# A theoretical framework for isotope production at the SPES ISOL facility

## $^{28}$Mg as a case-study

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Florence 15-19 Feb 2026
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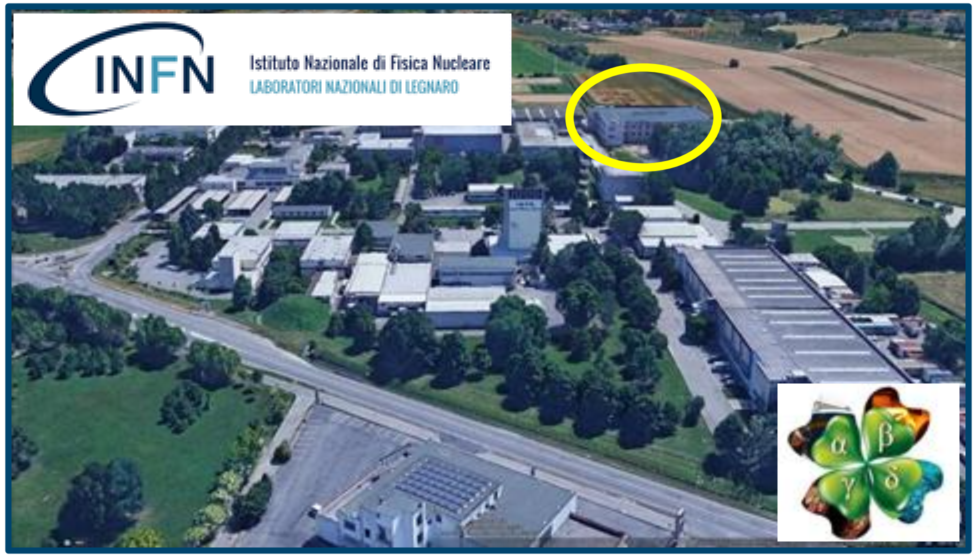
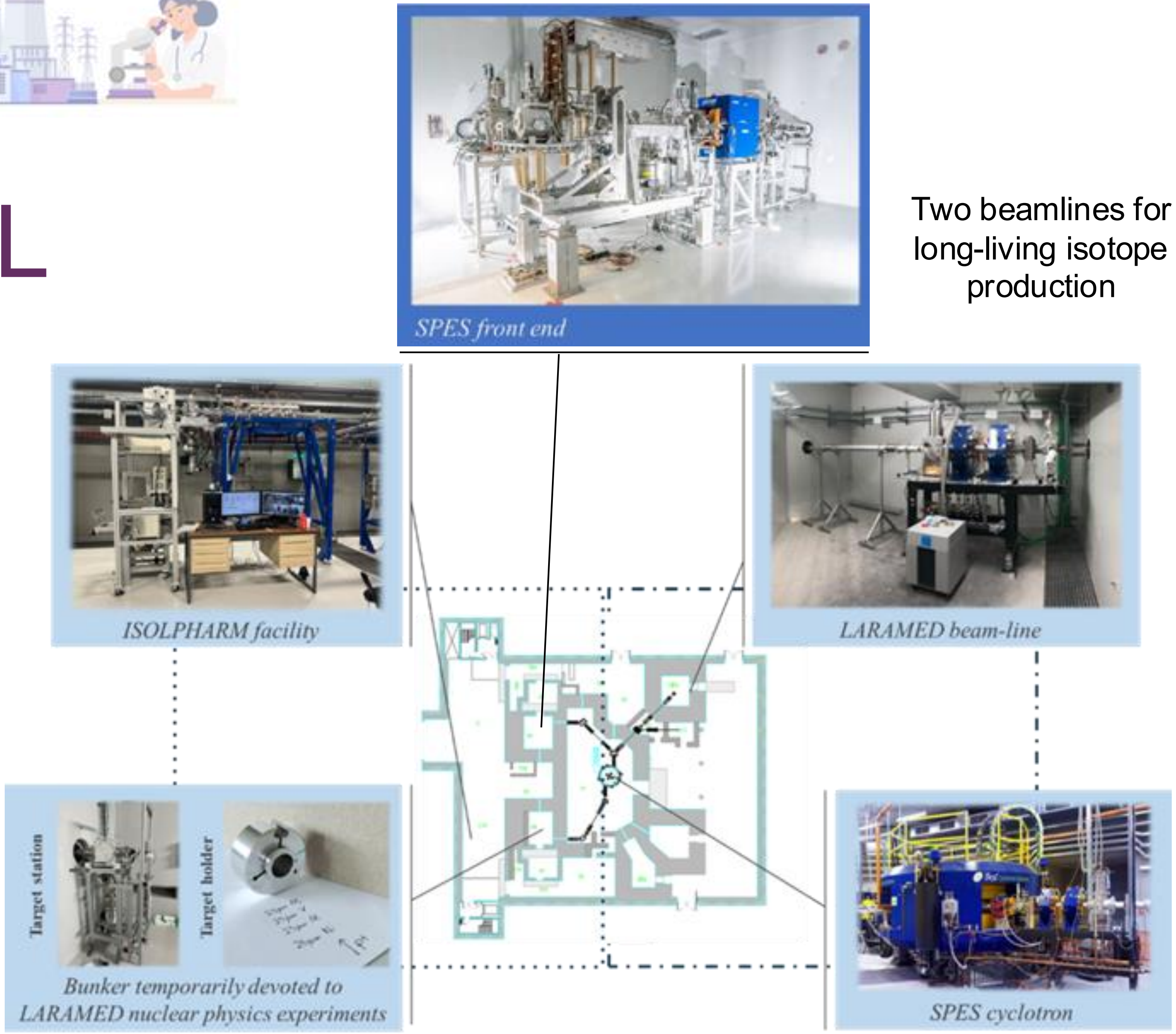
12th International Conference on Isotopes

# SPES at INFN-LNL




**SPES**: B70 cyclotron (BEST Cyclotron Systems) with energy 30-70 MeV and maximum intensity 750 μA. First Isotope Separation On-Line (**ISOL**) beam in November ‘24

# The SPES_MED project

SPES MED

INFN-CSN3

**General aim**: study the production of medical radionuclides at SPES

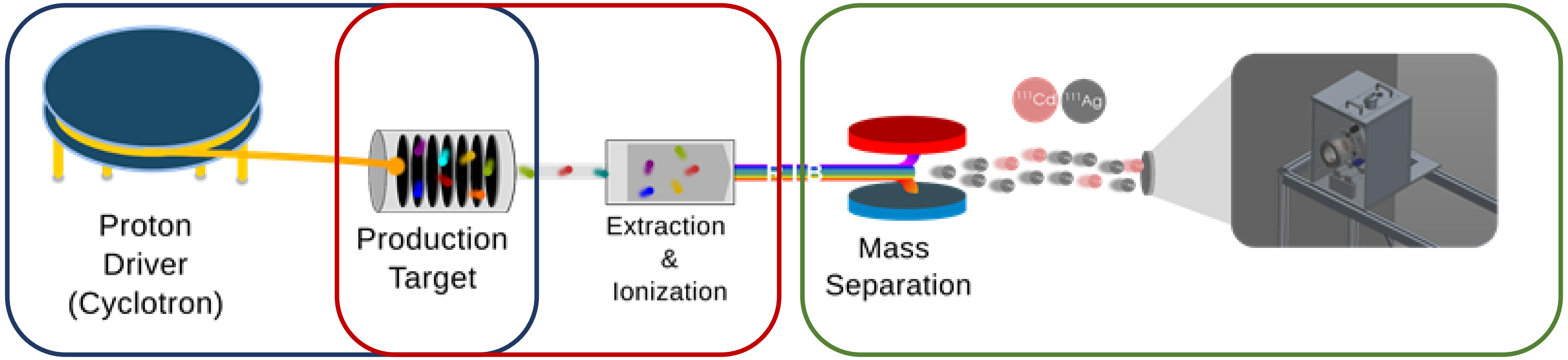
**WP1**
Cross-section measurements for direct production

**WP2**
Yield measurements for ISOL production

**WP3**
Models and simulations for nuclear reactions and ISOL processes

# A theoretical framework for ISOL

SPES ion sources:
- surface
- plasma
- laser (LIS)




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

Atom population in the target box:

$$\dot{N}_t = R - \kappa N_t - \lambda N_t$$

Atom population in the ion source:

$$\dot{N}_i = \kappa N_t - \varepsilon r N_i - \zeta N_i - \lambda N_i$$

Production ($R$), Extraction ($\kappa N_t$), Decay ($\lambda N_i$), Ionization (pulse efficiency × pulse rate) ($\varepsilon r N_i$), Loss ($\zeta N_i$)

This term represents the ion current coming out of the LIS

**Time-resolved** model:

- ✓ sensitive to more parameters
- ✓ allows for continuous optimization

# Case study: $^{28}$Mg in SiC targets

- ➢ **$^{28}$Mg**: $\beta^-$ and γ-emitting **radiotracer** with biological and biomedical applications
- ➢ $t_{1/2}$ = 20.9 h
- ➢ Mg isotopes can be produced by ISOL using **SiC targets**

Typical parameters of SiC targets

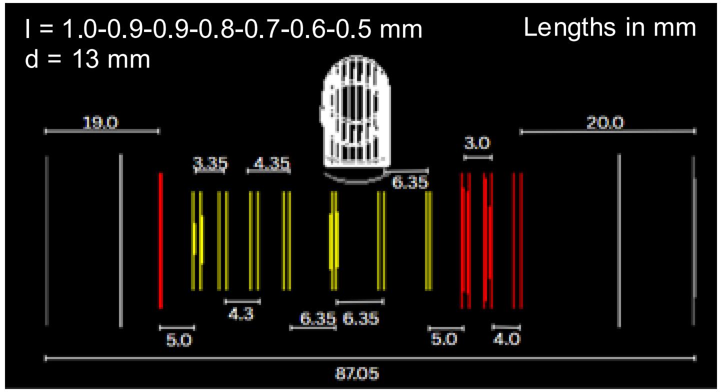
| | $\rho\ (g/cm^3)$ | $r\ (\mu m)$ | $r_{pori}(\mu m)$ |
|---|---|---|---|
| SiC SA | 3.10 | $[4-10]$ | no pori |
| SiC SP | 3.04 | $[4-10]$ | 50 |

Good resistance up to $T$ ~ 1800 °C

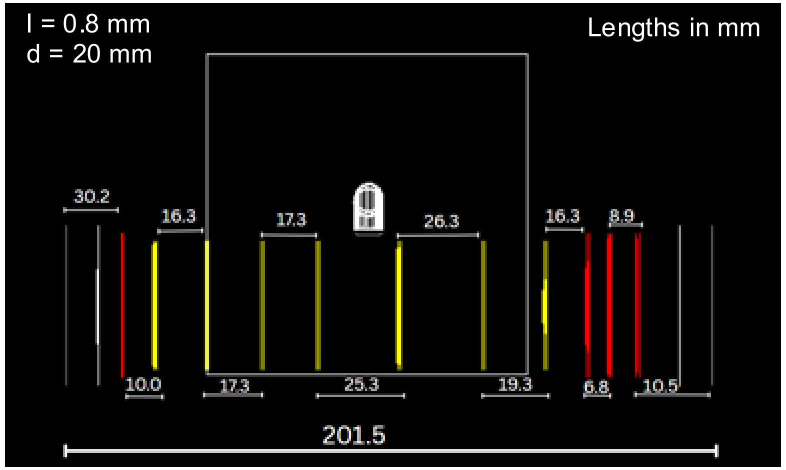
T Ogura et al 2018
WS Watson et al 1979
M Manzolaro et al 2021

Two SPES target geometries

"small"

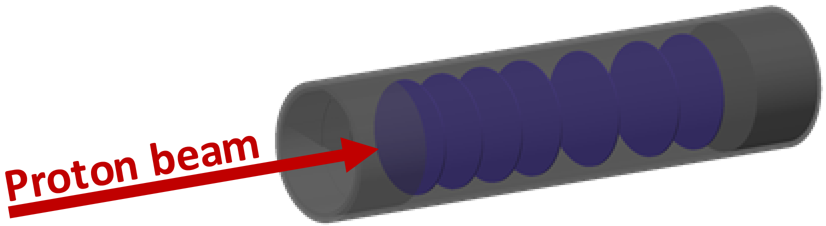



"big"



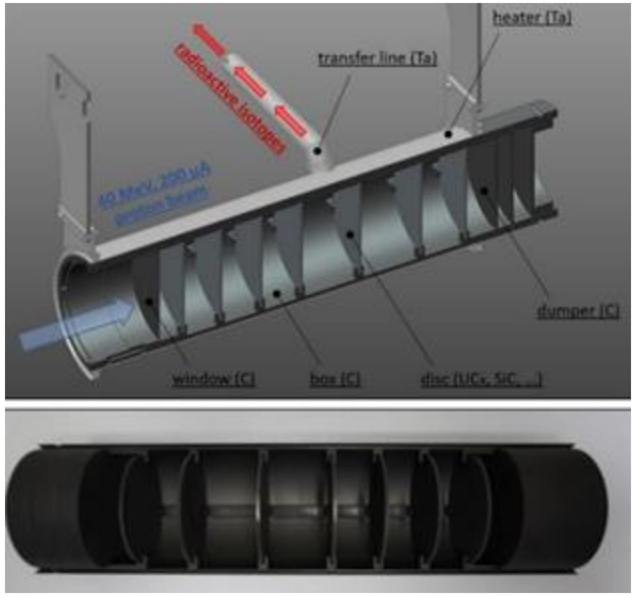
# Generation of isotopes

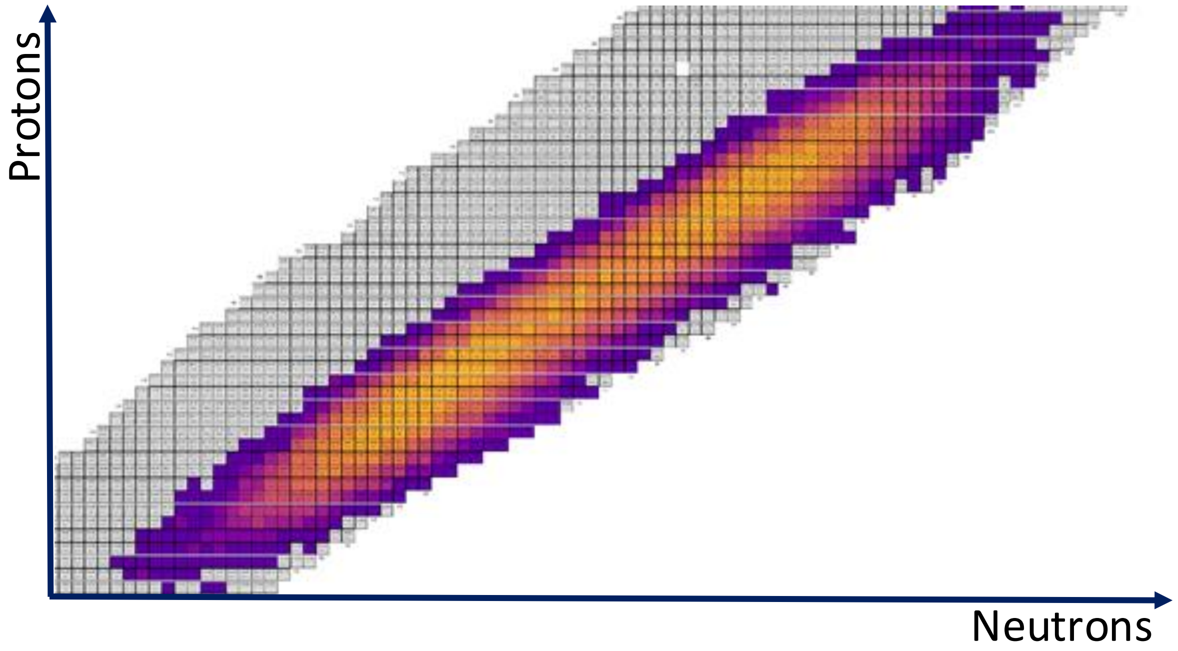
- ➢**Standard procedure** using Monte Carlo codes
- ➢The peculiar 7-disk geometry of the SPES target can be built




FLUKA

GEANT4
A SIMULATION TOOLKIT



# $^{28}$Mg production

Simulations performed in the *CloudVeneto* infrastructure ($10^{10}$ events, uncertainty < 3%)

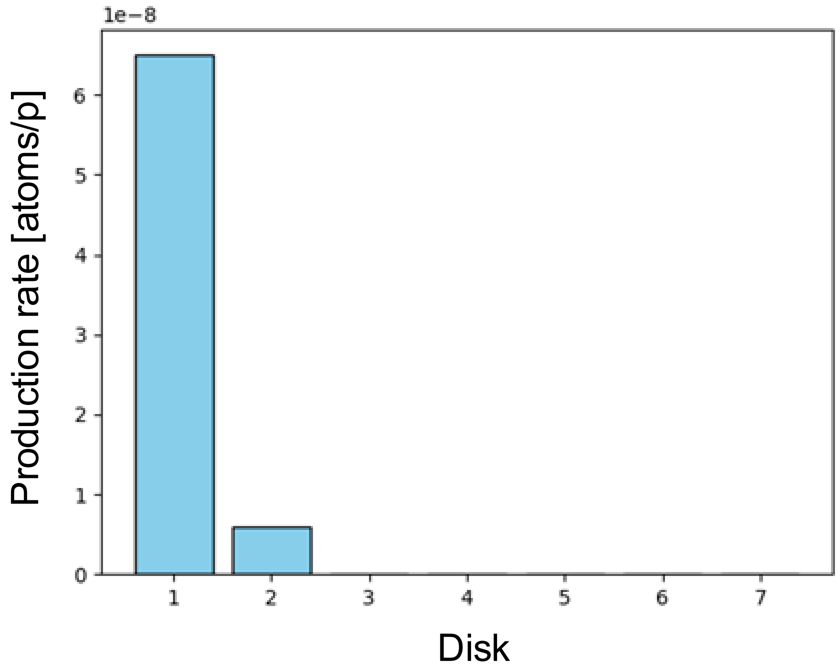
With a 40 MeV, 200 µA proton beam, the main production channel is likely to be **$^{30}$Si(p,3p)$^{28}$Mg** (compound nucleus and proton evaporation).

Production rates predicted by Geant4:

- ➢ "Small" target: **$8.2 \times 10^{-8}$ atoms/p**
- ➢ "Big" target: **$6.4 \times 10^{-8}$ atoms/p**

Disk distribution is also useful information.

$^{28}$Mg distribution in small SiC target discs



# Diffusion

**Geant4** application `G4_ISOL_RELEASE`

M Ballan et al 2020

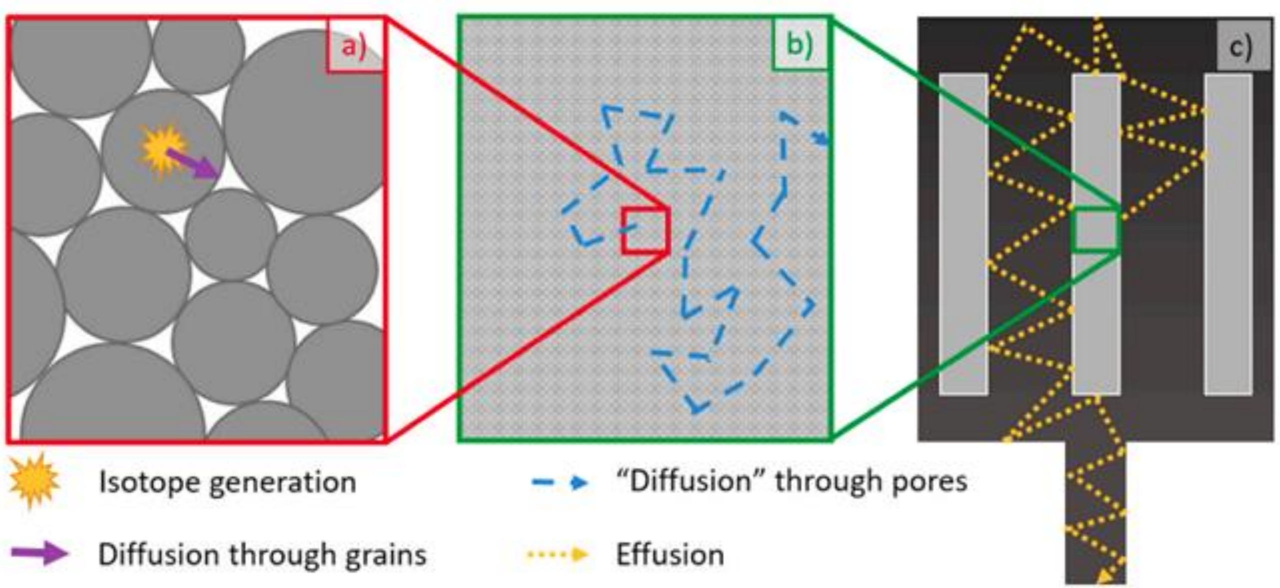
From the solution of Fick's laws in a sphere, the mean escape time of an **atom diffusing in a target grain** with radius *a* is

$$\langle t \rangle_{\text{diff}} = \frac{a^2}{15D}$$

with (*Arrhenius equation*)

$$D(T) = D_0 \exp\left(-\frac{E_a}{kT}\right)$$

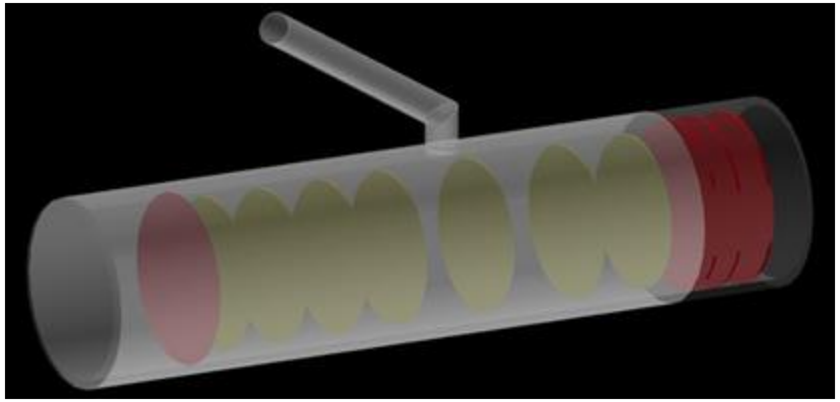
$\langle t \rangle_{\text{diff}}$ computed for each event using a normal distribution for *a*.

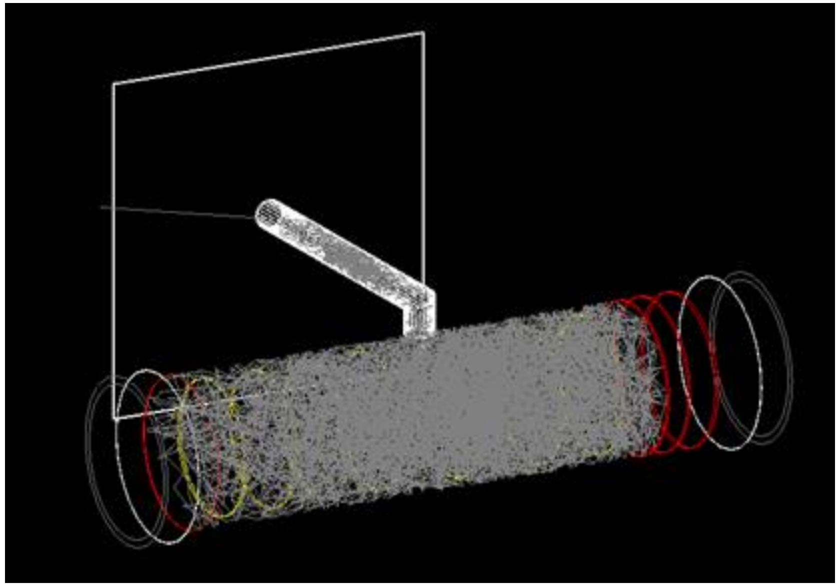



**Generalized diffusion through pores** can be modeled with a different $D_0$.

M Fujioka, Y Arai 1981

# Effusion





The **porous diffusion** and **effusion** time is simulated by letting the particles bounce until they reach the transfer line. Mean free path for porous diffusion: MFP = $2D_p/v$.

**Sticking** time in the Ta box walls and **reabsorption** probability in the disks can also be set.

$\langle t \rangle = \langle t \rangle_{diff} + \langle t \rangle_{diff,p} + \langle t \rangle_{eff} = \kappa^{-1}$

*Free path of a single atom before exiting the target box*

[W Jiang et al 2015](#)
U Köster 1999

# Diffusion and effusion of $^{28}$Mg

$10^6$ events: uncertainty < 0.1%

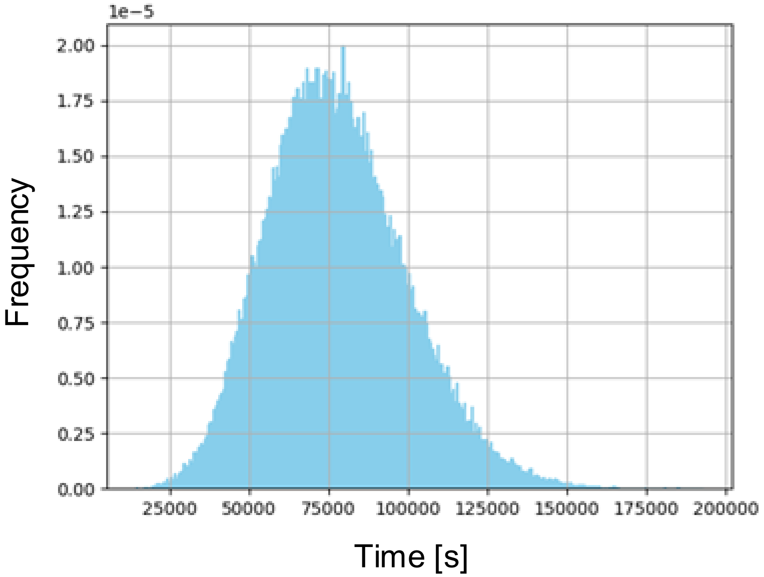
| $T$ | $< a >$ | $\sigma_a$ | $D_0$ | $E_a$ |
|---|---|---|---|---|
| $1873\ K$ | $7\ \mu m$ | $1\ \mu m$ | $0{,}024871\ cm^2/s$ | $92{,}2436\ kcal/mol$ |

$D_{0,p}$ between $10^{10}$ cm²/s (“slow”) and $10^{20}$ cm²/s (“fast”).

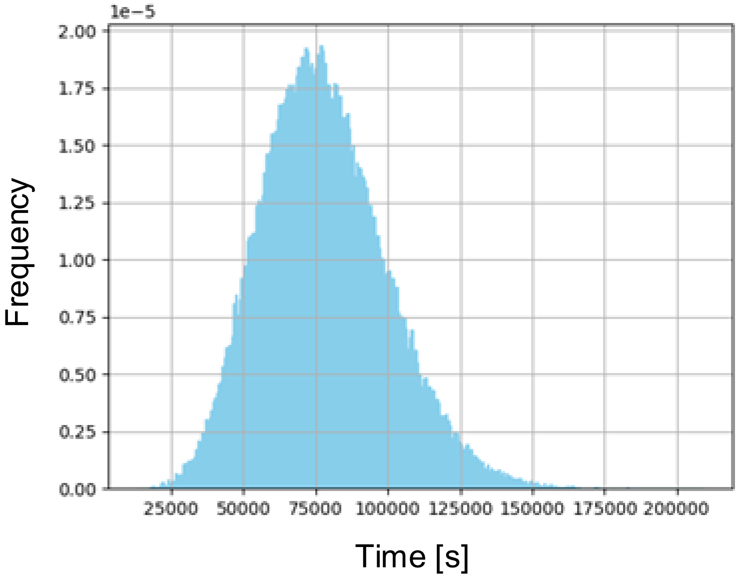
Sticking times < 1 ms: neglected.

- ➢ No significant difference between discs and target configuration
- ➢ $\langle t \rangle_{eff}$ < 1 s, $\langle t \rangle_{diff,p}$ << 1 s
- ➢ **$\langle t \rangle_{diff}$ = 21.6 h** dramatically high even in porous target and **comparable with $t_{1/2}$**

Fast release, disk 1




Fast release, disk 2



# Diffusion and effusion of $^{28}$Mg improved

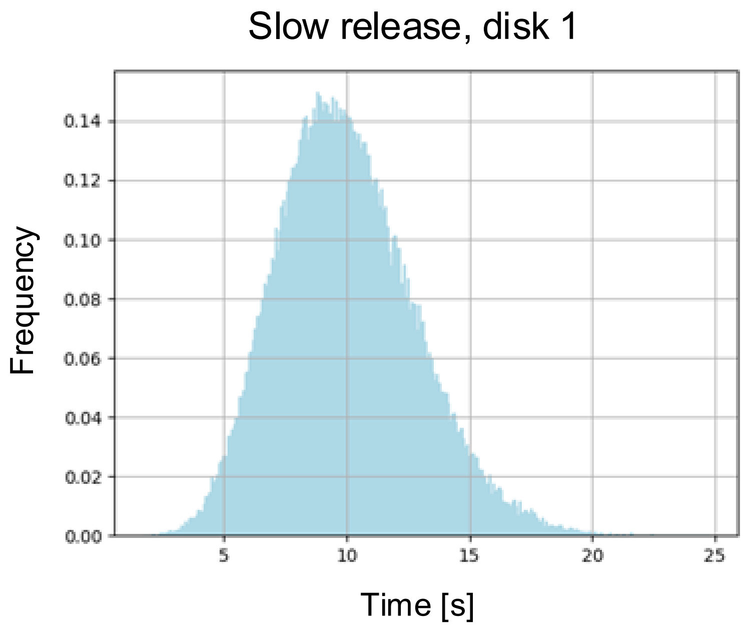
A suitable release could be obtained by slightly improving

- **grain size** (reduction by 1 order of magnitude)
- **thermal resistance** (up to 2000 °C)

| $T$ | $<a>$ | $\sigma_a$ | $D_0$ | $E_a$ |
|---|---|---|---|---|
| $2273\ K$ | $0.7\ \mu m$ | $0.1\ \mu m$ | $0,024871\ cm^2/s$ | $92,2436\ kcal/mol$ |

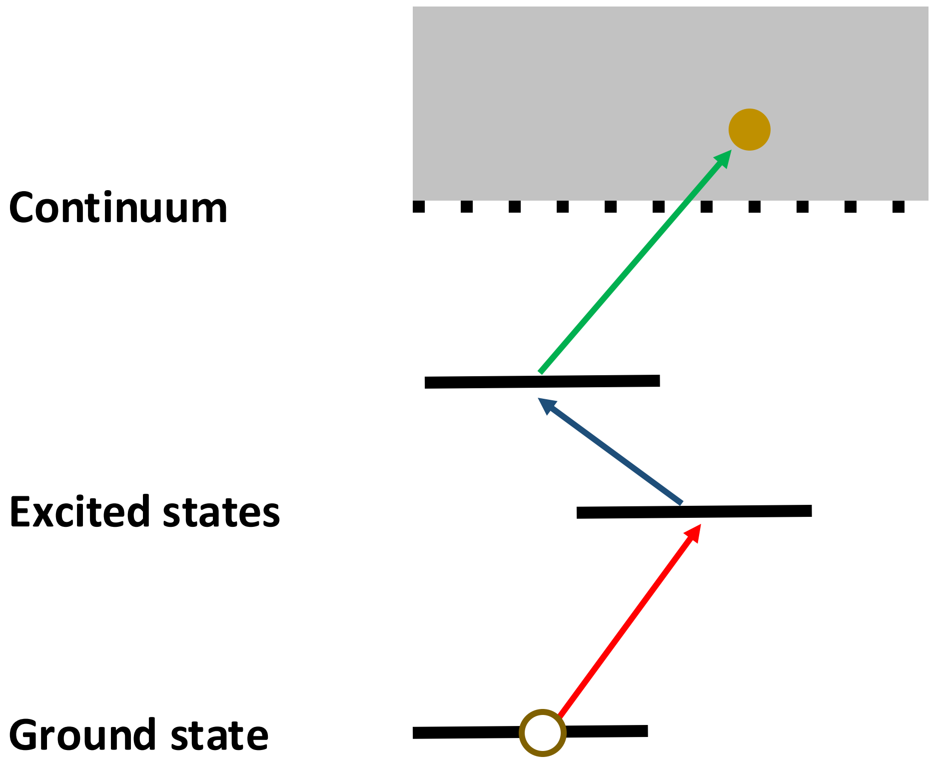
In this way:

- **⟨*t*⟩ = 9.961(3) s** in the small target
- **⟨*t*⟩ = 10.271(3) s** in the big target



# Photo-ionization in the SPES LIS

- ➢**Level population dynamics** of a laser photo-ionization scheme studied with the quantum **density matrix**
- ➢This, combined with a **volume factor** *η*, gives the **single-pulse ionization efficiency** of the photon-atom interaction, *ε*
- ➢Global **photo-ionization rate** obtained multiplying *ε* times the laser **pulse rate** *r*



# Photo-ionization scheme

**Populations**

$$\dot\rho_{11}(t) = -\frac{i}{2}\,\Omega_{21}(t)\,\rho_{12}(t) + \frac{i}{2}\,\Omega_{12}(t)\,\rho_{21}(t) + 2(A_{21}\,\rho_{22}(t) + A_{31}\,\rho_{33}(t)),$$

$$\dot\rho_{22}(t) = -\frac{i}{2}\,\Omega_{12}(t)\,\rho_{21}(t) + \frac{i}{2}\,\Omega_{21}(t)\,\rho_{12}(t) - \frac{i}{2}\,\Omega_{32}(t)\,\rho_{23}(t) + \frac{i}{2}\,\Omega_{23}(t)\,\rho_{32}(t) + 2A_{32}\,\rho_{33}(t) - 2A_{21}\,\rho_{22}(t),$$

$$\dot\rho_{33}(t) = -\frac{i}{2}\,\Omega_{23}(t)\,\rho_{32}(t) + \frac{i}{2}\,\Omega_{32}(t)\,\rho_{23}(t) - 2(A_{32} + A_{31} + \gamma_i(t))\,\rho_{33}(t),$$

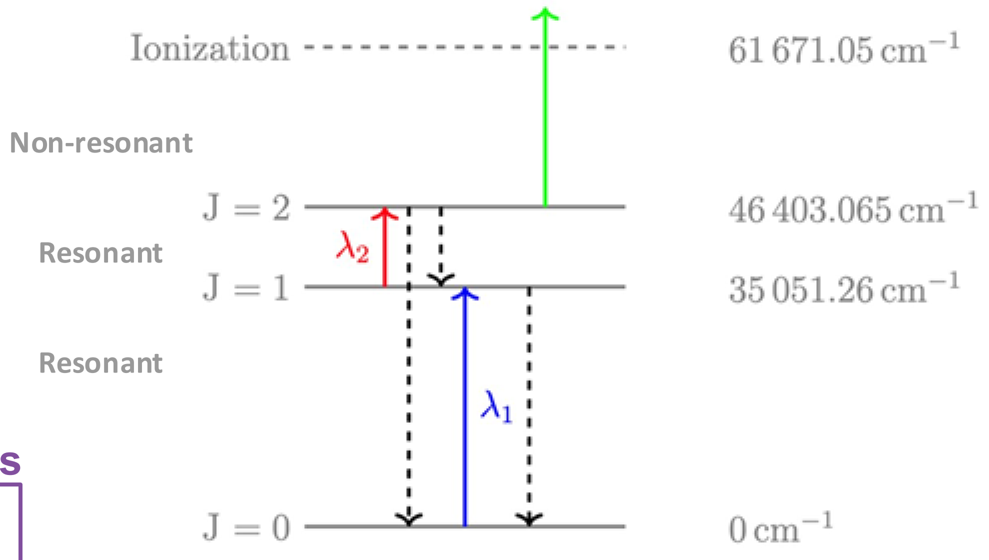
$$\dot\rho_{\mathrm{ion}}(t) = 2\,\gamma_i(t)\,\rho_{33}(t).$$

**Coherences**

$$\dot\rho_{12}(t) = \frac{i}{2}\,\Omega_{12}(t)\,(\rho_{22}(t) - \rho_{11}(t)) - \frac{i}{2}\,\Omega_{32}(t)\,\rho_{13}(t) - \left(i\Delta_1 + A_{21} + A_{32} + A_{31} + 2\gamma_{L1}\right)\rho_{12}(t),$$

$$\dot\rho_{23}(t) = \frac{i}{2}\,\Omega_{23}(t)\,(\rho_{33}(t) - \rho_{22}(t)) - \frac{i}{2}\,\Omega_{21}(t)\,\rho_{13}(t) - \left(i\Delta_2 + A_{21} + A_{32} + A_{31} + \gamma_i(t) + 2\gamma_{L2}\right)\rho_{23}(t),$$

$$\dot\rho_{13}(t) = \frac{i}{2}\,\Omega_{12}(t)\,\rho_{23}(t) - \frac{i}{2}\,\Omega_{23}(t)\,\rho_{12}(t) - \left(i(\Delta_1 + \Delta_2) + A_{21} + A_{32} + A_{31} + \gamma_i(t) + 2\gamma_{L1} + 2\gamma_{L2}\right)\rho_{13}(t).$$

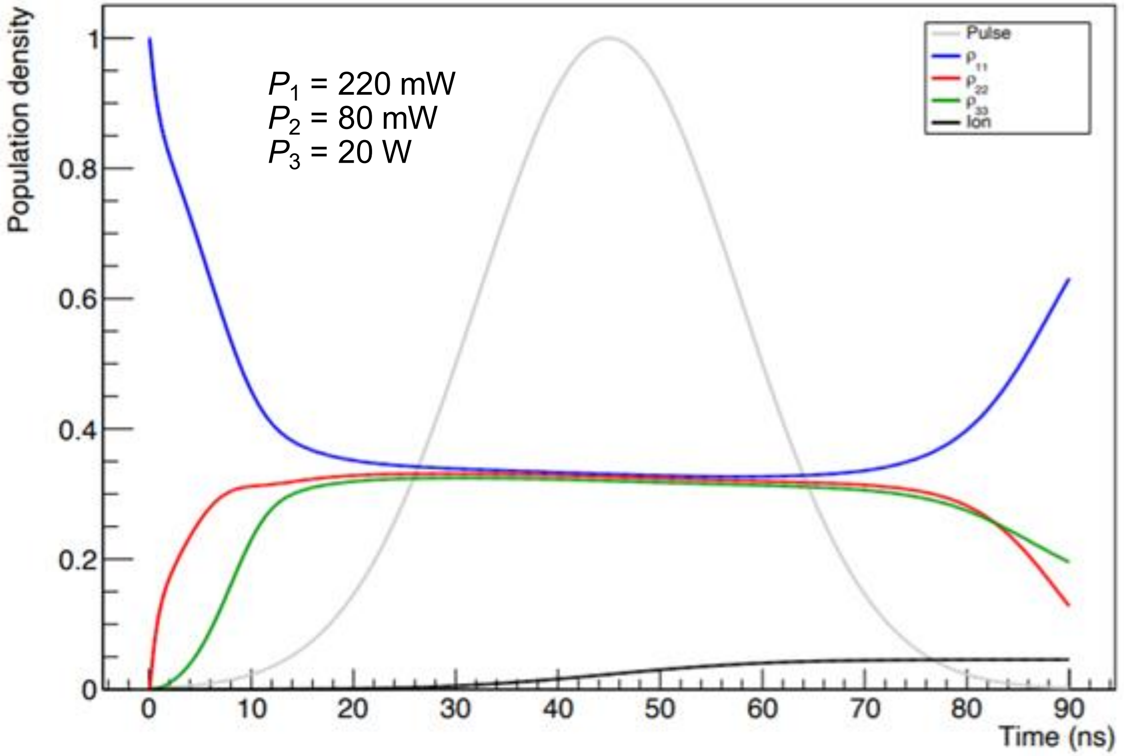



$A_{ji}$ : *Einstein coefficients* (decay rates)

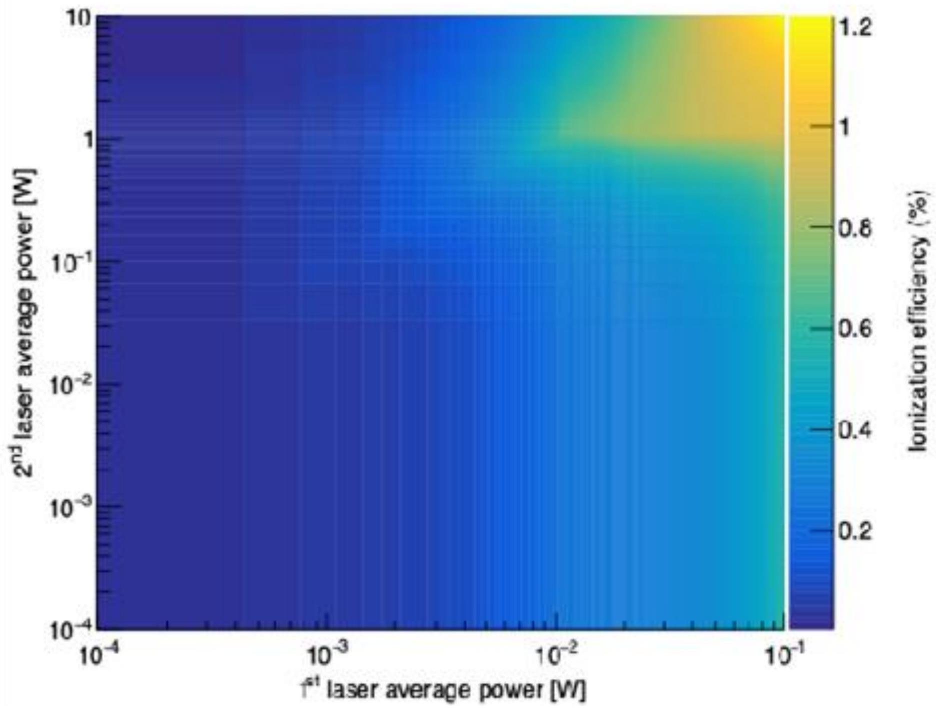
$\Omega_{ij}$ : *Rabi frequencies* (oscillation frequencies between levels, $\propto P^{1/2}$)

$\gamma_i$ : non-resonant ionization rate ($\propto P$)

# Photo-ionization efficiency




$t = t_{sat}$




With powers reachable in the SPES Online Laser Lab:

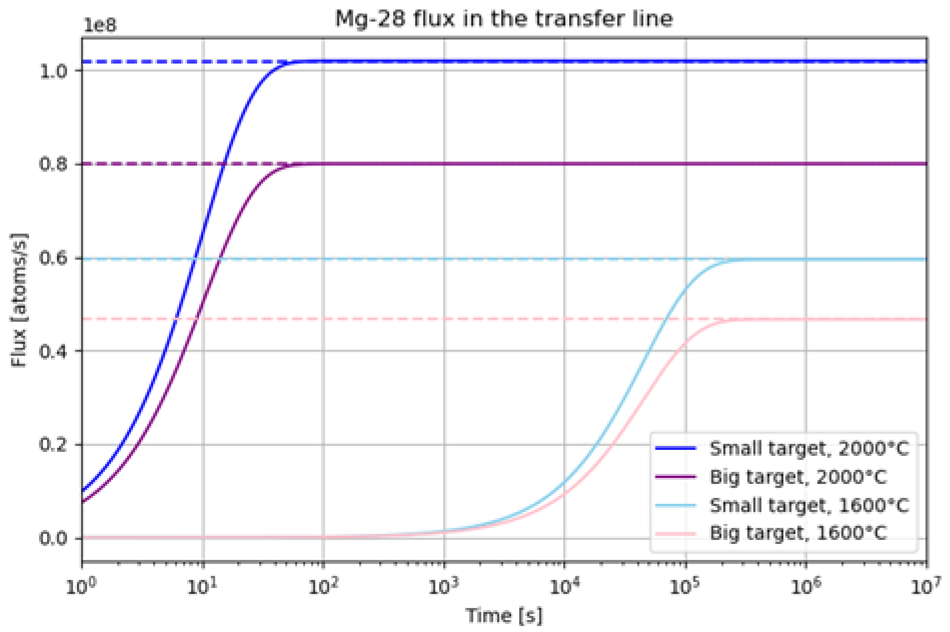
$$\varepsilon = \rho_{\mathrm{ion}}(t_{\mathrm{sat}}) \cdot \eta \sim 1\%$$

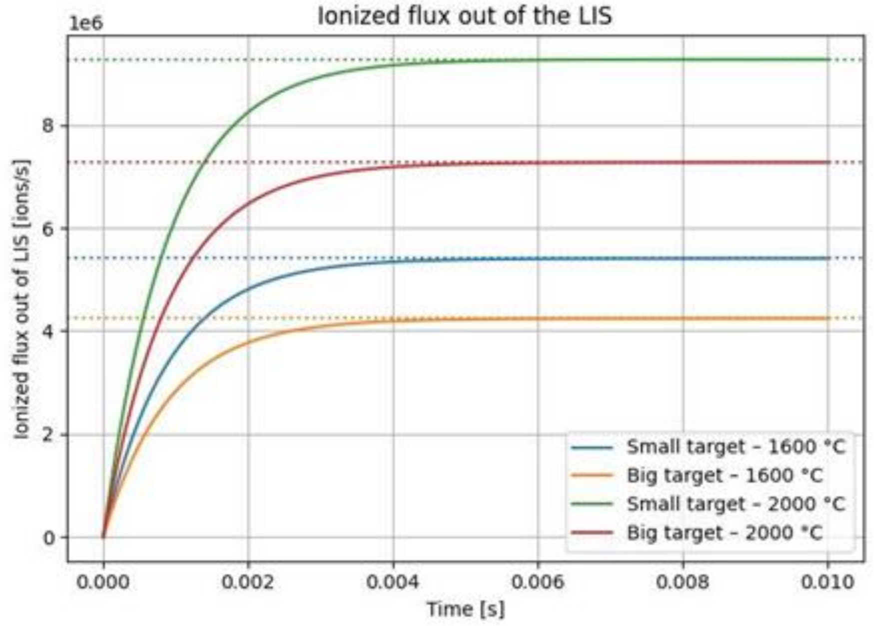
$\eta$ ~ 0.2 is the ratio between the **laser interaction volume** and the SPES LIS. This is a good result, as $r = 10^4\ \mathrm{s}^{-1}$.

A Arzenton et al 2025

# Overall ion flux

- ➢ $^{28}$**Mg flux in the transfer line** becomes steady in an acceptable time only at high *T*
- ➢ Once the steady state in the transfer-line flux is achieved, the **ion flux** from the LIS becomes steady in a negligible time
- ➢ The steady state of the ion flux is strongly **influenced by the loss rate** (here $10^3$ s$^{-1}$), which is tunable with experimental data
- ➢ Under this assumption, **~ 0.3 MBq** would be produced in **1h**



# Conclusions

- **Theoretical workflow** developed, needs experimental validation
- New **Mg laser photo-ionization scheme** proposed
- The production of $^{28}$**Mg** is critically **hindered by diffusion in grains**
- According to calculations, SiC targets with slightly smaller grain size and higher thermal resistance could produce $^{28}$Mg

# Thank you!