SPES MED

Conceptual Design Report for INFN CSN3 Experiment 2024

Principal Investigator

Prof. Emilio Mariotti, INFN-PI.

INFN Research Units

Pisa, Padova, Milano, Pavia, LNL.

Research Fields

Nuclear Physics, Medical Radionuclides, Cross Section Measurements, Radiation Detectors.

Duration

3 years.

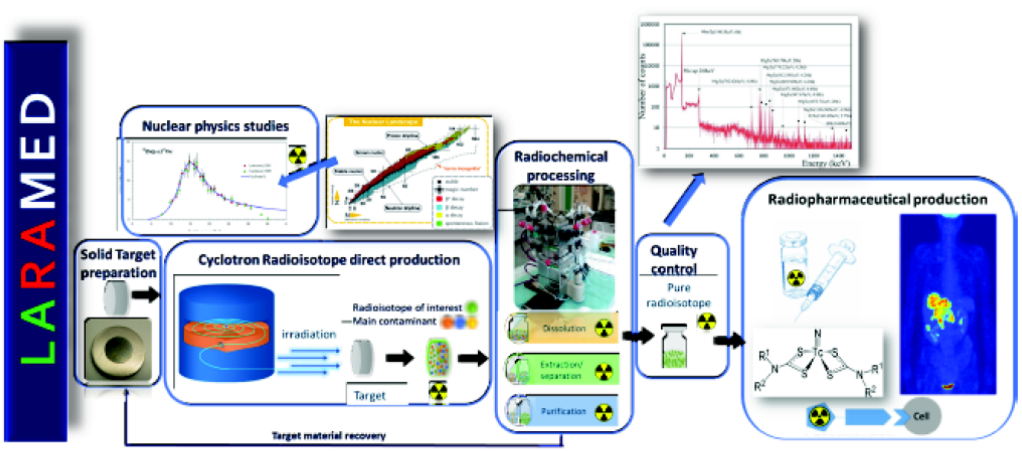
INFN
Istituto Nazionale di Fisica Nucleare

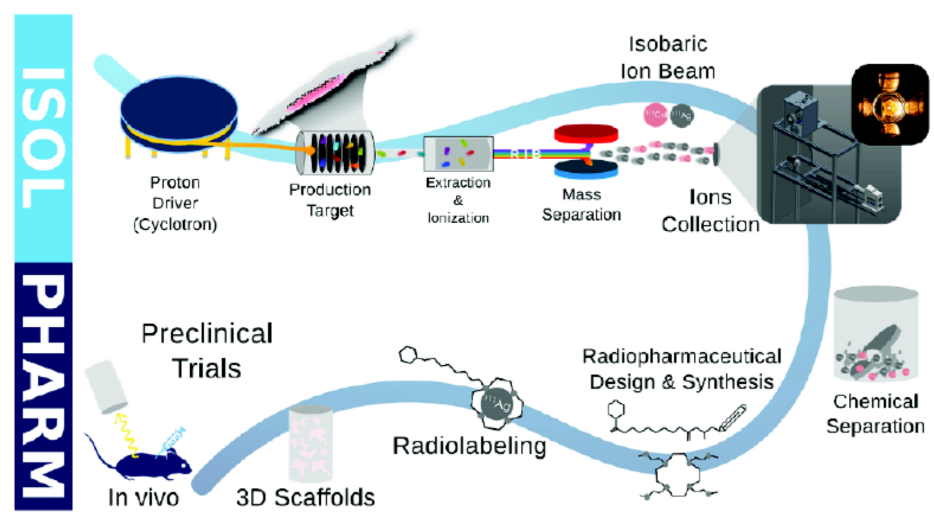
General goals

- The **measurement of unexplored nuclear reactions**, considering the production of both the radionuclides of interest and their contaminants, to find out the best irradiation parameters for each specific case.

- The precise evaluation of the **production yield** of several medical radionuclides applying the **ISOL technique** to targets of interest for the SPES project.

- The possibility to employ the new experimental data to **improve both the nuclear data libraries and theoretical models**, particularly in the low- and intermediate-energy regions which are so crucial for radionuclide production. The theoretical models of the main nuclear reaction mechanisms are implemented in nuclear reaction codes, and their input parameters are bench-marked in the RIPL (Reference-Input-Parameter-Library) database, maintained by IAEA. New measurements in selected regions can improve the nuclear models input parameters, particularly for nuclear reactions relevant for medical applications.





WP1 (leaders: L.DeDominicis, M.Colucci)

WP1: Nuclear cross section measurements

Main goal: measure unexplored nuclear reactions leading to the production of both the radionuclide of interest and its contaminants, aiming to find out the best irradiation parameters for each specific case.

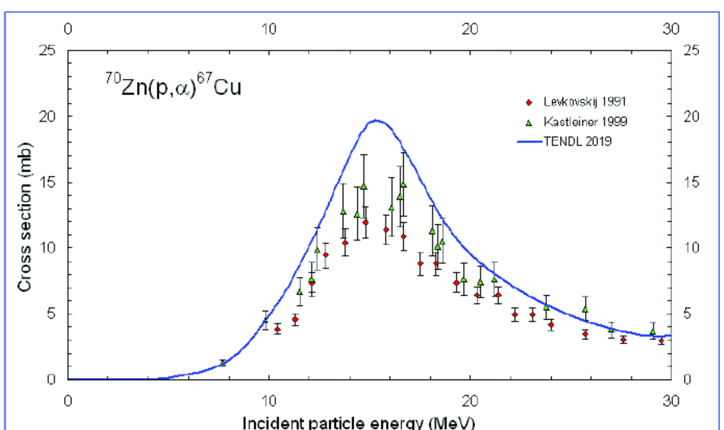
The main nuclear reactions of interest are listed below:

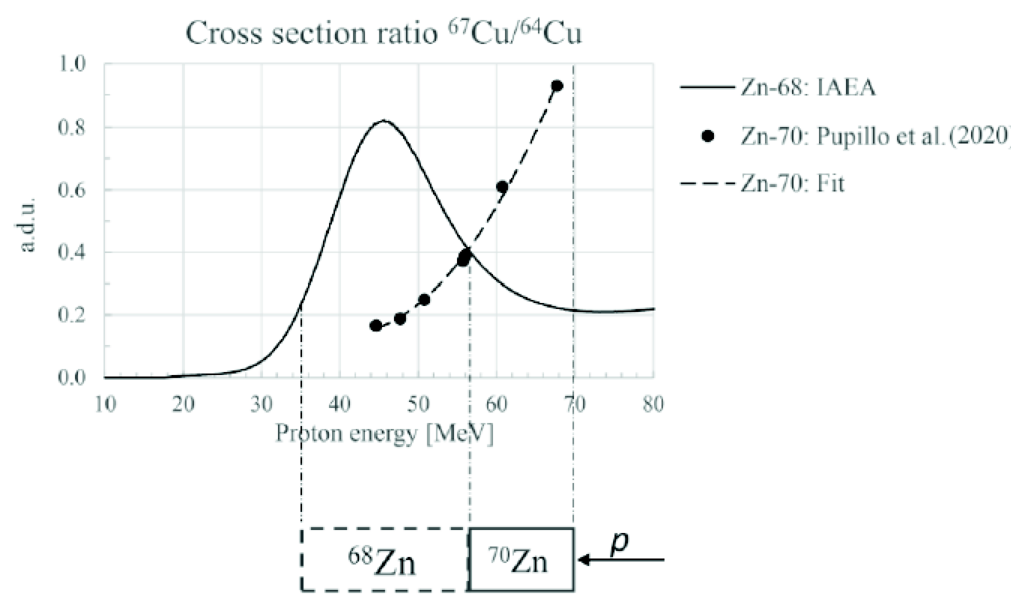
- ^{49}Ti(d,x)^{47}**Sc** up to 30 MeV, in collaboration with the ARRONAX facility (LNL team, 1 year);
- ^{68}Zn,^{70}Zn(p,x)^{67}**Cu,**^{64}**Cu** for proton beams with energy higher than 70 MeV, in collaboration with the i-Themba facility (LNL team, 1 and 2 year);
- ^{70}Zn(p,x)^{67}**Cu,**^{64}**Cu** in the energy range 25-50 MeV at SPES (LNL team, 3 year);
- ^{159}Tb(p,5n)^{155}**Dy** $\rightarrow$^{155}**Tb** up to 70 MeV at SPES, also in the framework of the PRIN PNRR 2022 entitled "APHRODITE-155" and focused on ^{155}Tb production (LNL and MI team, 1 year);
- ^{nat}Eu(a,x)^{155}**Tb** in the energy range 10-30 MeV in collaboration with ARRONAX facility (1 year) and with Czech Nuclear Physics Institute CAS (1 and 2 year) (MI team);
- ^{nat}Gd(p,x)^{152,149}**Tb** in the energy range 40-70 MeV at SPES (LNL and MI team, 2 and 3 year) and at energies up to 200 MeV in collaboration with i-Themba facility (LNL and MI team, 2 and 3 year);
- ^{nat}Gd(a,x)^{152,155}**Tb** in the energy range 10-70 MeV in collaboration with ARRONAX facility (MI team, 1 and 2 year) and CAS (MI team, 2 and 3 year).

WP1

^{67}Cu, β^- (E_m = 141 keV) and γ (93 keV, 185 keV) emitter, for Targeted Radionuclide Therapy (TRT), Single-Photon Emission Computed Tomography (SPECT) imaging

	Half-Life	Main γ-ray Energy, Intensity (keV) (%)	Mean β^+ Energy, Intensity (keV) (%)	Mean β^- Energy, Intensity (keV) (%)	Auger and IC Electrons
^{67}Cu	61.83 h	184.577 (48.7)	-	141 (100)	Yes
^{64}Cu	12.701 h	1345.77 (0.475)	278 (17.6)	191 (38.5)	Yes
^{61}Cu	3.336 h	282.956 (12.7) 656.008 (10.4)	500 (61)	-	Yes
^{60}Cu	23.7 m	826.4 (21.7) 1332.5 (88.0) 1791.6 (45.4)	970 (93)	-	Yes





WP1

^{47}Sc, β^- (E_m = 162 keV) and γ (159 keV) emitter, for therapeutic treatment, SPECT imaging, possibility to be paired with ^{44g}Sc and ^{43}Sc, β^+ emitters for PET imaging

Table 3. Main decay characteristics of ^{47}Sc, ^{44g}Sc, and ^{43}Sc radionuclides.

	Half-life	**Main γ-ray energy, intensity (keV) (%)**	**Mean β^+ energy, intensity (keV) (%)**	**Mean β^- energy, intensity (keV) (%)**	**Auger and IC electrons**
^{47}Sc	3.3492 d	159.381 (68.3)	-	162.0 (100)	Yes
^{44g}Sc	4.0420 h	1157.022 (99.8867)	630.2 (94.278)	-	Yes
^{43}Sc	3.891 h	372.9 (22.5)	476 (88.1)	-	Yes

WP1

isotopes of Tb

^{149}Tb ($T_{1/2}$ = 4.1 h), β^+ and α emitter(E_m = 3967 keV, 17%), α radiotherapy and PET studies

^{152}Tb ($T_{1/2}$ = 17.5 h), β^+ emitter (E_m = 1080 keV, 17%), PET Imaging

^{155}Tb ($T_{1/2}$ = 5.32 d), γ emitter (86.55 keV, 32%; 105.3 keV, 25%), SPECT imaging

^{161}Tb ($T_{1/2}$ = 6.89 d), β^- e γ emitter
(25.65 keV, 23.2%; 48.92 keV, 17%; 57.19 keV, 1.8%, 74.57 keV, 10%),

Table 4. Main decay characteristics of Tb isotopes suitable for medical applications (^{149}Tb, ^{152}Tb, ^{155}Tb, ^{161}Tb).

	Half-life	Main γ-ray energy, intensity (keV) (%)	Mean β^+ energy, intensity (keV) (%)	Mean β^- energy, intensity (keV) (%)	α energy, intensity (keV) (%)	Auger and IC electrons
^{149}Tb	4.1 h	352.24 (29.8), etc	720 (7.11)	-	3967 (16.7)	Yes
^{152}Tb	17.5 h	344.2785 (63.5), etc	1140 (20.3)	-	-	Yes
^{155}Tb	5.32 d	86.55 (32.0), etc	-	-	-	Yes
^{161}Tb	6.89 d	74.56669 (10.2)	-	154 (101)	-	Yes

WP2 (Leaders: A.Arzenton, P.Delogu)

WP2: ISOL production yield measurements

Main goal: measure the ISOL production yield of relevant medical radionuclides and acquire in-depth understanding of the elements that can increase their production.

This measurements will help to establish the yield database of the SPES facility, focusing the main efforts on the study of:

- silicon carbide (**SiC**) targets, for the production of **^{28}Mg**;
- titanium carbide (**TiC**) targets, for the production of **^{43}K**, **$^{43,44,47}Sc$** and **^{51}Cr**.

Further measurements will then allow to determine, for each element of interest, the two main factors affecting the global ISOL production yield, explicitly

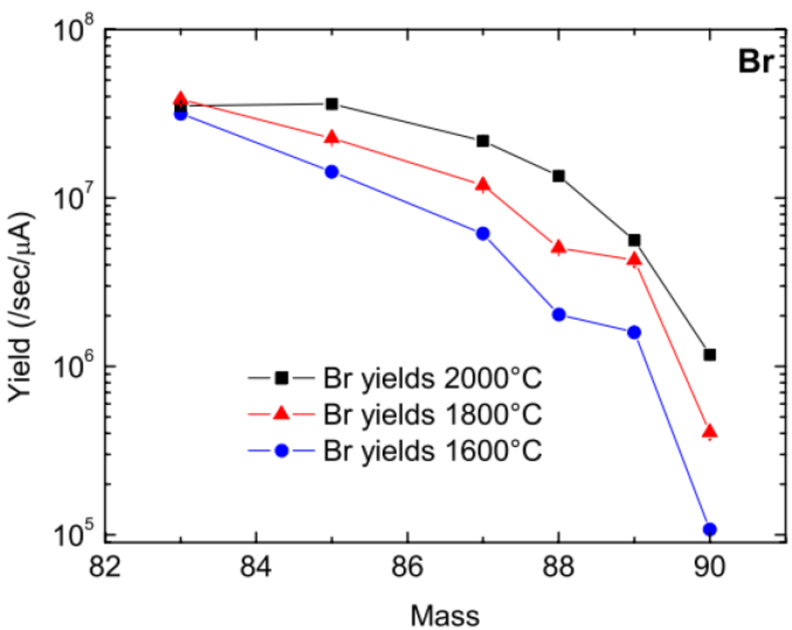
- the SPES target release efficiency;
- the best ion source technology and its efficiency.

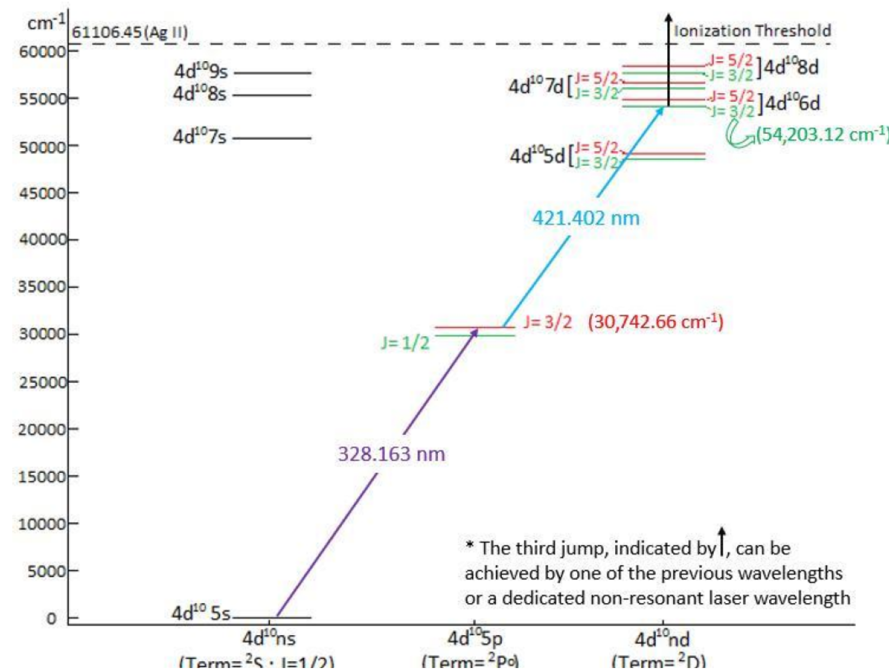
Led by the INFN-LNL team, the collection target handling station IRIS (ISOLPHARM Radionuclide Implantation Station) has already been manufactured. A dedicated γ-spectroscopy system including High Purity Germanium (HPGe), $LaBr_3$ and Lanthanum BromoChloride (LBC) detectors will be coupled to IRIS.

WP2

Based on the results attained before, SPES_MED intends to investigate further the dependence of isotope yields on experimental set-up and target characteristics with a novel detection system and the first exotic beams run by SPES. The information obtained in this investigation will be useful for the rest of the CSN3 SPES users that will use the same targets to generate the RIBs.

$$Y = \sigma \Phi N \varepsilon_d \varepsilon_e \varepsilon_i \varepsilon_t$$



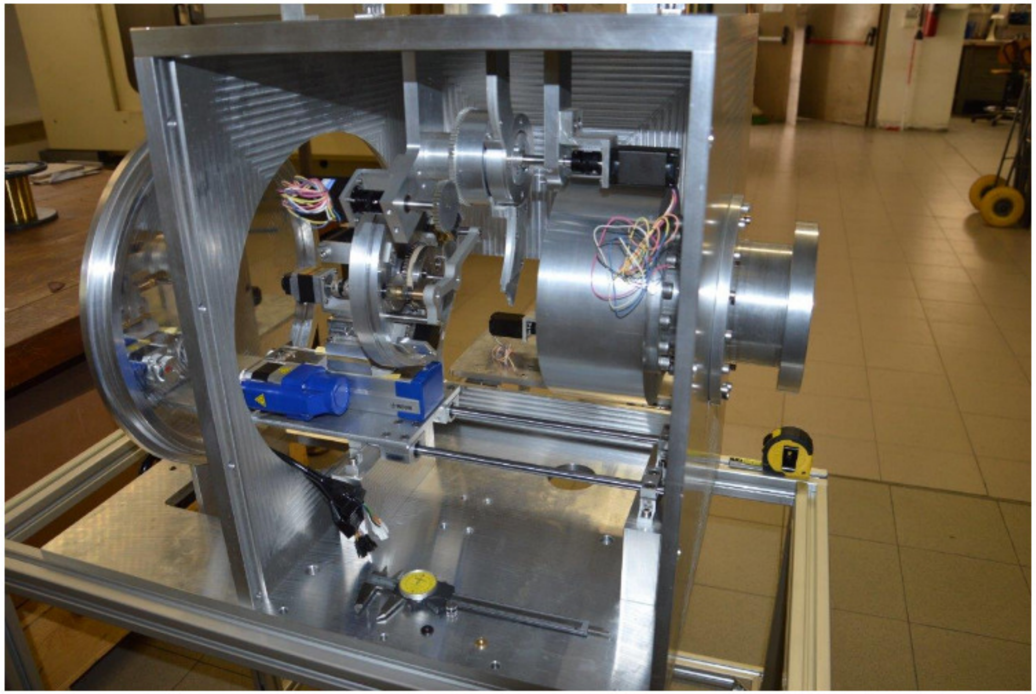


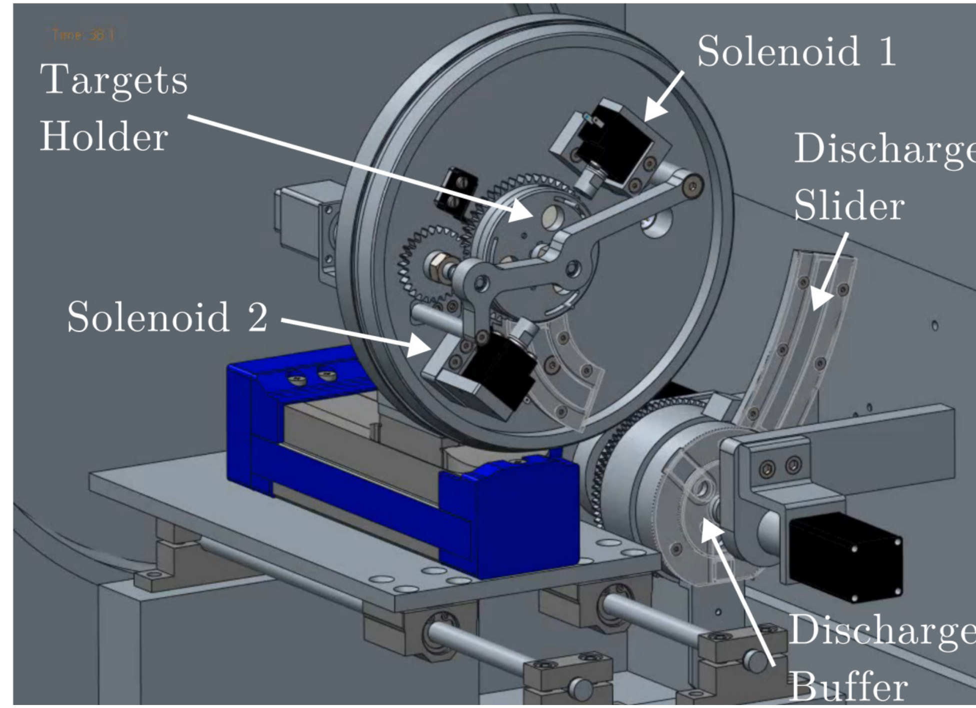
WP2

	Half-life	Main γ-ray energy, intensity (keV) (%)	Mean β energy, intensity (keV) (%)	In-target production @ 40 MeV, 200 μA (nuclides/s)	Expected release efficiency	First ionisation potential (eV)
^{28}Mg	20.915 h	30.6383 (89), etc	156.0 (94.8) β^-	5.0e7 (SiC)	very good	7.61
^{43}K	22.3 h	372.760 (86.2), etc	304.85 (90.9) β^-	3.4e9 (TiC)	very good	4.32
^{43}Sc	3.3492 d	159.381 (68.3)	162.0 (100) β^-	6.4e11 (TiC)	sufficient	6.57
^{44}Sc	4.0420 h	1157.0 (99.89)	630.2 (94.278) β^+	6.1e12 (TiC)	"	"
^{47}Sc	3.3492 d	372.9 (22.5)	476 (88.1) β^+	2.5e12 (TiC)	"	"
^{51}Cr	27.704 d	320.0824 (9.91)	-	3.5e8 (TiC)	sufficient	6.74
^{111}Ag	7.45 d	342.13 (6.7), etc	360.4 (92) β^-	6.1e8 (UCx) *	good	7.54

* ^{111}Ag production is actually much bigger due to the contribution of its decay chain

WP2

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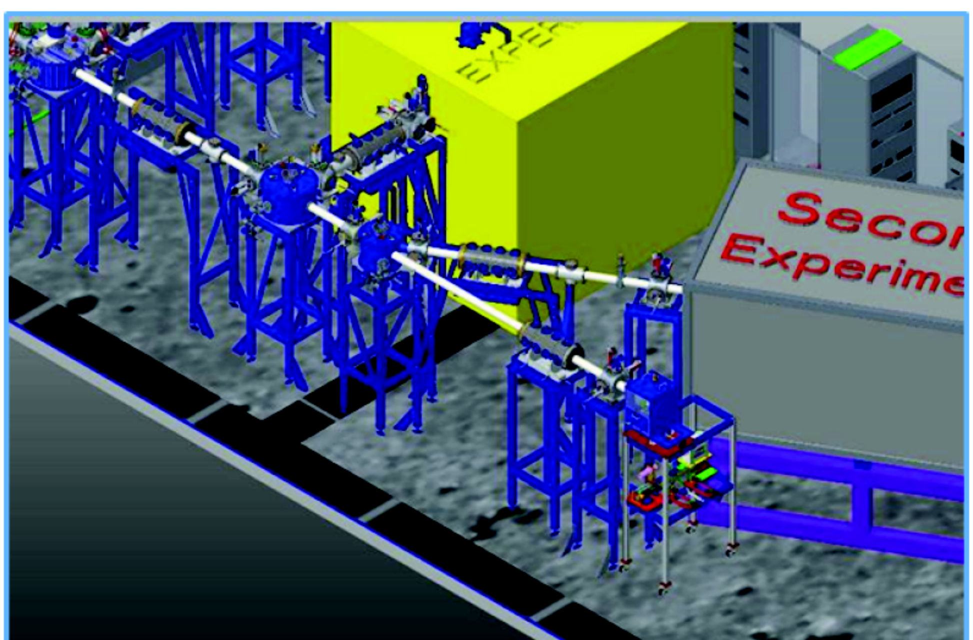
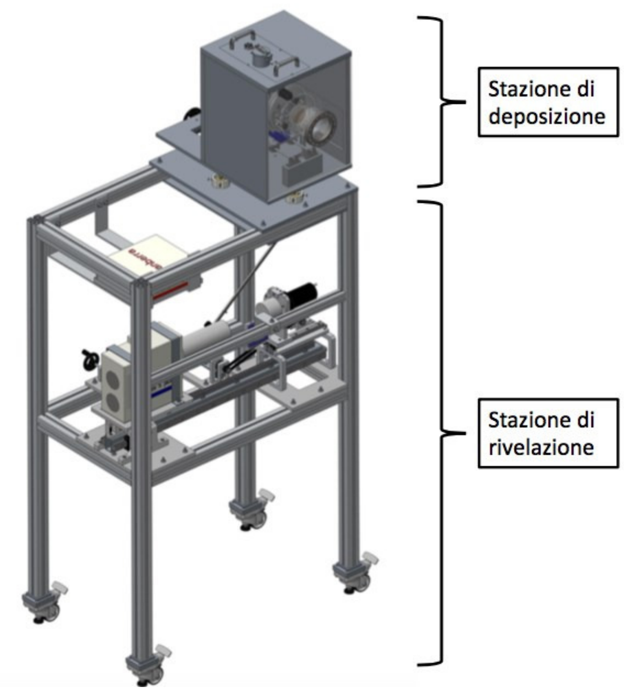
Solenoid 1
Discharge
Slider
Solenoid 2
Discharge
Buffer




Stazione di deposizione
Stazione di rivelazione

WP3 (Leaders: F.Barbaro, L.Zangrando)

WP3: Modeling and Monte Carlo simulations

Main goal: simulate high-purity radionuclide production for medical applications through nuclear reactions and examine different models for the nuclear reaction mechanisms analysis.

Two main sets of simulations will be run:

- **Cross sections studies**: cross sections will be computed using codes such as TALYS or EMPIRE, and different models will be considered for the analysis, with the main objective of optimising the irradiation parameters. The simulations' outcomes will then be compared with experimental results. A collaboration with experimentalists and medical physicists will guide measurements and dosimetric assessments, particularly focusing on the impact of contaminants.

- **In-target production analysis**: different Monte Carlo codes (MCNP, PHITS, FLUKA, and Geant4) will be employed to precisely simulate the nuclear interactions. To simulate the radioisotope formation and decay at different times during the irradiation period and in the following cooling phase, the aforementioned codes have to interface with nuclide evolution programs. Due to the complexity of the calculation procedure, a high number of simulation events is requested to reach a reliable statistical precision. Therefore, the CloudVeneto infrastructure, which provides an advanced IT Platform for parallelizing MC codes (FLUKA and Geant4) in Cloud, will be employed.

FTE

PI			
Name	**Expertise – Activity in the project**	**WP**	**FTE**
Emilio Mariotti (National and PI local resp.)	Experimental physicist, associate professor	2	0.8
Pasquale Delogu	Experimental physicist, associate professor	2	0.2
Alen Khanbekyan	Experimental physicist, researcher	2	0.2
Total PI FTE			1.2

LNL			
Name	**Expertise – Activity in the project**	**WP**	**FTE**
Gaia Pupillo (LNL local resp.)	Experimental physicist	1	0.5
Liliana Mou	Tecnhologist	1	0.3
Juan Esposito	Technology executive	1	0.2
Sara Cisternino	Technologist	1	0.2
Lucia De Dominicis	Experimental physicist	1	0.5
Daniele Scarpa	Electronical engineer, technologist	2	0.1
Alberto Andrighetto	Technology executive	2	0.2
Alberto Arzenton	Physicist	2,3	0.5
Davide Serafini	Physics PhD student at Siena University	2,3	1.0
Aurora Leso	Physics PhD student at Ferrara University	2,3	1.0
Omorjit Singh Khwairakpam	Experimental physicist, Post-Doc	2	0.1
Total LNL FTE			4.6

FTE

PD			
Name	**Expertise – Activity in the project**	**WP**	**FTE**
Sandra Moretto (PD local resp.)	Experimental physicist, associate professor	2	0.5
Marcello Lunardon	Experimental physicist, associate professor	2	0.2
Lisa Zangrando	Technologist	3	0.2
Daiyuan Chen	Physics PhD student at Padova University	2,3	1.0
Luciano Canton	Theoretical physicist, researcher	3	0.2
Laura De Nardo	Experimental physicist, researcher	3	0.2
Francesca Barbaro	Physicist	3	0.3
Yuliia Lashko	Theoretical physicist	3	0.3
Total PD FTE			2.9
MI			
Name	**Expertise – Activity in the project**	**WP**	**FTE**
Simone Manenti (MI local resp.)	Experimental physicist	1	0.5
Flavia Maria Groppi Garlandini	Experimental physicist, associate professor	1	0.4
Michele Colucci	Experimental physicist	1	0.3
Elisa Persico	Experimental physicist	1	0.5
Total MI FTE			1.7
PV			
Name	**Expertise – Activity in the project**	**WP**	**FTE**
Andrea Gandini (PV local resp.)	Chemist, technologist	2	0.5
Antonietta Donzella	Monte Carlo simulation, technologist	3	0.2
Giancarlo D'Agostino	Metrologist, researcher	2	0.3
Marco Di Luzio	Metrologist, researcher	2	0.3
Giorgio Grosso	Chemist, Post-Graduate	2	1.0
Total PV FTE			2.3
Total project FTE			12.7

Gantt and Milestones

		Year 1				Year 2				Year 3			
		M3	M6	M9	M12	M15	M18	M21	M24	M27	M30	M33	M36
	WP1 - Nuclear cross-section measurements												
MS1.1	159Tb(p,5n)155Dy → 155Tb up to 70 MeV at SPES	→			●								
MS1.2	49Ti(d,x)47Sc at ARRONAX facility up to 35 MeV	→				●							
MS1.3.1	natEu(a,x)155Tb at ARRONAX	→				●							
MS1.3.2	natEu(a,x)155Tb at Czech Nuclear Physics Institute CAS			→				●					
MS1.4	68,70Zn(p,x)67,64Cu up to 200 MeV at i-Themba lab			→					●				
MS1.5.1	natGd(p,x)152,149Tb in the energy range 40-70 MeV at SPES				→						●		
MS1.5.2	natGd(p,x)152,149Tb up to 200 MeV at i-Themba lab						→						●
MS1.6.1	natGd(a,x)152,155Tb at ARRONAX			→				●					
MS1.6.2	natGd(a,x)152,155Tb at Czech Nuclear Physics Institute CAS							→					●
MS1.7	70Zn(p,x)67Cu,64Cu in the 25-50 MeV range at SPES												●
	WP2 - ISOL yield measurements												
MS2.1	Testing and refinement of IRIS and tape system	→			●								
MS2.2	Measurement of ISOL transport and ionization efficiencies with stable beams	→			●								
MS2.3	Resonant laser studies of Mg photo-ionisation schemes	→				●							
MS2.4.1	Yield measurements of Mg-28 from SiC targets					→			●				
MS2.4.2	Optimisation of SiC targets					→				●			
MS2.5	Resonant laser studies of Sc/Cr/Ag photo-ionisation schemes					→							●
MS2.6.1	Yield measurements of K-43, Cr-51 and Sc isotopes from TiC targets									→			●
MS2.6.2	Optimisation of TiC targets									→			●
MS2.7	Yield measurements of Ag-111 from UCx targets [only if UCx is available]											→	●
	WP3 - Models and simulations												
MS3.1	X-sect, yields and purity modelling for 47Sc production	→						●					
MS3.2	X-sect, yields and purity modelling for 155Tb and other terbium radionuclides	→							●				
MS3.3	X-sect, yield and purity modelling for 67Cu and other innovative theranostics			→									●
MS3.4	Models and simulations for target release	→					●						
MS3.5	Models and simulations for photo-ionisation experiments	→							●				
MS3.6	Monte Carlo simulations of ISOL in-target production					→							●
→	Activity started												
●	Milestone reached												

Budget (per WP)

		Year 1 [k€]	Year 2 [k€]	Year 3 [k€]	Total [k€]
	WP1 - Nuclear cross-section measurements (LNL, MI)				
EQUIPMENT (INV)	Electrodeposition system - LNL	3	0	0	3
CONSUMABLES	Enriched material (Zn-70, Zn-68) and custom clearance - LNL	20	0	0	20
	Consumables for experiments - LNL	4	4	4	12
	Targets and custom clearance - MI	20	5	0	25
	Maintenance - MI	2	2	2	6
	Radioactive transport - MI	8.5	8.5	8	25
TRAVELS	Travels for experimental activity and meetings - LNL	12	21	6	39
	Travels for experimental activity - MI	13.5	18.5	21	53
PUBLICATIONS	Publication fees - LNL	5	5	5	15
	Publication fees - MI	3	3	3	9
	TOTAL WP1	**91**	**67**	**49**	**207**
	WP2 - ISOL yield measurements (PI, LNL, PV, PD)				
EQUIPMENT (INV)	Computing machines - PI	3	0	0	3
	Computing machines - LNL	3	0	0	3
	Sigmatek modules - LNL	11	0	0	11
	Bosch profiles and accessories - LNL	3	0	0	3
	RS components - LNL	2	0	0	2
	Platform for IRIS maintenance - LNL	3	0	0	3
	Optical micrometer for INRiM - PV	6	0	0	6
CONSUMABLES	Laboratory equipment - PI	2	2	2	6
	Electrical components for IRIS - LNL	1	0	0	1
	Consumables for experiments - PD	1	1	1	3
TRAVELS	Travels for experimental activity and meetings - PI	2	5	5	12
	Travels for experimental activity and meetings - LNL	3	3	3	9
	Travels for experimental activity and meetings - PV	3	4	4	11
	Travels for experimental activity and meetings - PD	3	3	3	9
PUBLICATIONS	Publication fees - LNL	0	3	3	6
	TOTAL WP2	**46**	**21**	**21**	**88**
	WP3 - Models and simulations (PD, PV)				
EQUIPMENT (INV)	CloudVeneto server - PD (and PV)	12	0	0	12
TRAVELS	Travels for meetings and exchange collaborations - PD	3	3	3	9
PUBLICATIONS	Publication fees - PD	2	2	2	6
	TOTAL WP3	**17**	**5**	**5**	**27**
	TOTAL BUDGET	**154**	**93**	**75**	**322**

Budget (per year)

	Year 1	Year 2	Year 3	Total
	[k€]	[k€]	[k€]	[k€]
INFN Pisa				
Equipment (inv)	3	0	0	3
Consumables	2	2	2	6
Travels	2	5	5	12
TOTAL PI	**7**	**7**	**7**	**21**
INFN LNL				
Equipment (inv)	25	0	0	25
Consumables	25	4	4	33
Travels	15	24	9	48
Publications	5	8	8	21
TOTAL LNL	**70**	**36**	**21**	**127**
INFN Padova				
Equipment (inv)	12	0	0	12
Consumables	1	1	1	3
Travels	6	6	6	18
Publications	2	2	2	6
TOTAL PD	**21**	**9**	**9**	**39**
INFN Milano				
Equipment (inv)	0	0	0	0
Consumables	30.5	15.5	10	56
Travels	13.5	18.5	21	53
Publications	3	3	3	9
TOTAL MI	**47**	**37**	**34**	**118**
INFN Pavia				
Equipment (inv)	6	0	0	6
Consumables	0	0	0	0
Travels	3	4	4	11
TOTAL PV	**9**	**4**	**4**	**17**
TOTAL BUDGET	**145**	**89**	**71**	**322**

Conclusions

The SPES_MED collaboration

- **allows for data acquisition and human power collection in order to help the realisation of the phase “Gamma” of SPES**

- **Gives a contribution to the operativity of the LARAMED and ISOLPHARM lines**

- **Permette un miglioramento dei modelli di spettroscopia**

- **Collects unpublished experimental data**

- **Reinforces the collaboration between nuclear physicist interested to medical application**