Numerical Calculations Of Gas Flows In COMSOL Multiphysics For Nuclear Structure Studies

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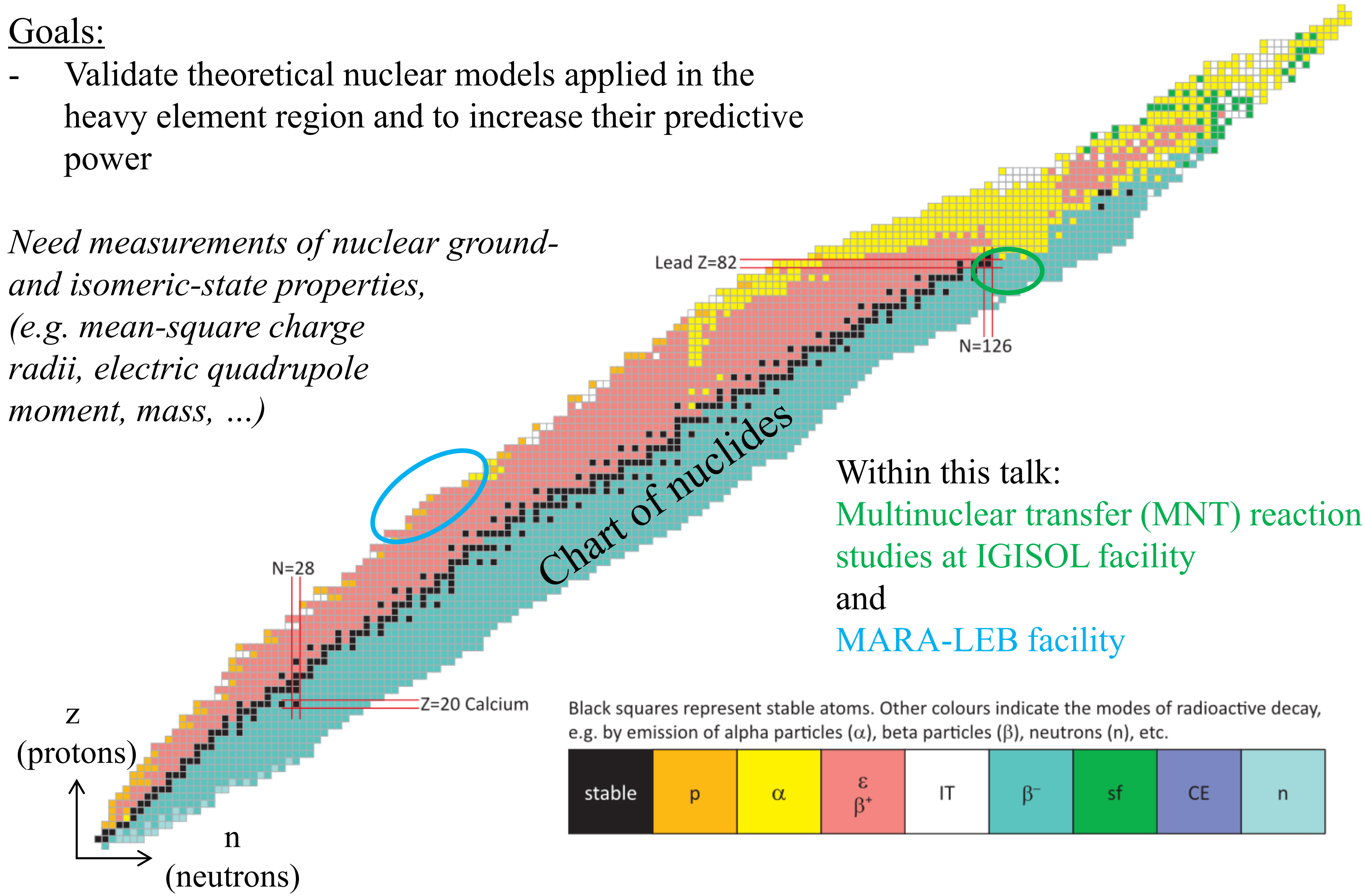
Outline

- Nuclear structure studies: motivation and goals
- Gas cells and supersonic jets in nuclear physics
- Gas cell design:
    - geometry optimization for high efficiency and fast transport
    - numerical calculations vs. measurements
    - experimental results with gas cell designed in CDF Module
- Supersonic gas jets:
    - ion transport by supersonic gas flow *and by electrical fields*
- Conclusions and Outlook

Motivation and goals

Goals:
- Validate theoretical nuclear models applied in the heavy element region and to increase their predictive power

Need measurements of nuclear ground- and isomeric-state properties, (e.g. mean-square charge radii, electric quadrupole moment, mass, ...)

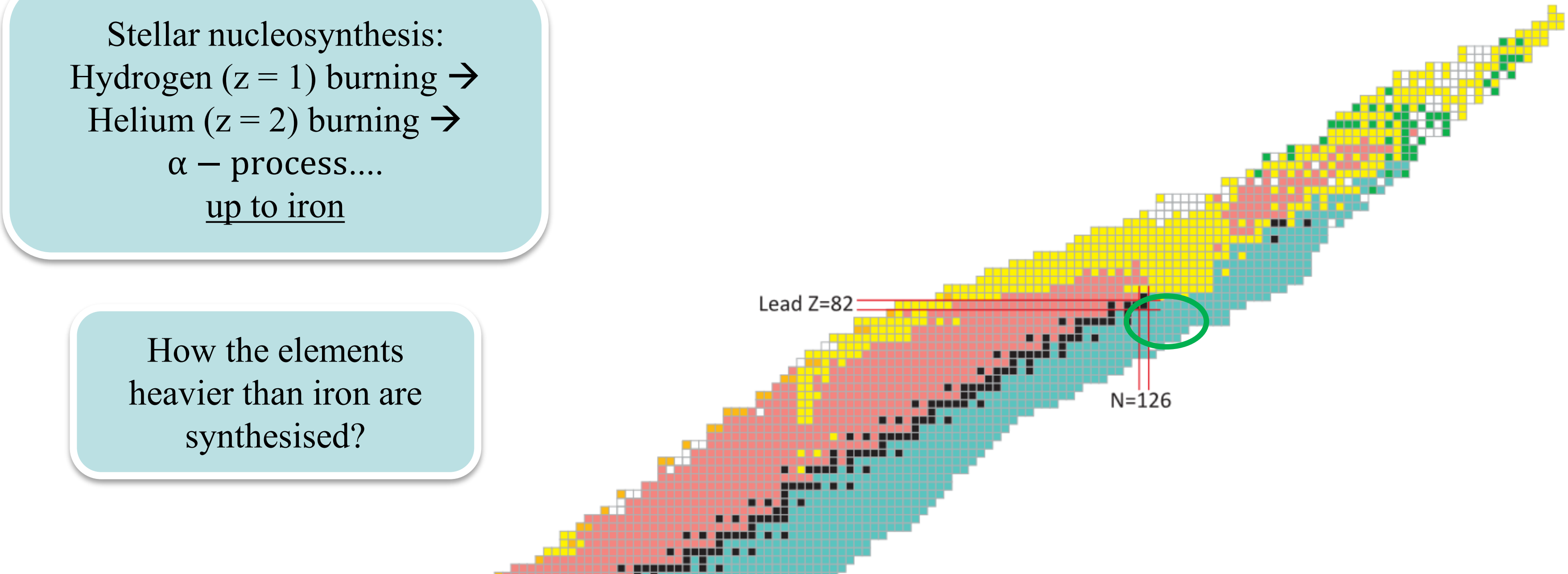


Within this talk:
Multinuclear transfer (MNT) reaction studies at IGISOL facility
and
MARA-LEB facility

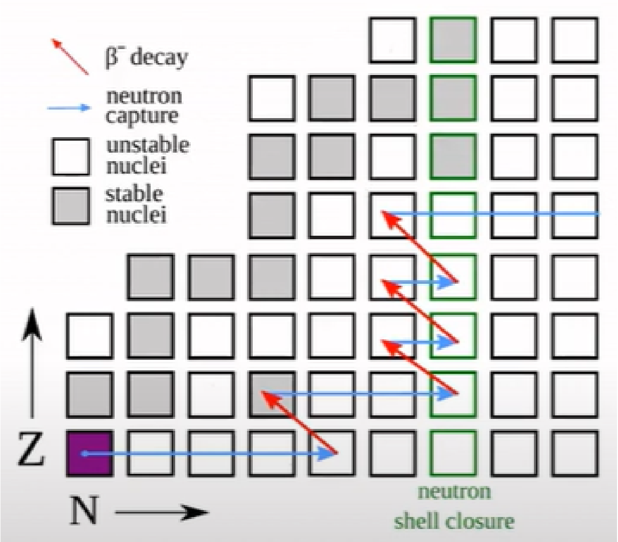
Z. Sóti, J. Magill and R. Dreher, EPJ Nuclear Sci. Technol. **5**, 6 (2019)

Stellar nucleosynthesis:
Hydrogen (z = 1) burning →
Helium (z = 2) burning →
α – process....
up to iron

How the elements heavier than iron are synthesised?



1957, B2FH paper (theory: heavy elements can be synthesized via **r-process**)
→ **2017, GW170817** a merger of two neutron stars (first confirmation)



Z. Sóti, J. Magill and R. Dreher, EPJ Nuclear Sci. Technol. 5, 6 (2019)
B2FH paper: M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle, Rev. Mod. Phys. 29, 547 (1957)

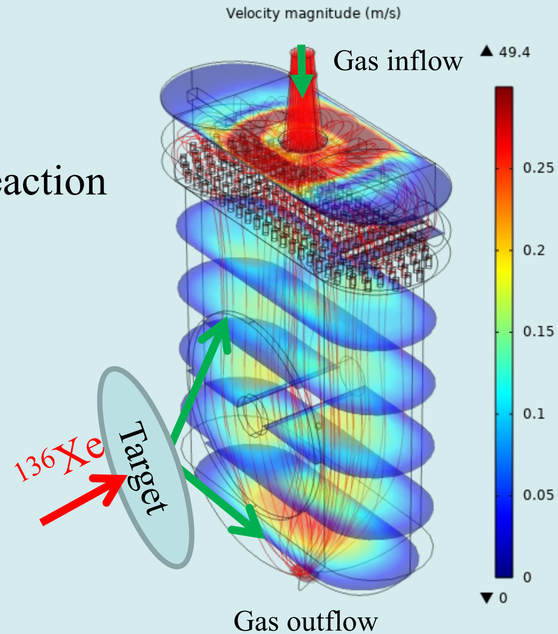
Gas cells and supersonic jets in nuclear physics

^{211}Po	^{215}Ac	^{100}Sn
$z = 84, n = 127$	$z = 89, n = 126$	$z = 50, n = 50$
$T_{1/2} = 0.516$ s	$T_{1/2} = 0.17$ s	$T_{1/2} = 1.18$ s

- Short half-lives and low production rates and often impose requirements to have highly sensitive, efficient and fast experimental technique

Gas cells filled noble gasses (subsonic helium/argon) used for:
- stopping
- thermalization
- (neutralization)
- transport of nuclear reaction products

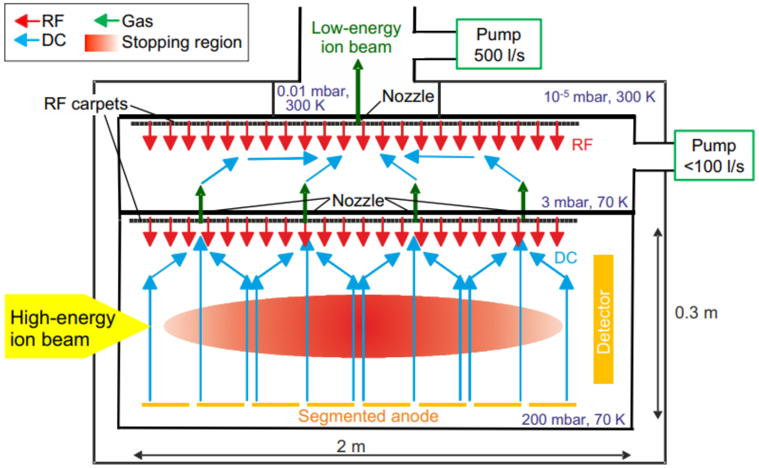
Requirements:
- evacuation time < 1 s
- efficiency against diffusion losses ~ 100%



MNT gas cell:
helium, room-temperature

Gas cell consisting of 2 chambers:
- transport by supersonic free jets between chambers

Requirements:
- jet does not disturb transport by elec. fields



HADO-CSC:
helium, cryogenic

T. Dickel et al., NIM B, 376 (2016) 216-220

Design of gas cell: MARA-LEB

Initial design: Institute for Nuclear and Radiation Physics, KU Leuven (Leuven, Belgium)

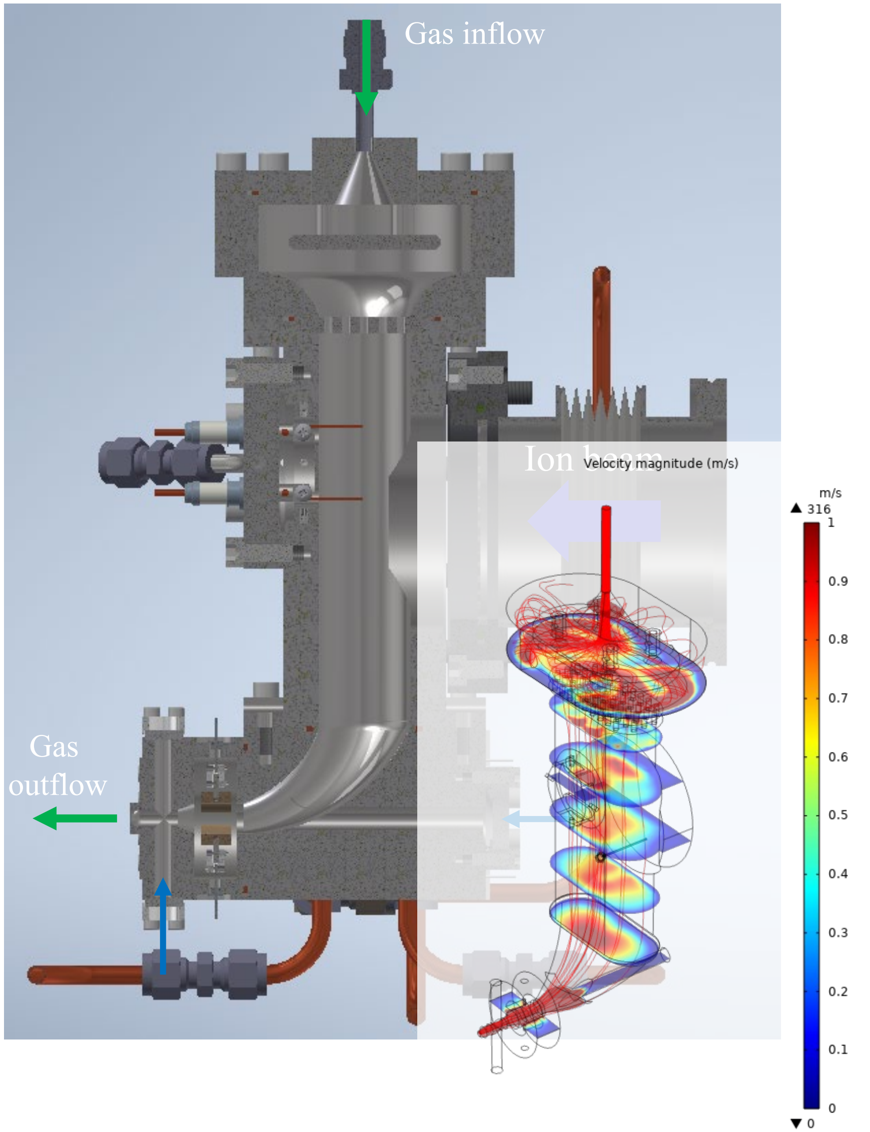
Gas cell commissioned (with minor modifications from the initial design) and in use at: S3-LEB (Caen, France) and **IGISOL (Jyvaskyla, Finland)** online facilities

- Nuclear reaction products:

1) stopped and neutralized in the gas cell filled with argon gas
2) selective laser ionization of elements of interest

→ argon as a buffer gas and the gas cell should consist of two chambers (not in a direct view one from another!)

Optimization of gas cell design was performed with numerical calculations in CFD Module



Yu. Kudryavtsev et al., NIM B, 376 (2016) 345-352

Design of gas cell: MNT

Initial design: **IGISOL (Jyvaskyla, Finland) facility**

Requirements:

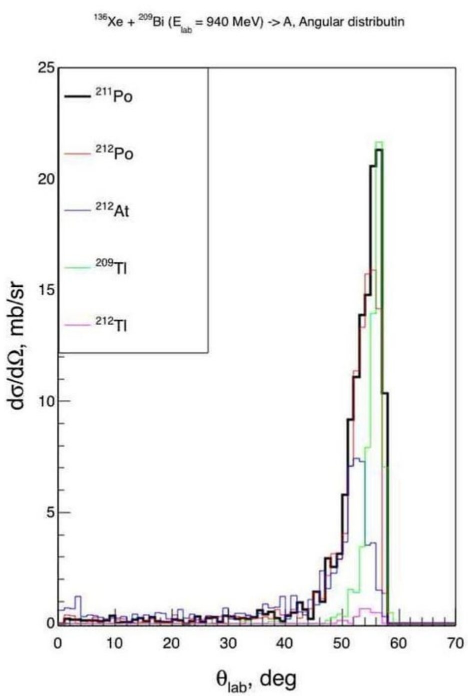
- MNT reaction products leave the target at large angles

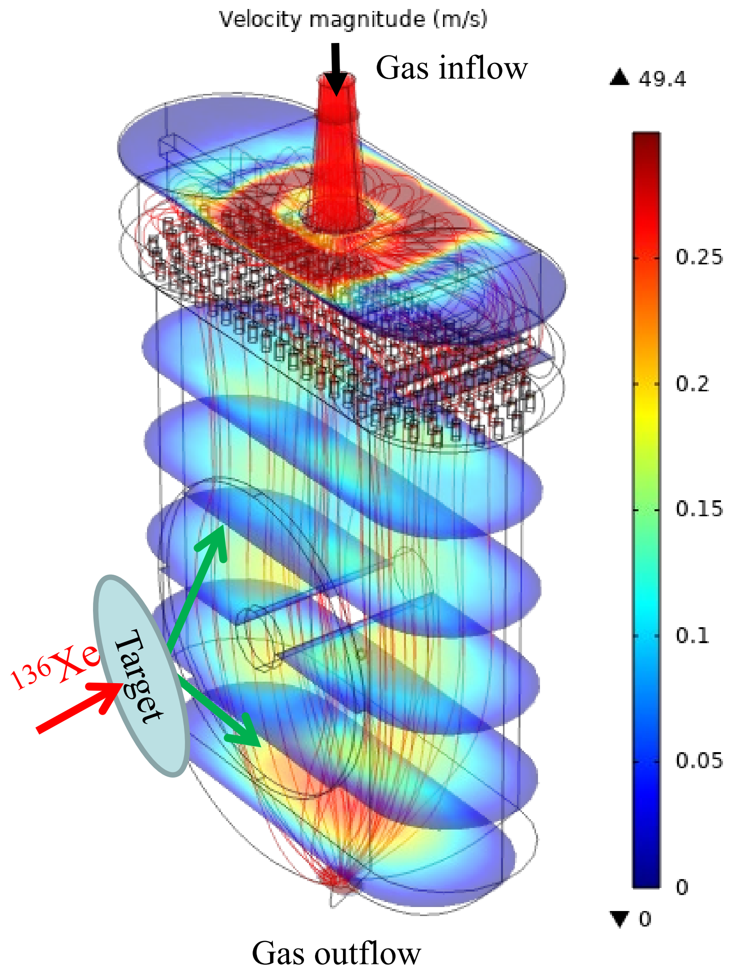
  → angular acceptance of up to 70 degrees
- Fast and efficient extraction of MNT reaction products from the gas cell

  → optimization in

CFD Module

Angular distribution for $^{136}Xe + ^{209}Bi$ reaction ($E_{lab.} = 940$ MeV) [by A.V.Karpov and V.V.Saiko]:

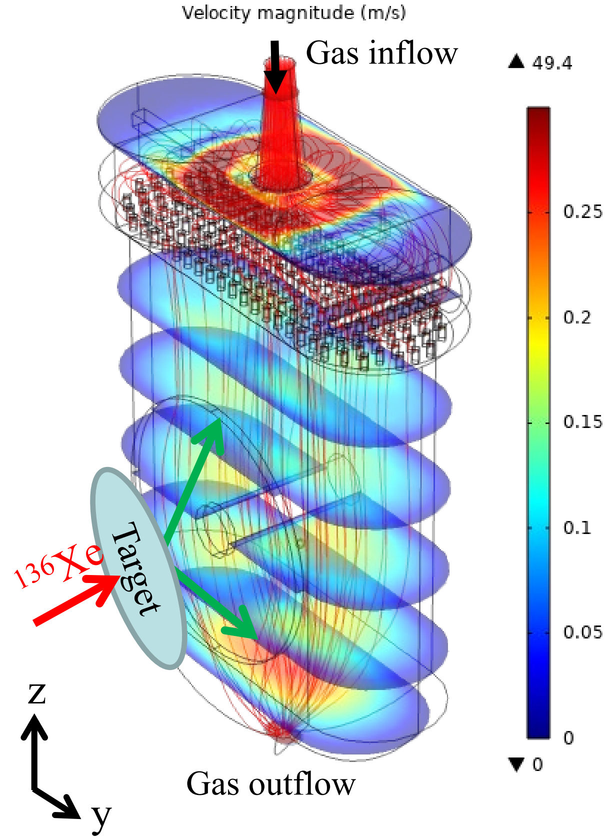




Challenge: larger gas cell → slower gas flow → evacuation time increases

Design of gas cells: MNT

- Optimization of gas cell design with numerical calculations in CFD Module of COMSOL Multiphysics



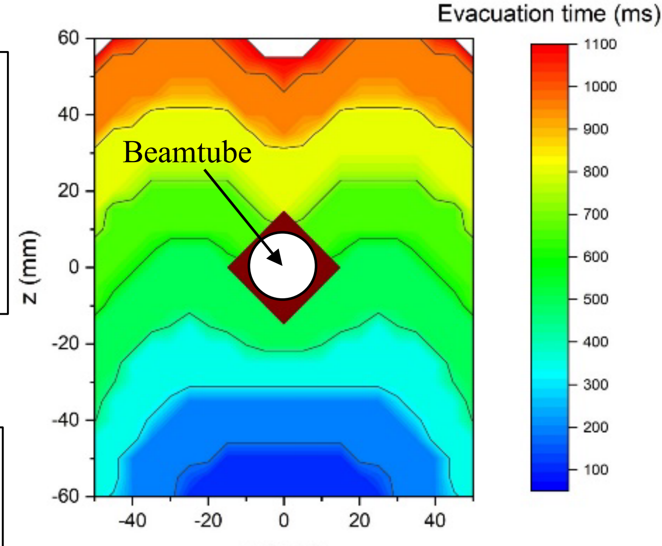
<u>Subsonic flow inside gas cells</u>

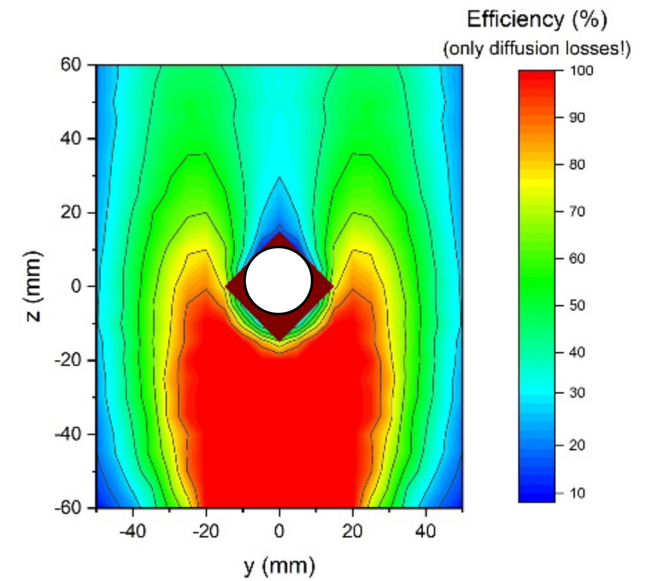
Laminar Flow:
compressible flow;
boundary conditions – no slip

<u>Evacuation time and efficiency for various starting points in the gas</u>

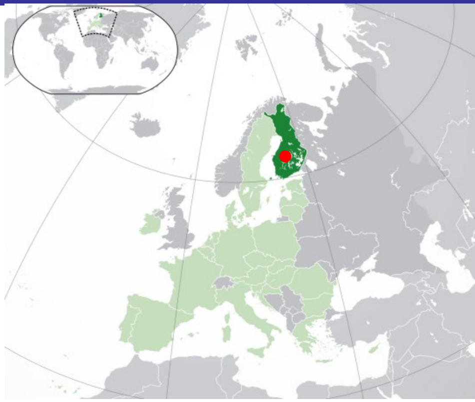
Transport of Diluted Species:
convection and diffusion.

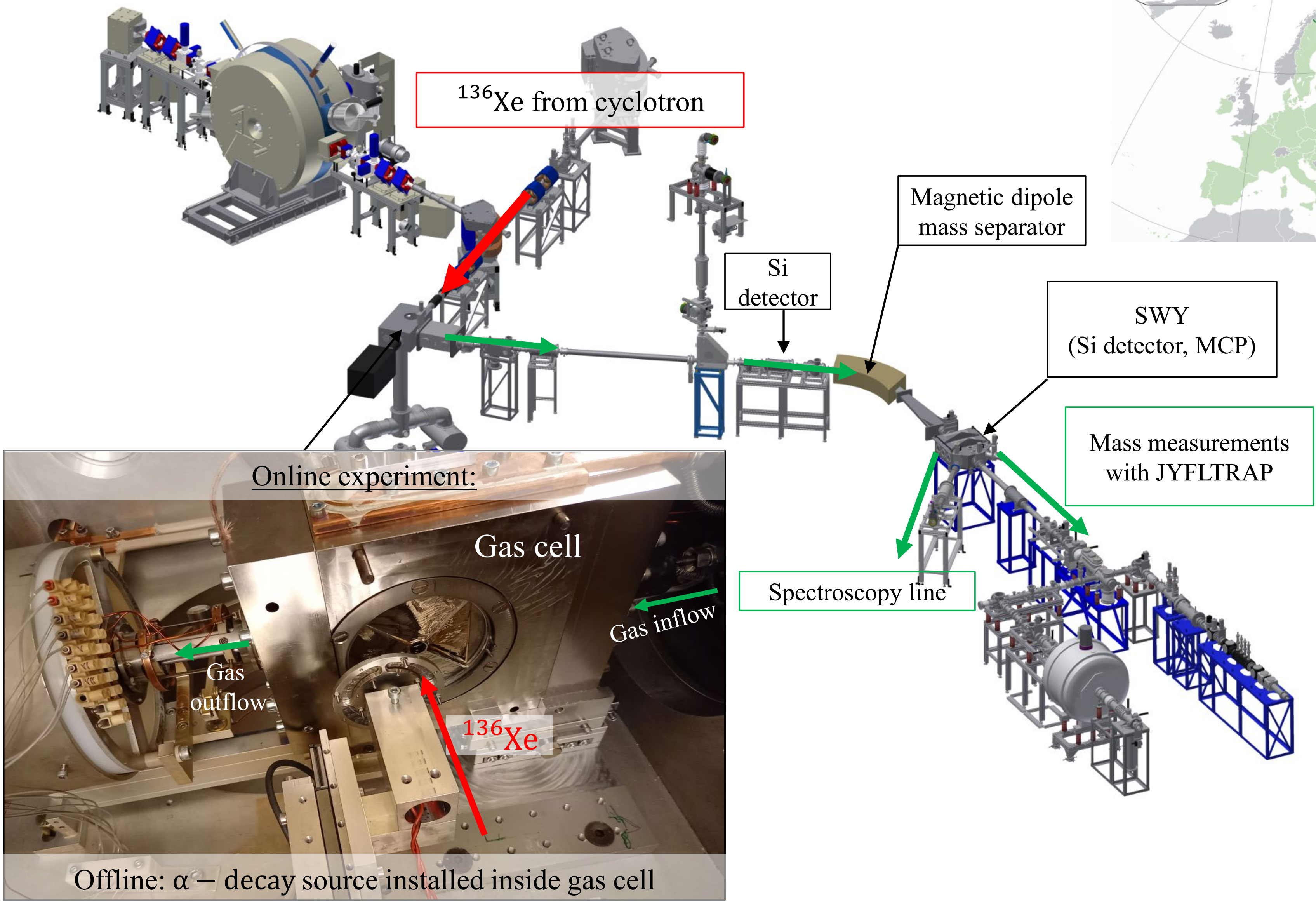
Gas: helium
Temperature $T_0 = 300$ K
Exit diameter of 1.2 mm





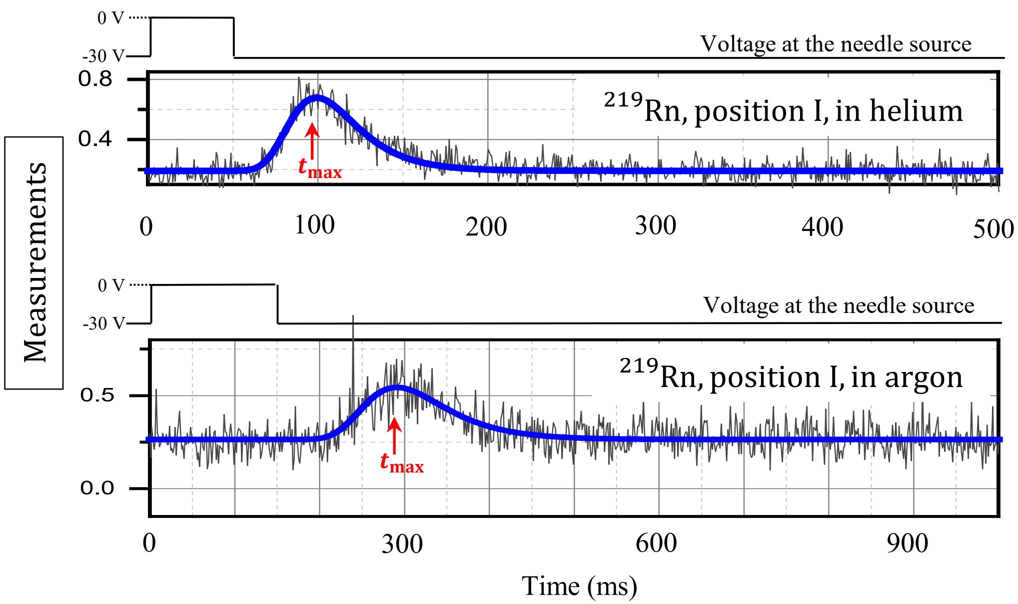
IGISOL facility (Jyvaskyla, Finland)

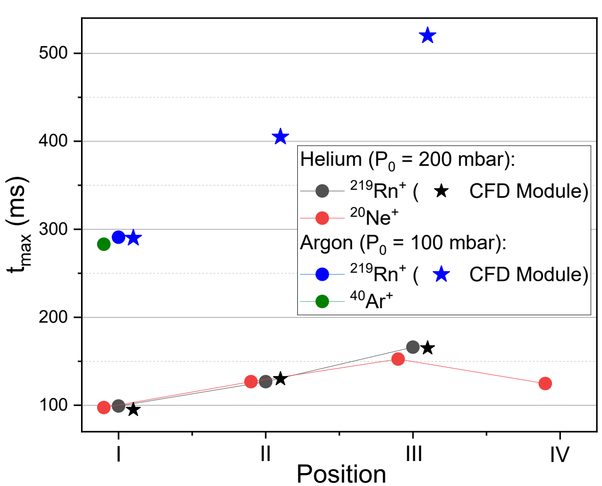




CFD Module vs. measurements: evacuation time

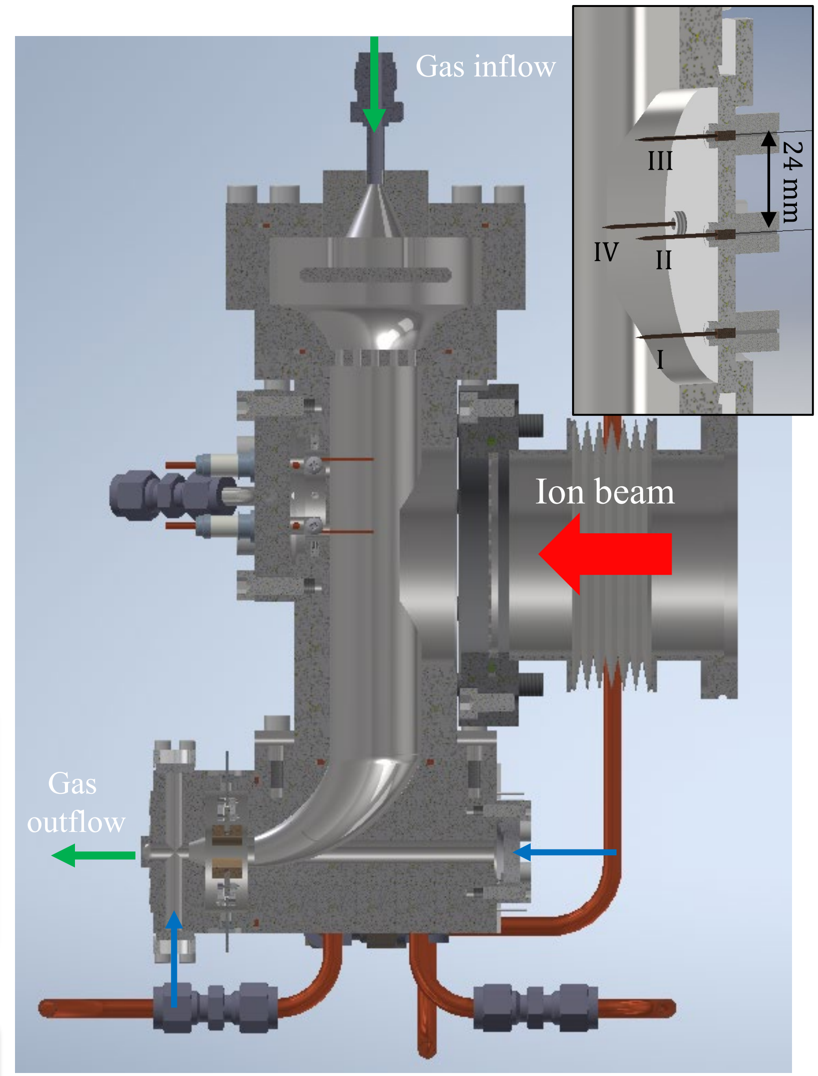
➢ MARA-LEB gas cell with 223Ra α – decay source





→ nice agreement between measurements and num. calculations in CFD Module for evacuation time

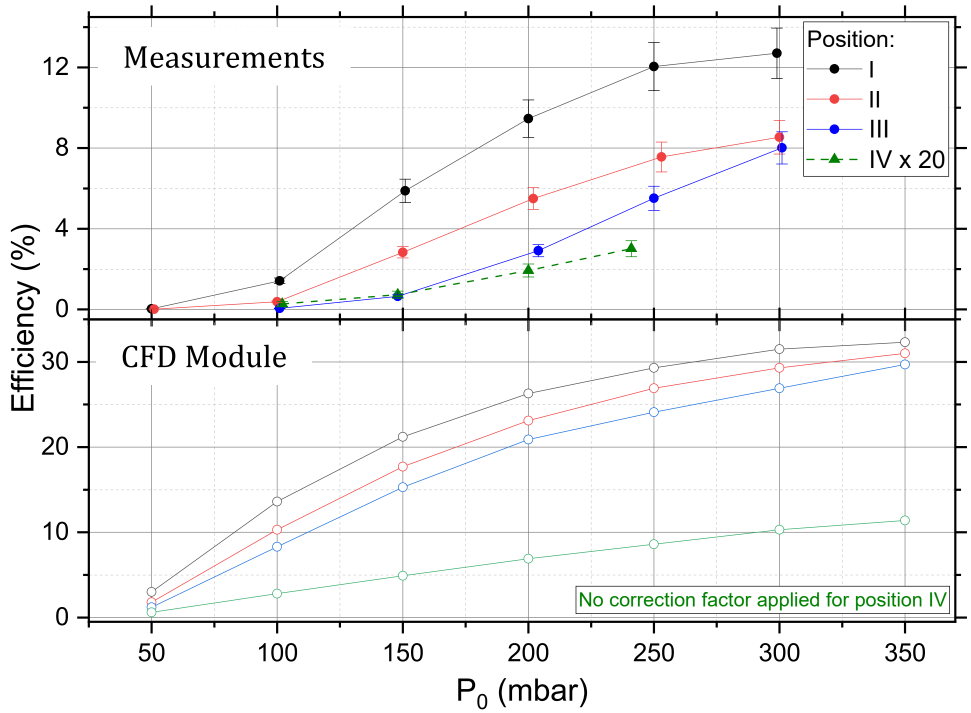
(the same for MNT gas cell)

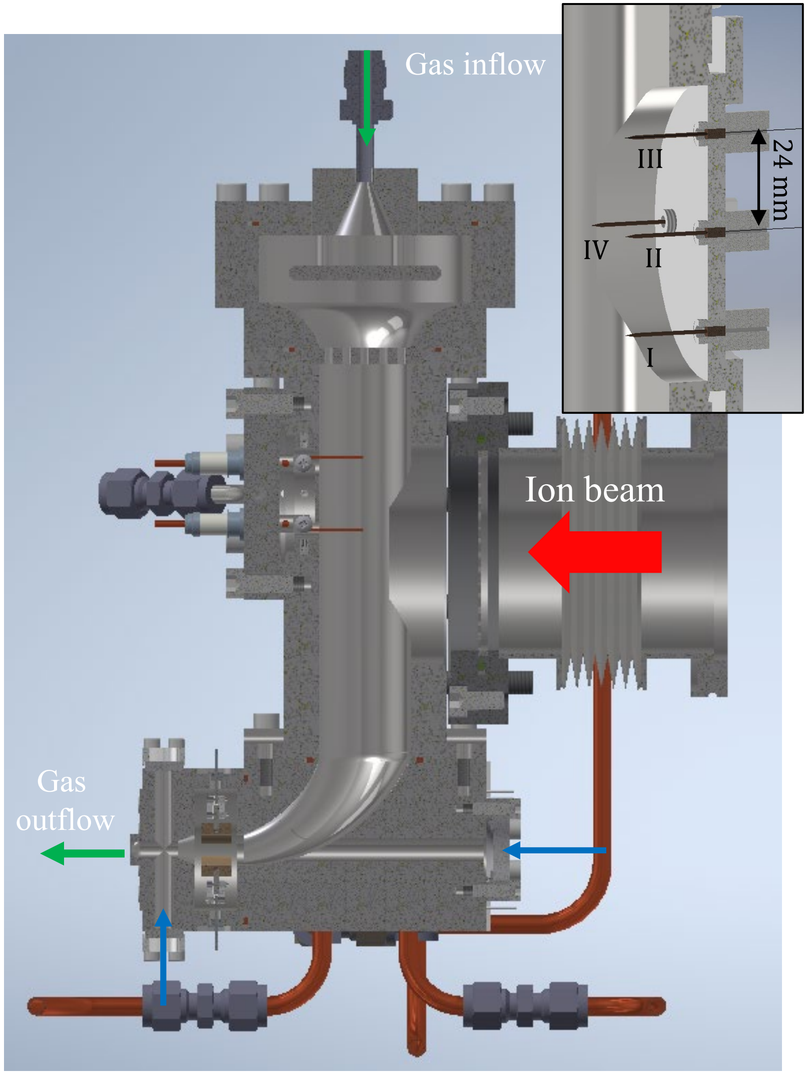


A. Zadvornaya et al., NIM B, 539 (2023) 33-42

CFD Module vs. measurements: efficiency

- MARA-LEB gas cell with ^{223}Ra α – decay source





→ general trends agree, but numerically there is a disagreement between measurements and num. calculations

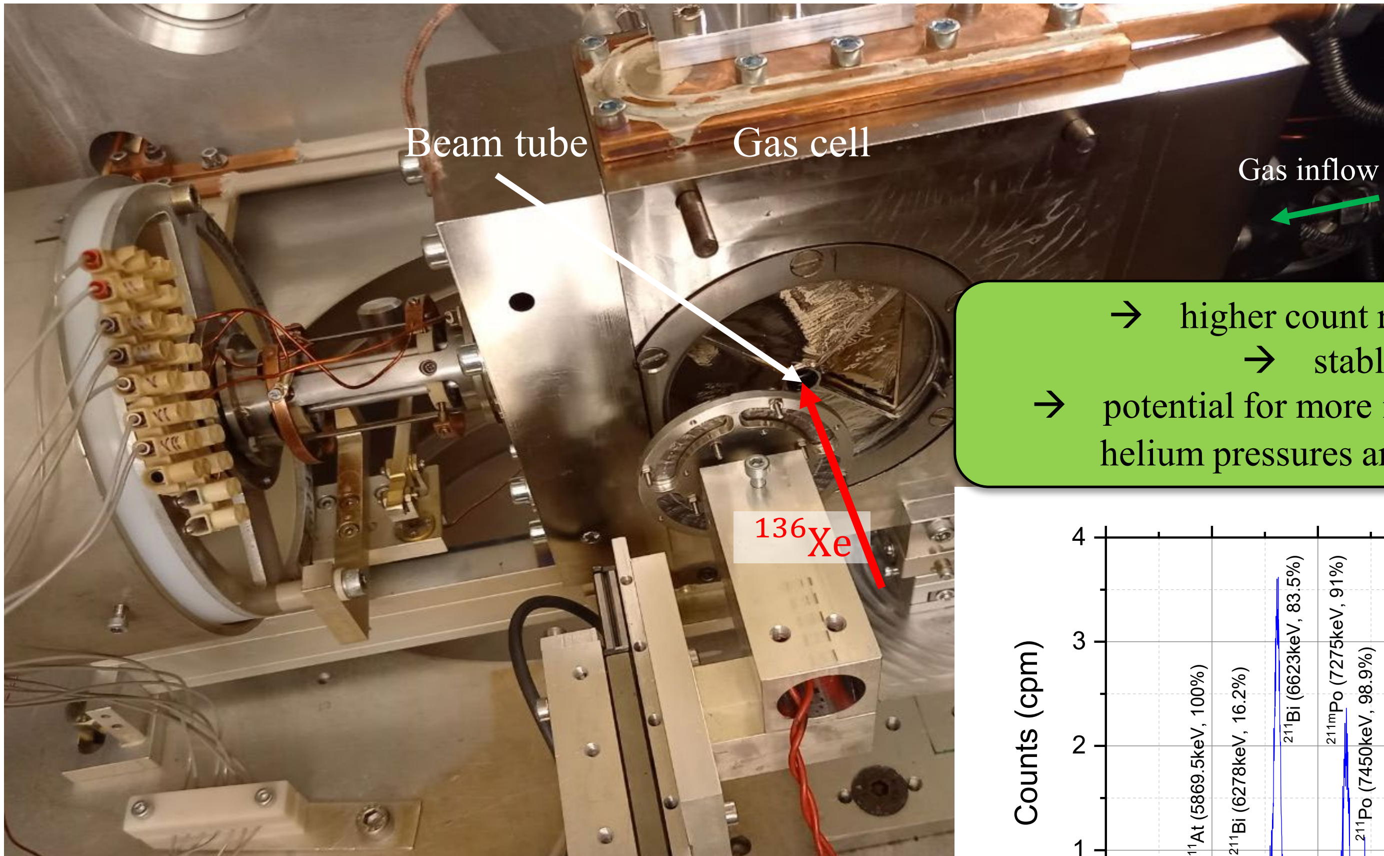
(the same for MNT gas cell)

Possible reasons are investigated. Probably, has to do with measurement geometry and/or with presence of remaining impurities in helium.

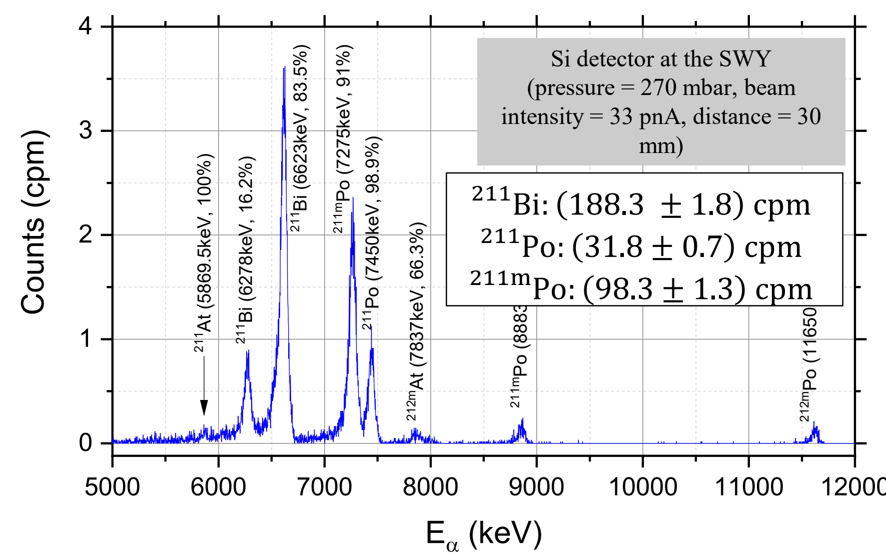
Online experiments with MNT gas cell

$$^{136}\text{Xe}\ (E = 945\ \text{MeV}) + {}^{209}\text{Bi}\left(\sim 5\ ^{\text{mg}}/_{\text{cm}^2}\right)$$

- ^{136}Xe beam with intensity up to 33 pnA
- Entrance window: Ø = 90 mm, nickel foil (5 µm thick)



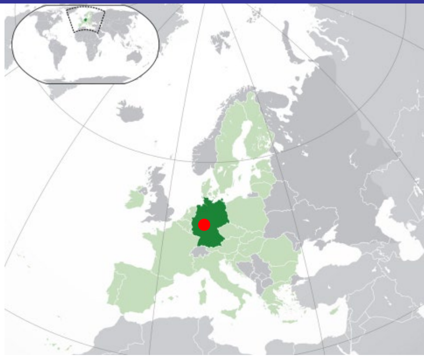
→ higher count rates by a factor of 3
→ stable operation
→ potential for more improvement with higher helium pressures and ^{136}Xe beam intensities

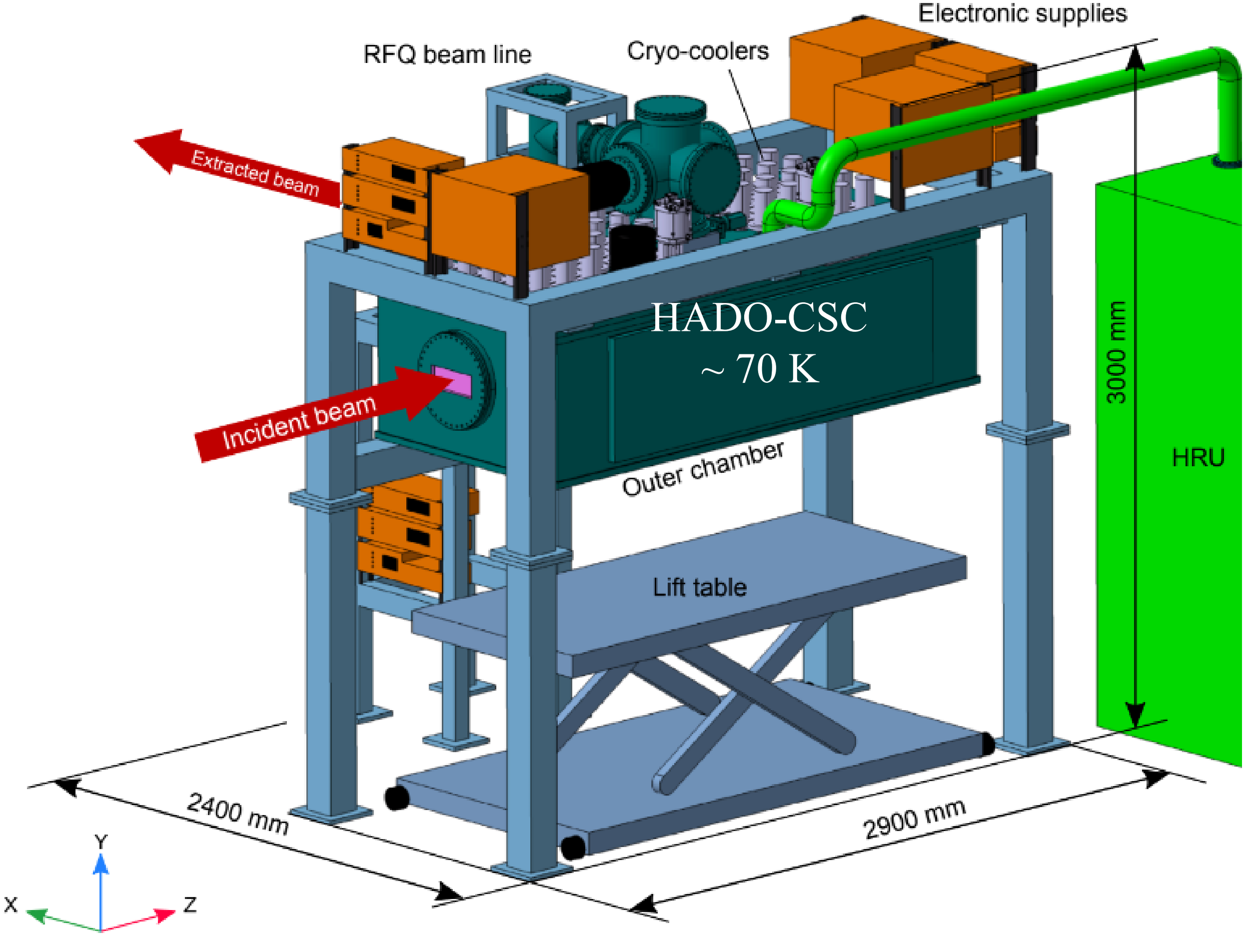


T. Dickel et al 2020 J. Phys.: Conf. Ser. 1668 012012
A. Spataru et al., Acta Phys. Pol. 51 (2020) 817

Supersonic gas jets in gas cell

HADO-CSC (high-areal-density orthogonal-extraction cryogenic stopping cell) for GSI facility

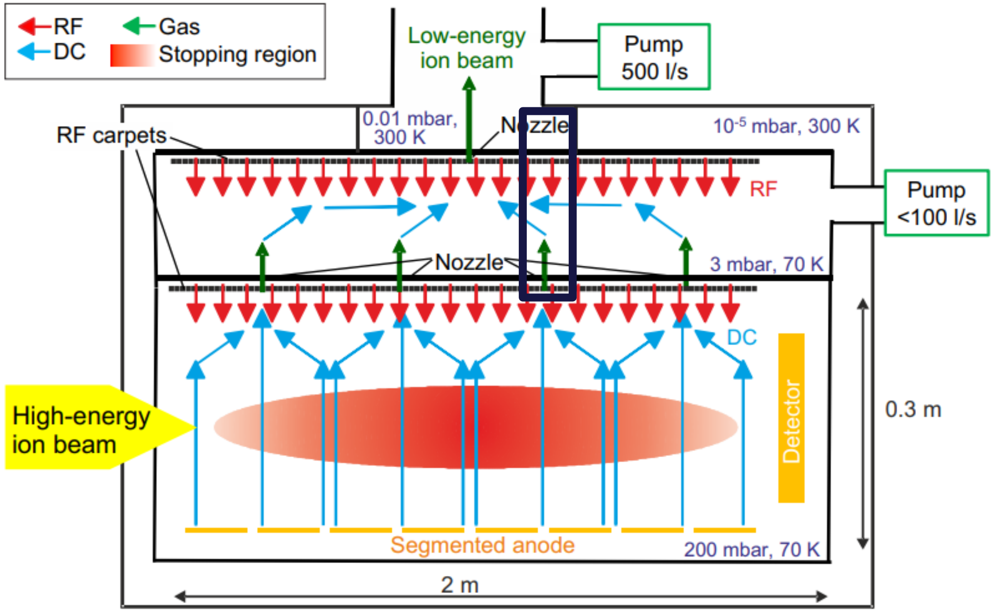


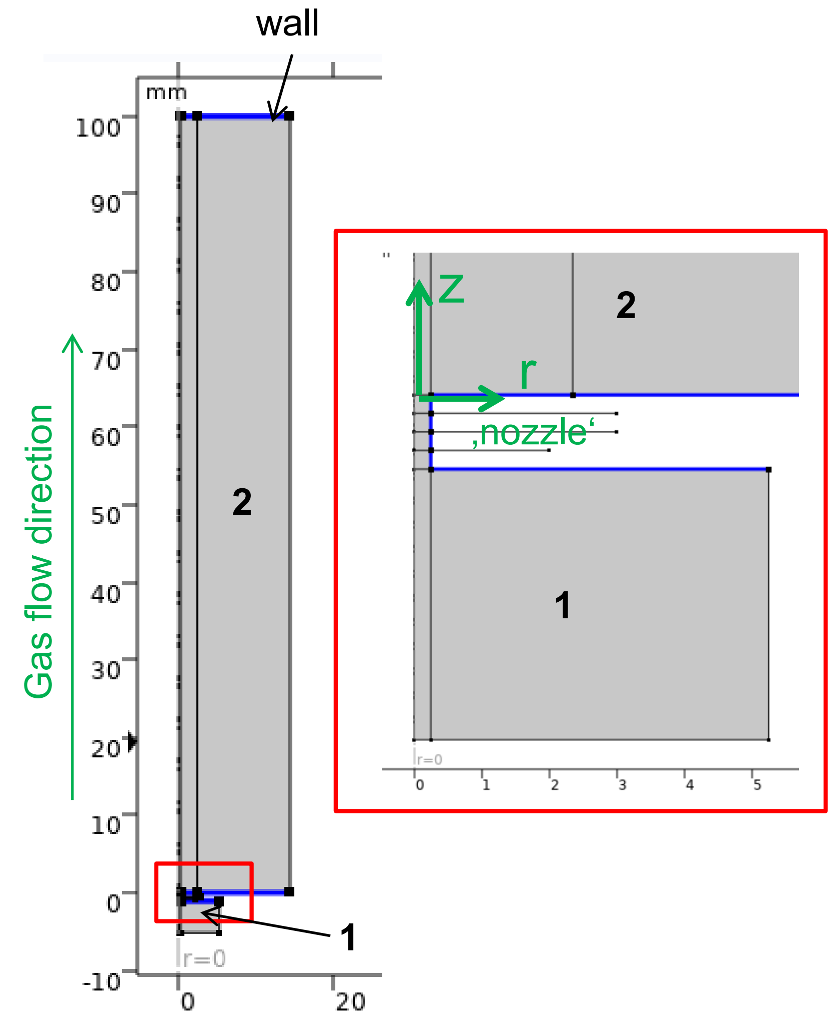


T. Dickel et al., NIM B, 376 (2016) 216-220

Supersonic gas jets in gas cell

HADO-CSC (high-areal-density orthogonal-extraction cryogenic stopping cell)

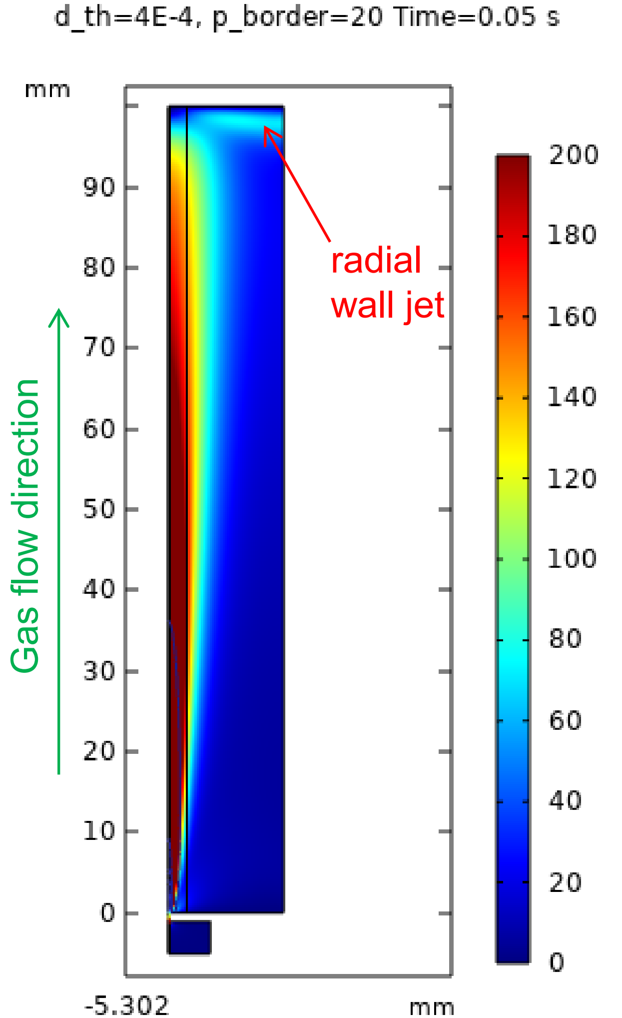


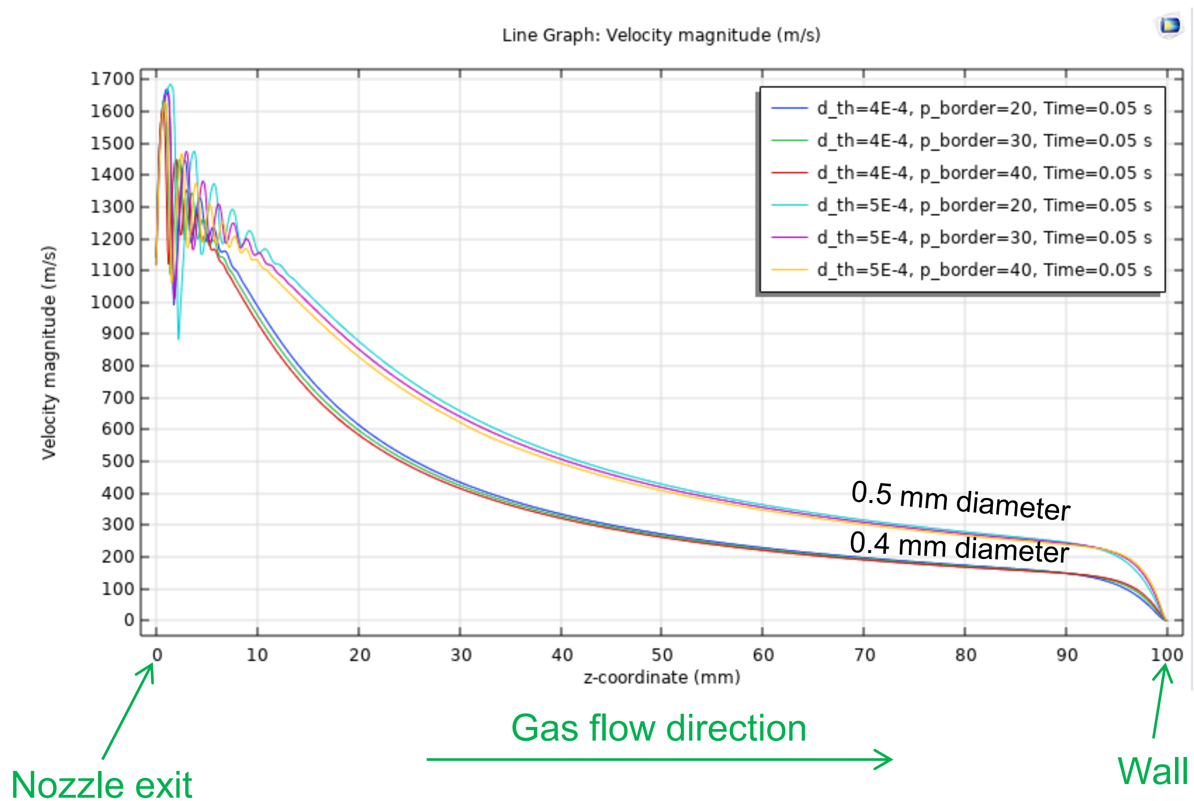


<u>Supersonic free jets inside gas cell</u>

High Mach Number Flow:
Turbulence model type: none
Wall condition: no slip
Inlet ← pressure
Outlet ← static pressure (flow condition = hybrid)
Axial symmetry
User-controlled mesh: rather fine mesh (~0.1 mm)

Supersonic gas jets in gas cell





Conclusions and Outlook

- Subsonic gas flows are used for stopping, thermalization, (neutralization) and transport of nuclear reaction products . Therefore, optimization of gas cells geometry is required

- Gas cells designed in CFD Module of COMSOL Multiphysics are used at a number of online facilities

- Offline experiments using ^{223}Ra α-decay source with gas cells designed in CFD Module:
  - ➢ Evacuation time: numerical calculations and measurements showed good agreement
  - ➢ Efficiency: some discrepancy, but there is a couple of possible reasons to be investigated

- Online experiments with gas cells designed in CFD Module:
  - ➢ MNT reaction studies:

    MNT products can be produced, slowed down, extracted and studied at the IGISOL facility with the MNT gas cell. A higher count rate and stable operation was achieved.
  - ➢ MARA-LEB facility:

    the facility is under construction, online results are upcoming

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Thank you for attention!

Questions?