Making radioactive ion beams
Detecting reaction products

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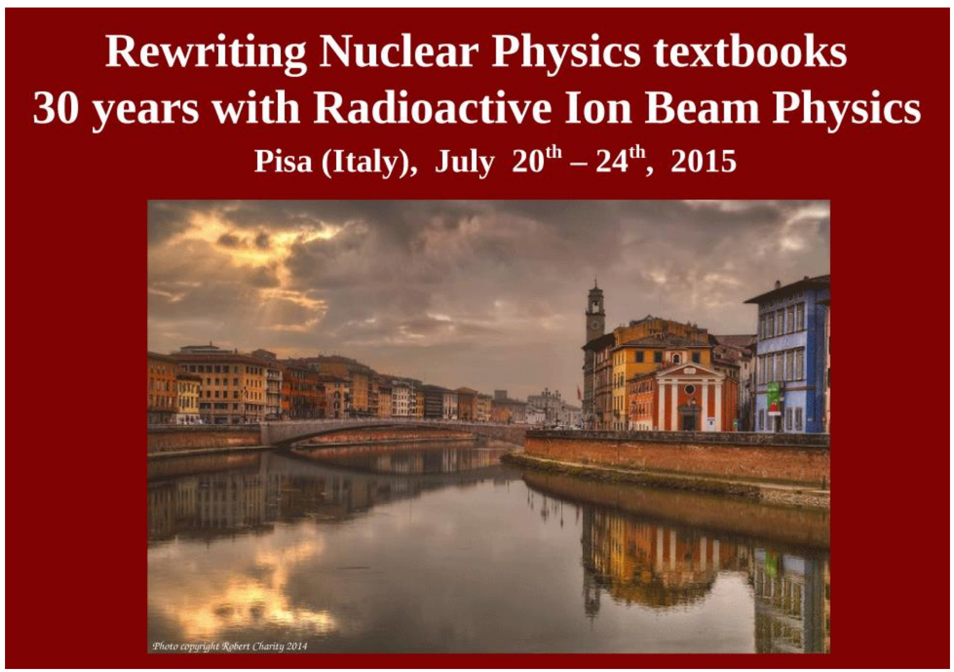

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Overview

Introduction

- Exotic nuclei: what and why

Production and handling of radioactive isotopes

- Methods: ISOL and in-flight
- Overview of facilities

Measurements with RIBs

- Detection of radiation
- Detection setups for reactions with RIBs
- New developments

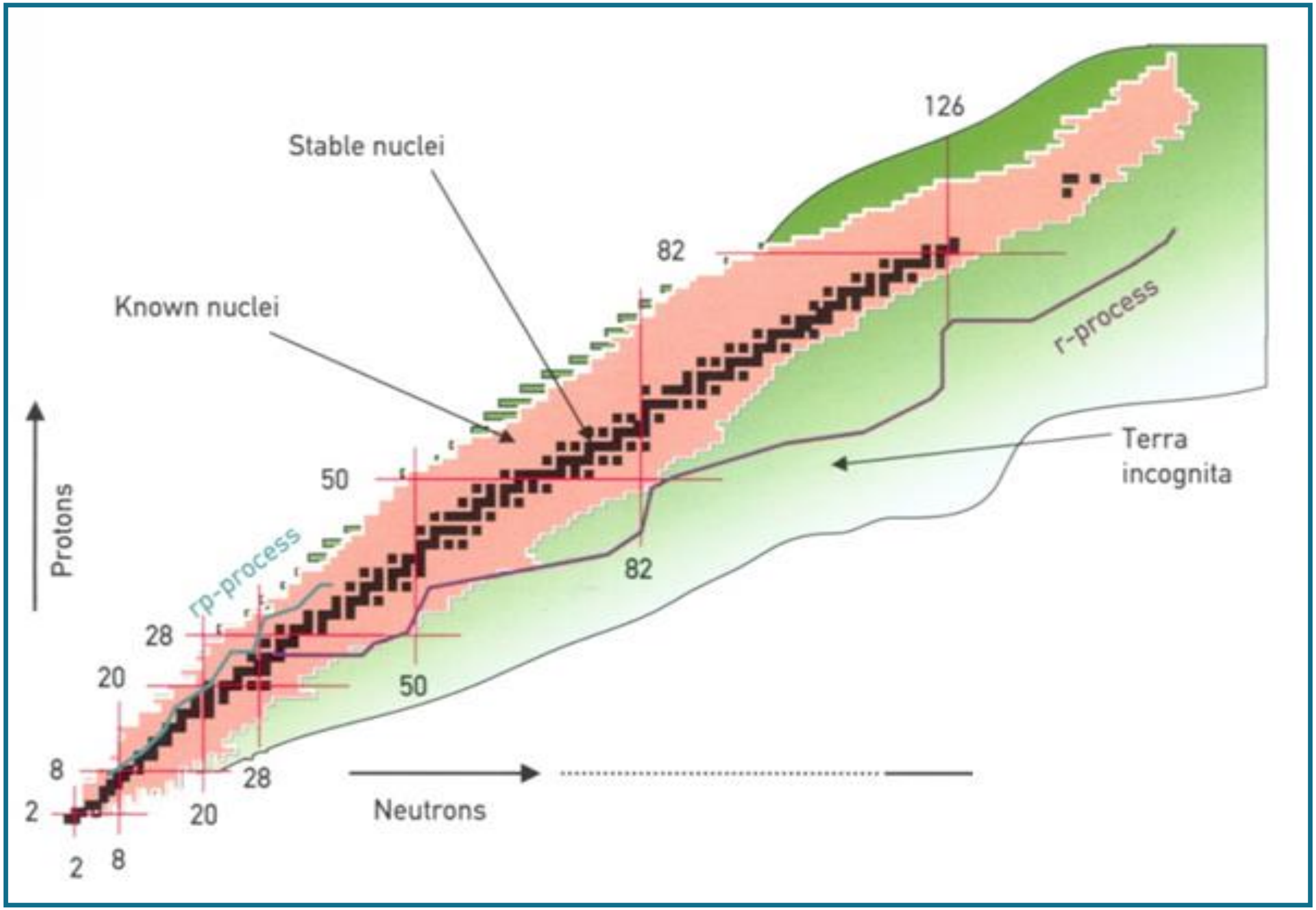
Aims of the lecture

- Give a flavour of present-day research with RIBs:
  Still active? Clear direction?
- Learn (through examples) about the main techniques for production, manipulation and detection of unstable isotopes

- Pay attention to orders of magnitude!
- Very good reference:
  Nobel Symposium 152: Physics with Radioactive Beams
  in Physica Scripta T152 (2013)

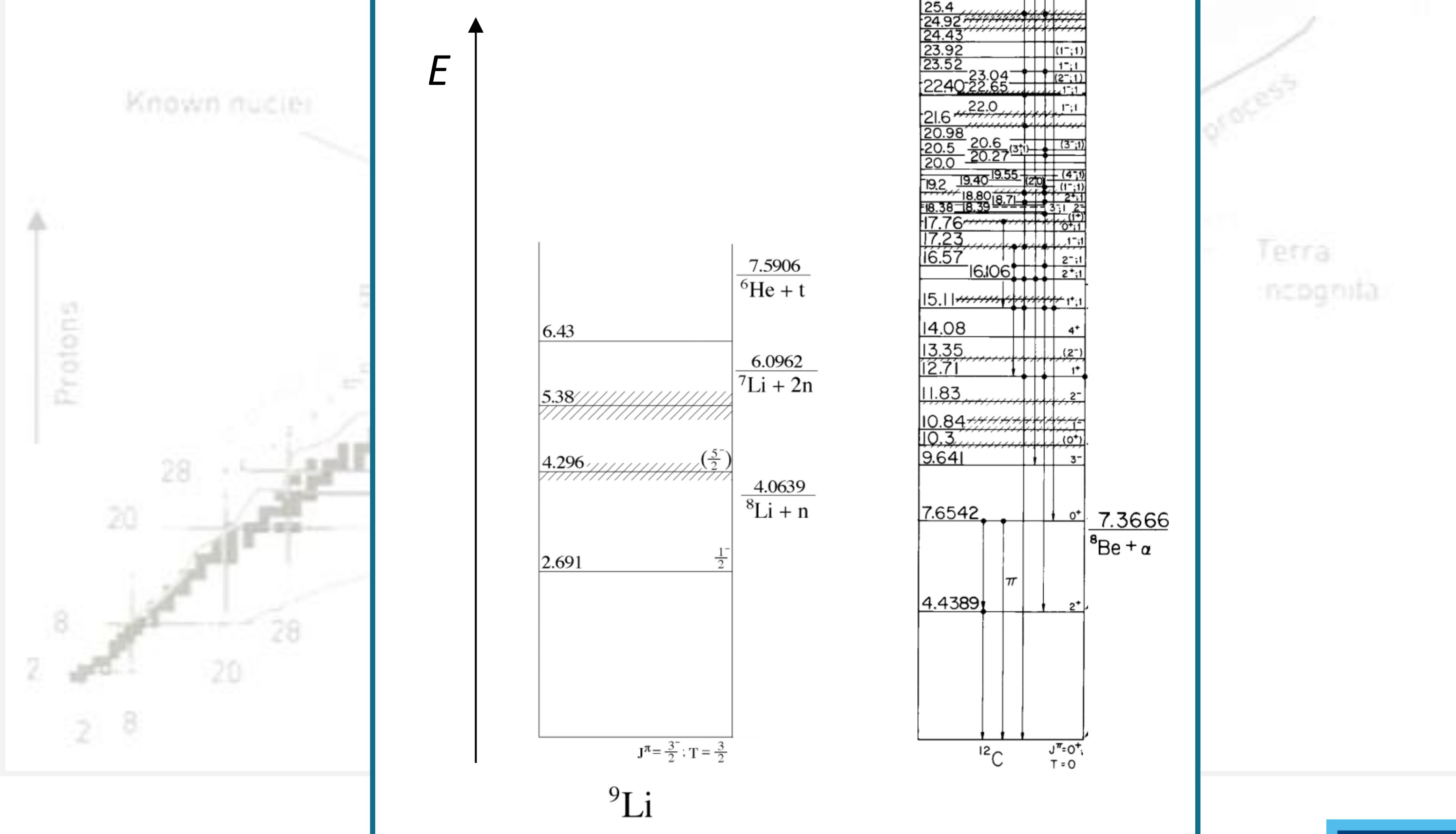
For example
Y Blumenfeld, T Nilsson and P Van Duppen, Facilities and methods for radioactive ion beam production, Phys. Scr. T152 (2013) 014023

The chart of nuclei



The chart of nuclei

3rd dimension:
excitation energy



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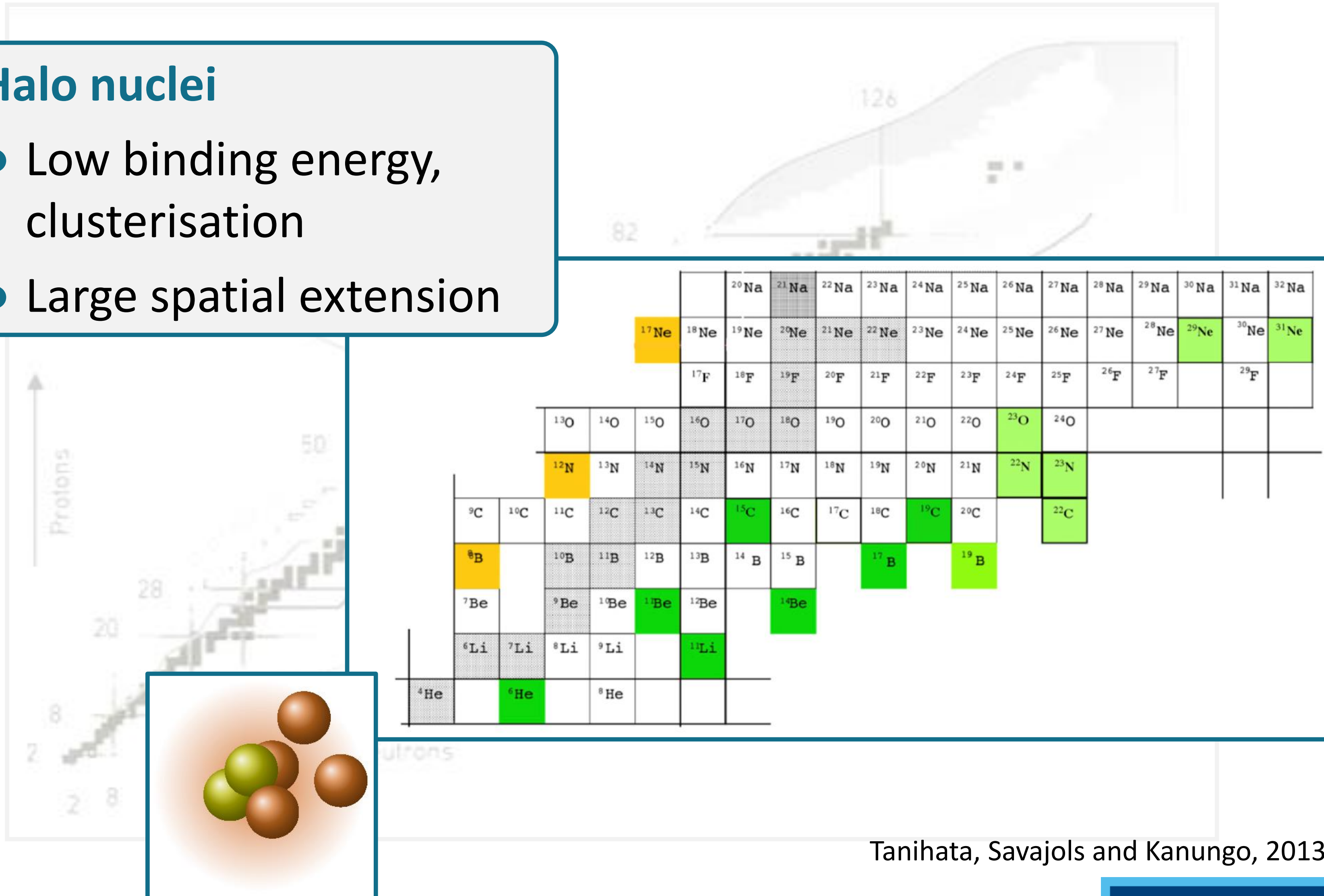
Exotic nuclei: halo nuclei

Halo nuclei

- Low binding energy, clusterisation
- Large spatial extension



Tanihata, Savajols and Kanungo, 2013

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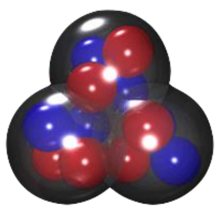
Exotic nuclei: cluster structures, molecular-type bonds

Clusters

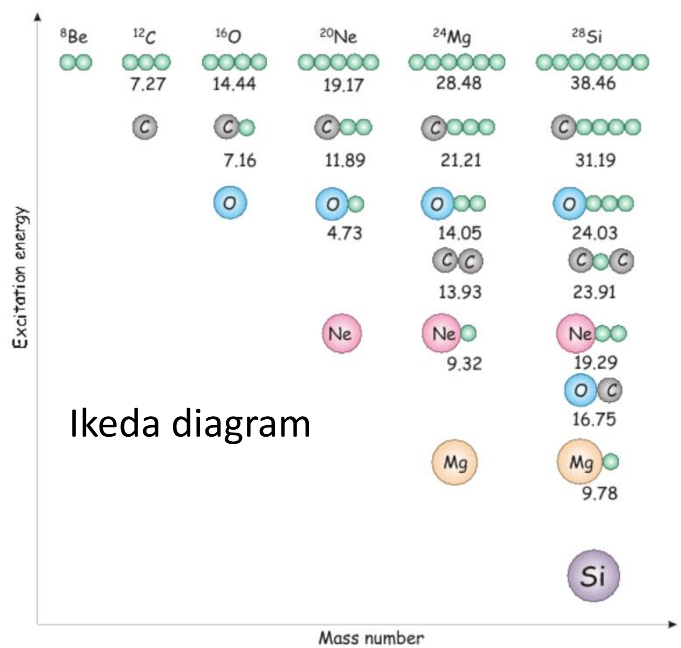
- Appear close to the corresponding breakup threshold

Molecular bonds

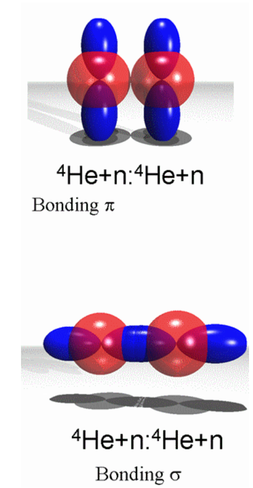
- Nucleons exchanged between the clusters



^{12}C: Hoyle state at 7.6 MeV



Ikeda diagram

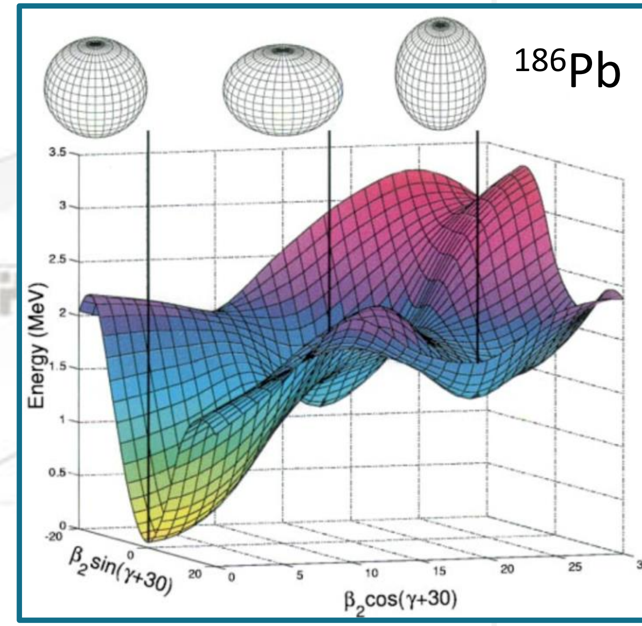


Be isotopes: 2 α clusters and exchange neutrons

Figures: M. Freer

Exotic nuclei: shape coexistence

A. Andreyev et al., Nature 405 (2000) 430



Shape coexistence

- States with different shapes appear at similar excitation energies

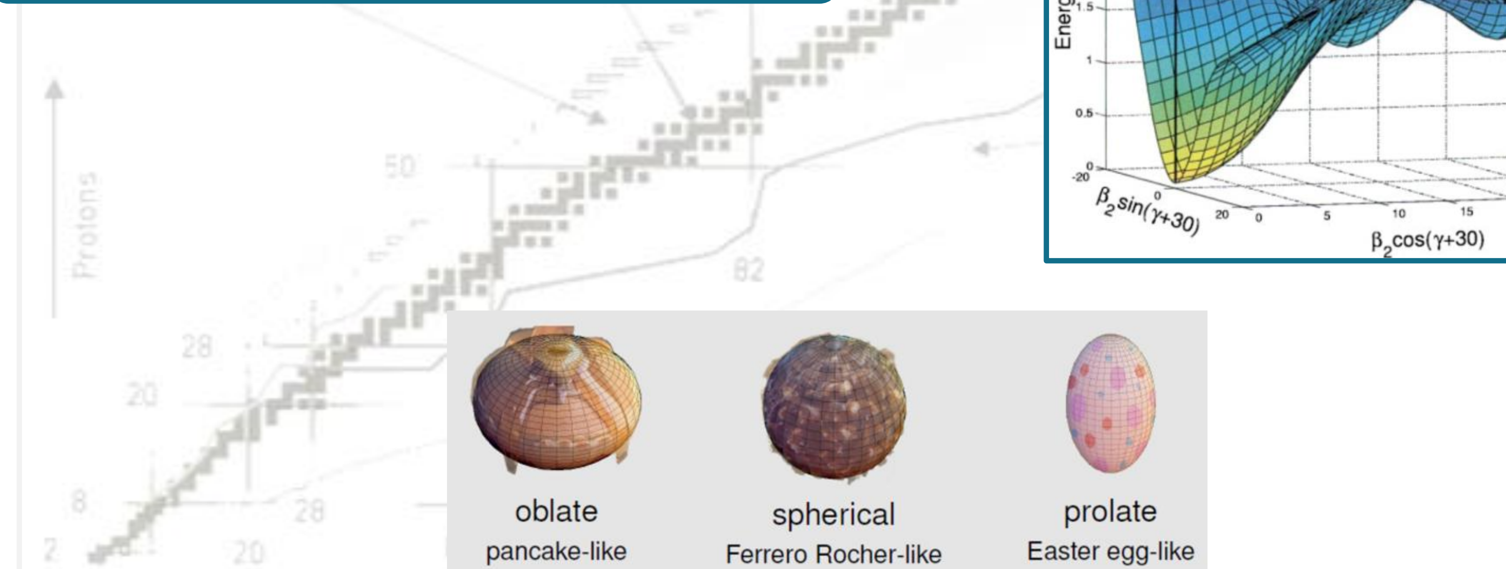
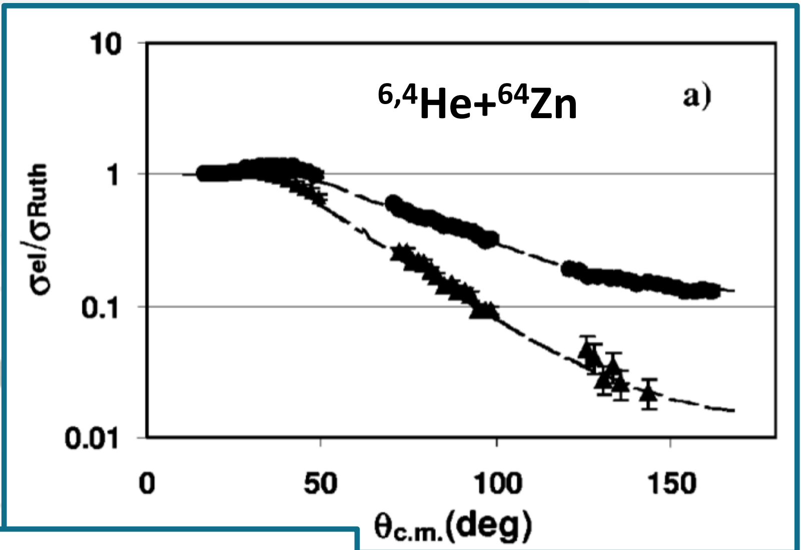


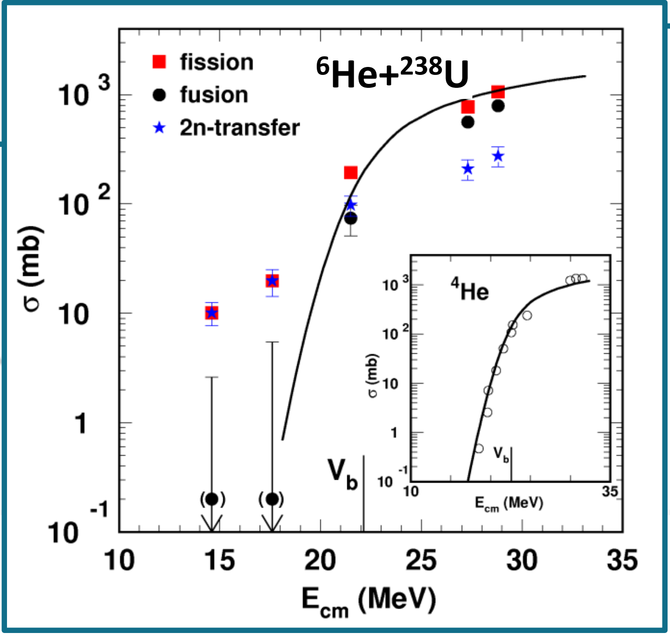
Figure: T. Cocolios (2010)

Exotic nuclei: role in reaction processes

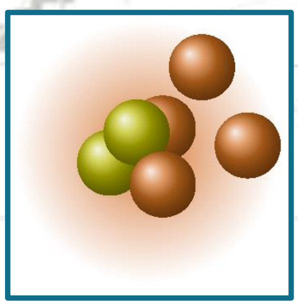
- 30 years ago: unstable nuclei become available for reactions
- Large interaction cross section, narrow momentum distribution of fragments
- Role in elastic scattering and fusion processes, role of the continuum



A. Di Pietro et al., PRC 69 (2004) 044613

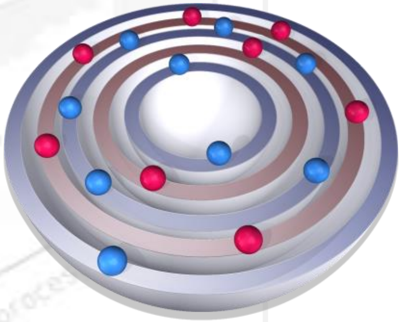


RR et al., Nature 431 (2004) 823



Exotic nuclei: the nucleon-nucleon interaction revealed

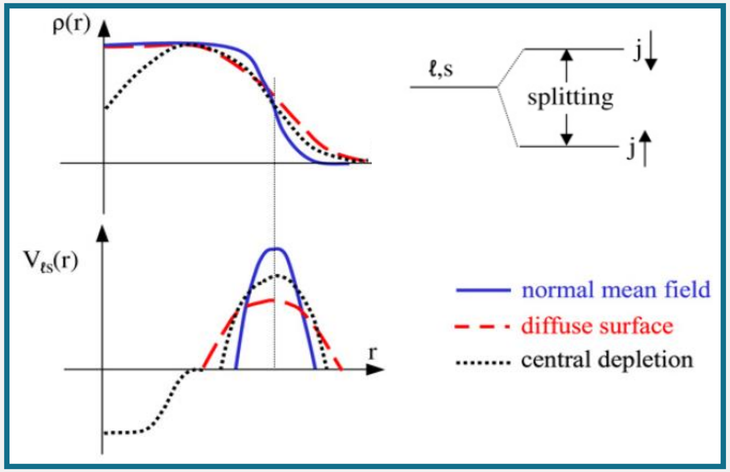
- Shell model describes well the properties of stable nuclei
- Far from stability: **new structures, new magic numbers**



- Spin-Orbit potential:

$$\boxed{V_{\ell s}(r) = \frac{1}{r}\frac{d\rho}{dr}\,\vec{\ell}\cdot\vec{s}}$$

O. Sorlin, M.-G. Porquet, PPNP 61 (2008) 602



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Studying "exotic" states

Production

- Reactions, Decay

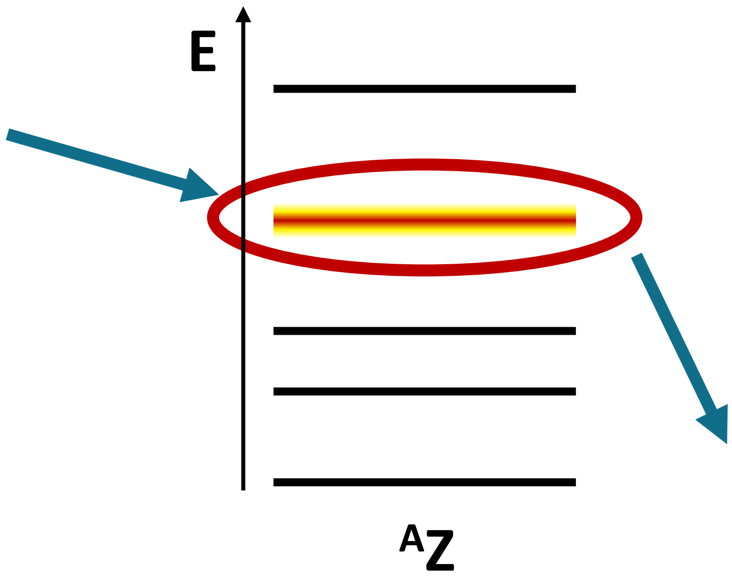
Manipulation

- Ionisation, selection, transport

Measurement: radiation

- Identification of channel
- Transition probability

$$\Gamma_{i\to f} = \frac{2\pi}{\hbar} |\langle f|\boldsymbol{T}|i\rangle|^2 \rho_f$$



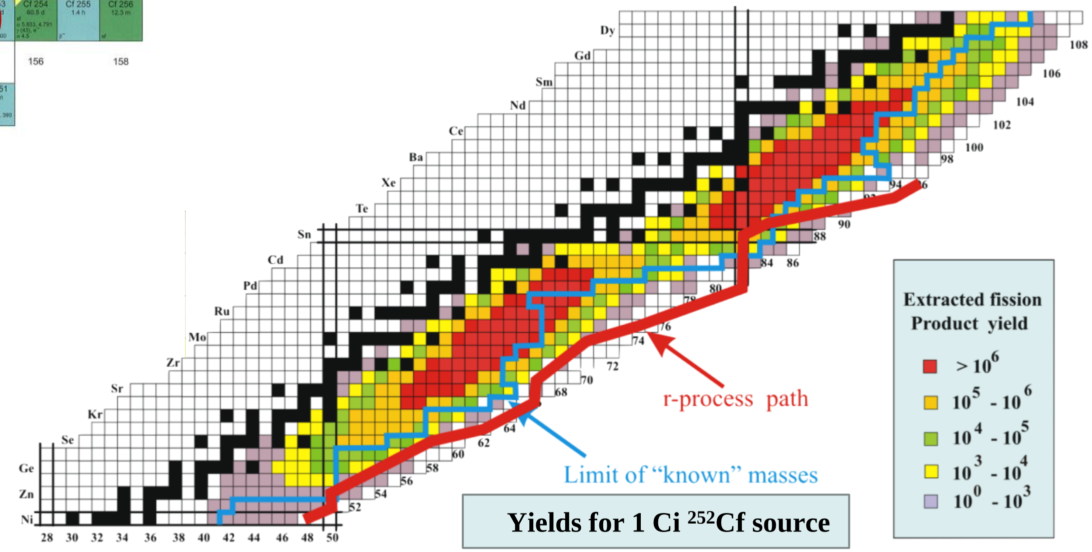
Details depend upon

- The characteristics of the state(s) to be studied
- The chosen process(es)
- The kind of radiation

Production of radioactive species

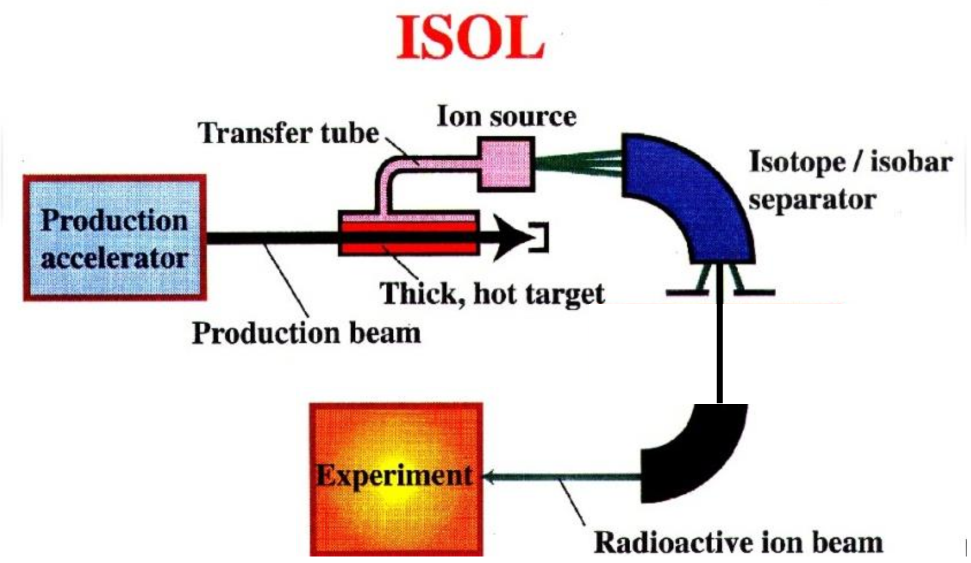
- Decay of primordial nuclides (very long half lives)
- Neutron capture followed by decay
  - Nuclei in the vicinity of stability
  - Fission sources

CARIBU facility
at ARGONNE National Labs
(near Chicago)



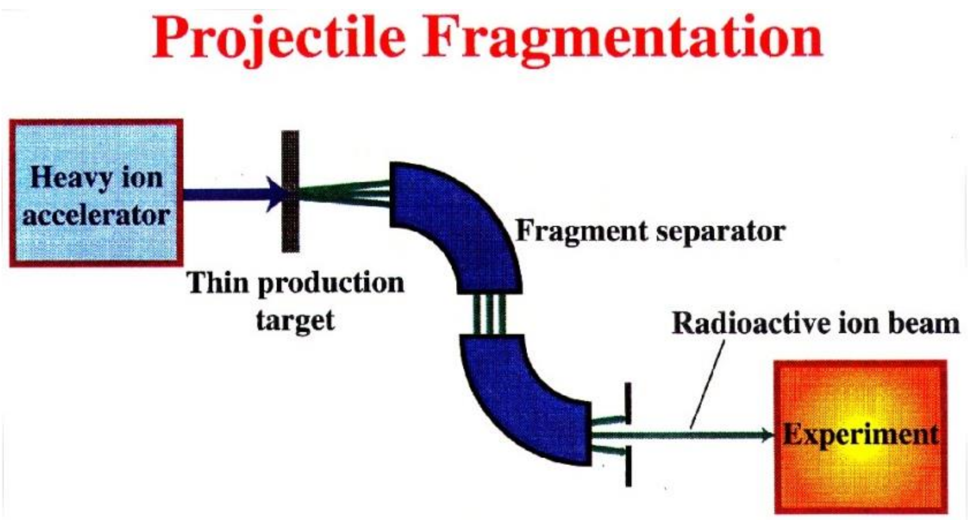
The Isotope Separation-On-Line (ISOL) method

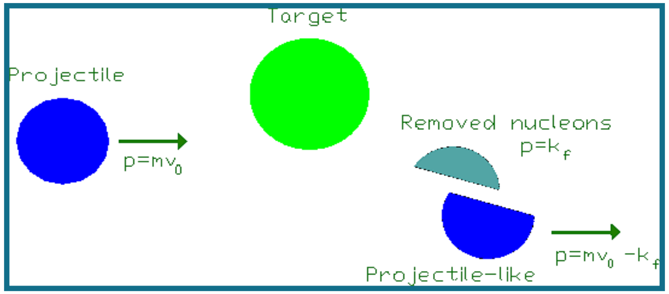
- Idea: create a source that can be “switched” on and off
- Process:
  - Irradiate a material with a beam to induce reactions
  - Extract the (reaction or decay) products
  - Manipulate them (ionise, separate, guide to detection station)



The "in-flight" method

- Heavy-ion accelerator, E ≈ some hundreds MeV/A
- Thin production target (light element, rotating wheel)
- Fragment separator
- Transport to the experiment

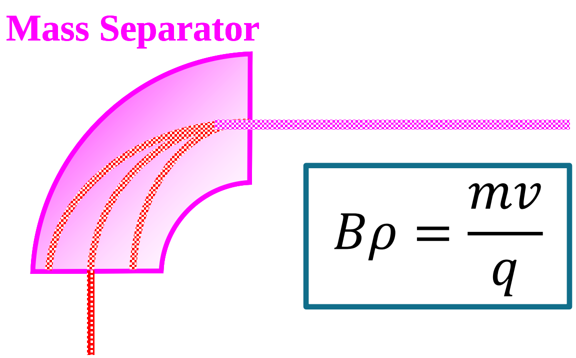




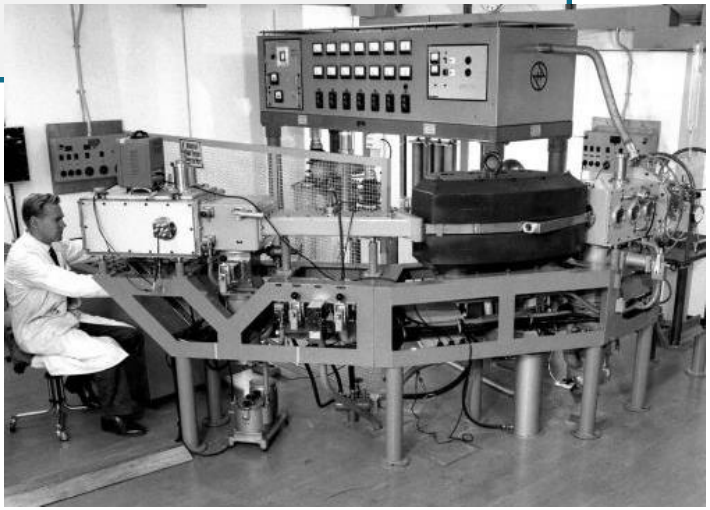
Isotope Separators

ISOL

- Low-energy beam (30 to 60 keV), charge 1^+
- Goal: selection of one mass, possibly separation of isobars
  $M/\Delta M \approx 5000$ to 10000
- Essentially a mass separator based on magnetic rigidity
- Sometimes: Wien filter (cross E and B fields),
  MR-TOF, traps for bunching



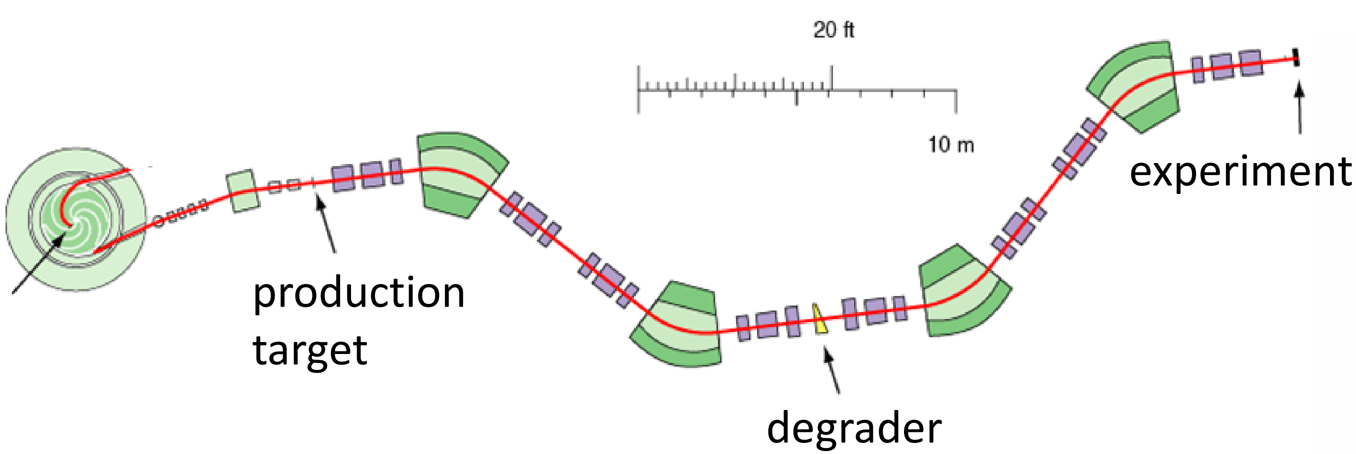
$$\boxed{B\rho = \frac{mv}{q}}$$

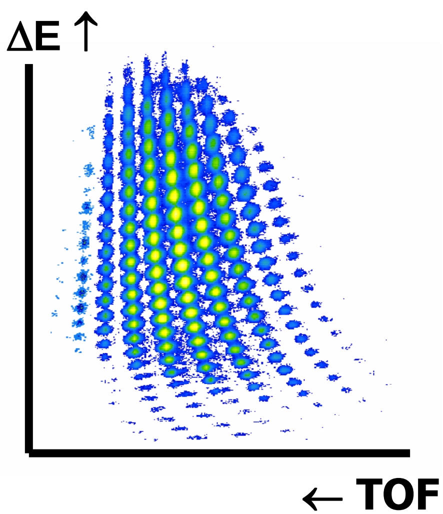


Isotope Separators

In-flight

- High-energy beam (50 MeV/A to 1 GeV/A), fully stripped
- Goal: time and spatial separation
  particle-by-particle identification by ΔE and TOF
- Magnetic elements and degraders





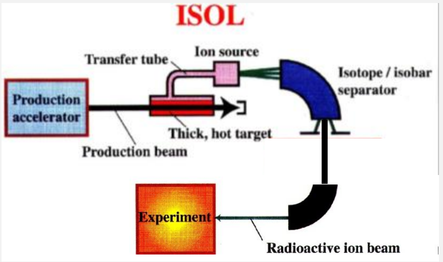
Comparison ISOL – in flight

Challenges

- Low production cross sections
- Overwhelming presence of unwanted species
- (Very) short half lives for the species of interest

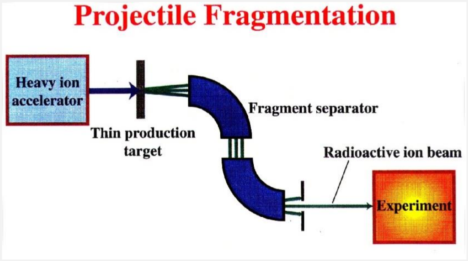
ISOL

- **High-quality beams** (purity, emittance)
- Depends on chemistry
- Slow (diffusion from the target)

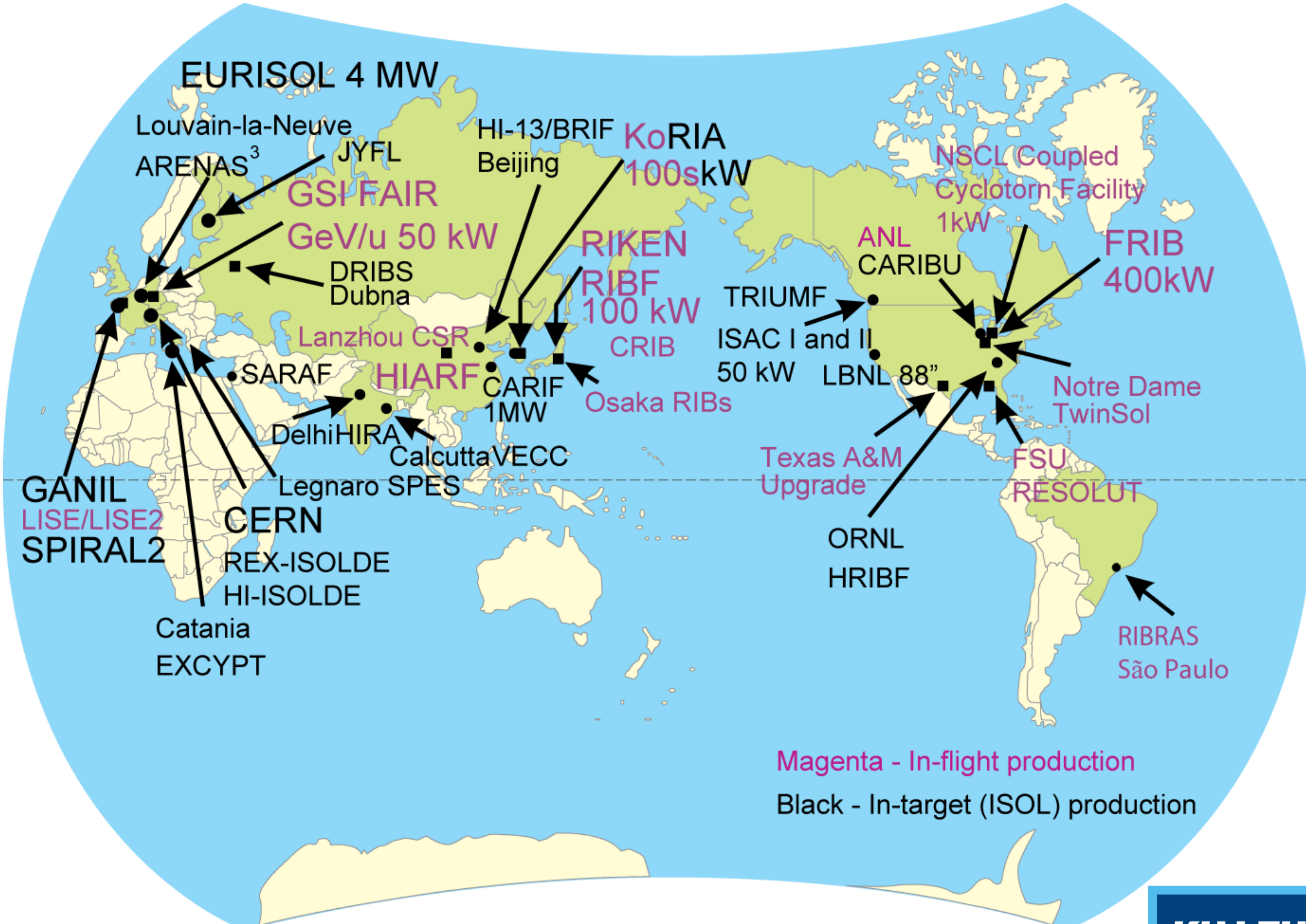


In-flight

- **Fast and universal**
- Ions readily available at high energy
- Low-quality beams

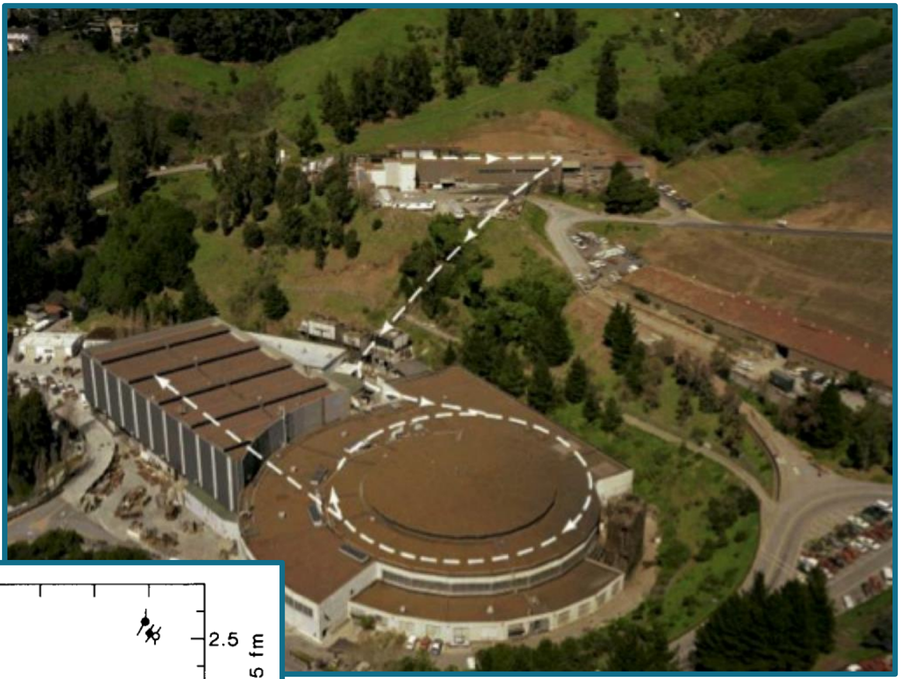


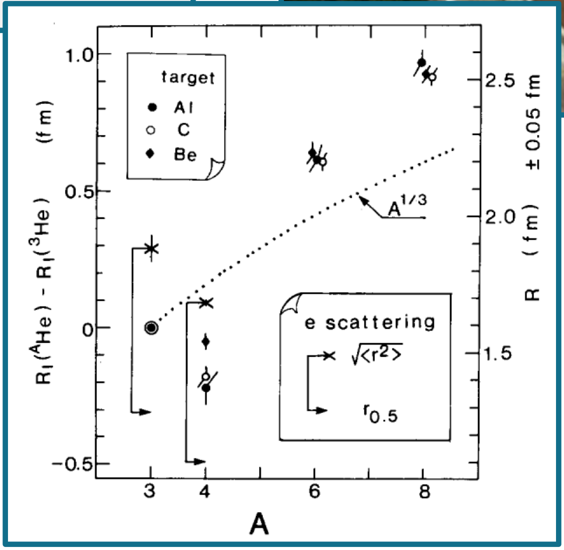
RIB facilities: world map



In-flight: BEVALAC at Lawrence Berkeley Laboratory

- Combination of a low-energy heavy ion linear accelerator and a proton synchrotron
- Transfer line from the Linac to the Bevatron
- Heavy ion ^{11}B and ^{20}Ne beam at 800 MeV/A
  fragmented on a Be target





I. Tanihata et al
Phys. Lett. 160B (1985) 380

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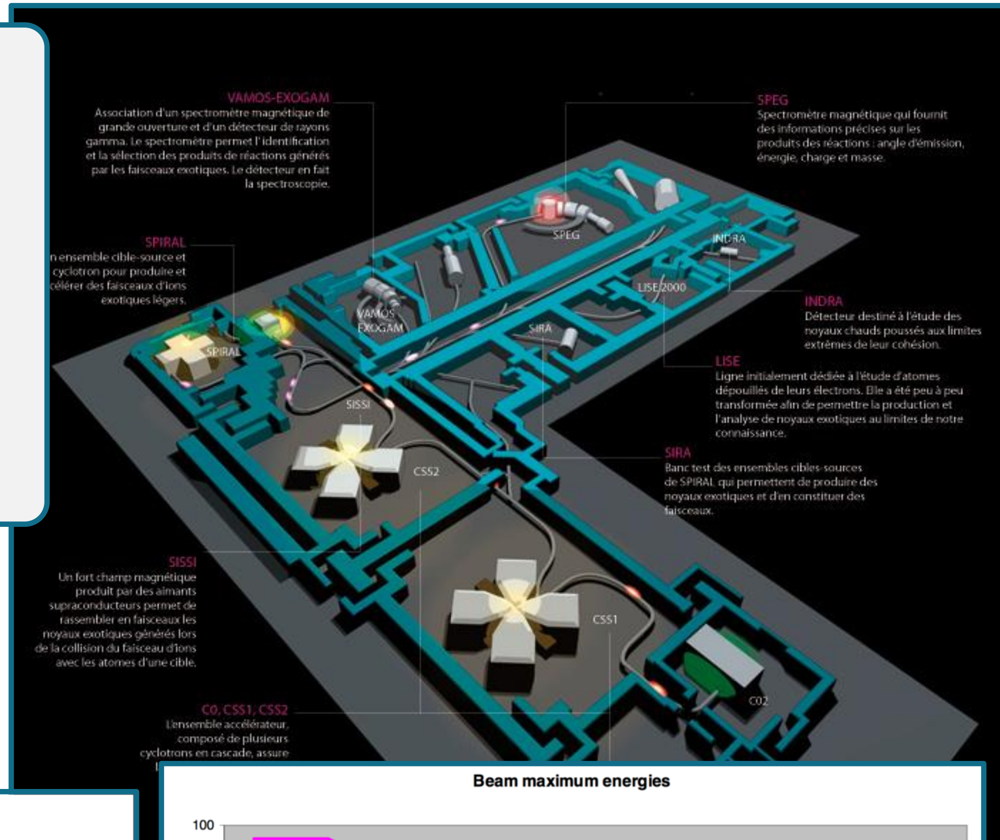
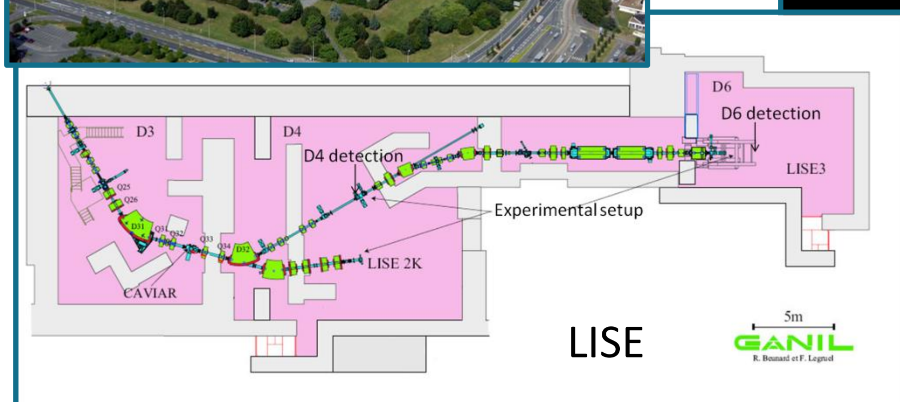
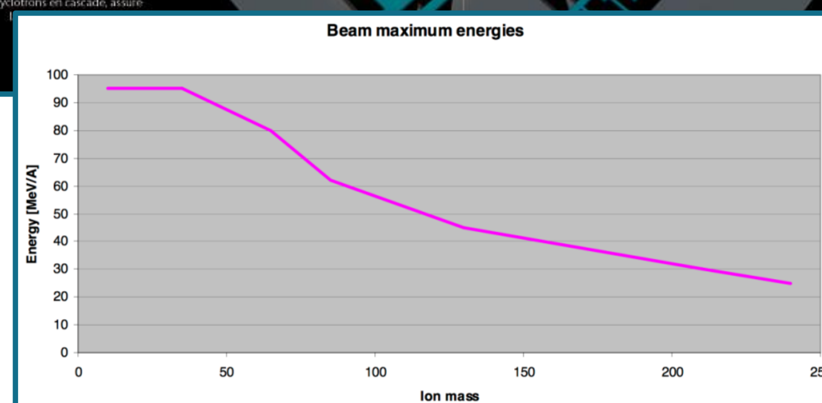
In-flight: Europe

GANIL (Caen, France)

- Two coupled cyclotrons
  E < 100 MeV/A
- Fragment separator LISE
- ^{36}S 10^{13} pps, ^{48}Ca 2×10^{12} pps



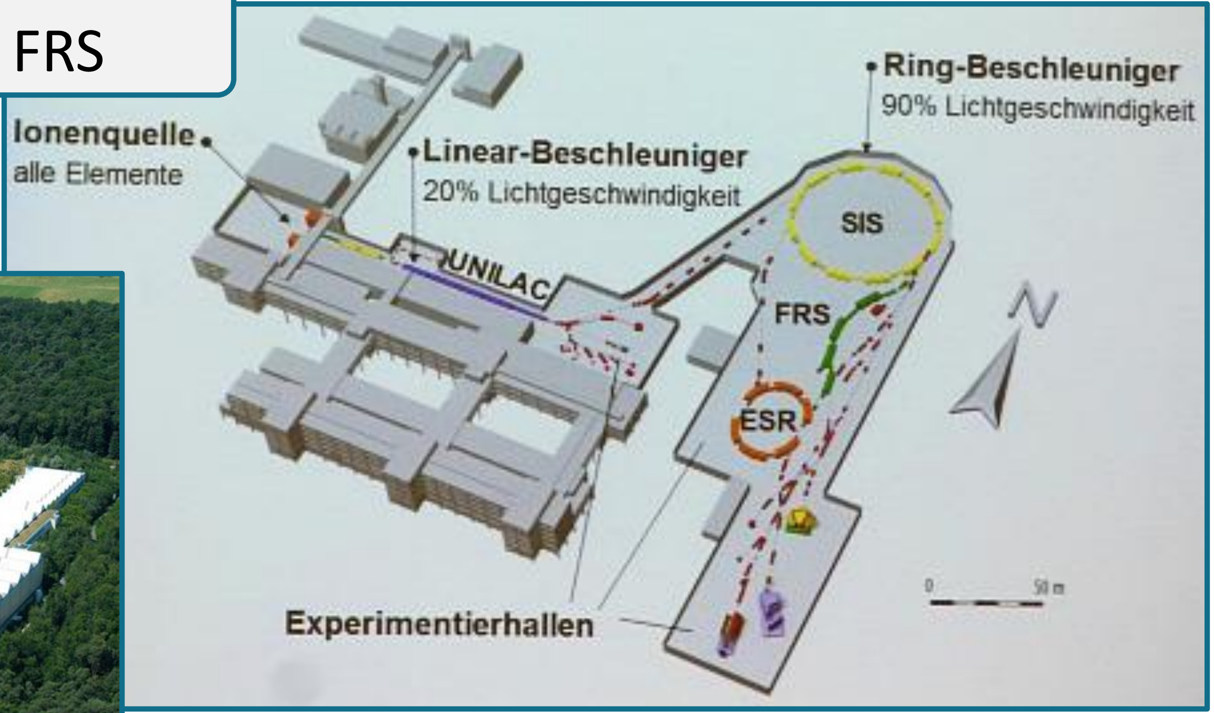




In-flight: Europe

GSI (Darmstadt, Germany)

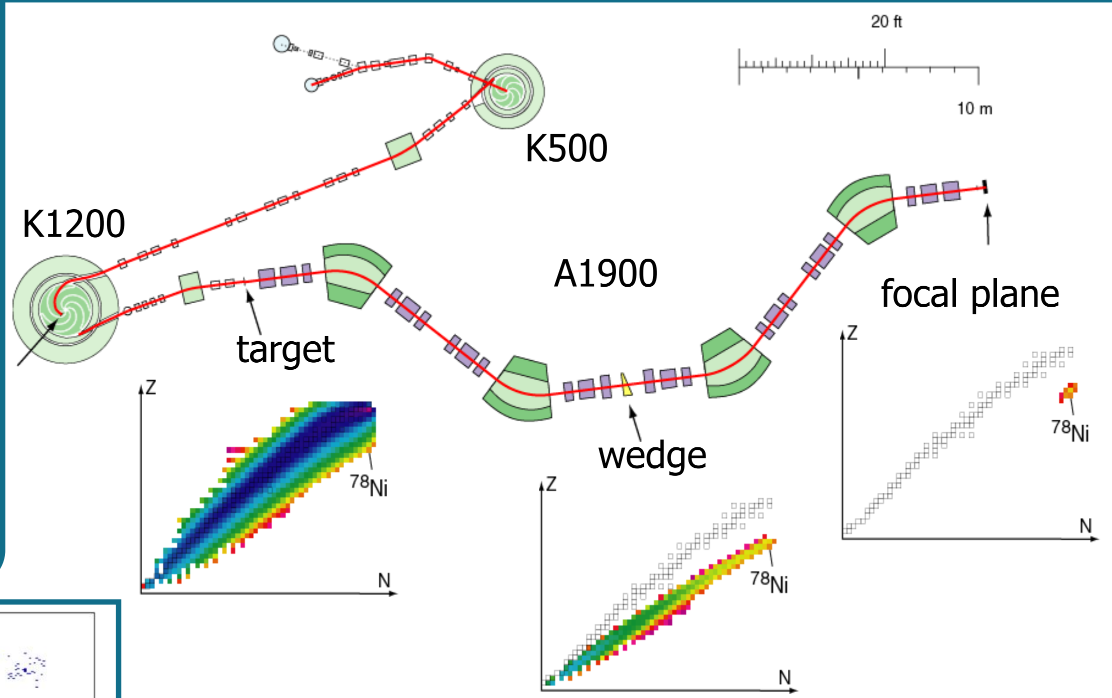
- LINAC+ Synchrotron
  Energy 2 GeV/A, 10^{10} pp spill
- FRagment Separator FRS

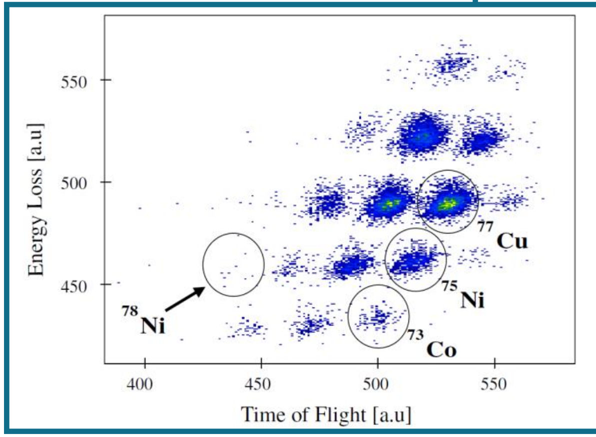


In-flight: National Superconducting Cyclotron Laboratory

NSCL at MSU, USA

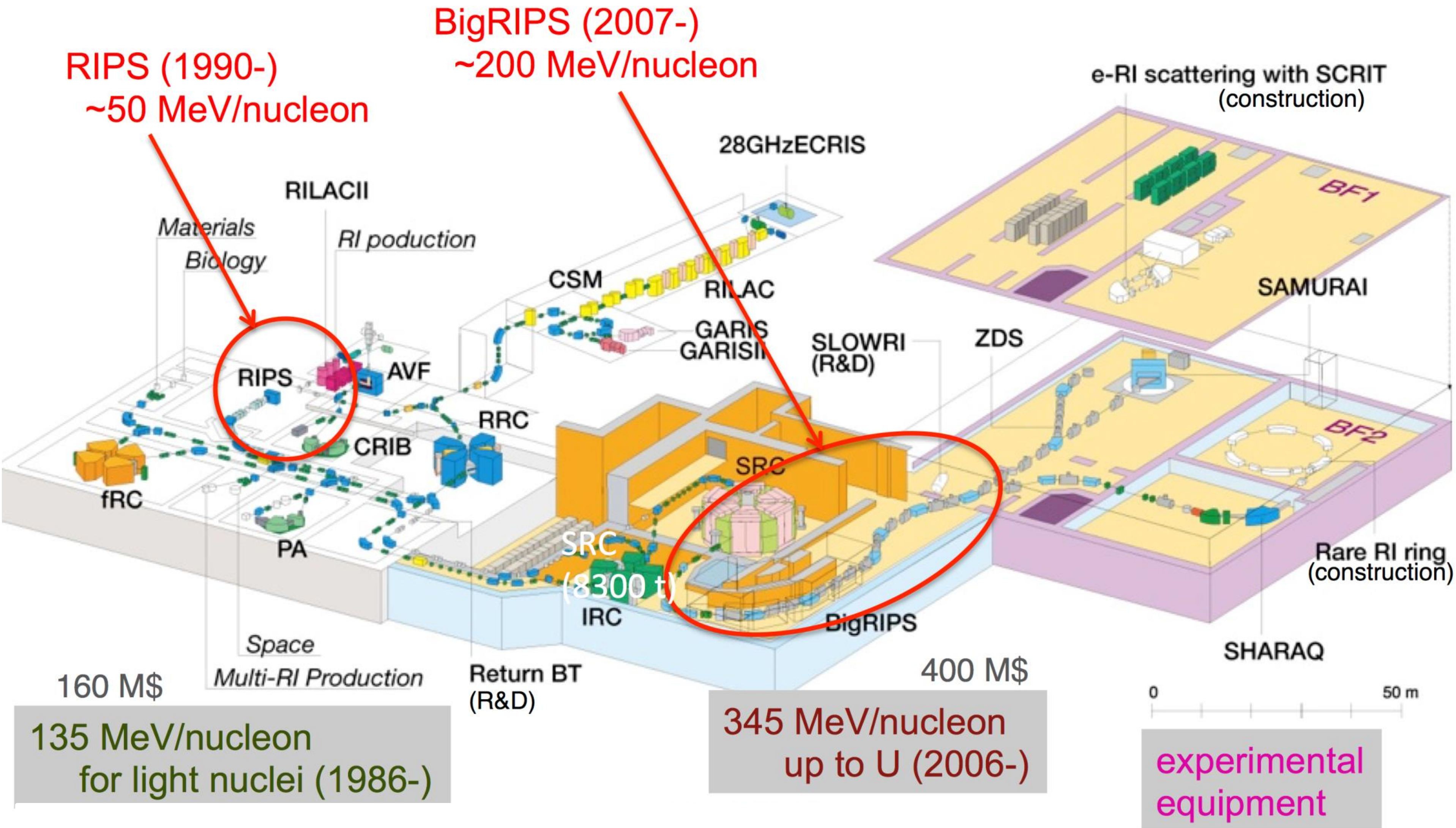
- Two cyclotrons for the acceleration, E≈150 MeV/A ^{40}Ar 5×10^{11} pps
- Liquid-cool
  Be production target
- A1900 fragment separator
- Example:
  Production of ^{78}Ni
  from 140 MeV/A ^{86}Kr



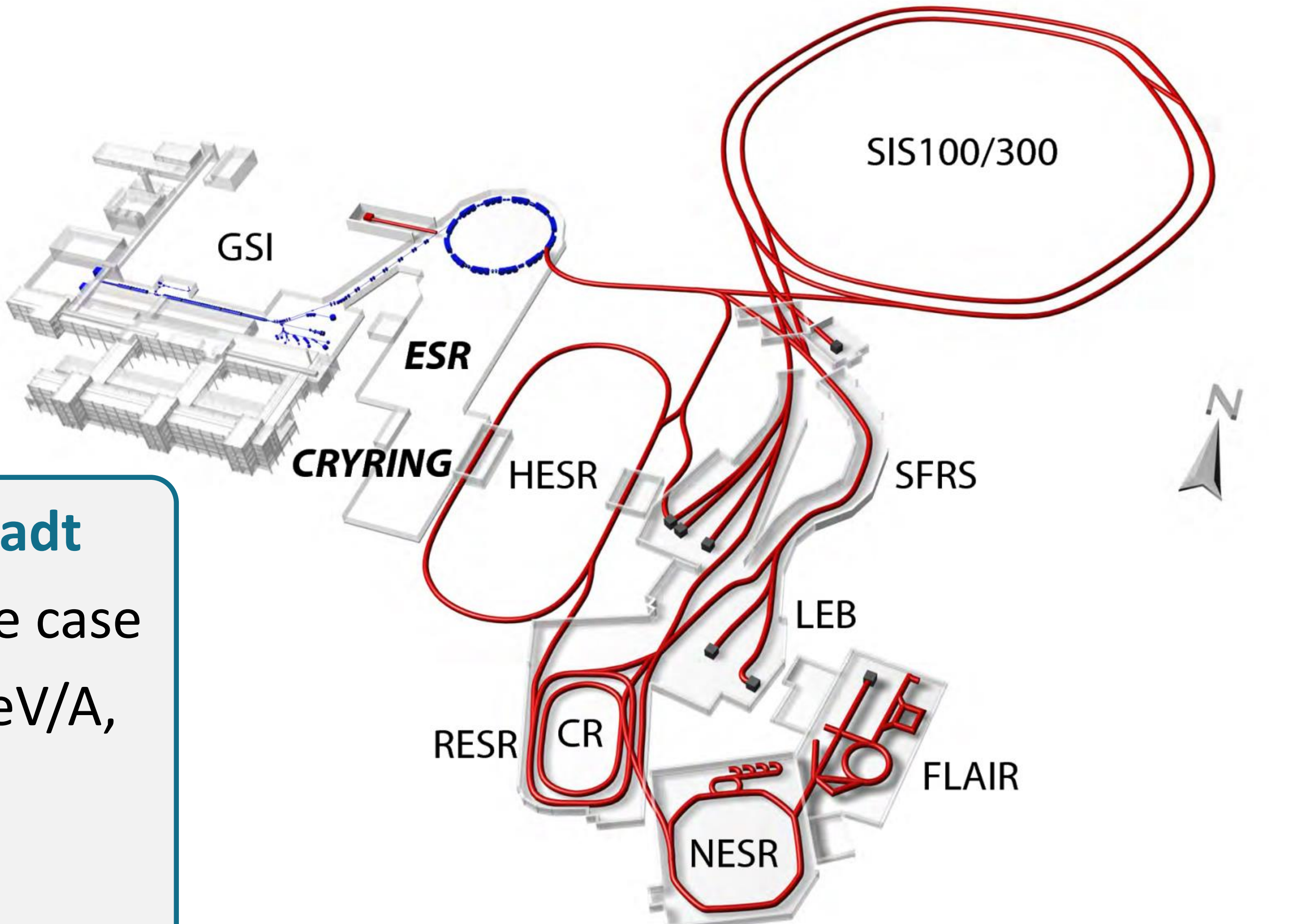


Morrissey et al., NIM B 204, 90 (2003)
P. Hosmer et al., Phys. Rev. Lett. 94, 112501 (2005)

New generation in-flight: RIKEN



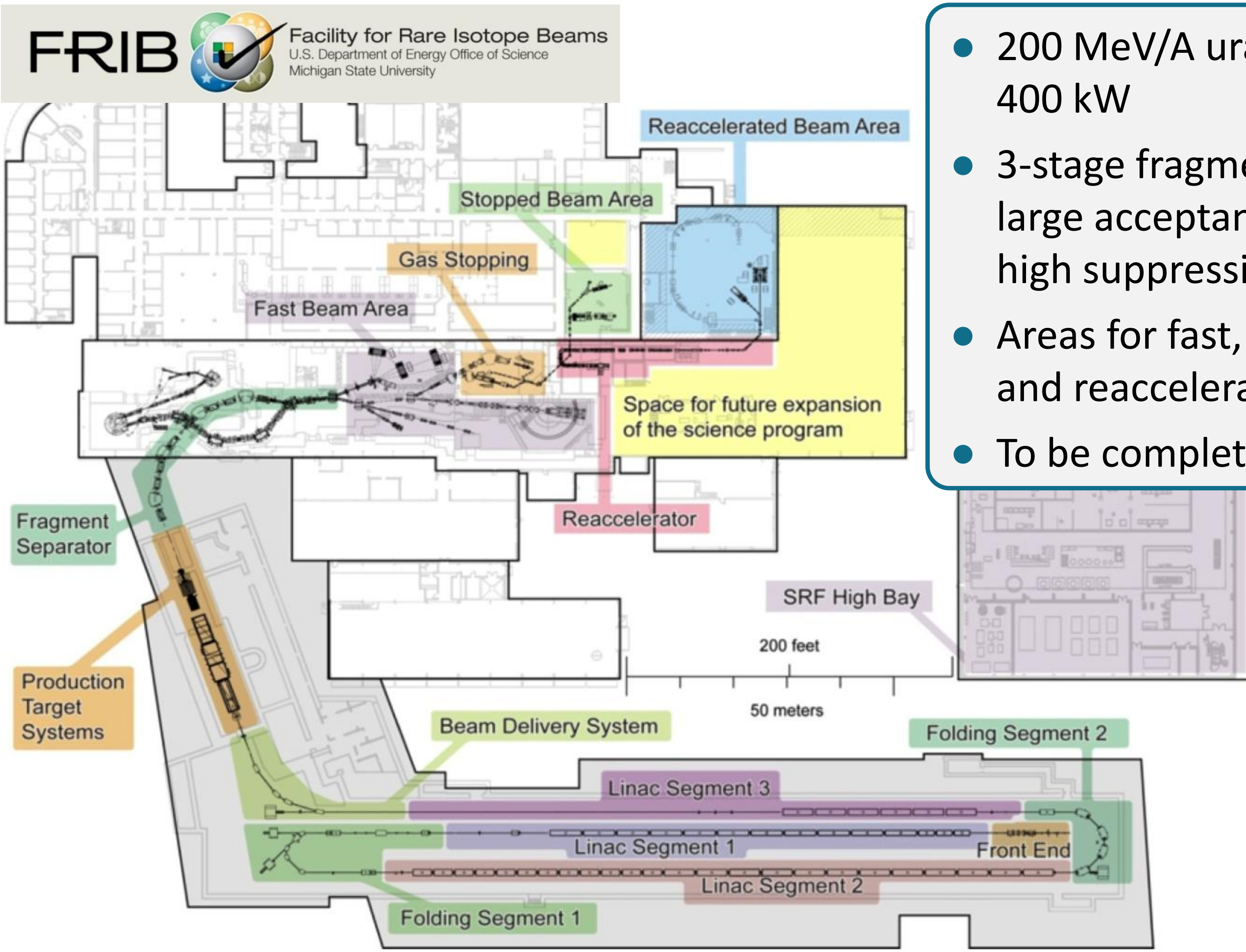
New generation in-flight: FAIR



FAIR at Darmstadt

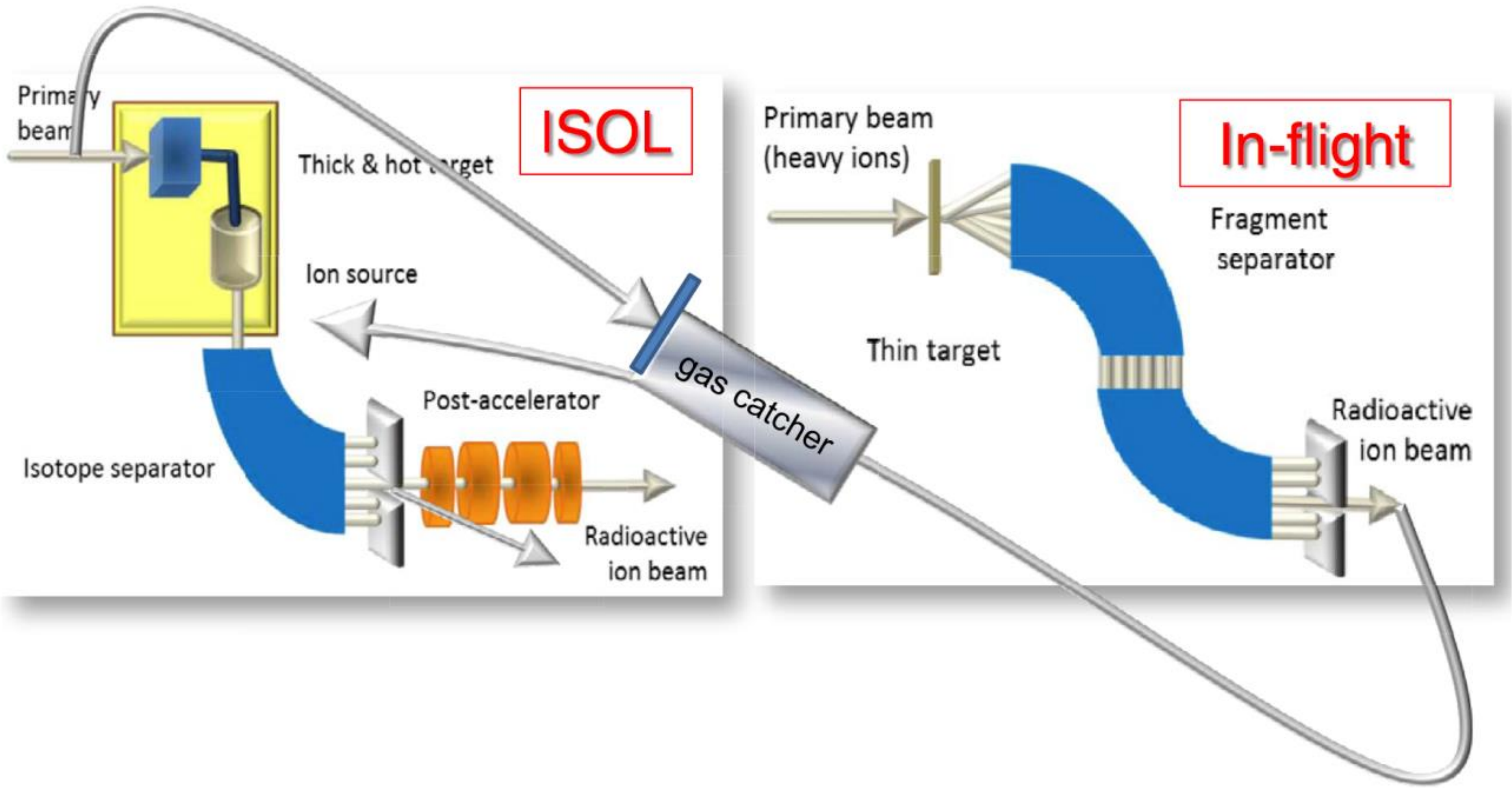
- Broad science case
- ^{238}U at 1.5 GeV/A, 10^{12} pp spill
- Super-FRS high acceptance separator

New generation in-flight: FRIB



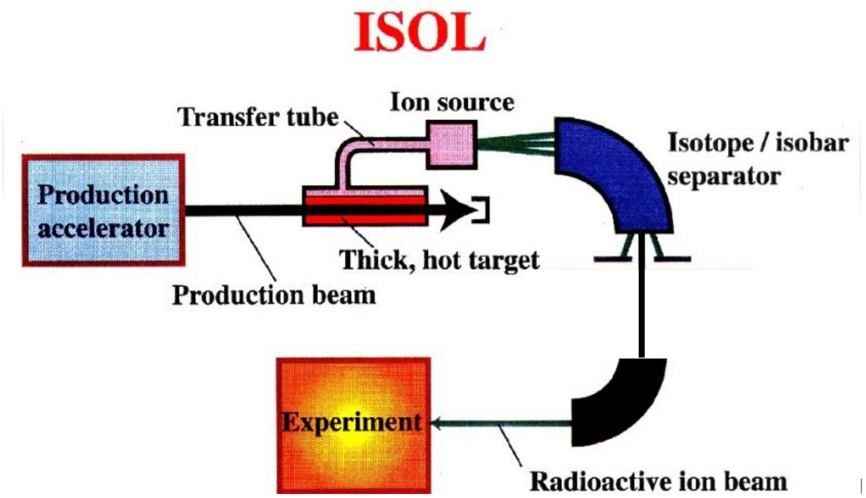
- 200 MeV/A uranium, 400 kW
- 3-stage fragment separator large acceptance, high suppression
- Areas for fast, stopped and reaccelerated beams
- To be completed in 2020

Combining ISOL and in-flight

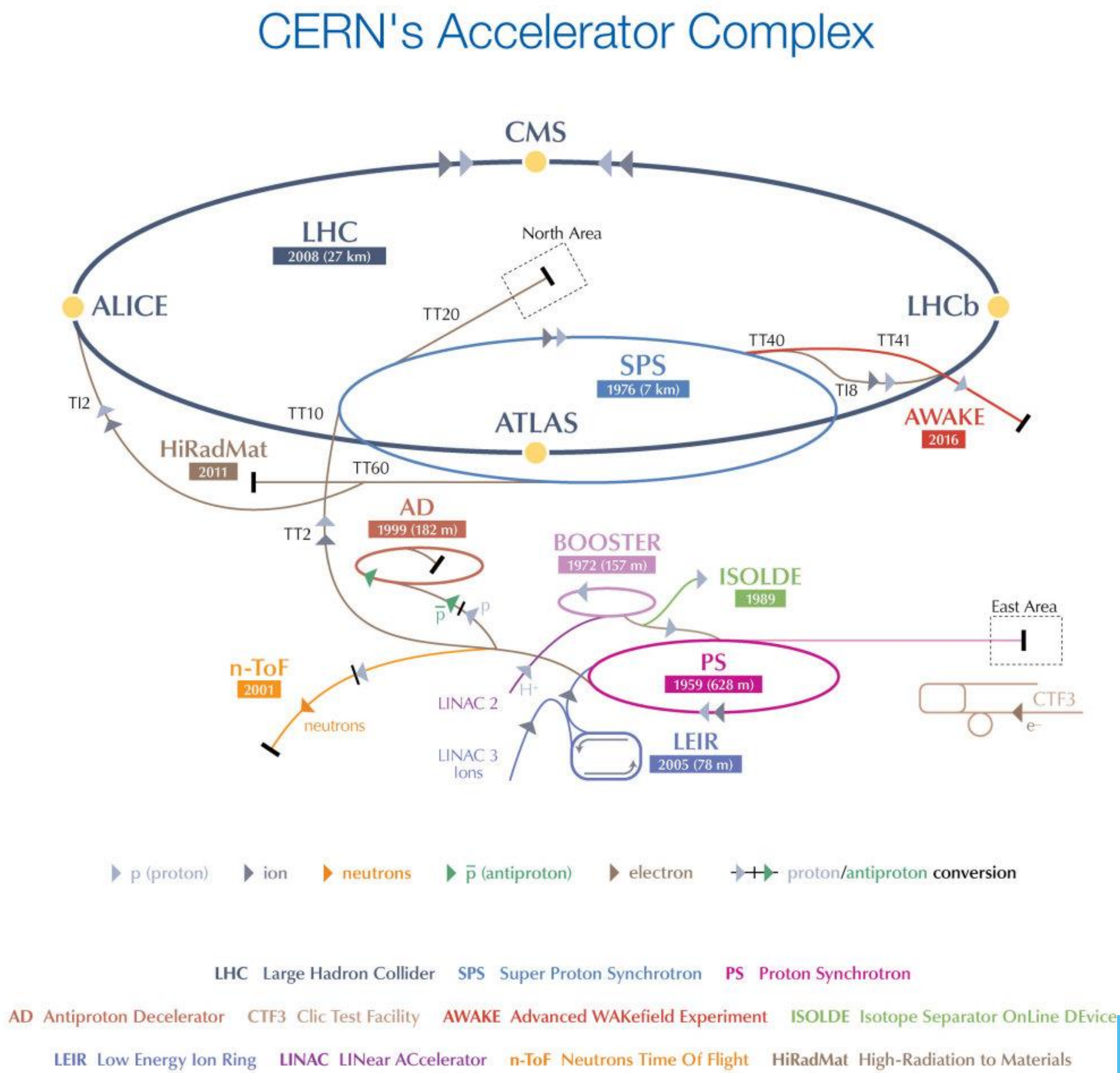


ISOL: brief history

- 1951, Niels Bohr Institute Copenhagen
  Deuteron beam, neutron converter, n-induced fission
  on a uranium target. ^{89,90,91}Kr isotopes extracted
- 1965: Orsay
  Protons on a stack of C foils. ^{6,7,8,9}Li extracted
- 1964 start of the ISOLDE project
  600 MeV protons (now 1.4 GeV)
  on fissile targets
  1967 first measurements



ISOLDE at CERN



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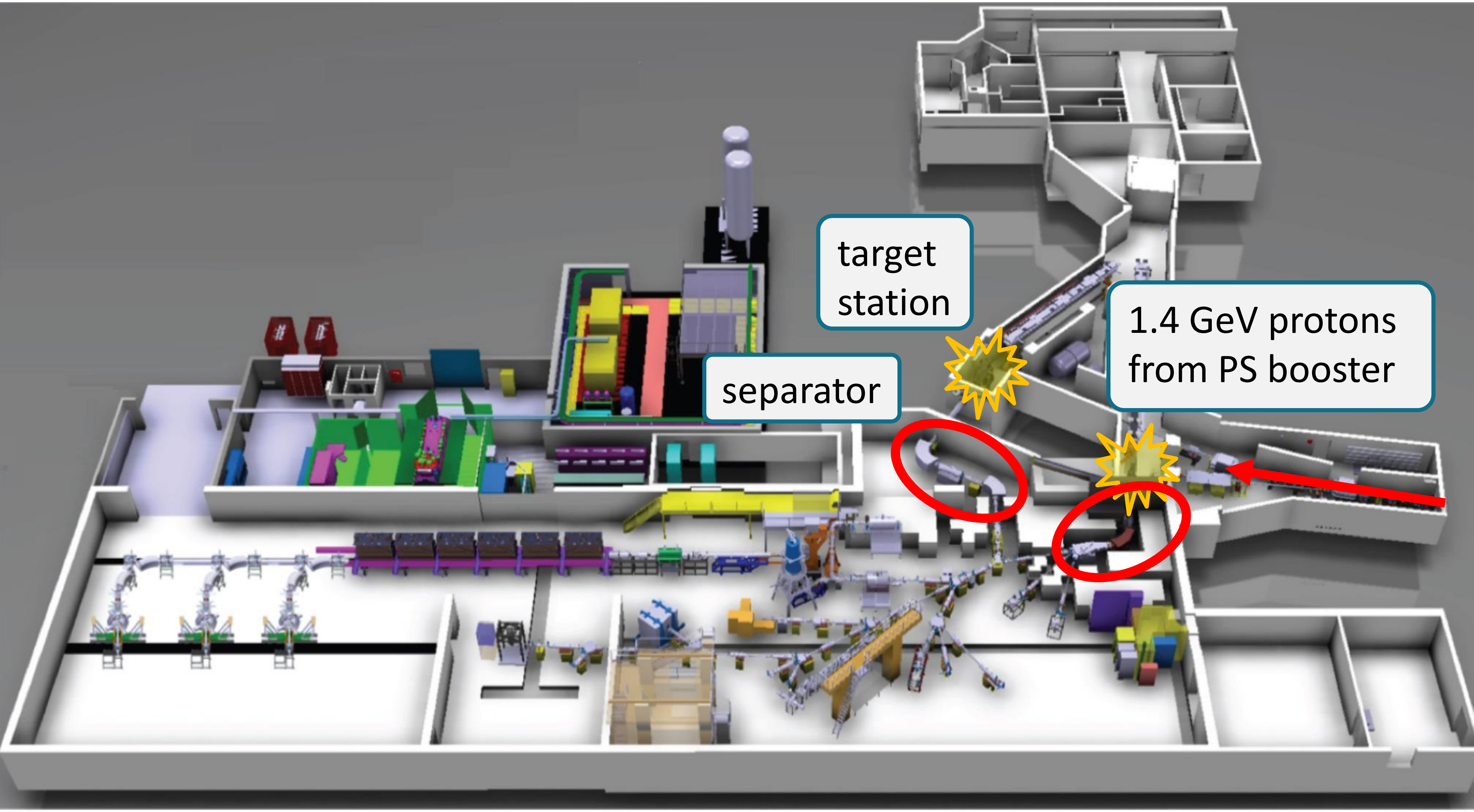
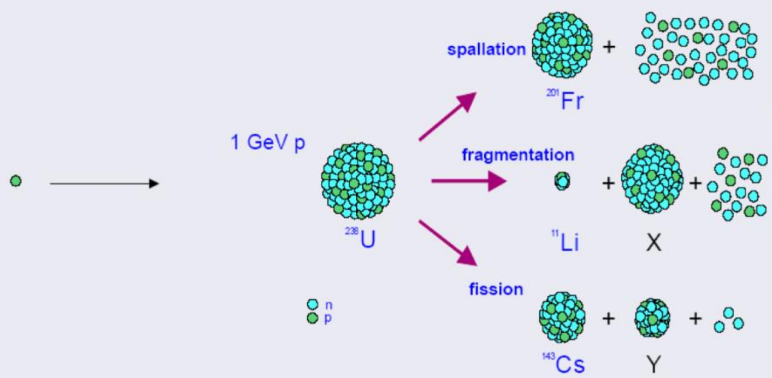
ISOLDE at CERN

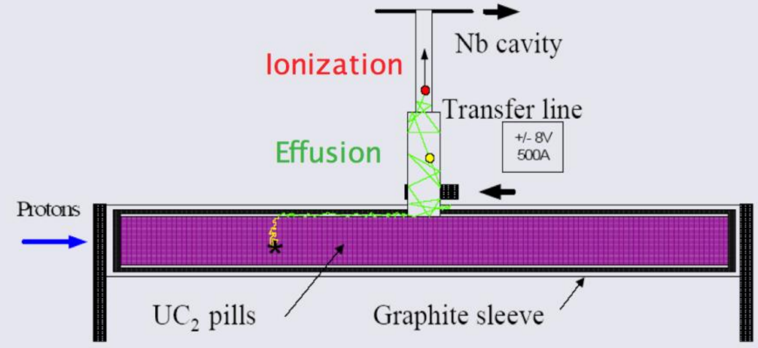


ISOL method once again

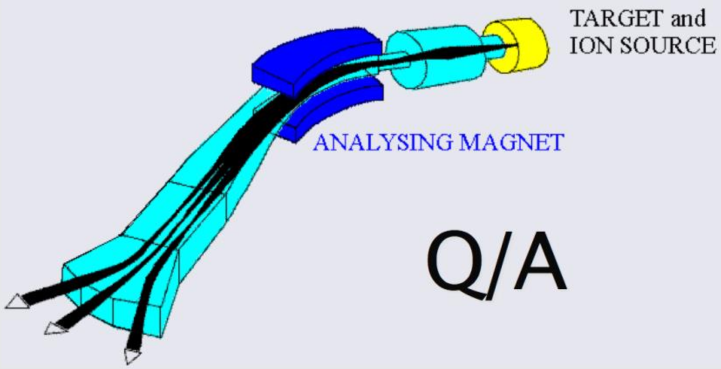
Production



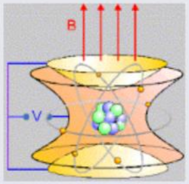
Extraction/Ionization



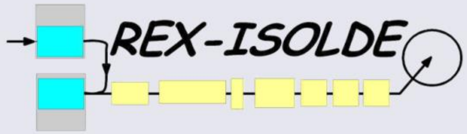
Isotope Separation

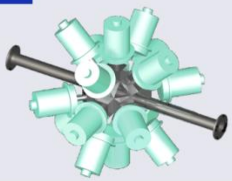


Delivery or post Acceleration



ISOLTRAP





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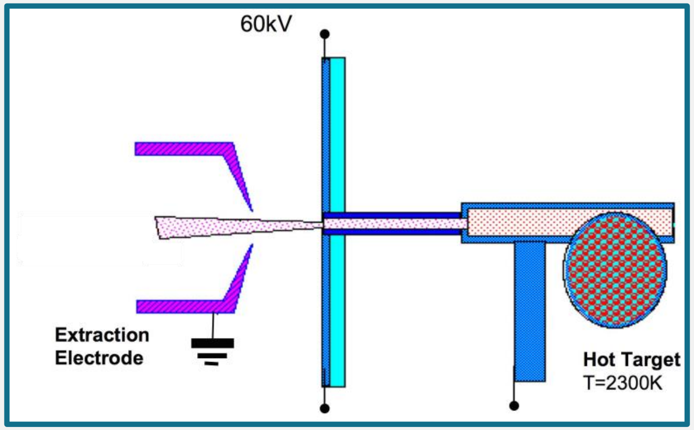
Ion sources

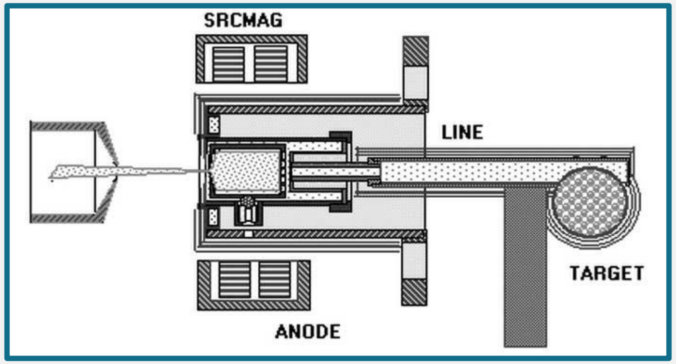
Hot surface ion source

- The ioniser is a hot tube
- Material with a higher work function than the element of interest
- Heated up to 2400 degrees



Plasma ion source

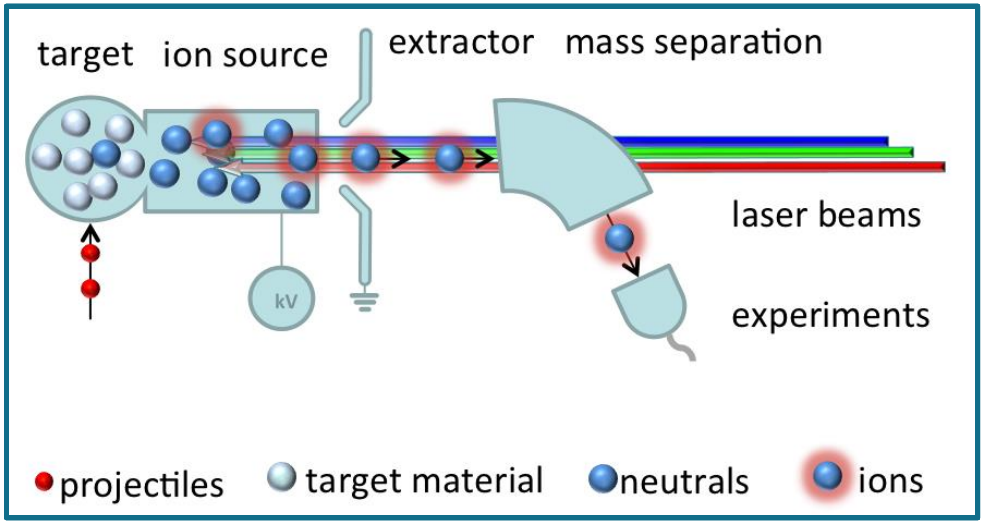
- Plasma: gas mixture (Ar and Xe) ionised by accelerated electrons
- Hot or cool transfer line

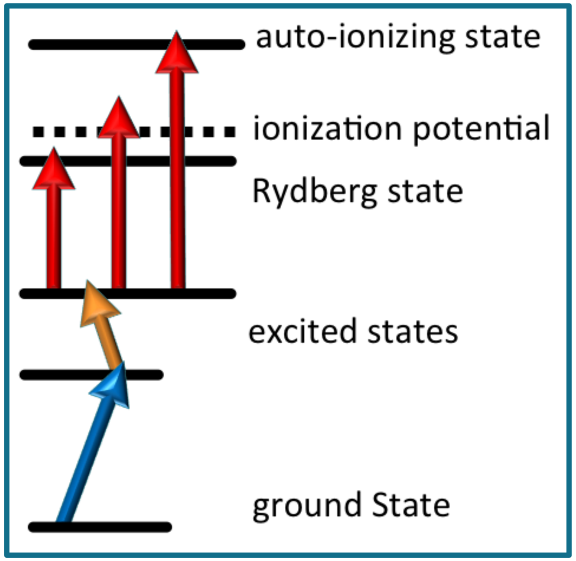


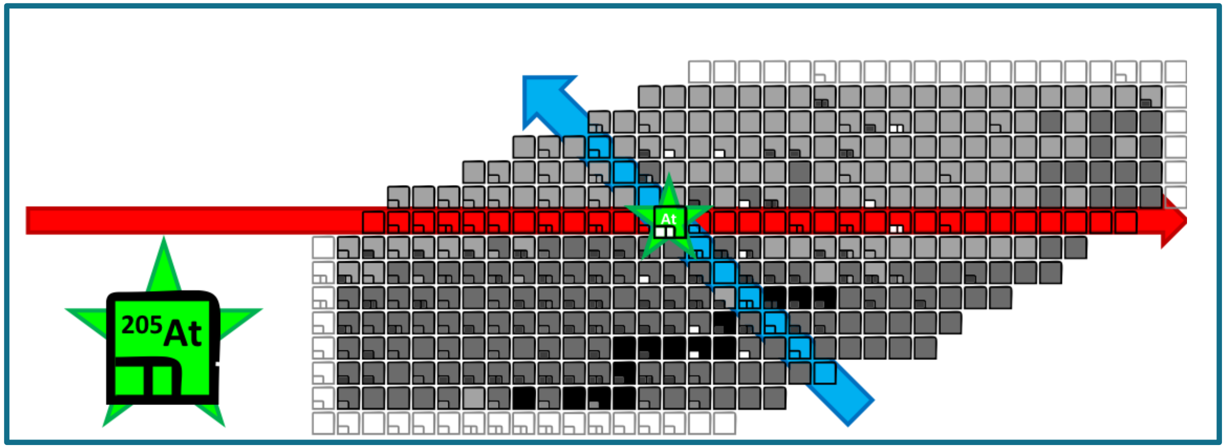
Ion sources

Laser ion source

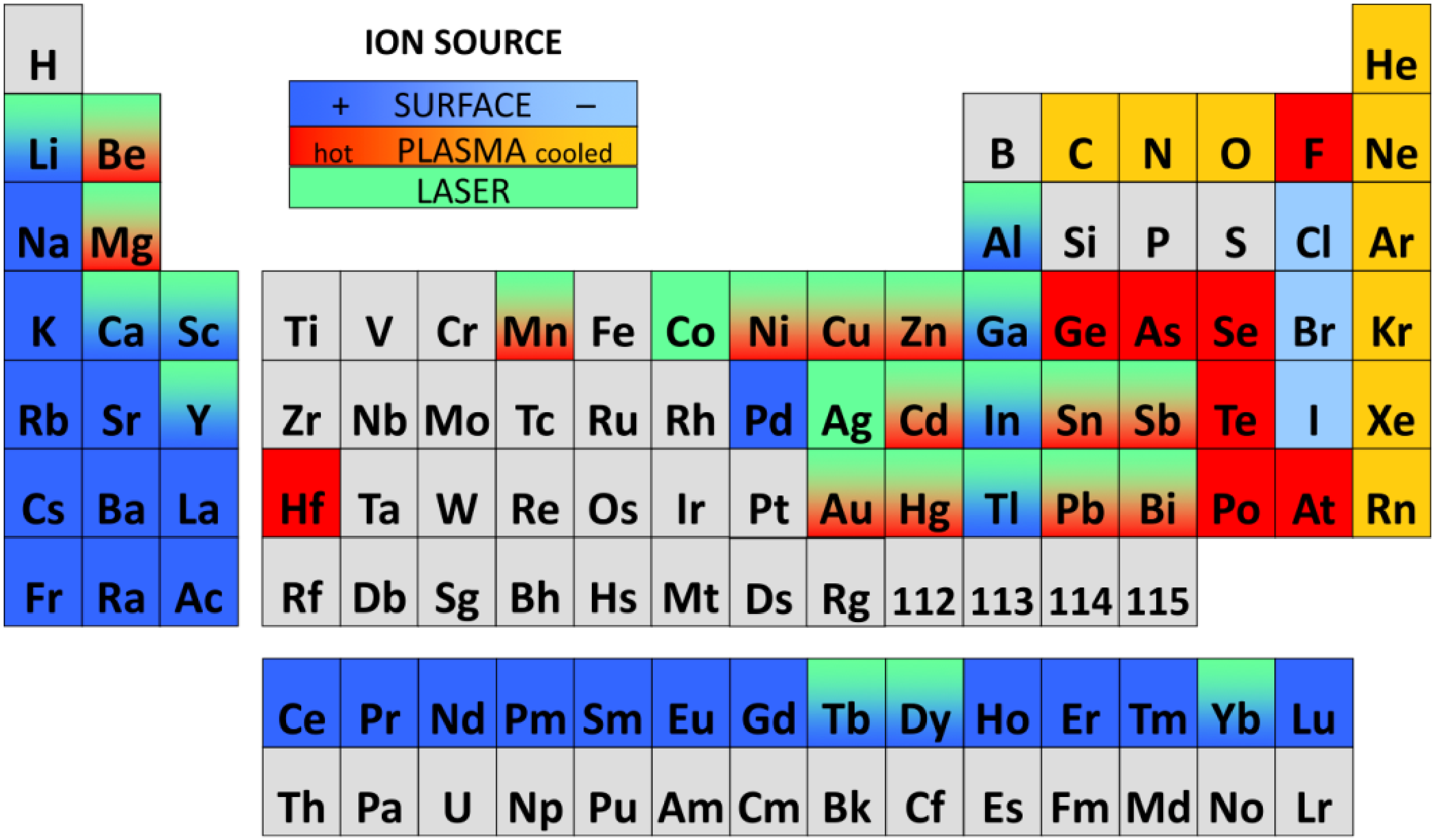
- 2- or 3-step ionisation
- Isotope and isomer selection
- Universal (almost)







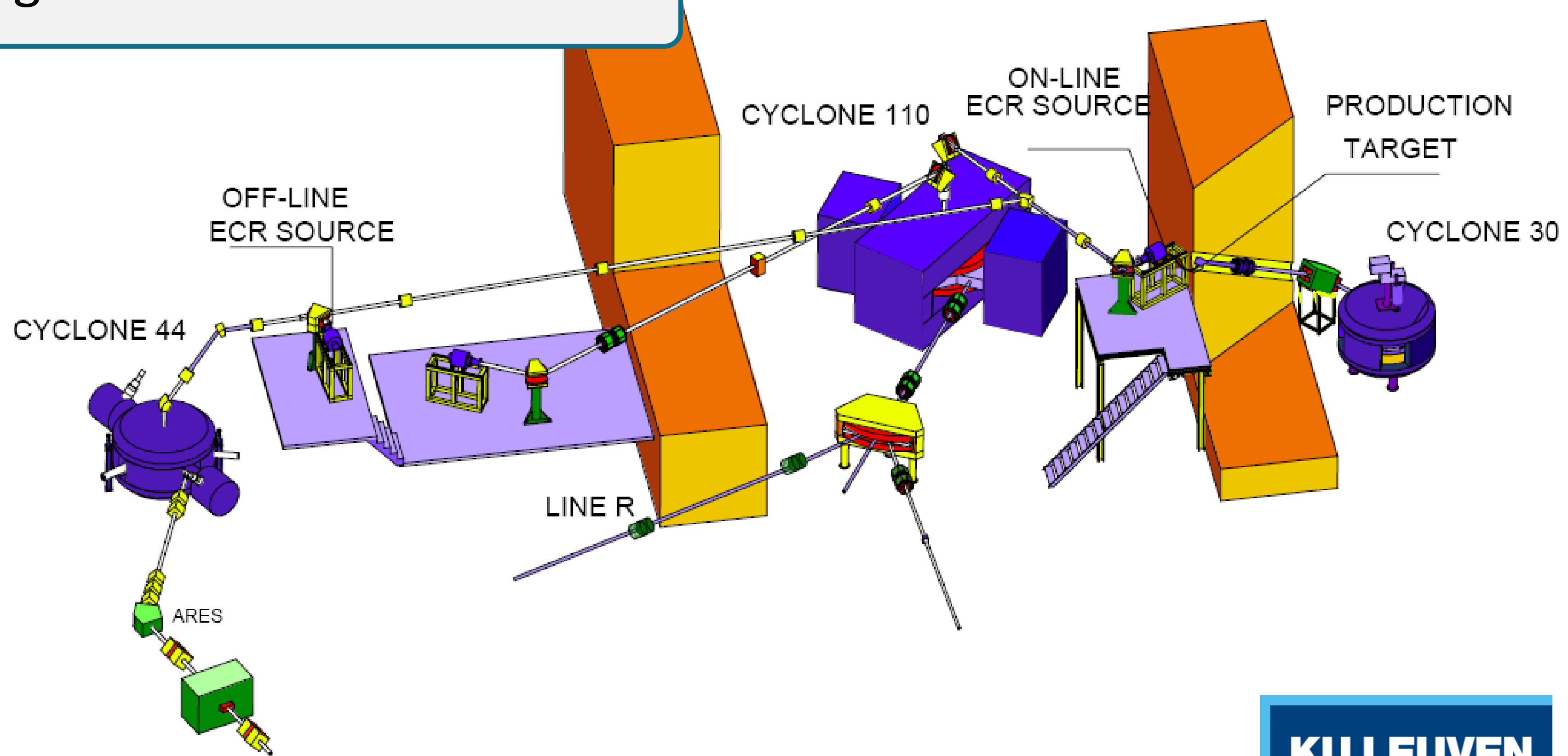
Isotopes produced at ISOLDE



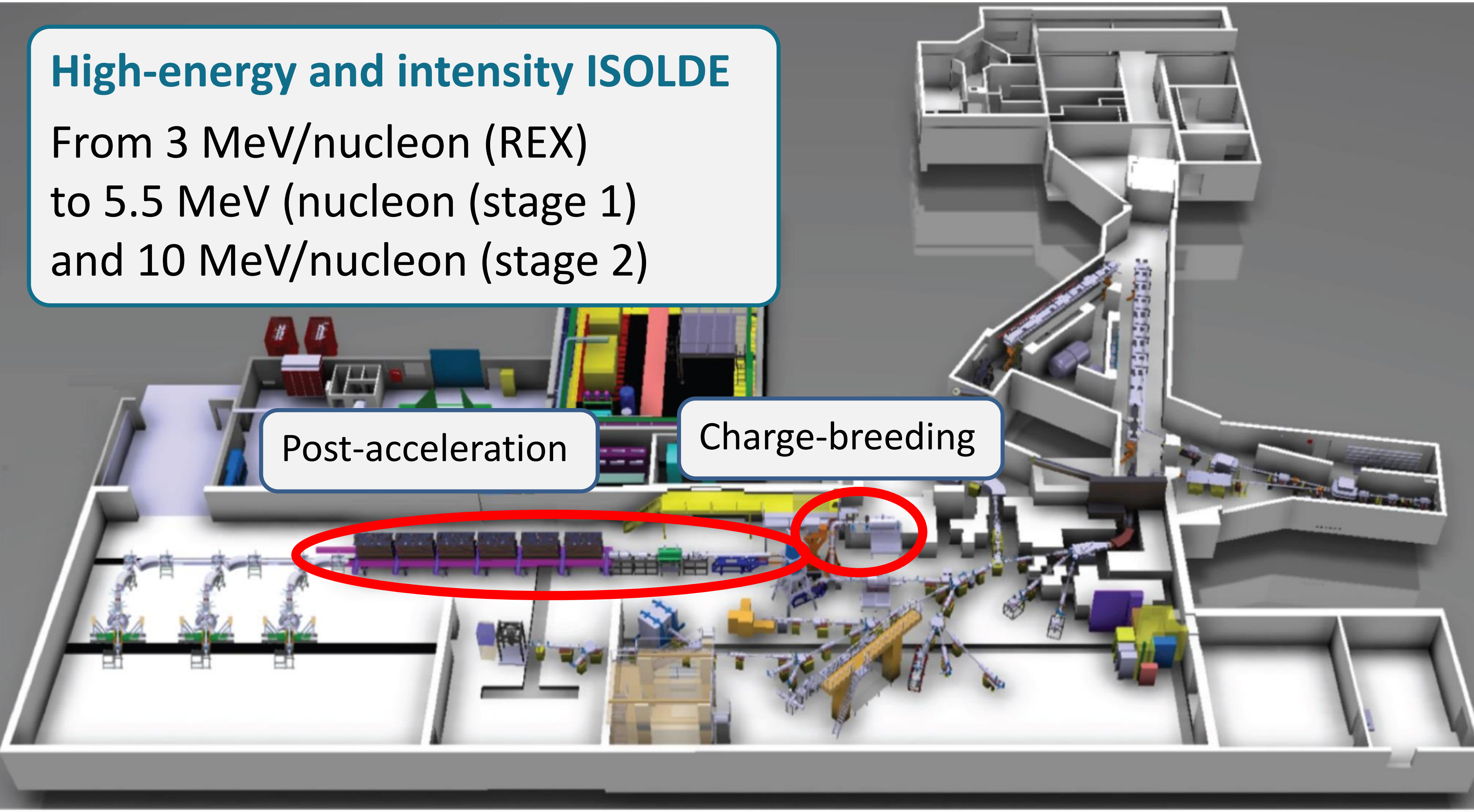
ISOL: Post-acceleration

Cyclotron Research Centre at Louvain-la-Neuve, Belgium

- 2 coupled cyclotrons
- Light beams from He to Ne



Other ISOL + post-acceleration: HIE-ISOLDE



High-energy and intensity ISOLDE

From 3 MeV/nucleon (REX)
to 5.5 MeV (nucleon (stage 1)
and 10 MeV/nucleon (stage 2)

Other ISOL facilities

TRIUMF at Vancouver, Canada

- Primary beam: protons 500 MeV
  New: electrons, γ-induced fission
- Post-acceleration: LINAC, 10 MeV/A

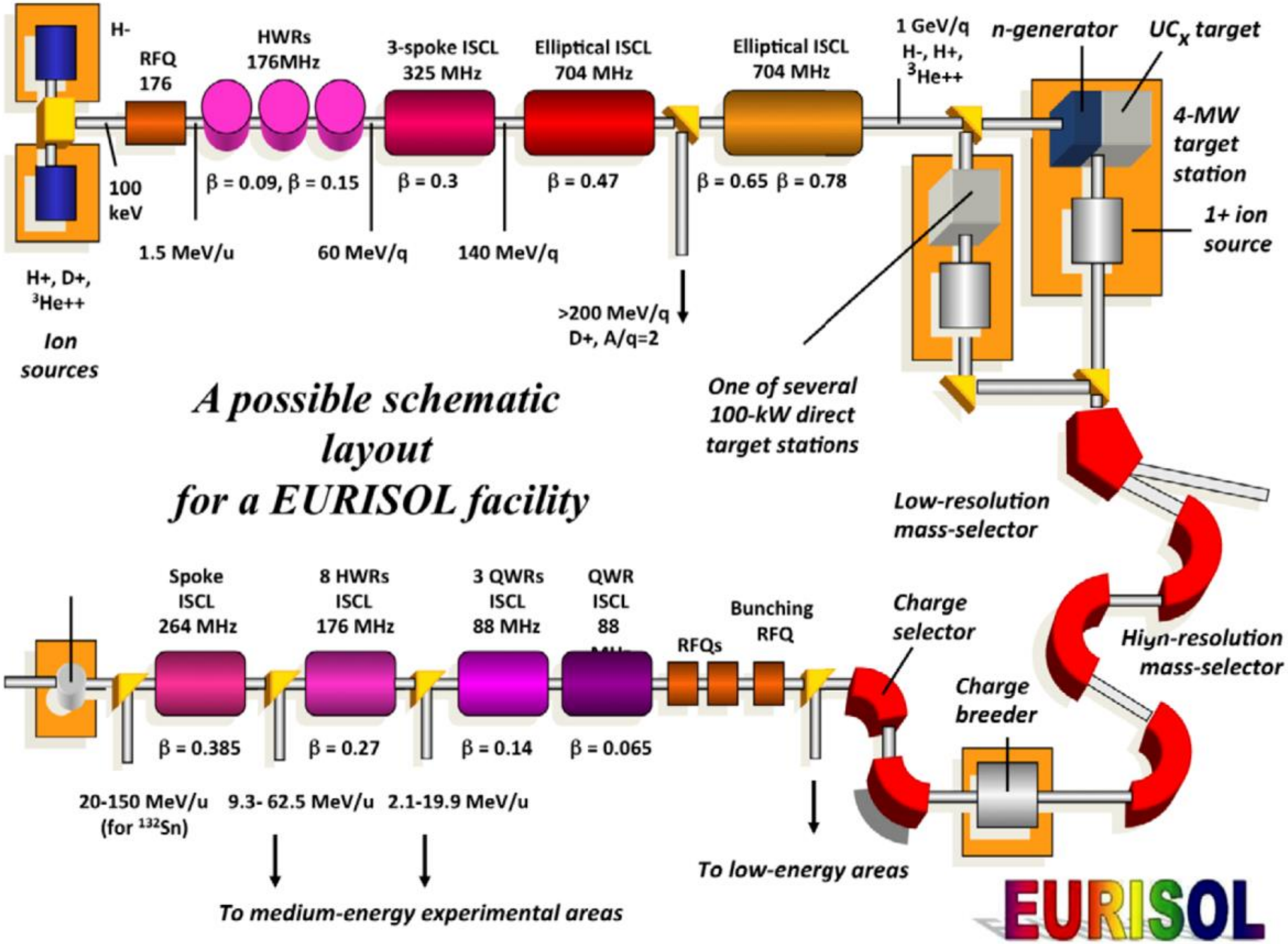
SPIRAL at GANIL

- GANIL beams on carbon target
  → light beams
- Post –acceleration: cyclotron, 10 to 30 MeV/A

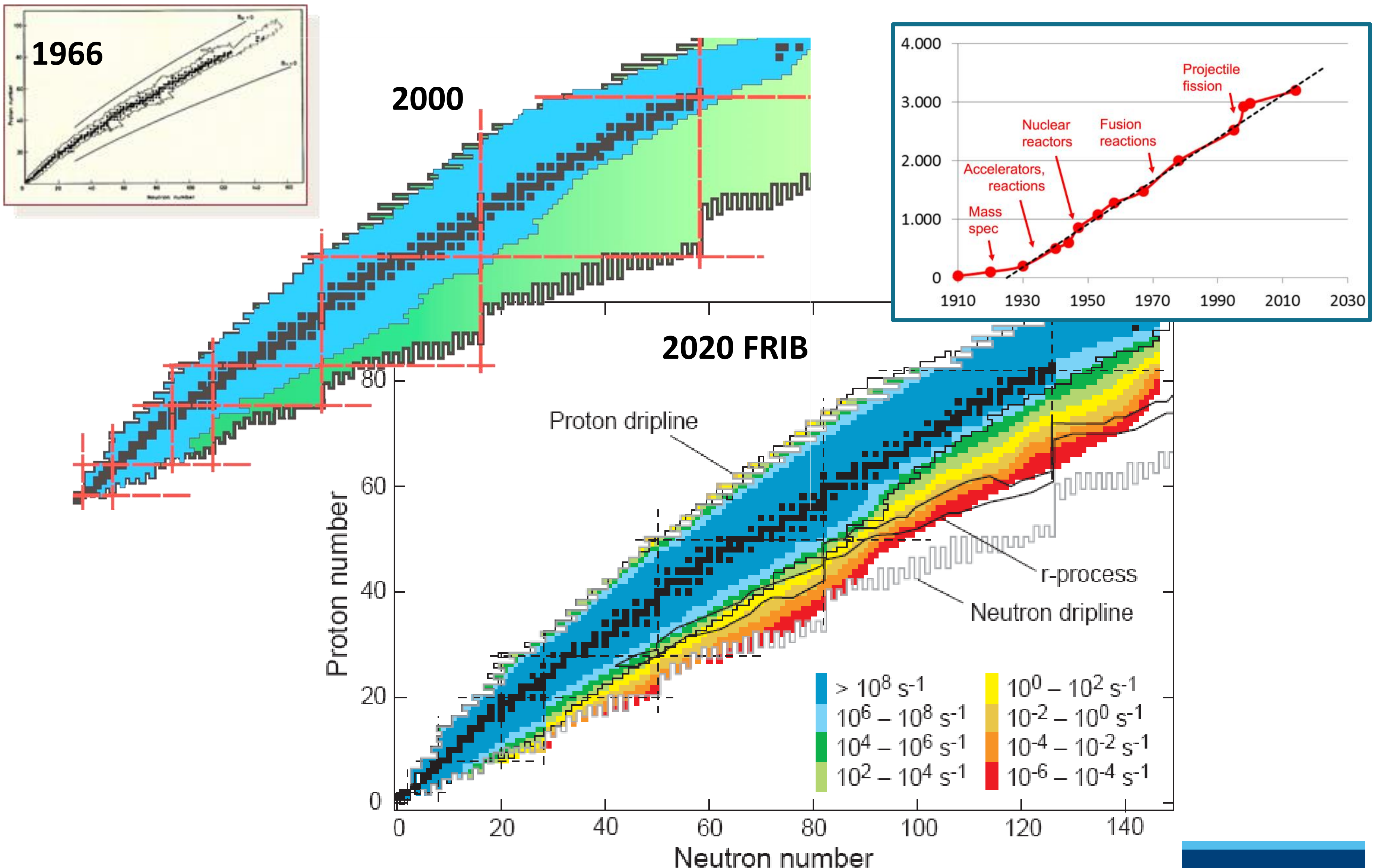
Future

- SPES at Legnaro:
  p 60 MeV, fission target, +LINAC
- SPIRAL2: LINAC injector, fission, +cyclotron

Ultimate goal: EURISOL



Progress in isotope production



Detection of radiation

Principle of detection:

"transfer of all or a part of the radiation energy to the detector mass"

- General characteristics
- Ionization chambers
- Scintillators
- Semiconductors
- Magnetic analysers

- G.F. Knoll
  Radiation Detection and Measurement
  John Wiley & Sons, 2000
- W.R. Leo
  Techniques for Nuclear and Particle Physics Experiments
  Springer-Verlag, 1987

Mechanisms to detect radiation

Main mechanism:

atomic excitations and ionizations

- Charged particles:
  - inelastic collisions with atomic electrons
  (+ bremsstrahlung for electrons and positrons)
  statistical, formulas for dE/dx
- Photons: small cross sections
  - photoelectric effect (absorption)
  - Compton scattering
  - pair production
- Neutrons:
  capture (slow neutrons)
  elastic scattering (fast neutrons)
  reactions

Characteristics of detectors

Sensitivity

- Which radiation and which energy range

Response Function

- Recorded energy vs. incident energy

Resolution

- Depend on the number of elementary charges created by the radiation

Efficiency

- Intrinsic and geometrical

Timing properties

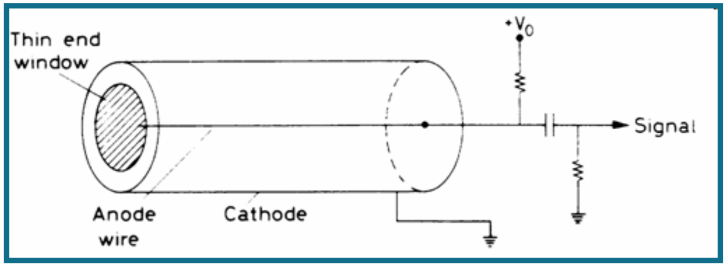
- Response time and dead time

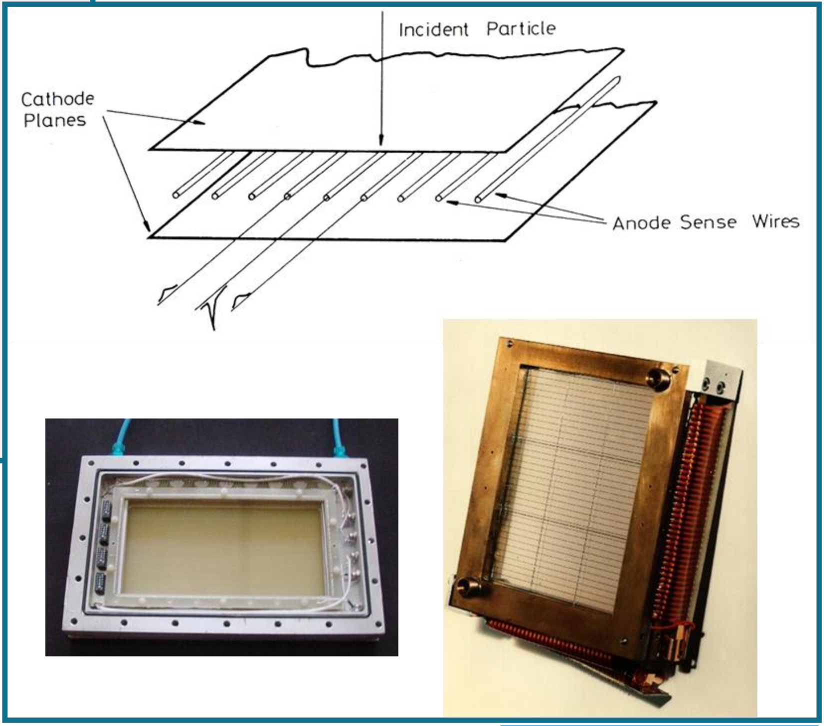
Type of detectors – 1

Ionisation detectors (gases)

Electric field between a cathode (plate) and an anode (wire)

- Very versatile (different geometries)
- Used for charged particles;
  position information
  E_{loss} for particle identification
- Efficient but slow
  (count rate < 10^4 pps)





Type of detectors – 2

Scintillation detectors

Materials that emit light when struck by radiation
Light is collected and amplified

- Cheap, very fast, versatile
  different geometries
  different materials
- Used for
  charged particles (low *Z* material)
  γ-rays (high *Z*)
  neutrons (proton recoil or capture)
- Allow discrimination between radiation
- Poor energy resolution

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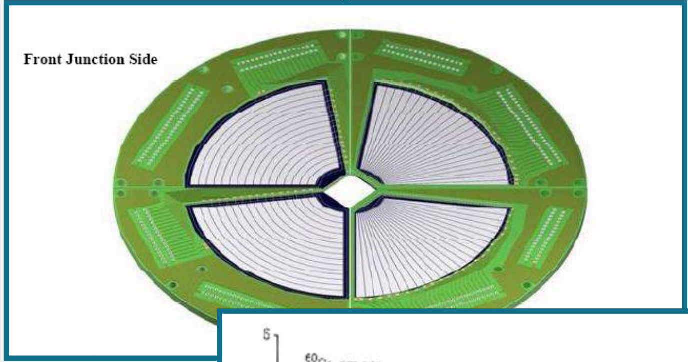
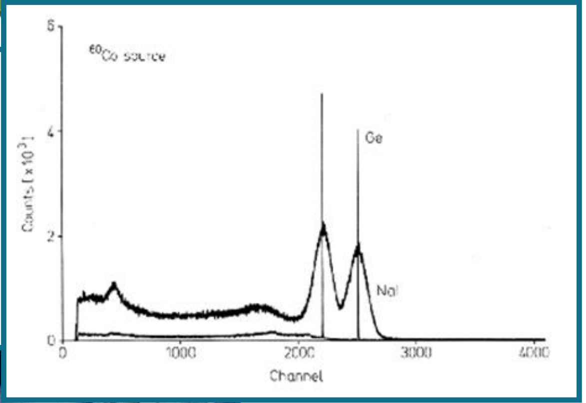
Type of detectors – 3

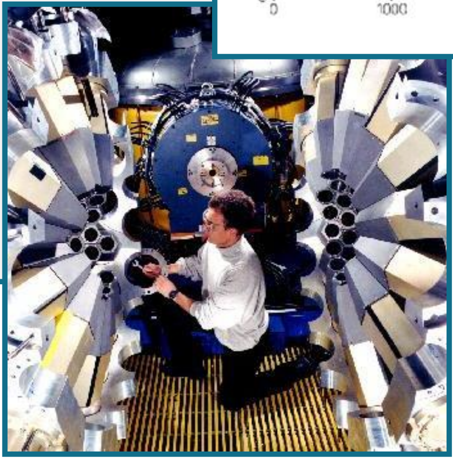
Semiconductor detectors

Incident radiation creates electron-hole pairs

- Large stopping power
- Very good resolution
  Used to measure energy spectra
- Good timing resolution (ns)
- Si for charged particles (res 30 keV)
  Ge for γ-rays (res 2 keV)
- Expensive, subjected to damage
  Germanium needs to be cooled







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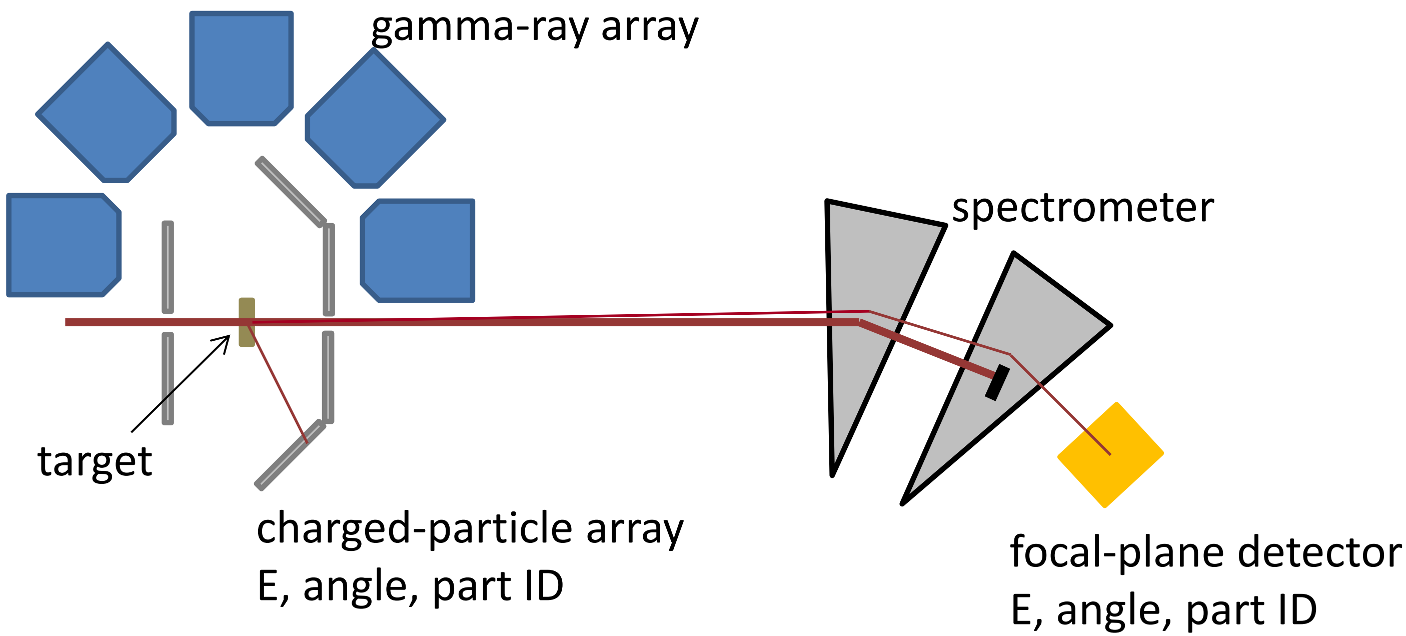
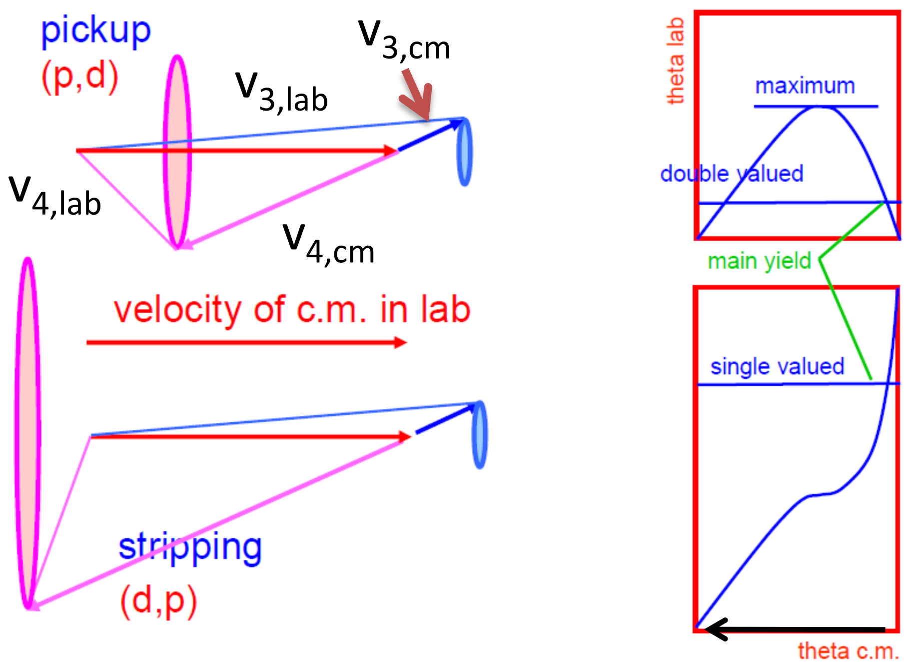
Reactions: detection setup when using RIBs

Keys:
- Efficiency
- Energy and position resolution
- Sensitivity (background suppression)



Reactions with RIBs: inverse kinematics

Light (ejectile) recoil



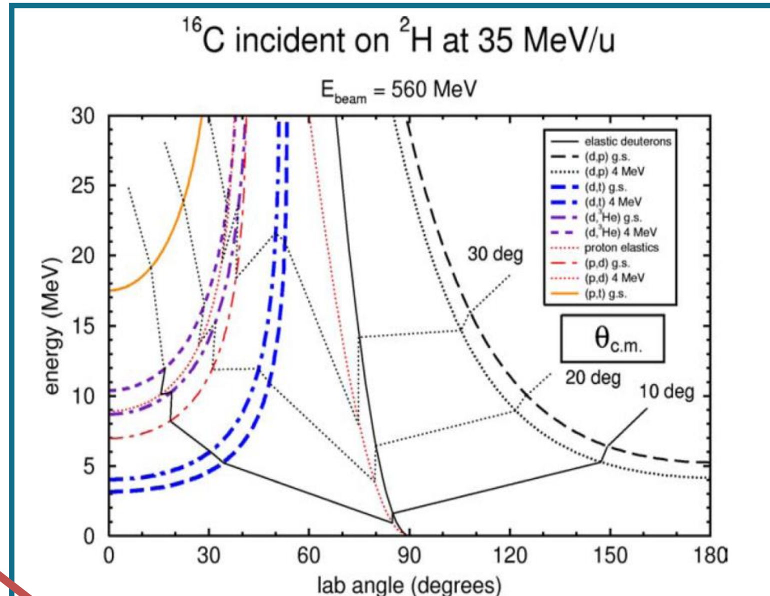
$m_{recoil} > m_{target}$

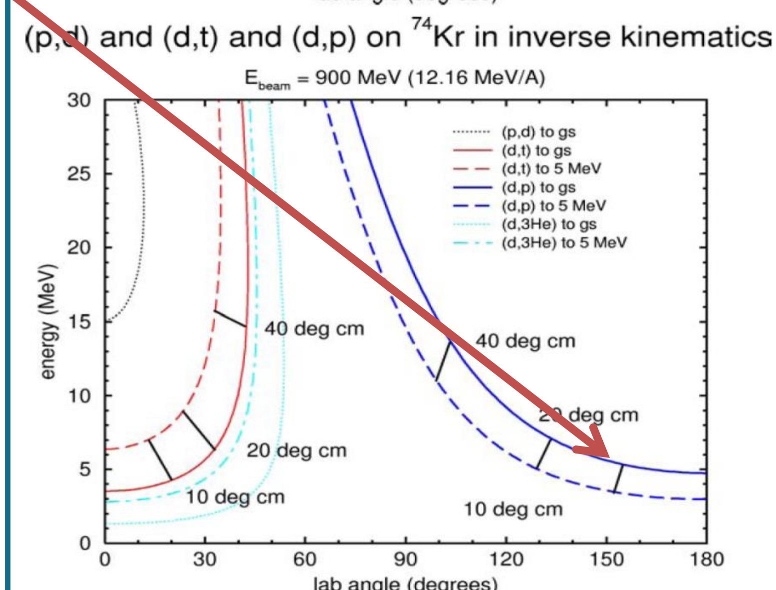
$m_{recoil} < m_{target}$

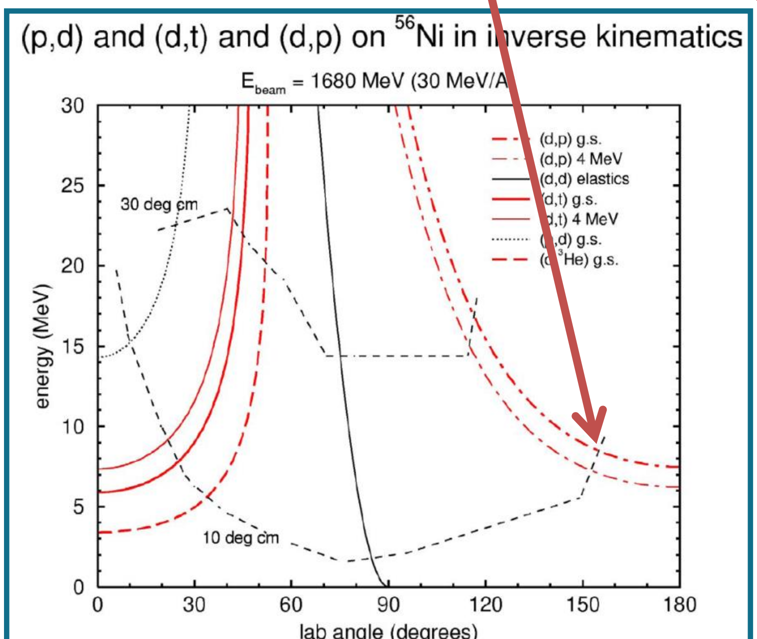
Reactions with RIBs: inverse kinematics

Light particles

- Kinematics depends mainly on the masses
- Kinematic compression: very small differences in energy of the light particle for different E*







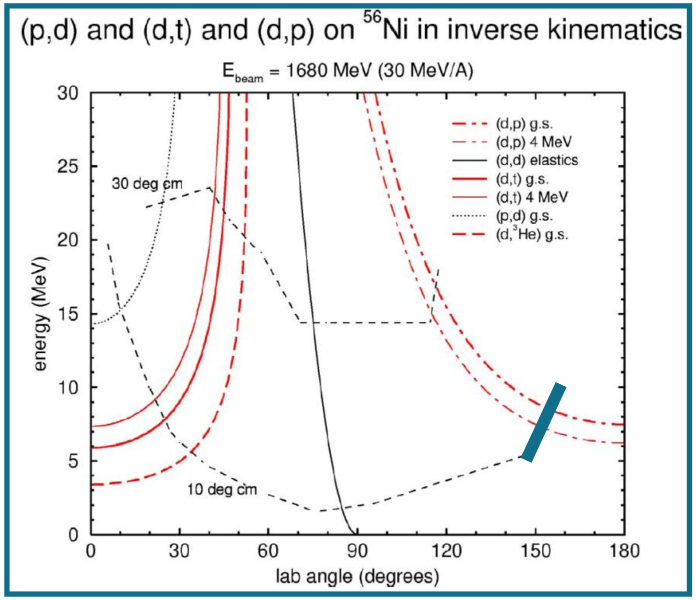
Reactions with RIBs: inverse kinematics

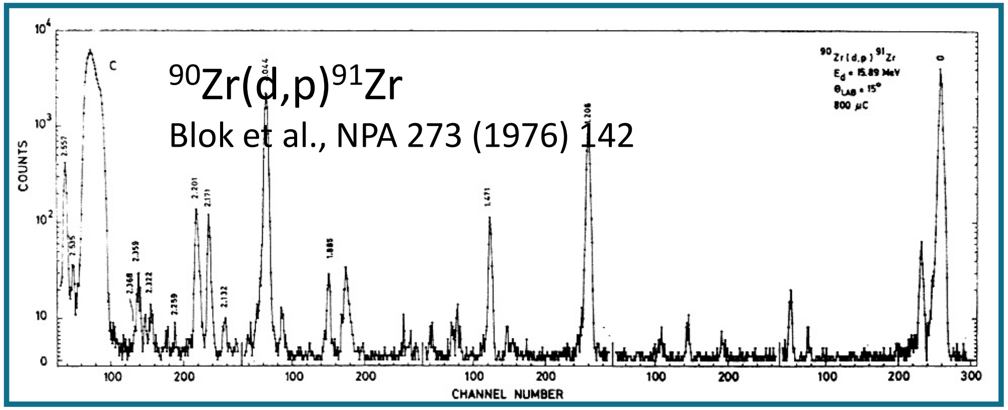
Problems

- Low beam intensity
  → increase target thickness

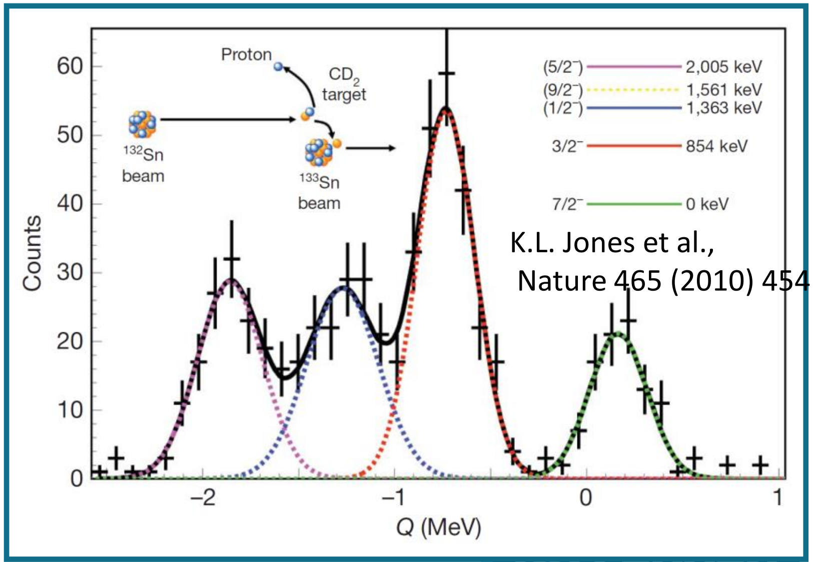
BUT

- Energy resolution is affected
- Kinematic compression:
  very small differences in energy of the light particle for different E*





^{90}Zr(d,p)^{91}Zr
Blok et al., NPA 273 (1976) 142



K.L. Jones et al., Nature 465 (2010) 454

Reactions with RIBs: inverse kinematics

Resolution in E*

- Light beam: better detect beam-like particle (limit on angular resolution)
- Heavier beam: better detect light recoil (limit on E resolution from straggling in the target)
- In general: much worse than direct kinematics

152 J.S. Winfield et al. / Nucl. Instr. and Meth. in Phys. Res. A 396 (1997) 147–164

Table 2

Major contributions in keV to the resolution of the excitation energy spectra of single neutron stripping and pickup reactions in inverse kinematics, where the heavy ion is detected in a spectrometer. The detection angle corresponds to $10^{\circ}_{\rm cm}$. The last column is an approximate estimate as a sum in quadrature of the net effect of five non-Gaussian contributions. Other symbols are explained in the text

Reaction	E_i/A (MeV)	$\theta_{\rm lab}$	Origin of contribution					$\Sigma_{\rm quad}$
			$\Delta\theta$	Δp	$E_{\rm stragg}$	$\Theta_{1/2}$	dE/dx	
p(^{12}Be, ^{11}Be)d	30	1.07°	172	147	101	74	23	259
p(^{12}Be, ^{11}Be)d	15	1.06°	84	71	99	74	37	169
p(^{77}Kr, ^{76}Kr)d	30	0.16°	1404	811	808	723	56	1952
p(^{77}Kr, ^{76}Kr)d	10	0.10°	334	143	502	570	268	883
d(^{76}Kr, ^{77}Kr)p	10	0.21°	1140	614	2177	1859	1321	3408

Table 3

Major contributions in keV to the resolution of the excitation energy spectra of single neutron pickup and stripping reactions in inverse kinematics, where the light particle is detected in a silicon detector. Symbols as described in text and Table 2

Reaction	E_i/A (MeV)	$\theta_{\rm lab}$	Origin of contribution					$\Sigma_{\rm quad}$
			$\Delta\theta$	ΔE_f	ΔE_i	$\Theta_{1/2}$	dE/dx	
p(^{12}Be, d)^{11}Be	30	19.0°	136	74	114	96	649	685
p(^{12}Be, d)^{11}Be	15	17.8°	66	72	55	89	984	995
p(^{77}Kr, d)^{76}Kr	30	15.0°	124	55	64	63	186	249
p(^{77}Kr, d)^{76}Kr	10	6.0°	26	24	23	19	775	777
d(^{76}Kr, p)^{77}Kr	10	155.3°	52	93	37	60	1309	1316

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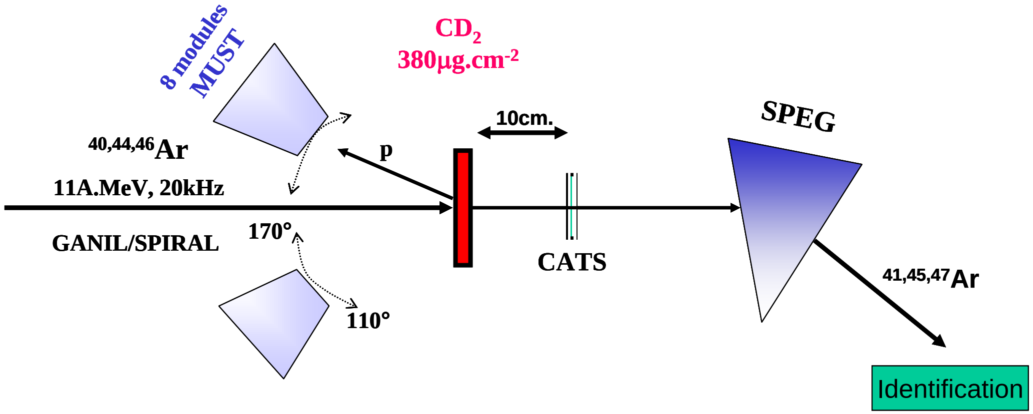
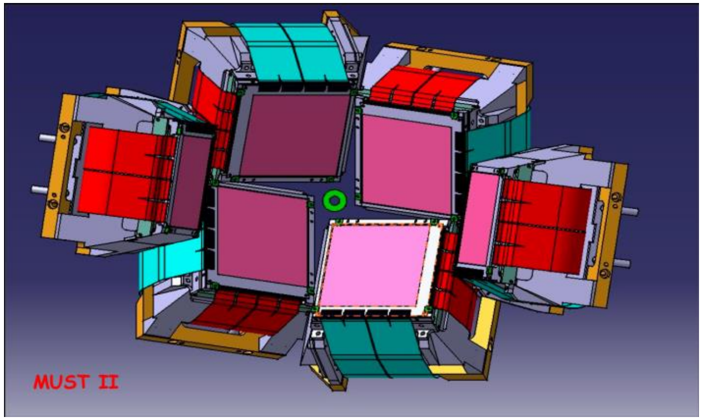
Examples of setups for reactions in inverse kinematics

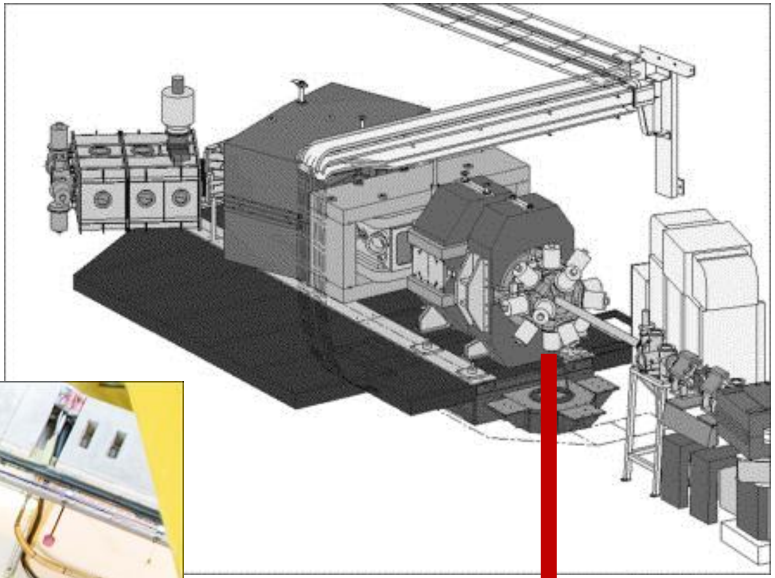
GANIL: MUST2+SPEG

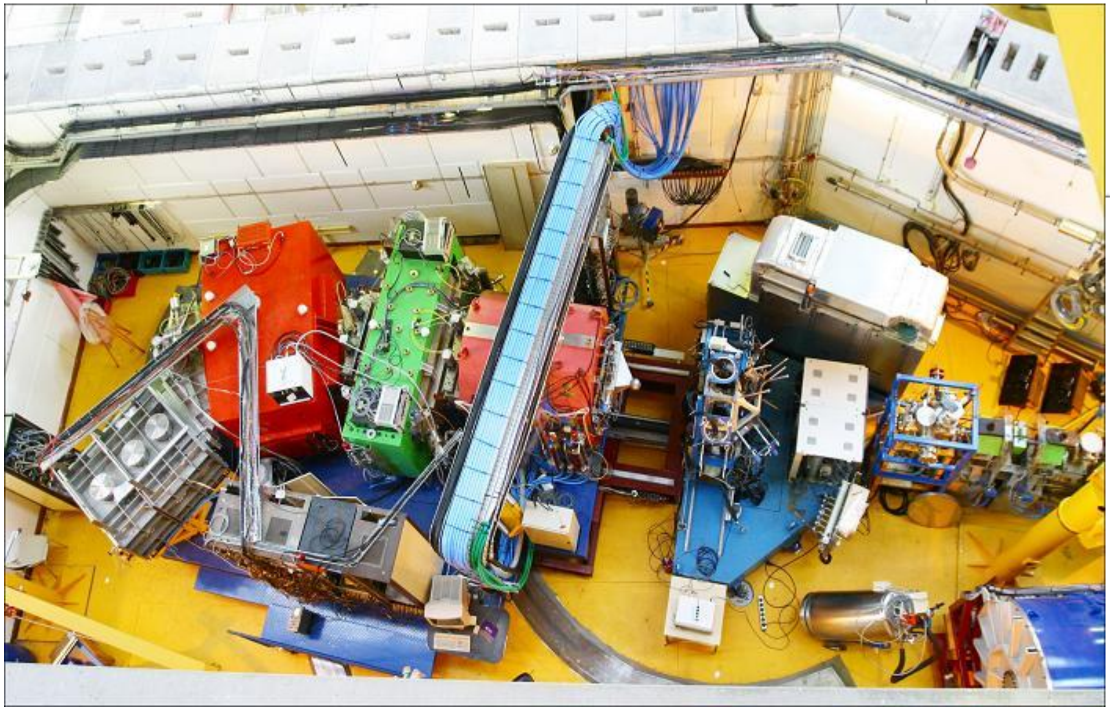


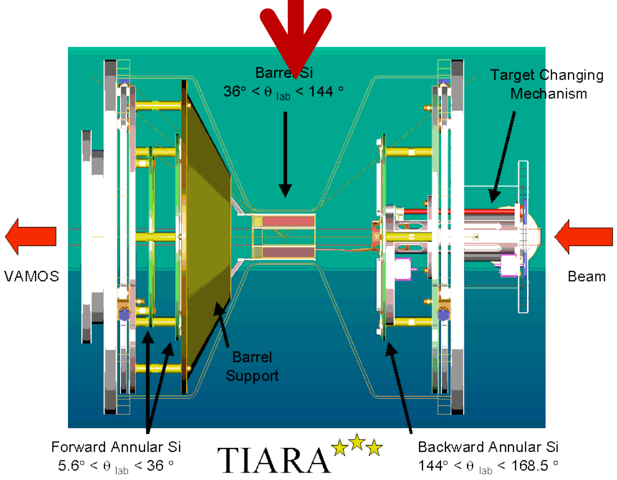


Examples of setups for reactions in inverse kinematics

GANIL: TIARA+VAMOS+EXOGAM







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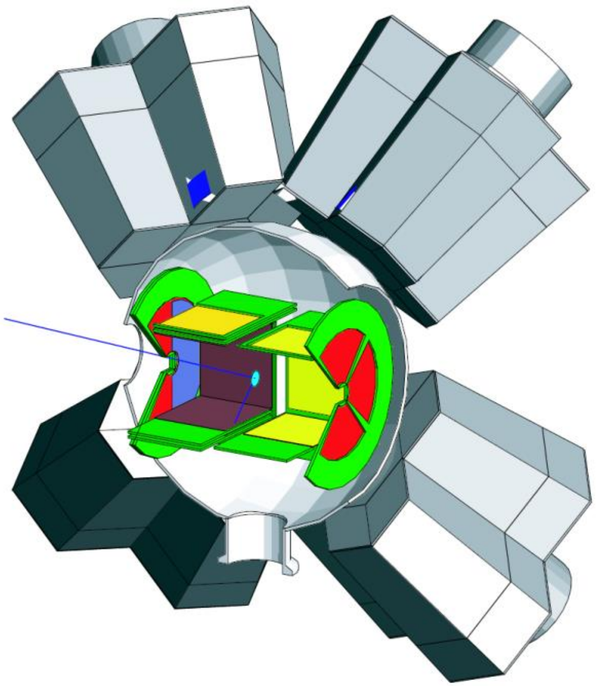
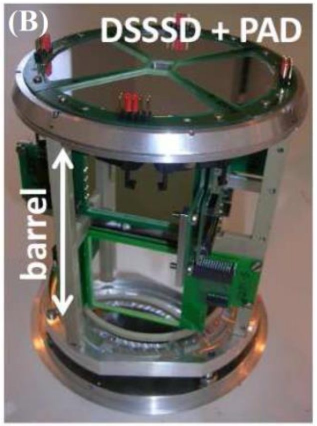
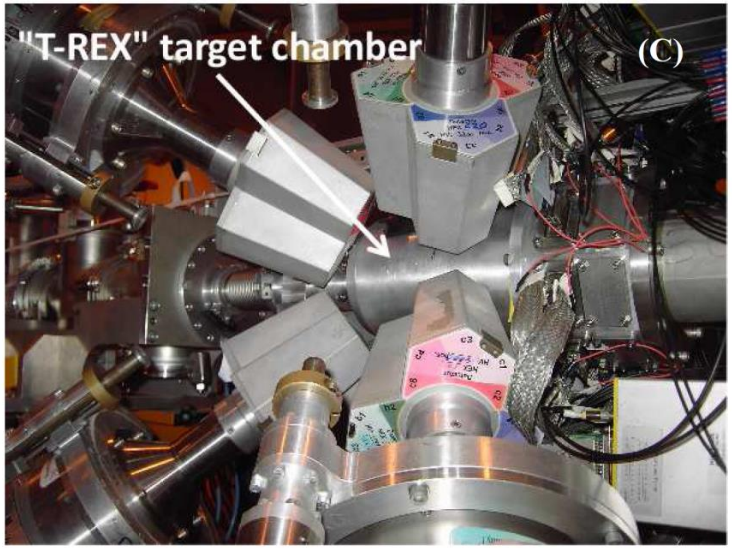
Examples of setups for reactions in inverse kinematics

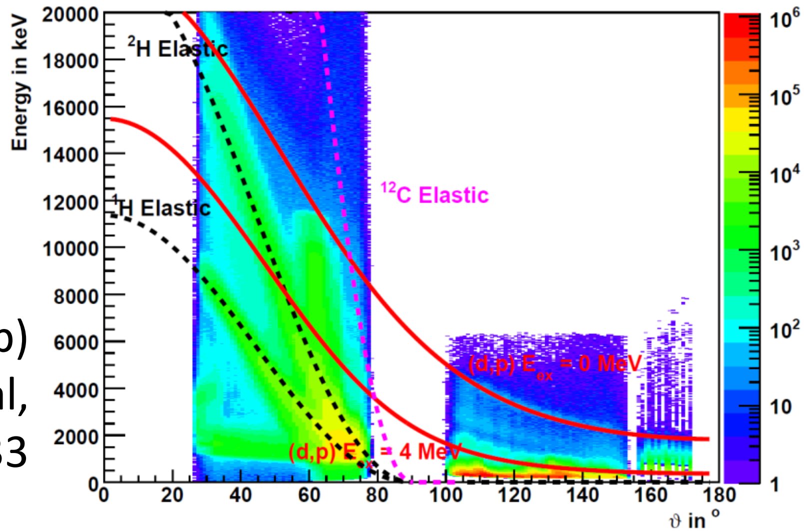
ISOLDE: T-REX+MINIBALL



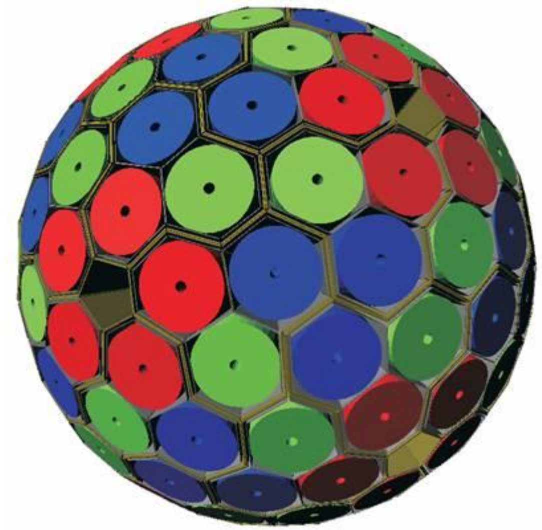




^{66}Ni(d,p)
Jan Diriken et al,
PLB 736 (2014) 533

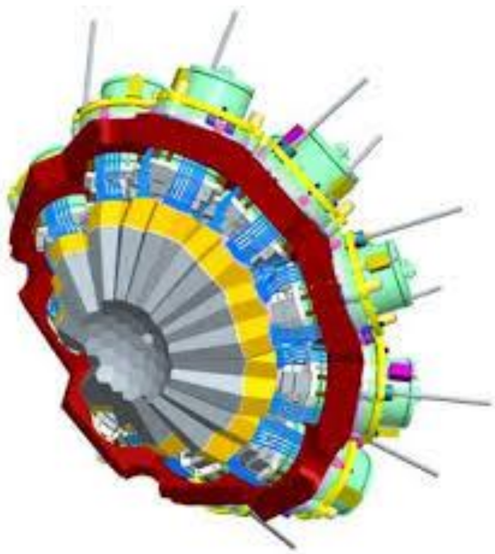


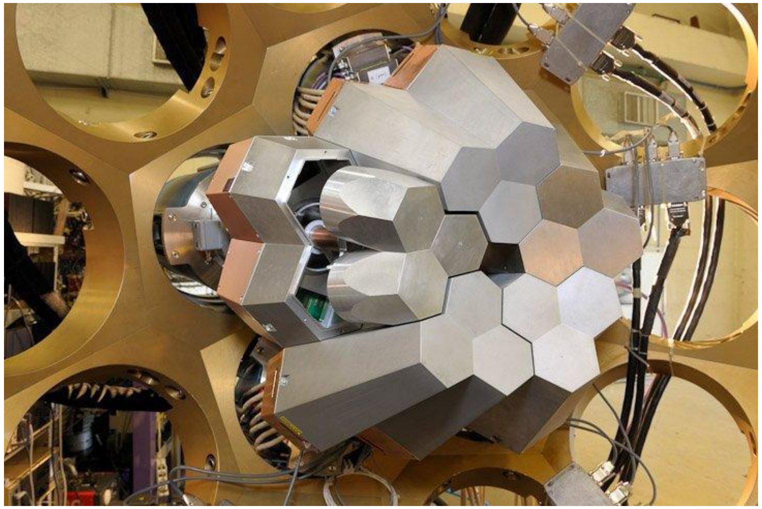
The present and future: γ-ray detection



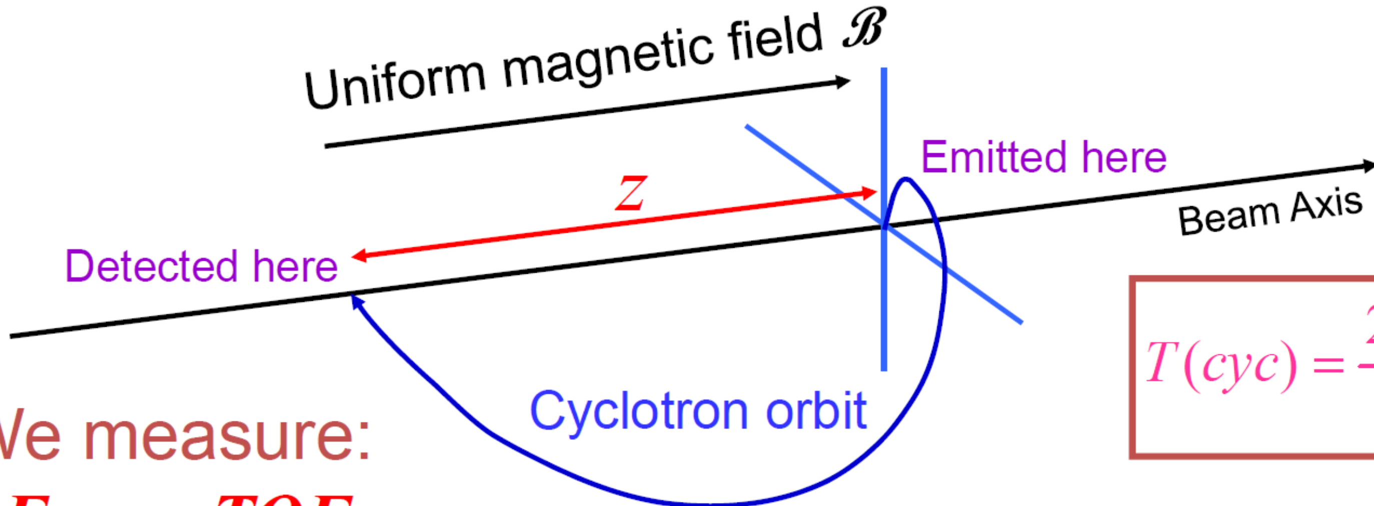
AGATA and GRETA

- Segmented Ge detectors
- Digital readout
- Tracking





Dealing with kinematic compression: HELIOS



$$T(cyc) = \frac{2\pi m}{qB}$$

We measure:

E_{lab}, z, TOF

We deduce:

E_{CM}, θ_{CM}

$$z \propto \cos\theta_{CM}$$

$$E_{lab} = E_{CM} - A + Bz$$

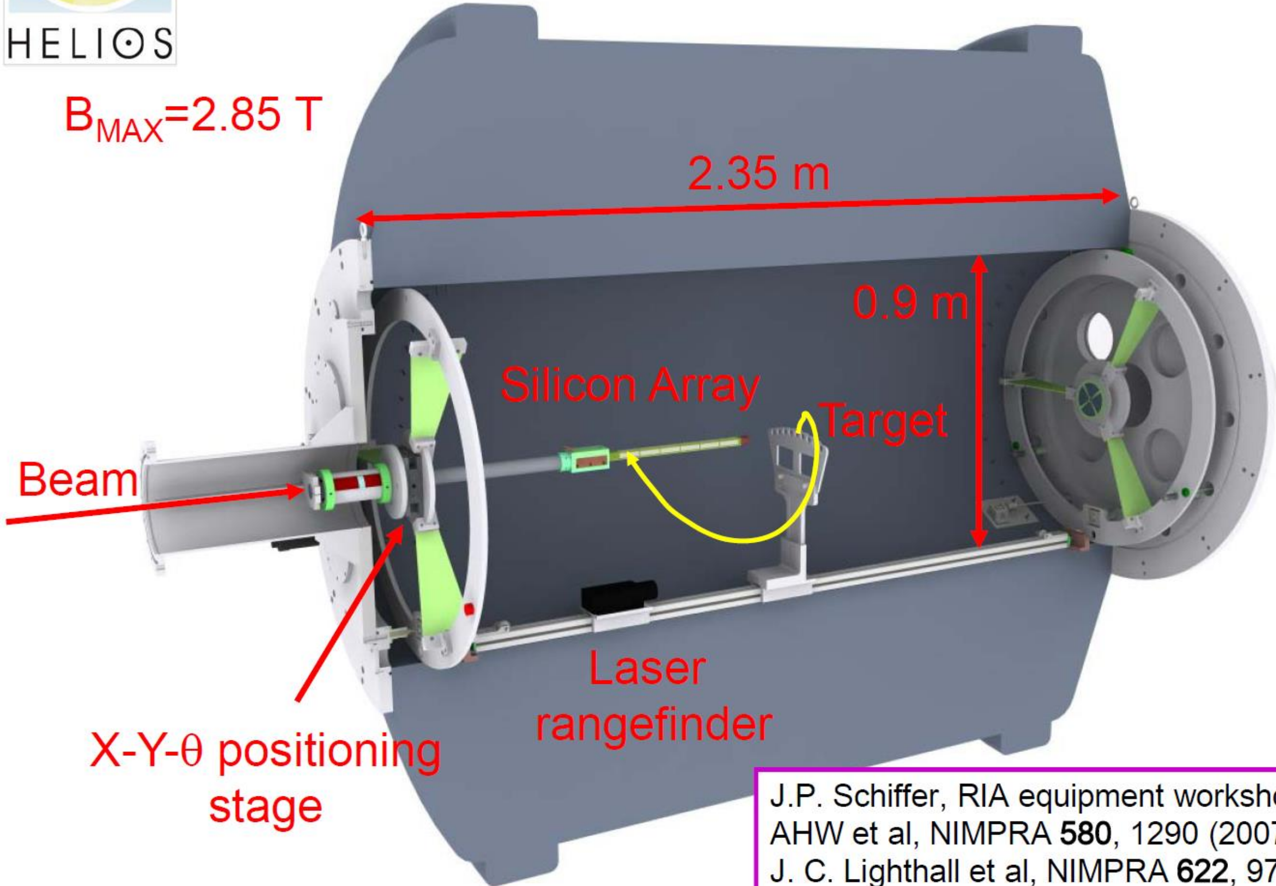
$$\Delta E_{lab} = \Delta E_{CM}$$

For a given state

For two states at fixed z

Dealing with kinematic compression: HELIOS

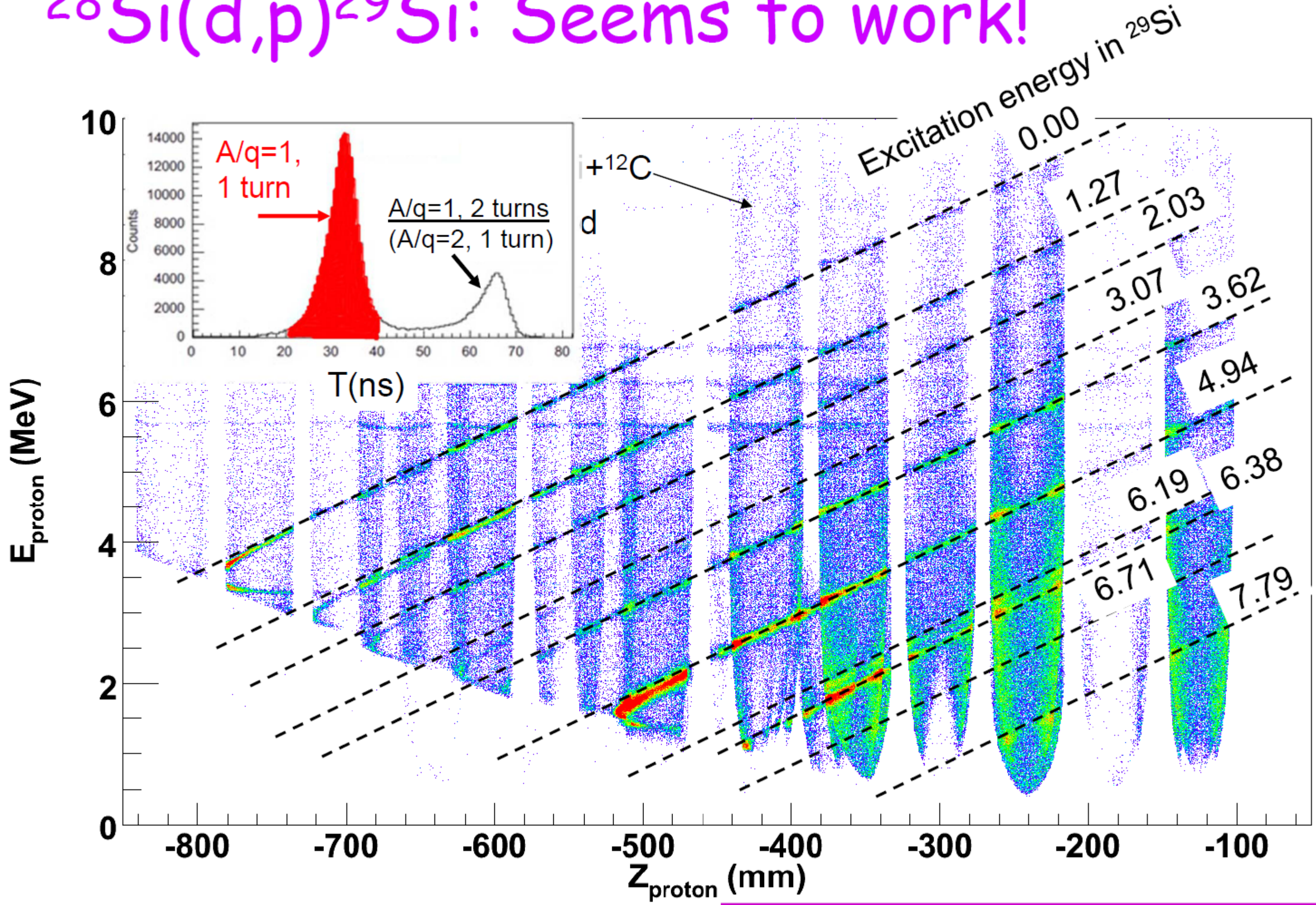
HELIcal Orbit Spectrometer -HELIOS



J.P. Schiffer, RIA equipment workshop 1999,
AHW et al, NIMPRA **580**, 1290 (2007)
J. C. Lighthall et al, NIMPRA **622**, 97 (2010)

Dealing with kinematic compression: HELIOS

^{28}Si(d,p)^{29}Si: Seems to work!

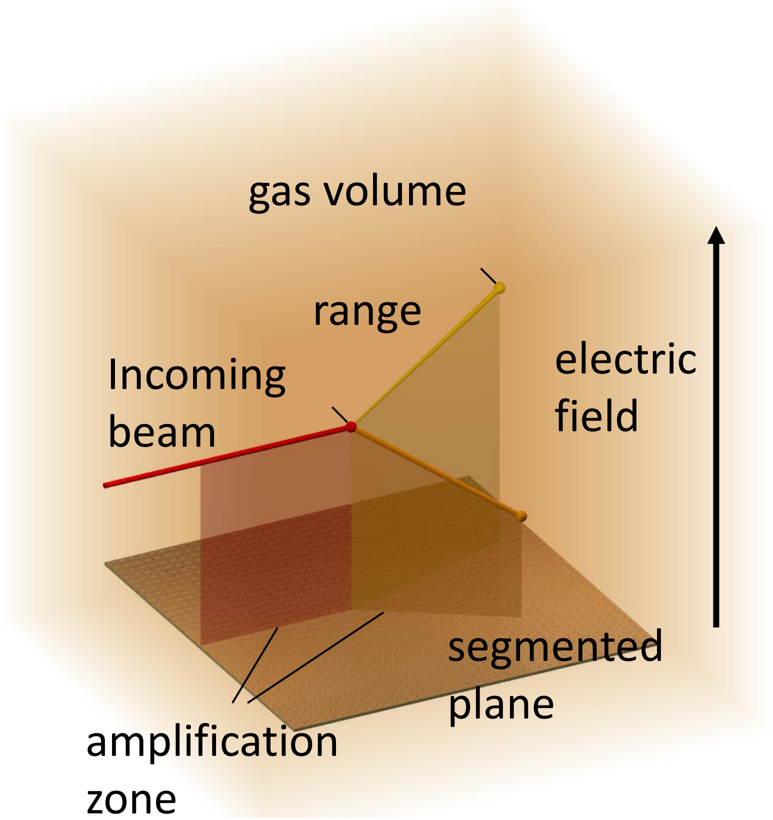


J. C. Lighthall et al, NIMPRA **622**, 97 (2010)

Charged particle detection in an active target

Time-Projection Chamber (TPC)
+ gas is the target

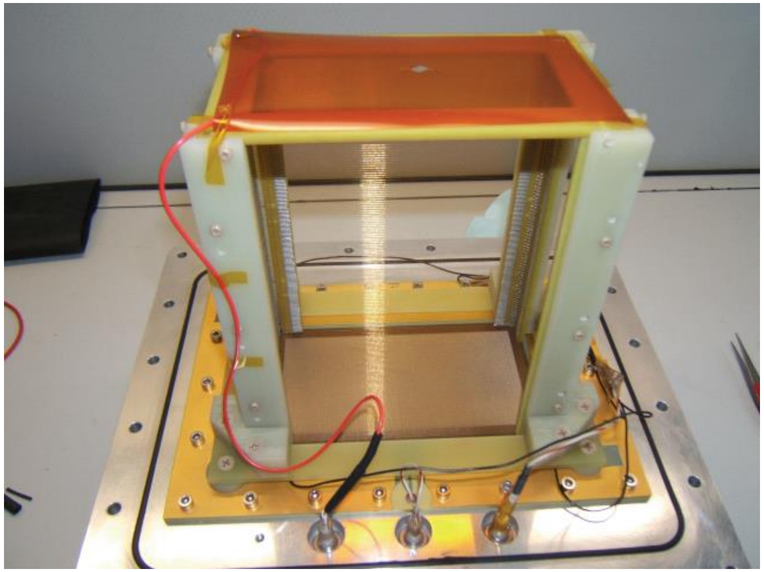
- Electrons produced by ionization drift to an amplification zone
- Signals collected on a segmented "pad" plane ⇒ 2d-image of the track
- 3rd dimension from the drift time of the electrons
- Information:
  - angles
  - energy (from range or charge)
  - particle identification

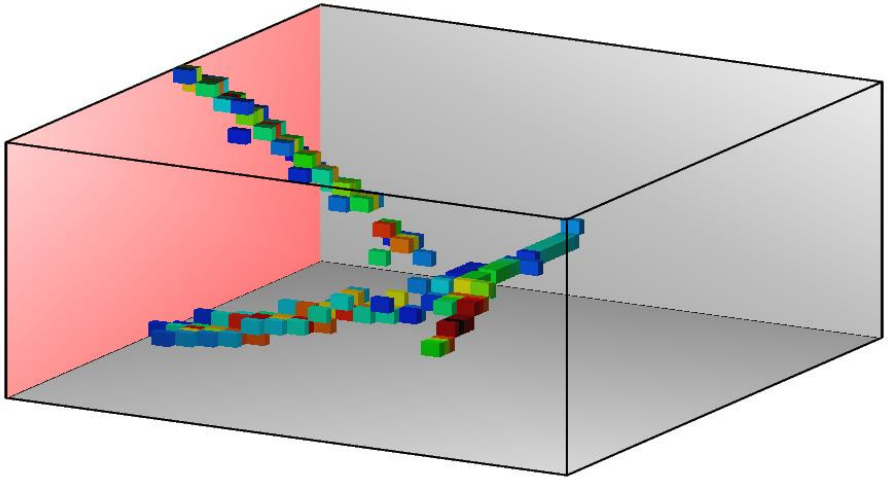


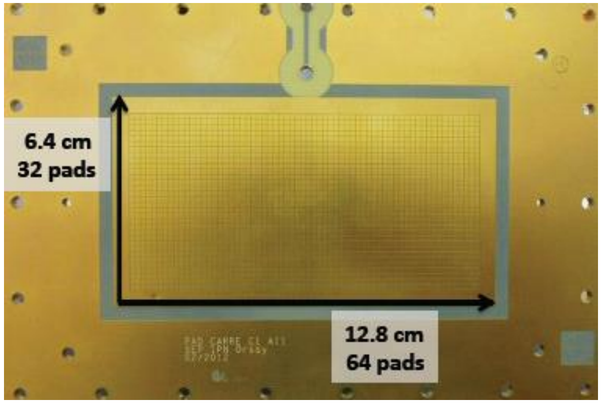
- Efficient
- Versatile

Charged particle detection in an active target

ACTAR TPC Demonstrator







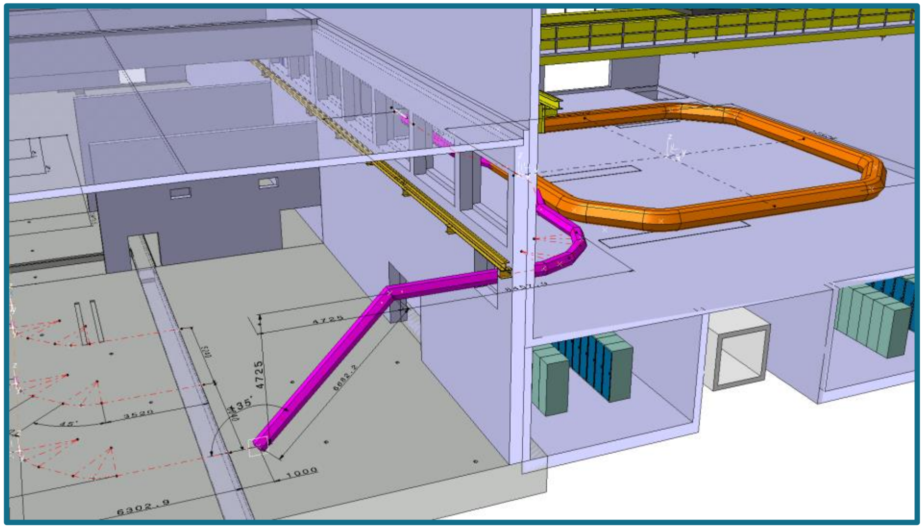
A Storage Ring for nuclear reactions

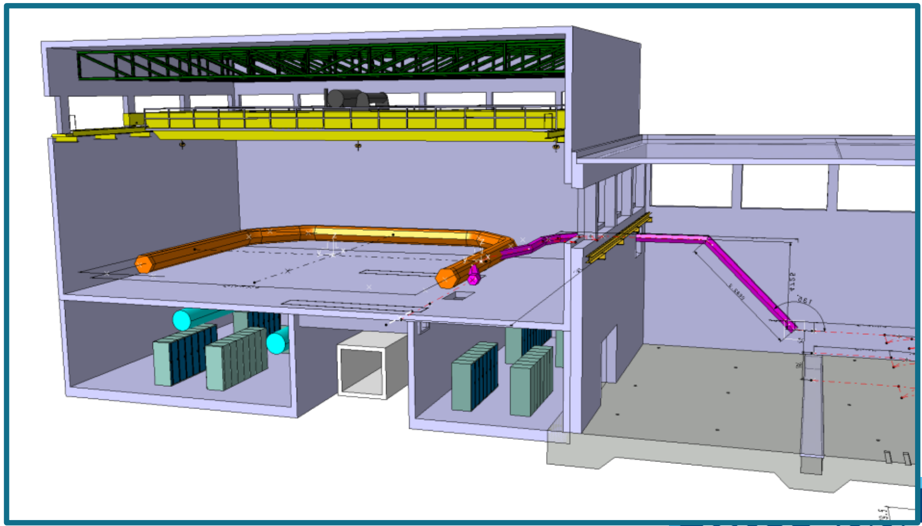
K. Blaum and many others

TSR@ISOLDE

Physics programme

- Astrophysics
  Capture, transfer reactions
  ^{7}Be half life
- Atomic physics
  Effects on half lives
  Di-electronic recombination
- Nuclear physics
  Reaction studies
  Isomeric states
  Decay of halo states
  Laser spectroscopy
- Neutrino physics





Aims of the lecture

- Give a flavour of present-day research with RIBs:
  Still active? Clear direction?
- Learn (through examples) about the main techniques for production, manipulation and detection of unstable isotopes

- **Succeeded?**
- **Comments?**