

Producción y uso de haces radioactivos

Master Interuniversitario de Física Nuclear

Berta Rubio IFIC (CSIC-Univ. Valencia)

B. Rubio. Master FN, Valencia 2026

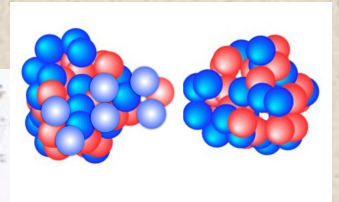
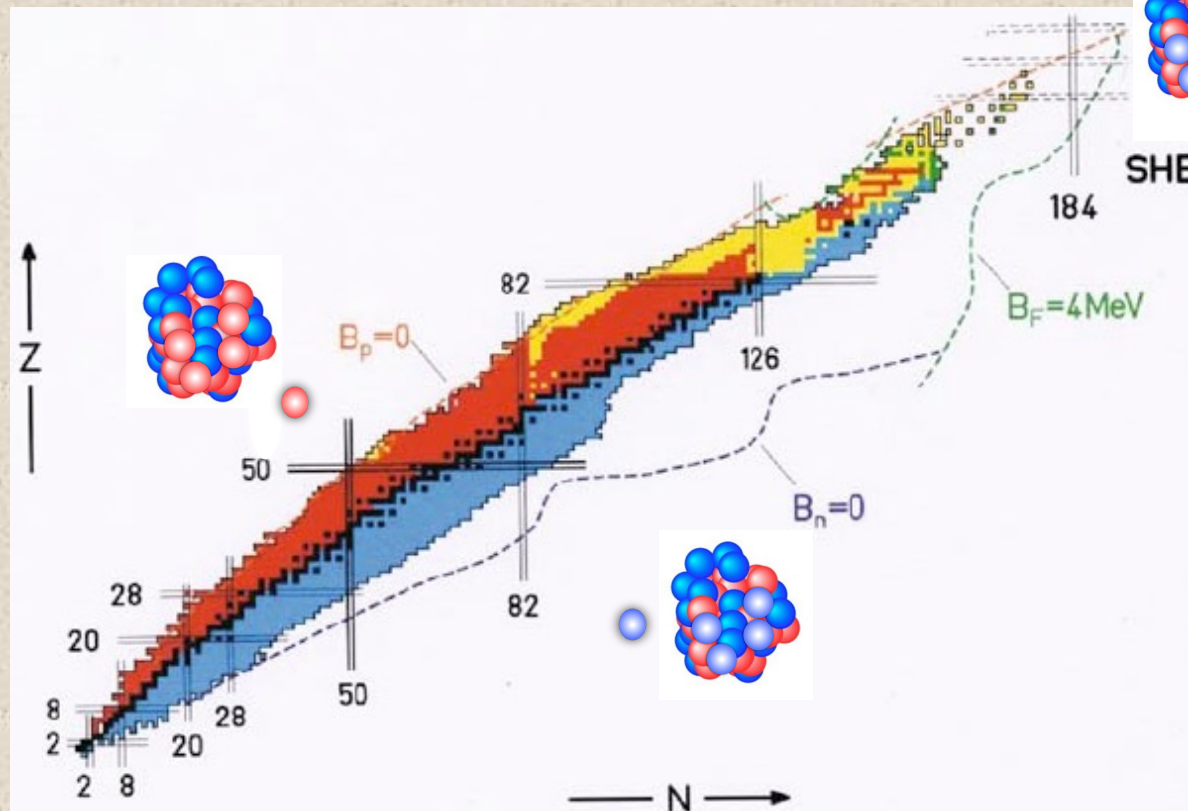
Porqué la producción de haces radioactivos ha marcado un antes y un después en la Física Nuclear

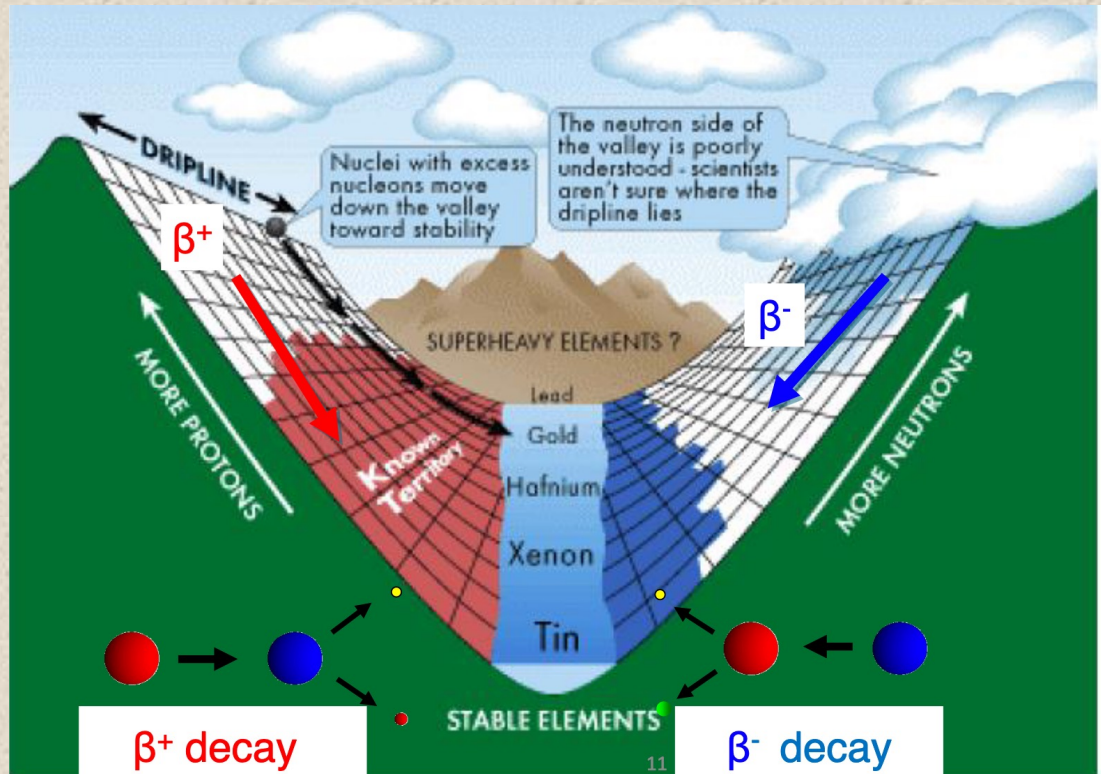
Reacciones nucleares y lo que nos enseñan de la estructura de los núcleos (M.J. García Borge, D. Cortina).

**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.

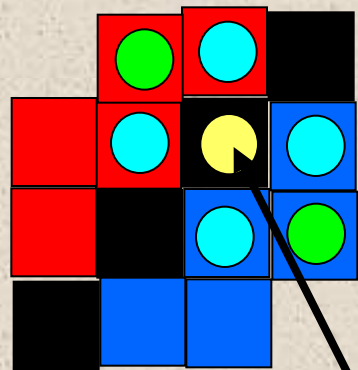




Similarly to the chemical elements, the nuclei are better known and understood if they lie close to the stability

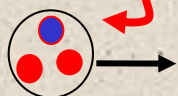
Let us see an example

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

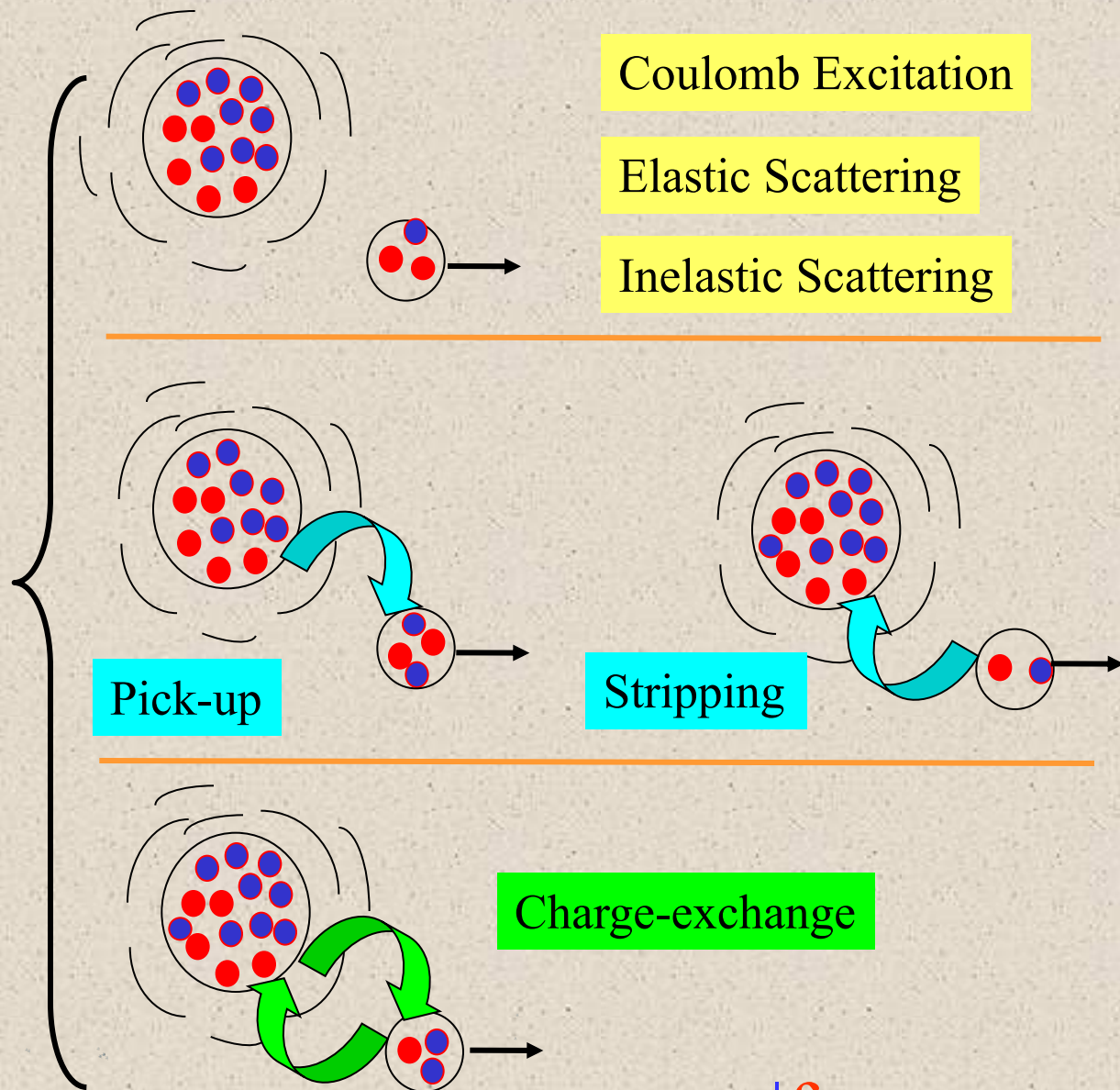
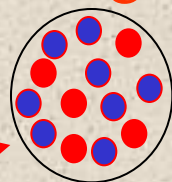


Target

interaction
(operator)



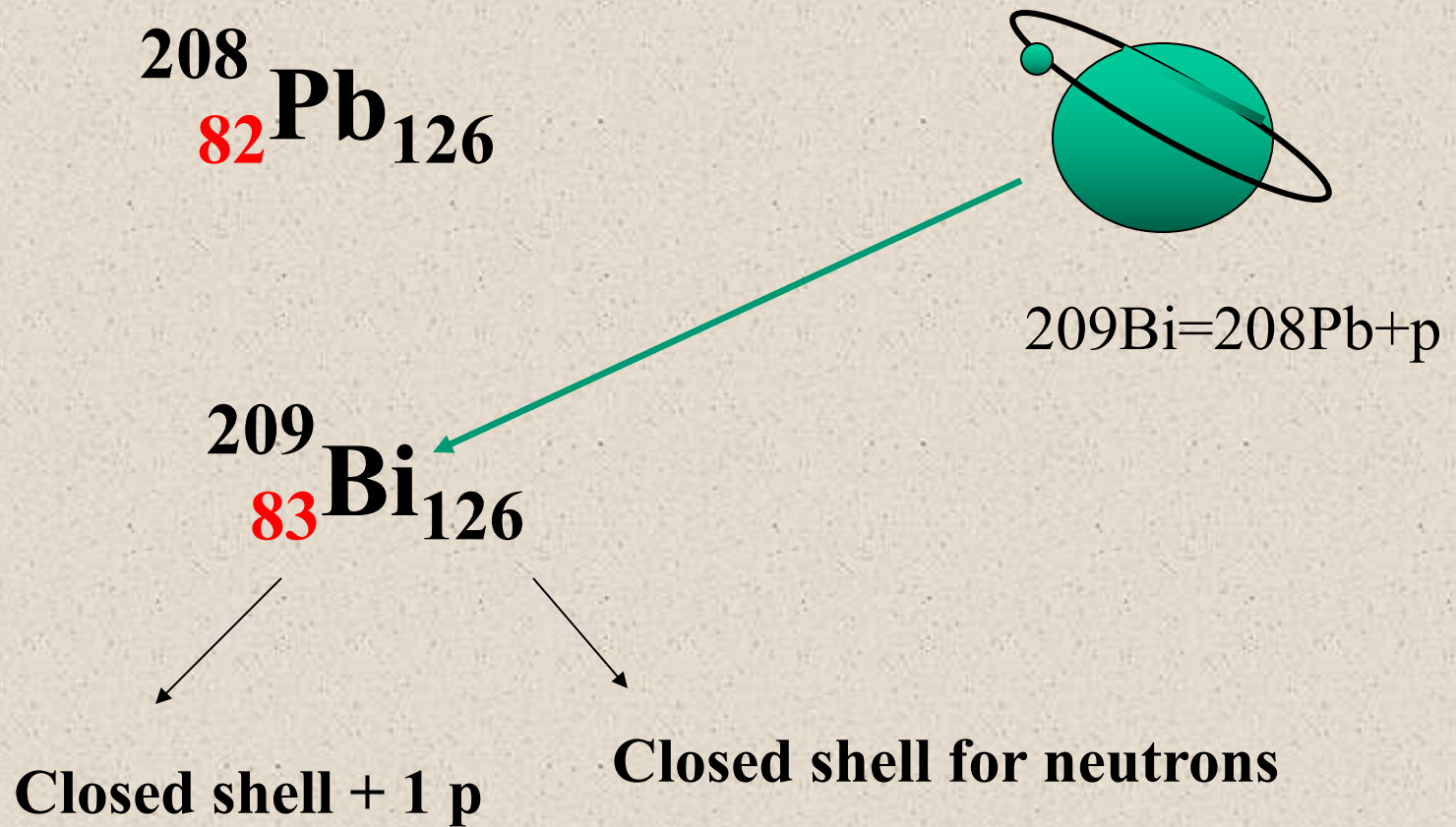
Projectile



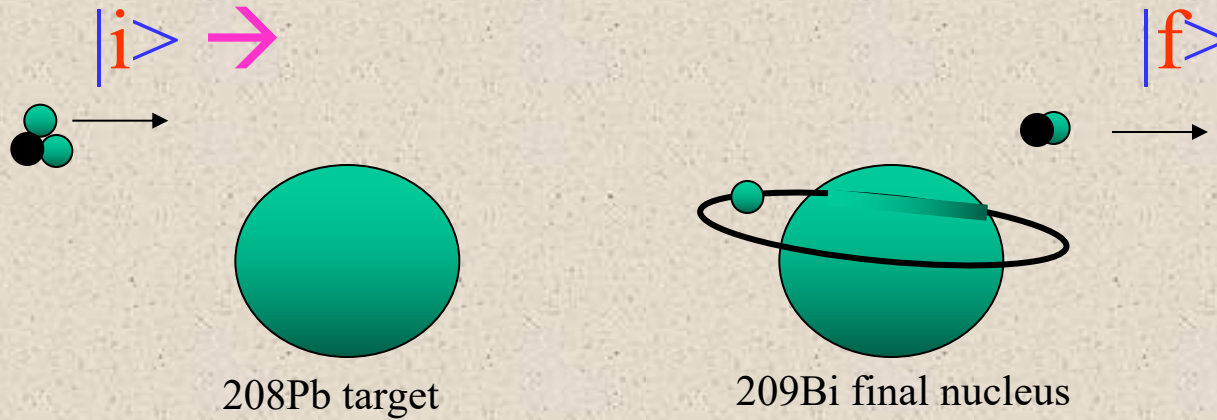
$|i\rangle \rightarrow$

$|f\rangle$

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



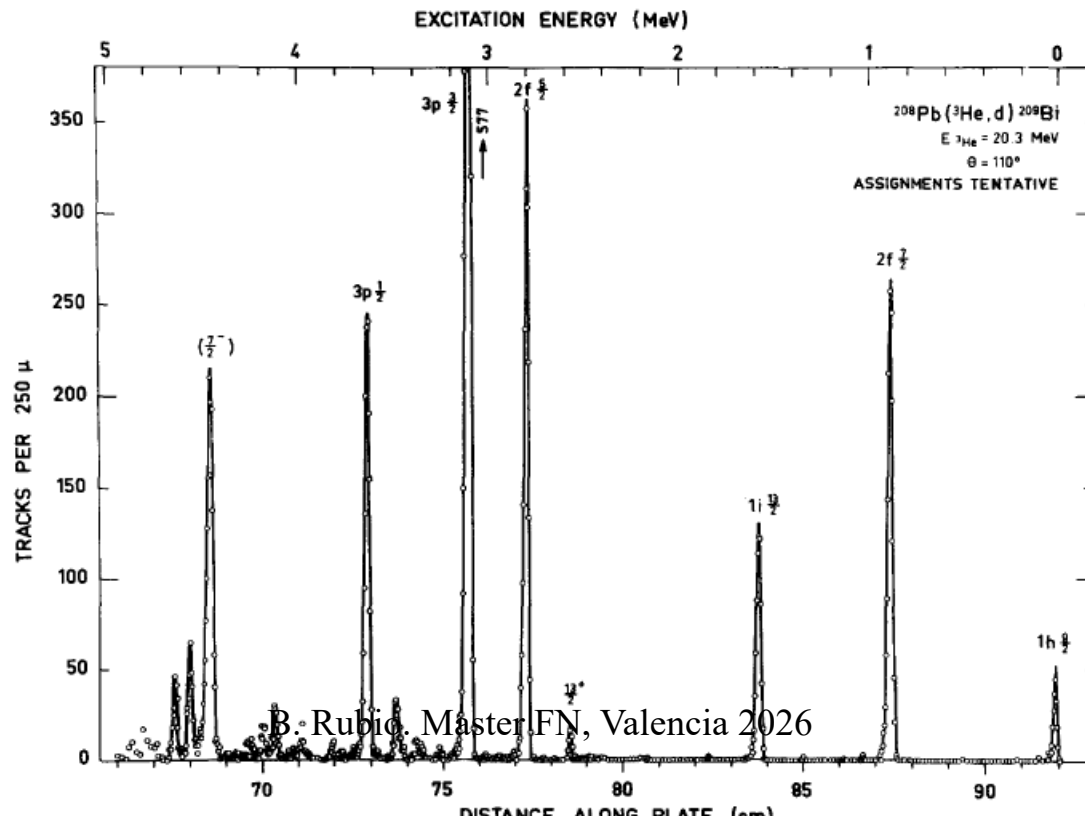
Reaction: $^{208}\text{Pb}(^3\text{He},d)^{209}\text{Bi}$



Volume 26B, number 3

PHYSICS LETTERS

8 January 1968



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Shell Model and Residual Interactions

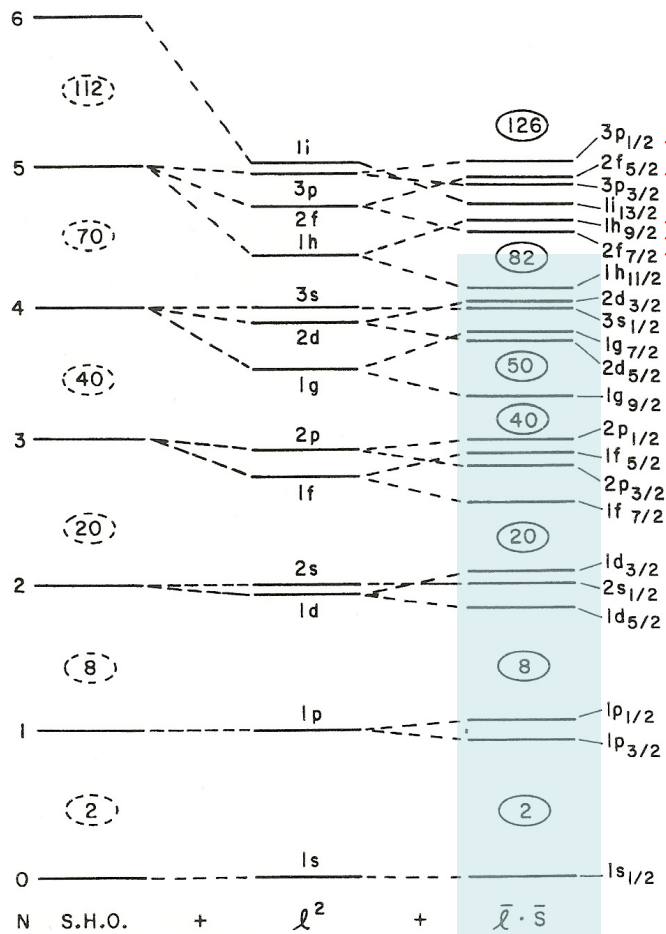
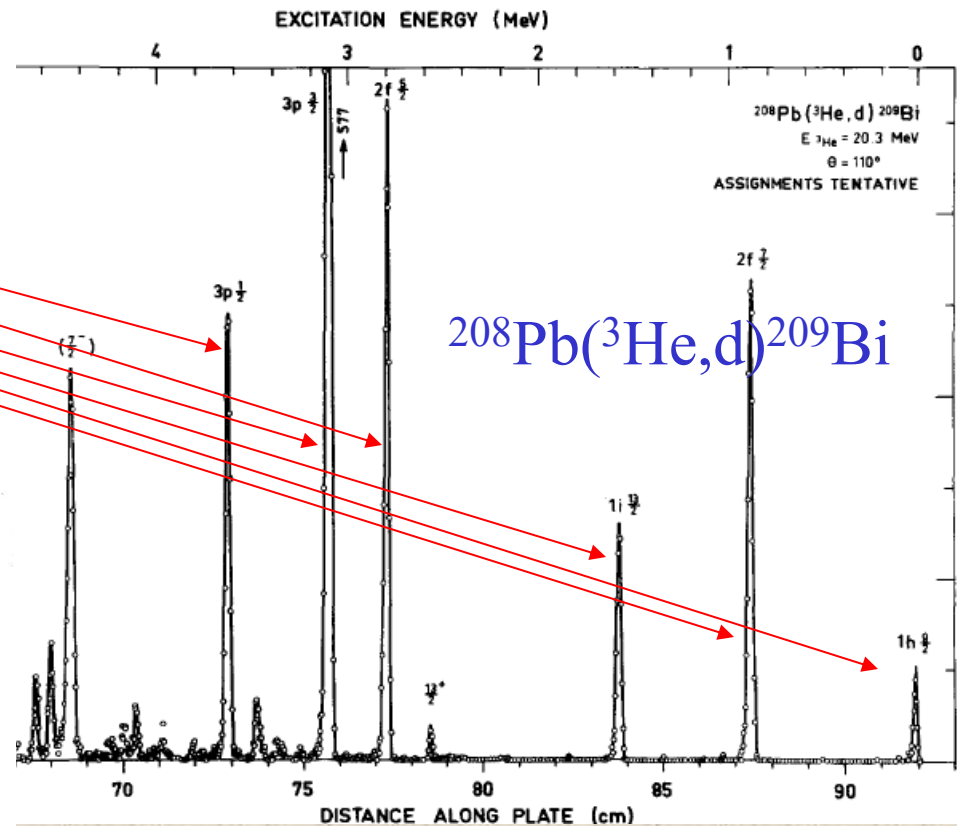
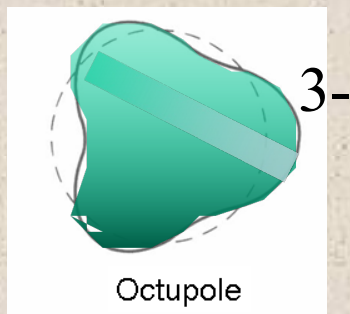


Fig. 3.2. Single-particle energies for a simple harmonic oscillator (S.H.O.), a modified harmonic oscillator with l^2 term, and a realistic shell model potential with l^2 and spin orbit ($l \cdot s$) terms.

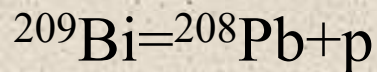
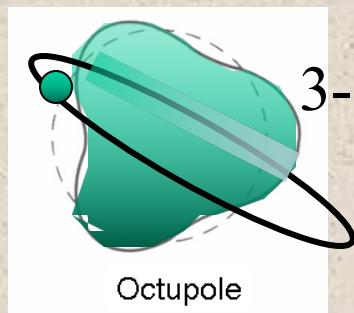


$$^{209}\text{Bi} = ^{208}\text{Pb} + p$$

^{208}Pb



$h_{9/2}$

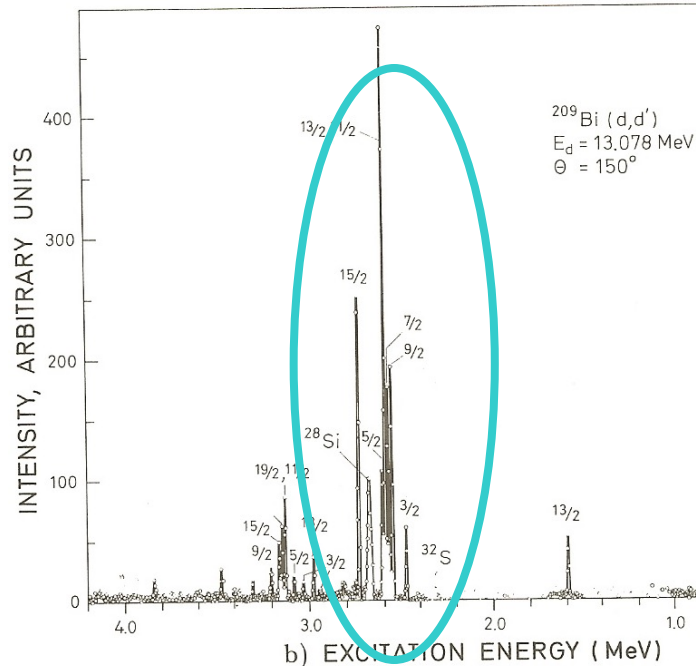
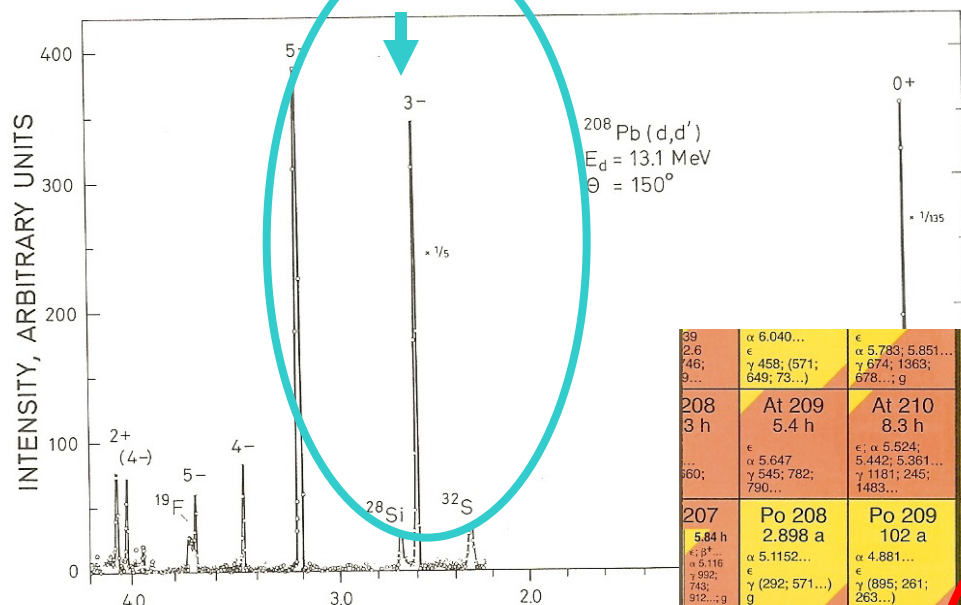


$3^- \times h_{9/2}$

572



VIBRATIONAL SPECTRA Ch. 6



39 2.6 46; 9...	α 6.040... ϵ 5.783; 5.851... γ 458; 571; 649; 73...	ϵ 5.783; 5.851... γ 474; 1363; 678...; g	α 6.264... γ	α 8.088; 7.252... γ 540...	ly 16... m 10...
208 3 h	At 209 5.4 h	At 210 8.3 h	At 211 7.22 h	At 212 119 ms 314 ms	α
ϵ 5.647 α 5.45; 782; 790...	ϵ 5.524; 5.442; 5.361... γ 1181; 245; 1483...	ϵ 5.867... γ (687...) g	α 7.84; α 7.68; 7.90... 7.62... γ 63... g	α 7.84; α 7.68; 7.90... 7.62... γ 63... g	α
207 5.84 h	Po 208 2.898 a	Po 209 102 a	Po 210 138.38 d	Po 211 25.2 s 0.516 s	451... 11.6... 26... 383... ly
ϵ 5.116... α 5.1152... γ 992; 745; 912...; g	α 4.881... α 5.033... γ (292; 571...) g	α 4.881... α 5.033... γ (895; 261; 263...)	α 5.033... α 5.033... γ (895; 261; 263...)	α 5.033... α 5.033... γ (895; 261; 263...)	α
206 4 d	Bi 207 31.55 a	Bi 208 3.68 · 10 ⁵ a	Bi 209 100	Bi 210 5.013 d	α 11.6... β 11.6... γ 11.6... α 11.6... β 11.6... γ 11.6...
ϵ 5.116... α 5.1152... γ 992; 745; 912...; g	ϵ 5.116... α 5.1152... γ 992; 745; 912...; g	ϵ 5.116... α 5.1152... γ 992; 745; 912...; g	ϵ 5.116... α 5.1152... γ 992; 745; 912...; g	ϵ 5.116... α 5.1152... γ 992; 745; 912...; g	ϵ 5.116... α 5.1152... γ 992; 745; 912...; g
205 10 ⁷ a	Pb 206 24.1	Pb 207 22.1	Pb 208 52.4	Pb 209 3.253 h	β 1.8... γ 1.8... α 1.8... β 1.8... γ 1.8... α 1.8...
σ 0.027	σ 0.027	σ 0.61	σ 0.00023 σ_n α < 8E-6	β 0.6 no γ	β 0.6 no γ
204 8 a	Tl 205 70.48	Tl 206 3.7 m 4.20 m	Tl 207 1.3 s 4.7 m	Tl 208 3.053 m	β 1.8... γ 1.8... α 1.8... β 1.8... γ 1.8... α 1.8...
ϵ	ϵ	ϵ	ϵ	ϵ	ϵ
203 59 d	Hg 204 6.87	Hg 205 5.2 m	Hg 206 8.15 m	Hg 207 2.9 m	β 1.8... γ 1.8... α 1.8... β 1.8... γ 1.8... α 1.8...
σ 0.4	σ 0.4	σ 0.4	σ 0.4	σ 0.4	σ 0.4
202 3 s	Au 203 60 s	Au 204 39.8 s	Au 205 31 s		β 1.8... γ 1.8... α 1.8... β 1.8... γ 1.8... α 1.8...
ϵ	ϵ	ϵ	ϵ		ϵ
201 5 m	Pt 202 ~43.6 h				β 1.8... γ 1.8... α 1.8... β 1.8... γ 1.8... α 1.8...
β	β				β

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

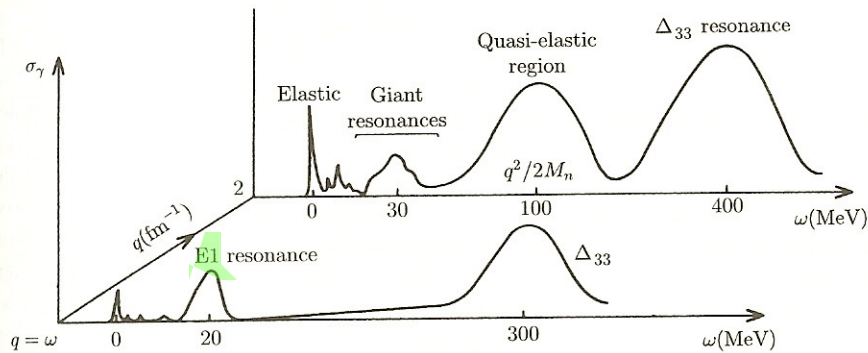
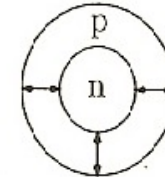


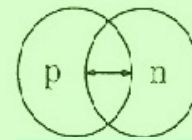
FIG. 1.1. Characteristic response (cross section σ) of an atomic nucleus as a function of the energy transfer ω and momentum transfer q . The lower curve is for photon absorption, the upper one for particle scattering with $q = 2 \text{ fm}^{-1} \neq \omega$.

Isovector

$\Delta T=0 \ 1$

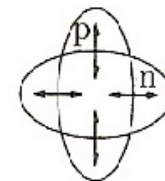


IVGMR



IVGDR

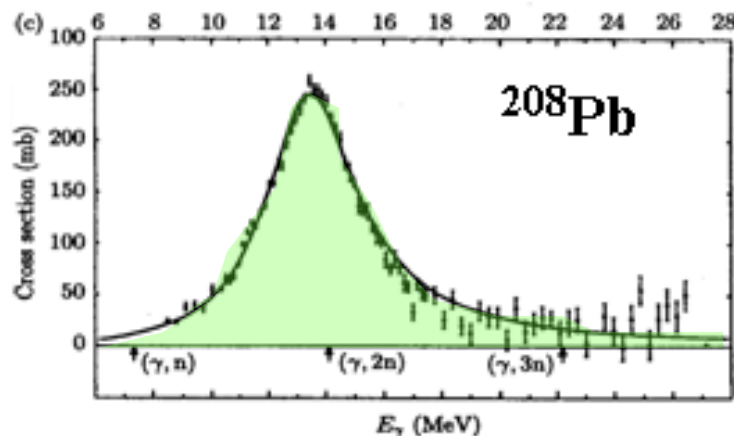
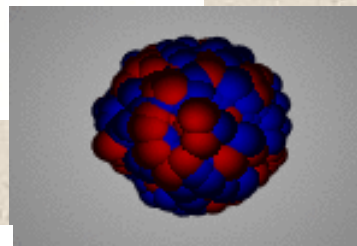
E1



IVGQR

$\Delta T = 1$

$\Delta S = 0$



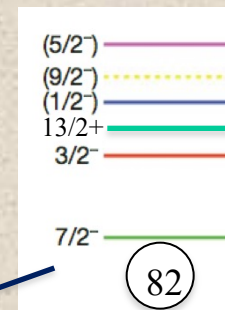
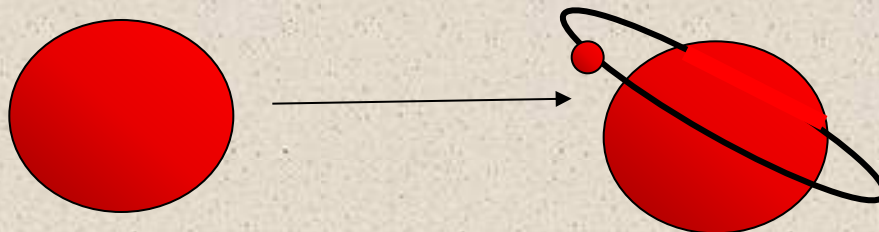
Qué ha sido necesario para poder hacer estos experimentos

1. Definir la reacción nuclear de interés.
2. Blancos de núcleos estables: ^{208}Pb y ^{209}Bi 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, $T_{1/2}=40\text{s}$





Sb 132 4.1 m β ⁻ 3.7... γ 974, 697 151, 104...	Sb 133 2.34 m β ⁻ 1.2, 2.9... γ 1096, 818 2755, 837... g, m	Sb 134 10.1 s β ⁻ 6.1... γ 1279 297, 707 115...	Sb 135 0.75 s β ⁻ 8.4... γ 1279 2631 1352...
Sn 131 50 s β ⁻ 3.4... γ 1226 460, 305 1229...	Sn 132 39 s β ⁻ 1.8... γ 341, 86, 899 247, 993...	Sn 133 1.46 s β ⁻ 8.1... γ 962... βn 0.48	Sn 134 1.050 s β ⁻ 7.0... γ 672, 318, 554 962...
In 130 0.54 s β ⁻ 1221 774... g, m	In 131 0.32 s β ⁻ 6.6... γ 1905 130 1221... g, m	In 132 207 ms β ⁻ 6.4, 8.9... γ 375, 4041 299... βn 0.23, 0.33	In 133 180 ms β ⁻ 802, 854 1561 854
Cd 129 242 ms β ⁻ 995, 359, 1796... βn	Cd 130 162 ms β ⁻ 6.2, 8.3... γ 1669, 451 950, 1170... βn	Cd 131 98.0 ms β ⁻ βn?	
Ag 128 59 ms β ⁻ 645, 784... βn?	Ag 129 ~160 ms β ⁻ βn	Ag 130 42 ms β ⁻ 957 βn?, β2n?	
Pd 127 38 ms β ⁻ βn? β2n?	Pd 128 35 ms β ⁻ βn?	Pd 129 31 ms β ⁻ βn? β2n?	

¹³³₅₀Sn₈₃⁻¹

From ENSDF - Evaluated October 2010

¹³³In β⁻ decay [1996Ho16,2000Ho32](#)

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

Parent: ¹³³In: E=0.0; J^π=(9/2⁺); T_{1/2}=165 ms 3; Q(β⁻)=12917 SY; %β⁻ decay=100.0
[1995JoZZ, 1996Ho16, 2000Ho32](#): ¹³³In β⁻ [from ²³⁸U(p,f), E=1 GeV]; measured E_γ, I_γ, γγ-, nγ-, βγ-c
 (βn)γ(t). ISOLDE facility; plastic scin β detector, two liquid scin n detectors, two Ge γ-ray detectors

¹³³Sn Levels

E(level) [†]	J ^π [‡]
0.0	7/2 ⁻
853.7 3	3/2 ⁻
1560.9 5	(9/2 ⁻)
2004.6 10	(5/2 ⁻)

¹/₂- missing
 (and the 13/2+ too)



nature

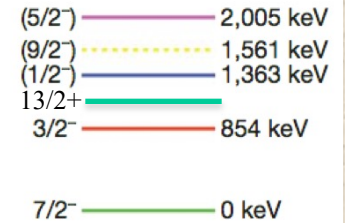
Vol 465 | 27 May 2010 | doi:10.1038/nature09048

LETTERS

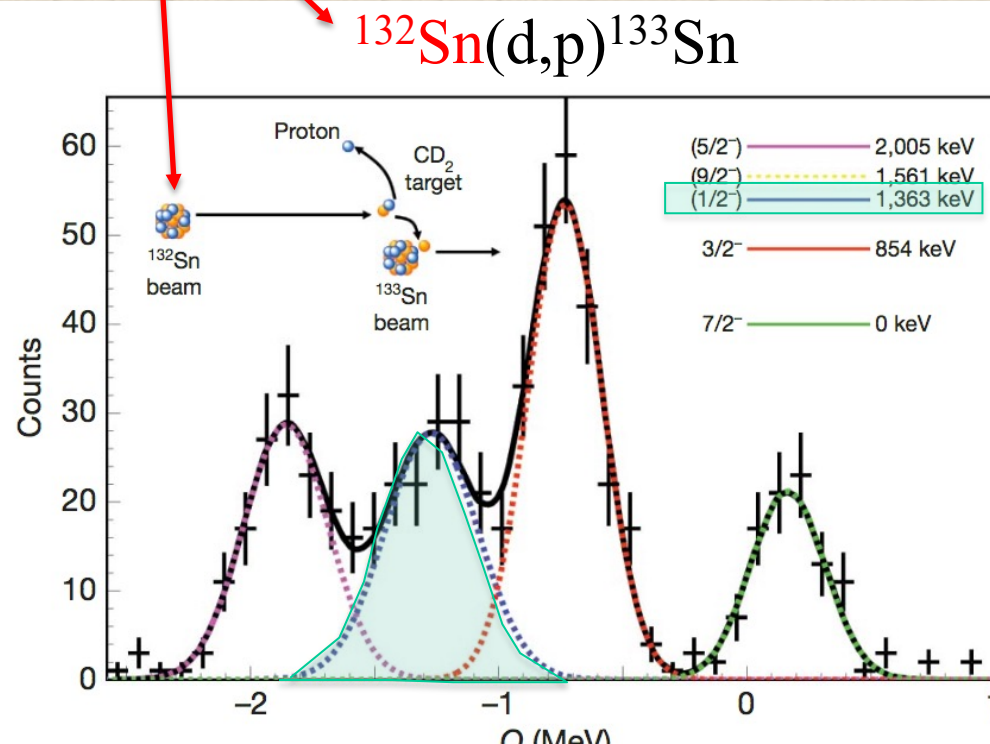
Year 2010

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

K. L. Jones^{1,2}, A. S. Adekola³, D. W. Bardayan⁴, J. C. Blackmon⁴, K. Y. Chae¹, K. A. Chipps⁵, J. A. Cizewski², L. Erikson⁵, C. Harlin⁶, R. Hatarik⁶, R. Kapler¹, R. L. Kozub⁷, J. F. Liang¹, R. Livesay³, Z. Ma¹, B. H. Moazen¹, C. D. Nesaraja⁴, F. M. Nunes⁸, S. D. Pain², N. P. Patterson⁶, D. Shapira⁴, J. F. Shriner Jr⁷, M. S. Smith⁴, T. P. Swan^{2,6} & J. S. Thomas⁶



Radioactive beam of ^{132}Sn



Curiosity, for complition: the $13/2^+$ level has just have been identified few months ago

PHYSICAL REVIEW LETTERS **135**, 152501 (2025)

First β -Delayed Two-Neutron Spectroscopy of the r -Process Nucleus ^{134}In and Observation of the $i_{13/2}$ Single-Particle Neutron State in ^{133}Sn

P. Dyszel¹, R. Grzywacz¹, Z. Y. Xu¹, N. Kitamura,² M. Karny³, A. Korgul³, M. Madurga¹, S. Neupane⁴,
A. Algora⁵, A. N. Andreyev⁶, M. Araszkiewicz^{3,7}, R. A. Bark,⁸ J. Benito,⁹ N. Bernier⁹, M. J. G. Borge¹⁰,
M. Caballero⁹, P. Chuchala,³ T. E. Cocolios,¹¹ C. Costache,¹² J. G. Cubiss^{6,13}, H. DeWitte,¹¹ J. E. Escher⁴,
D. Fernandez-Ruiz¹⁰, A. Fijalkowska³, L. M. Fraile⁹, H. O. U. Fynbo¹⁴, J. Gouge¹, J. L. Herraiz,⁹ A. Illana⁹,
P. M. Jones⁸, D. S. Judson,¹⁵ P. Kamińska,³ T. Kawano,¹⁶ K. Kolos⁴, M. Labiche,¹⁷ R. Lică¹⁸, M. Llanos-Expósito,⁹
G. G. DeLorenzo⁹, N. Marginean,¹² I. Michelon,¹⁹ C. Mihai,¹⁸ E. Nácher,²⁰ C. Neacsu,¹⁸ J. S. Nielsen,¹⁴ B. Olaizola¹⁰,
J. N. Orce²¹, C. A. A. Page,⁶ R. D. Page¹⁵, J. Pakarinen,^{22,23} A. Perea,¹⁰ M. Piersa-Silkowska^{1,9,24}, Zs. Podolyák²⁵,
J. S. Prieto,¹⁰ M. Rajabali²⁶, J. Shaw¹¹, A. I. Sison,⁹ K. Solak,³ M. Stryczyk^{27,22}, O. Tengblad,¹⁰ P. G. T. Vicente⁹,
N. Warr,²⁸ J. Wilson²⁹, Z. Yue,²⁹ and S. Zajda³

This manuscript reports on the direct observation of a β -delayed two-neutron emission in a study of ^{134}In at the ISOLDE Decay Station using neutron spectroscopy. We also report on the first measurement in β^- decay of the long-sought $13/2^+$ excited state in ^{133}Sn , attributed to be the neutron single-particle $i_{13/2}$

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

Step1: The first thing to worry about is how to produce radioactive nuclei

Condition of step 1: to produce the radioactive nuclei them in a “clean” way

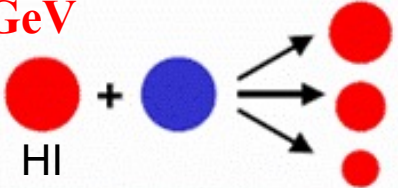
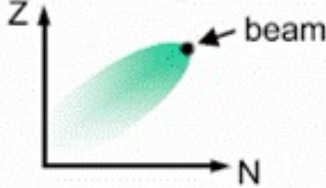
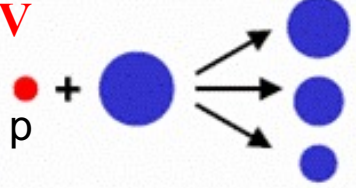
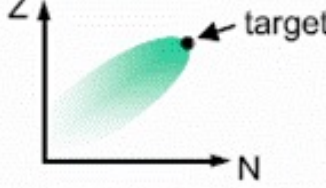
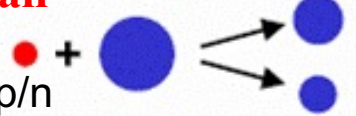
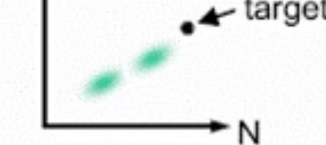
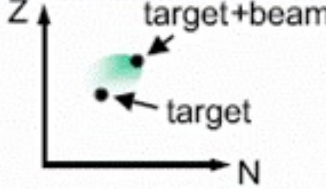
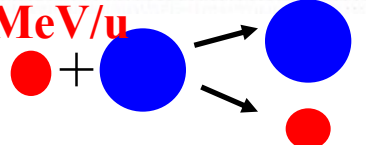
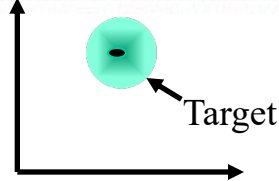
Methodology: to separate them from other radioactive products, Isol method or in-flight separation.

Step 2: produce the beam at a certain energy

Step1

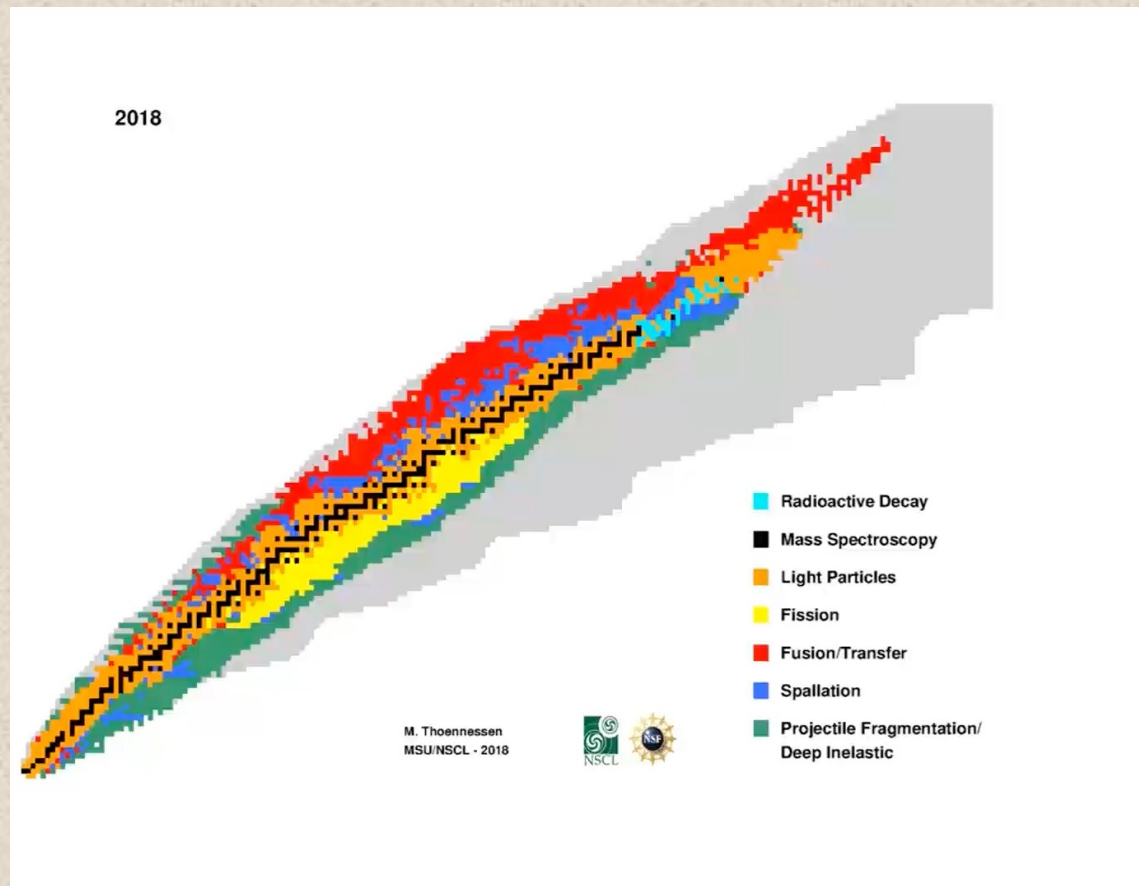
How to produce radioactive nuclei.
Tool: Reaction or Fission

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

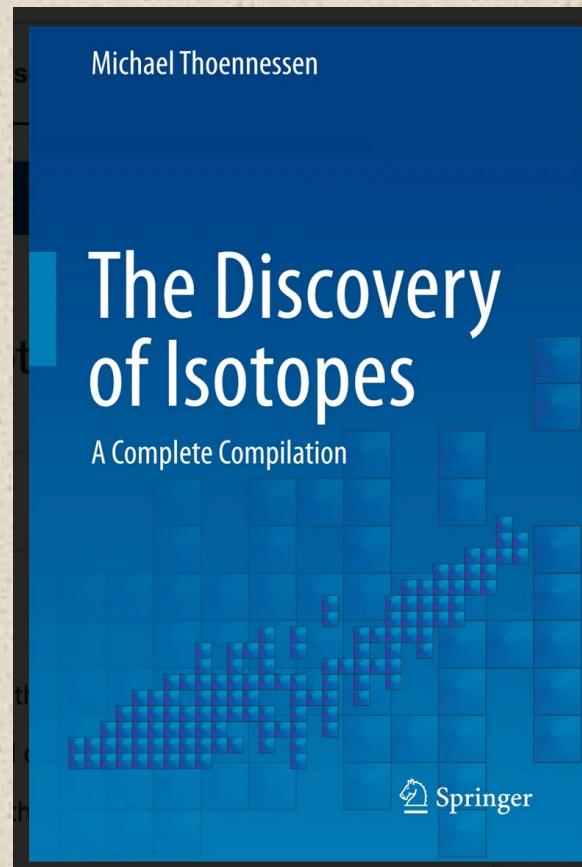
Beam + target → products		Product energy	Number of Products	
GeV  HI	fragmentation RIKEN, GSI/FAIR, FRIB	“All nuclei” $v_{\text{product}} = v_{\text{beam}}$	up to 1000	
GeV  p	spallation ISOLDE	“All nuclei” few MeV/u	up to 1000	
small  p/n	fission Reactors, ISOLDE...	“mainly neutron rich” ~1 MeV/u	few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

Historical view to the discovery of new isotopes

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



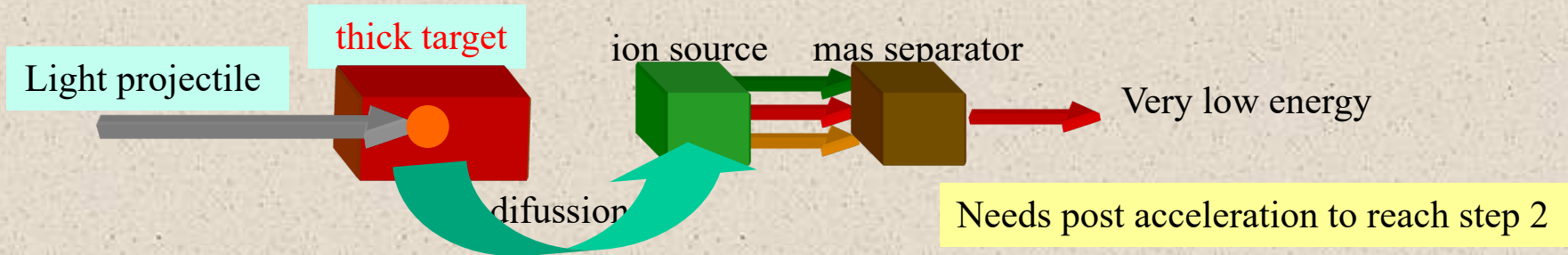
I you want to learn how all that happened, read this book



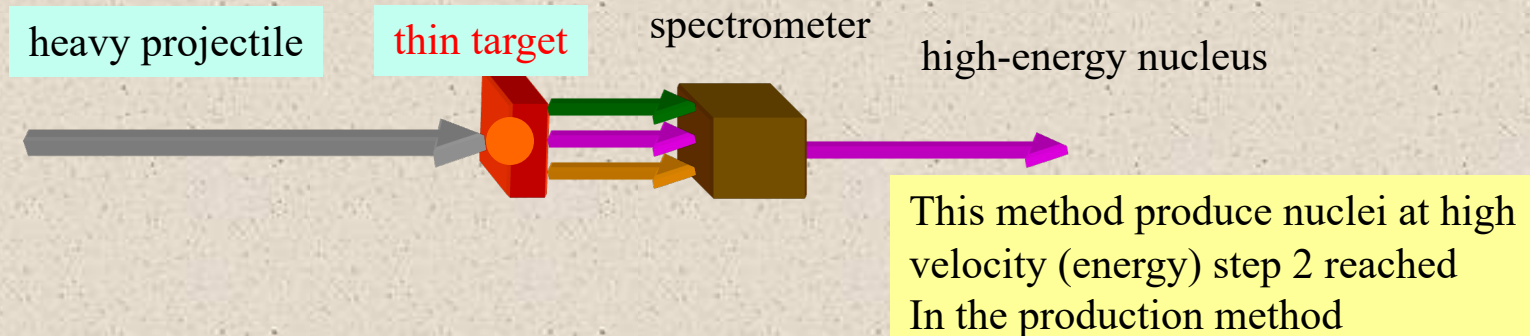
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The condition is to separate them from other radioactive products:
Radioactive nuclei production techniques

Isotopic Separation On-Line (ISOL)

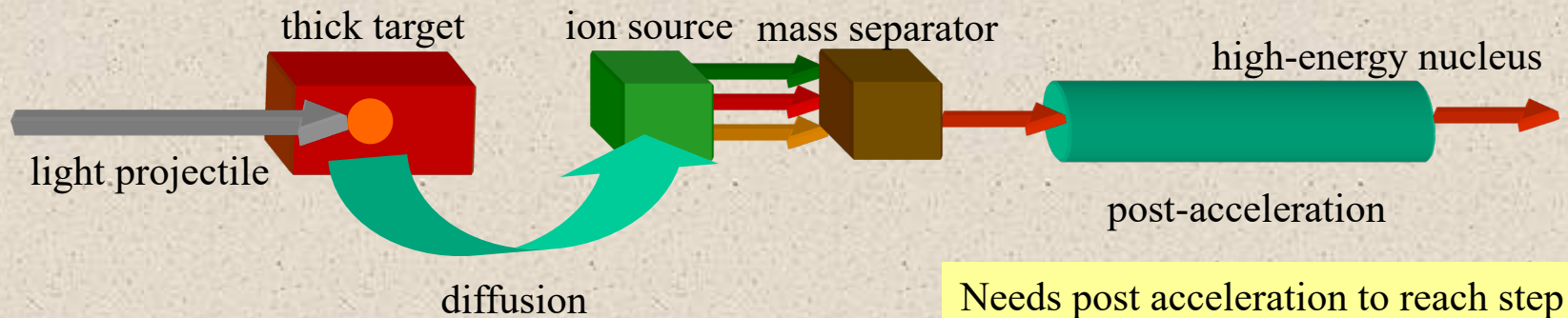


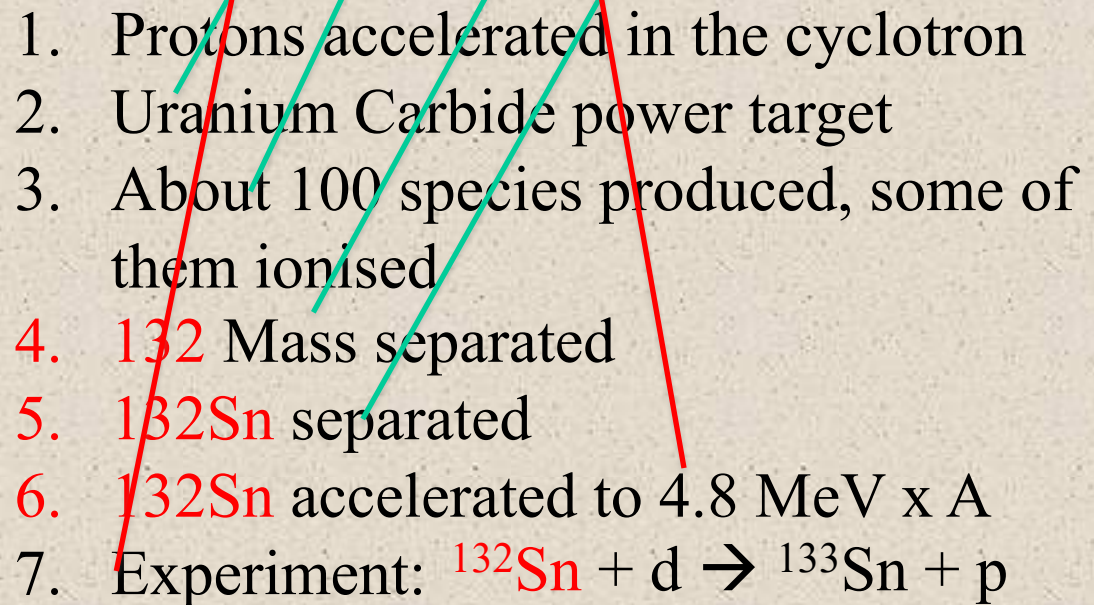
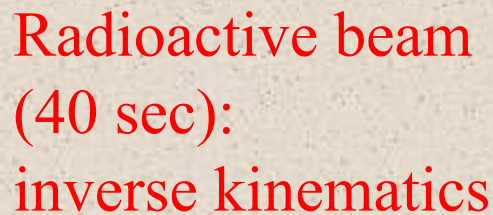
In-flight fragmentation



Production techniques Rad Beams: post acceleration

➤ Isotopic separation on-line (ISOL)





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

CERN's longest serving experimental facility

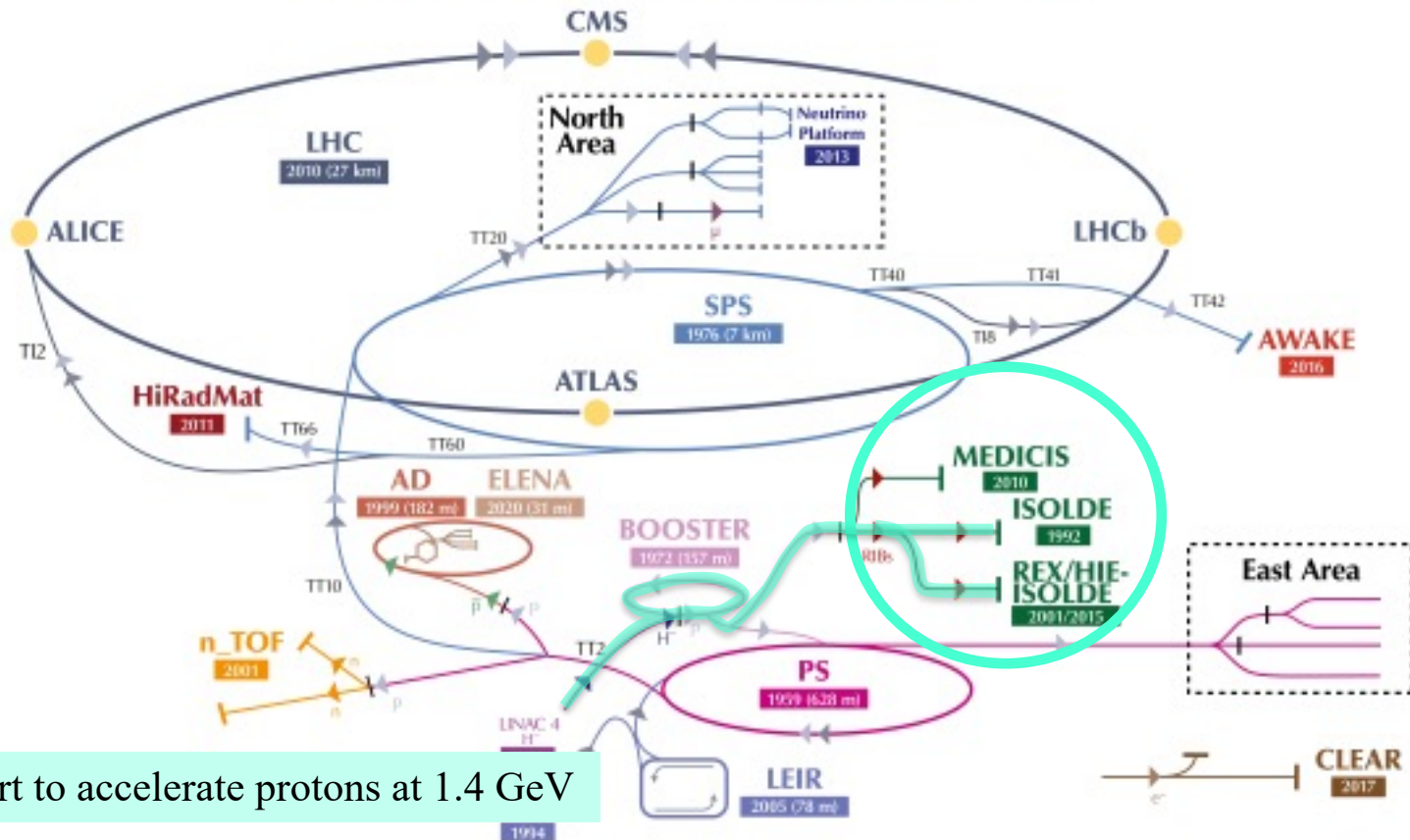
Physics Reports 403–404 (2004) 459–469

Juha Äystö

B. Rubio. Master FN



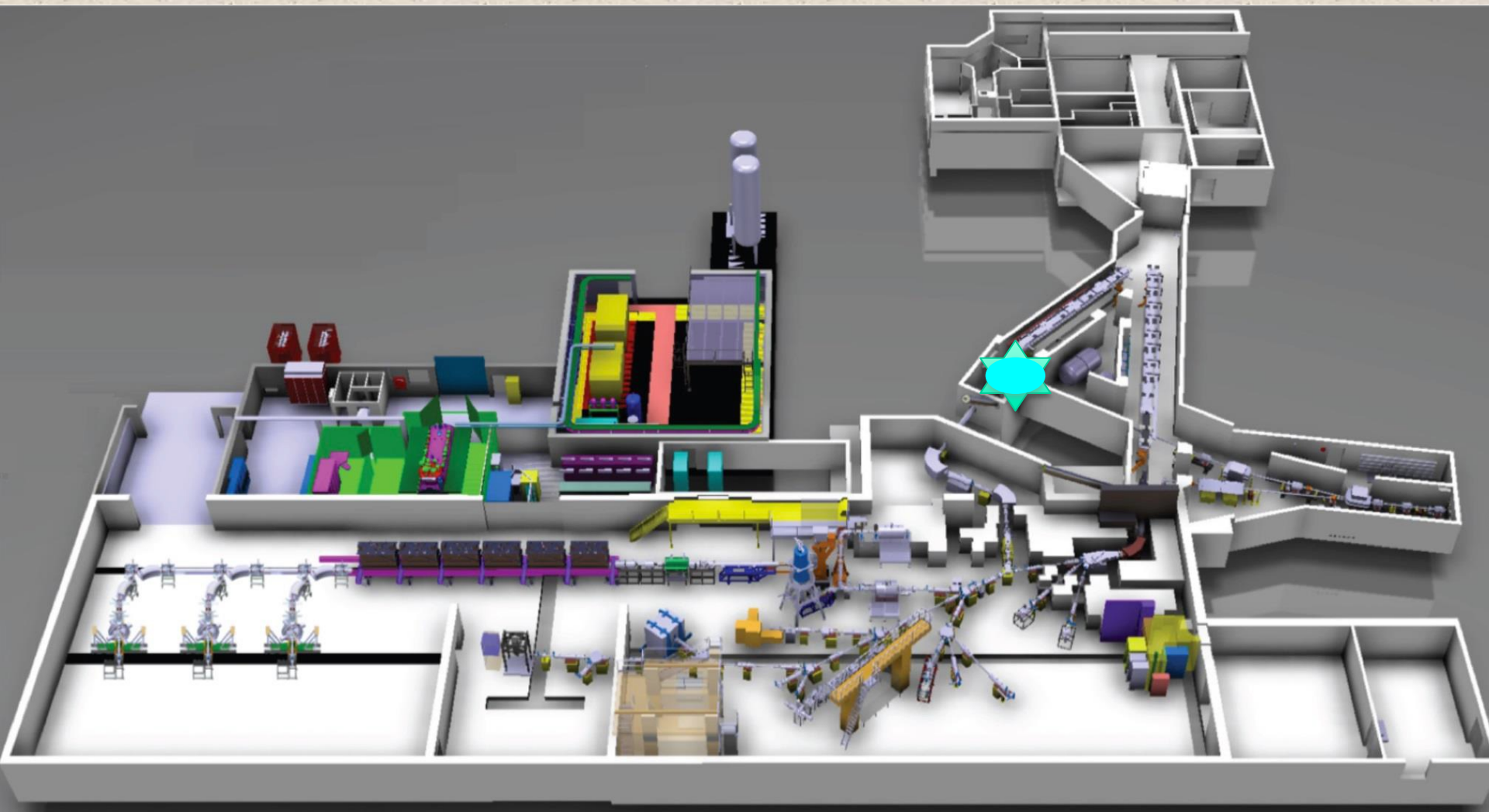
The CERN accelerator complex Complexe des accélérateurs du CERN



This part to accelerate protons at 1.4 GeV

► 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



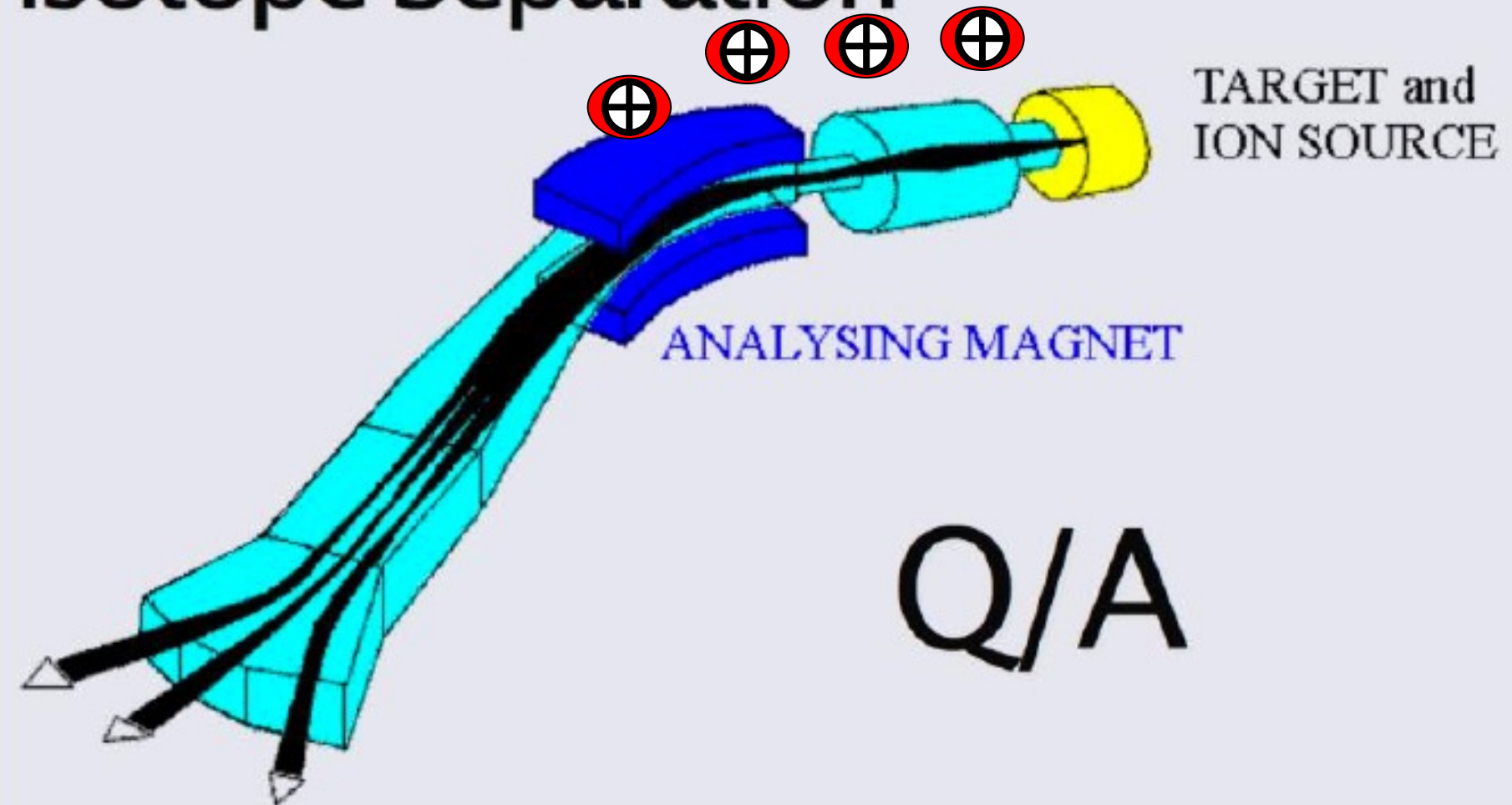
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- 😊 High intensity p beam (upto 10^{16} s^{-1}) the same beam that serves LHC
- 😊 thick target (100% energy range of p)
- 😞 long extraction and ionization time (hundred's ms)
- 😞 Not clean
- 😞 Chemistry dependent

The Separator: in general, only
isobaric separation

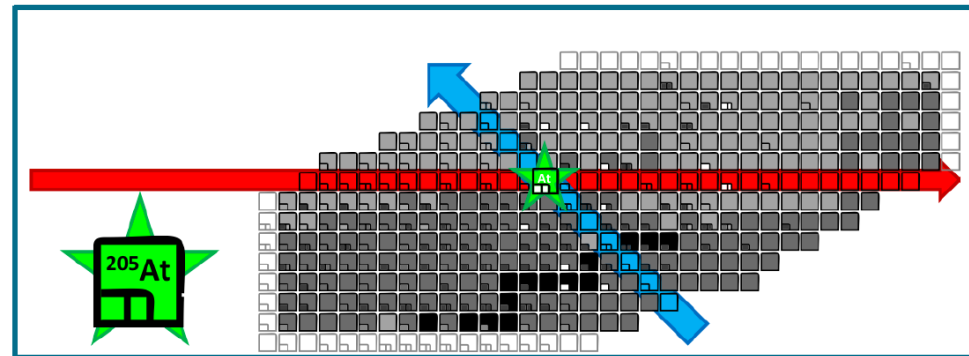
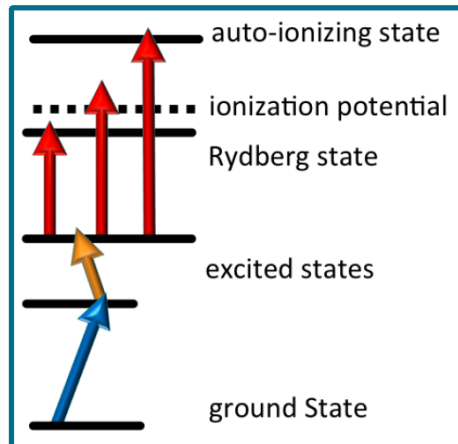
Isotope Separation





Ion sources

Many methods have been developed along the years to help ionisation and cleanliness:
Example: Laser ion source

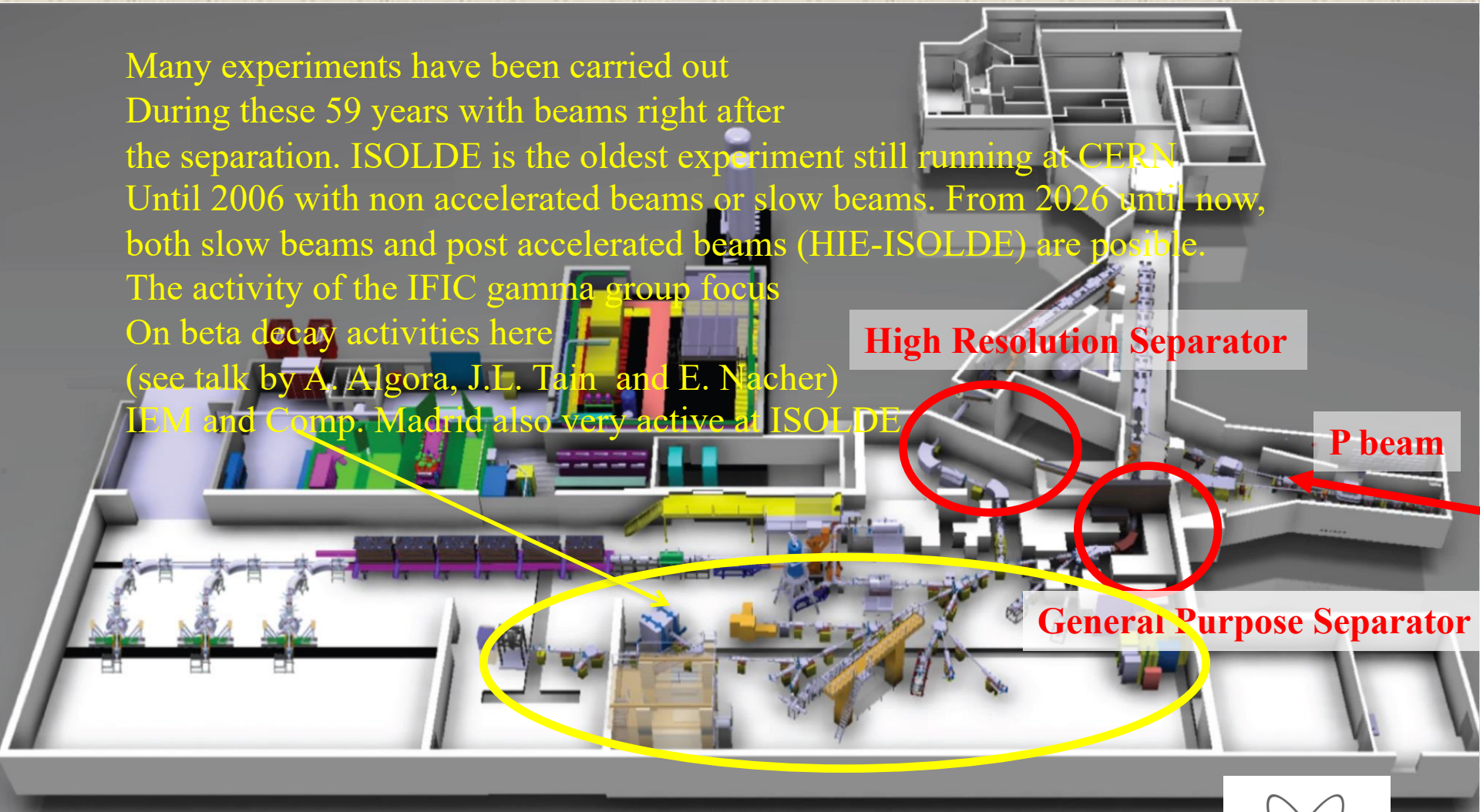


Find the produced isotopes independent on the target

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
	1A	2A	3B	4B	5B	6B	7B	8B			1B	2B	3A	4A	5A	6A	7A	8A	
Period																			
1	1 H																	2 He	
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
4	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	
5	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	
6	55 Cs	56 Ba	*	71 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
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg							
* Lanthanides			*	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		
** Actinides			**	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		

Ion source:		
+	Surface	-
hot	Plasma	cool
	Laser	

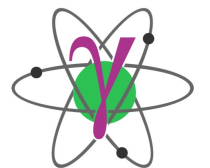
Many experiments have been carried out
During these 59 years with beams right after
the separation. ISOLDE is the oldest experiment still running at CERN.
Until 2006 with non accelerated beams or slow beams. From 2026 until now,
both slow beams and post accelerated beams (HIE-ISOLDE) are possible.
The activity of the IFIC gamma group focus
On beta decay activities here
(see talk by A. Algora, J.L. Tain and E. Nacher)
IEM and Comp. Madrid also very active at ISOLDE



High Resolution Separator

P beam

General Purpose Separator



ISOLDE

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

View 



ISOLDE

The On-Line Isotope Mass Separator ISOLDE is a facility dedicated to the production of a large variety of radioactive ion beams

26 JUNE 1992

First experiment at the ISOLDE Proton-Synchrotron Booster

View 



ISOLDE

The On-Line Isotope Mass Separator ISOLDE is a facility dedicated to the production of a large variety of radioactive ion beams

31 OCTOBER 2001

New accelerator, REX-ISOLDE, goes live

View 



ISOLDE

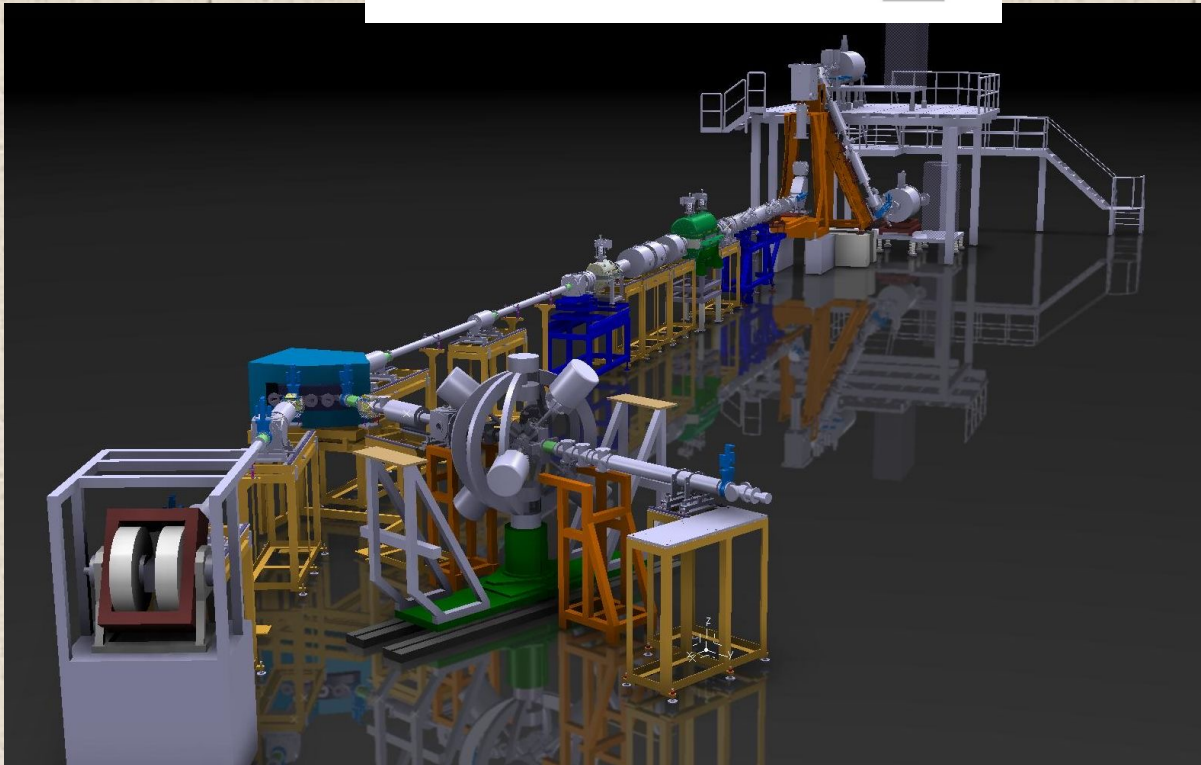
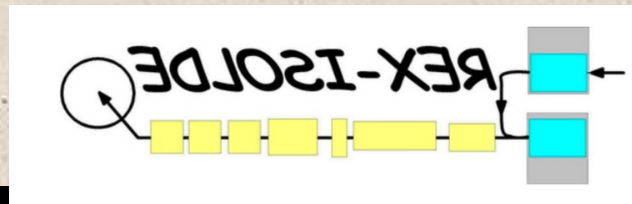
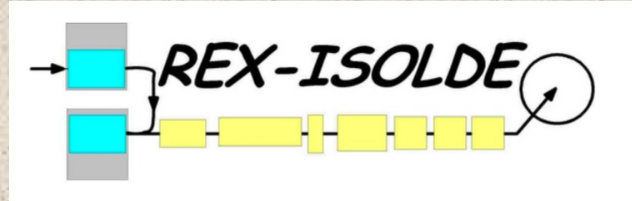
The On-Line Isotope Mass Separator ISOLDE is a facility dedicated to the production of a large variety of radioactive ion beams

22 OCTOBER 2015

First radioactive isotope beam accelerated in HIE ISOLDE

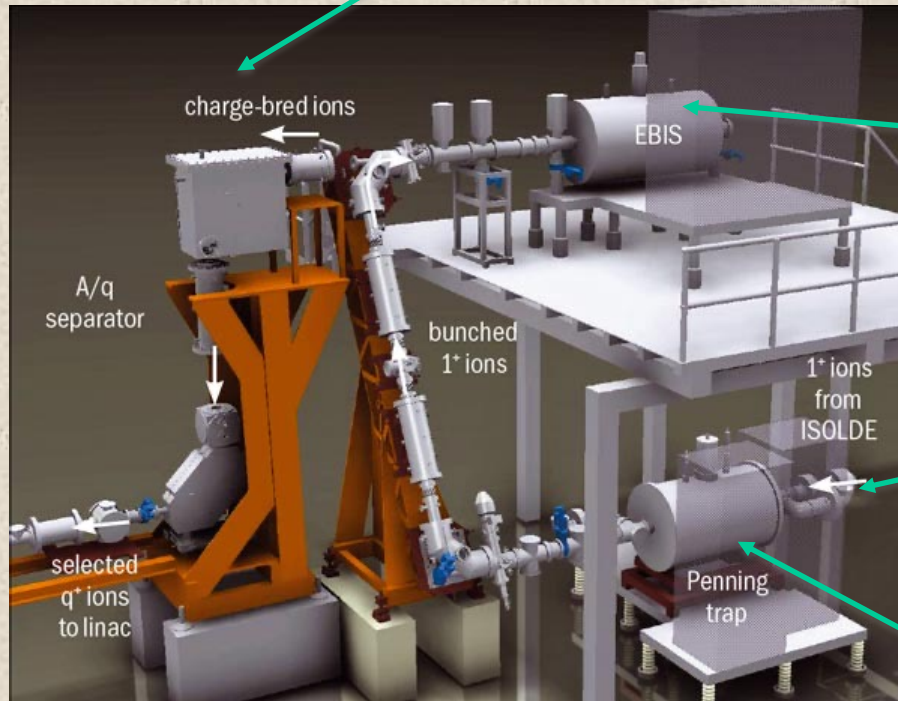
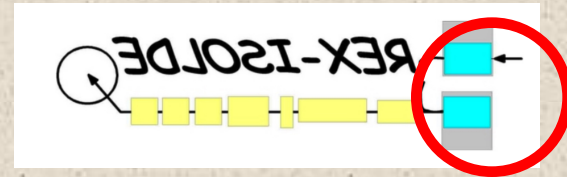
View 





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

A/q separator

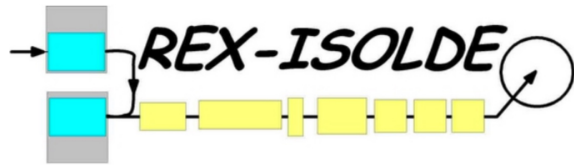


In the EBIS the 1^+ to n^+ ion conversion takes place

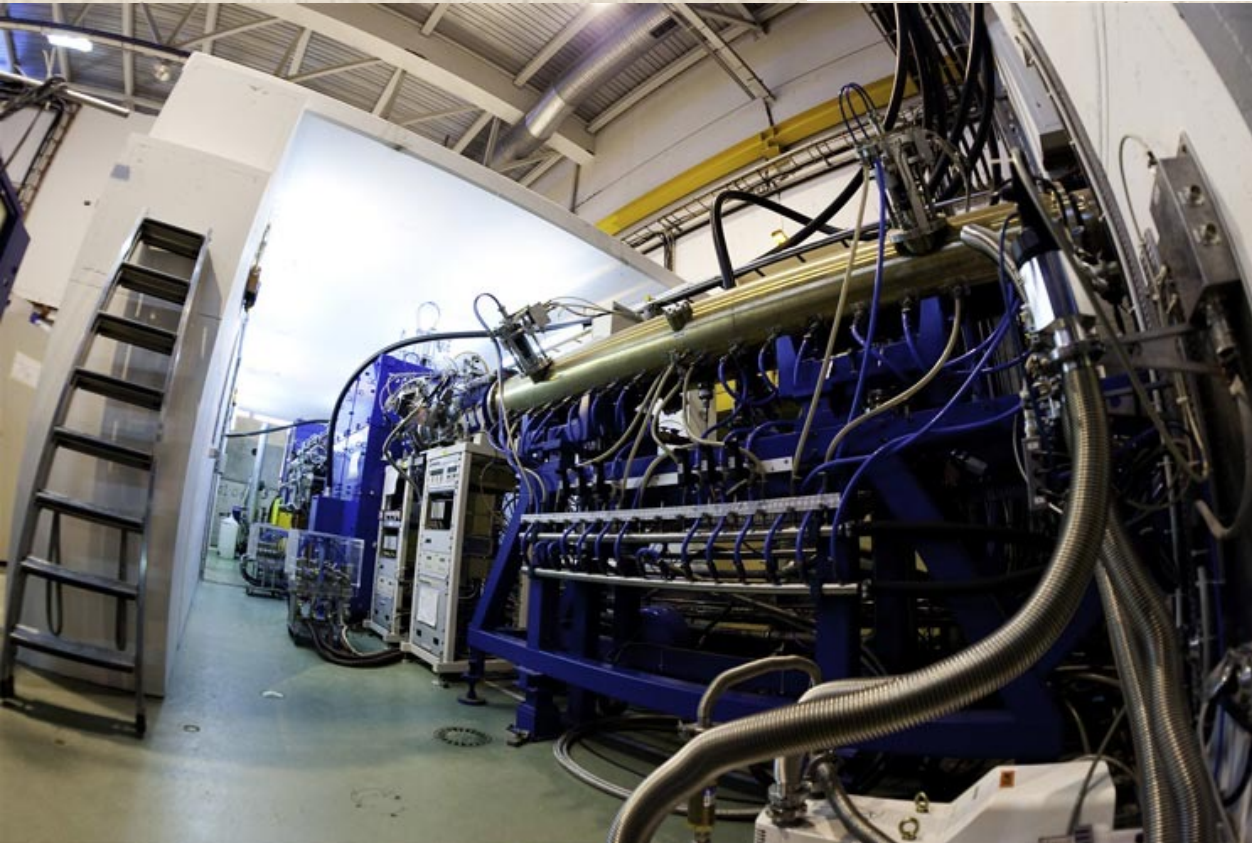
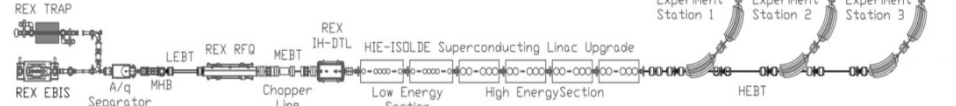
Beams from ISOLDE with 1^+ charge state

Preparation trap

Post accelerator: Normal Conducting LINAC

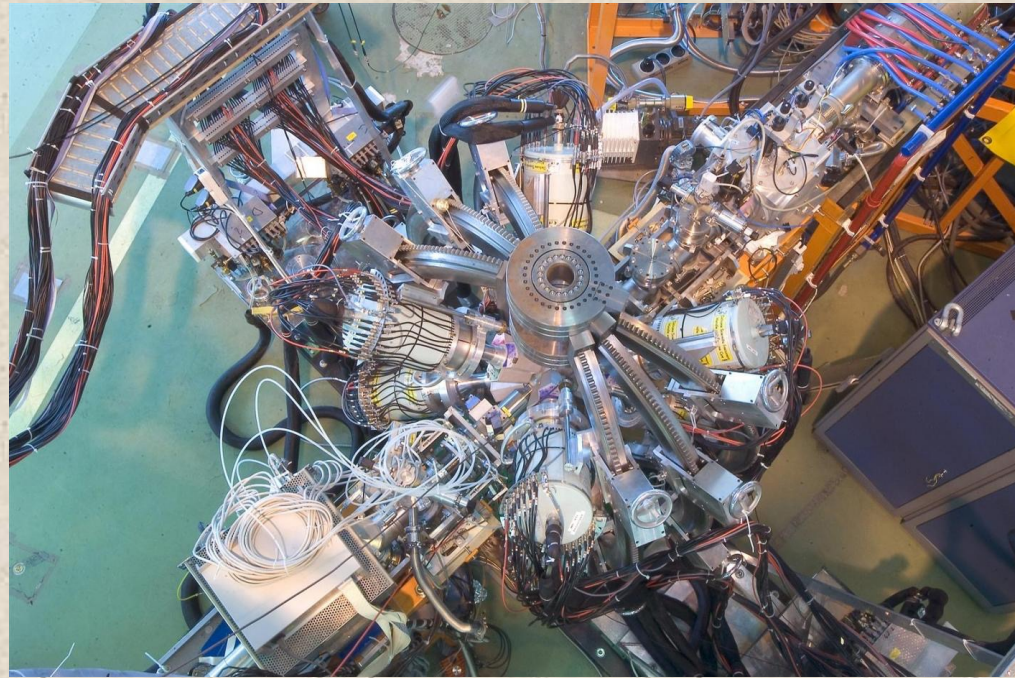
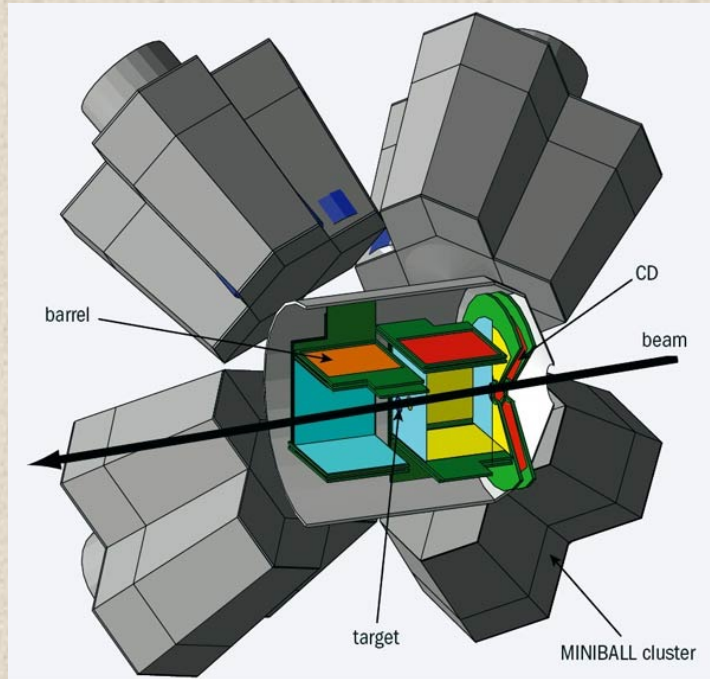


HIE-ISOLDE



HIE-ISOLDE has been upgraded along the years, today it can reach **5.5 MeV/u**, just the right energy for nuclear reactions(in general)

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



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

ISOLDE lei out as it appears in the NUPECC long range plan 2024



ISOLDE

VITO laser-polarised beams for nuclear physics, chemistry and biology

TAS-Lucretia total absorption spectrometer

HIE-ISOLDE post accelerator

Scattering Chamber
scattering and reactions

Solenoidal Spectrometer
transfer reactions

MINIBALL
γ-ray array

PUMA
Coming soon
RIB & antiprotons

IDS
decay station

ISOLTRAP
nuclear masses

WISArD
 $\beta\nu(\theta)$

mass
separators
HRS GPS

MEDICIS
medical isotopes
research

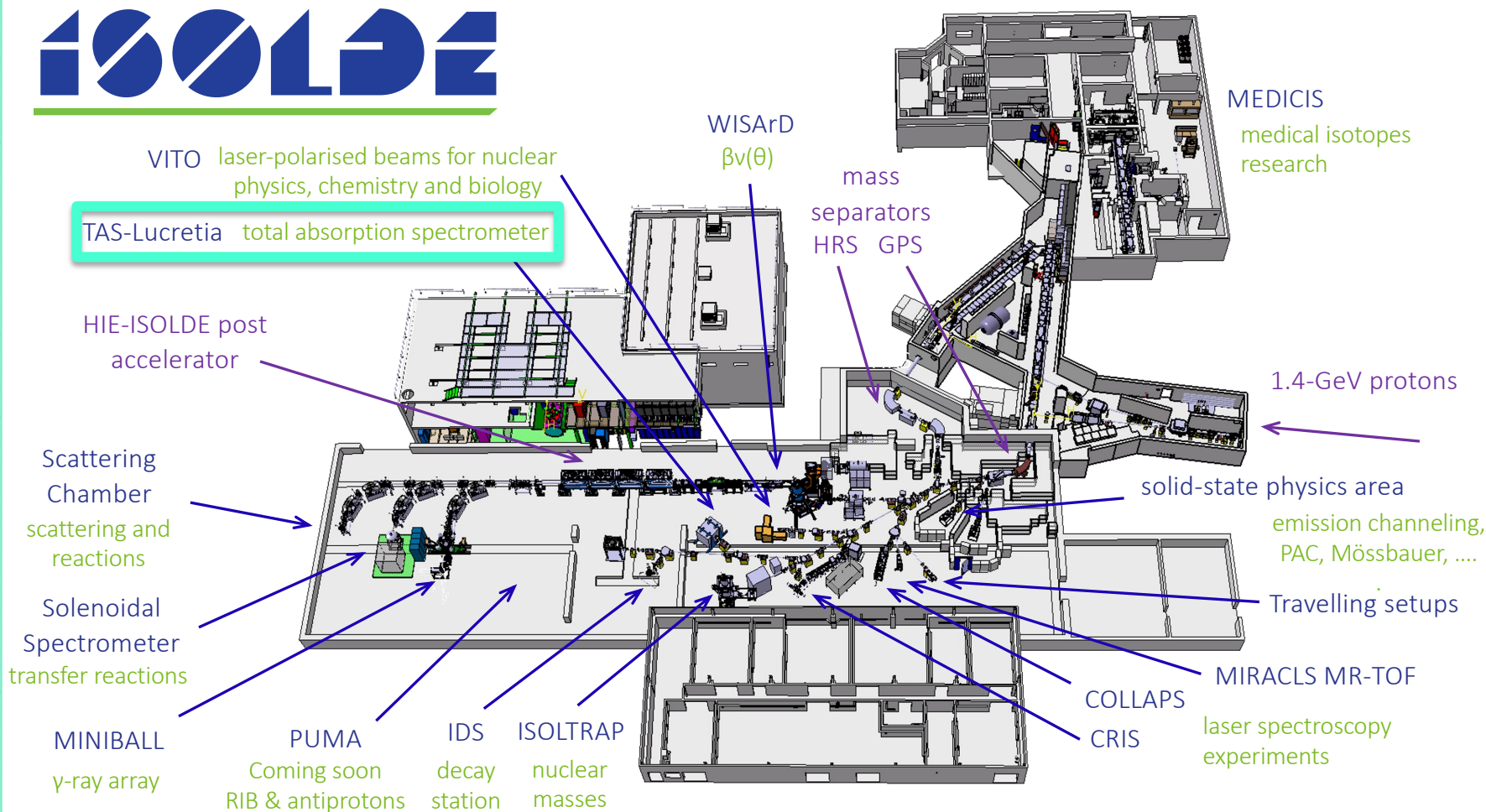
1.4-GeV protons

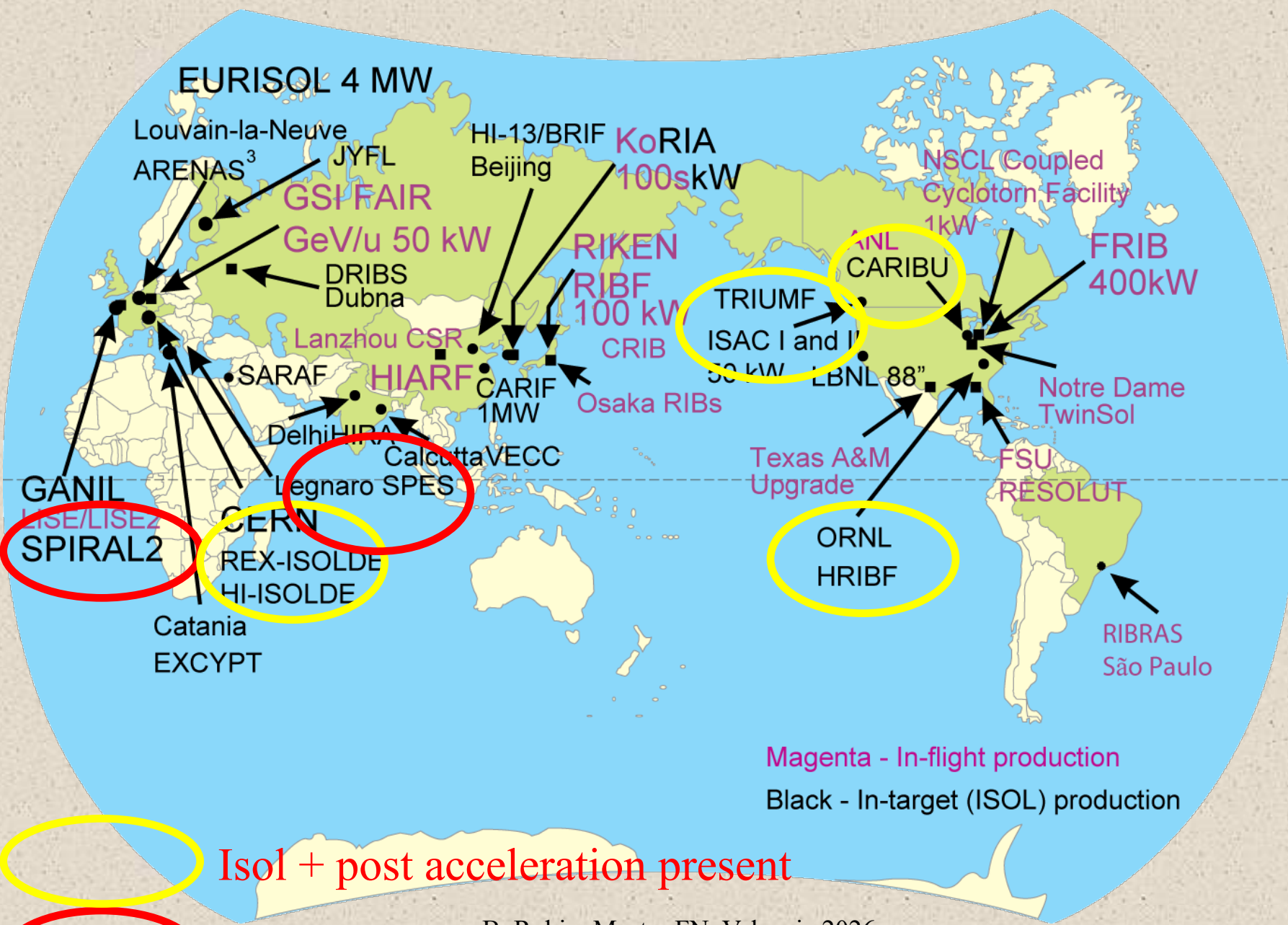
solid-state physics area
emission channeling,
PAC, Mössbauer,

Travelling setups

MIRACLS MR-TOF
laser spectroscopy
experiments

COLLAPS
CRIS





Isol + post acceleration present

Isol + post acceleration future

Future ISOL facilities

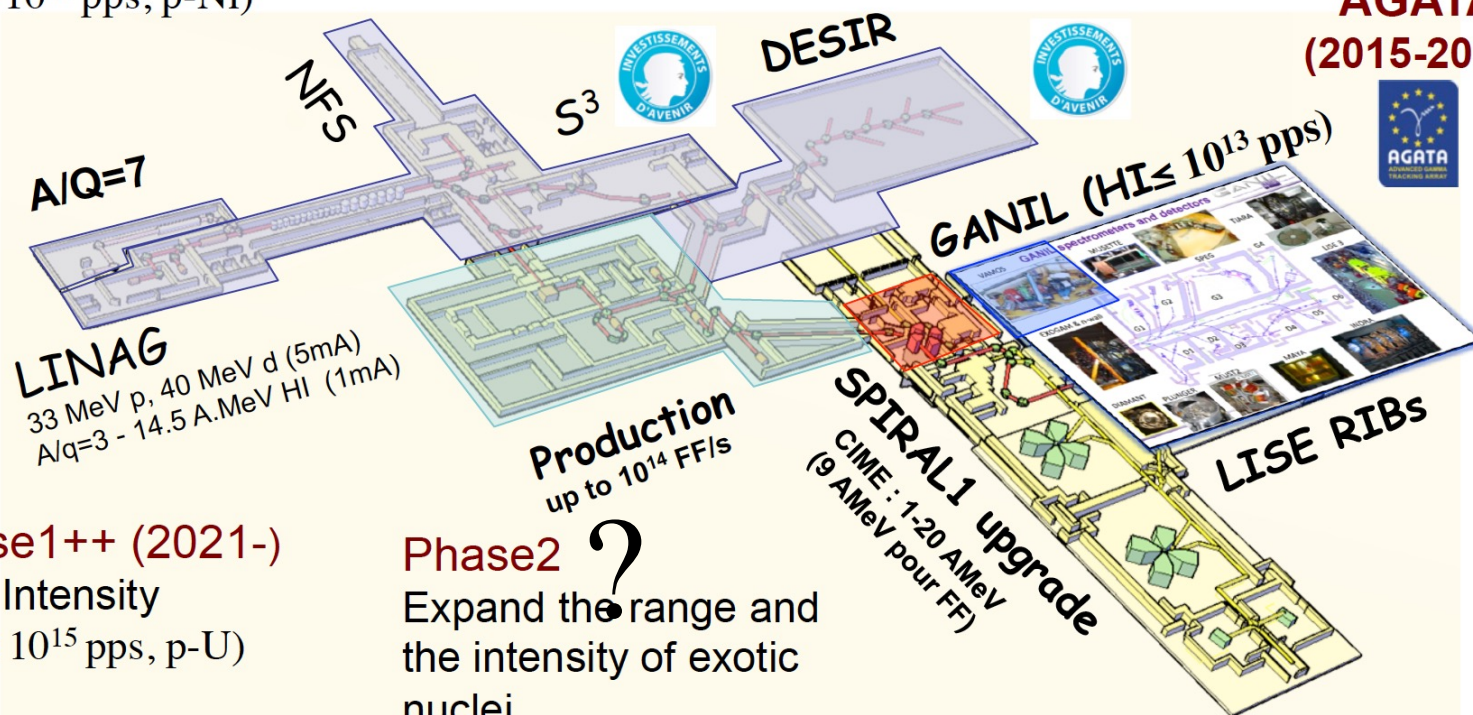
Phase1 (2016-)

Increase the intensity of stable beams
High intense neutron source
($HI \leq 10^{15}$ pps, p-Ni)

DESIR Phase1+ (2020-)

Low energy facility

AGATA (2015-2018)



Phase1++ (2021-)

High Intensity
($HI \leq 10^{15}$ pps, p-U)

Phase2 ?

Expand the range and
the intensity of exotic
nuclei

SPIRAL1 Upgrade (2017-)

New light RIBs from
beam/target fragmentation

Unfortunately, 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



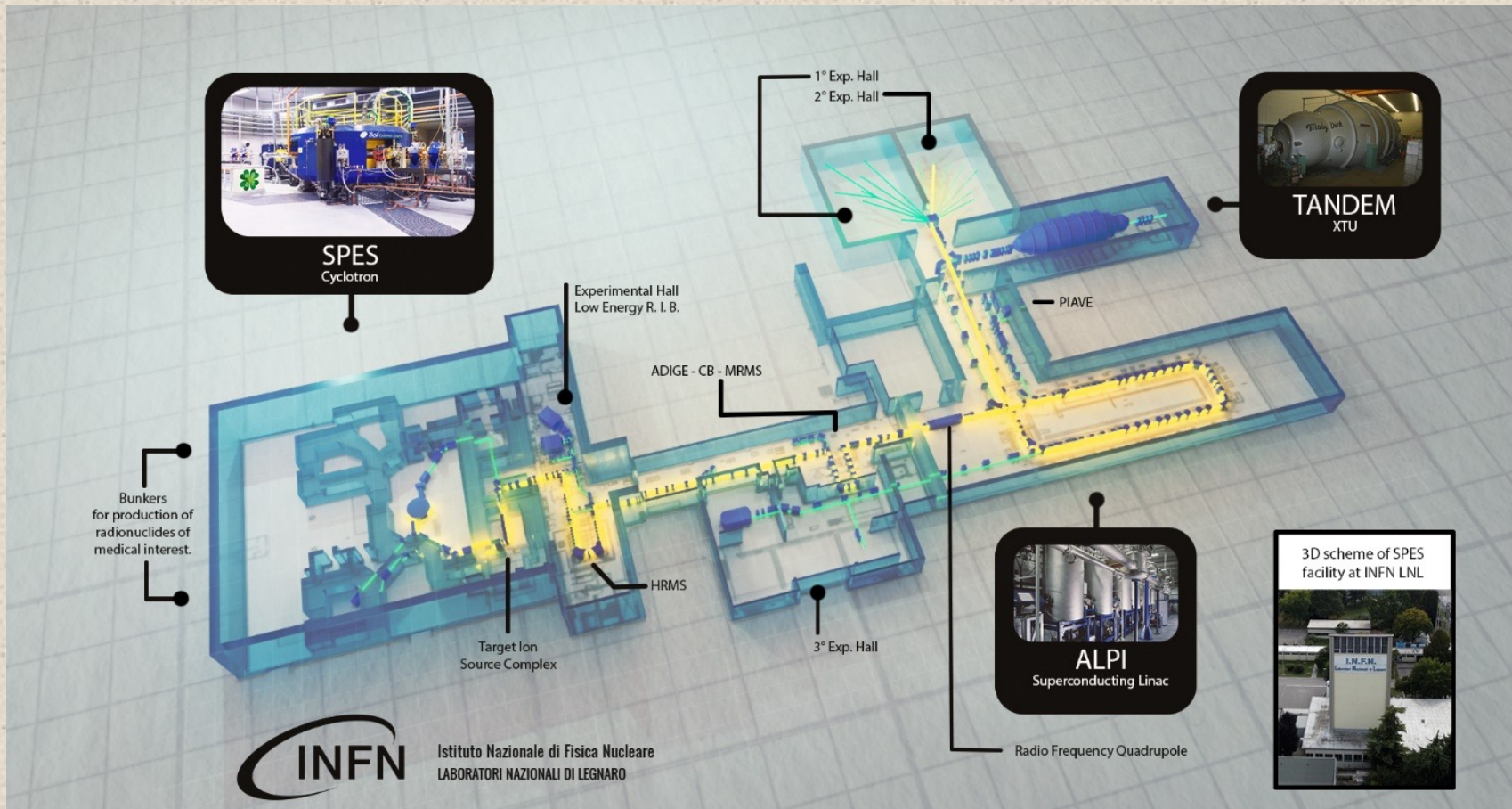
SPES

Selective Production of Exotic Species

Under construction

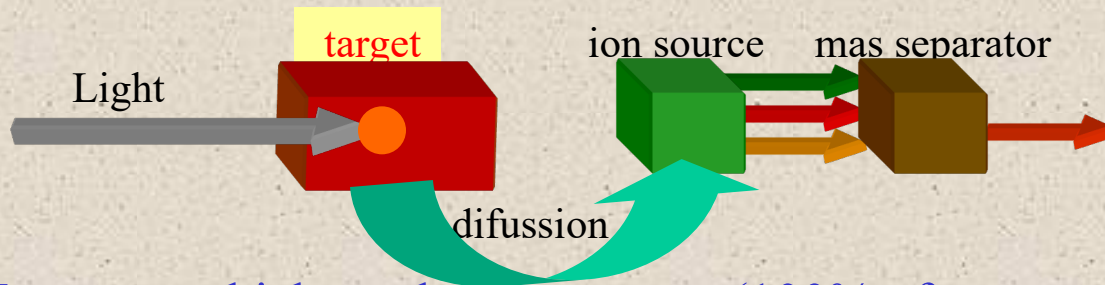


SPES Project



Radioactive nuclei production techniques

Isotopic separation on-line (ISOL)



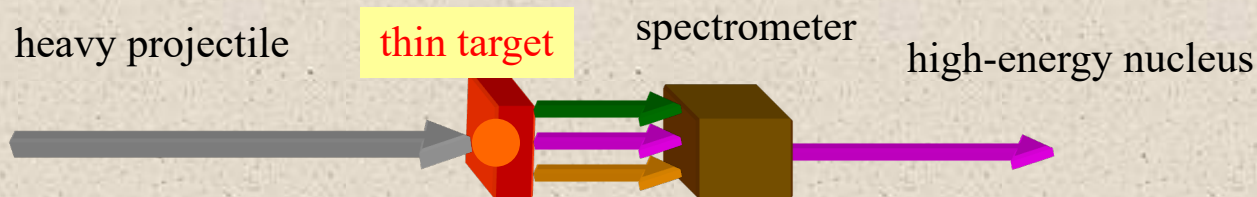
😊😊 We can use thick production targets (100% of energy range) => and high injector beam current (upto 10^{16} s^{-1})

😊 Post accelerated beams of high quality

😞 long extraction and ionization time (100 ms)

😞 chemistry dependent

In-flight fragmentation



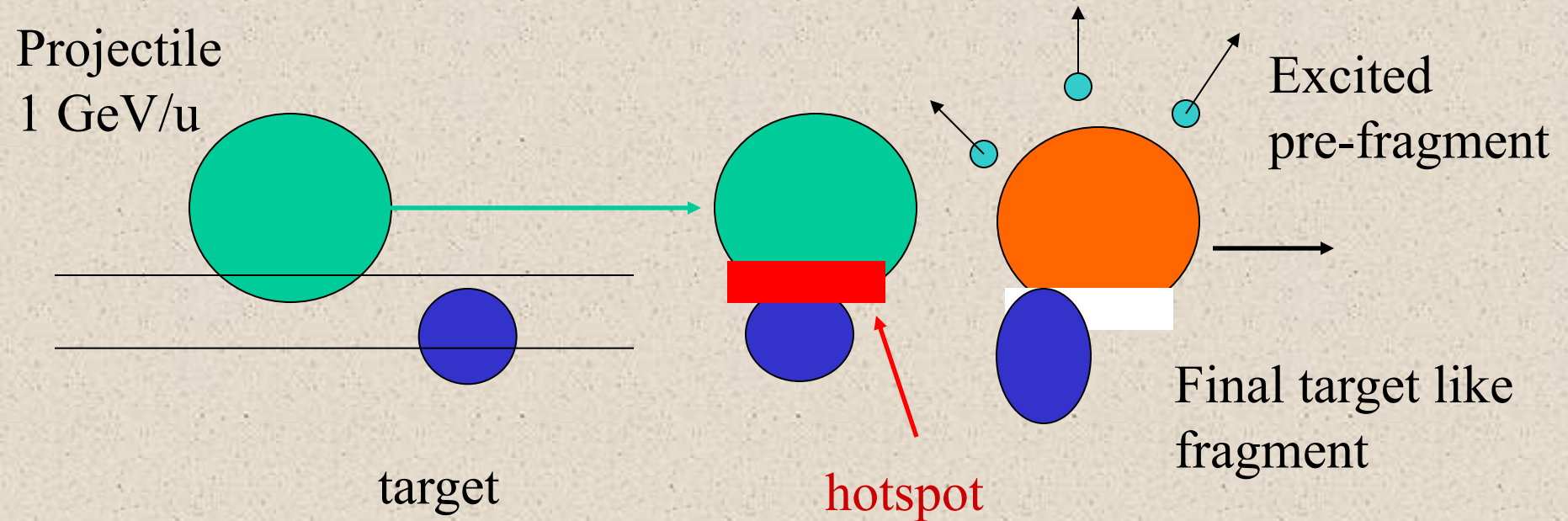
😞 thinner targets (10% of range) => lower beam currents (upto 10^{12} s^{-1})

😊 short separation+identification time (100 ns)

😊 chemistry independent

😊 relativistic energies (but poor energy definition)

Projectile Fragmentation Reactions

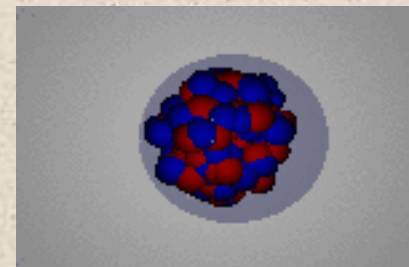
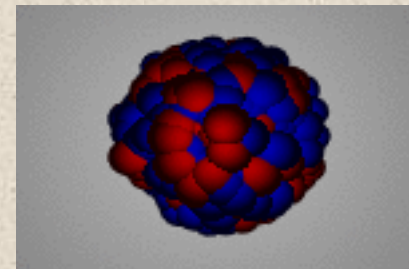
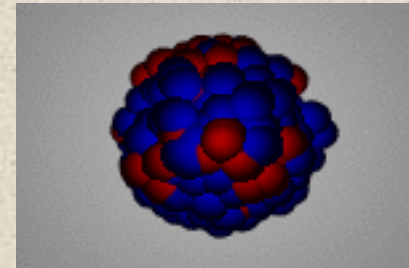
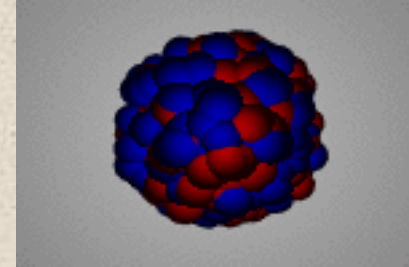
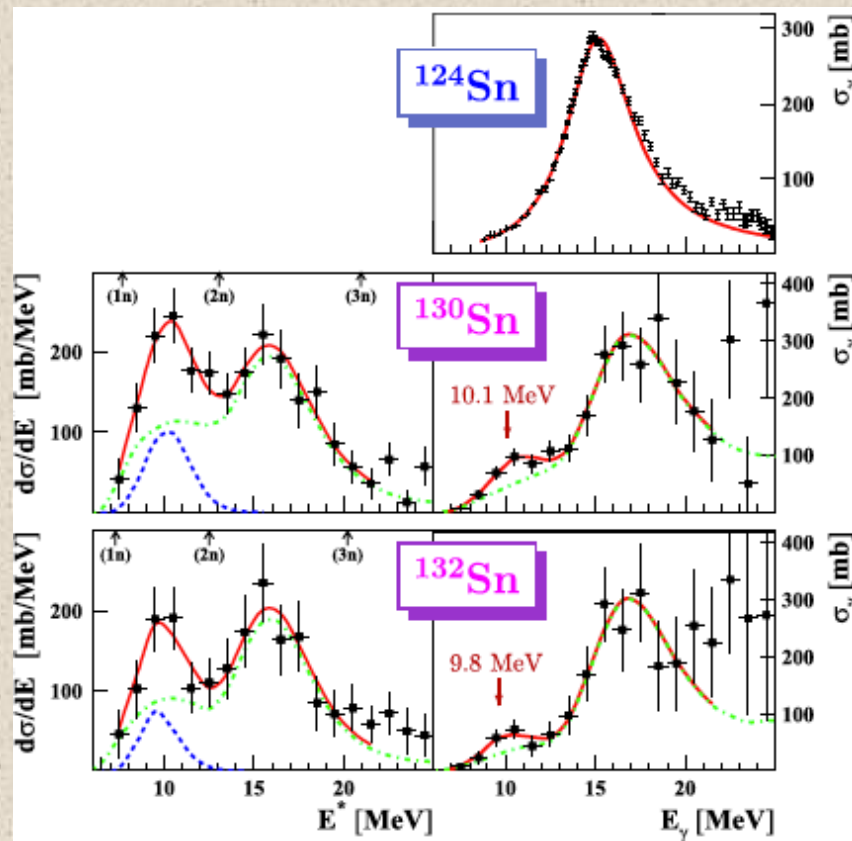


1 GeV/u energy (velocity) of beam > Fermi velocity inside nucleus ~ 30 MeV/u

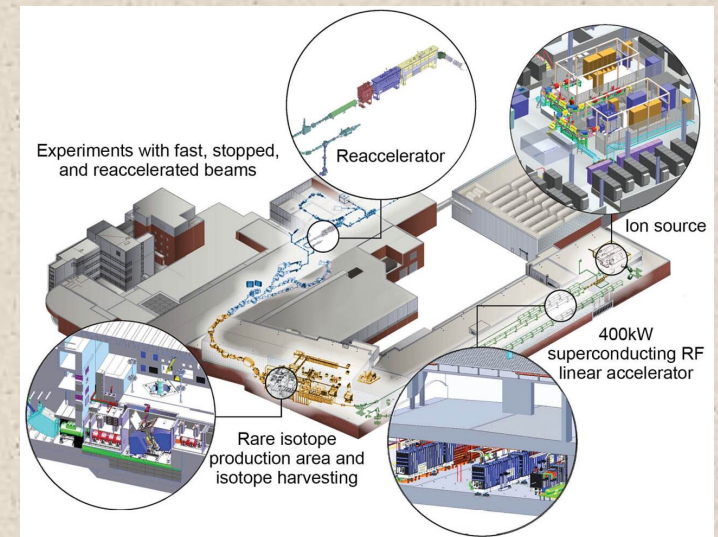
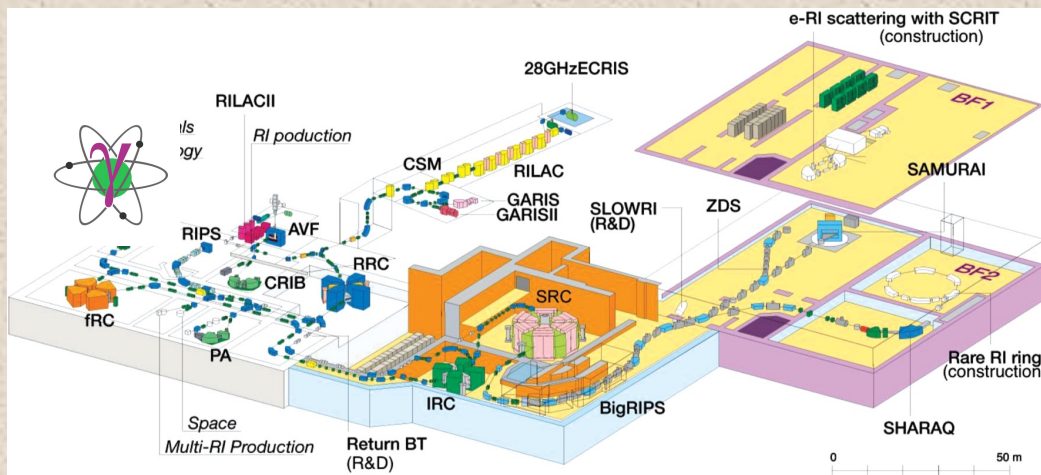
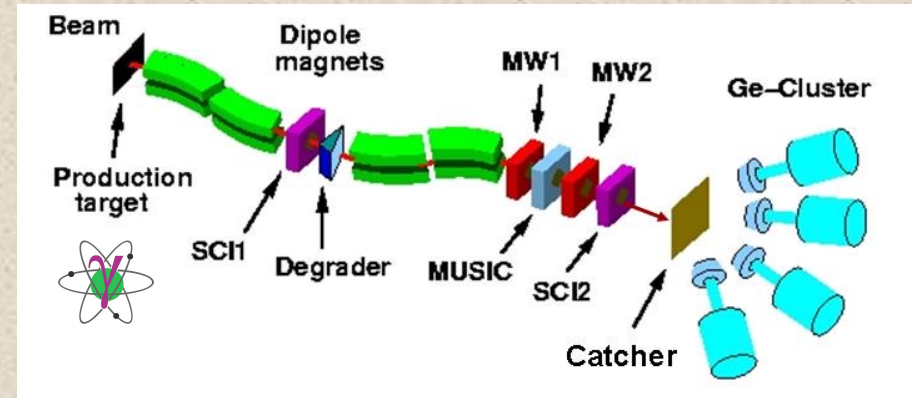
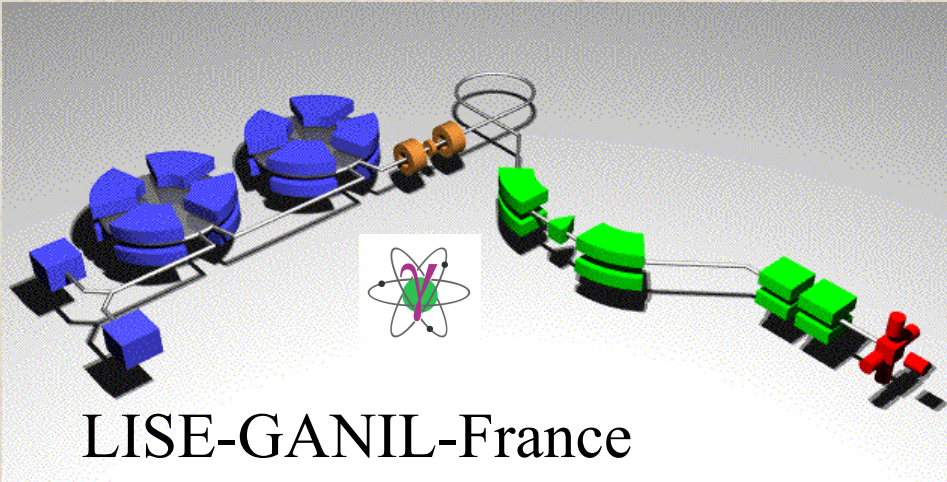
Can 'shear off' different combinations of protons and neutrons.

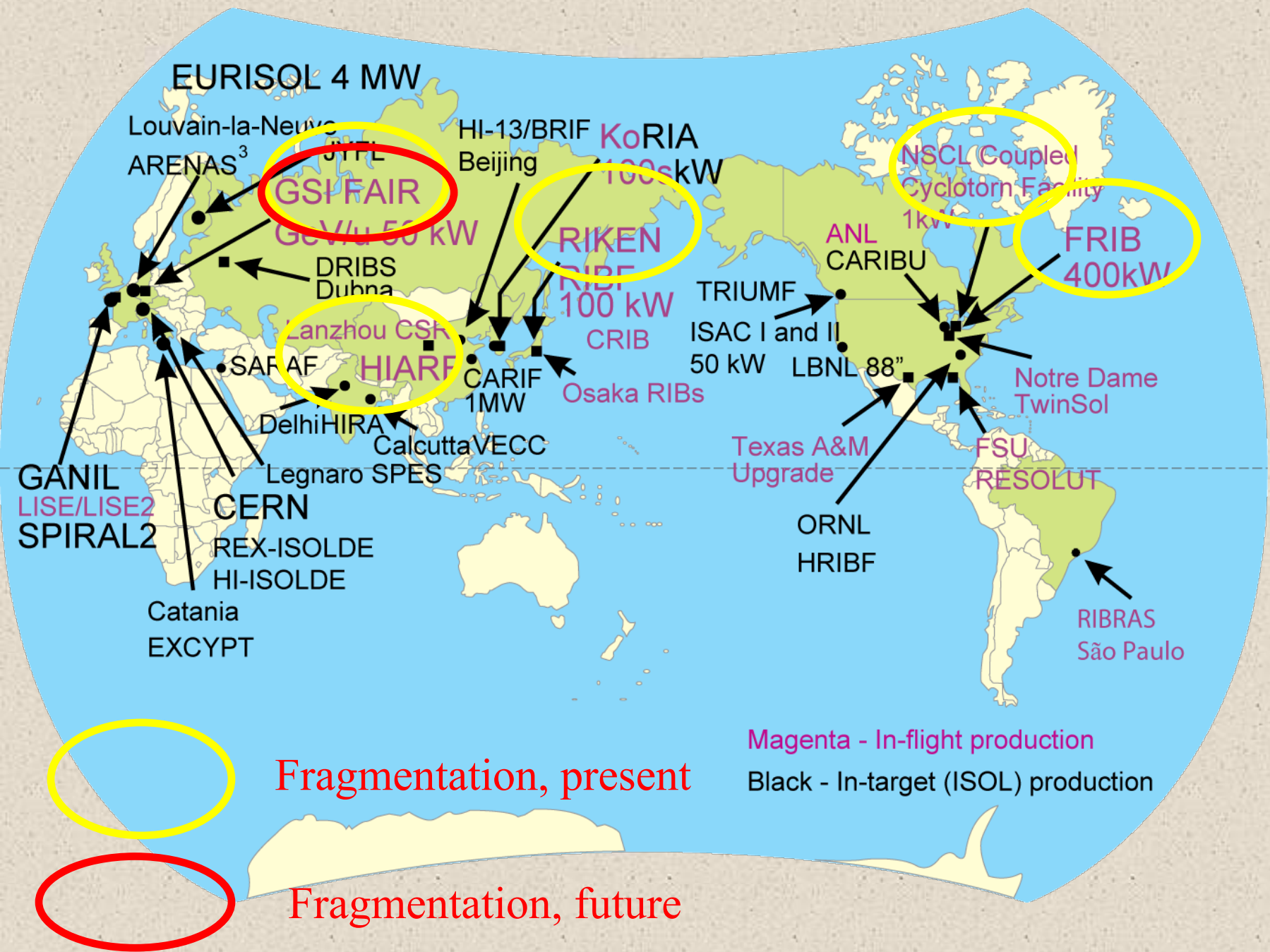
Large variety of exotic nuclear species created, all at forward angles with $\sim$ beam velocity.

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

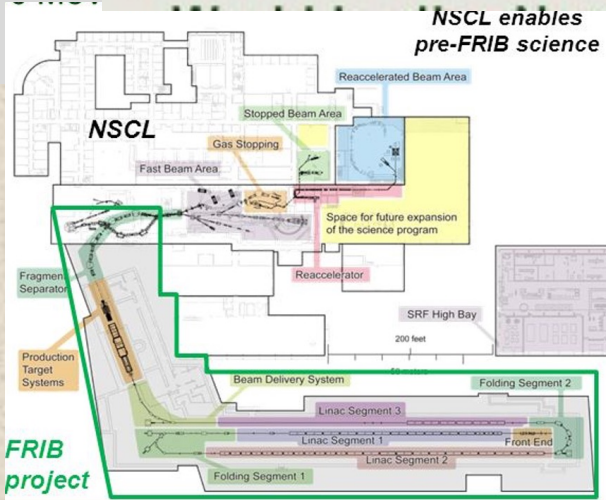


Actual Fragment Separators

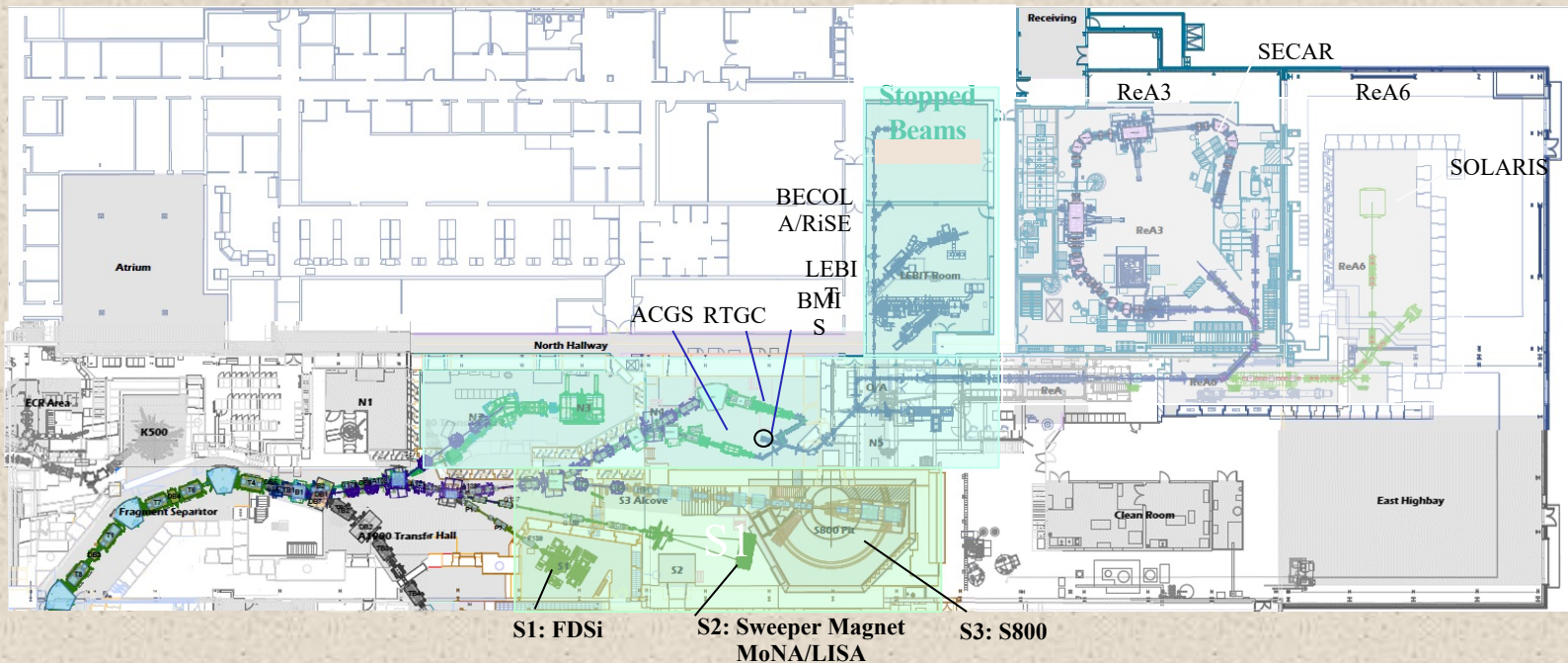




FRIB - Facility for Rare Isotope Beams



400 kW, 200 MeV/u
Uranium
Operative since 2022



The FRS fragment separator at GSI



Hans Geissel
1950-2024

$B\rho$ - ΔE - $B\rho$ Separation Method

Thin target

Primary beam

69 m

170 mm

Experimental Area

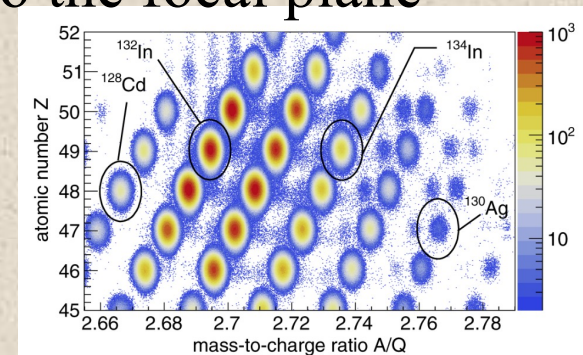
$B\rho$

Degrader, ΔE

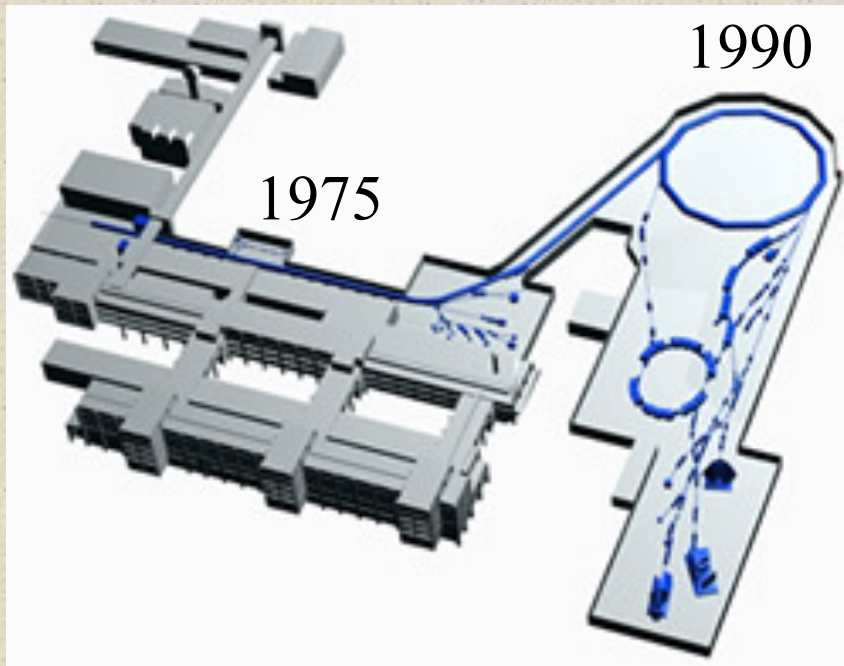
Different ions lose
A different amount
of energy

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

Cocktail of ions arriving
to the focal plane



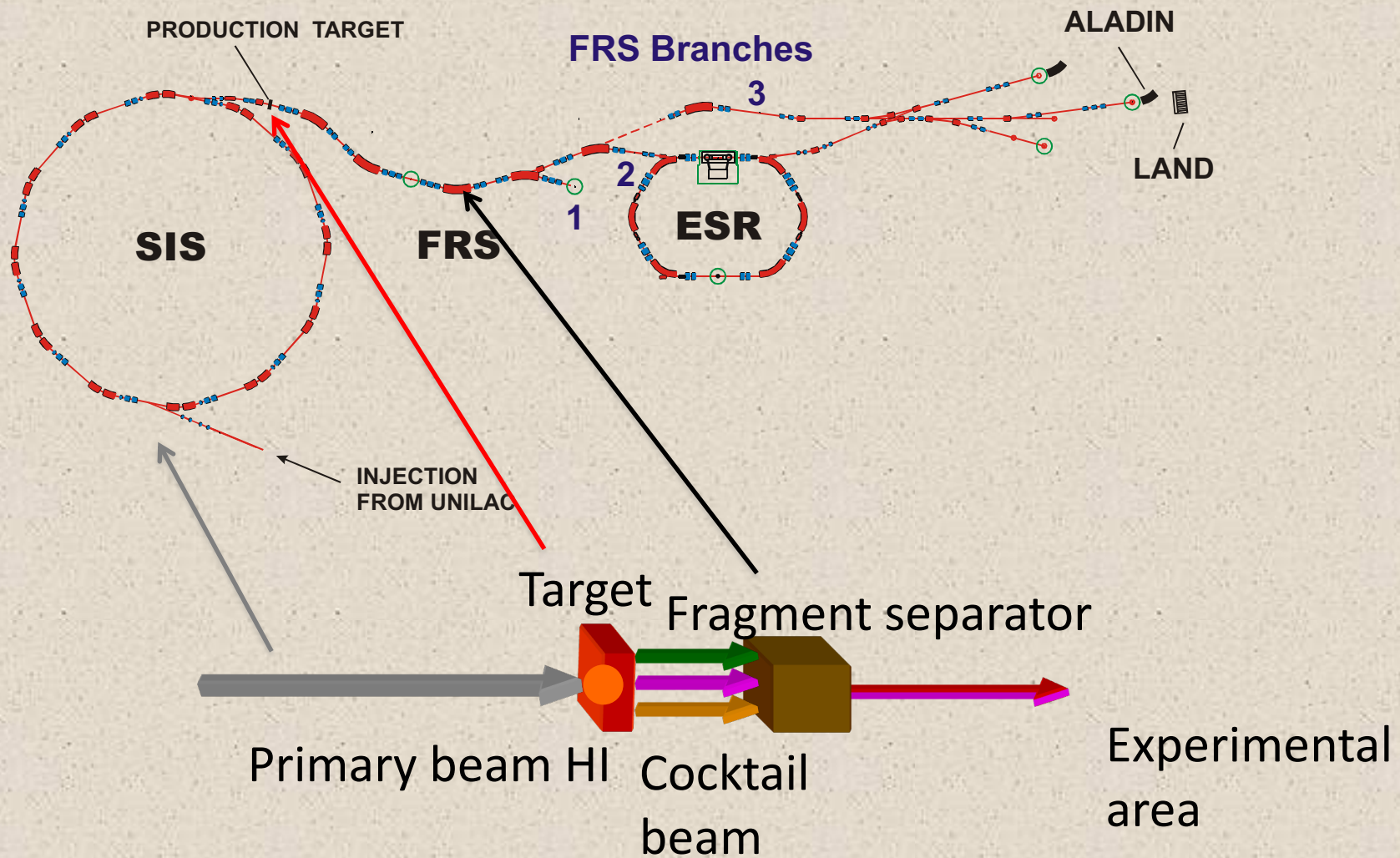
The GSI fragmentation facility



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**





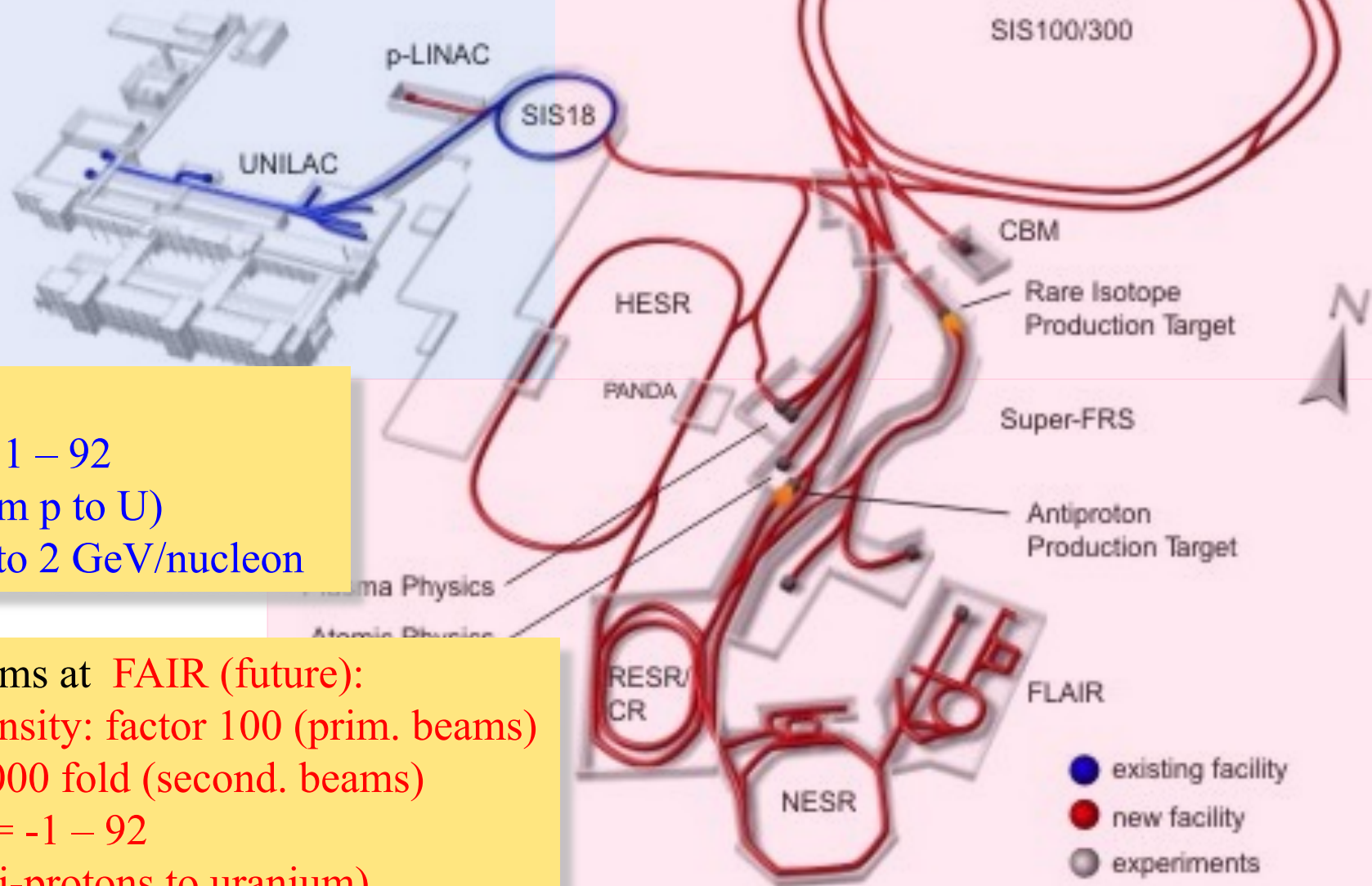
Very near Future



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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

B ρ - Δ E-B ρ Separation Method

FRS

69 m

170 mm

Degradar

Super-FRS

Degradar 2

380 mm

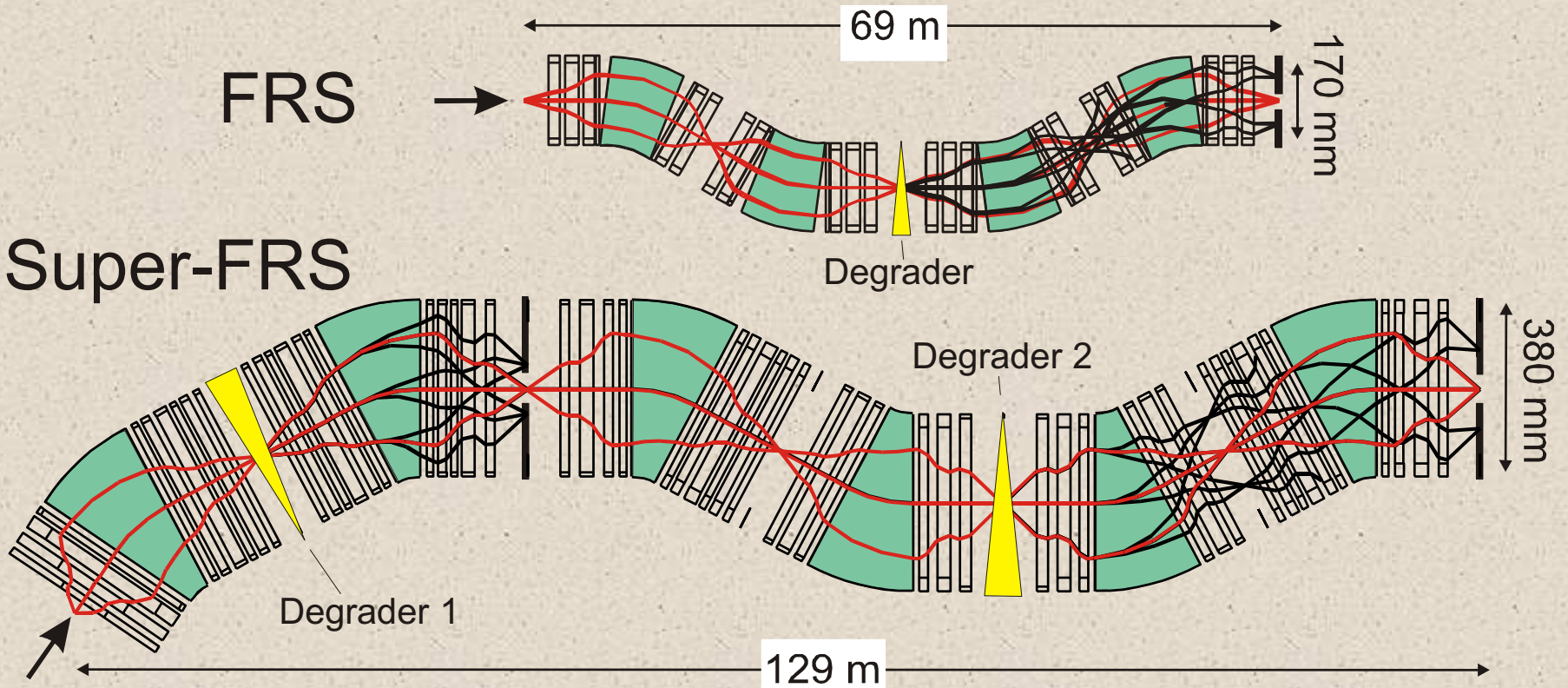
Degradar 1

129 m

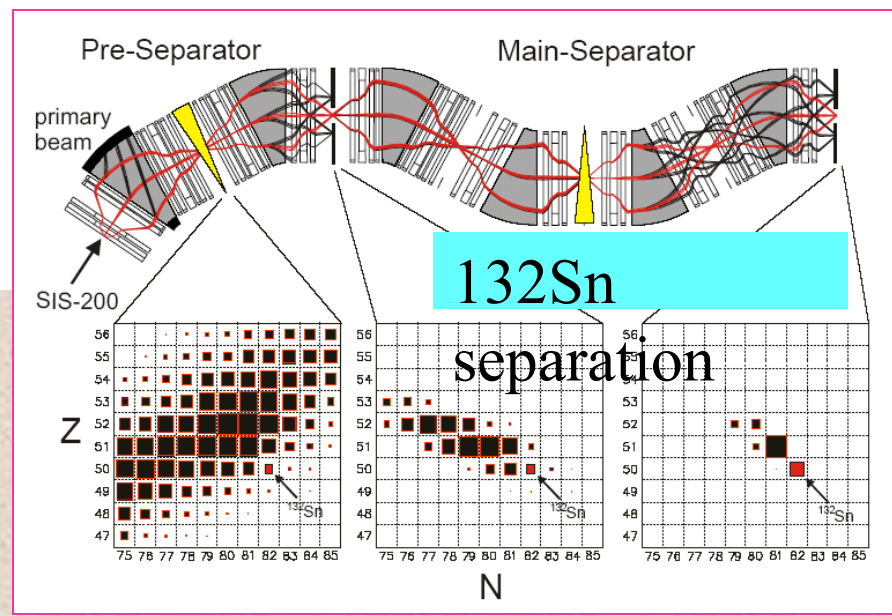
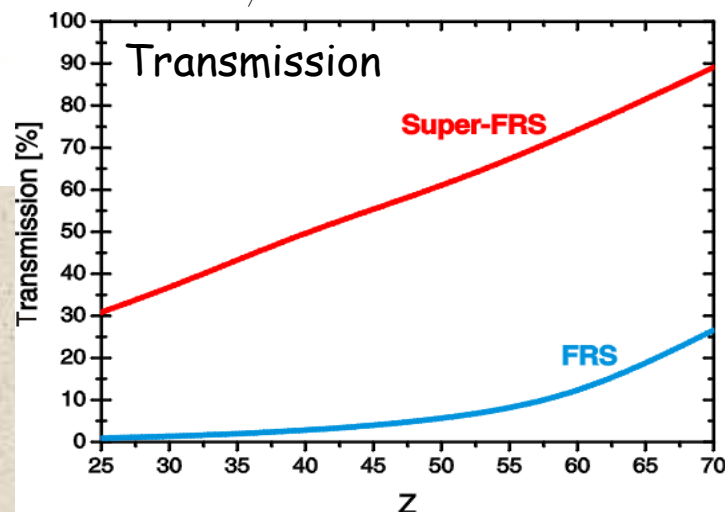
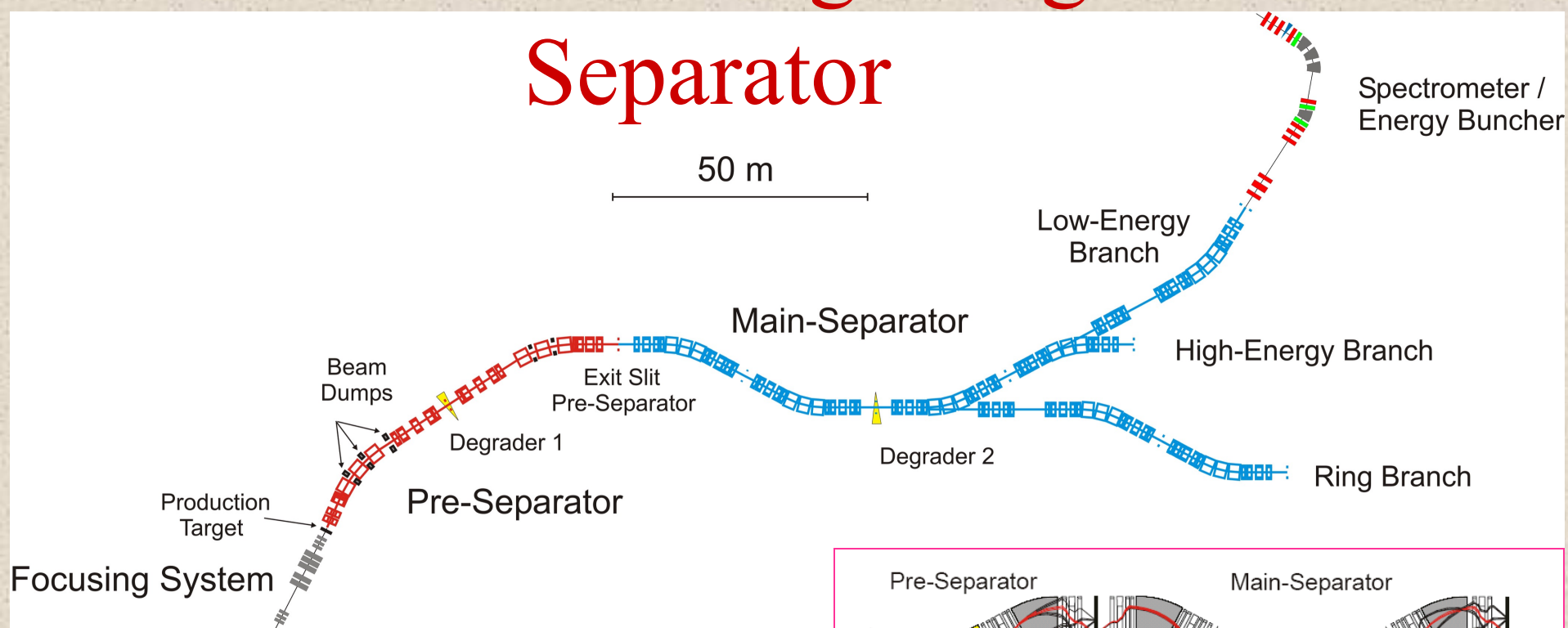
Optimised to separate
very fast fragment or
fission products

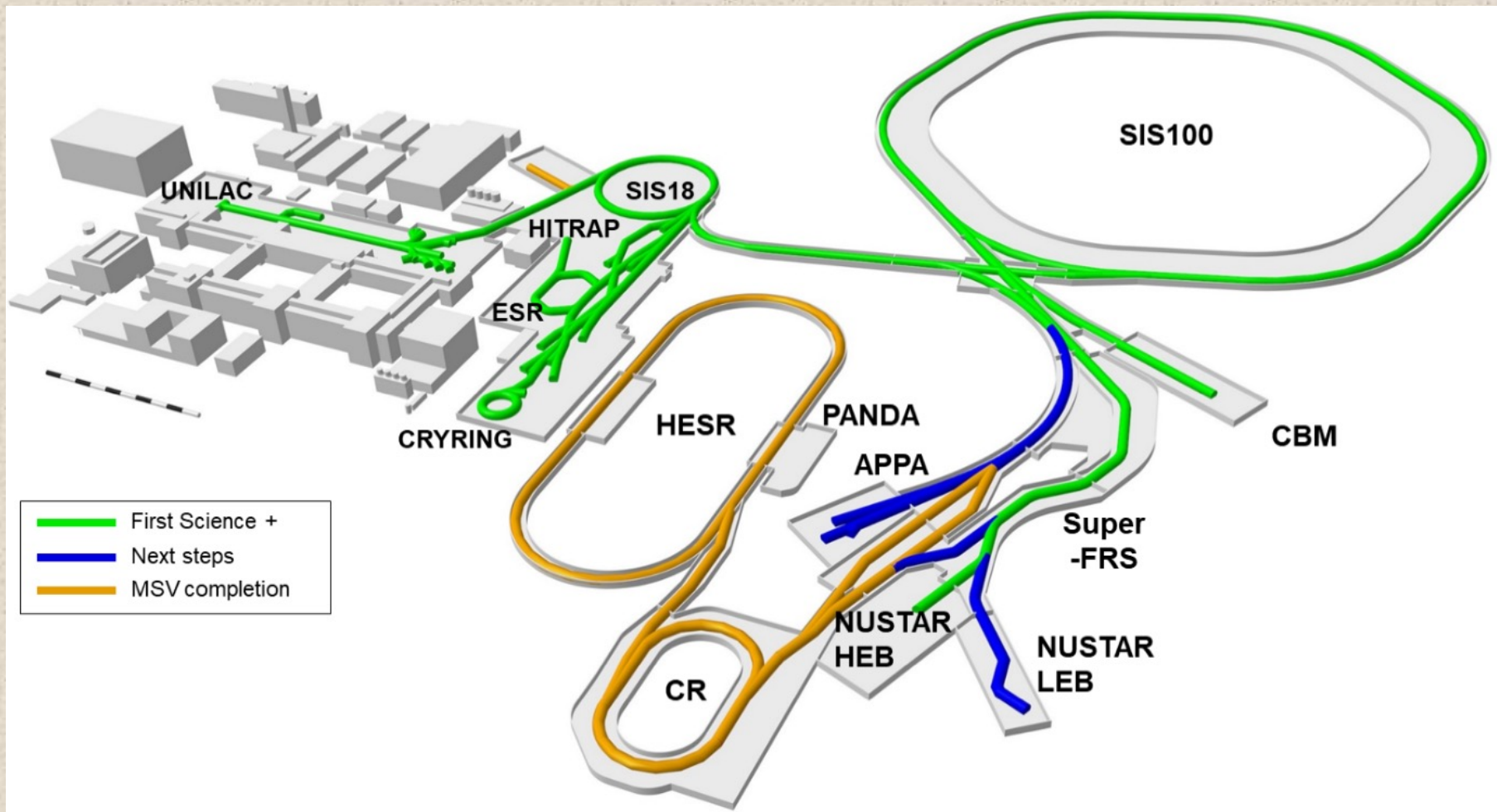
H. Geissel et al. NIM B 204 (2003) 71

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SUPERconducting FRagment Separator





FAIR Construction Field



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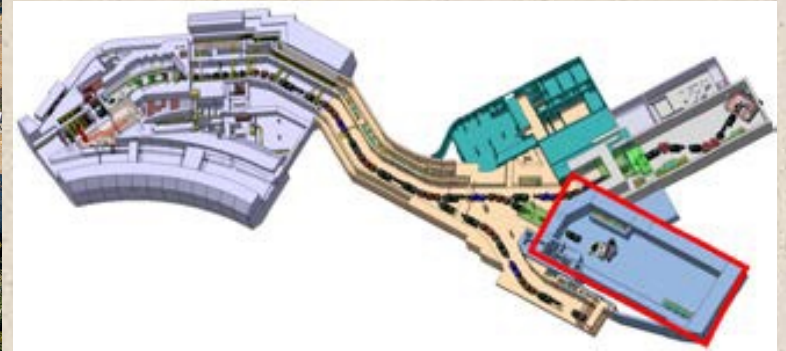


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B. Rubio.
Master FN.



Recommendation, to visualise the construction, have a look at this video:
<https://www.youtube.com/watch?v=wTCkZdeqI8I>

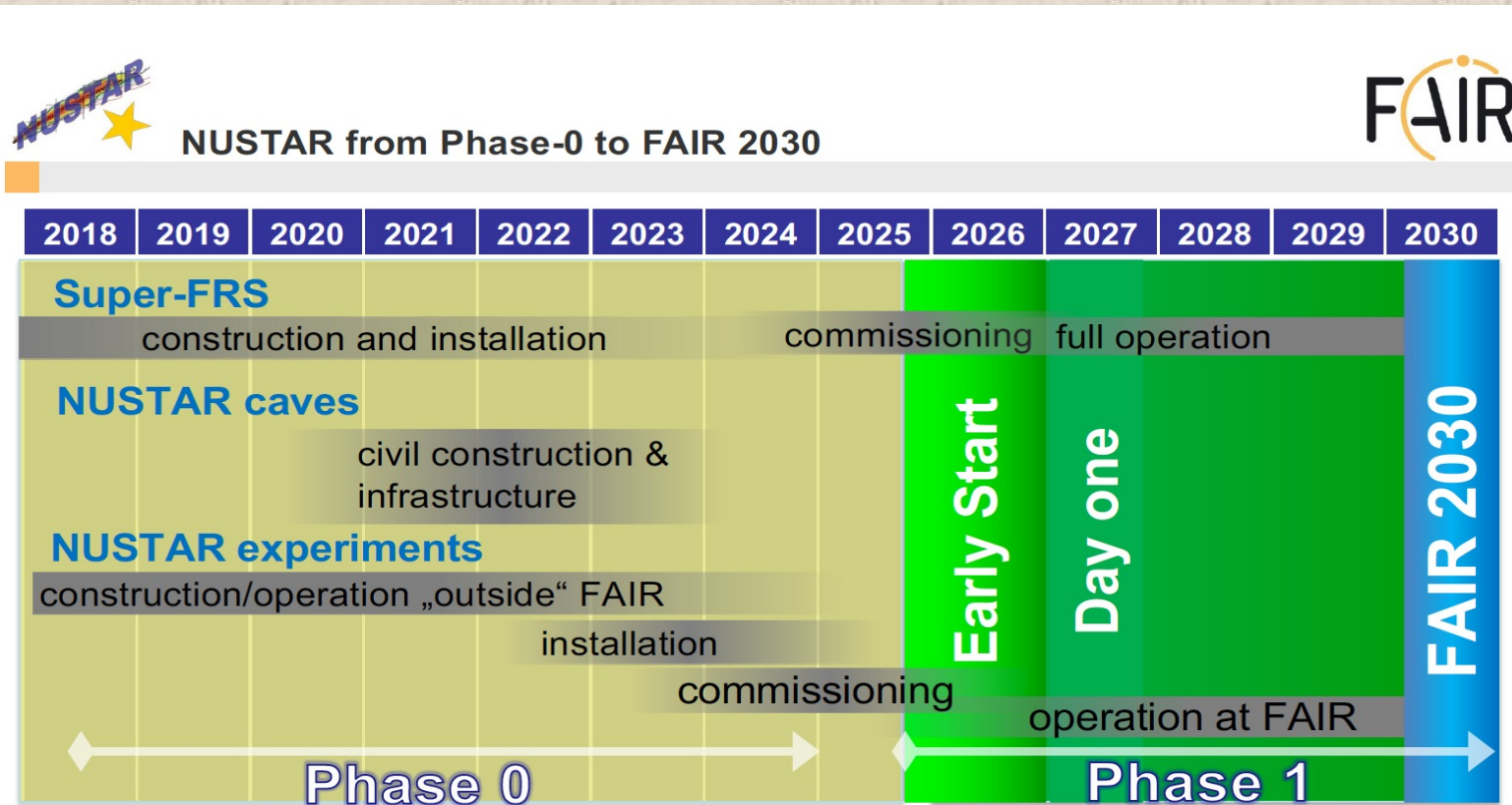


The high Energy Cave 2023

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



FAIR - NUSTAR schedule



ISOL and In-Flight facilities-Partners

Depending on the physics you want to achieve,
you will choose on or the other: 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

New oportunities are just coming up!!!

FIN



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