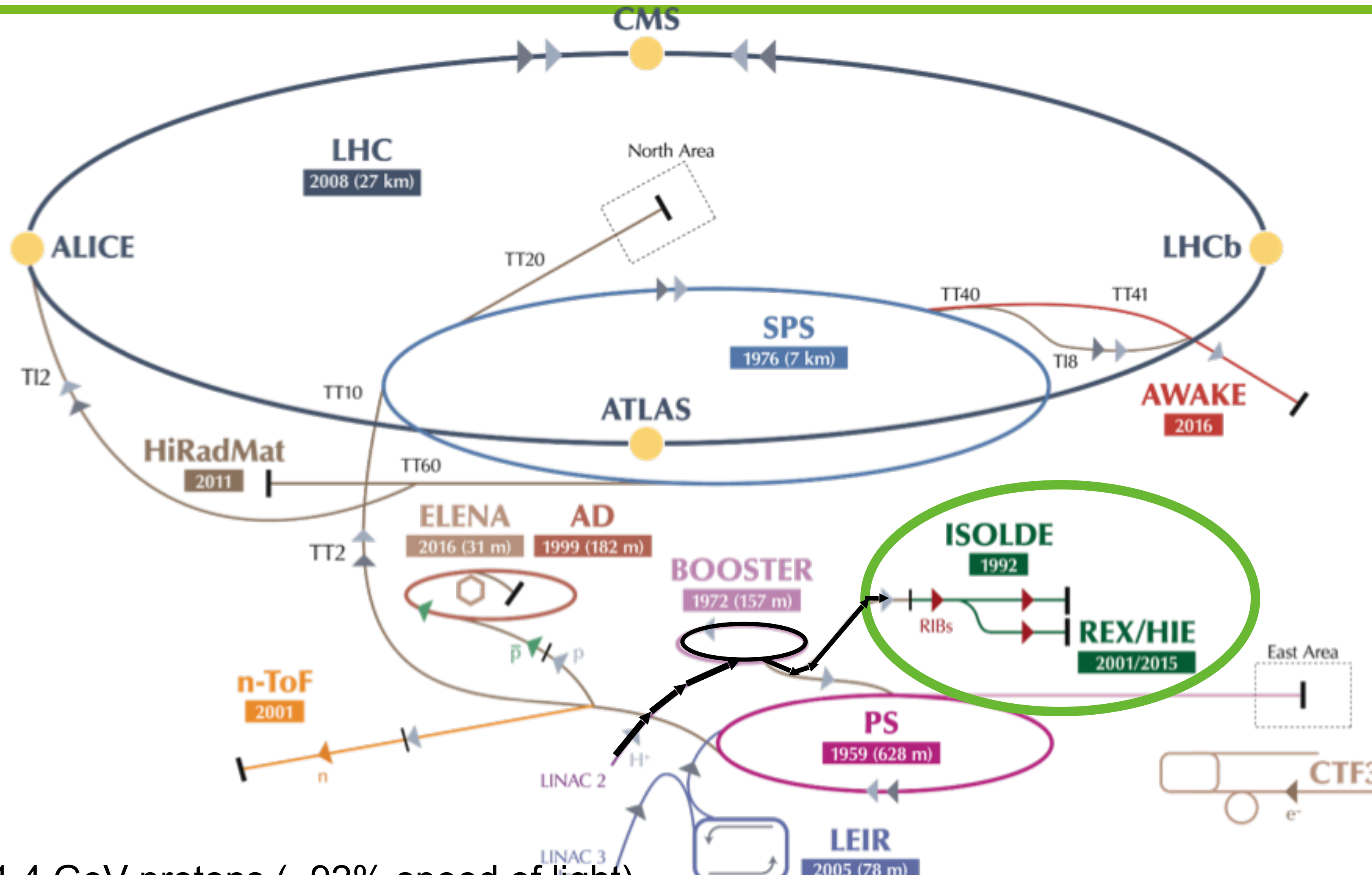


- Isotope Separator On-line Device

- First beam in 1967: more than 50 years of expertise
  - Originally at SC, Moved to PSB in 1992
  - World-wide reference for RIB production
    - First isol-facility
    - Continuous upgrades

- ~50 staff/fellows/students
  few 100 users each year

ISOLDE at CERN



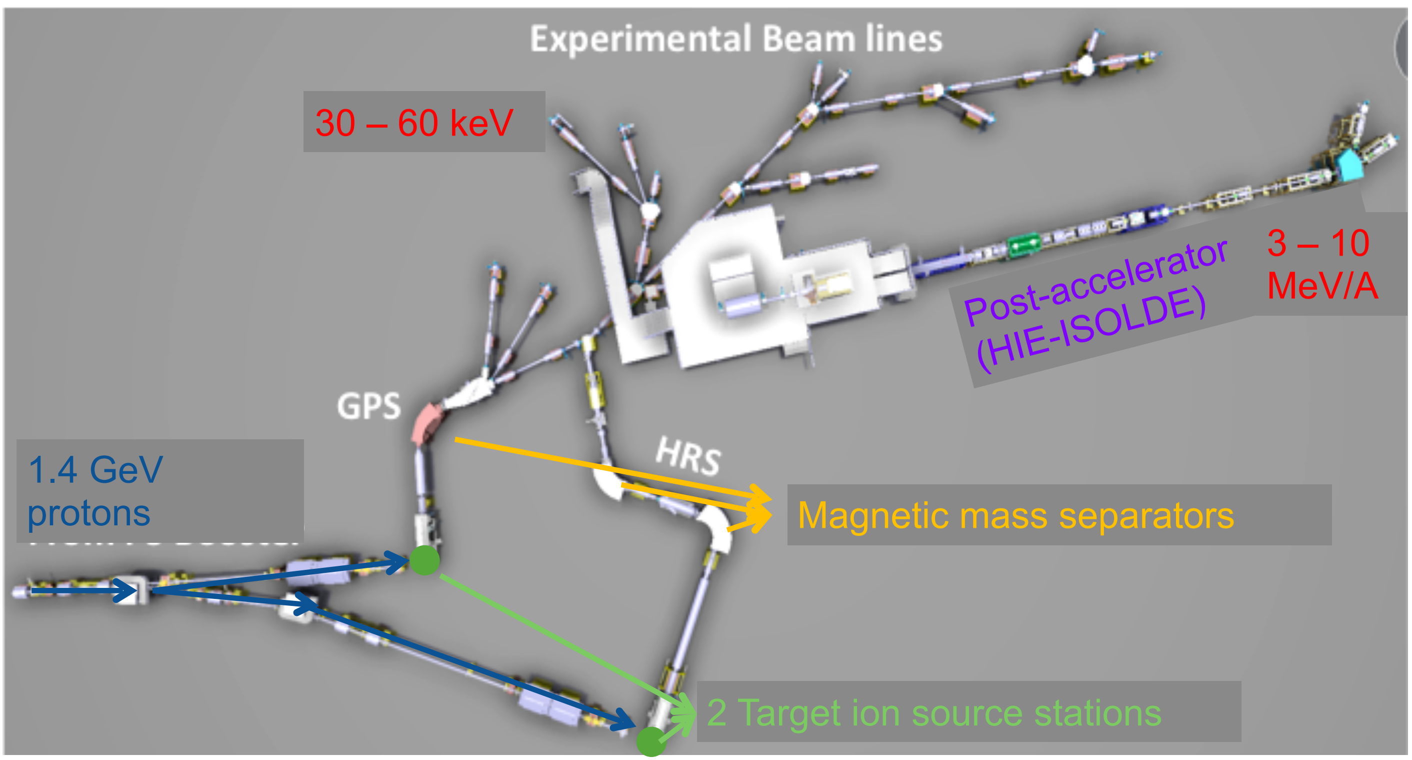
- 1.4 GeV protons (~92% speed of light)
- 50% of CERN's protons

Isotope production at ISOLDE

1. Production and extraction from target
2. Ionisation (singly-charged)
3. Mass separation
4. Low-energy RIB (30 – 60 keV)
   a. To experimental set-ups
   b. Post-acceleration 3 - 10 MeV/A

Not to forget

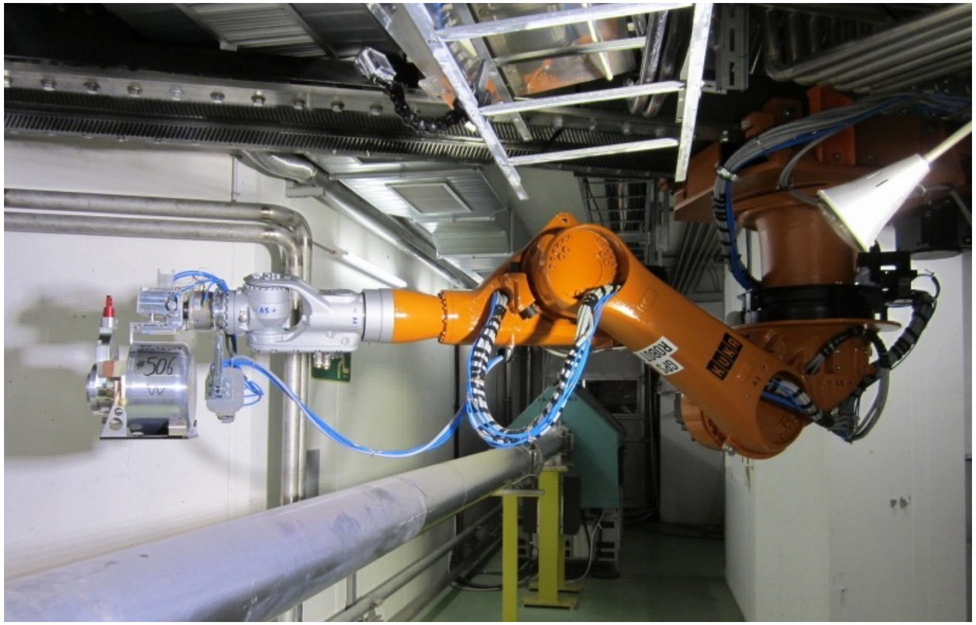
- Ion optical elements (steerers, focussing elements, …)
- Beam diagnostics (faraday cups, wire grids)



Isotope production at ISOLDE

Targets

- Over 20 target materials and ionizers, depending on beam of interest
- Target heating to enhance diffusion/effusion
- Target area is highly irradiated
  - Lasts ~1 week
  - Well shielded from rest of experimental hall
  - Operations by robots

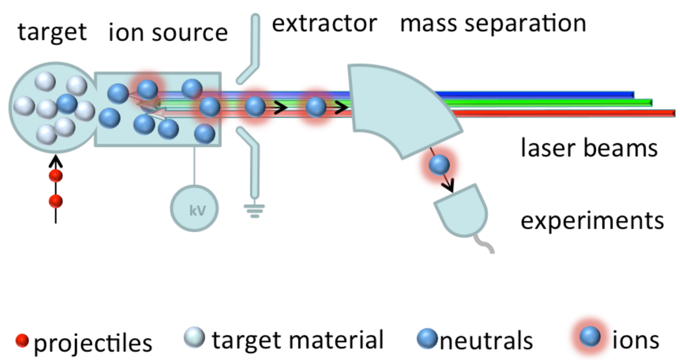


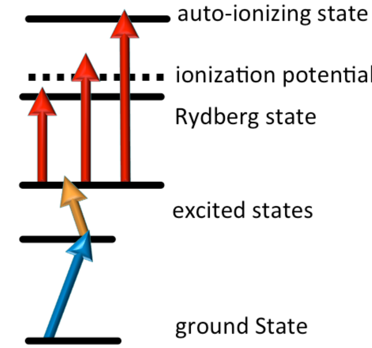
Ionisation

RILIS

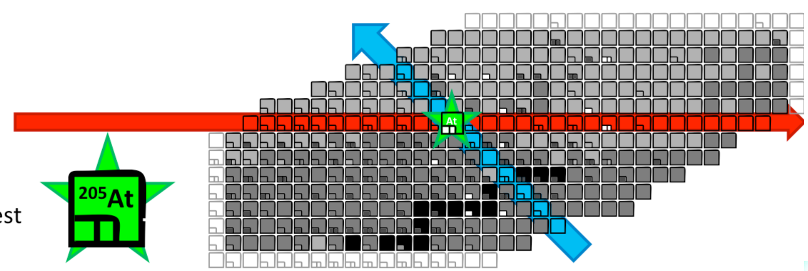
Atomic (electronic) structure =
Fingerprint of element

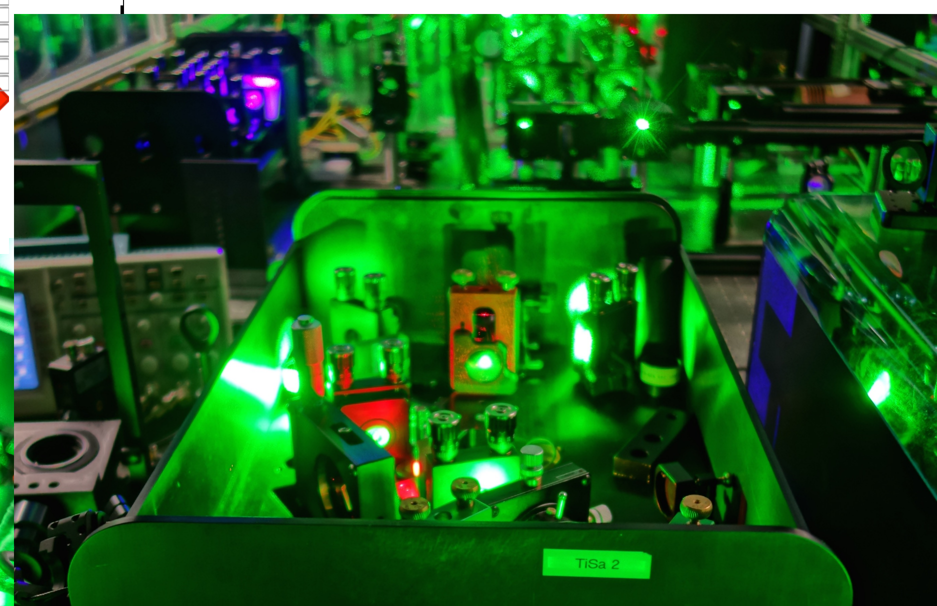
- Several options (chemistry)
  - Surface
  - Plasma
  - Laser (RILIS)
- Laser ion source advantages
  - Selectivity
  - Efficiency





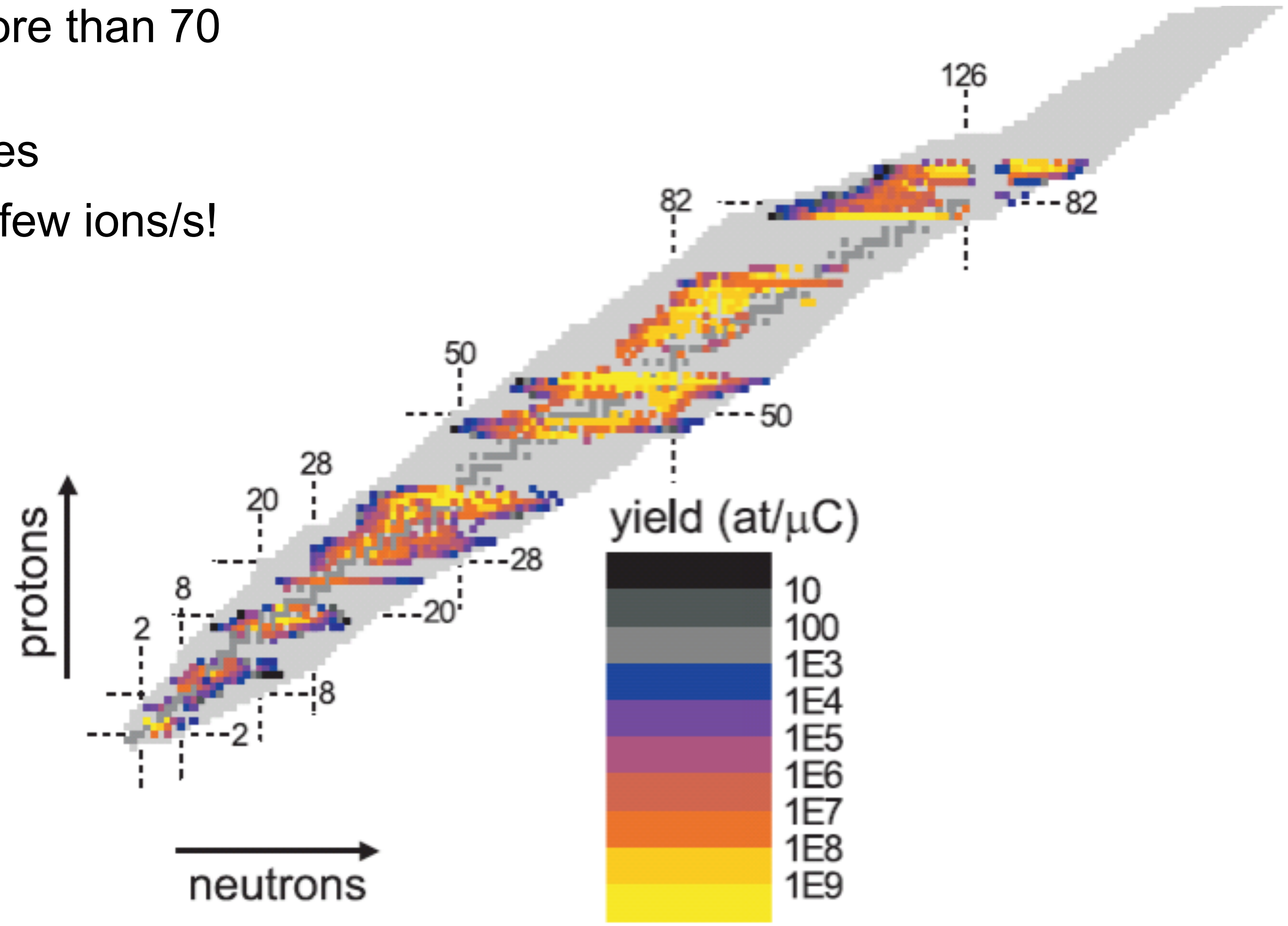
Isotope of interest



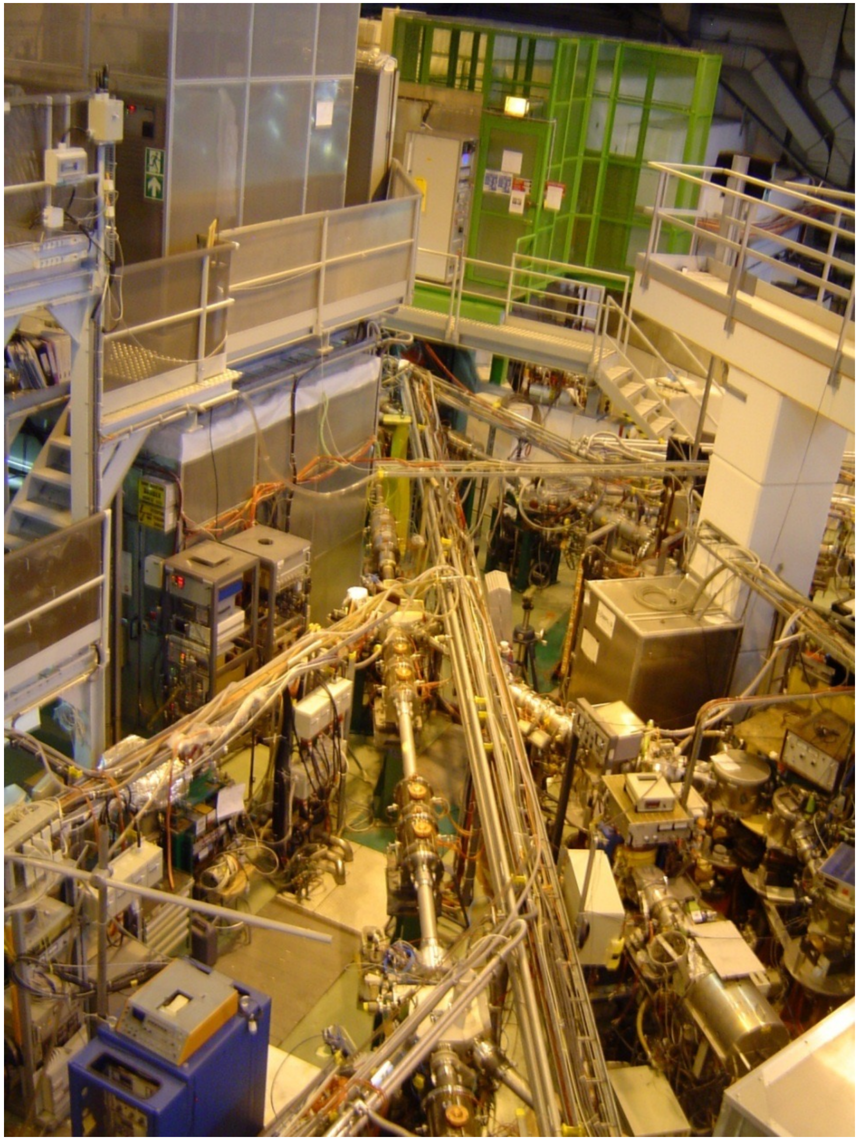


RIBs at ISOLDE

- 1300 isotope of more than 70 chemical elements
- ms – stable isotopes
- Sometimes only a few ions/s!



View of experimental area

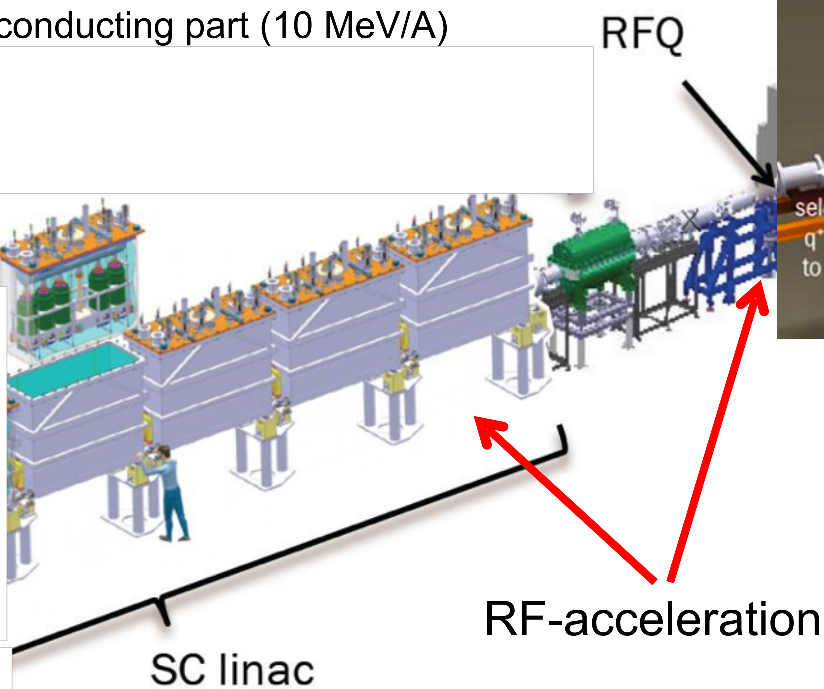


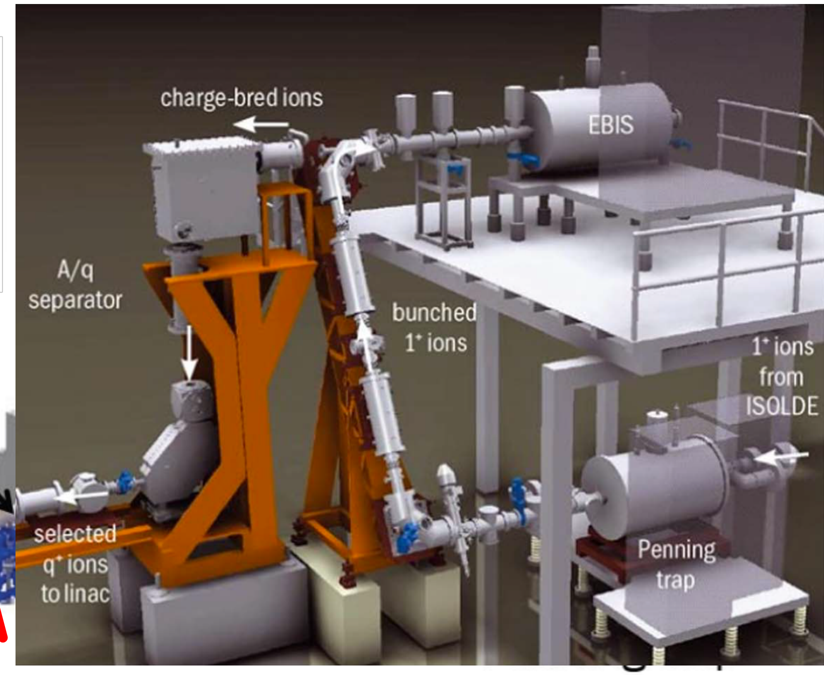
Post-acceleration: REX + HIE-ISOLDE

1. Start from mass separated beam from ISOLDE
2. Beam cooling/bunched in buffer-gas filled Penning trap
3. Charge-state breeding using electron-beam ionisation

(2.5 < A/q < 4.5

1. A/q selection
2. Linear accelerator
   - Room temperature part (3 MeV/A)
   - Superconducting part (10 MeV/A)



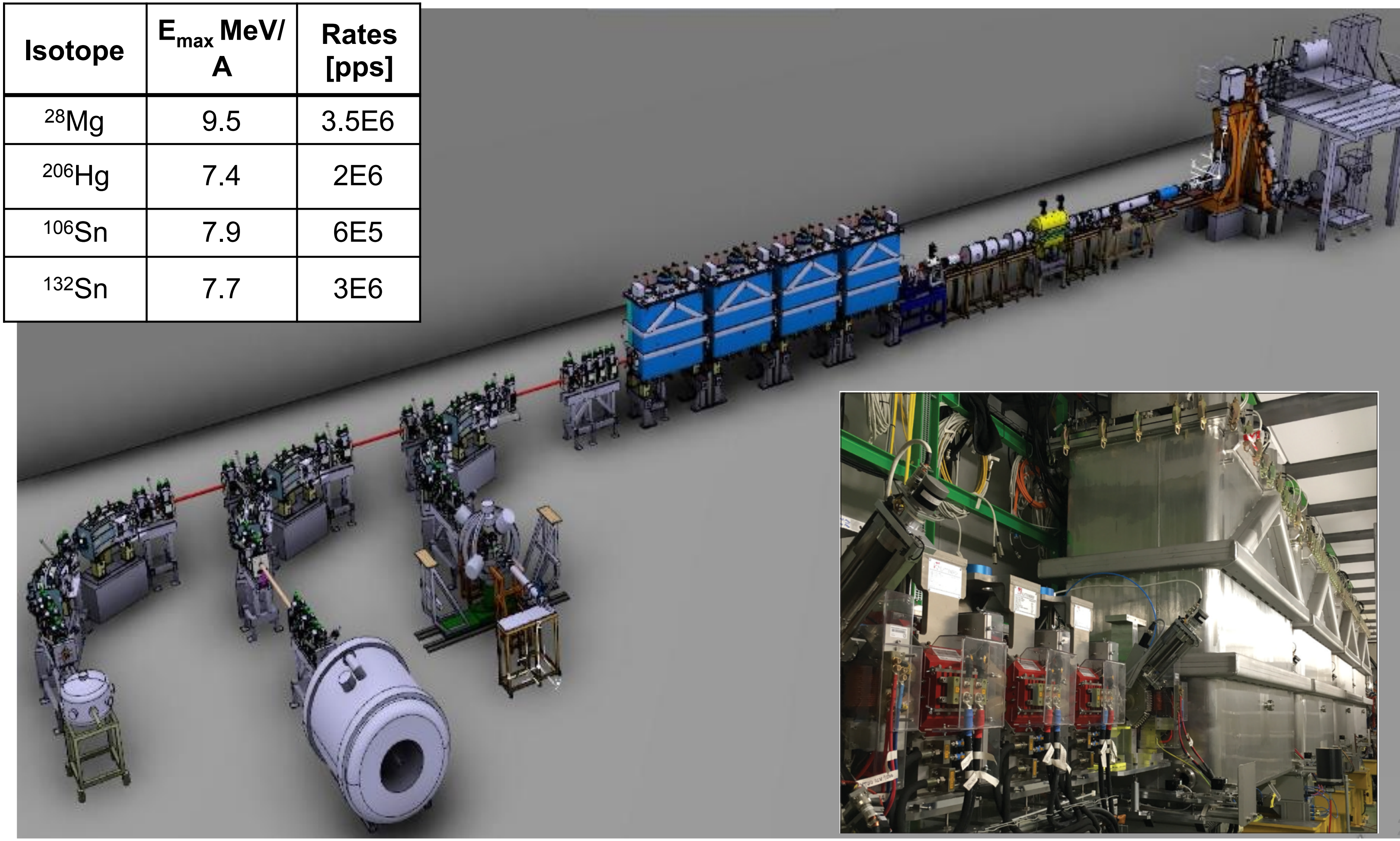


More info: Y Kadi et al,. J. Phys. G: Nucl. Part. Phys. 44 084003 (2017)

Post-acceleration: REX + HIE-ISOLDE

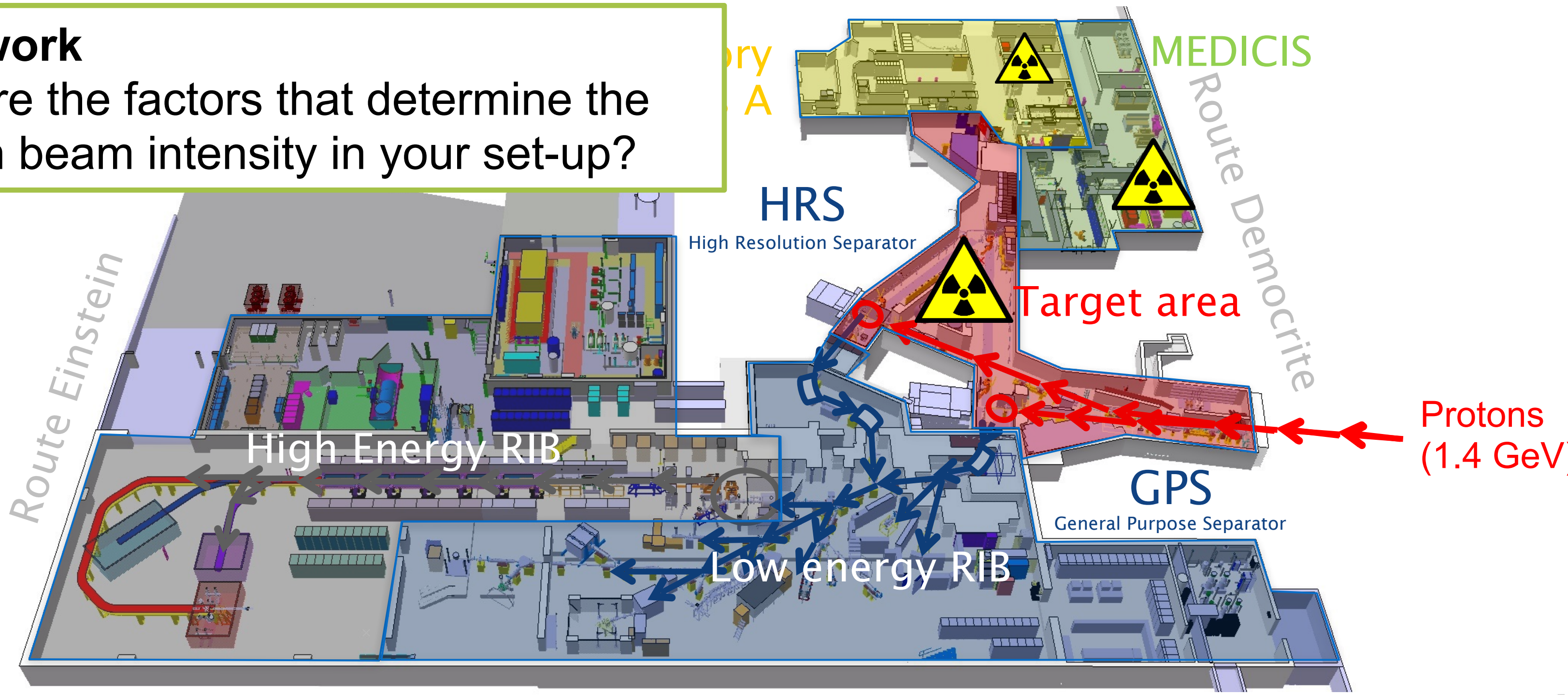
2018: All 4 cryomodules installed

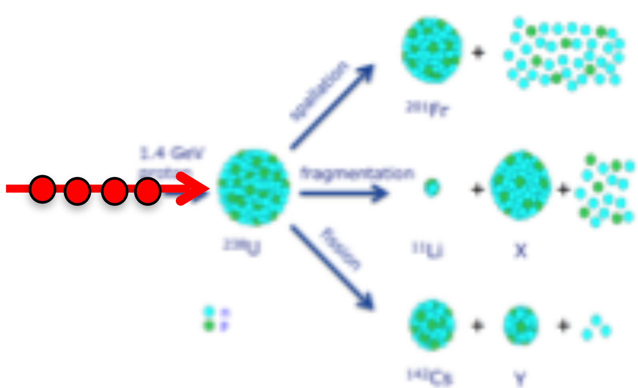
Isotope	E_{max} MeV/ A	Rates [pps]
^{28}Mg	9.5	3.5E6
^{206}Hg	7.4	2E6
^{106}Sn	7.9	6E5
^{132}Sn	7.7	3E6

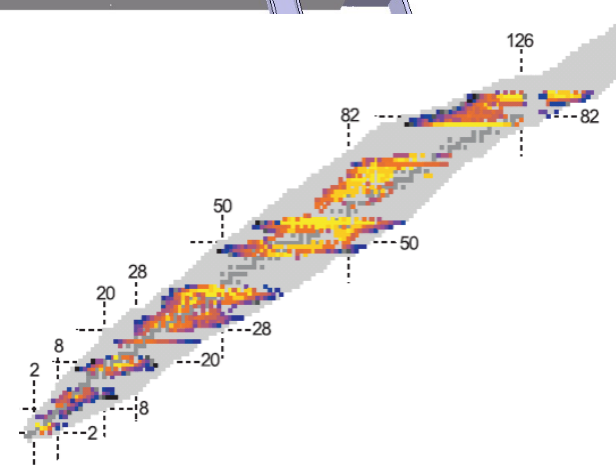


The ISOLDE facility - summary

Homework
What are the factors that determine the final ion beam intensity in your set-up?

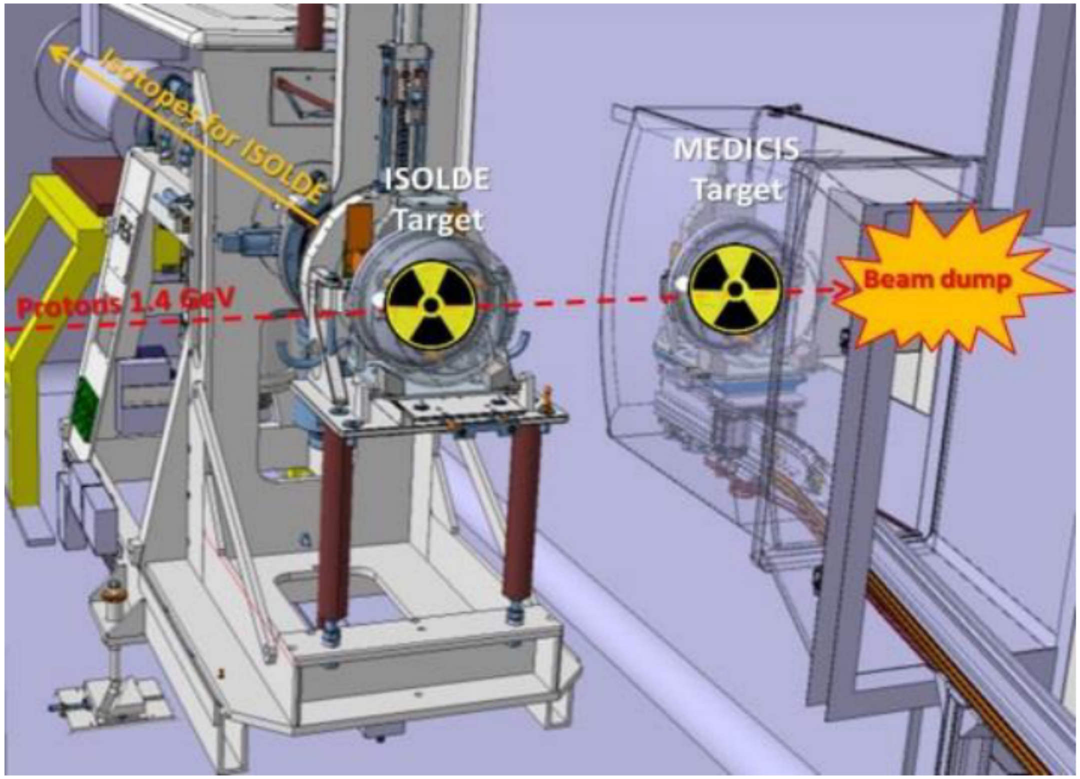






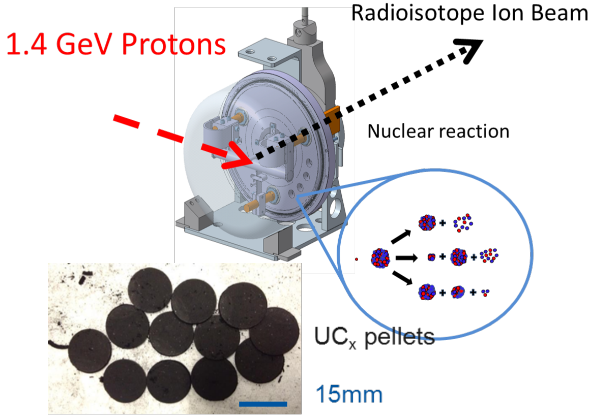
4. The MEDICIS facility

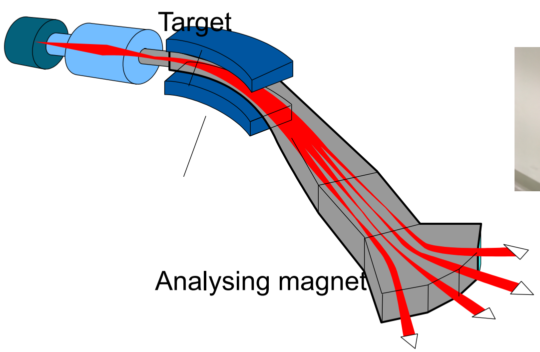
MEDICIS

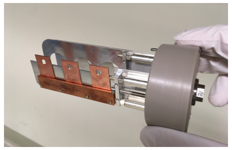


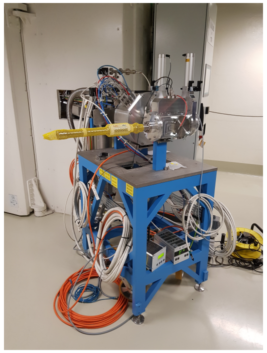
- MEDical Isotopes Collected from ISolde
- Production of non-conventional radioisotope for medical research
  - 80 – 90% of the proton beam goes through the ISOLDE target unaffected
  - Use these (free!) protons to create more radioisotopes
- Benefit from 50 years of ISOLDE experience

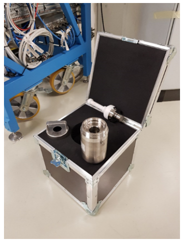
MEDICIS process

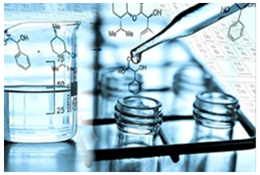


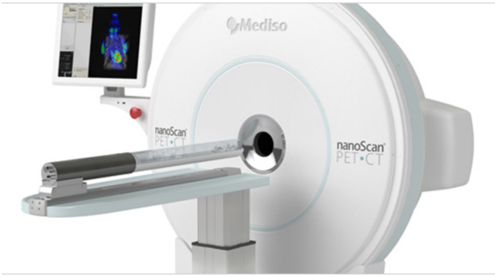


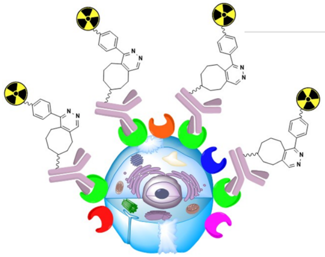












Questions?