Production of Radionuclides Using Deuterons or Alpha Particles

Arnaud Guertin et al. on behalf of PRISMA and GIP ARRONAX teams

Subatech

PRISMA
Physics of Radiation InteractionS with Matter and Applications

ARRONAX

21-25 Sept. 2026
Bussang
France

Production of Radionuclides Using Deuterons or Alpha Particles for Medical Applications

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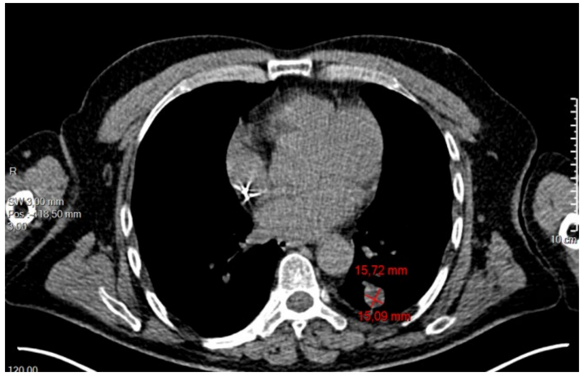
Conventional imaging

Visualize and localize tumors, measure them and evaluate the response to treatments

Centre François Baclesse

Radiography



Centre René Gauducheau

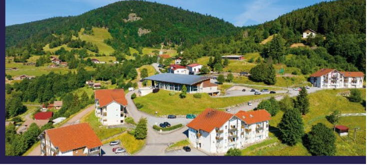
Computed Tomography Scanner

Institut Roi Albert II

Magnetic Resonance Imaging

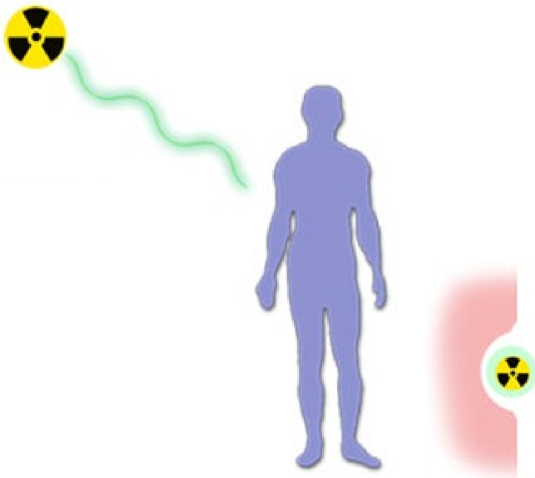
These techniques allow to get accurate information on the morphology but give limited information on the metabolism

A gain can be obtain by coupling them with nuclear medicine technique (SPECT or PET) which gives these information

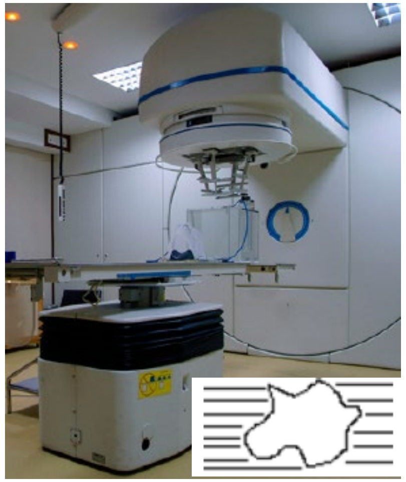


Conventional therapy

External beam radiotherapy:
- X rays, gamma, electrons
- Hadrontherapy



Brachytherapy
“Curietherapy”



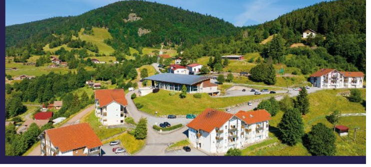
Institut de cancérologie de l’Ouest

ProteusOne, IBA

Institut de cancérologie de l’Ouest

These techniques are very efficient to treat a localized disease but does not target disseminated or residual disease

This can be address by nuclear medicine techniques (Targeted Radiotherapy)

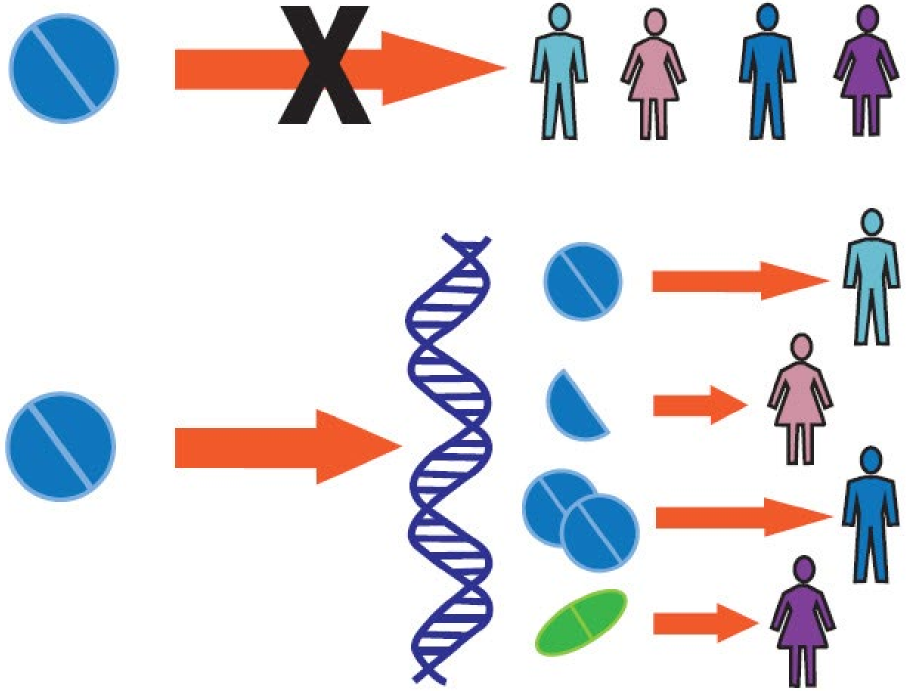


Personalized nuclear medicine

Imaging and diagnosis

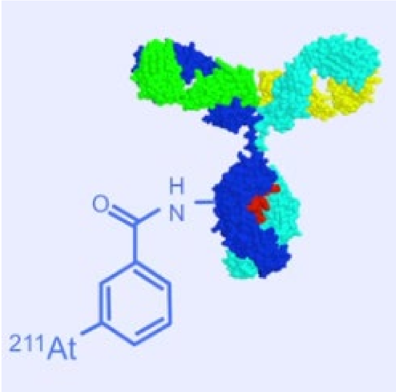
Choose the best treatment

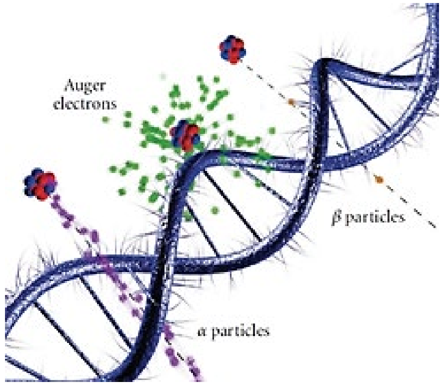
Evaluate its efficacy



Therapy

Destroy tumor cells

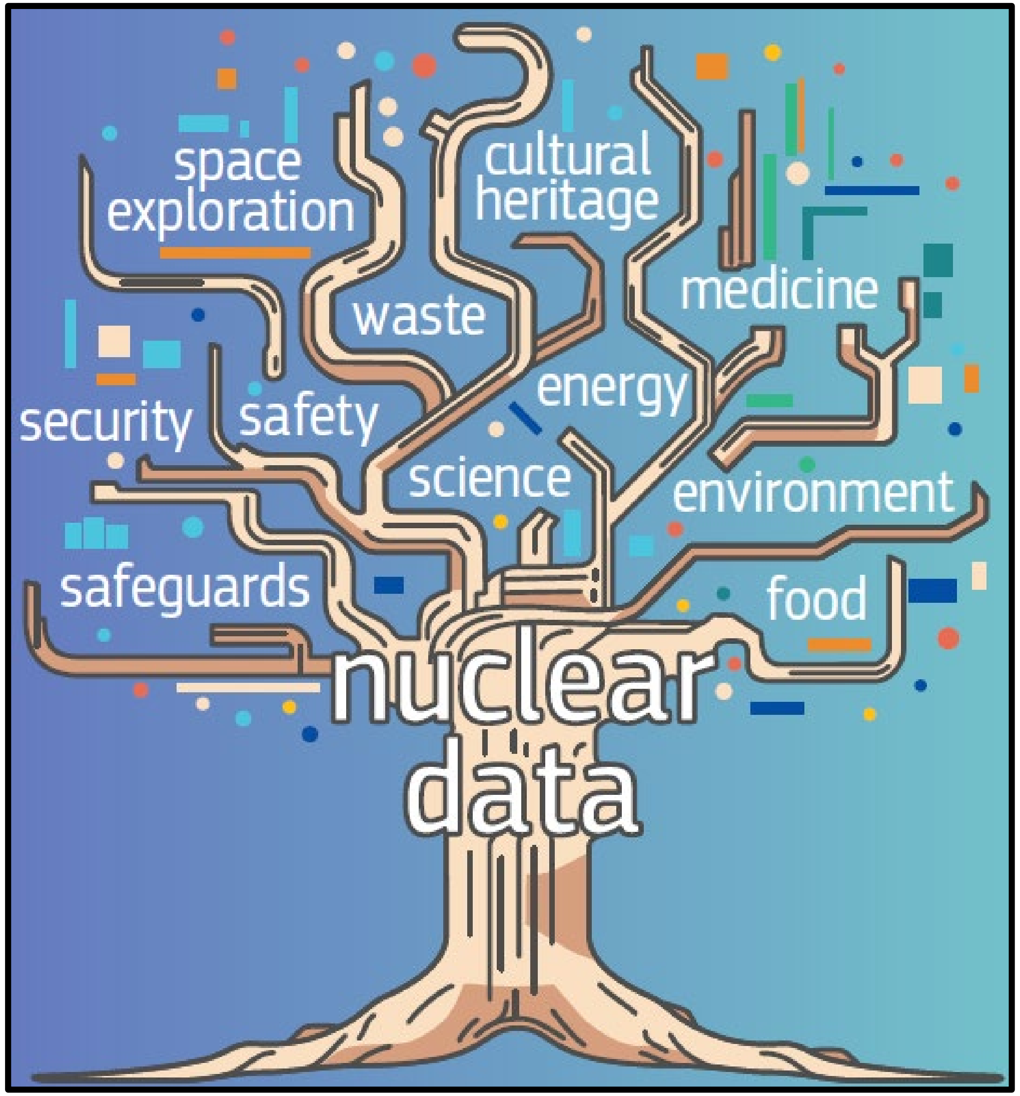




The Right Drug **To The Right Patient** **For The Right Disease**
At The Right Time **With The Right Dosage**

Adapted from F. Haddad

Nuclear data: cross section measurements

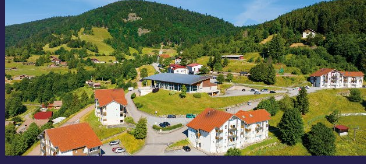


Requirements:

- **Accurate and reliable** data sets
- **Well-defined production pathways** and **decay properties**
- **Optimal production** of specific radionuclides, minimisation/elimination of **impurities, realistic dose** calculations
- Provide **a broad set of nuclear data** in terms of targets, projectiles and energy range in order **to constrain** and **develop** predictive **simulation tools** for nuclear reactions.

Outcomes:

- **Impact on production**
- **Impact on modeling nuclear reactions**



Where medical isotopes are coming from?

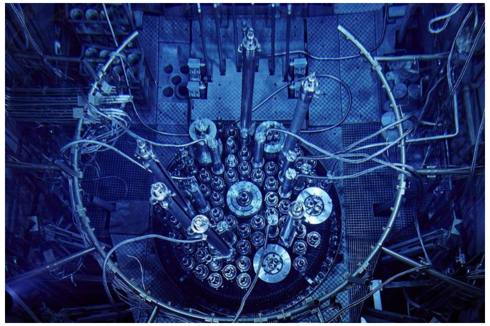
Few directly available in nature, belonging to radioactive chain of heavy nuclei

- **Ra-233**: belongs to the radioactive chain of U-235
  Xofigo ($RaCl_2$) available for bone metastases
- **Pb-212/Bi-212**: belongs to thee radioactive chain of ^{232}Th
  2 clinical trials ongoing for NeuroEndocrineTumors (clinical.org)
- **Ac-225** : belongs to the radioactive chain of U-233

Most of them are produced artifically

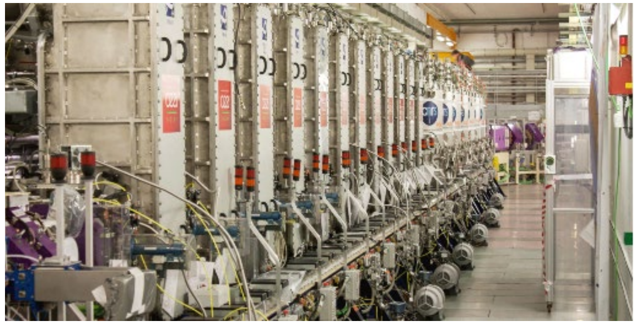
Many of them using neutron induced reactions in **nuclear reactors**

Quick progress and achievements using charged particle induced reactions in **accelerators** like **cyclotrons** and **linacs**



BR2 reactor @ SCK•CEN

C70XP @ ARRONAX



SPIRAL 2 @ GANIL

Facilities

Reactors:

- variable energy [0 up to ~ 100 MeV]
- flux [0 up to 10^{15} n/cm^2.s]
  - ✓ BR2 SCK•CEN, Belgium
  - ✓ ILL Grenoble, France

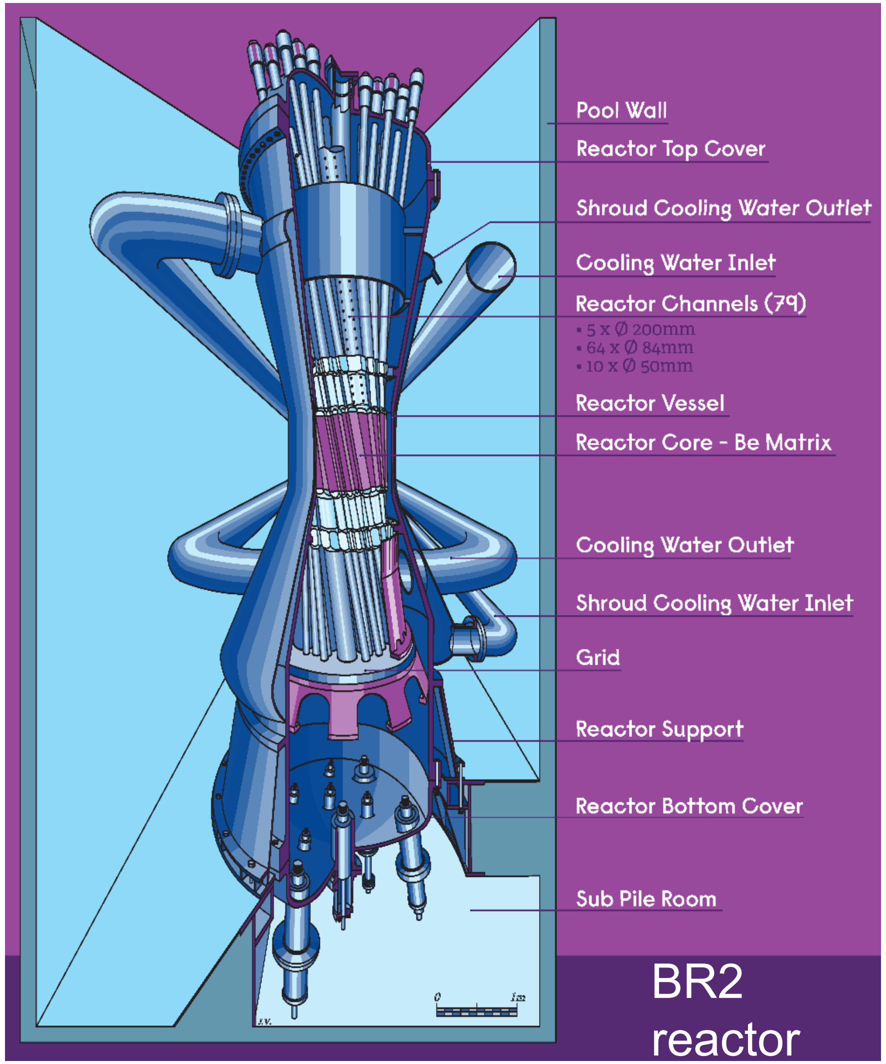
▪ Single neutron capture (n,γ):
most common route, Lu-177, Re-186, Ho-166 …

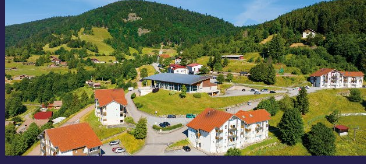
▪ Double neutron capture (2n,2γ):
W-188/Re-188

▪ Inelastic reactions (n,n'γ):
Sn-117m

▪ Exchange reaction (n,p):
Cu-67

▪ Fission reaction (n,f):
Mo-99/Tc-99m, I-131, Xe-133 …





Facilities

Cyclotrons:

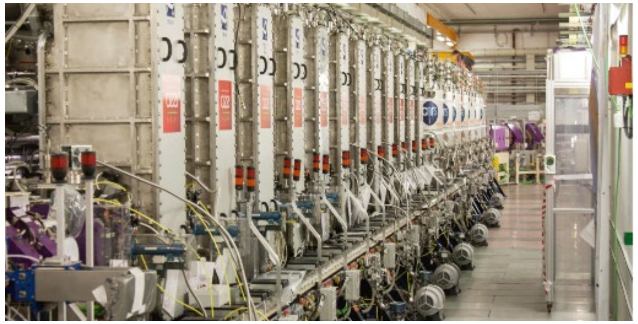
- Fixed energy [0 up to ~ 100 MeV]
- Low intensity [0 up to ~ 50 µA]
  - ✓ Cyclone 30XP IBA
    Polatom - CERAD, Poland – FZ Jülich, Germany
  - ✓ Cyclone 70XP IBA
    GIP ARRONAX, France

C70XP @ GIP ARRONAX

Extracted	Energy (MeV)	Max. current (µA)
H^+	30 – 70	2 x 375
D^+	15 – 35	2 x 50
He^{2+}	68	70
HH^+	17	50

LINACS:

- Variable energy [0 up to ~ 20 MeV/A]
- High intensity [0 up to ~ mA*]
  - ✓ ATLAS
    Argonne National Laboratory, USA
  - ✓ SPIRAL 2
    GIE GANIL, France



SPIRAL 2 @ GIE GANIL

Beam	P+	D+	Ions	Ions
A/Q	1	2	< 3	< 6 or 7
Imax (mA)	5	5	1	1
Emin (MeV/A)	2	2	2	2
Emax (MeV/A)	33	20	14.5	8
Max. power (kW)	165	200	44	48

*High LET and “thin targets” [~ tens of µm up to ~ hundreds of µm], ! thermal load

There is not one fit all accelerator

C-11, N-13,
O-15, F-18,
Cu-64

11 MeV

Ga-67, In-111, I-123,
Tl-201, Ge-68

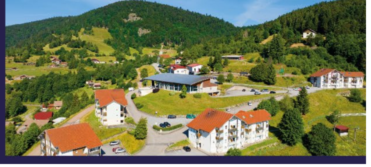
30 MeV

Sr-82, Sn-117m ...

70 MeV

Linear Accelerator
160 MeV

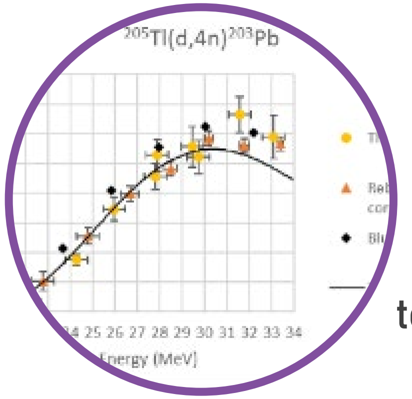
Sr-82, Sn-117m, Ac-225 ...



PRISMA @ Subatech lab

26 people including students

Isotopes for therapy and diagnosis



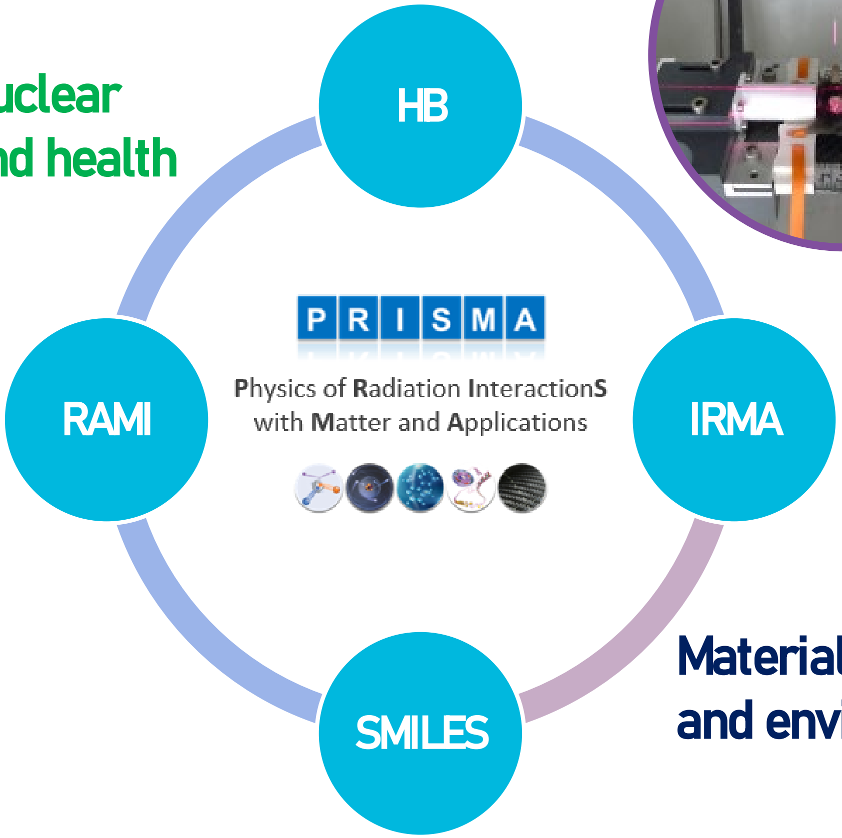
Which isotopes for tomorrow's nuclear medicine?

Cross section measurements

Mass separation

Nuclear and health

Hadronbiology at very high dose rates



Detection, ion beam analysis

Materials and environment

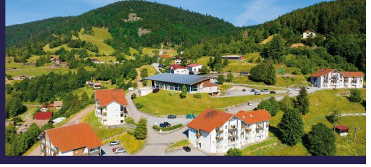
Mass separation coupled with laser ionisation

Flash radiotherapy

Radiolysis

Detector testing

Archeometry



GIP ARRONAX

Accelerator for **R**esearch in **R**adiochemistry and **O**ncology at **N**antes **A**tlanti**X**

3 main fields of investigations:

Radionuclides and **radiopharmaceuticals production** for nuclear medicine

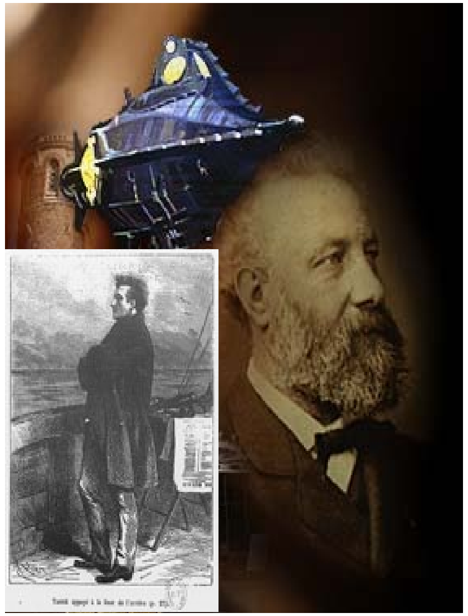
Research in related fields: radiolysis, radiobiology, nuclear physics …

Training of students

The name ARRONAX is a tribute to
Jules Verne, born in Nantes in 1828.

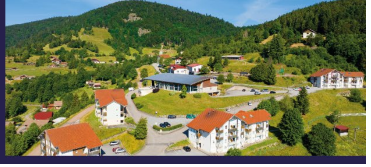
Aronnax is the name of the main character of the novel «Twenty thousands leagues under the sea » published in 1870

Nautilus



Professor ARONNAX

Jules Verne

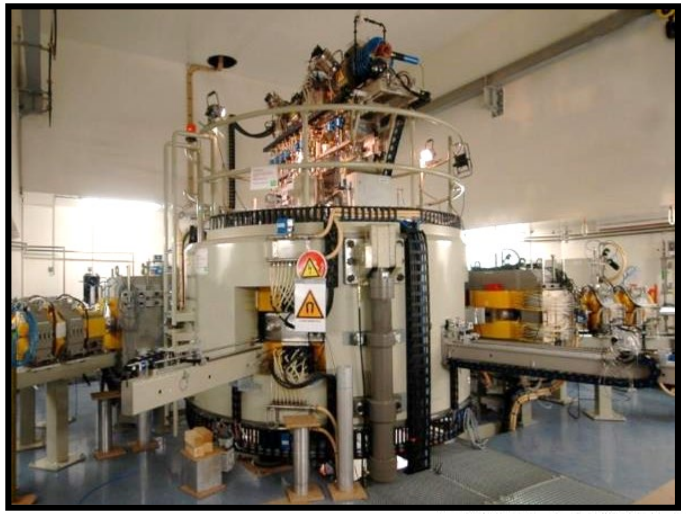


ARRONAX Facility

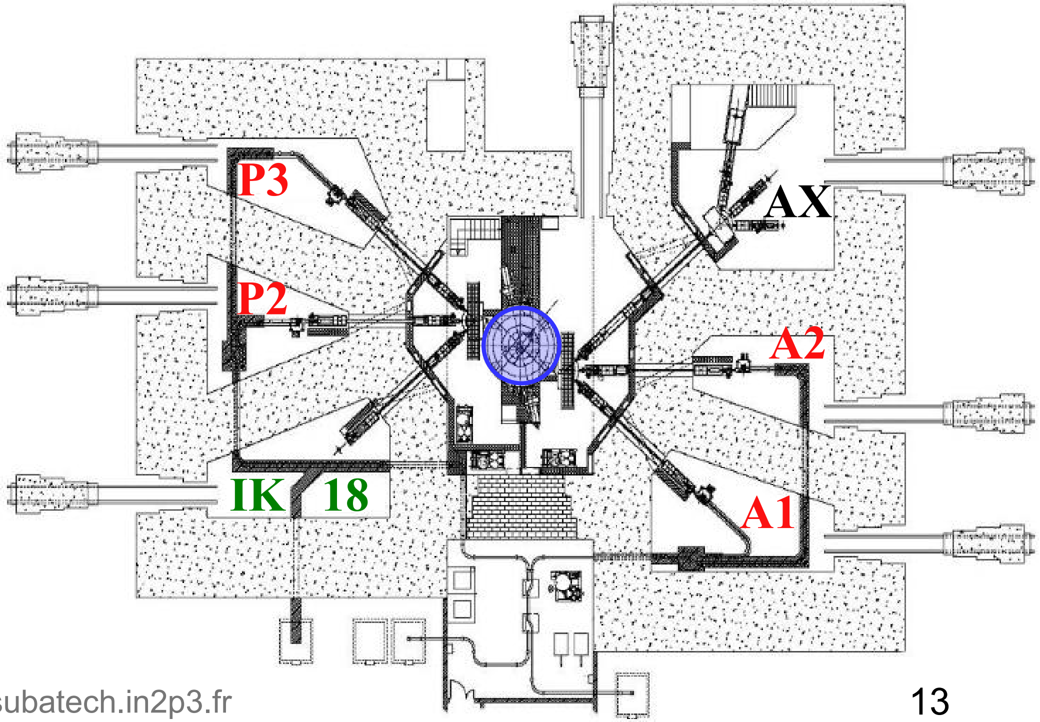
- **Key numbers:**
  - Creation **2008**, commissioned **2010**
  - **70 people** including students
  - **C70XP** and **Kiube 180** coming soon
- **Key features:**
  - Multi-particles
  - High energy
  - High intensity

	Beam	Accelerated ions	Energy (MeV)	Intensity (eμA)	Dual beam
C70XP	**Proton**	H-	30-**70**	< **375**	**Yes**
		HH+	17	< 50	No
	Deuton	D-	15-35	< 50	Yes
	Alpha	He++	**68**	< 70	No
IK18	**Proton**	H-	18	180	Yes

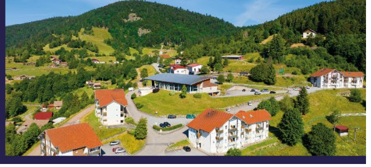
- **A range of associated laboratories, 2000 m²:**
  - radiochemistry, biochemistry, radiolabelling,
  - cell culture, chemical analyses,
  - nuclear metrology, quality control, etc.



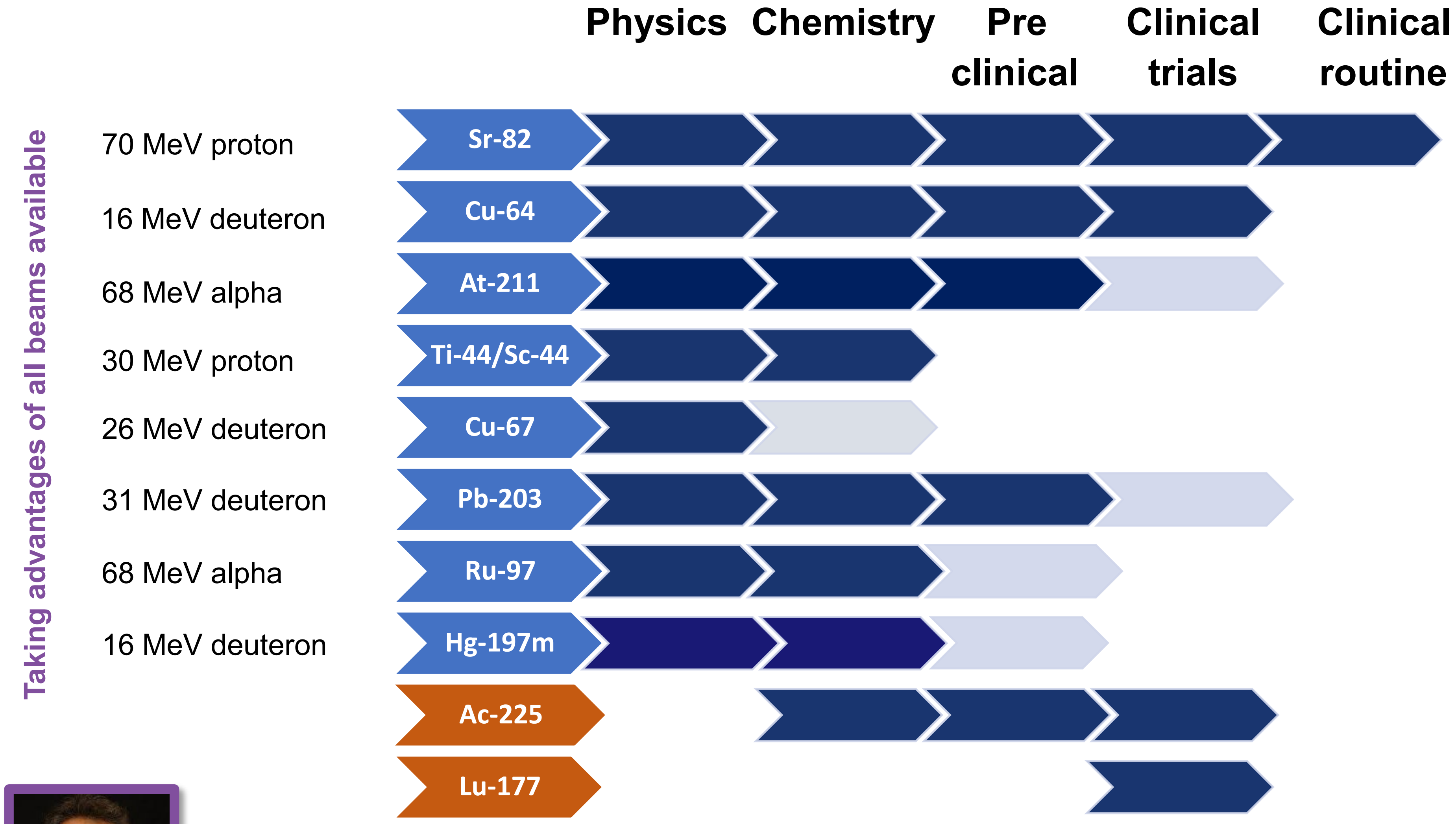
C70XP cyclotron @ GIP ARRONAX



Cross-section view of the reaction casemates located around the C70XP



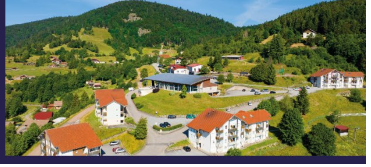
Pipeline ARRONAX



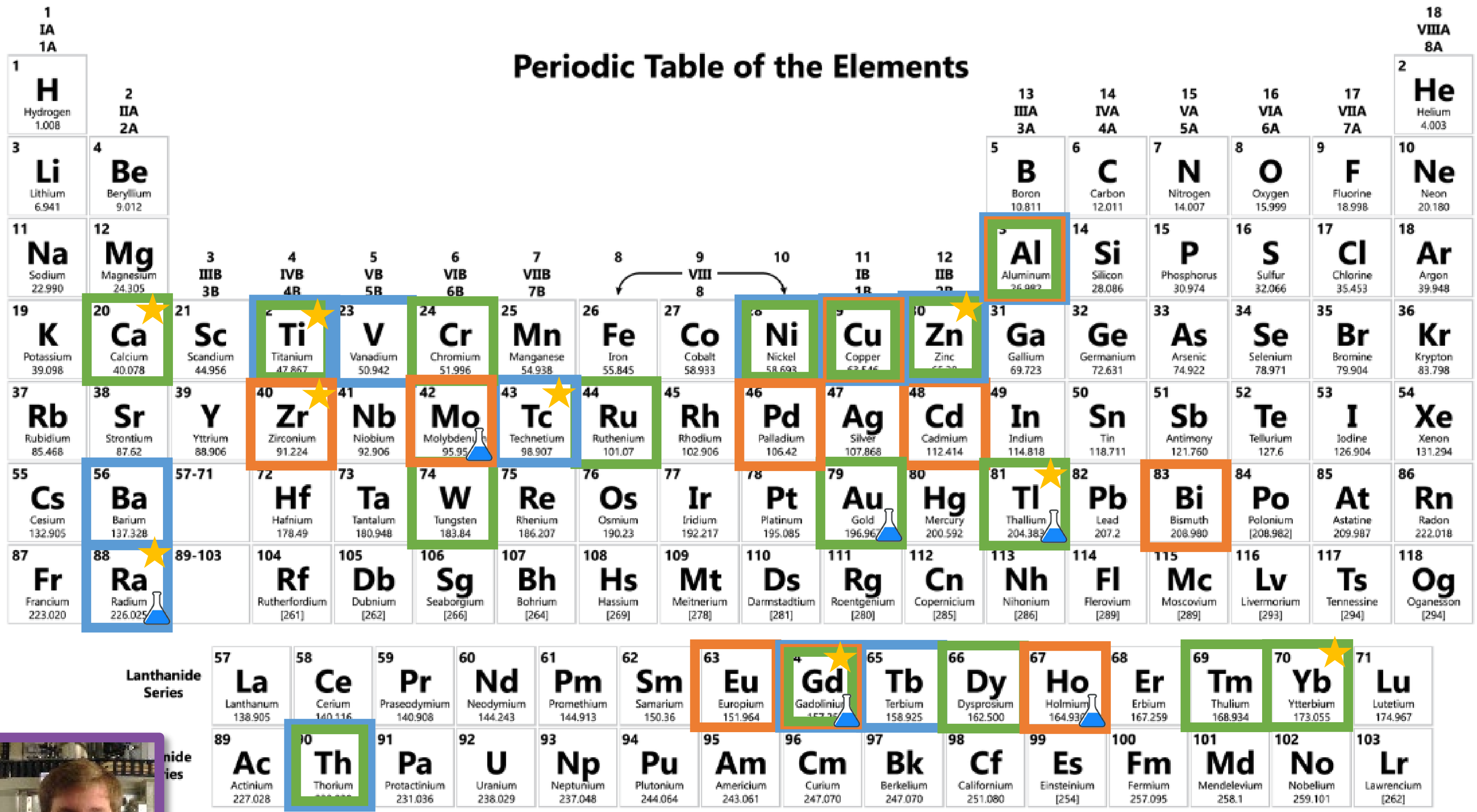
New developments on Auger emitters

Taking advantage of the radiopharmacy

Adapted from F. Haddad



Wide use of available beams: explore the realm of possibilities



Proton beam

Deuton beam

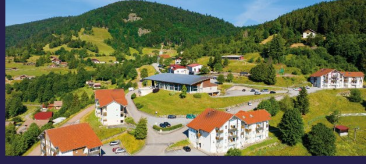
Alpha beam

And more :

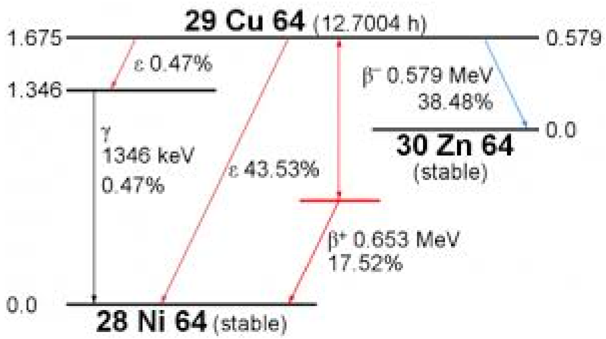
★ Enriched target investigated

Chemical separation studies

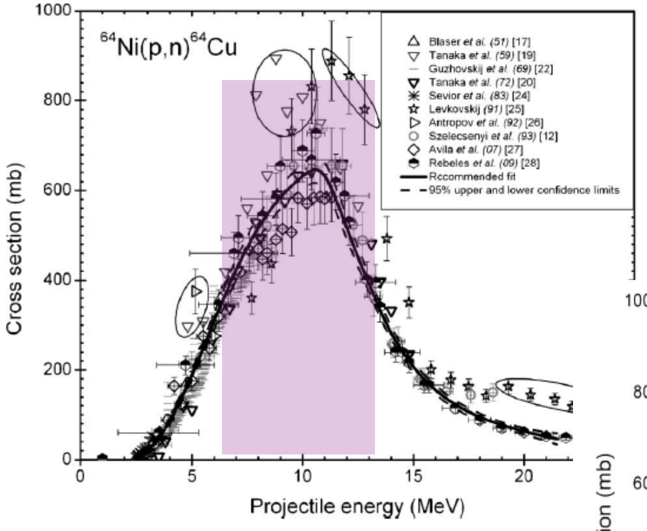
Prepared by E. Nigron



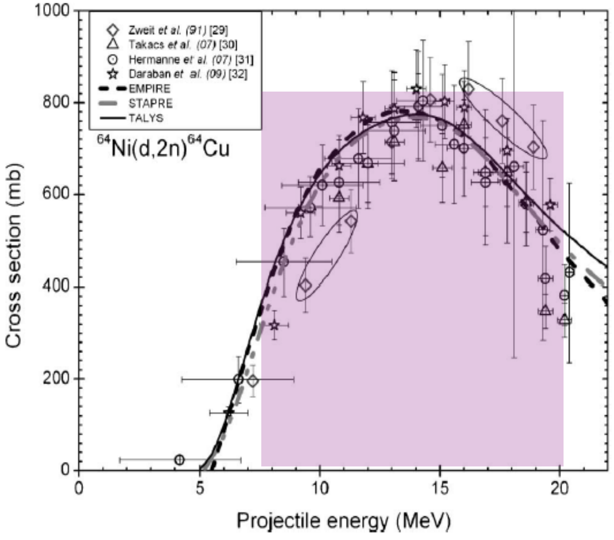
Cu-64, what is it for?



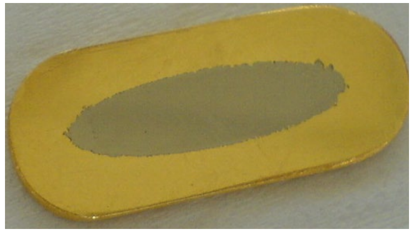
- **Cu-64, main interests:**
  - **Half-life**: **12.7 hours** - not too short, not too long
    - ➢ Suitable for **P**ositron **E**mission **T**omography
  - **Theranostic pair** with Cu-67
    - ➢ **What you see is what you treat**
  - **Applications**
    - ➢ PET imaging of NET - Detectnet (Curium Pharma) - FDA approval date: September 3, 2020



- **Production routes:**
  - **Main:** Ni-64 + p → Cu-64 + n
  - **Alternative:** Ni-64 + d → Cu-64 + 2n



- **Production scheme:**
  - **Enriched Ni-64** electroplated on Au backing
  - Monthly production of $CuCl_2$

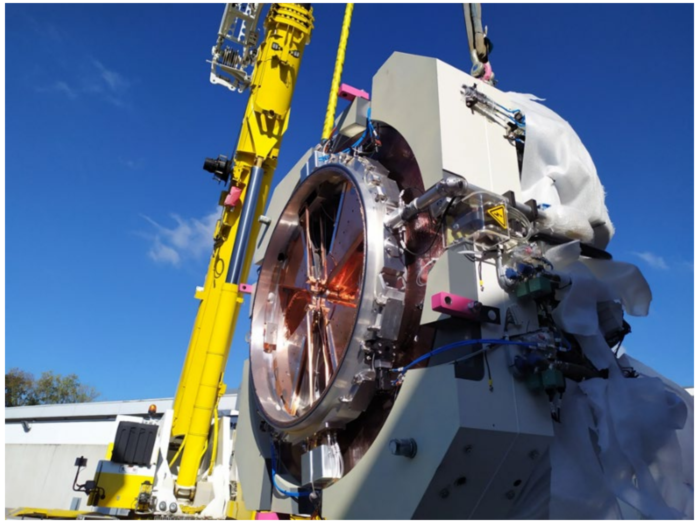


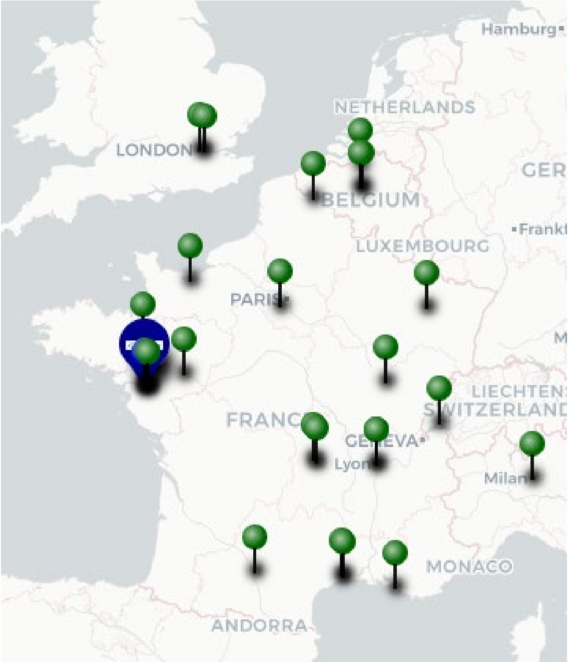
⇨ **To develop theranostic approach**

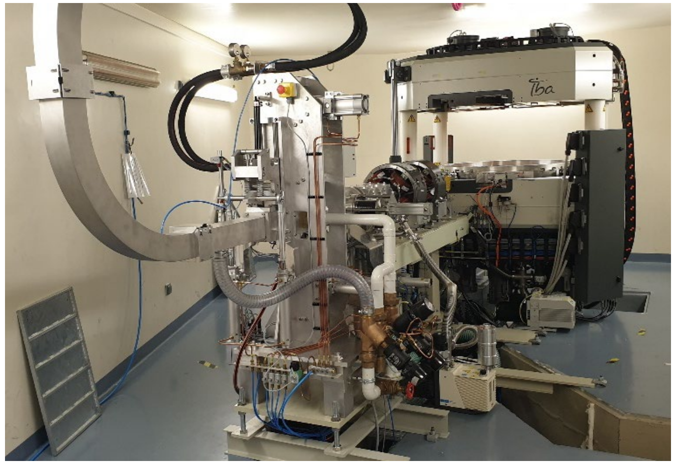
Kiube 180 for Cu-64 (F-18)

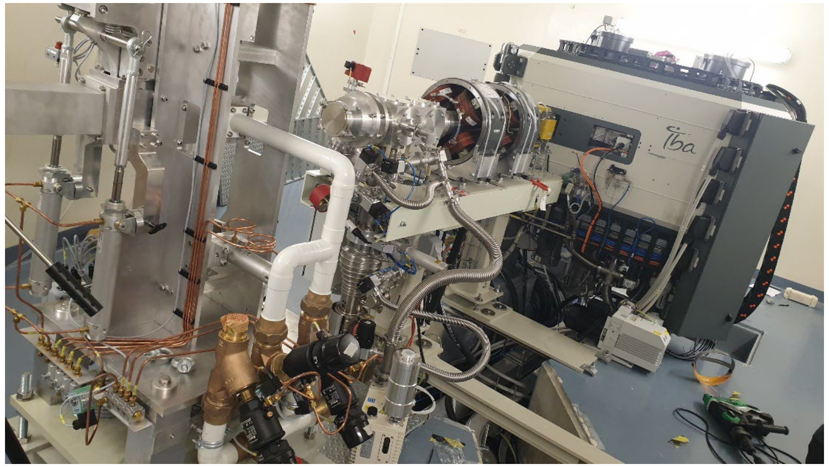
How to improve Cu-64 availability in France and neighbouring countries (current partners) ?

- Installation of a 18 MeV cyclotron, IK18, IBA Kiube 180, with a solid target system customized connected to the existing one for C70XP
- Still leave room for research with deuteron beam

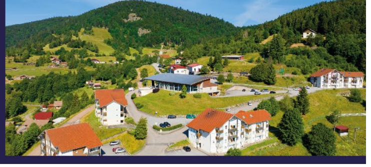








24ème COLLOQUE GANIL
21 au 25 septembre 2026
Bussang, France



Objectives: explore alternative production route of Lu-177 from Yb-nat - $T_{1/2}$ = 6.7 d
Suitable for **β- targeted therapy**

Outcomes:
- Extend the cross section at higher energy
- Measure the ratio Lu-177m/Lu-177g

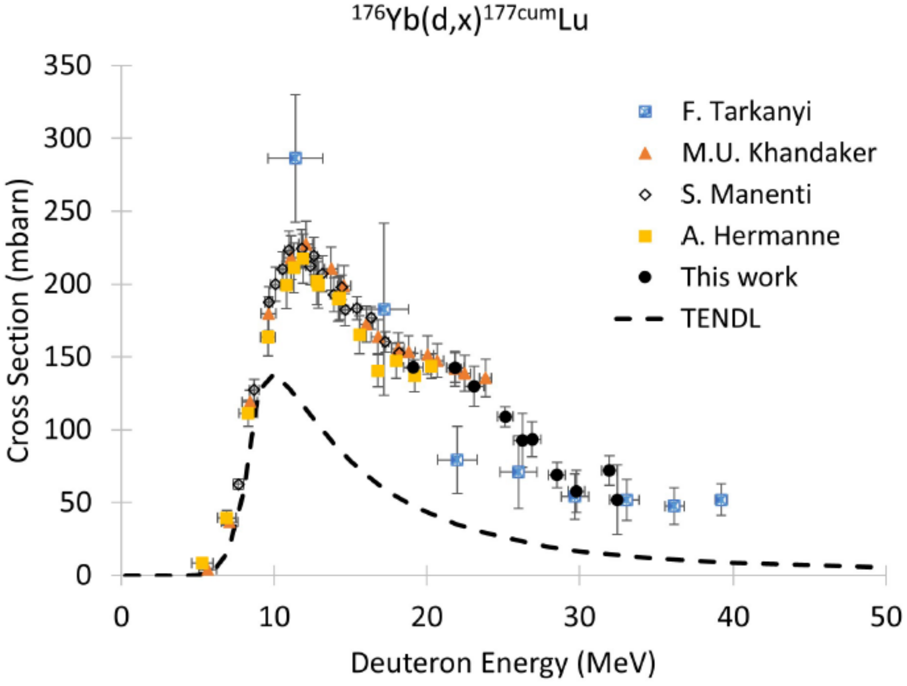


Figure 3: Excitation function of $^{176}Yb(d,x)^{177cum}Lu$ nuclear reaction compared to other published data and TENDL (2023).

ELSEVIER
Applied Radiation and Isotopes
Volume 227, January 2026, 112263

Deuteron-induced nuclear reactions to produce ^{177}Lu: Extension of cross-sections data up to 33 MeV and impact on purity

E. López-Melero [a], E. Nigron [b], F. Haddad [b c], J. Praena [a]

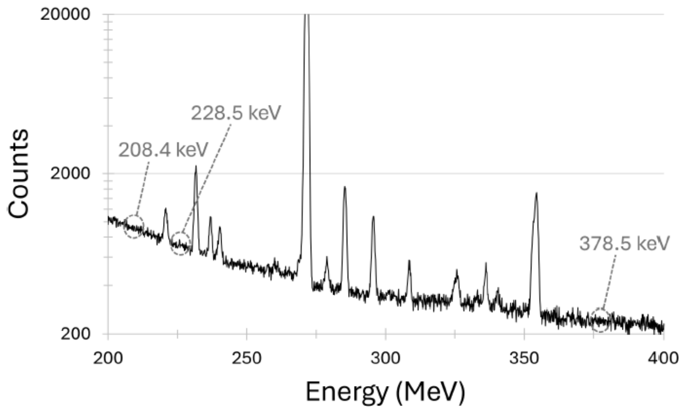
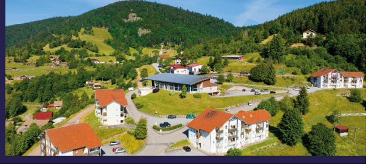


Figure 2: HPGe spectrum acquired six months after EOB with a counting time of 13 days. The marked regions indicate the most relevant γ-lines associated with the decay of ^{177m}Lu

- Define the lowest detection limit for Lu-177m measurement ($T_{1/2}$ = 160.44 d)

E. Lopez



Alpha beam interests

Some interesting considerations for production of medical isotopes

- Access to a **higher cross section**: 700 mb Ca-40[96.941%](α,x)Sc-43 – 350 mb Ca-43[0.135%](p,n)Sc-43
- Reuse **existing process** in targetry, chemistry: Cu-64 target, chemistry and recycling of Ni-64 for Cu-67 prod.
- Facilitate **target manufacturing**, irradiation and enhanced specific activity: use of Cd/Cd-116 for Sn-117m prod
- Use a **monoisotopic target**: Cs-133 [alkaline !] for La-135 instead of Ba-nat [low thermal conductivity]
  Non-standard positron emitters, Auger-based targeted internal radiotherapy …
- Avoid **radioactive target material**: Tc target for Ru-97, Po target for At-211

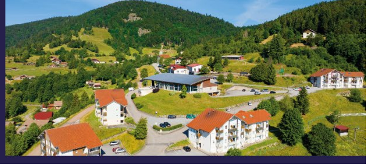
Z									
	207At 1.81 H ε: 91.40% α: 8.60%	208At 1.63 H ε: 99.45% α: 0.55%	209At 5.42 H ε: 95.90% α: 4.10%	210At 8.1 H ε: 99.82% α: 0.18%	211At 7.214 H ε: 58.20% α: 41.80%	212At 0.314 S α: 100.00% ε < 0.03%	213At 125 NS α: 100.00%	214At 558 NS α: 100.00%	215At 0.10 MS α: 100.00%
84	206Po 8.8 D ε: 94.55% α: 5.45%	207Po 5.80 H ε: 99.98% α: 0.02%	208Po 2.898 Y α: 100.00% ε: 4.0E-3%	209Po 124 Y α: 99.55% ε: 0.45%	210Po 138.376 D α: 100.00%	211Po 0.516 S α: 100.00%	212Po 0.299 µS α: 100.00%	213Po 3.72 µS α: 100.00%	214Po 163.6 µS α: 100.00%
83	205Bi 15.31 D ε: 100.00%	206Bi 6.243 D ε: 100.00%	207Bi 31.55 Y ε: 100.00%	208Bi 3.68E+5 Y ε: 100.00%	209Bi 2.01E19 Y 100% α: 100.0%	210Bi 5.012 D β-: 100.00% α: 1.3E-4%	211Bi 2.14 M α: 99.72% β-: 0.28%	212Bi 60.55 M β-: 64.06% α: 35.94%	213Bi 45.61 M β-: 97.80% α: 2.20%

Spallation reaction

- lower yield
- higher level of impurity

Bi-209(α,2n)At-211

- monoisotopic target
- high radionuclidic purity
- GBq quantities



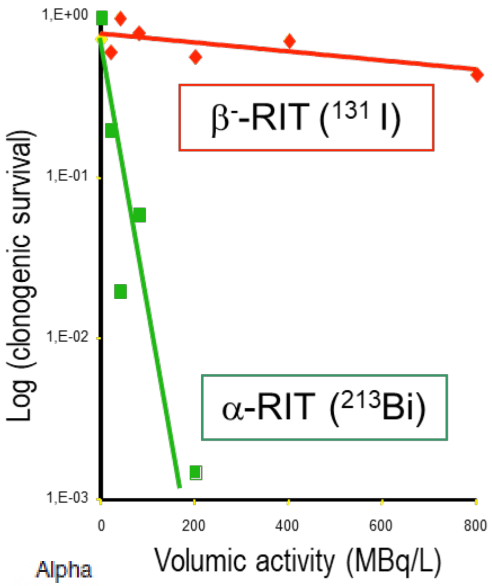
At-211, what is it for ?

A limited number of alpha emitter candidates

Radionucliide	Half life	# α / decay	Eγ (keV)
Tb-149	4,1 h	0,17 (β et ε)	165
At-211	**7,2 h**	**1**	79
Bi-212	1 h	1 (β)	727
Bi-213	45 m	1 (2β)	440
Ra-223	11,4 d	4 (2β)	269
Ac-225	10 d	4 (2β)	100
Th-226	31 m	4	111
Th-227	18,7 d	5 (2β)	256

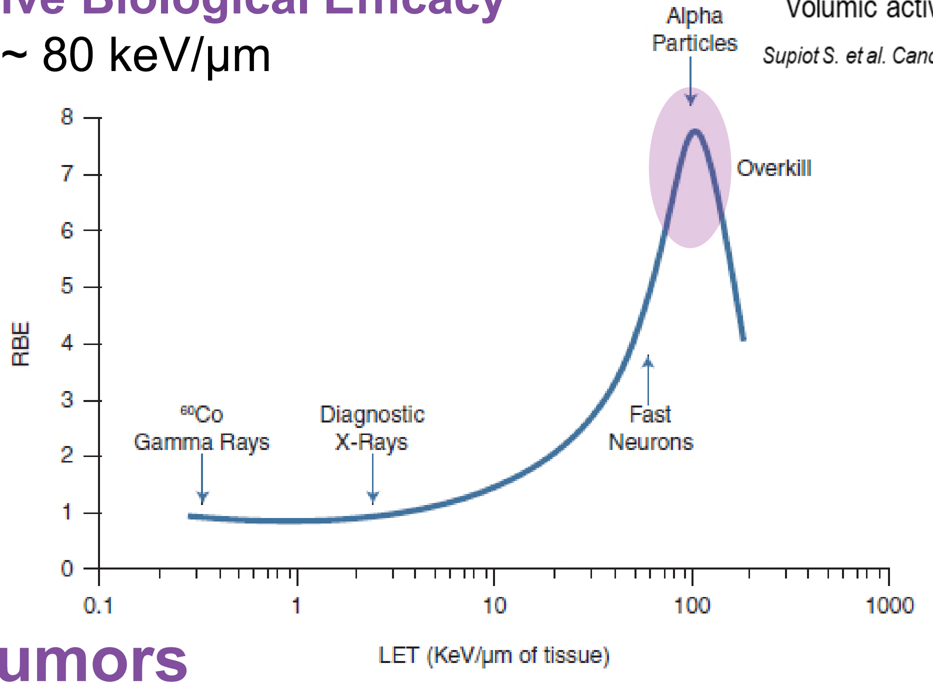
Highly cytotoxic, Eα [5-9] MeV potentially more than β radiation

Better preservation of healthy tissue, range of 40 to 100 μm in water, a few cell's length



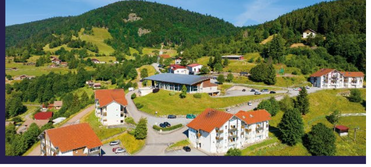
Supiot S. et al. Cancer 2002. 94: 1202-9

High Relative Biological Efficacy
High LET, ~ 80 keV/μm



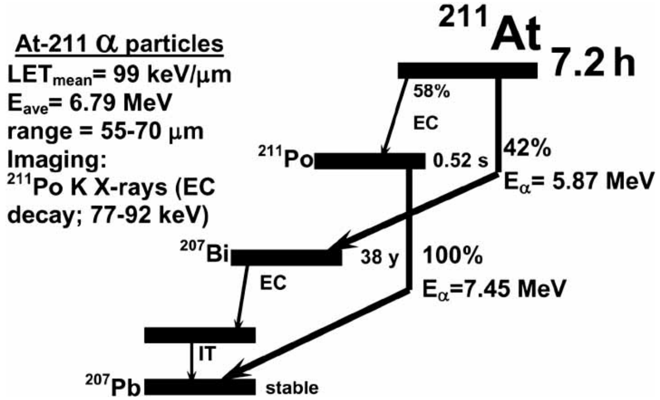
The essential Physics of Medical Imaging, Book, Bushberg et al., 2002

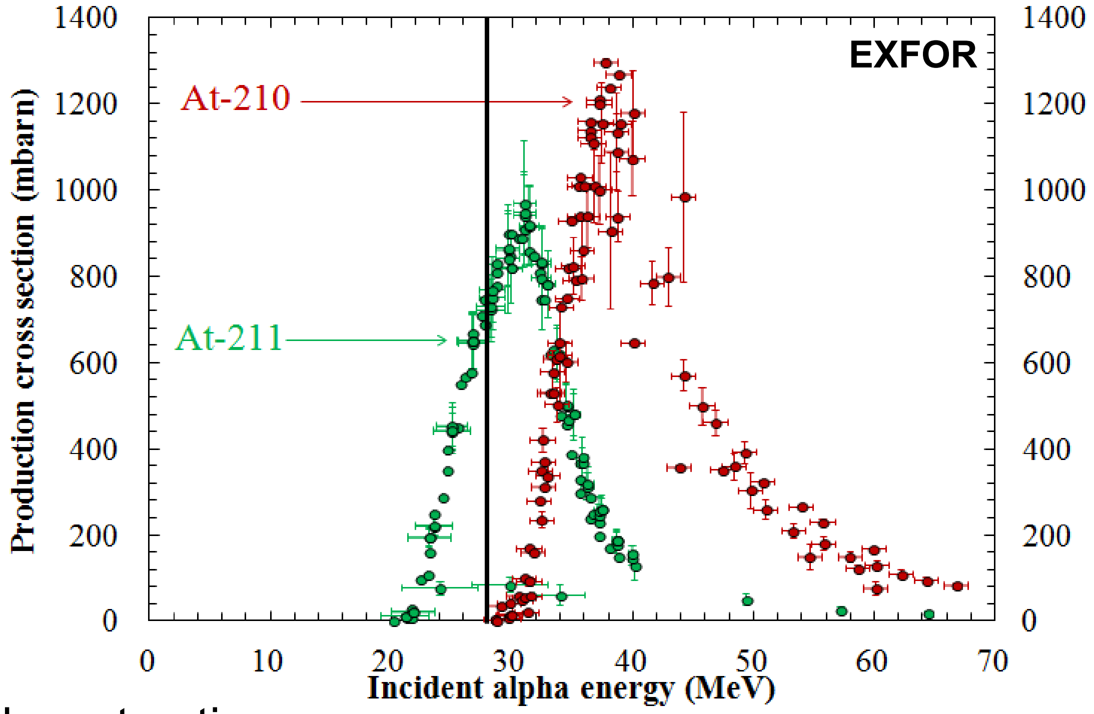
⇨ **To eradicate tumors**

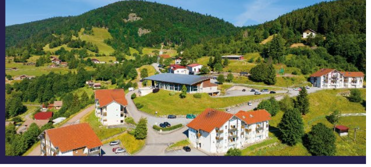


At-211 interests and production

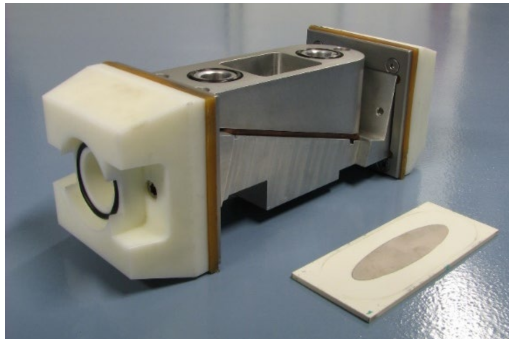
- **At-211, main interests:**
  - **Half-life**: **7.2 hours** - not too short, not too long
    - ➢ Suitable for **R**adio**P**harmaceutical **T**herapy
  - **One alpha particle** per decay
    - ➢ Better **control of the deposited dose**
  - **Accelerator** production
    - ➢ IBA : C30XP, multi-particules
    - ➢ ACSI : TR-ALPHA, 30 MeV "only alpha"
- **Production route:** **Bi-209 + α → At-211 + 2n**
- **Keep in mind:**
  - **Precise beam energy** adjustment
    - ➢ **Avoiding the production of At-210 - (α,3n) reaction**
  - The At-210 begins to be produced above 28.613 MeV
    - ➢ Half-life 8.1 hours
    - ➢ 99.8% CE towards **Po-210** with a half-life of 138.4 days
- **Production scheme:** **energy degrader**, home made target, dry extraction







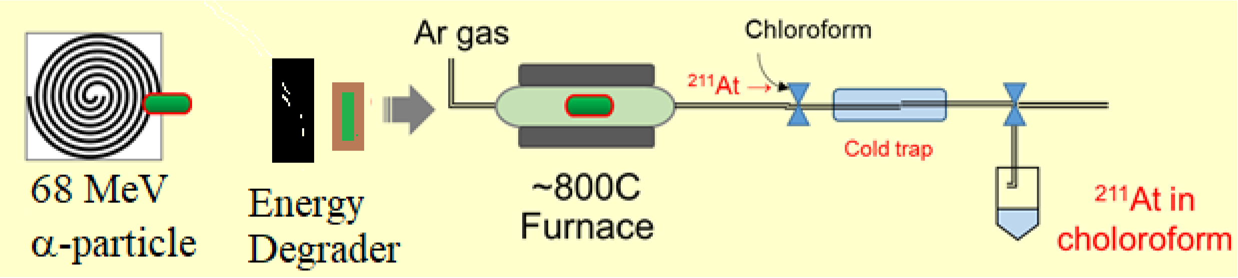
At-211 production: C70XP ARRONAX



The IBA rabbit system (left) and
a target for astatine production (right)

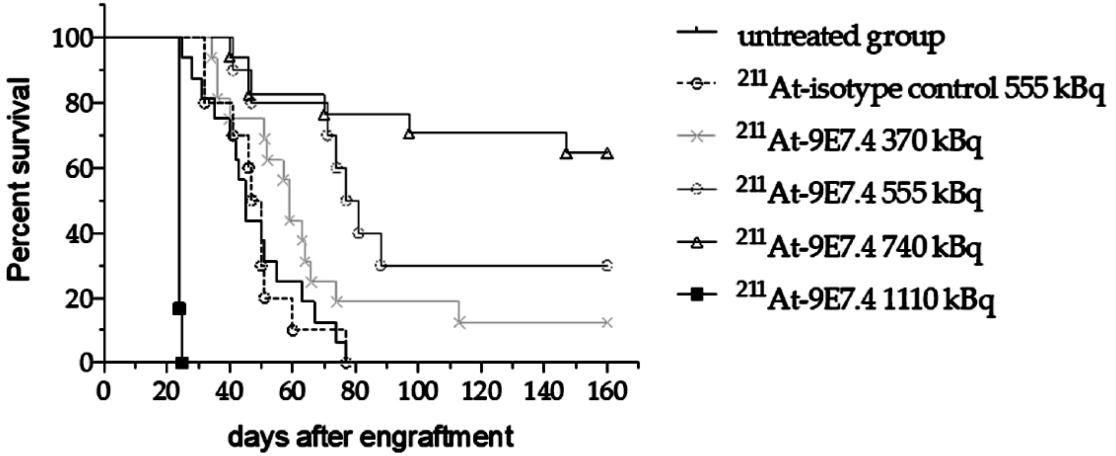
Production route: $^{209}Bi + \alpha \rightarrow {}^{211}At + 2n$

Production scheme:
- 68 MeV alpha particle beam
- **Energy degrader in Al or graphite to reach 28 MeV**
- Target material evaporated under vacuum
- Irradiated in an IBA rabbit system
- At-211 extraction using dry chemistry
- At-211 recovered in chloroform

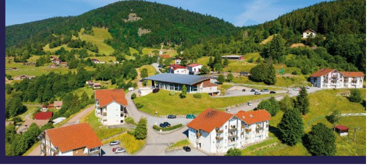


In vivo application:
- At-211-labelled anti-mCD138 in mouse syngeneic multiple myeloma

Production capacity:
- 3-4 batches/month
- Between 0.9 and 1.2 GBq EOB



Gouard S et al. Cancers (Basel). 2020 Sep 22;12(9):2721



Optimizing ^{211}At production SPIRAL 2

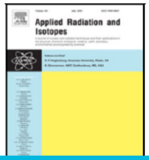
- **Alpha beams available at GIE GANIL**
  - SPIRAL2 : He2+ 80 MeV to 8 MeV
  - ^{209}Bi irradiation possible
    Bi-209(α,3n)At-210 until 35 MeV
  - Experiment carried out in late September 2022
    Energies around the threshold
  - Measurement techniques for the isotopes of interest
    Gamma spectroscopy

- **Analysis of the experience and publication**
  - S. Ansari-Chauveau, A-M. Frelin Labalme
  - Publication in Physics in Medicine and Biology in 2025


Applied Radiation and Isotopes 225 (2025) 112061
Contents lists available at ScienceDirect
Applied Radiation and Isotopes
journal homepage: www.elsevier.com/locate/apradiso
ELSEVIER

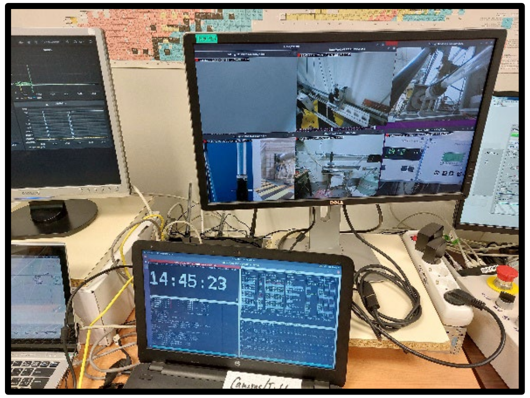
Optimizing ^{211}At production cross section by studying the rise of ^{210}At cross section: First measurement using Linac SPIRAL2

S. Ansari-Chauveau [a,*], A-M. Frelin [a], G. de France [a], A. Guertin [b], F. Haddad [b,c], X. Ledoux [a], J. Mrázek [d], E. Šimečková [d]
[a] GANIL, Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DSM-CNRS/IN2P3, Boulevard H. Becquerel, Caen 14076, France
[b] SUBATECH, Nantes Université, IMT Atlantique, CNRS/IN2P3, 3 Rue Alfred Kastler, Nantes 44300, France
[c] GIP ARRONAX, 1 rue Aronnax, Saint-Herblain 44817, France
[d] Nuclear Physics Institute CAS, Řež 25068, Czech Republic

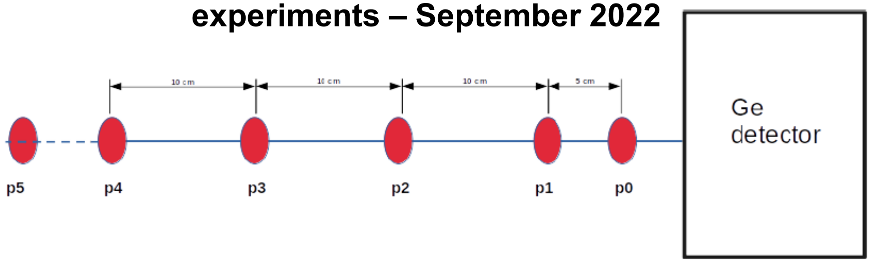


A.M. Frelin

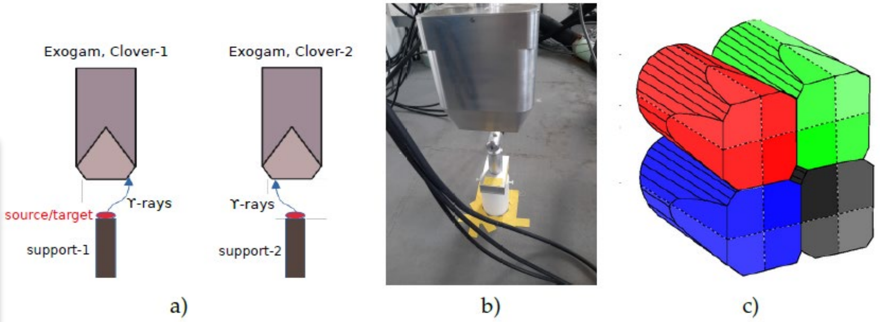
S. Ansari-Chaveau



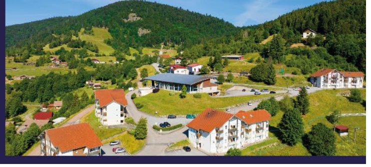
SPIRAL2 building and data acquisition room dedicated to experiments – September 2022



Device for the 'on-line' measurement of gamma radiation



'Offline' gamma radiation measurement device



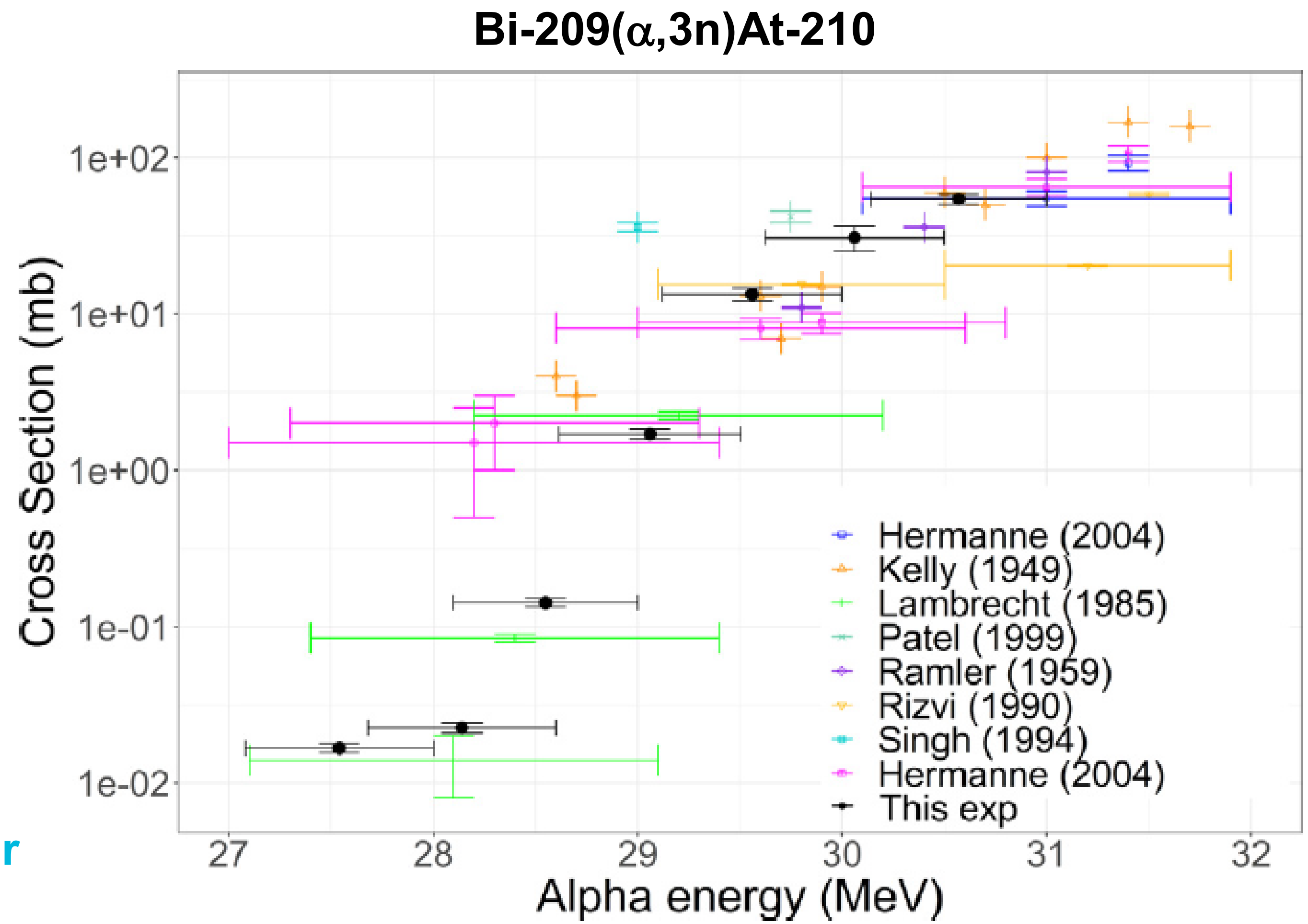
At-210 production near the threshold

- **Alpha beams available at GIE GANIL**
  - Measurement of the reaction threshold
  - In particular, with regard to contaminants
    - ➢ **Improved purity**

- **High-efficiency γ-spectrometry device**
  - Accuracy
  - Statistics
    - ➢ **Lower production cross-section values**

- **Analysis of the experience and publication**
  - Confirmation of Lambrecht's work
  - **Target thickness** affects the energy error

- **Perspectives**
  - Measurements of cross-sections for the **monitor reactions**
  - Exploring the **different mass regions**
  - Setting up **a current measurement device**

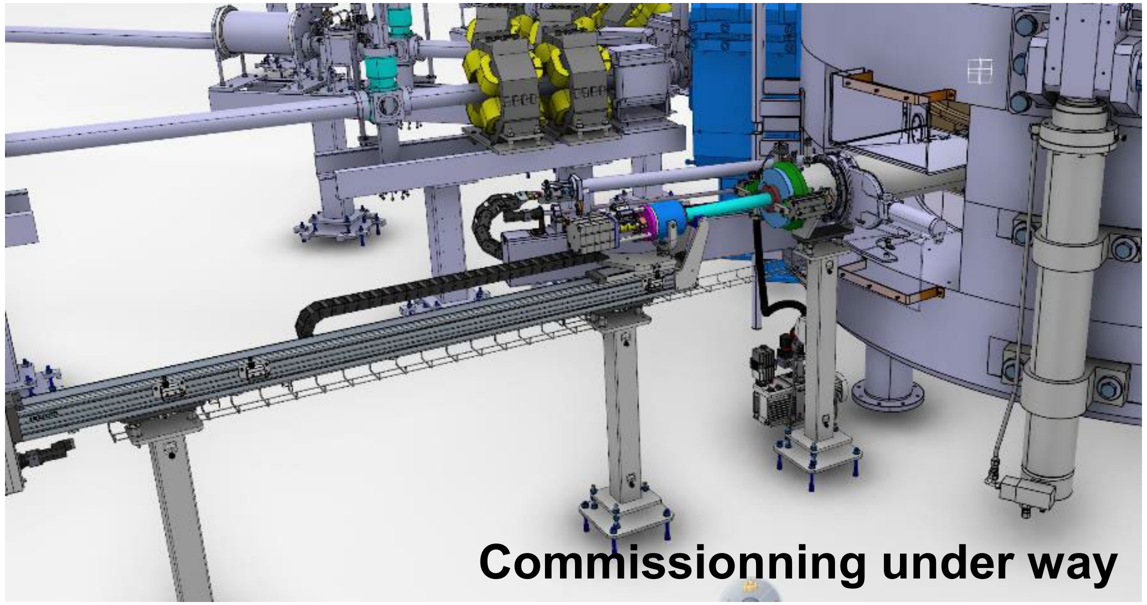


Internal Target for At-211

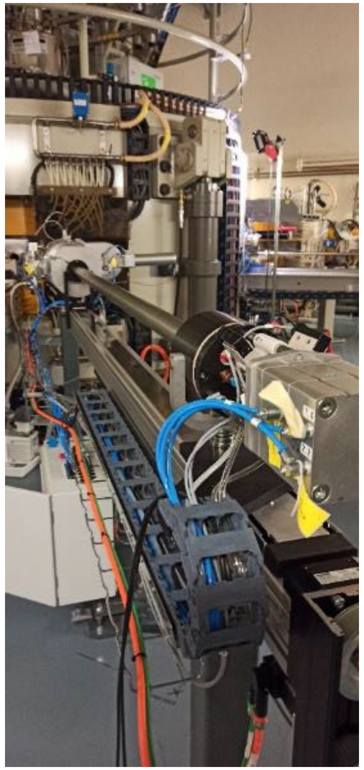
How to improve the availability of At-211@ ARRONAX?

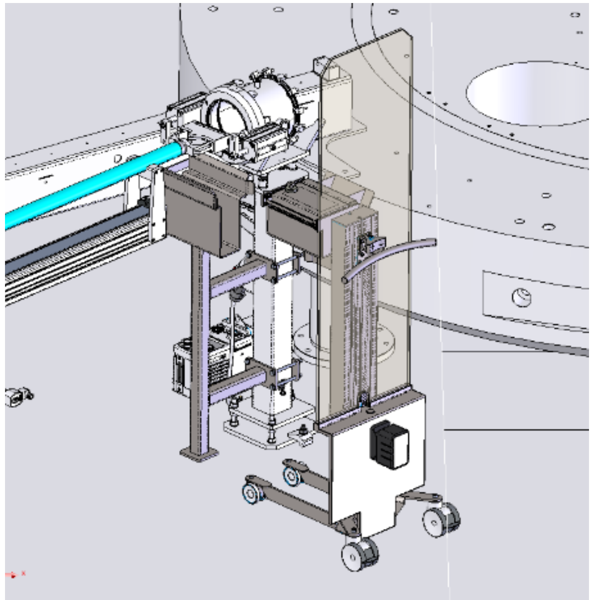
Upgrade of the machine: development of an internal target to intercept the beam at the right energy (28-29 MeV)

- No more need to degrade the beam energy and better control of At-210 production
- Limitation will be now the target itself



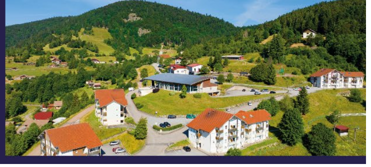
Commissionning under way





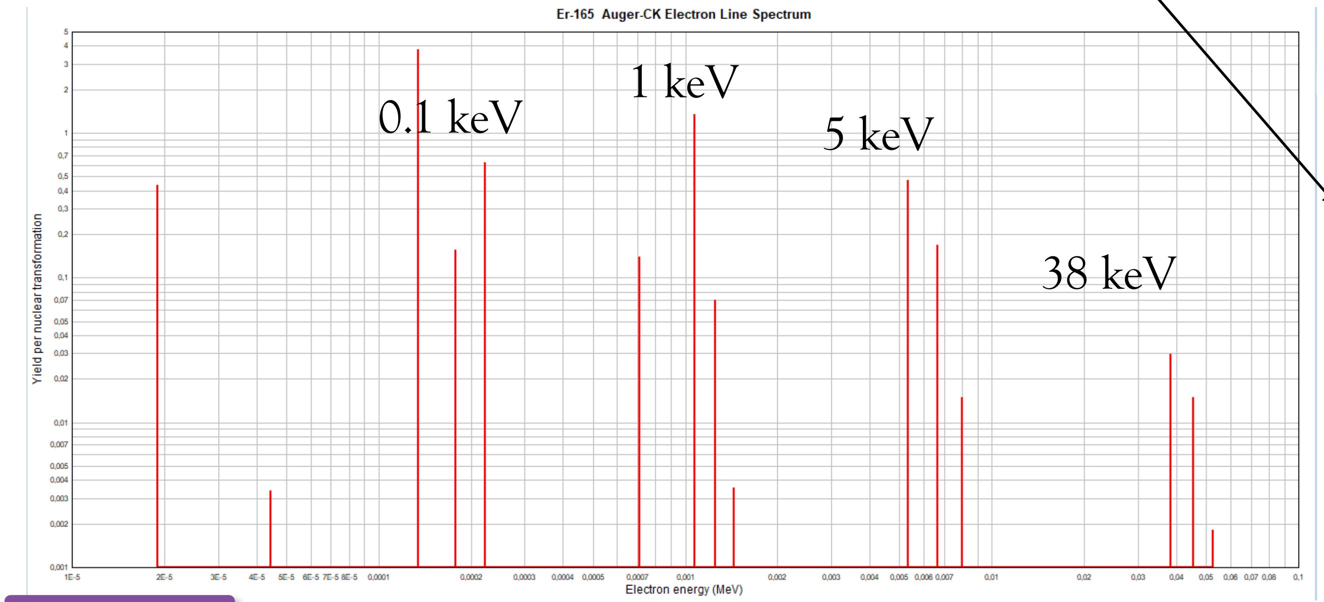
Target handling after irradiation

Our goals: improve both the quality and the quantities of the final product – participation to Accelerate.EU

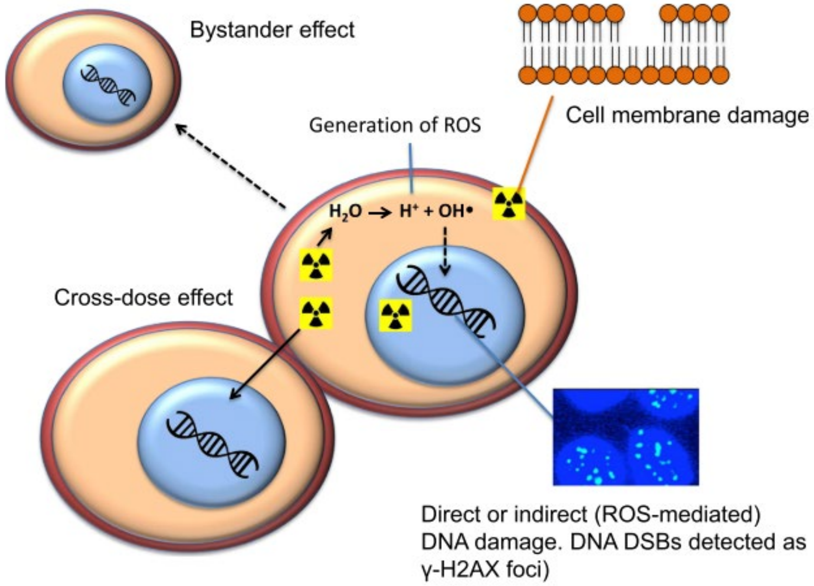


Er-165 ID card and interests

- $T_{1/2}$ = 10.36 h
- Er-165 decays at 100% to Ho-165 (stable)
- **Pur Auger electron** (AE) and X emitter. 7 AEs/decay
- **No gamma emissions.**



0.5 AE at 20 eV
4 AE at 100 eV
1.5 AE at 1 keV
0.5 AE at 5 keV



Ku et al. EJNMMI Radiopharmacy and Chemistry, 2019

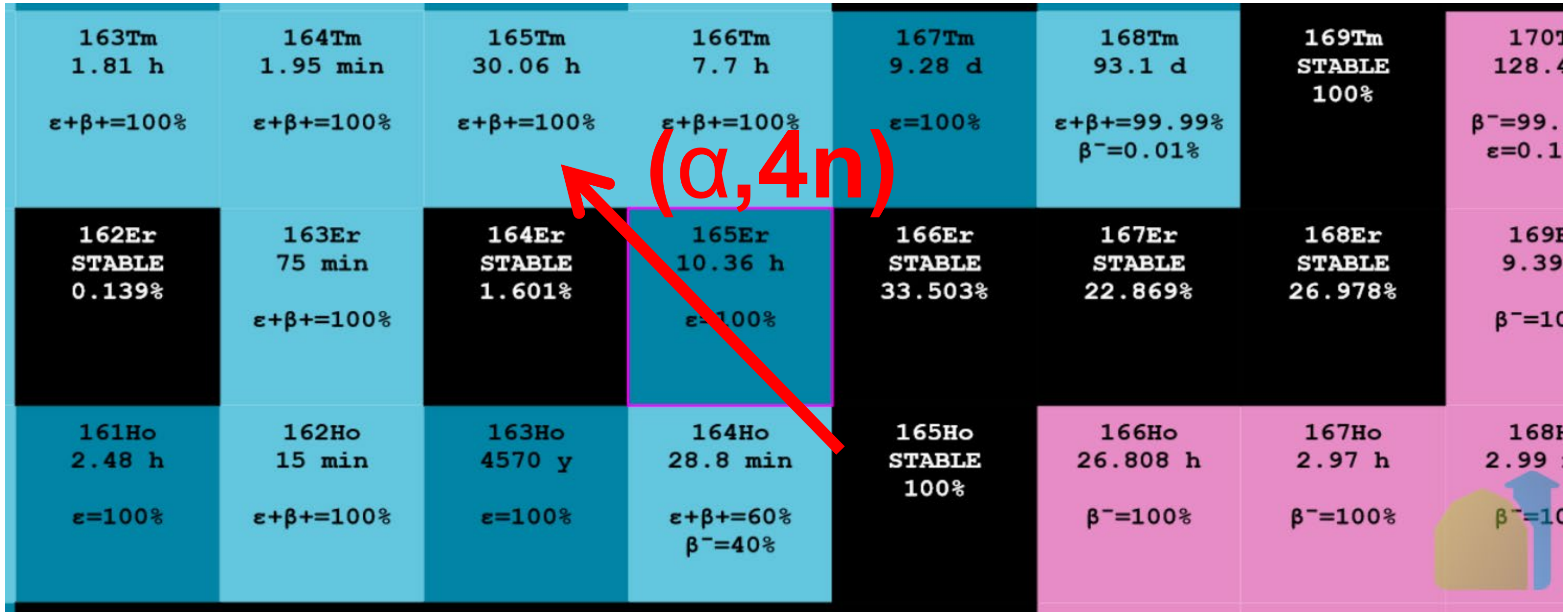
→ Ideal for **Auger electron dosimetry studies**.

Prepared by E. Nigron

Er-165 production route

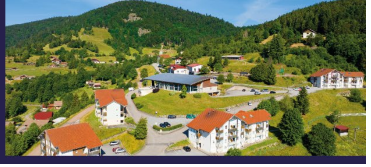
It can be produced directly → but the decay time must be managed.

Route identified



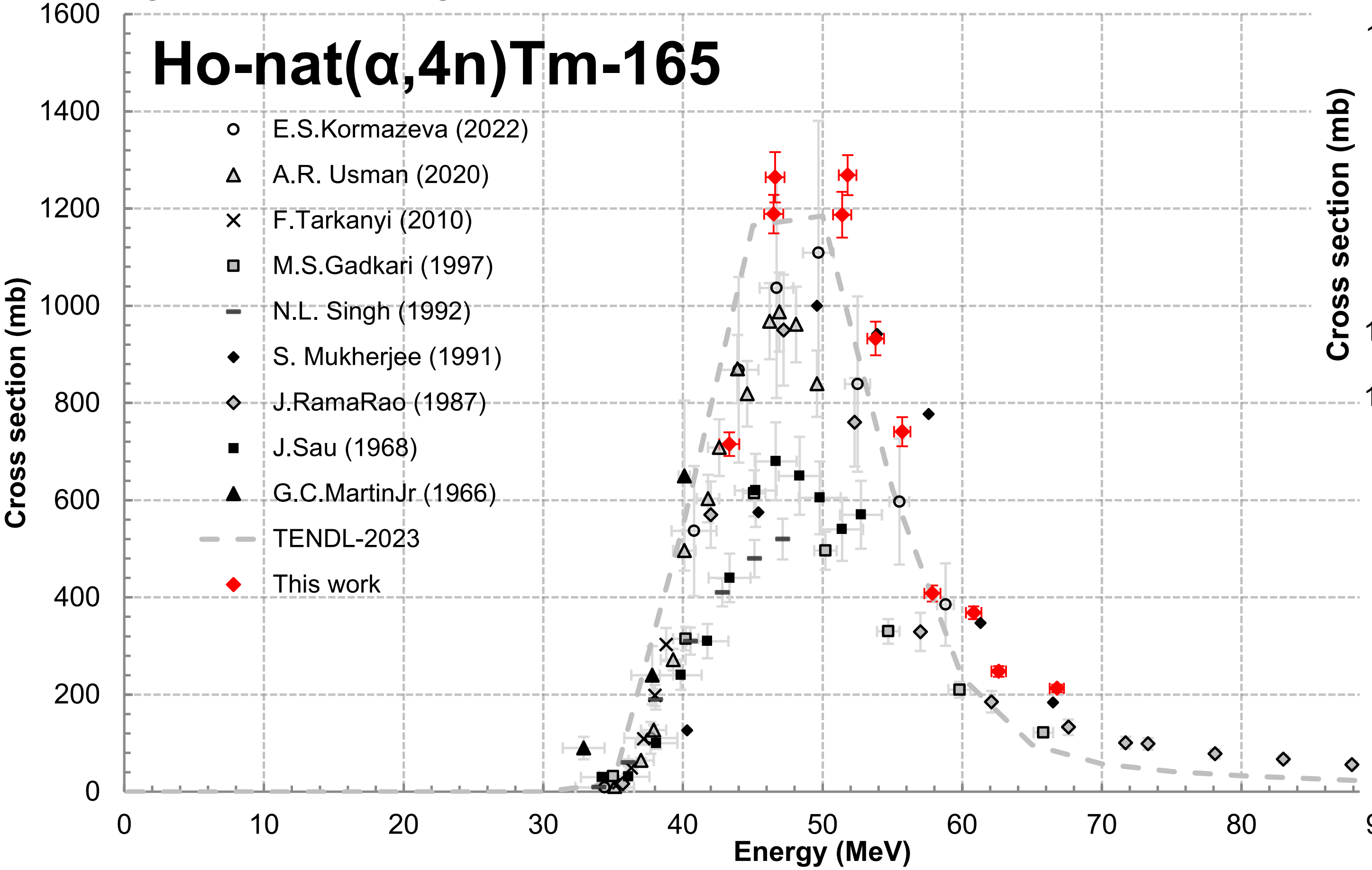
- Tm-165 (30h)/ Er-165 (10h)
- Ho mono-isotopic target
- Close Tm contaminants decay into stable nuclei
  - ➢ High **Radionuclidic purity**
- Requests a high-energy alpha beam (~60 MeV)

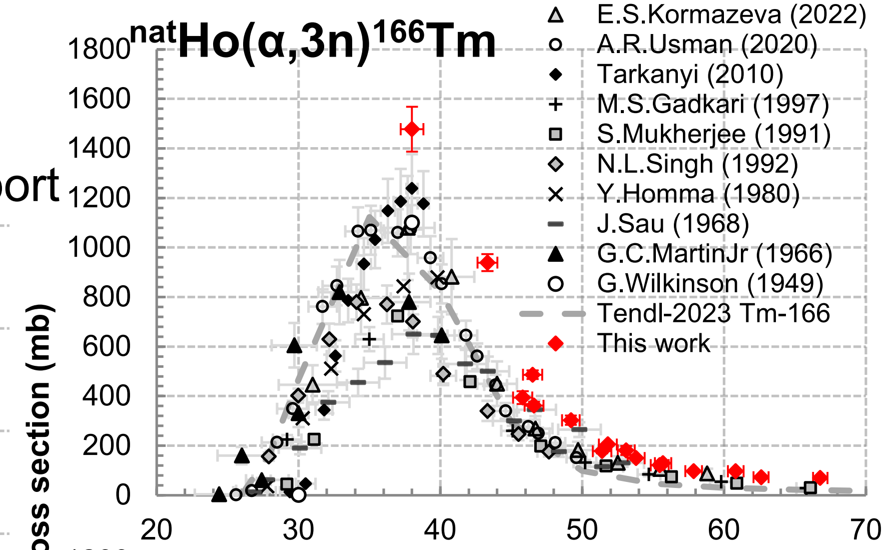
Prepared by E. Nigron

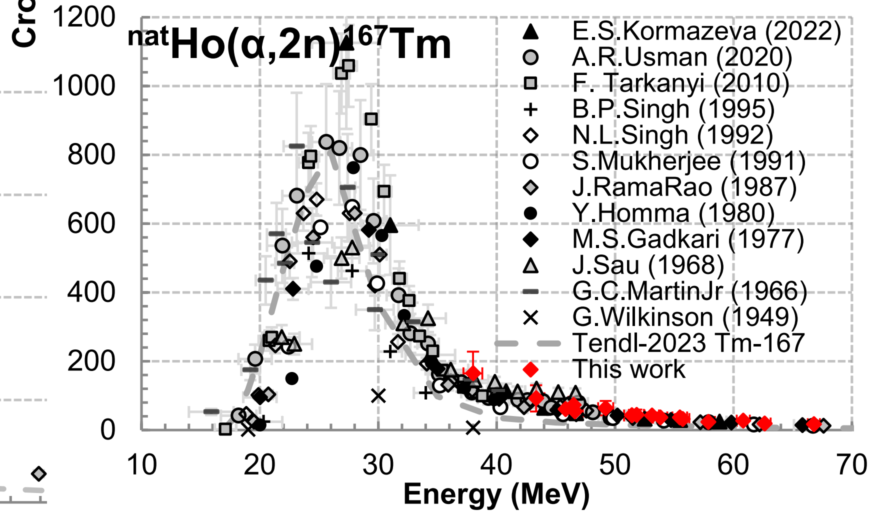


Tm-165/Er-165 generator

Objective: production of Er-165,a pure AE-emitting radionuclide chemically matched to clinical therapeutic radionuclide Lu-177, from a generator using functionalized porous materials as a support

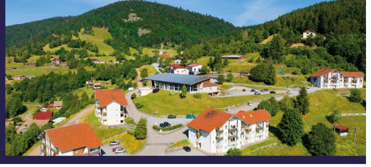






E. Nigron
and
A.C. Bonraisin

Outcomes: setup of Tm-165 production of 100 MBq for research in radiochemistry and Er-165 radiolabeling.
The establishment of **thick-target production** has **confirmed production yields**.

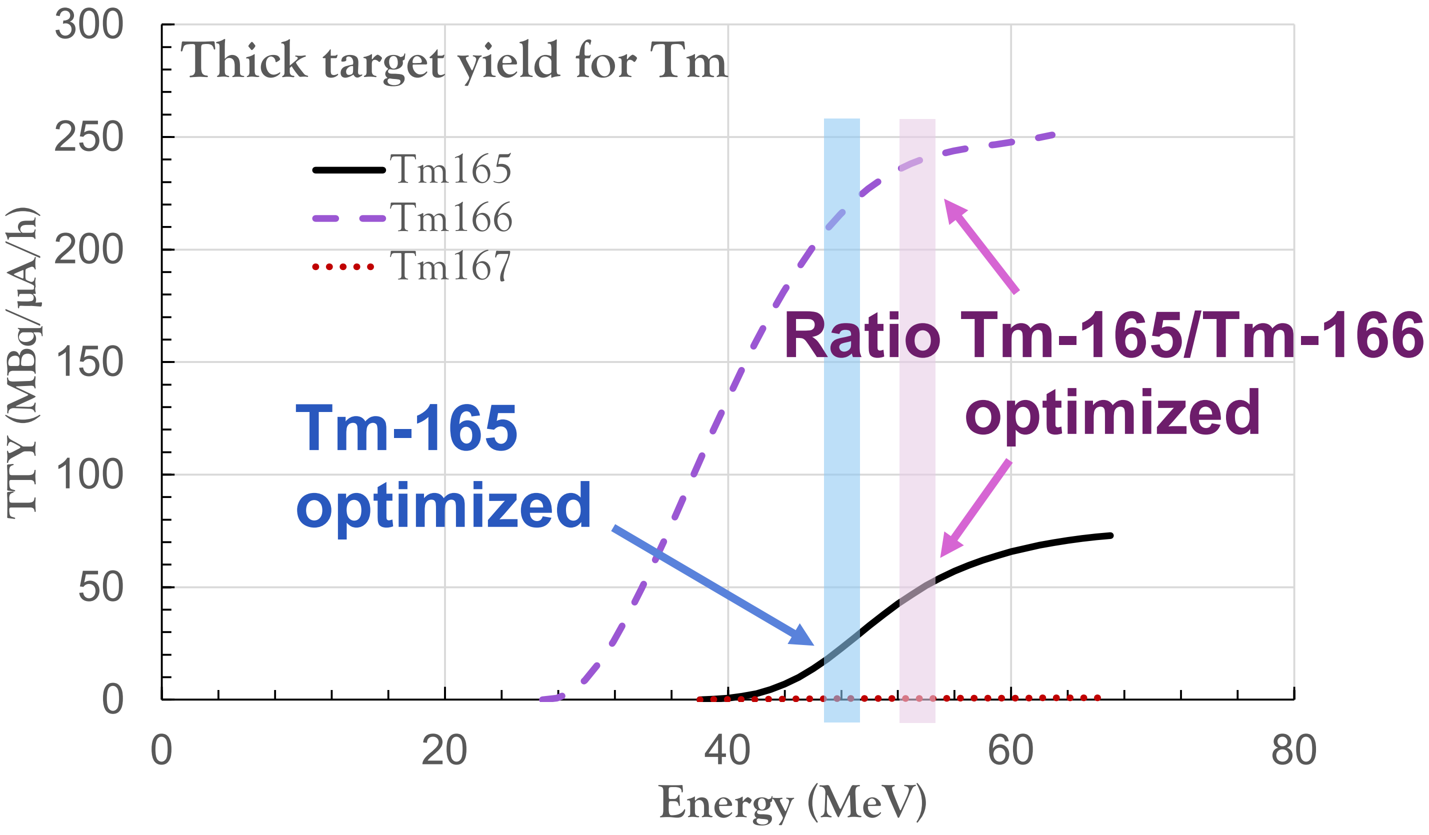


Tm-165 Thick Target Yield

- A range around 50 MeV **optimize the production of Tm-165**.
- Another range around 56 MeV **limit the production of Tm-166.**

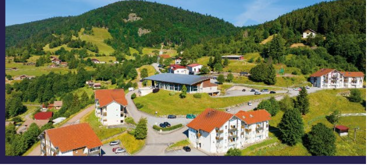
Post-production scenario defined with
a chemical separation EOB +2h.

180% of Tm-165 activity is recovered as Er-165 after 3 days with an 8-hour elution cycle.



What are **the purity and molar activity**? How does it compare to the direct route?

Prepared by E. Nigron



Comparison of production routes

Calculations for a 50 µm target at 100% Ho-165 at 7 µA for 2 h (production characteristics used at GIP ARRONAX).

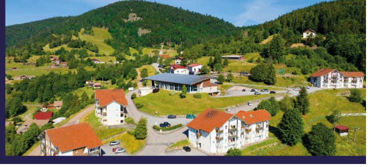
Route	Energy range (MeV)	Activity (MBq)		Molar activity (GBq/nmol)
Ho-165(p,n)Er-165	9.9 – 9	146		1.8
Ho-165(d,2n)Er-165	13.2 – 12.0	524		2.9
Ho-165(α,4n)Tm-165	49.8 – 46.7	204 of Tm-165	367 of Er-165	1.9* – 3.9
	57.8 – 55.0	101 of Tm-165	182 of Er-165	2.5* – 3.9

Target purity not taken into account

*for 1st elution

- The deuton pathway has the **highest production yield**.
- The alpha route has **the highest molar activity**.
- And the alpha route, Er is **available over a longer period of time**.

Prepared by E. Nigron



A dynamic collaborative network

E. Nigron

Publications since 2025 :

INFN Milano
INFN Legnaro
CEA
IFMIF-Dones
CEMHTI (soon)
IJClab
New collaborations under discussion

Applied Radiation and Isotopes
Volume 229, March 2026, 112377

Experimental cross sections and production feasibility of ^{61}Cu via ^{59}Co(α, 2n) for PET imaging using medium-energy alpha beams

Irene Cardani [a 1], Michele Colucci [a 1], Etienne Nigron [b], Arnaud Guertin [c], Mariagabriella Marrella [a d], Ferid Haddad [b c], Flavia Groppi [a], Simone Manenti [a]

Journal of Physics G: Nuclear and Particle Physics

PAPER • OPEN ACCESS

Nuclear cross-section of the ^{nat}Eu(α, x) reactions up to 65 MeV: focus on the production of theranostic radioisotopes of terbium

Michele Colucci*, Etienne Nigron, Ferid Haddad, Arnaud Guertin, Eugenio Gibertini, Luca Magagnin, Flavia Maria Groppi Garlandini and Simone Manenti

Published 13 November 2025 • © 2025 The Author(s). Published by IOP Publishing Ltd

Applied Radiation and Isotopes
Volume 226, December 2025, 112106

First cross section measurement of the ^{49}Ti(p,x)^{47}Sc nuclear reaction and coproduced ^{43}Sc, ^{44m,g}Sc, $^{46g+m}$Sc, ^{48}Sc, ^{48}V, ^{43}K radionuclides

Lucia De Dominicis [a b], Sara Cisternino [b], Laura De Nardo [a c], Juan Esposito [b], Ferid Haddad [d e], Laura Meléndez-Alafort [f], Etienne Nigron [d], Gaia Pupillo [b], Liliana Mou [b]

Applied Radiation and Isotopes
Volume 225, November 2025, 112079

Cross section measurements with enriched ^{50}Ti targets for the production of the theranostic ^{47}Sc and its contaminants ^{46}Sc, ^{48}Sc, and ^{48}V

Lucia De Dominicis [a b], Gaia Dellepiane [c], Saverio Braccini [c], Sara Cisternino [b], Juan Esposito [b], Ferid Haddad [d e], Etienne Nigron [d], Gaia Pupillo [b], Liliana Mou [b]

Applied Radiation and Isotopes
Volume 229, March 2026, 112375

Measurements of the proton-induced reaction ^{155}Gd(p,n)^{155}Tb at energies between 7 and 26 MeV with highly-enriched ^{155}Gd targets

Morgane Bouteculet [a b], Charles-Olivier Bacri [a b], Marie-Alix Duval [a b], Hervé Lefort [a b], Radomír Běhal [c], Anastasia Cassisa [c], Alkiviadis Gourgiotis [d], Vadim Glagolev [c], Arnaud Guertin [e], Ondřej Lebeda [c], Xavier Ledoux [f], Jaromír Mrázek [c], Etienne Nigron [g], Jean-Charles Thomas [f], Eva Šimečková [c]

Applied Radiation and Isotopes
Volume 227, January 2026, 112263

Deuteron-induced nuclear reactions to produce ^{177}Lu: Extension of cross-sections data up to 33 MeV and impact on purity

E. López-Melero [a], E. Nigron [b], F. Haddad [b c], J. Praena [a]

Cornell University

We gratefully acknowl

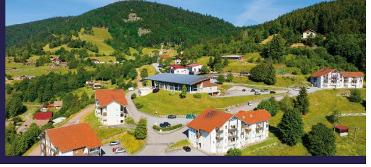
arXiv > physics > arXiv:2602.12836

Physics > Instrumentation and Detectors

[Submitted on 13 Feb 2026]

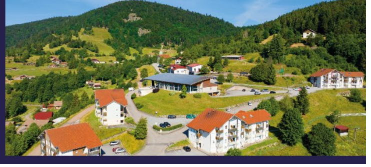
Measurements of absolute gamma-ray energies using an ultra-high energy resolution magnetic microcalorimeter

Matias Rodrigues, Mostafa L. Zahir, Martin Loidl, Lucille Chambon, Quentin Drenne, Michael Müller, Sebastian Kempf, Etienne Nigron, Ferid Haddad



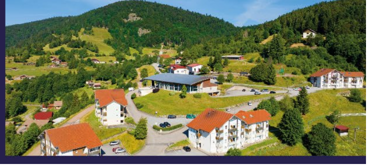
Data collected: proton beam

Ac-225 from Th-232(p,x)	C. Duchemin et al, Phys Med Biol **60** (2015) **931-946**
Ra-223 from Th-232(p,x)	C. Duchemin et al, Phys Med Biol **60** (2015) **931-946**
Fission fragment distribution from Th-232(p,x)	V. Métivier et al, EPJ Web of Conf. **146** (2017) **08008**
Dy-155/Tb-155 from Tb-159	R. Formento Cavaier, Radiat Phys and Chem 224 (2024) 112069
Dy-157,159, Gd-151,153, Tb-153,154m1,154m2,156	
Tb-155 new data set for $^{h.e.155}$Gd(p,x)	M. Bouteculet et al, Appl Radiat Isot **213** (2024) **111485**
	M. Bouteculet et al, Appl Radiat Isot **229** (2026) **112375**
Tb-149 from Gd-nat(p,x)	R. Formento Cavaier, PhD thesis (2019)
Tb-150,151,152,153,154,154m2,155,156	Nucl Instr Meth Phys Rev B **478** (2020) **174-181**
Cu-67 from Zn-68(p,2p)	G. Pupillo et al., Nucl Instr Meth Phys Res B **415** (2018) **41-47**
Ga-67 from (p,2n), Ga-66 from (p,3n)	
Cu-67 and Cu-64 from Zn-70(p,x)	G. Pupillo et al., Radiochimica Acta **108** (2020) **593-602**
Ga-67, Ga-66, Zn-65 and Zn-69m	
Sc-47,Sc-44m,Sc-44 from V-nat(p,x)	G. Pupillo et al., Il Nuovo Cimnto **42 C** (2019) **139**
Sc-48,46,43, K-43,42 ,V-48, Cr-51,49,48	G. Pupillo et al., J Radioanal Nucl Chem **322** (2019) **1711**
Sc-47,Sc-44m,Sc-44 from Ti-48(p,x)	F. Barbaro et al., Phys. Rev. C **104** (2021) **044619**
Sc-47,Sc-46, Sc-44m, Sc-44g, Sc-43, V-48	L. Mou et al., Pharmaceuticals **17** (2024) **26**
Sc-47 first set of data from Ti-49(p,x)	
Sc-43,44m,44g,46g,46m,48, V-48, K-43	L. de Dominis et al., Appl Radiat Isot **226** (2025) **112106**
Sc-47 from enriched Ti-48,49,50	L. de Dominis et al., ND2025 oral presentation (2025)
Sc-43 from V(p,x)	G. Pupillo et al., Nucl Instr Meth Phys Res B **464** (2020) **32-35**
Monitor reactions on Ti, Ni and Cu	E. Garrido et al., Nucl Instr Meth Phys Res B **383** (2016) **191-212**



Data collected: deuteron beam

Pa-230 for U-230/Th-226 New data set for Th-232(d,x)	C. Duchemin et al., Nucl Med Biol **41** (2013) **19-22**
Fission fragment distribution from Th-232(d,x)	V. Métivier et al, EPJ Web of Conf. **146** (2017) **08008**
Pb-203 from Tl-205(d,4n)	T. Sounalet et al., Appl Radiat Iso **205** (2024) **111190**
Hg-197m New data set for Au-197(d,x)	E. Nigron, PhD thesis 2019, to be published
Re-186g New data set for W-186(d,x)	C. Duchemin et al, Appl Radiat Isot **97** (2015) **52-58**
Lu-177cum,g+m from Yb-nat(d,x) Lu-176cum,175cum,174g+m,m,g,173,172g+m,171g+m,170g+m,169cum,g+m,Tm-167,168	M. E. Lopez Melero, Appl Radiat Isot **227** (2026) **112263**
Tb-161 from Gd-160(d,n)	E. Nigron et al., Appl Radiat Iso **200** (2023) **110927**
Tb-155 New data set for Gd-nat(d,x)	C. Duchemin et al, Appl Radiat Isot **118** (2016) **281-289**
Tb-155,156,160,161 from Dy-nat(d,x)	M. Colucci et al., Eur Phys Jour Plus **137** (2022) **1180**
Tb-155 from Gd-155(d,2n)	Y. Wang et al. Appl Radiat Isot **201** (2023) **110996** V. Rhoden et al. **WTTC19** (2024)
Rh-105 New data set for Ru-104(d,x)	M. Sitarz, PhD thesis 2019
Cu-67 New data set for Zn-70(d,x)	E. Nigron, PhD thesis 2019 and Front. Med. **8** (2021) **674617**
Cu-61 from Ni-nat(d,x)	L. Puren et al., Proceedings ND2025 (2025) **in review**
Mn-52g from Cr-nat(d,x)	F. Bianchi et al., Appl Radiat Isot **166** (2020) **109329**
Sc-44 New data set for Ca-44(d,x)	C. Duchemin et al, Phys Med Biol **60** (2015) **6847-6864**
Monitor reactions on Ti, Ni	C. Duchemin et al, Appl Radiat Isot **103** (2015)**160-165**



Data collected: alpha beam

Tm-165/Er-165 from Ho-165
Tm-166,167

E. Nigron et al. , CYCLEUR oral pres. (2025) article **in preparation**

Tb-155 from Eu-nat(α,x)
Tb-156,154,153,152,151,150,149

M. Colucci et al., Journal of Physics G **52** (2025) **115102**

Sn-117m New data set from Cd-116(α,x)
Sn-110,113, In-109,110g,111,114m1+m2 Cd-115g

C. Duchemin et al, Appl. Radiat. Isot. **115** (2016) **113-124**

Ag-111 from Pd-nat(α,x)
Ag-105,106,110m

L. Puren et al., Proceedings ND2025 **in review**

Mo-99 New data set from Zr-96(α,n)

G. Pupillo et al., J. Radioanal. Nucl. Chem. **302** (2014), 2, **911-917**

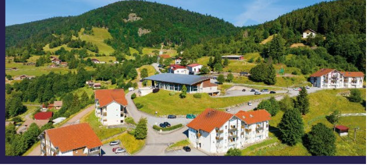
Ru-97 New data set from Mo-nat(α,x)
Zr-89, Tc-95g,96, Mo-99

M. Sitarz et al, Instruments **3** (2019) **7**

Cu-61 from Co-59(α,2n)
Cu-60, Co-61

M. Colucci et al., Appl. Radiat. Isot. **229** (2026) **112377**

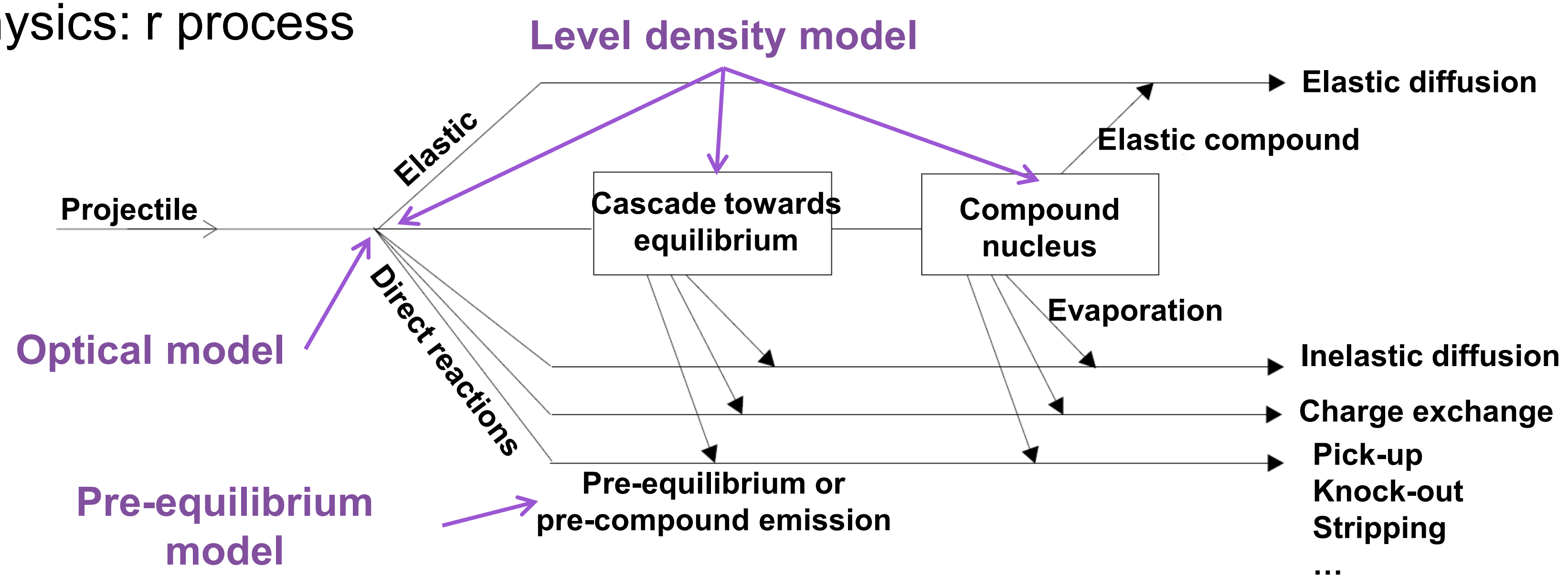
Monitor reactions on Cu, Ti, Ni



Fundamental and applied research

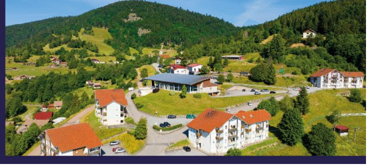
Activation of materials for both applied and basic research, especially with alpha particles

- ✓ Nuclear data: cross section measurements, comparison with nuclear model calculations
  - Reaction mechanism, excitation function, isomeric cross section
- ✓ Radioisotope production
  - Optimum production, minimization of impurities
  - Realistic dose calculation
- ✓ Nuclear structure data: high-spin level
- ✓ Astrophysics: r process



Adapted from S. Benck, PhD thesis, 1999

⇨ Influence on the calculated production cross section values



Activities framework

GIP ARRONAX possesses 2 cyclotrons:

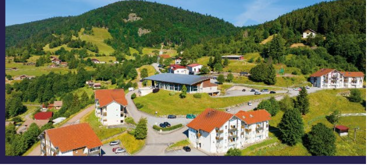
- a versatile C70XP cyclotron allowing a wide range of radionuclide production as well as irradiation research.
- a Kiube-180 cyclotron, IK18, under final commissioning

GIP ARRONAX and PRISMA are developing and producing radionuclides but also radiopharmaceuticals for research in nuclear medicine

PRISMA is also working on:

- Which isotopes for tomorrow's nuclear medicine?
    - Systematic cross section measurements => impact on modeling
- Hadronbiology at very high dose rates
- Detection, ion beam analysis
- Mass separation coupled with laser ionisation

These work can only be achieved through **collective work at all scales** (local, national and international) and with all partners (academia and industry)



Thank you

Thank you for your attention

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