



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

Stephan Malbrunot-Ettenauer
CERN, TRIUMF, and University of Toronto

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

ISOLDE

(Lecture 1 based on slides by Hanne Heylen)





Outline

 **Lecture 1:** ISOLDE-CERN: radioactive ion beam production

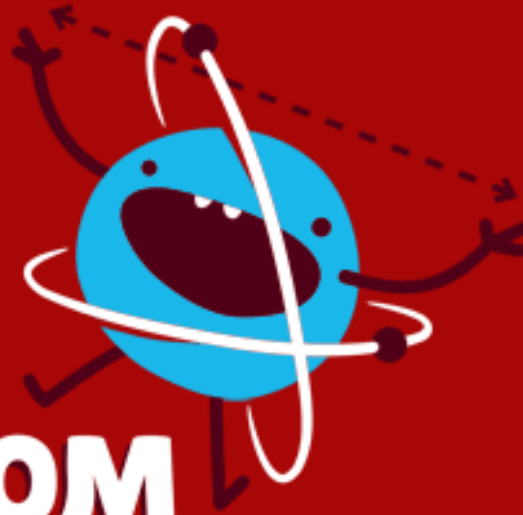
 **Lecture 2:** Nuclear Physics and Applications at ISOLDE

Who am I?

Stephan Malbrunot-Ettenauer
stephan.ettenauer@cern.ch

- 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, ...

**NEVER
TRUST
AN ATOM**
*They Make Up
Everything*



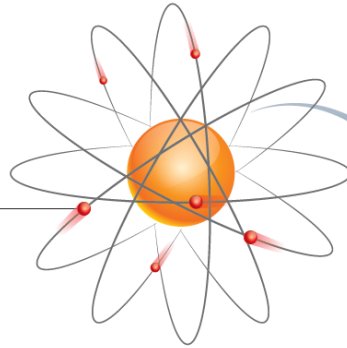
1. Introduction

Atomic nuclei: the heart of matter

10^{-10} m

ATOM

Electron
Mass **0.5 MeV**



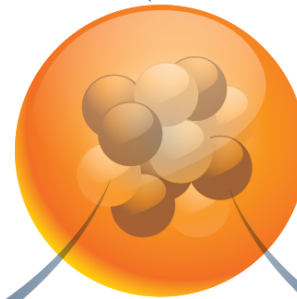
Scope of these lectures:
physics on **femtometer** scale

→ Protons and neutrons are
our building blocks

10^{-14} m

ATOMIC NUCLEUS

The protons and neutrons in the nucleus
make up the vast bulk of matter's mass



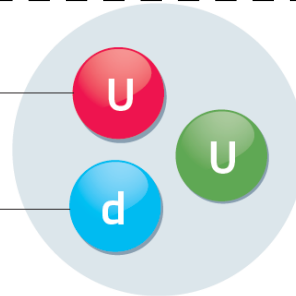
10^{-15} m

PROTON
938.3 MeV

NEUTRON
939.6 MeV

Up quark
2.3 MeV

Down quark
4.8 MeV



The masses of the three
up and down quarks
that make up the charge
of protons and
neutrons account
for only a tiny fraction
of their total mass

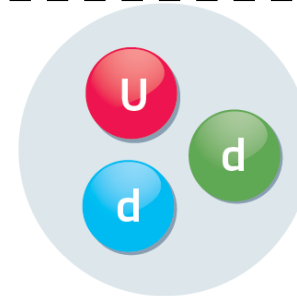


Chart of isotopes

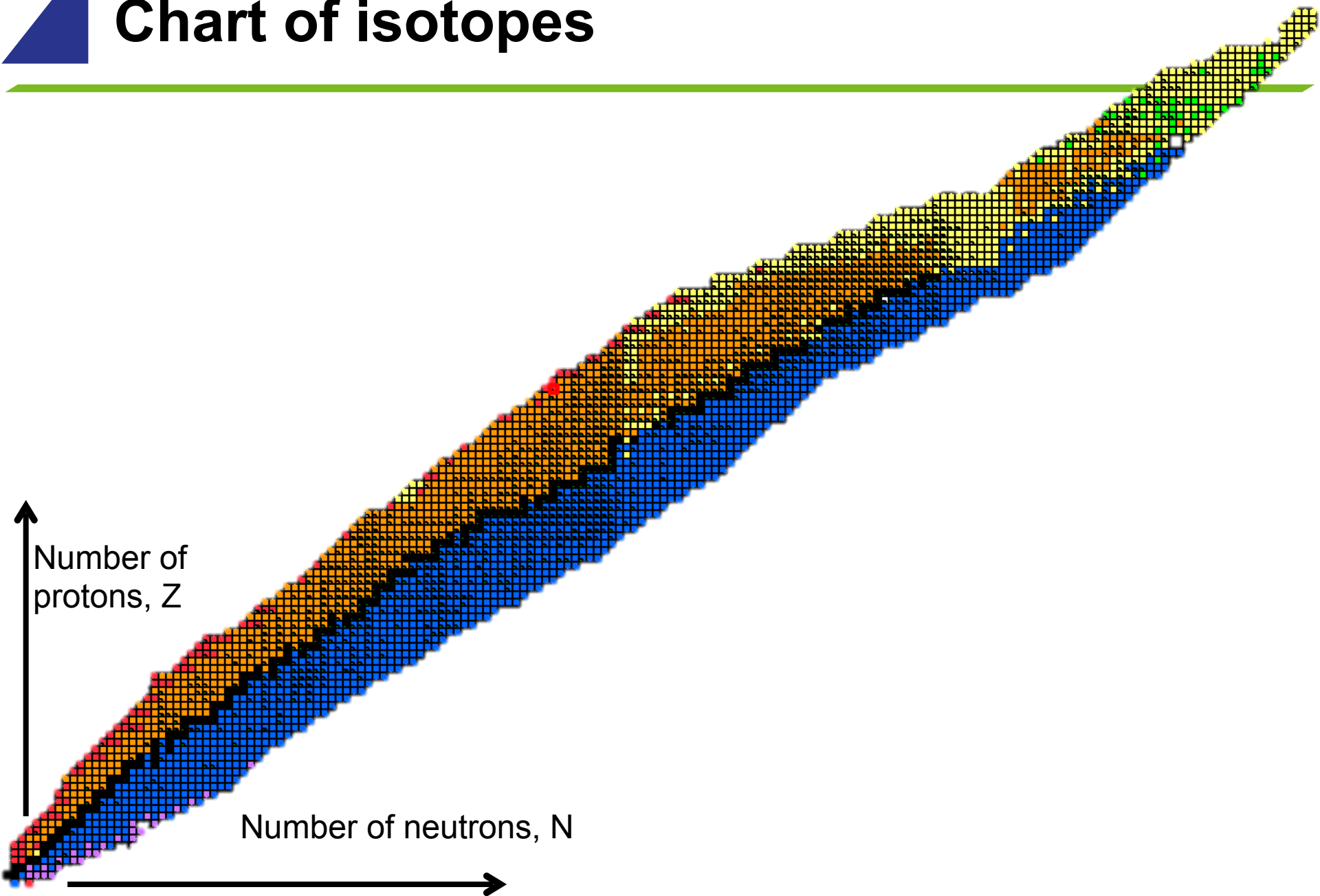


Chart of isotopes

 Nucleus/Isotope:



- 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”

48 22 Ti 26 <small>M⁻ 48491.7 (0.4) Abundance=73.72 (3)%</small>	49 22 Ti 27 <small>M⁻ 48562.8 (0.4) Abundance=5.41 (2)%</small>	50 22 Ti 28 <small>M⁻ 51430.7 (0.4) Abundance=5.18 (2)%</small>	51 22 Ti 29 <small>M⁻ 49731.9 (0.6) β⁻=100%</small>	52 22 Ti 30 <small>M⁻ 49469 (7) β⁻=100%</small>	53 22 Ti 31 <small>M⁻ 46830 (100) β⁻=100%</small>	54 22 Ti 32 <small>M⁻ 45600 (120) β⁻=100%</small>	55 22 Ti 33 <small>M⁻ 41500 (100) β⁻=100% β⁻n?</small>
47 21 Sc 26 <small>272 ms (3/2)⁺ β⁻=100%</small>	48 21 Sc 27 <small>3382 d 7/2⁻ β⁻=100%</small>	49 21 Sc 28 <small>43.67 h 6⁺ β⁻=100%</small>	50 21 Sc 29 <small>57.18 m 7/2⁻ β⁻=100%</small>	51 21 Sc 30 <small>102.5 s 5⁺ β⁻=100%</small>	52 21 Sc 31 <small>12.4 s (7/2)⁻ β⁻=100%</small>	53 21 Sc 32 <small>8.2 s 3^(*) β⁻=100%</small>	54 21 Sc 33 <small>2.4 s (7/2)⁻ β⁻=100%</small>
46 20 Ca 26 <small>stable 0⁺ M⁻ 43138.4 (2.3) Abundance=0.004 (3)% 28⁻?</small>	47 20 Ca 27 <small>4.536 d 7/2⁻ β⁻=100%</small>	48 20 Ca 28 <small>53 Ey 0⁺ M⁻ 44224.76 (0.12) Abundance=0.187 (21)% 28⁻=75 (25=38)...</small>	49 20 Ca 29 <small>8.718 m 3/2⁻ β⁻=100%</small>	50 20 Ca 30 <small>13.9 s 0⁺ β⁻=100%</small>	51 20 Ca 31 <small>10.0 s (3/2)⁻ β⁻=100%</small>	52 20 Ca 32 <small>4.6 s 0⁺ β⁻=100%</small>	53 20 Ca 33 <small>461 ms 3/2⁻# M⁻ 28460# (400#) β⁻=100% β⁻n=30%</small>

Chart of isotopes

Nucleus/Isotope:



- 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

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)

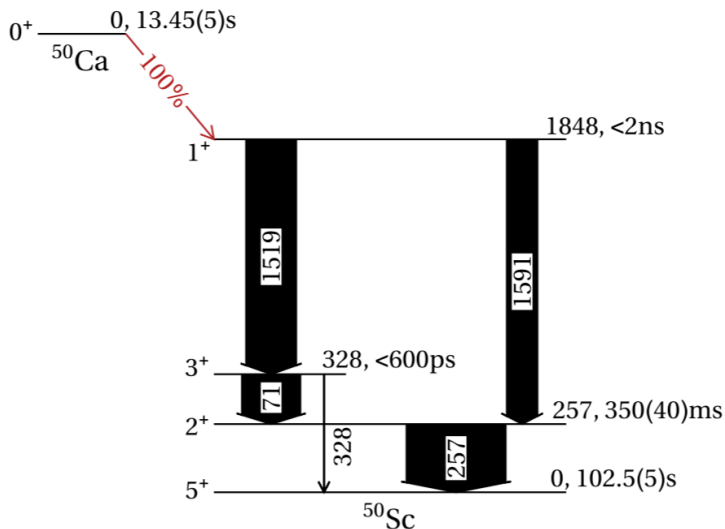
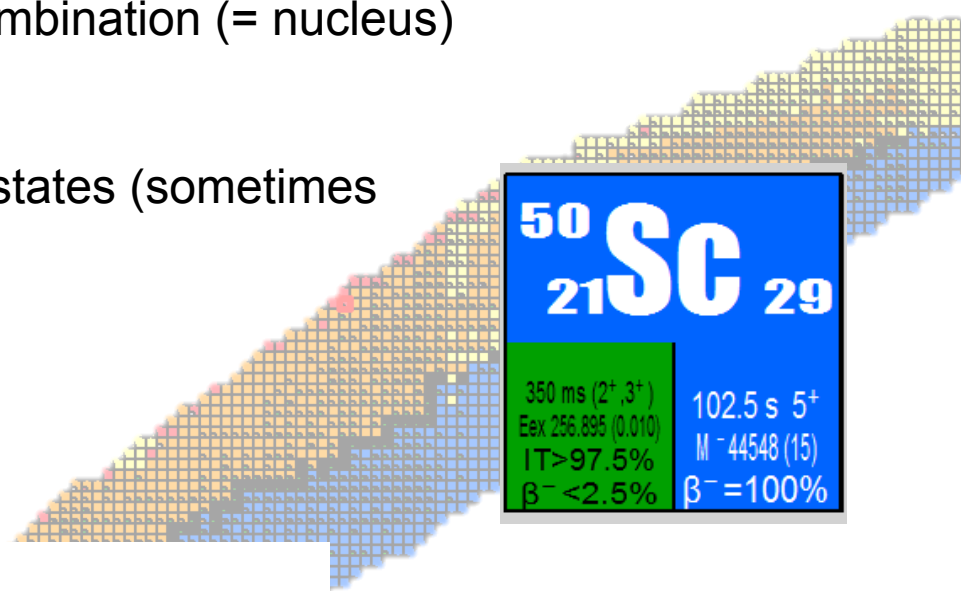
48 22 Ti M ⁻ 48491.7 (0.4) Abundance=73.72 (3%)	49 22 Ti M ⁻ 48710.2 (0.4) Abundance=5.41 (2%)	50 22 Ti M ⁻ 51430.7 (0.4)	51 22 Ti M ⁻ 49731.9 (0.6) β ⁻ =100%	52 22 Ti M ⁻ 49469 (7) β ⁻ =100%	53 22 Ti M ⁻ 46830 (100) β ⁻ =100%	54 22 Ti M ⁻ 45600 (120) β ⁻ =100%	55 22 Ti M ⁻ 41500 (100) β ⁻ =100% β ⁻ =n?
47 21 Sc 272 ms (3/2) E _{ex} 76.8 (0.1) IT=100%	48 21 Sc 43.6 ms (1/2) M ⁻ 44031.1 (0.3) β ⁻ =100%	49 21 Sc 57.18 m 7/2 ⁻ M ⁻ 46561.1 (2.7) β ⁻ =100%	50 21 Sc 350 ms (2 ⁺ 3 ⁻) E _{ex} 25.89 (0.1) IT=97.5% β ⁻ <2.5%	51 21 Sc 102.5 s 5 ⁺ M ⁻ 44548 (16) β ⁻ =100%	52 21 Sc 12.4 s (7/2) ⁻ M ⁻ 43229 (20) β ⁻ =100% β ⁻ =n?	53 21 Sc 8.2 s 3 ^(*) M ⁻ 40170 (140) β ⁻ =100% β ⁻ =n?	54 21 Sc 2.4 s (7/2) ⁻ M ⁻ 38110 (270) β ⁻ =100% β ⁻ =n?
46 20 Ca stable 0 ⁺ M ⁻ 43138.4 (2.3) Abundance=0.004 (3%) 28 ⁺ ?	47 20 Ca 4.53 s 7/2 ⁻ M ⁻ 42733.5 (2.2) β ⁻ =100%	48 20 Ca 53 ms (1/2) M ⁻ 44224.6 (0.12) Abundance=0.187 (21%) 28 ⁺ =75 (26-38)...	49 20 Ca 8.718 m 3/2 ⁻ M ⁻ 41299.89 (0.21) β ⁻ =100%	50 20 Ca 13.9 s 0 ⁺ M ⁻ 39589.2 (1.6) β ⁻ =100%	51 20 Ca 10.0 s (3/2) ⁻ M ⁻ 36339 (22) β ⁻ =100% β ⁻ =n?	52 20 Ca 4.6 s 0 ⁺ M ⁻ 34260 (60) β ⁻ =100% β ⁻ =n<2%	53 20 Ca 461 ms 3/2 ⁻ # M ⁻ 28460# (400#) β ⁻ =100% β ⁻ =n>30%

Properties of isotopes

DECAY MODES	
	β^+ (EC + e^+)
	β^-
	α
	Internal Transition
	Spontaneous Fission
	p
	n
	Stable nuclide
	Unknown decay

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^+
- ... (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

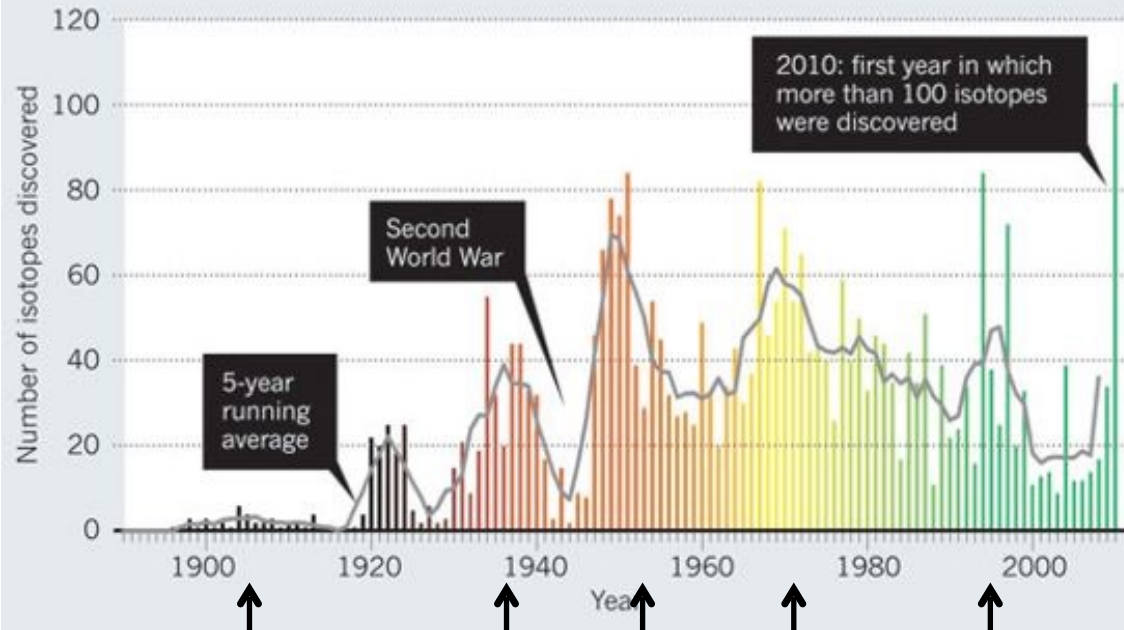
- Research with radioactive isotopes

Some vocabulary

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

THE NUCLIDE TRAIL

Isotope discovery over the past 100 years (below) has jumped with each introduction of new technology. 2,700 radioactive isotopes have been discovered so far (below right), but about 3,000 more are predicted.



Radioactivity

Reactors

Fragmentation

First
accelerators

Fusion-
evaporation

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

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

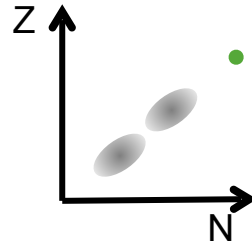
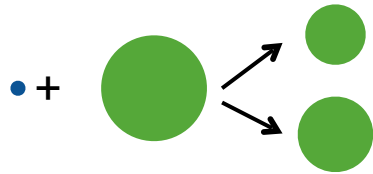
Homework

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

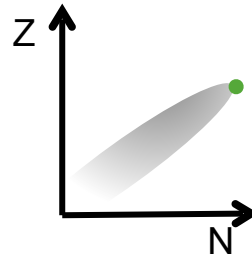
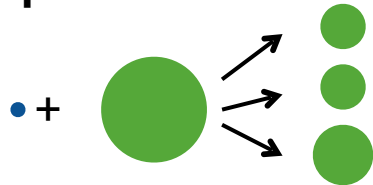
→ Focus on ISOLDE

Production: nuclear reactions

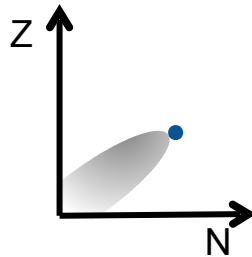
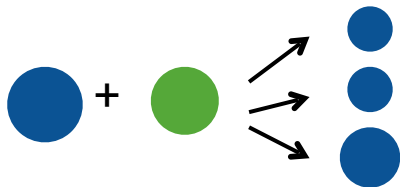
Fission



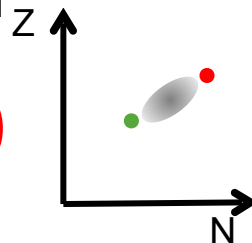
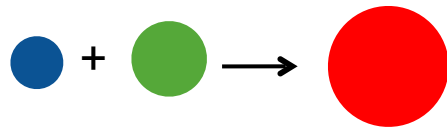
Spallation



Fragmentation



Fusion-evaporation



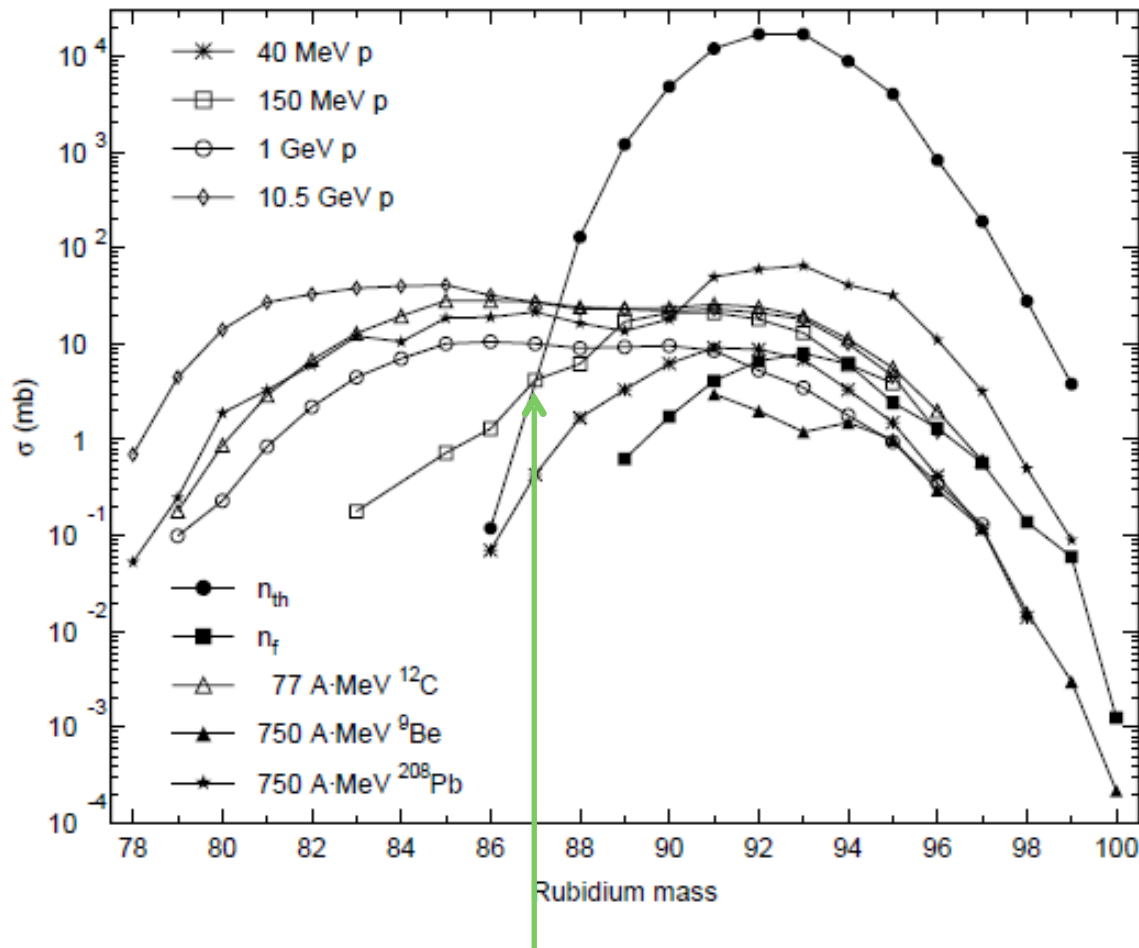
Accelerated **primary beam** (projectile)

- Proton, neutrons, alpha-particles, heavy ions

Target

- Heavy nuclei

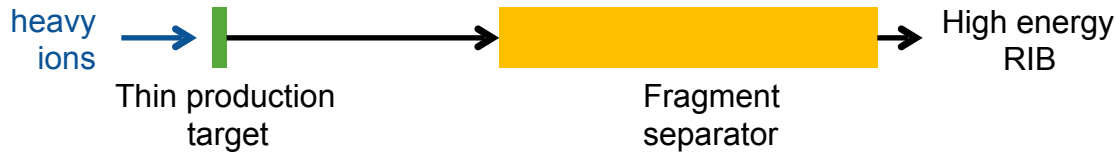
Production: nuclear reactions



Primary beam type and energy are important!

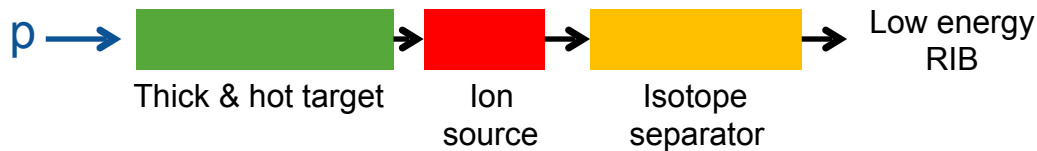
RIB production methods

In-flight



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

ISOL

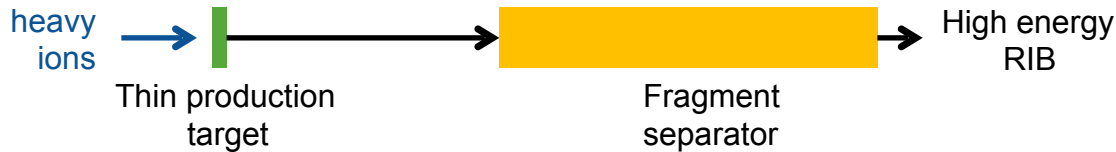


- Chemistry dependent
- Slow release from target
- Good beam quality

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

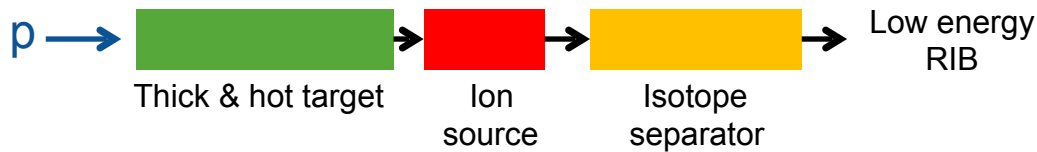
RIB production methods

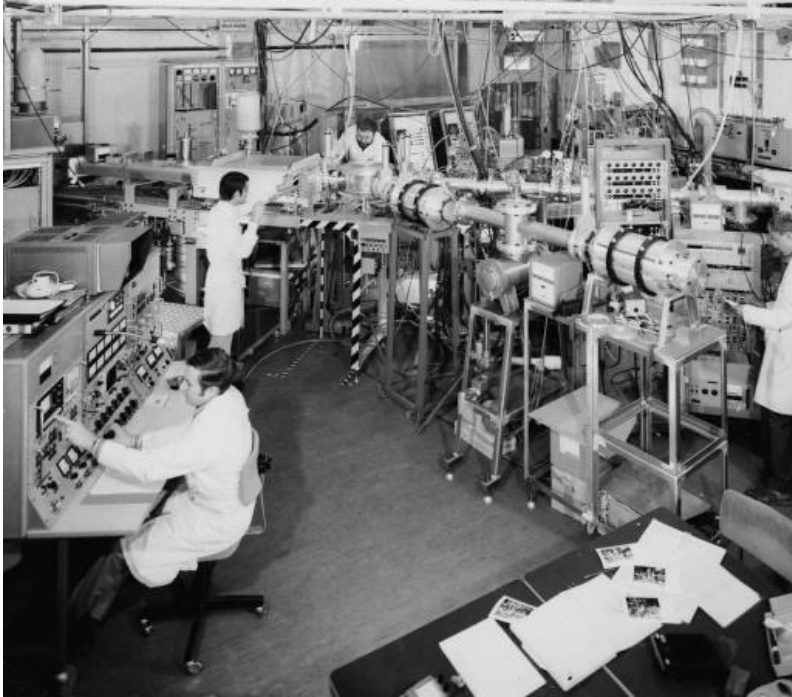
In-flight



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

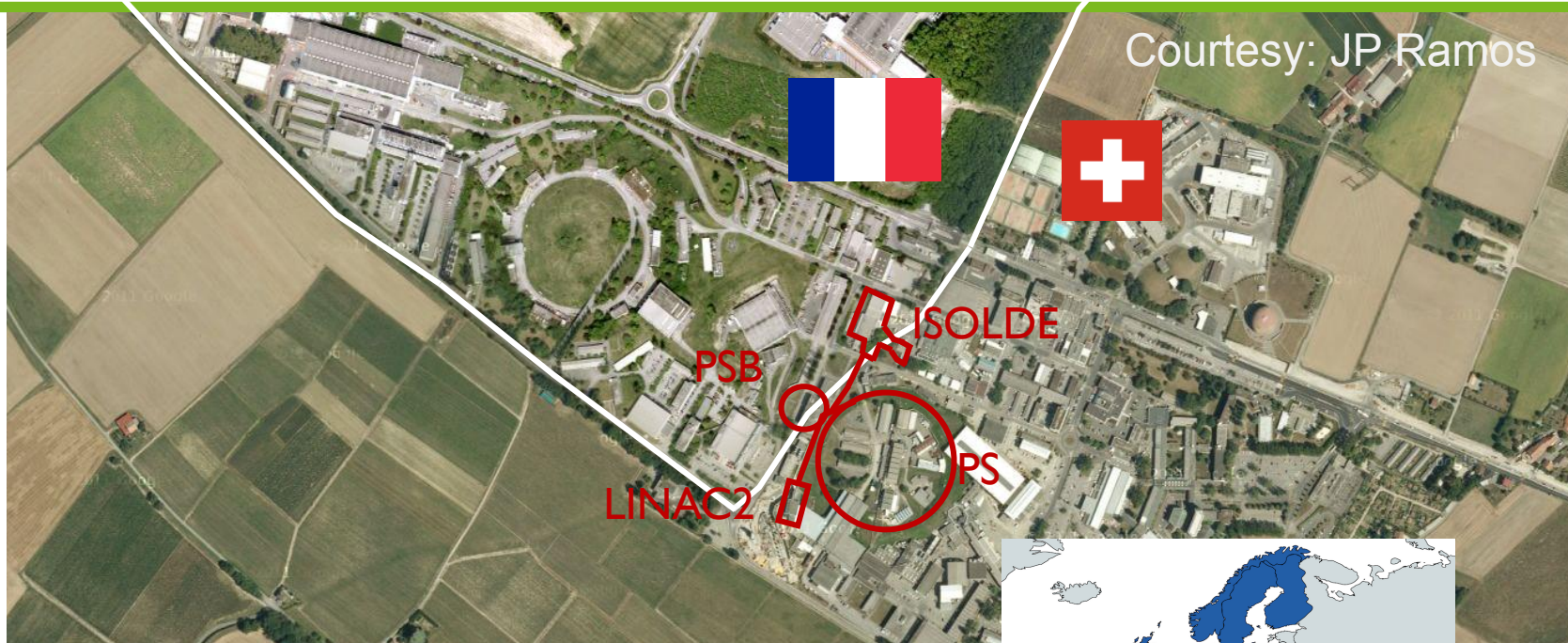
ISOL



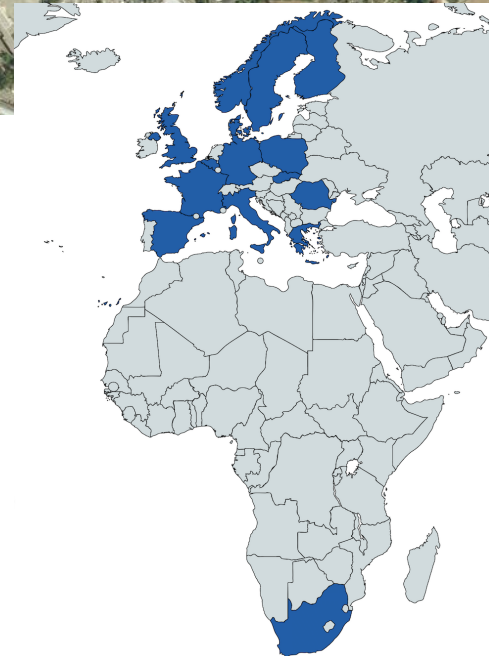


3. ISOLDE-CERN

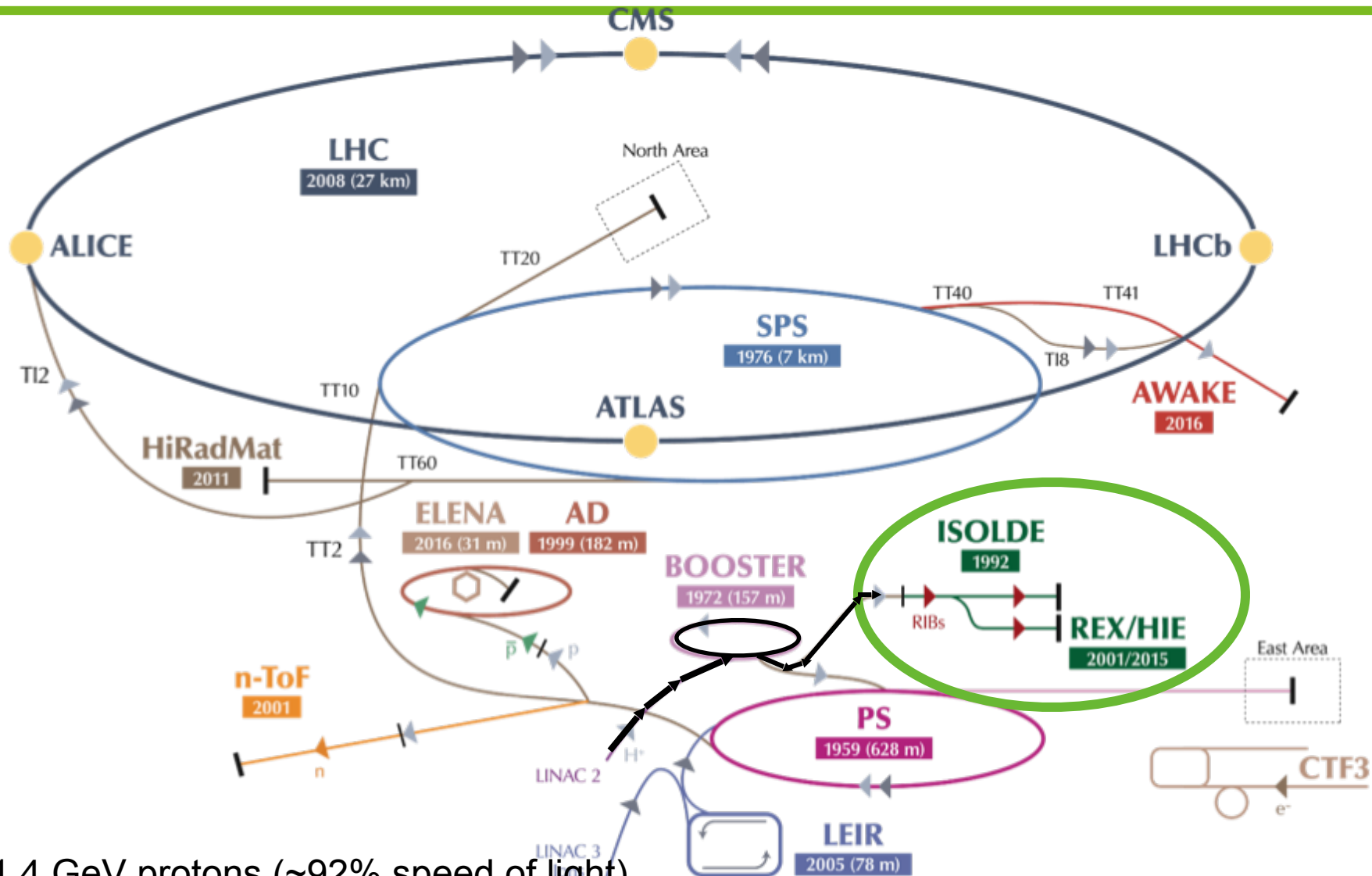
ISOLDE at CERN



- 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



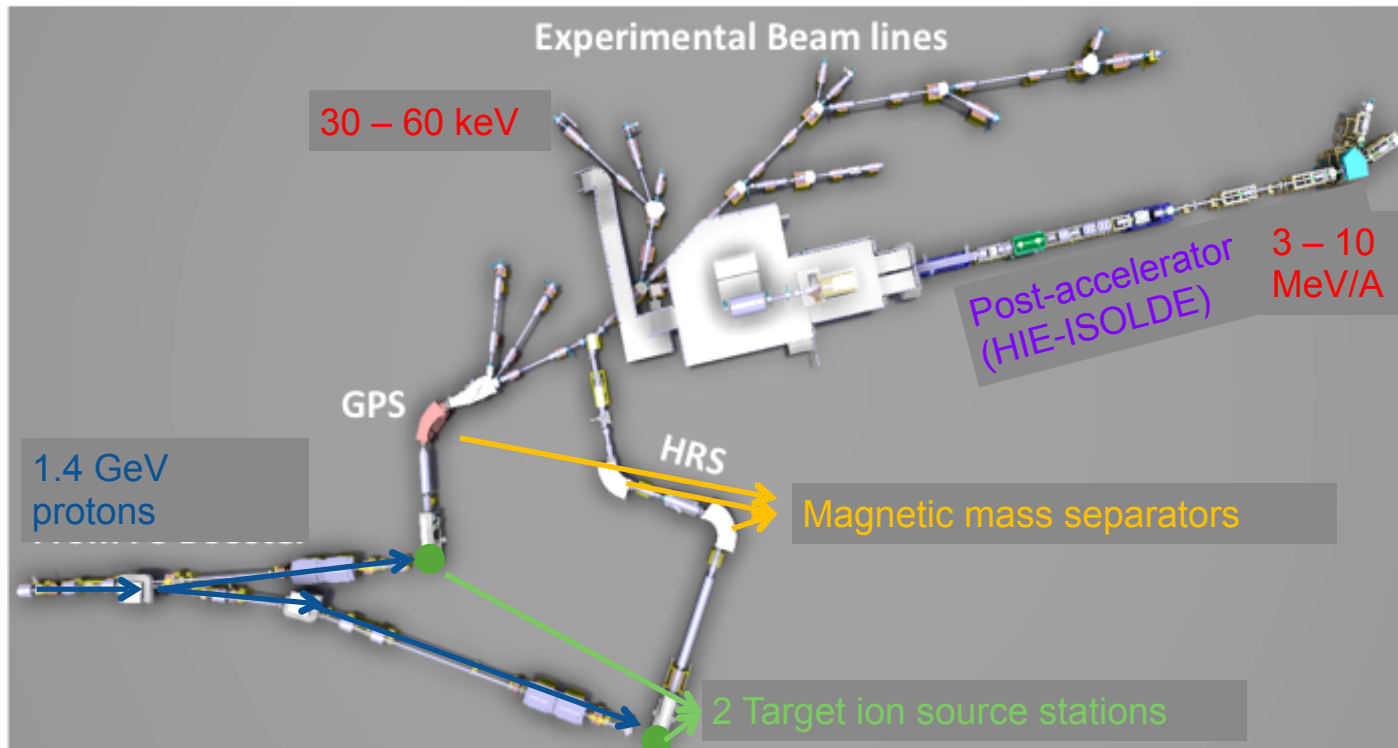
- 1.4 GeV protons ($\sim 92\%$ speed of light)
- 50% of CERN's protons

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)

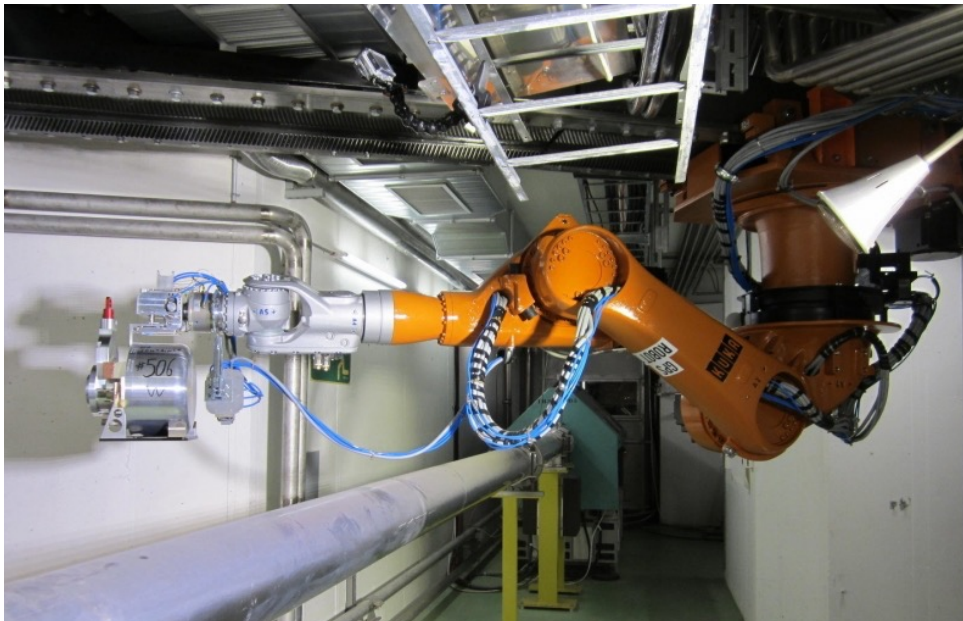


Isotope production at ISOLDE



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

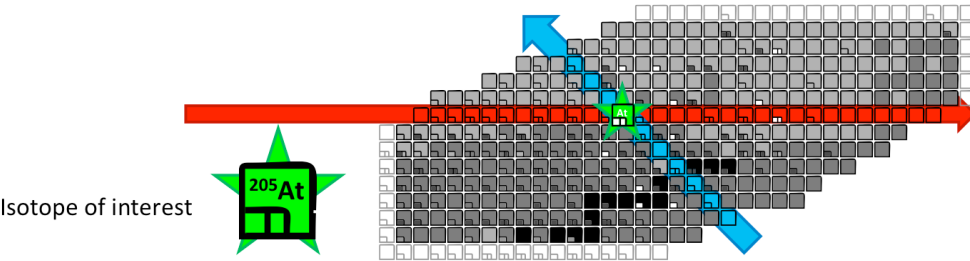
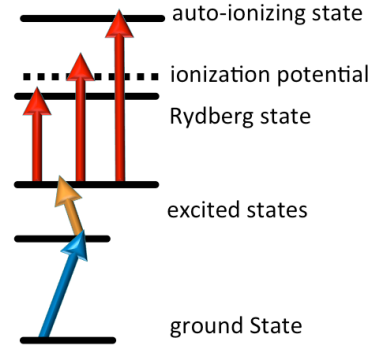
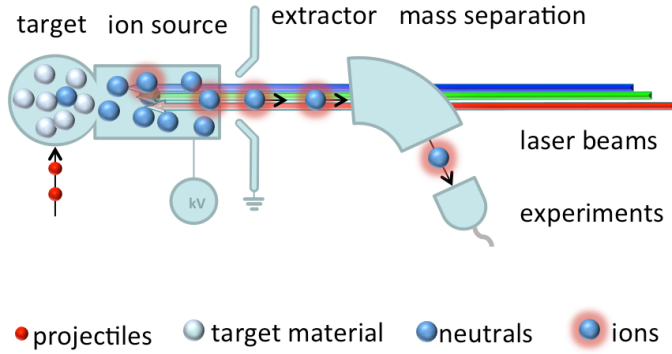




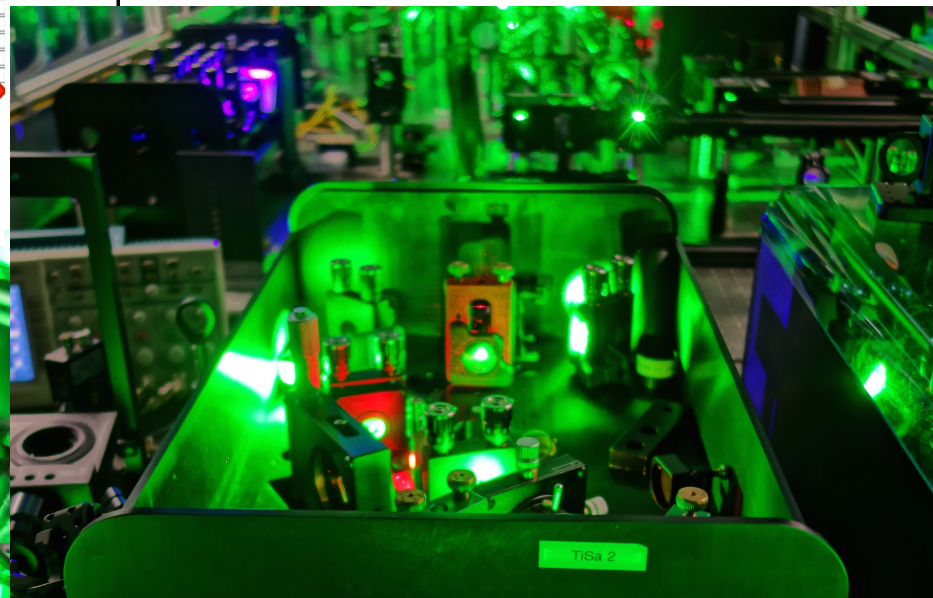
Ionisation

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

Atomic (electronic) structure = Fingerprint of element

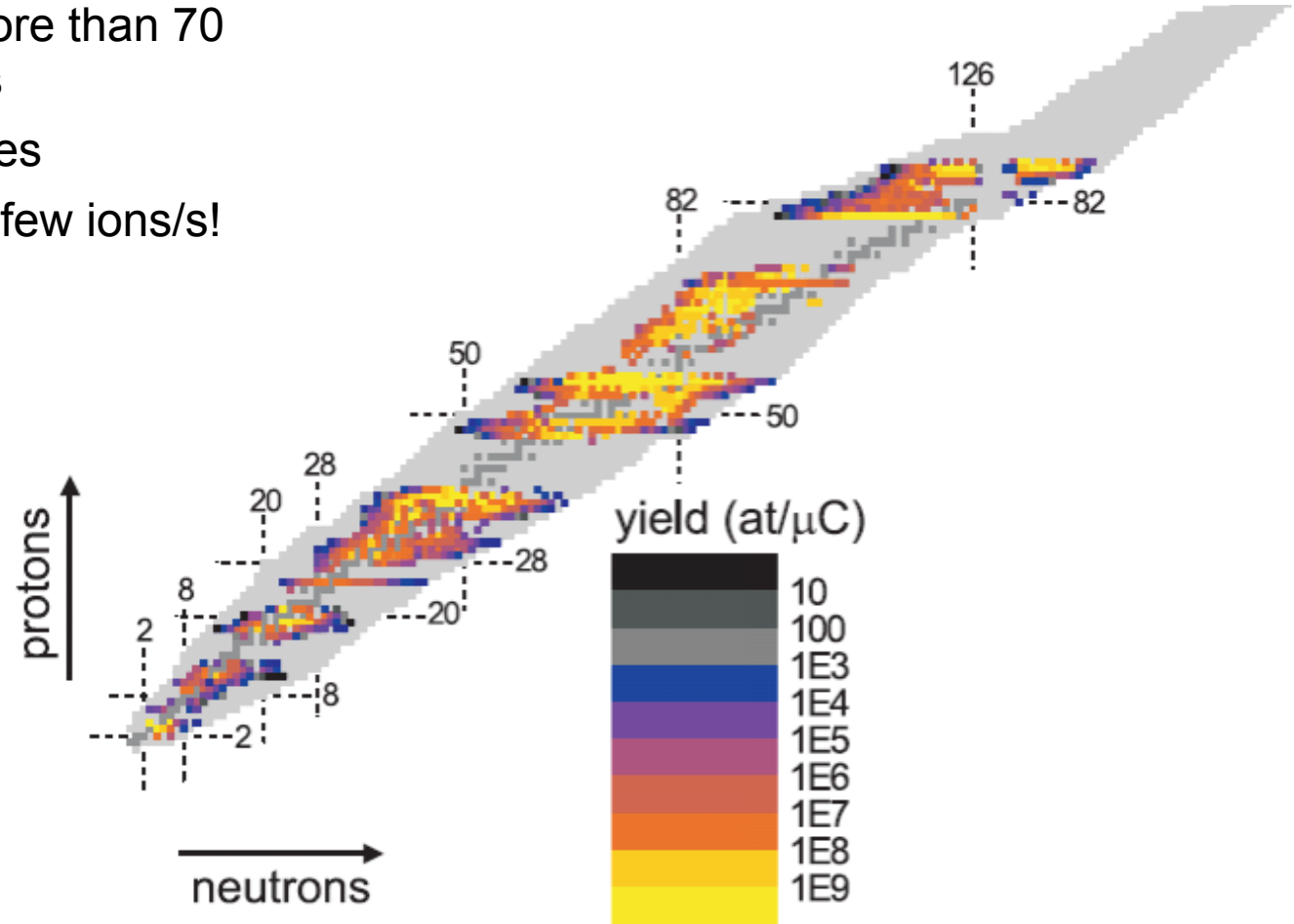


Isotope of interest

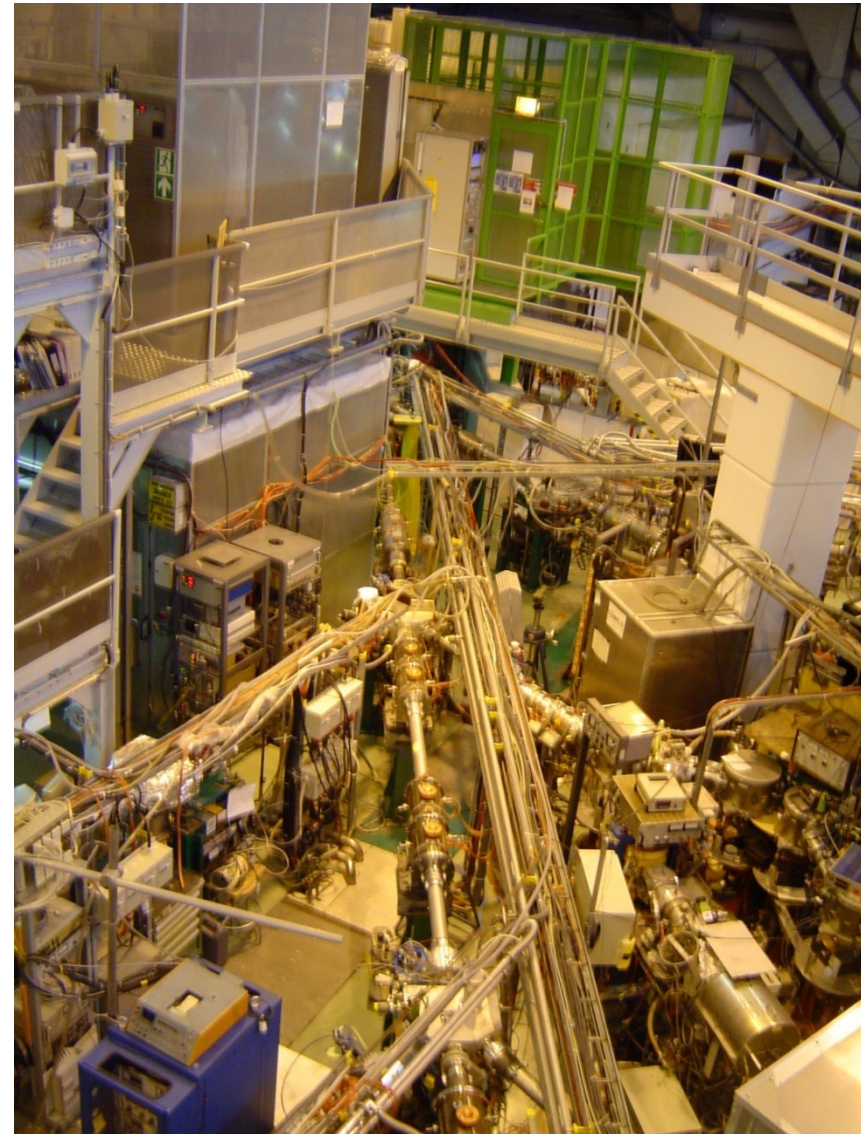


RIBs at ISOLDE

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

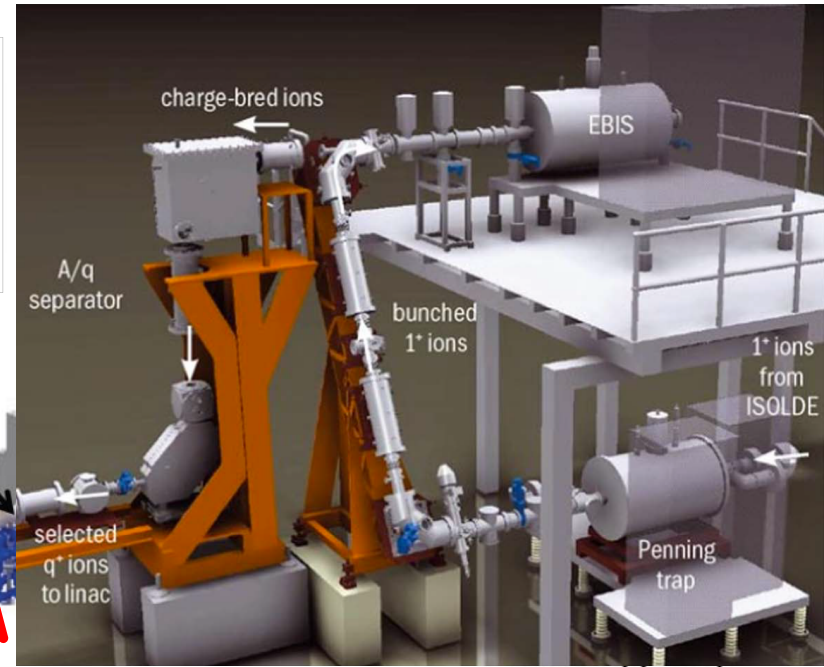
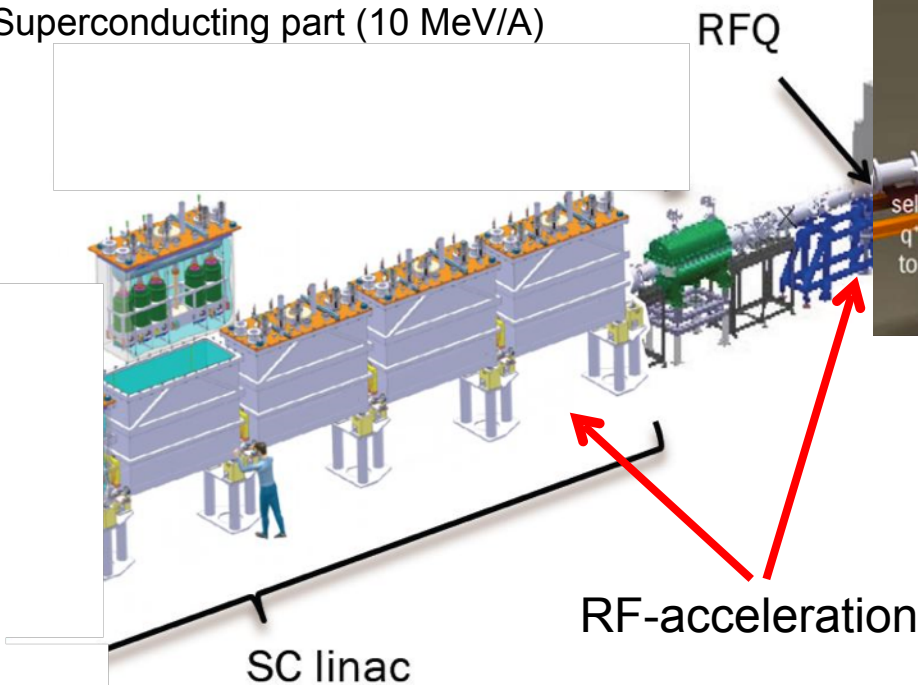


View of experimental area



Post-acceleration: REX + HIE-ISOLDE

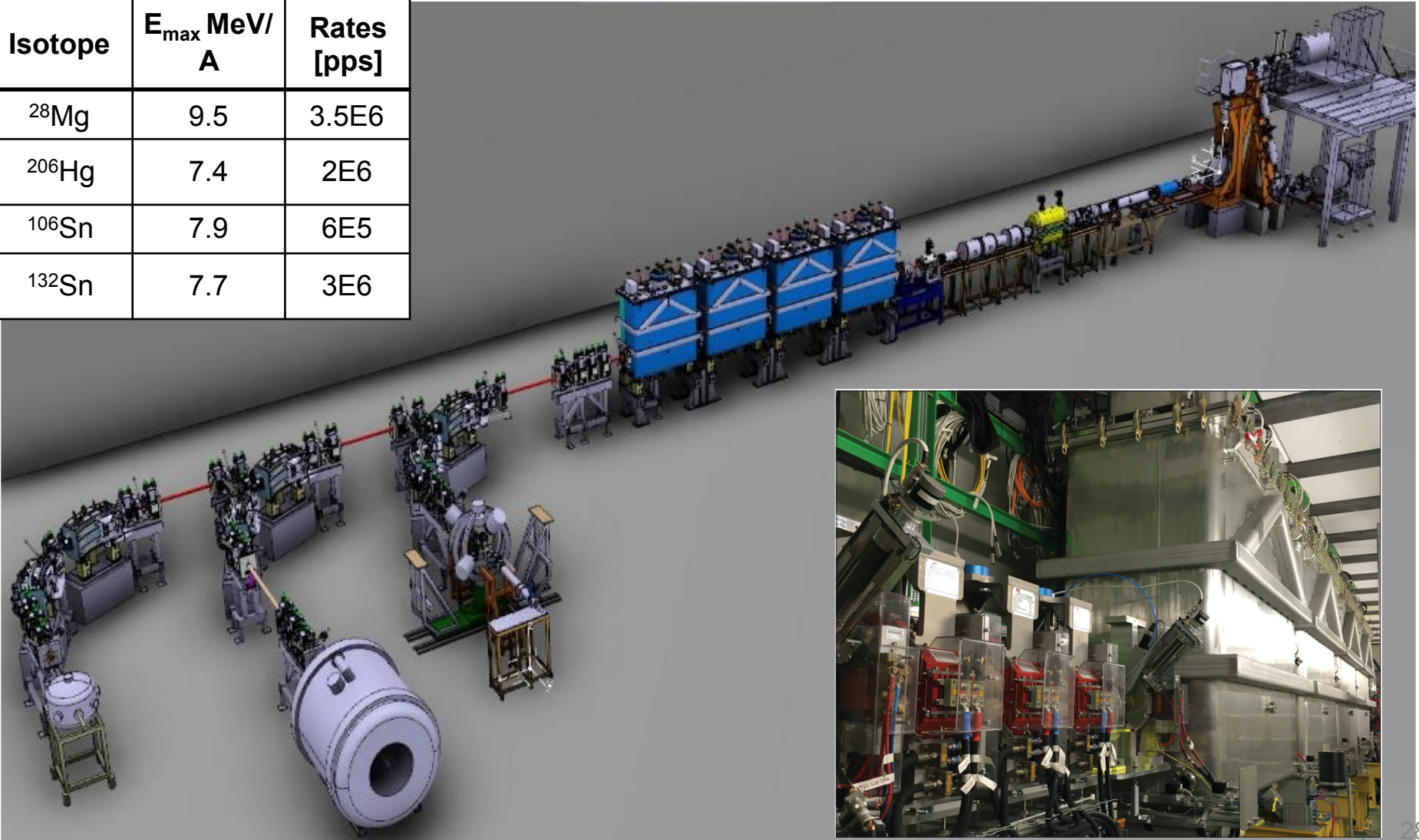
1. Start from mass separated beam from ISOLDE
2. Beam cooling/bunched in buffer-gas filled Penning trap
3. Charge-state breeding using electron-beam ionisation
($2.5 < A/q < 4.5$)
 1. A/q selection
 2. Linear accelerator
 - Room temperature part (3 MeV/A)
 - Superconducting part (10 MeV/A)



Post-acceleration: REX + HIE-ISOLDE

2018: All 4 cryomodules installed

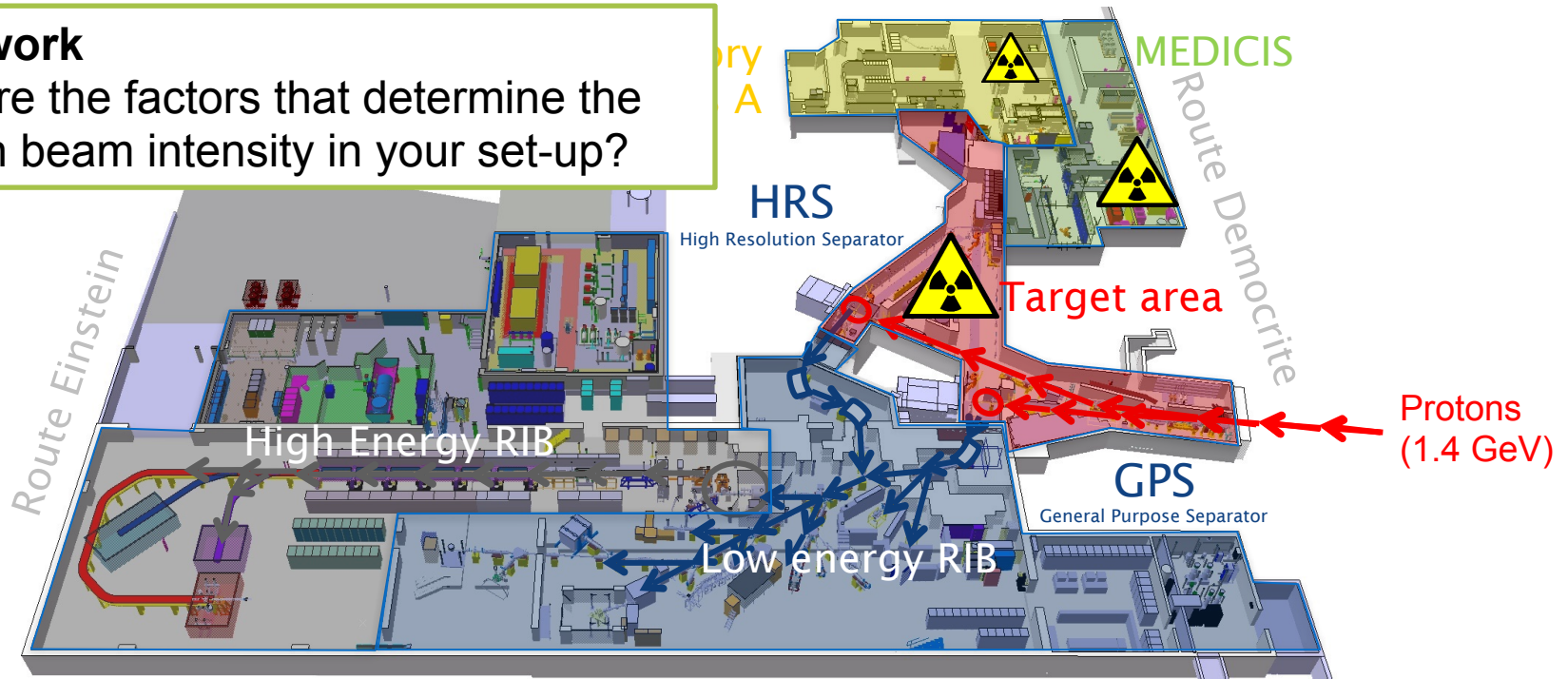
Isotope	E_{max} MeV/ A	Rates [pps]
^{28}Mg	9.5	3.5E6
^{206}Hg	7.4	2E6
^{106}Sn	7.9	6E5
^{132}Sn	7.7	3E6



The ISOLDE facility - summary

Homework

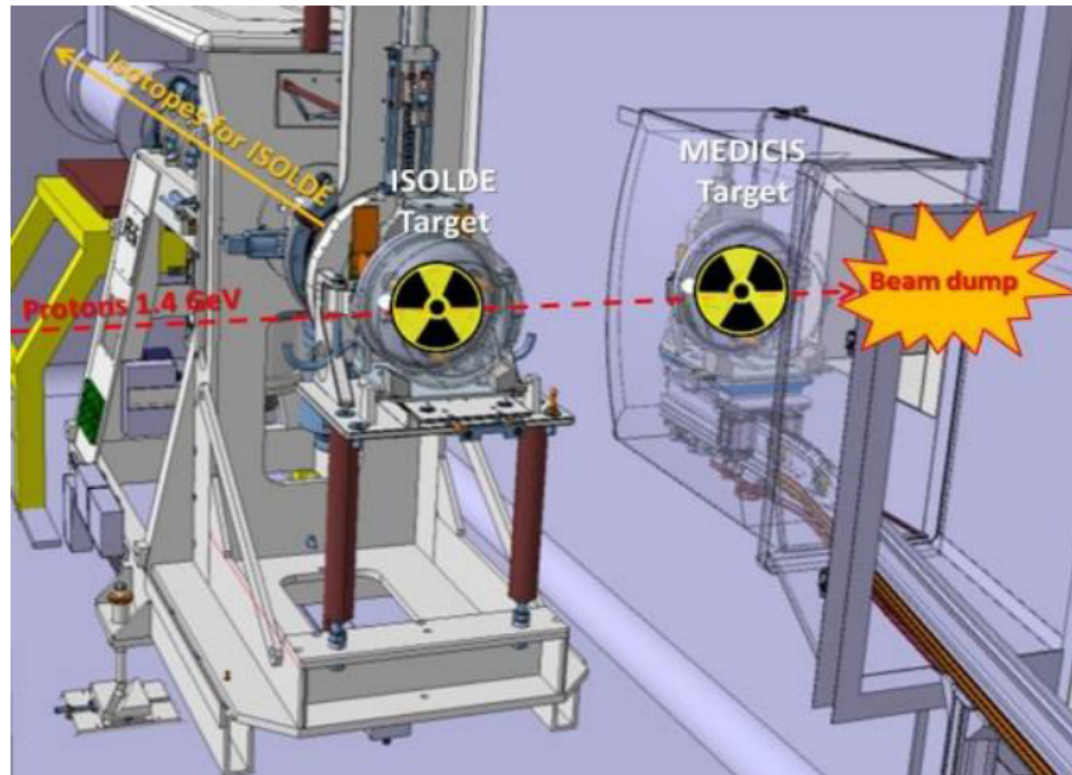
What are the factors that determine the final ion beam intensity in your set-up?





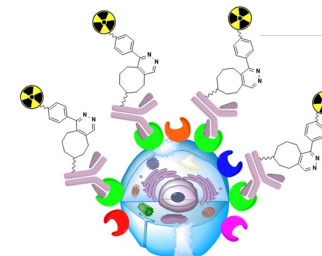
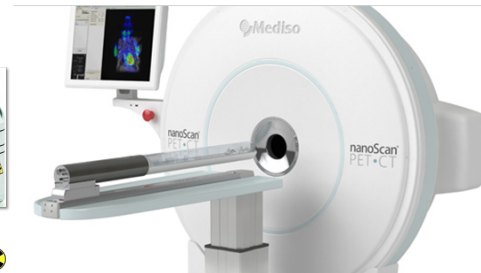
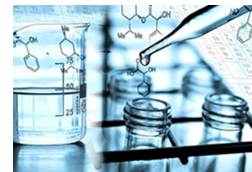
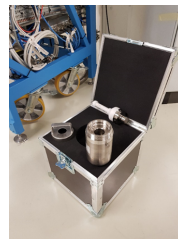
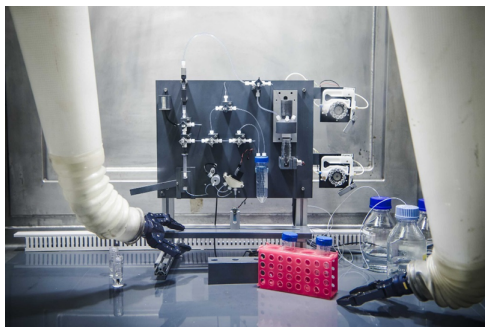
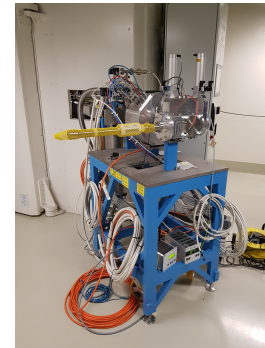
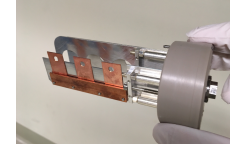
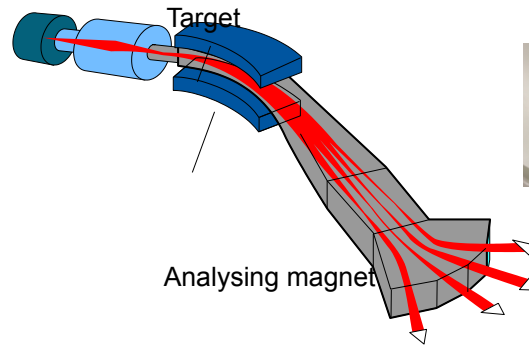
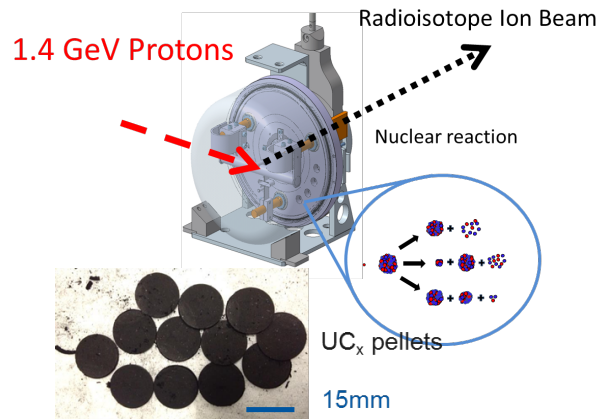
4. The MEDICIS facility

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





ISOLDE workshop and users meeting 2018

Questions?