Making radioactive ion beams
Detecting reaction products

Riccardo Raabe
KU Leuven, Instituut voor Kern- en Stralingsfysica

Rewriting Nuclear Physics textbooks
30 years with Radioactive Ion Beam Physics
Pisa (Italy), July 20th – 24th, 2015

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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

Overview of the lecture.

Aims of the lecture

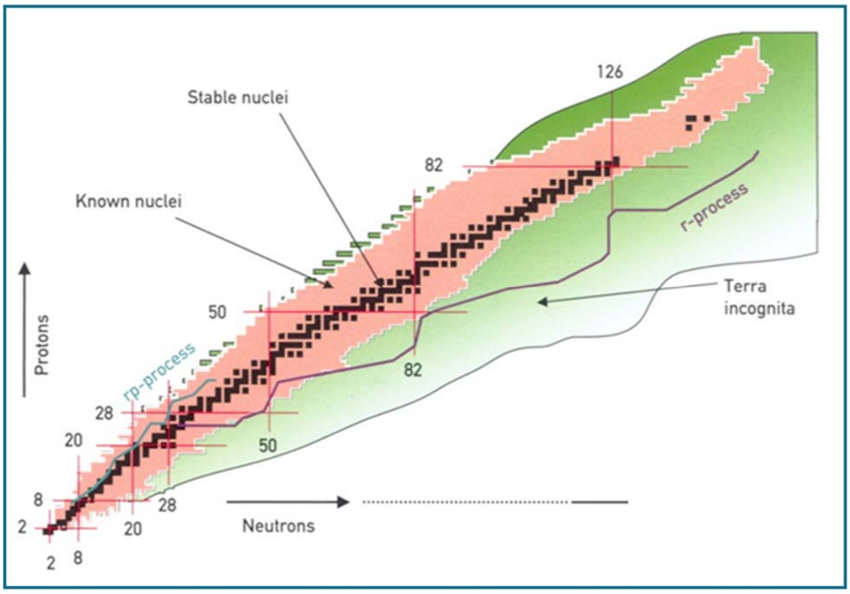
- Give a flavour of present-day research with RIBs:
  Still active? Clear direction?
- Learn (through examples) about the main techniques for production, manipulation and detection of unstable isotopes

- 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

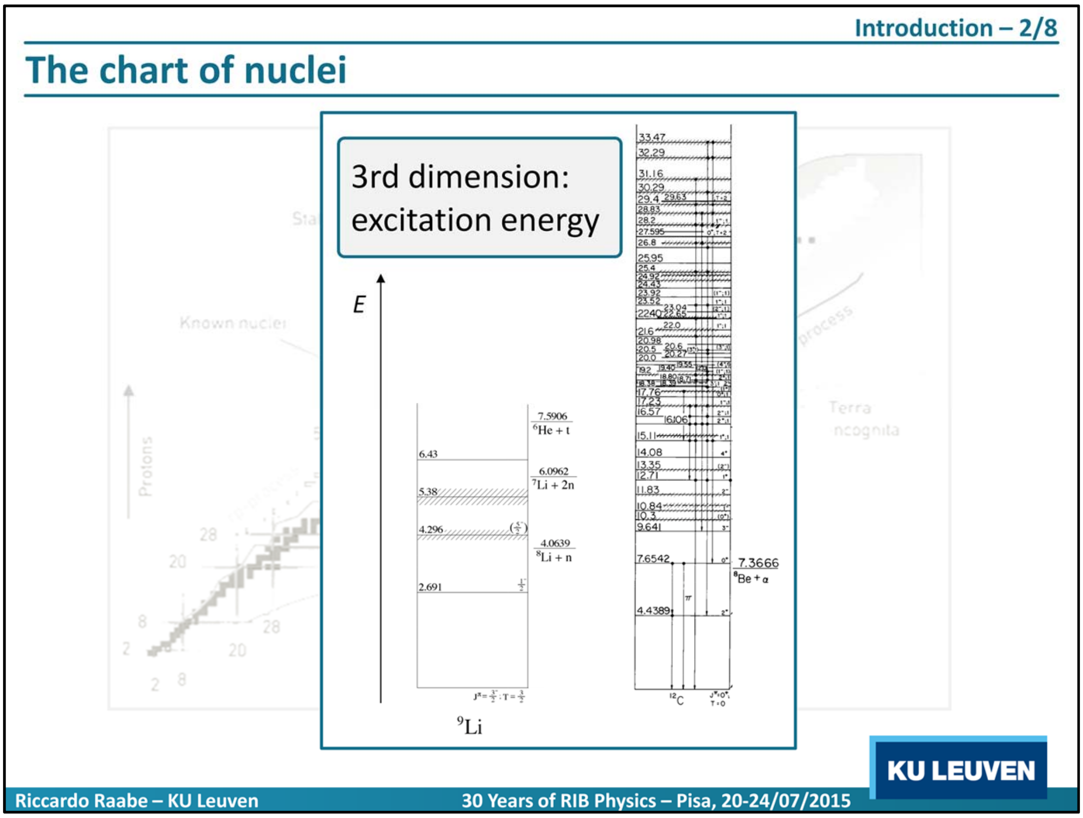
Aims of the lecture. And some tips.

The chart of nuclei



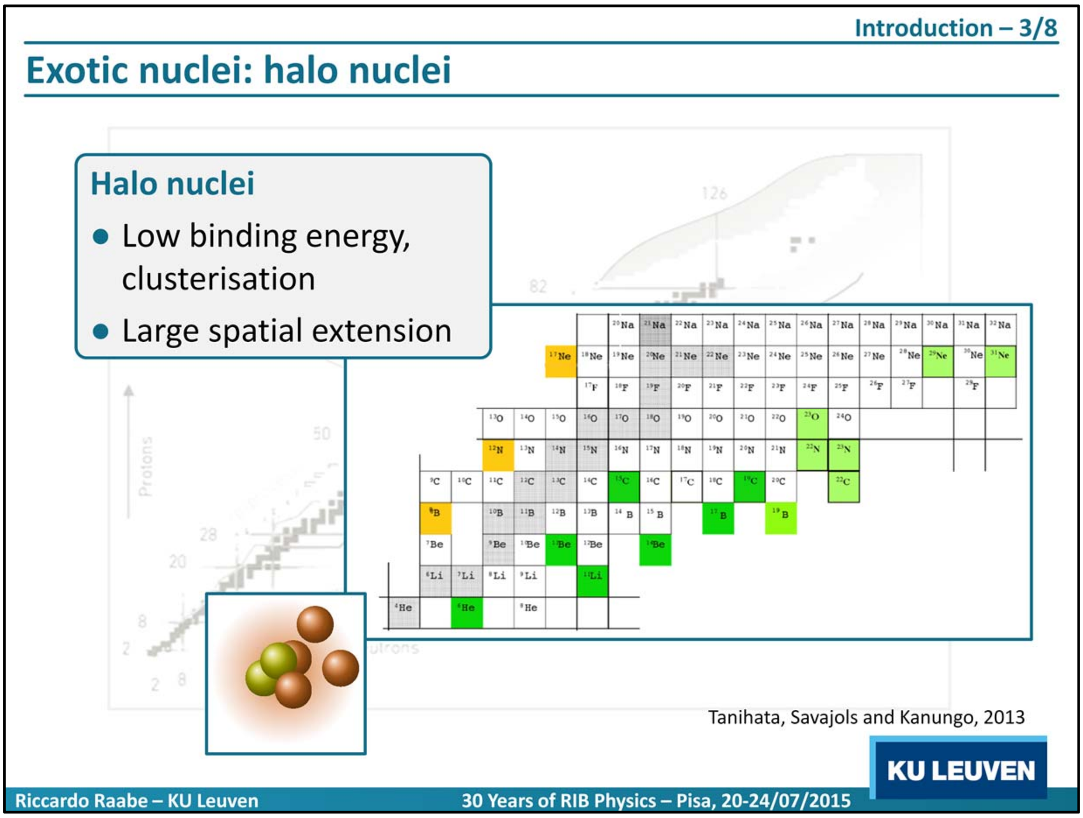
Get acquainted with the chart of nuclei: nuclei are displayed according to the number of protons and neutrons.

- Identify stable and unstable nuclei, known nuclei, drip lines, shell closures.
- Which nuclei are "exotic"? The definition is not unique. In any case, exotic does not mean unstable. Exotic nuclei have short lifetimes, peculiar structures.



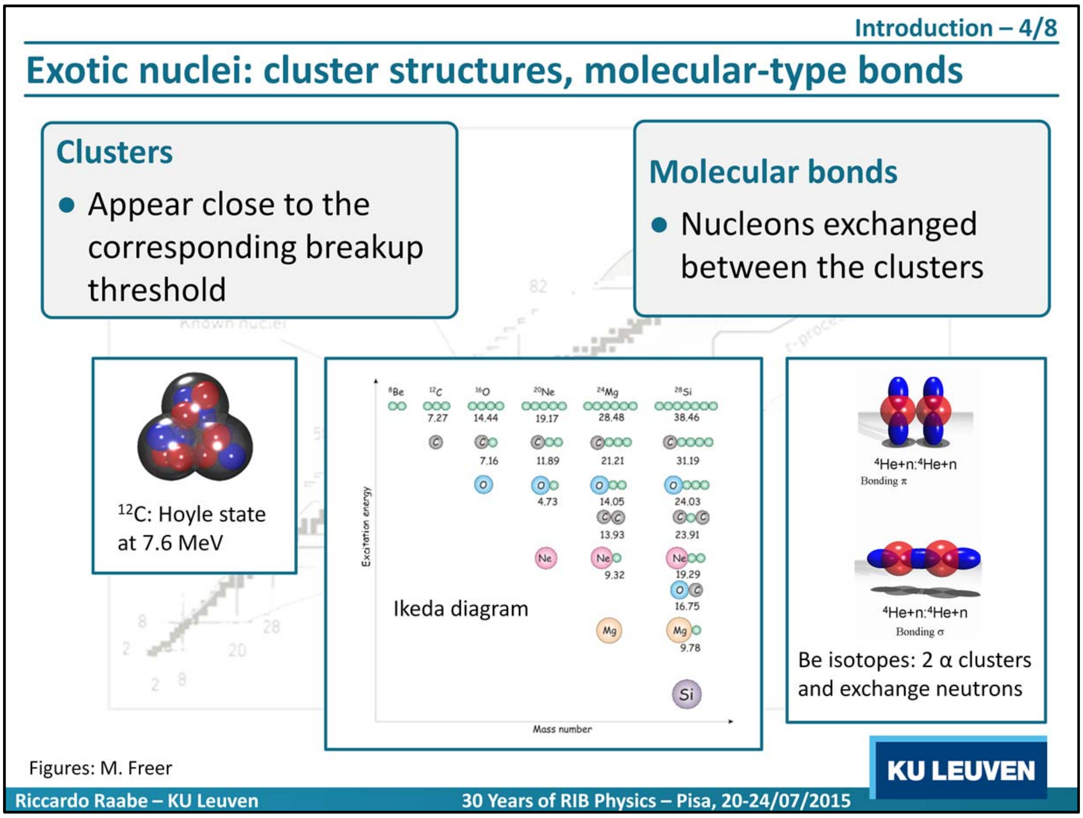
Third dimension: the excitation energy of each nucleus.
With this, we can find exotic structures in stable nuclei!

- Examples: 9Li (short-living, but not so exotic) and 12C (cluster structure of the Hoyle state).



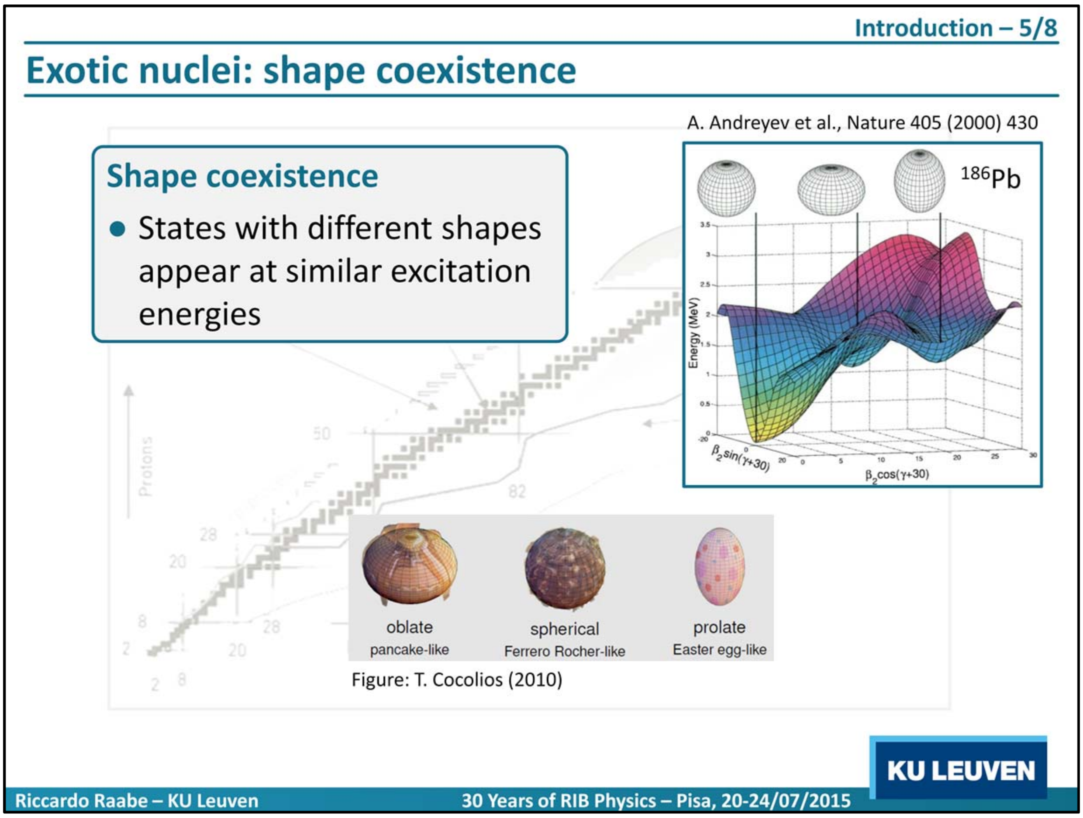
Examples of “exotic” features: halo nuclei.

- Threshold effect: combination of a small binding energy, a cluster structure and a low angular momentum.
- Experimental probes: large interaction cross section, narrow distribution of momenta of fragments.



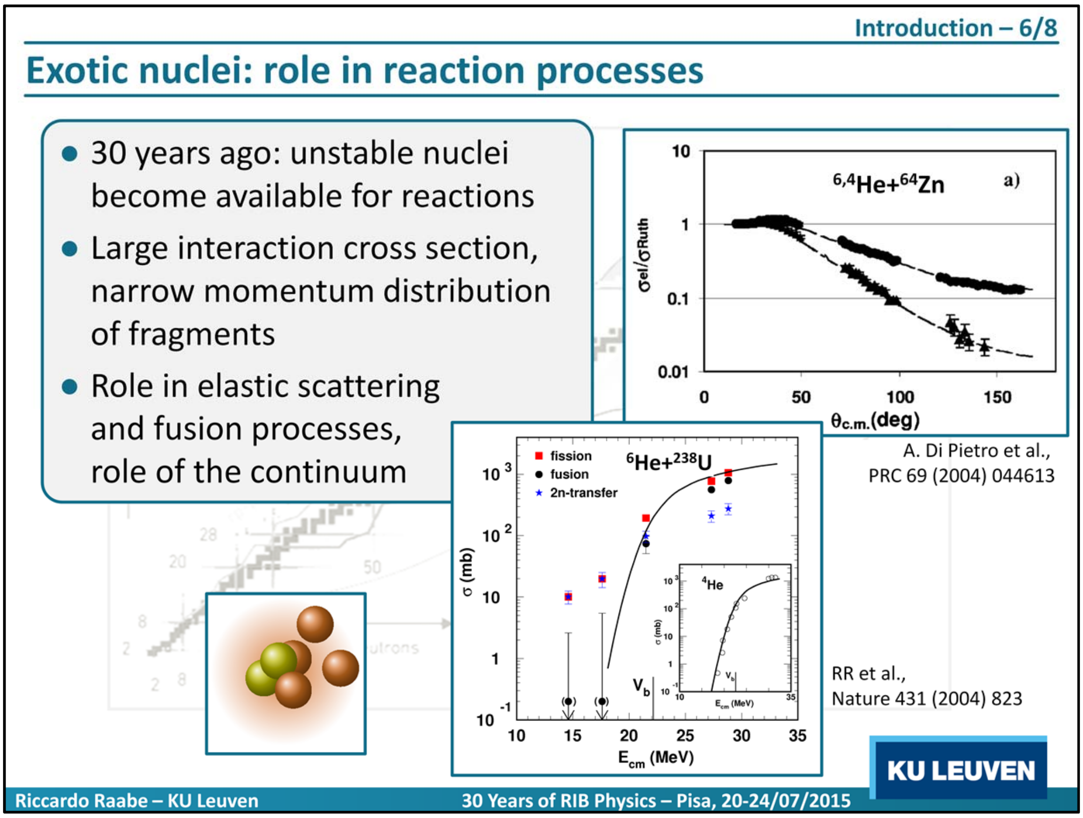
More in general: cluster structures appear close to the thresholds.

- Examples: 3 alpha-cluster structure of the Hoyle state in 12C; Ikeda diagram.
- Molecular bonds can develop, with nucleons exchanged between clusters. Here the Be isotopes.



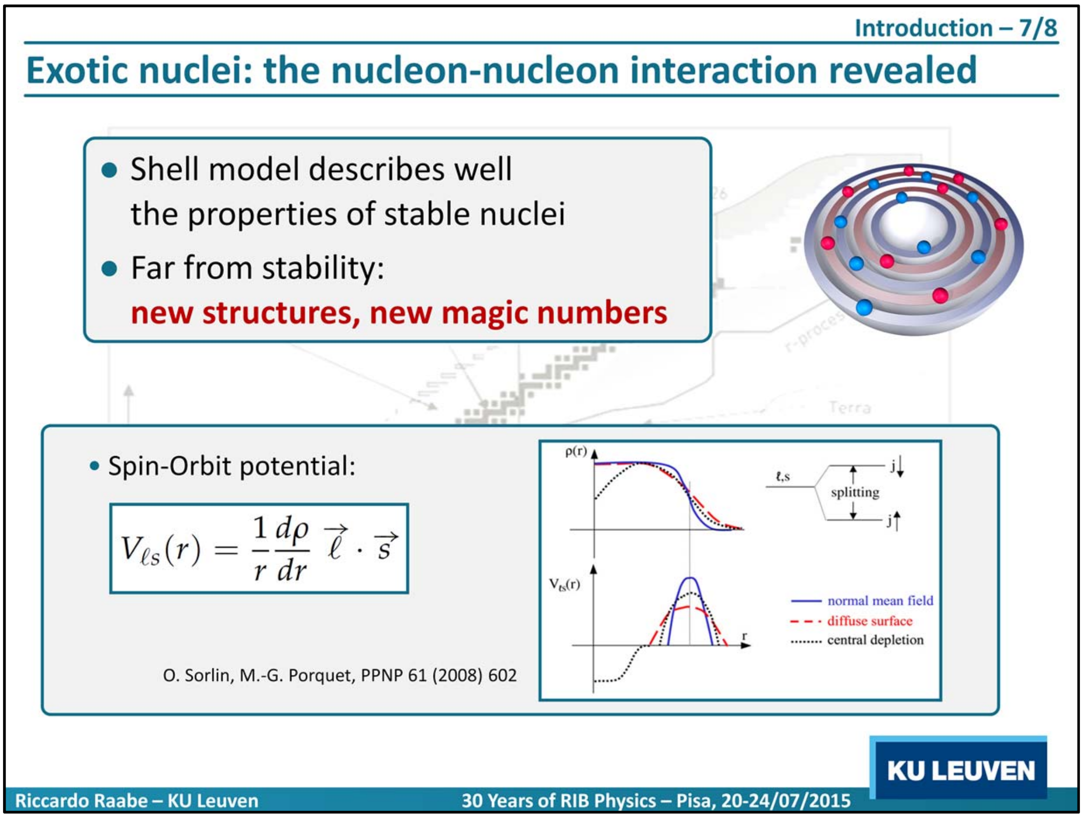
Another example of exotic features: shape coexistence.

- States with different macroscopic deformations coexist at similar excitation energies.
- In this and other cases: signatures are found by looking at a number of different states.



Another very important aspect is the role of exotic nuclei in reaction processes. Historically, that is why we celebrate 30 years RIB physics in 2015: the availability of radioactive beams at energy high enough to perform reaction measurements.

- The first ones were measurements of total interaction cross section, and of the distribution of momenta following breakup.
- The focus shifted after about 10 years (with the advent of better-quality beams) to the measurement of elastic scattering and fusion cross sections.

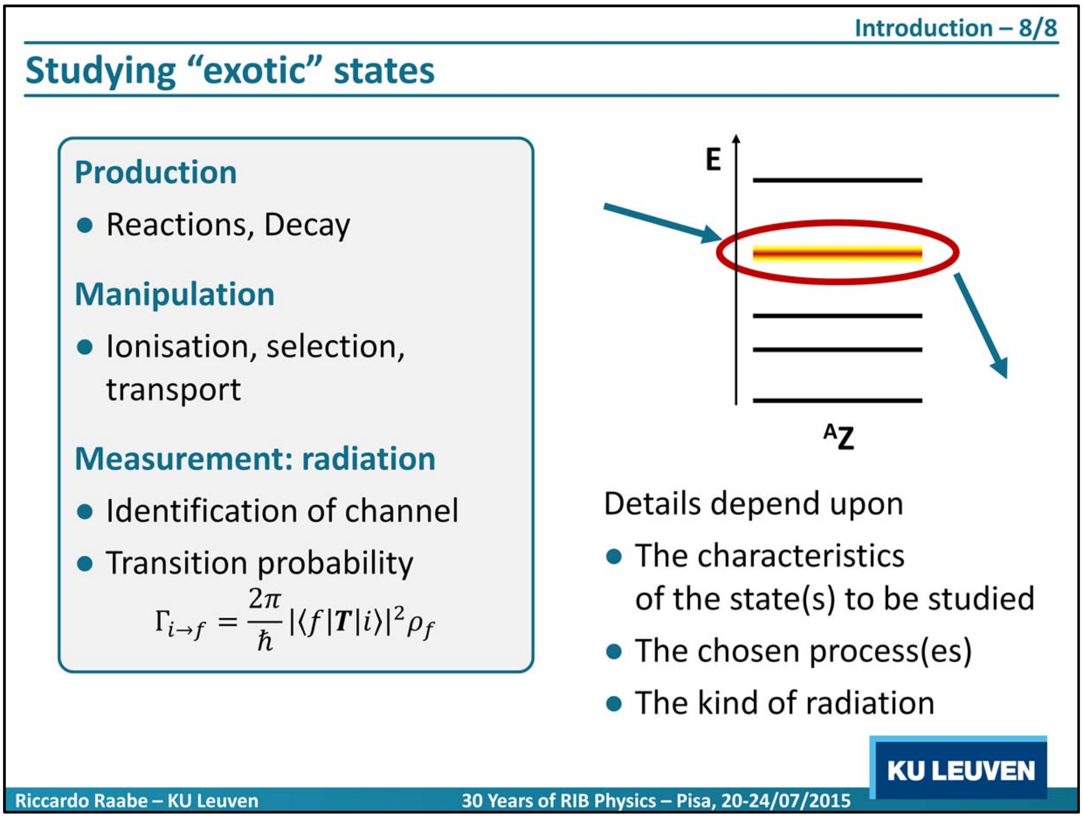


Focus of the research on “nuclei far from the stability” in present days:

- Apply well-established reaction and decay methods to investigate the structure of these nuclei.
- Use nuclei far from stability as a key to access information on the fundamental underlying nucleon-nucleon interaction that binds nucleons together.

For example, from a shell-model point of view:

- The shell model predicts enhance stability of closed-shell configurations, translating in “magic numbers”.
- But far from the stability some shell closures seem to vanish or migrate. Why?
- The large unbalance between neutrons and protons enhances particular features of the nucleon-nucleon interaction. These, in turn, modify the energy of orbitals and thus the gaps between them.
- An example (but not proven experimentally): the spin-orbit term.
  Other terms have been found experimentally to be important: tensor part of the interaction, three-body forces…

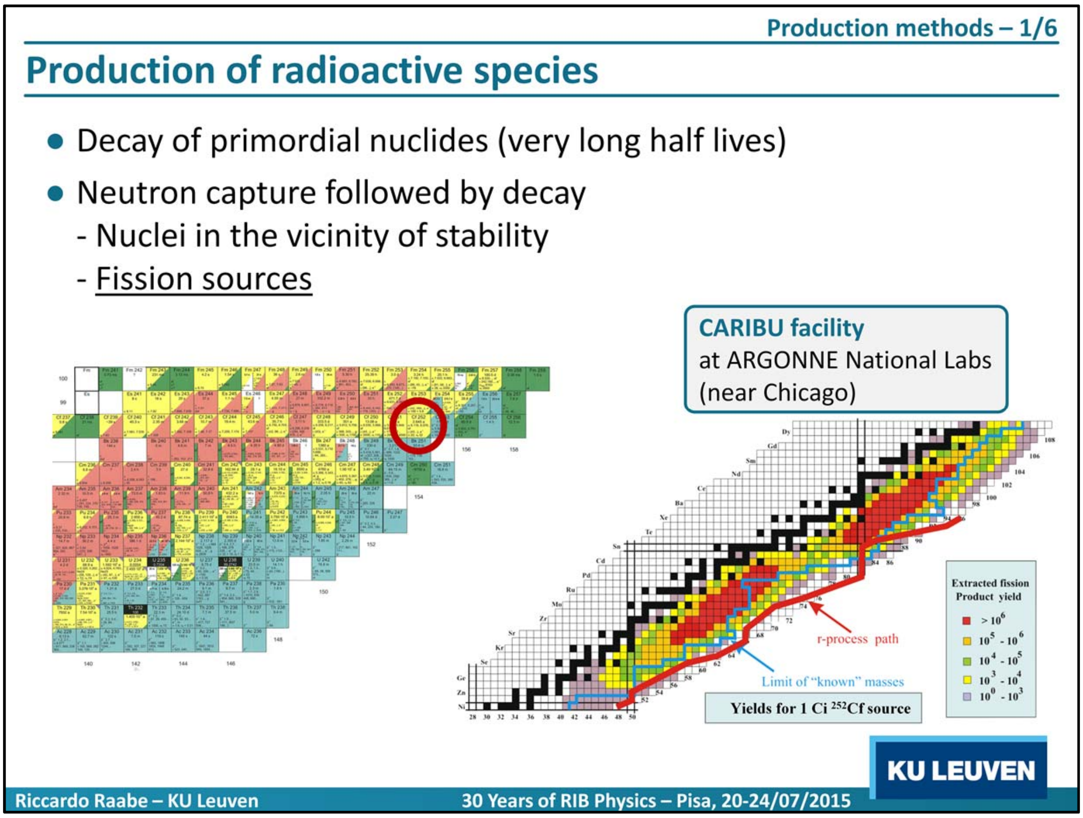


The study of an "exotic" state will always involve the following moments:

- Production: the theory of decay processes is usually well-known, but they only give access to a limited number of states (what is available in nature).
  Reactions give potentially access to everything (with different probabilities…) but sometimes they are not well known.
- Manipulation: there are "chemical" aspects (ionisation) and others related to the use of magnetic/electric fields (selection and transport).
- Measurement: the detection of radiation serves two purposes: to identify the populated channel (more in general the production/annihilation channel), and to determine the probability of creating/destroying the state of interest.
  The latter give direct information on the properties of the state of interest: think about Fermi's Golden Rule, where the transition probability is determined by some sort of perturbation connecting initial and final states. If we have some knowledge about some of the elements, we can learn about the others.

This general (generic) picture can vary enormously depending on several factors:

- Which are the characteristics of the state to be studied: mainly the half life, which can vary from seconds/minutes down to the time scale of nuclear interactions.
- Which processes are used to create/destroy the state(s) of interest (reactions, decays).
  Often one wants to study several channels connecting different states at the same time.
- The kind of radiation to be detected.

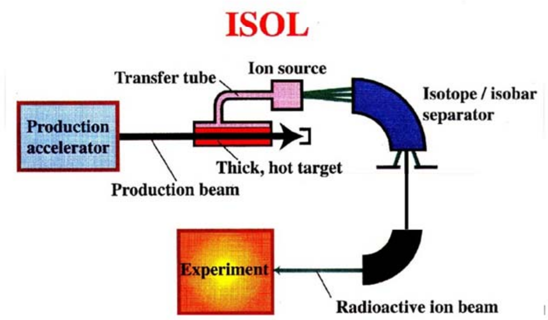


We go in order of increasing (conceptual) complexity.

- First possibility: use the decay of naturally occurring radioisotopes (40K, Th, U, Pu…), they alpha- or beta-decay to excited states in the daughters.
  Very limited to the available isotopes.
- Historically: use neutron flux from reactors to create unstable isotopes through neutron capture.
  One can populate nuclei in the immediate vicinity of the stability line, nuclei that will beta-decay back to stability.
  But using very heavy elements and intense neutron sources, one can create fission sources. Fission generates a large number of neutron-rich isotopes with Z from ~30 to ~70.
- A suitable isotopes is for example 252Cf. The CARIBU project at ARGONNE (Chicago, USA) uses a very strong (1 Ci) 252Cf source to produce radioactive isotopes. Project started ~10 years ago, they now have the 1 Ci source.

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)



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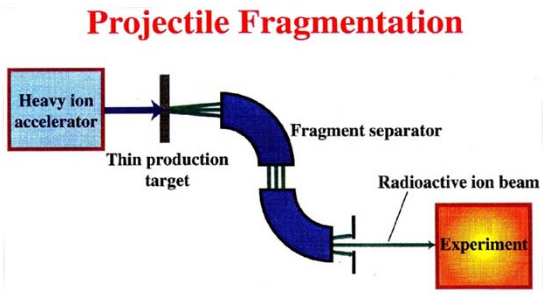
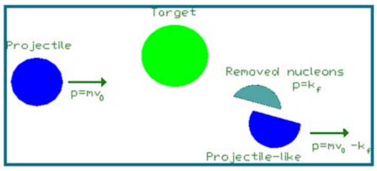
A permanent source has problems related to handling etc.
The ISOL method overcomes this problems.

- Radioactive species are produced in the interaction of (some kind of) beam with a target. Usually the target is thick, to utilize as much beam as possible.
- Products (directly from reactions, or from the decay of reaction products) diffuse out of the target into an ion source.
- After ionisation, the species of interest are selected magnetically and guided to the experimental station.
- All the elements: production beam, production mechanism, target, diffusion process, ion source, separator, have to be carefully consider in their specific characteristics and as a whole system.

The “in-flight” method

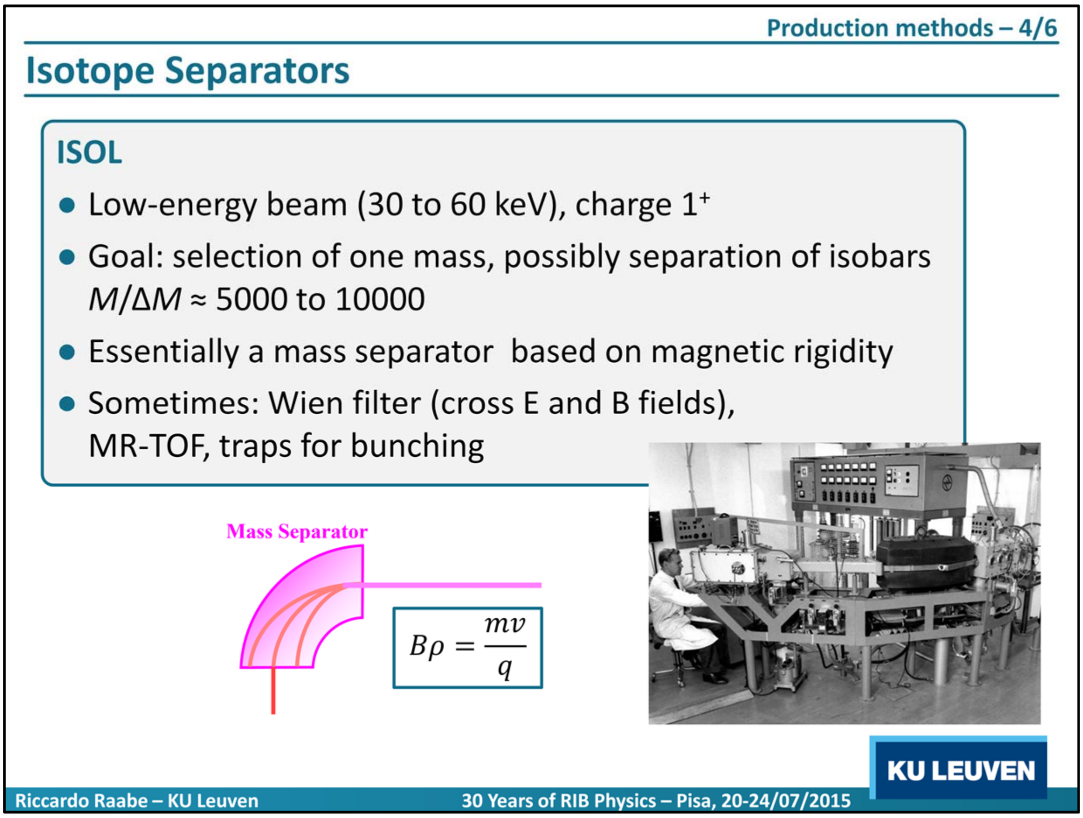
- Heavy-ion accelerator, E ≈ some hundreds MeV/A
- Thin production target (light element, rotating wheel)
- Fragment separator
- Transport to the experiment





The second method to produce radioactive isotopes is the “in-flight” (-fragmentation, -separation).

- A very high energy beam of heavy ions impinges on a thin target of a light material.
- All sorts of nuclei are produced mainly in fragmentation of the projectile, but also (depending on the beam/target combination) by fission and spallation.
- The target must dissipate a very high energy, usually is a cooled-down rotating foil.
- A fragment separator purifies (at least partly) the beam on its way to the experimental station.



The separators for the two methods are very different, and they serve different purposes.

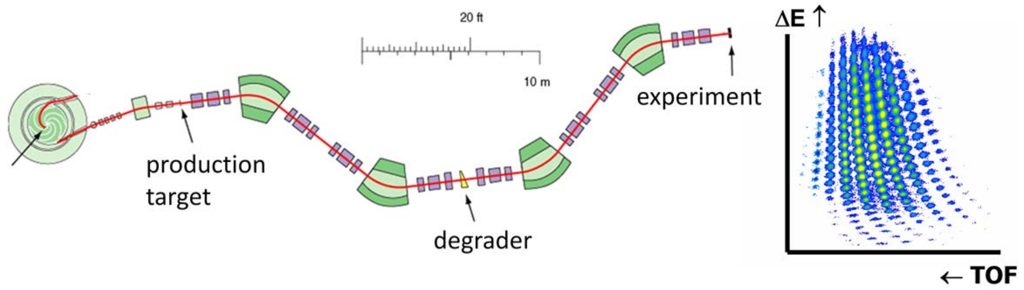
With the ISOL beam

- the radioactive isotopes are at low energy (30 to 60 keV) and thus they can easily be manipulated by relatively small magnets.
- Combination of magnets but also traps and other devices (MRTOF) can be used to manipulate the ions.

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



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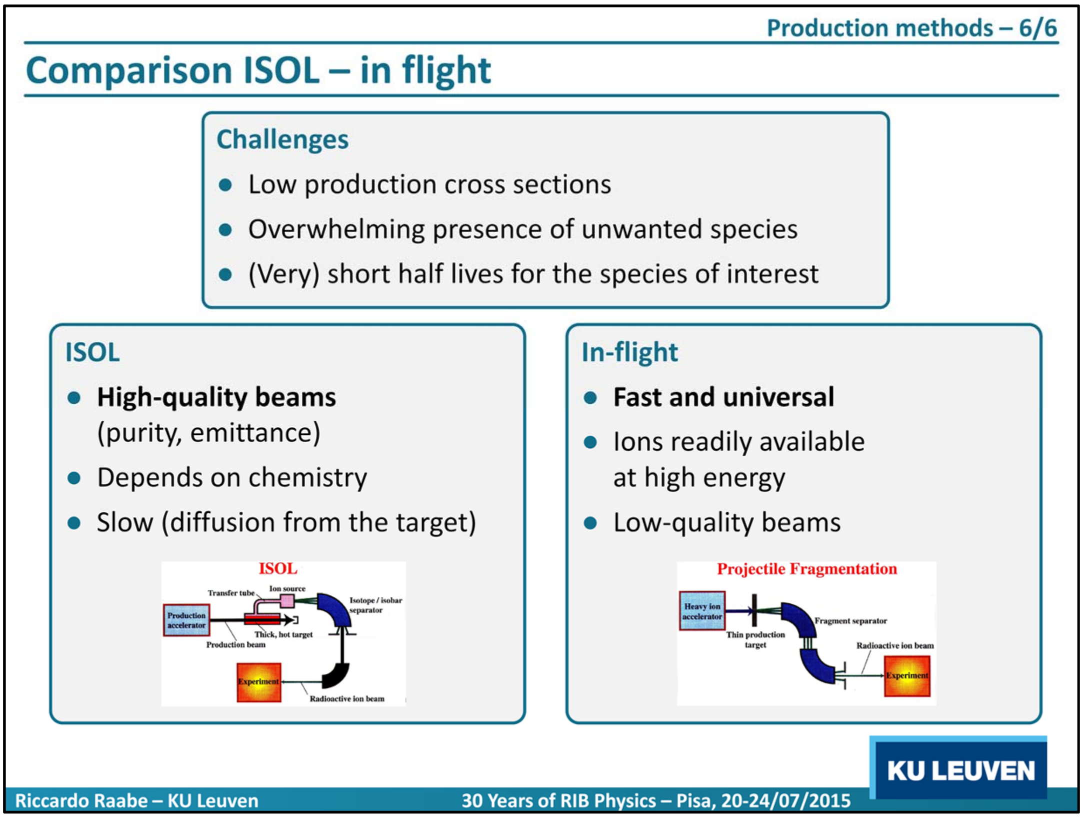
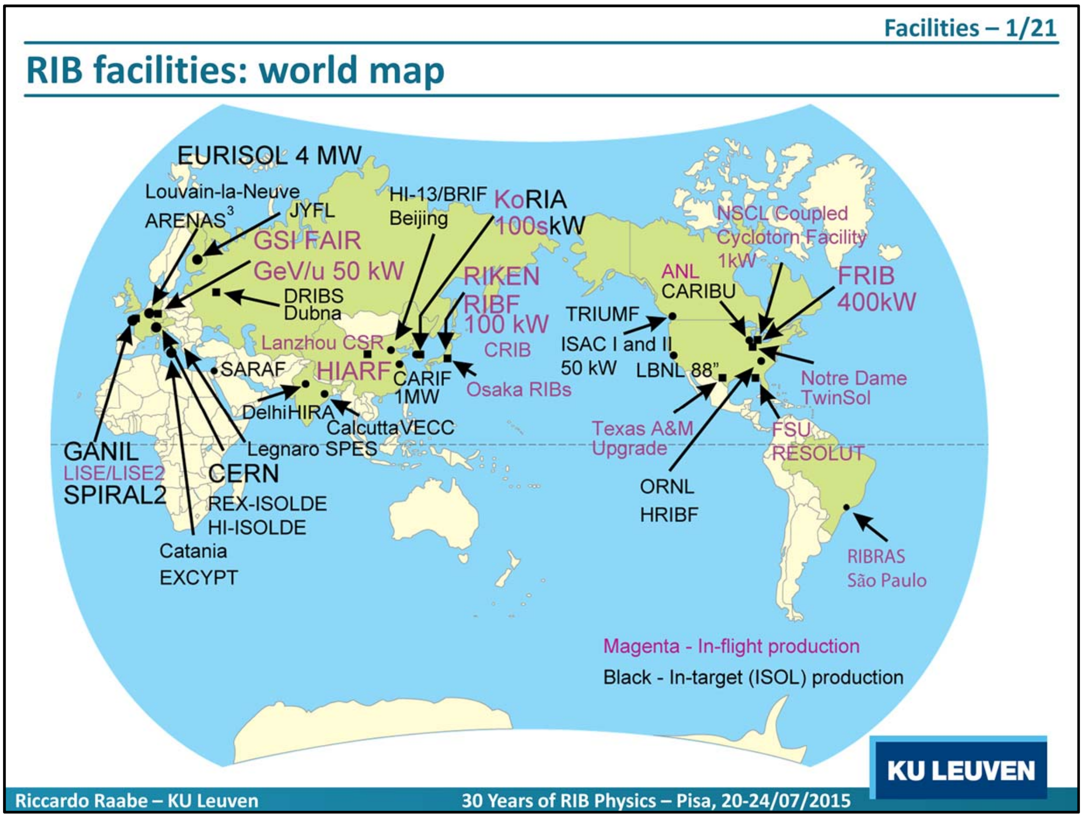
With the in flight method

- The beams are at high energy thus very large magnets are needed.
- The goal is to identify and possibly separate the isotopes of interest, so that a gate can be put on those events in off-line analysis.
- The isotopes are identified by their energy (measured as time-of-flight through the separator) and their energy loss in a given (usually gaseous) detector.



The two methods have each their merit and some disadvantages.

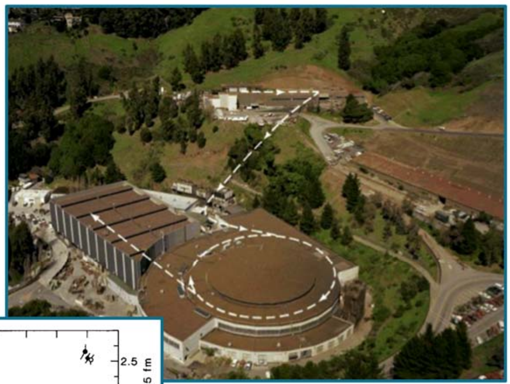
- The ISOL method delivers very good-quality beams.
  Purification takes place through selective ionisation (thus also depending on chemistry) and magnetic selection at low energy, thus it is more effective.
  However it is a slow method due to the diffusion through and out of the thick target (several seconds).
  It is thus more adapted for detailed spectroscopic studies of isotopes which can be produced in reasonable quantities.
- The in-flight method is very fast and does not depend on chemistry.
  It is thus more adapted to produce and identify new isotopes, pushing the boundaries of the observed ones by increasing the primary beam intensity and the sensitivity of the detection.
  The separation takes place at high energy (very large magnets) and often can help identify each produced nucleus that goes through, without cleaning the beam completely.
  Even though the radioactive beams are directly available at high energy, only a limited class of reaction studies can be performed.

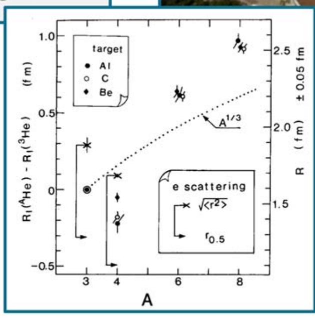


This is a world map of the facilities. ISOL and in-flight.
We cannot see them all (not our purpose). We will discuss selected examples to show the diversity of the solutions adopted within the two production schemes.

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

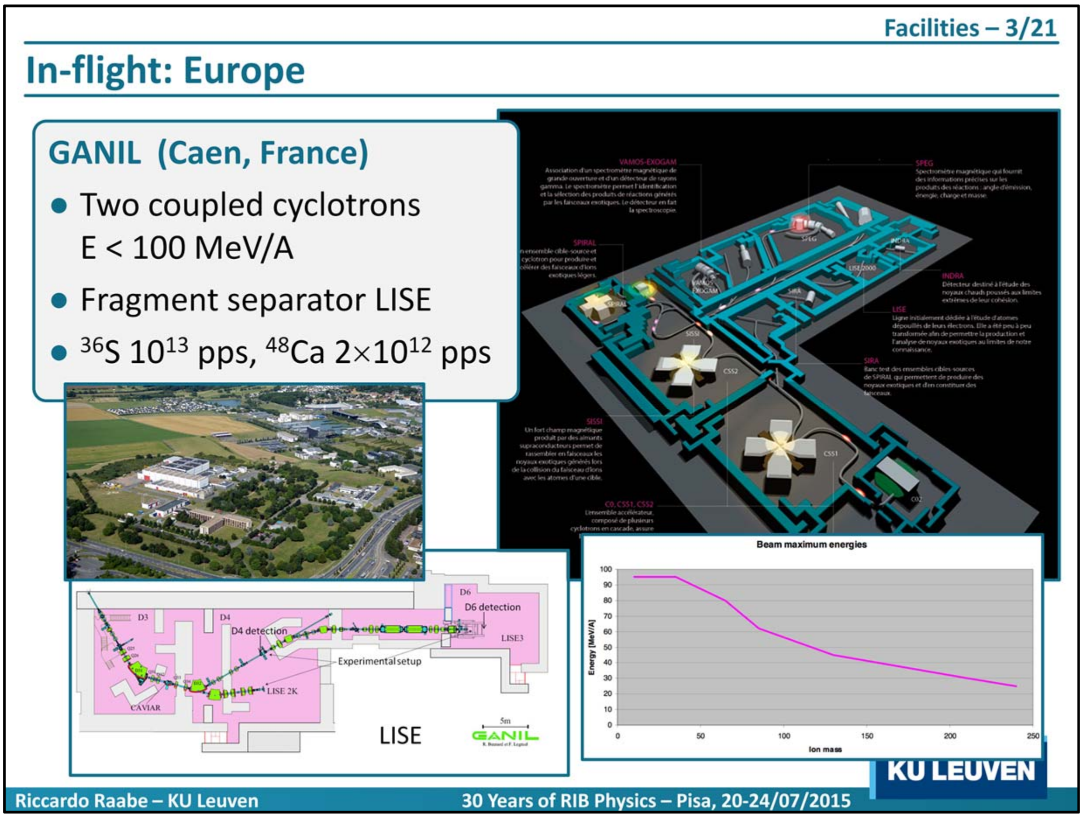




I. Tanihata et al
Phys. Lett. 160B (1985) 380

This is historically important, the first in-flight facility.

- Two existing accelerator (one producing low energy heavy ions and a synchrotron) were connected to obtain heavy ions at high energy.
- The beams were sent on a light target, and the fragment were selected.
- The first results on the interaction radius of He, Li and Be isotopes opened the field of exotic nuclei.



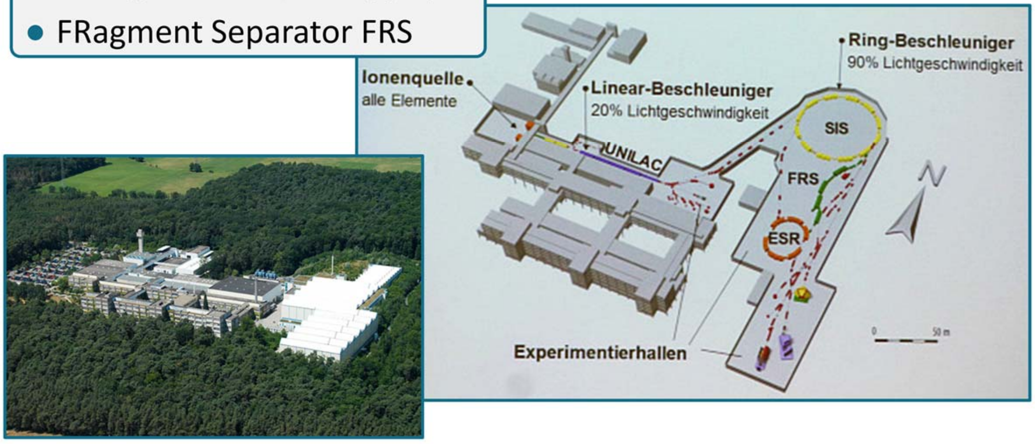
This is the Grand Accélérateur National d'Ions Lourds in Caen (France).

- Two coupled cyclotrons are used to bring the heavy ions to high energy.
- In between the cyclotrons a stripper foil is placed to increase the charge state of the ions.
- The fragment separator, after the production target, is LISE.
- The energies at GANIL are relatively low, which is kind of unique. The energy of the fragment is well-adapted to attempt nucleon transfer reactions (difficult, because the quality of the beam is not good).

In-flight: Europe

GSI (Darmstadt, Germany)

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



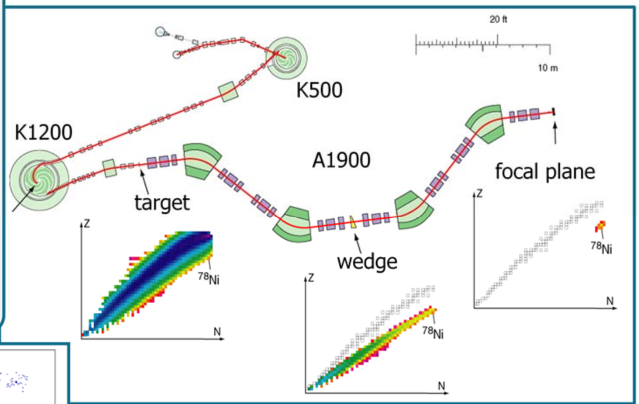
GSI at Darmstadt.

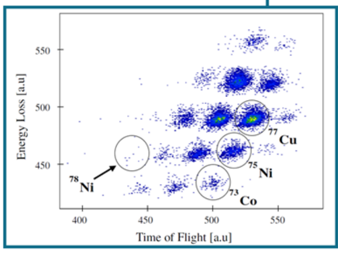
- A Linac followed by a synchrotron. The latter delivers the most energetic beams of all, but at low intensities (one spill every few seconds).
- The fragments are very much forward focused, which helps the acceptance of the separator that follows: the FRS.
- Home of several measurements of the dissociation cross sections of light exotic nuclei and the momentum distribution of their fragments.

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)

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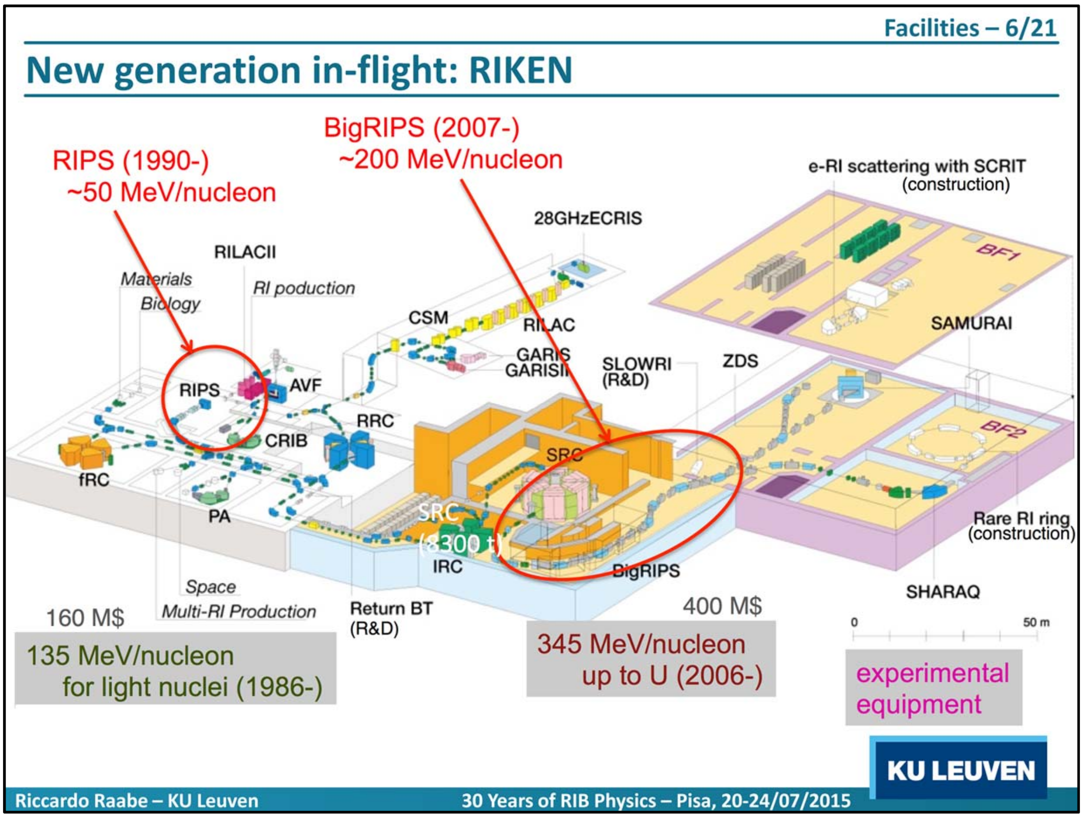
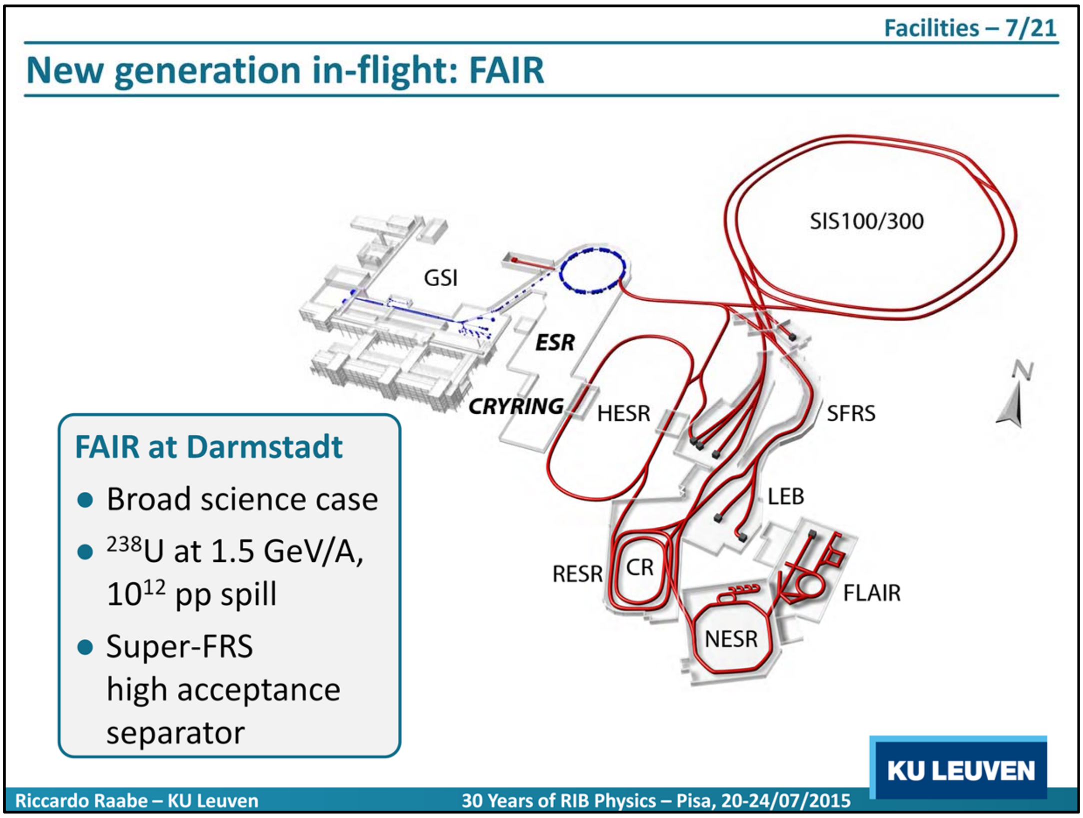
The in-flight facility at NSCL, Michigan State University, in USA.

- Like in GANIL, two coupled cyclotrons.
- The separator has a very good acceptance.
- They measured here the half life of 78Ni, after identification through ΔE-TOF.
- Here too, light exotic nuclei were measured in the `90s.



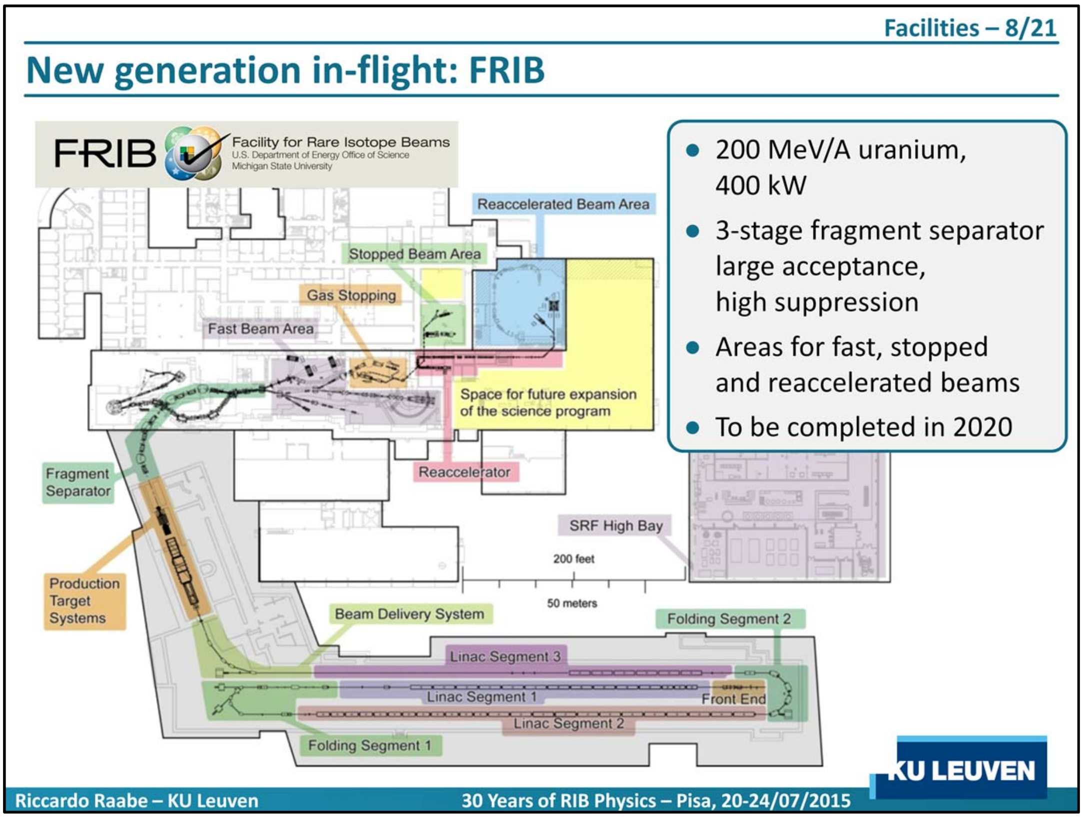
RIKEN at Tokyo, Japan.

- The RIPS n-flight facility was used in the 90s for the measurement of dissociation of exotic light nuclei.
- This is also the first new-generation facility. BigRIPS has recently allowed the study of 78Ni (see lecture Obertelli).



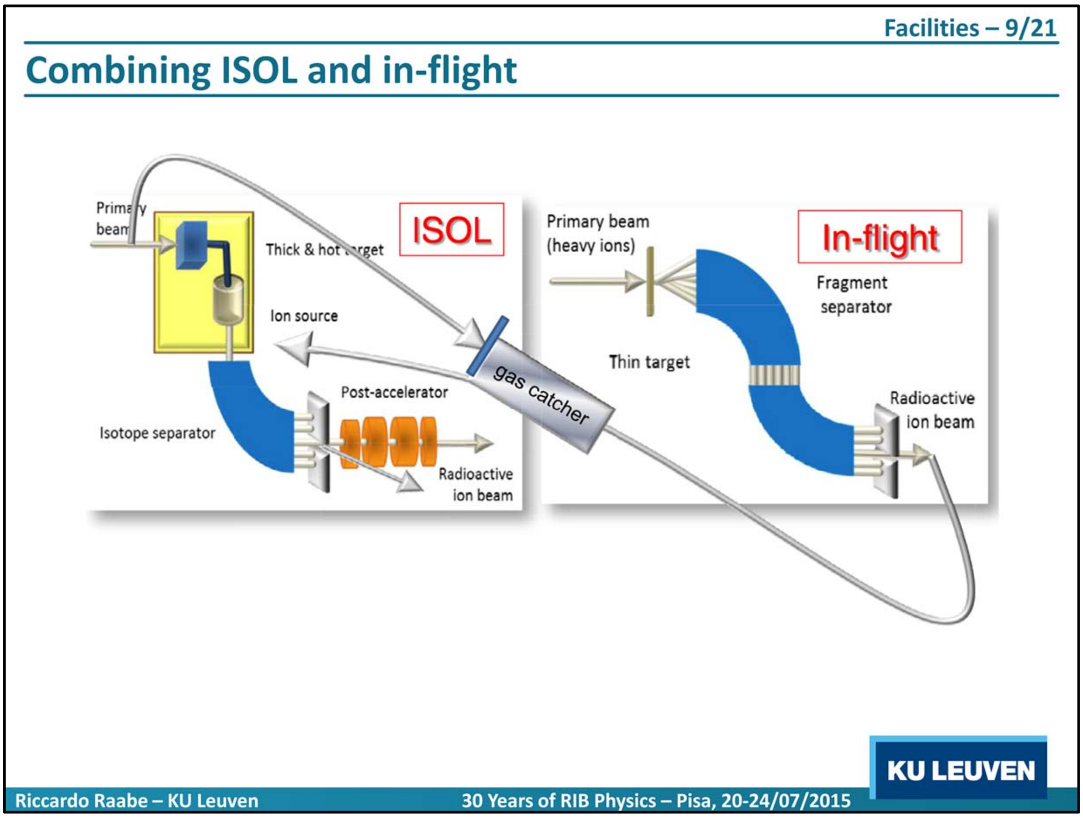
The importance of studying unstable nuclei has generated a great effort towards the construction of new-generation facilities worldwide.

- The facilities are very complex and large. A broad science case has to be put together to justify their construction.
- For FAIR the science case spans high-energy nuclear physics (nucleon structure), application, antiproton physics, applications…
- Strong increase in intensity with respect to the present GSI.
- The SuperFRS has an improved acceptance. An intensity improvement of 10^4 with respect to GSI is expected.
- Beams can be directly used at high energy, or cooled and stored in rings, or slowed down and used at lower energy for reaction and decay studies.



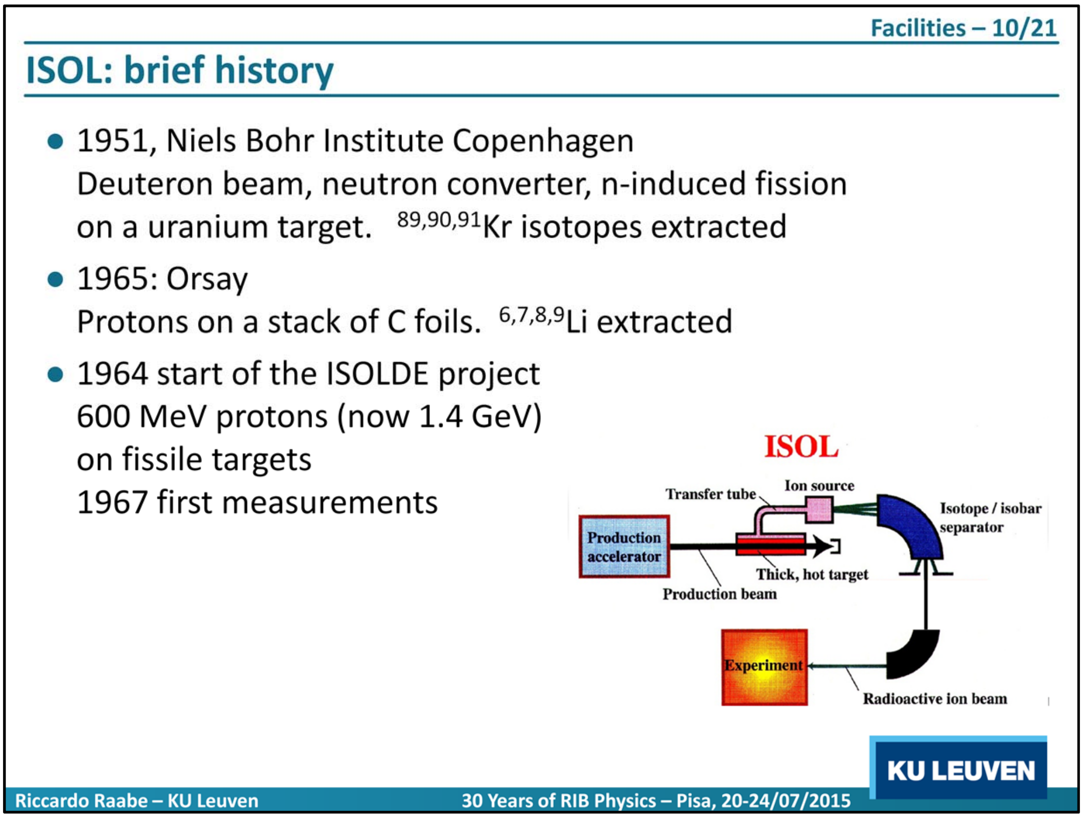
The FRIB at MSU will provide beams at most energy ranges.

- A LINAC delivers heavy ion beams at high energy and intensity for in-flight production.
- After separation the beams can be directly used or slowed down in gas catchers.
- Post-acceleration is also possible at 3 MeV/nucleon.



The idea of a gas catcher to slow down beams is to take advantage of

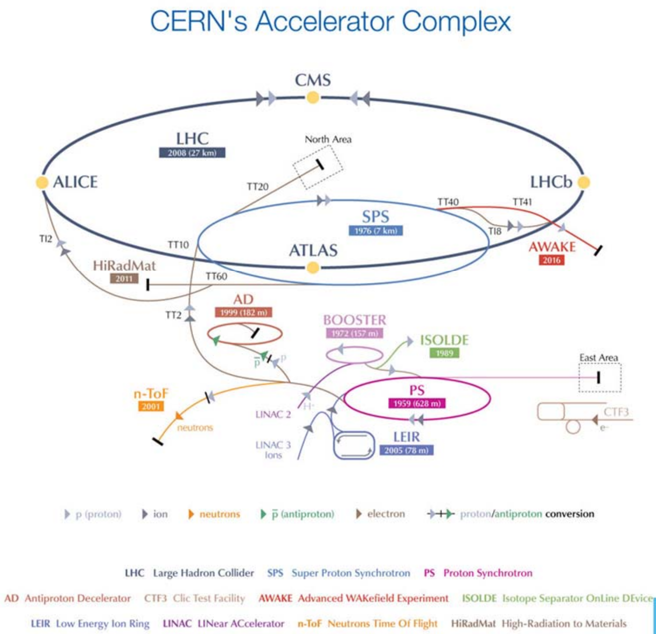
- The universality of isotope production by the in-flight method, combined with
- The manipulation of ions at low energy typical of the ISOL method.



Now an overview of ISOL facilities. First a historical note.

- First appearance of the method was in the 50s in Copenhagen.
- More than ten years later another example at Orsay.
- In the 60s the proposal for ISOLDE at CERN was entered. Construction began in 1964, first beams delivered in 1967.
- We will focus on ISOLDE as this is the oldest facility, and the one that can deliver the widest range of isotopes.

ISOLDE at CERN



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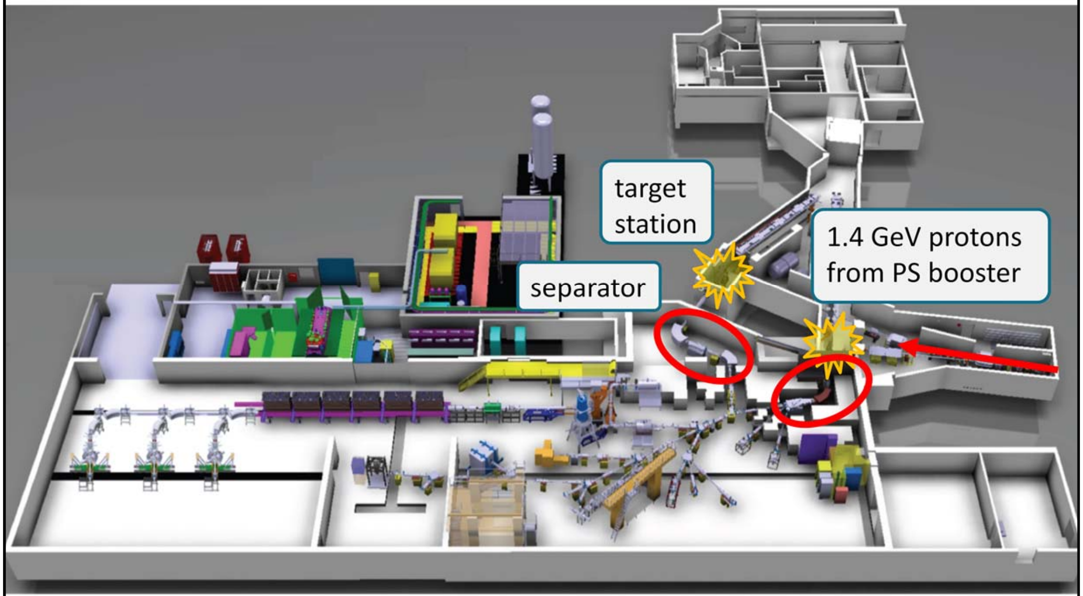
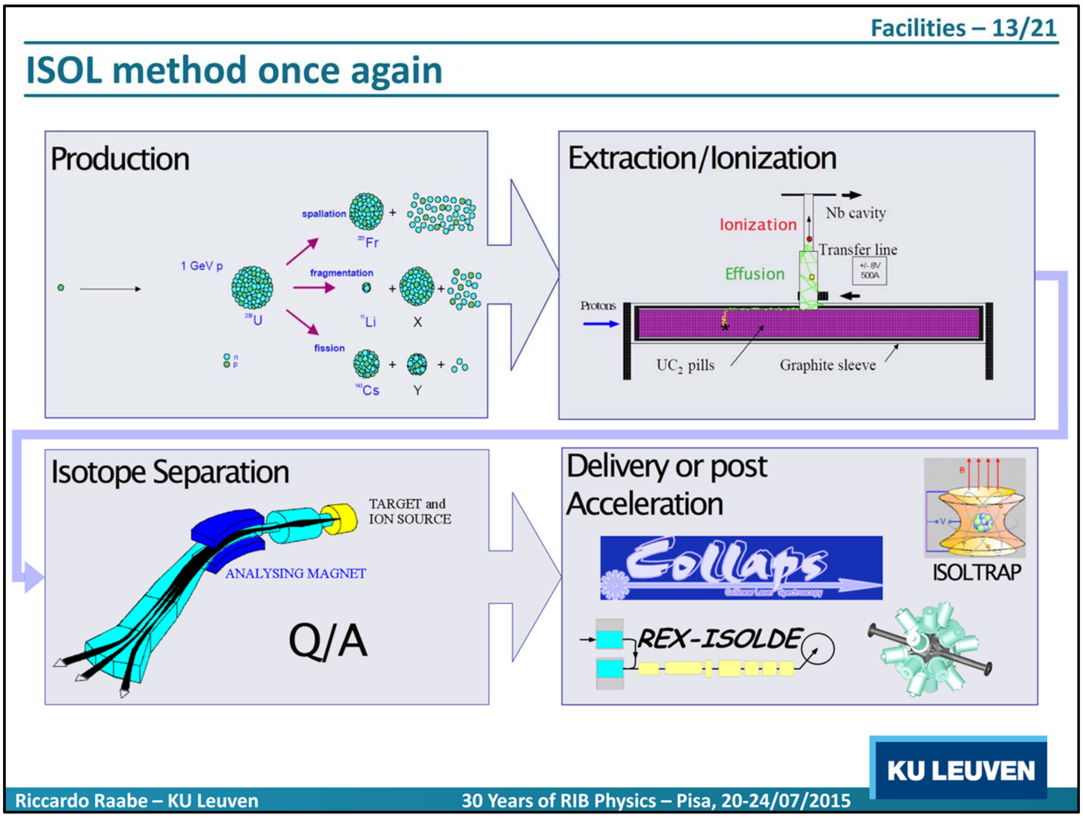
Location of ISOLDE within the CERN accelerator complex.

ISOLDE at CERN



Overview of present-day ISOLDE.

- Two target stations are coupled to separators
- General Purpose Separator GPS and High-Resolution Separator HRS.
- Beams are delivered at low energy (60 keV) to a number of detection stations, or post-accelerated (see later).



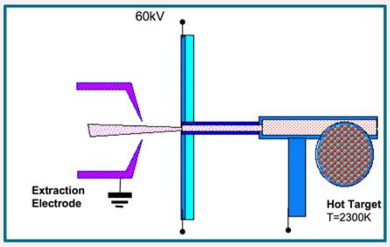
Here again an overview of the stages of the ISOL method for producing radioactive isotopes.

- With protons at 1.4 GeV different reaction mechanisms are at work. Spallation is quite unique for ISOLDE among ISOL facilities.
- The ion source is crucial. Different types are used according to the desired isotope.

Ion sources

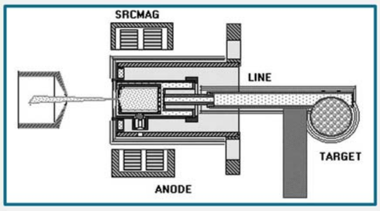
Hot surface ion source

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

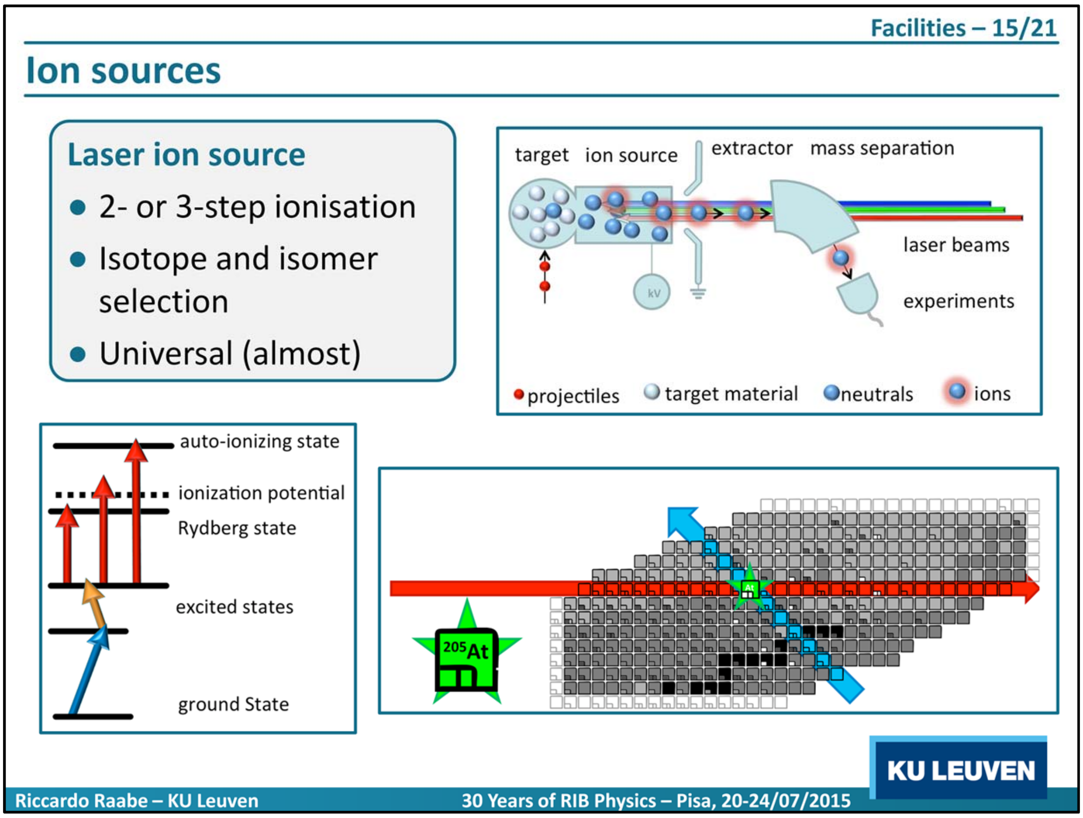


Plasma ion source

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

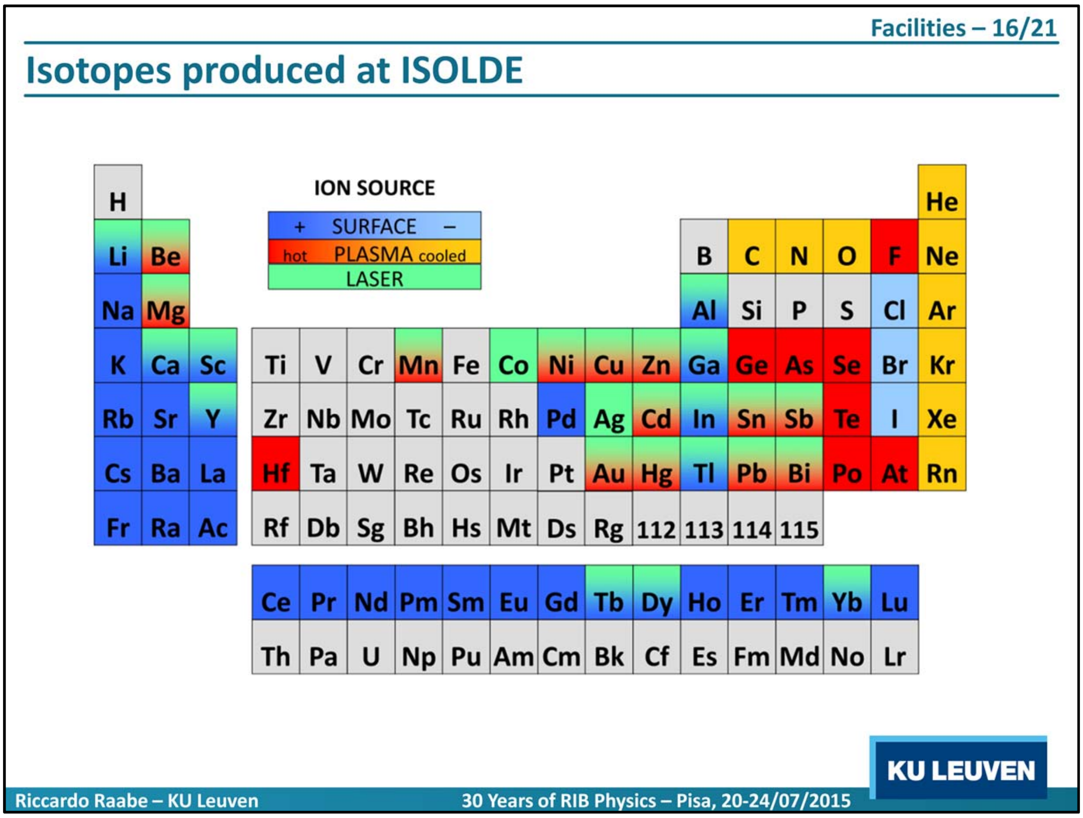


- The hot surface ion source is used with elements that are easily ionised (alkaline, alkaline-earth).
- The plasma source uses the plasma to ionise the species. Can be used in principle with all elements, but it gets the best results in terms of suppression of contaminants with volatile elements. With the latter a cool transfer line is used to suppress the non-volatile elements.

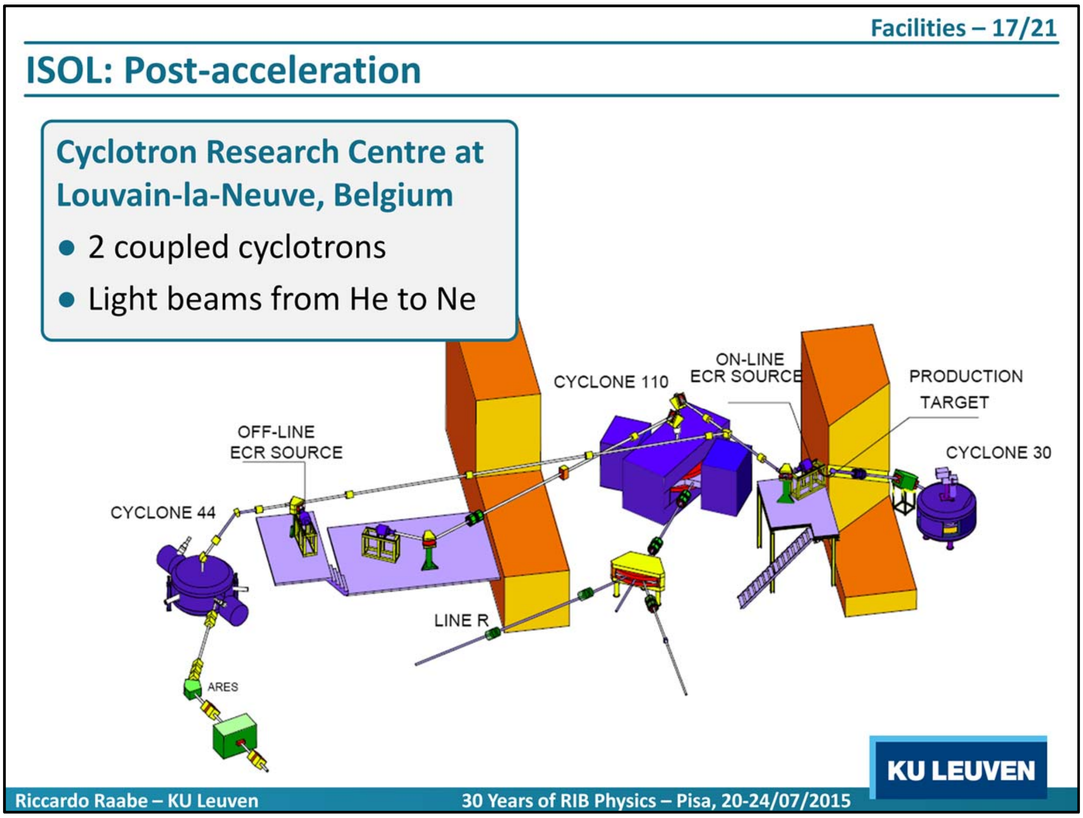


The laser ion source has been absolutely crucial in extending the range of available beams.

- Laser light is sent into the source cavity. The frequencies (two or three) correspond to atomic transitions unique for the element of interest.
- The element is ionised and extracted from the source.
- It is in principle universal, though efficient ionisation is difficult for noble gases and some light elements with high ionisation potential.
- Combined with mass separation, the method selects uniquely one isotopes.
- In fact, even isomer selection is possible!
- In reality, contamination may be present by more stable isobars that do not neutralise in the source.

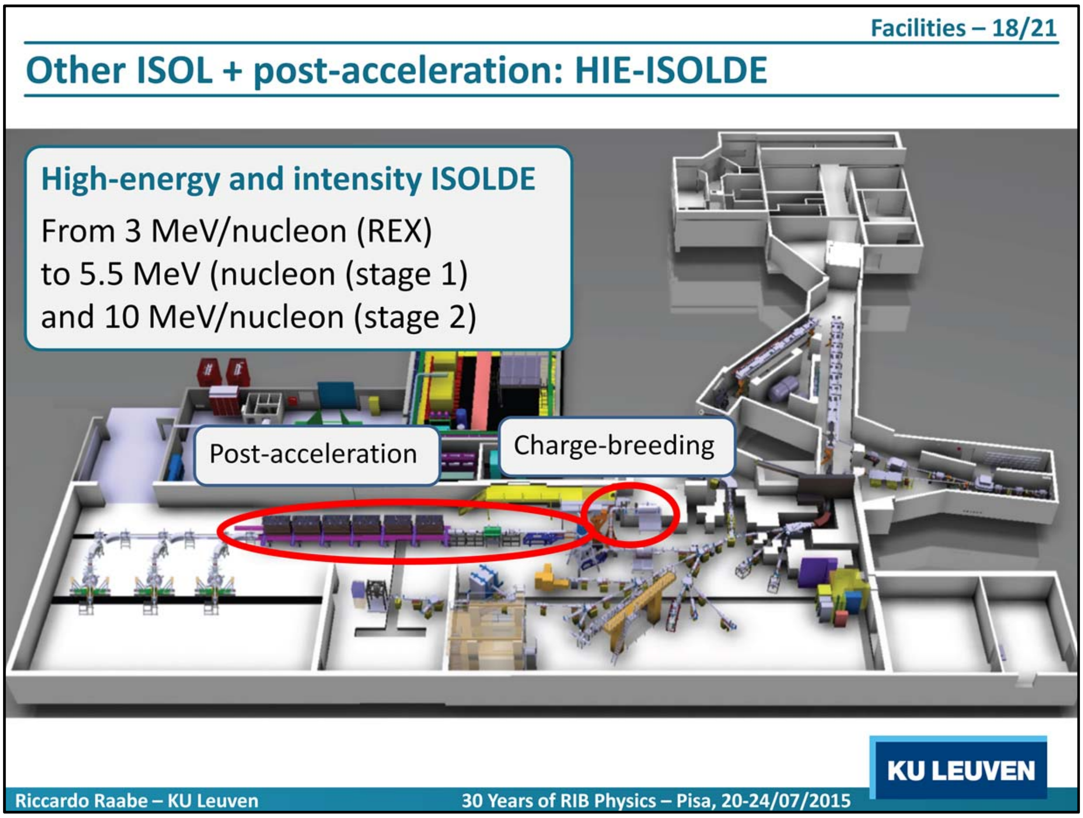


An overview of the elements produced at ISOLDE.



What about post-acceleration of ISOL beams?
Important because it allows using more sophisticated reaction methods (in particular transfer reactions) for detailed spectroscopic studies of the unstable isotopes.

- It needs a second accelerator (post-accelerator) placed behind the target-ion source system.
- The first realisation was at Louvain-la-Neuve in the early 90s, in Belgium.
- The first cyclotron delivered 30 MeV protons on a carbon or LiF target.
- The products (light elements: 6He, up to Ne) were post-accelerated in the second cyclotron, which also worked as a mass separator (but with a low efficiency).



At ISOLDE:

- From the beginning of the 2000, the REX linear post-accelerator was installed.
- Key feature is the charge breeding in an Electron Beam Ion Source. The high charge state allows using a compact linear post-accelerator.
- REX delivered beams at 3 MeV/nucleon.
- The new superconducting HIE-ISOLDE accelerator will deliver beams at 5 MeV/nucleon from October this year, and 10 MeV/nucleon from 2017.

Facilities – 19/21

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

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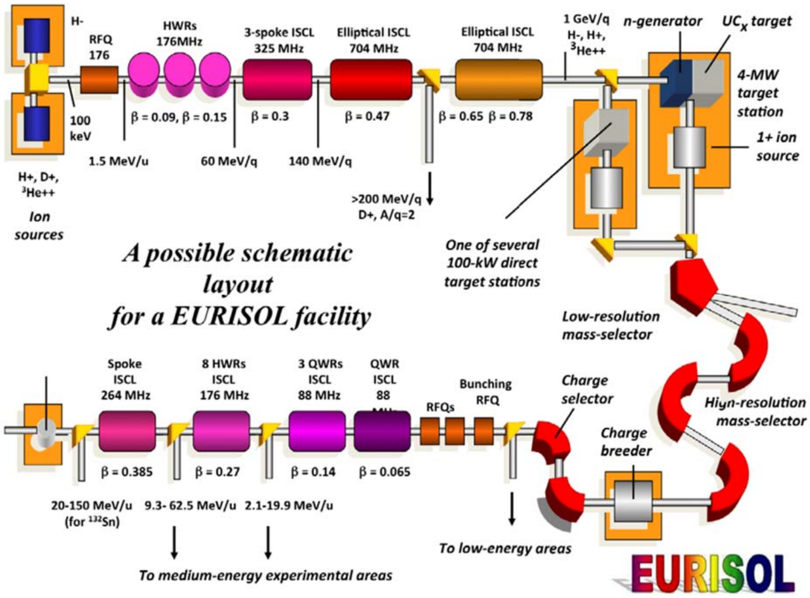
Riccardo Raabe – KU Leuven   30 Years of RIB Physics – Pisa, 20-24/07/2015

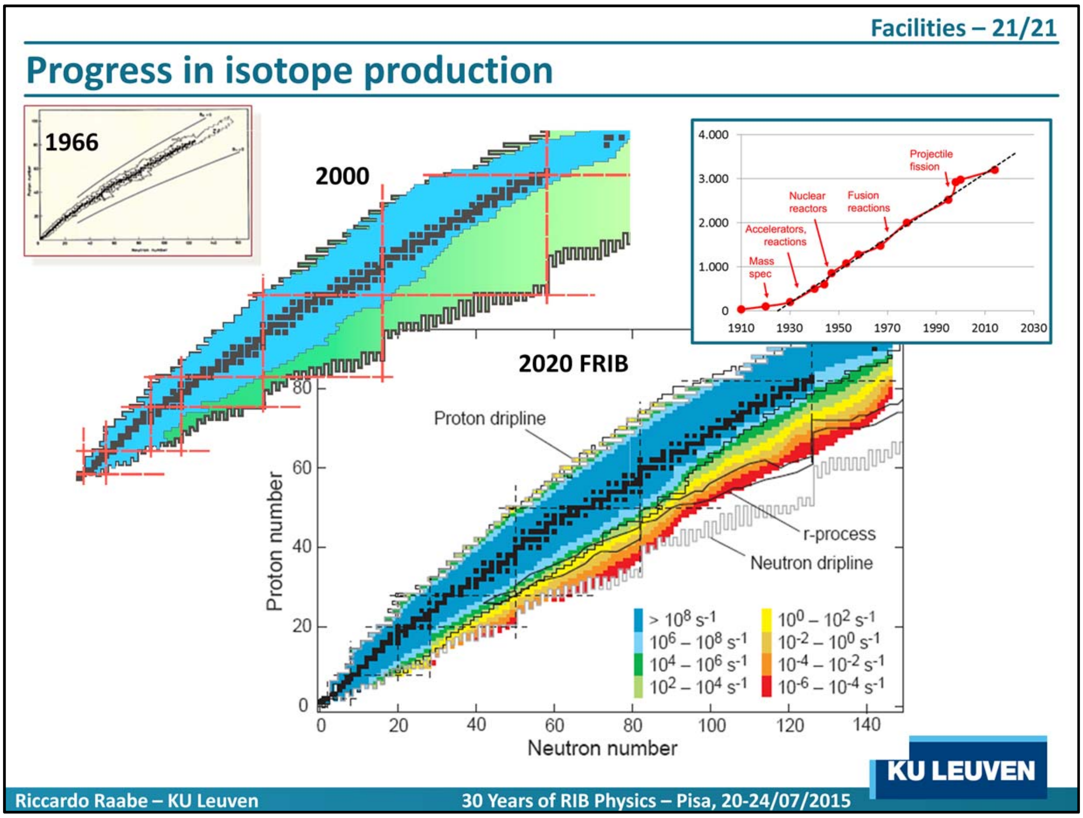
This is a fast overview of other ISOL facilities.

- TRIUMF in Canada is the only competitor for ISOLDE. They also use fission, induced by 500 MeV protons. They are finalising a new facility (ARIEL) where fission will be induced by gamma-rays. Post acceleration at 10 MeV/nucleon is readily available.
- SPIRAL at GANIL uses the heavy ions beams from GANIL to produce radioactive species in a light target (no permission for fissile targets). A cyclotron provides post-acceleration. Initially a “niche” facility, it has been nicely exploited by a strong community and there are plans in place for further developments.
- For the future in Europe: the SPES facility at Legnaro and the SPIRAL2 facility at GANIL (the latter is delayed).

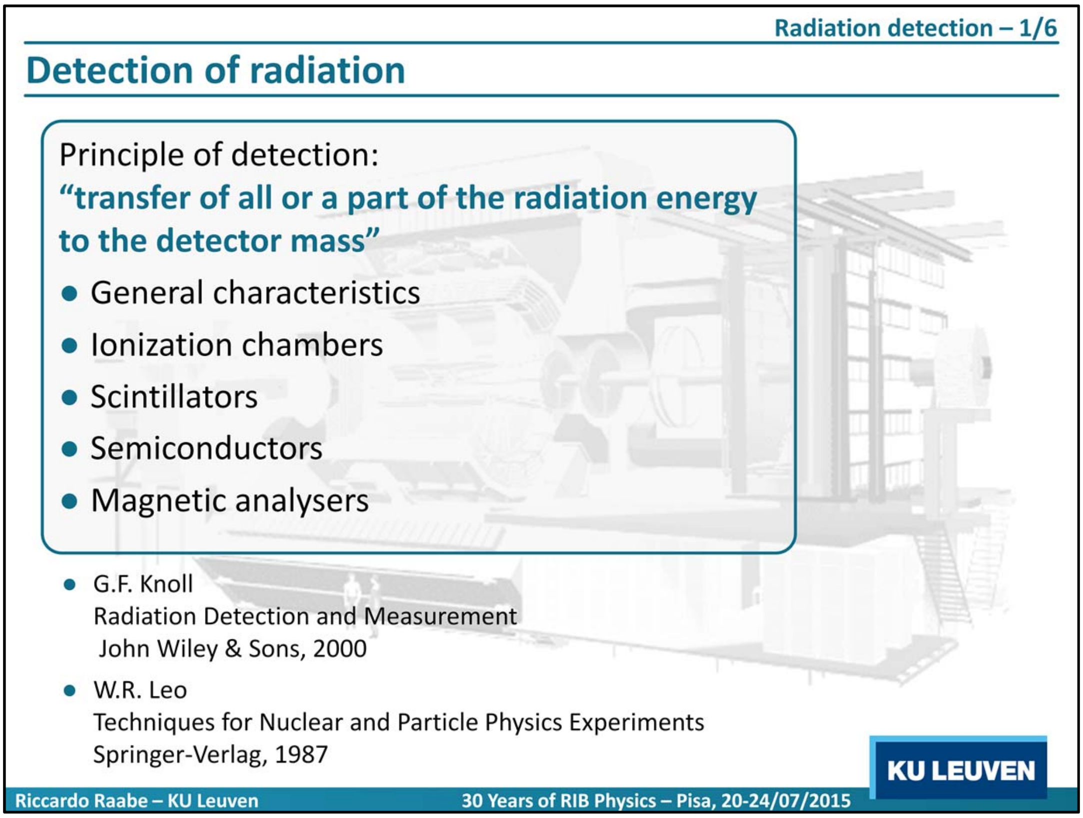
Ultimate goal: EURISOL



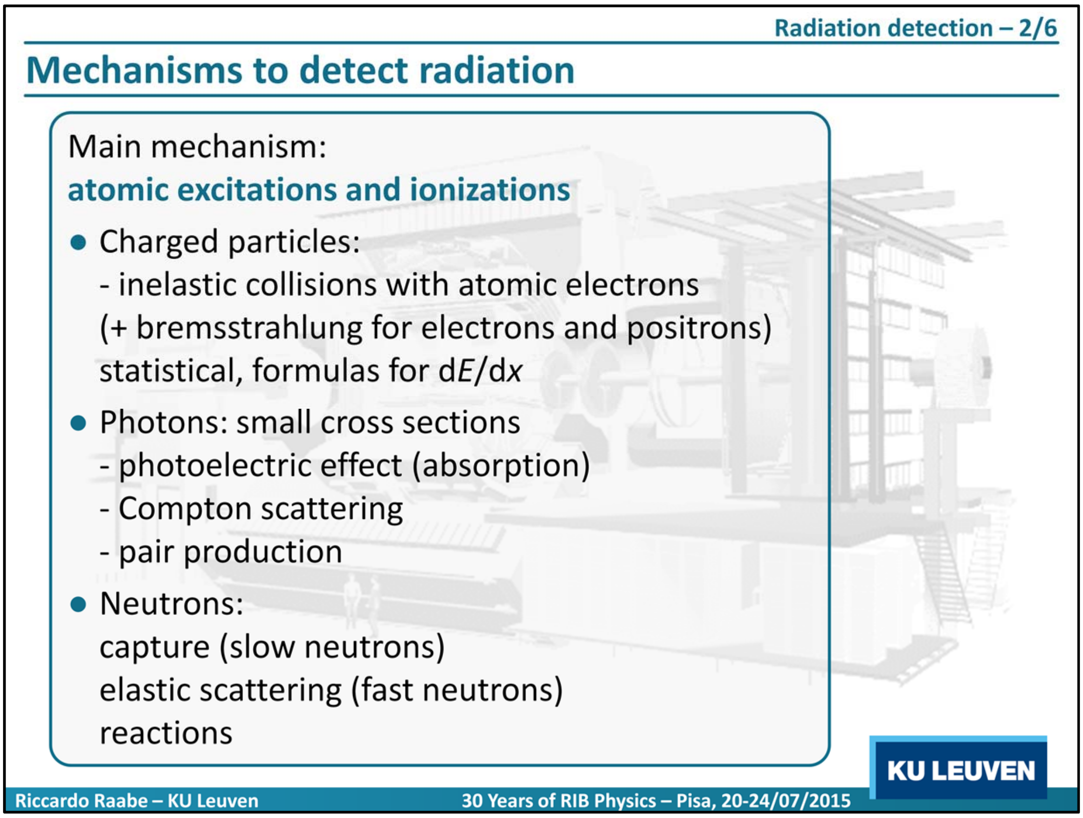
EURISOL is the ultimate facility, which combines a high-power multi-target system and a 4MW target .
Ions from the latter can be post-accelerated to energies sufficient for fragmentation: in-flight method, starting from an exotic beam, to reach very far-from-stability isotopes.



- The production of new isotopes has increased steadily for almost a century now.
- The new facilities will allow continuing this trend on one side, but also will allow using these isotopes for spectroscopic studies.

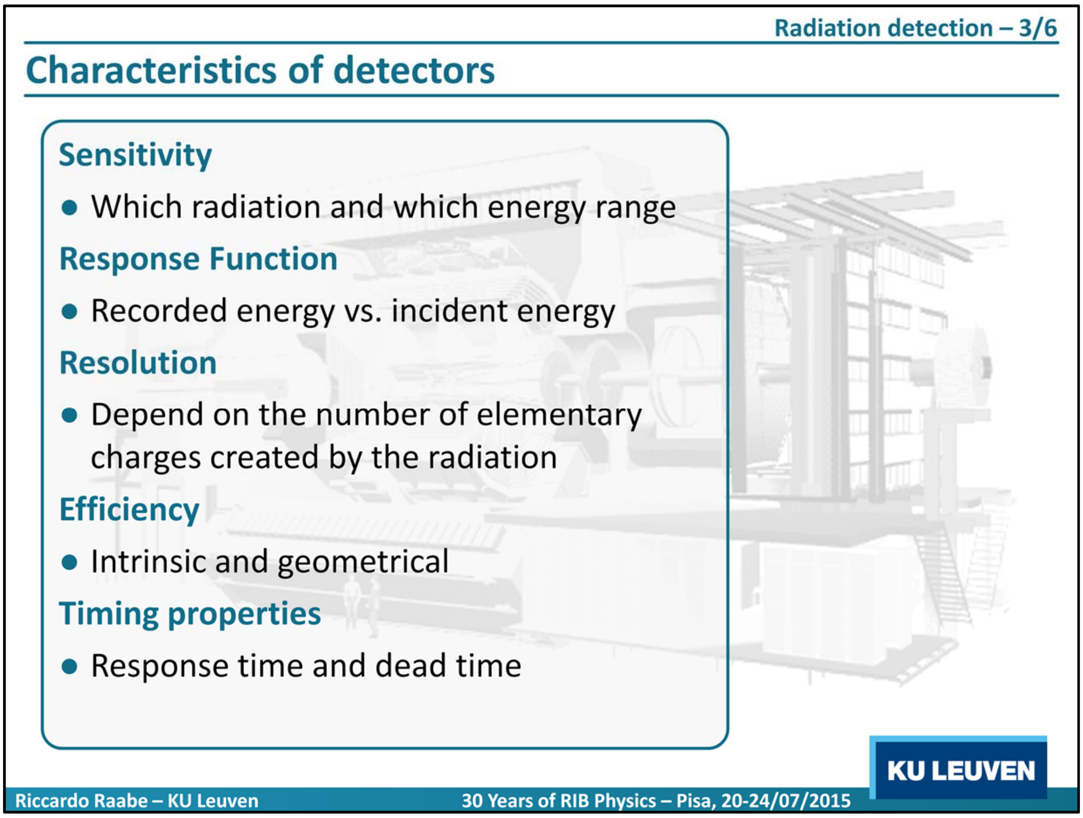


After production and manipulation of the radioactive isotopes we come to their measurement.
We need to detect radiation. Here is what we will very briefly see to introduce the topic.



The mechanism of energy transfer from the radiation to the detection material depends on the type of radiation.

- Charged particles interact with the electrons of the material in a continuous way. The efficiency is 100%, though backscattering should be taken into account.
- Photons have very small cross section for interaction (different processes). They deposit their energy in specific places.
- Neutrons are very difficult to detect. We rely on capture for slow ones (thermal), and on reactions for fast neutrons.



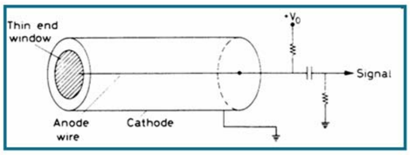
Here are the characteristics of a detection device, very briefly summarised.
The energy deposited by the radiation creates a number of elementary charges (or photons, or electron-hole pairs; see further). The exact number is not fixed, it is statistically distributed → the same radiation energy can produce slightly different signals. The more elementary charges are produced, the smaller is the spread (better resolution).

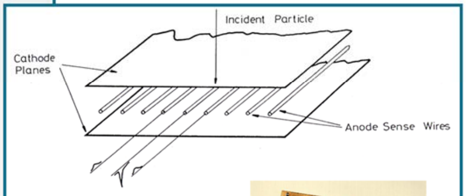
Type of detectors – 1

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)





Characteristics of ionisation detectors (gaseous detectors).

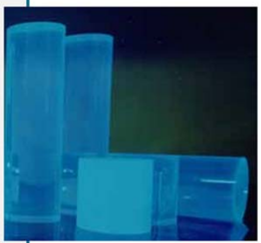
- They are very much used in high-energy physics, to measure to high precision the trajectory of particles.
- For low-energy nuclear physics there is the problem of the very different energy deposited by ions according to their Z.

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



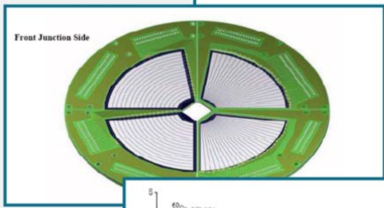
Scintillation detectors are best used for timing purposes and as a general coincidence signal, when the energy is not crucial.
They are also used for gamma-ray as their efficiency can be much higher than that of semiconductor, though the energy resolution is worse (a few % against a few ‰).
They are also used for neutrons. The energy is derived from the time-of-flight of neutrons from the target.

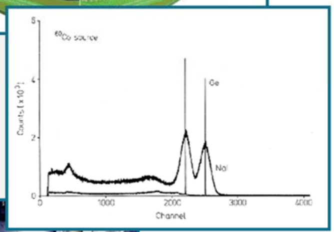
Type of detectors – 3

Semiconductor detectors

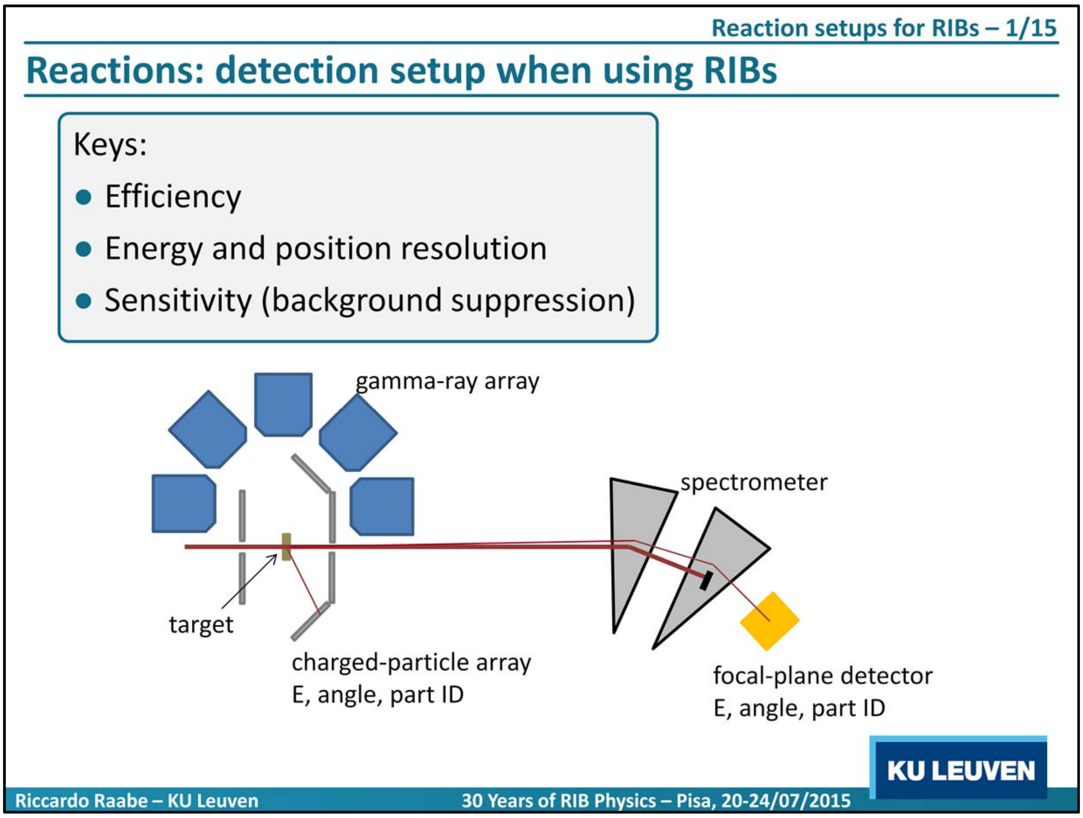
Incident radiation creates electron-hole pairs

- 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



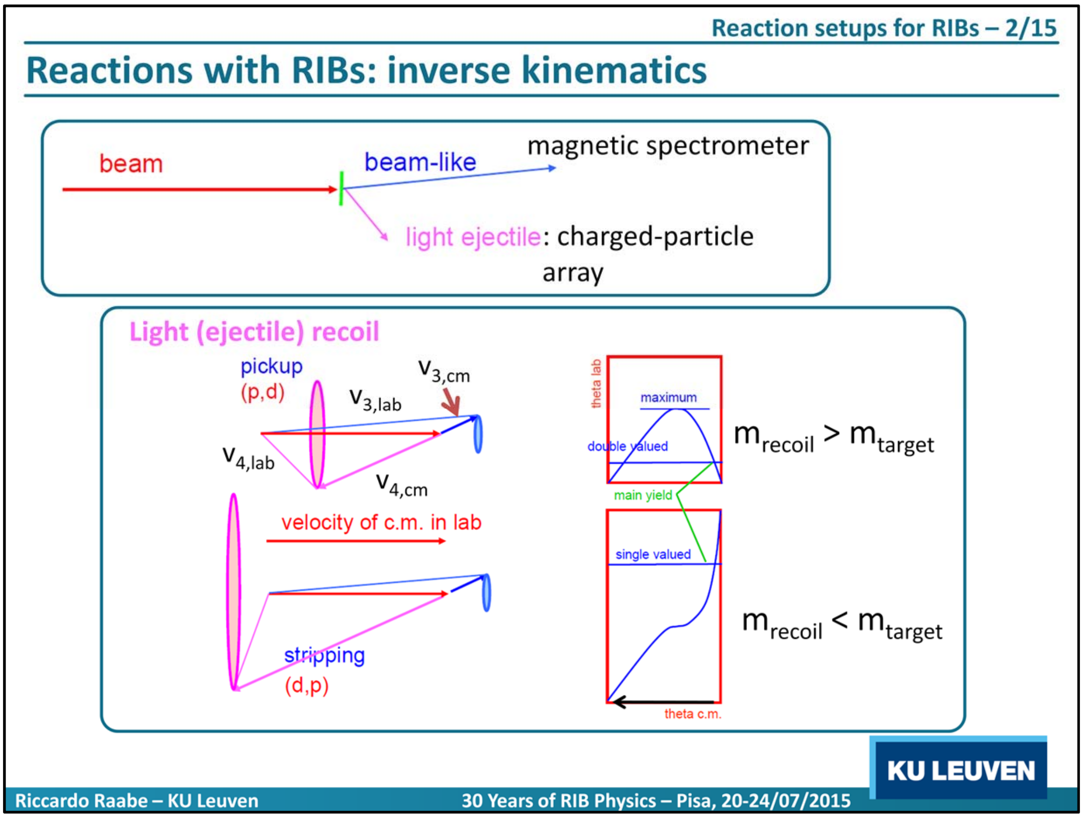


Semiconductor detectors offer the best energy resolution.
They are however very expensive.

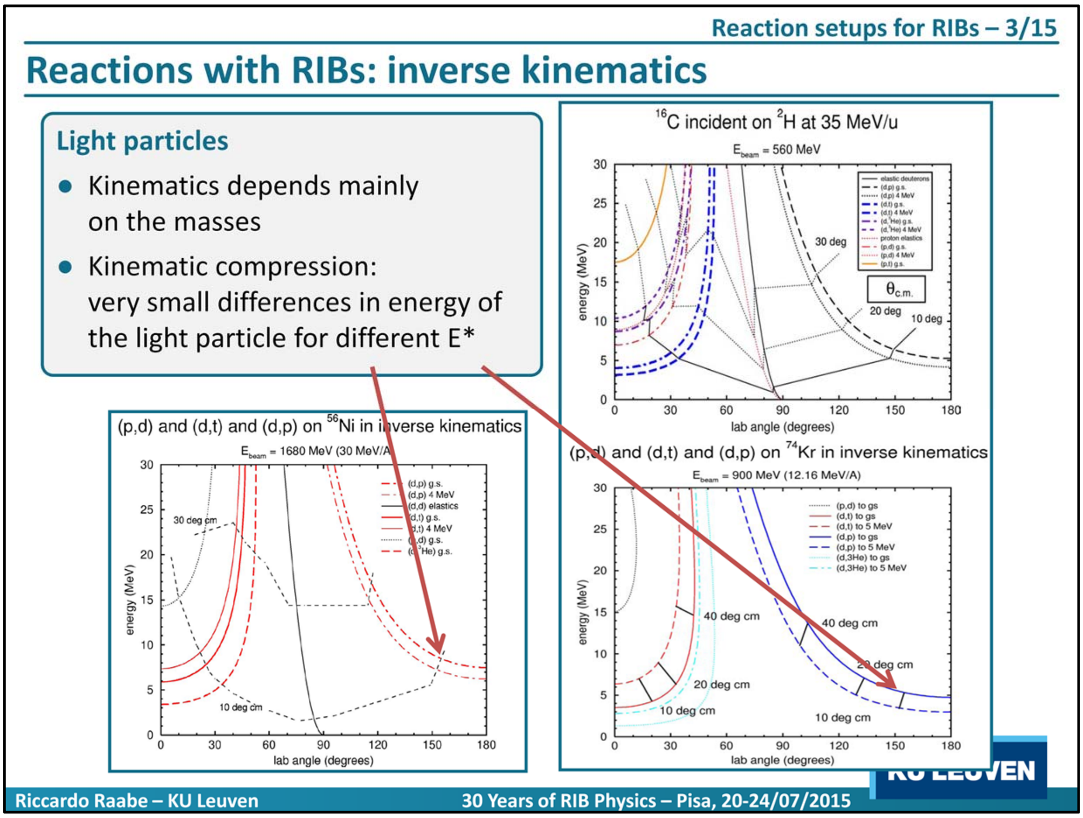


We focus on detection setups for reactions.

- The setup should ensure a high detection efficiency, good energy and possibly position resolution, and the best possible suppression of background.
- The latter is crucial when using radioactive ion beams, as the ions will decay emitting unwanted radiation. Coincidence detection of different signals is the best way (trying not to compromise efficiency).
- There is an additional crucial difference with respect to arrangements for stable nuclei, where the nucleus to be studied is the target: here the beam is heavier, and it will be only barely deviated from its path by a collision with the light target nucleus.

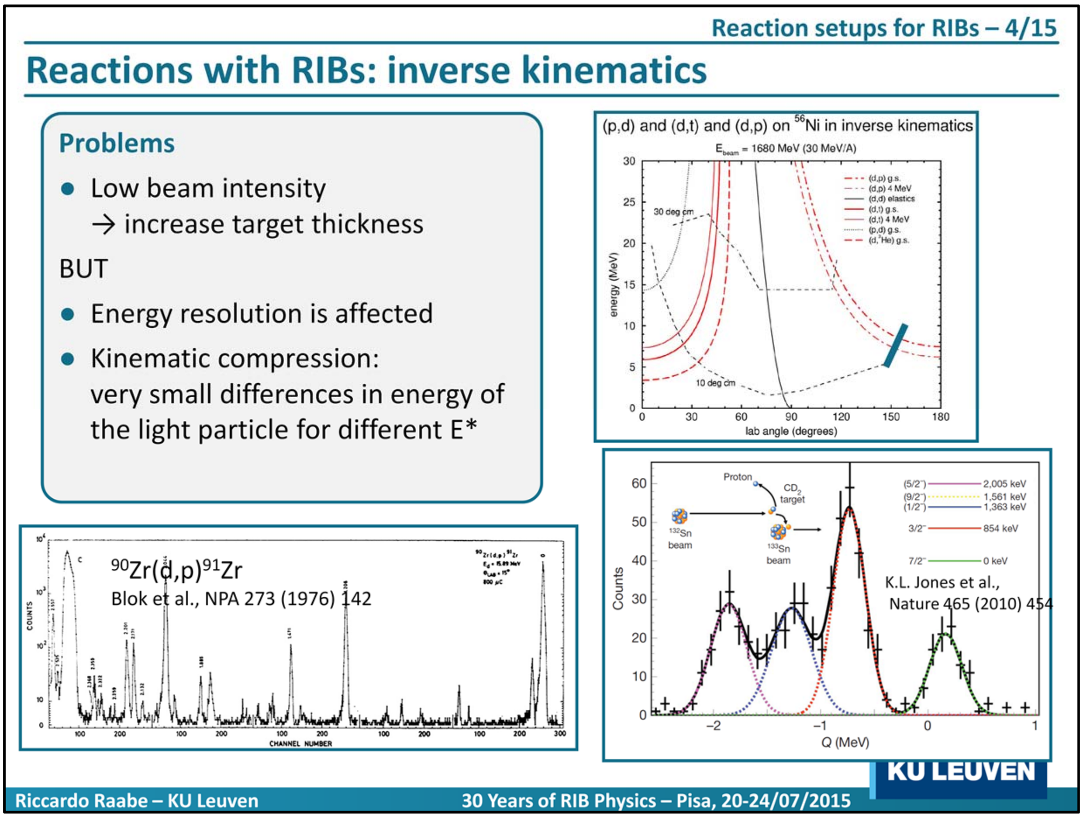


This is “inverse kinematics”.
Can be calculated with conservation of momentum and energy principles.
Sometimes the result (where the particle come out and at which energy) can be surprising. Try to think in terms of centre-of-mass of the colliding system.



Here are kinematic plots for different kind of reactions (elastic, nucleon transfer).

- They look very similar. In fact the kinematic mostly depend on the masses of the incoming and outgoing light particle.
- Another feature is the kinematic compression: different Q-values of the reaction, due to excitation in the heavy projectile, are detected as small variation in energy of the outgoing charged particle.



The inverse kinematics induces resolution problems through

- The thickness of the target.
- The kinematic compression.

The two effects combine for the worst:
The projection in Q-value already suffers from the target thickness problem, and this is amplified by the kinematic compression.
Compare a spectrum obtained in direct kinematics with tat from the 132Sn(d,p) reaction in inverse kinematics.

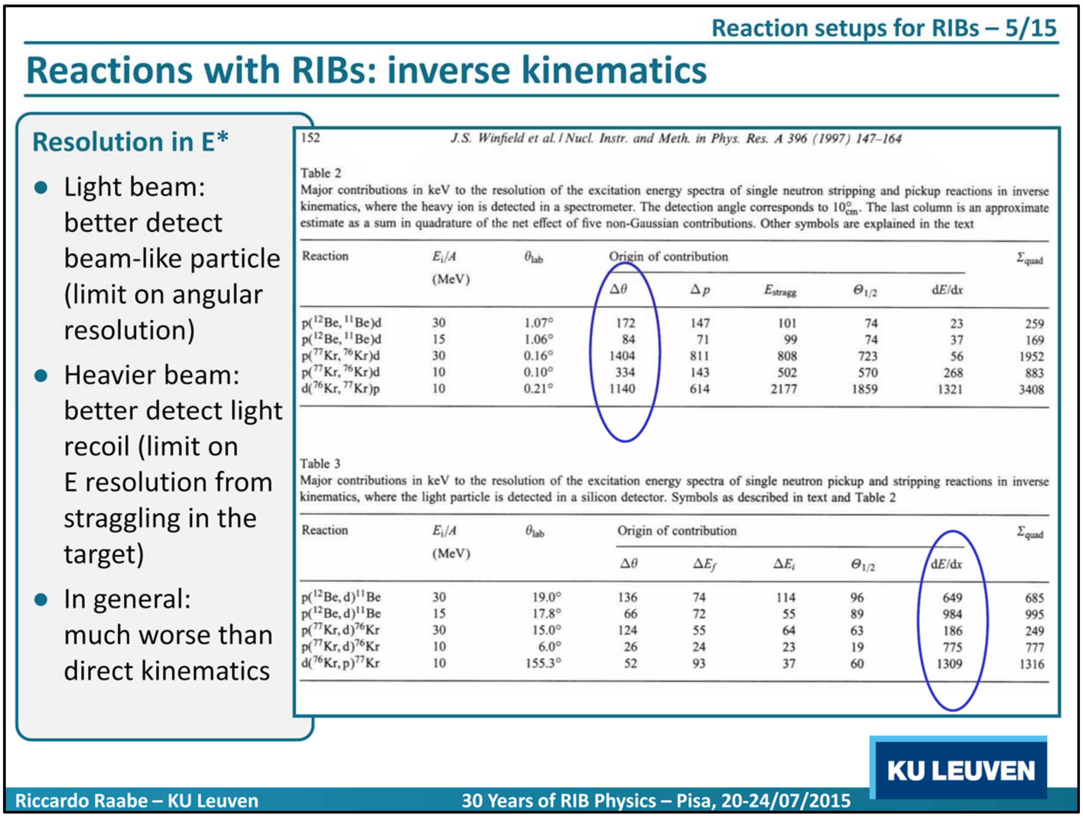


Table 2
Major contributions in keV to the resolution of the excitation energy spectra of single neutron stripping and pickup reactions in inverse kinematics, where the heavy ion is detected in a spectrometer. The detection angle corresponds to 10°_{cm}. The last column is an approximate estimate as a sum in quadrature of the net effect of five non-Gaussian contributions. Other symbols are explained in the text

Reaction	E_i/A (MeV)	θ_{lab}	Origin of contribution $\Delta\theta$	Δp	E_{stragg}	$\Theta_{1/2}$	dE/dx	Σ_{quad}
$p(^{12}Be, ^{11}Be)d$	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)	θ_{lab}	Origin of contribution $\Delta\theta$	ΔE_f	ΔE_i	$\Theta_{1/2}$	dE/dx	Σ_{quad}
$p(^{12}Be, d)^{11}Be$	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

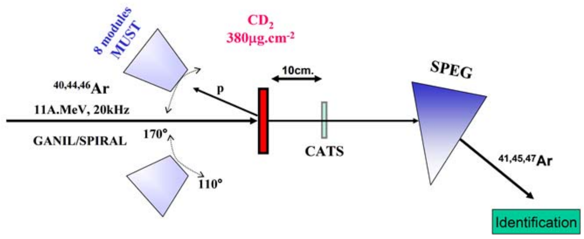
When do we need a zero-degree spectrometer?
The table compares the contribution to the measured resolution of the excitation energy of the beam-like particles. A loss in resolution comes from:

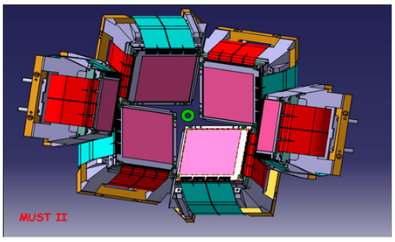
- The limited angular resolution Δθ of the detected particle (in a zero-degree spectrometer in the table above, in an array of silicon detectors around the target for the table below).
- The momentum resolution Δp in the spectrometer.
- Energy straggling (statistical differences in energy loss) when the projectile passes through the target.
- Small-angle multiple scattering $\Theta_{1/2}$.
- Energy loss difference dE/dx between the beam and the detected particle in the target thickness.
- Energy resolution of the Si detector ΔE_f.
- Spread in beam energy ΔE_i.

We see that the uncertainty on angular resolution dominates for the detection of the quasi-projectile in the spectrometer. The energy loss in the target dominates for the detection of the light particle in the Si array.
The overall balance depends on the mass of the incoming beam: if it is rather light it will be deviated enough from its path, so that the use of a spectrometer is of advantage. One can build a better spectrometer, but it is not trivial.
The spectrometer can in any case at least serve as a "tagging" device, to identify beam particles of interest from contaminants.

Examples of setups for reactions in inverse kinematics

GANIL: MUST2+SPEG





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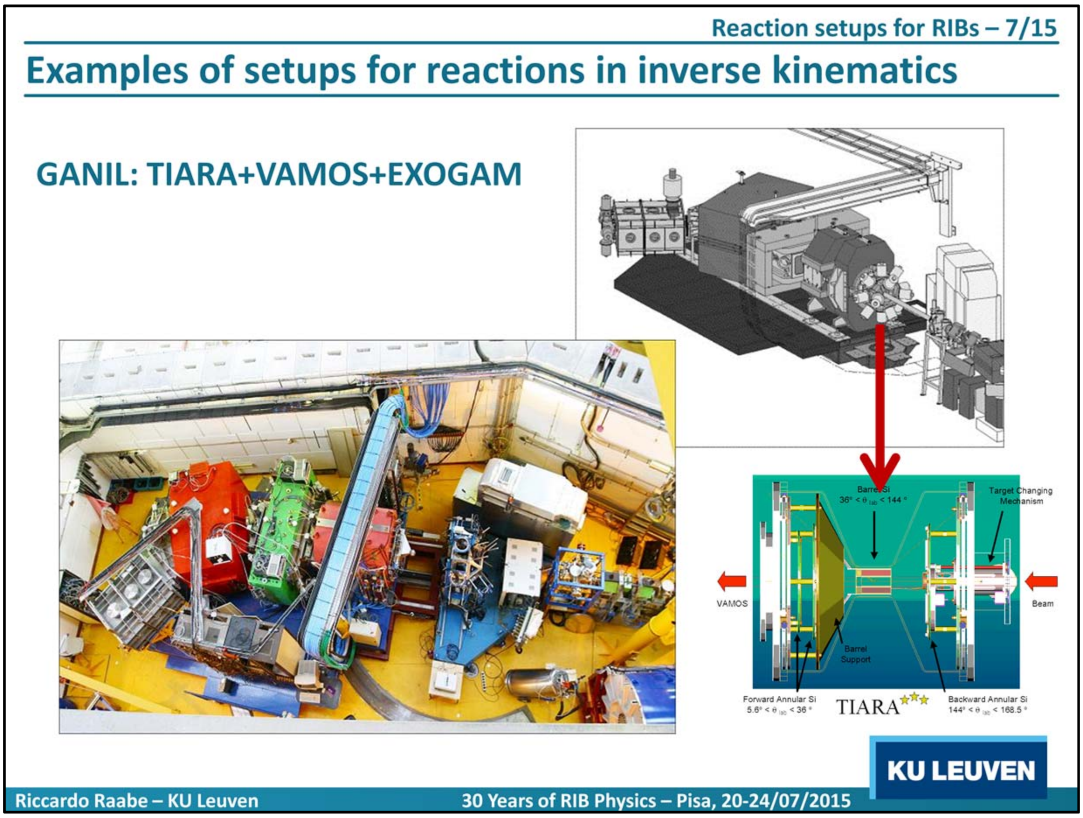
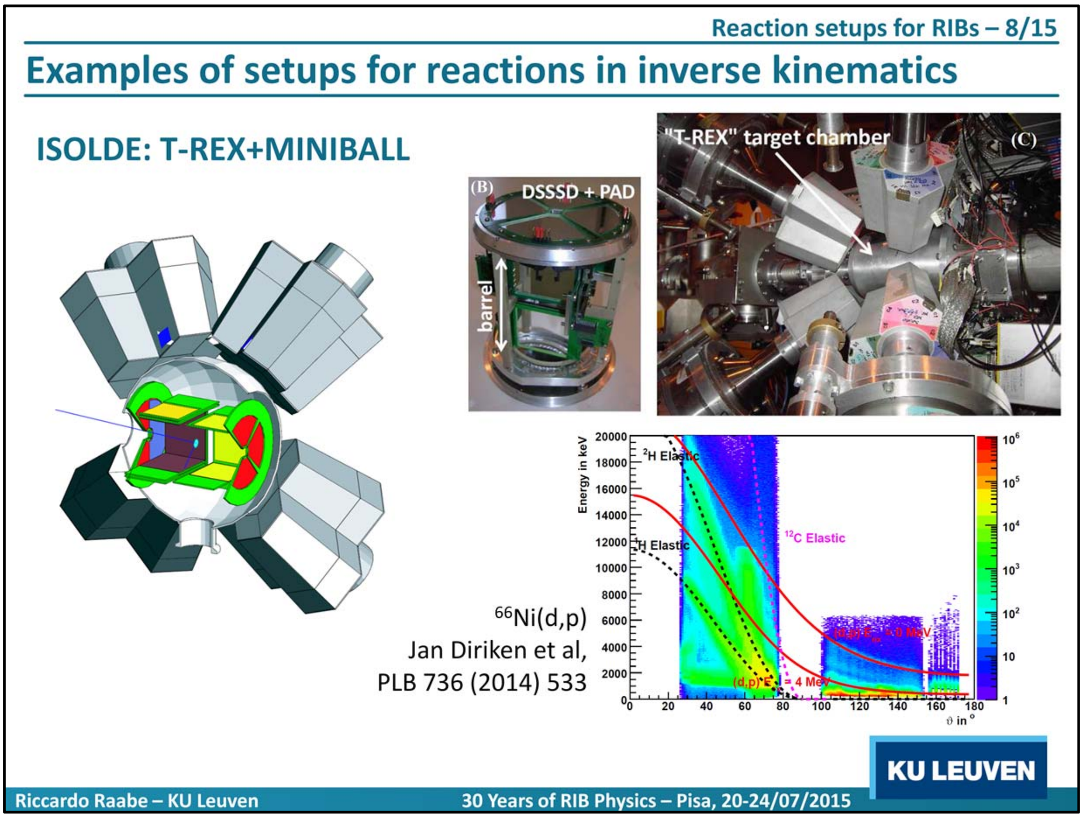
Some examples:

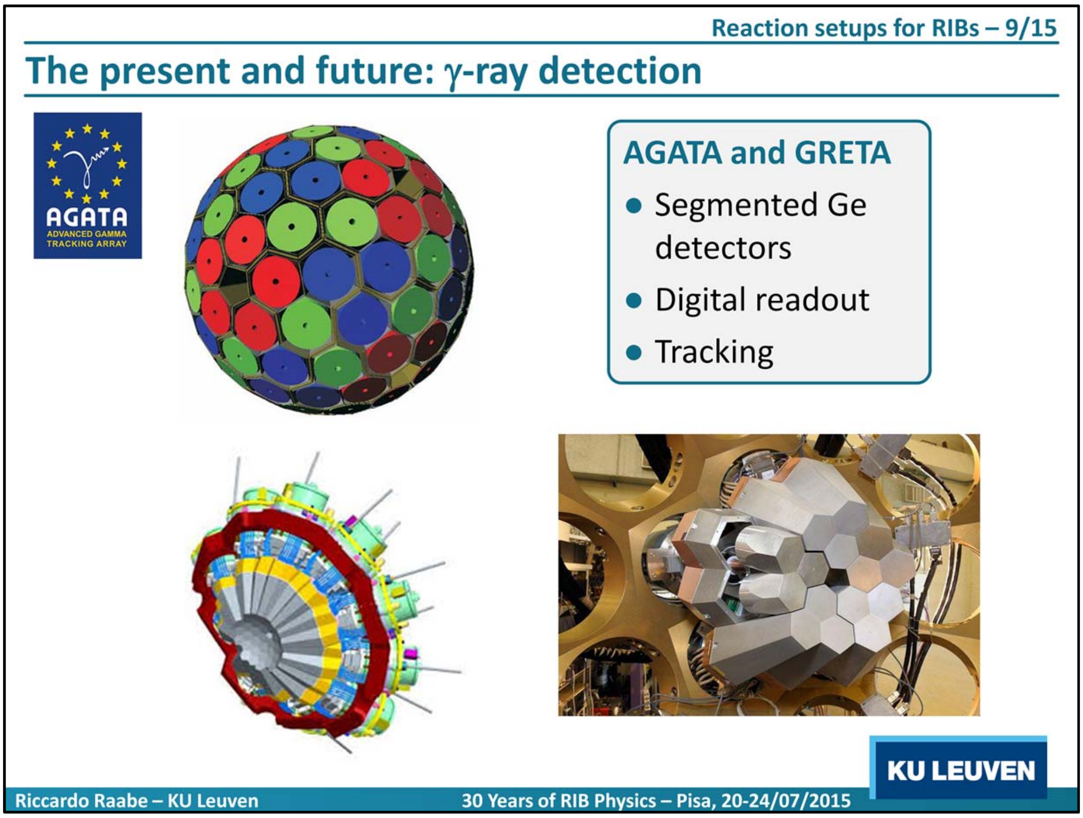
- The MUST2 array of silicon detectors. Double-sided silicon detectors, followed by other solid-stage detection stages. 128+128 strips each.
- SPEG is an old spectrometer, used as tagging device in some measurements with radioactive beams.



- VAMOS is still state-of-the-art concerning spectrometer. Very versatile.
- Exogam is one of the Ge arrays used for exotic beam physics. Large volume, segmentation.
- TIARA is an array of Si detectors optimised for use with Exogam.

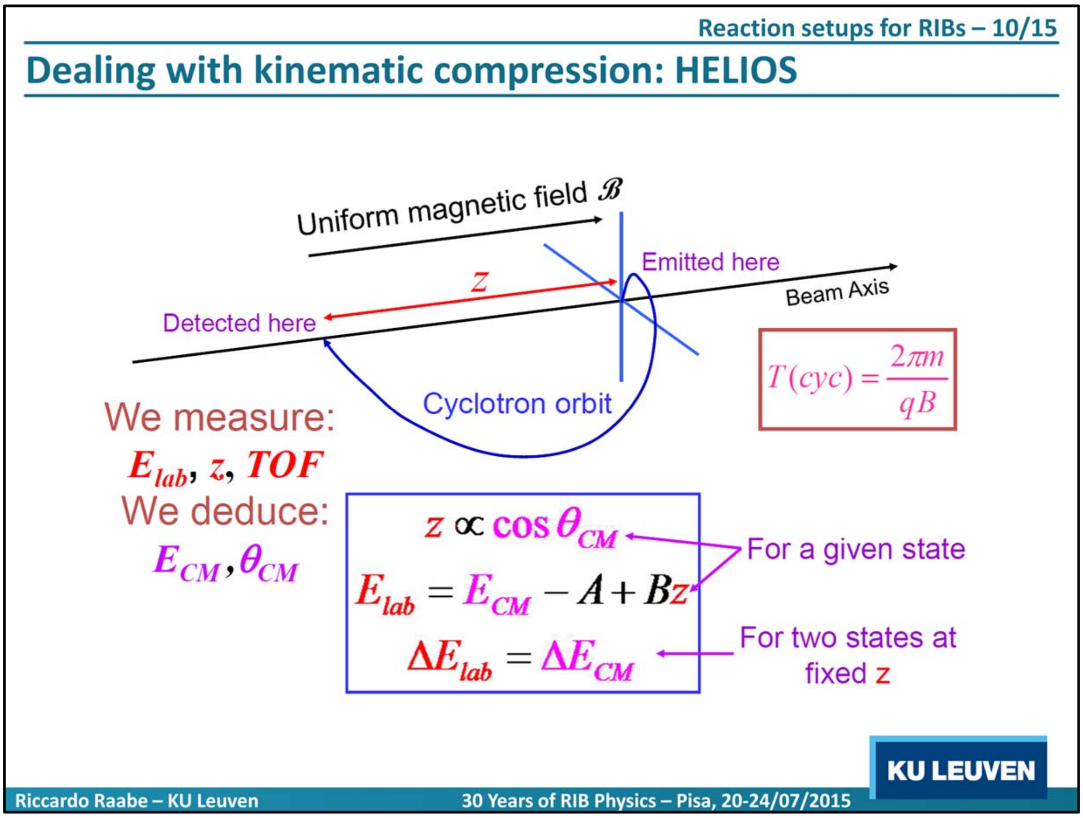


- Miniball is another array of Ge detectors for gamma-rays. Optimised for low multiplicity.
- It is combined with the charge-particle detection array T-REX.



Here are some examples of present developments:

- The new-generation arrays for gamma-ray detection: AGATA in Europe, GRETA in the USA.
- It uses segmented Ge detectors and digital read-out. The idea is to reconstruct the track of a gamma ray, to reduce Compton background and increase photopeak efficiency.
- The Demonstrator has already been used at LNL Legnaro, GSI, GANIL.

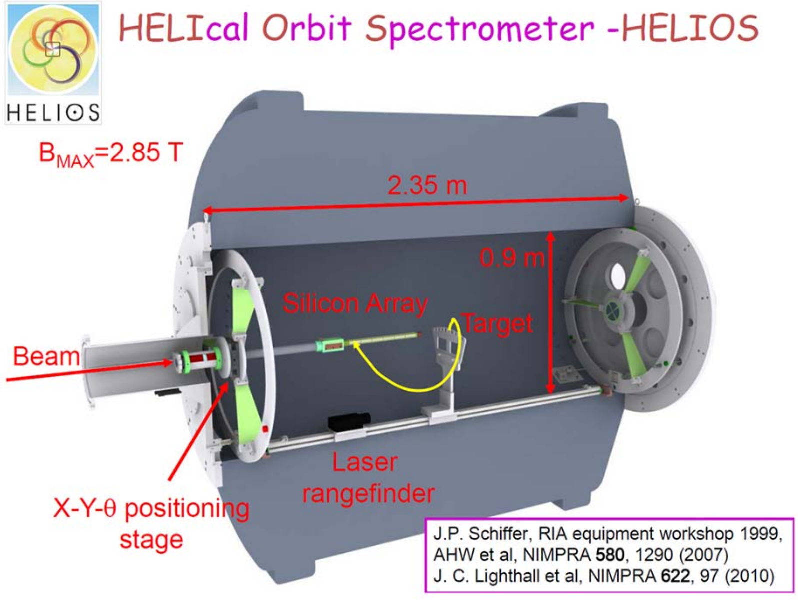


To eliminate the problem of kinematic compression, the HELIOS approach was developed.

- The target foil is surrounded by a magnetic field directed along the beam axis.
- The outgoing light particles are bent according to their magnetic rigidity.
- It turn out that the energy in the centre-of-mass (Q-value of the reaction) depends linearly on the measured lab energy and the position where the particles return to the axis.
- The uncertainty on the Q-value is the same as that on the detected energy at a given position.

Dealing with kinematic compression: HELIOS

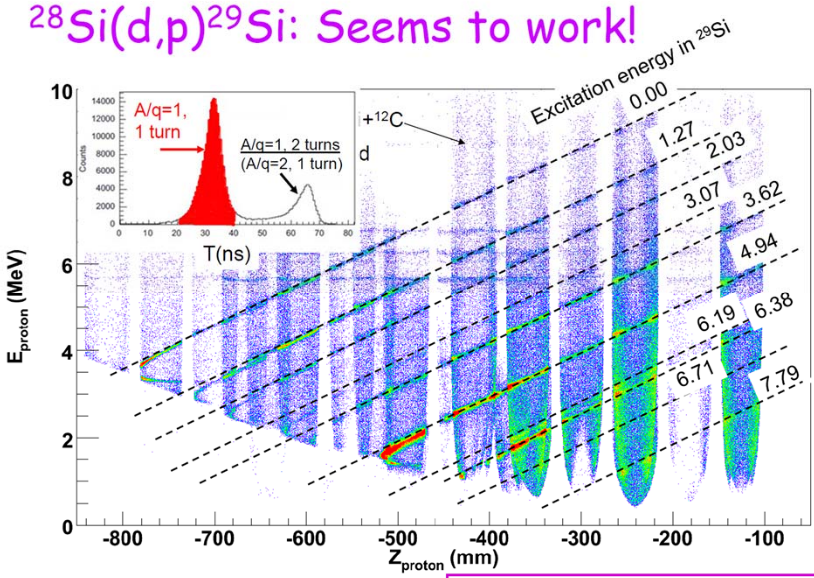
HELIcal Orbit Spectrometer -HELIOS



Implemented in the HELIOS setup at Argonne (Chicago).

Dealing with kinematic compression: HELIOS

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



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

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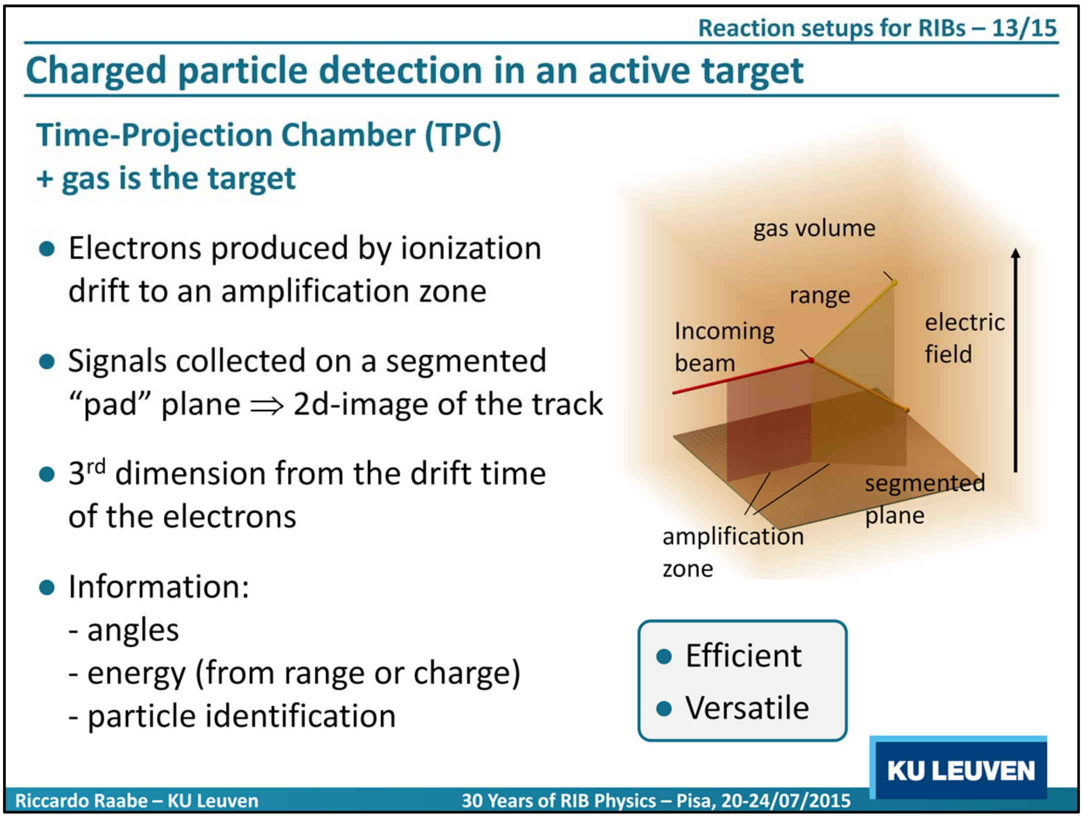
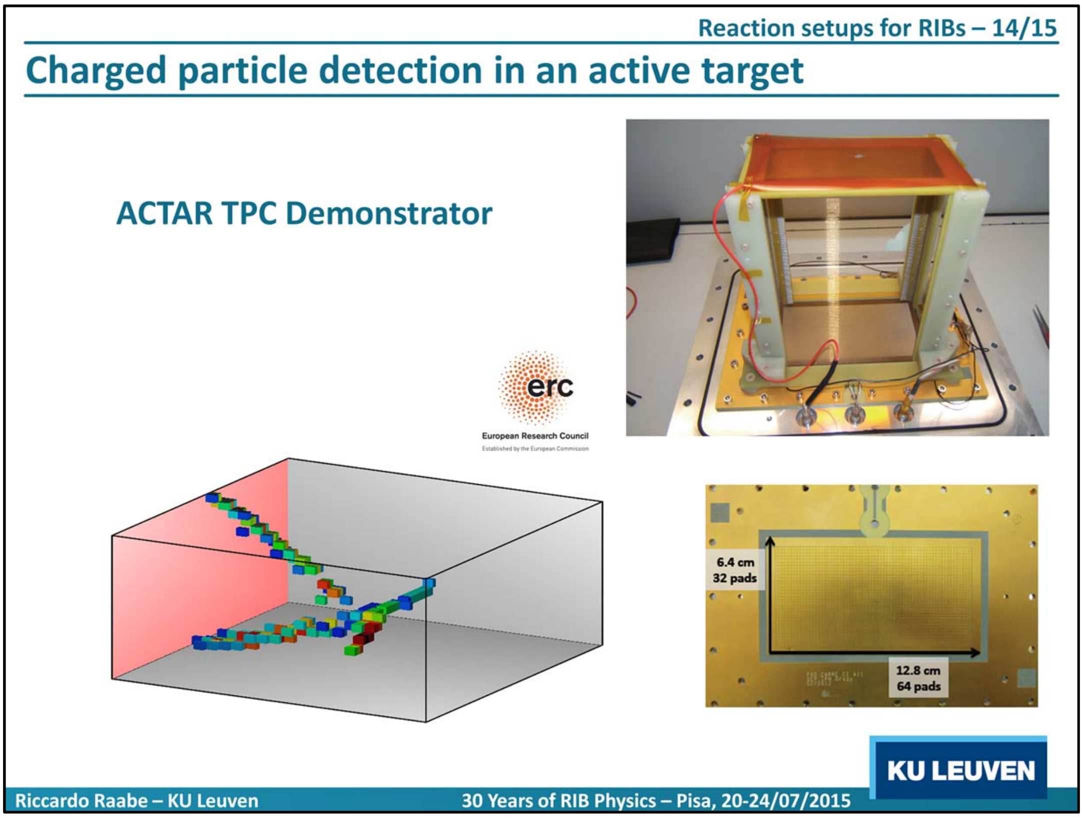
An example of energy spectrum: The lines of fixed Q-value are parallel, there is no kinematic compression.

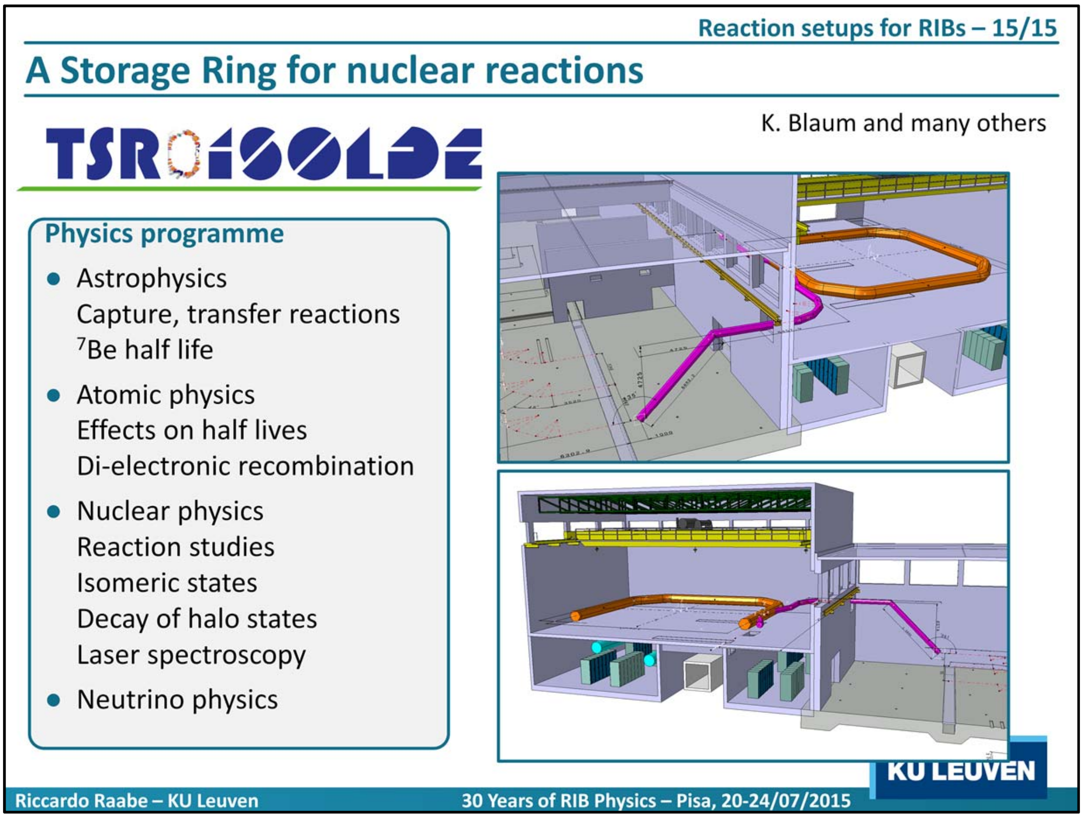


Another possibility for the detection of charged particles is the use of an active target.

- It is a gaseous detector, where the nuclei of the detection gas are also the target of the reaction to be studied.
- The tracks are recorded: the vertex, and thus the energy at the interaction point, can be reconstructed to high precision. At the same time one can use a very large target thickness without losing in resolution.
- It is extremely versatile: different gases can be used, at different pressures, etc.



A Demonstrator of the Active target has already been used in measurements.
There is a growing number of such devices being built at many facilities.



Advantage: the beam which does not react keeps on circulating in the ring. The beam intensity is thus multiplied by the revolution frequency, about 10^6.
There is a trade off in terms of target thickness: it has to be very low in order to not disturb the non-reacting beam particles. A gas-jet target is used.
The resolution that can be achieved is potentially much better than with a traditional external target.

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?**