

Development and benchmark of an analytical model for isotope release from ISOL thin-foils targets

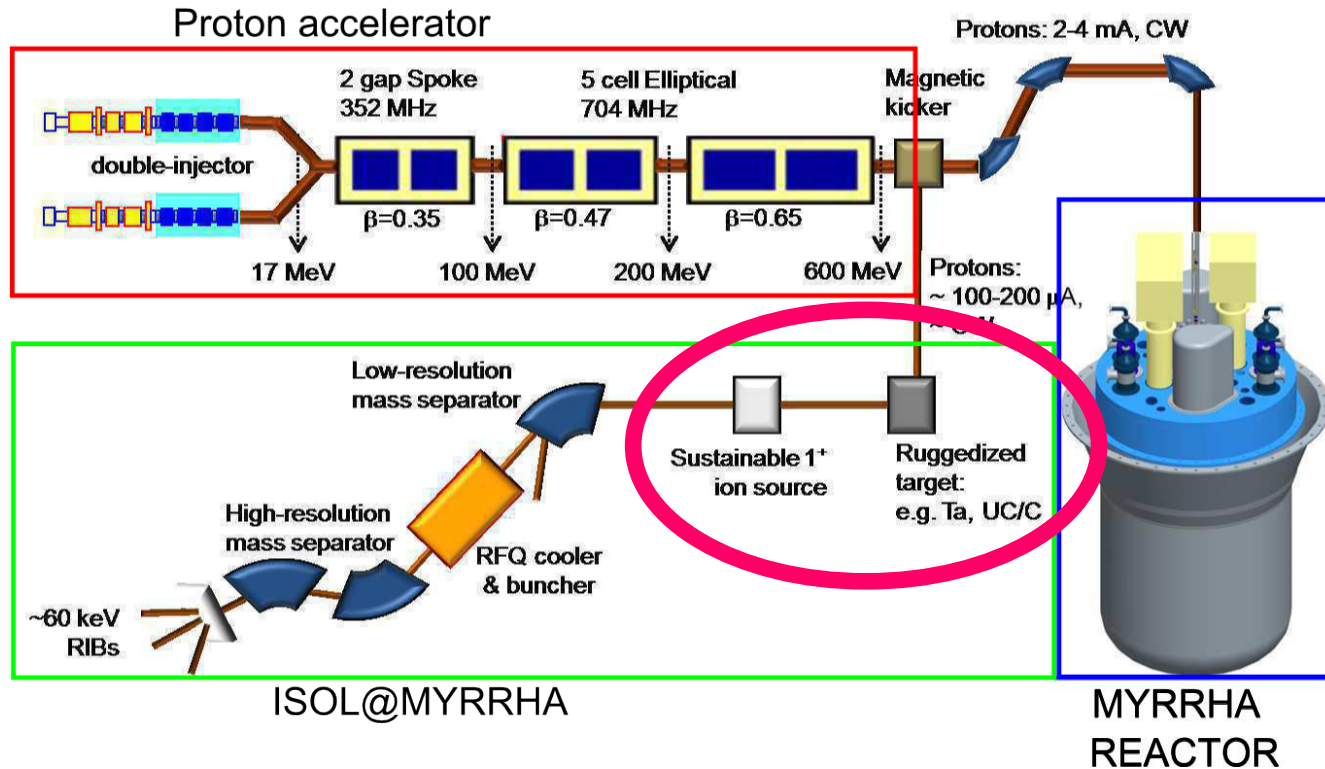
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ISOL@MYRRHA & ISOL method



Protons

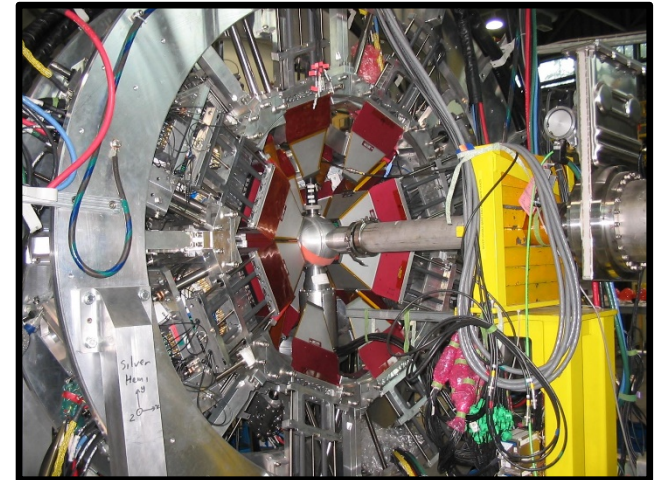
Isotope Separation
On Line (ISOL)

Radioactive Ion
Beam (RIB)

Radioactive Ion Beams (RIBs) used for:

- Nuclear physics (^{11}Li , $^{200,202}\text{Fr}, \dots$)
- Fundamental interactions (^{10}C , ^{14}O , ...)
- Atomic physics ($^{7,9,10,11}\text{Be}$, ...)
- Solid state physics ($^8\text{Li}, \dots$)
- Medical applications (^{225}Ac , ^{149}Tb , ...)
- ...

$$\begin{array}{lcl} T_{1/2} & ^{11}\text{Li} & = 8.75 \text{ ms} \\ & ^8\text{Li} & = 840 \text{ ms} \\ & ^{200}\text{Fr} & = 49 \text{ ms} \end{array}$$



$t \sim 1 - 100 \mu s$



Low-resolution
mass separator

Sustainable 1^+
ion source

Ruggedized
target:
e.g. Ta, UC/C

$t \sim 10 ms - 10 s$

600 MeV

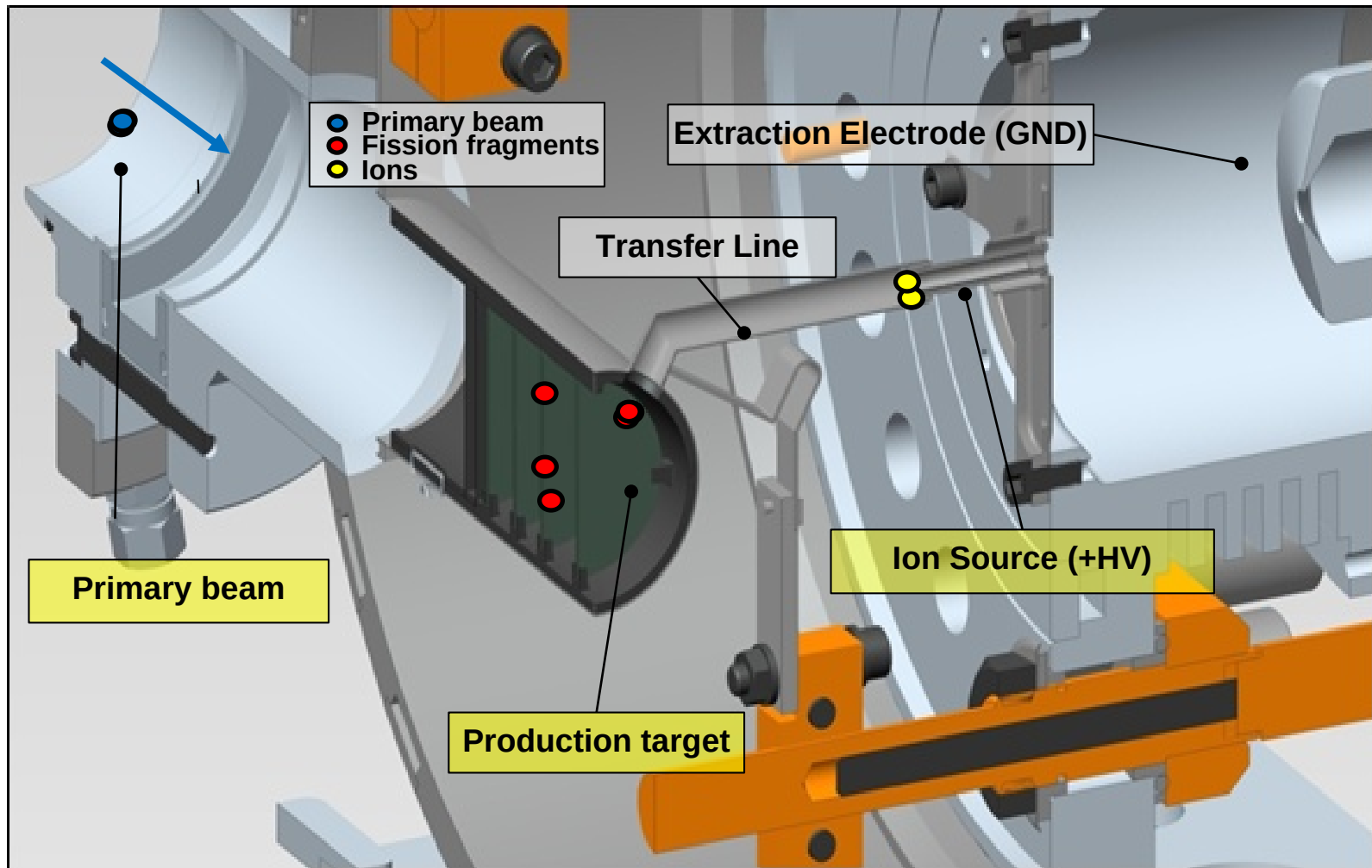
Protons:
 $\sim 100-200 \mu A$
 $\sim CW$

ator

Target and Ion Source



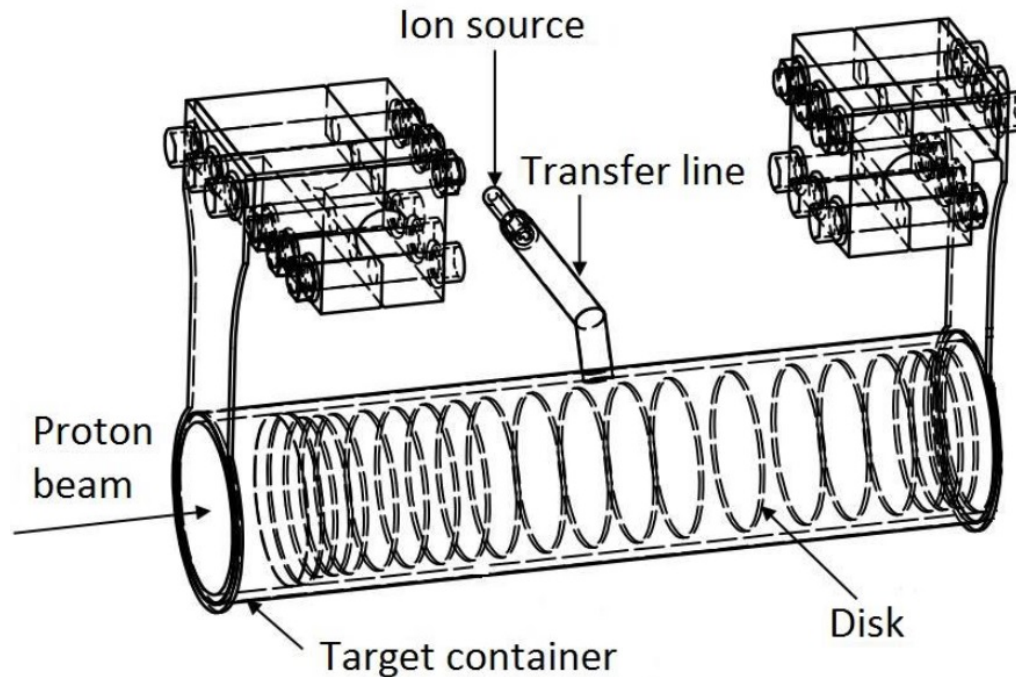
The Target and Ion Source unit



Alberto Andrichetto, INFN – Laboratori di Legnaro
EURISOL DF 2016, Leuven, October 20, 2016

The Target and Ion Source unit

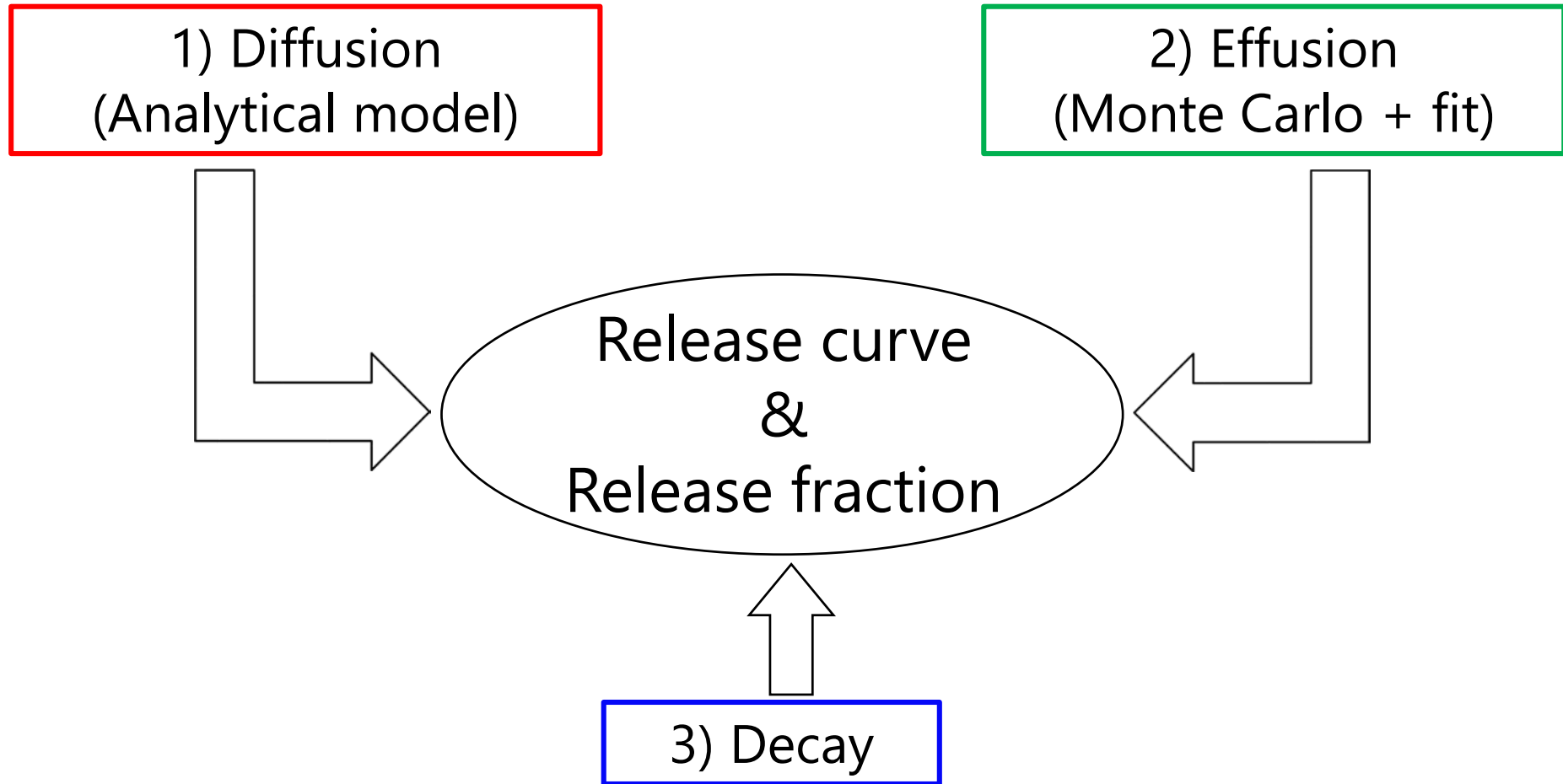
RIB production processes



- In target production
- Release:
 - Diffusion (solid)
 - Effusion (vacuum)
- Ionization, mass separation

$$RIB_I = \int \sigma(E) \Phi(E, x) \rho(x) \frac{N_{av}}{A} dx dE \varepsilon_{Rel} \varepsilon_{Ion} \varepsilon_{MS}$$

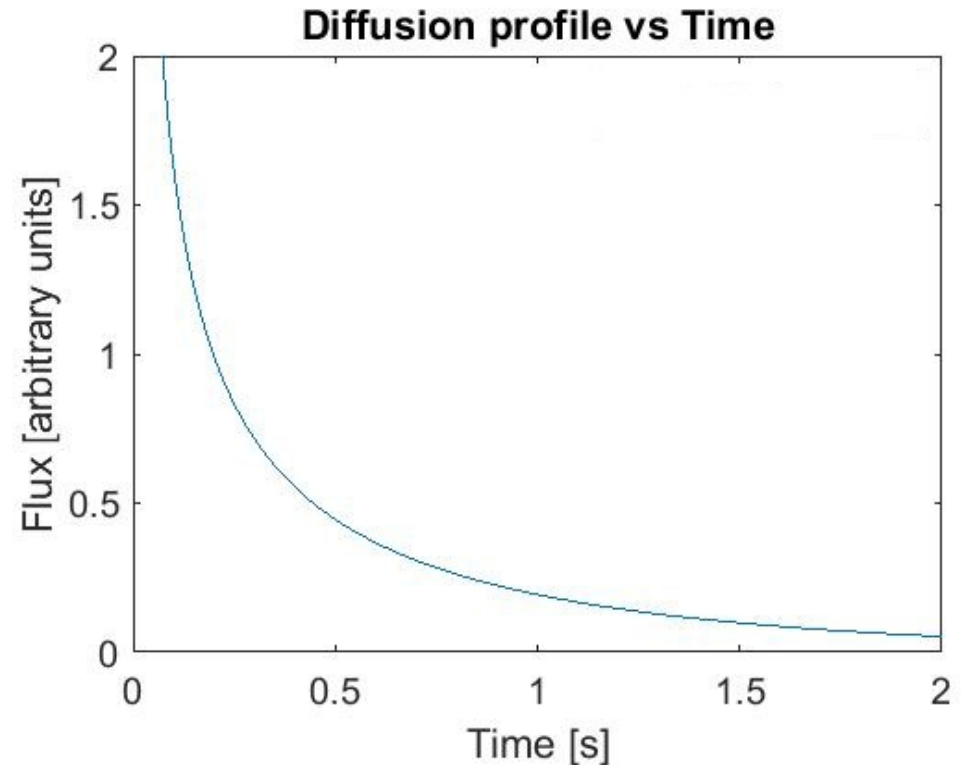
Isotope release calculations - Methodology



Isotope release calculations - Methodology

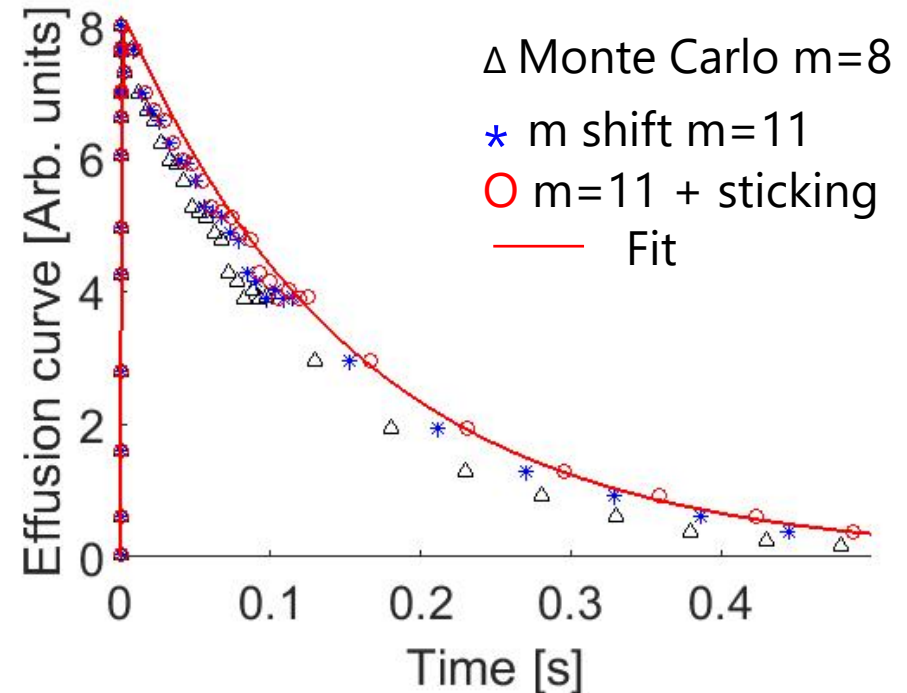
1) Diffusion

- $\frac{\partial C(x,t)}{\partial t} = \nabla \cdot D \nabla C(x,t)$
- Solution: concentration profile
- Flux: $J = -D \frac{dC}{dx}$



2) Effusion

- Monte Carlo code (MolFlow+): ideal effusion profile.
- MATLAB analysis to get results:
 - At a different operational temperature
 - For a different isotope
 - For non-zero sticking time
- Fit with analytical function:
$$E(t) = A * (1 - e^{-Bt}) * e^{-Ct}$$



Isotope release calculations - Methodology

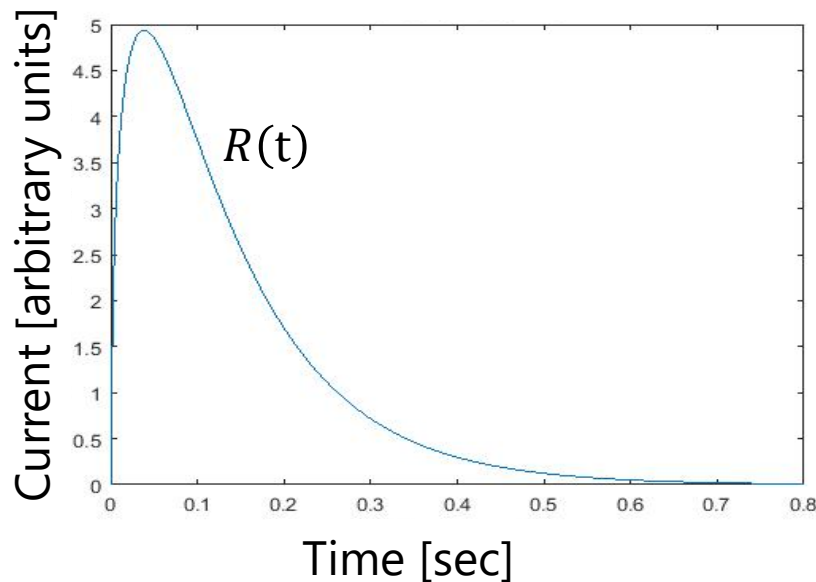
- Convolution of diffusion and effusion curves to get the overall isotope release curve

$$R(t) = e^{-\lambda t} * \int_0^t D(t') * E(t - t') dt'$$

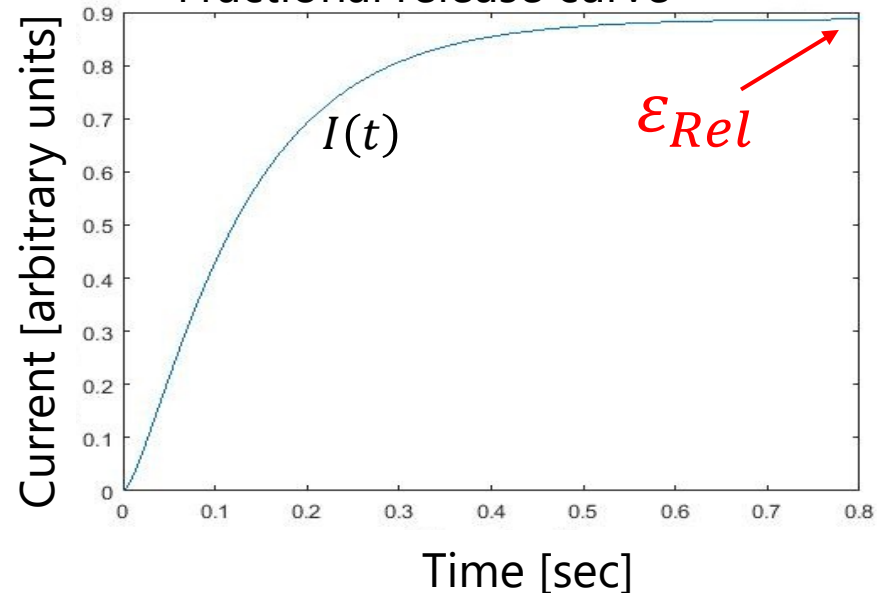
- Integration to get the fractional release

$$I(t) = \int_0^t R(t') dt'$$

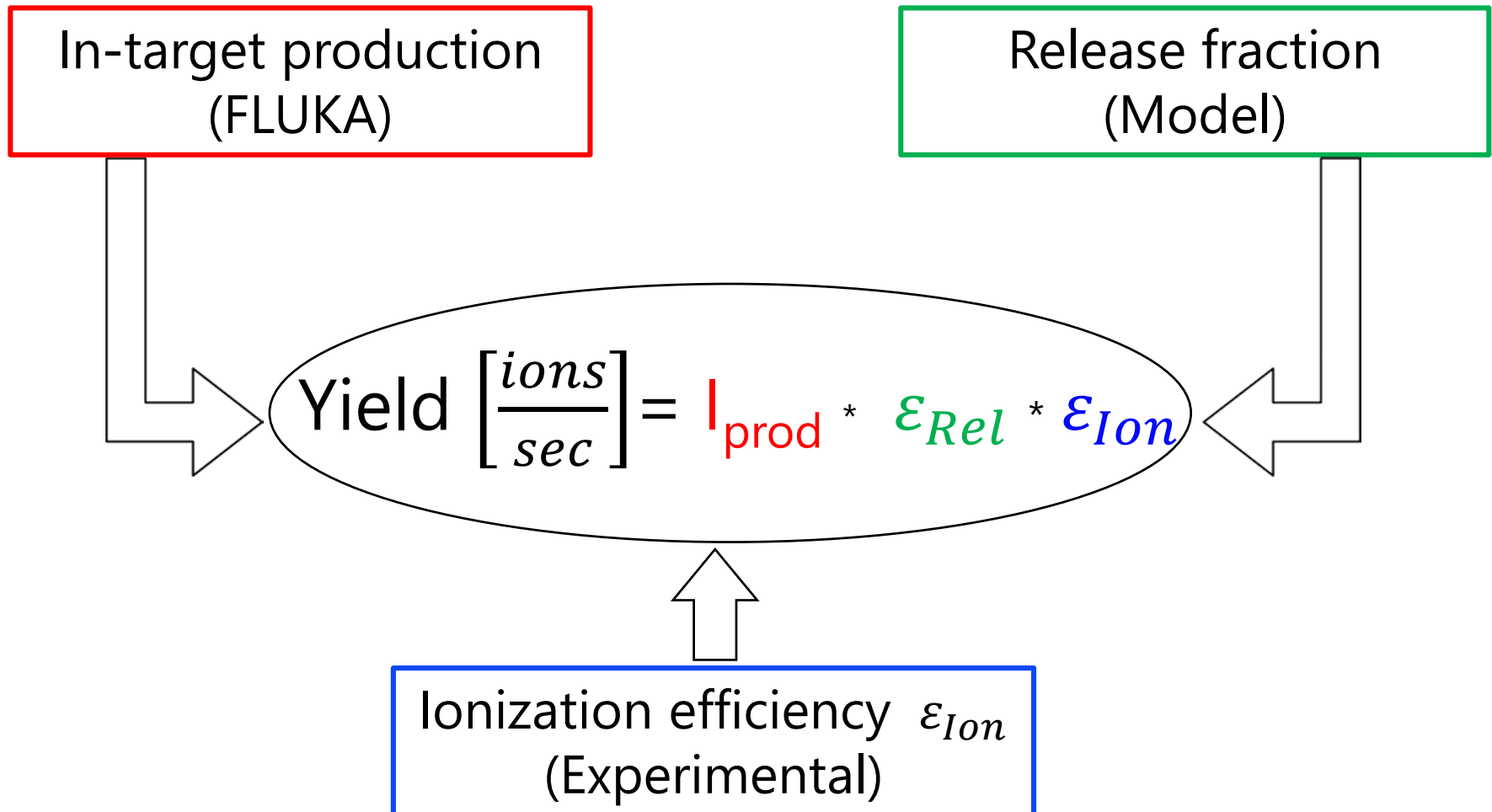
Release curve



Fractional release curve

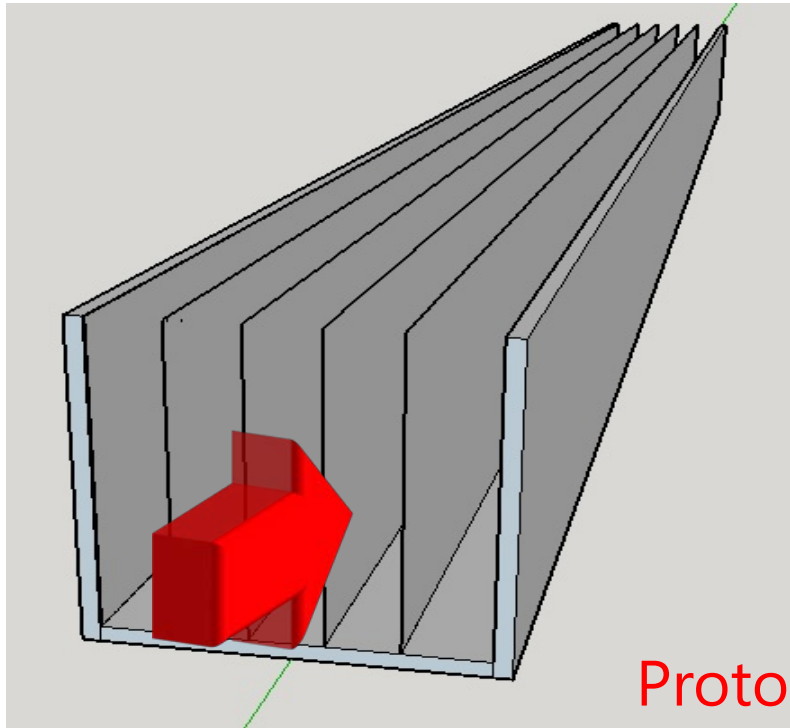


Isotope release calculations - Methodology

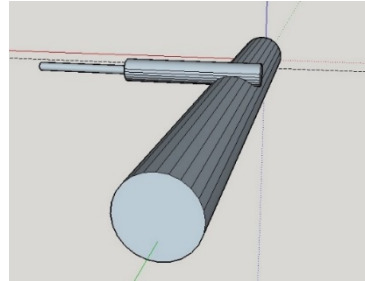


Isotope release calculations – Benchmark results

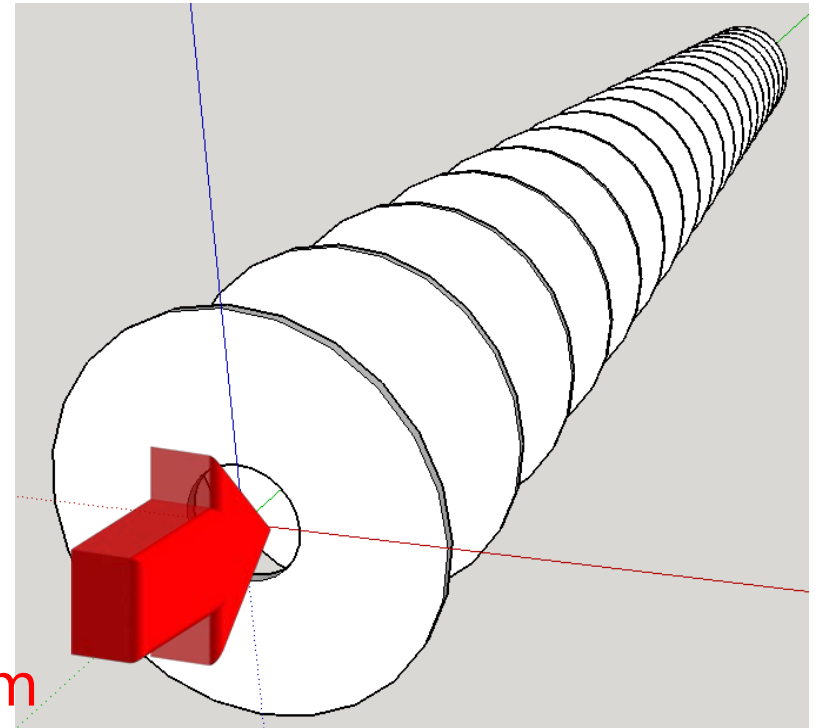
200 tantalum foils
2 μm thick 15 cm long
50 μm spacing



Target container

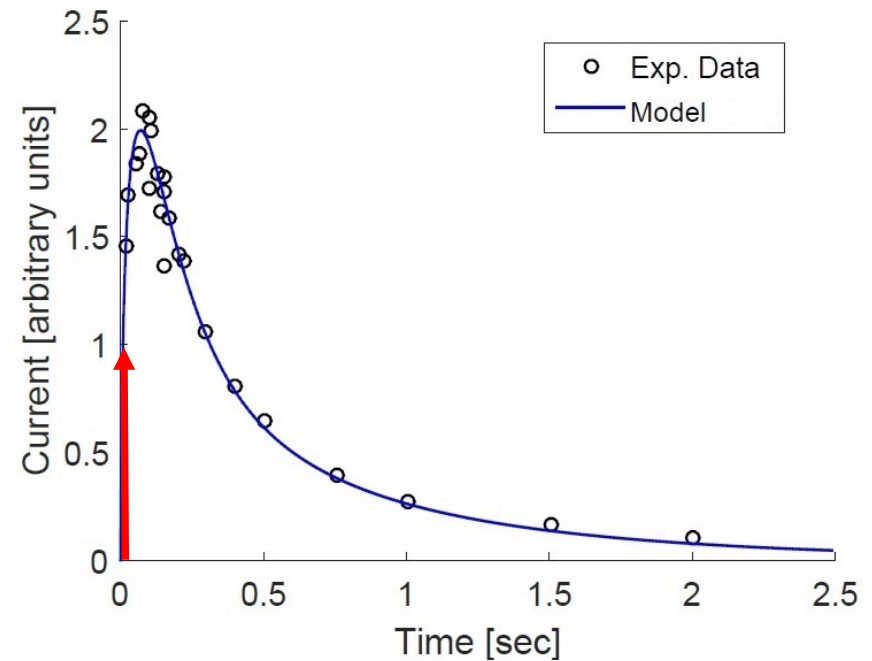
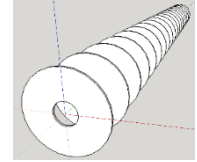
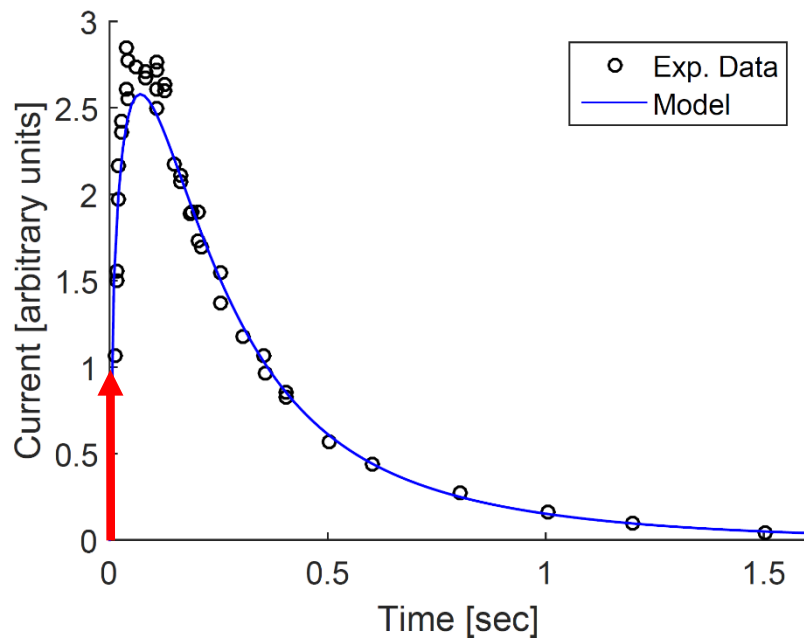
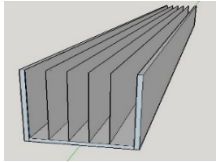


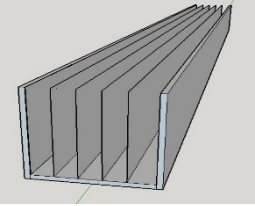
3600 tantalum annular discs
(RIST-ISOLDE geometry)
25 μm thick 8.75mm diameter
25 μm spacing



Proton beam

Isotope release calculations – Benchmark results





Isotope release calculations – Benchmark results

$$\text{Yield} = I_{\text{prod}} \cdot \varepsilon_{\text{Rel}} \cdot \varepsilon_{\text{Ion}}$$

Ion	$T_{1/2}$ [ms]	In-trg prod. [1/ μC]	ε_{Rel} (Our model)	Yield [1/ μC]	Exp. yield [1/ μC]
^7Li	Stable	$3.14(1) \cdot 10^9$	1	$2.82 \cdot 10^9$	$2.0 \cdot 10^9$
^8Li	839.9	$5.16(5) \cdot 10^8$	0.68	$3.17 \cdot 10^8$	$5.8 \cdot 10^8$
^9Li	178.3	$9.6(2) \cdot 10^7$	0.32	$2.7 \cdot 10^7$	$1.7 \cdot 10^7$
^{11}Li	8.75	$8.7(20) \cdot 10^5$	0.01	$7.6 \cdot 10^3$	$7.0 \cdot 10^3$

$$\varepsilon_{\text{Ion}} = 90\%$$

- Develop of release model for ISOL facility
 - Analytical release curve
 - Detailed 3D Monte Carlo model
- Strengths and innovations:
 - No free parameters
 - Design and optimization for future targets
- Benchmark: agreement with experimental data
 - Release curves
 - Yields

Acknowledgements



Thank you for your attention

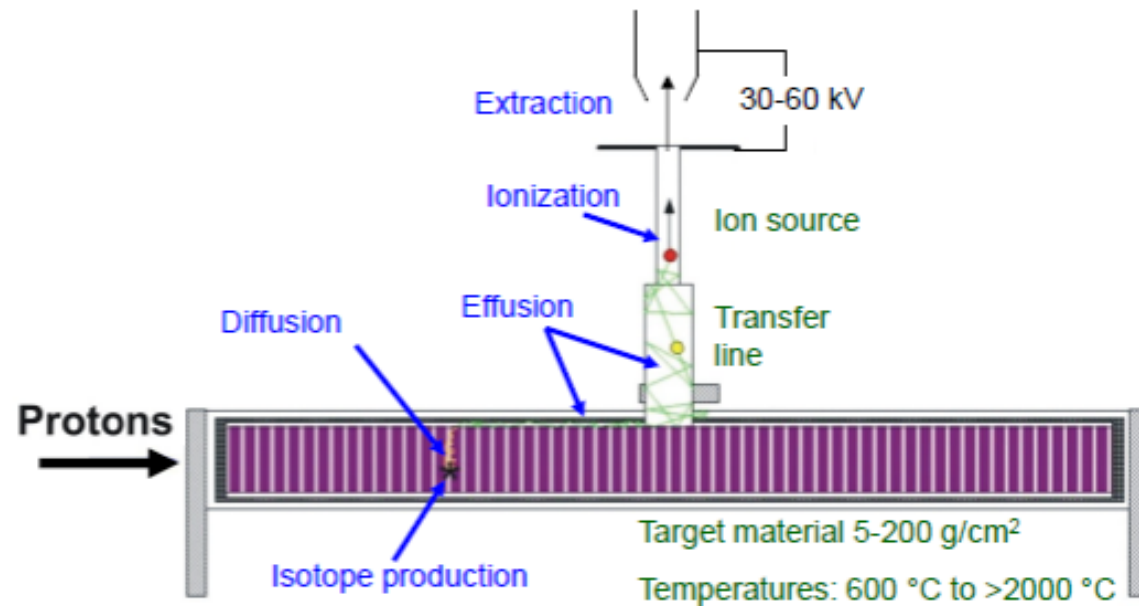


- Introduction: ISOL@MYRRHA & ISOL method
- Isotope release calculations
 - Methodology
 - Results of the benchmark study
- MAX phases: a possible new material for ISOL targets
- Summary

MAX phase: a possible new material for ISOL targets

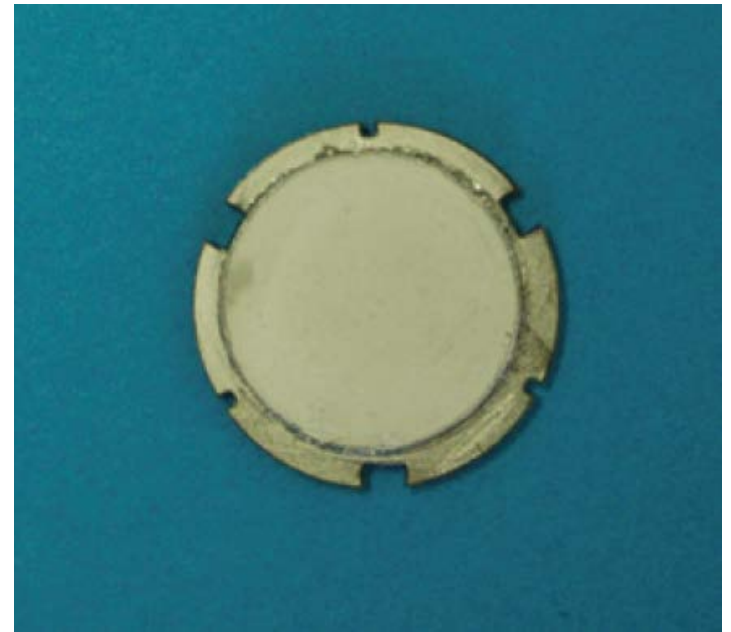
Requirements

- High cross sections for isotope production
- High resistance to radiation damage & thermal shocks
- Minimize diffusion & effusion time

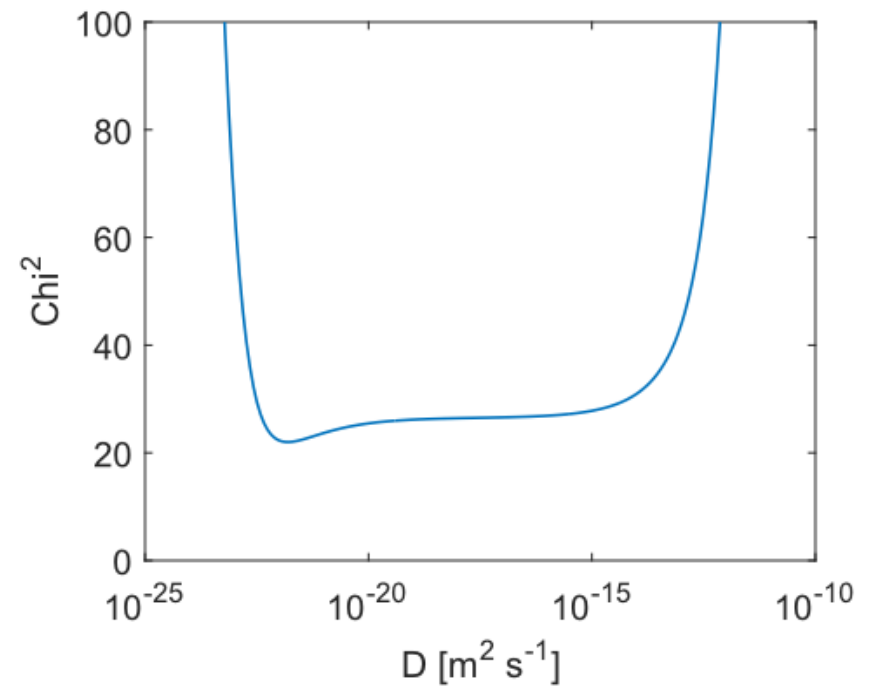
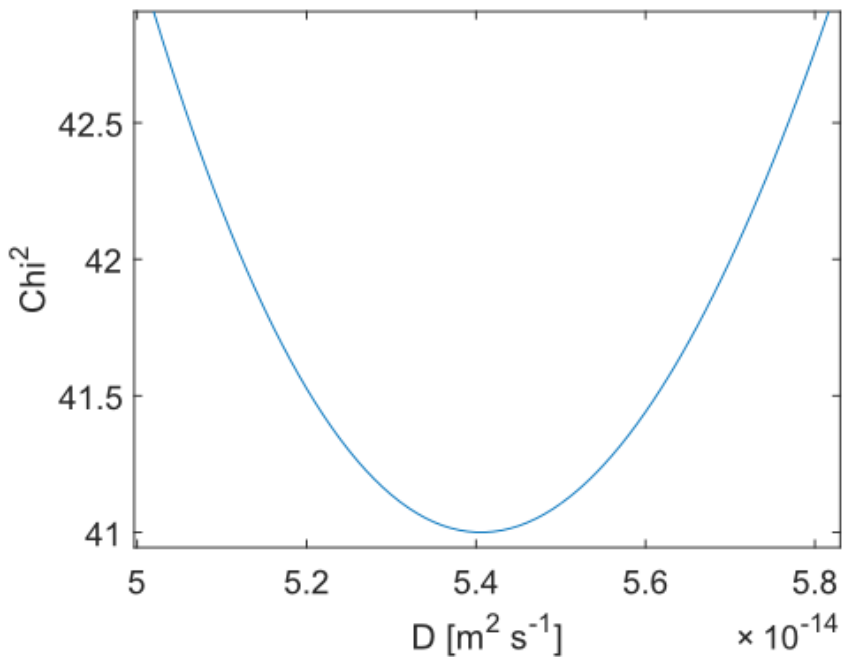
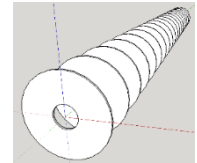
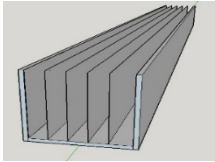


Target materials: e.g. refractory (Ta) metal and (TaCx) carbide

Benchmark - geometry



χ^2 from fitting



Time-correction formula

$$t'(i) = t(i) * \sqrt{\left(\frac{T_s m_r}{T_r m_s}\right)} + t(i) * \left(\frac{\tau N_{coll}}{t_{av}}\right)$$

- T_s and T_r = Simulating and real temperature
- m_s and m_r = Simulating and real mass
- τ = Average sticking time
- N_{coll} = Total average number of collisions per particle.
- t_{av} = Total average time per particle

$$\langle v \rangle = \sqrt{\frac{8RT}{\pi m}}$$

Some models present in literature

- Fully analytical
 - Fitting of 2 or more parameters required
 - Effusion described in a non-physical way
- Effusion treated by Monte Carlo simulation to compute:
 - τ_E = characteristic effusion delay time
 - Average total path

$$R(t) =$$

$$\frac{8C_0DA}{l} * \left\{ \sum_{n=0}^{+\infty} \left[\frac{e\left(-\frac{(2n+1)^2\pi^2D}{l^2}*t\right) - e^{(-C*t)}}{C - \frac{(2n+1)^2\pi^2D}{l^2}} - \frac{e\left(-\frac{(2n+1)^2\pi^2D}{l^2}*t\right) - e^{-(B+C)*t}}{B + C - \frac{(2n+1)^2\pi^2D}{l^2}} \right] \right\} * e^{-\lambda t}$$

Fractional release formula

$$R_I(t) = \int_0^t R(t') dt' =$$

$$\frac{8C_0DA}{l} \sum_{n=0}^{+\infty} \left[\frac{1}{\left(C - \frac{(2n+1)^2\pi^2D}{l^2}\right)} \left(\frac{e^{\left(-\left[\frac{(2n+1)^2\pi^2D}{l^2} + \lambda\right]*t\right)} - 1}{\left(-\frac{(2n+1)^2\pi^2D}{l^2} - \lambda\right)} - \frac{e^{-(C+\lambda)*t} - 1}{(-C - \lambda)} \right) \right] +$$

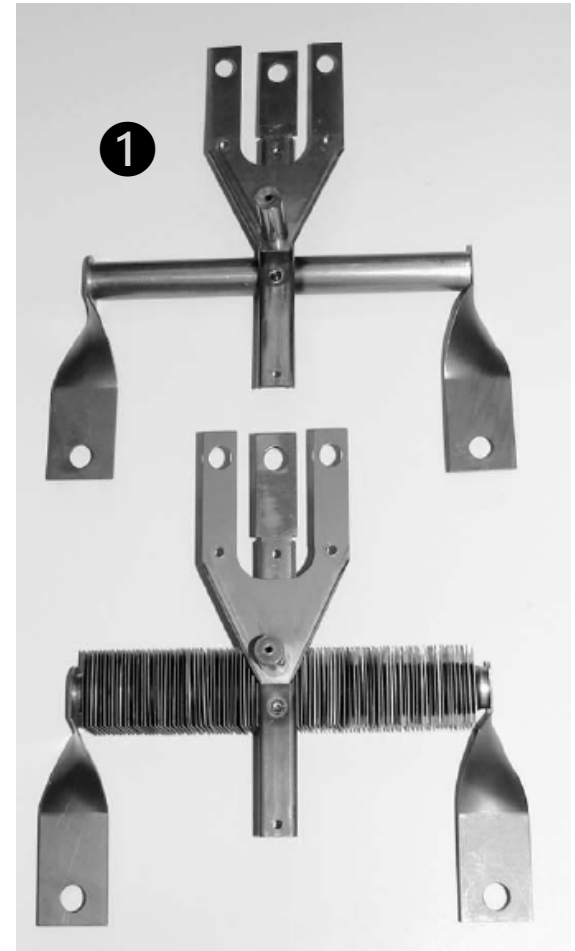
Heating / Cooling

Figure 1

- Operated with powers < 40 kW
- Thermally shielded

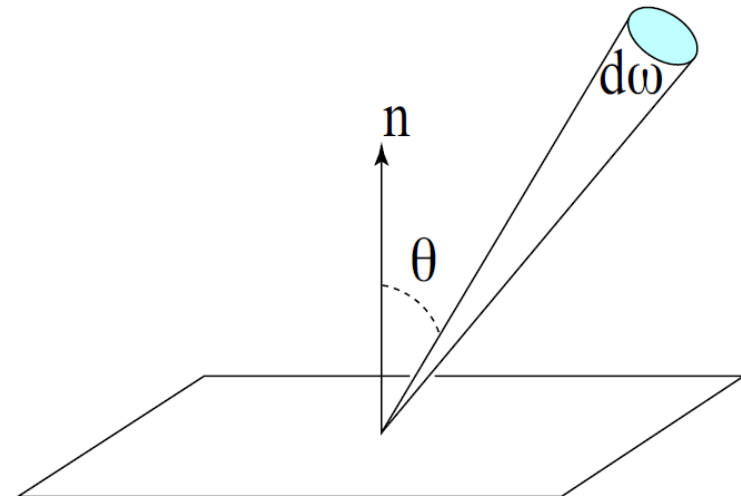
Figure 2

- Operated with powers > 40 kW
- Finned to enhance radiation cooling



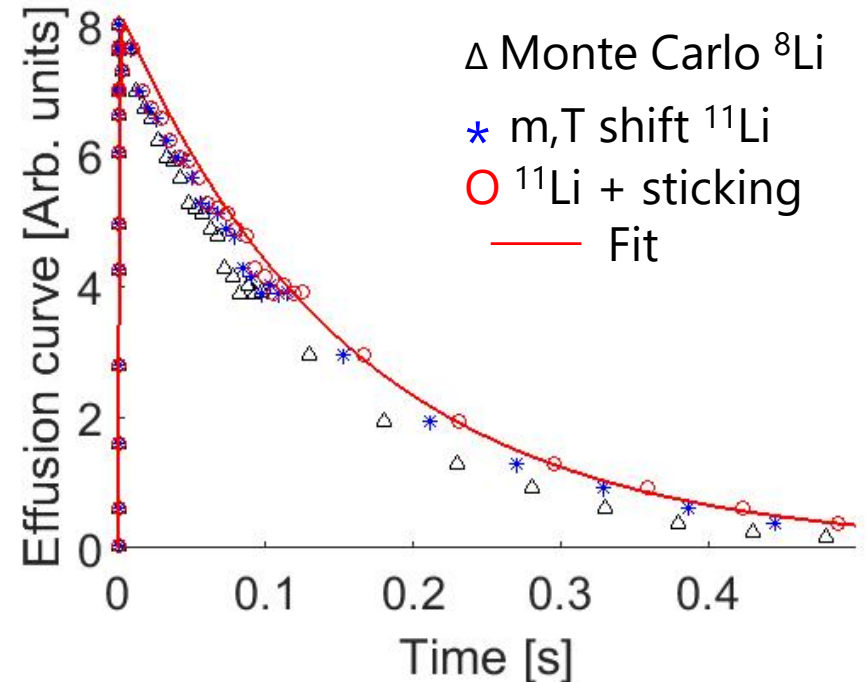
Effusion physics

- Free flight path in vacuum (*Pressure* = 10^{-6} [mbar])
 - $\lambda \sim 10^2 - 10^3$ [m] from kinetic theory
 - $L \sim 10$ [cm]
- Cosine law distribution ($dP = \frac{\cos \theta}{\pi} d\omega$)



2) EFFUSION

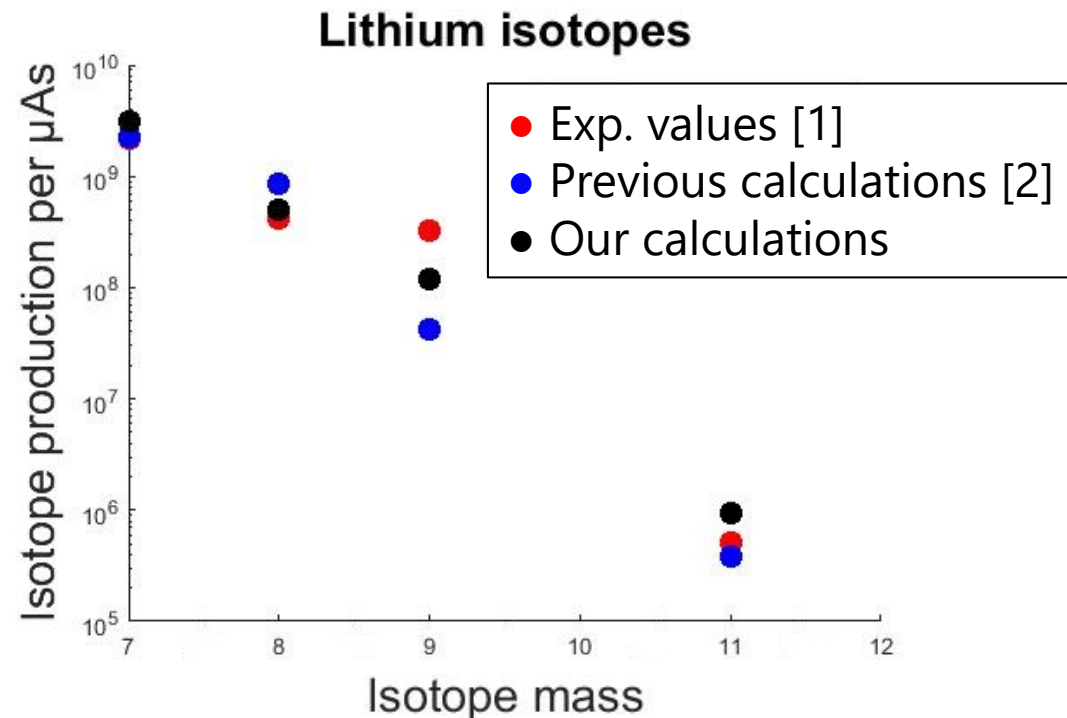
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Isotope release calculations - Methodology

1) IN-TARGET PRODUCTION

(FLUKA simulation)



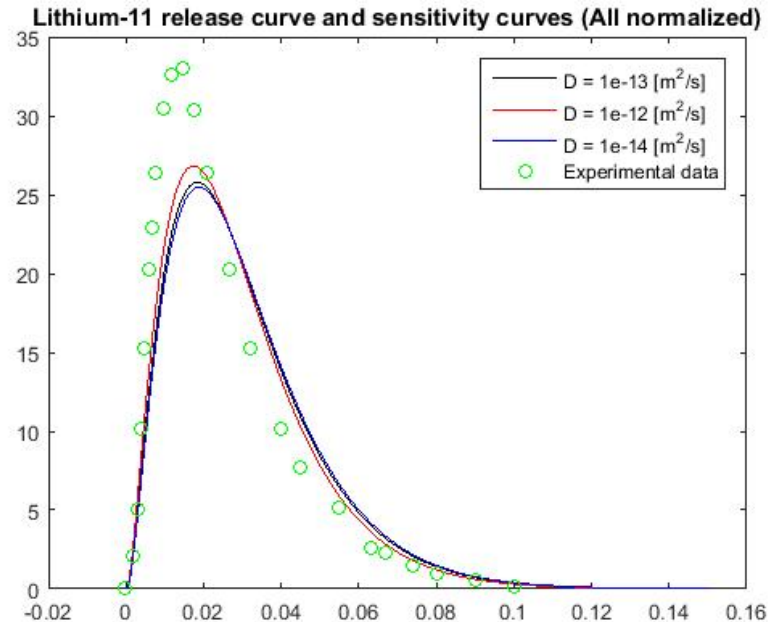
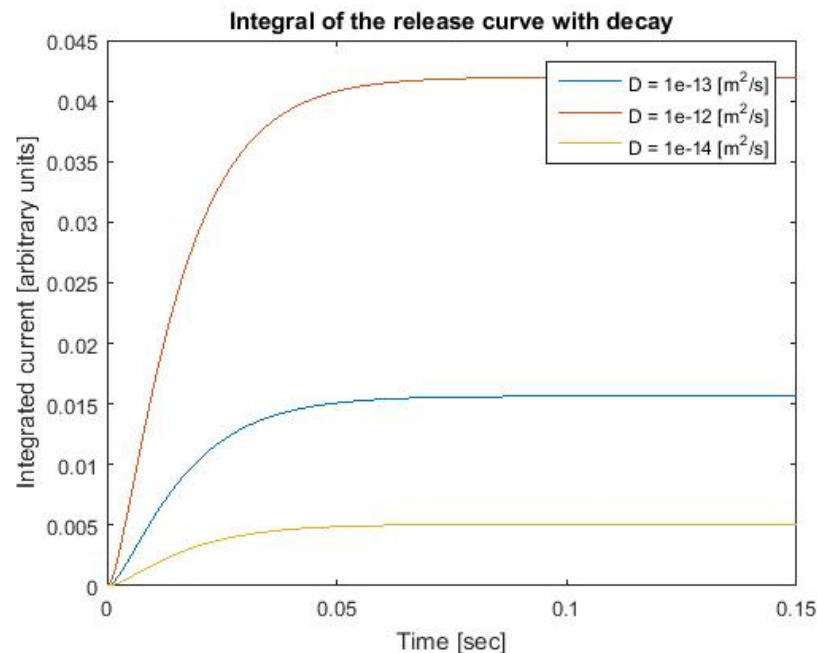
[1] U.C.Bergmann et al. Nuclear Physics A 701 (2002) 363c–368c

[2] R. Silberberg, C.H. Tsao, Astrophys. J. Suppl. Ser. 220 25 (II) (1973) 335.

Isotope release calculations - Results

TANTALUM FOIT TARGET-LITHIUM 11

$$R(t) = e^{-\lambda t} * \int_0^t D(t') * E(t - t') dt'$$



← Integral release curve

Yields:

Our simulation: $R_f = 1.6\%$ ($D = 10^{-13} \left[\frac{\text{m}^2}{\text{s}}\right]$)

Literature: $R_f = 2\%$ ($D = 10^{-12} \left[\frac{\text{m}^2}{\text{s}}\right]$)







