Producción y uso de haces radioactivos

Master Interuniversitario de Física Nuclear

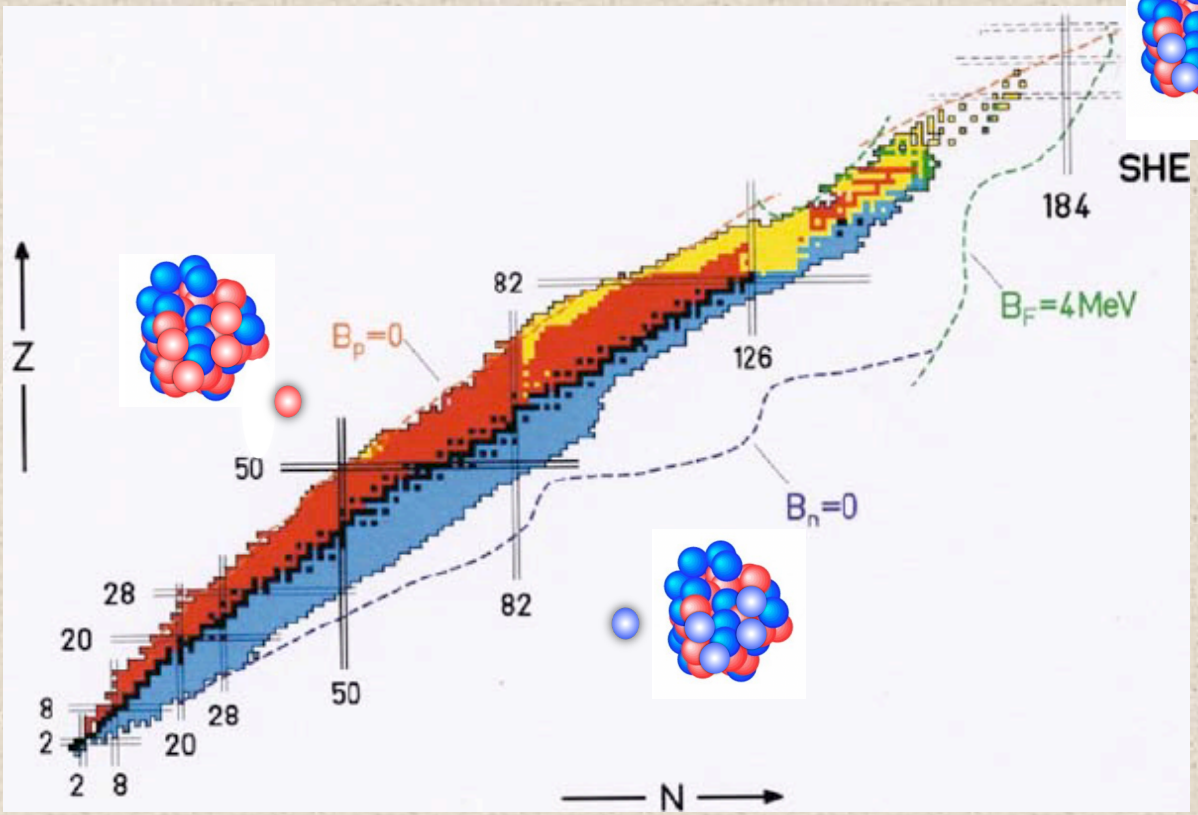
Berta Rubio IFIC (CSIC-Univ. Valencia)

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

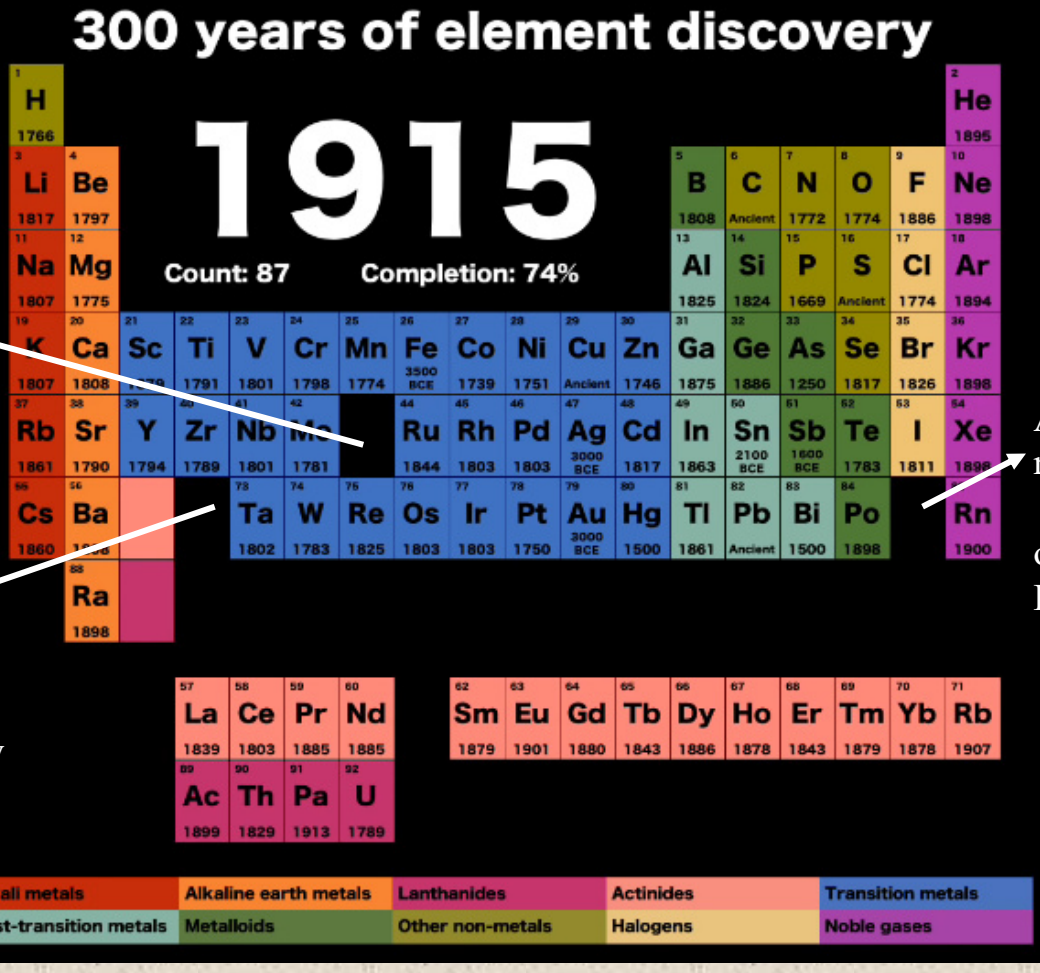
Reacciones nucleares y lo que nos enseñan de la estructura de los núcleos (M.J. García Borge, D. Cortina).
Porqué necesitamos haces post acelerados
Porqué necesitamos alejarnos de la estabilidad (J.L. Taín, A. Gadea, E. Nácher).

265 stable

About 3000 out of 6000 synthesised in our laboratories.



Tachnetium (“artificial”), unstable, discovered in 1934 by Segre from a piece of cyclotron mailed by Ernest Lawrence from Berkely to Sicily. (used in millions of medical diagnosis)



Astatine is the rarest element existing in our planet with a total of 25gr. Isolated by Berta Kerlik in the 40’s

Hafmium, relatively abundant in nature but very difficult to separate from Zn (X-yay spectrometry) (1923)

Search for Super Heavy elements Z>100

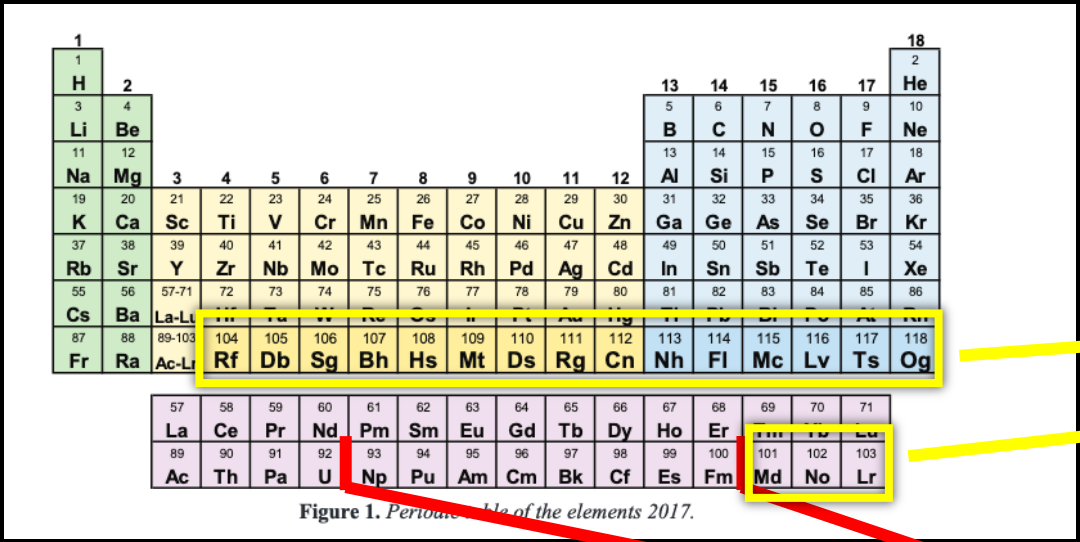
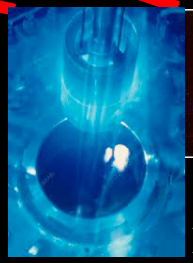


Figure 1. *Periodic table of the elements 2017.*

Super Heavy elements Can only be produced at accelerato rs facilities

Z	Name	Symbol	Year of Discovery	Discoverer
104	Rutherfordium	Rf	1969	Ghiorso et al. (LBNL Berkeley)
105	Dubnium	Db	1970	Ghiorso et al. (LBNL Berkeley)
106	Seaborgium	Sg	1974	Ghiorso et al. (LBNL Berkeley)
107	Bohrium	Bh	1981	Münzenberg et al. (GSI Darmstadt)
108	Hassium	Hs	1984	Münzenberg et al. (GSI Darmstadt)
109	Meitnerium	Mt	1982	Münzenberg et al. (GSI Darmstadt)
110	Darmstadtium	Ds	1995	Hofmann et al. (GSI Darmstadt)
111	Roentgenium	Rg	1995	Hofmann et al. (GSI Darmstadt)
112	Copernicium	Cn	1996	Hofmann et al. (GSI Darmstadt)
113	Nihonium	Nh	2004	Morita et al. (RIKEN Wako-shi)
114	Flerovium	Fl	2004	Oganessian et al. (FLNR Dubna)
115	Moscovium	Mc	2010	Oganessian et al. (FLNR Dubna)
116	Livermorium	Lv	2004	Oganessian et al. (FLNR Dubna)
117	Tennessine	Ts	2010	Oganessian et al. (FLNR Dubna)
118	Oganesson	Og	2006	Oganessian et al. (FLNR Dubna)



Reactors

Fm discovered in the 50ths

Meitnerium, the only element named after a woman scientist

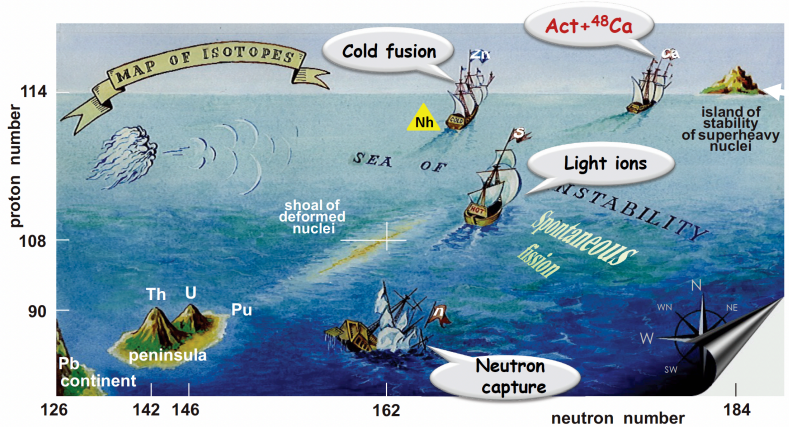
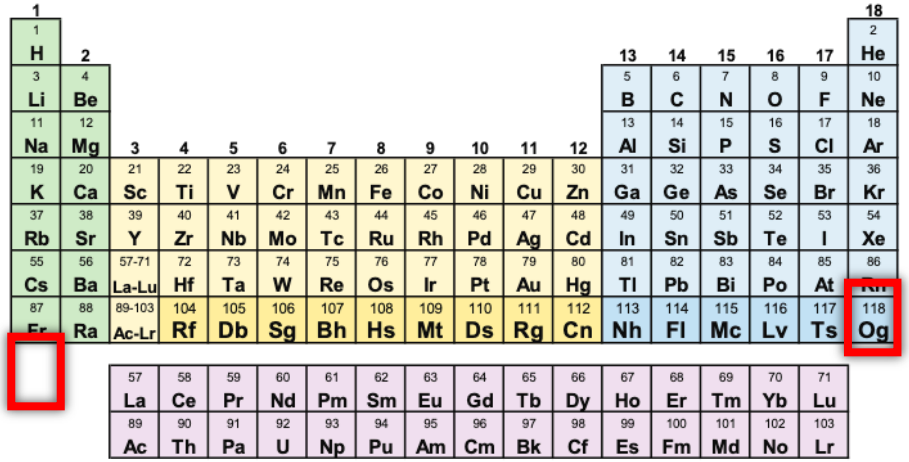


Figure 2. *Voyage to the heaviest nuclei.*

Will we prove the existence of the island of stability?



1																	18
1 H	2											13	14	15	16	17	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg	3	4	5	6	7	8	9	10	11	12	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57-71 La-Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89-103 Ac-Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

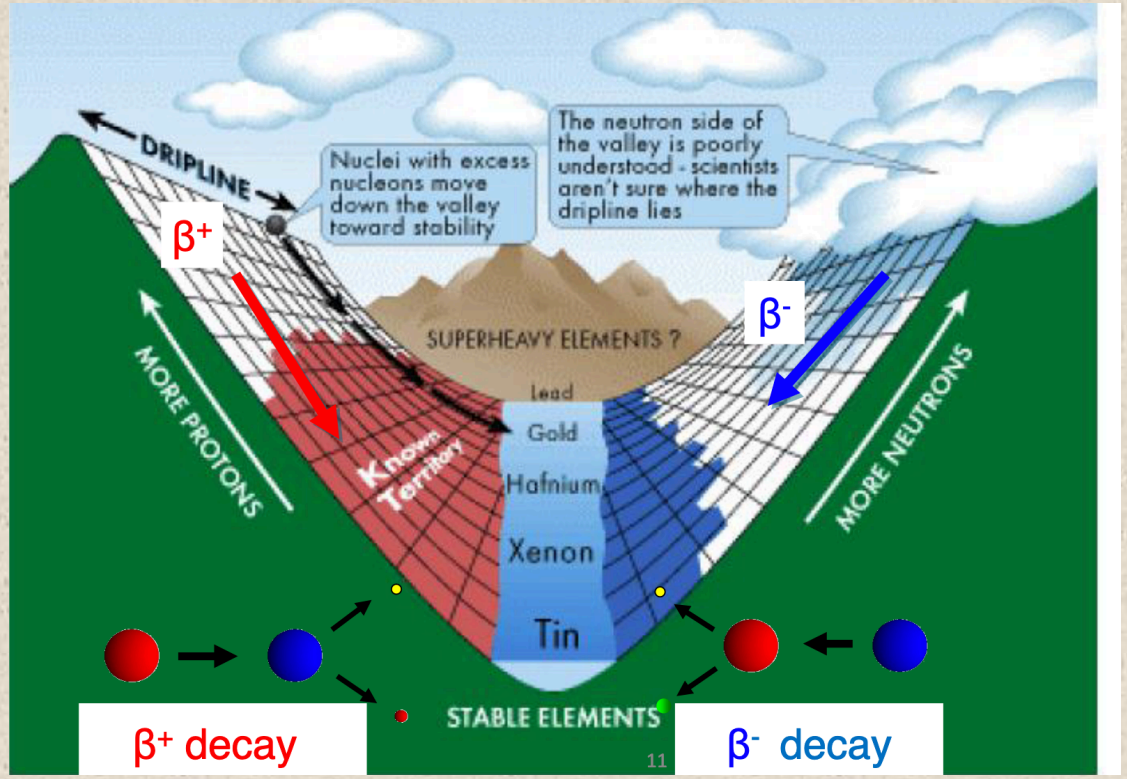
57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Figure 1. *Periodic table of the elements 2017.*

Is Oganesson a nobel gas or is neither nobel nor a gas

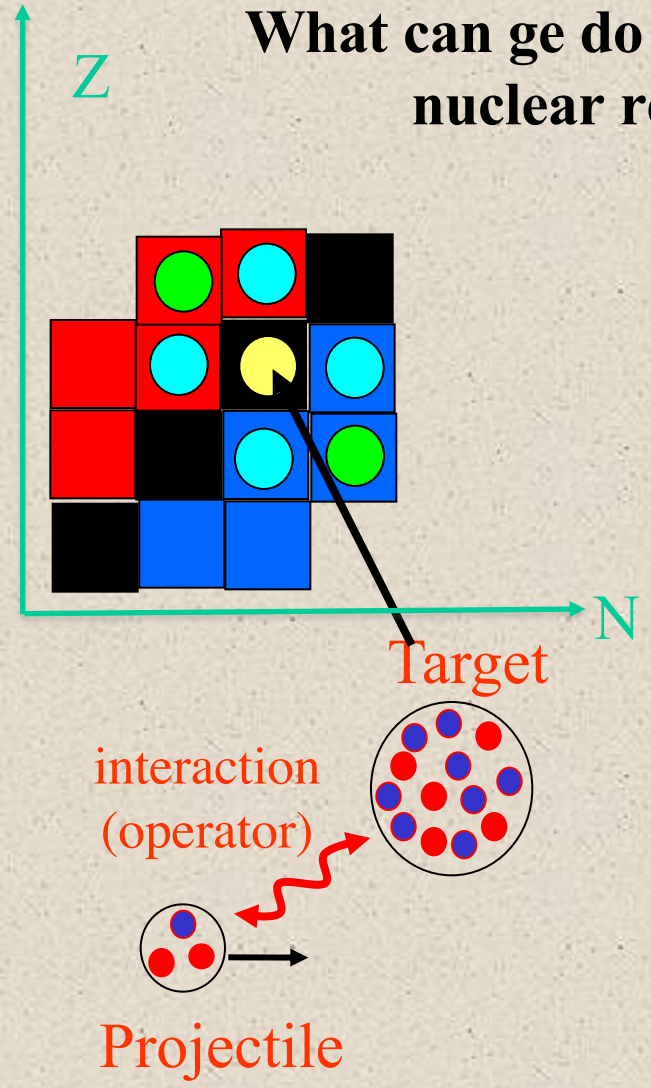
Does period number 8 exists?

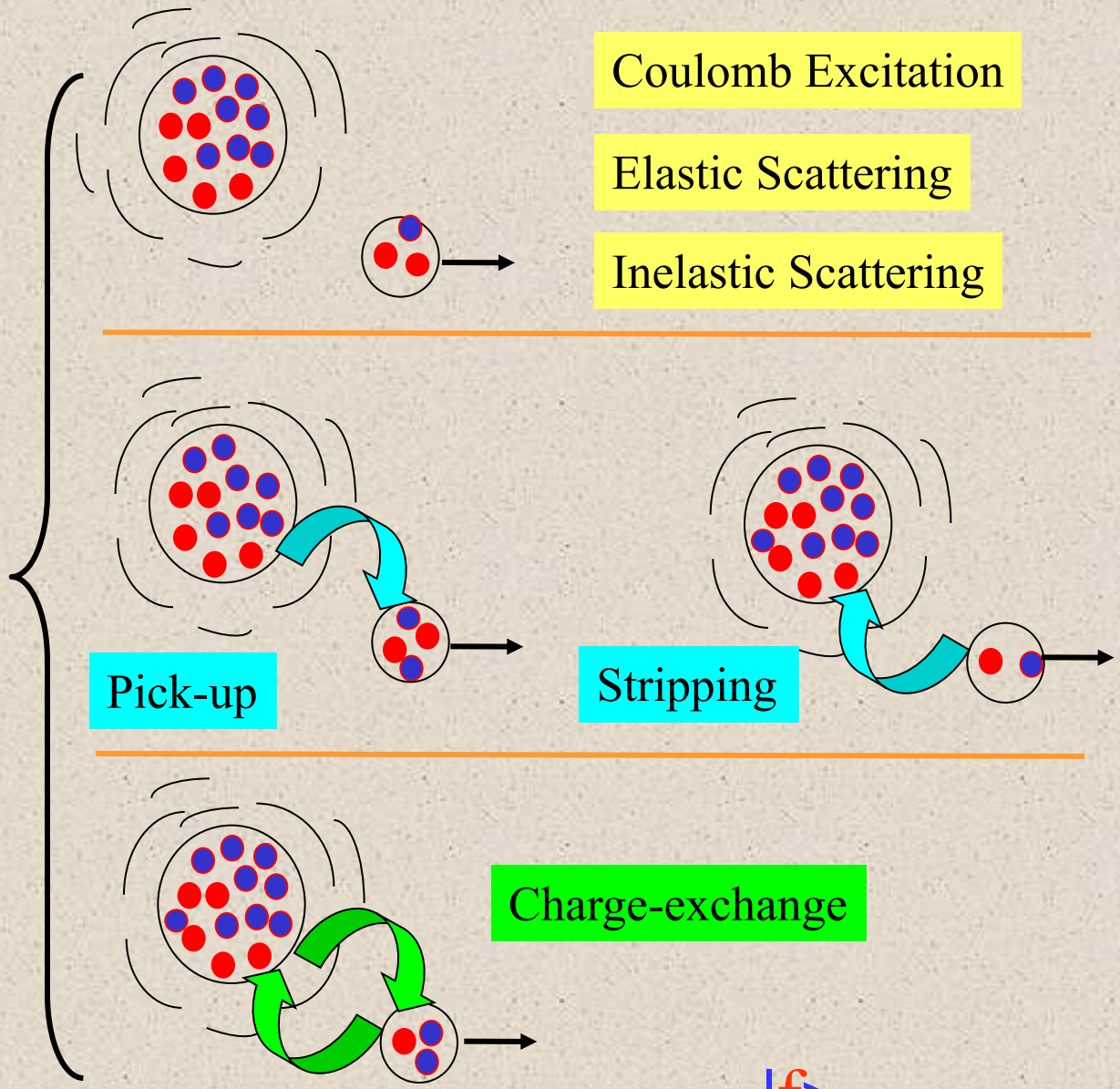
Similarly to the chemical elemets, the nuclei
are better known and understood if the lie closse to the stability



Let us see an example

What can ge do if we have an stable target : we can perform nuclear reactions, for instance with light nuclei

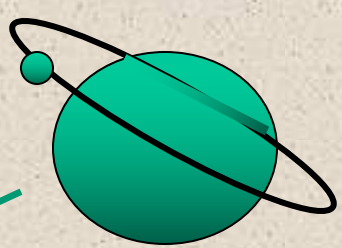




|i> → |f>

Let us use an illustrative example: ^{209}Bi

$^{208}_{82}Pb_{126}$



209Bi=208Pb+p

$^{209}_{83}Bi_{126}$

Closed shell + 1 p

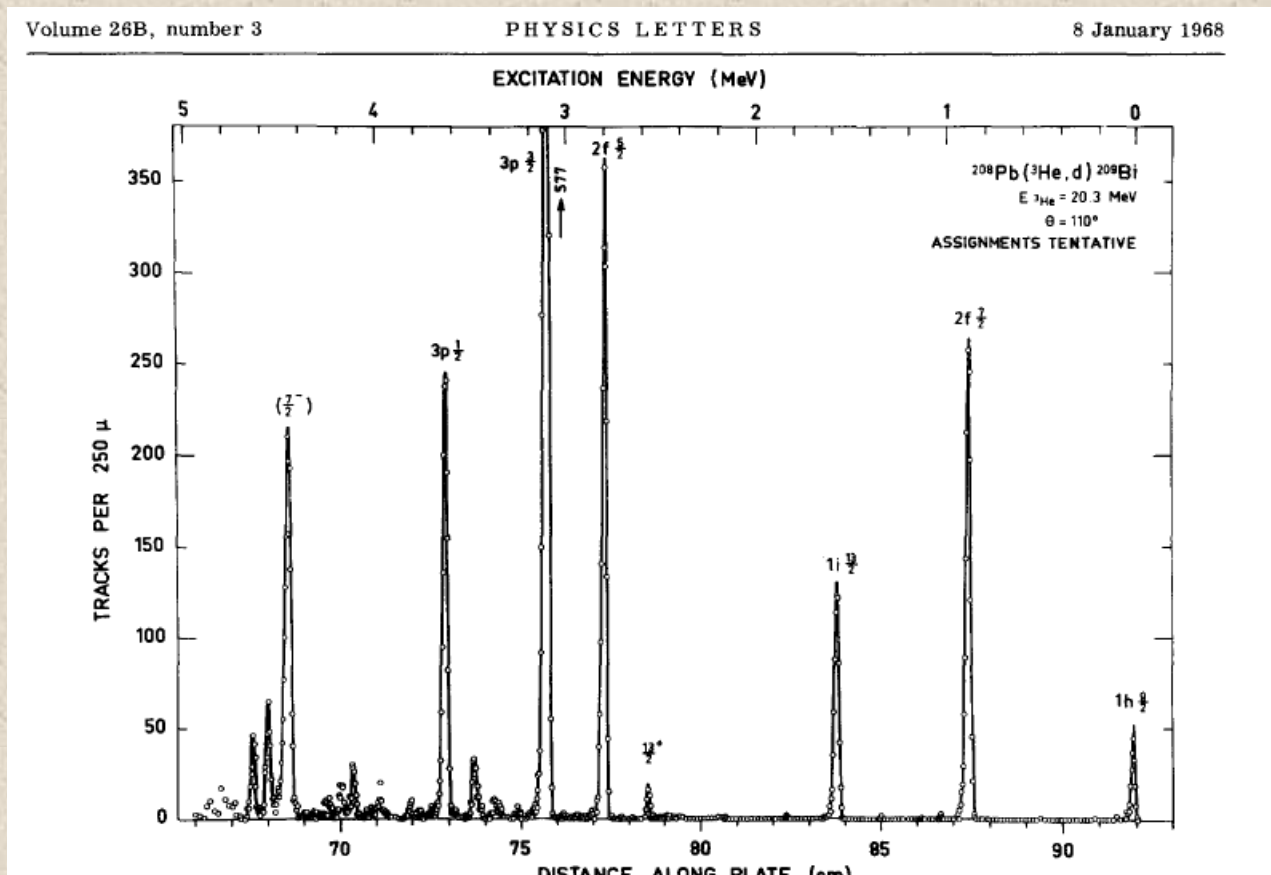
Closed shell for neutrons

Reaction: 208Pb(3He,d)209Bi

|i> → |f>

208Pb target

209Bi final nucleus



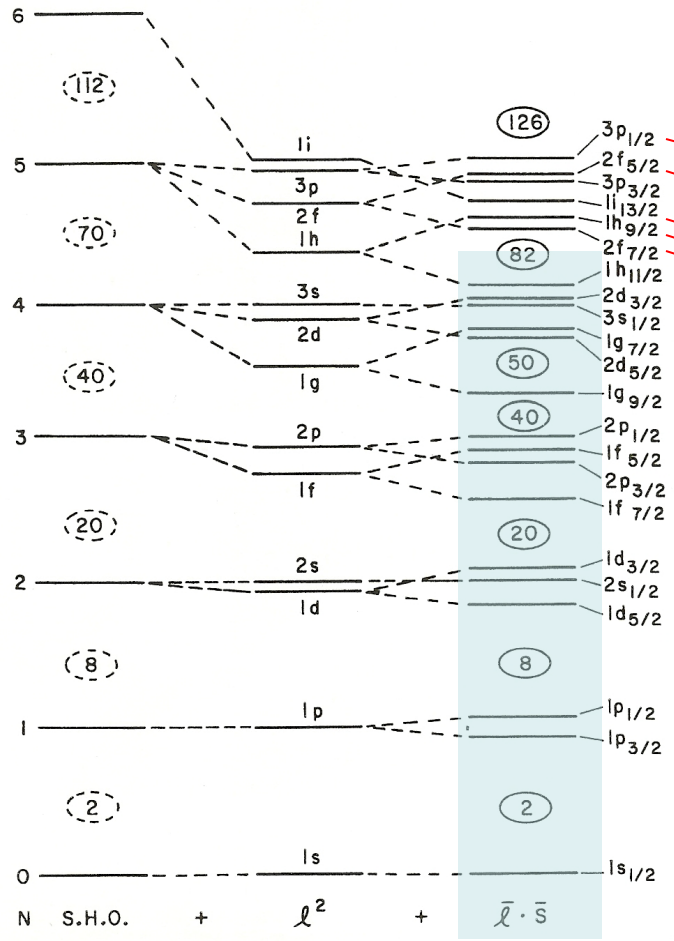
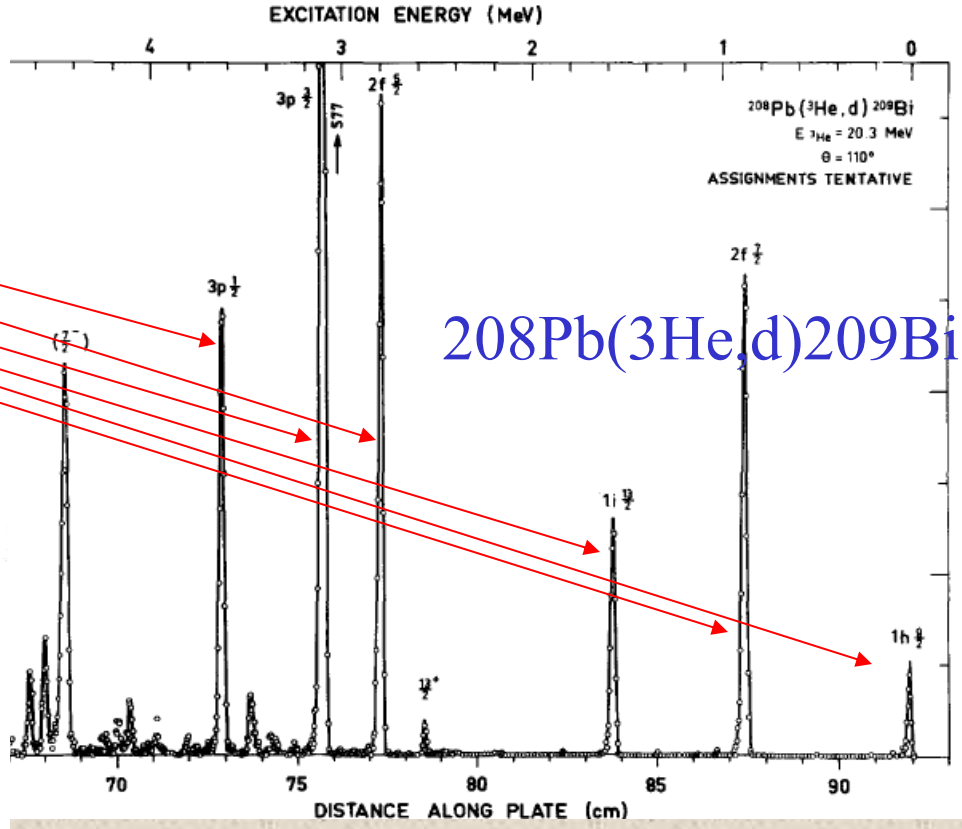


Fig. 3.2. Single-particle energies for a simple harmonic oscillator (S.H.O.), a modified harmonic oscillator with l^2 term, and a realistic shell model potential with l^2 and spin orbit ($l \cdot s$) terms.

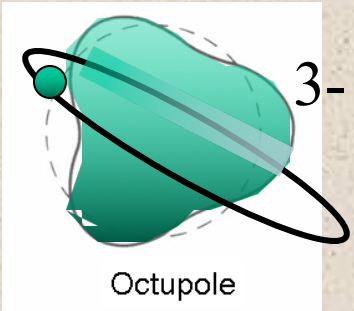


208Pb(3He,d)209Bi

209Bi=208Pb+p

208Po

$h_{9/2}$



209Bi=208Pb+p

$3^- \times h^{9/2}$

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

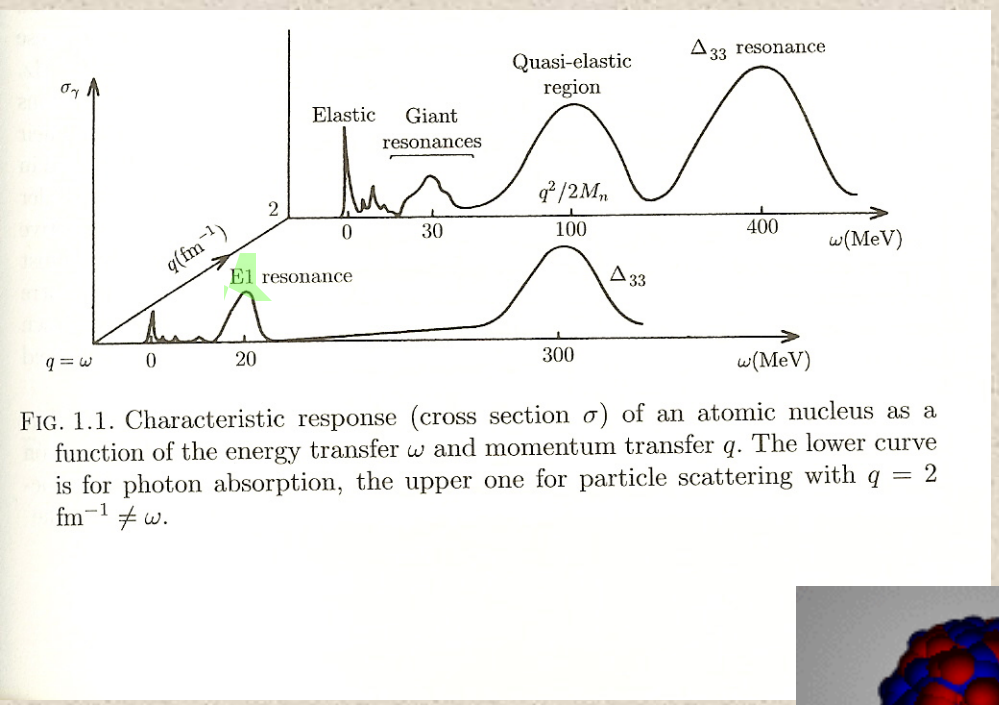
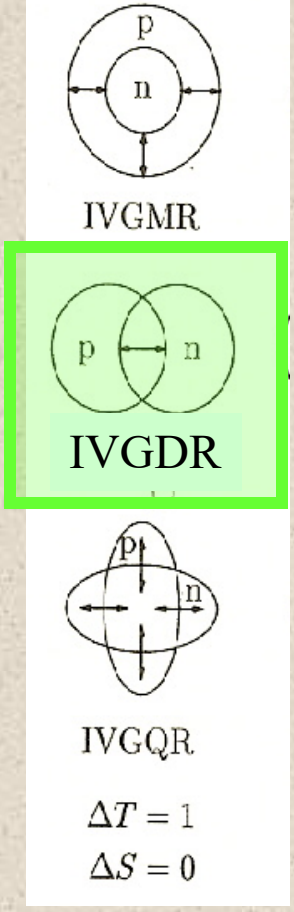


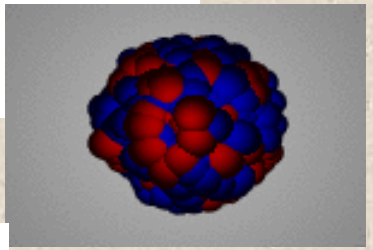
FIG. 1.1. Characteristic response (cross section σ) of an atomic nucleus as a function of the energy transfer ω and momentum transfer q. The lower curve is for photon absorption, the upper one for particle scattering with $q = 2$ fm$^{-1} \neq \omega$.

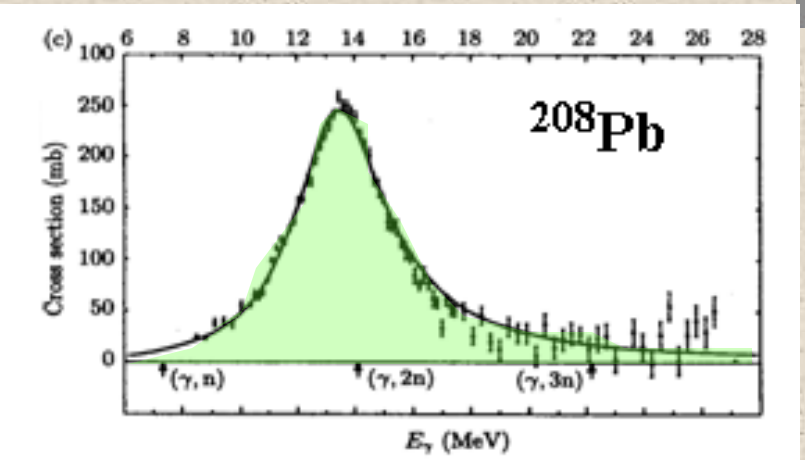
Isovector

ΔT=0 1



E1



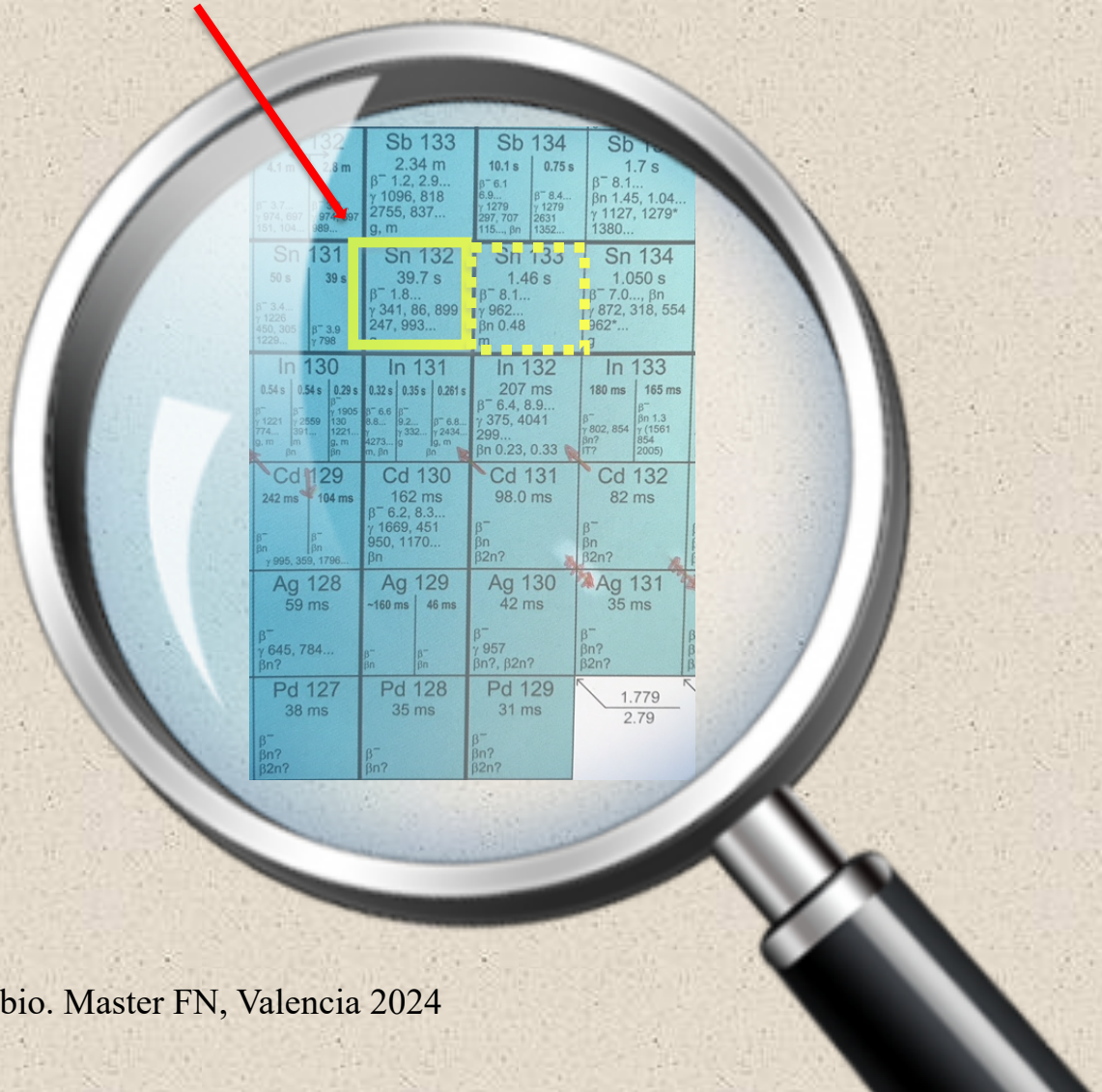


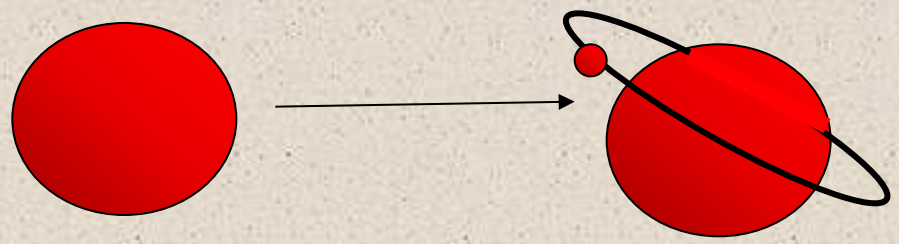
Qué ha sido necesario para poder hacer estos experimentos

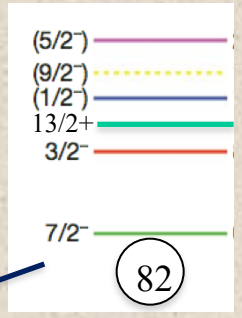
1. Definir la reacción nuclear de interés.
2. Blancos estables: 208Pb y 209Bi en este caso
2. (Un proyectil “sin estructura”)
3. (Un proyectil ligero (struggling))

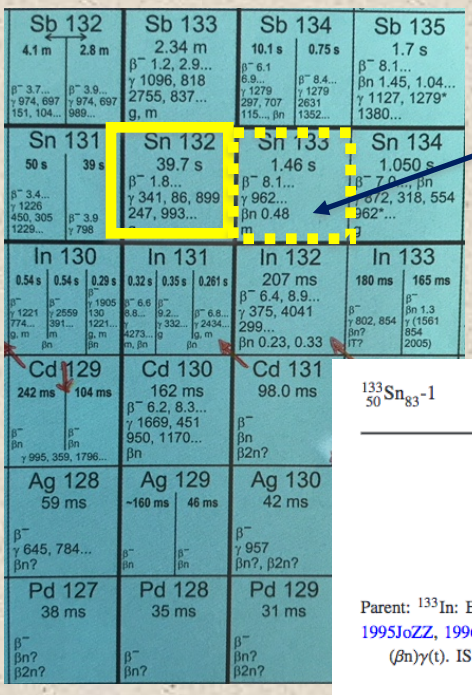
Vamos a intentar aproximarnos a otro núcleo doblemente mágico: ^{132}Sn (Z=50, N=82)

^{132}Sn, unstable, $T_{1/2}$=40s









$^{133}_{50}Sn_{83}$-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^π=(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, γγ-, nγ-, βγ-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)†	Jπ‡
0.0	7/2⁻
853.7 *3*	3/2⁻
1560.9 *5*	(9/2⁻)
2004.6 *10*	(5/2⁻)

½- missing

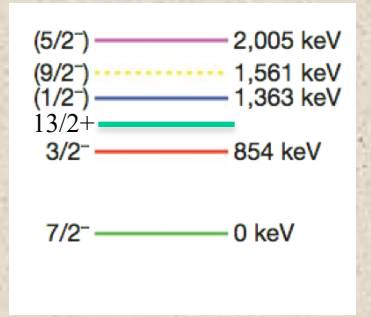
nature Vol 465|27 May 2010|doi:10.1038/nature09048

LETTERS

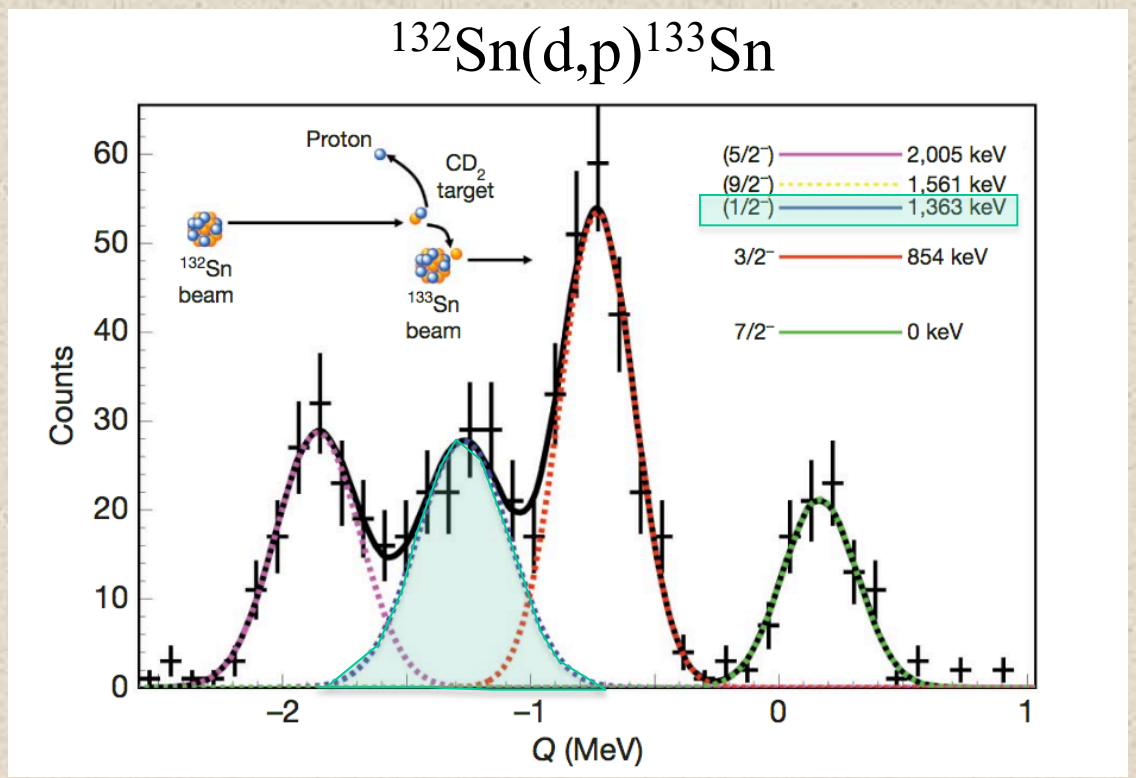
Year 2010

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]



^{132}Sn(d,p)^{133}Sn



Conclusion of this part

It is important to have the possibility to perform reactions where either the target or the projectile are radioactive. But for most of the cases, a radioactive beam is more feasible than a radioactive target

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

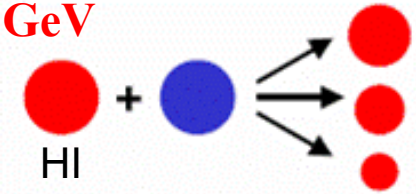
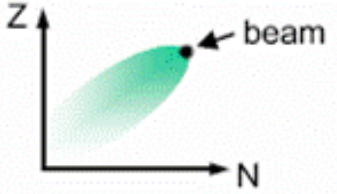
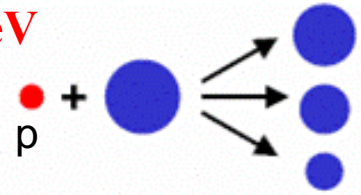
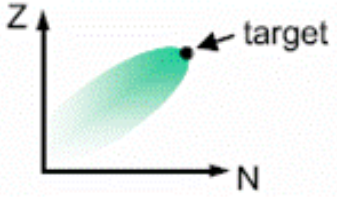
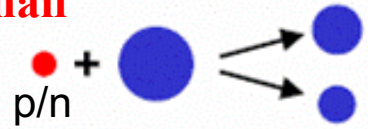
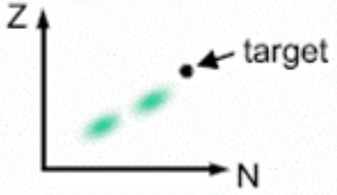
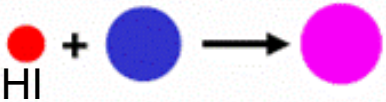
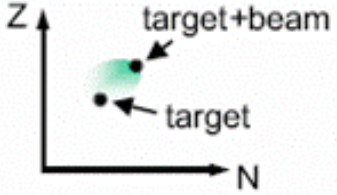
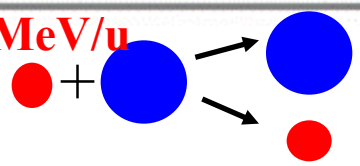
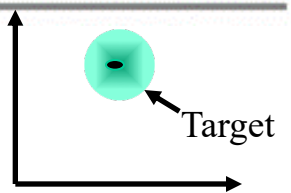
Postaceleration

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

The first one is known since many years
(Isolde-CERN, since 1967)

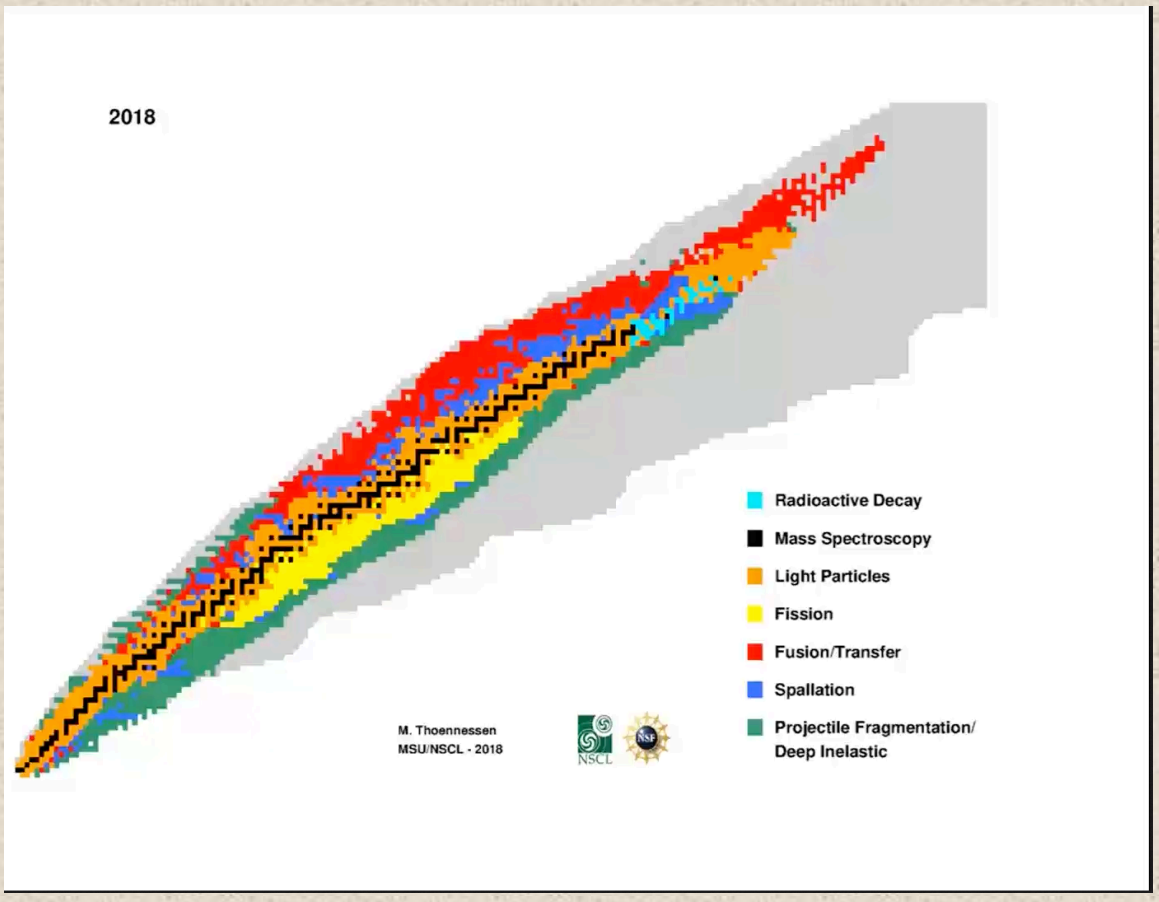
The first thing to worry about is how to produce radioactive nuclei.
Tool: Reaction or Fission

The reaction to produce Radioactive beams starting with stable beam and stable target

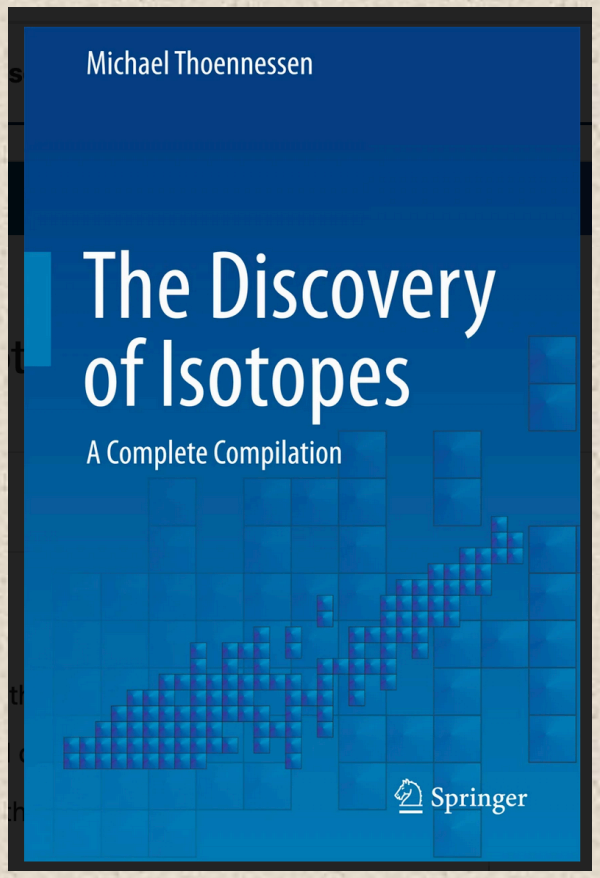
Beam + target → products		Product energy	Number of Products	
GeV 	fragmentation	"All nuclei" $v_{product} = v_{beam}$ RIKEN, GSI, MSU,FAIR, FRIB	up to 1000	
GeV 	spallation	"All nuclei" few MeV/u ISOLDE	up to 1000	
small 	fission	"mainly neutron rich" ~1 MeV/u Reactors, ISOLDE…	few 100	
5MeV/u 	fusion-evaporation	"mainly proton rich rich" $E_R = \frac{m_p}{m_p + m_t} E_P$ "SPIRAL2"	few (≤ 20)	
20 MeV/u 	Transfer reactions	"close to the stability" 5-100 MeV/u "Small facilities"	Very few: 2-5	

Historical view to the discovery of new isotopes

https://people.nscl.msu.edu/~thoennes/isotopes/2018-Isotope-Movie.mp4

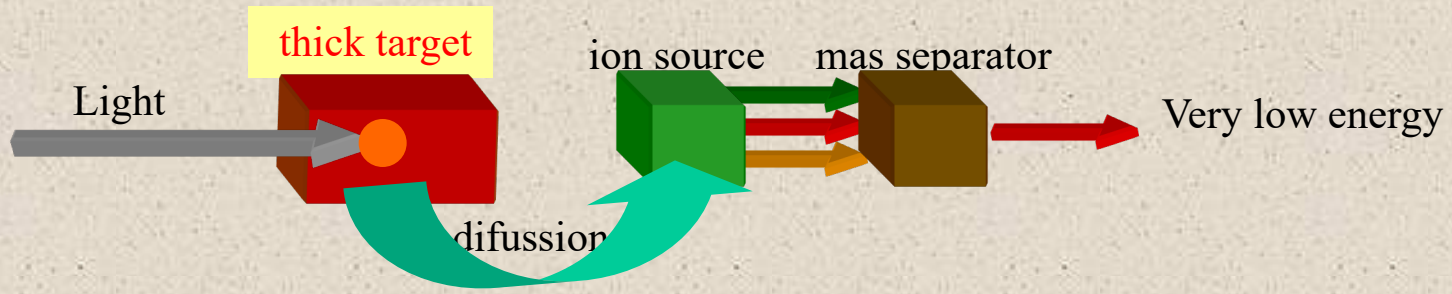


I you want to learn how all that happened, read this book

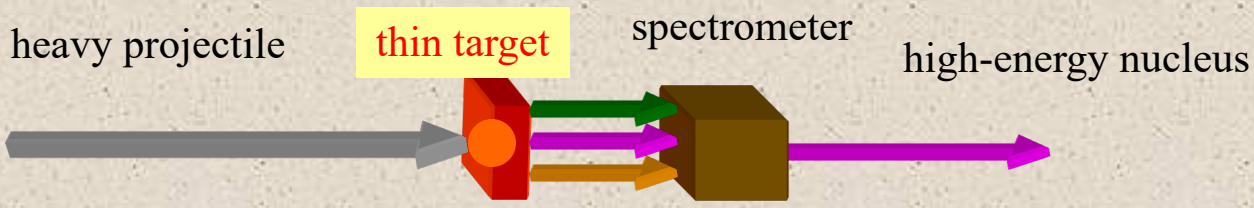


The second thing is to separate them from other radioactive products:
Radioactive nuclei production techniques

Isotopic Separation On-Line (ISOL)

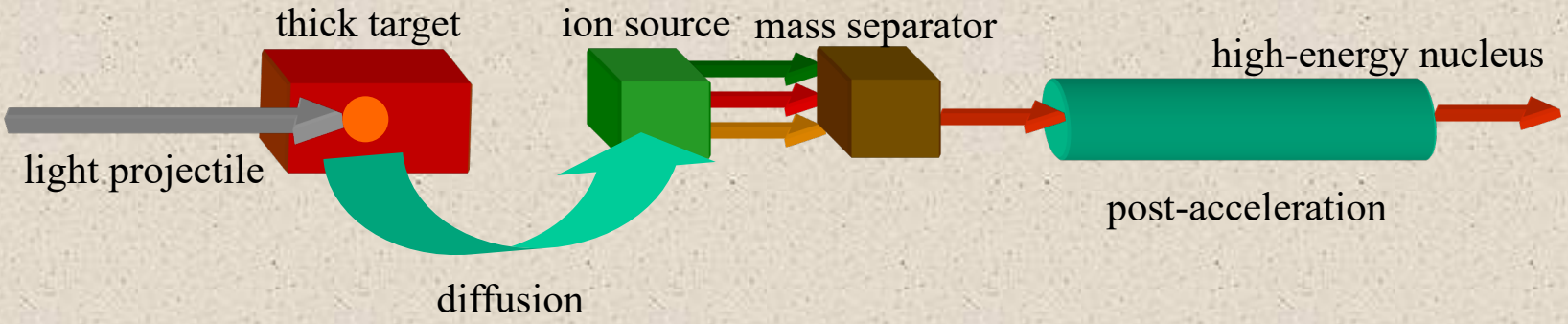


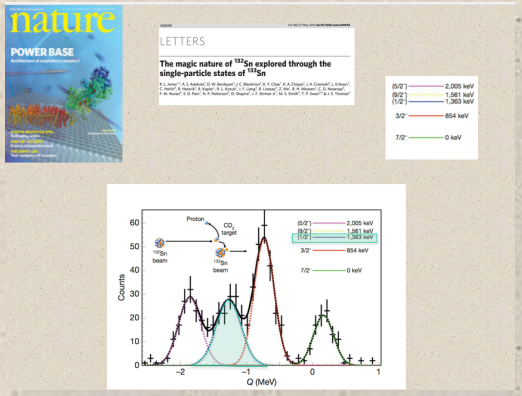
In-flight fragmentation



Production techniques Rad Beams: post acceleration

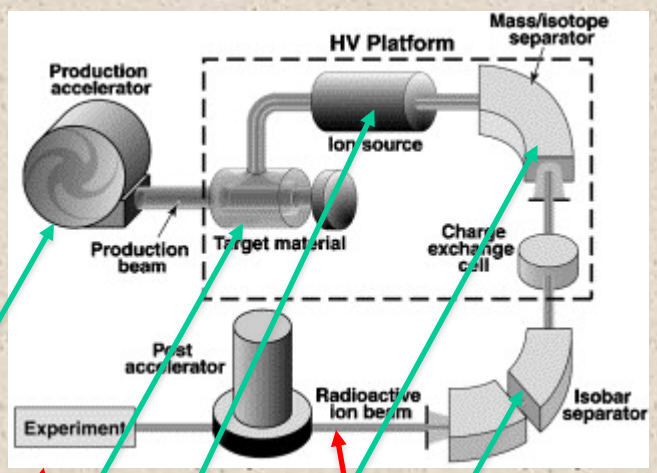
- Isotopic separation on-line (ISOL)





$^{132}Sn + d \rightarrow {}^{133}Sn + p$

Radioactive beam (40 sec): inverse kinematics



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

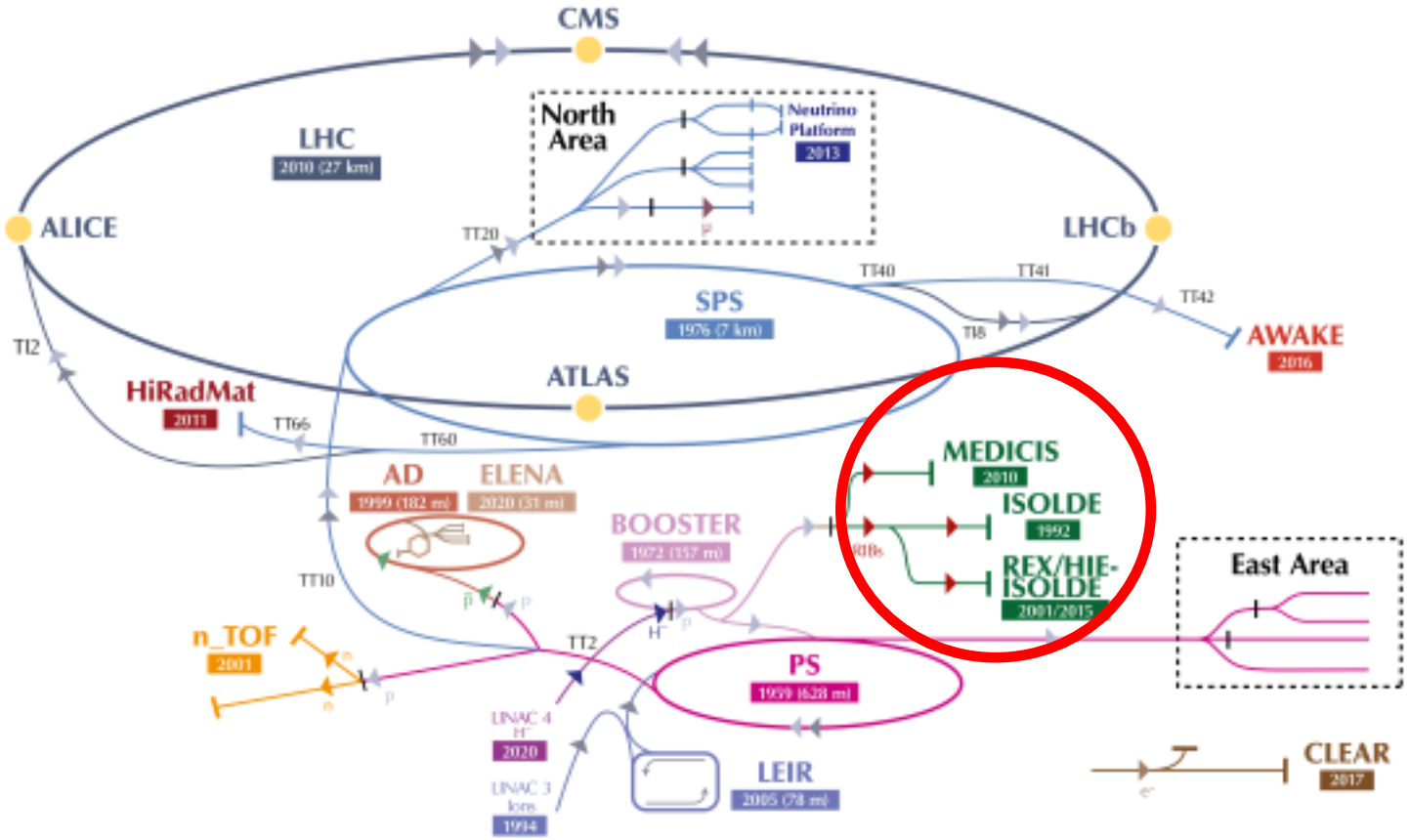
On 16 October 1967, the first experiments were carried out at the Isotopic Separator On Line ISOLDE CERN.

CERN's longest serving experimental facility

Physics Reports 403–404 (2004) 459–469

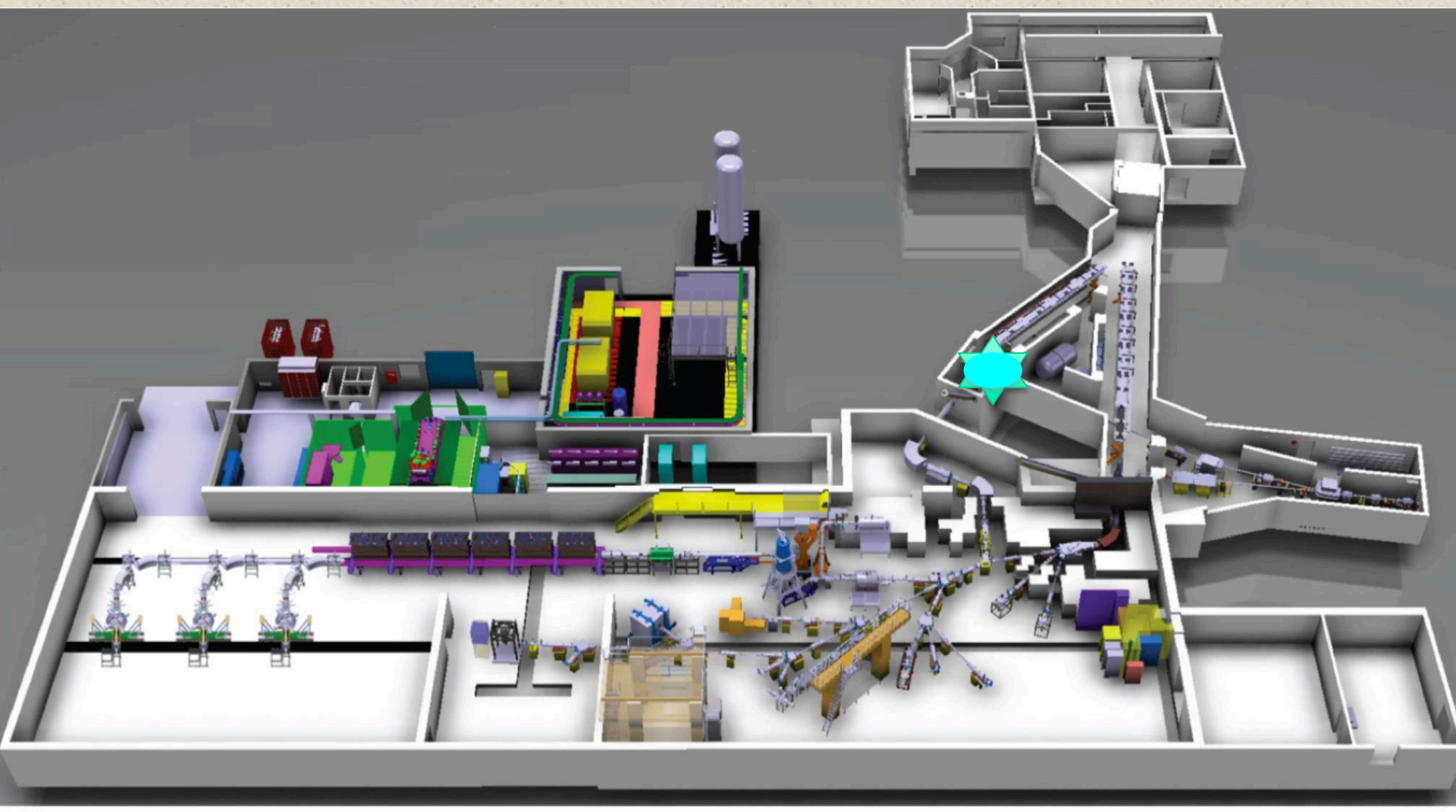
Juha Äystö

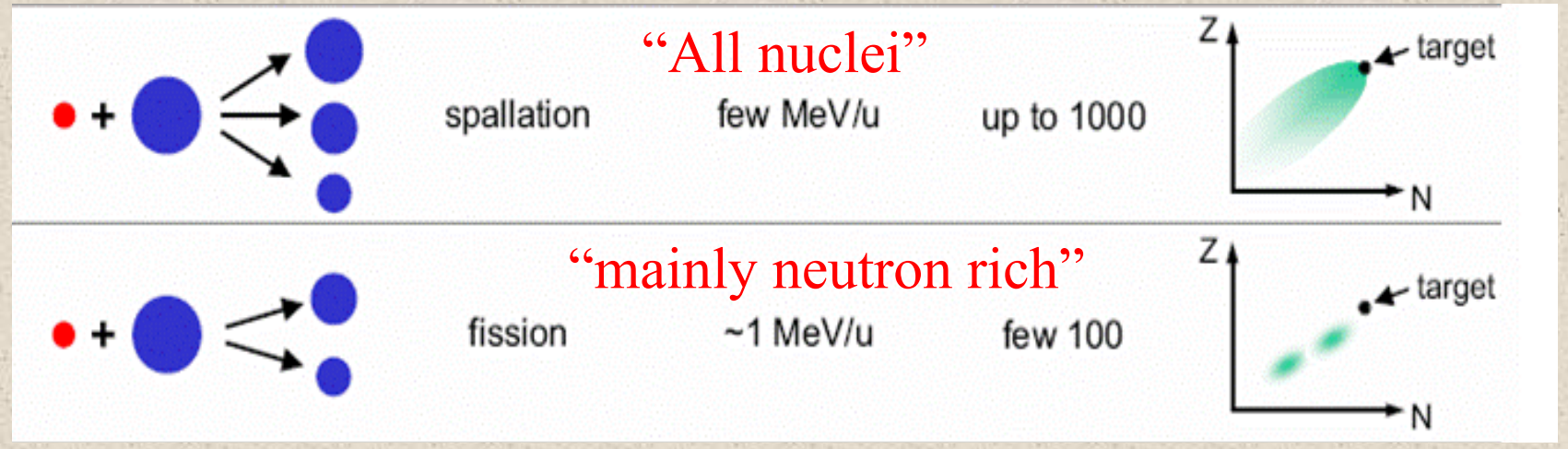
The CERN accelerator complex
Complexe des accélérateurs du CERN



H⁻ (hydrogen anions) · p (protons) · ions · RIBs (Radioactive Ion Beams) · n (neutrons) · $\bar{p}$ (antiprotons) · e^- (electrons) · μ (muons)

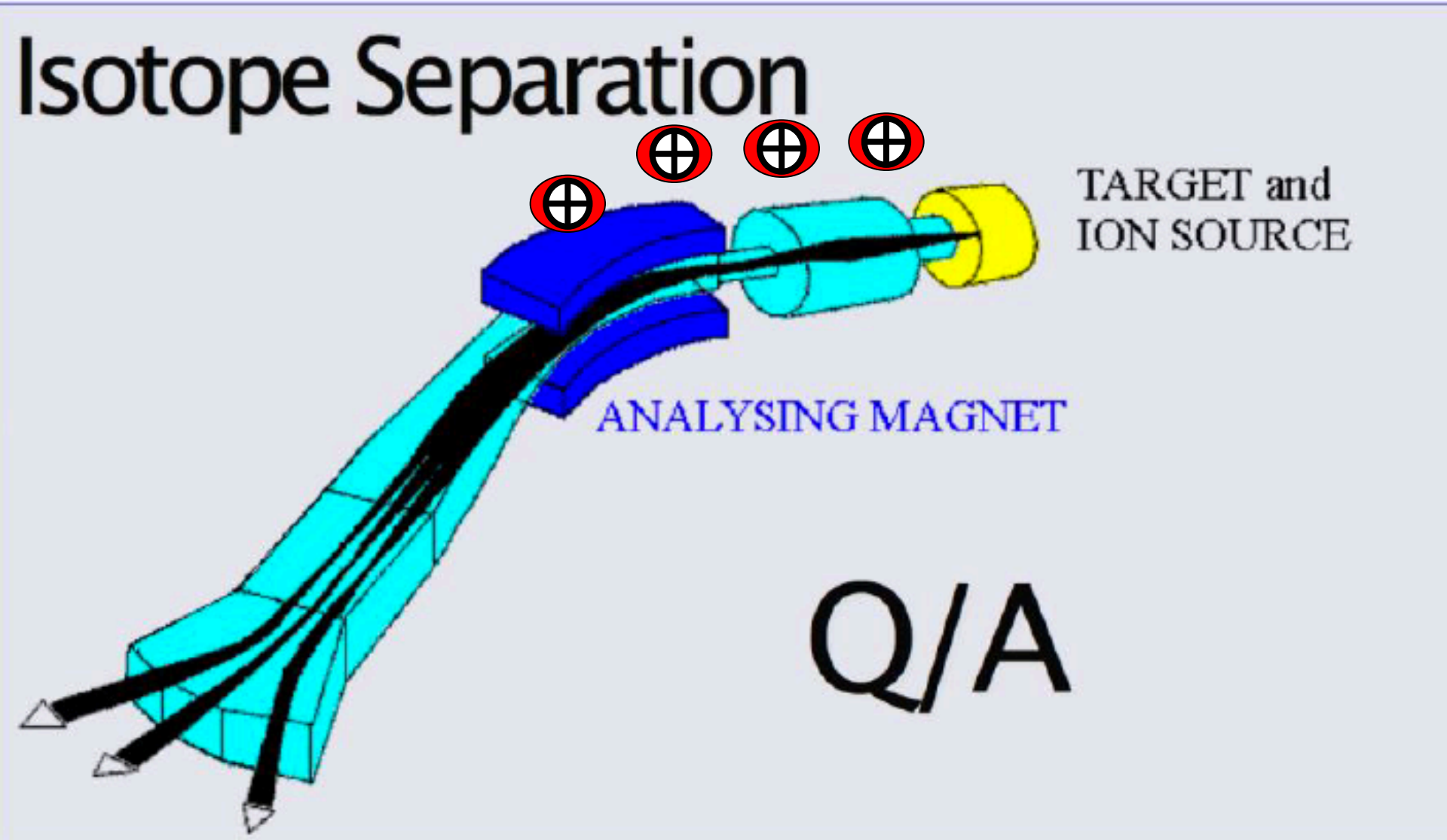
LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform





- 😃 High intensity p beam (upto10^{16} s^{-1}) the same beam that serves LHC)
- 😀 thick target (100% energy range of p)
- 😕 long extraction and ionization time (hundred's ms)
- 😐 Chemistry dependent

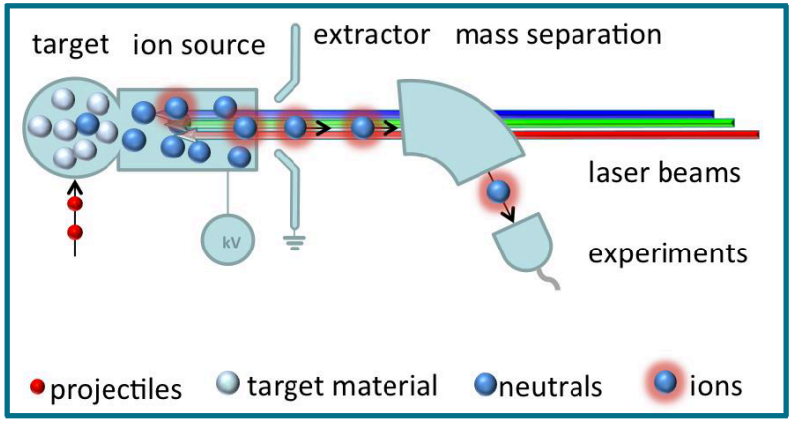
The Separator: in general, only isobaric separation

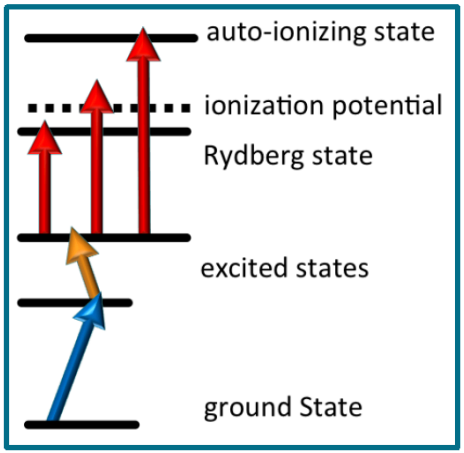


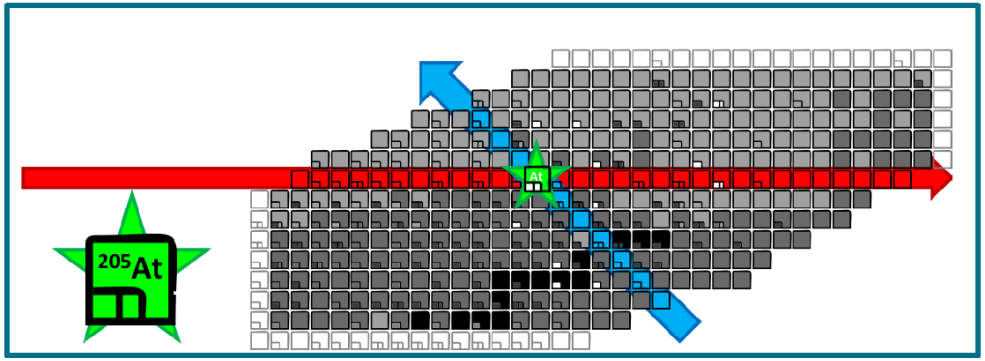
Ion sources

Laser ion source

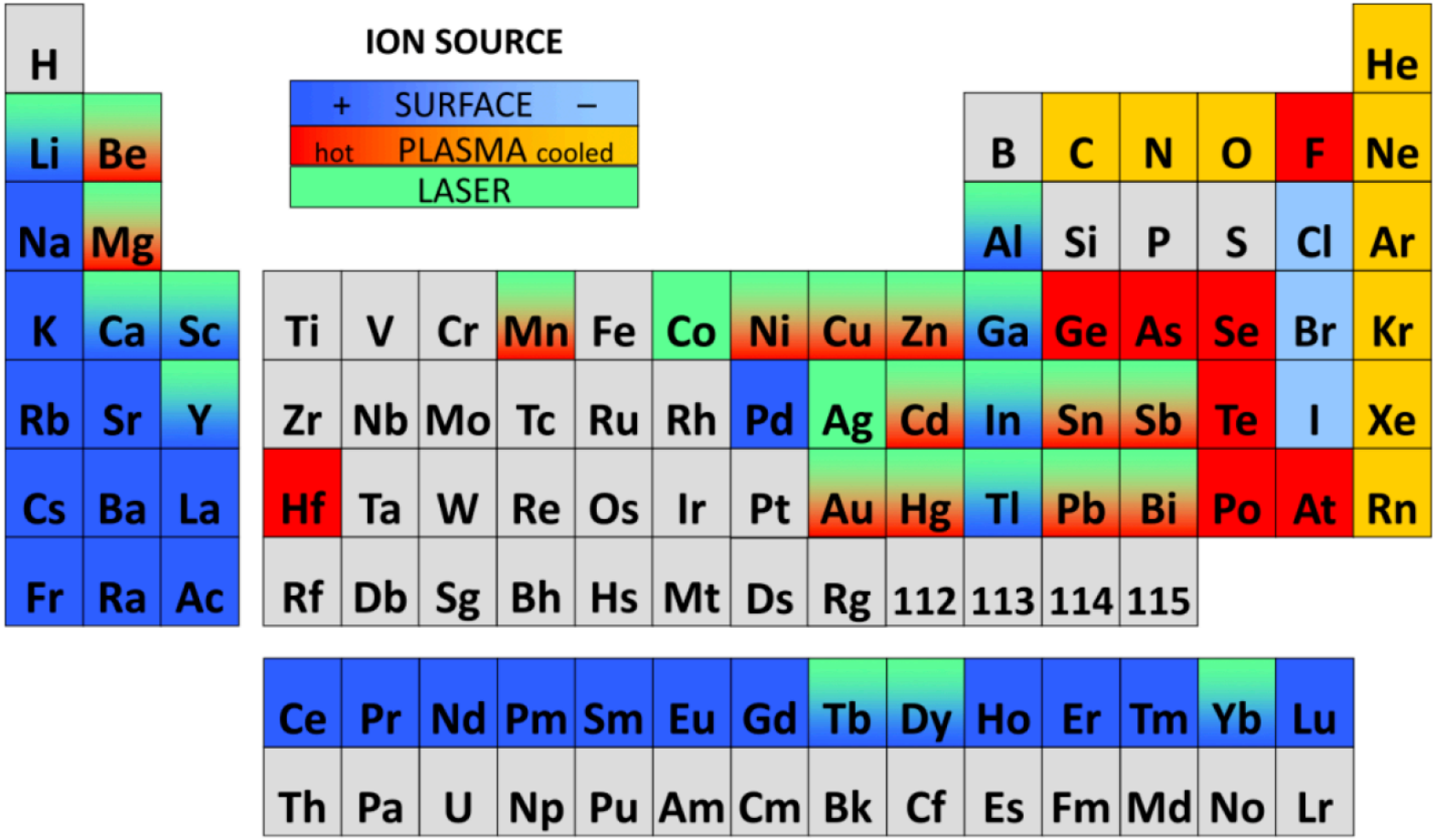
- 2- or 3-step ionisation
- Isotope and isomer selection
- Universal (almost)

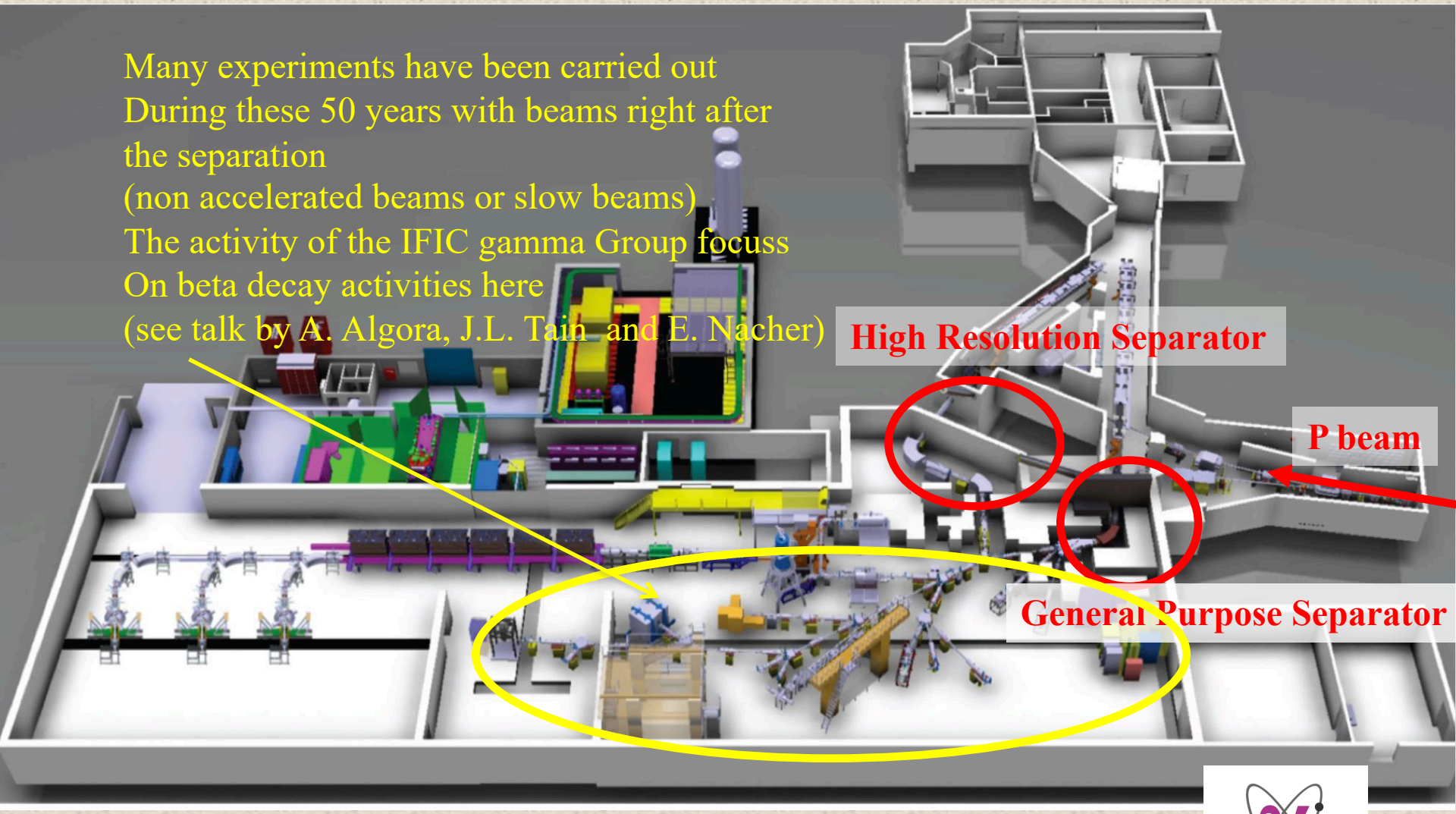


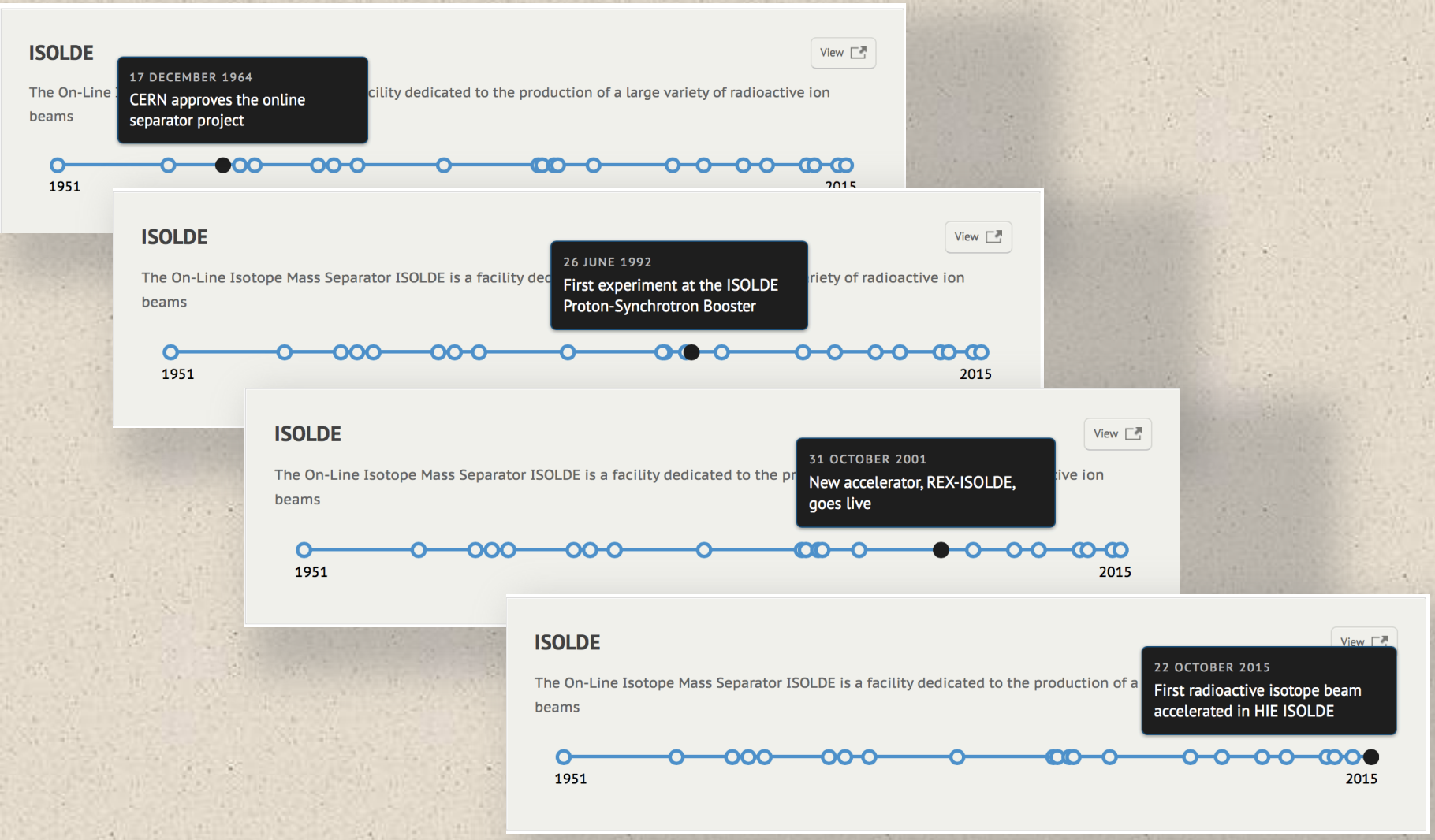


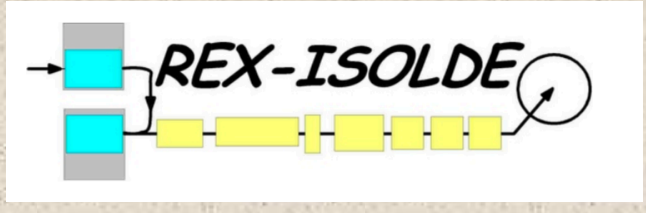


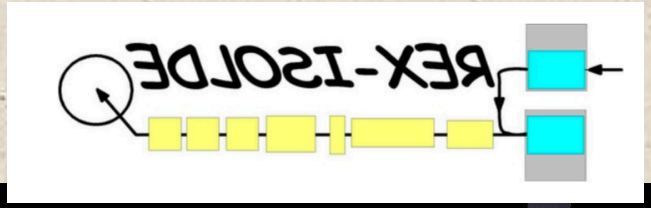
Isotopes produced at ISOLDE

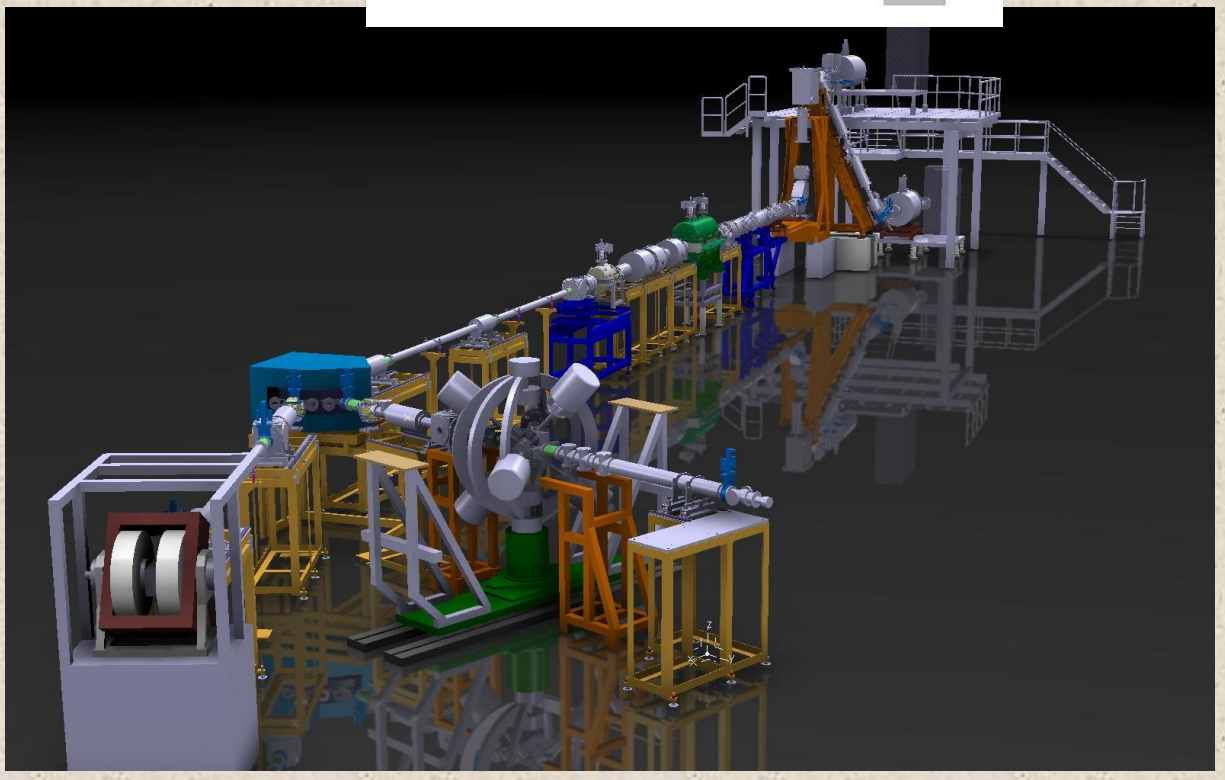



Many experiments have been carried out
During these 50 years with beams right after
the separation
(non accelerated beams or slow beams)
The activity of the IFIC gamma Group focuss
On beta decay activities here
(see talk by A. Algora, J.L. Tain and E. Nacher)
High Resolution Separator
P beam
General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


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

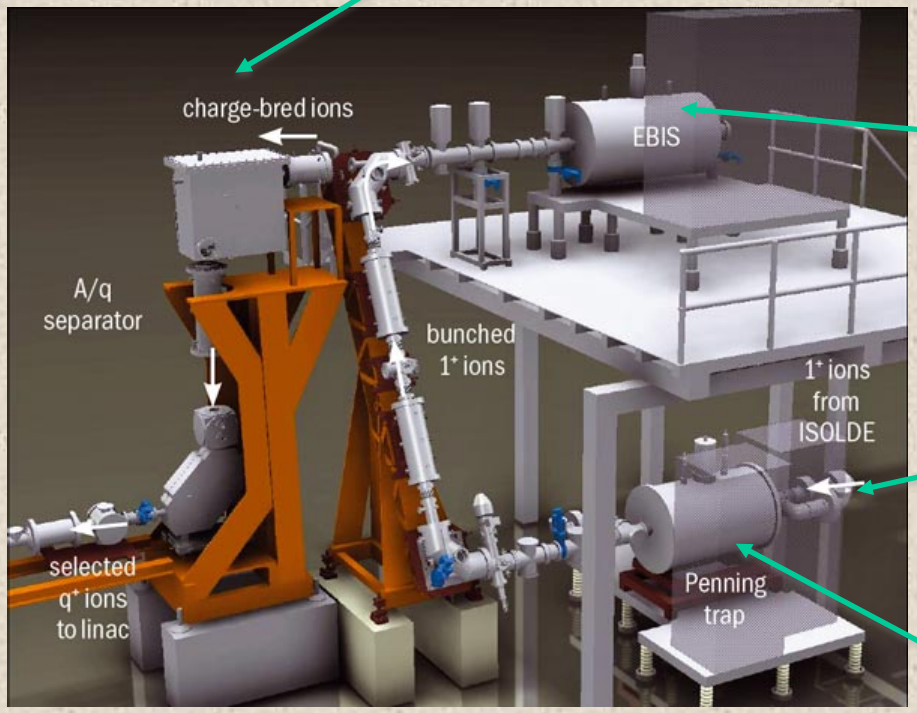

REX-ISOLDE

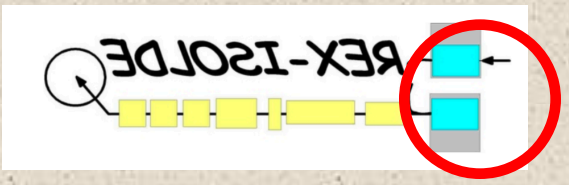

REX-ISOLDE



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

A/q separator



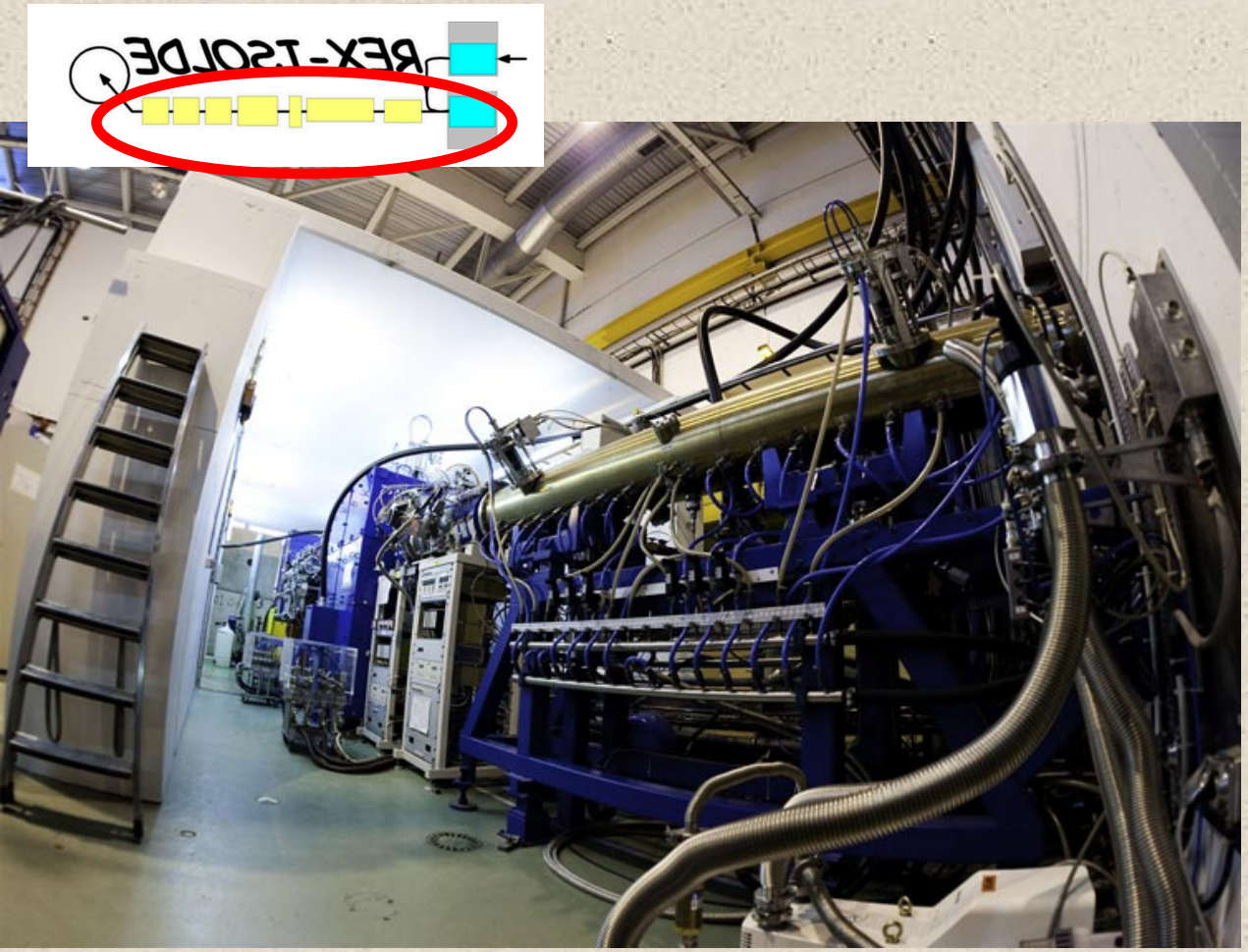


In the EBIS the 1^+ to n^+ ion conversion takes place

Beams from ISOLDE with 1+ charge state

Preparation trap

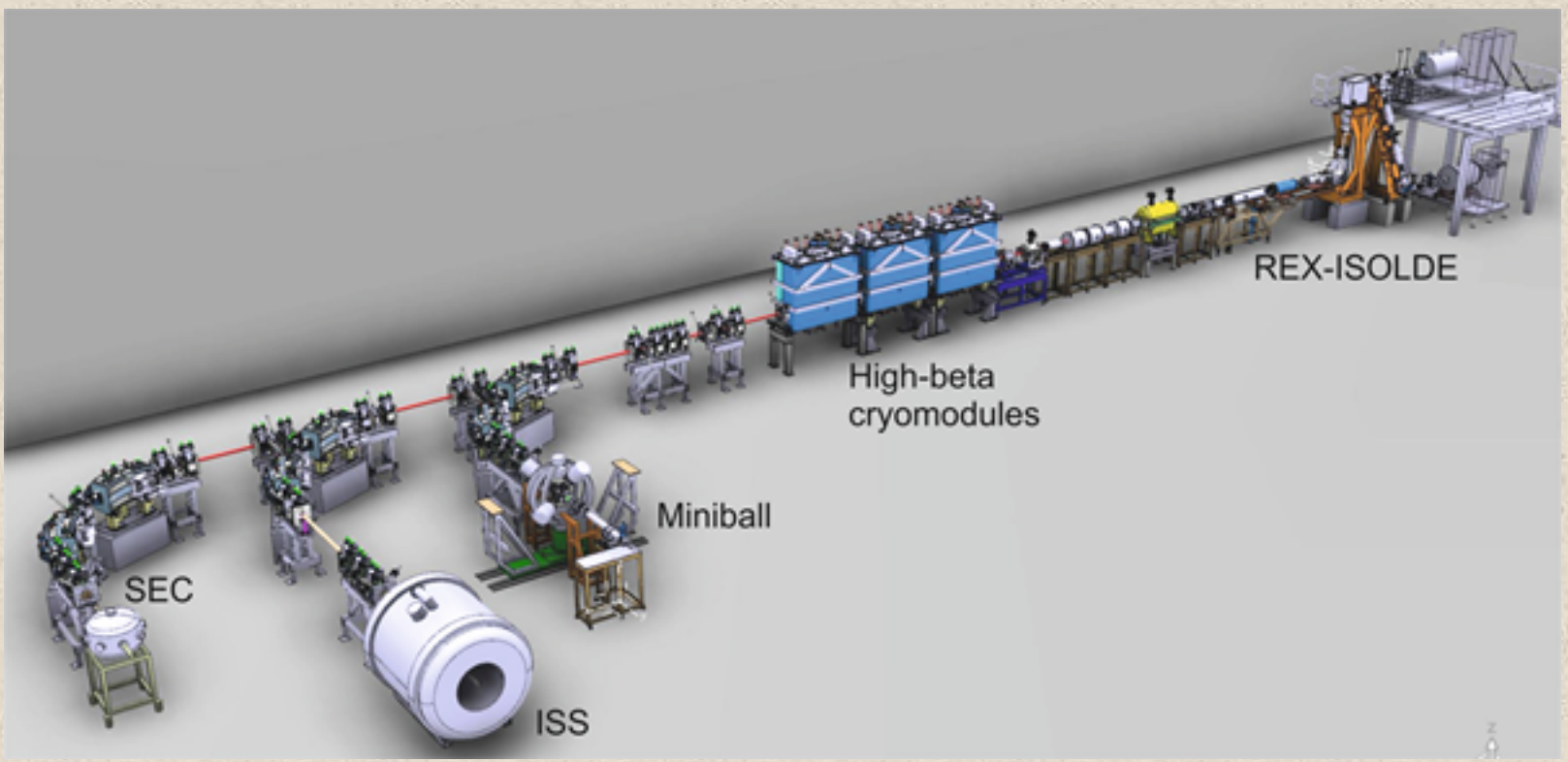
Post accelerator: Normal Conducting LINAC



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

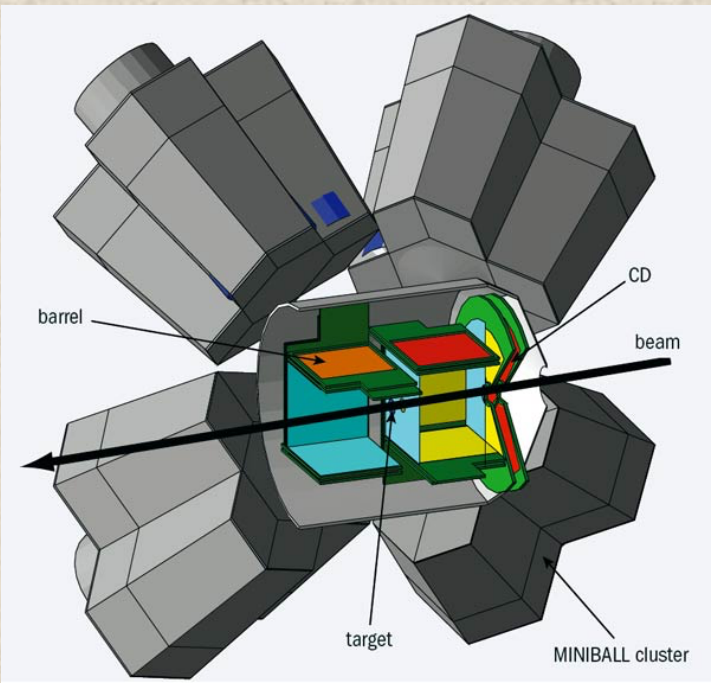
HIE ISOLDE (Superconducting)
High Intensity and Energy ISOLDE (soon 10 MeV per nucleon)

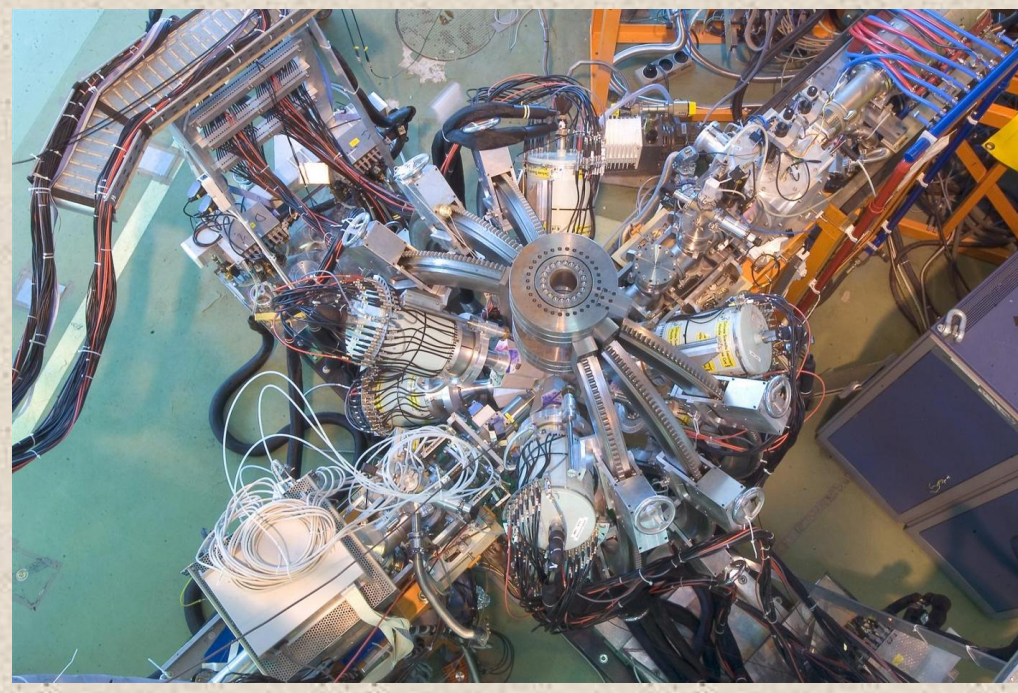
4.3 MeV per nucleon



First experiments in 2015

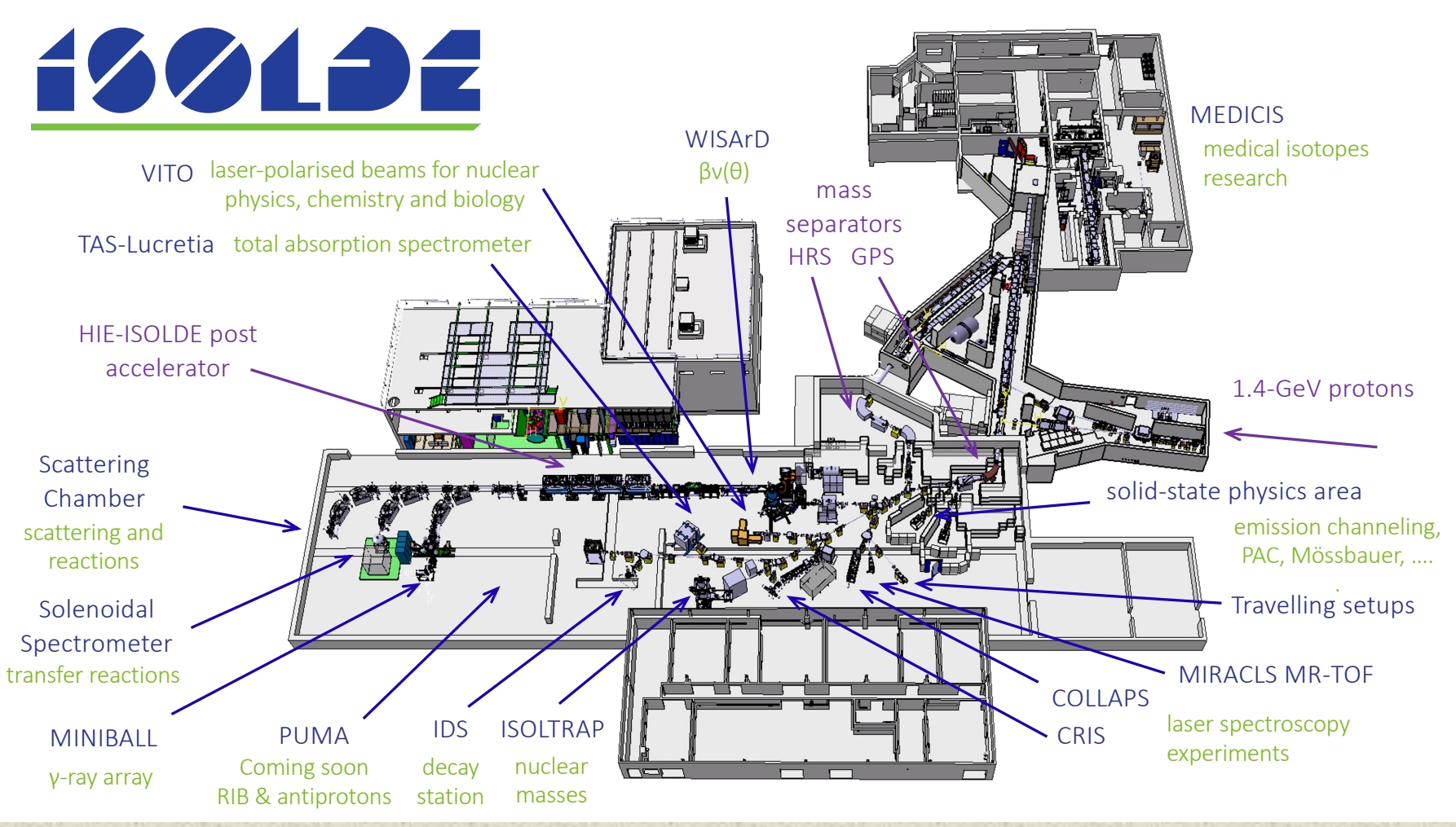
Post accelerated beams + sophysticated detection set-up: Miniball gamma array





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

ISOLDE lei out as will appear in the NUPECC long range plan 2024



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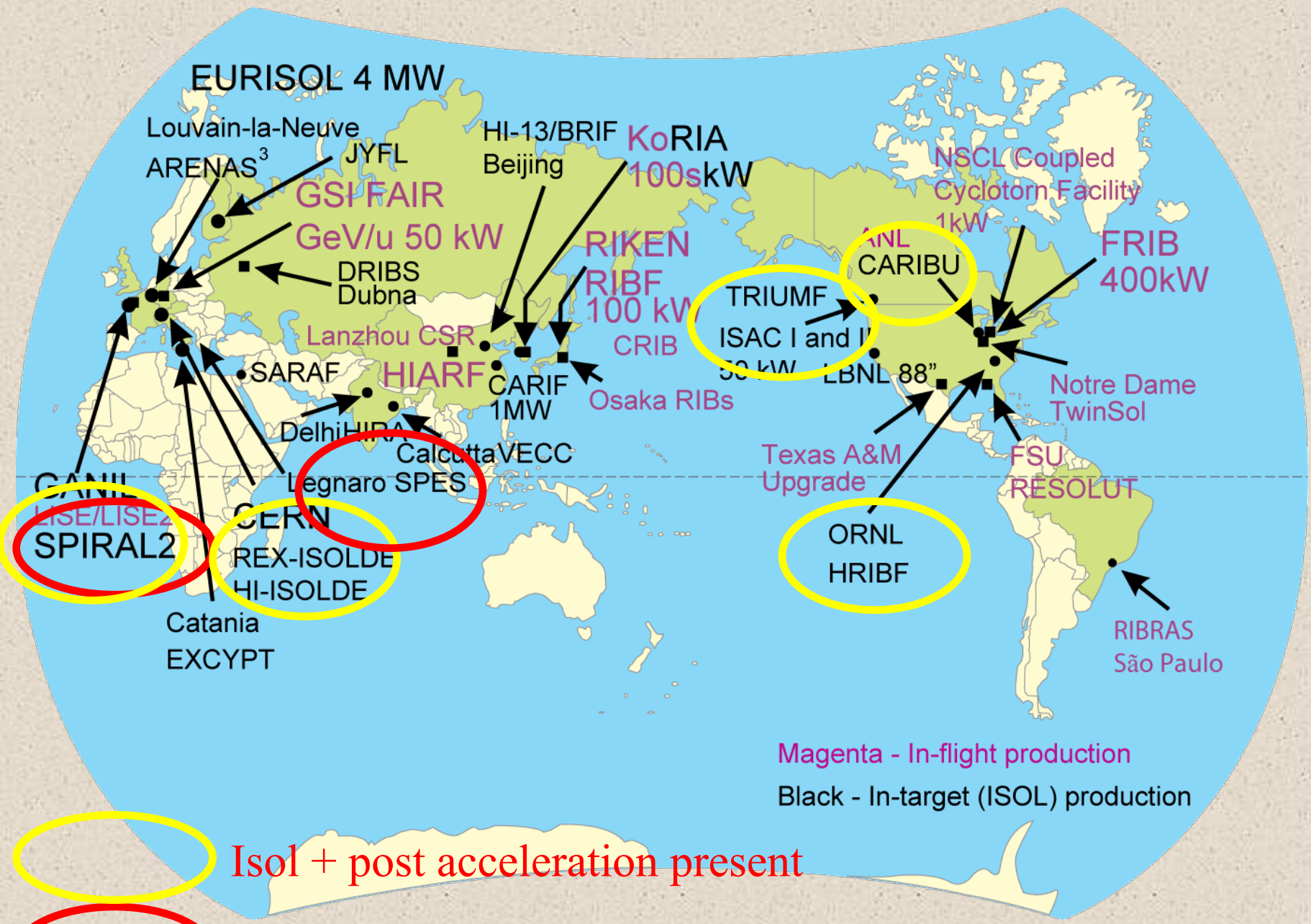

EURISOL 4 MW
Louvain-la-Neuve
ARENAS
JYFL
GSI FAIR
GeV/u 50 kW
DRIBS
Dubna
HI-13/BRIF
Beijing
KoRIA
100sKW
RIKEN
RIBF
100 kW
CRIB
Lanzhou CSR
HIARF
SARAF
CARIF
1MW
Osaka RIBs
DelhiHIRA
CalcuttaVECC
Legnaro SPES
GANIL
LISE/LISE2
SPIRAL2
CERN
REX-ISOLDE
HI-ISOLDE
Catania
EXCYPT
TRIUMF
ISAC I and II
50 kW
ANL
CARIBU
LBNL 88"
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
Isol + post acceleration present
Isol + post acceleration future

Future ISOL facilities

Mid-term Roadmap

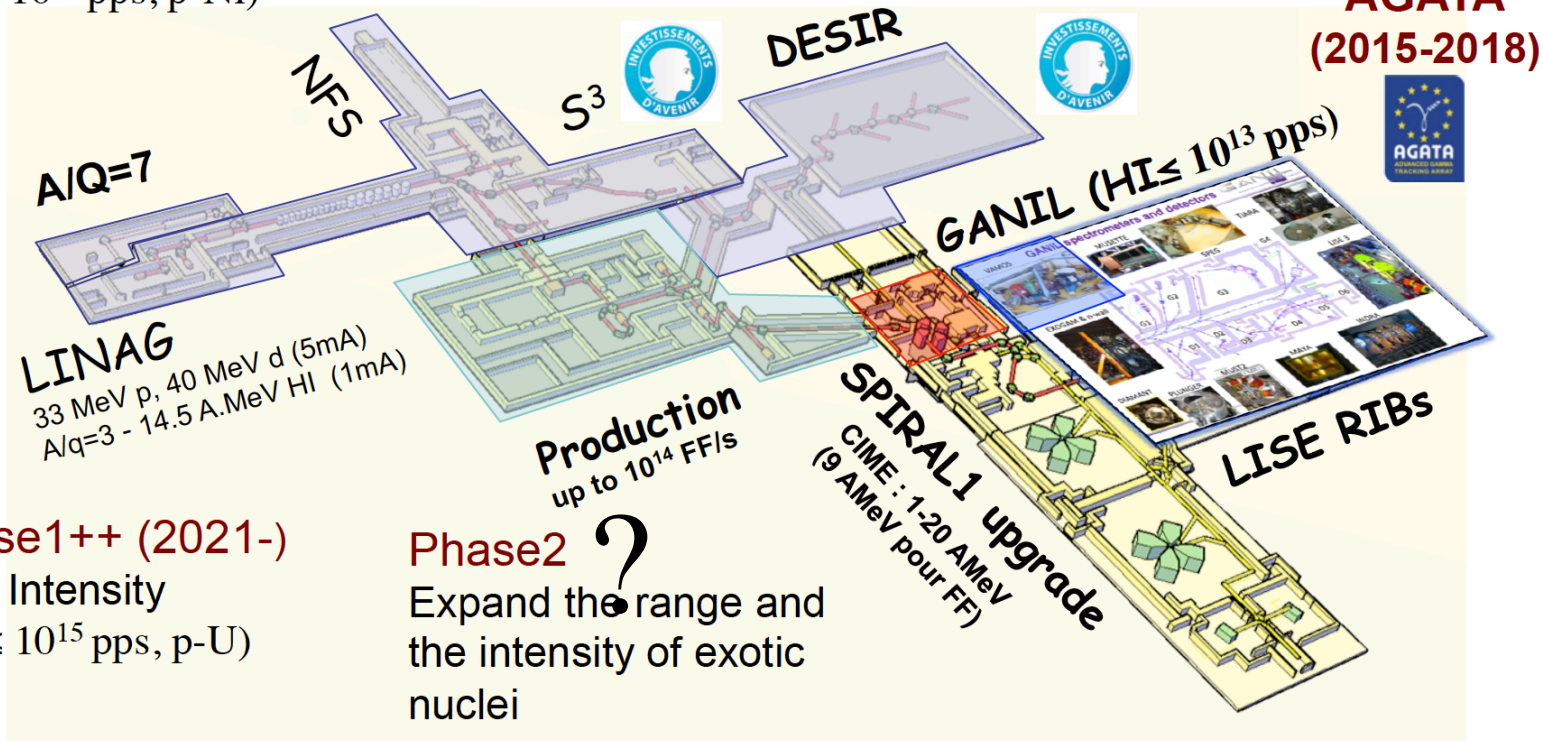
Phase1 (2016-)

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)

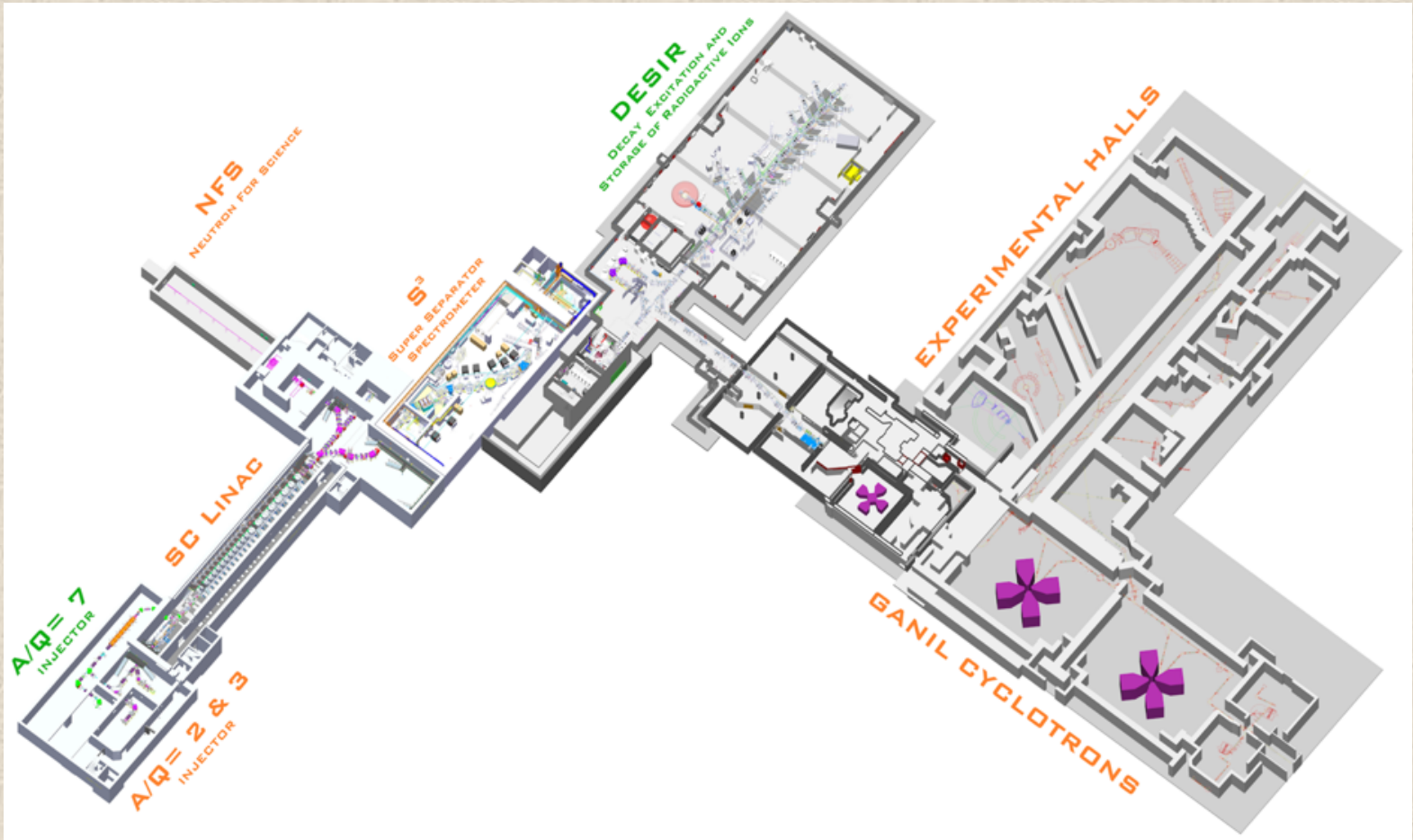
Phase2 ?

Expand the range and the intensity of exotic nuclei

SPIRAL1 Upgrade (2017-)

New light RIBs from beam/target fragmentation

Unfortunatelly, the SPIRAL lei out, as it will appear in the Long Range plan 2024, does not include the ISOL part, but it is mentioned as future plan



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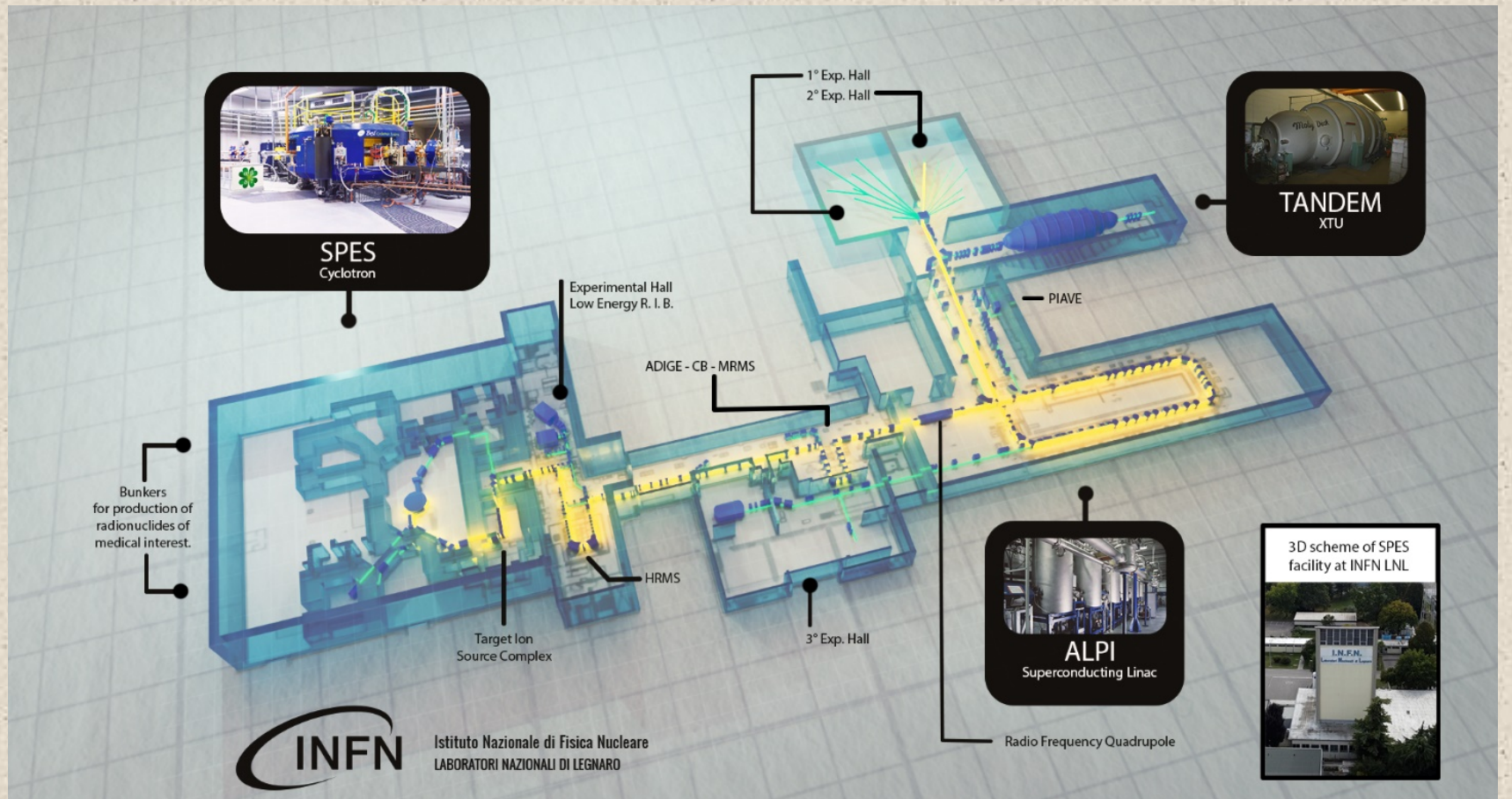
SPES
Selective Production of Exotic Species
Under construction

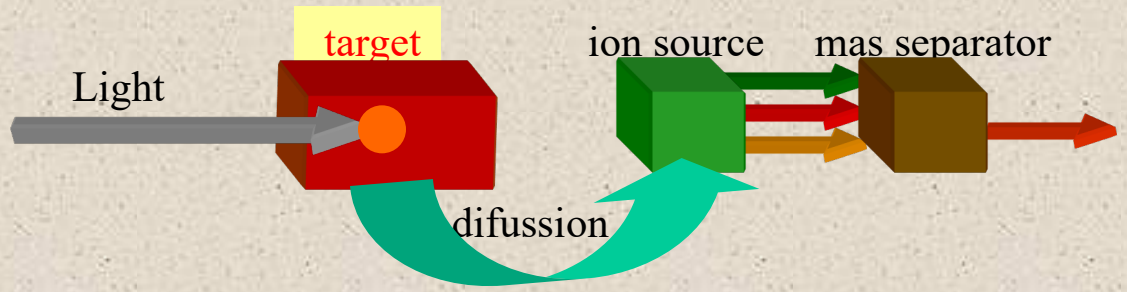
INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

SPES Project



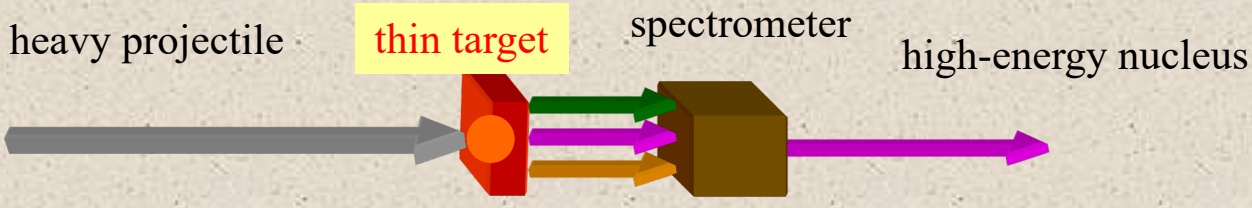
Radioactive nuclei production techniques

Isotopic separation on-line (ISOL)



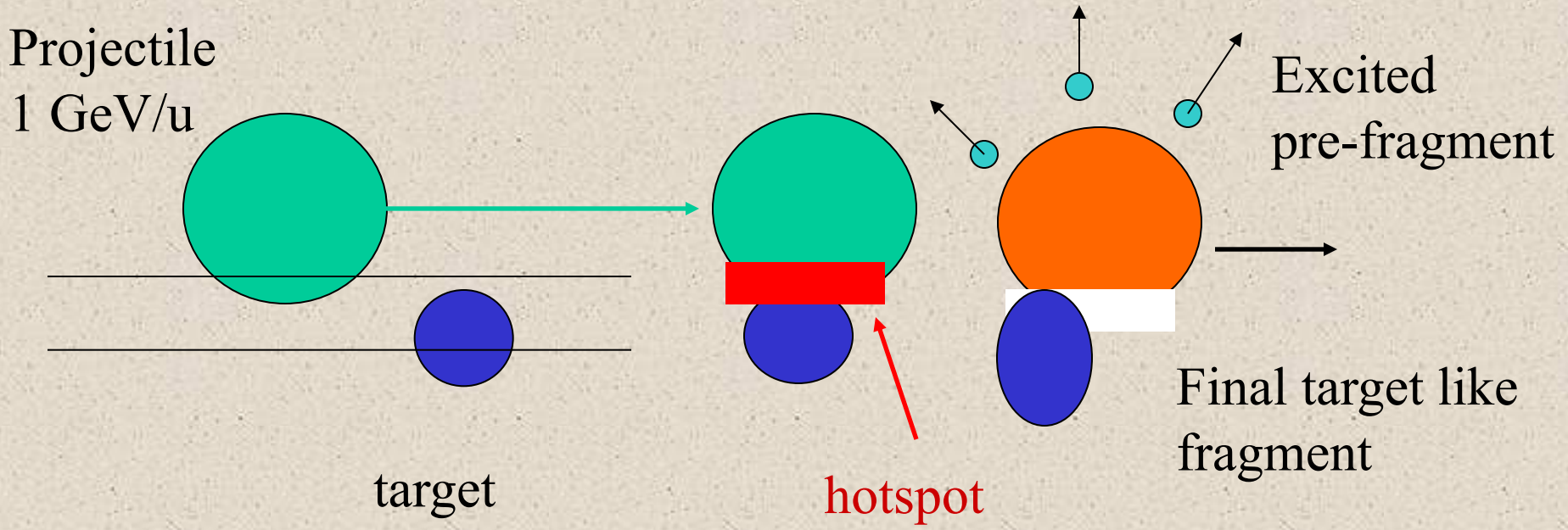
☺😃We can use thick production targets (100% of energy range)
–> and high injector beam current (upto10^{16} s^{-1})
😕 long extraction and ionization time (100 ms)
😐 chemistry dependent

In-flight fragmentation



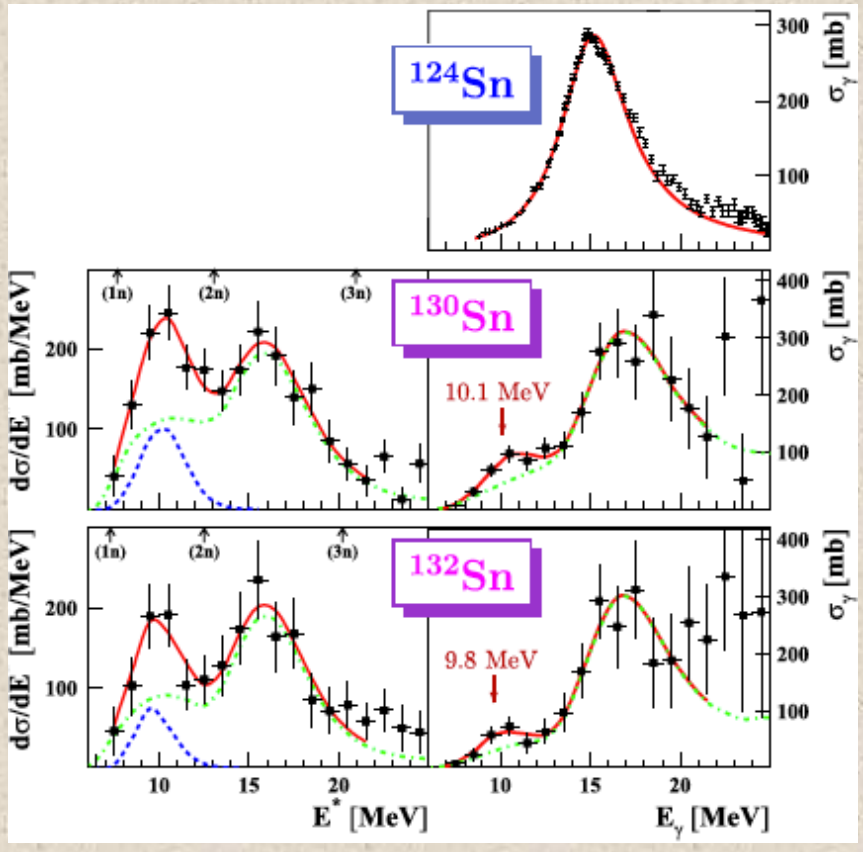
😕 thinner targets (10% of range) =>lower beam currents (upto 10^{12} s^{-1})
😀 short separation+identification time (100 ns)
😀 chemistry independent
😀 relativistic energies

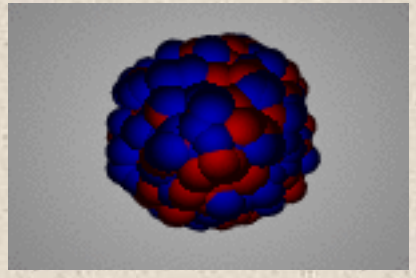
Projectile Fragmentation Reactions

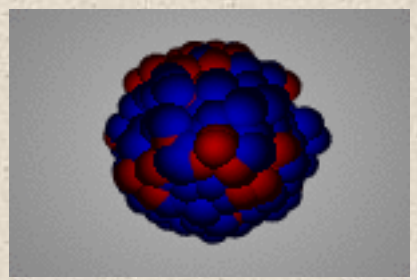


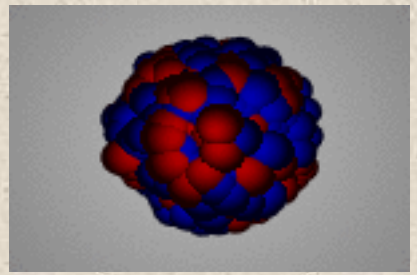
Energy (velocity) of beam > Fermi velocity inside nucleus ~30 MeV/u
Can 'shear off' different combinations of protons and neutrons.
Large variety of exotic nuclear species created, all at forward angles with ~beam velocity.

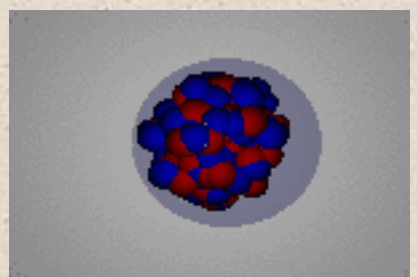
The energy issue: Some physics can only be reached with relativistic energies











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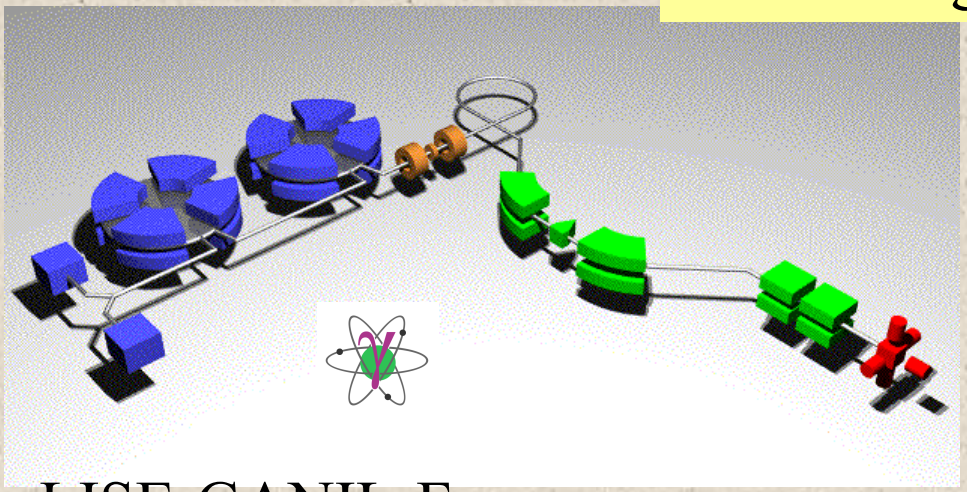
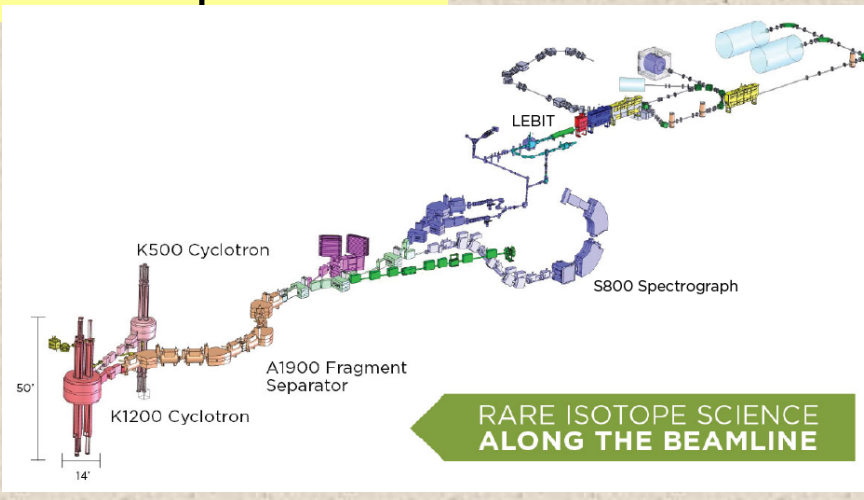
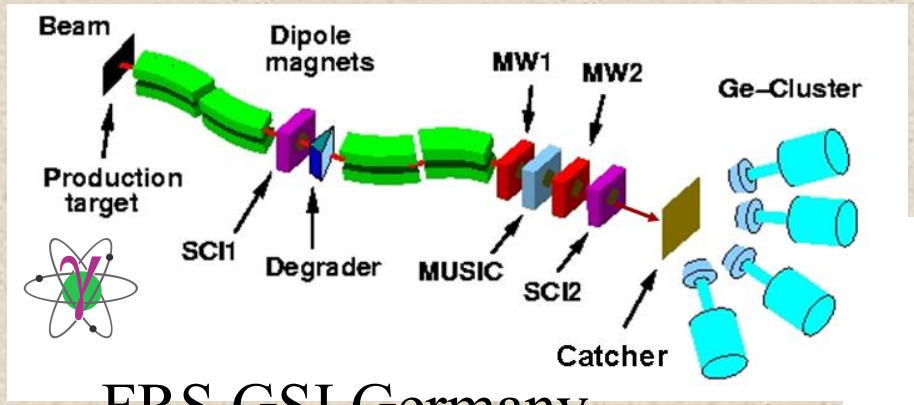
Actual Fragment Separators



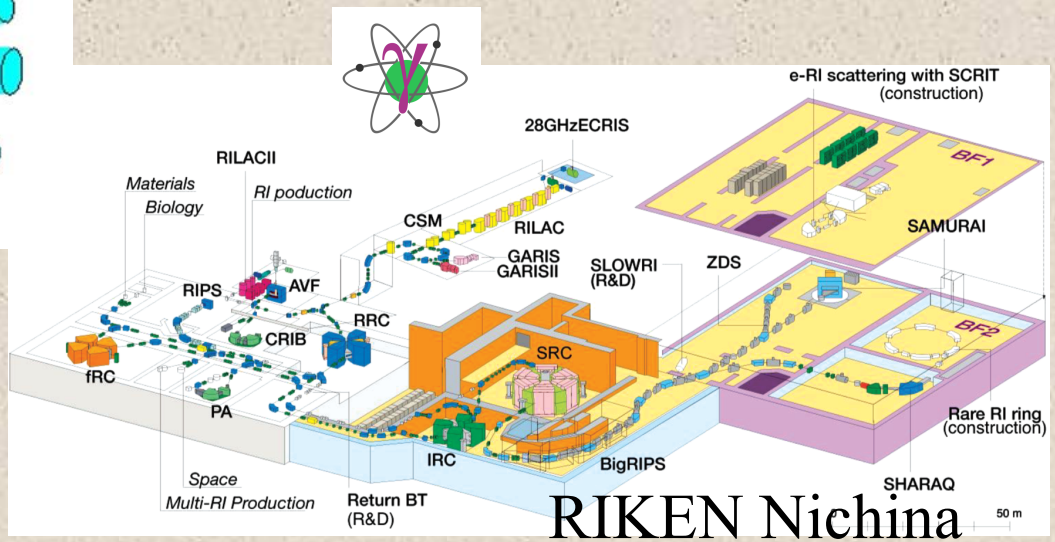
LISE-GANIL-France



NSCL-RIA-→FRIB USA



FRS GSI Germany



RIKEN Nichina Center, Japan

FRIB - Facility for Rare Isotope Beams

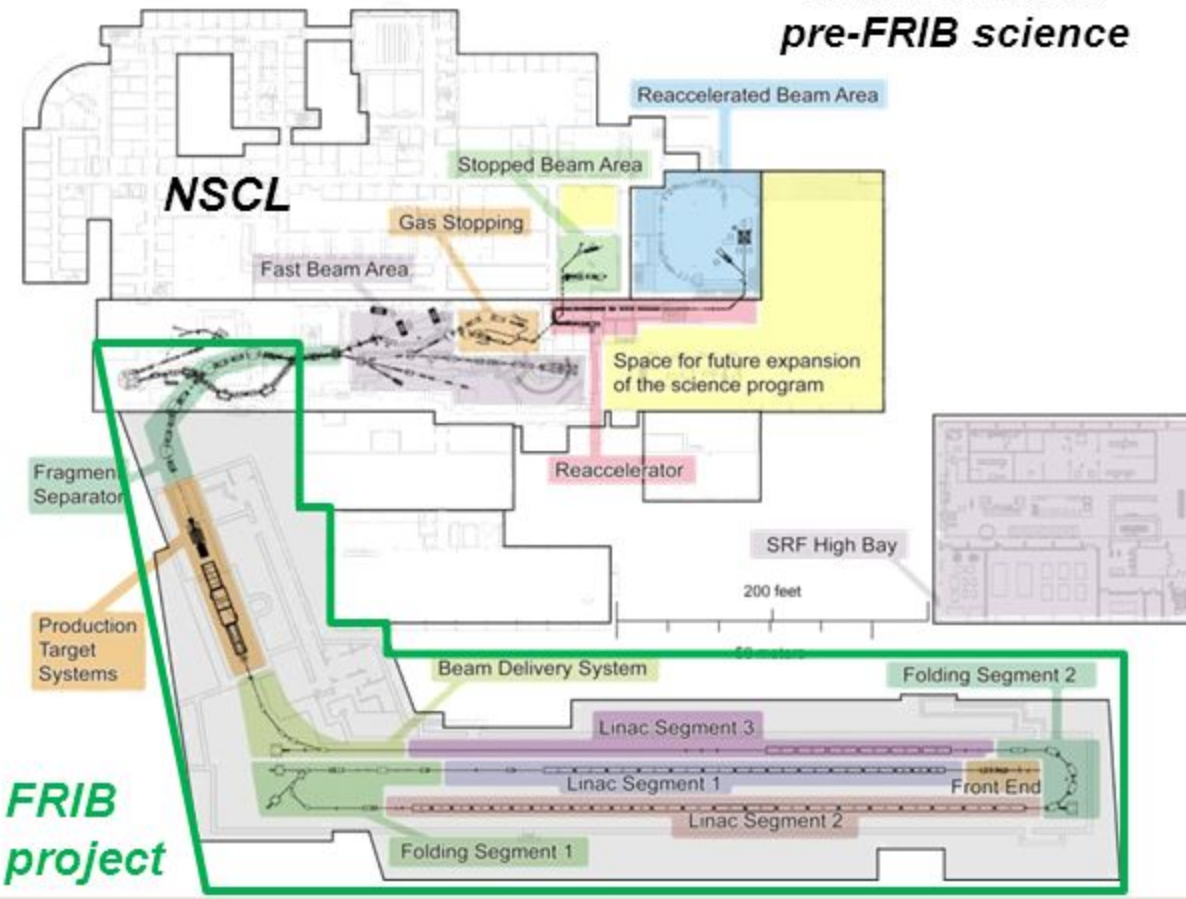
World-leading Next-generation Rare Isotope Beam Facility

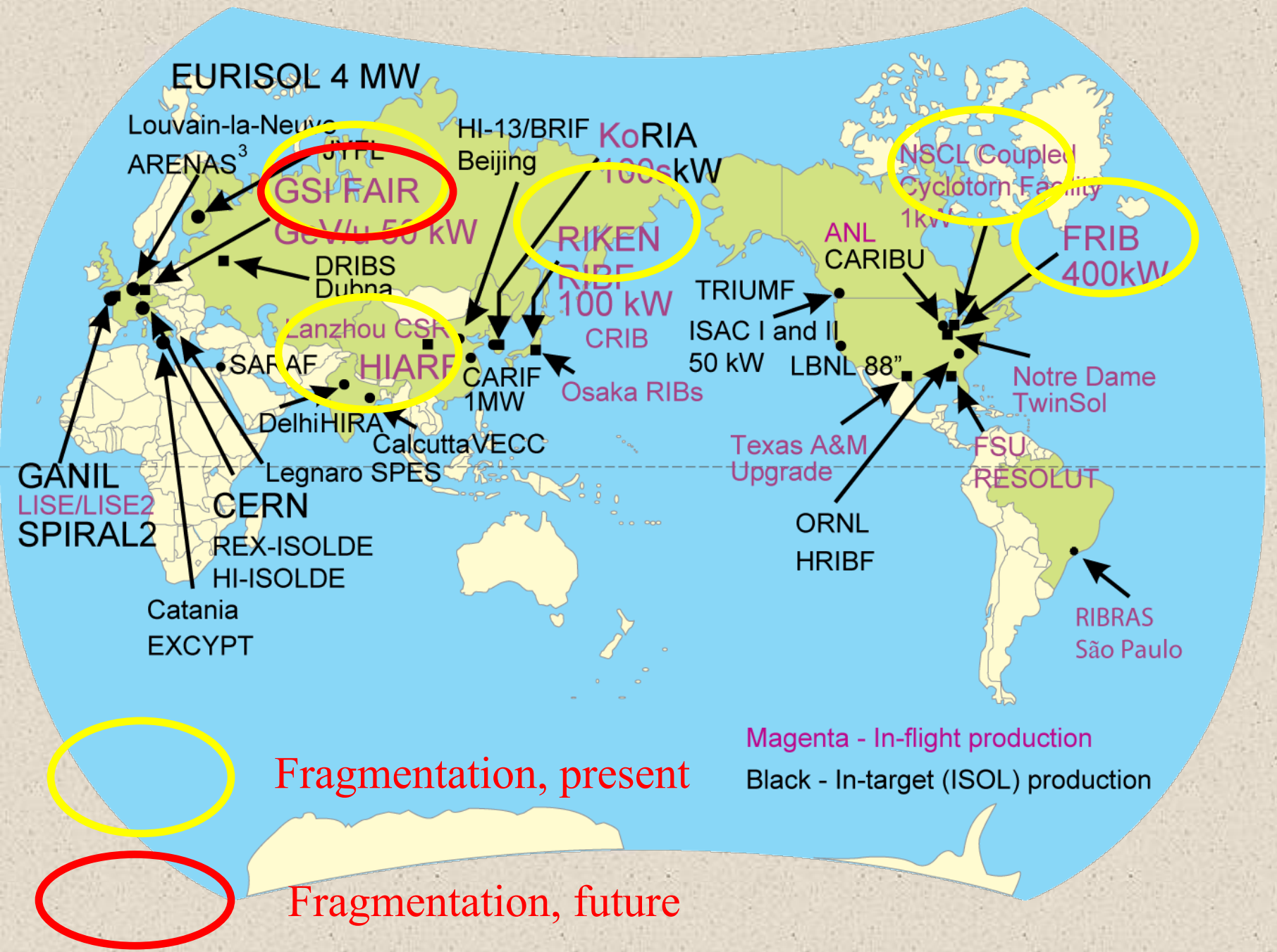
- Rare isotope production via in-flight technique with primary beams up to 400 kW, 200 MeV/u uranium
- Fast, stopped, and re-accelerated beam capability
- Upgrade options
  - 400 MeV/u for uranium
  - ISOL production – multi-user capability

FRIB project start 6/2009
Civil construction started 3/2014
Technical construction started 10/2014
Managed to early completion 12/2020
CD-4 (project completion) 6/2022

Total project cost $730 million

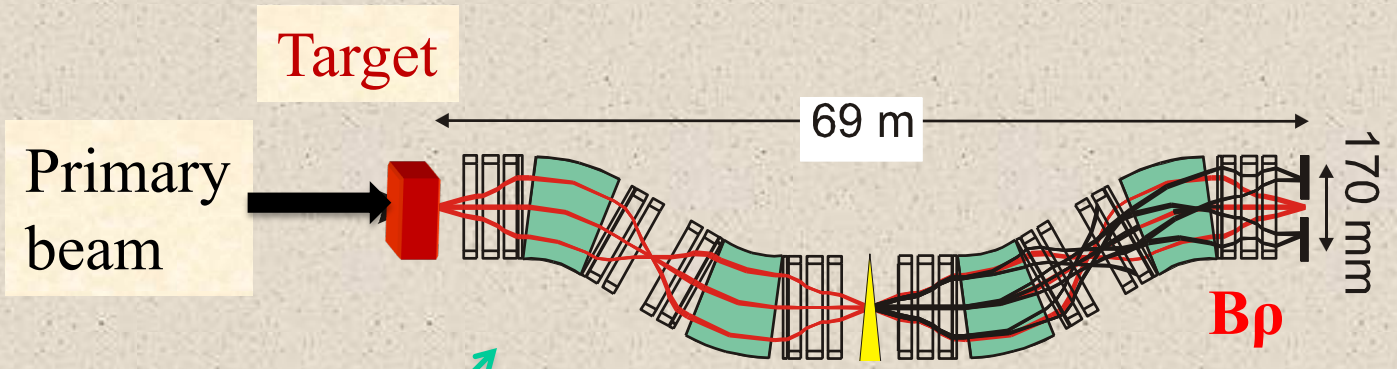
NSCL enables pre-FRIB science




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

The FRS fragment separator at GSI

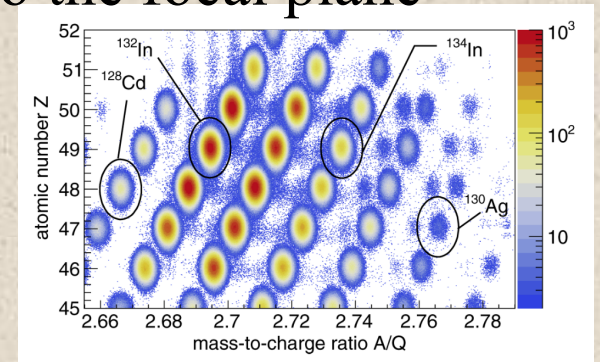
Bρ-ΔE-Bρ Separation Method



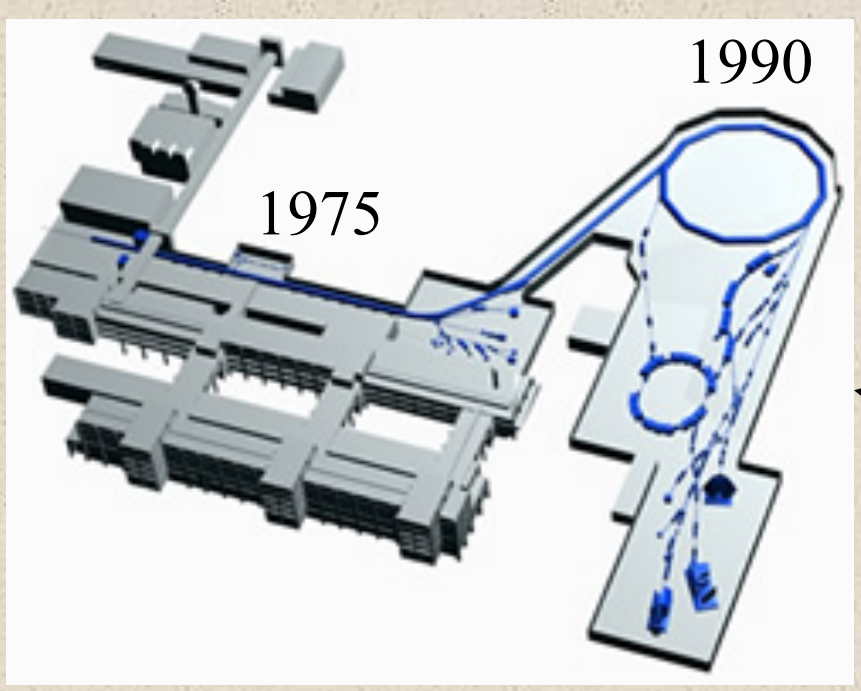
Degrader, **ΔE**
Different ions lose
A different amount
of energy

Ions are selected according
to the momentum to charge ratio
Mv/q=Mv/Z=**Bρ**. Primary beam is rejected.

Cocktail of ions arriving
to the focal plane

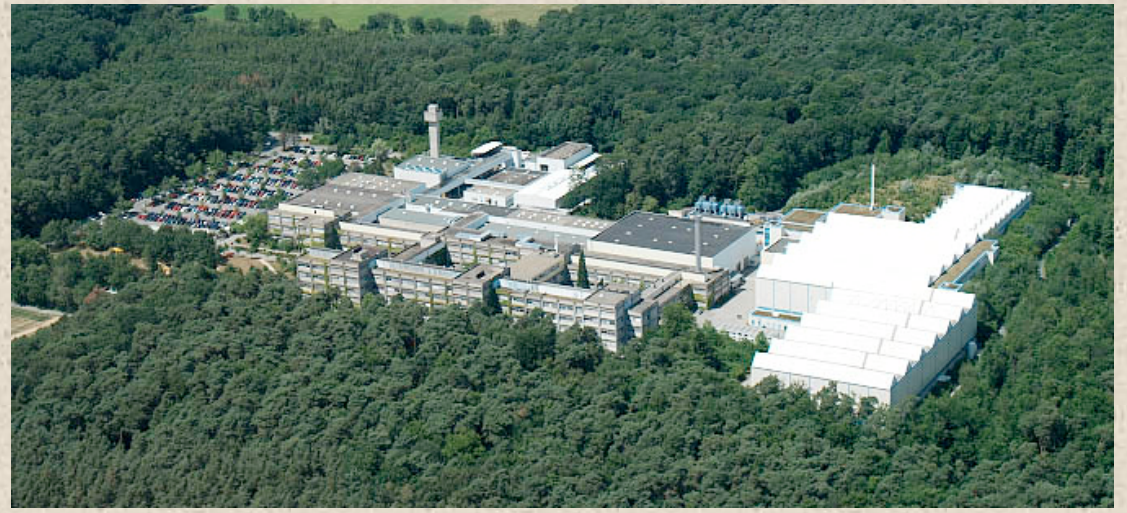


The GSI fragmentation facility

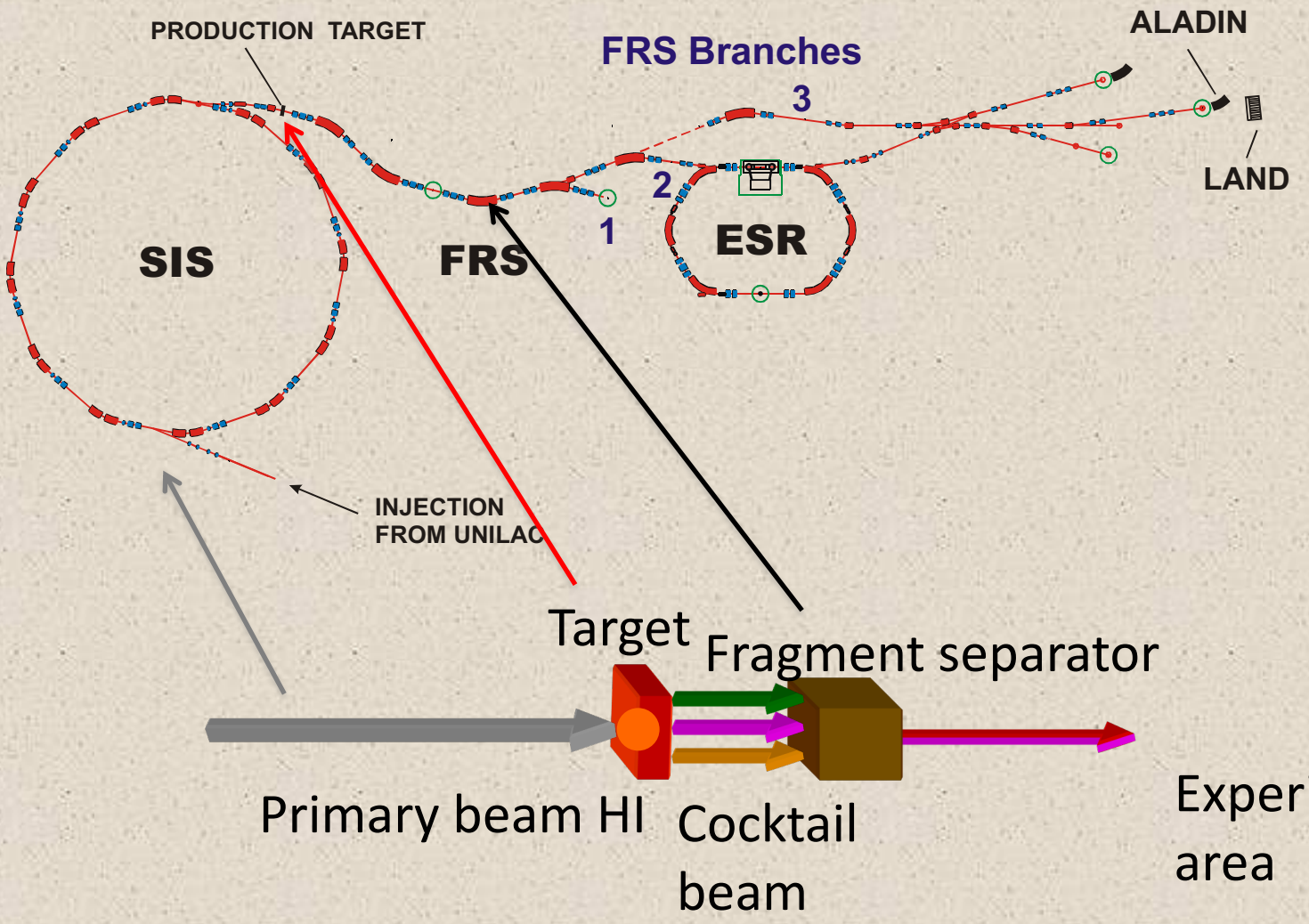


It is possible to accelerate stable Nuclei from H (Z=1) to U (Z=92), in the UNILAC + Synchrotron.

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



2019


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

Near Future

Existing GSI facility

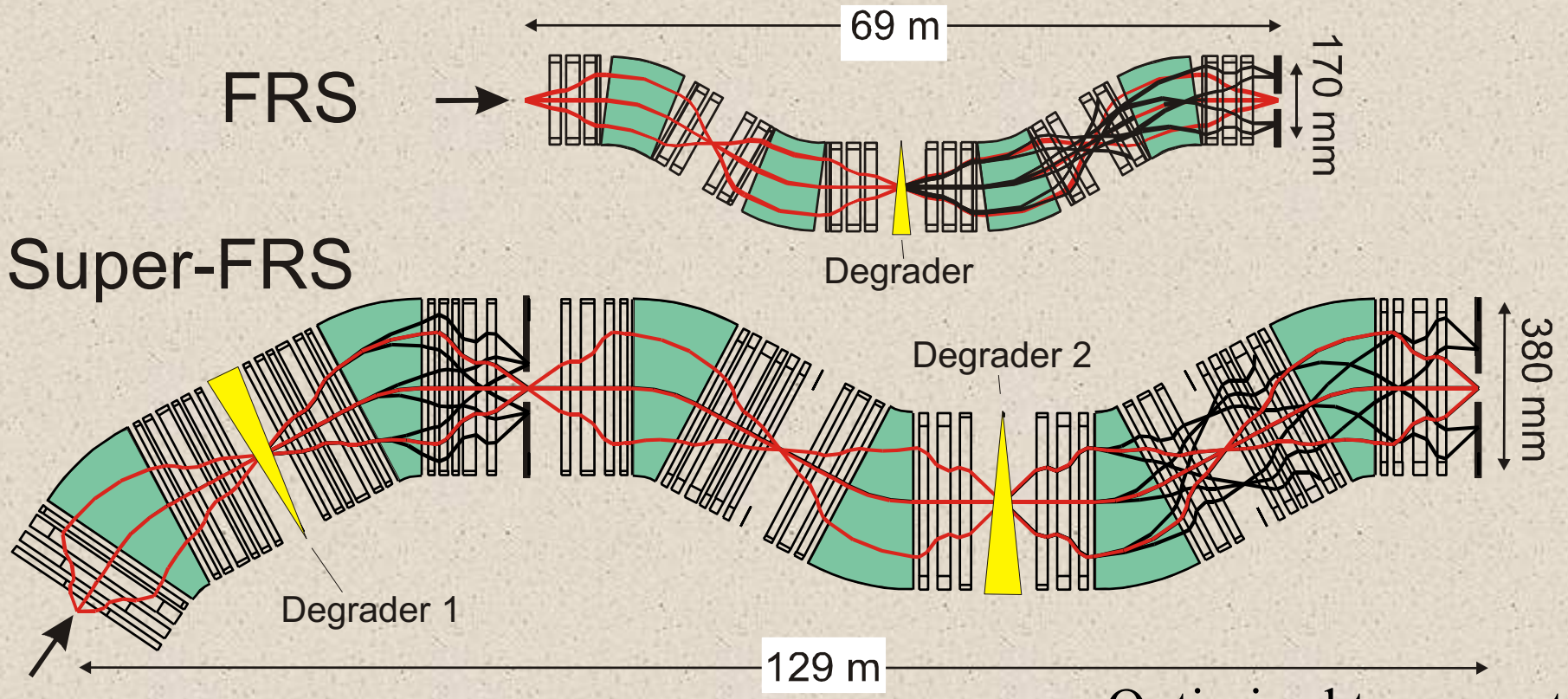
New facility

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

FRS to Super-FRS

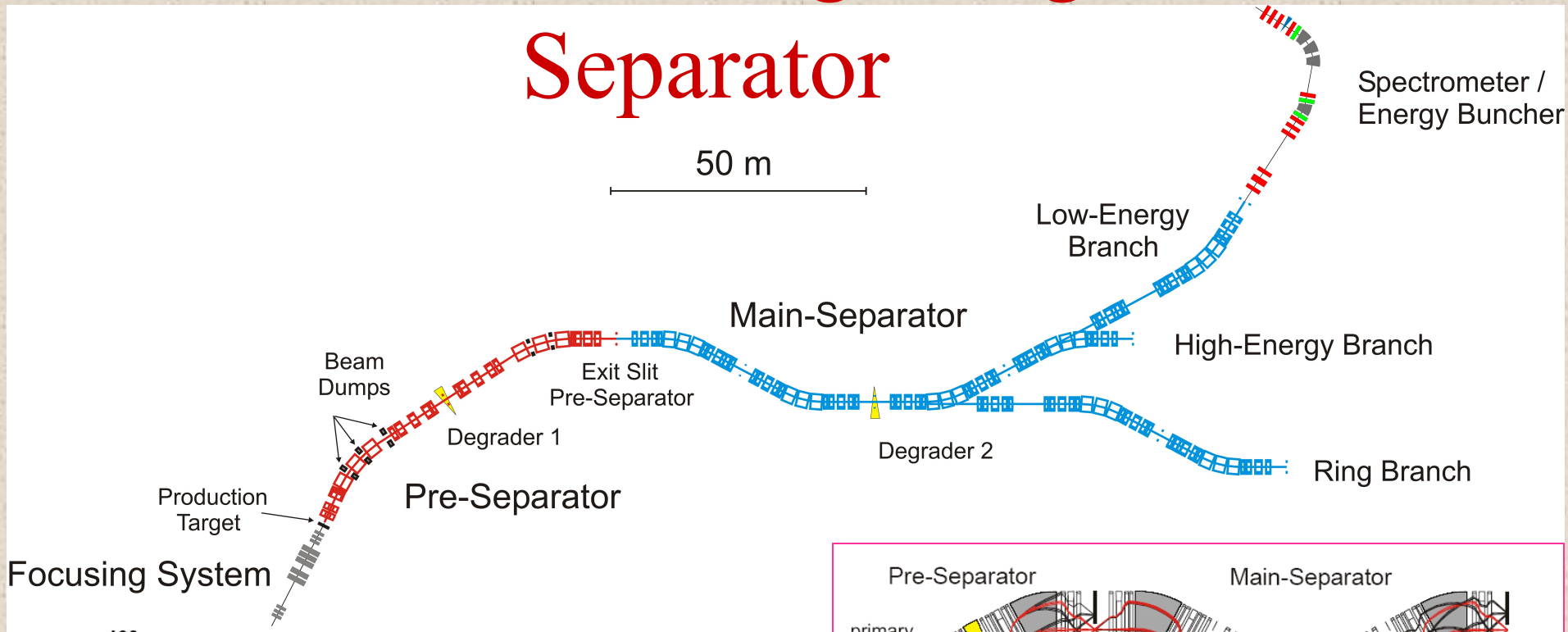
Bρ-ΔE-Bρ Separation Method

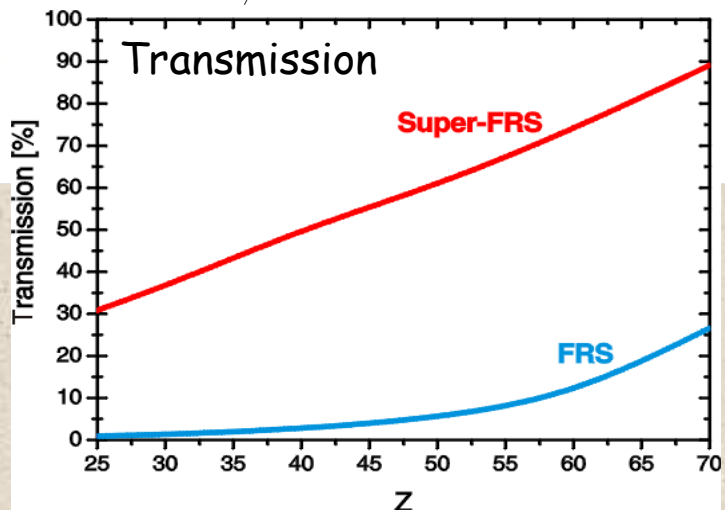


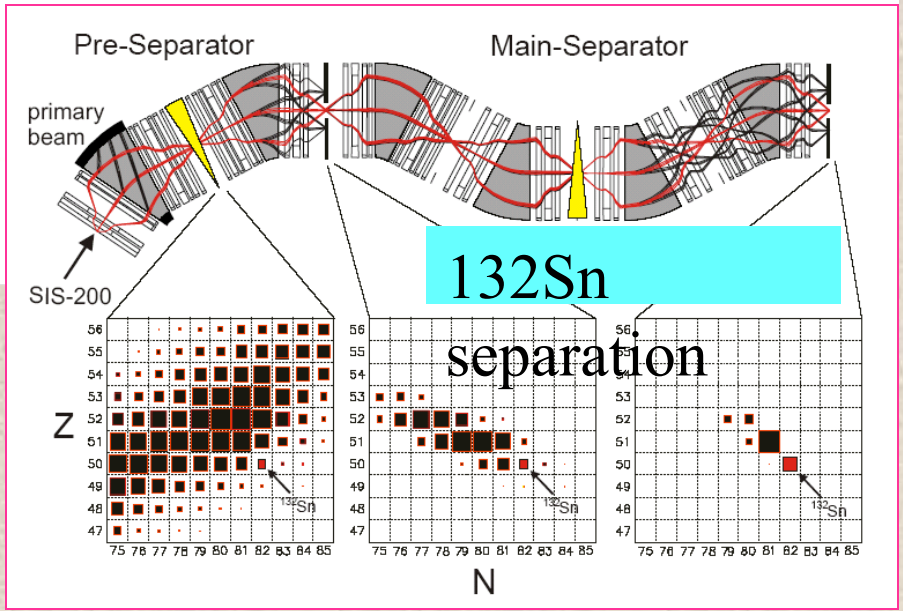
Optimised to separate very fast fragment or fission products

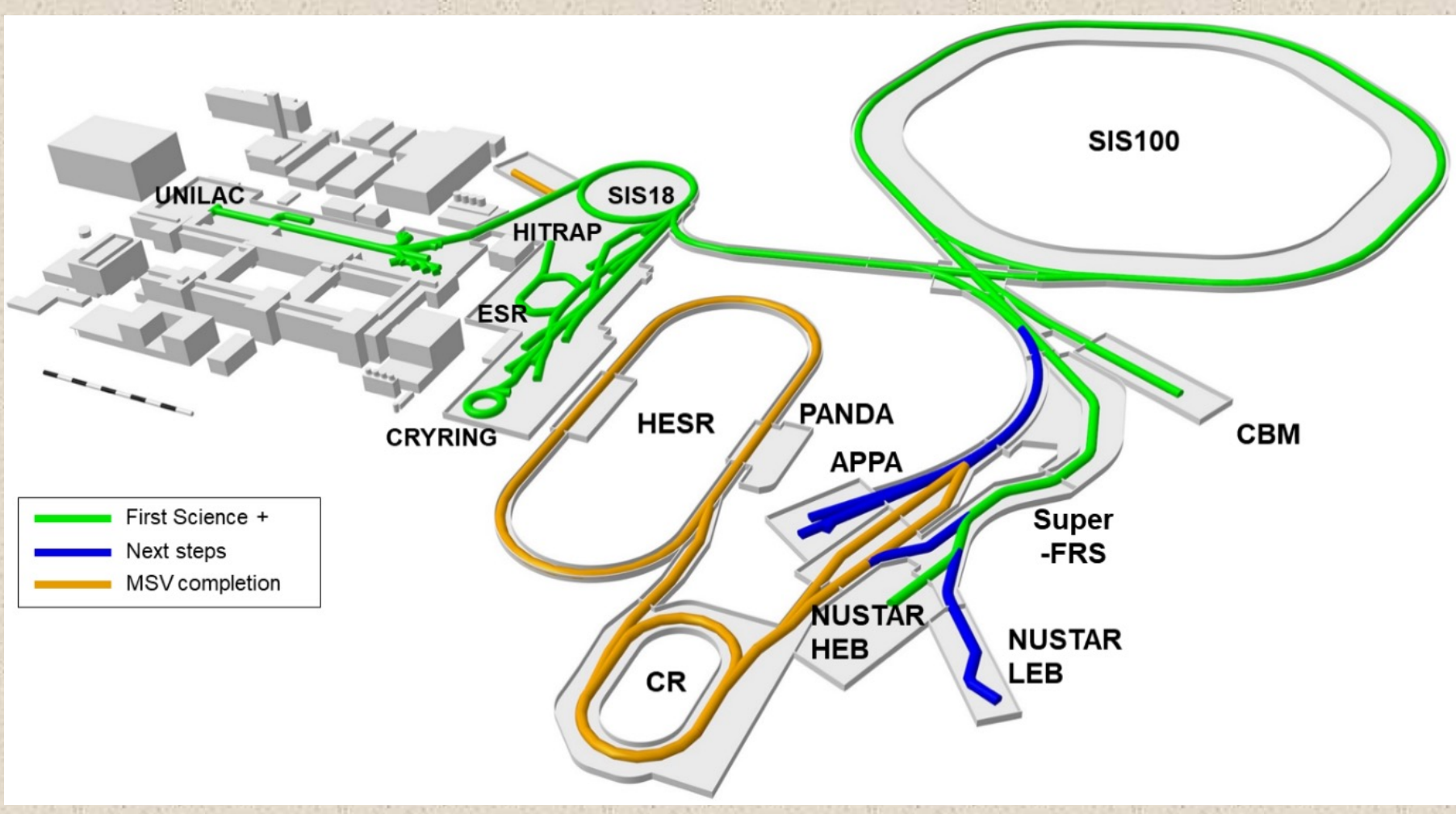
H. Geissel et al. NIM B 204 (2003) 71

SUPERconducting FRagment Separator





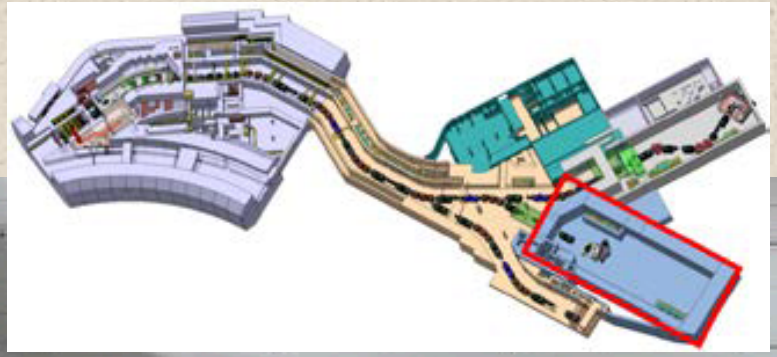



SIS100
UNILAC
SIS18
HITRAP
ESR
CRYRING
HESR
PANDA
APPA
CBM
Super
-FRS
NUSTAR
HEB
NUSTAR
LEB
CR
First Science +
Next steps
MSV completion

FAIR Construction Field


FAIR in construction as it was the last Master Curse in 2022

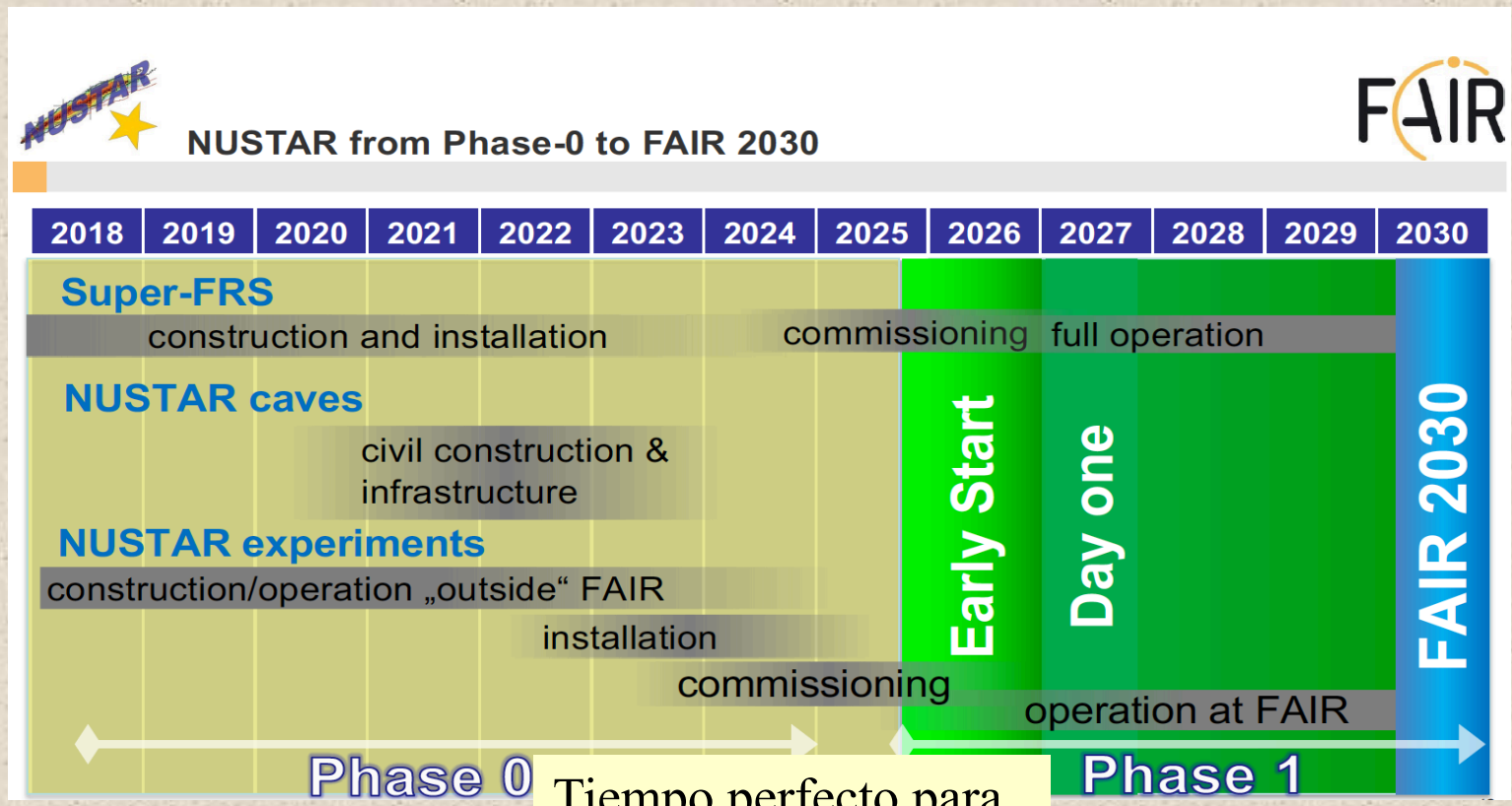
- FAIR GmbH
- GSI GmbH



The high Energy Cave 2023

(See talk by Dolores Cortina on Reactions at Relativistic Energies)

FAIR - NUSTAR
schedule



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 $T_{1/2}$
- 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

FIN