Nuclear Physics Mid Term Plan in Italy

LNL – Session

Legnaro, April 11th-12th 2022

Nuclear Physics
Mid Term Plan in Italy

ISOL and laser applications at the SPES facility

Topics:

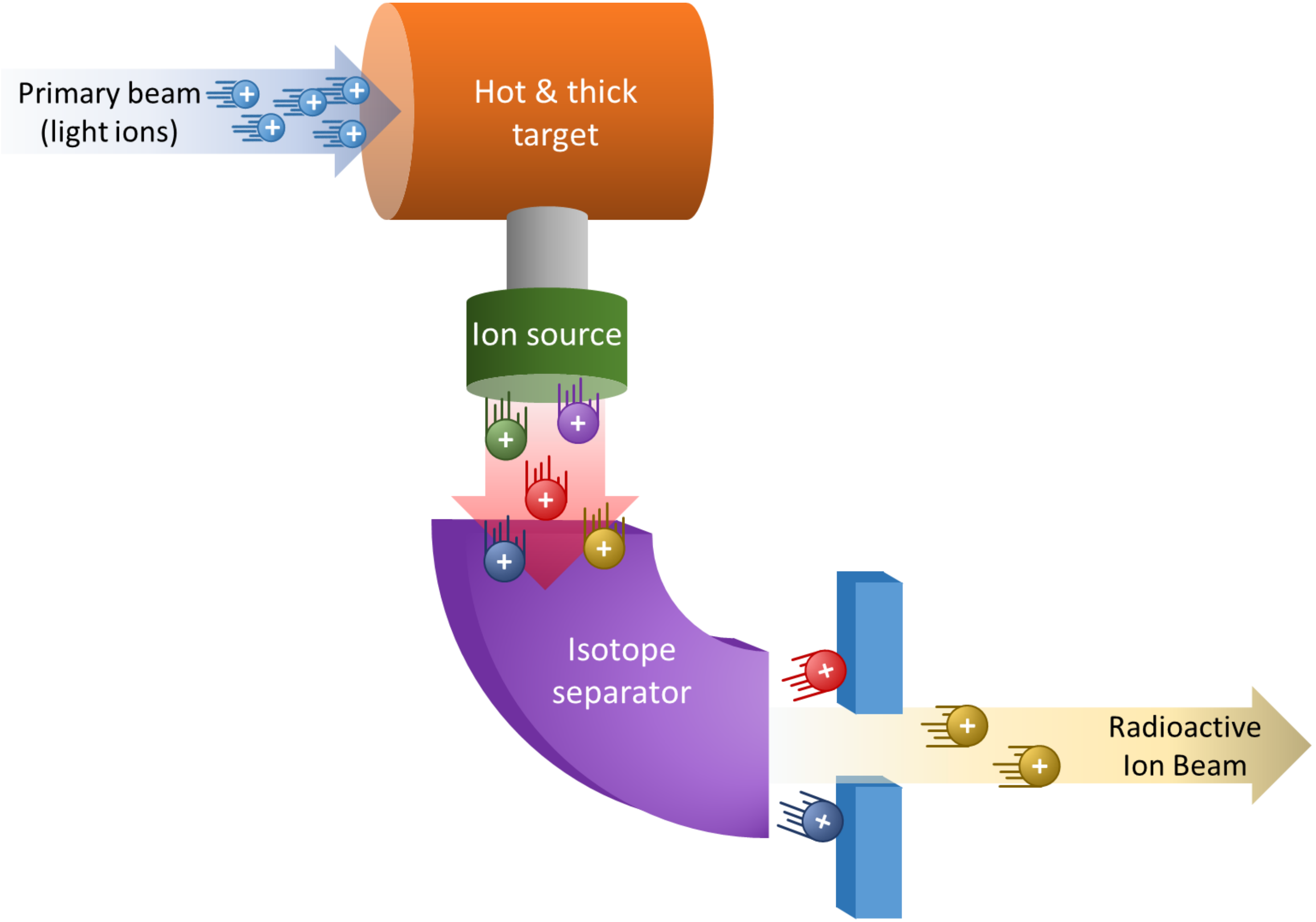
- Laser spectroscopy and applications
- Nuclide production with ISOL for medicine and nuclear physics
- Decay spectroscopy of nuclide of medical interest

Michele Ballan
INFN-LNL, Legnaro, Italy

On behalf of the SPES WP6 & ISOLPHARM collaboration

Istituto Nazionale di Fisica Nucleare

The ISOL technique for the production of Radioactive Ion Beams (RIBs)

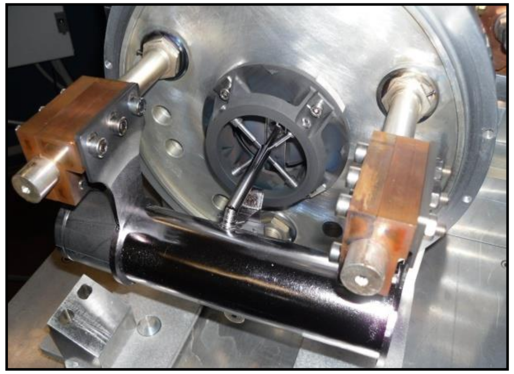


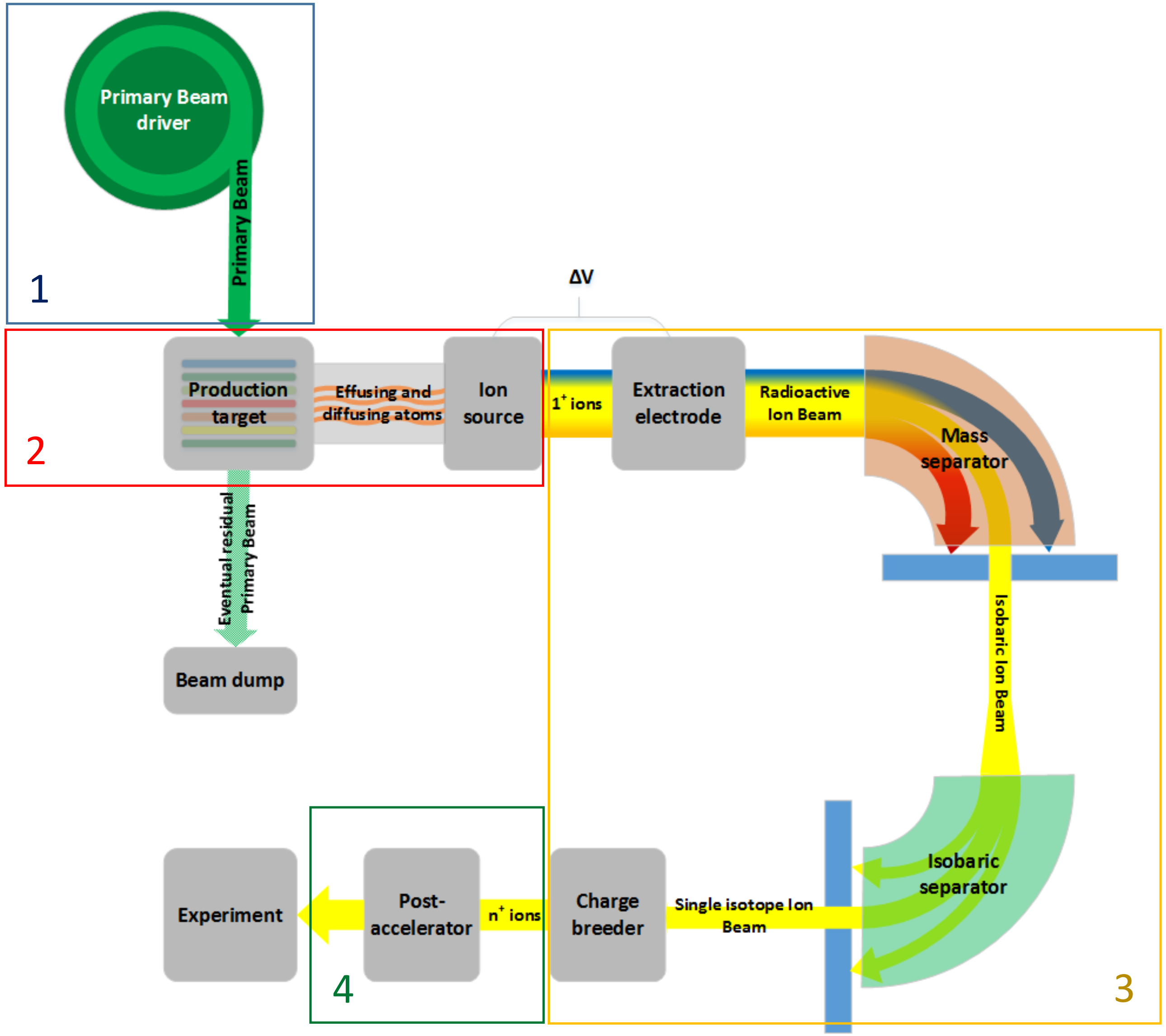
The SPES facility

1 - Driver

70 MeV commercial cyclotron

2 – Target-Ion Source unit





3- RIB manipulation

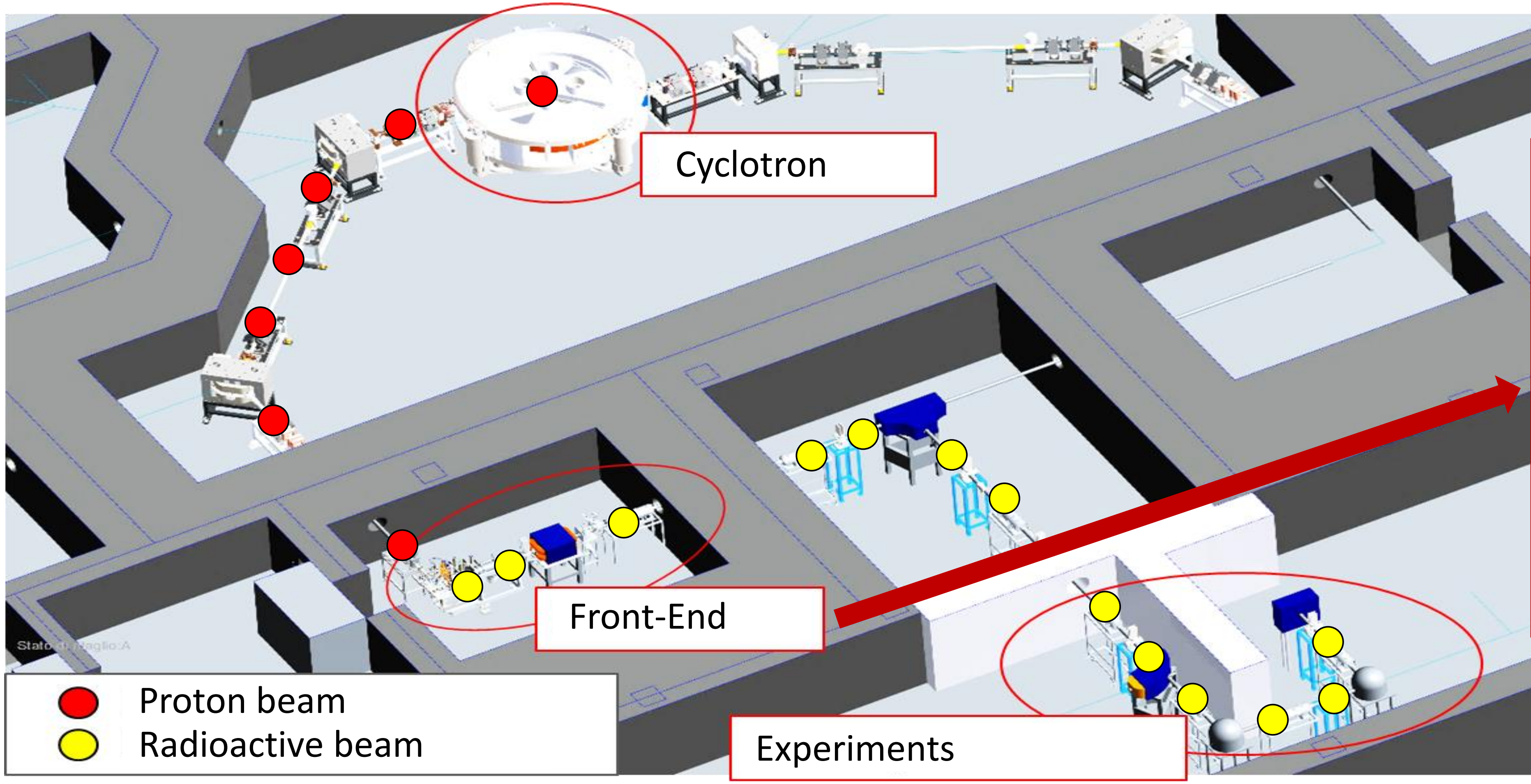
- Mass Separator (WF)
- Beam Cooler
- HRMS
- ECR Charge Breeder
- RFQ

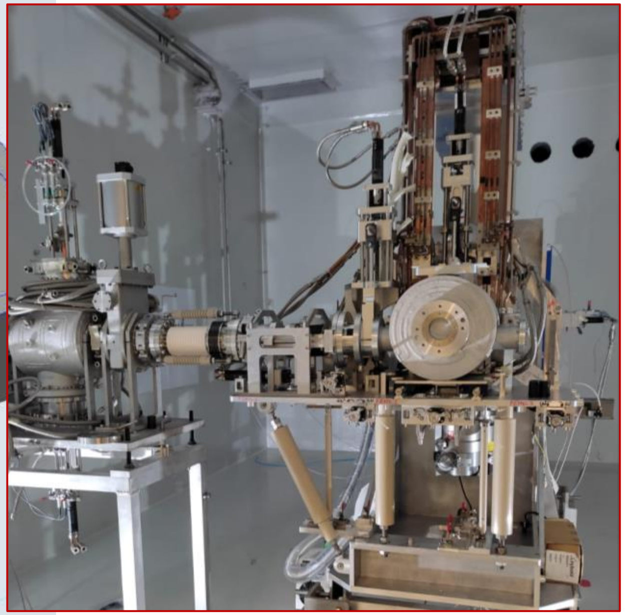
4 - Post Accelerator:

ALPI existing complex

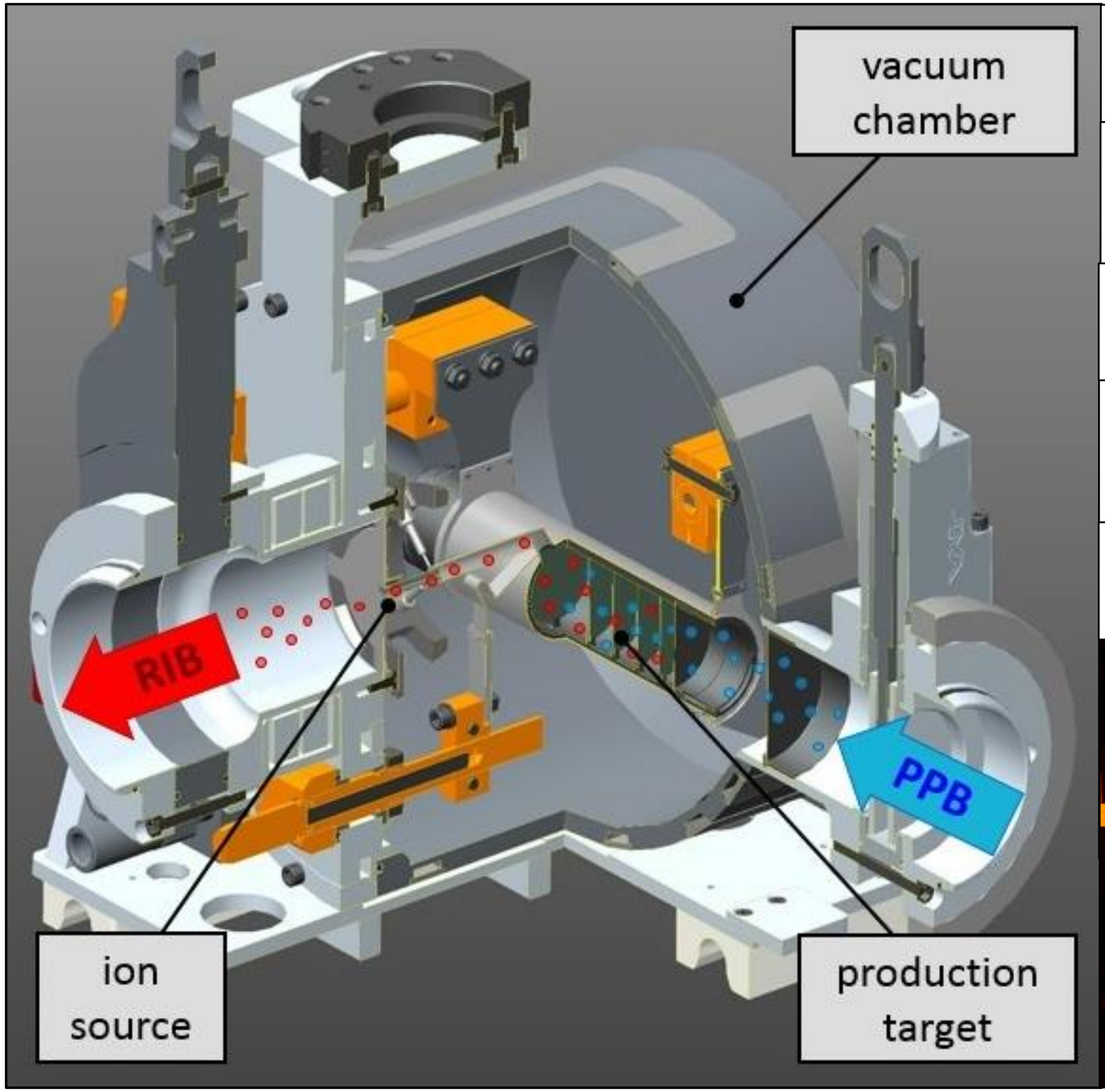
The SPES facility

The ISOL machine is currently being installed

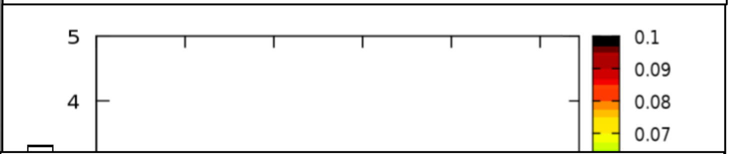




The SPES UC$_x$ target

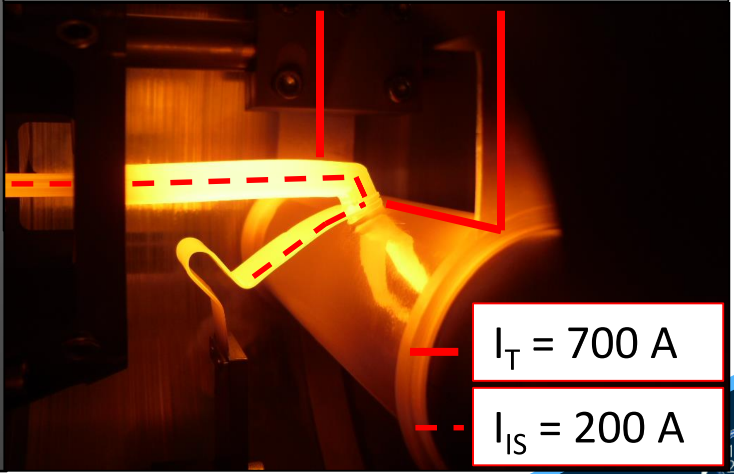


Desgined for stopping a 40 MeV 200µA PPB (FLUKA)

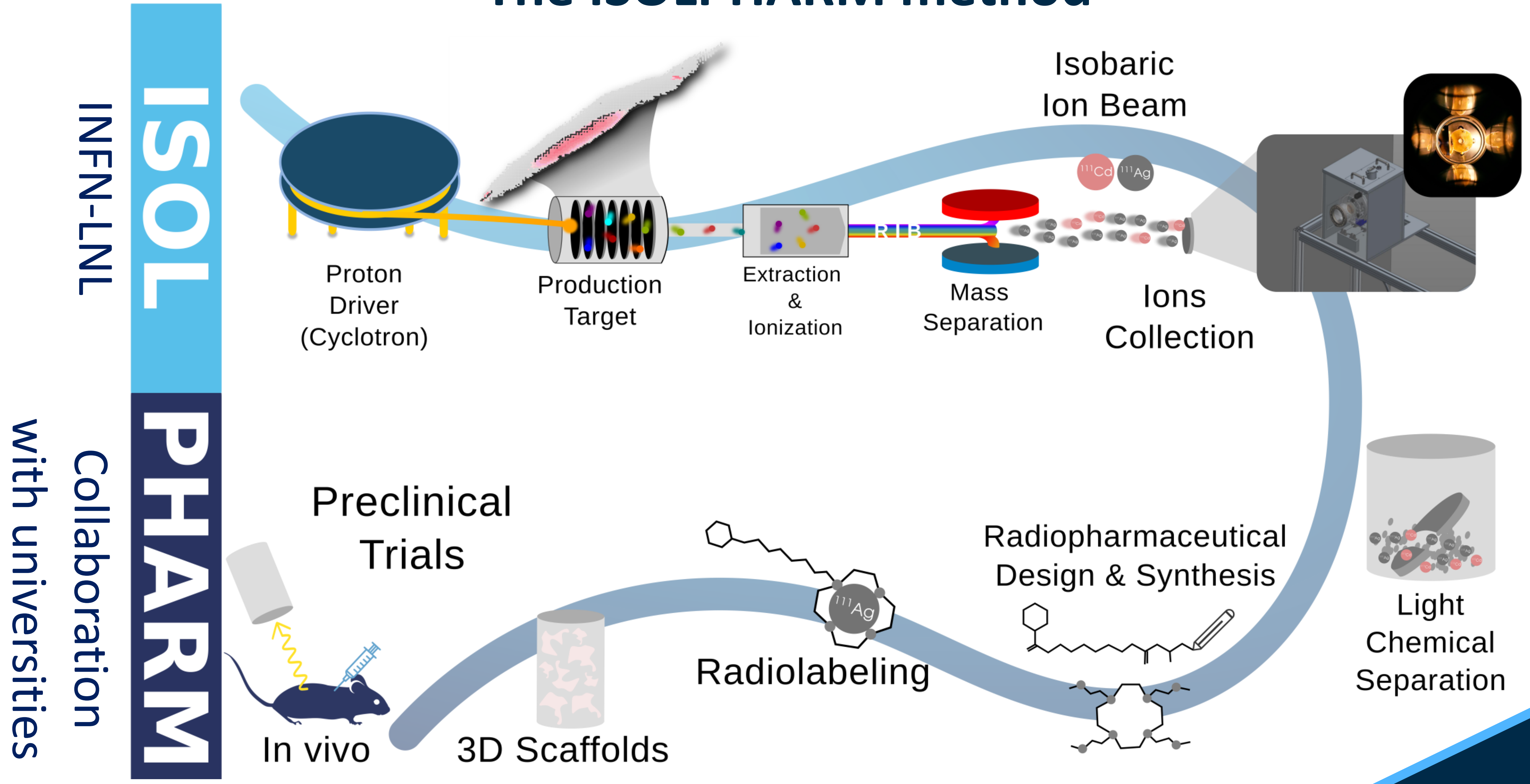


Designed for working temperatures above 2000°C (ANSYS®)

Tested and commissioned for high temperature operation



The ISOLPHARM method



The ISOLPHARM method: highlights

1. Method

Innovative production @SPES of several (medical) Carrier Free + High Purity radionuclides (^{111}Ag,^{89}Sr,^{136}Cs..)

2. Collaboration

Broad, focused on radio-phamaceutical development: synthesis,characterization and preclinical tests (*vitro/vivo*)

3. Set-up

An irradiation station, using the SPES Low Energy Beams, is planned in the SPES building

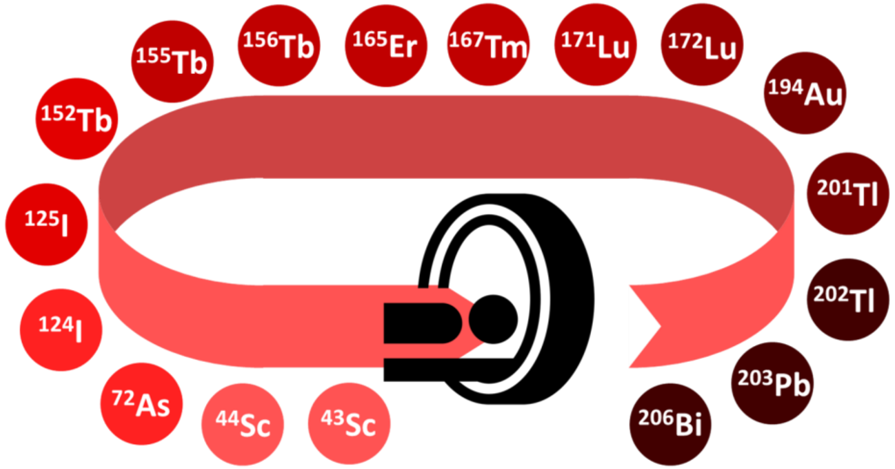
4. Experiment

Financed by CSN5 (physics application): ISOLPHARM_Ag + ISOLPHARM_EIRA.

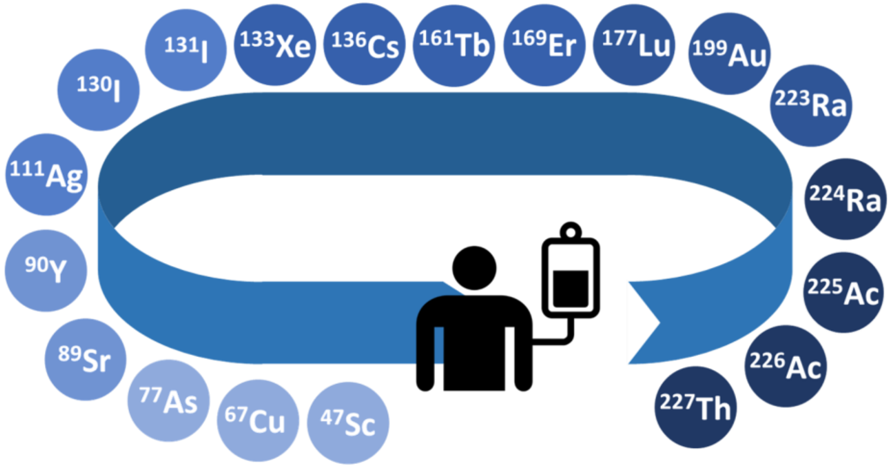
ISOLPHARM
SPES exotic beams for medicine

Possible ISOL nuclides of medical interest

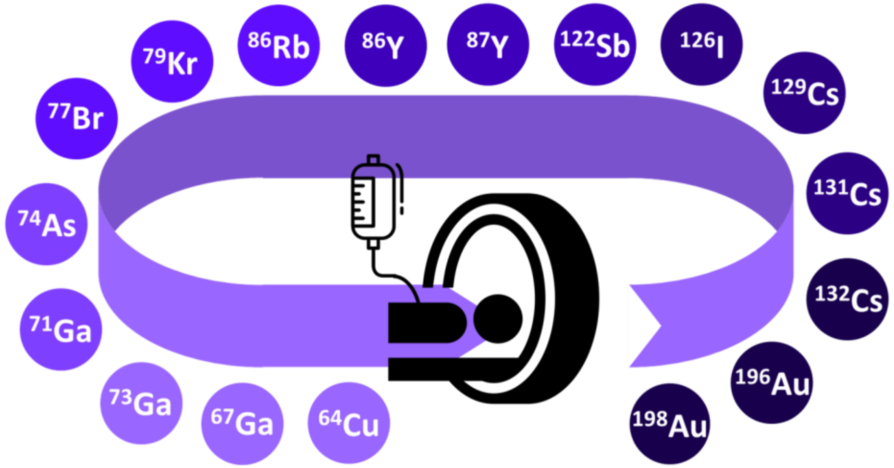
Diagnostic isotopes



Therapeutic isotopes

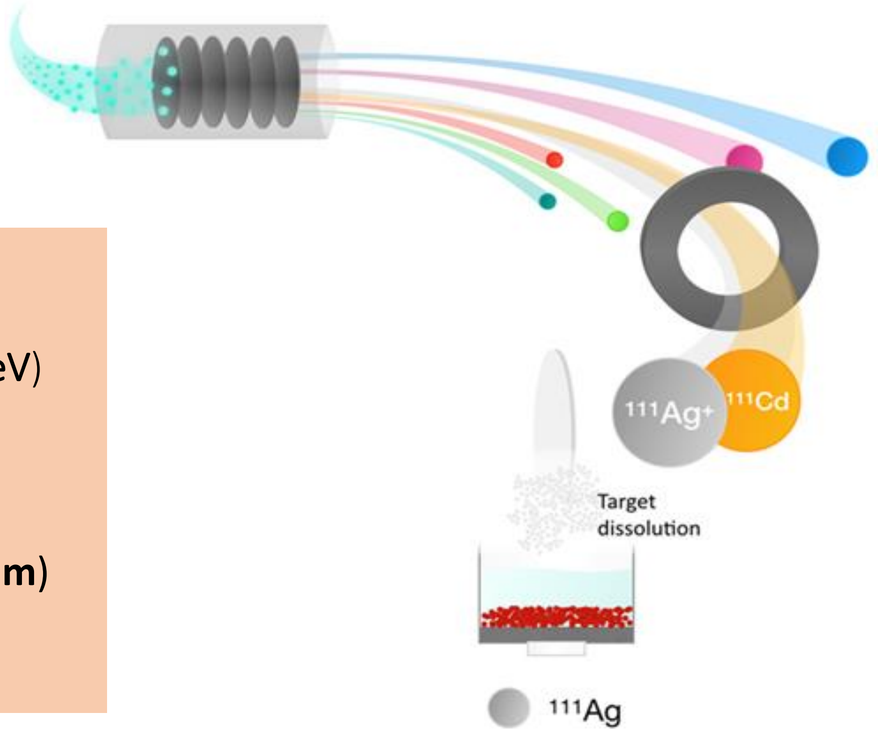


Theragnostic isotopes



Among the wide set of **ISOL producible nuclides**, a large number shows relevant properties for medicine, in terms of **half-life**, **decay radiation** and **chemical behavior**

Possible ISOL nuclides of medical interest: the case of ^{111}Ag



^{111}Ag properties

- ☐ **β^- emitter** (average energy **360 keV**)
- ☐ Good half-life (**7.45 days**)
- ☐ Average issue penetration (**1.8 mm**)
- ☐ Medium energy γ rays -> SPECT

111 Isobaric chain	$t_{½}$	Decay	Target Yield
^{111}Cadium	Stable		Low yield production
^{111}Silver	7.45 days	β^-	Good yield production
^{111}Palladium	23.4 min	β^-	Bad release, short $T_{1/2}$
^{111}Rhodium	11 sec.	β^-	No release, very short $T_{1/2}$

- ☐ In the market **No radiopharmaceuticals** Silver-based!
- ☐ ^{111}Ag can be produced @ SPES **with high purity** & also with **high production rate.**
- ☐ **No Isobaric radioactive contamination** in the secondary target (also with LASER off)!

ISOLPHARM: the collaboration

ISOLPHARM started as a scientific gathering of local competences, now coordinated by **INFN-LNL**

TIFPA Trento Institute for Fundamental Physics and Applications
UNIVERSITÀ DI TRENTO
BIOtech Biomedical Technologies
CIBIO Centre for Integrative Biology

Development of cell-lines, *in-vitro* and *in-vivo* studies, imaging

Cancer cell

UNIVERSITÀ DEGLI STUDI DI PADOVA
dsf
UNIVERSITÀ degli STUDI di CATANIA
CAPiR Center for Advanced Preclinical *in vivo* Research

Development and synthesis of small molecules for cancer treatment

UNIVERSITÀ DEGLI STUDI DI PADOVA
dsf
SERVIZIO SANITARIO REGIONALE EMILIA-ROMAGNA
Azienda Unità Sanitaria Locale di Reggio Emilia
Azienda Ospedaliera di Reggio Emilia
Arcispedale S. Maria Nuova
Istituto in tecnologie avanzate e modelli assistenziali in oncologia
Istituto di ricovero e cura a carattere scientifico

ISOLPHARM SPES exotic beams for medicine
INFN LNL

UNIVERSITÀ DI SIENA 1240
DSFTA
UNIVERSITÀ DEGLI STUDI DI BRESCIA
IMI

Unconventional radionuclide (e.g. ^{111}Ag) production with an innovative method

^{111}Ag

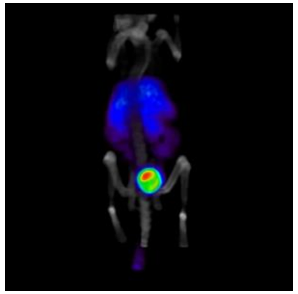
INFN
UNIVERSITÀ DEGLI STUDI DI PADOVA
Dipartimento di Fisica e Astronomia Galileo Galilei

UNIVERSITÀ DEGLI STUDI DI PADOVA
dsf

Study and development of tumor targeting agents for specific targets (e.g. CCK2R)

UNIVERSITÀ DEGLI STUDI DI PADOVA
DiSC
UNIVERSITÀ DI PAVIA
L.E.N.A.

Development of chemical purification procedures and innovative chelators



PET imaging of a mouse treated with a ^{64}Cu-labelled radiopharmaceutical developed by the ISOLPHARM collaboration

Laser spectroscopy and applications

Contributors:
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Daniele Scarpa, *INFN-LNL*
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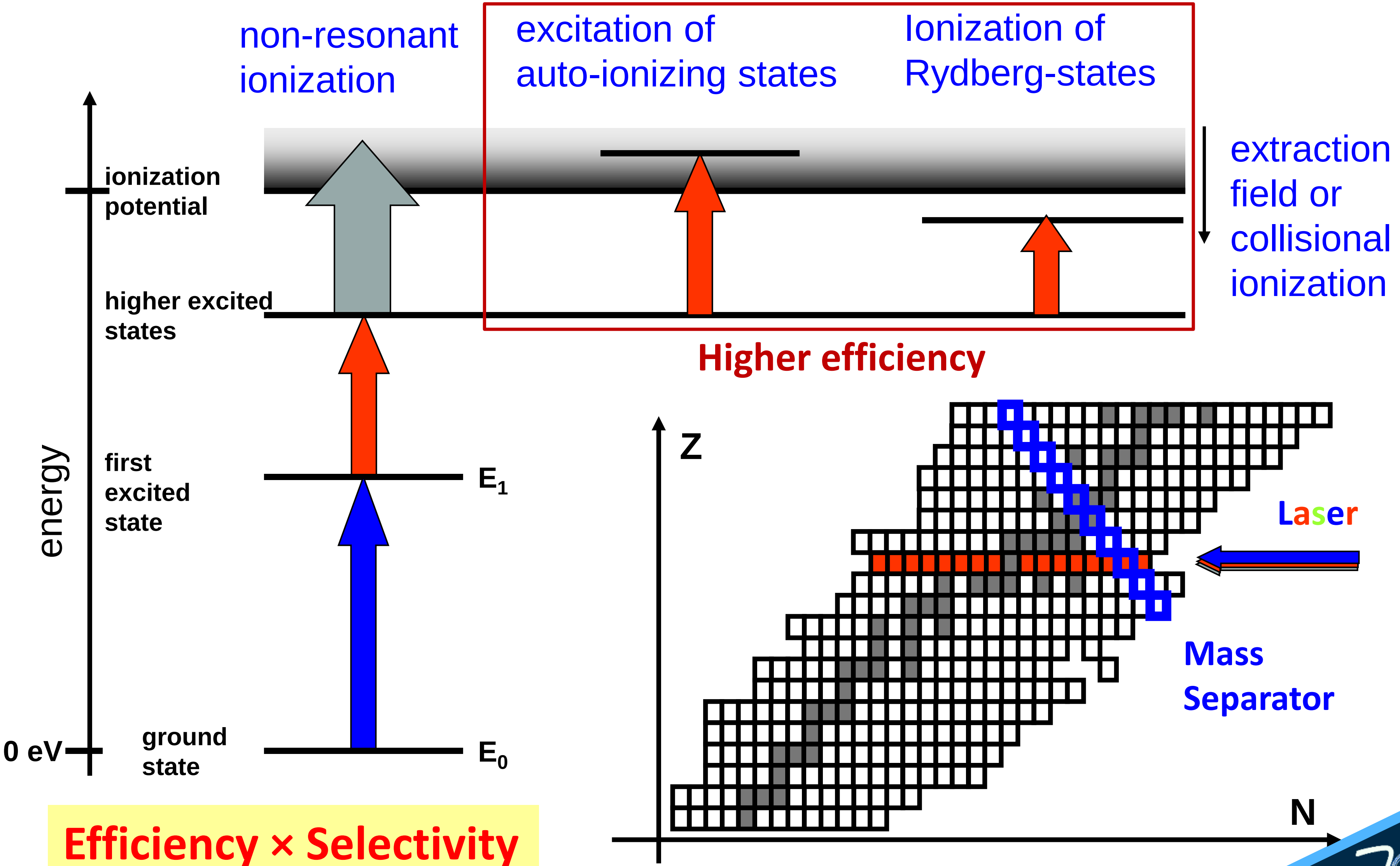
Principles of resonant laser ionization



Higher efficiency

Efficiency × Selectivity

Challenges to high efficiency laser ionization

- More than 50 % of the elements for which photoionization has been realized **rely on a non-resonant ionization step.**
- For these elements, the ionization step is **not saturated,** and the efficiency is proportional to the **available pump laser power** for this step.
- The efficiency can be significantly **improved if** the final step populates **an Auto-Ionizing State (AISs).**
- The main limitations in looking for AISs are
    1) time-consuming process
    2) For many elements, a suitable AIS does not exist.

Such activity benefits of the active collaboration with the community of Laser facilities

CERN ISOLDE JYVÄSKYLÄN YLIOPISTO UNIVERSITY OF JYVÄSKYLÄ PNPI - NRC KI OAK RIDGE National Laboratory

The Laser laboratories at SPES

Offline: spectroscopy studies

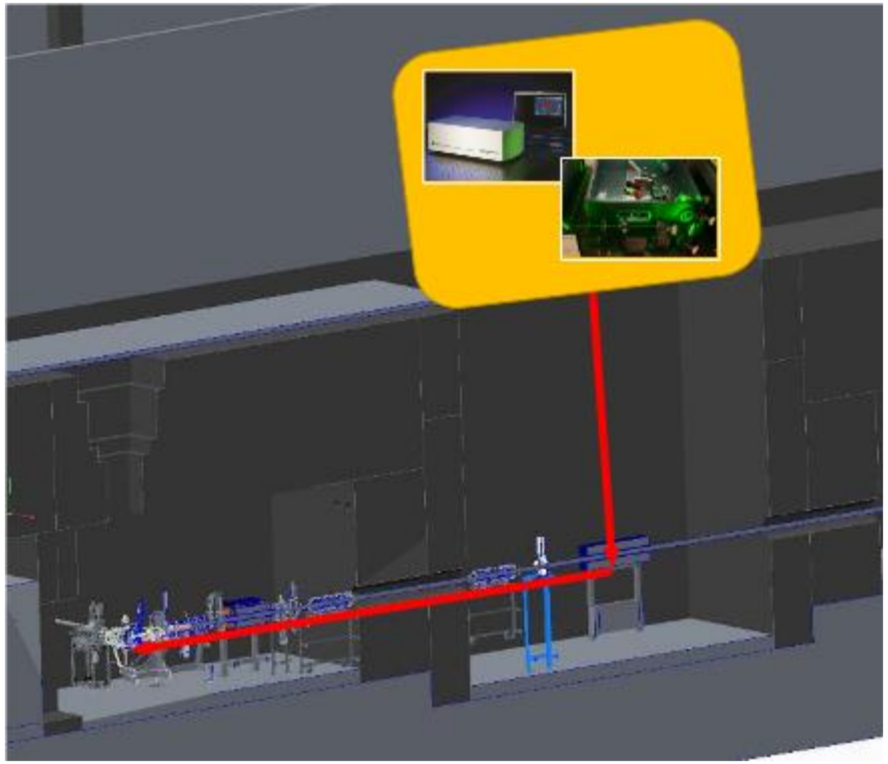
3 Dye Laser @ 10 Hz rep. rate

Diagnostic tools:

- Monochromator
- HCL
- ToF Mass Spectrometer

Online (SS laser): RIB production

3 Dye Laser @ 10 Hz rep. rate

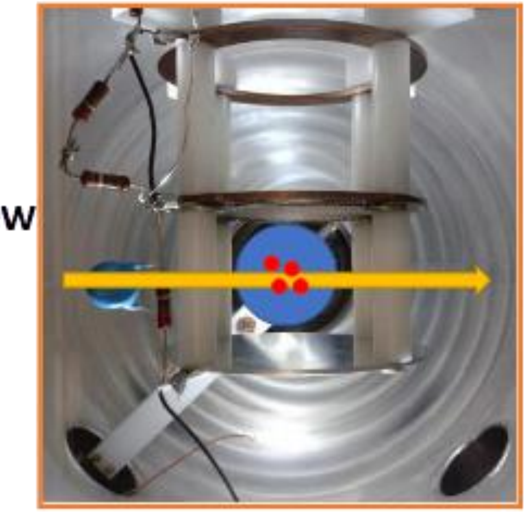


Diagnostic tools:

- Λ-meter
- Alignment system
- Ion-beam

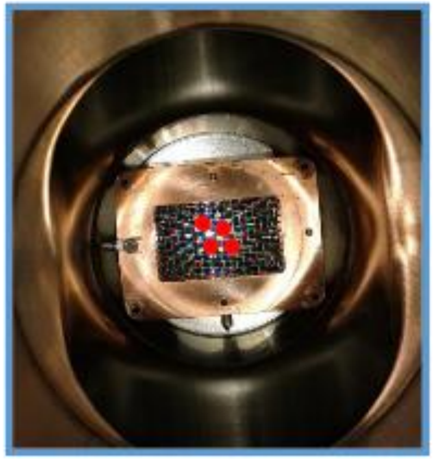
Home-made Time-of-Flight (TOF)

Top view



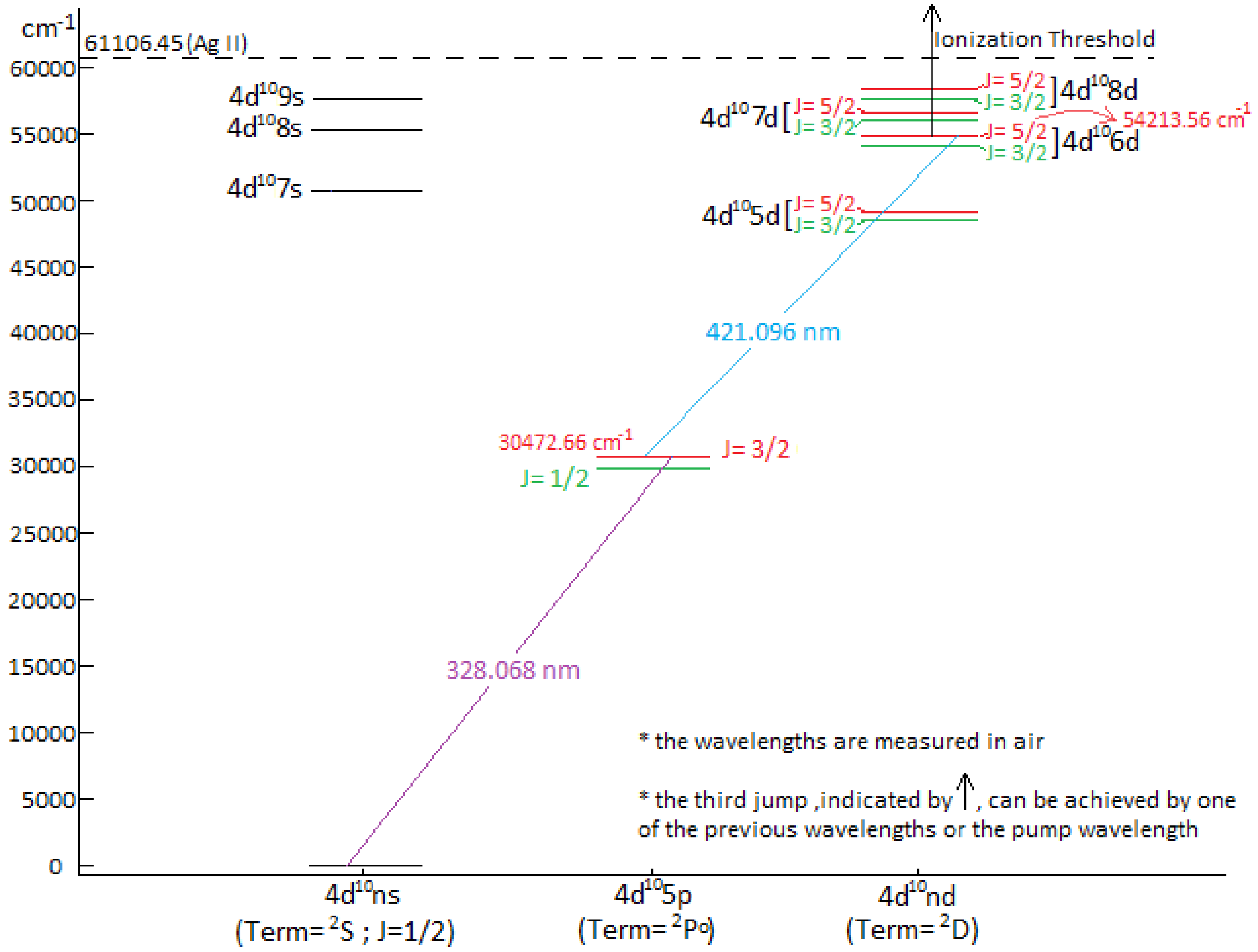
Front view
(as seen by the ionization laser)

Measure Sequence:



1) Ablation
2) Plume Expansion
3) Photoionization
4) Flight
5) Collection

Example: ionization scheme of Ag



* the wavelengths are measured in air

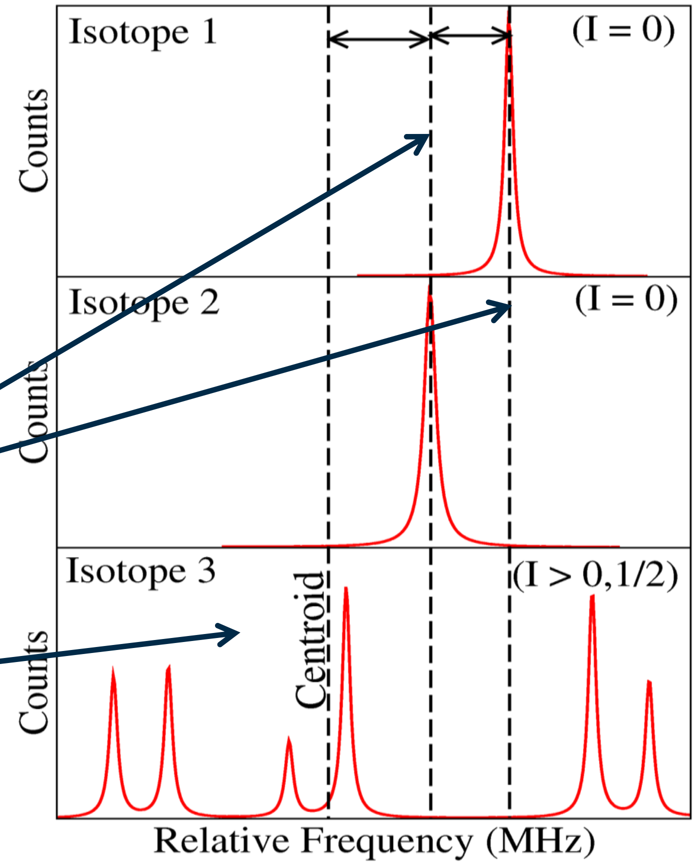
* the third jump ,indicated by ↑, can be achieved by one of the previous wavelengths or the pump wavelength

A nuclear fingerprint in the atomic spectrum

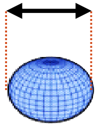
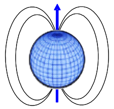
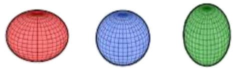
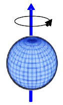
The nucleus is not a point charge –
the atomic energy levels are perturbed
by the electric and magnetic fields
at the nucleus (*part per million* effects)

Investigation of

- Isotope shifts
- Isomer shifts
- Hyperfine structure



provides **model-independent** data…

$\delta\langle r^2\rangle$  μ  Q_S  I 

Such activity could require an upgrade to the current laser set-ups

Nuclide production with ISOL for medicine and nuclear physics

Contributors:

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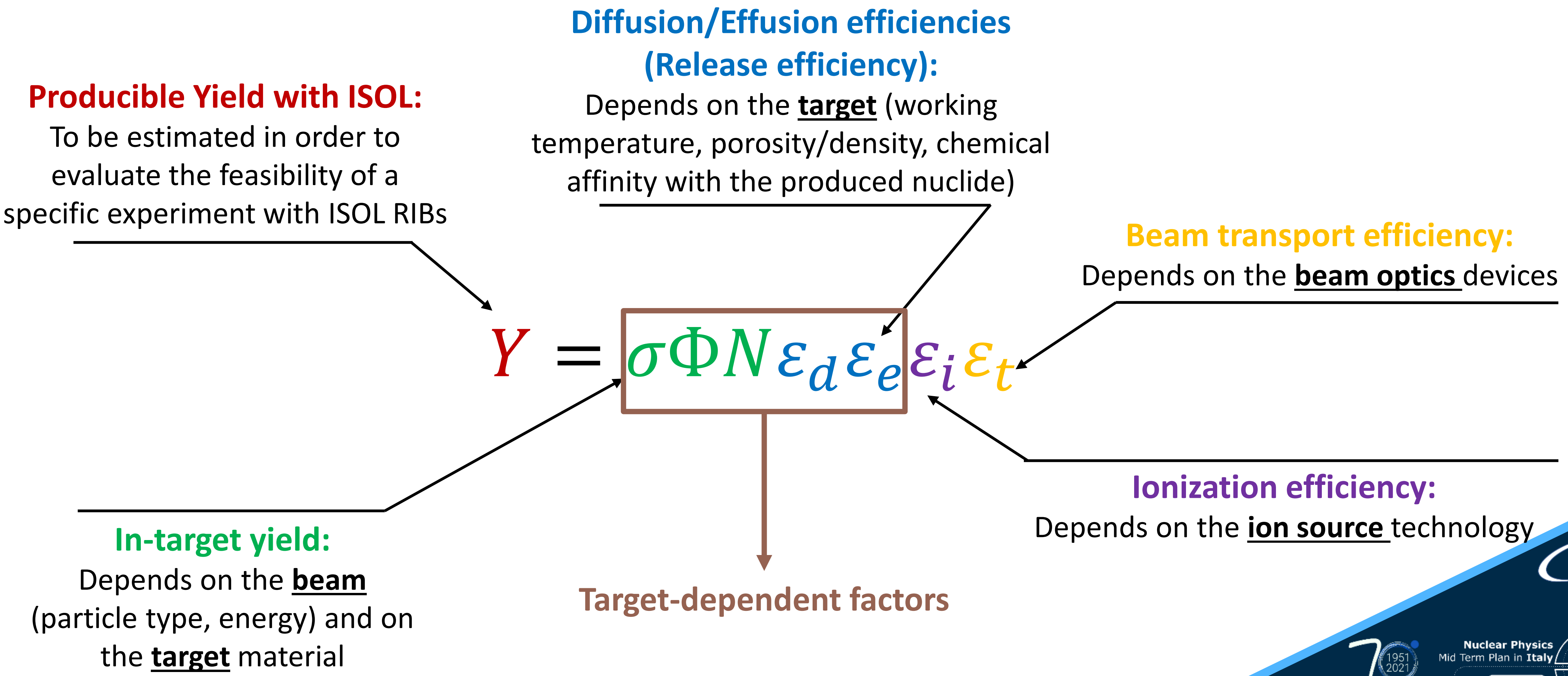
Antonietta Donzella, *UNIBS & INFN-PV*
João Pedro Ramos, *SCK CEN*
Lucia-Ana Popescu*, SCK CEN*

Feasibility of nuclide production with ISOL for medicine and nuclear physics



Producible Yield with ISOL:
To be estimated in order to evaluate the feasibility of a specific experiment with ISOL RIBs

Diffusion/Effusion efficiencies (Release efficiency):
Depends on the **target** (working temperature, porosity/density, chemical affinity with the produced nuclide)

Beam transport efficiency:
Depends on the **beam optics** devices

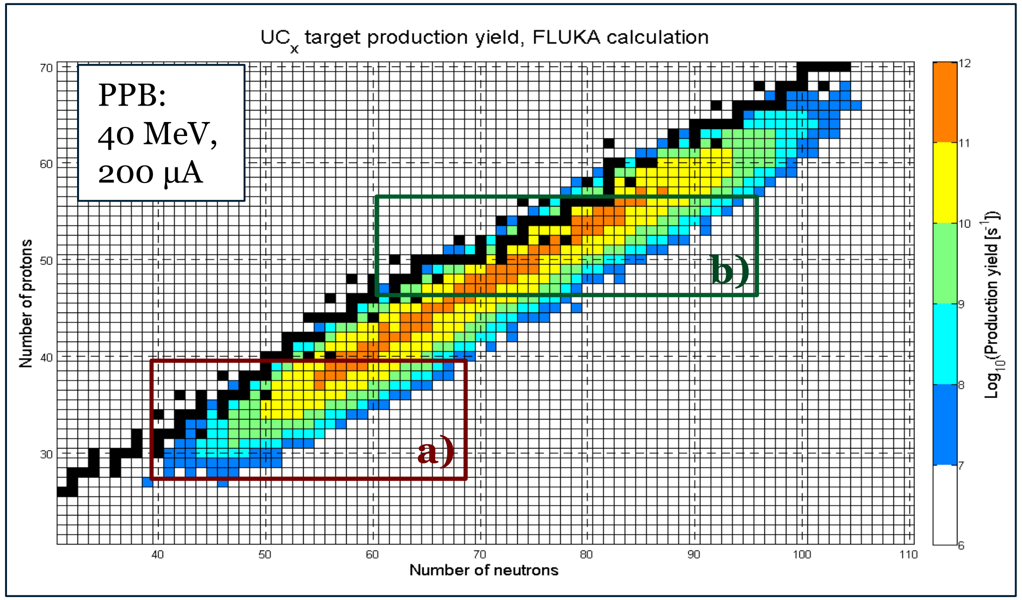
$$Y = \boxed{\sigma\Phi N\varepsilon_d\varepsilon_e}\varepsilon_i\varepsilon_t$$

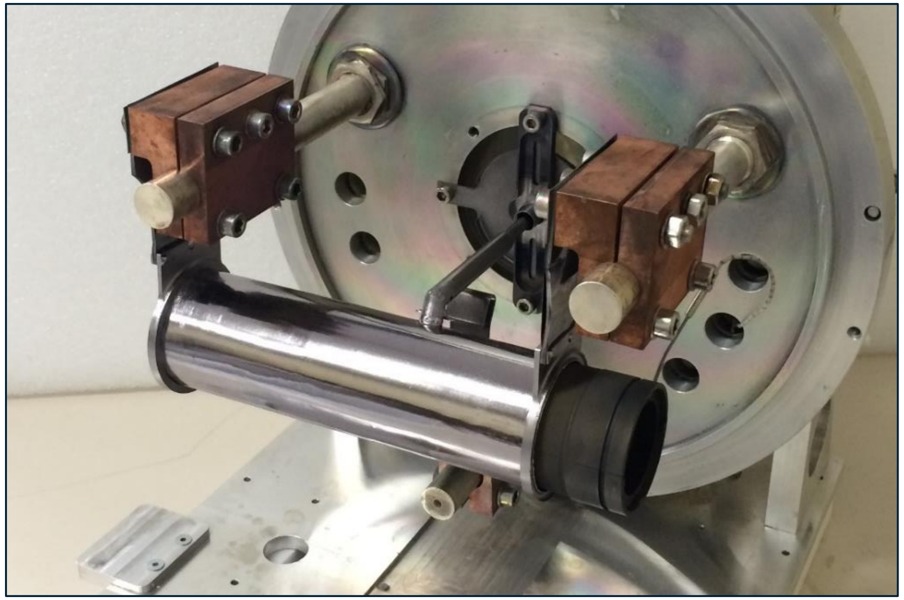
In-target yield:
Depends on the **beam** (particle type, energy) and on the **target** material

Target-dependent factors

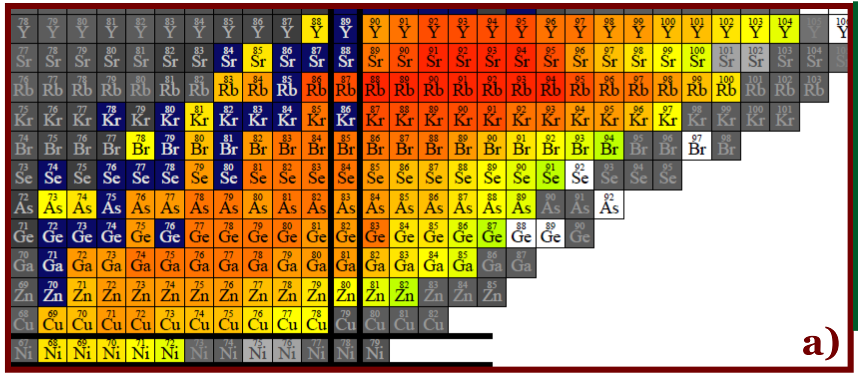
Ionization efficiency:
Depends on the **ion source** technology

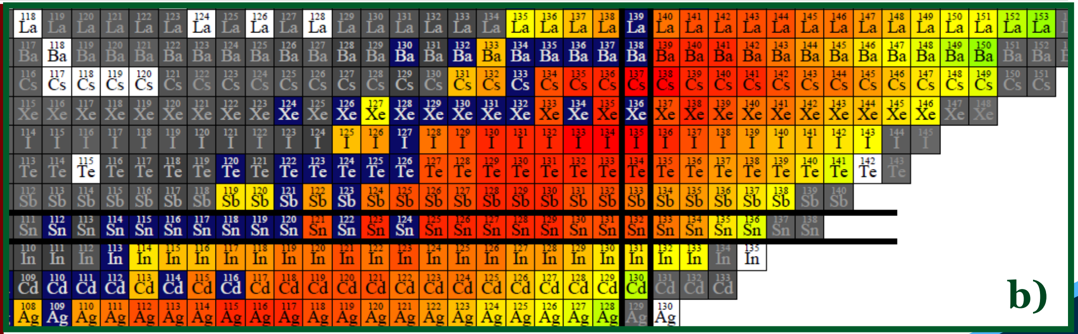
The SPES UC$_x$ target





🟥 > 10^11
🟥 10^10 - 10^11
🟧 10^9 - 10^10
🟧 10^8 - 10^9
🟧 10^7 - 10^8
🟨 10^6 - 10^7
🟨 10^5 - 10^6
🟨 10^4 - 10^5
🟨 10^3 - 10^4
🟩 10^2 - 10^3
🟩 10 - 10^2
🟩 < 10
[nuclide/s]



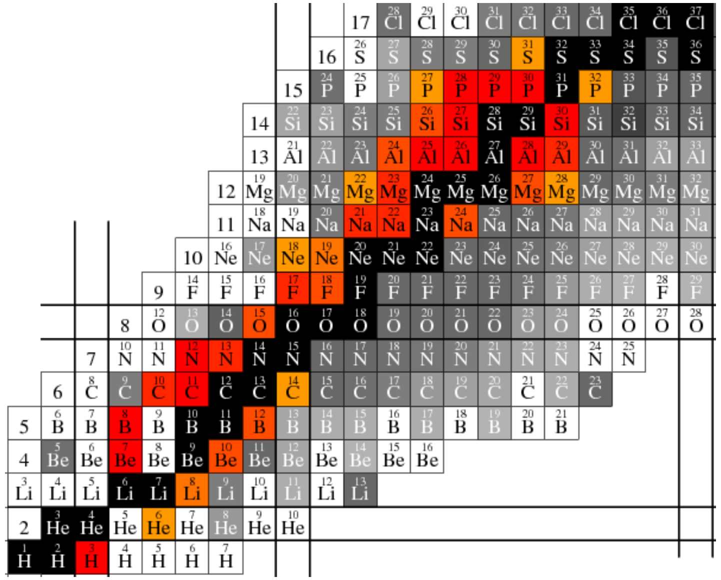


FLUKA calculations experimentally validated at ORNL

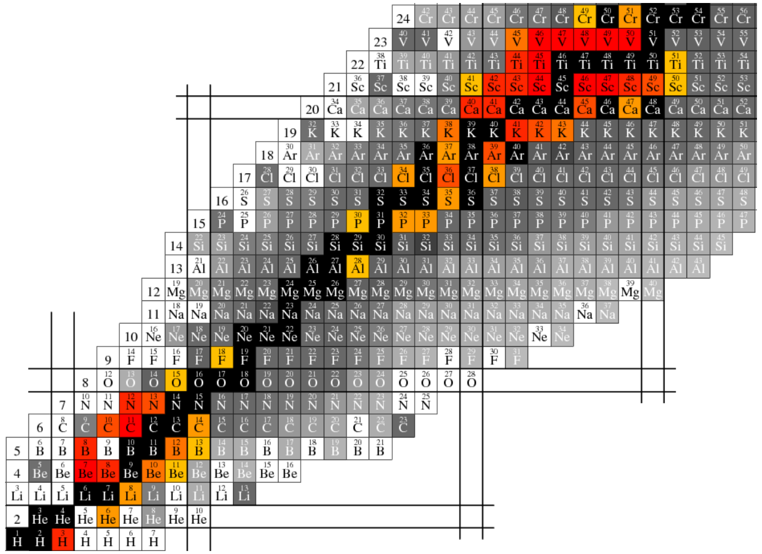
Other possible target materials

(some examples)

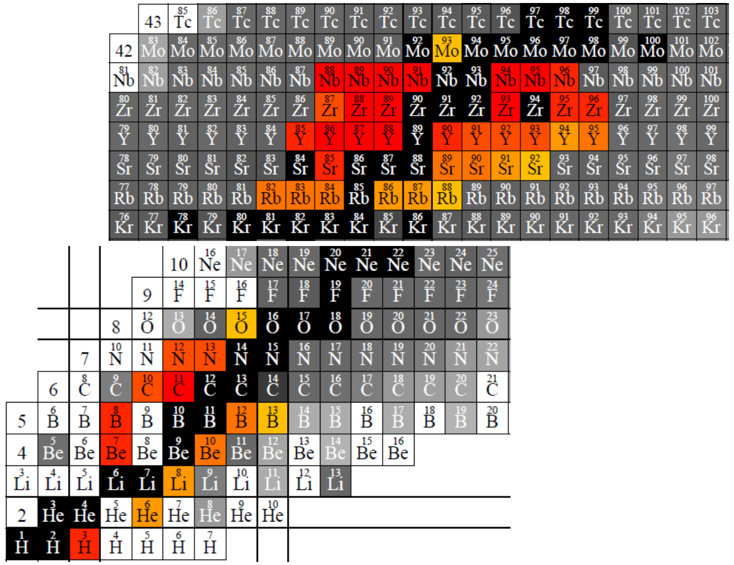
Silicon Carbide (SiC):



Titanium Carbide (TiC):



Zirconium Carbide (ZrC):



In-target FLUKA estimated yields

🟥	> 10^11	🟧	10^9 - 10^10	🟧	10^7 - 10^8	🟨	10^5 - 10^6	🟨	10^3 - 10^4	🟩	10 - 10^2
🟥	10^10 - 10^11	🟧	10^8 - 10^9	🟨	10^6 - 10^7	🟨	10^4 - 10^5	🟩	10^2 - 10^3	🟩	< 10

[nuclide/s]

Further examples: B_4C, LaC_x, ZrO_2, HfO_2, CeO_2, ZrGe, CeS

Further information: https://doi.org/10.1016/j.nimb.2016.01.020

ISOL target material requirements at SPES

In case of SPES, target materials have to meet some specific mandatory requirements:

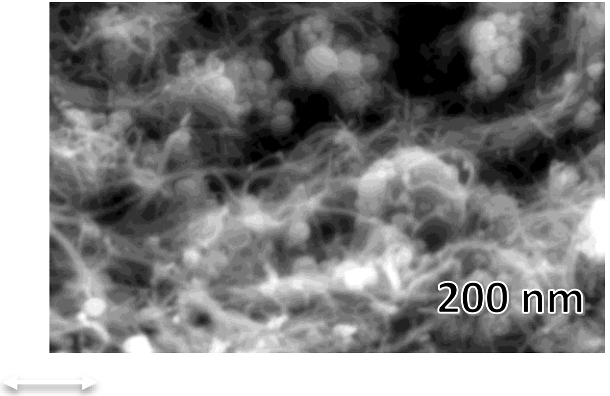
- They have to be **solid** (liquid target are not yet foreseen at SPES)
- They have to be **refractory** (the higher the working temperature the faster the release)
- They have to be **porous** (open porosity enhances the releases of the produced nuclides)
- They have to withstand **extreme conditions:** high power, thermal stresses, radiation damage, (direct particle irradiation and very high temperature, in the range of 2000 °C) with an impact on RIB yields.

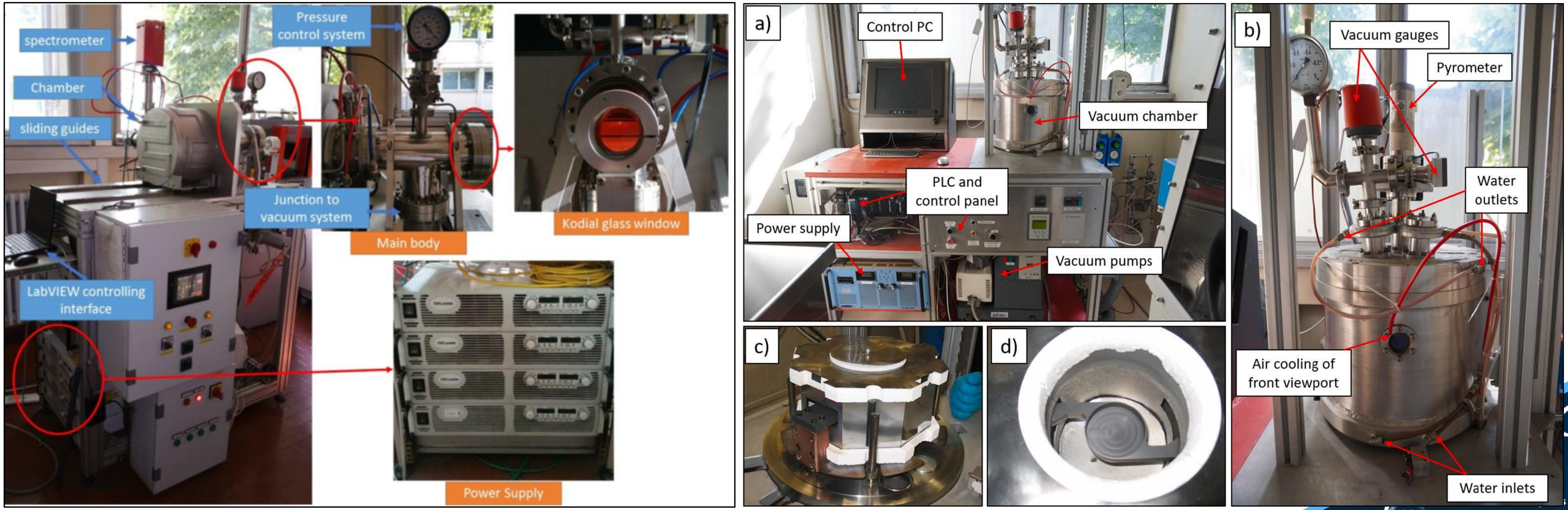
Each new target material requires efforts in its development and characterization before being ready for irradiation

Such activity benefits of the active collaboration with the community of ISOL facilities

Development of target materials

- Typical ceramic targets production methods:
  - Dry method (pressing and sintering of powders)
  - Sol-gel method (powder mixed with a gel solution)
- Micro- or Nano-structured materials with high porosity (usually 30-70%) are the state of the art

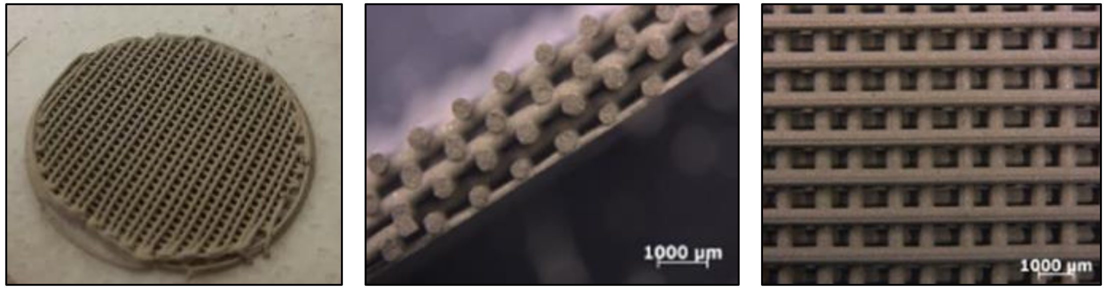




Furnaces for target development at INFN-LNL

Development of target materials: alternative production techniques

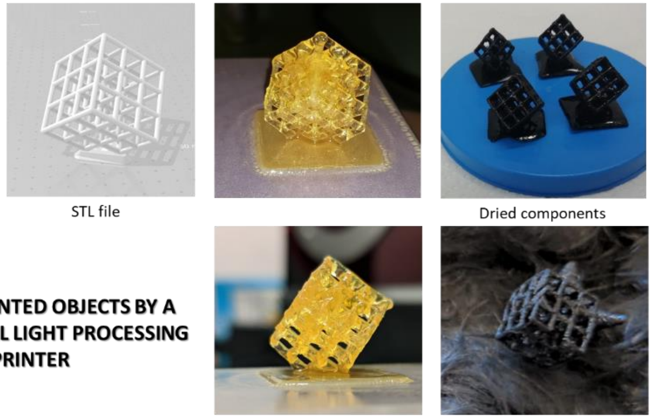
Fabrication of SiC disks by DIW (Direct Ink Writing)



Fabrication of TiC components

PRINTING OF PHOTOCURABLE TITANIUM-SUCROSE-BASED SOL-GEL INK BY DLP

→ 3D PRINTED OBJECTS BY A DIGITAL LIGHT PROCESSING (DLP) PRINTER


STL file
Dried components
Printed components
Sintered component at 1450°C

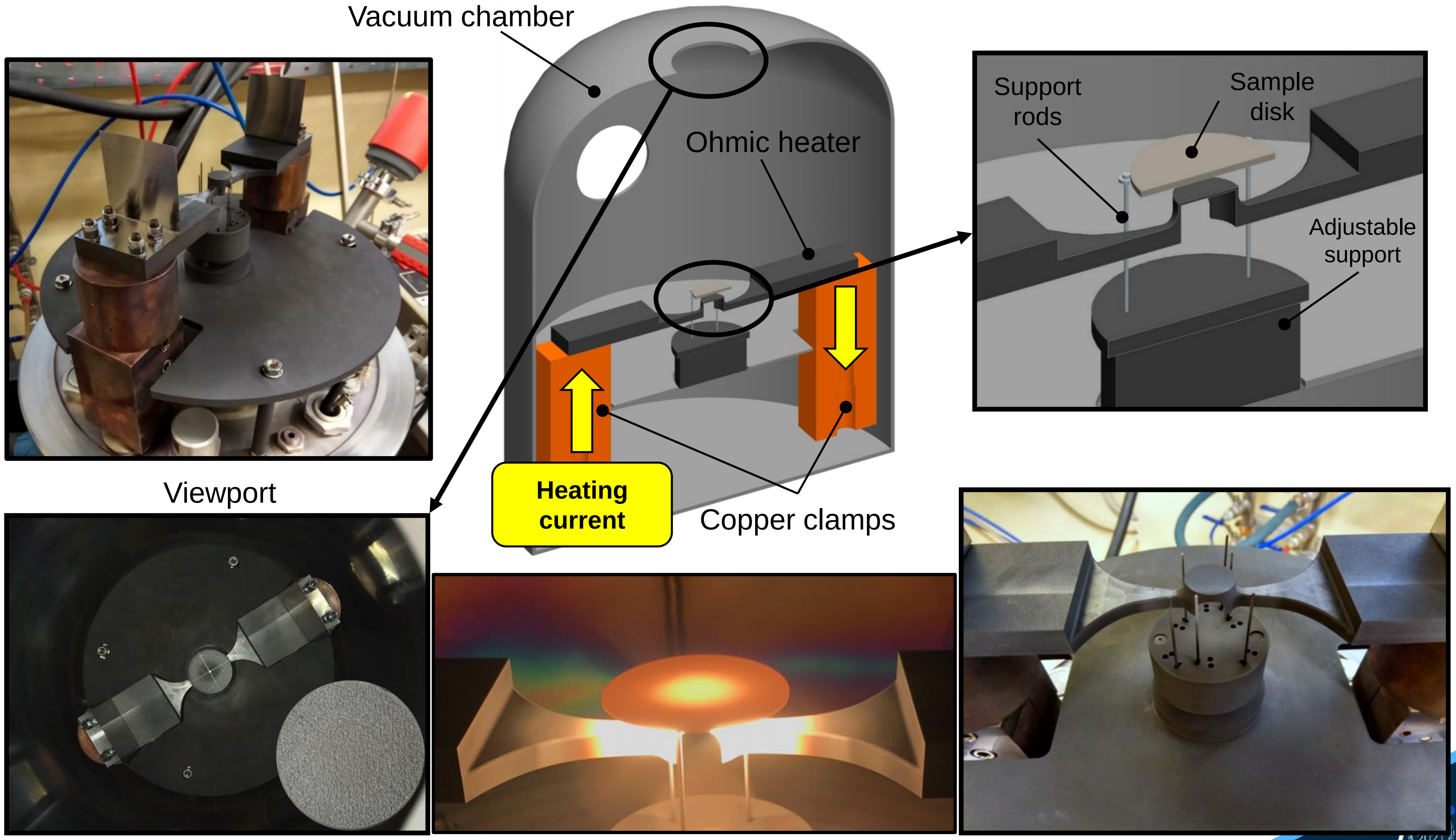
Additive Manufacturing of ceramic regular structures:

- **Maximization of radiative heat transfer** (increment of the sustainable primary beam intensity)
- **Improved release properties**

AM targets are expected to ensure higher RIB intensities

Activity in the framework of the INFN-E Project **AM4INFN,** in collaboration with INFN-PD and UNIPD

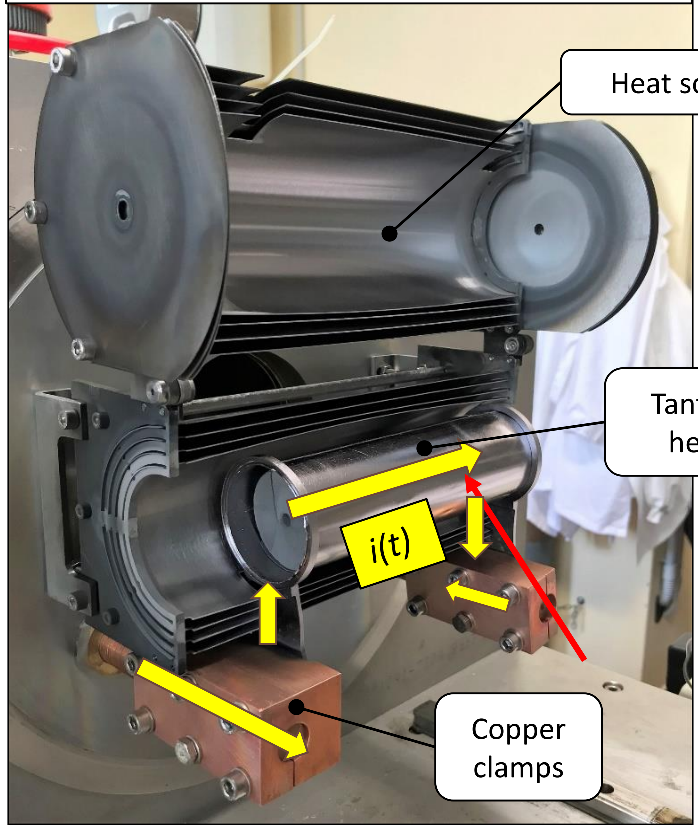
Characterization of target materials: thermal properties (thermal conductivity and emissivity)

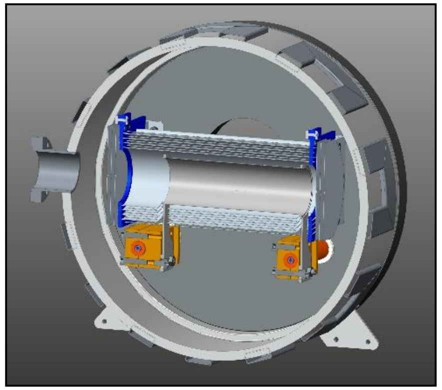


more information at: https://doi.org/10.3390/ma14102689

Characterization of target materials: limit temperature and stress resistance

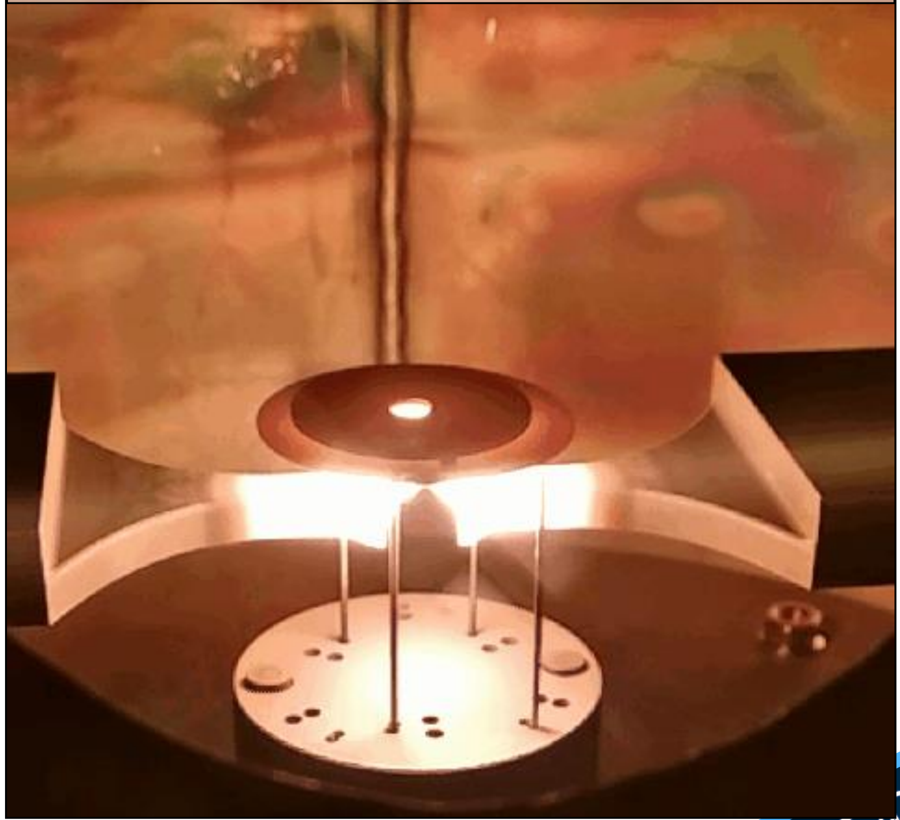
Experimental set-up





	SiC
T_{lim}	1700 °C

Example with a SiC sample



Characterization of target materials: post irradiation analysis

sck cen

Examples of equipment at SCK CEN for nuclear material handling and post irradiation analysis

- Target material research would greatly benefit for a **coordinated approach** and a **facilitated transnational access**.
- **Complimentary** laboratories including characterization techniques are present across all ISOL facilities, e.g.:
    - SCK CEN with very large **service infrastructure** for materials characterization (incl. nuclear materials and post-irradiation examination)
    - INFN-LNL with the expertise of thermal and structural characterization of multi-foil targets
- It also allows the development of **consistent characterization and material production protocols** to allow state of the art operation at all involved facilities.

Decay spectroscopy of nuclides of medical interest

Contributors:
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Luca Morselli, *INFN-LNL & UNIFE*
Luca Stevanato, *UNIPD*

IRIS – ISOL(PHARM) Radionuclide Implantation Station

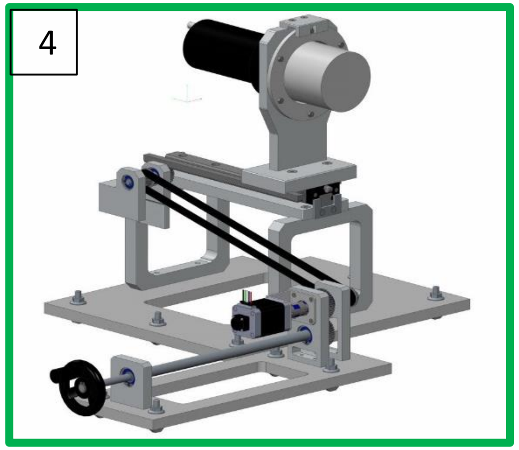
ISOLPHARM required the development of a device able to **handle the collection targets** and **perform spectroscopic analysis** for the quality control of the collected radionuclides.

Such device could also be used to **produce extremely pure radioactive sources** (monoisotopic if laser ionization is used) extremely **interesting for nuclear physics applications**

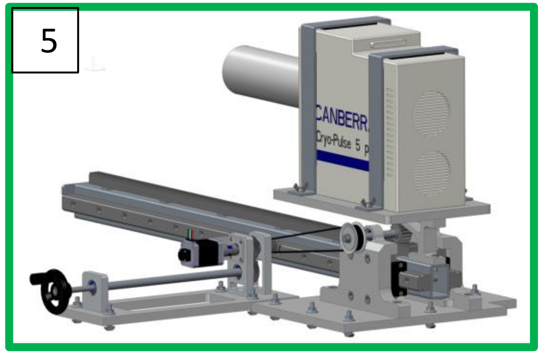
ISOL(PHARM) Radionuclide Implantation Station (IRIS) and its collocation in the SPES low energy experimental hall.

IRIS (ISOLPHARM Radionuclide Implantation Station)

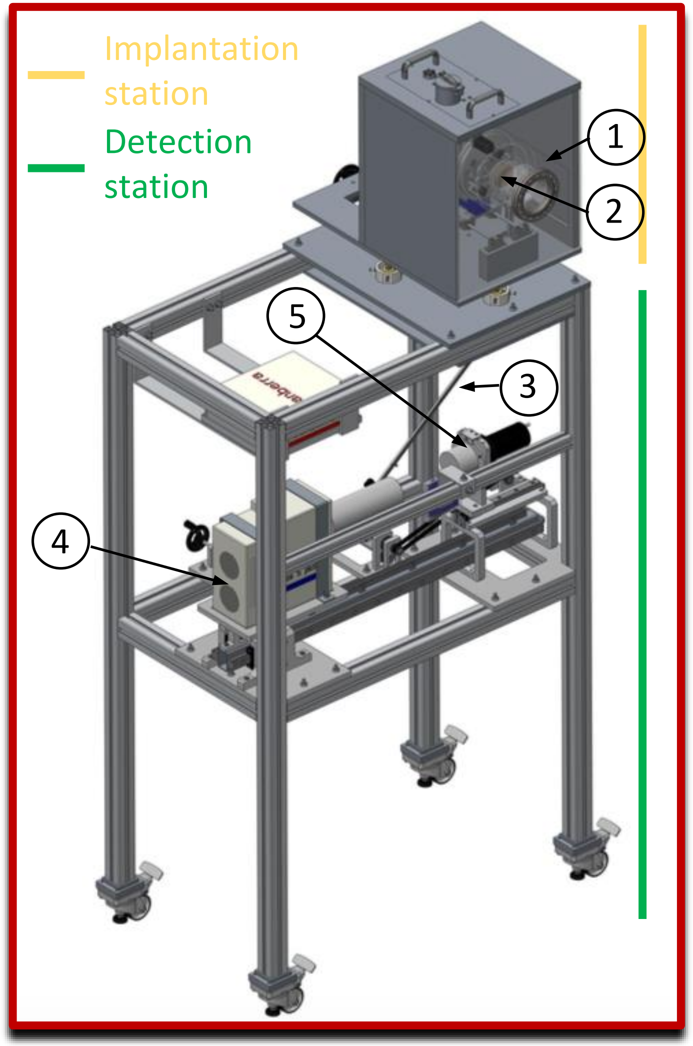
$LaBr_3$ Detector



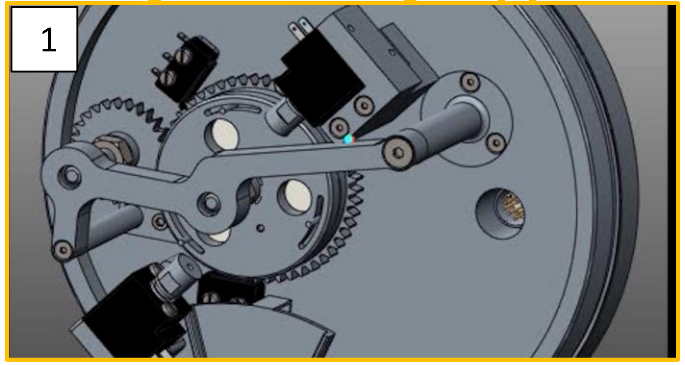
HPGe detector



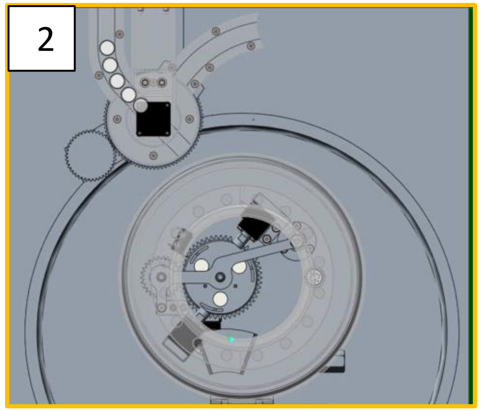
IRIS



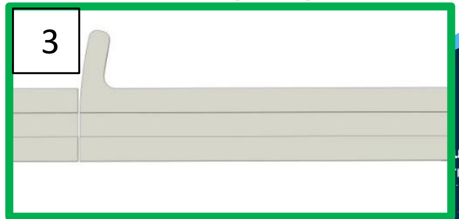
Target rotating support



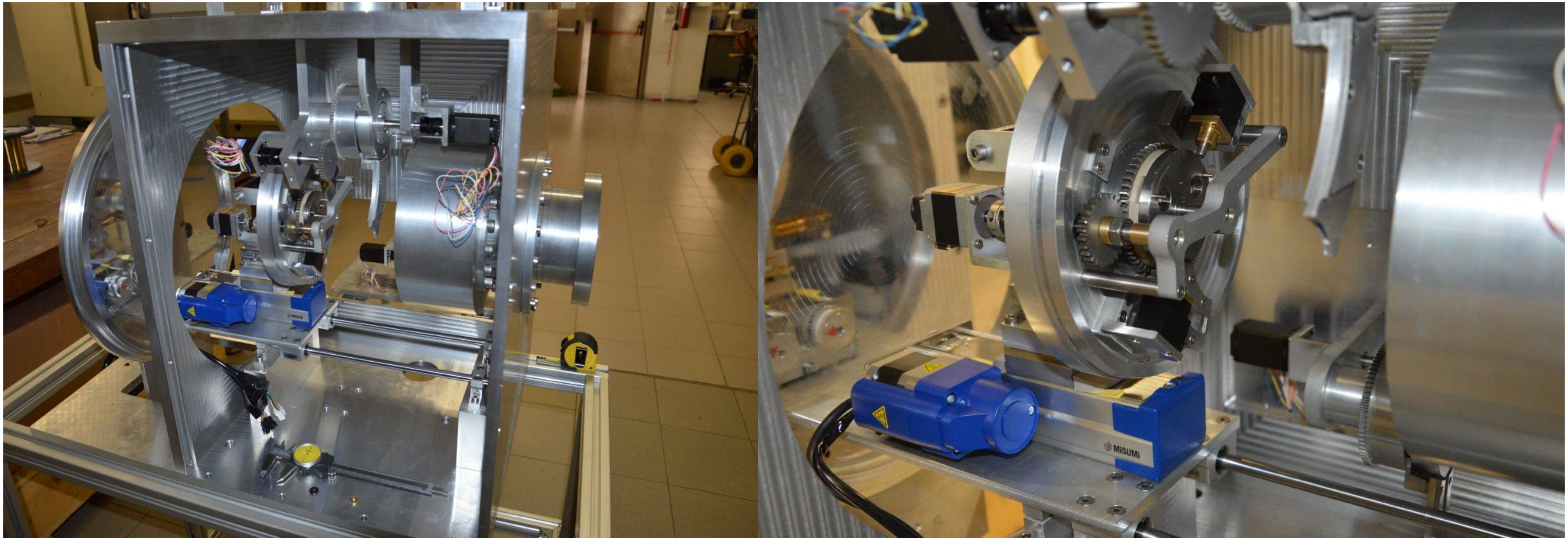
Target refill system



Discharge guide



IRIS deposition station



Deposition station of the ISOLPHARM Radionuclide Implantation Station (IRIS), realized in collaboration with INFN-BO.

IRIS possible spectroscopy system

The system had to satisfy the **following constraints**:

- Allowing for the characterization of elements and isotopes contained inside irradiated sample.
- Short Measuring Session (10-20 minutes)
- Allowing for the counting of pure β-emitters.

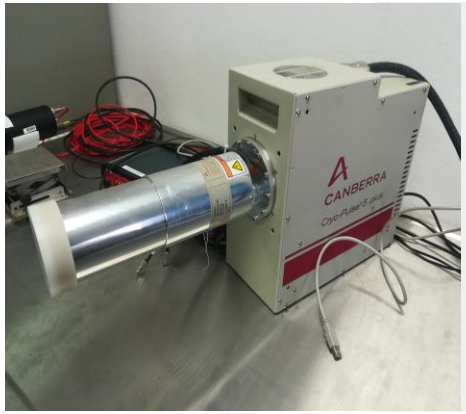
The whole system could also be used for decay spectroscopy exploiting β-γ coincidence.

Possible detectors:

3”x3” $LaBr_3$ Crystal

- Fair energy resolution < 30 keV at 1.3 MeV.
- Fast anode signal ~100ns.
- Fast acquisition rate up to 500 kcps.
- Significant intrinsic background to be considered (~ 1 kHz)

HPGe



- Very good energy resolution: 2 keV at 1.3 MeV.
- Slow preamplified signal (~ 100 μs).
- Typical acquisition rate < 10 kcps.

Conclusions

Conclusions

- **Laser spectroscopy and applications**
  - **Photoionization** can ensure **high quality RIBs**
  - At INFN-LNL the **ionization schemes** of several elements **can be studied with the offline test set-ups**
  - With eventual set-up upgrades, photoionization could be **selective towards isomers**

- **Nuclide production with ISOL for medicine and nuclear physics**
  - **Different solid target materials** could be used at SPES ensuring the availability of a **wide set of RIBs** for both nuclear physics studies and nuclear medicine applications
  - The development of an ISOL target is not trivial and requires several steps, that can be performed with the **available competences at LNL**
  - ISOL target development could benefit of **innovative technologies and collaborations** with other institutions

- **Decay spectroscopy of nuclide of medical interest**
  - For the **collection and quality control of ISOL produced radionuclides**, a specific device is being developed and tested
  - Such device could be also used to produce **isotopically pure radioactive sources**

Thank you for your kind attention