Exotic cyclotrons for innovative radionuclides

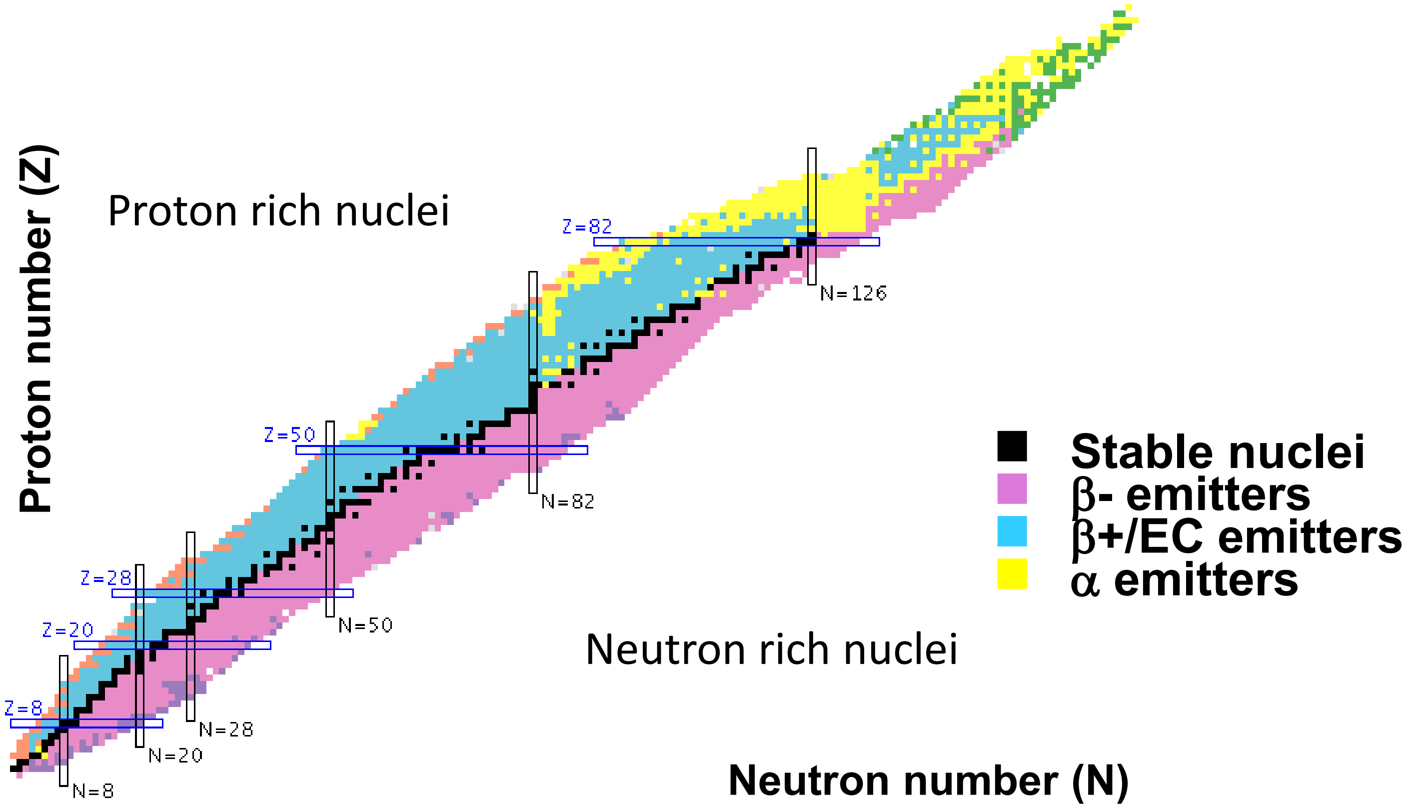
The ARRONAX cyclotron example

Dr Nathalie Michel on behalf of the ARRONAX team and the PRISMA team

Radionuclides for nuclear medecine

Highly penetrating radiations for diagnostic (X, γ , β^{+})

Low penetrating radiations for therapy (α, β-, Auger e-)



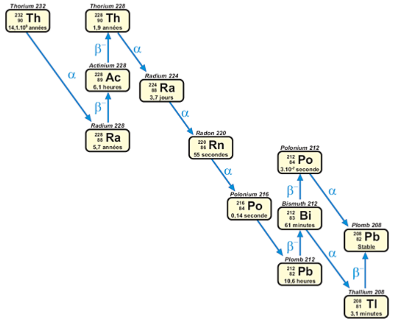
Where medical radionuclides are coming from ?

Few can be extracted directly from « nature » :

Those belong to radioactive decay chain of heavy nuclei

^{223}Ra: belongs to the radioactive chain of ^{235}U.
Xofigo® ($RaCl_2$) available for bone metastases.

^{212}Pb/^{212}Bi: belongs to the radioactive chain of ^{232}Th

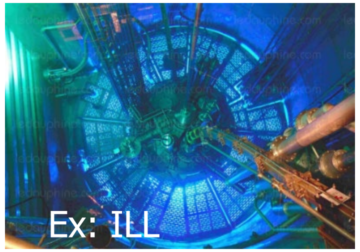


^{225}Ac : belongs to the radioactive chain of ^{233}U

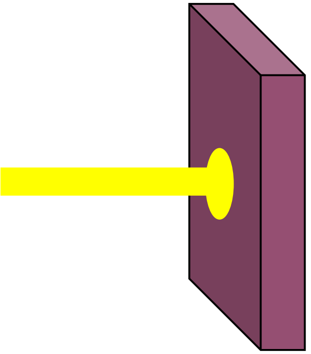
Where medical radionuclides are coming from ?

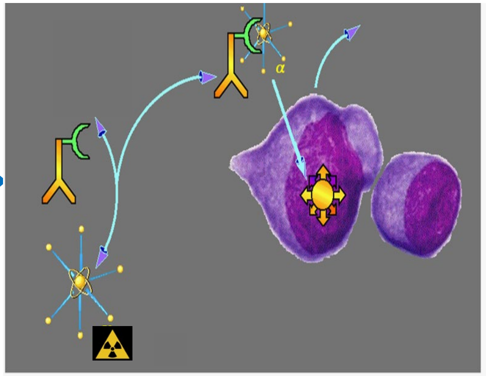
Otherwise they are artificially produced in reactors/accelerators

Nuclear Reactors



Extraction





Target irradiation

Synthetic drugs

Medical use

Accelerators: Cyclotrons or Lineac

Where medical radionuclides are coming from ?

PRISMA Physics of Radiation InteractionS with Matter and Applications

Reactors vs cyclotrons

- *Reactor advantages*

High yield

Low cost production

Ease of target preparation

- *Cyclotron advantages*

Easier supervision, safety

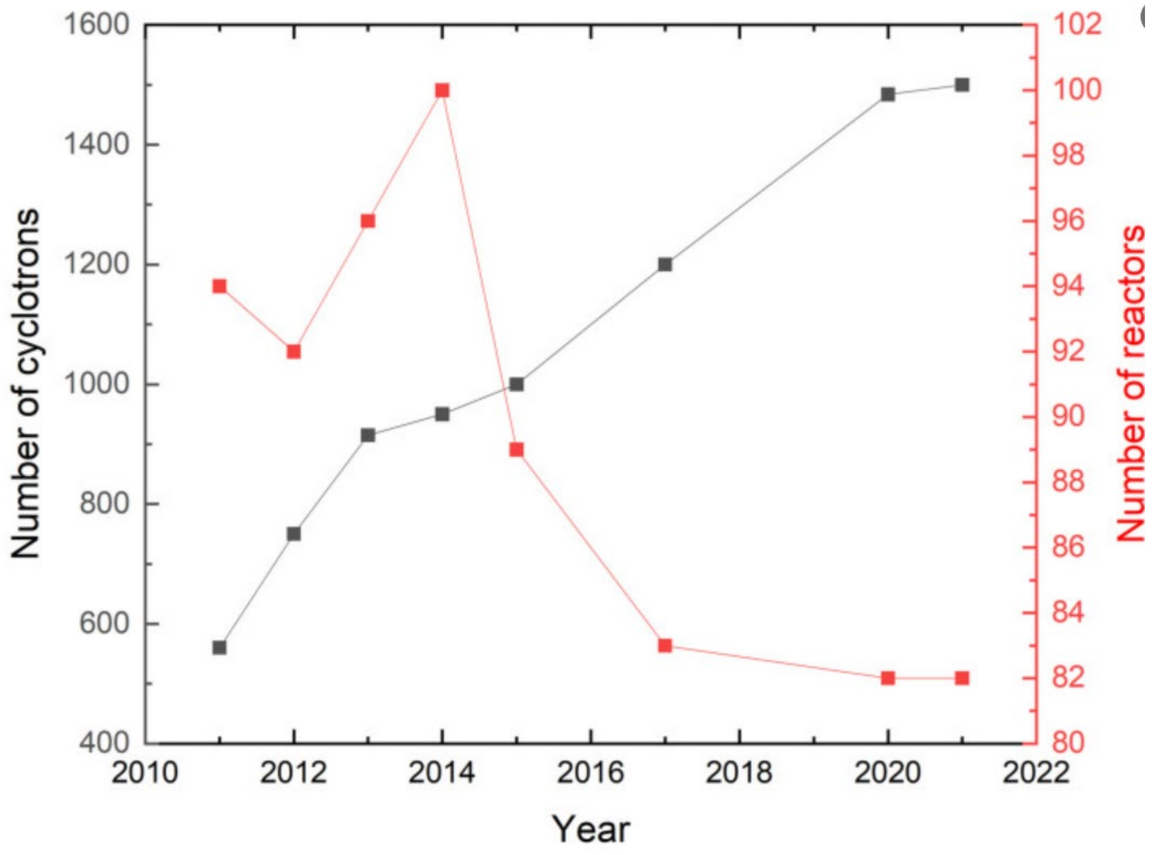
Maintenance and decommissioning costs lower

Radioactive waste less than 10% of the amount by reactor

Lower radiation level

No risk of nuclear proliferation

- *They are complementary*



Source : Wang et al *

Wang Y, Chen D, Augusto RDS, Liang J, Qin Z, Liu J, Liu Z. Production Review of Accelerator-Based Medical Isotopes. Molecules. 2022 Aug 19;27(16):5294. doi: 10.3390/molecules27165294.

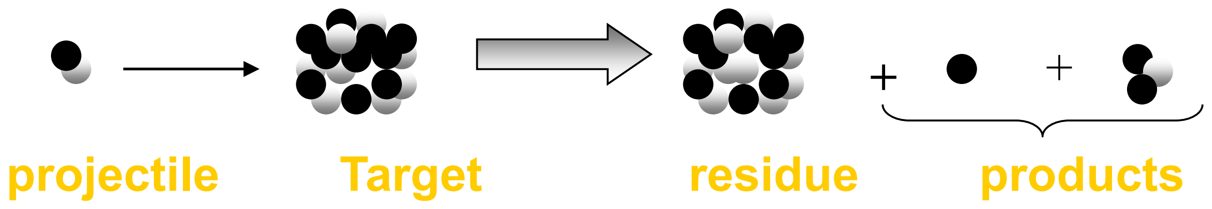
How to choose the best irradiation conditions ?

Identify all possible production route: different projectile/energy/target combinations

Select the most promising one based on production yield, contaminants, costs …

Remark:
Target material are often chosen amongst stable or very long lived radionuclides.

Reminder



It is mandatory to fulfil physics laws:

- Charge conservation and mass conservation
- Energy conservation → an energy threshold exists in most cases

Few examples for medical radionuclides:

$p + {}^{18}O \rightarrow {}^{18}F + n$ $E_{threshold} = 2{,}574$ MeV

$a + {}^{209}Bi \rightarrow {}^{211}At + 2n$ $E_{threshold} = 20{,}718$ MeV

$n + {}^{176}Yb \rightarrow {}^{177}Yb + \gamma$ $E_{threshold} = 0$ MeV

$\gamma + {}^{68}Zn \rightarrow {}^{67}Cu + p$ $E_{threshold} = 9{,}977$ MeV

There is not one fit all cyclotrons

^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{64}Cu

^{67}Ga, ^{111}In, ^{123}I, ^{201}Tl, ^{68}Ge

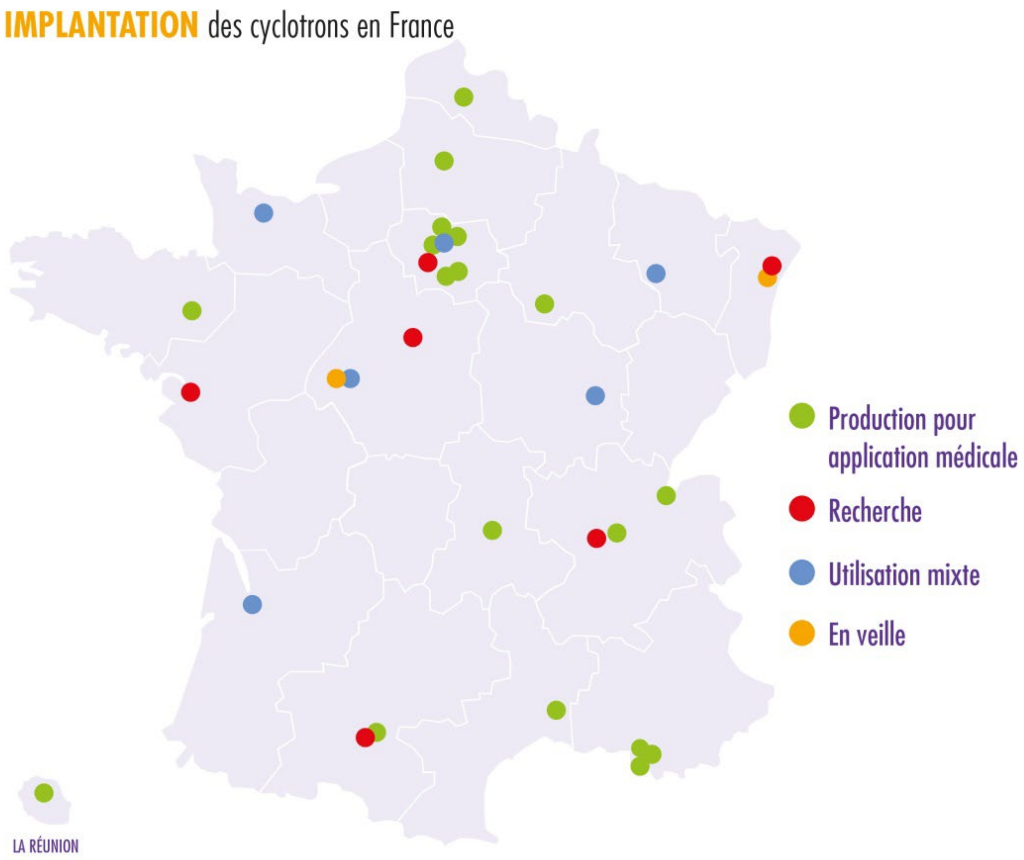
^{82}Sr, ^{117m}Sn

Type	The Energy of Particles [MeV]	Application
Small medical cyclotron	<20	Short-lived radioisotopes for PET
Medium-energy cyclotron	20–35	Production of SPECT and some PET radioisotopes
High-energy cyclotron	>35	Production of radioisotopes for therapy

Source : Wang et al *

**Wang Y, Chen D, Augusto RDS, Liang J, Qin Z, Liu J, Liu Z. Production Review of Accelerator-Based Medical Isotopes. Molecules. 2022 Aug 19;27(16):5294. doi: 10.3390/molecules27165294*

Medical cyclotrons in France

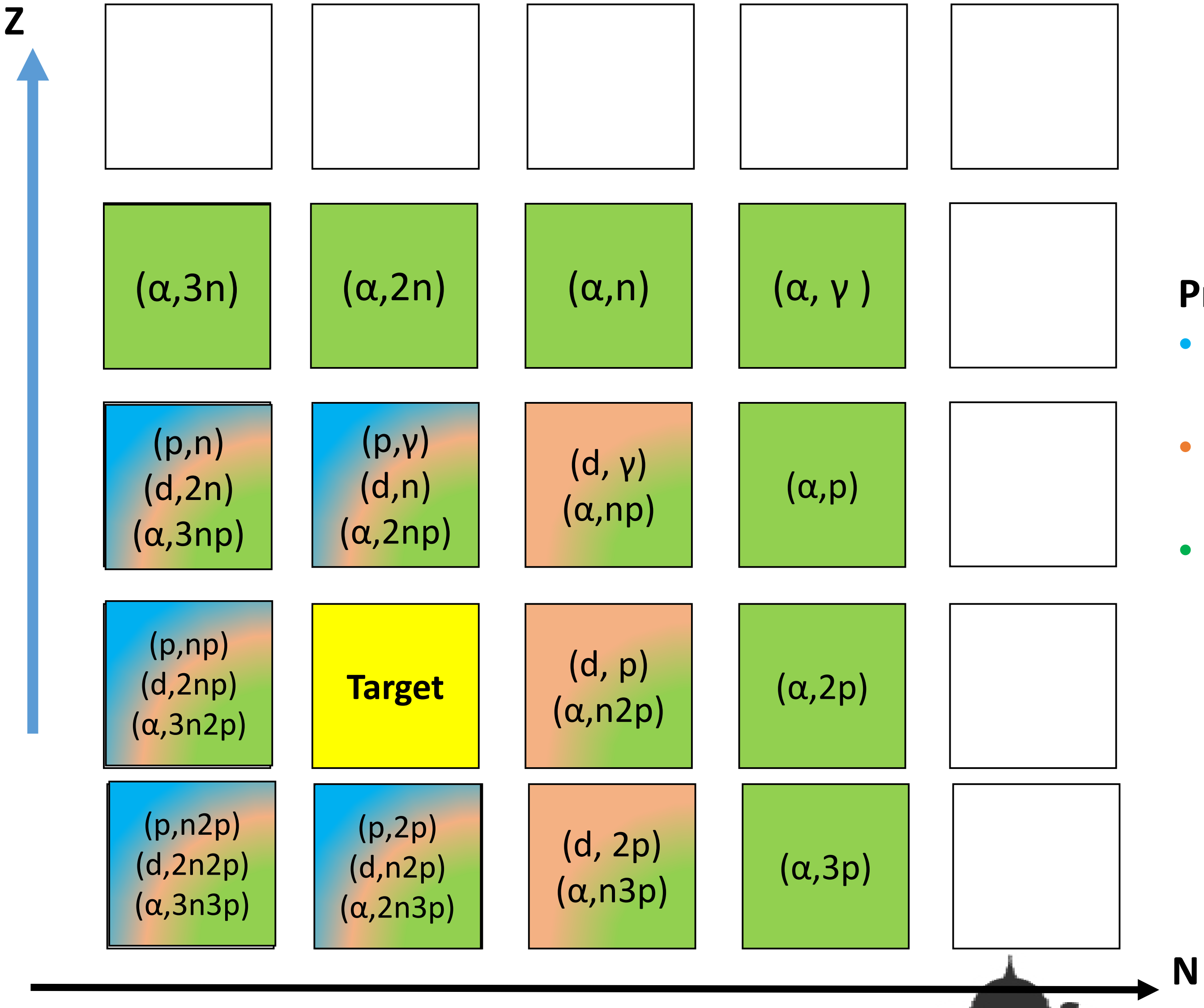


Source ASN - 2016

One 70 MeV
Two 30 MeV
Others are 18/24 MeV

Nuclear reactions

By changing the projectile and its incident energy, one can enlarge the choice of radionuclide that can be produced using a given target/energy couple



Projectiles:

- **Blue: proton**
- **Orange: deuteron**
- **Green: alpha**

Which parameters influence production yield ?

Irradiation conditions

Radioactive decay

Cross section

Produced activity (Bq)

$$Act = \Phi \cdot \chi \cdot \frac{Na.\rho}{A} \cdot \left(1 - \exp(-\lambda . t_{irr})\right) \cdot \int_{E_{fin.}}^{E_{in.}} \frac{\sigma(E)}{\frac{dE}{dx}} \cdot dE$$

Target properties

Which parameters influence production yield?

✓ Irradiation conditions : particle, beam energy, beam intensity, irradiation time

Projectiles are losing energy in the target

- Target heating

✓ Selecting the nuclear reaction and energy range to have the highest cross section value

✓ Target properties: increasing number of atoms

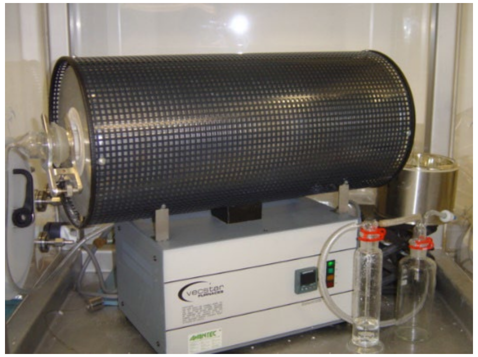
- By using a thicker target
- By using enriched material

Contaminants are a limiting factor for production

- Non isotopic contaminants can be eliminated by chemistry

Classical chemistry (chromatography using resin or liquid/liquid extraction …)

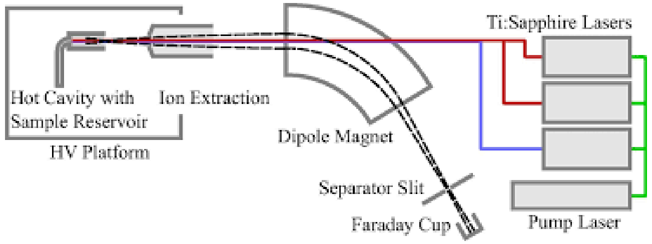
Dry chemistry



- Production of isotopic contaminants are controlled through a combination of
  - The use of highly enriched target material (when possible)
  - Choosing the adequate projectile energy/target thickness
  - Choosing different nuclear reaction as (d,x), (α,x) … or even indirect reactions
  - Using decay if half lives are different

However, this is not always sufficient

Mass separation can be another way to gain in purity.



ARRONAX: a cyclotron that enlarges the scope of possible

Beam	Accelerated particles	Energy range (MeV)	Intensity (eµA)	Dual beam
Proton	H-	30-70	<375	Yes
	HH+	17	<50	No
Deuteron	D-	15-35	<50	Yes
Alpha	He++	68	<70	No

Main characteristics:

Multi-particles
High energy
} enlarge the scope of possible nuclear reactions for isotope production

High intensity
→ low cross section phenomena achievable
→ Neutron source with industrial capabilities possible

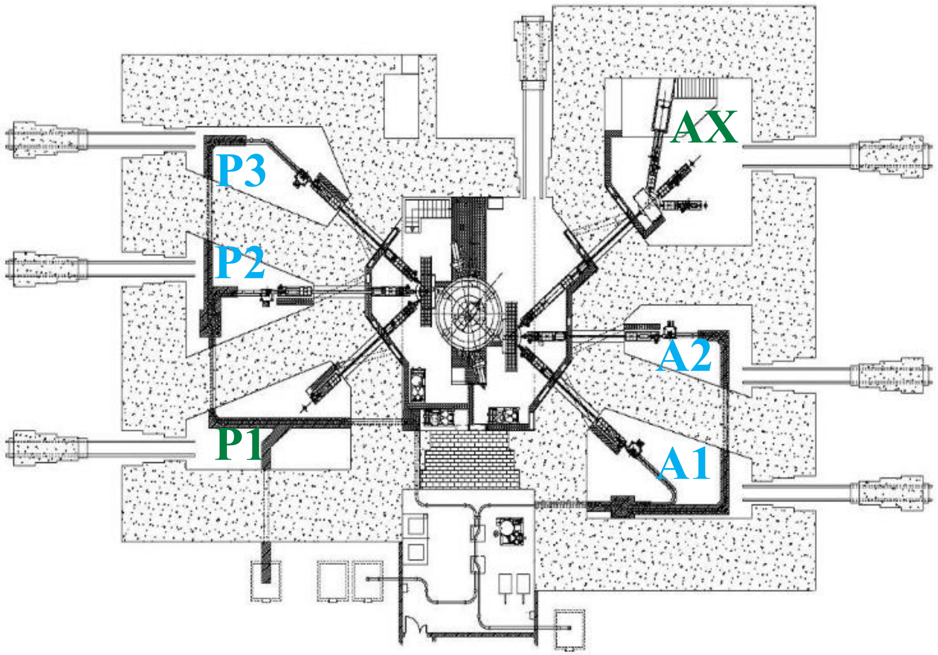
ARRONAX: a cyclotron that enlarges the scope of possible

A versatile facility:

4 Vaults devoted to isotope production and connected to ***hot cells*** through a **pneumatic system**

Vault **P1** to accommodate soon a 18 MeV accelerator for ^{64}Cu production

Vault **AX** devoted to physics, radiolysis and radiobiology experiments



ARRONAX: a cyclotron that enlarges the scope of possible

A range of laboratories: radiochemistry, biochemistry, radiolabelling, cell culture, chemical analysis, nuclear metrology, quality control, etc.

Example 1 : the theranostic radionuclide pair ^{64}Cu/ ^{67}Cu at ARRONAX

Motivations

A New trend in medicine: personalized treatment to specific cancer profile

Theranostic is a treatment strategy that combines therapeutics with diagnostics.

→ Use of a **pair of radionuclides** to make dosimetry prior therapy and/or see patient response

Several pairs have been identified:

$^{44}Sc/^{47}Sc$, $^{64}Cu/^{67}Cu$, $^{124}I/^{131}I$, $^{152}Tb/^{161}Tb$,...

Copper isotopes are good candidates with well known chemistry:

^{64}Cu ($T_{1/2}$ = 12.7h) can be produced quite easily

^{67}Cu ($T_{1/2}$= 61.8h) is well suited for targeted therapy

Copper 64

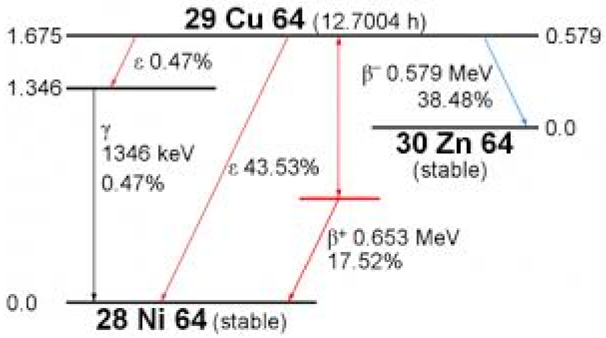
Main characteristics :

- + Positron emission 17.52%
- + $T_{1/2}$ = 12.7 h

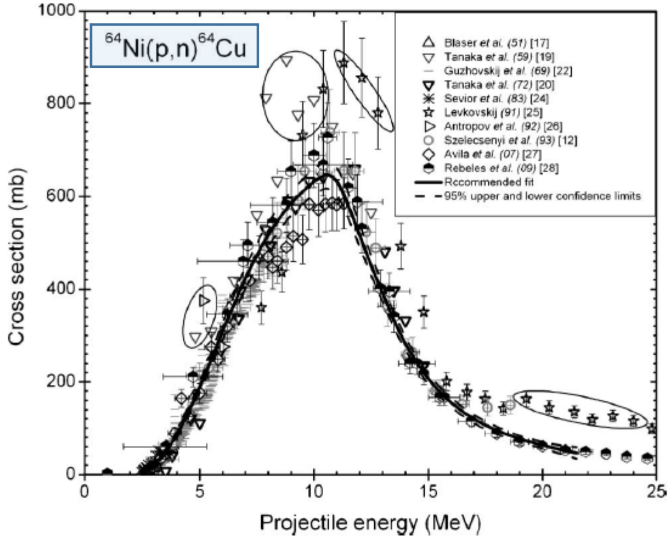
Application : PET imaging, therapeutic applications?

Main Production route : $^{64}Ni + p \rightarrow {}^{64}Cu + n$

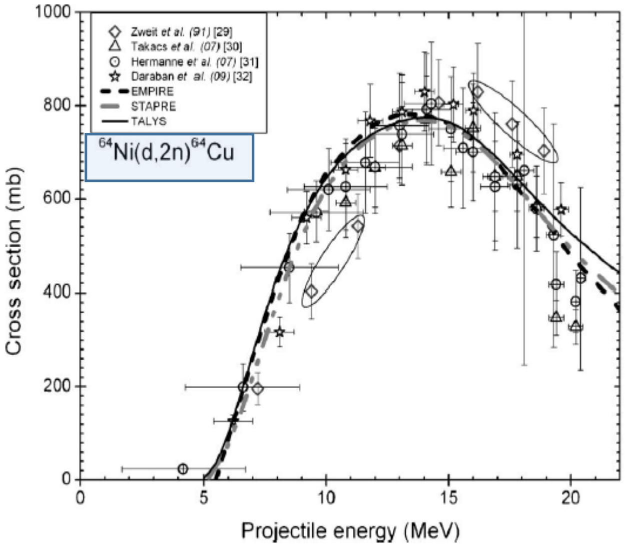
Alternative production route : $^{64}Ni + d \rightarrow {}^{64}Cu + 2n$



Max cross section around 12 MeV



Max cross section around 15 MeV



Deuteron route ^{64}Ni(d,2n) is competitive with (p,n) and we use it.
Irradiation twice a month

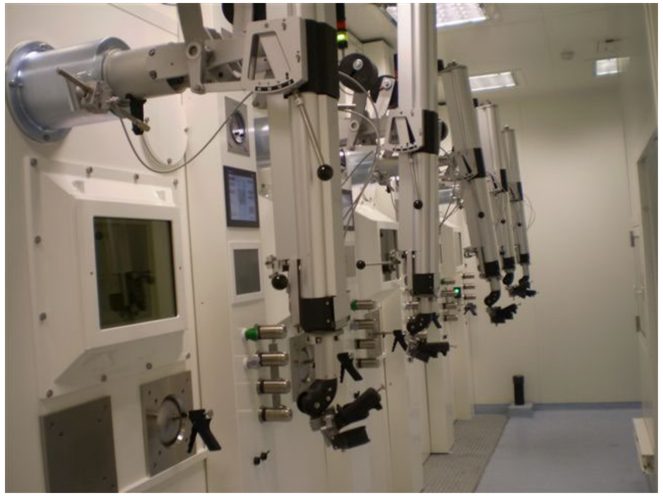
We are part of a Cu-64 intercomparison setup by PRISMAP (DTU, PSI, Arronax, Polatom)

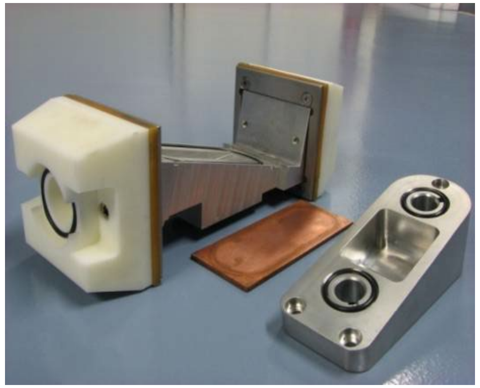
Which target for Copper 64 production ?

Dedicated target station

Pneumatic transportation

Processing hot cells





Target tilted at **15 °**
Beam diameter is 20 mm→ **target area 14 cm²**

Which target for Copper 64 production ?

Target at 15° allows to increase the heat exchange surface area

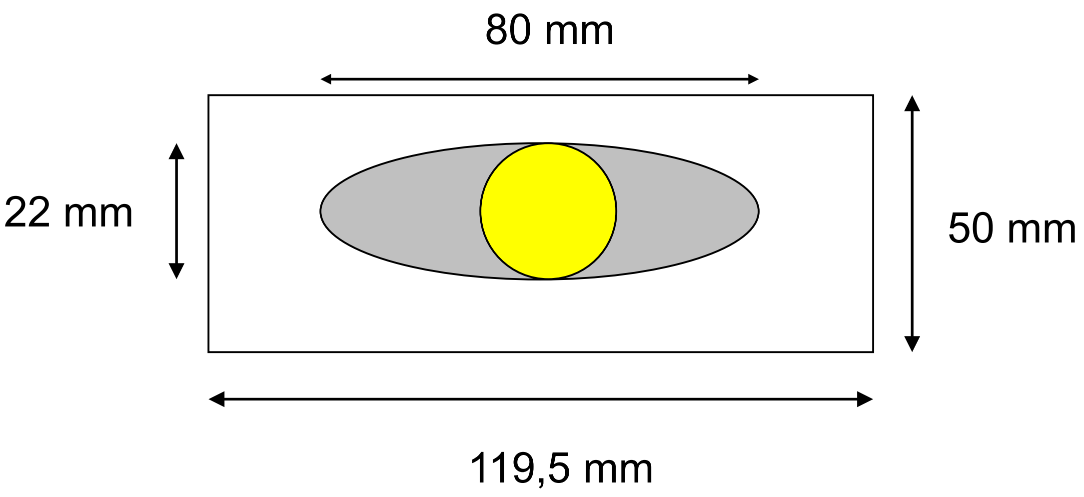
$$[W/mm^3] \quad P = \frac{dE}{dx} . i$$

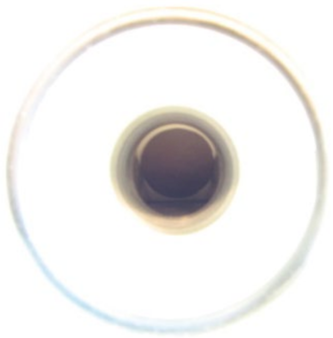
$$\left(\frac{dE}{dx}\right)_{moyen} \quad [MeV/mm] \quad \text{(obtained by SRIM)}$$

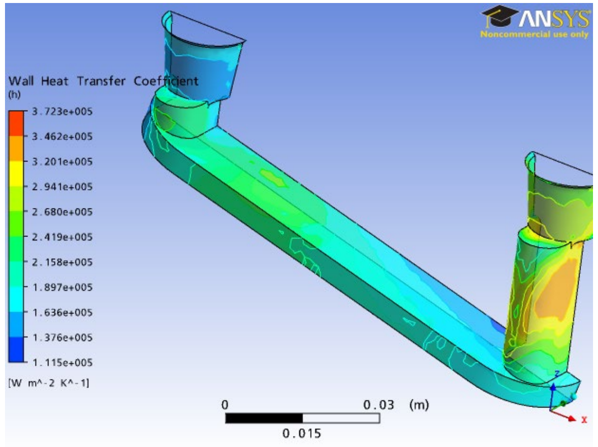
$$i = I/S \quad [\mu A/mm^2]$$

Power deposition decreases if target is tilted

Target area = 14 cm² instead of 4 cm² with same amount of material







Which target for Copper 64 production ?

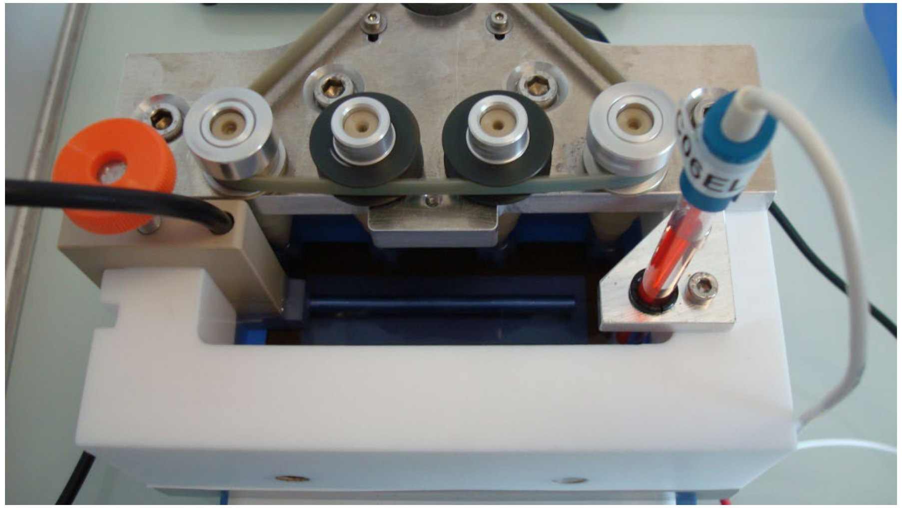
Thickness deposit - (p,n) vs (d,2n) : Production yields

Nuclear reaction	Energy range (MeV)	Calculated Yield (MBq/µAh)	Target thickness (µm)	Target thickness at 15°(µm)
$^{64}Ni(p,n)^{64}Cu$	12→9	**228**	120 µm	31.05 µm
$^{64}Ni(d,2n)^{64}Cu$	16→13	**206**	90 µm	23.29 µm

Comparable production yield can be achieved with thinner deposit of ^{64}Ni in the deuteron case
→a lower initial cost of ^{64}Ni

Copper 64: target

Electroplating :
[Ni] at 8g/L
Adjusted pH with NH_4OH



Target:
Enriched (>99%) ^{64}Ni
Electroplated on a gold backing (99,99% purity)
Thickness possible until 50 µm

Copper 64: (d,2n) molar activity

Co-produced isotopes are different:

For the (d,2n) → (d,n)^{65}**Cu**
(d,3n)^{63}**Cu**
(d,p)^{65}**Ni** ($T_{1/2}$= *2.52h*)
decays to ^{65}**Cu**

63Cu STABLE 69.15%	64Cu 12.701 H ε: 61.50% β-: 38.50%	65Cu STABLE 30.85%	66Cu 5.120 M β-: 100.00%
62Ni STABLE 3.6346%	63Ni 101.2 Y β-: 100.00%	64Ni STABLE 0.9255%	65Ni 2.5175 H β-: 100.00%
61Co 1.650 H β-: 100.00%	62Co 1.50 M β-: 100.00%	63Co 27.4 S β-: 100.00%	64Co 0.30 S β-: 100.00%

To determine the impact of these isotopes on the final product we use:

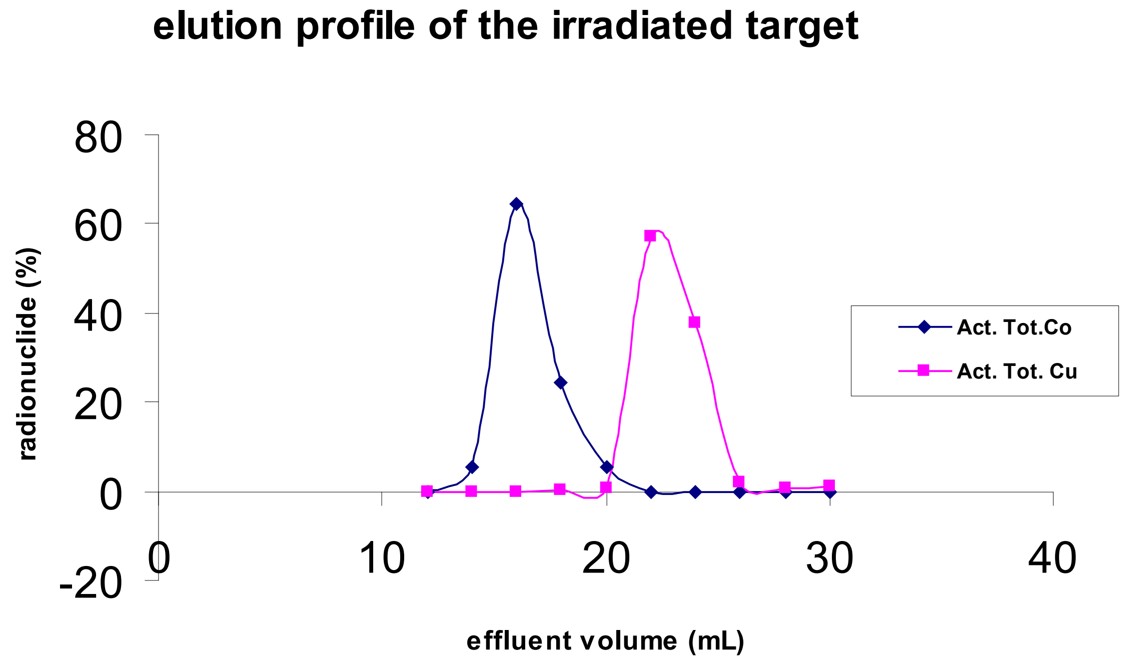
- Data from NNDC for radioactive isotopes
- TALYS code calculation for stable isotopes

http://www.talys.eu/

For (d,2n) at 16 MeV, 1h, 1µA, we calculate **3.8 atoms of ^{64}Cu** for 1 atom of cold copper (EOB) → **Acceptable**

Copper 64: purification / Co impurities

Chemistry: *dissolution in HNO_3, purification using chromatographic resin AG1X8*



^{64} Ni is recovered (the recovery yield around 95%) for reprocessing.

Copper 64: quality control

Typical irradiation conditions :

90µA deuteron beam on target
16 MeV
Deposit thickness: 10µm
Duration: one night

Radioisotopic purity: >99.90%
concentration: >890 MBq/mL

Radiochemical purity: Molar activity vs all metals (>10 MBq/nmol)
Main contaminants: Ni, Cu, Fe, Zn, Co

Activity distributed @ calibration time (26H after EOB) : 15 GBq

Certificate of analysis provided to the final user for 64 CuCl2

Certificat d'analyse

ARRONAX

Solution radiochimique de chlorure de cuivre-64

Site de production : CYCLOTRON ARRONAX, 1 rue aronnax CS 10112, 44817 Saint-Herblain cedex, France

La cuivre-64 est un radiochimique. Non destiné à l'usage humain

Definition

Solution de HCl 0.10±0.01 N, contenant du cuivre-64 sous forme de chlorure, dans un flacon de 3 mL

Production

Le cuivre-64 est produit par irradiation de deutons (64Ni(d,2n)) d'une cible de nickel-64 enrichi (minimum >98%) électrodéposé

Half-Life

12.701 heures

Numéro de lot : Cu64_220202

EOB (date/time) 1/2/22 6:37

Calibration Time (CT) : 2/2/22 8:00

Final media

Irradiation conditions :

- nuclear reaction used
- Target enrichment

Our reference time

Needed because we are dealing with radioactive species. Other reference time often defined :

- EOB : end of beam
- EOS : end of synthesis

Activity but also all derived quantities are dependent on that reference

Be careful when comparing products

Certificate of analysis provided to the final user for 64CuCl2

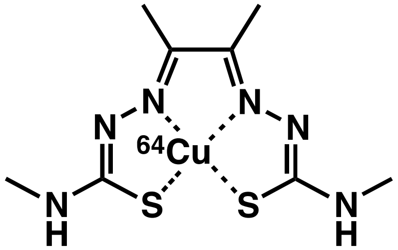
Caractéristiques	
Radioactive concentration	1250-3500 MBq/mL
Identification	présence du pic photoélectrique ayant une énergie de 1345,77 keV
Radionucleidic purity	$^{65}Ni/^{64}Cu$ $^{57}Co/^{64}Cu$ $^{58}Co/^{64}Cu$ $^{61}Co/^{64}Cu$
Chemical purity	Concentration totale des contaminants métalliques (<50ppm)
	Concentration toatle en cuivre (<25ppm)
Activité spécifique / Σmétaux	>10 MBq/nmol
Activité spécifique / Cu	>15 MBq/nmol
Apparence	limpide et incolore

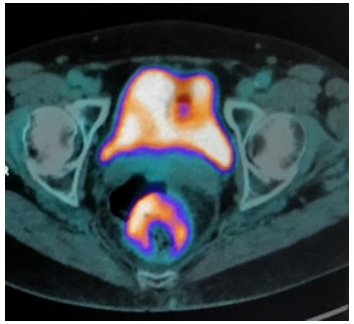
Potential dosimetry impact
(staff or patient)
Waste management

Copper 64: clinical trial

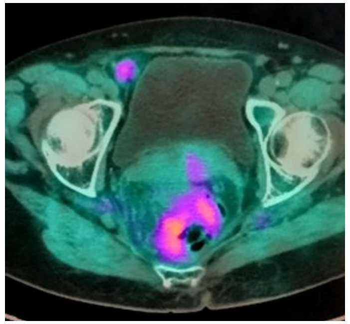
^{64}Cu-ATSM, a potential marker of hypoxia

Clinical trial: Evaluation of ^{64}Cu-ATSM PET-CT as a predictor of response to neoadjuvant therapy in locally advanced rectal cancers
29 patients included to date
5 French clinical centers: Nantes, Angers, Rennes, Brest, Rouen

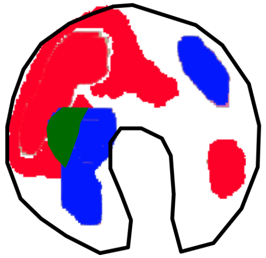




^{18}F-FDG



^{64}Cu-ATSM



^{18}F-FDG
^{64}Cu-ATSM
^{18}F-FDG / ^{64}Cu-ATSM

Work in progress

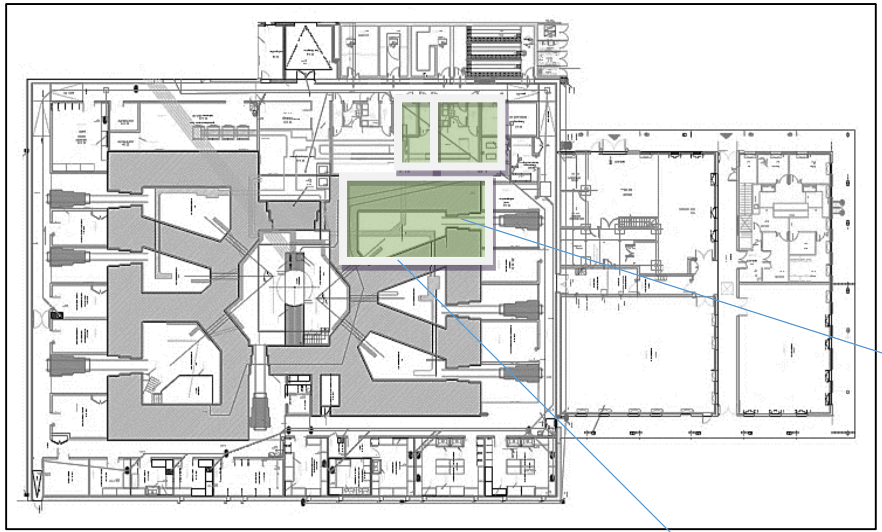
Copper 64: IK18 project

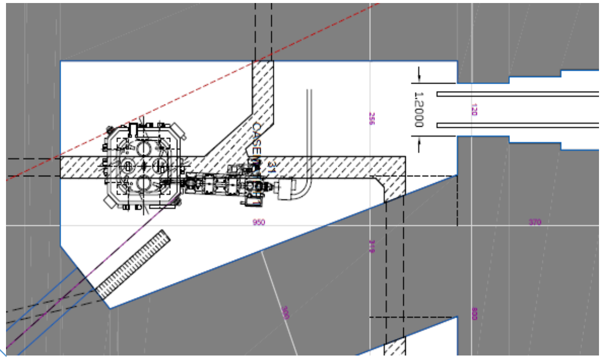
Physics of Radiation InteractionS with Matter and Applications

Acquire a 18 MeV accelerator to enlarge our production capabilities and free up beam time on the C70.

Cost effective :

- Use of an existing vault (P1)
- Use of existing radioprotection apparatus
- Use of existing hot cells





IBA Kiube selected
180 µA version
1 solid target station compatible with the existing system

Copper 67

Properties

- Half-life to match the **bio-distribution** time: 61.8 hours
- Chemical properties to attach to the **vector molecule**
- **Radiation types, energies and intensities** suitable for applications:
  SPECT, vectorized internal radiation therapy

$<E_\beta>$ (kev)	$E_{\beta max}$ (kev)	I_β (%)
121	377	57
154	468	22
189	562	20

E_γ (keV)	I_γ (%)
91.3	7.0
93.3	16.1
184.6	48.7

Production routes

Balance between :

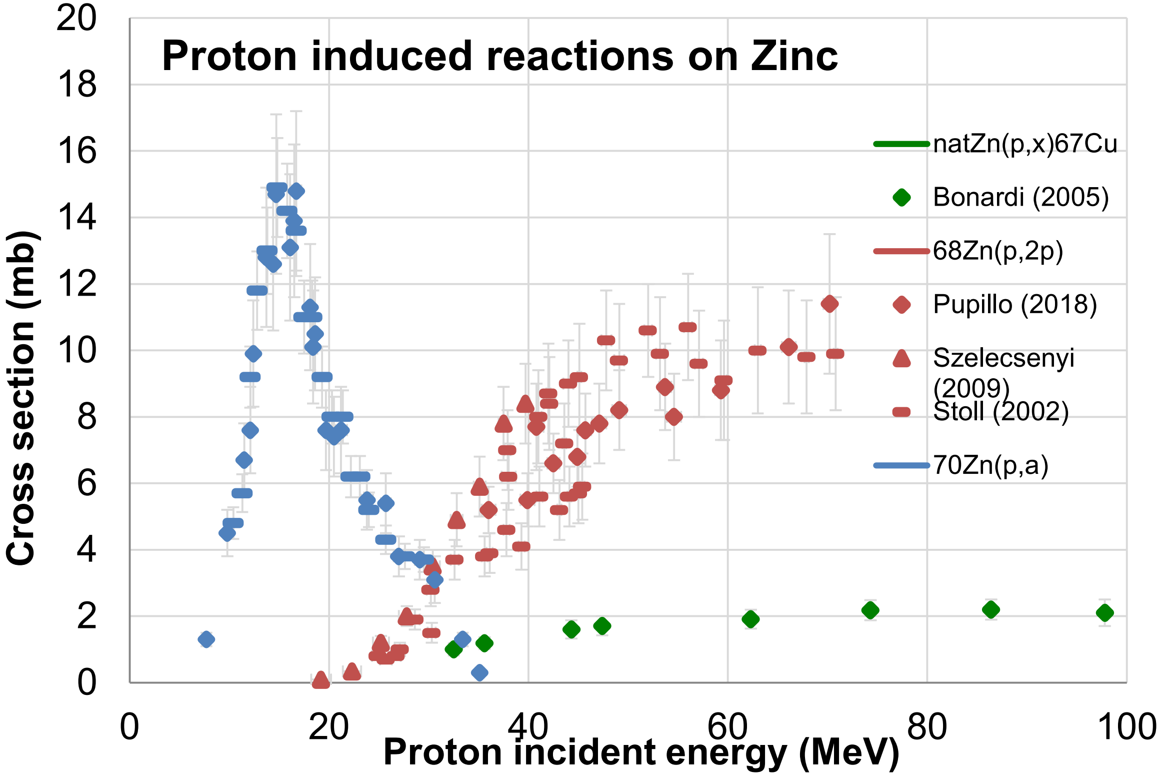
- Cross section
- Impurities coproduction : molar activity
- Target manufacturing and chemistry

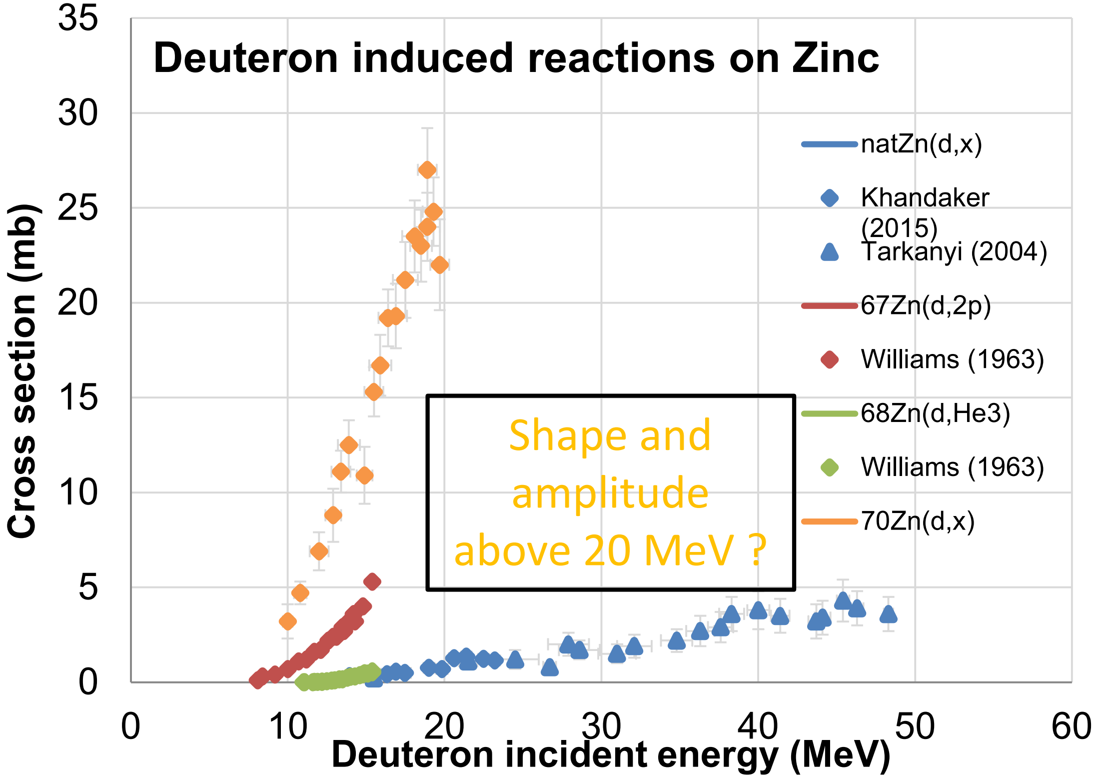
60	61	62	63	64	65
23.7 mn	3.3 h	9.7 mn	**Stable**	**12.7 h**	**Stable**
66	**67**	**68**	**68m**	**69**	
5.1 mn	**61.8 h**	30.9 s	3.7 mn	2.9 mn	

^{67}Cu production routes

Main possible production route on Zinc

^{64}Zn	^{66}Zn	^{67}Zn	^{68}Zn	^{70}Zn
48.3%	28%	4.1%	19%	0.6%





Low σ 2 mb, impurities ^{63,64,65}Cu
Better σ 10 mb, impurities ^{63,64,65}Cu
Low isotopic abundance, impurities ^{63,64,65}Cu

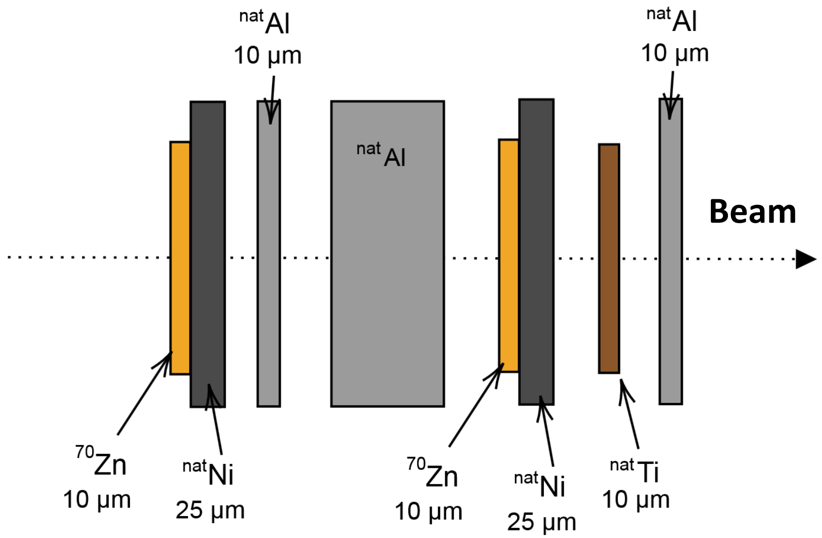
Low σ 5 mb, impurities ^{63,64,65}Cu
Low σ, impurities ^{63,64,65}Cu
Very low σ, impurities ^{63,64,65}Cu
Better σ, impurities ^{63,64,65}Cu

https://www-nds.iaea.org/radionuclides/zn867cu0.html

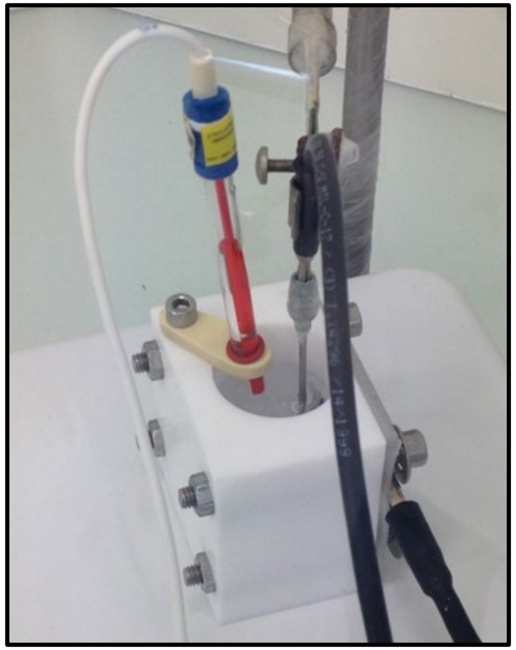
Target preparation and experiments

Electrodeposition of ^{70}Zn from ISOFLEX company on a ^{nat}Ni sheet @ GIP ARRONAX by T. Sounalet, PRISMA Team
Surface: 20x20 mm Thickness: approx. 10 µm

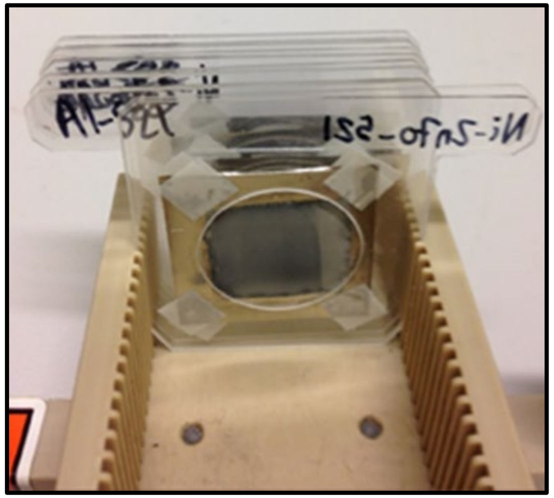
^{64}Zn	^{66}Zn	^{67}Zn	^{68}Zn	^{70}Zn
48.3%	28%	4.1%	19%	0.6%
0.1%	0.1%	0.1%	2.2%	97.5%



Stack



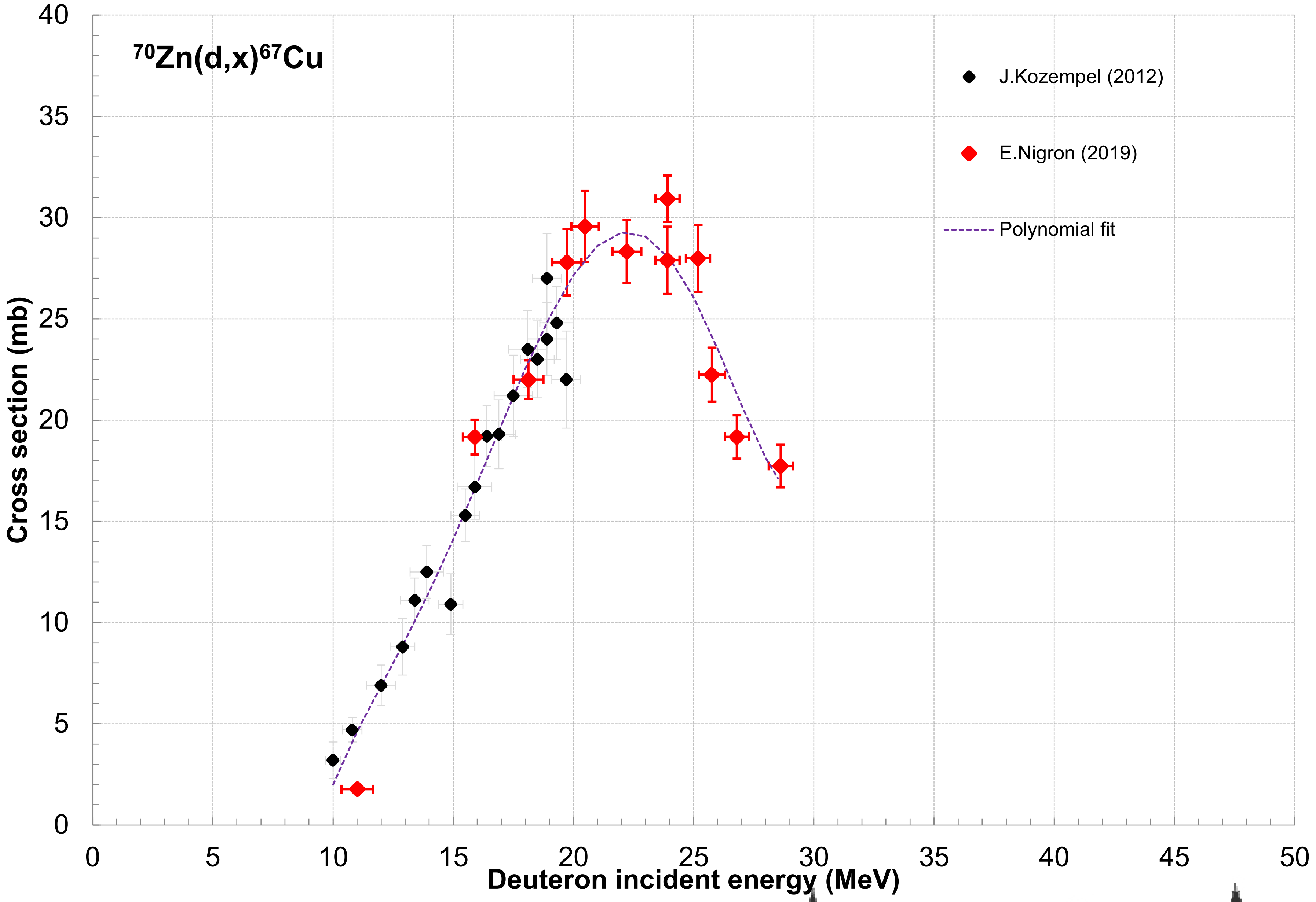
Electrodeposition setup



- 6 irradiations of 2 patterns
- under vacuum
- Faraday cup used for flux measurements

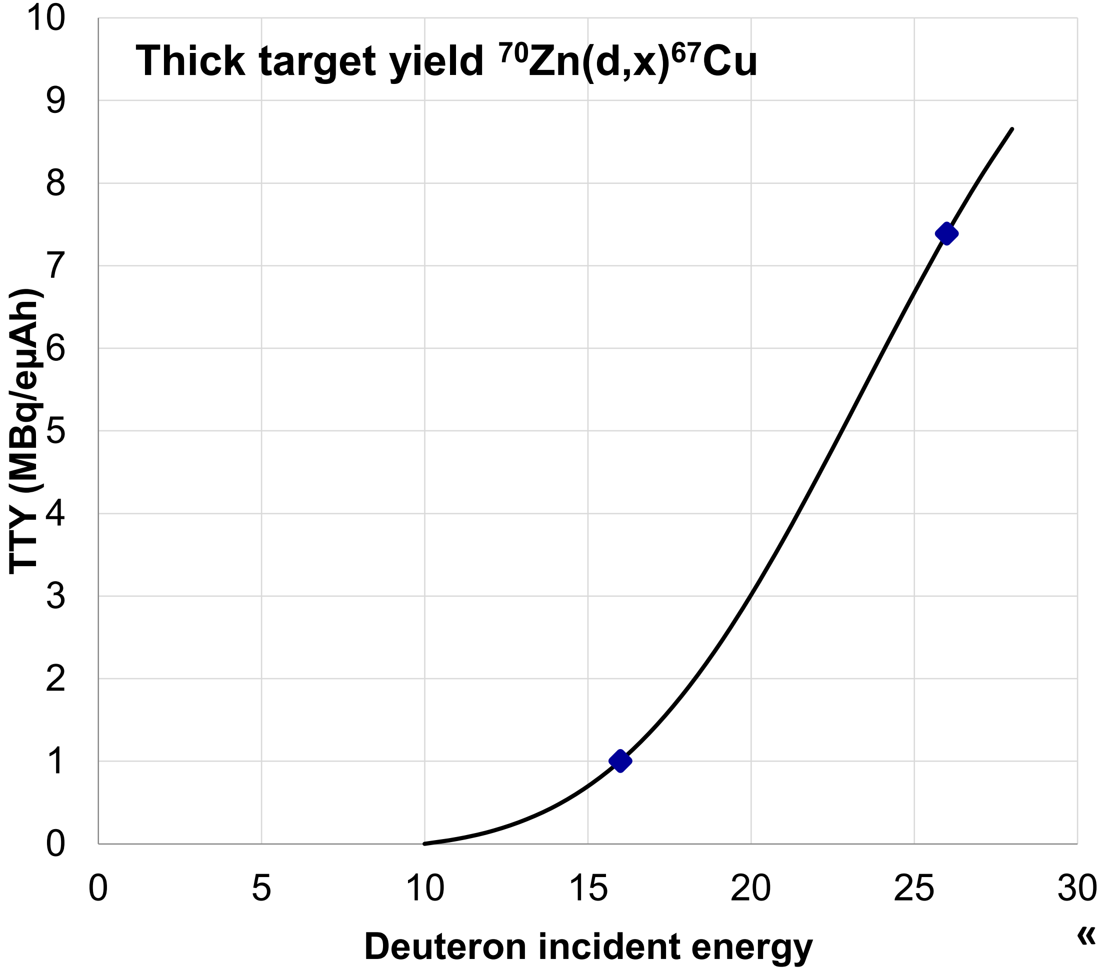
➢ 12 cross section values

^{67}Cu production cross section



^{67}Cu Thick Target Yield

To optimise production, considering ^{64}Cu threshold production at 26.4 MeV and the ^{70}Zn price, the energy range from 16 to 26 MeV is choosen, corresponding to a thickness of 575 µm of ^{70}Zn



Irradiation scenario C70XP:

- A beam intensity of 100 µA
- 72 hours of irradiation
- Clinical trials possible
- 97.5% target purity
- TTY = **30.9 GBq EOB**

« Is ^{70}Zn(d,x)^{67}Cu the Best Way to Produce ^{67}Cu for Medical Applications? »
E. Nigron et al., Font. Med. 8 (2021) 674617

TTY calculations done with RYC developped @ GIP ARRONAX by M. Sitarz,
https://www.arronax-nantes.fr/outil-telechargement/outils-radionuclide-yield-calculator/

Example 2 : Astate-211 (^{211}At) from alpha particles at ARRONAX

Why α-emitters are of interest ?

Deposited energy: **E_α ~5 – 9 MeV**

- Highly cytotoxic
- Potentially more efficient than β radiation

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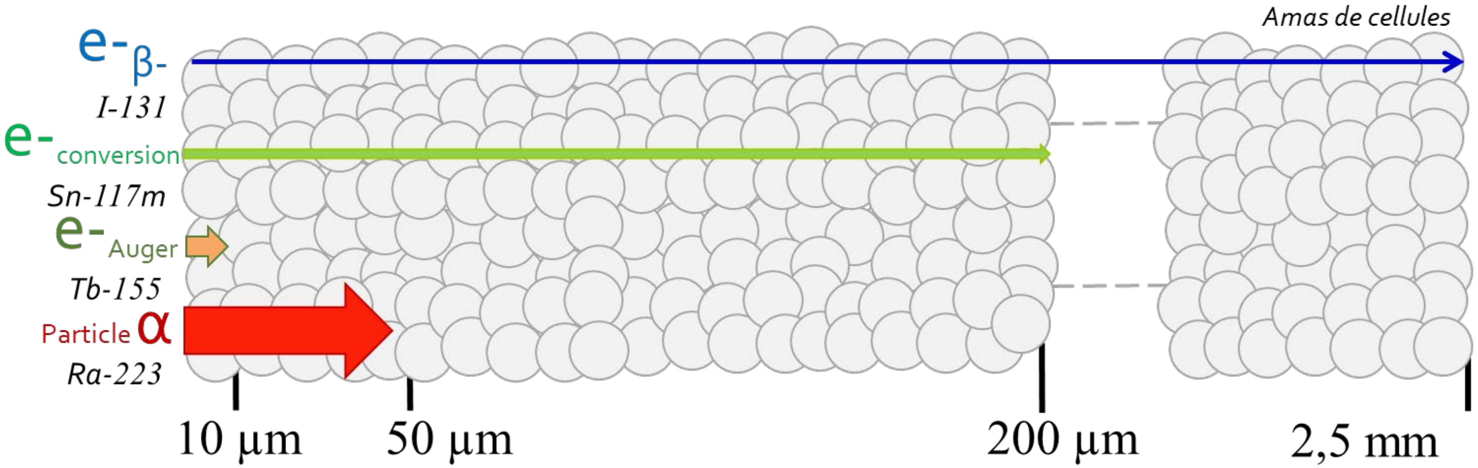
- ➢ Potentially more efficient than β radiation

Low penetration in water: **40 µm - 100 µm** (5-10 typical cell diameters)

- ➢ better preservation of healthy tissues



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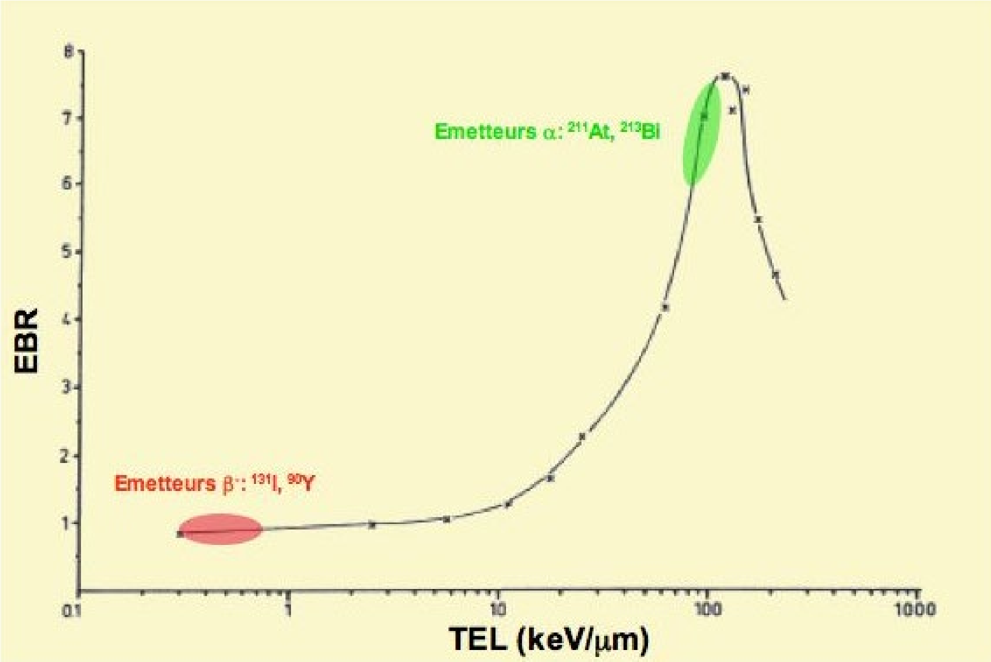
- better preservation of healthy tissues

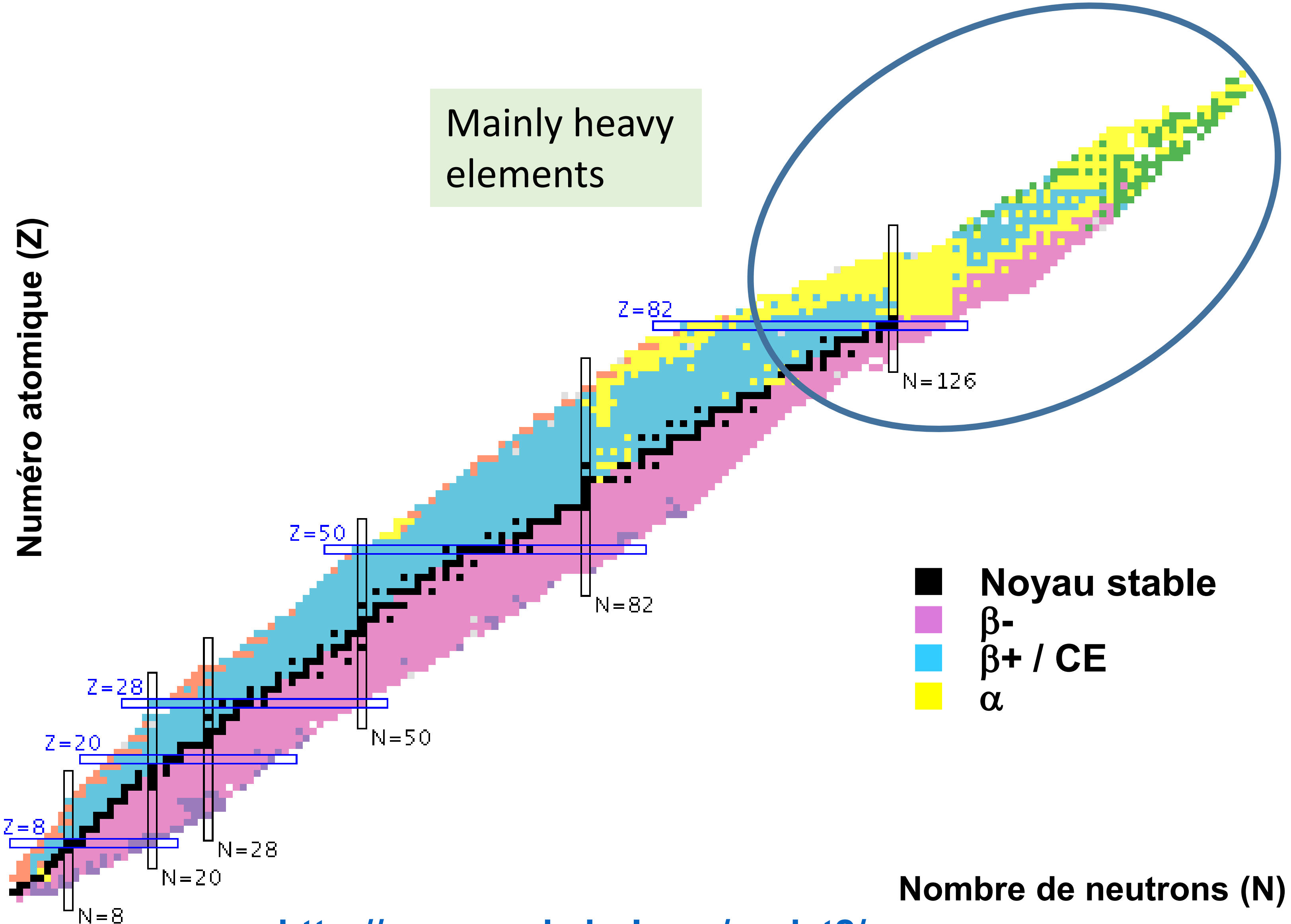
High Linear Energy transfer (~**80 keV/µm**)

- High biologic effectiveness (EBR)



- Less dependant on oxygen depletion
- Less impact of the cellular cycle

In radionuclide chart



http://www.nndc.bnl.gov/nudat2/

Main α-emitters of medical interest

Radionuclide	Half-life (h)	# of alpha particles / decay	Eγ (keV)
Tb-149	4,1 h	0,17 (β and 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

A limited number of potential candidates

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Only 4(+1) can be produced using accelerators.

Main α-emitters of medical interest

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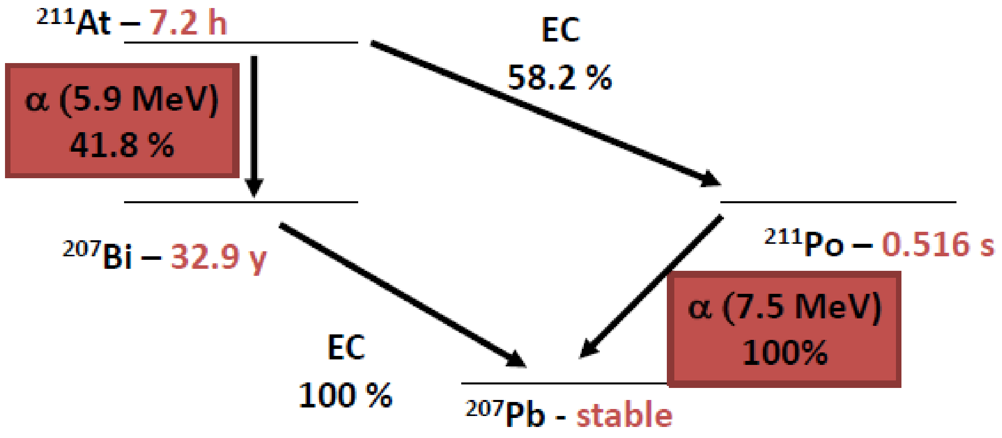
L' Astate 211



Advantages of ^{211}At:

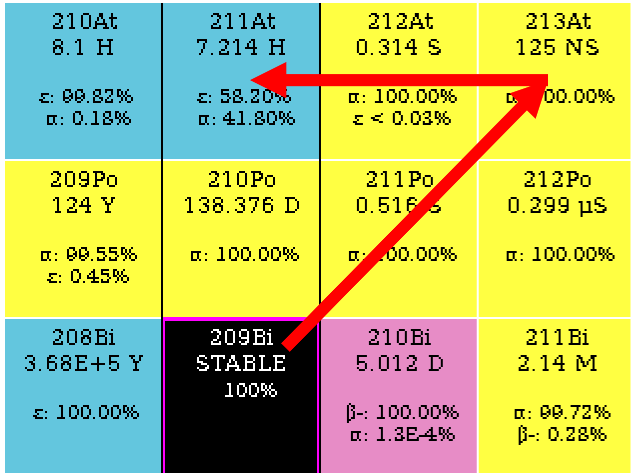
- $T_{1/2}$: neither too short nor too long (7,2 h)
- One α-particle emitted per decay
- Production is made using accelerator (28 MeV)
  → easy **scale-up by adding new facilities**

Astate 211 production

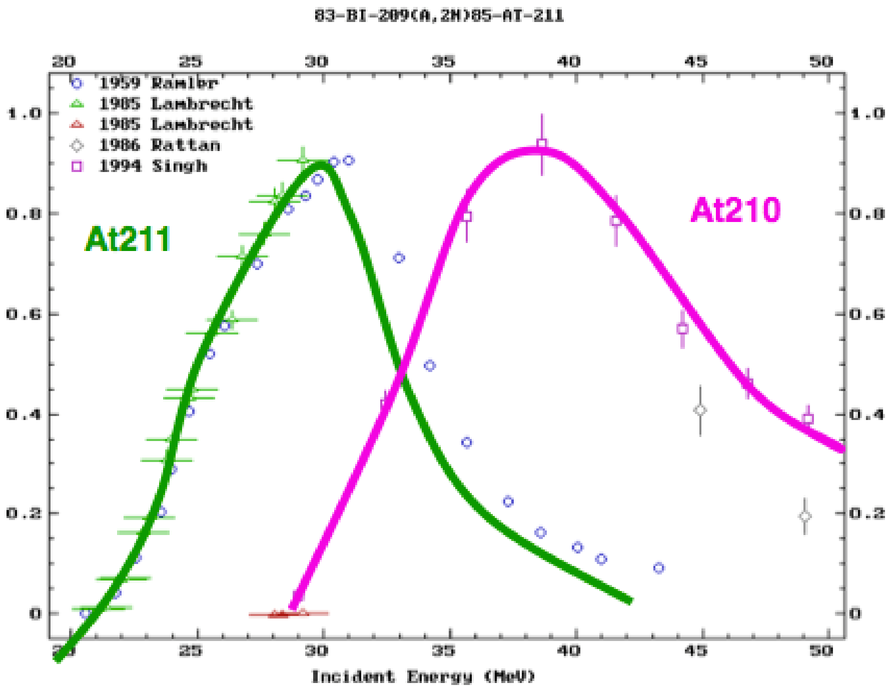
Which nuclear reaction?

$^{209}Bi + \alpha \rightarrow {}^{211}At + 2n$ $E_{threshold} > 20{,}718$ MeV

$^{209}Bi + \alpha \rightarrow {}^{210}At + 3n$ $E_{threshold} > 28{,}613$ MeV



Which energy to chose?



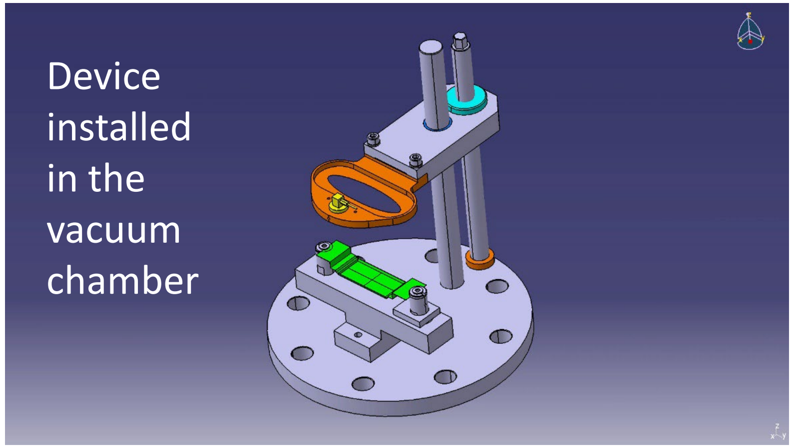
Maximum is around 30 MeV

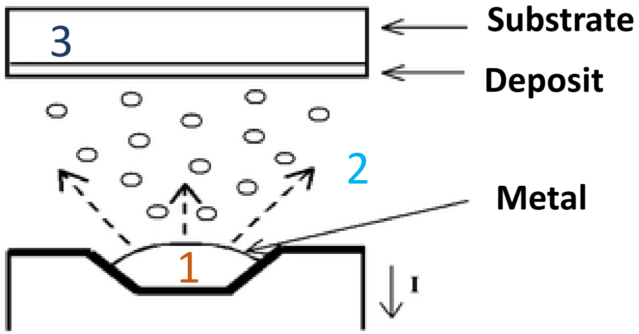
At210 impurities starts to be produced above $E_{\alpha} < 28{,}613$ MeV

Balance to be found to maximize production and minimize contaminants

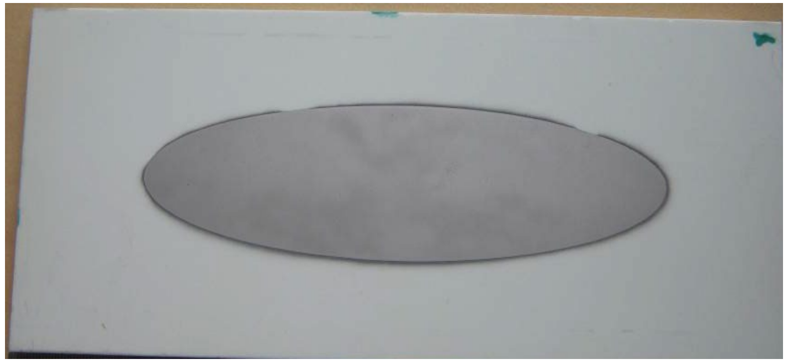
Source:www.nndc.bnl.gouv

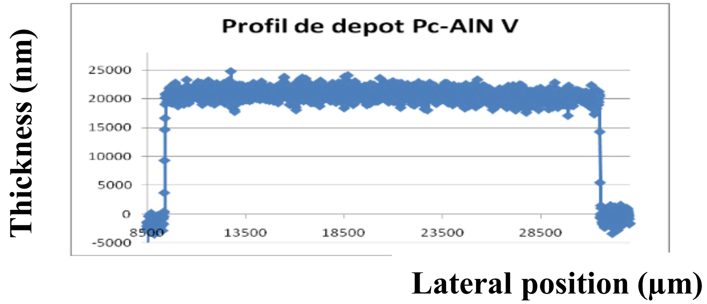
Bi target manufacturing



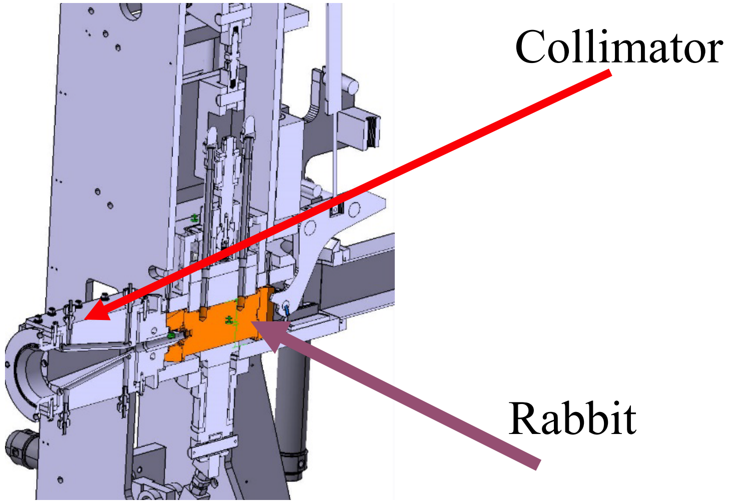


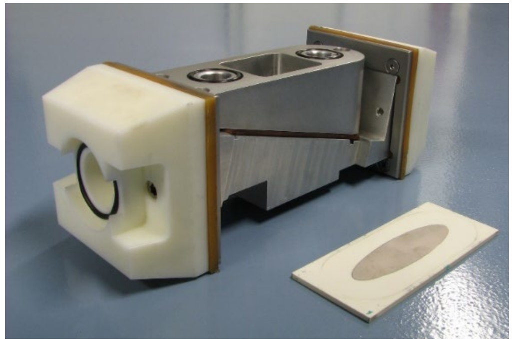
1) Vaporization: transition from the condensed phase (s/l) to the gas phase
2) Transit: transport of the gas phase
3) Condensation: construction of substrate layers





^{211}At production @ Arronax

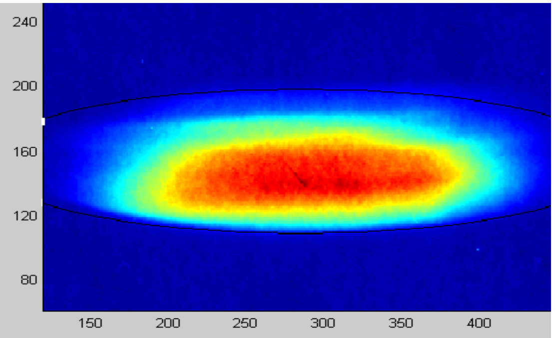




The IBA rabbit system (left) and a target for astatine production (right) to be used at ARRONAX.

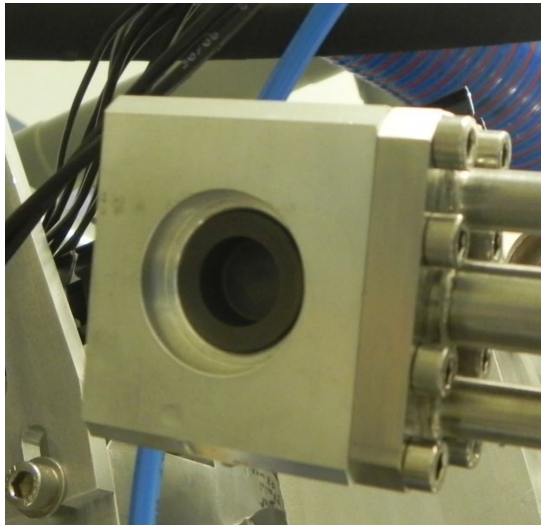
Beam profile extracted from an irradiated EBT2 Gafchromic

Red color → high irradiation
Blue color → area not irradiated



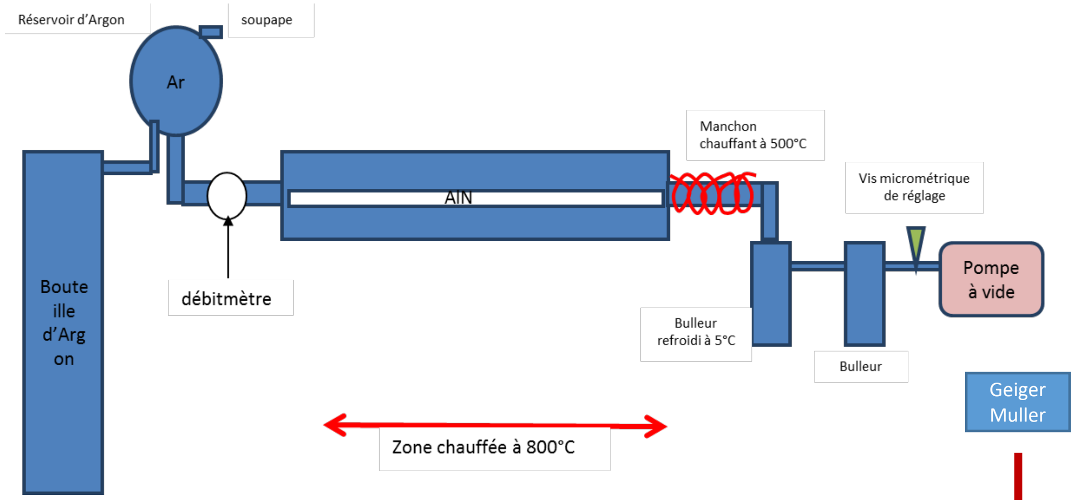
A beam energy degrader is required

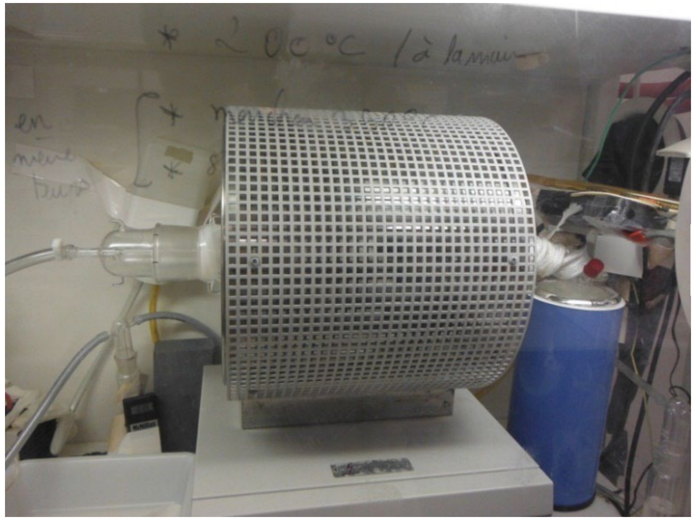
E_{init} 68 MeV → E_{out} ~28 MeV



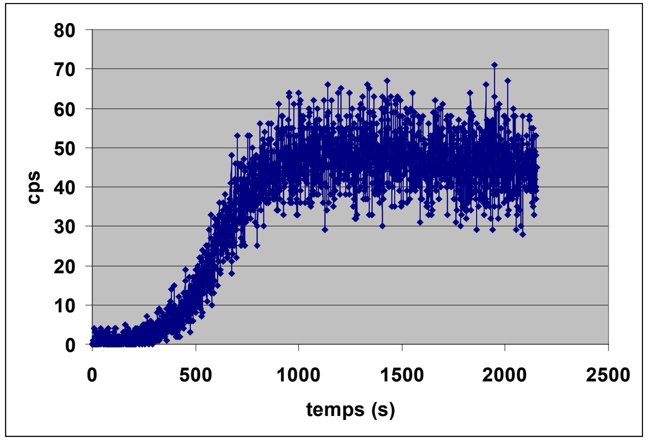
Graphite

^{211}At extraction using dry chemistry





T= -40° C



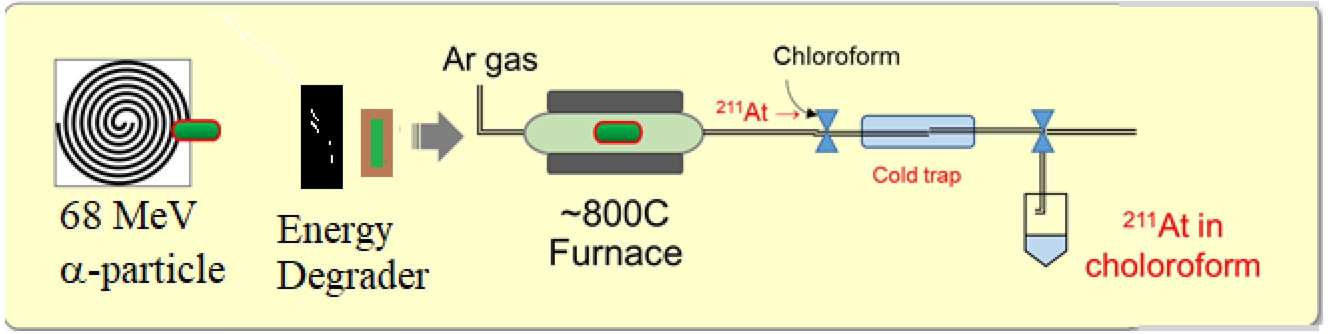
Astatine output: few minutes
Extraction yield: >80%

^{211}At: Production à ARRONAX

Astatine-211 production route:

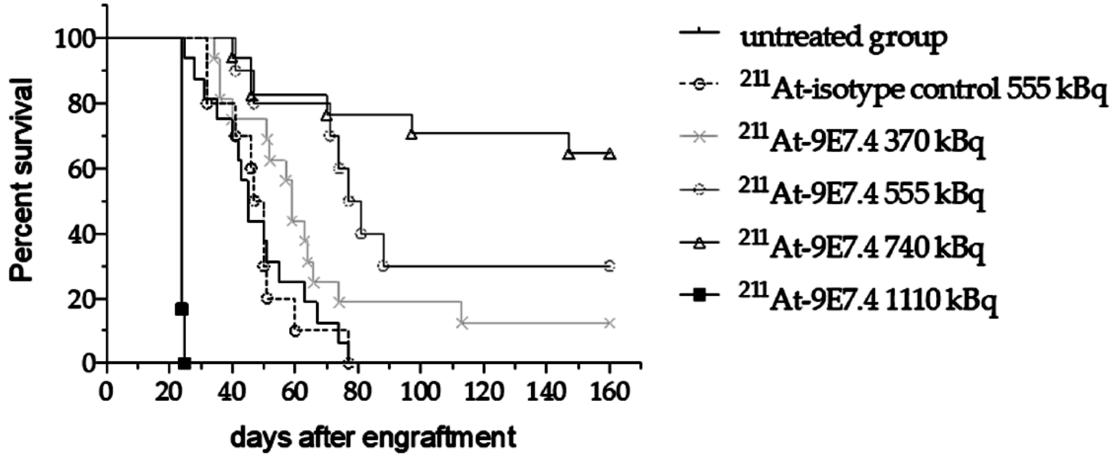
$^{209}Bi + \alpha \rightarrow {}^{211}At + 2n$

Production scheme @Arronax :

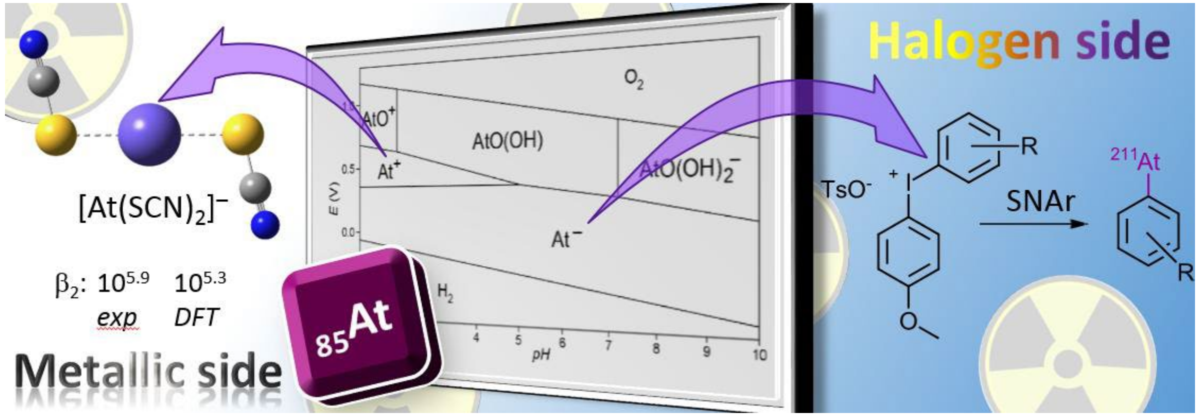


Astatine-211-labeled anti-mCD138 in mouse syngeneic multiple myeloma

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

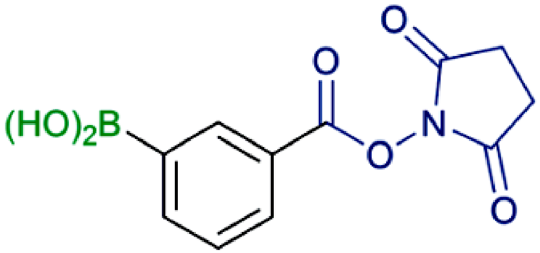


Basic and translational research



Chemical properties and quantum chemistry of astatine-211

Review: Guérard F et al. Acc Chem Res. 2021, 54, 16: 3264–3275



A new astatine-211 radiolabeling method based on boronic acids

Berdal M et al. Chem Sci. 2020 Nov 23;12(4):1458-1468

Arronax is producing 3-4 times a month At-211 (0.9-1.2GBq EOB)

^{211}At production sites in the world

We are part of the COST NOAR network:

^{211}At production facility in the world

- Running
- Potentially usable

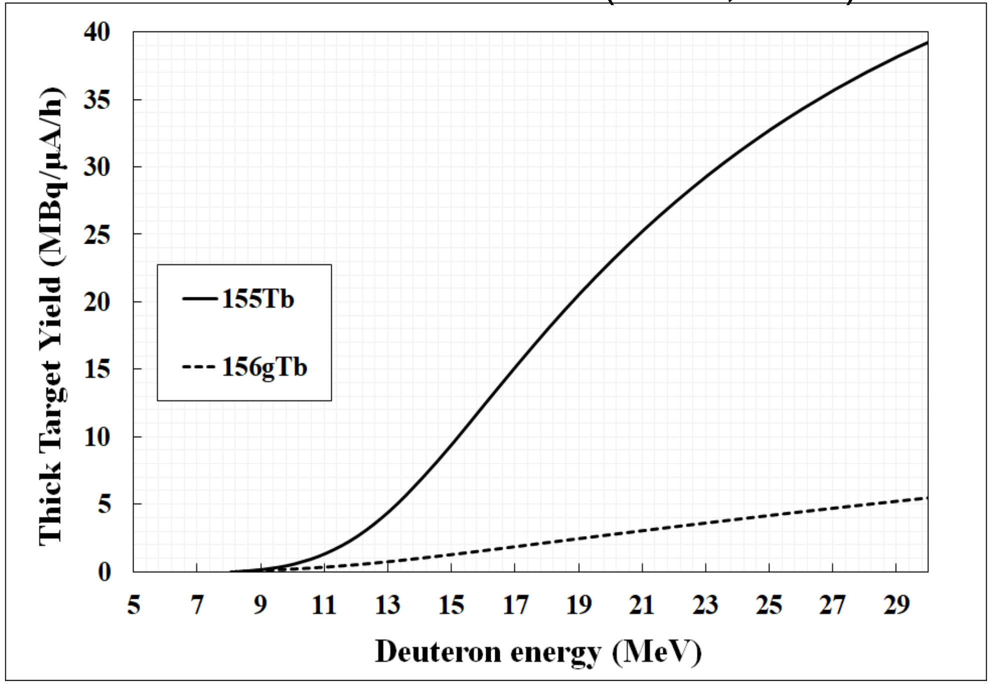
Pour participer à NOAR : https://astatine-net.eu/

Example 3 : Studies on Tb 155 production

Contaminants are a limiting factor for production

Terbium-155 production
from 155 Gd (d,x) – 93 % enrichment

Thick target yield (TTY) of ^{155}Tb and ^{156g}Tb
- RYC calculation tool (Sitarz, 2019)



Comparison between proton and deuteron

Particle	Proton	Deuteron
Target thickness (μm)	300	390
Energy (MeV)	10.4	15.1
TTY (MBq/μA/h)	3.4	10.2
Purity (%)	93	88

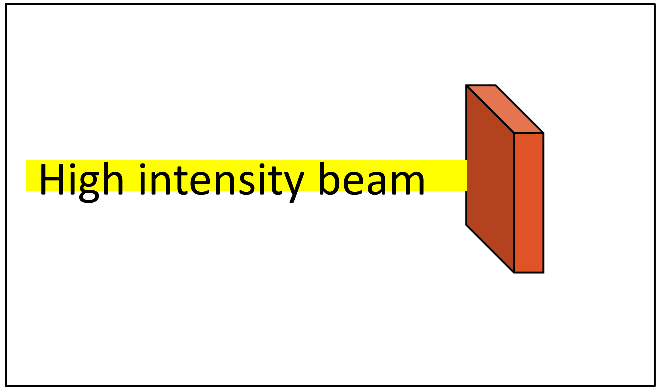
^{156}Tb always co-produced $T_{1/2}$ similar to ^{155}Tb

Contaminants are a limiting factor for production

We want to explore the possibility to couple chemical and physical separation methods (off-line).

Schematical view:

Irradiation step

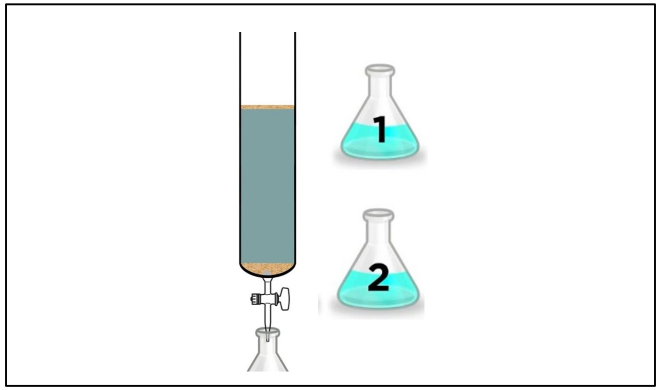


appropriate combination

target/projectile/energy

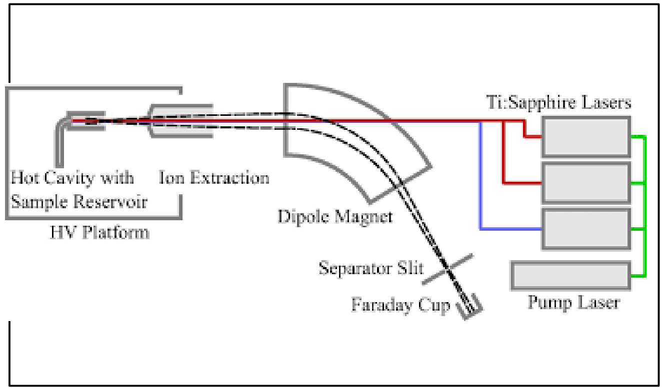
lead to few isobaric contaminants and high production

Chemical Step



remove a large part of the matrix to limit its impact on the mass separation step and ease recycling

Mass separation step

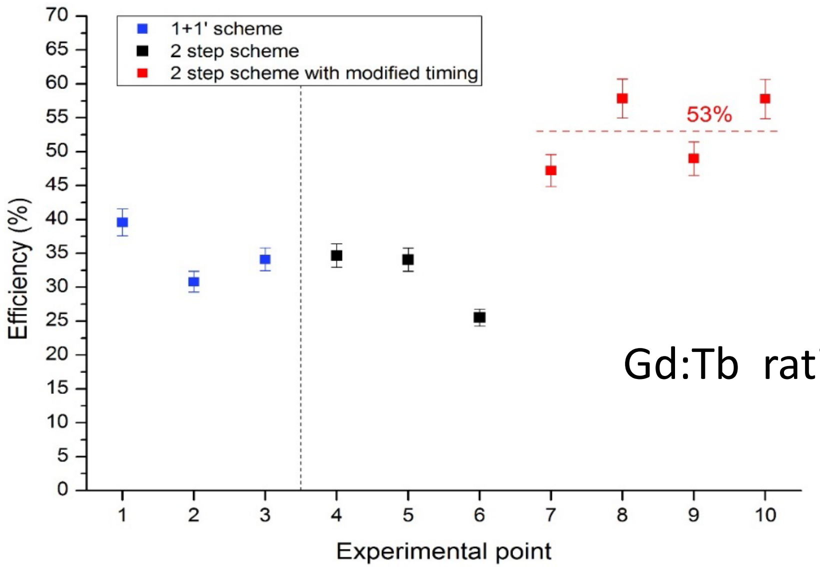


Operation of the accelerator and the mass separation are decorrelated

First experiences on off-line mass separation

1. Part of the PhD work of R. Formento (PhD 2019) - Collaborations : AAA, Arronax, Mainz, ILL, CERN-MEDICIS

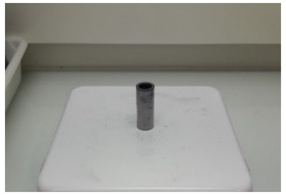
Studies conducted in Iarissa (Mainz) on
Resonant laser ionization for Terbium



Gd:Tb ratio 50/1

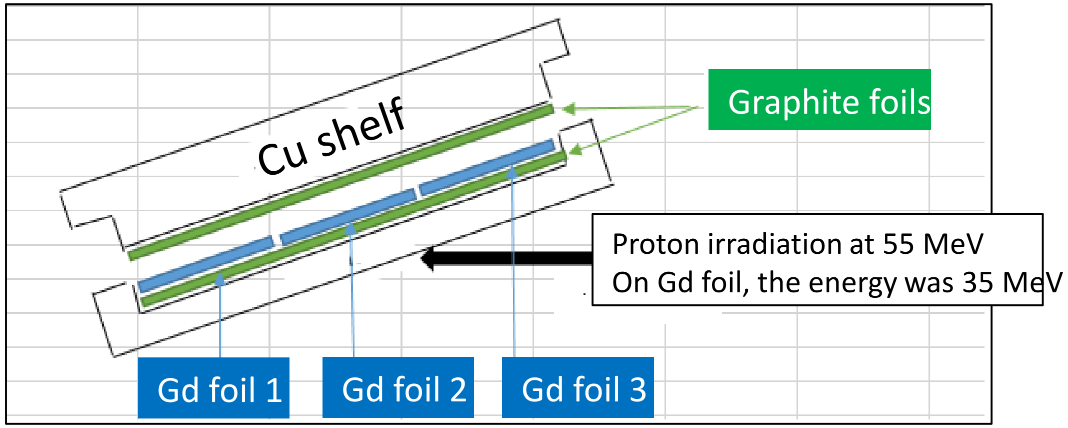
First experiences on off-line mass separation

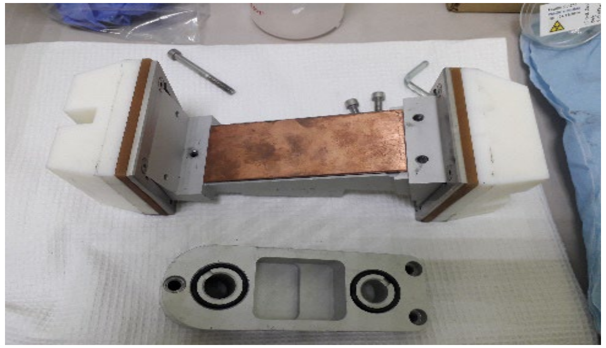
2. Production of ^{155}Tb as part of the MEDICIS program during Long shut down
   Collaborations : Arronax, CERN-MEDICIS
   Irradiation and Gd/Tb chemistry in Nantes
   Mass separation at CERN-MEDICIS

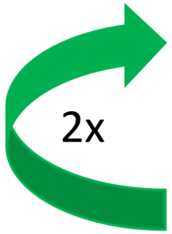


Boat sending to CERN-MEDICIS

Yield obtained 6.1% (decay corrected)







Step 1
- Dissolution of Gd foils in 0.75M HNO_3

Step 2
- Chemical separations using LN resin
- Solution used : 1 M HNO_3 for removing or recycling Gd, and 2M HNO_3 for retrieving Tb

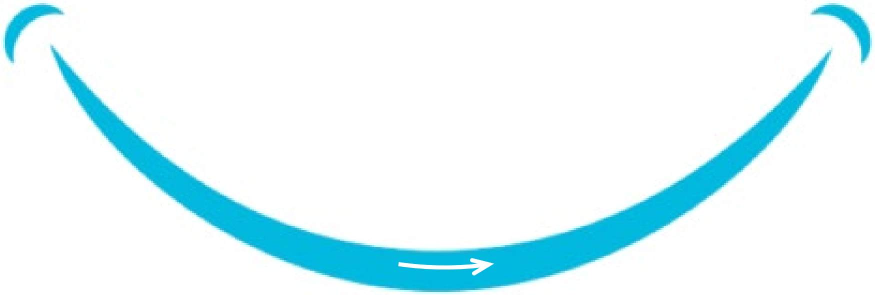
Step 3
- Evaporation to dryness
- Powder dissolution using 0.75 M
- Start again as Step 2 with new LN resin

Step 4
- Evaporation to dryness
- Powder dissolution using 0.01 M HNO_3
- Solution was filled into a boat provided by CERN-MEDICIS
- Boat delivered to CERN-MEDICIS for mass-separation

The SMILES project at Nantes

Physics of Radiation InteractionS with Matter and Applications

Séparation en **M**asse couplée à l'**I**onisation **L**aser pour des applications **E**nvironnementales et en **S**anté



Laser ionization and mass separation for environmental and health applications

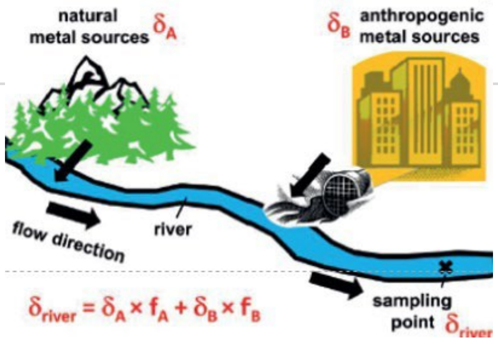
The Smiles project at Nantes

Physics of Radiation InteractionS with Matter and Applications

Our main objectives are to:

- Develop a mass separation device that includes resonant laser ionisation
- Be able to make analytical measurements on environmental sample (as for example from old uranium mines)
- Build expertise on these techniques and on simulation tools
- Prepare for off-line mass separator for radionuclide production

Environmental Applications



Health Applications

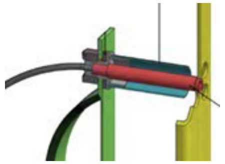
Stable element: Cu65/Cu63
Isotopic analysis : Pb , Am, Pu, Ra226/228
Ultra trace analysis: Pb210, Th230,U-236

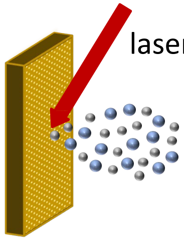
Stable element: Cu65/Cu63

The Smiles project at Nantes

The constructed devices will be installed in subatech (limited authorization to manipulate radioactive material)
We will explore different configurations:

thermal





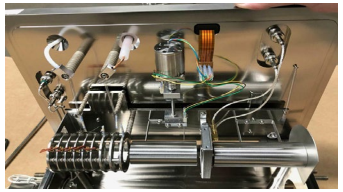
mapping

source

Laser ionisation

magnetic

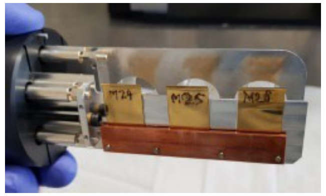
Ion transport and separation



electrostatic

Collection

Collection foils



detector

Conclusion

A multi-particle, high energy and high intensity machine is a very versatile tool for isotope production that allow:

use of p, d, alpha at different energies with different kinds of target (Tb 155 target with inside degrader)

Improve production capability and availability for clinical trials

Avaibility of particles and wide range of energy allow cross section studies to choose the best production routes

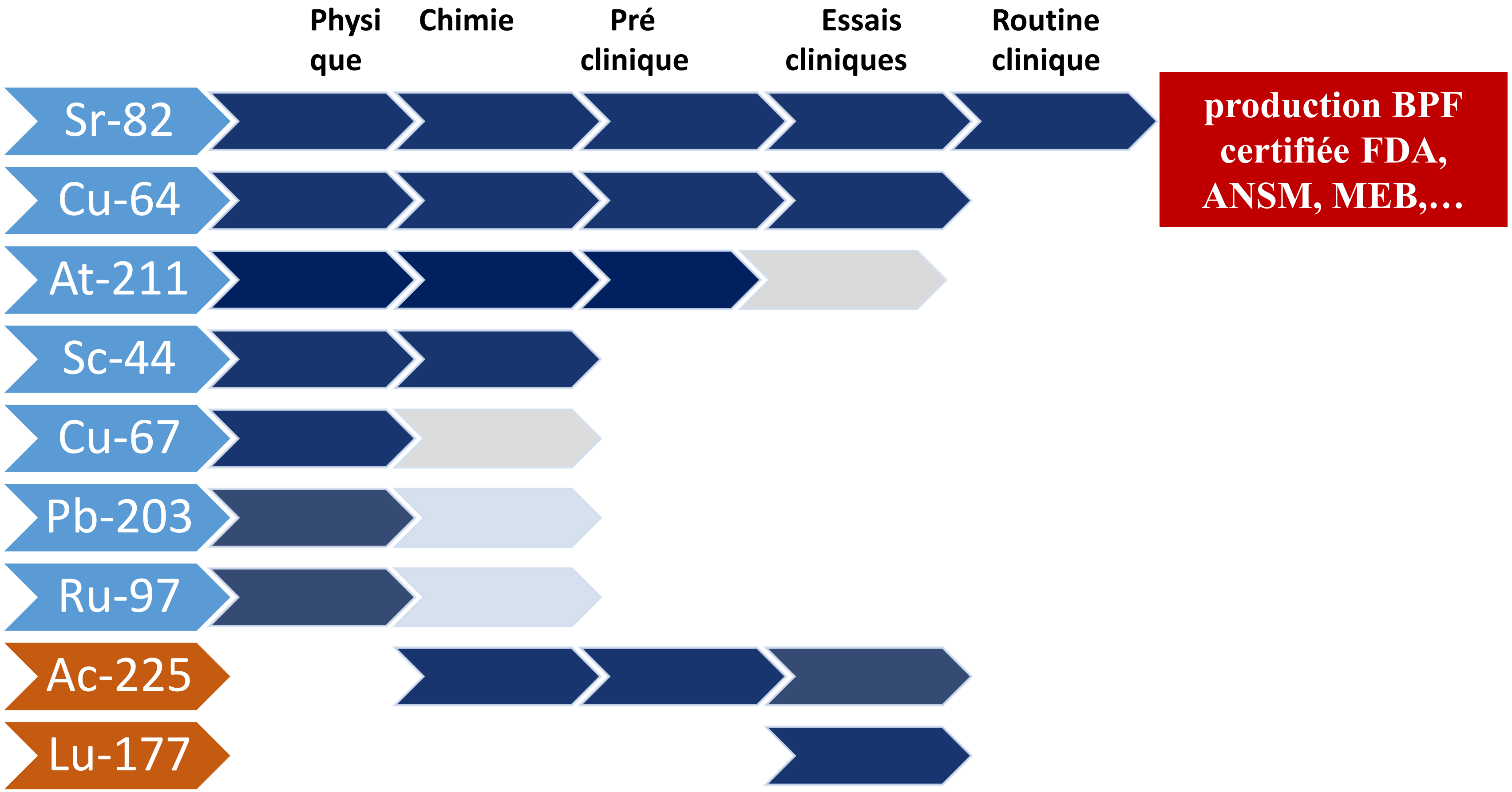
Technological improvement can be tested
Cu 64: A new accelerator will be installed in Arronax (**IK18 project**)
At211 : **Internal target** design is underway to use the right energy on target
Tb 155: development of mass separation tool

We explore other radionuclides

- ^{44}Ti to make available ^{44}Ti/^{44}Sc generator
- ^{97}Ru
- ^{203}Pb interesting for imaging associated to ^{212}Pb

Conclusions

Pipeline Arronax



PRISMA Team

PRISMA
Physics of Radiation InteractionS with Matter and Applications

Permanent positions





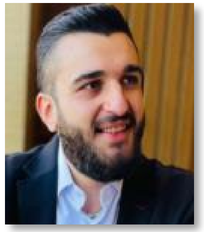






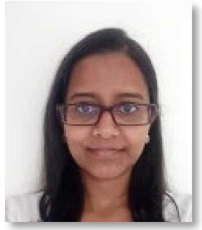

Subatech ARRONAX Institut de Cancérologie de l'Ouest
unicancer PAYS DE LA LOIRE
PRISMA
Physics of Radiation InteractionS with Matter and Applications

Post- doctoral fellows




PhD students





Thank you for your attention