Development of nanostructured materials for ISOLDE targets

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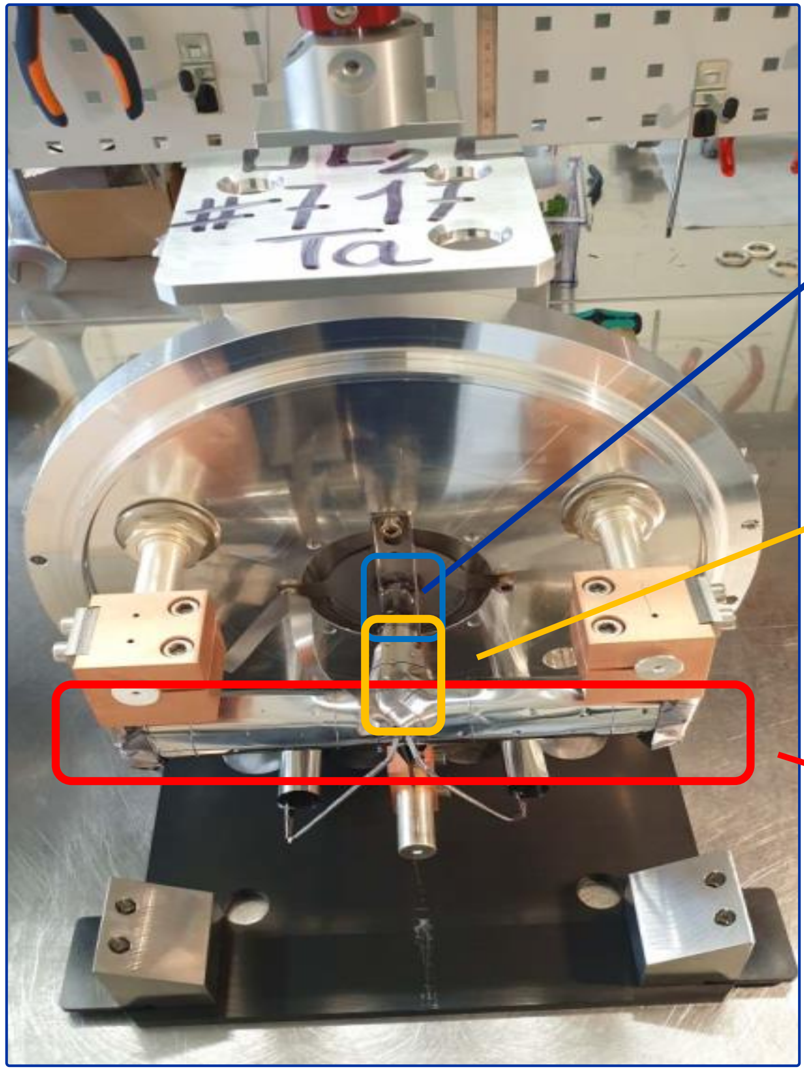
Radioactive Ion Beams @ ISOLDE

Target unit



Ion source:
surface, laser, plasma, …

Transfer line
controls transport to ion source, Ta, Cu or quartz

Target container
typically heated to $\sim 2000^{o}$ C

<u>Each target is custom-tailored to the physics experiment</u>

30+ targets per year!

The Isotope Separation On-Line (ISOL) method

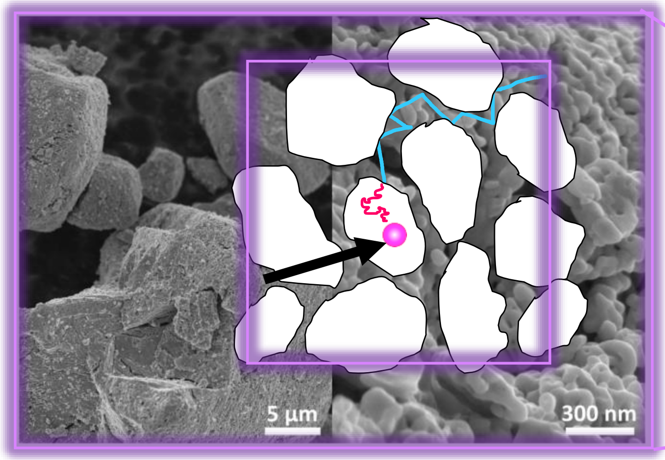
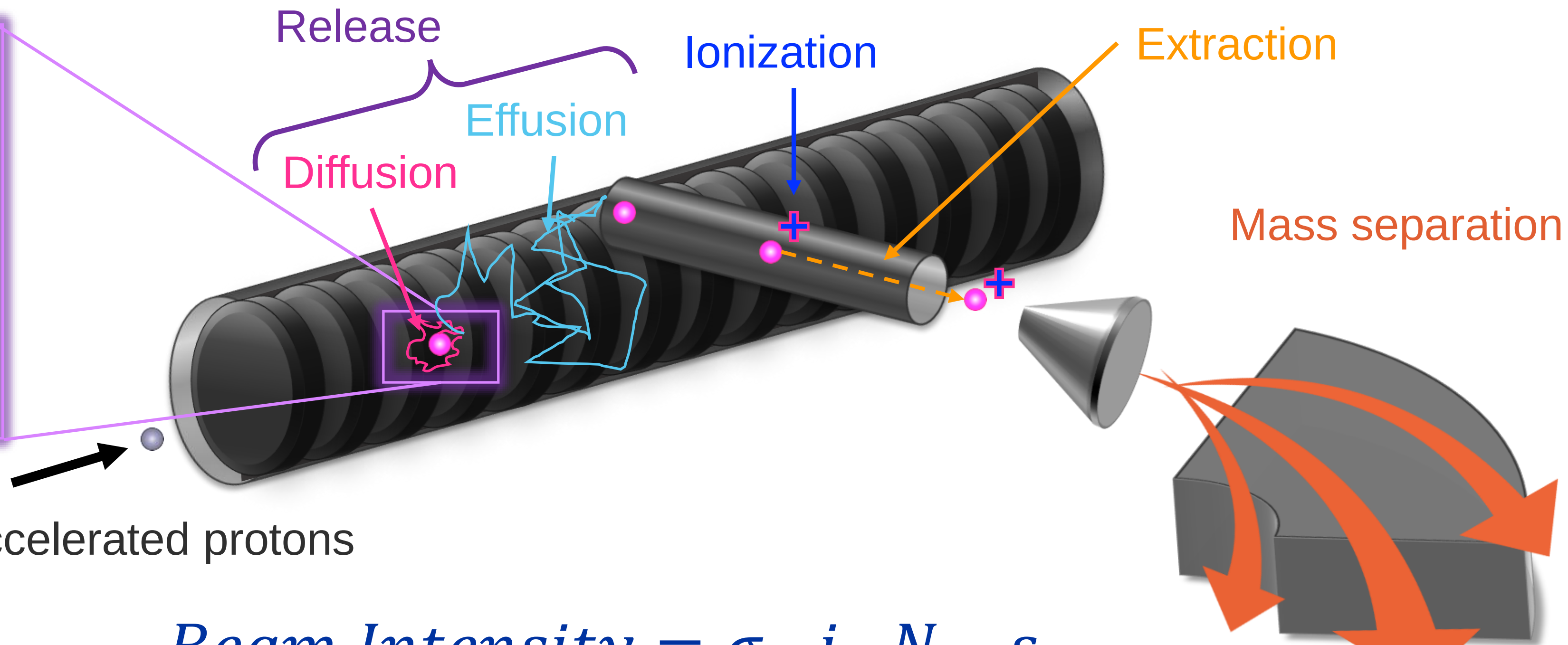


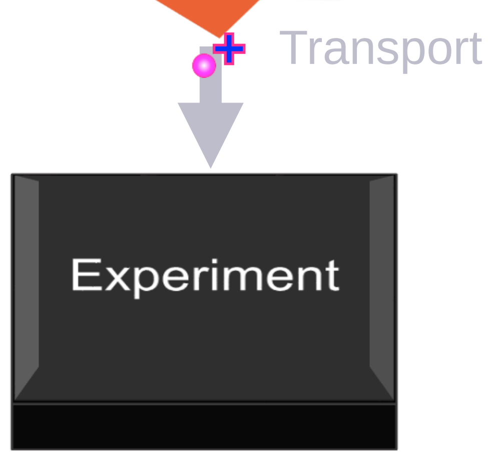
Figure published in Ramos *et al.*, (2020)
NIM B **463**, 201



1. Production
2. Release
3. Ionization
4. Mass separation
5. Delivery to experiments

$$Beam\ Intensity = \sigma \cdot j \cdot N_t \cdot \varepsilon$$

N_t – Number of target atoms
j – Proton flux [cm^{-2}]
σ – Cross section [mb]
ε – Efficiency [%]



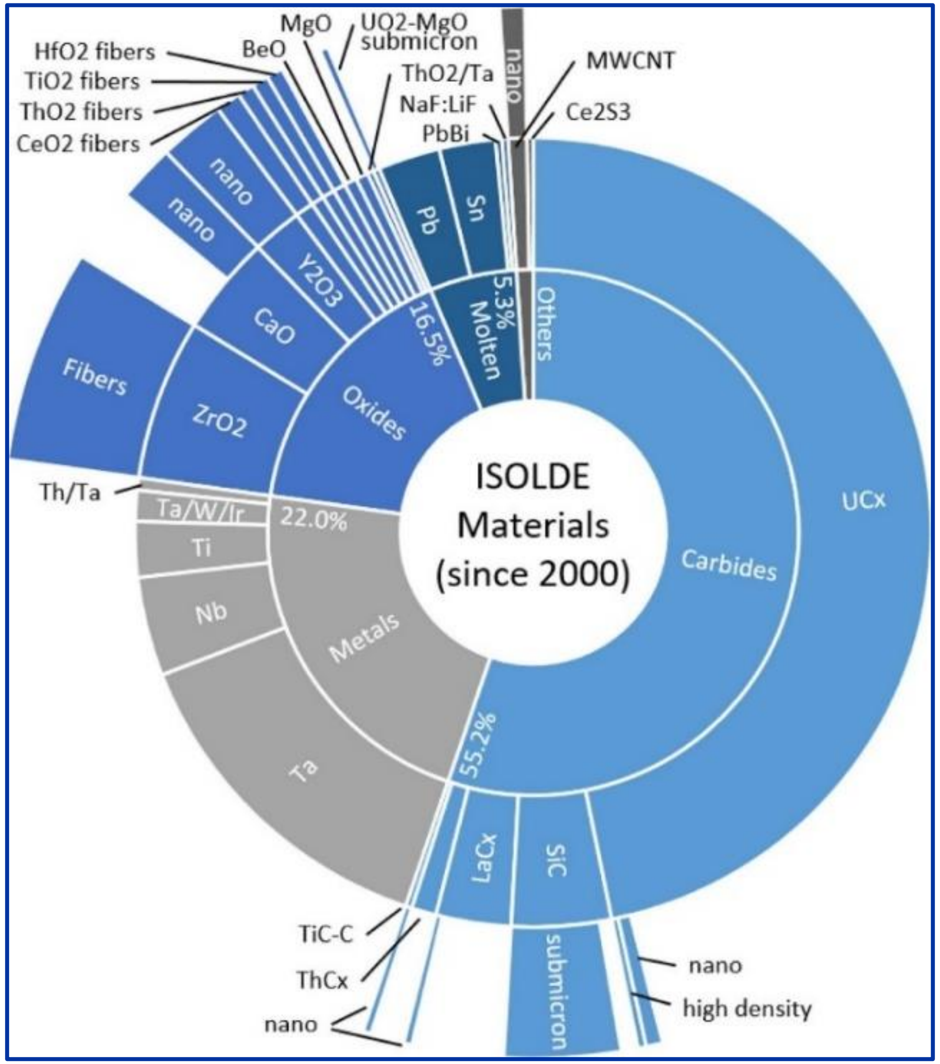
ISOLDE Target Materials

Material requirements

- High **production cross section** of the isotope(s) of interest
- Stability at **high temperatures**
- Chemically **stable and inert**
- Resistance to radiation damage
- Rapid **diffusion** and **effusion** rates of the element(s) of interest

Operation temperature limitations

- **Sintering** (preserve target microstructure)
- Limited reactivity with surrounding materials
- Reduced stable beam contaminants (chemical impurities)
- Moderate equilibrium vapor pressure compatible with ion source (~10^{-4} mBar)

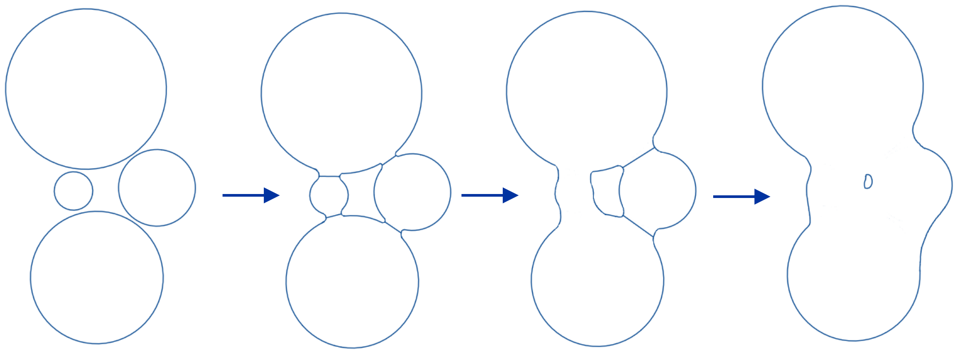


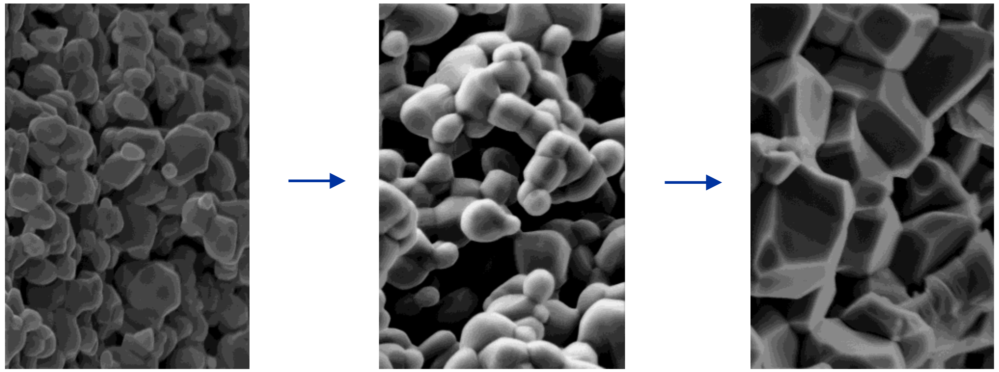
[1] J.P.Ramos, Thick solid targets for the production and online release of radioisotopes: The importance of the material characteristics – A review, in NIM-B, pp. 201-210, Vol. 463, 2020

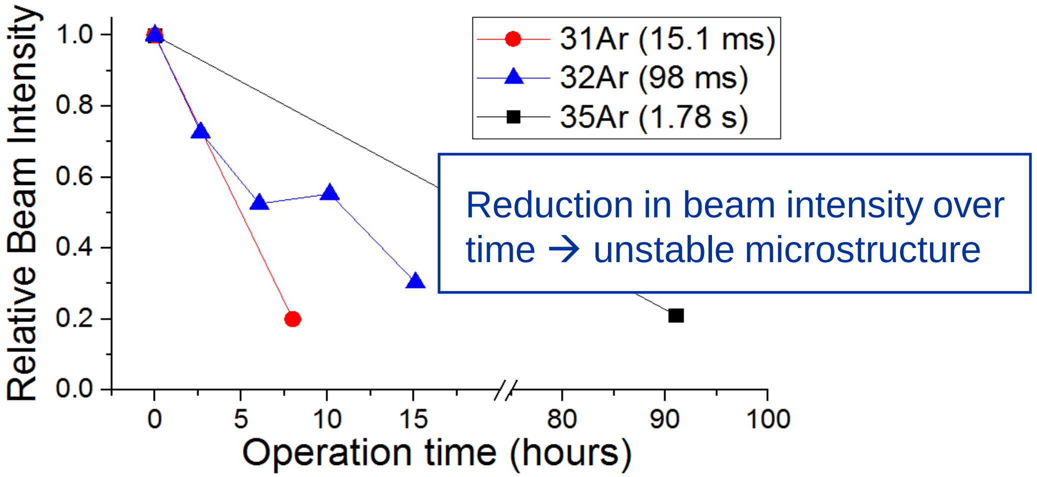
Operations limit

Sintering temperature (densify):

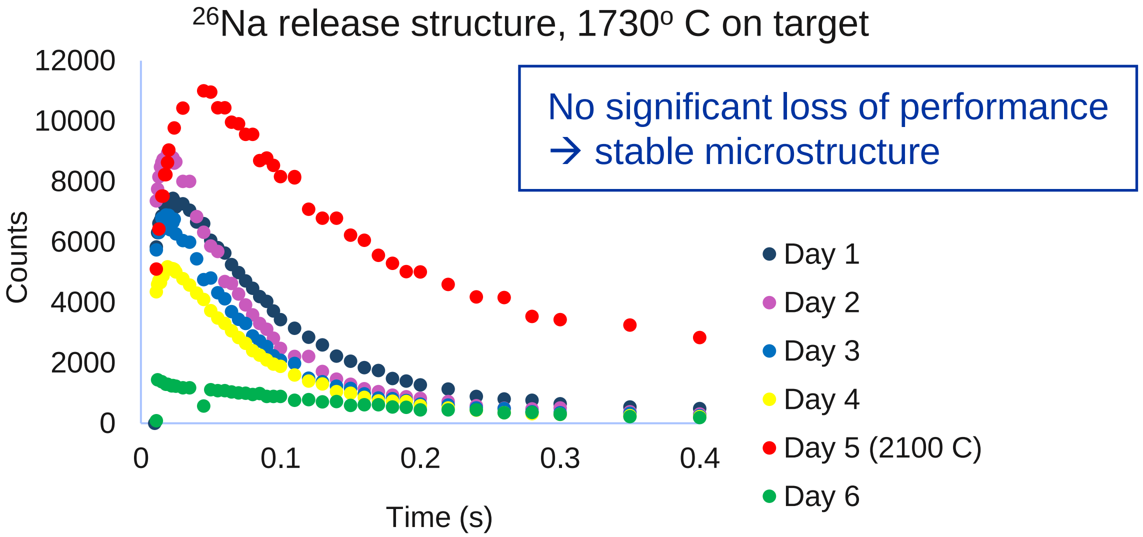
- function of the material melting point (T_m)





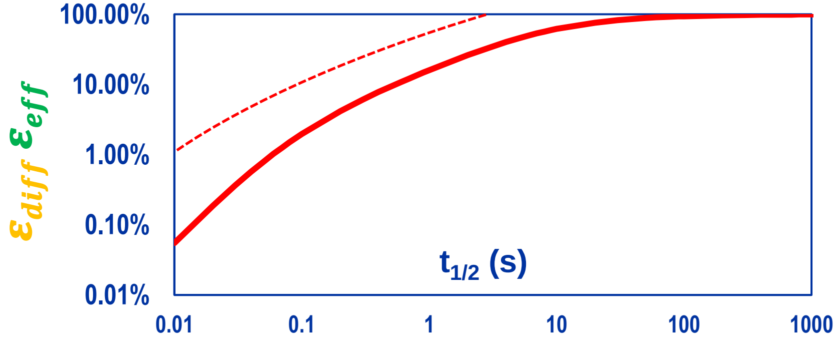


Preliminary results, in preparation (Edgar Reis)



Isotope production: target microstructure

In most cases $\varepsilon_{diff}\varepsilon_{eff}$ limit by far the yields.



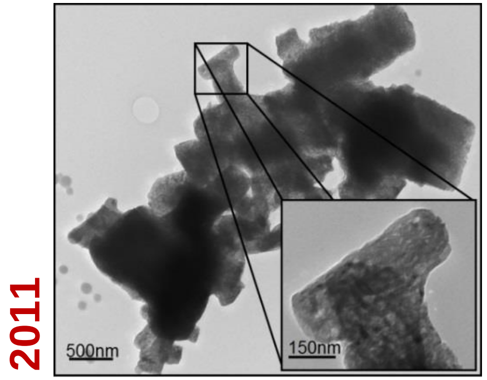
Diffusion limited release: $\lambda \leq 2\mu$

$$\varepsilon_{diff} = \frac{3}{\pi}\sqrt{\frac{\mu}{\lambda}}, \mu = \frac{\pi^2 D}{G^2} \rightarrow G/10 \rightarrow \varepsilon_{diff}\text{x}10$$

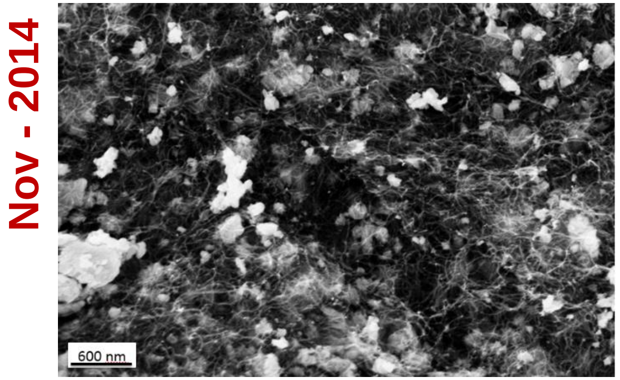
Same T!

Operation T ⟷ Sintering - Grain size/Porosity

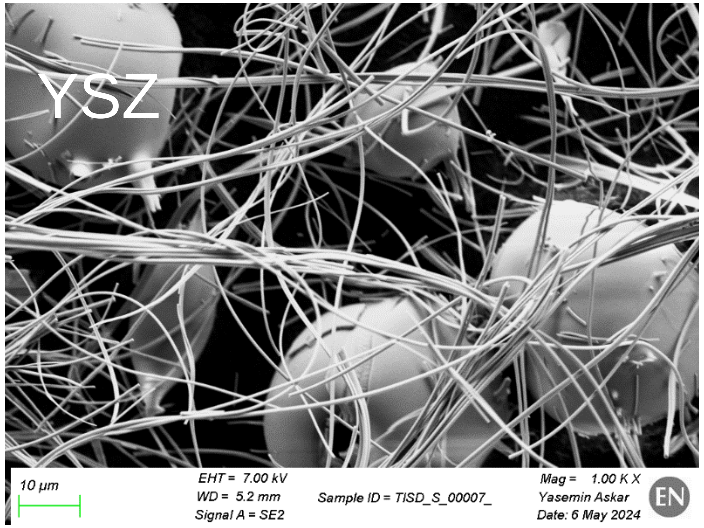
Specific surface area ⟷ Reactivity

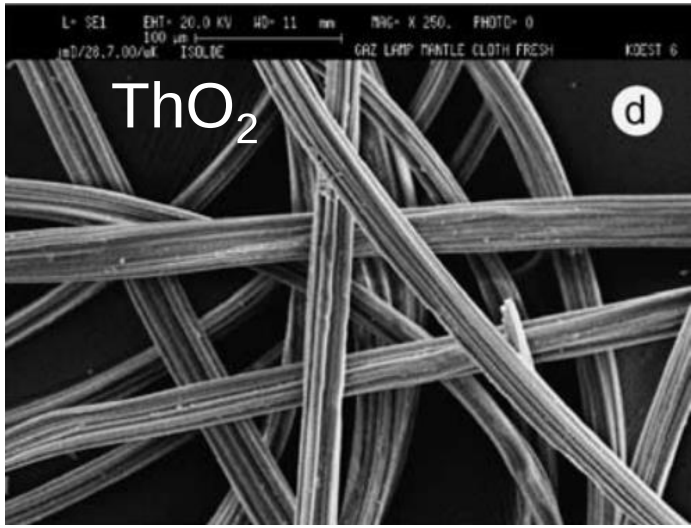


CaO – J.P. Ramos, et al.



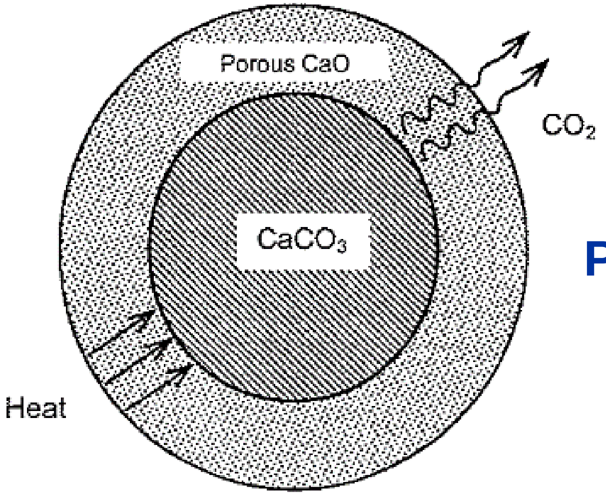
UC_2 + 2C – A. Gottberg, et al.





J.P. Ramos, et al. NIM B 320 (2014). 10.1016/j.nimb.2013.12.009
U. Köster, et al. NIM B 204 (2003). 1016/S0168-583X(03)00505-6
J. Guillot. PhD thesis. (2017)

E.g. Nano CaO : material production and operation



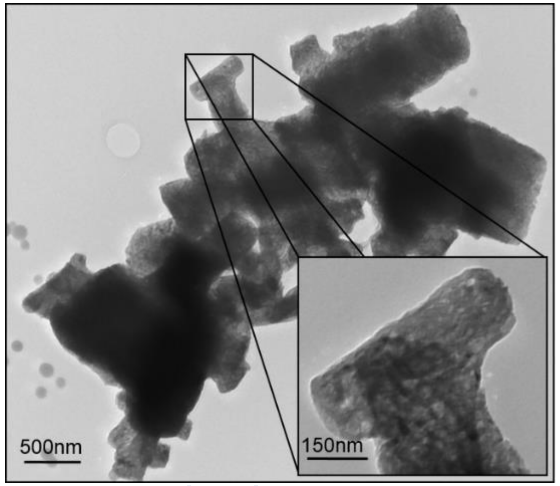
$CaCO_3 \rightarrow CaO + CO_2$

In vacuum!

Pseudomorphous reaction

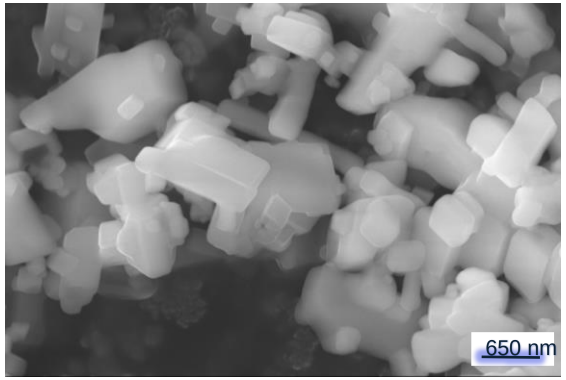
Very reactive powder to H_2O and CO_2

CaO

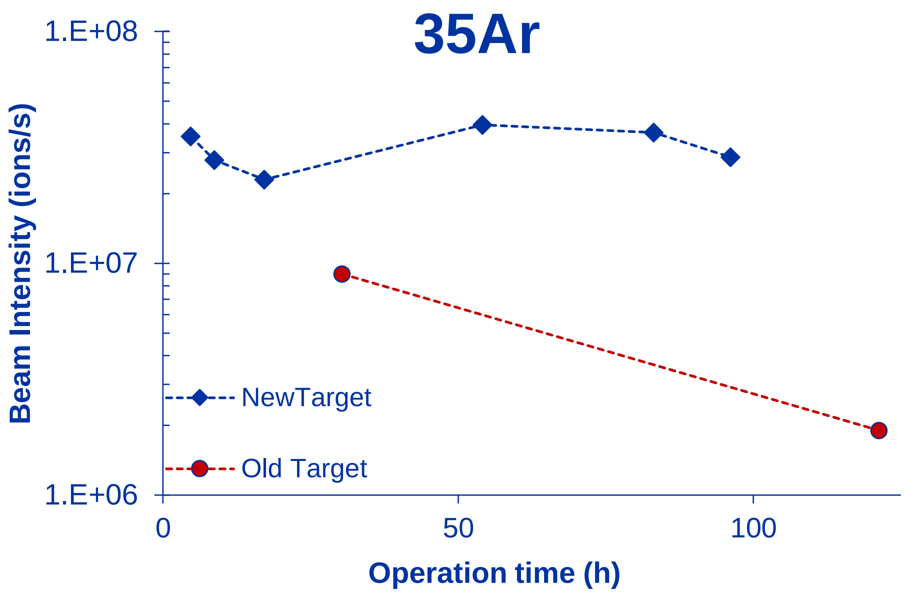


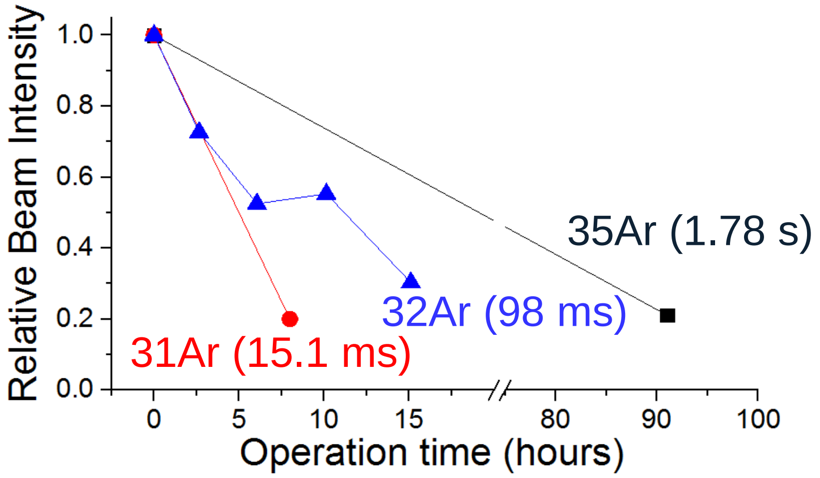
Grain size ~40 nm

$CaCO_3$



Grain size ~1 µm





Operation limited to 800 °C

No temp. limit

Nano-actinide targets: development and production

Nanomaterials production and safety

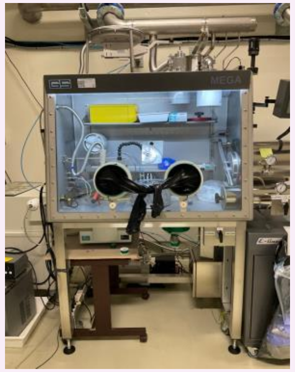
Criticalities to be addressed:

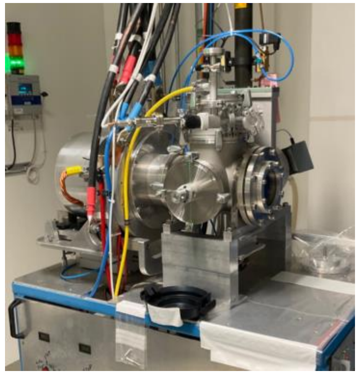
- **Safety:** High radiotoxicity and chemical reactivity require advanced shielding, containment (glove boxes, hot cells), and HEPA filtration.
- **Regulatory Compliance**: Adherence to strict international and national standards for radioactive and nanomaterial handling.
- **Environmental Protection**: Prevent airborne or environmental contamination through advanced ventilation and waste management systems.
- **Material Stability**: Controlled storage in inert atmospheres and thermal regulation to manage reactivity and degradation.
- **Specialized Monitoring**: Real-time detection systems for radiological, chemical, and nano-scale risks.

Following the Nano UCx combustion incident and the Moratorium for any nano-related activity at CERN, the construction of the **Actinide NanoLab** started.

The ISOLDE Nanolab

Current status of the Nanolab

179/R-022				179/R-024	179/R-021
					
Glovebox 1 Powder Preparation	Glovebox 2 Ball milling	Glovebox 3 Mixing and drying	Glovebox 4 Pill press	Glovebox 5 Transfer into the target unit	Glovebox 7 Oxidation



Partica LA-960V2
Laser Scattering Particle Size Distribution Analyzer

Dynamic Light Scattering (DLS) particle size analyser

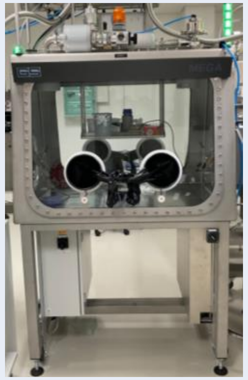
Retsch PM100 Planetary ball mill

Fritsch Pulverisette 7 Planetary Mill

Nano UC_x production

Transferring uranium carbide material production from R-001 to NanoLAB

1 UO_2 powder preparation



2 Grinding and sampling

3 MWCNT preparation

4 MWCNT + UO_2 Mixing and drying

5 Pill pressing

6 Transfer in C-sleeve

7 Storage capsule

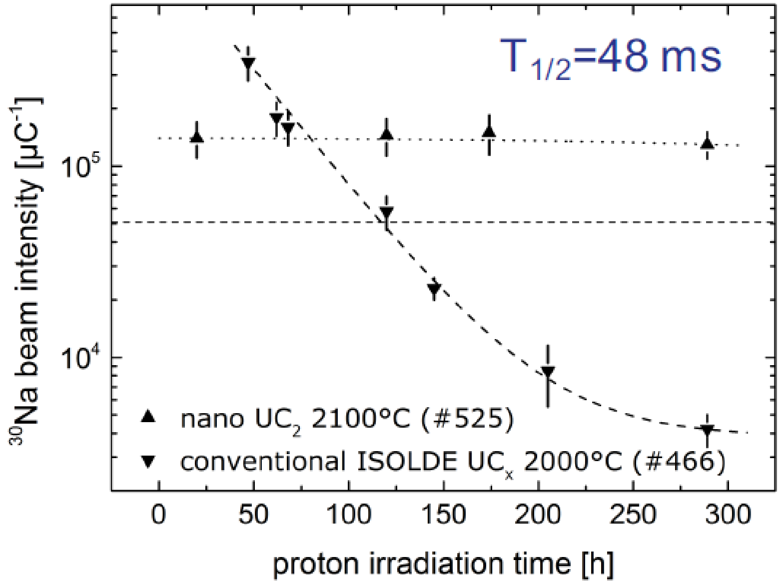
8 Carburization

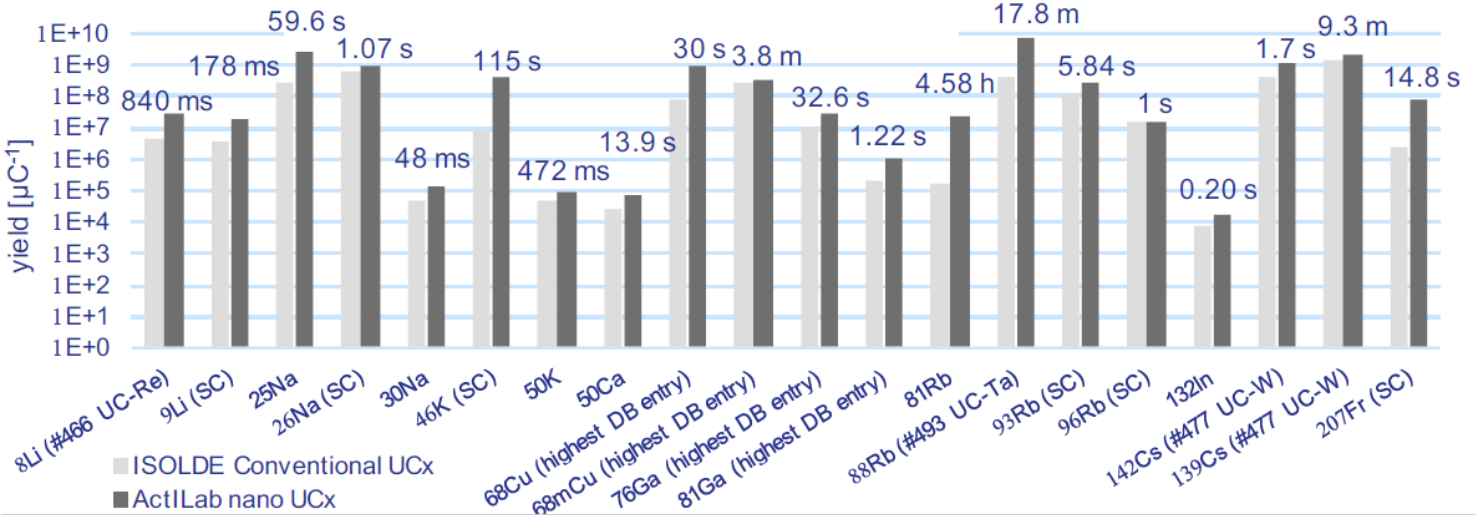
Coming soon 2025

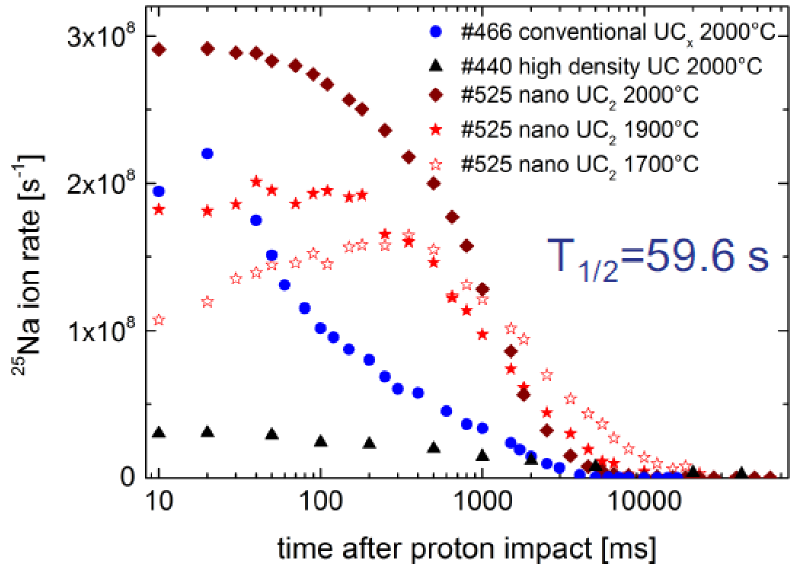
Nano UC_x at ISOLDE (2015)

❖ A collaboration formed within the European FP7 Joint Research Activity "ActiLab" in ENSAR had carried out systematic online and offline investigations of current and novel uranium carbide matrices.

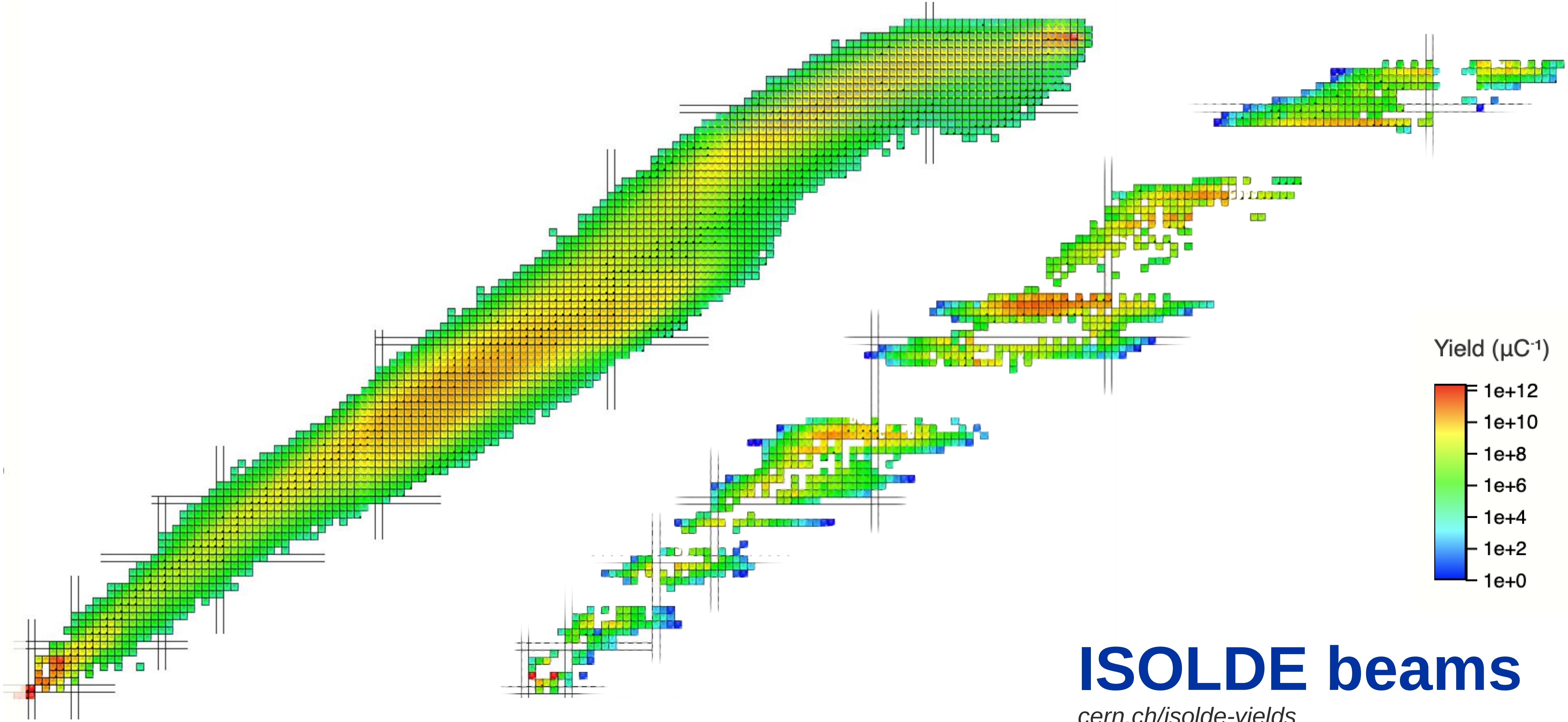
❖ **The highest release efficiency** and overall intensity was measured from the low-density ($\rho \approx 1.4$ g/cm^3) UC_x made from **nanometric UO_2 and MWCNT**, followed by conventional UC_x ($\rho \approx 3.5$ g/cm^3).







Nano UC_x at ISOLDE (2015)



ISOLDE beams

cern.ch/isolde-yields

UC_x target production: a timeline

UO_2 powder preparation

UC_x target production: a timeline

UO_2 powder preparation

Wet grinding of UO_2 powders
(from few µm to ~100 nm)

UC_x target production: a timeline

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UO_2 powder preparation

Powder sampling; ideally narrow size distribution peak

UC_x target production: a timeline

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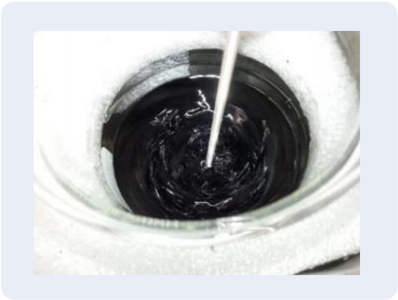
UO_2 powder preparation

Powder sampling; ideally narrow size distribution peak

Mixing MWCNT
Ultrasound + agitation



UC_x target production: a timeline

UO_2 powder preparation

Wet grinding of UO_2 Powders (from few µm to ~100 nm)

Powder sampling; ideally narrow size distribution peak

Mixing MWCNT
Ultrasound + agitation

Addition of nano UO_2 to MWCNT
Ultrasound + agitation

UC_x target production: a timeline

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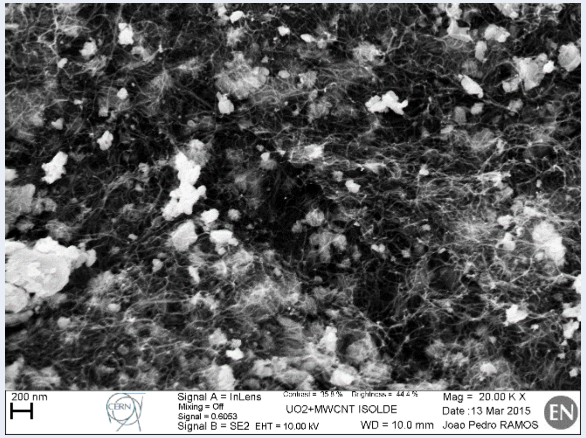
Powder sampling; ideally narrow size distribution peak

Mixing MWCNT Ultrasound + agitation

Addition of nano UO_2 to MWCNT Ultrasound + agitation

Drying and crushing of nano UO_2 + MWCNT mixture



UC_x target production: a timeline

UO_2 powder preparation

Wet grinding of UO_2 Powders (from few µm to ~100 nm)

Powder sampling; ideally narrow size distribution peak

Mixing MWCNT Ultrasound + agitation

Addition of nano UO_2 to MWCNT Ultrasound + agitation

Drying and crushing of nano UO_2 + MWCNT mixture

Pressing UO_2 + C pellets

UC_x target production: a timeline

UO$_2$ powder preparation

Wet grinding of UO$_2$ Powders (from few µm to ~100 nm)

Powder sampling; ideally narrow size distribution peak

Mixing MWCNT Ultrasound + agitation

Addition of nano UO$_2$ to MWCNT Ultrasound + agitation

Drying and crushing of nano UO$_2$ + MWCNT mixture

Pressing UO$_2$ + C pellets

Insertion of UO$_2$ + C pellets in graphite sleeve

UC_x target production: a timeline

UO_2 powder preparation

Wet grinding of UO_2 Powders (from few µm to ~100 nm)

Powder sampling; ideally narrow size distribution peak

Mixing MWCNT Ultrasound + agitation

Addition of nano UO_2 to MWCNT Ultrasound + agitation

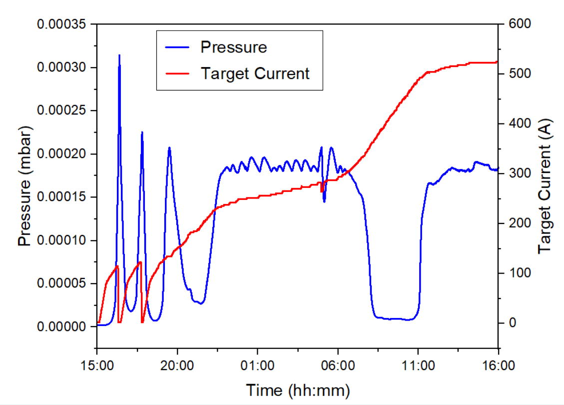
Drying and crushing of nano UO_2 + MWCNT mixture

Pressing UO_2 + C pellets

Insertion of UO_2 + C pellets in graphite sleeve

Carburisation on pumpstand to produce UC_x

$$UO_3 + 6C \xrightarrow{1800^o\,C} UC_2 + 2C + 2CO_2$$



UC_x target production: a timeline

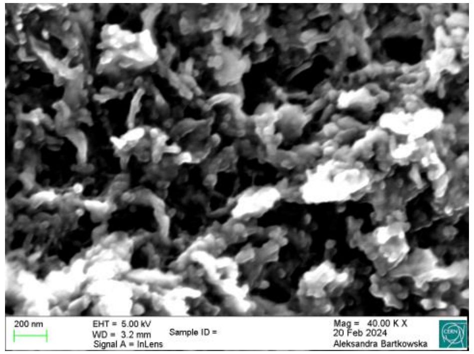
- UO_2 powder preparation
- Wet grinding of UO_2 Powders (from few µm to ~100 nm)
- Powder sampling; ideally narrow size distribution peak
- Mixing MWCNT Ultrasound + agitation
- Addition of nano UO_2 to MWCNT Ultrasound + agitation
- Drying and crushing of nano UO_2 + MWCNT mixture
- Pressing UO_2 + C pellets
- Insertion of UO_2 + C pellets in graphite sleeve
- Carburisation on pumpstand to produce UC_x
- Target unit ready to be sent online

The process takes **~2 weeks** from powder preparation to target production, with **grinding** as the primary bottleneck

Alternative routes for nanomaterial production

Sonochemical methods

- Based on precipitation of nanostructures by reaction of lanthanum acetate, nitrate and chloride with ammonia or sodium hydroxide
- The cation are assembled within the template of surfactants micelle in an aqueous solution
- Ultrasound irradiation helps with controlling the particles size



$La(OH)_3$ + PVP10
Is it nano? Yes but we can do better

$$PVP10 \xrightarrow{25^oC, 1\ bar} PVP10\ Micelles$$

$$NaOH \xrightarrow{H_2O} OH^- + Na^+$$

$$La(NO_3)_3 \cdot 6H_2O \xrightarrow{H_2O} La^{3+} + 3NO_3^- + 6H_2O$$

$$La^{3+} + 3OH^- \xrightarrow{H_2O} La(OH)_3$$

$$CTAB \xrightarrow{25^oC, 1\ bar} CTAB\ Micelles$$

$$LaCl_3 \cdot 7H_2O \xrightarrow{H_2O} La^{3+} + 3Cl^- + 7H_2O$$

$$NH_3 + H_2O \rightarrow OH^- + NH_4^+$$

$$La^{3+} + OH^- \rightarrow La(OH)_3$$
(Nanorod)

$$La(NO_3)_3 * H_2C_2O_{4\,(exc.)} \rightarrow La(C_2O_4)_3$$

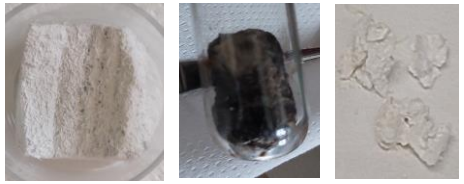
$$La(C_2O_4)_3 \xrightarrow{250^oC, > 20\ bar} La_2O_3\ (nano)$$

Cellulose impregnation method

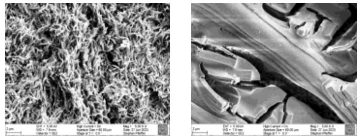
- Based on an old ISOLDE target material precursor (thorium gas lamps), prepared by impregnation of cellulose with a saturated thorium nitrate solution
- Tests were done at JRC-Karlsruhe in January on lab-scale and attempted up-scaling at CERN ran into issues
- Heavily **nitrated cellulose** combusts very quickly in the process even at low temperatures (around 150º C)
- Option to explore: Starting from **chloride and ethoxide** or other functional groups (Th nitrate chemistry is quite rich and well-known)
- Studies ongoing on **Hafnium ethoxide** impregnated cellulose fibers

$$HfCl_4 + EtOH_{(exc.)} \rightarrow Hf(OEt)_4 + 2Cl_2$$

$$Hf(OEt)_4 + (C_6H_{10}O_5)^n \xrightarrow{800^o\ C} HfO_2$$



Cellulose impregnated with Hafnium ethoxide before pyrolysis (left), at 300º C (middle) and 850º C (right)



Sintering and grain growth during heat treatment

$$ThCl_4 + EtOH_{(exc.)} \rightarrow Th(OEt)_4 + 2Cl_2$$

$$Th(OEt)_4 + (C_6H_{10}O_5)^n \xrightarrow{800^o\ C} ThO_2$$

UCl_4?
Can we translate this method to uranium? Studies ongoing

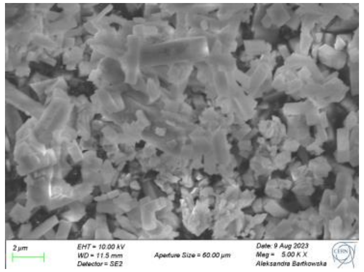
Material development and infrastructure

Hydrothermal methods

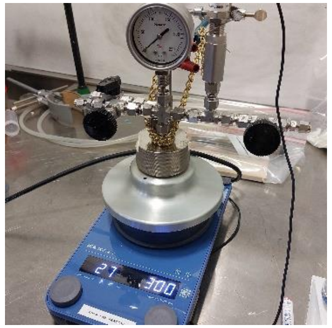
- ❖ Narrow particle size distribution and good degree of control of particle size down to 10s of nm
- ❖ Process can be done in water-based dispersions and does not require usage of a binder (surfactant) agent
- ❖ Tests with lanthanum at room pressure already led to formation of interesting platelet microstructure
- ❖ Further tests required to test stability at operational temperatures

$$La(NO_3)_3 * H_2C_2O_{4\,(exc.)} \rightarrow La(C_2O_4)_3$$

$$La(C_2O_4)_3 \xrightarrow{250^oC, >20\ bar} La_2O_3\ (nano)$$



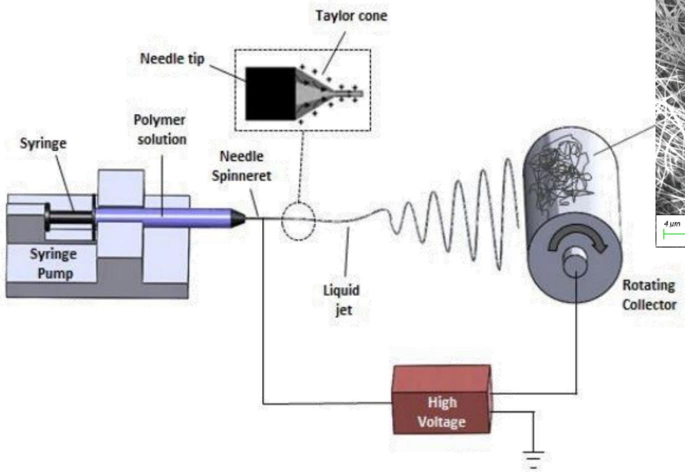
La_2O_3 platelets formed in normal pressure conditions



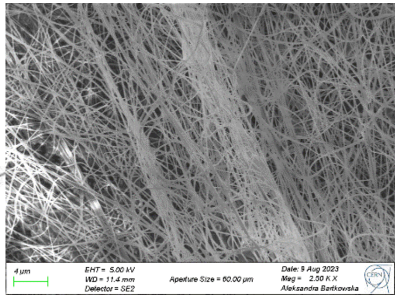
High pressure reactor (200 bar, 270^o C)

Nanofibers via Electrospinning

- ❖ Oxides are known at ISOLDE to sinter too fast. **The main idea** is to reduce the coordination number → **Avoid/reduce sintering**



Electrospun zirconia fibers



Metallic Oxides
(Zr, Y, Hf, Th, U)
Carbides
(Si, La, U, Th)

Advantages

- ❖ Nano safety – materials are encapsulated in a polymeric matrix until heat-treatment
- ❖ Flexibility – can be applied to a wide range of materials and explored for other applications
- ❖ Uniformity – the process is consistent and produces uniform nanomaterials with enhanced physical properties
- ❖ Further tests required to test stability at operational temperatures

Dismantling & oxidation of irradiated targets

Addition of nano UO_2 to MWCNT
Ultrasound + agitation

Drying and crushing of nano UO_2 + MWCNT mixture

Carburisation on pumpstand to produce UC_x

Target unit ready to be sent online

Particularly sensitive topic when talking about a nanostructured target materials

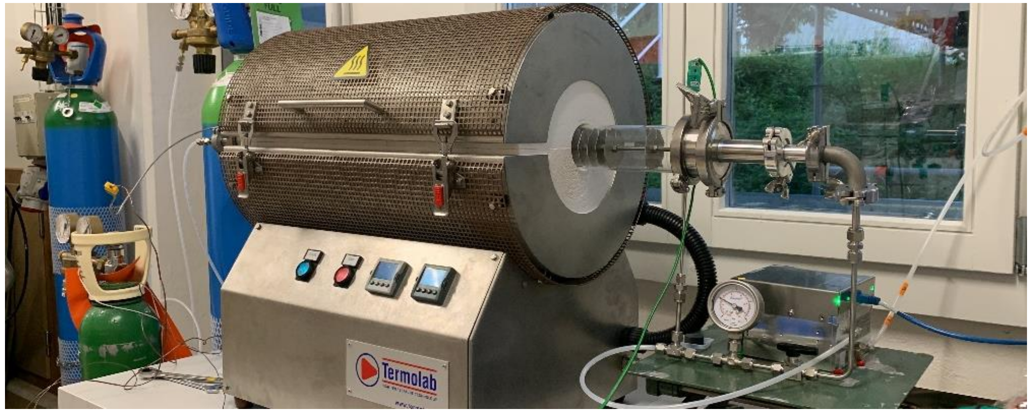
Irradiated actinide/lanthanide carbide (UCx, ThCx and LaCx) as target materials became **pyrophoric radioactive waste**

Dismantling & oxidation of irradiated targets

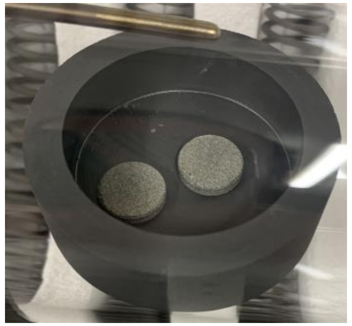
Objectives

- Develop a **controlled oxidation process** in ISOLDE hot cells focused on stabilization of core material (i.e. $UO_2.xH_2O$, $ThO_2.xH_2O$ and $La(OH)_3$)
- Searching **lowest stabilization temperature** to minimize release of radioactive volatile compounds
- Estimation of outgassing for radioactive volatile compounds
- Packaging and conditioning for **long-term disposal** in the Swiss deep geological repositories

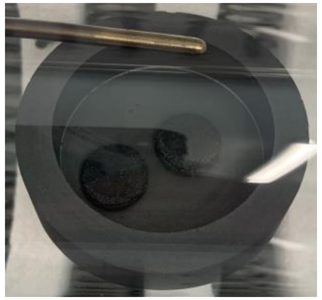
Oxidation setup



LaCx wet and dry oxidations



20% O_2/Ar (dry)



Unknown phase/mixture at 380ºC for 20 hours (15.6% mass increase) 1074 J/g heat of reaction

Humid air

$La(OH)_3$ and graphite mixture at 50ºC for 10 hours (14.4% mass increase). 1485 J/g heat of reaction

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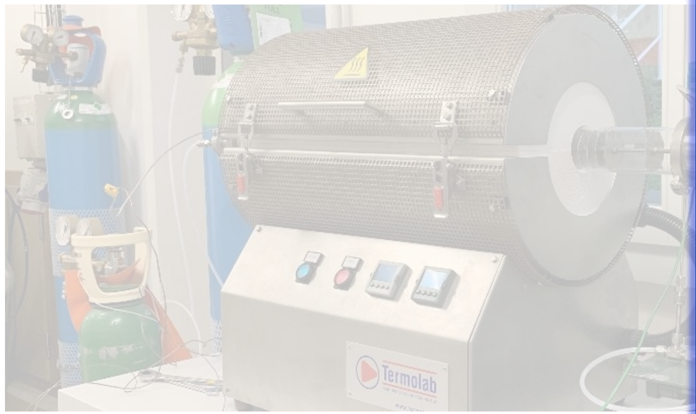

LaCx wet and dry oxidations

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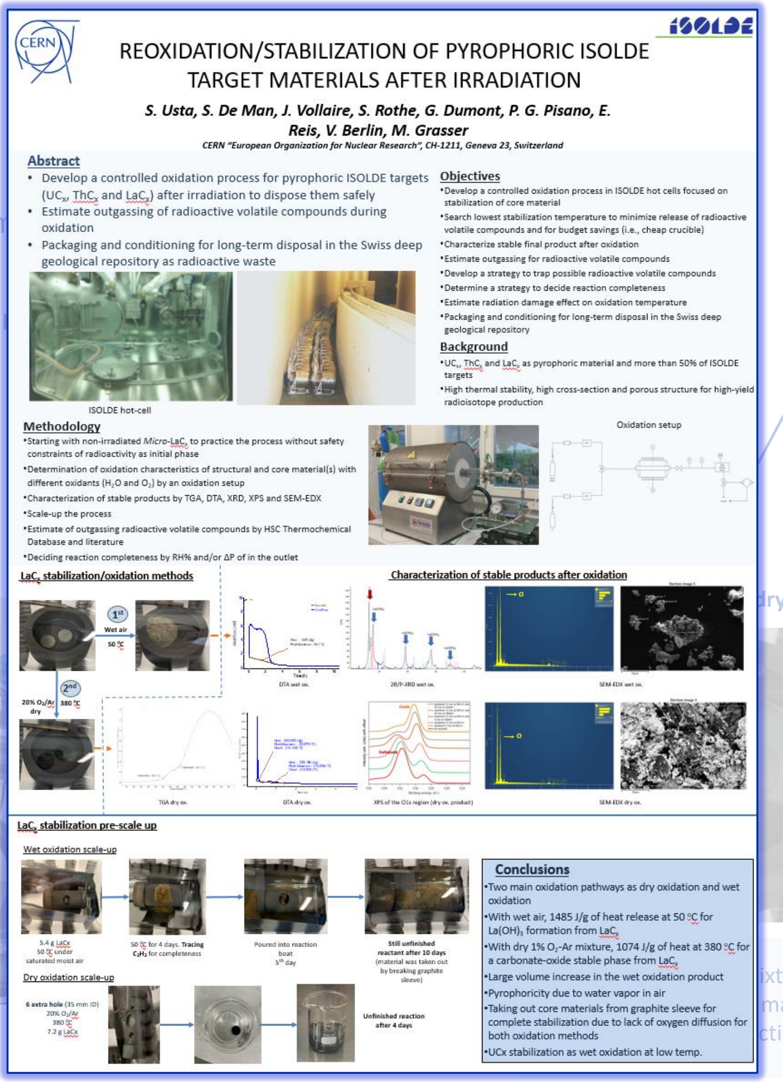
Humid air

$La(OH)_3$ and graphite mixture at 50ºC for 10 hours (14.4% mass increase). 1485 J/g heat of reaction



REOXIDATION/STABILIZATION OF PYROPHORIC ISOLDE TARGET MATERIALS AFTER IRRADIATION

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Abstract

- Develop a controlled oxidation process for pyrophoric ISOLDE targets (UC_x, ThC_x and LaC_x) after irradiation to dispose them safely
- Estimate outgassing of radioactive volatile compounds during oxidation
- Packaging and conditioning for long-term disposal in the Swiss deep geological repository as radioactive waste

ISOLDE hot-cell

Objectives

- Develop a controlled oxidation process in ISOLDE hot cells focused on stabilization of core material
- Search lowest stabilization temperature to minimize release of radioactive volatile compounds and for budget savings (i.e., cheap crucible)
- Characterize stable final product after oxidation
- Estimate outgassing for radioactive volatile compounds
- Develop a strategy to trap possible radioactive volatile compounds
- Determine a strategy to decide reaction completeness
- Estimate radiation damage effect on oxidation temperature
- Packaging and conditioning for long-term disposal in the Swiss deep geological repository

Background

- UC_x, ThC_x and LaC_x as pyrophoric material and more than 50% of ISOLDE targets
- High thermal stability, high cross-section and porous structure for high-yield radioisotope production

Methodology

- Starting with non-irradiated *Micro*-LaC_x to practice the process without safety constraints of radioactivity as initial phase
- Determination of oxidation characteristics of structural and core material(s) with different oxidants (H_2O and O_2) by an oxidation setup
- Characterization of stable products by TGA, DTA, XRD, XPS and SEM-EDX
- Scale-up the process
- Estimate of outgassing radioactive volatile compounds by HSC Thermochemical Database and literature
- Deciding reaction completeness by RH% and/or ΔP of in the outlet

Oxidation setup

LaC_x stabilization/oxidation methods

1st Wet air 50 ºC

2nd 20% O_2/Ar dry 380 ºC

Characterization of stable products after oxidation

DTA wet ox. | 2θ/P-XRD wet ox. | SEM-EDX wet ox.

TGA dry ox. | DTA dry ox. | XPS of the O1s region (dry ox. product) | SEM-EDX dry ox.

LaC_x stabilization pre-scale up

Wet oxidation scale-up

5.4 g LaCx 50 ºC under saturated moist air → 50 ºC for 4 days. **Tracing C_2H_2 for completeness** → Poured into reaction boat 5th day → **Still unfinished reactant after 10 days** (material was taken out by breaking graphite sleeve)

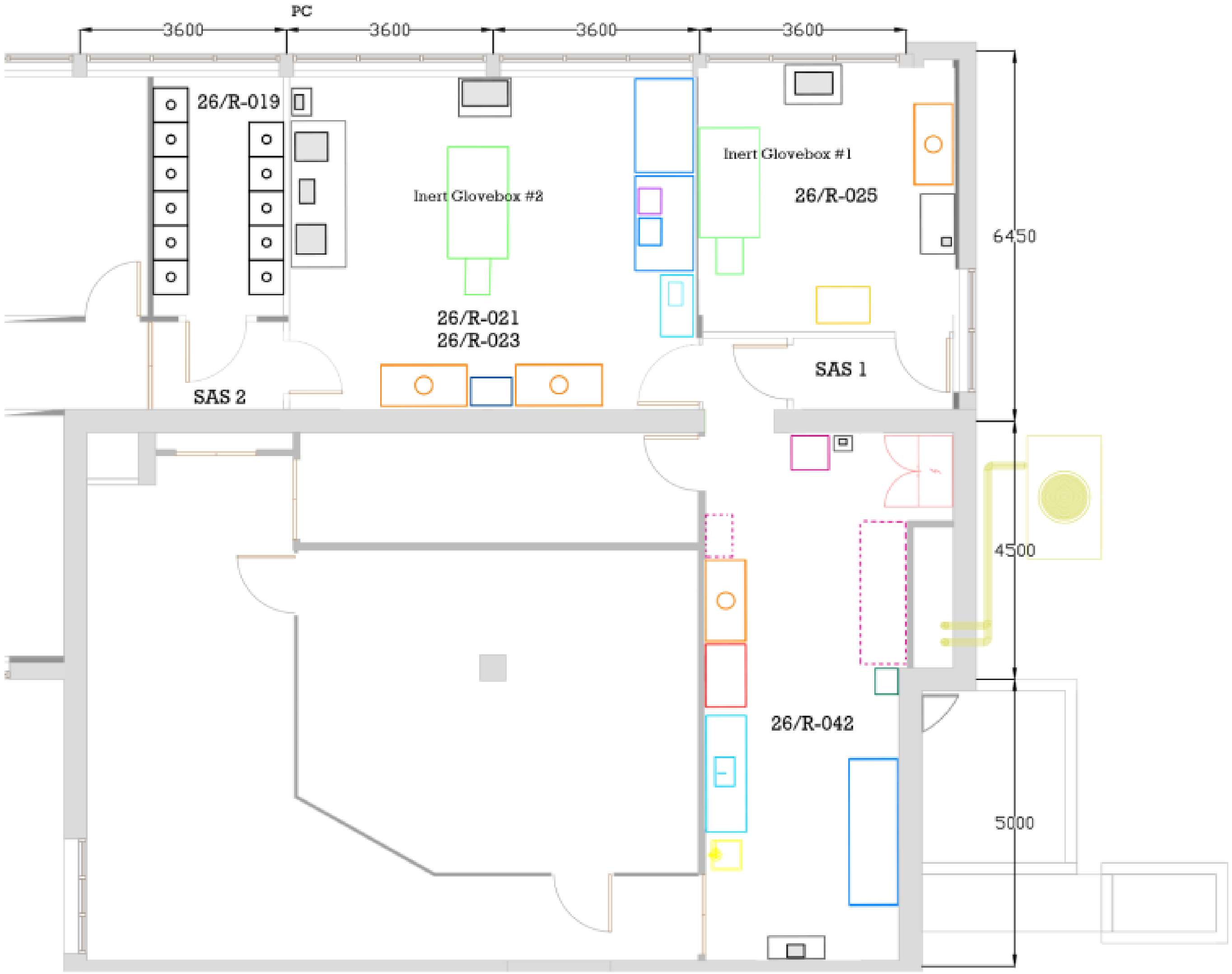
Dry oxidation scale-up

6 extra hole (35 mm ID) 20% O_2/Ar 380 ºC 7.2 g LaCx → → → **Unfinished reaction after 4 days**

Conclusions

- Two main oxidation pathways as dry oxidation and wet oxidation
- With wet air, 1485 J/g of heat release at 50 ºC for $La(OH)_3$ formation from LaC_x
- With dry 1% O_2-Ar mixture, 1074 J/g of heat at 380 ºC for a carbonate-oxide stable phase from LaC_x
- Large volume increase in the wet oxidation product
- Pyrophoricity due to water vapor in air
- Taking out core materials from graphite sleeve for complete stabilization due to lack of oxygen diffusion for both oxidation methods
- UCx stabilization as wet oxidation at low temp.

Chemical lab extension – non-actinide nanomaterials

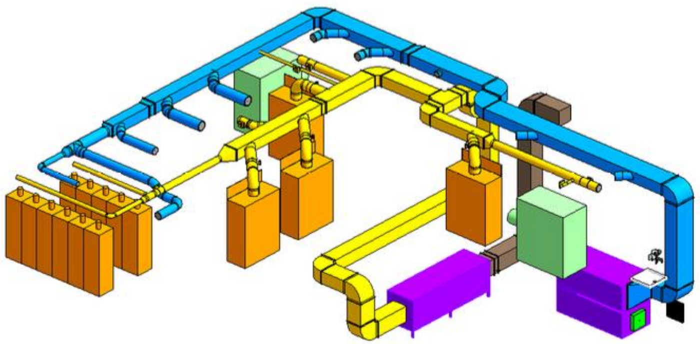


Extension and upgrade of the current chemical and thermal laboratories:

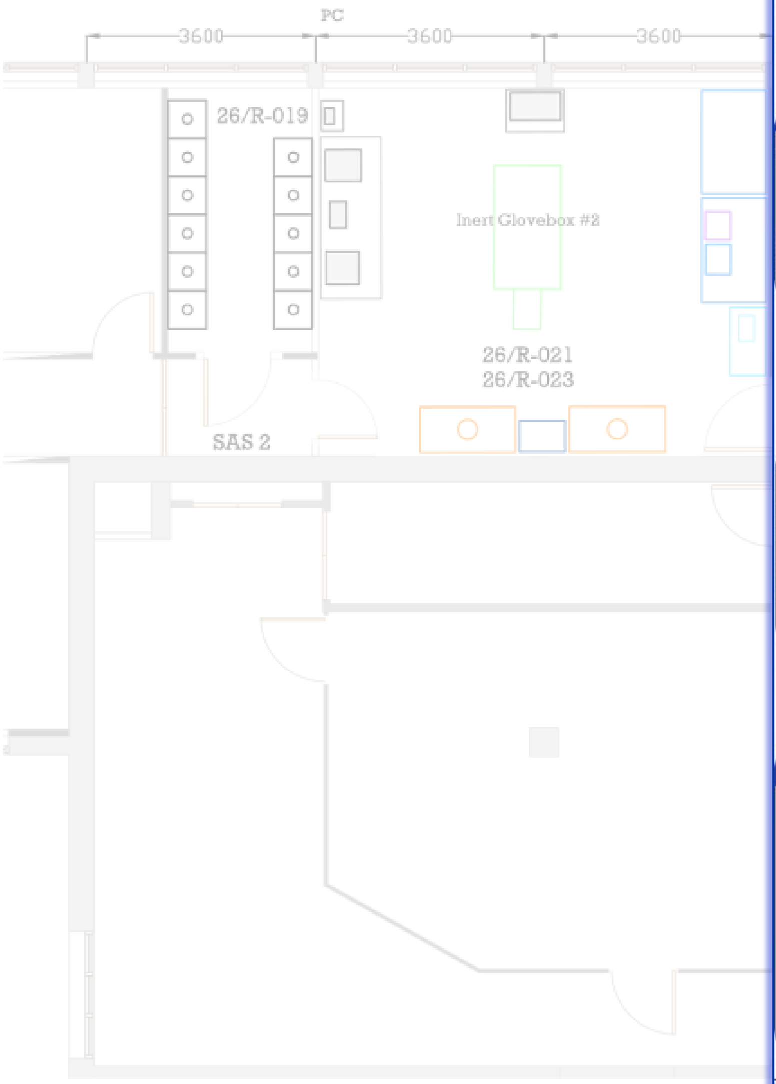
- Chemical storage, thermal activities, process area → only one facility, relocated from office area to dedicated Nano-2 and Nano-3 lab

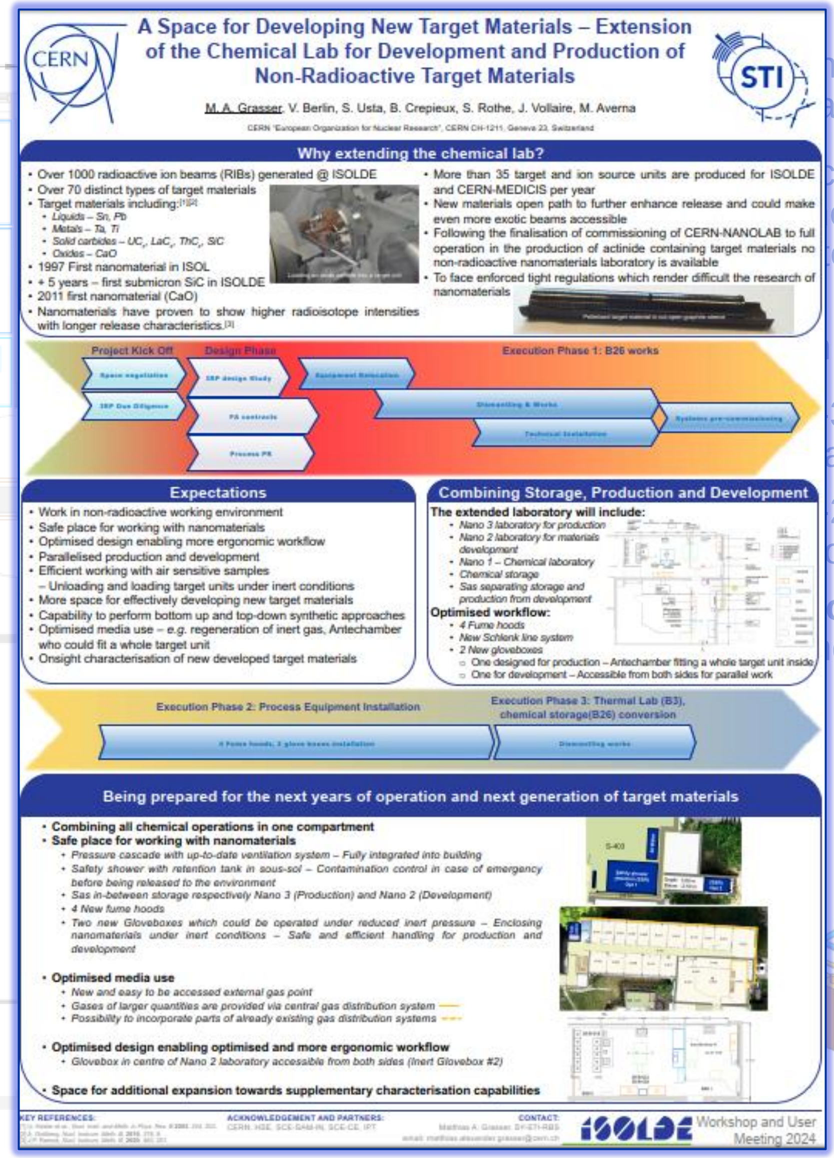
Foreseen construction of:

- NANO-3 **Production** laboratory for non-actinide nanomaterials target production
- NANO-2 **Characterization & Development** laboratory for target materials development
- ***Chemical and Thermal*** laboratory for bulk materials handling and thermal treatments



Chemical lab extension – non-actinide nanomaterials





A Space for Developing New Target Materials – Extension of the Chemical Lab for Development and Production of Non-Radioactive Target Materials

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Why extending the chemical lab?

- Over 1000 radioactive ion beams (RIBs) generated @ ISOLDE
- Over 70 distinct types of target materials
- Target materials including:[1][2]
  - *Liquids – Sn, Pb*
  - *Metals – Ta, Ti*
  - *Solid carbides – UC_x, LaC_x, ThC_x, SiC*
  - *Oxides – CaO*
- 1997 First nanomaterial in ISOL
- + 5 years – first submicron SiC in ISOLDE
- 2011 first nanomaterial (CaO)
- Nanomaterials have proven to show higher radioisotope intensities with longer release characteristics.[3]
- More than 35 target and ion source units are produced for ISOLDE and CERN-MEDICIS per year
- New materials open path to further enhance release and could make even more exotic beams accessible
- Following the finalisation of commissioning of CERN-NANOLAB to full operation in the production of actinide containing target materials no non-radioactive nanomaterials laboratory is available
- To face enforced tight regulations which render difficult the research of nanomaterials

Project Kick Off | Design Phase | Execution Phase 1: B26 works

Expectations

- Work in non-radioactive working environment
- Safe place for working with nanomaterials
- Optimised design enabling more ergonomic workflow
- Parallelised production and development
- Efficient working with air sensitive samples
  – Unloading and loading target units under inert conditions
- More space for effectively developing new target materials
- Capability to perform bottom up and top-down synthetic approaches
- Optimised media use – *e.g.* regeneration of inert gas, Antechamber who could fit a whole target unit
- Onsight characterisation of new developed target materials

Combining Storage, Production and Development

The extended laboratory will include:

- *Nano 3 laboratory for production*
- *Nano 2 laboratory for materials development*
- *Nano 1 – Chemical laboratory*
- *Chemical storage*
- *Sas separating storage and production from development*

Optimised workflow:

- *4 Fume hoods*
- *New Schlenk line system*
- *2 New gloveboxes*
  - One designed for production – Antechamber fitting a whole target unit inside
  - One for development – Accessible from both sides for parallel work

Execution Phase 2: Process Equipment Installation | Execution Phase 3: Thermal Lab (B3), chemical storage(B26) conversion

Being prepared for the next years of operation and next generation of target materials

- **Combining all chemical operations in one compartment**
- **Safe place for working with nanomaterials**
  - *Pressure cascade with up-to-date ventilation system – Fully integrated into building*
  - *Safety shower with retention tank in sous-sol – Contamination control in case of emergency before being released to the environment*
  - *Sas in-between storage respectively Nano 3 (Production) and Nano 2 (Development)*
  - *4 New fume hoods*
  - *Two new Gloveboxes which could be operated under reduced inert pressure – Enclosing nanomaterials under inert conditions – Safe and efficient handling for production and development*
- **Optimised media use**
  - *New and easy to be accessed external gas point*
  - *Gases of larger quantities are provided via central gas distribution system*
  - *Possibility to incorporate parts of already existing gas distribution systems*
- **Optimised design enabling optimised and more ergonomic workflow**
  - *Glovebox in centre of Nano 2 laboratory accessible from both sides (Inert Glovebox #2)*
- **Space for additional expansion towards supplementary characterisation capabilities**

KEY REFERENCES: | ACKNOWLEDGEMENT AND PARTNERS: CERN, HSE, SCE-SAM-IN, SCE-CE, IPT | CONTACT:

ISOLDE Workshop and User Meeting 2024

…n and upgrade of the current chemical and …aboratories:

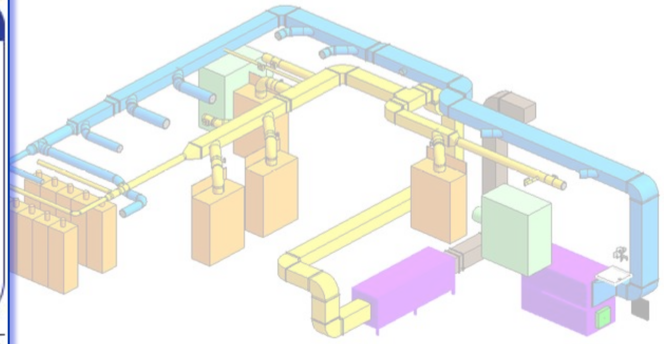
…cal storage, thermal activities, process area → …e facility, relocated from office area to …ted Nano-2 and Nano-3 lab

… construction of:

…3 **Production** laboratory for non-actinide …aterials target production

…2 **Characterization & Development** …ory for target materials development

…**cal and Thermal** laboratory for bulk materials …g and thermal treatments



Conclusions and future outlooks

- **Enhanced Release Efficiency**: Development of nanostructured materials ensures faster isotope release, enabling the exploration of very short-lived isotopes and broadening research capabilities.

- **Material Optimization**: The integration of nanoengineering techniques has improved stability and performance under high-temperature and radiation conditions.

- **Operational Advancements**: The incorporation of nanomaterials enables users to investigate a broader range of species within a single beam time.

- **Safety and Compliance**: The construction of the new nano-laboratories addressed critical safety and environmental concerns with robust containment, monitoring systems, and adherence to regulatory standards.

- **Next-Generation Targets**: Research into innovative nanomaterials, including hybrids and novel composites, to further enhance isotope production efficiency and stability.

- **Sustainability in Operations**: Focus on minimizing environmental impact through better recycling and waste management strategies for radioactive and nanomaterial byproducts.

References and acknowledgments

[SR21] Sebastian Rothe, SY Technical Meeting, 11 NOV 2021
[SR22] Sebastian Rothe, EMIS XIX, Daejeon Korea, 5 Oct. 2022
[JPR18] J.P Ramos, Presentation at EMIS 2018
[JPR17b] J.P.Ramos, MEDICIS-Promed Specialized Training on Radioisotope production
[ER24] E.M.D.S.Reis, Radioactive Ion Beam Production via the ISOL method, KU Leuven

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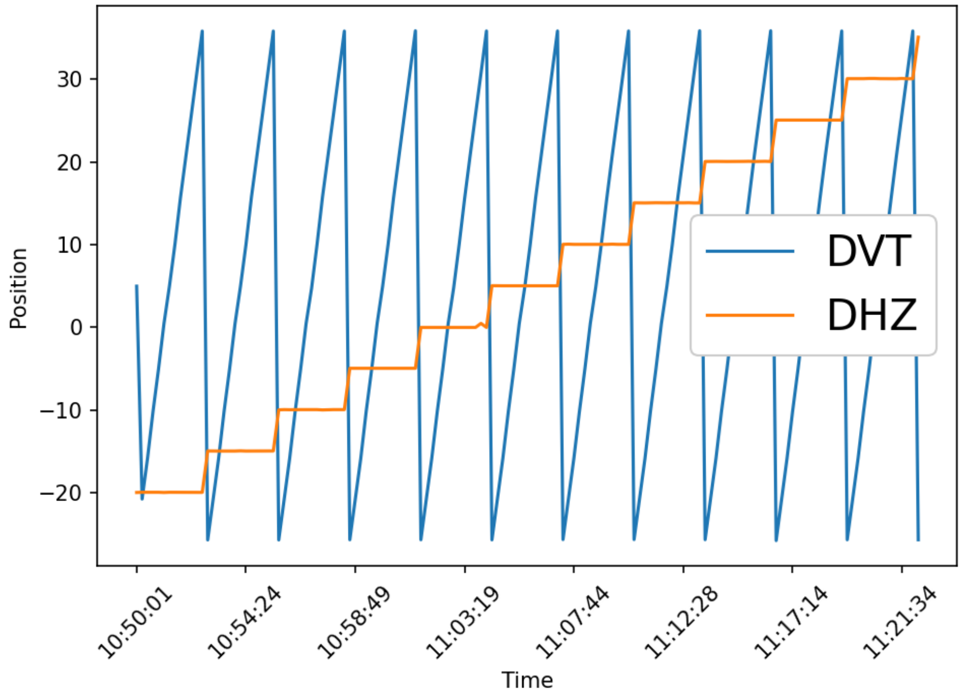
Edgar Miguel SOBRAL DOS REIS
Simon Thomas STEGEMANN
Thierry STORA
Serdar USTA
Joachim VOLLAIRE
Kevin Raphael ZINKE
Alexander DORSIVAL
Elodie AUBERT
Nadine CONAN
Matthieu DESCHAMPS

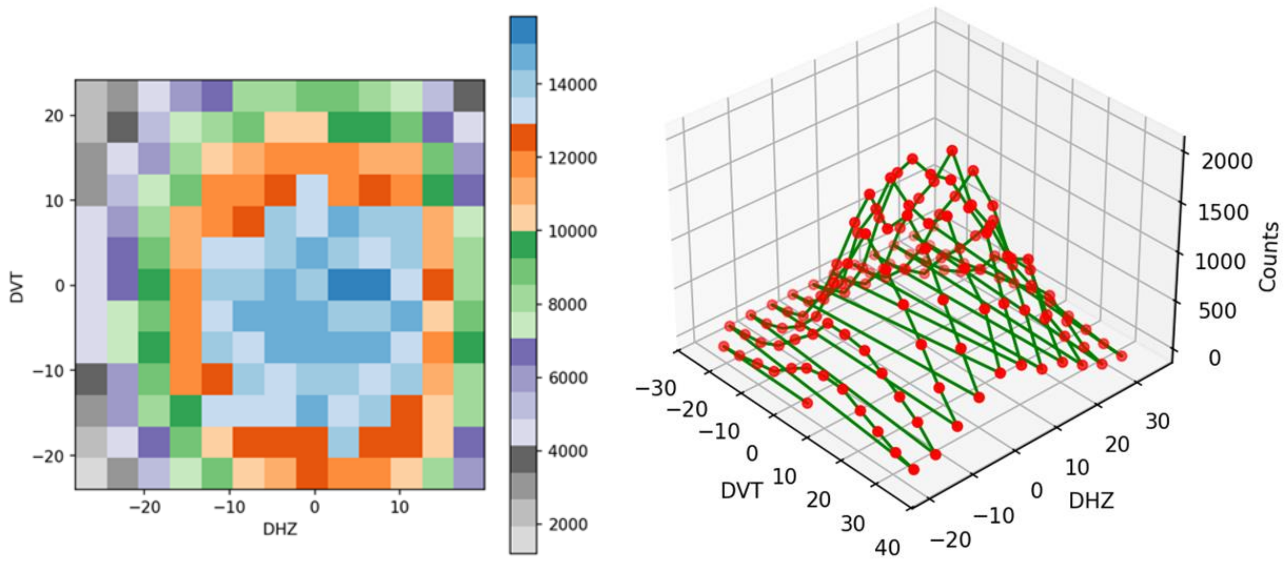
Thank you for your attention

Backup slides

2D proton scan

Measurements of the number of counts at the tape station (CA0…) as a function of the position of the proton beam.

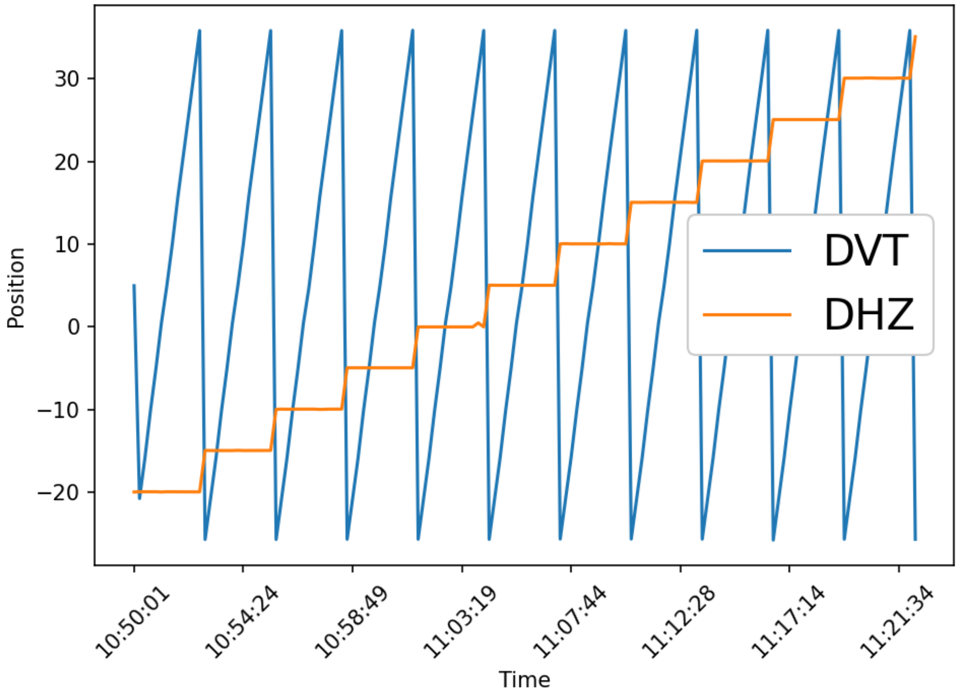




Useful tool for the tuning of the proton beam, as often the optimal position of the latter is **off-centered** with respect to the middle axis of the target container.

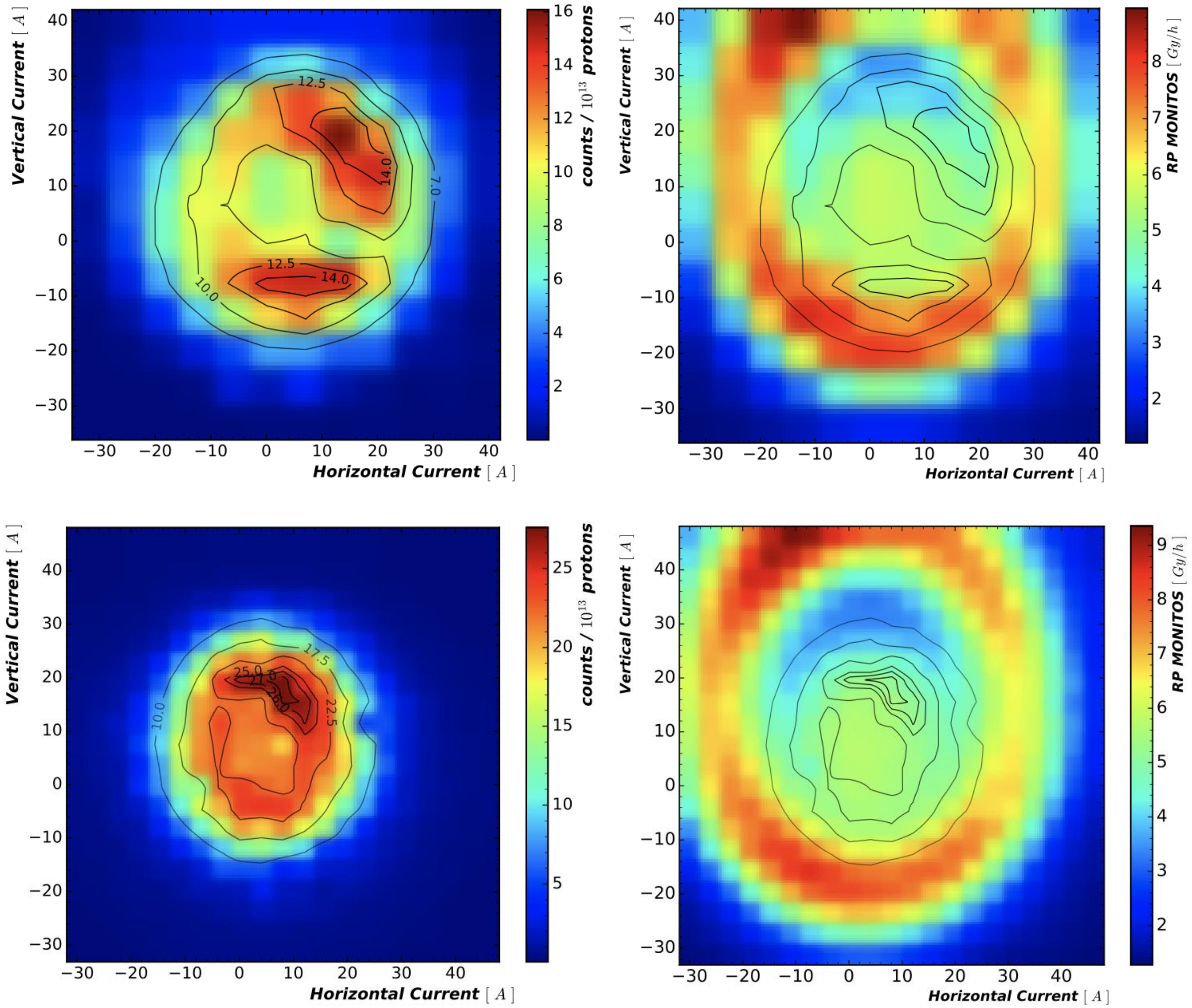
2D proton scan

Measurements at the tape station and on the RP monitorsas a function of the position of the proton beam.

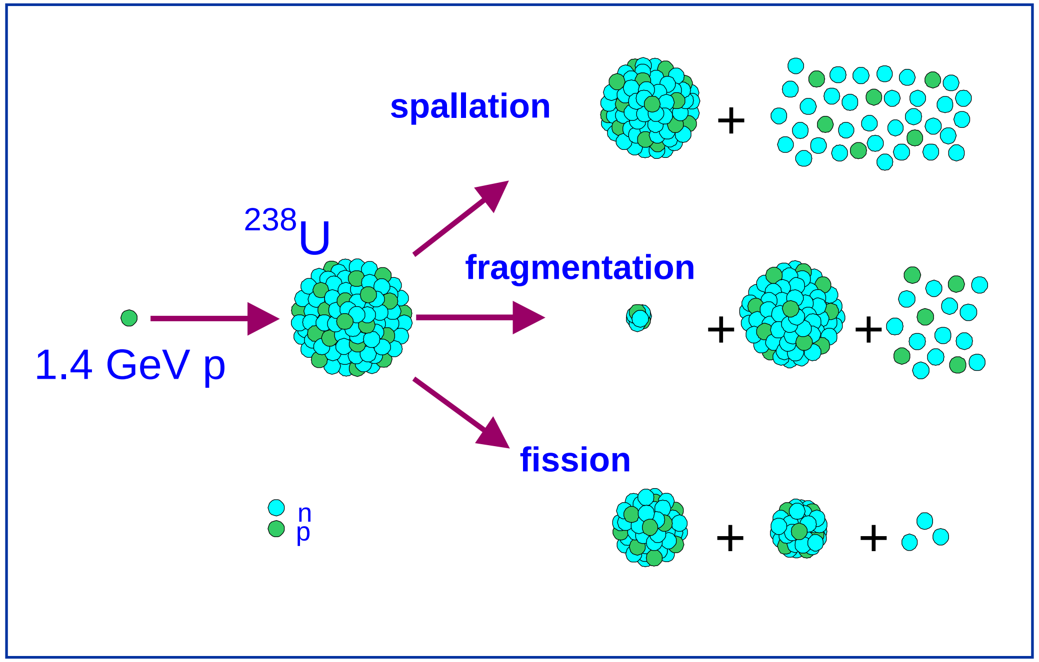


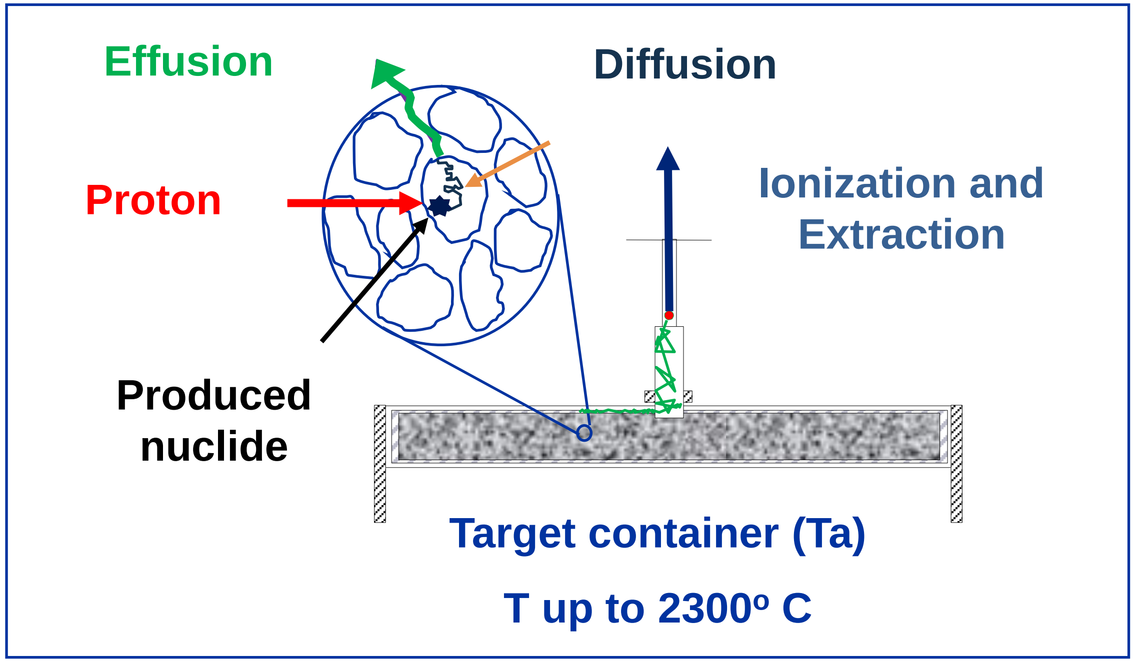
Tape station measurements

RP monitors



Radioisotope production @ ISOLDE





$$Beam\ Intensity = \sigma \cdot j \cdot N_t \cdot \varepsilon$$

$$\varepsilon = \varepsilon_{diff}\ \varepsilon_{eff}\ \varepsilon_{is}\ \varepsilon_{sep}\ \varepsilon_{transp}$$

Target-material dependent variables (and largest loss factors for short-lived radioisotopes)

Isotope production: target material

$$Beam\ Intensity = \underline{\sigma} \cdot j \cdot \underline{N_t} \cdot \varepsilon$$

σ

The cross-section to produce the desired isotope

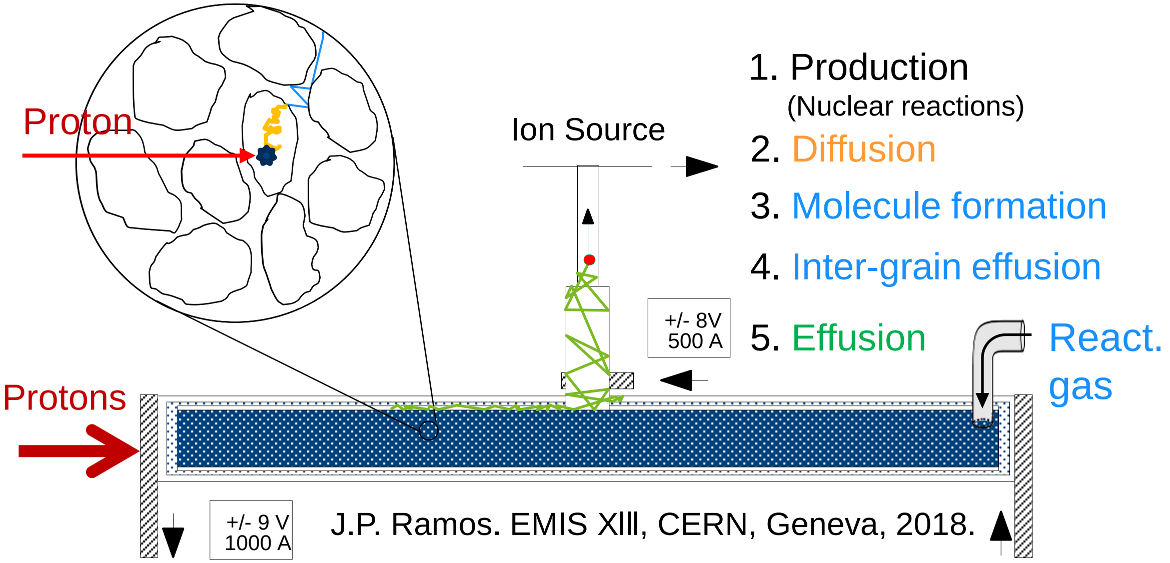
Dependent on the target-isotope chemistry

N_t

Number of target atoms exposed to the primary beam per unit of area

High ρ → high production
But low release

$$\varepsilon = \underbrace{\varepsilon_{diff}\varepsilon_{eff}}_{\varepsilon_{rel}}\varepsilon_{is}\varepsilon_{sep}\varepsilon_{transp}$$



Typical target operation conditions:

T~ 2000 °C (UCx, Ta, ThCx)
P~ $10^{-5} – 10^{-6}$ mbar c

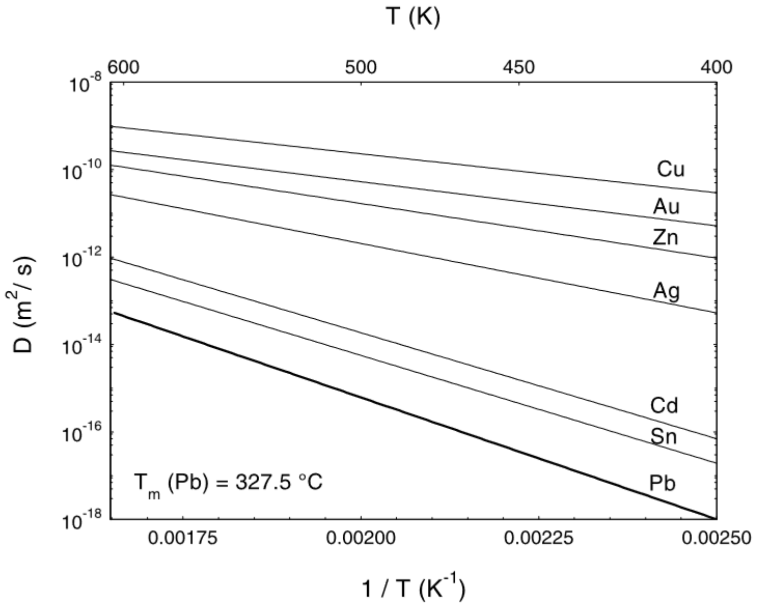
Diffusion vs effusion

Diffusion

$$\varepsilon = \varepsilon_{diff}\varepsilon_{eff}\varepsilon_{is}\varepsilon_{\mathrm{sep}}\varepsilon_{transp}$$

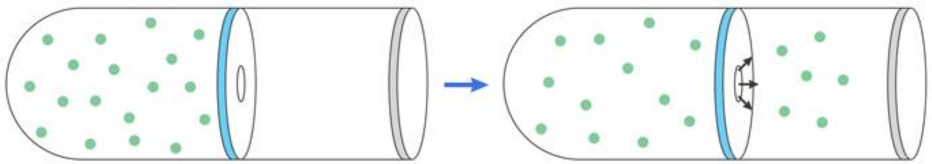
- Slowest step in many systems
- Critical for short-lived isotopes!

$$D = D^0 \exp\left(-\frac{\Delta H}{k_b T}\right)$$



Effusion

$$\varepsilon = \varepsilon_{diff}\varepsilon_{eff}\varepsilon_{is}\varepsilon_{\mathrm{sep}}\varepsilon_{transp}$$



Effusion is much faster than diffusion for porous materials (mostly depending on the pore size and interconnectivity)

Therefore, porosity is good for short-lived radioactive species even if it decreases their production cross-section from nuclear reactions

Target production oven control system

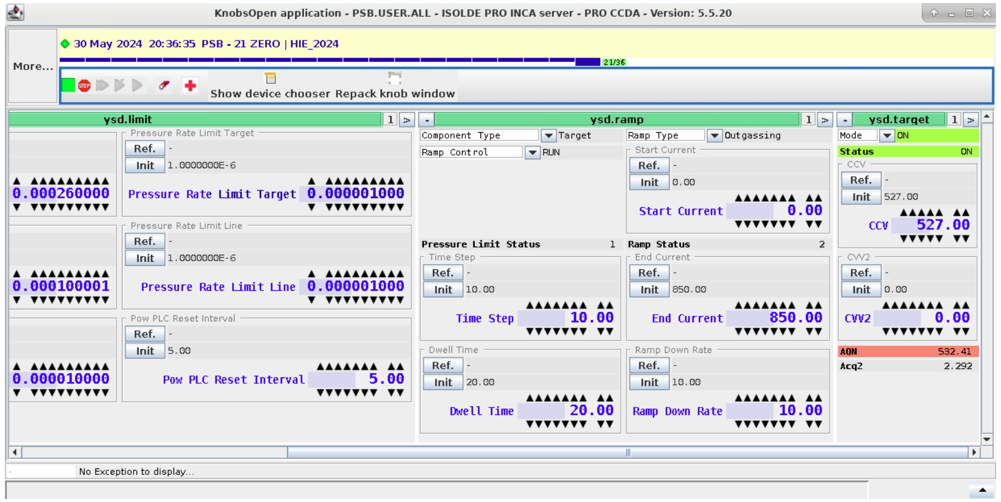
Carburization is the heating of the UO_2/C pills up to 2000C under vacuum, to transform UO_2 to UC_x. To avoid interlock trigger caused by pressure spikes during CO_2 evolution, the **SW monitors**:

- Pressure
- Pressure Rate
- Drain Voltage Rate

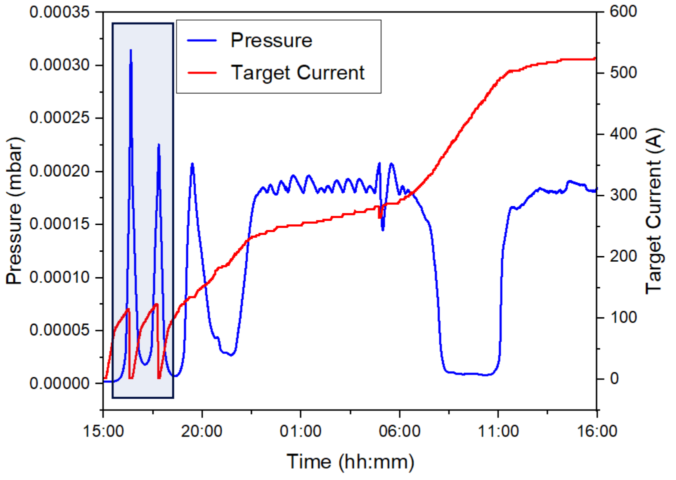
And **it adjusts by**:

- Increasing/decreasing the ramp up speed
- Ramping down to decrease pressure
- Automatic restart of devices if system shuts down

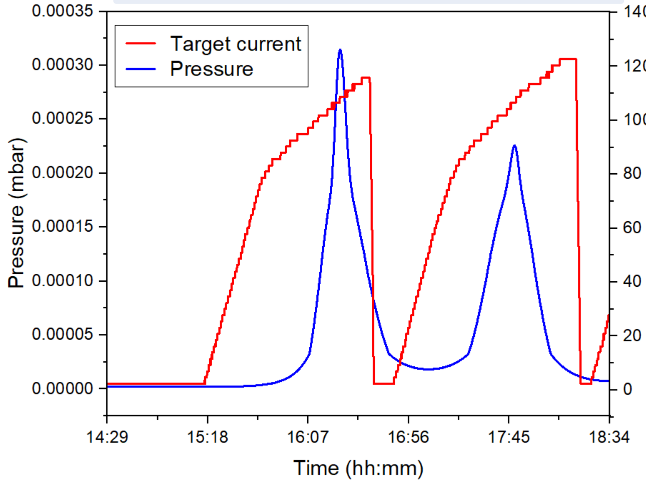
Monitor in a dedicated **WRAP dashboard** (wrap.cern.ch)

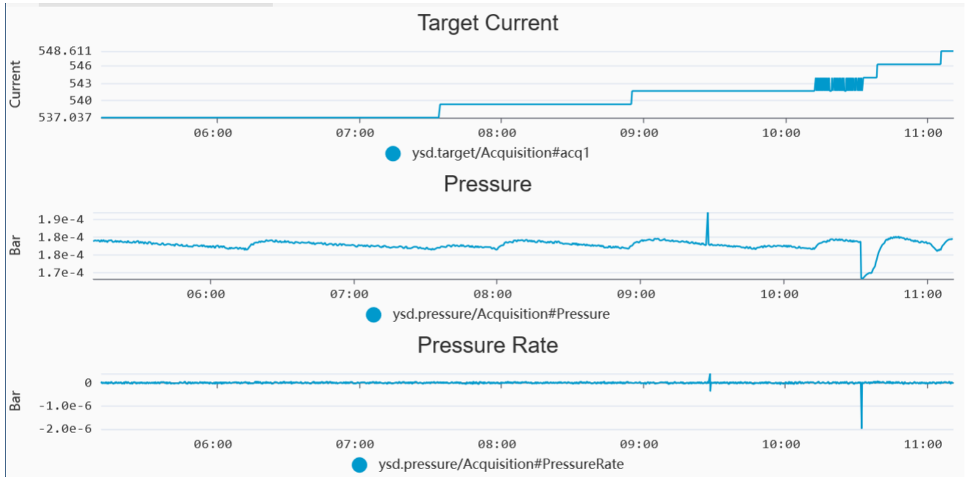


Software control for UC_x production



$$UO_3 + 6C \xrightarrow{1800^o\,C} UC_2 + 2C + 2CO_2$$





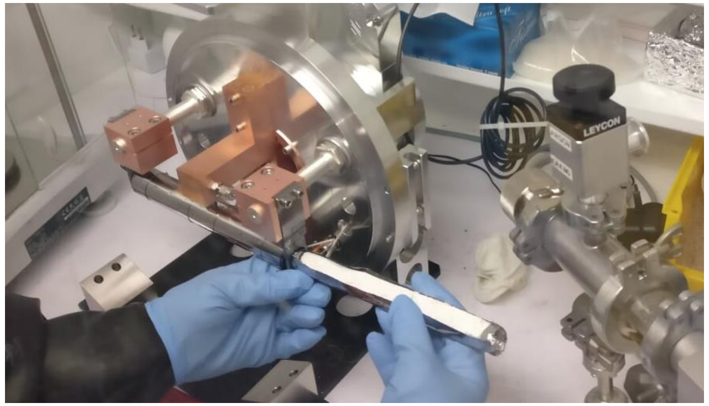
WRAP Dashboard for UC_x production

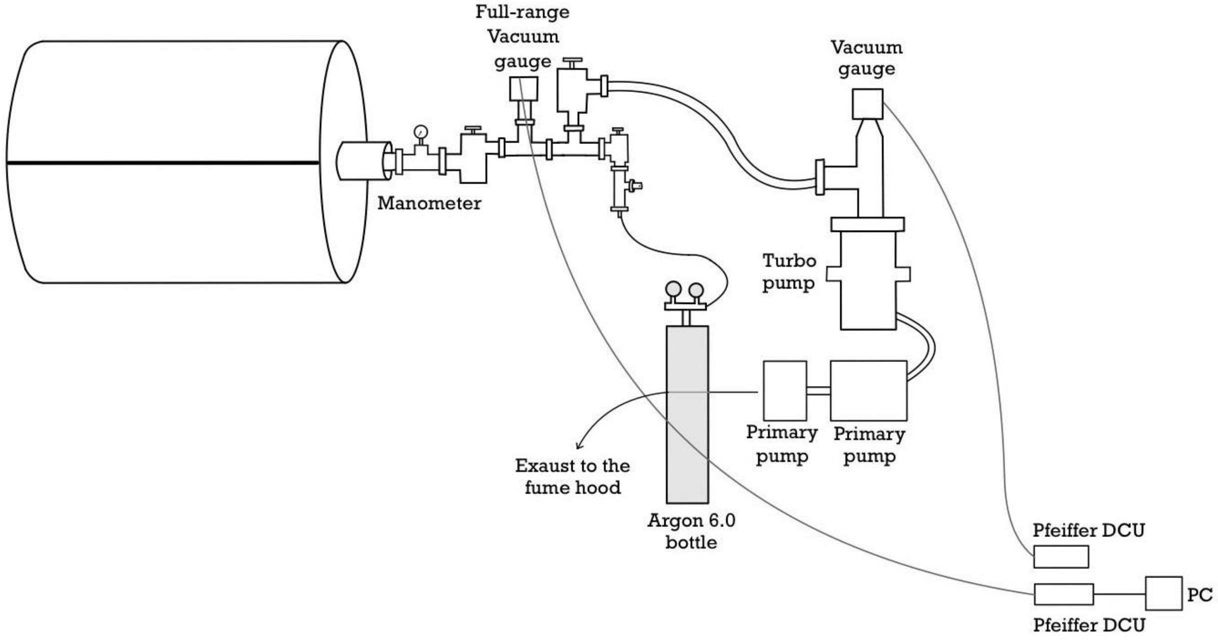
Alternative routes for nanomaterial production

Nano-calcium oxide production

- Produced by decomposition of commercial calcium carbonate

$$CaCO_3 \xrightarrow{800^{o}C, 10-3\ mbar} CaO(nano) + CO_2$$





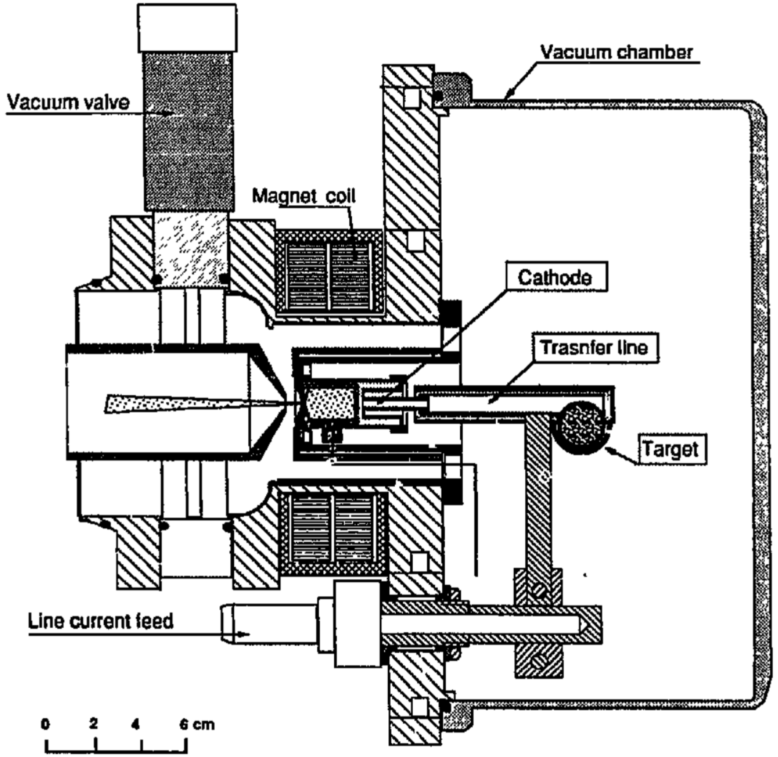
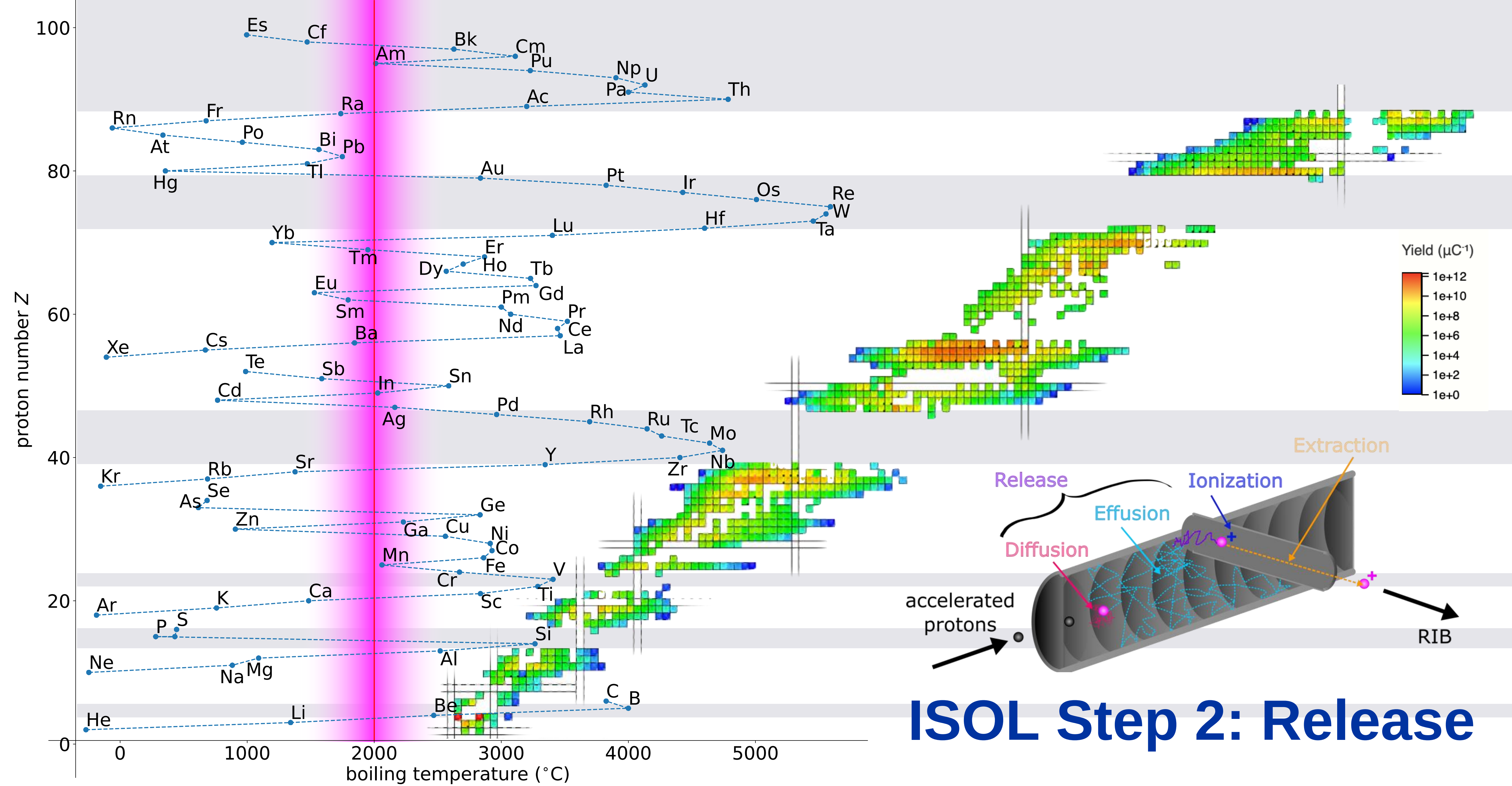


Fig. 1. Target and ion source assembly with plasma ion source MK5. The vacuum valve is part of the assembly.

DOI 10.17181/cds.2289929



ISOL Step 2: Release

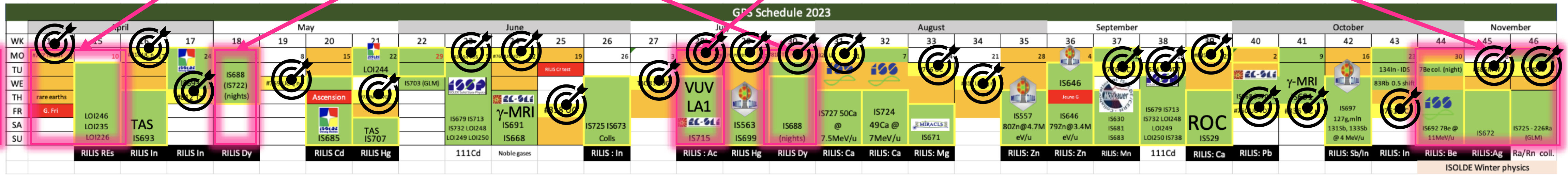
TISD 2023

Back-of-line heating: Dy collections

Batch mode: Ra → Ac

LIST: lanthanides

Winter physics: long-lived isotopes + external samples

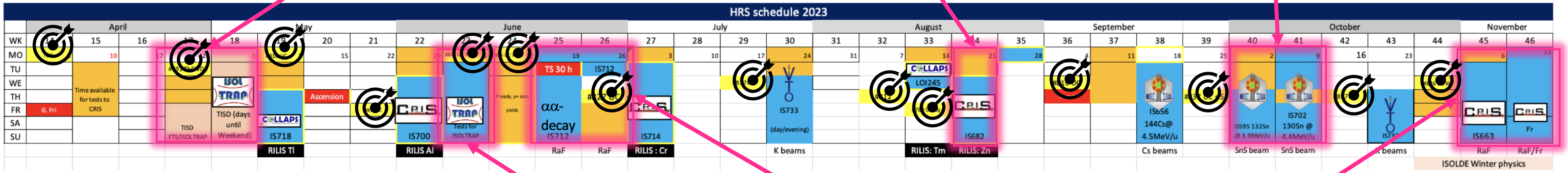


LIST: actinides

ThC_x VD5+CF_4

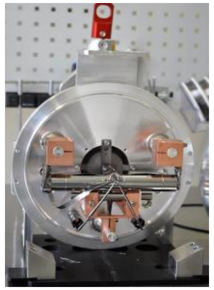
Prototype hot quartz: CRIS Zn

SnS



Prototype target + prototype ion source: ISOLTRAP Cd

RaF online + winter physics now standard beam

=  (~ 50 kCHF)

= Yield measurements, proton scans, setup

RILIS 23 : U, Np, Pu, Dy, Tm, Pm, Er, Gd, Yb, In, Cd, Hg, Al, Cr, Ac, Ca, Mg, Zn, Mn, Pb, Sb, Be, Ag

ISOL step 1: Production

Ballof et al. (2020) *NIM B* **463**, 211-215
cern.ch/isolde-yields

Target selection

- Cross sections
- Bulk
- Half-lives

At ISOLDE

- 1.4-GeV p
- ^{232}Th, ^{238}U