Producción y uso de haces radioactivos

Master Interuniversitario de Física Nuclear

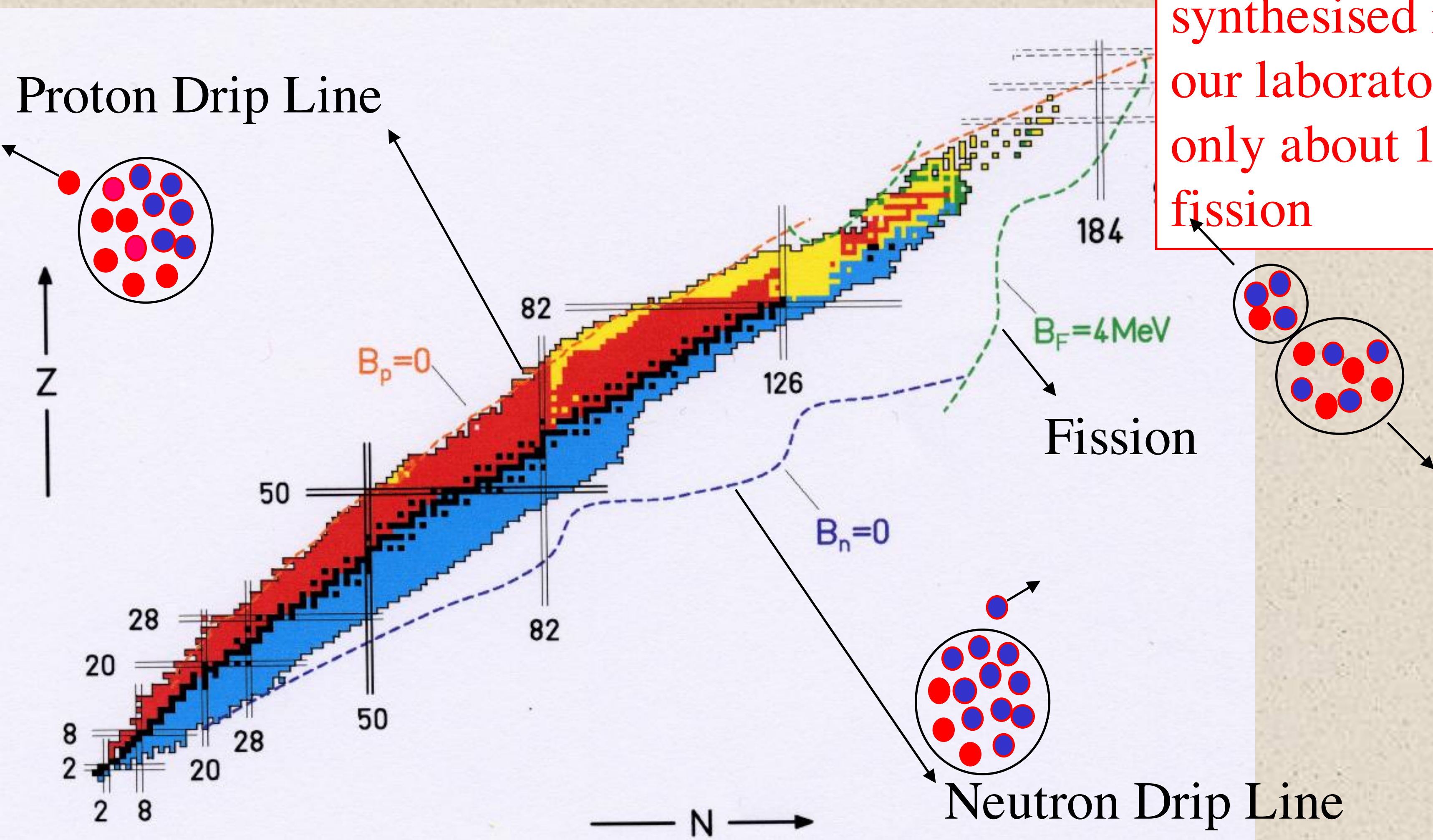
Berta Rubio IFIC (CSIC-Univ. Valencia)

Porqué la producción de haces radioactivos ha marcado un antes y un después en la Física Nuclear

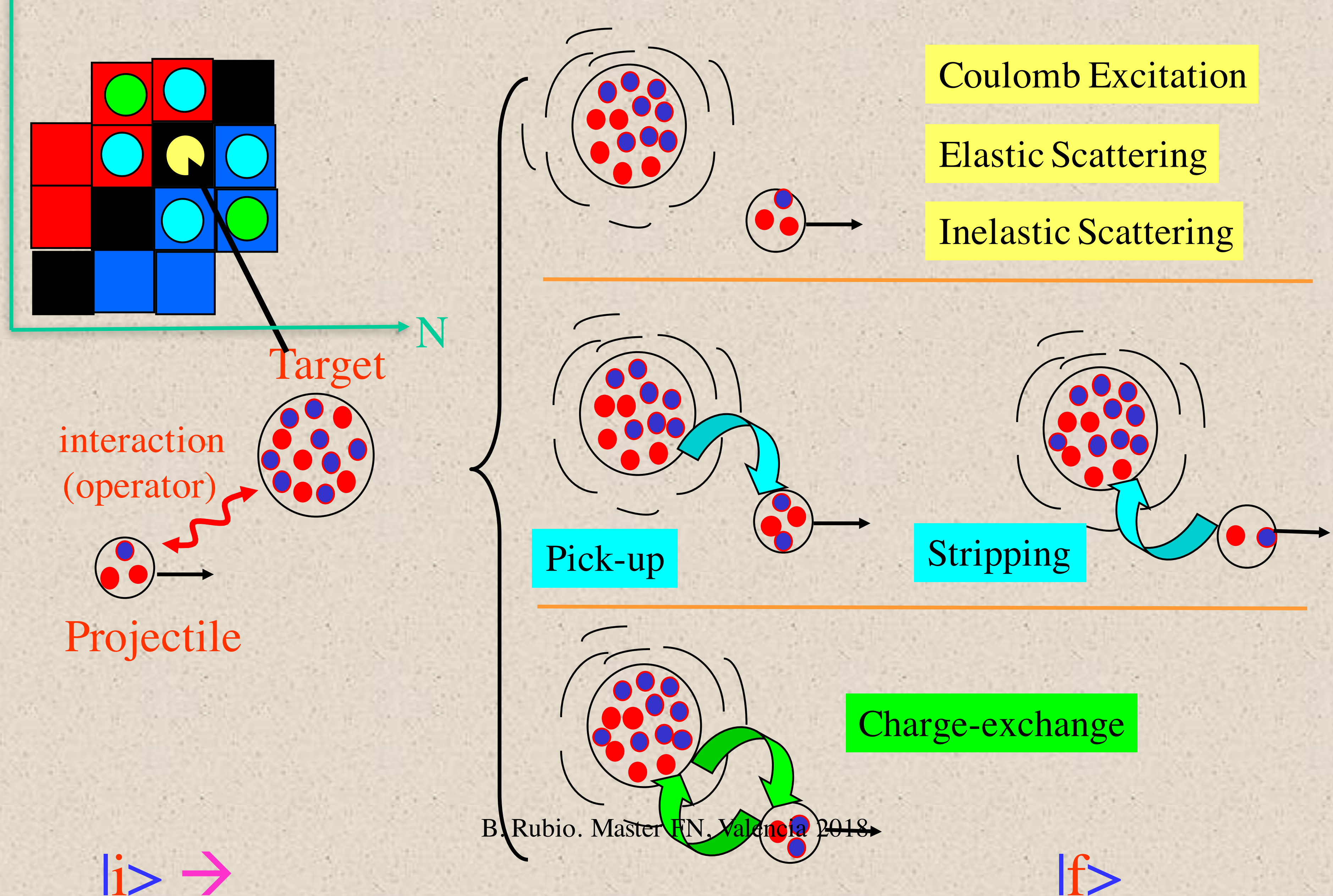
Reacciones nucleares y lo que nos enseñan de la estructura de los núcleos.
Porqué necesitamos haces postacelerados
Porqué necesitamos alejarnos de la estabilidad.

265 stable

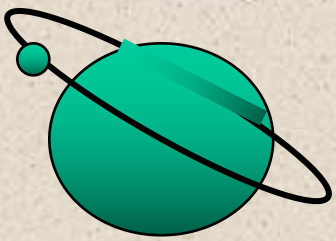
About 3000 out of 6000 synthesised in our laboratories, only about 100 fission



Close to the stability Direct Reactions with Light Projectiles, p, d, α, e-, γ, etc.. give us detailed information on the structure of the target nucleus



Let us use an illustrative example



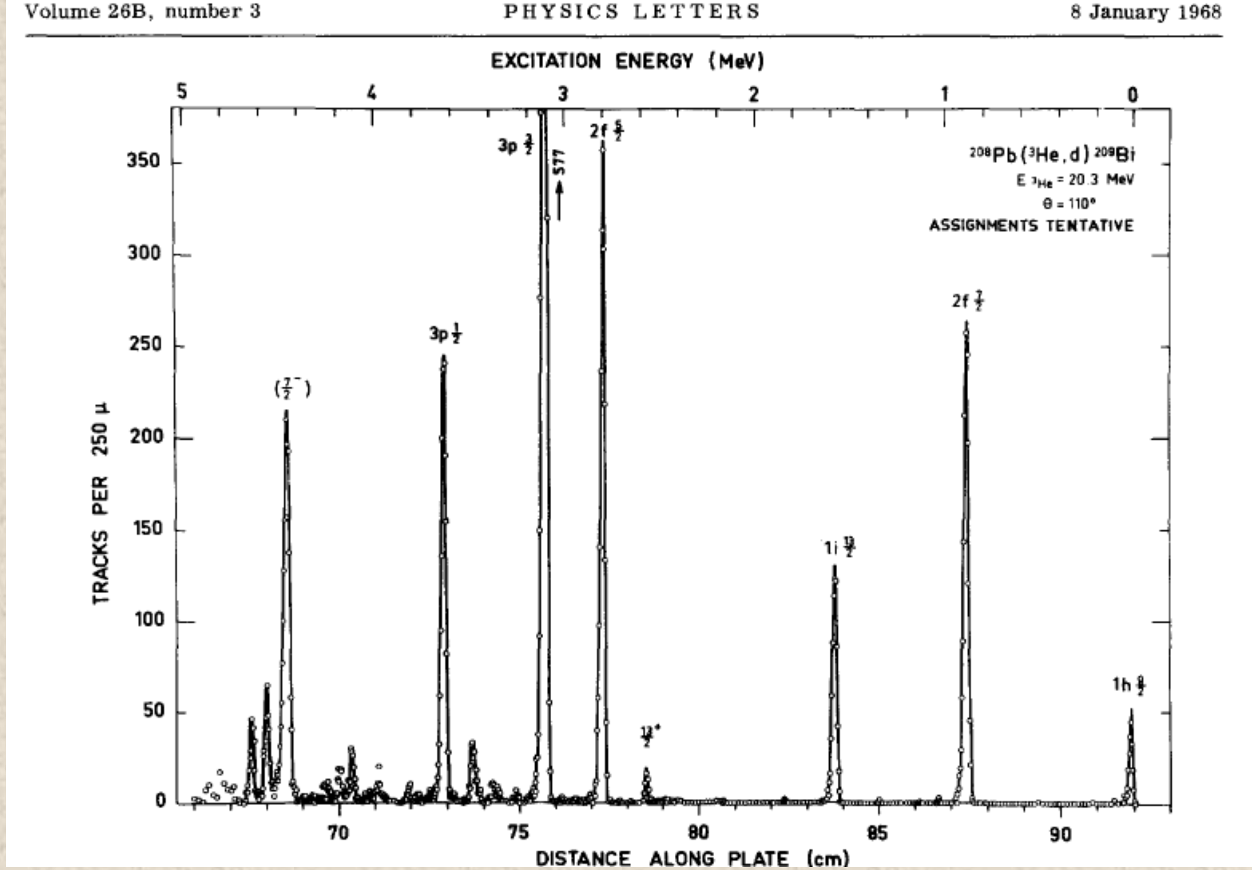
209Bi=208Pb+p

$$^{209}_{83}\mathrm{Bi}_{126}$$

Closed shell + 1 p

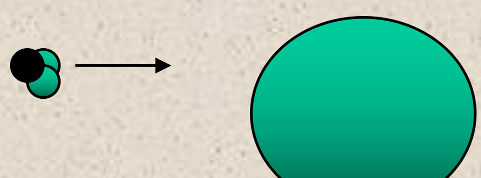
Closed shell for neutrons

Z



Reaction:

208Pb(3He,d)209Bi
E(3He)=20 MeV



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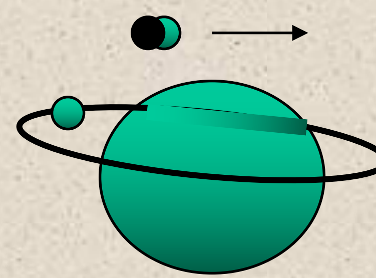
208Pb target



209Bi final nucleus

52 Shell Model and Residual Interactions

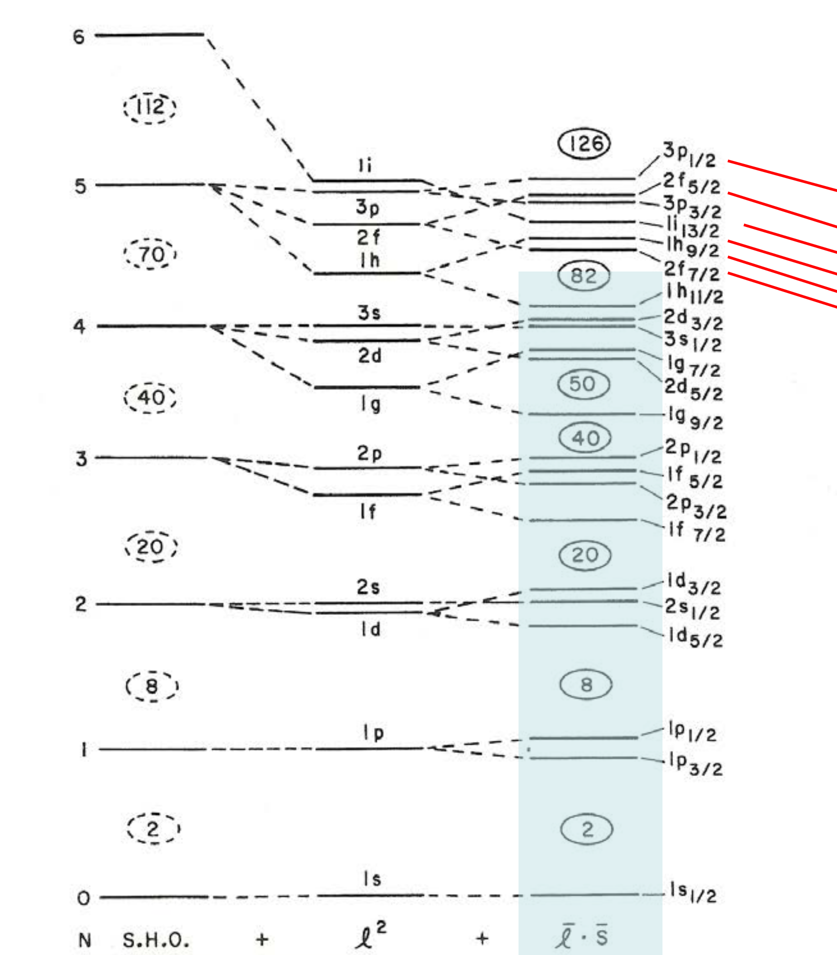
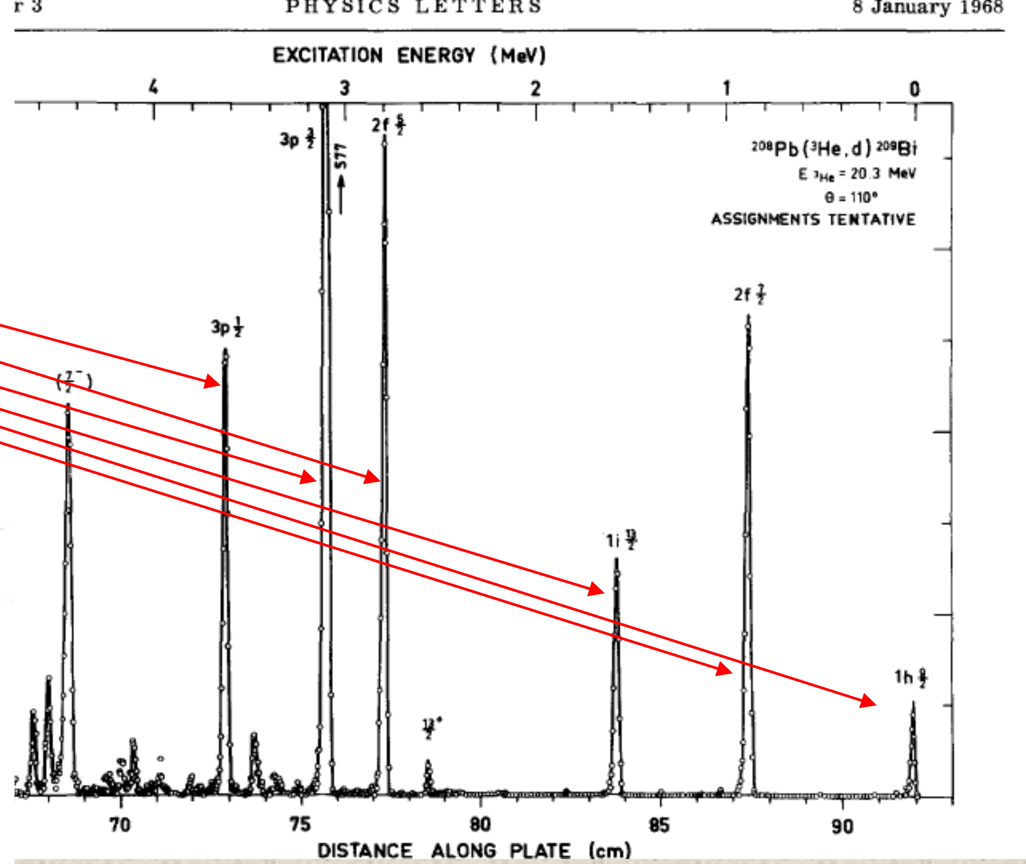


Fig. 3.2. Single-particle energies for a simple harmonic oscillator (S.H.O.), a modified harmonic oscillator with l^2 term, and a realistic shell model potential with l^2 and spin orbit ($l \bullet s$) terms.



208Pb(3He,d)209Bi
E(3He)=20 MeV

209Bi=208Pb+p

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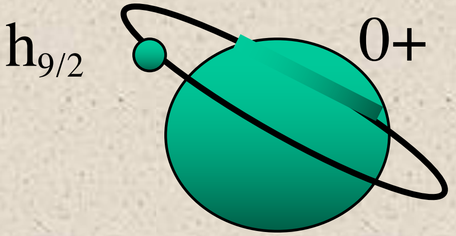
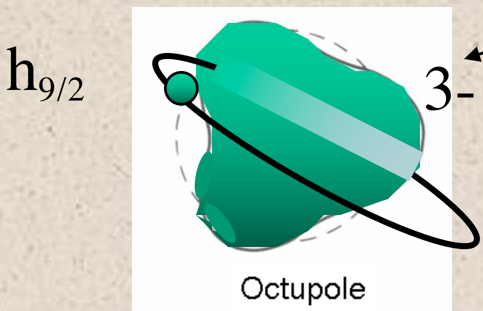


This is the gs of 209Bi

209Bi=208Pb+p



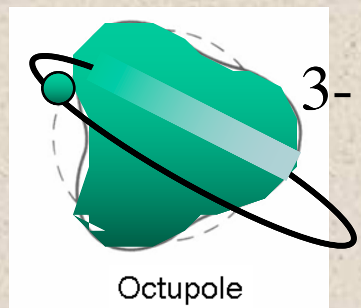
The first excited state
In 208Pb is an octupole excitation, 3-, at 2415 keV

One expects at the same energy in 209Bi
A septuplet:

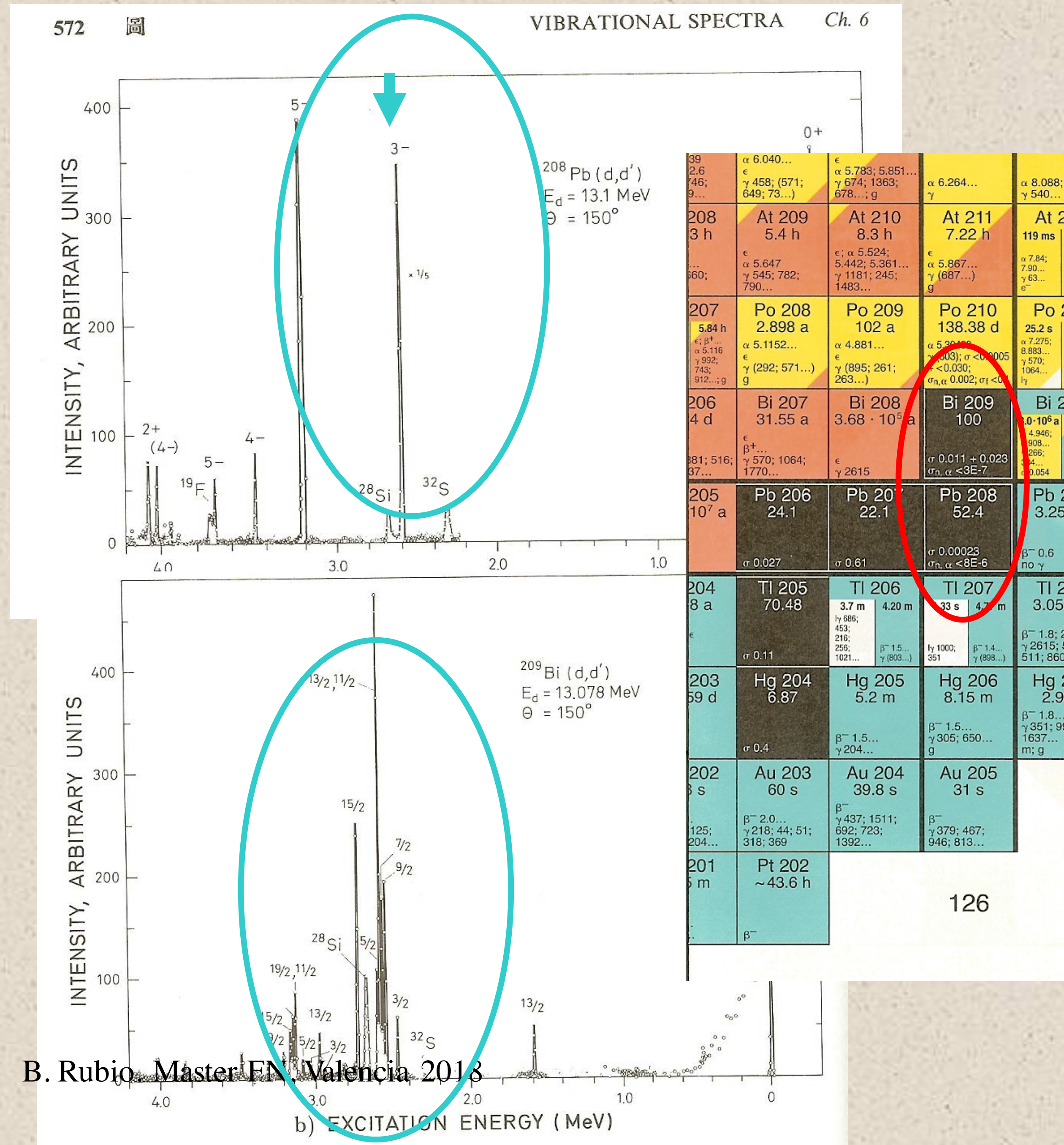
$$[3^{-}(^{208}Pb) \text{ x } h^{9/2}]_{3/2\ldots15/2}{}^{+}$$

The appropriate reaction is inelasctic scattering, for instance (d,d´)

$h_{9/2}$



209Bi=208Pb+p



One could go to more sophisticated excitation modes such as An isovector dipole resonance (E1)

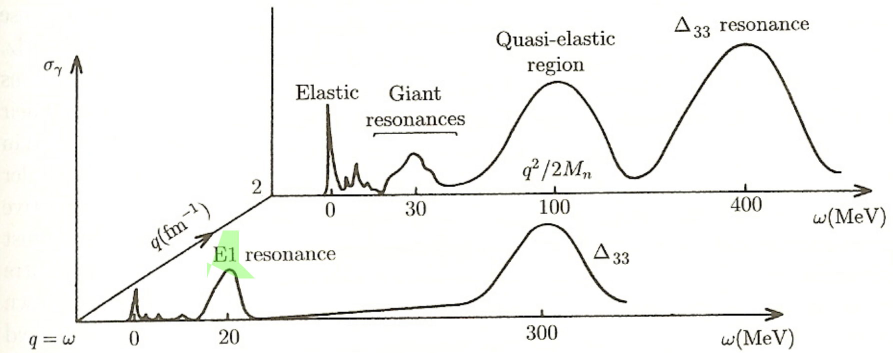
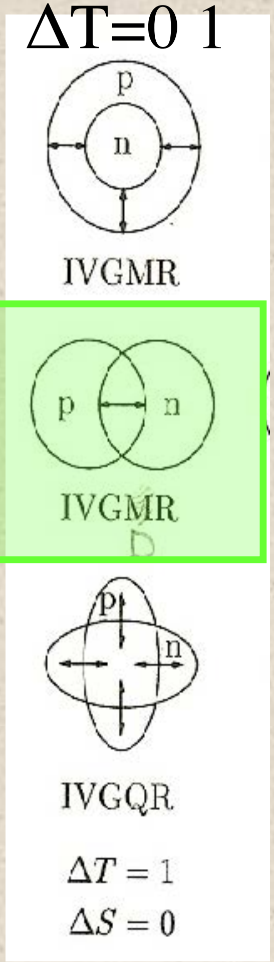
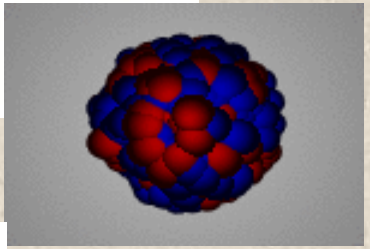


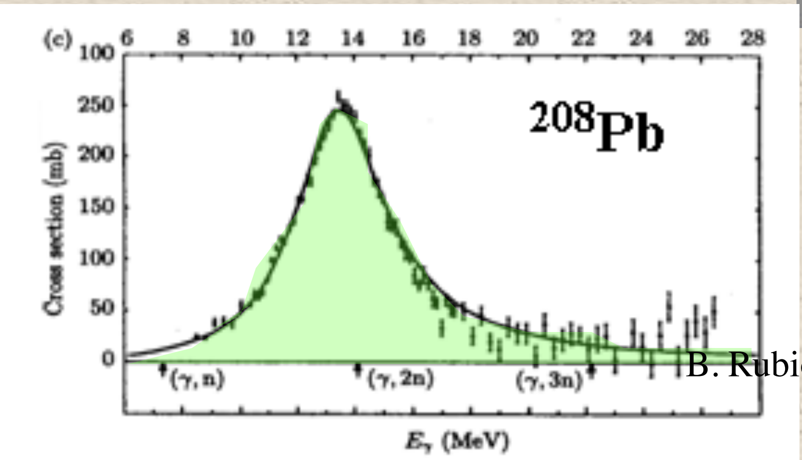
FIG. 1.1. Characteristic response (cross section σ) of an atomic nucleus as a function of the energy transfer ω and momentum transfer q. The lower curve is for photon absorption, the upper one for particle scattering with $q = 2$ $\mathrm{fm}^{-1} \neq \omega$.

Isovector
ΔT=0 1



E1

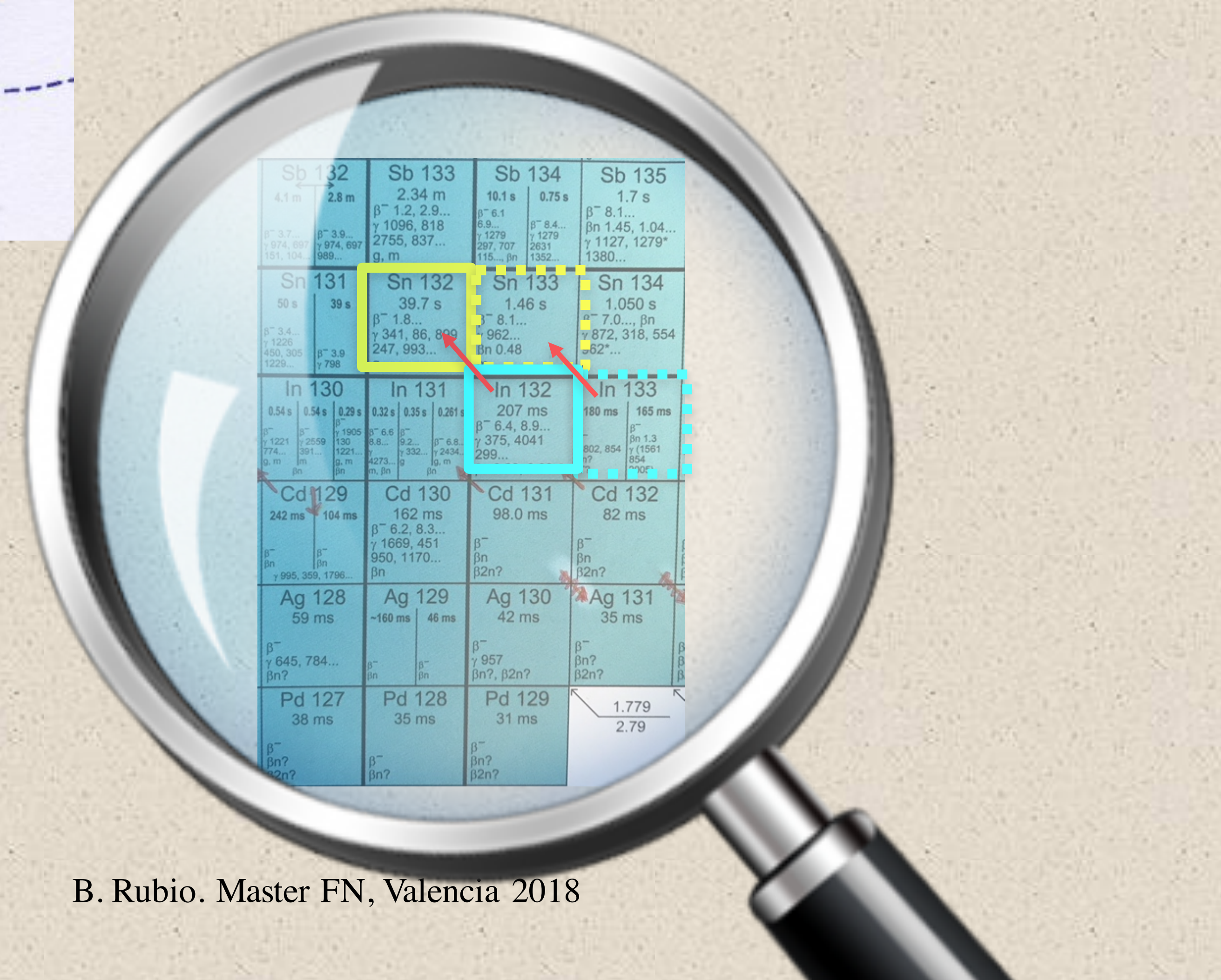




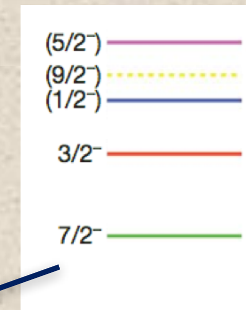
Qué ha sido necesario para poder hacer estos experimentos

1. Definir la reacción nuclear de interés.
2. Blanco estable: 208Pb y 209Bi en este caso
2. Un proyectil “sin estructura”
3. Un proyectil ligero (struggling)

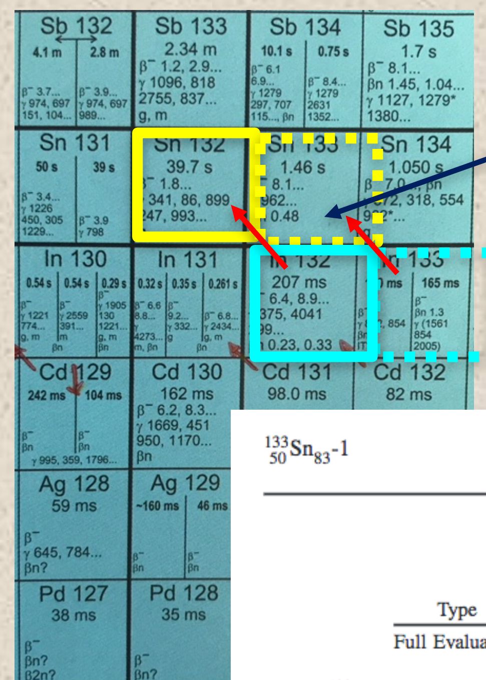
Vamos a intentar aproximarnos a otro núcleo doblemente mágico: 132Sn

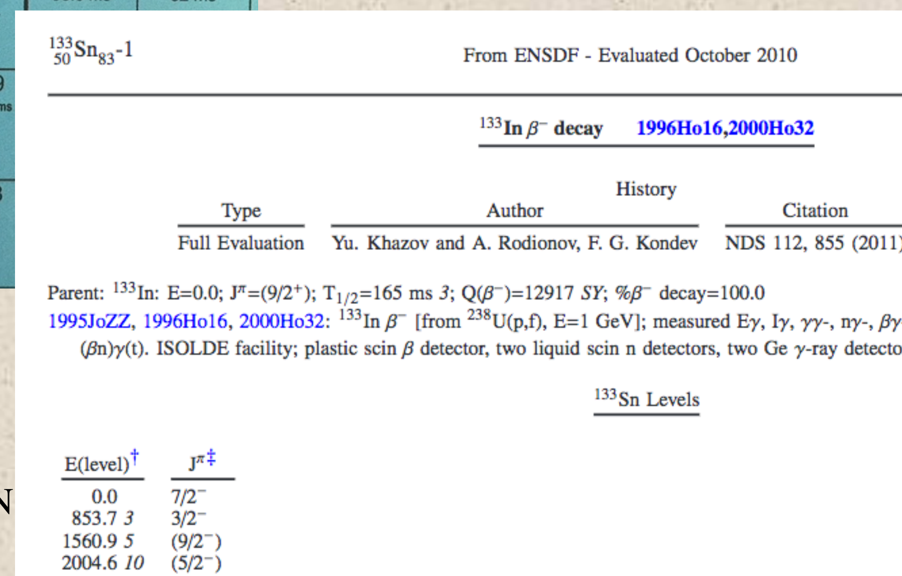


Vamos a intentar aproximarnos a otro núcleo doblemente mágico: 132Sn



Vidas medias, T1/2
207 ms !
180/165 ms !





$^{133}_{50}Sn_{83}$-1 From ENSDF - Evaluated October 2010

^{133}In β^- decay 1996Ho16,2000Ho32

History

Type	Author	Citation
Full Evaluation	Yu. Khazov and A. Rodionov, F. G. Kondev	NDS 112, 855 (2011)

Parent: ^{133}In: E=0.0; J$^\pi$=(9/2$^+$); $T_{1/2}$=165 ms 3; Q(β^-)=12917 SY; %β^- decay=100.0

1995JoZZ, 1996Ho16, 2000Ho32: ^{133}In β^- [from ^{238}U(p,f), E=1 GeV]; measured Eγ, Iγ, $\gamma\gamma$-, nγ-, $\beta\gamma$-c (βn)γ(t). ISOLDE facility; plastic scin β detector, two liquid scin n detectors, two Ge γ-ray detectors

^{133}Sn Levels

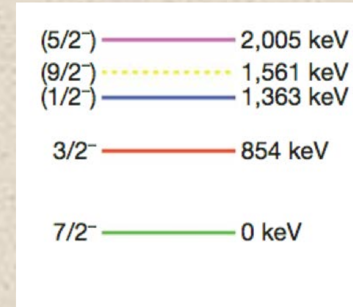
E(level)†	J$^\pi$‡
0.0	7/2⁻
853.7 3	3/2⁻
1560.9 5	(9/2⁻)
2004.6 10	(5/2⁻)

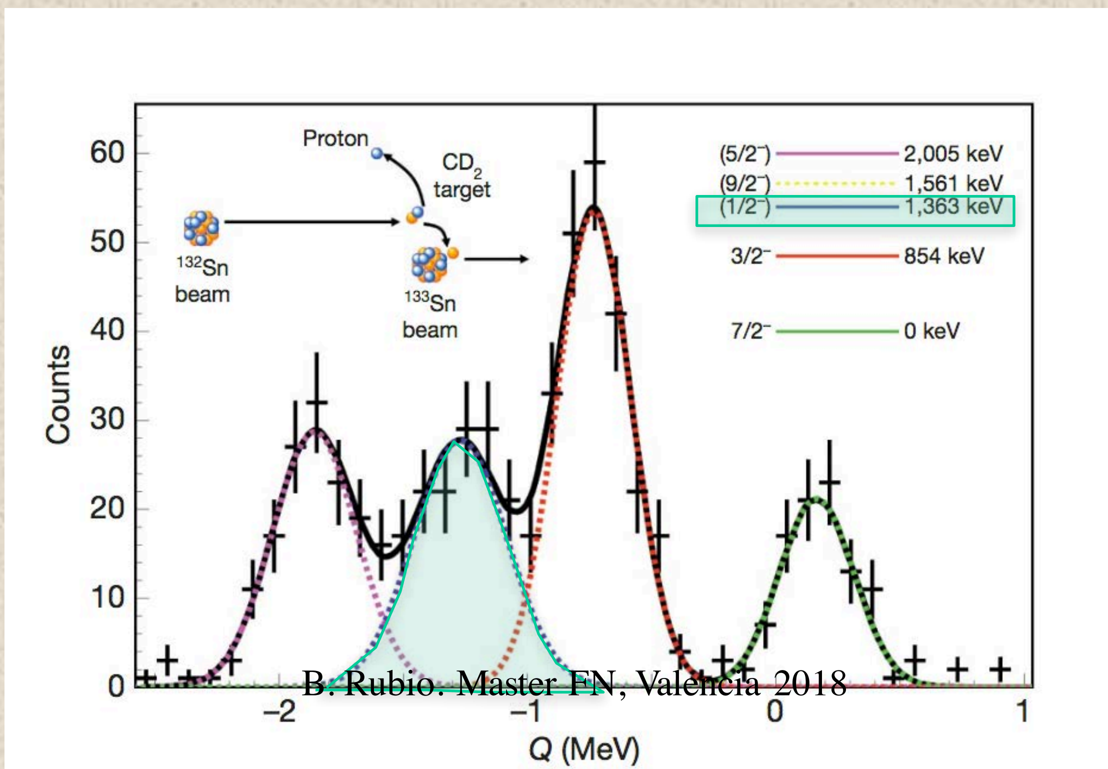
nature Vol 465 | 27 May 2010 | doi:10.1038/nature09048

LETTERS

The magic nature of ^{132}Sn explored through the single-particle states of ^{133}Sn

K. L. Jones[1,2], A. S. Adekola[3], D. W. Bardayan[4], J. C. Blackmon[4], K. Y. Chae[1], K. A. Chipps[5], J. A. Cizewski[2], L. Erikson[5], C. Harlin[6], R. Hatarik[2], R. Kapler[1], R. L. Kozub[7], J. F. Liang[4], R. Livesay[5], Z. Ma[1], B. H. Moazen[1], C. D. Nesaraja[4], F. M. Nunes[8], S. D. Pain[2], N. P. Patterson[6], D. Shapira[4], J. F. Shriner Jr[7], M. S. Smith[4], T. P. Swan[2,6] & J. S. Thomas[6]

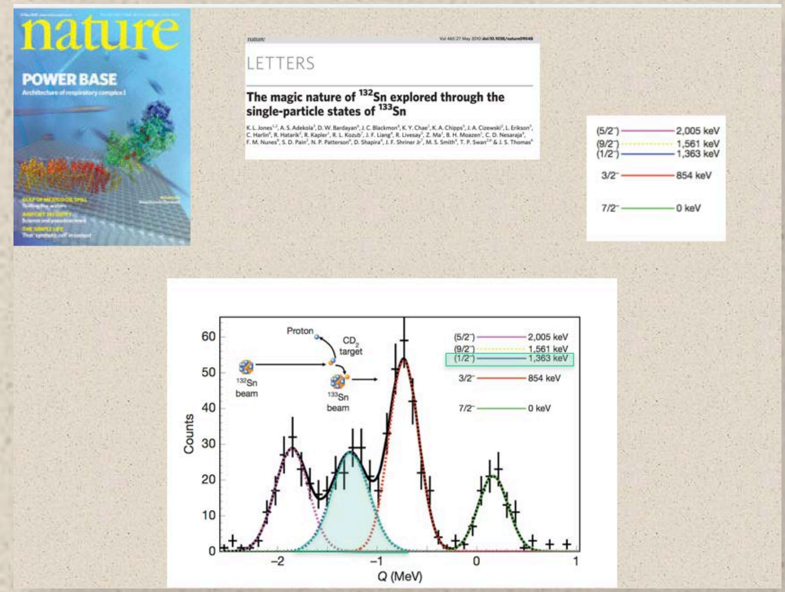




Conclusion of this part

It is important to go as far as possible from the stability because The primary information on the structure of a nucleus normally comes from the study of its decay.

It is important to have the possibility to perform reactions where either the target or the projectile are radioactive.



Haz radioactivo o target
Radioactivo?

132Sn + d → 133Sn + p

To produce a beam of 132Sn is possible (not easy),
To produce a target of 132Sn (T1/2=40 s) is impossible

We need to produce a beam of radioactive nuclei

The first thing to worry about is how to produce radioactive nuclei:
Tool: Reaction or Fission

The second thing to worry is to produce them in a “clean” way

For that it is important to separate them from other radioactive products

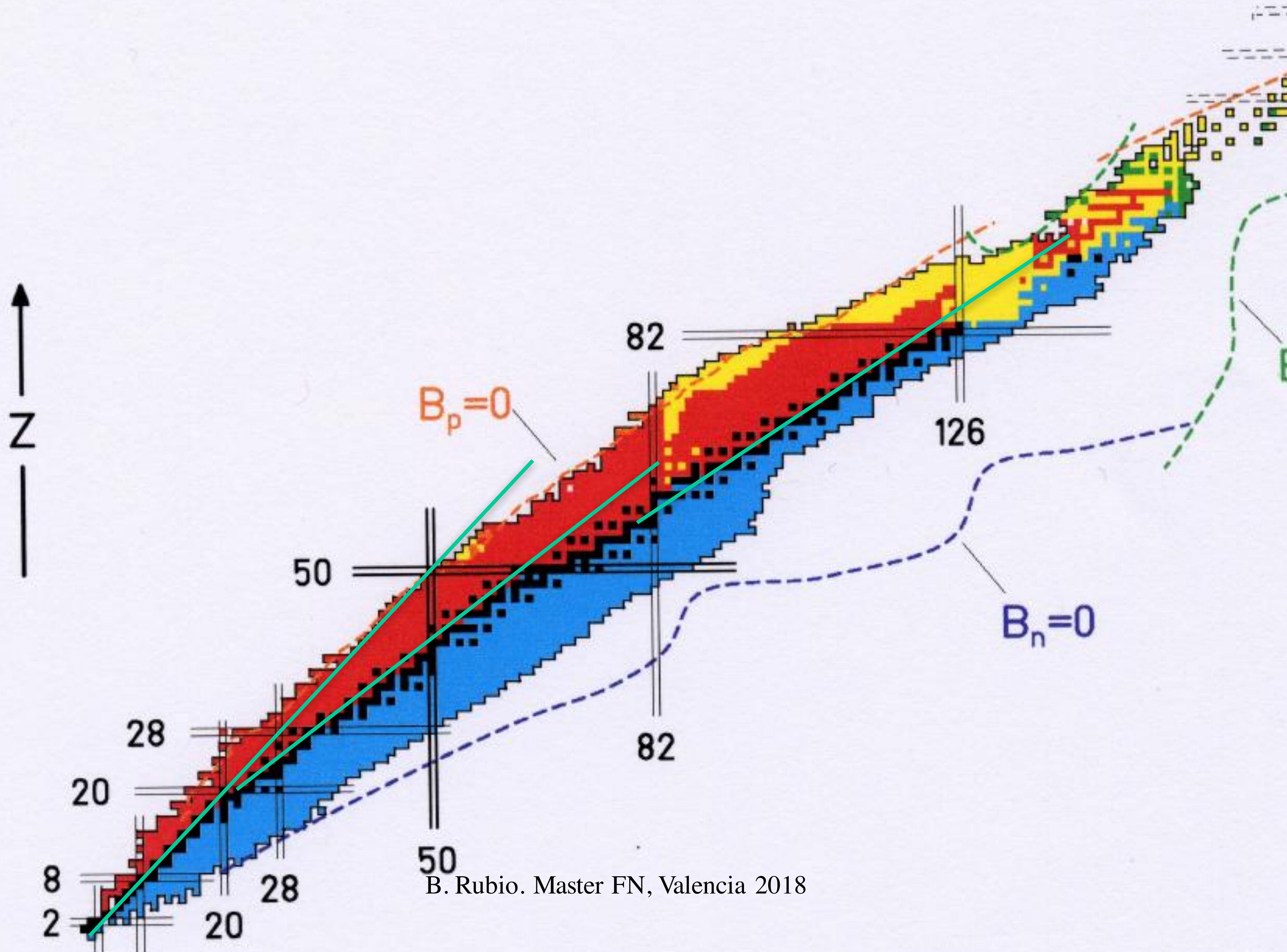
There are two main ways: the Isol method and the fragmentation method

Postaceleration

The first one is known since many years ago

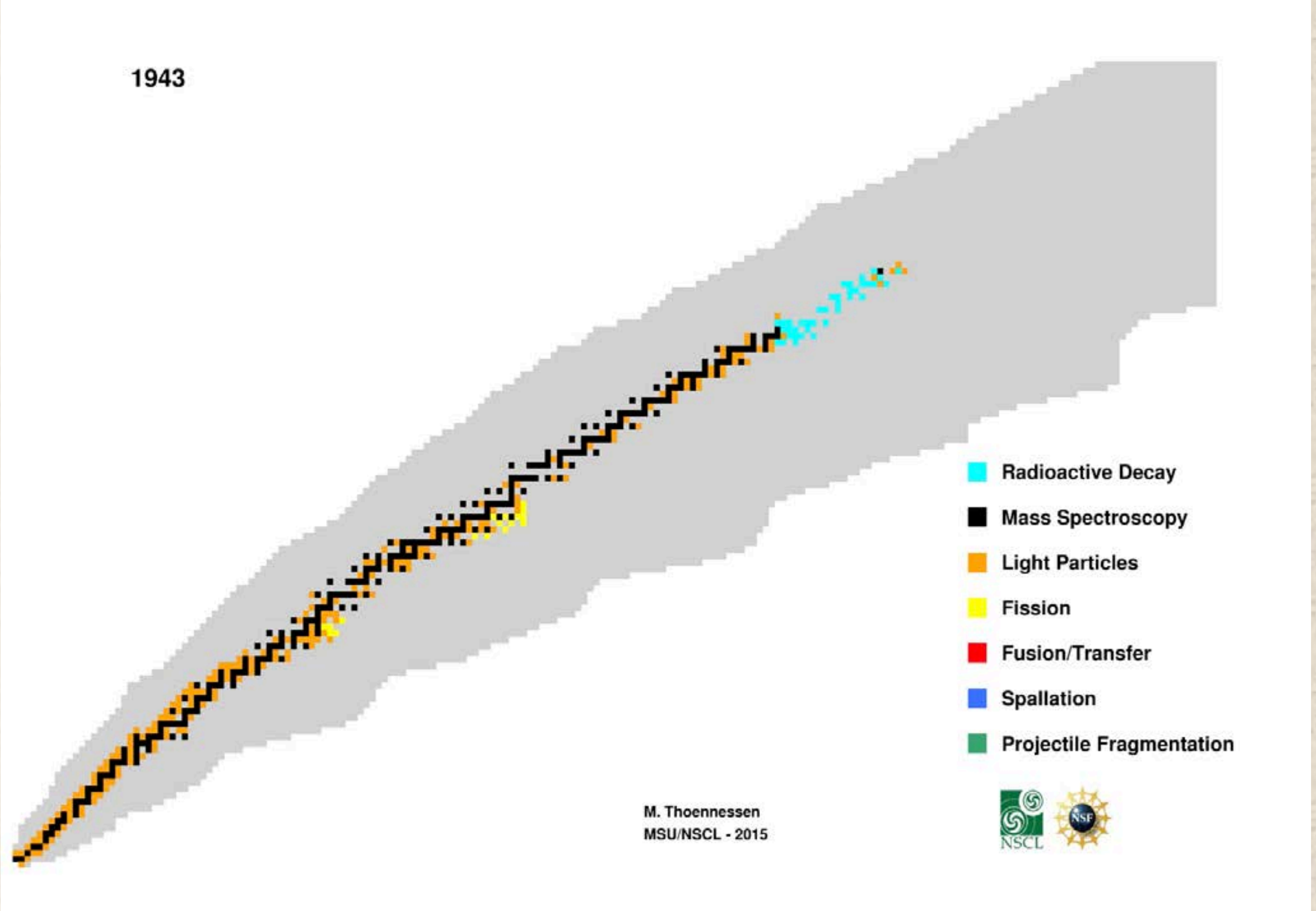
The reaction to produce Radioactive beams

Beam + target → products		Product energy	Number of Products	
GeV HI + (target)	fragmentation	"All nuclei" $v_{product} = v_{beam}$	up to 1000	Z, N; beam
GeV p + (target)	spallation	"All nuclei" few MeV/u	up to 1000	Z, N; target
small p/n + (target)	fission	"mainly neutron rich" ~1 MeV/u	few 100	Z, N; target
5MeV/u HI + (target)	fusion-evaporation	"mainly proton rich rich" $E_R = \frac{m_p}{m_p + m_t} E_P$	few (≤ 20)	Z, N; target+beam; target
20 MeV/u (beam) + (target)	Transfer reactions	"close to the stability" 5-100 MeV/u	Very few: 2-5	Target


Z
B_p=0
B_n=0
82
126
50
28
20
8
2
50
82
28
20

Historical view to the discovery of new isotopes

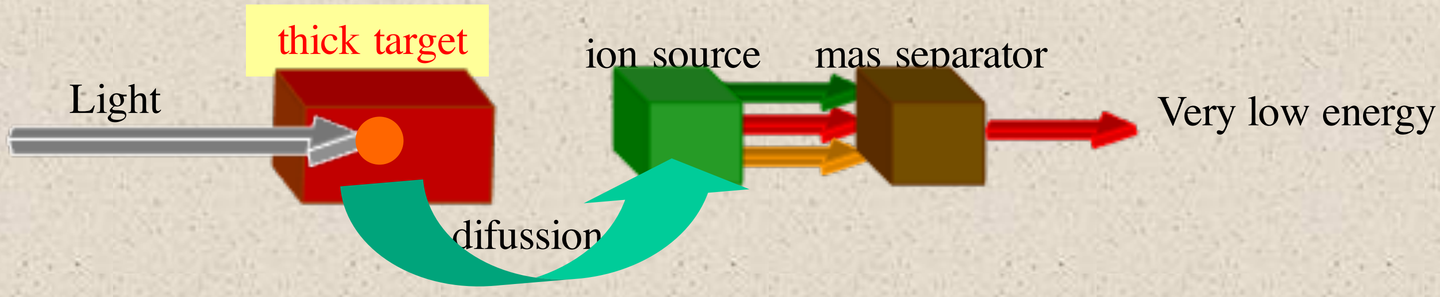
https://people.nscl.msu.edu/~thoennes/isotopes/yearchart-2015.mp4



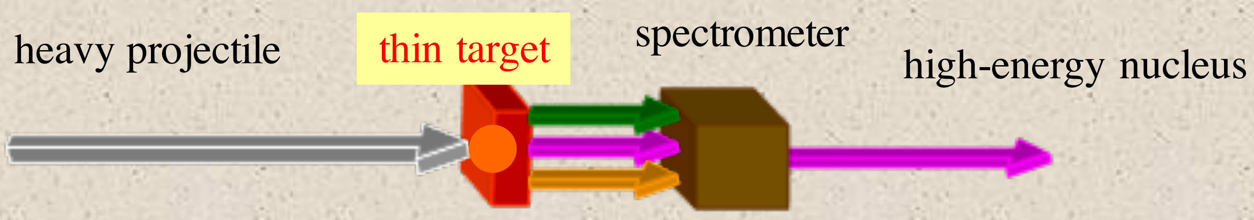
The second thing is to separate them from other radioactive products

Radioactive nuclei production techniques

Isotopic separation on-line (ISOL)

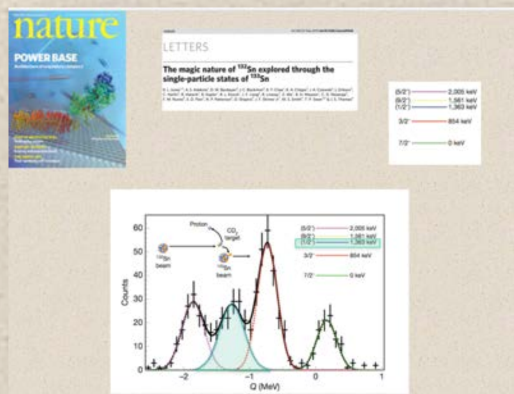


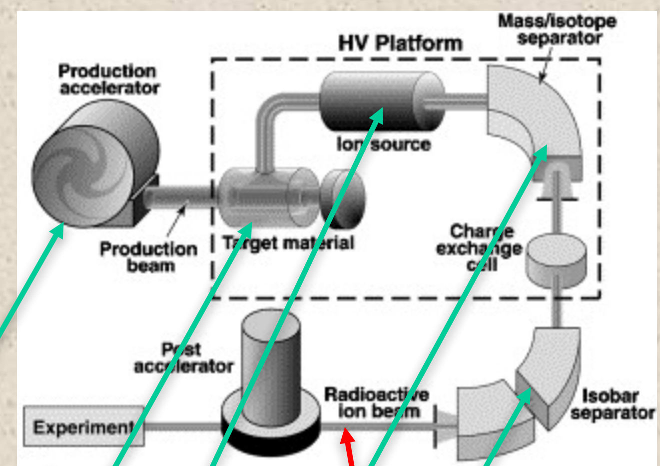
In-flight fragmentation



Production techniques Rad Beams: post acceleration

- Isotopic separation on-line (ISOL)





132Sn + d → 133Sn + p

1. Protons accelerated in the cyclotron
2. Uranium Carbide power target
3. About 100 species produced, some of them ionised
4. 132 Mass separated
5. 132Sn separated
6. 132Sn accelerated to 4.8 MeV x A
7. Experiment

Phys. Scr. **T152** (2013) 014023 Y Blumenfeld *et al*

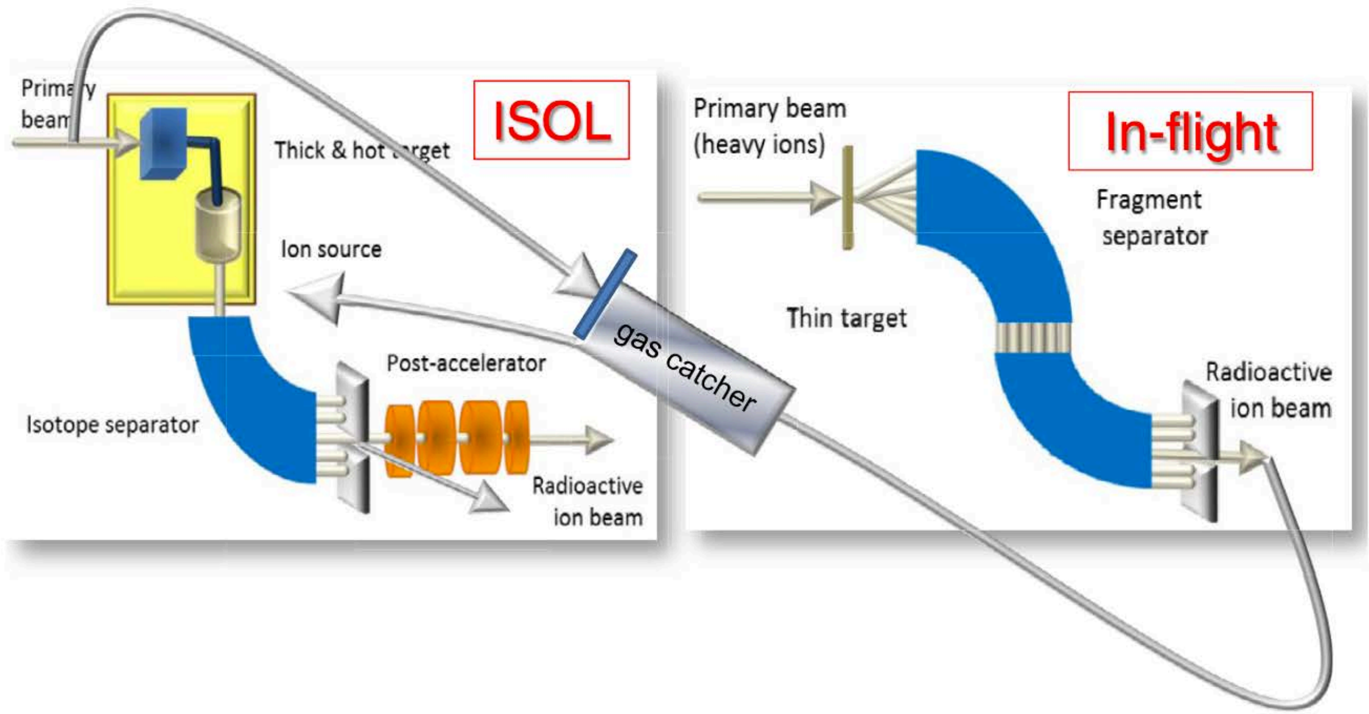


Figure 1. A schematic drawing of the ISOL and in-flight based production methods for RIBs.

http://iopscience.iop.org/article/10.1088/0031-8949/2013/T152/014023/pdf

difficulties

- extremely low production cross sections,
- overwhelming production of unwanted species in the same nuclear reaction,
- very short half lives of the nuclei of interest.

chalenges

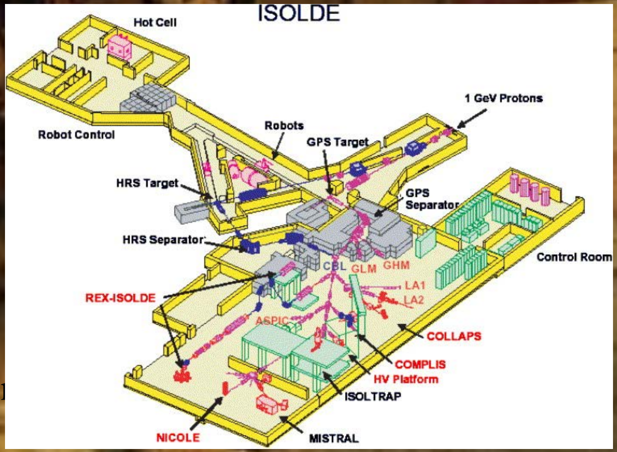
- As much intensity as possible (good driver, targets to stand the intensity)
- Good separation
- Bring the species to a “clean environment” Make the process as fast as possible

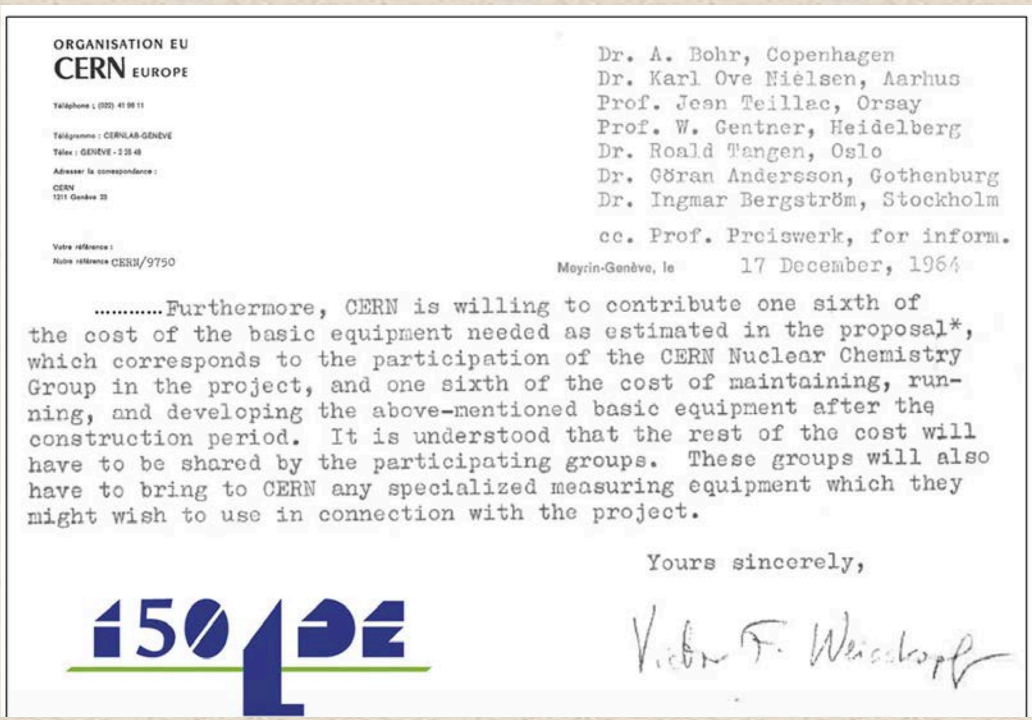
On 16 October 1967, the first experiments were carried out at the Isotopic Separator On Line ISOLDE CERN.

CERN's longest serving experimental facility

Physics Reports 403–404 (2004) 459–469

Juha Äystö





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cc. Prof. Preiswerk, for inform.

Votre référence :
Notre référence CERN/9750

Meyrin-Genève, le 17 December, 1964

............Furthermore, CERN is willing to contribute one sixth of the cost of the basic equipment needed as estimated in the proposal*, which corresponds to the participation of the CERN Nuclear Chemistry Group in the project, and one sixth of the cost of maintaining, running, and developing the above-mentioned basic equipment after the construction period. It is understood that the rest of the cost will have to be shared by the participating groups. These groups will also have to bring to CERN any specialized measuring equipment which they might wish to use in connection with the project.

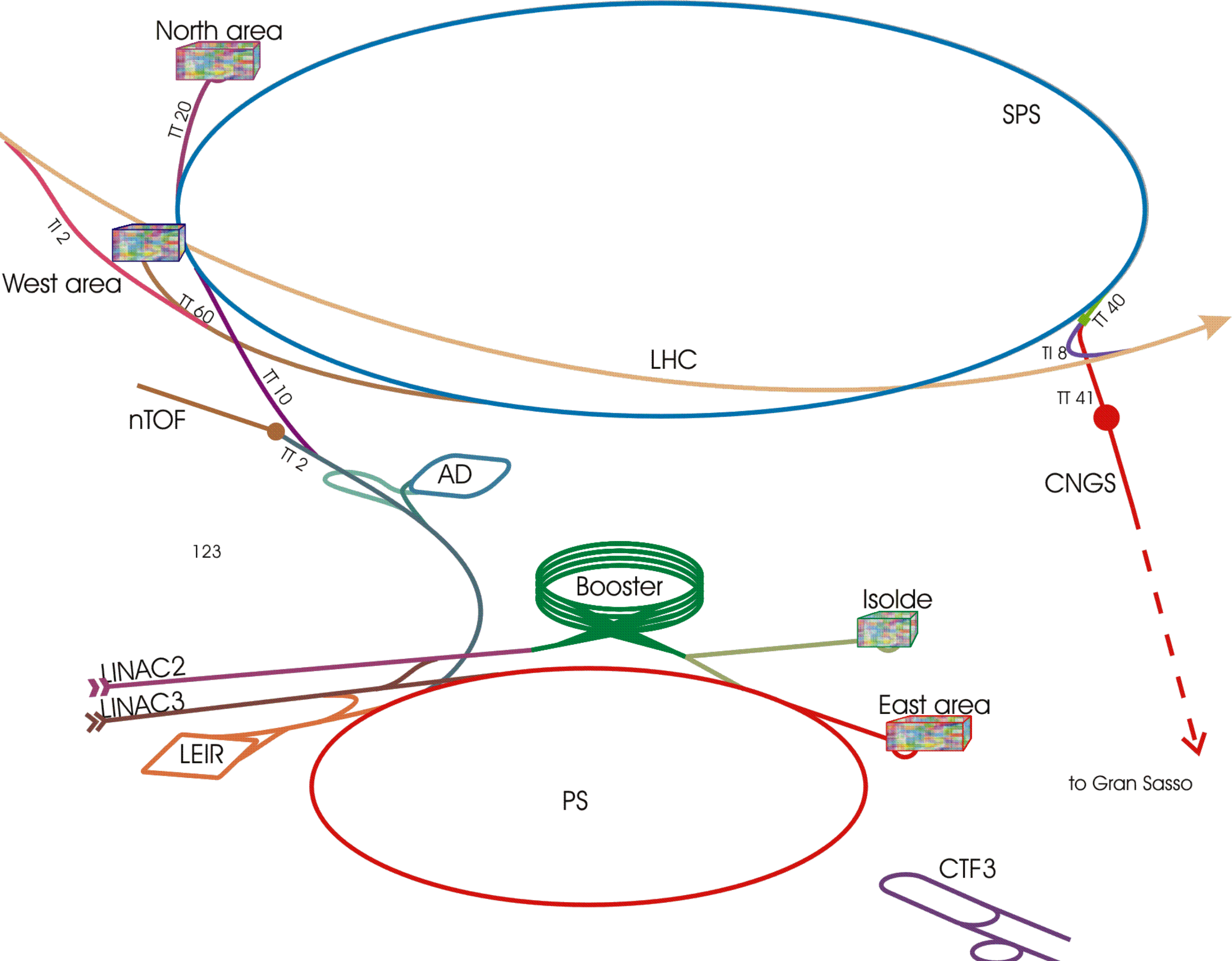
Yours sincerely,

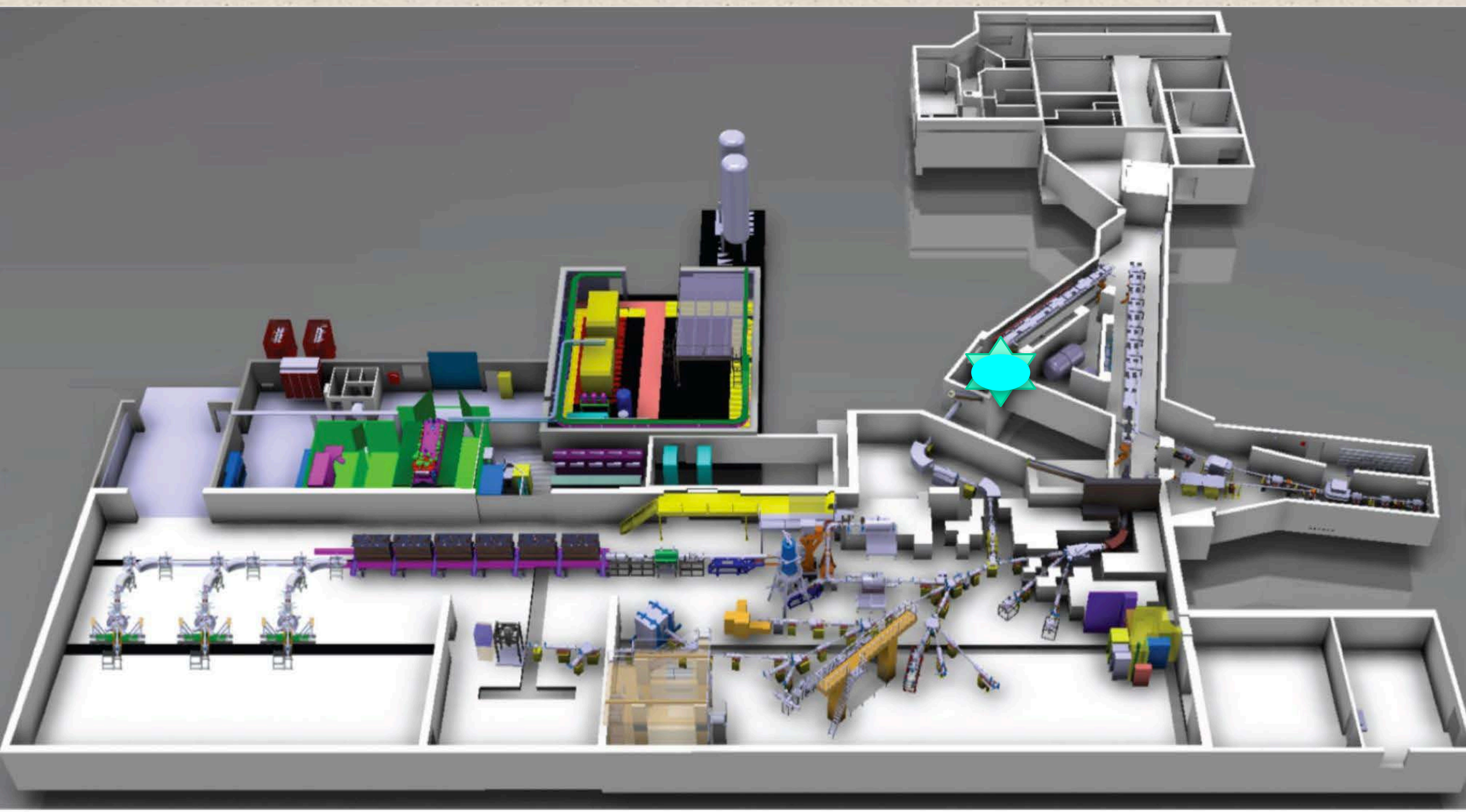
Victor F. Weisskopf

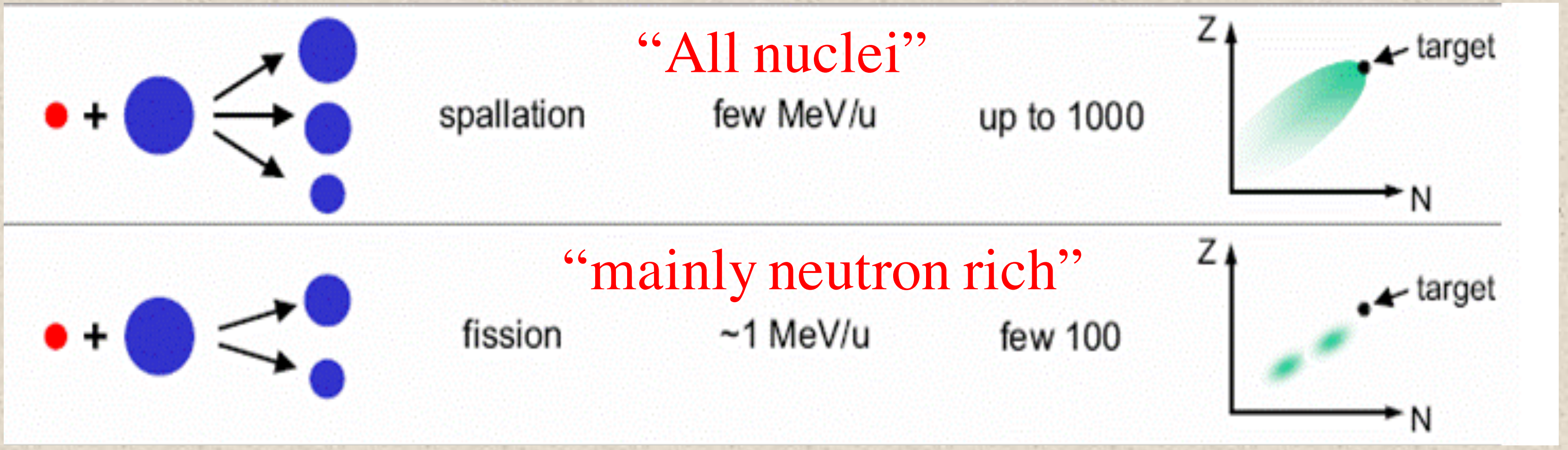
1967 First experiment
P of 600 MeV from the PSC

1992 moved to PS booster (today)
(last year 50 years celebration)

CERN accelerators







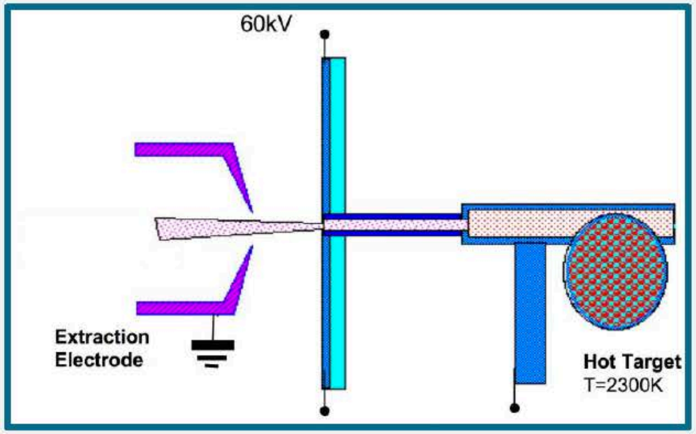
- 😃 High intensity p beam
- 😃 thick target (100% of range) => high beam current (upto10^{16} s^{-1})
- 🙁 long extraction and ionization time (ms)
- 😐 Chemistry dependent

Ion sources

A place were the newly produced atom is isonised

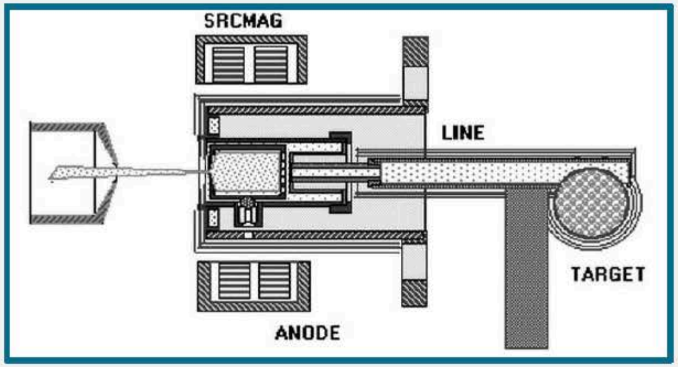
Hot surface ion source

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

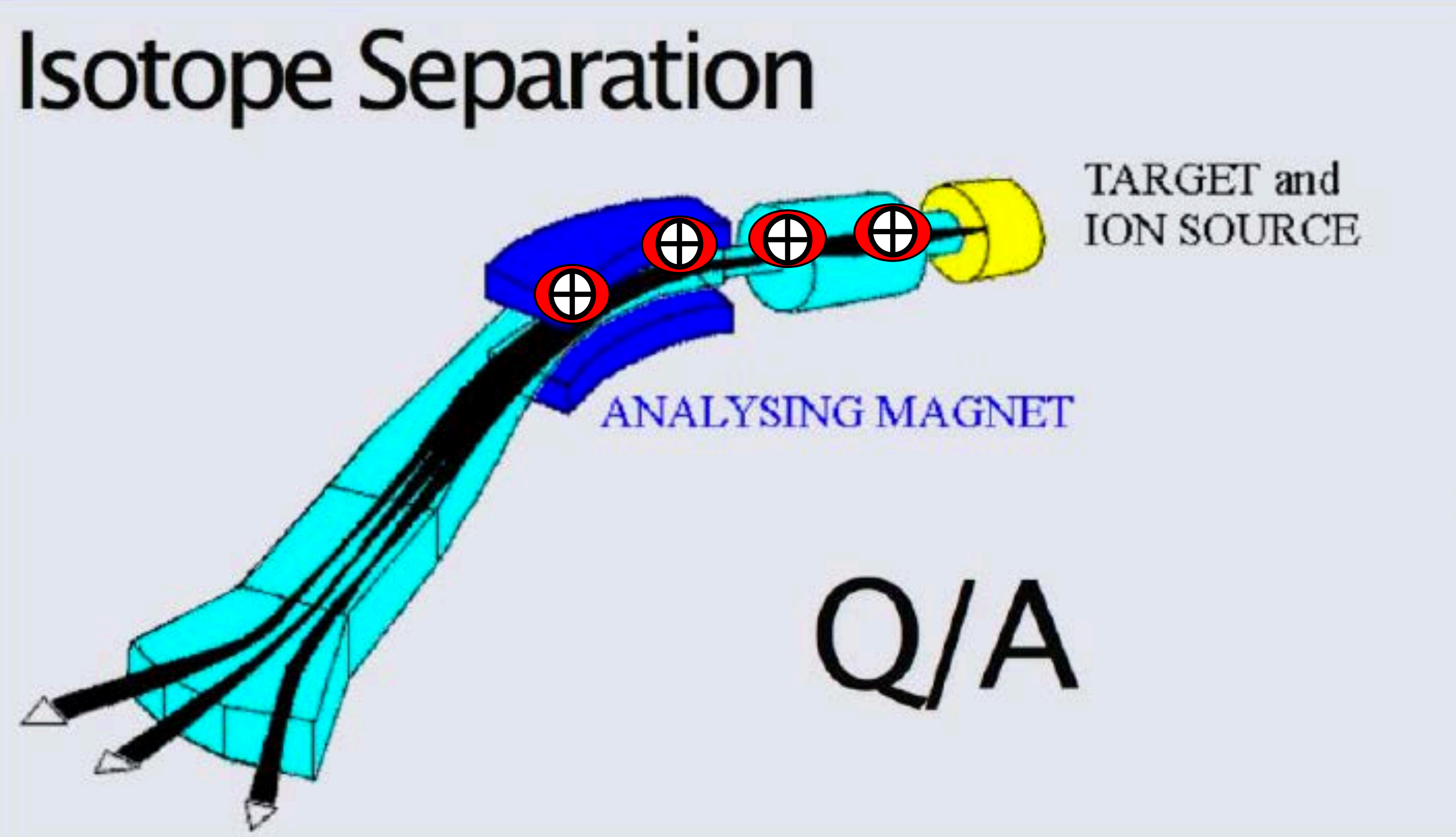


Plasma ion source

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



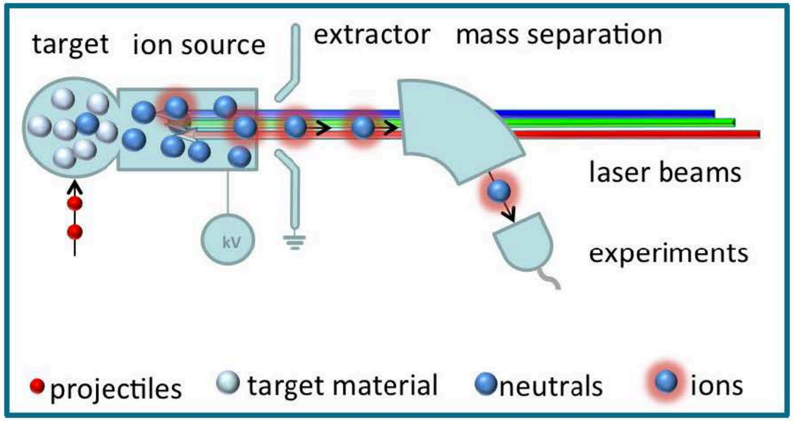
The Separator

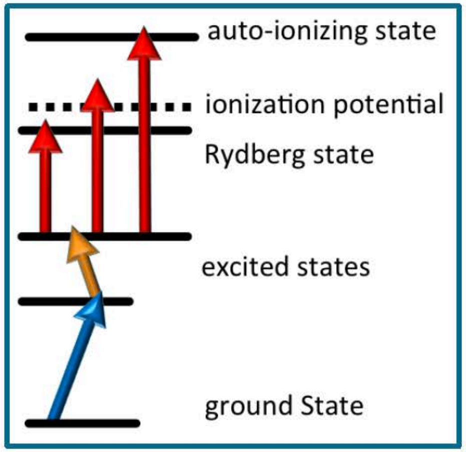


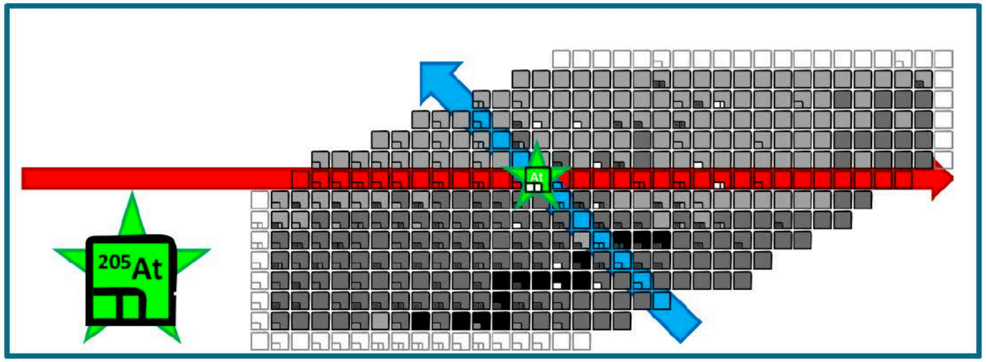
Ion sources

Laser ion source

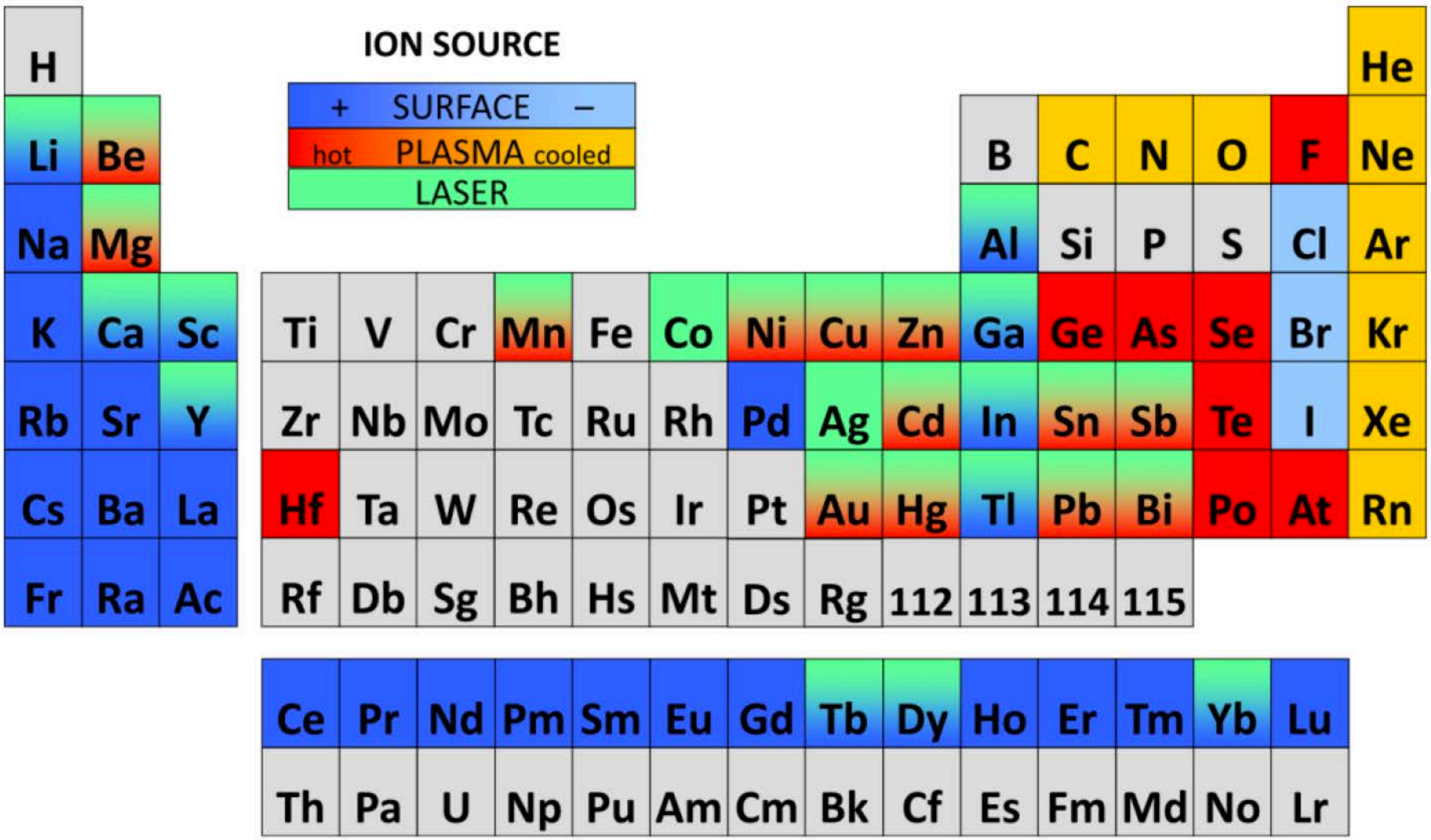
- 2- or 3-step ionisation
- Isotope and isomer selection
- Universal (almost)

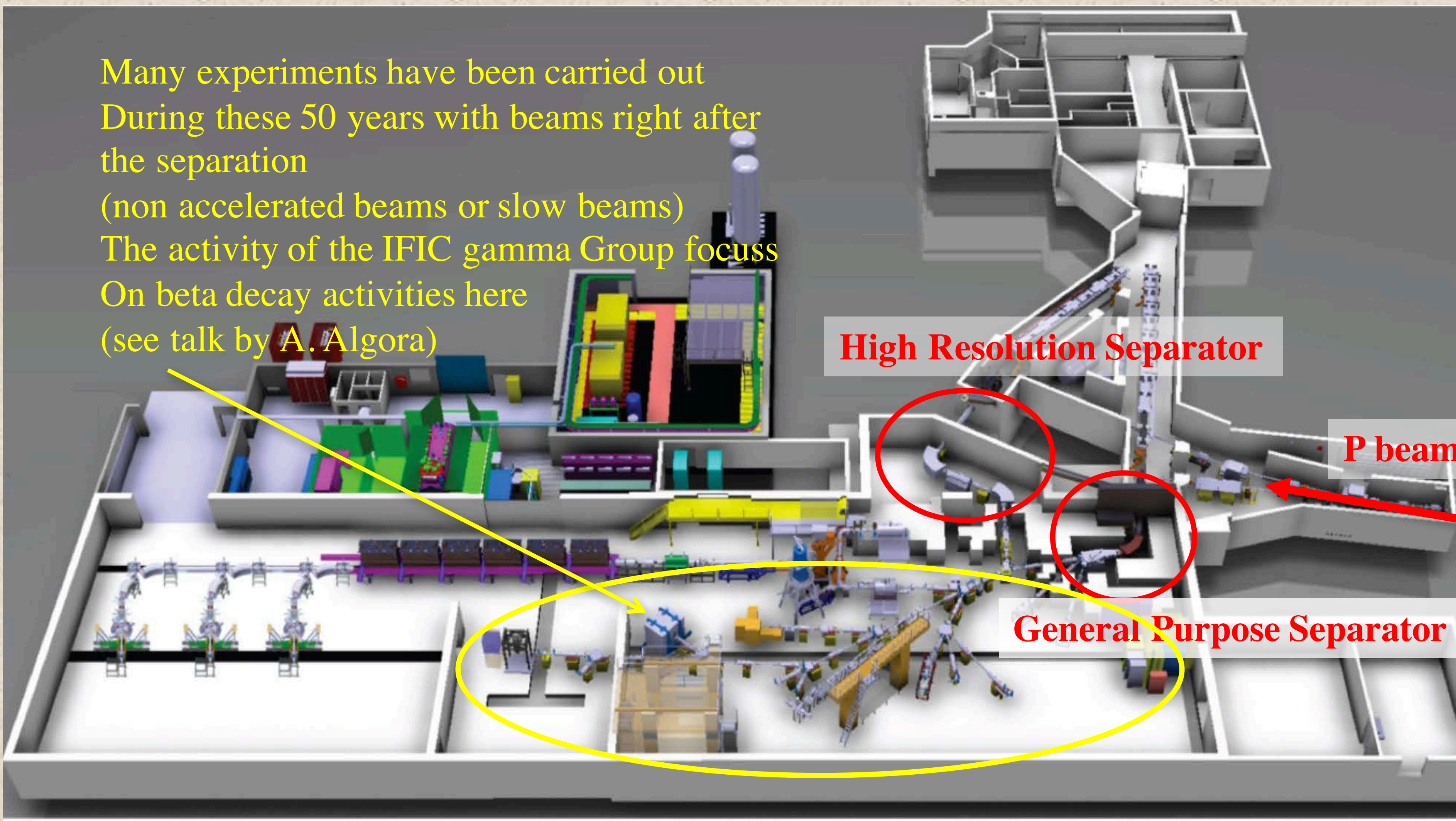


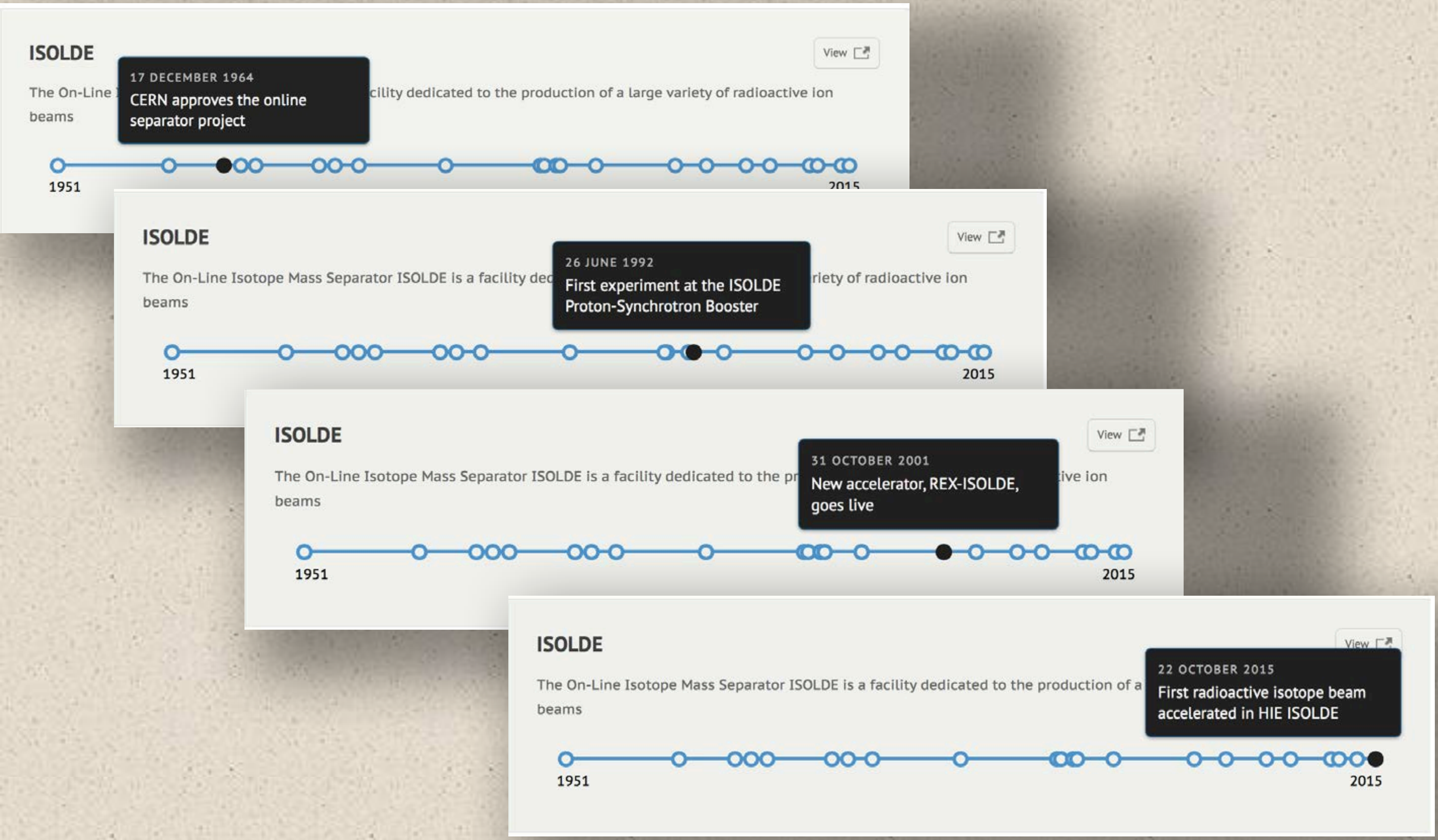




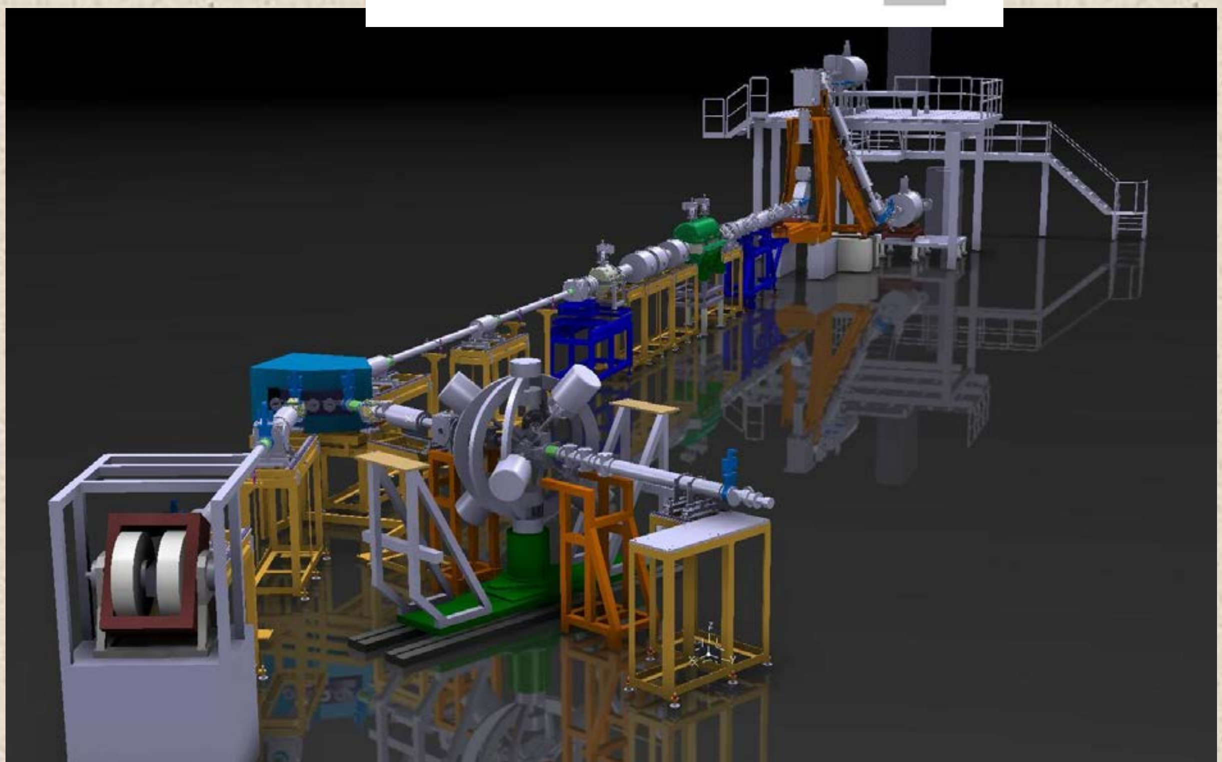
Isotopes produced at ISOLDE



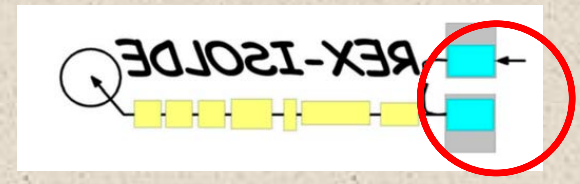

Many experiments have been carried out
During these 50 years with beams right after
the separation
(non accelerated beams or slow beams)
The activity of the IFIC gamma Group focuss
On beta decay activities here
(see talk by A. Algora)
High Resolution Separator
P beam
General Purpose Separator


ISOLDE
View
The On-Line Isotope Mass Separator ISOLDE is a facility dedicated to the production of a large variety of radioactive ion beams
17 DECEMBER 1964
CERN approves the online separator project
26 JUNE 1992
First experiment at the ISOLDE Proton-Synchrotron Booster
31 OCTOBER 2001
New accelerator, REX-ISOLDE, goes live
22 OCTOBER 2015
First radioactive isotope beam accelerated in HIE ISOLDE
1951
2015

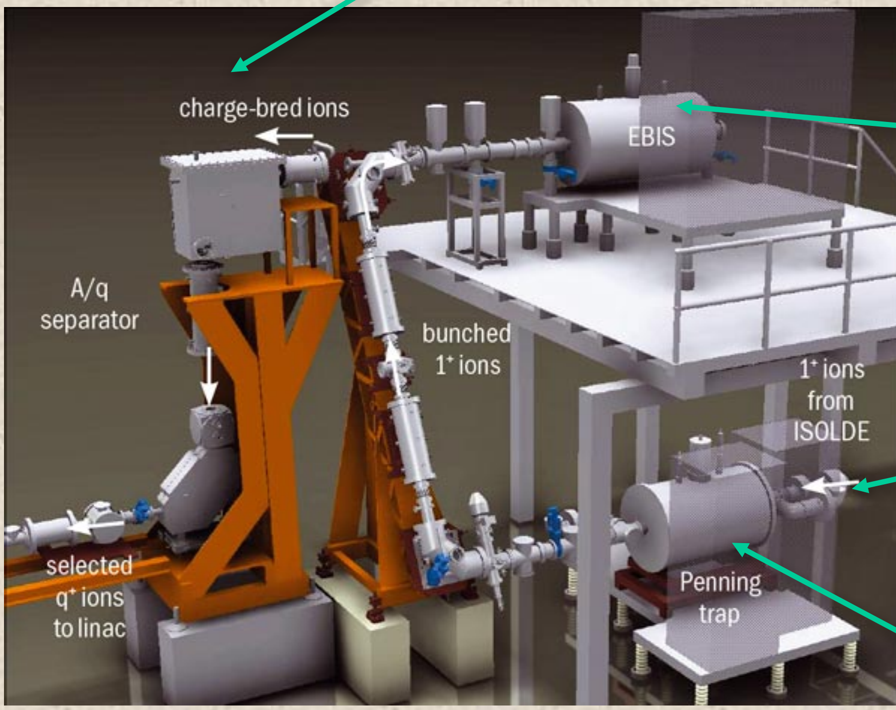
REX-ISOLDE



EBIS Ion Source and beam handling: 5-15% efficiency



A/q separator

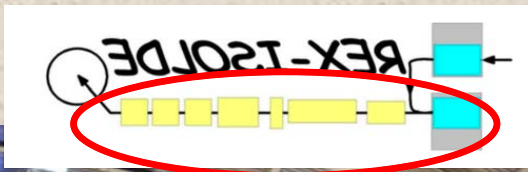


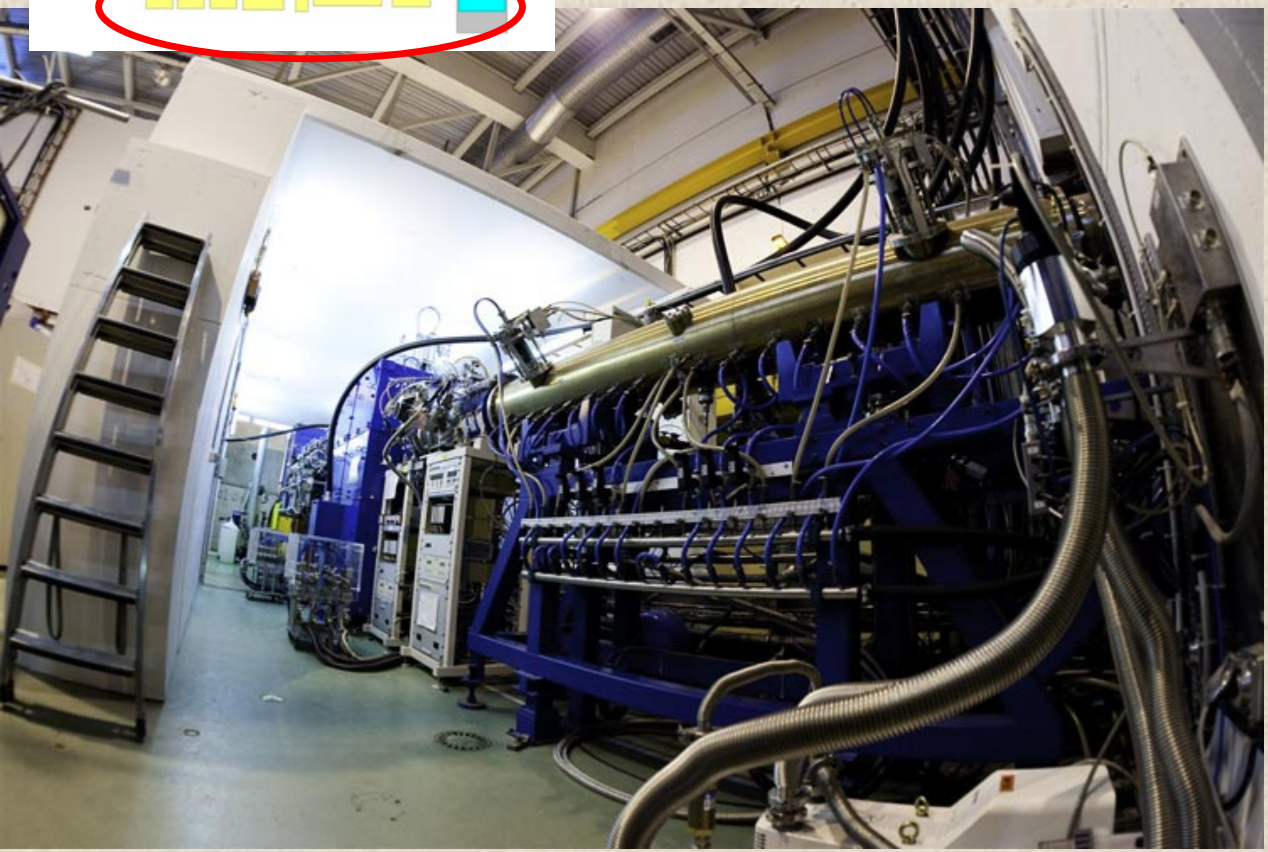
In the EBIS the 1^+ to n^+ ion conversion takes place

Beams from ISOLDE with 1+ charge state

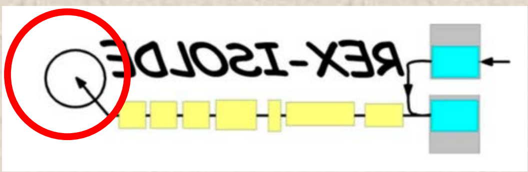
Preparation trap

Post accelerator: Normal Conducting LINAC

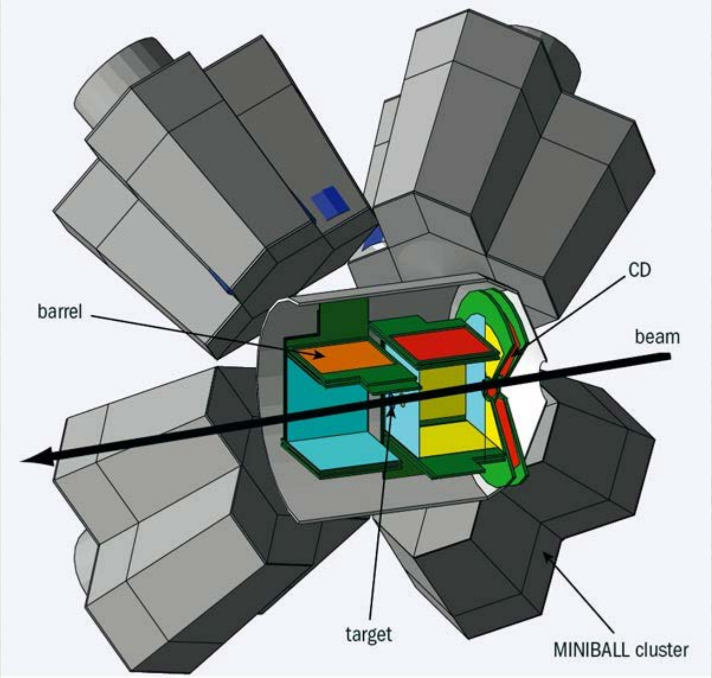


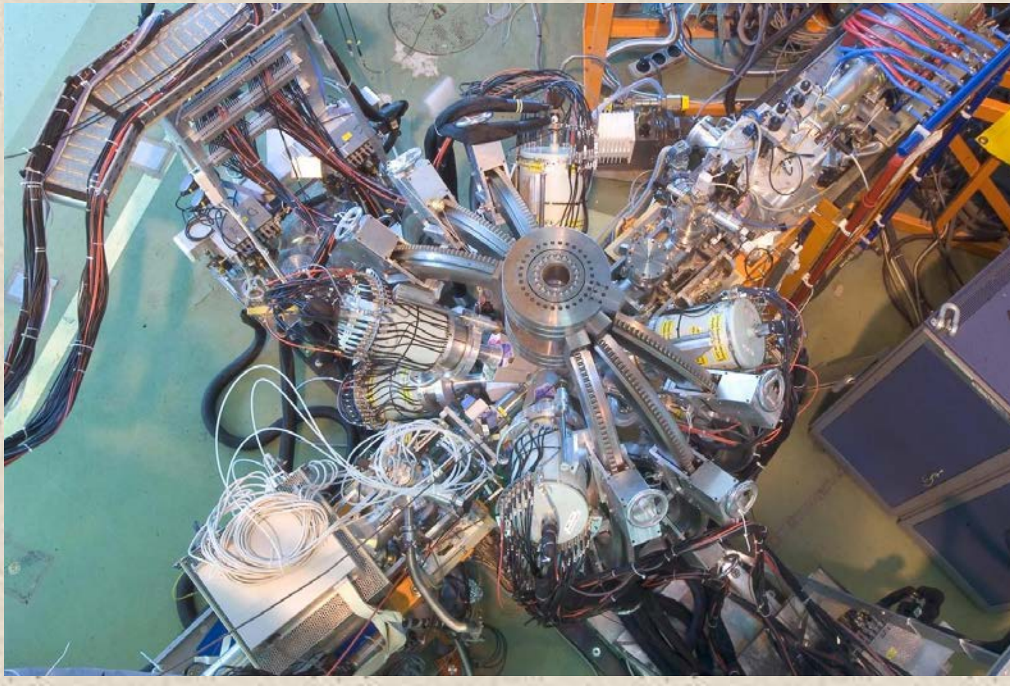


However, energies only 0.8 to 3 MeV/u which too low for Nuclear reactions



Miniball gamma array

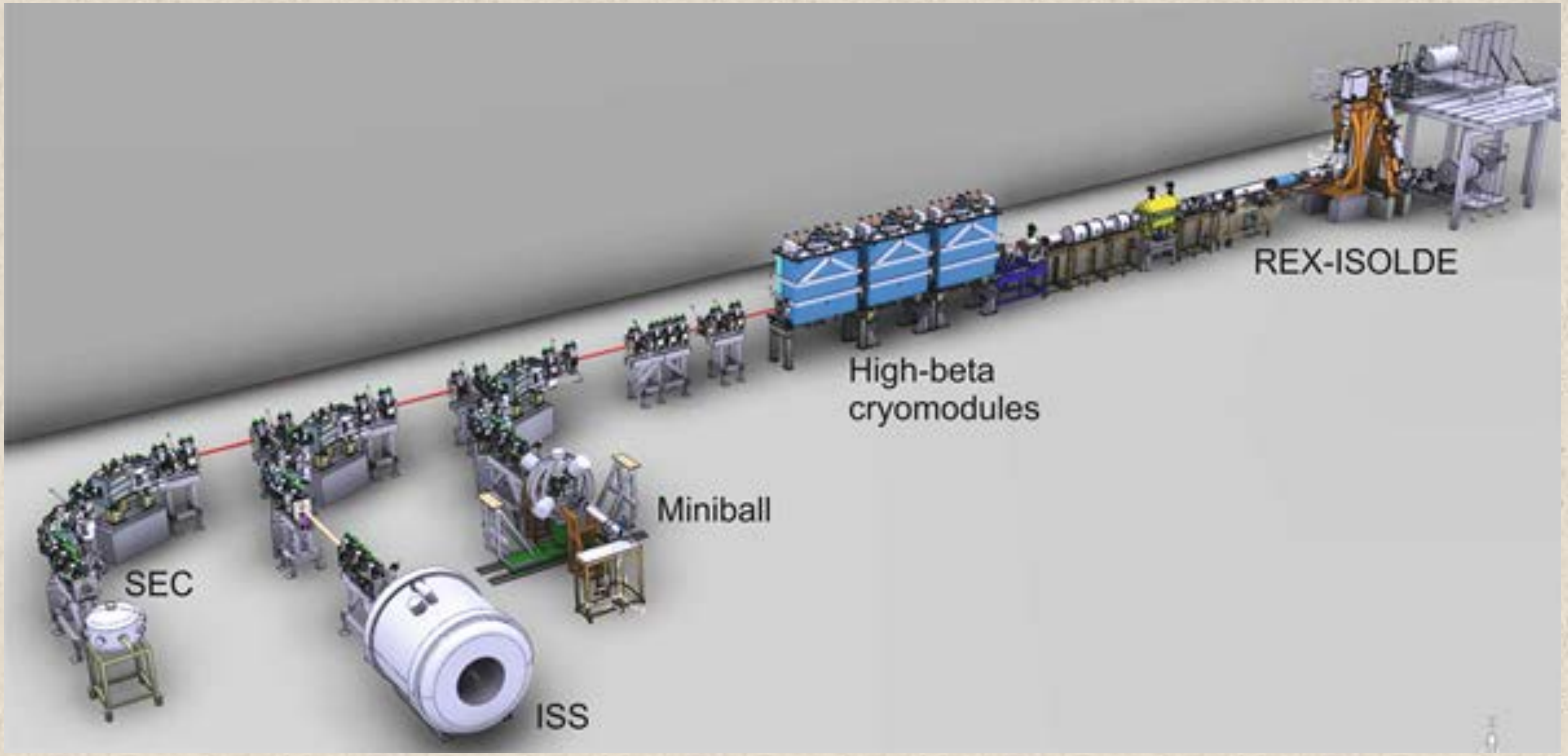




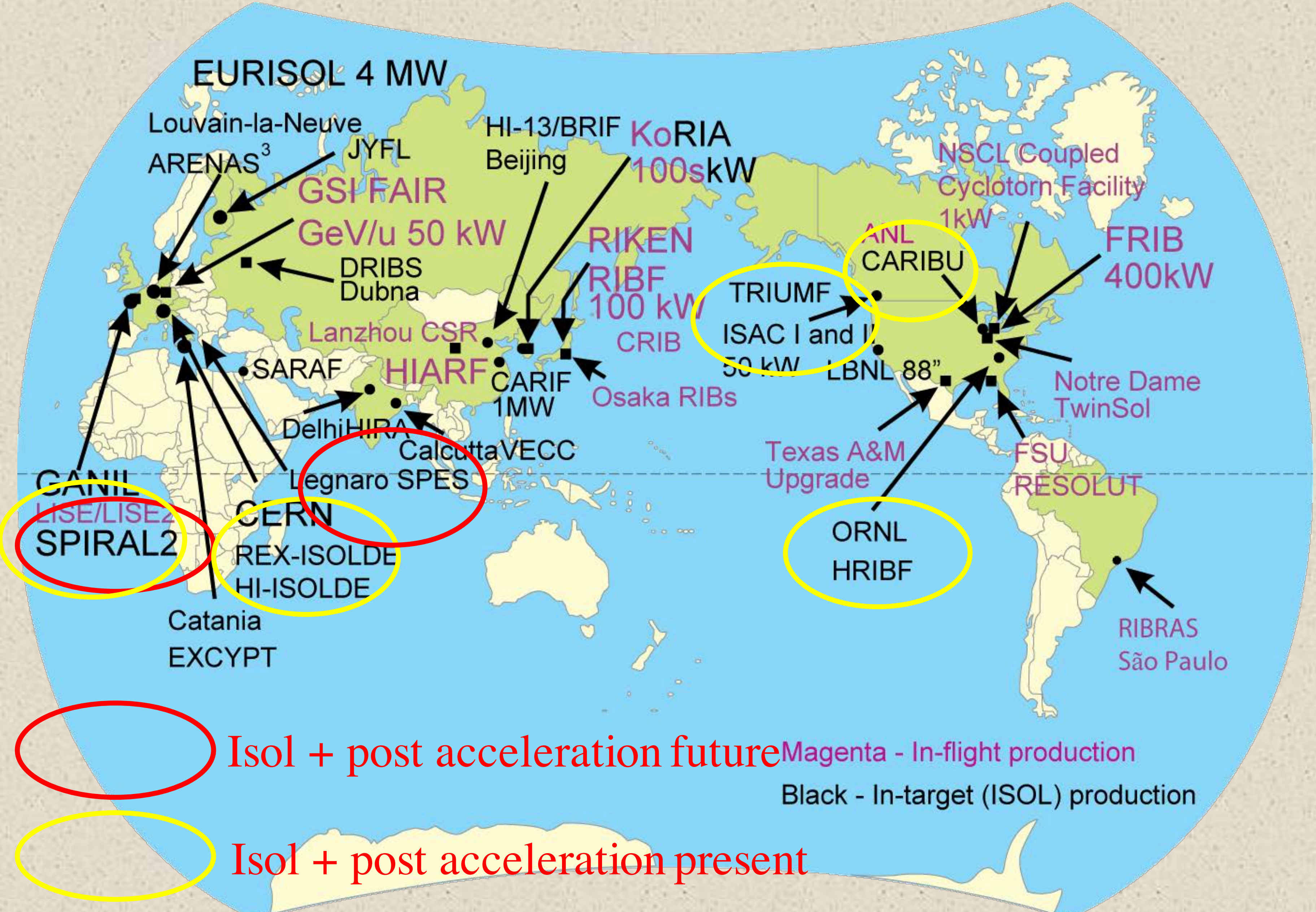
24 six-fold segmented, tapered, encapsulated high-purity germanium crystals

HIE ISOLDE
High Intensity and Energy ISOLDE (up to 10 MeV per nucleon)

4.3 MeV per nucleon



First experiments in 2015



Isol + post acceleration future

Isol + post acceleration present

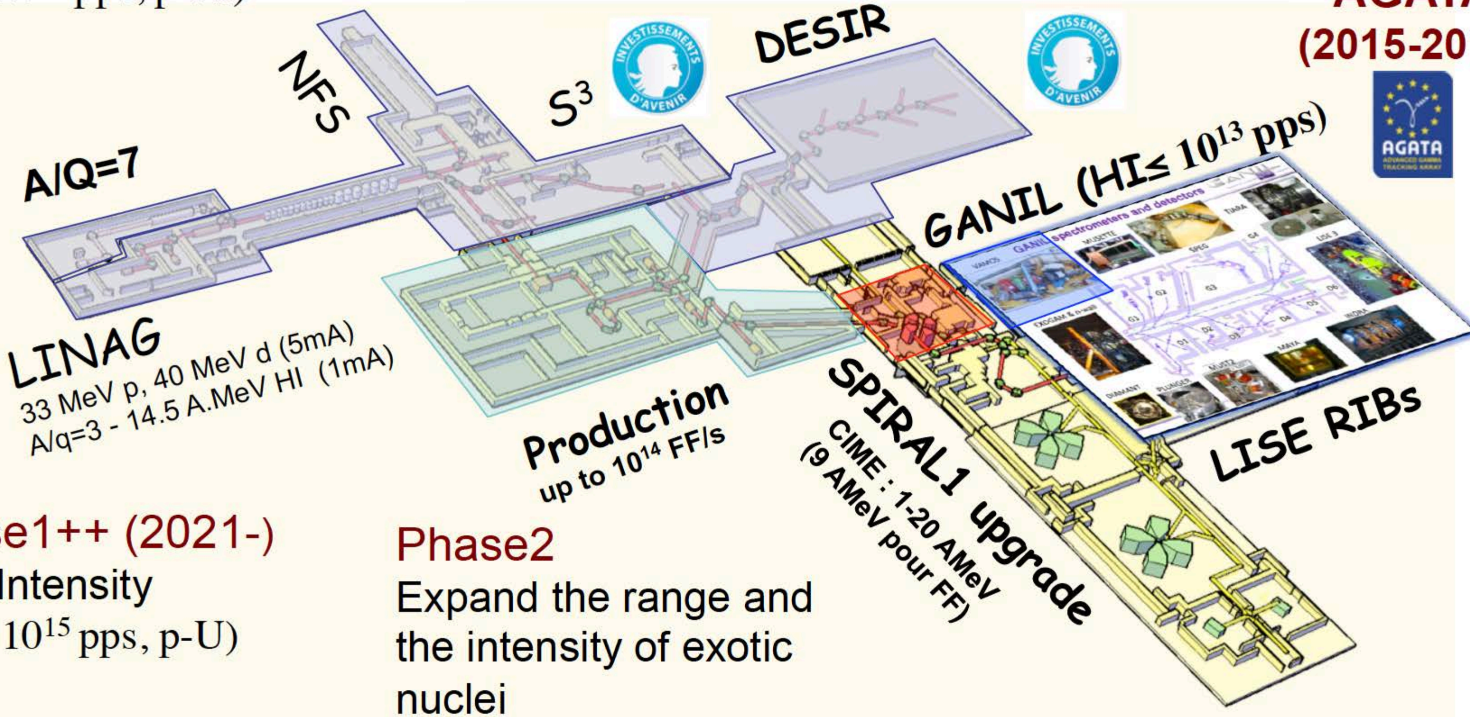
Future ISOL facilities

Mid-term Roadmap

Phase1 (2016-)
Increase the intensity of stable beams
High intense neutron source
(HI≤ 10^{15} pps, p-Ni)

DESIR Phase1+ (2020-)
Low energy facility

AGATA
(2015-2018)

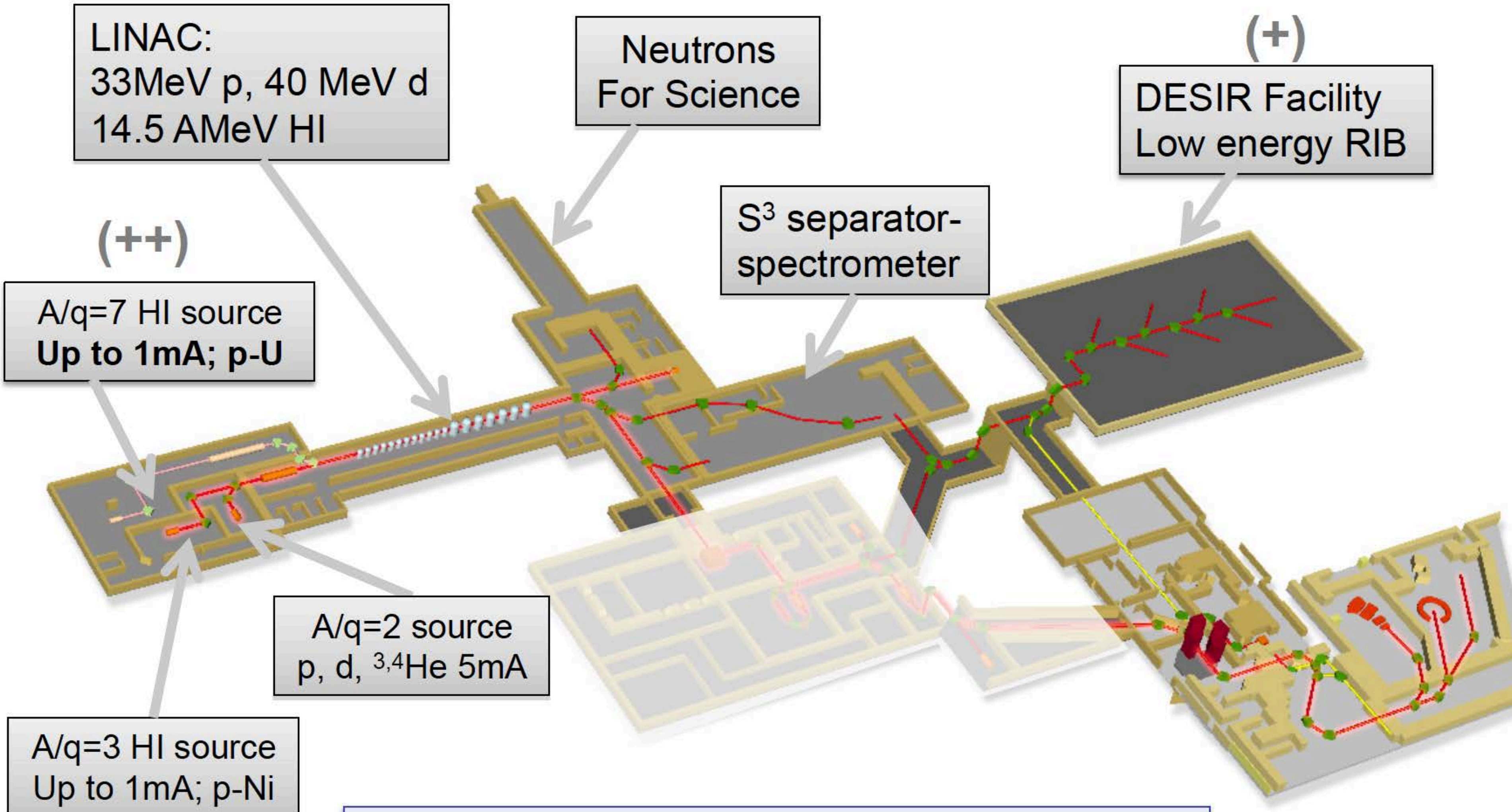


Phase1++ (2021-)
High Intensity
(HI≤ 10^{15} pps, p-U)

Phase2
Expand the range and the intensity of exotic nuclei

SPIRAL1 Upgrade (2017-)
New light RIBs from beam/target fragmentation

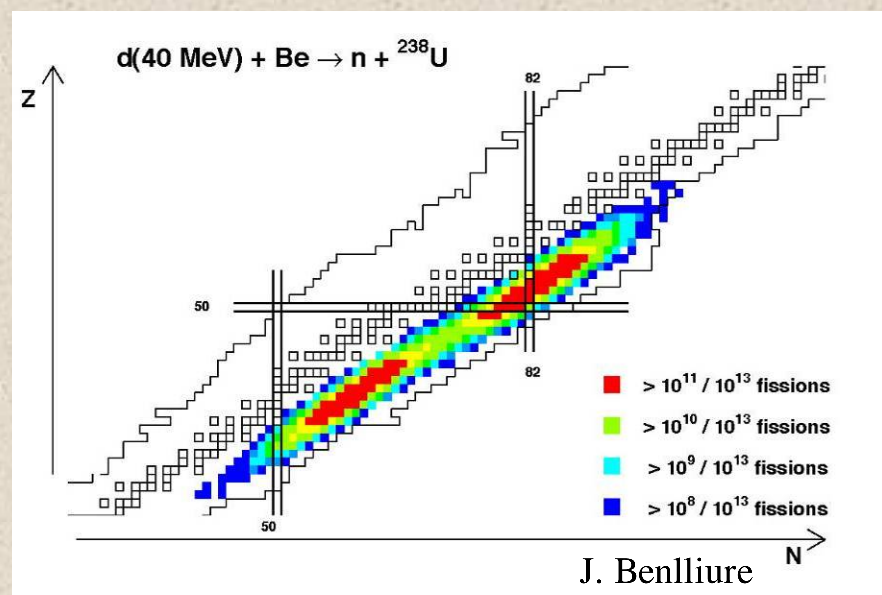
Near Future : SPIRAL2 Phase 1

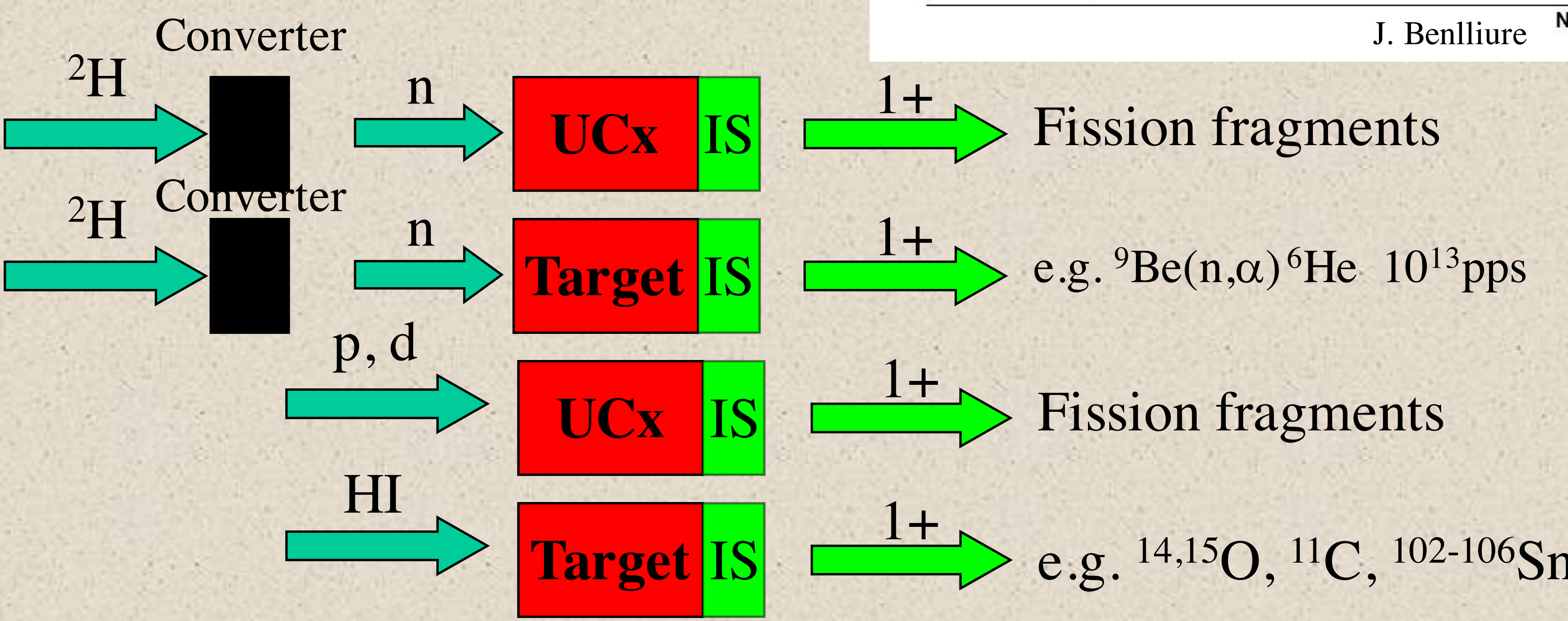


LINAC : Average beam intensity equivalent to that of ESS or EURISOL driver

ISOL Rare Isotope Beams at SPIRAL 2

Unfortunatelly the neutron rich side of
The Spiral 2 Facility is not financed at
The moment



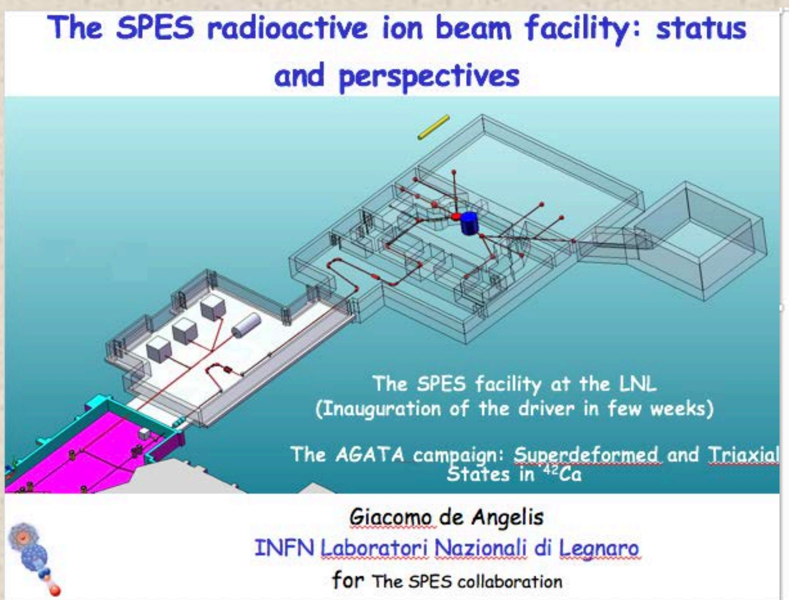


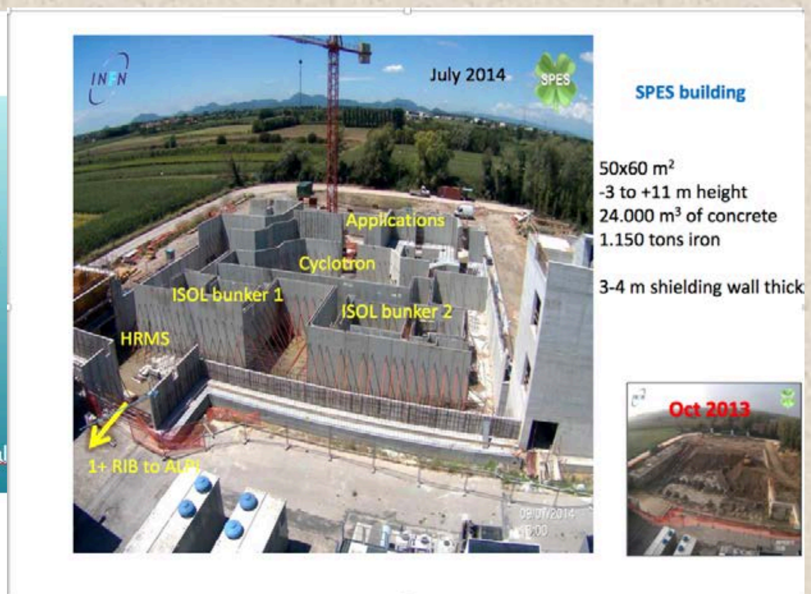
Fortunatelly and startegically a new project for neuron rich (fission), has been aproved in Legnaro (Italy), and is already under construction

SPES
Selective Production of Exotic Species

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Legnaro

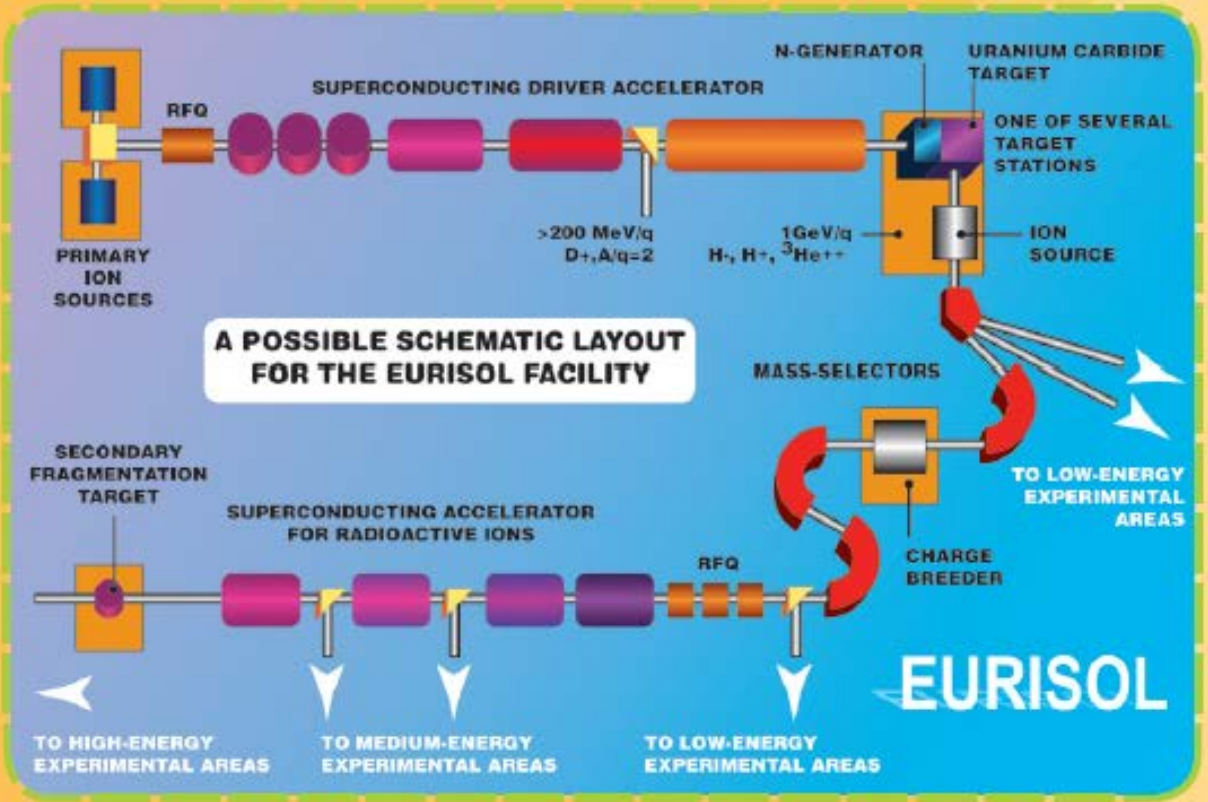
SPES Project





Far in the Future ISOL facility

Furthering target and accelerator technology



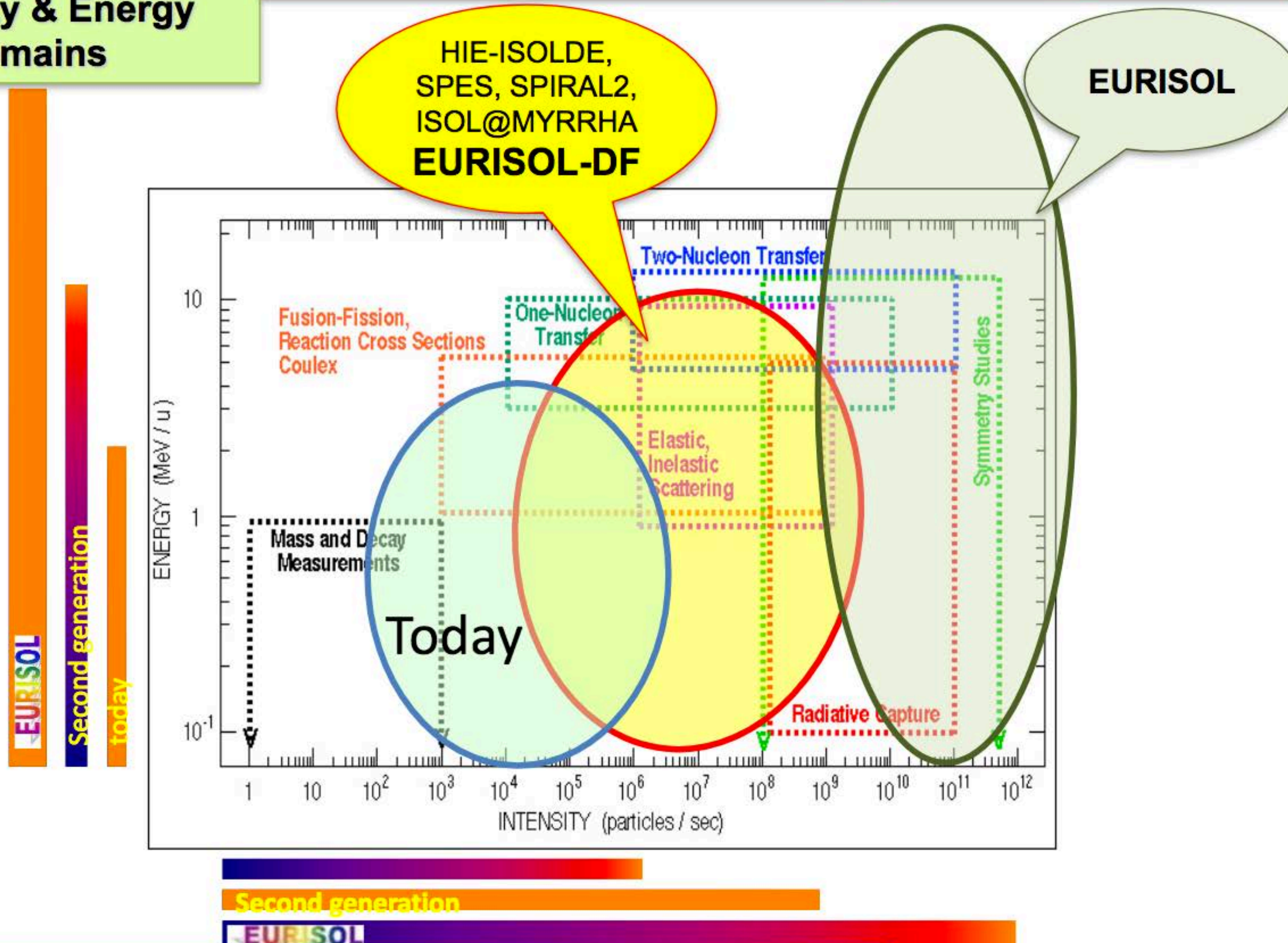
A 4-year Design Study began in 2005 in order to work on the technologically challenging aspects of the project, the instrumentation and the radiation safety issue. Synergy with other projects is being examined, including a feasibility study for the new 'beta-beam' neutrino proposal, forming an integral part of the Design Study. After this, possible sites will be evaluated, and the community will be ready for a full Engineering Design, to be followed by construction of the facility.

Researchers and engineers of several European laboratories are collaborating in twelve tasks to further the EURISOL design.

The EURISOL layout consists of a superconducting linear accelerator providing protons of energy 1 GeV and an impressive power of 5 MW, but also capable of accelerating deuterons, ^{3}He and ions up to mass 40. The beams will impinge simultaneously on two types of targets, either directly or after conversion of the protons into neutrons through a loop containing 1 ton of mercury surrounded by kilograms of fissile material. The unstable nuclei produced diffuse out of the target, are ionized and selected, and can be used directly at low energy or reaccelerated by another linear accelerator to energies up to 150 MeV per nucleon in order to induce nuclear reactions.

Physics with ISOL RIB Intensity & Energy domains

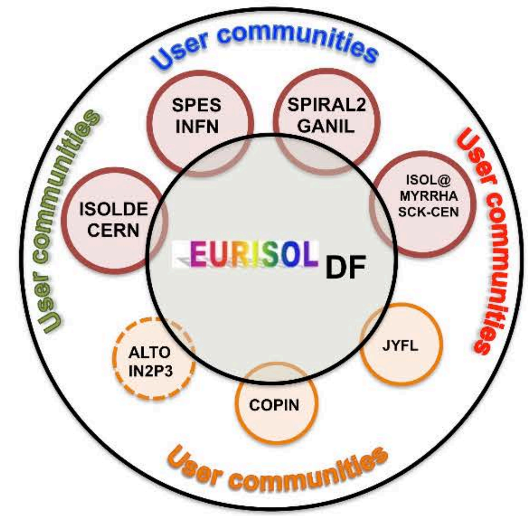
Precision nuclear structure physics & applications



-> EURISOL-DF (Distributed Facility) Initiative from 2014 as an intermediate step towards EURISOL

EURISOL DF

EURISOL – Distributed Facility (DF)



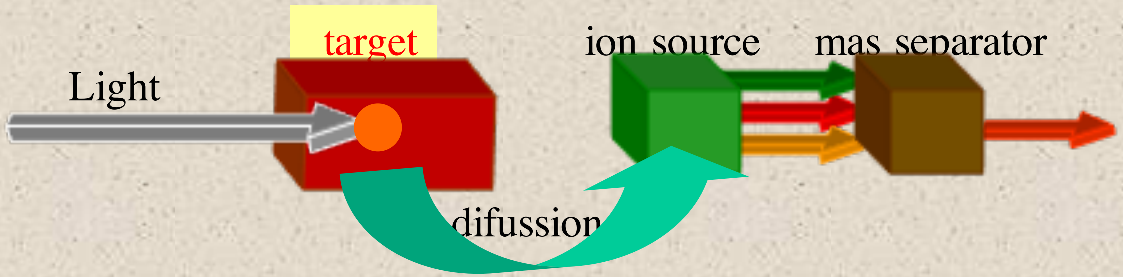
Core members :
- **HIE-ISOLDE/CERN**
- **SPES-INFN**
- **SPIRAL2-GANIL**
- **ISOL@MYRRHA-SCK*CEN**

Associated Members
- **JYFL, Finland**
- **COPIN Consortium, Poland**
- **(ALTO, Orsay)**

EURISOL DF

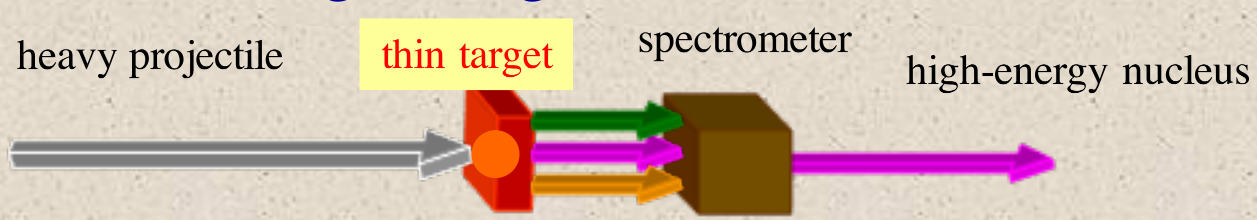
Radioactive nuclei production techniques

Isotopic separation on-line (ISOL)



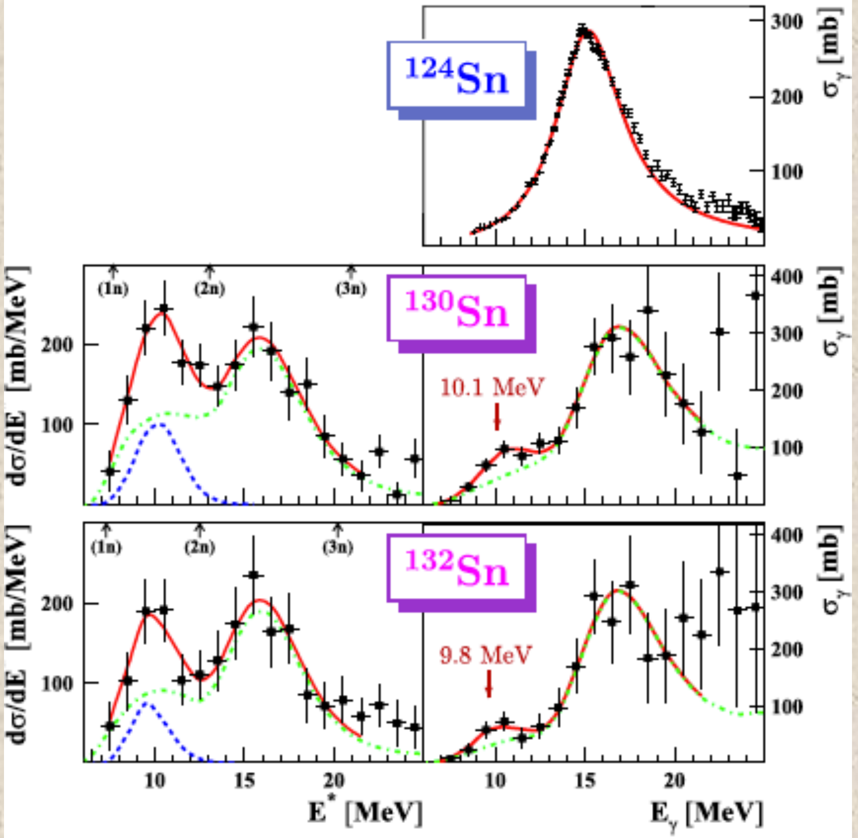
We can use thick production targets (100% of energy range)
=> and high injector beam current (upto10^{16} s^{-1})
long extraction and ionization time (ms)
chemistry dependent (disadvanages and some advantages)

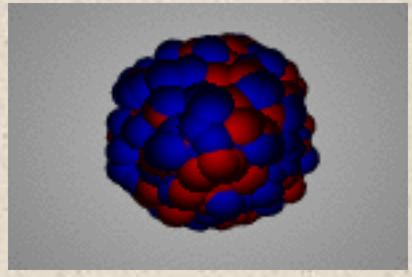
In-flight fragmentation

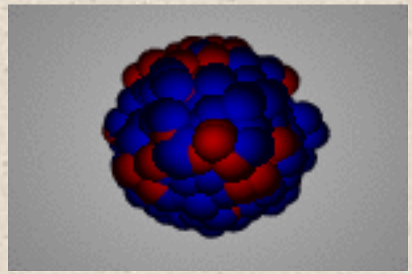


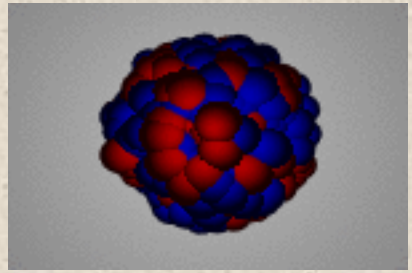
short separation+identification time (100 ns)
thinner targets (10% of range) =>lower beam currents (upto 10^{12} s^{-1})
chemistry independent

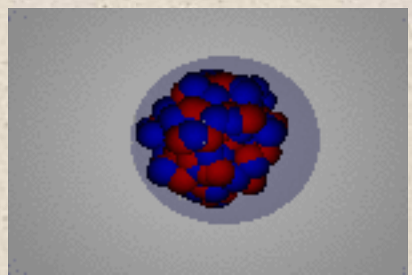
Los haces radioactivos



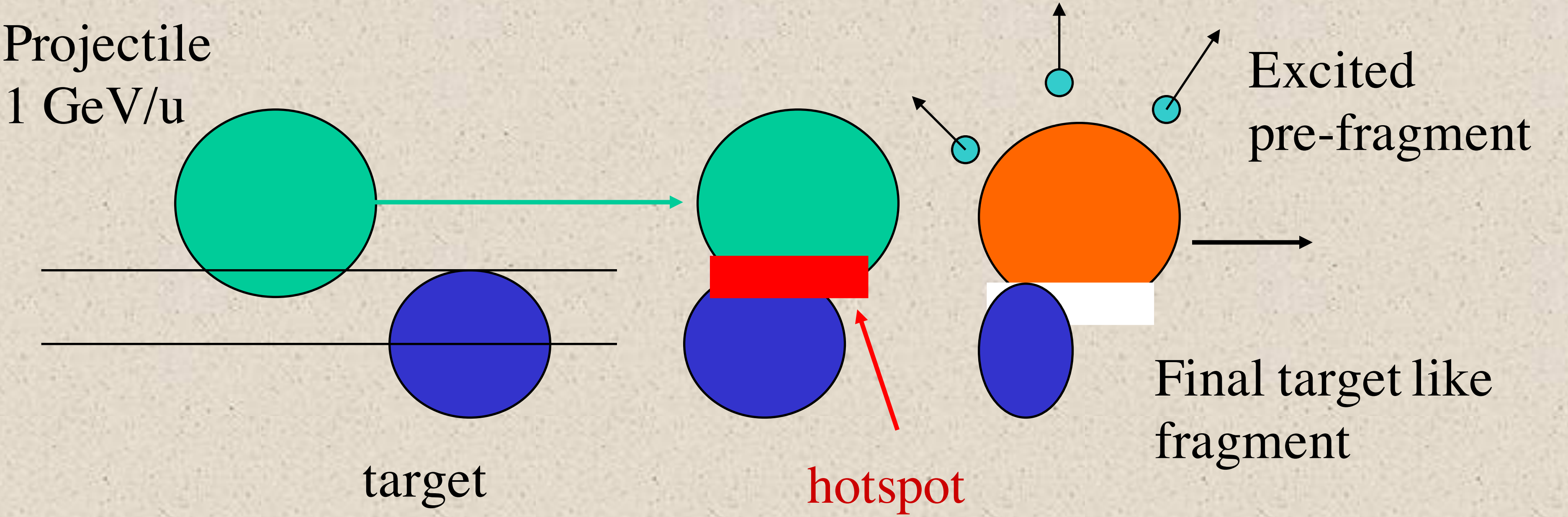






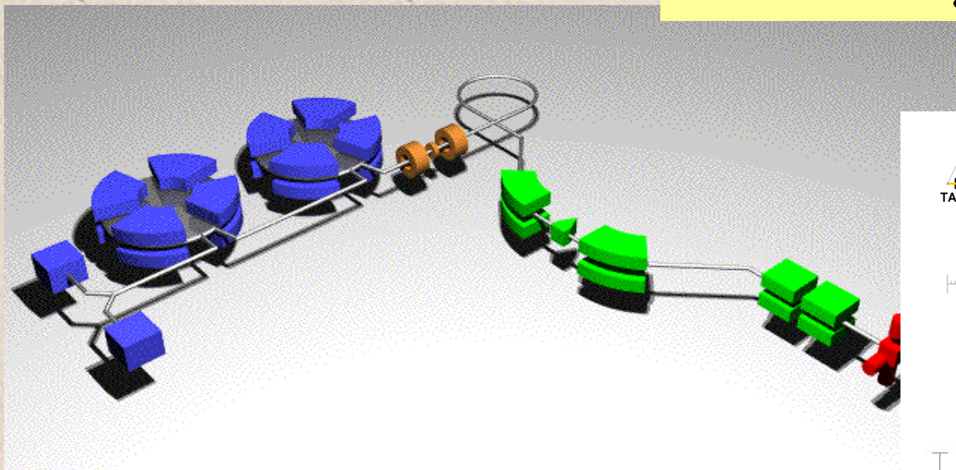


Projectile Fragmentation Reactions

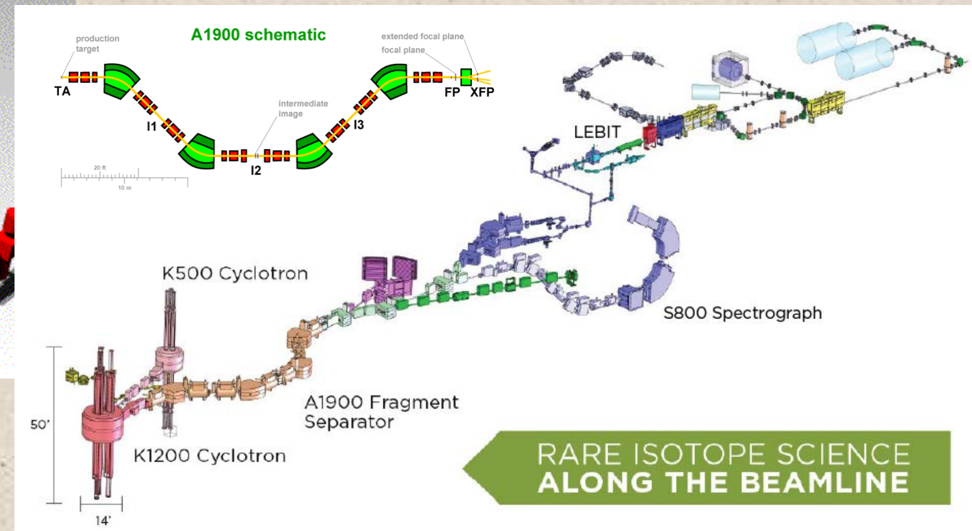


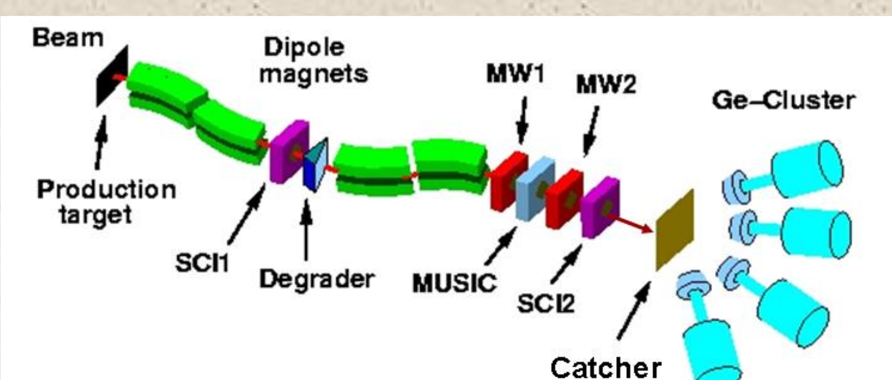
Energy (velocity) of beam > Fermi velocity inside nucleus ~30 MeV/u
Can 'shear off' different combinations of protons and neutrons.
Large variety of exotic nuclear species created, all at forward angles with ~beam velocity.

Actual Fragment Separators

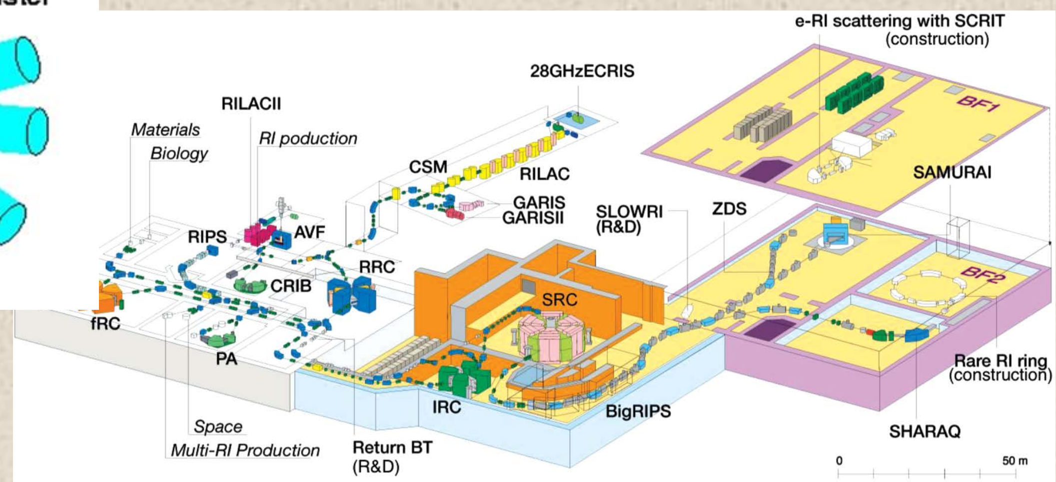


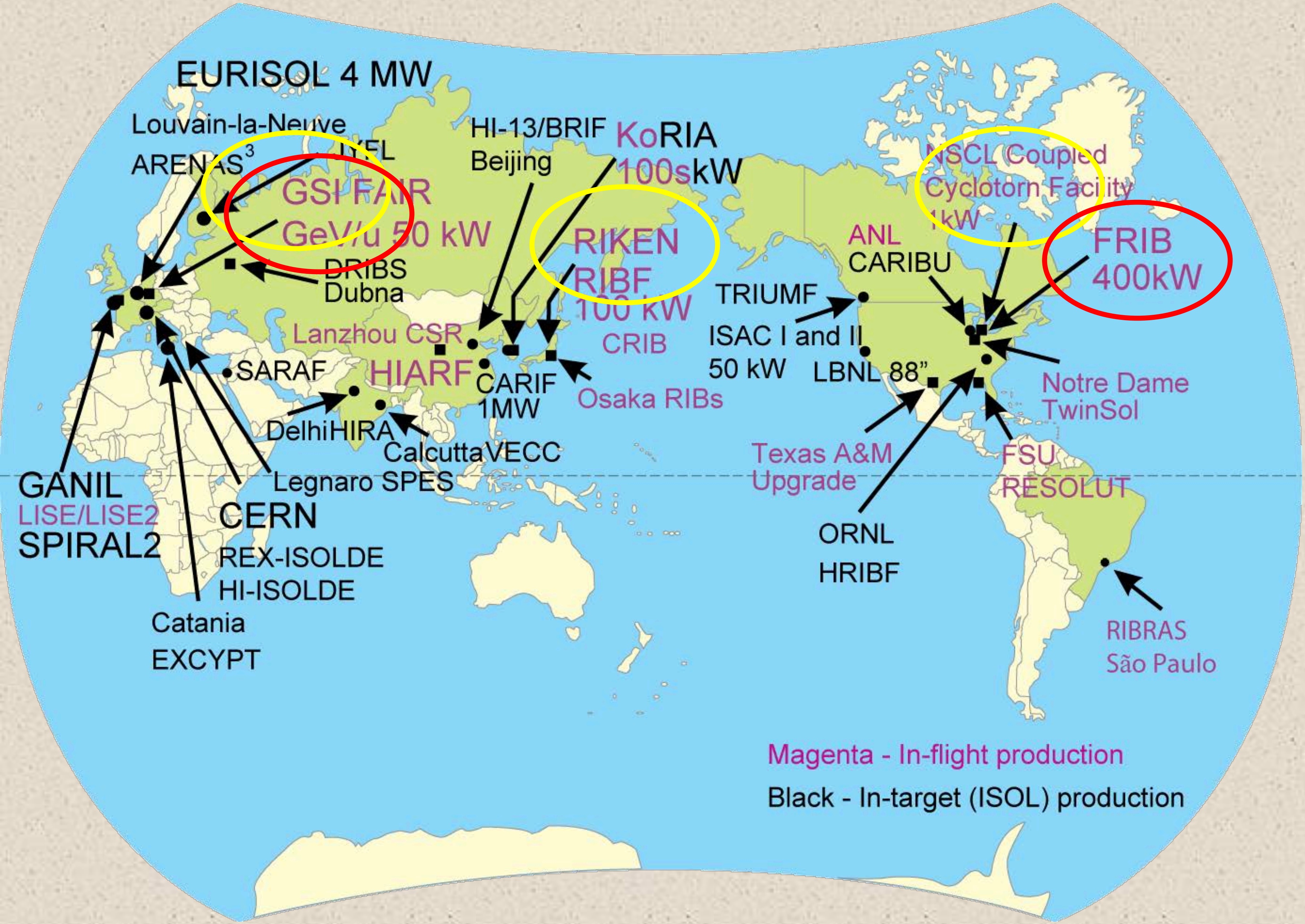
LISE-GANIL





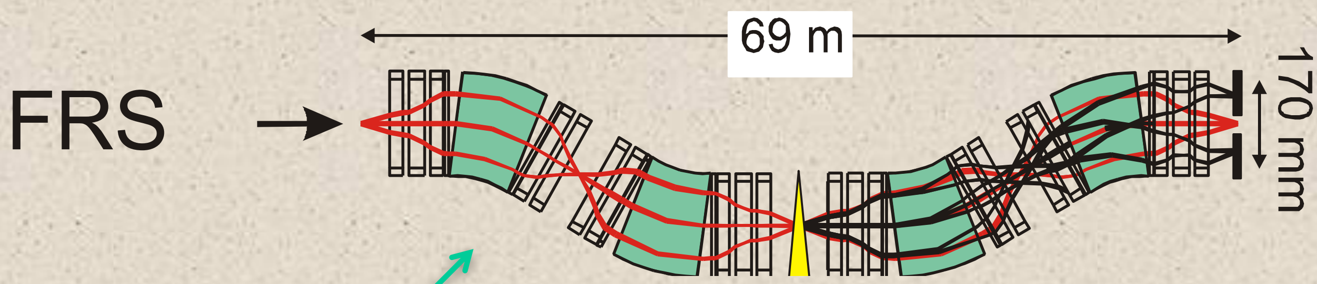
FRS GSI




EURISOL 4 MW
Louvain-la-Neuve
ARENAS3
JYFL
GSI FAIR
GeV/u 50 kW
DRIBS
Dubna
HI-13/BRIF
Beijing
KoRIA
100s kW
RIKEN
RIBF
100 kW
CRIB
Osaka RIBs
Lanzhou CSR
HIARF
CARIF
1MW
SARAF
DelhiHIRA
CalcuttaVECC
Legnaro SPES
GANIL
LISE/LISE2
SPIRAL2
CERN
REX-ISOLDE
HI-ISOLDE
Catania
EXCYPT
TRIUMF
ISAC I and II
50 kW
LBNL 88"
ANL
CARIBU
NSCL Coupled
Cyclotorn Facility
1kW
FRIB
400kW
Notre Dame
TwinSol
Texas A&M
Upgrade
FSU
RESOLUT
ORNL
HRIBF
RIBRAS
São Paulo
Magenta - In-flight production
Black - In-target (ISOL) production

Optimised to separate very fast fragment or fission products

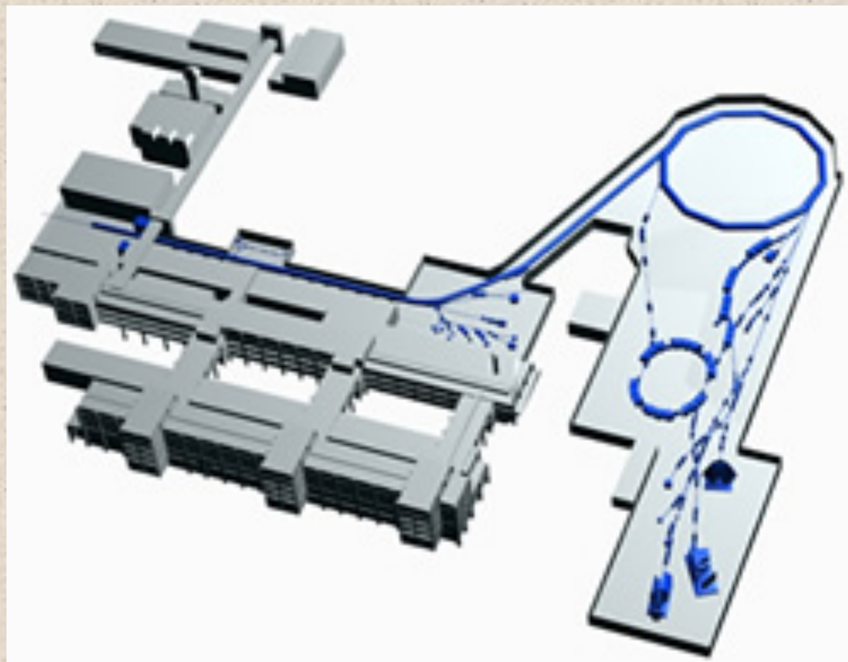
Bρ-ΔE-Bρ Separation Method



degrader

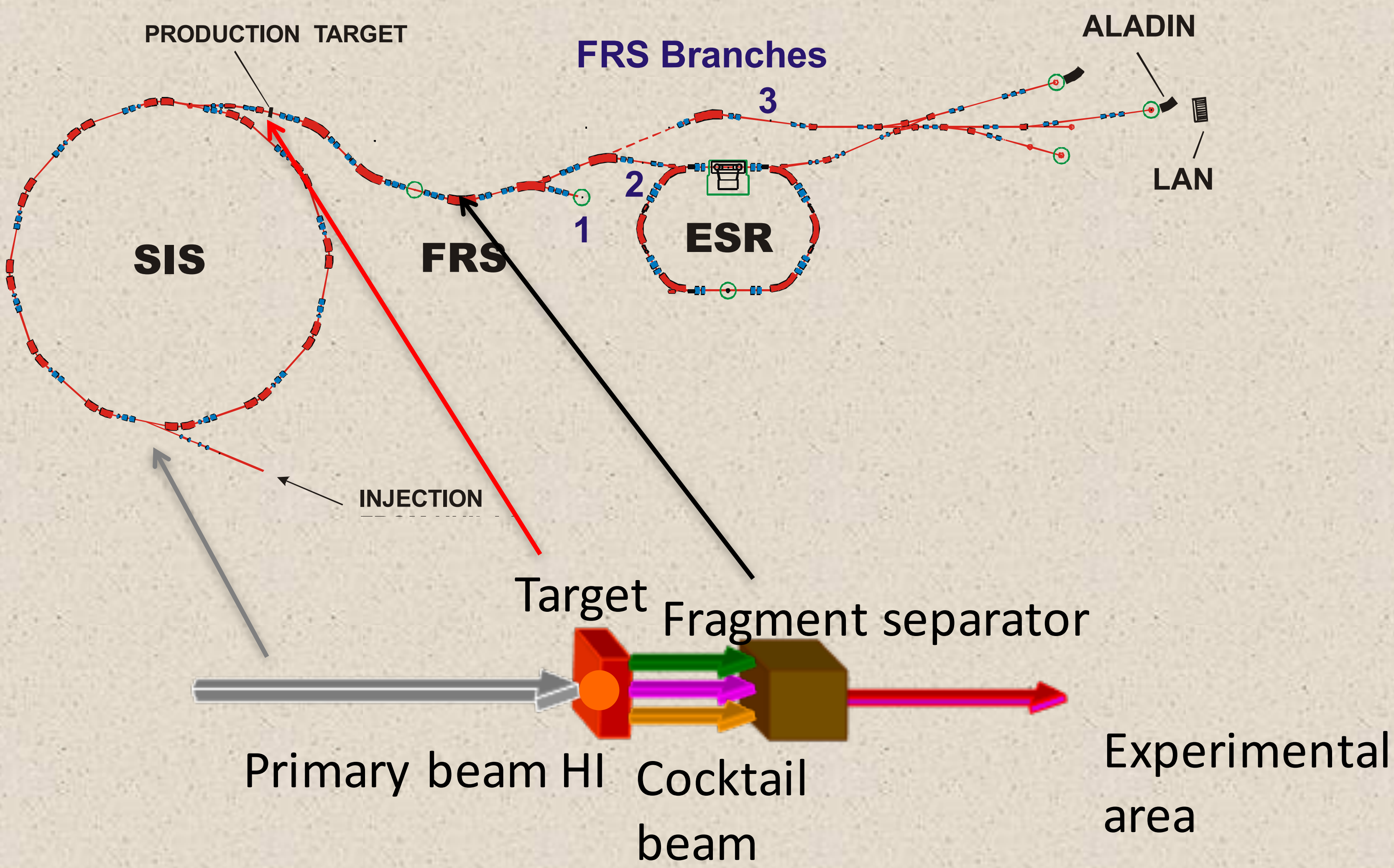
Ions are selected according to the momentum to charge ratio $Mv/q=Mv/Z=B\varrho$. Primary beam is rejected.

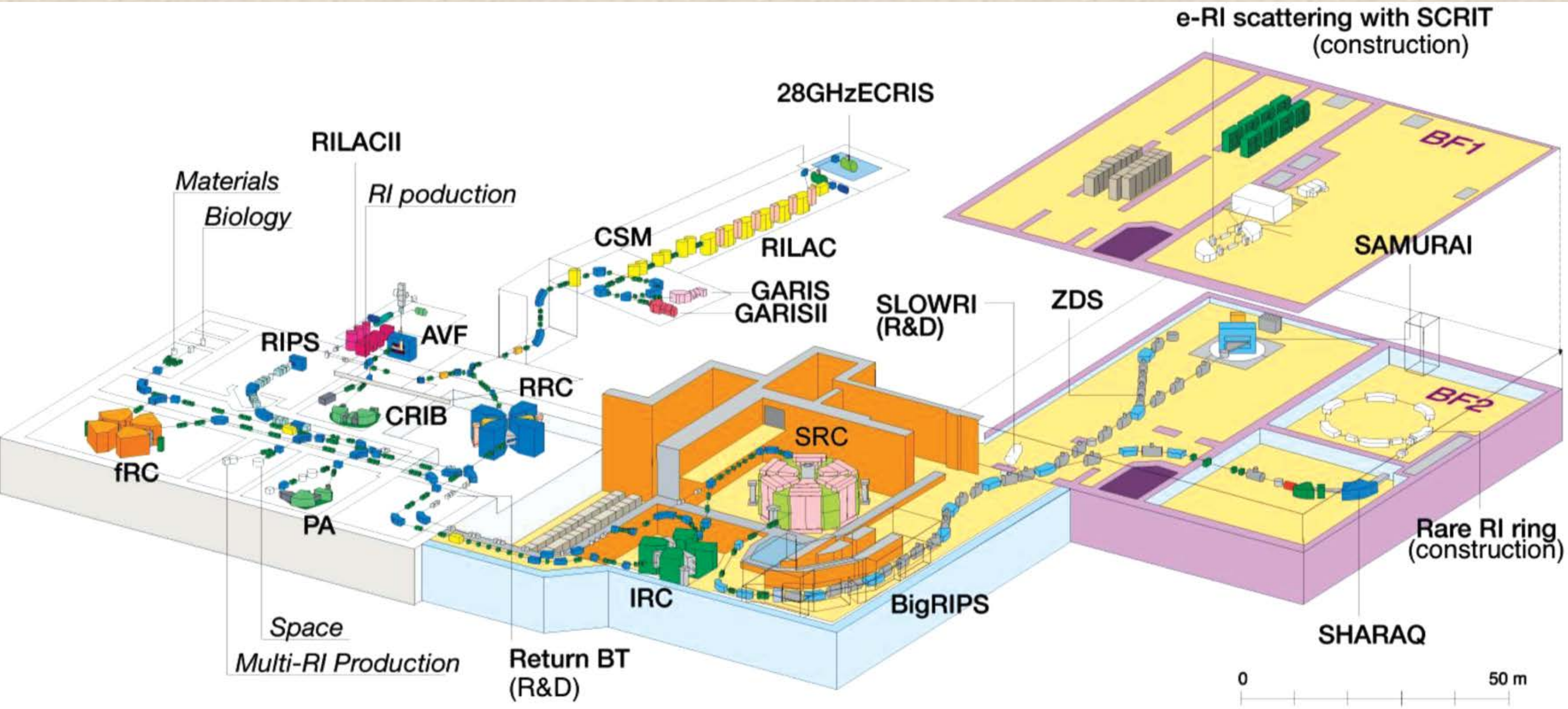
The GSIfragmentation facility

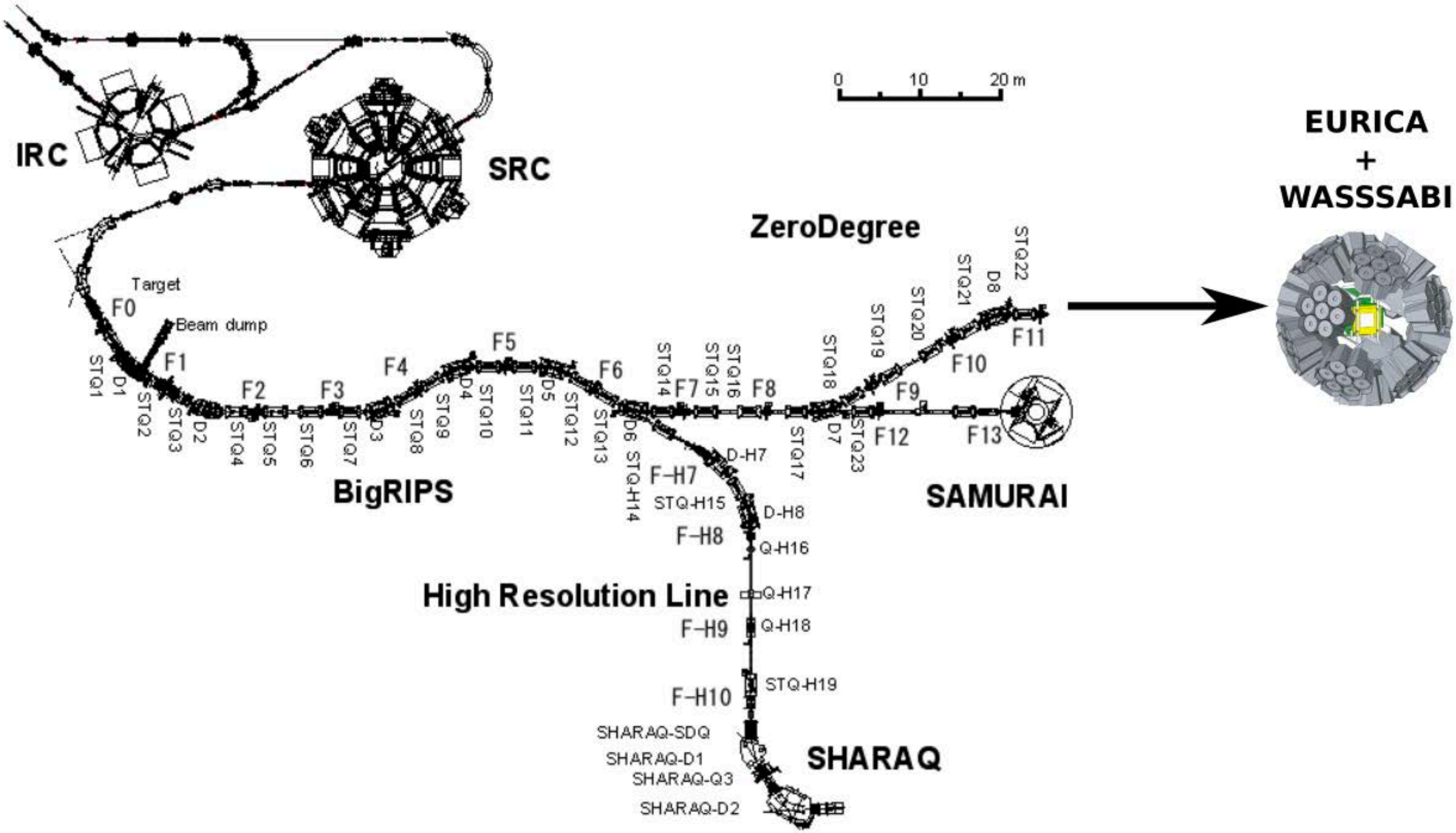


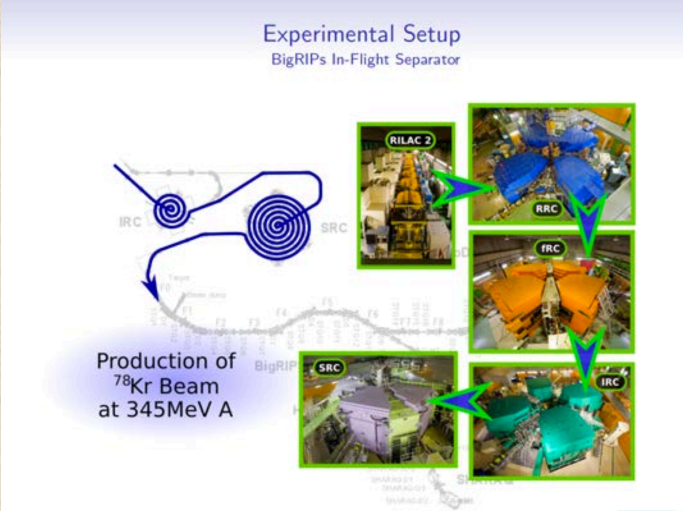
It is possible to accelerate stable Nuclei from H (Z=1) to U (Z=92), in the UNILAC + Synchrotron.

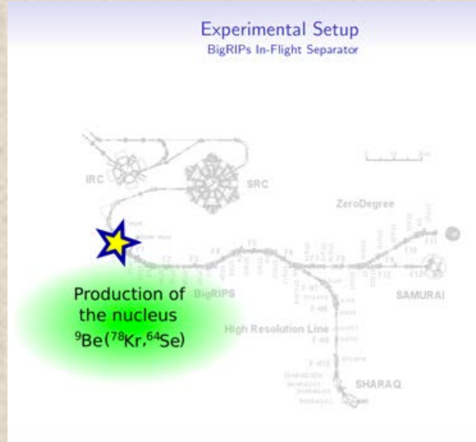
Fragmentation of the primary ion beam: "cocktail" of ions

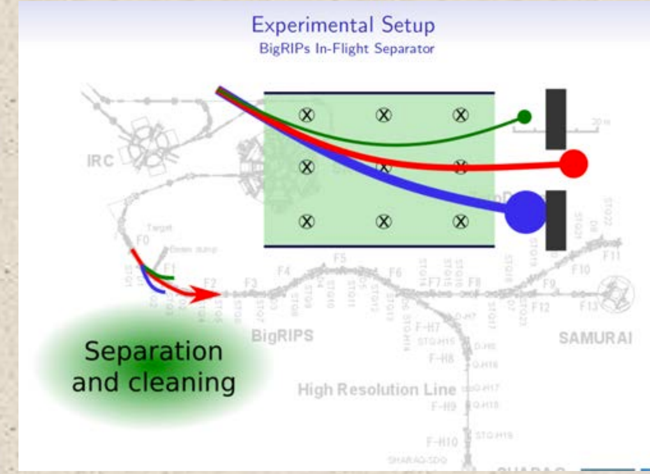

PRODUCTION TARGET
FRS Branches
ALADIN
3
2
1
LAN
SIS
FRS
ESR
INJECTION
Target
Fragment separator
Primary beam HI
Cocktail beam
Experimental area

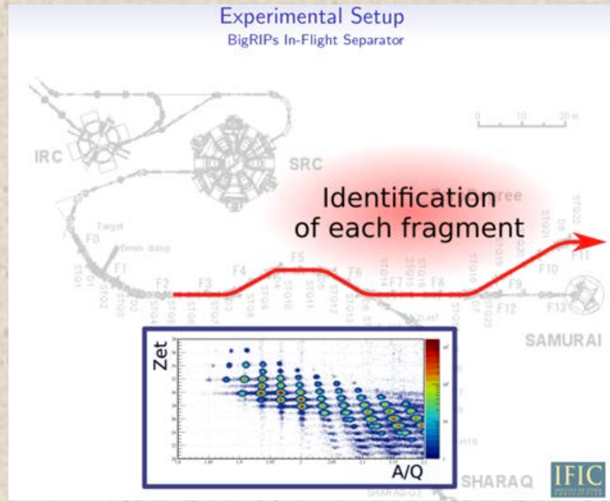

e-RI scattering with SCRIT
(construction)
28GHzECRIS
RILACII
Materials
Biology
RI poduction
CSM
RILAC
BF1
SAMURAI
GARIS
GARISII
SLOWRI
(R&D)
ZDS
RIPS
AVF
RRC
CRIB
SRC
BF2
fRC
PA
IRC
BigRIPS
Rare RI ring
(construction)
SHARAQ
Space
Multi-RI Production
Return BT
(R&D)
0
50 m

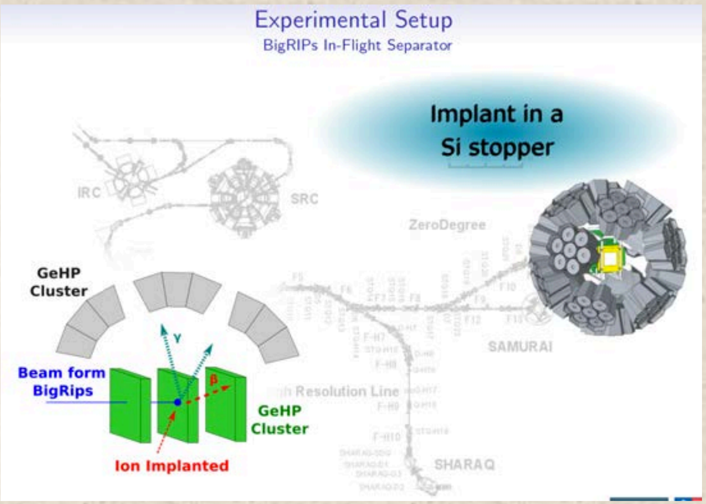

IRC
SRC
0 10 20 m
EURICA
+
WASSSABI
ZeroDegree
Target
F0
Beam dump
F1
F2
F3
F4
F5
F6
F7
F8
F9
F10
F11
F12
F13
STQ1
D1
STQ2
STQ3
D2
STQ4
STQ5
STQ6
STQ7
D3
STQ8
STQ9
D4
STQ10
STQ11
D5
STQ12
STQ13
D6
STQ-H14
STQ14
STQ15
STQ16
STQ17
STQ18
D7
STQ23
STQ19
STQ20
STQ21
D8
STQ22
BigRIPS
SAMURAI
D-H7
F-H7
STQ-H15
D-H8
F-H8
Q-H16
High Resolution Line
Q-H17
F-H9
Q-H18
STQ-H19
F-H10
SHARAQ-SDQ
SHARAQ-D1
SHARAQ-Q3
SHARAQ-D2
SHARAQ


Experimental Setup
BigRIPs In-Flight Separator
RILAC 2
RRC
fRC
IRC
SRC
Production of
78Kr Beam
at 345MeV A


Experimental Setup
BigRIPs In-Flight Separator
Production of
the nucleus
9Be(78Kr,64Se)


Experimental Setup
BigRIPs In-Flight Separator
Separation
and cleaning
BigRIPS
High Resolution Line
SAMURAI


Experimental Setup
BigRIPs In-Flight Separator
Identification
of each fragment
Zet
A/Q
SAMURAI
SHARAQ
IFIC


Experimental Setup
BigRIPs In-Flight Separator
Implant in a
Si stopper
GeHP
Cluster
Beam form
BigRips
GeHP
Cluster
Ion Implanted
SAMURAI
SHARAQ

Estudios de núcleos exóticos en RIKEN (Japón)

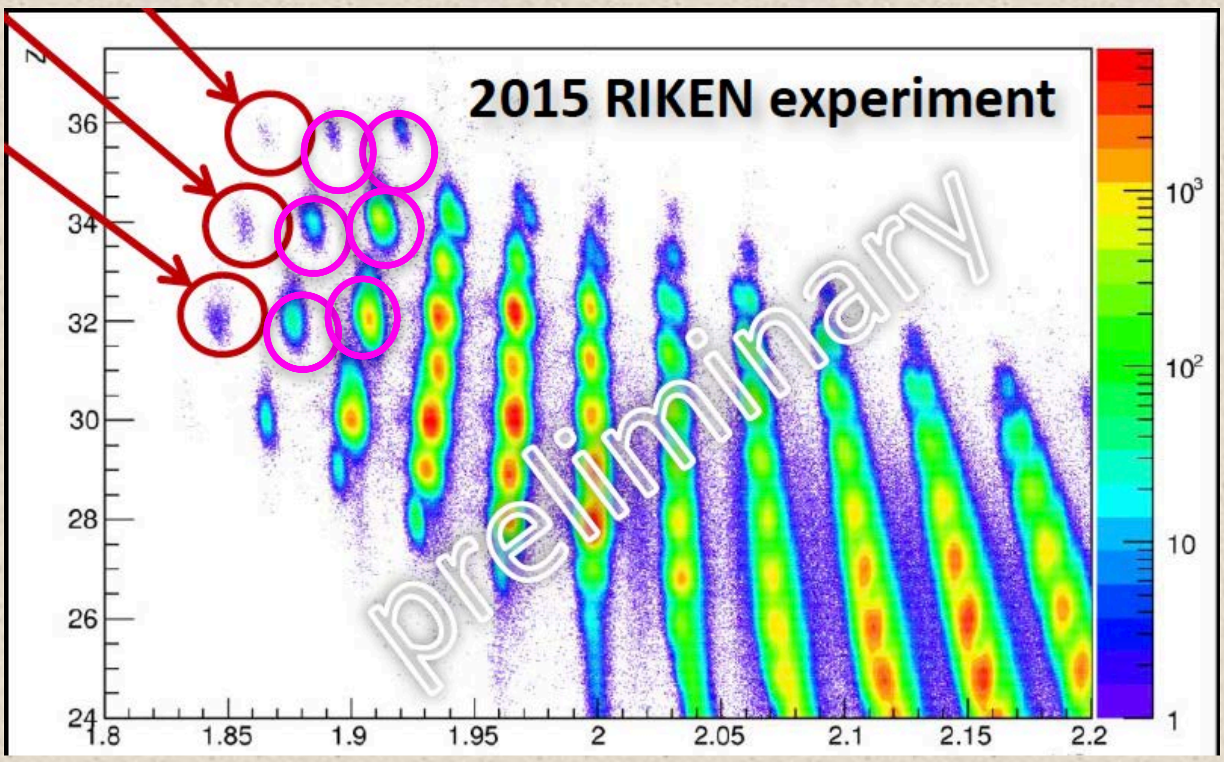
A. Algora et al.

B. Blank et al.

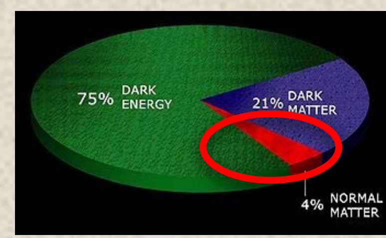
B. Rubio et al.

Descubrimiento de nuevos isótopos

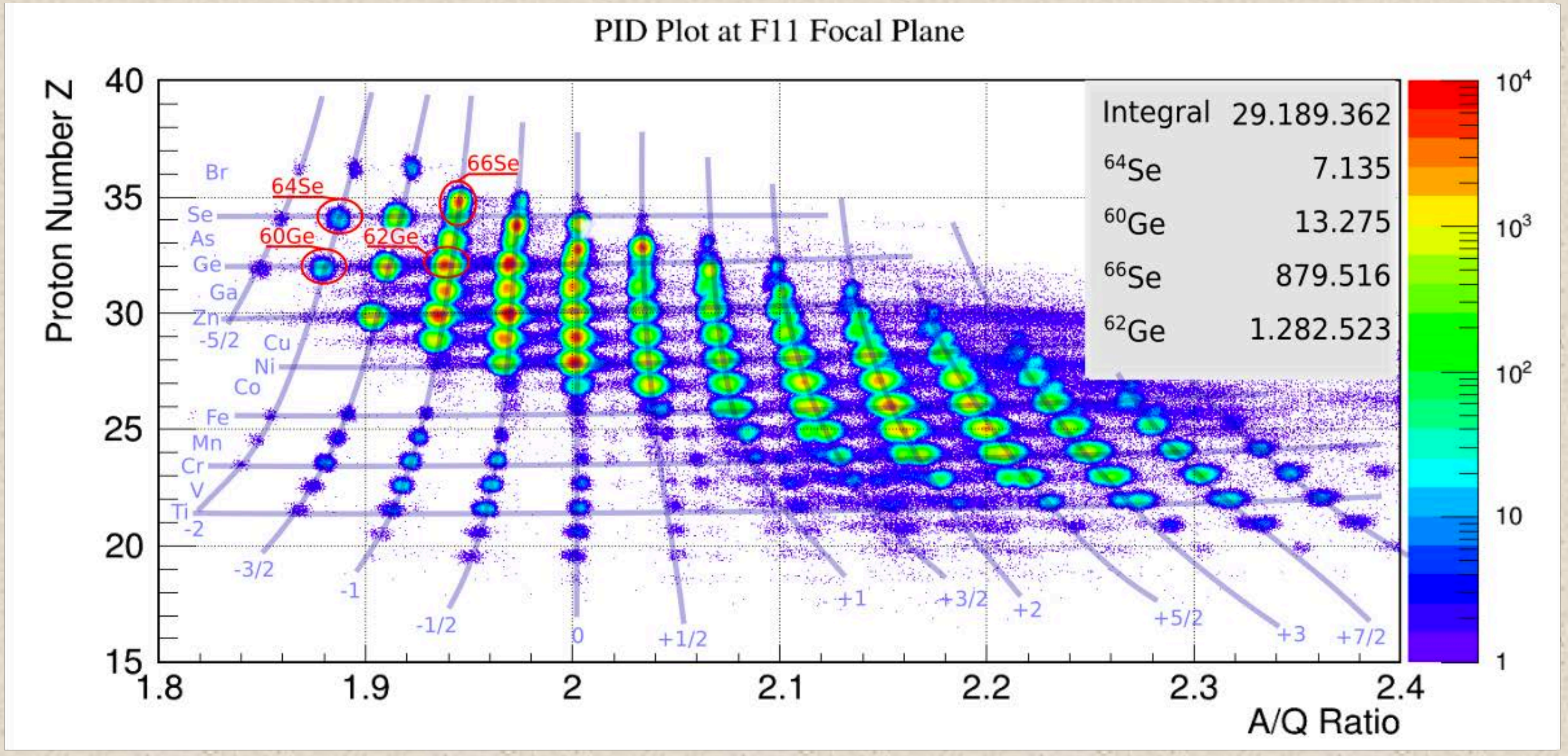
Estudio de los núcleos de Ge, Se, y Kr más exóticos



Alcanzado el límite de Existencia de los núcleos



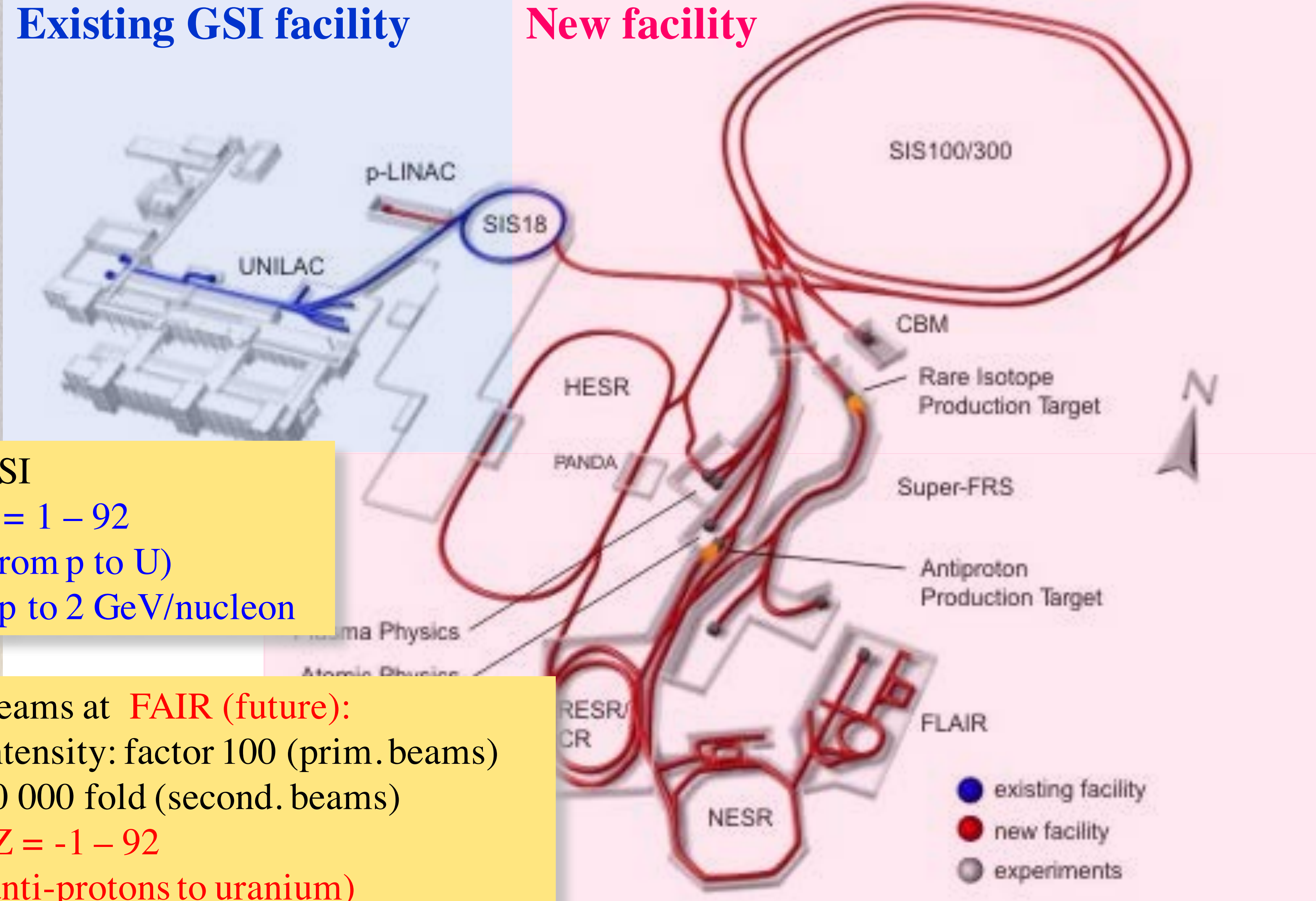
At a fragmentation Facility, normally, many nuclei arrive AT THE SAME TIME at the experimental set up area (implantation detector, secondary target….),.
But in an event by event data taking mode, they can be separated (characterised) a posteriory.



Future (in Europe)

Existing GSI facility

New facility

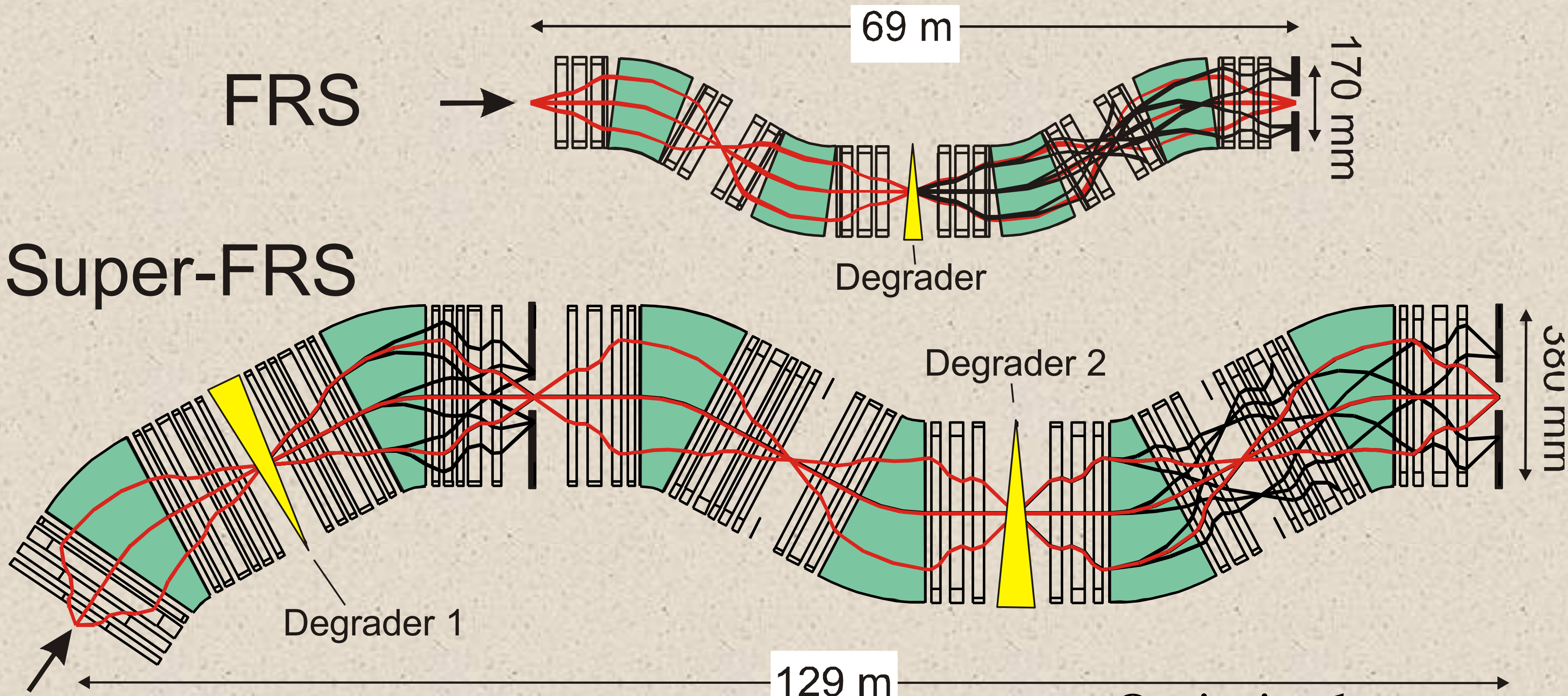


GSI
Z = 1 – 92
(from p to U)
Up to 2 GeV/nucleon

Beams at FAIR (future):
Intensity: factor 100 (prim. beams)
10 000 fold (second. beams)
Z = -1 – 92
(anti-protons to uranium)
Up to 35 - 45 GeV/u
„full beam cooling“

FRS to Super-FRS

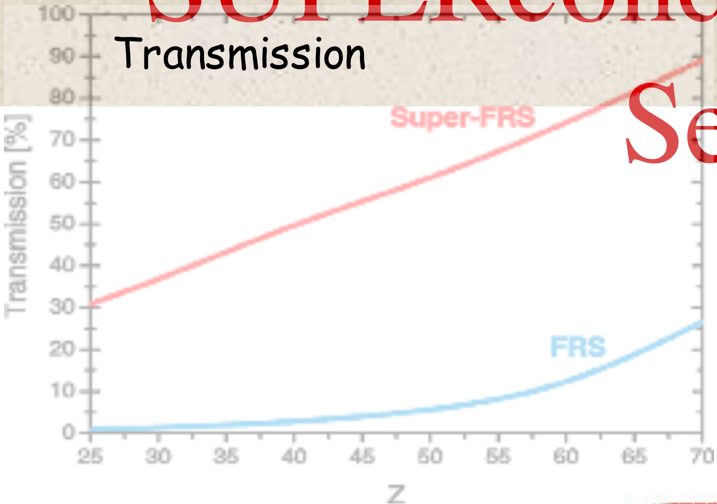
Bρ-ΔE-Bρ Separation Method

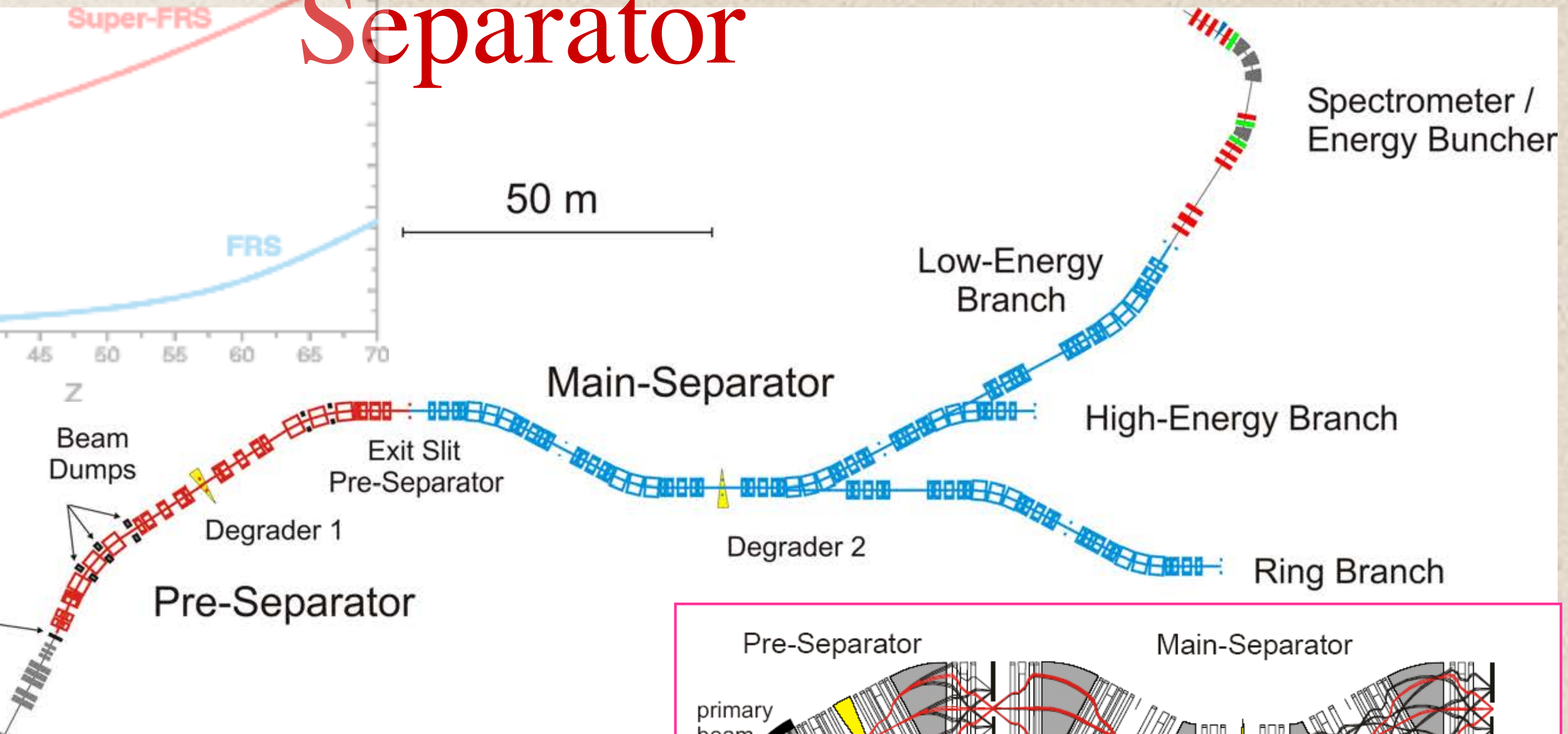


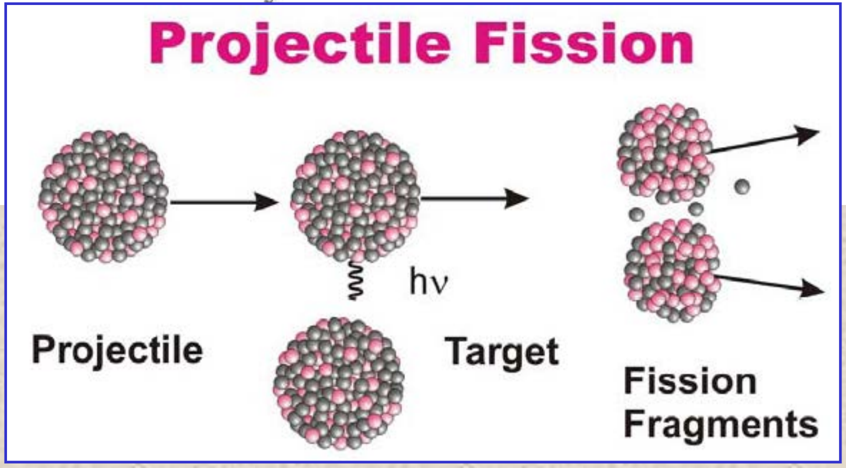
Optimised to separate very fast fragment or fission products

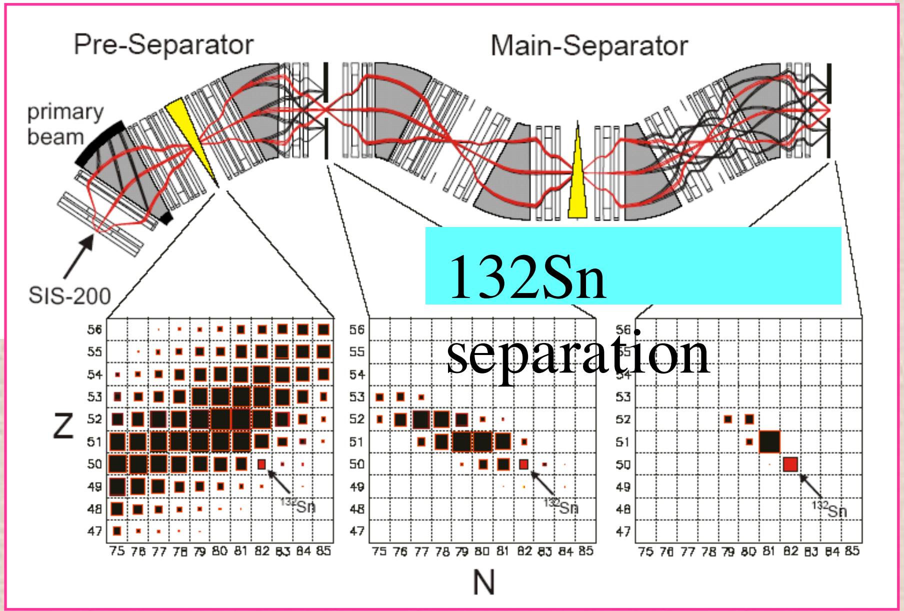
H. Geissel et al. NIM B 204 (2003) 71

SUPERconducting FRagment Separator









132Sn

separation

FAIR Project Progress – Civil Construction

SIS 18 in direction of pLinac :
Preparation of western transfe
channel (WTK)

SIS 100:
trench sheeting
(first 8 meters
sheet piling)

FAIR Construction Field

Scenario for NUSTAR: **Day one**

2016	2017	2018	2019	2020	2021	2022	2023	2024	2025

Super-FRS

construction and installation

commissioning

opera

NUSTAR caves

civil construction

NUSTAR experim

construction and op

installation

commissioning

operation at I

Phase 1

Day one

Tiempo perfecto para un postdoc!!

ISOL and In-Flight facilities-Partners

It is probably true to say that if we worked at it virtually all experiments could be done with both types of facility but they are complementary.

In-Flight

- Relativistic beams
- Universal in Z
- Down to very short $T_{1/2}$
- Easily injected into storage rings
- More exotic beams

ISOL

- High intensity beams with ion optics comparable to stable beams
- Easy to manipulate beam energies from keV to 10s of MeV
- Cleaner