G-22-00117
In-cell MNT reactions at the FRS Ion Catcher

Paul Constantin *(spokesperson),* ***Timo Dickel*** *(co-spokesperson)*
and the ***Super-FRS Experiment Collaboration***

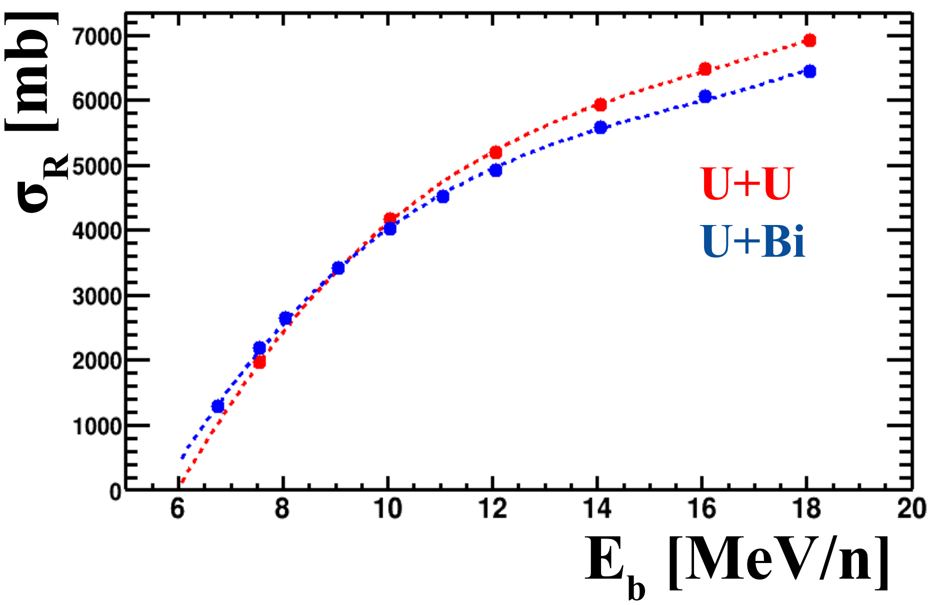
- **Long-term goal**: establish MNT reactions with slowed-down radioactive beams at the Super-FRS to produce
  - and measure heavy (A=190-260) neutron-rich isotopes.

- **Exploratory program**: in-cell MNT reactions with slowed-down ^{238}U beam on targets inside CSC @ FRS-IC
  1) proof-of-principle measurements: 5 shifts
  2) n-rich actinides from ^{238}U MNT: 8 shifts

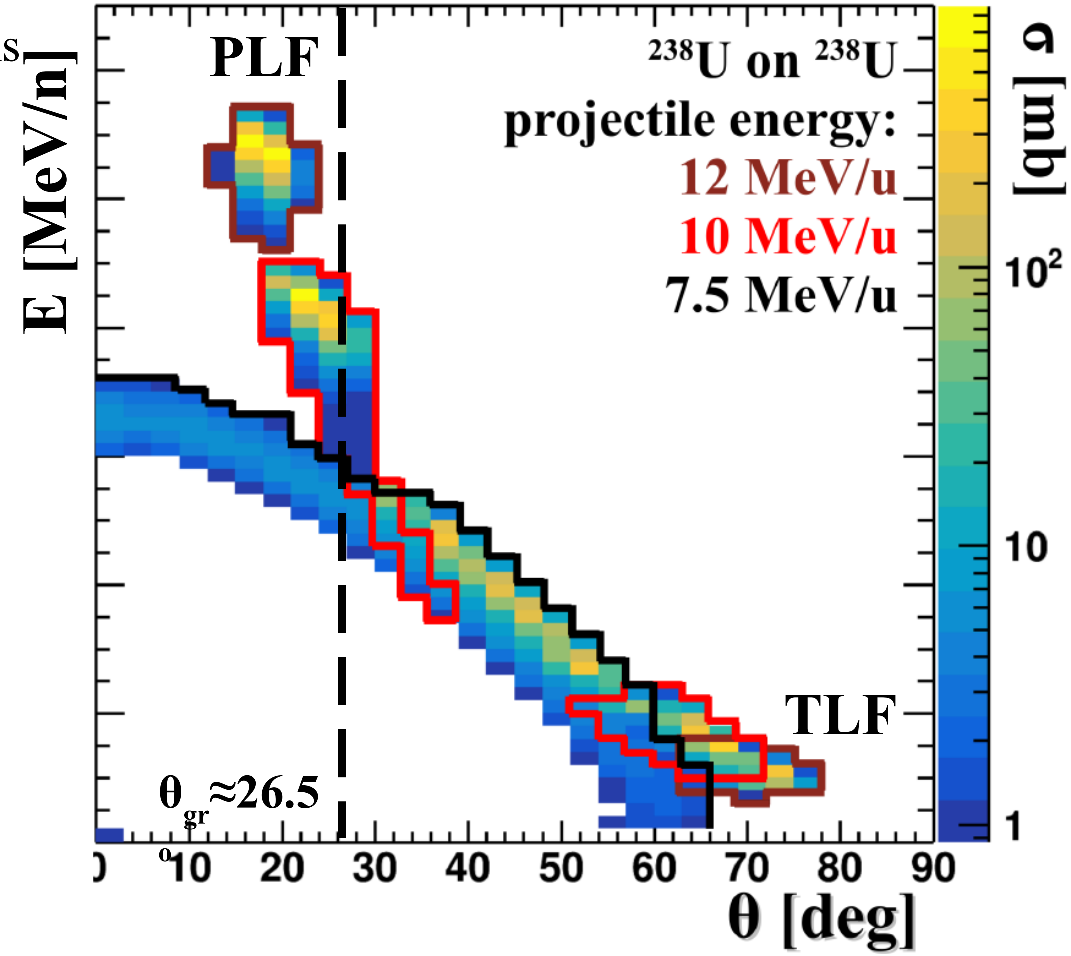
- **Expected challenges**:
  1) slow-down of relativistic beam to Coulomb barrier + fine focusing
  2) space charge effects in the gas cell
  3) high-density, high-purity gas cell

Beam slow-down and focusing

Langevin model (**Karpov & Saiko**):
– **adiabatic at $E_b \approx B_C$**: slow with large nuclear deformations
→ several nucleon transferred
→ broad kinematic (E, θ, A, Z) distributions
– multi-nucleon transfer: **$E_b = B_C + (1\text{-}2)$MeV/u**
– at high E_b (excitation): **high fission prob.**

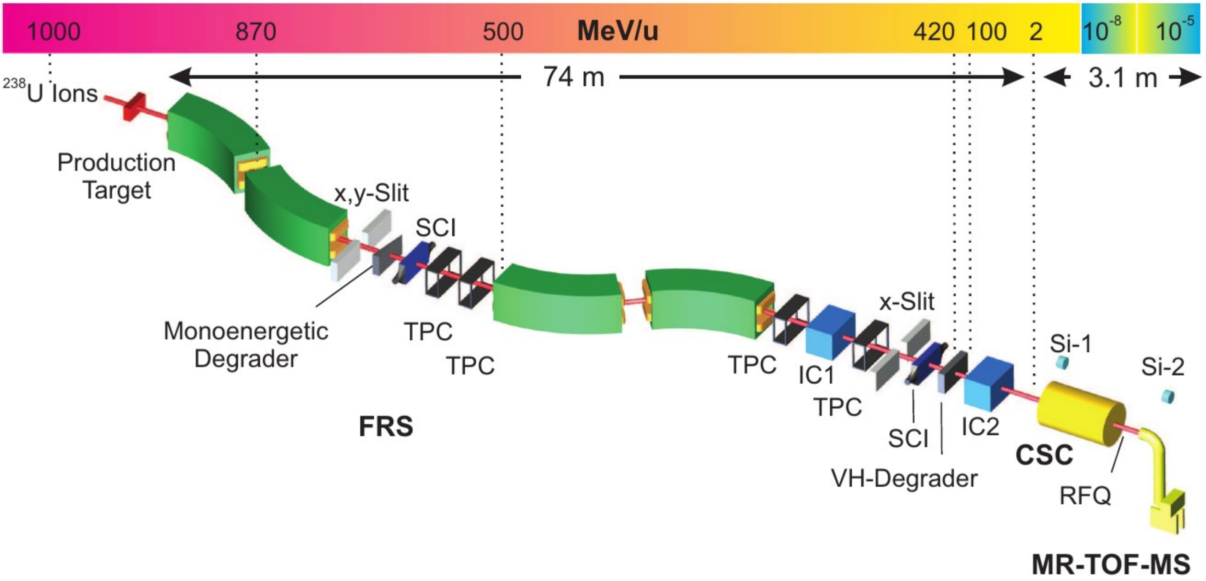


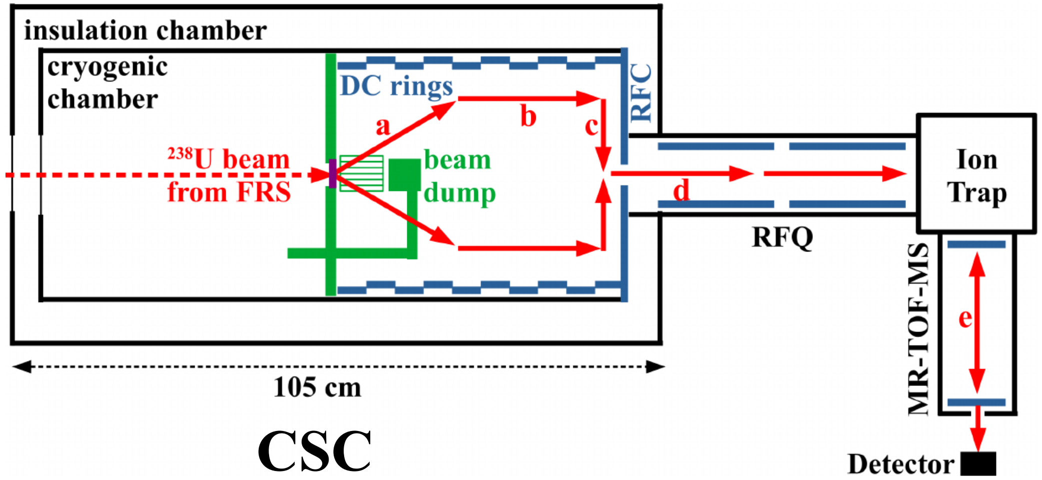
actinide production cross section vs. E_b (σ>1mb)



Beam degrading from relativistic energies (500MeV/u at SEETRAM)
to above Coulomb barrier (**~8MeV/u**) needs to be rather precise (**±1-2MeV/u**)

Beam slow-down and focusing





Distance from last FRS quadrupole to target: 530cm
Focus beam on 1 cm target, instead of 20 cm beam window
Dedicated ion optics and measurements to setup the beam on target:
Ionization current on beam dump
Beam range optimization with the MR-ToF

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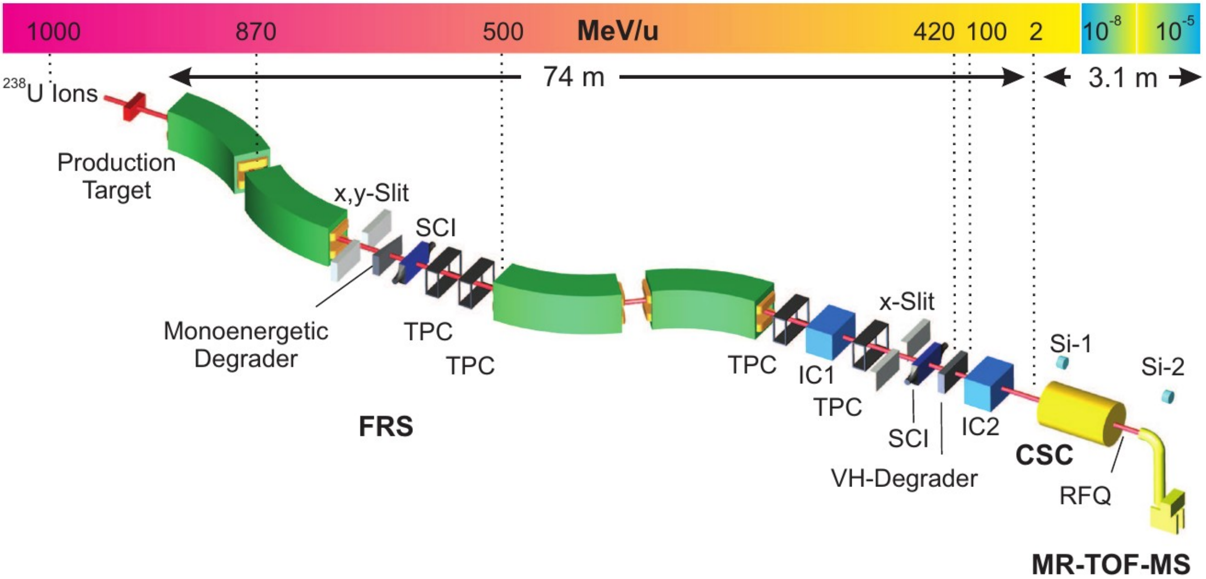
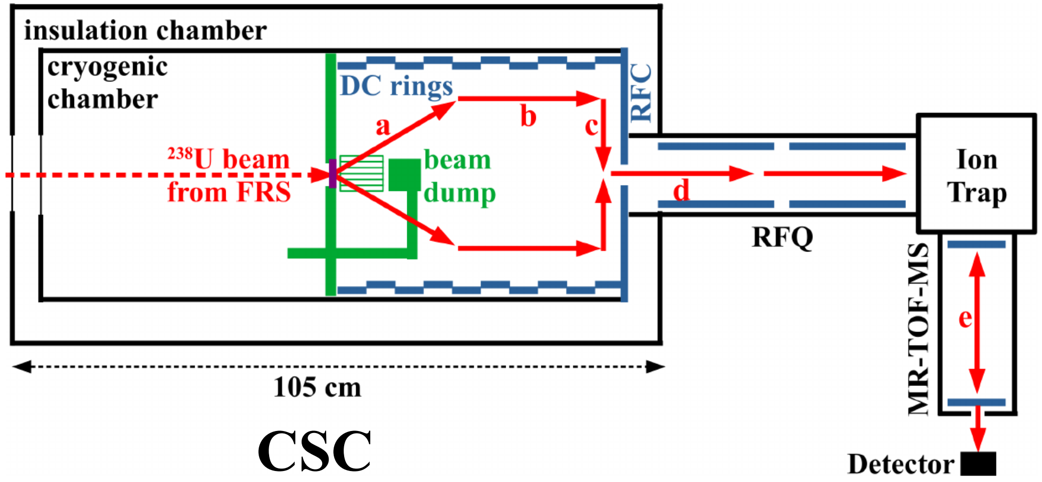
Super-FRS EC

Beam slow-down and focusing





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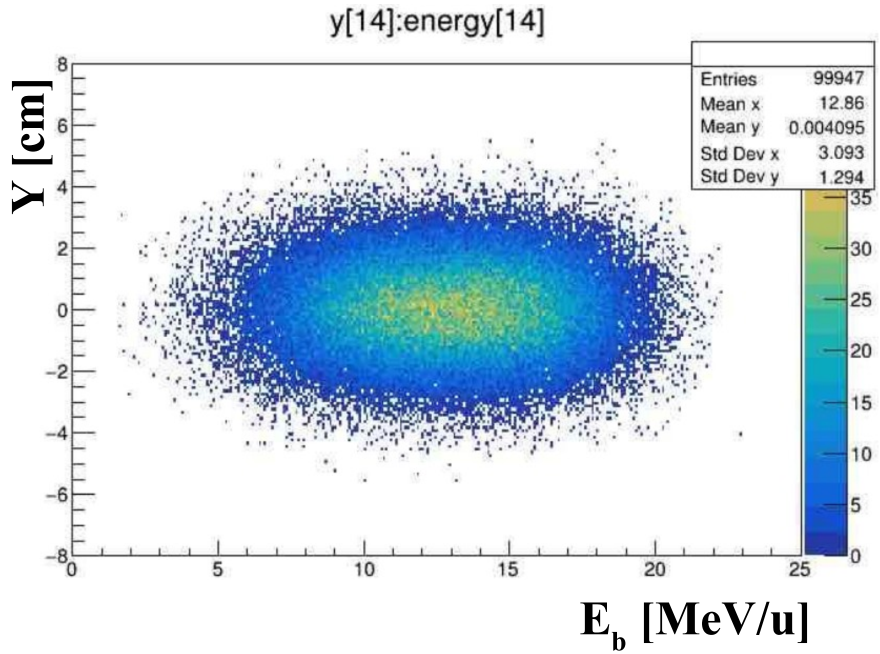
MOCADI (by **Deepak Kumar**):

– at CSC entrance: E=156MeV/u, σ_E=1MeV/u, σ_X=1.7cm, σ_Y=0.9cm

– on ^{209}Bi target: E=12.9MeV/u, σ_E=3MeV/u, σ_X=1.9cm, σ_Y=1.3cm



Higher energy by ~5MeV/u, broader spread and spot by ~x2

Discussion below...

Space charge effects

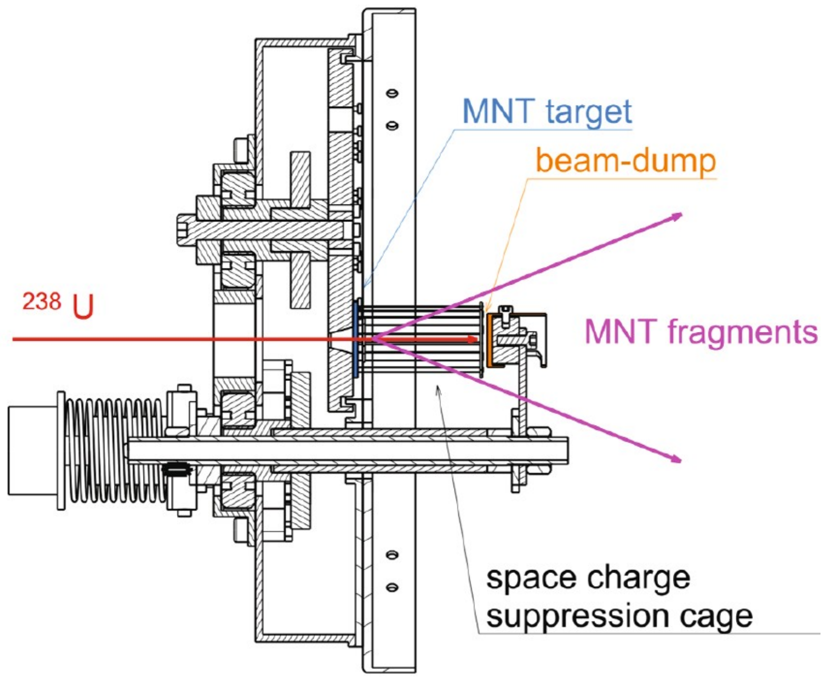
Extraction with electric fields: ε≥50%, τ~10ms, broadband

Drop in extraction efficiency of stopped fragments:
– $E_{induced}/E_{applied}$≈0.1-0.9: partial ion loss by field distortion
– $E_{induced}/E_{applied}$≥1: complete ion loss (neutralization)

Space charge effects

Extraction with electric fields: ε≥50%, τ~10ms, broadband

Drop in extraction efficiency of stopped fragments:
– $E_{induced}/E_{applied} \approx 0.1\text{-}0.9$: partial ion loss by field distortion
– $E_{induced}/E_{applied} \geq 1$: complete ion loss (neutralization)



A. Rotaru et al., Nucl. Instr. Meth. B 512 (2022)

MNT in INCREASE has two sources:
1) primary space charge
– by penetrating U beam: between target and beam dump
2) secondary space charge
– by MNT products: whole volume

Space charge effects

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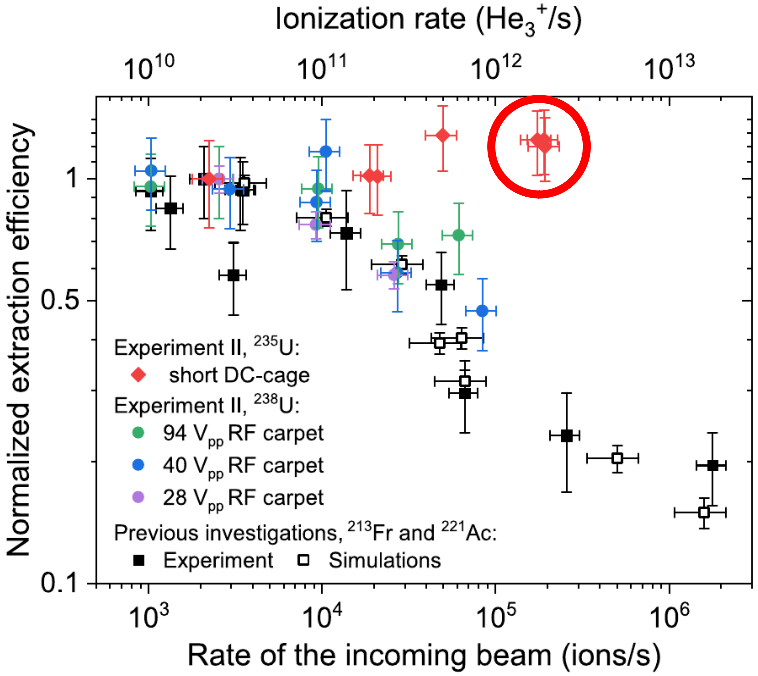
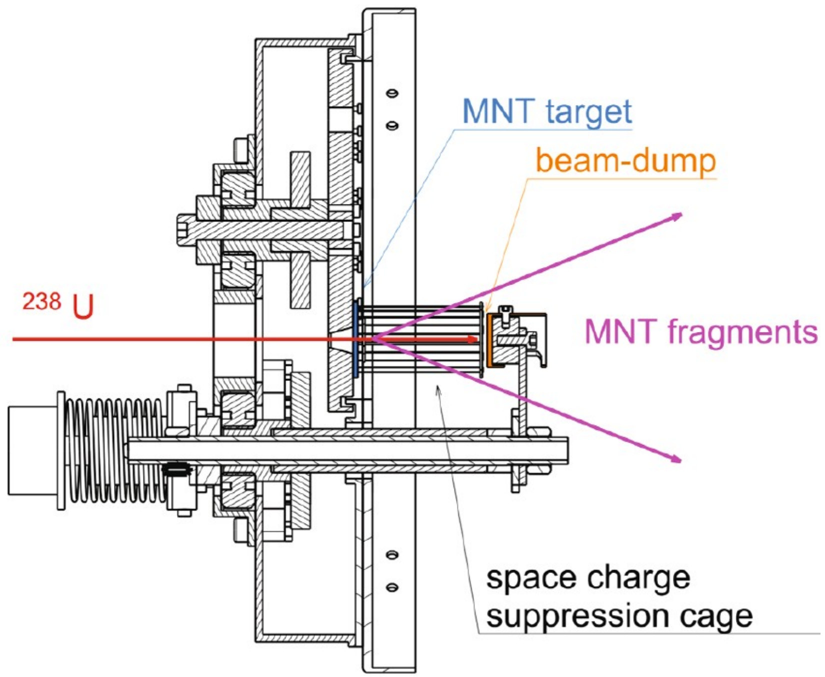
J.W. Zhao et al., NIM B 547 (2024)



No impact in INCREASE *at least* up to $2 \cdot 10^{12}$ He_3^+/s

→ **$Q \geq 7.4 \cdot 10^4$ He_3^+/mm³/s, $I_{beam} \geq 2 \cdot 10^5$ ions/s**



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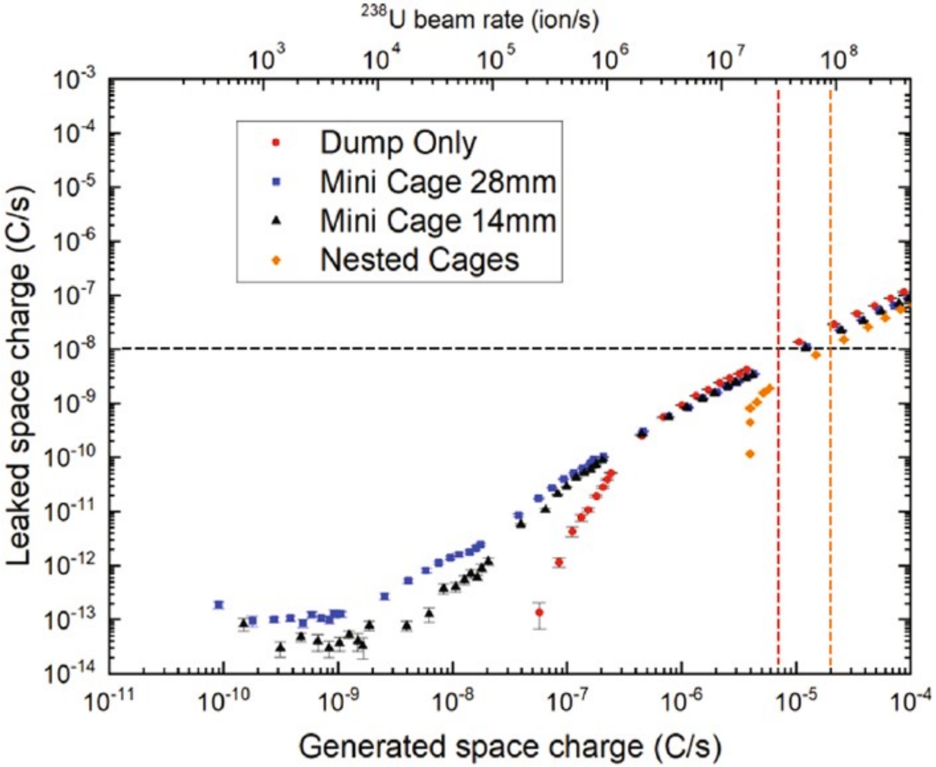
Space charge effects

1) primary space charge

– by penetrating U beam

– strong: for $I_b = 10^7$ ions/s

Q≈3.5·10⁹ He₃⁺/mm³/s >> 10^5 He_3^+/mm/s



A. Rotaru et al., Nucl. Instr. Meth. B 512 (2022)

Space charge effects

1) primary space charge

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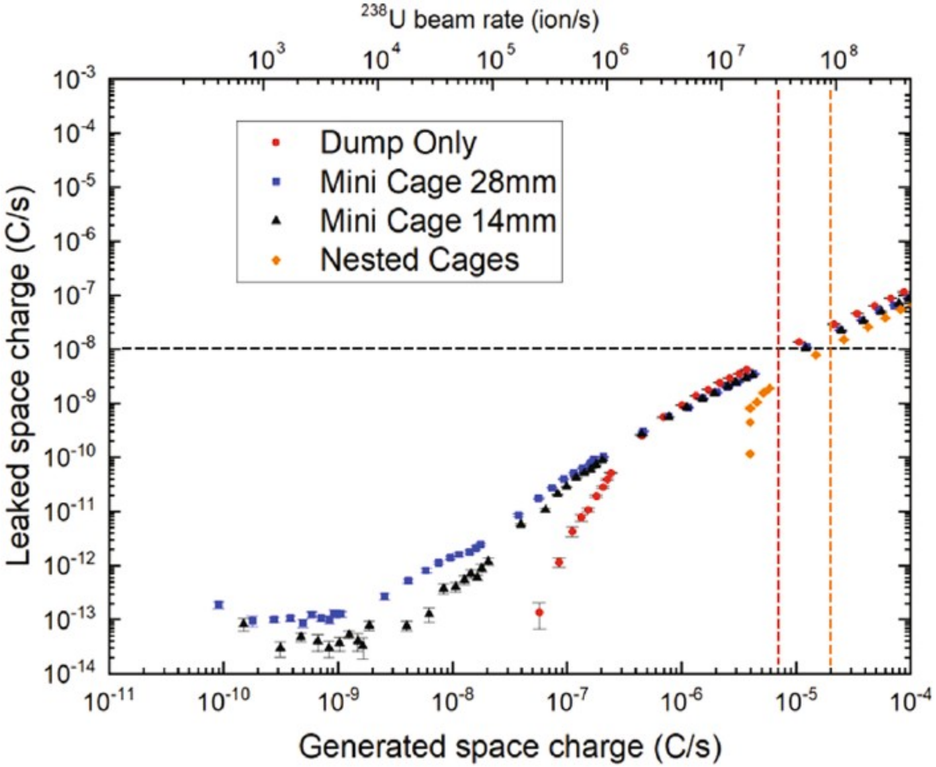
– strong: for $I_b=10^7$ ions/s

$Q\approx3.5\cdot10^9$ $He_3^+/mm^3/s$ >> 10^5 $He_3^+/mm/s$



A. Rotaru et al., Nucl. Instr. Meth. B 512 (2022)

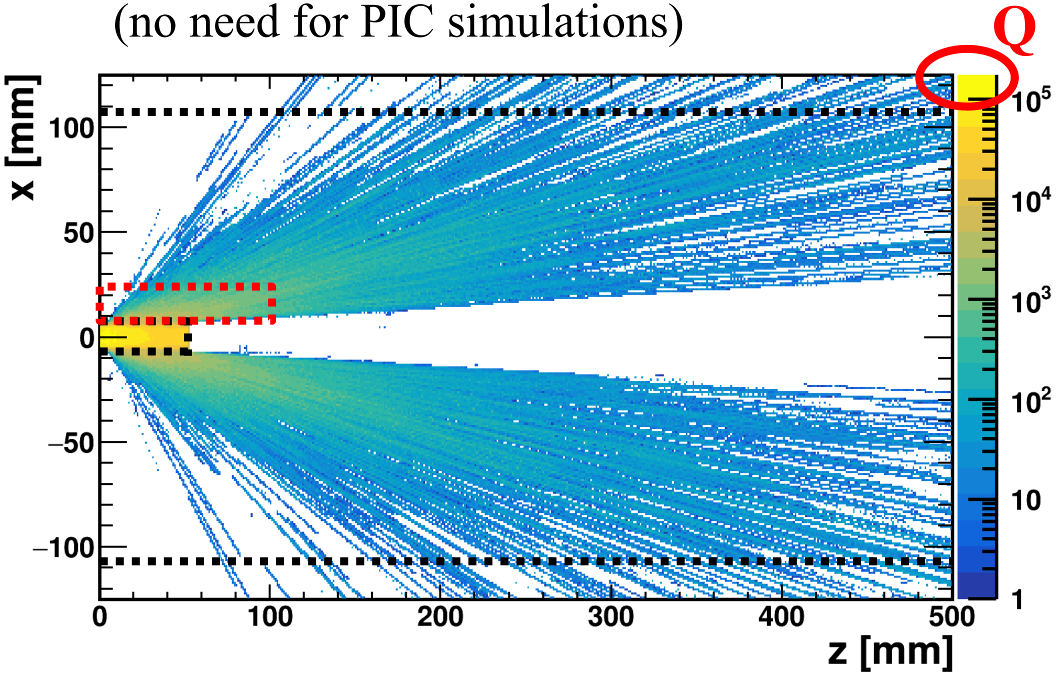
2) secondary space charge

– by MNT products: whole volume

– dominated by primary space charge in target-beam dump region:
$Q\approx2\cdot10^5$ $He_3^+/mm^3/s$ << $3.5\cdot10^9$ $He_3^+/mm/s$

– no impact in adjacent volume:
$Q\approx7\cdot10^3$ $He_3^+/mm^3/s$ << $7.4\cdot10^4$ $He_3^+/mm/s$

(no need for PIC simulations)



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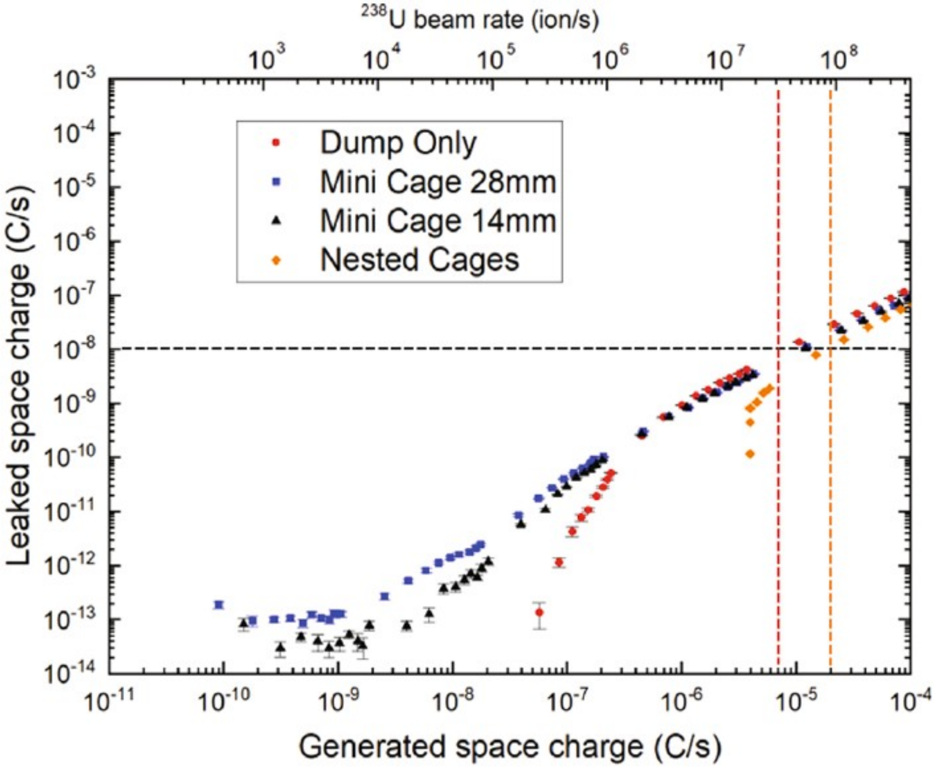

A. Rotaru et al., Nucl. Instr. Meth. B 512 (2022)

2) secondary space charge

– by MNT products: whole volume

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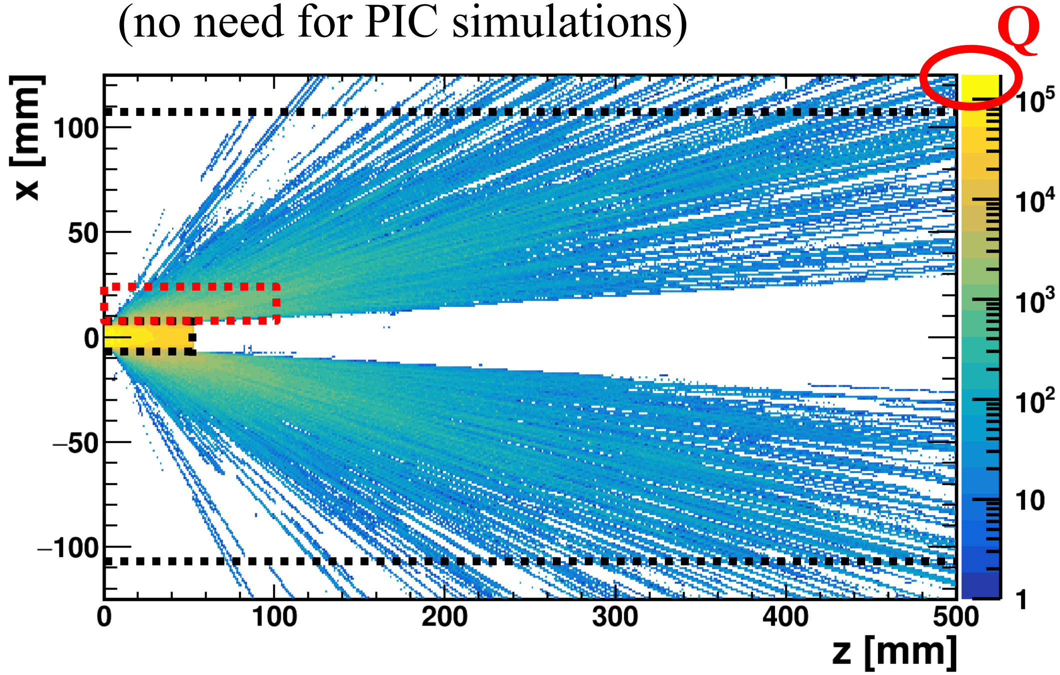
$Q \approx 2\cdot10^5\ He_3^+/mm^3/s << 3.5\cdot10^9\ He_3^+/mm/s$

– no impact in adjacent volume:

$Q \approx 7\cdot10^3\ He_3^+/mm^3/s << 7.4\cdot10^4\ He_3^+/mm/s$

(no need for PIC simulations)

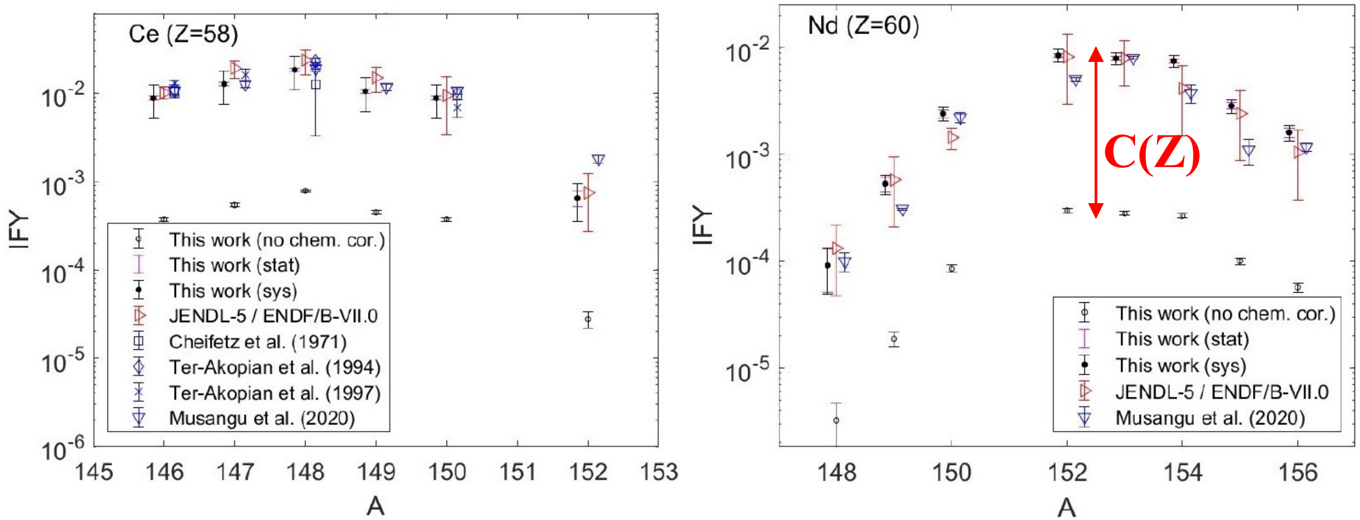


Does space charge containment (voltage beam dump + mini-cages) work?
Up to what beam intensity?

High-purity He gas

– checked with sources: 228Th, 252Cf, etc.
– method developed for 252Cf independent fission fragment yields IFY(N,Z)
– for an experiment at non-optimal gas purity, the extracted the chemical efficiency C<10%
Analysis by **Israel and his students**

Y. Waschitz et al., EPJ Web of Conferences 284 (2023)



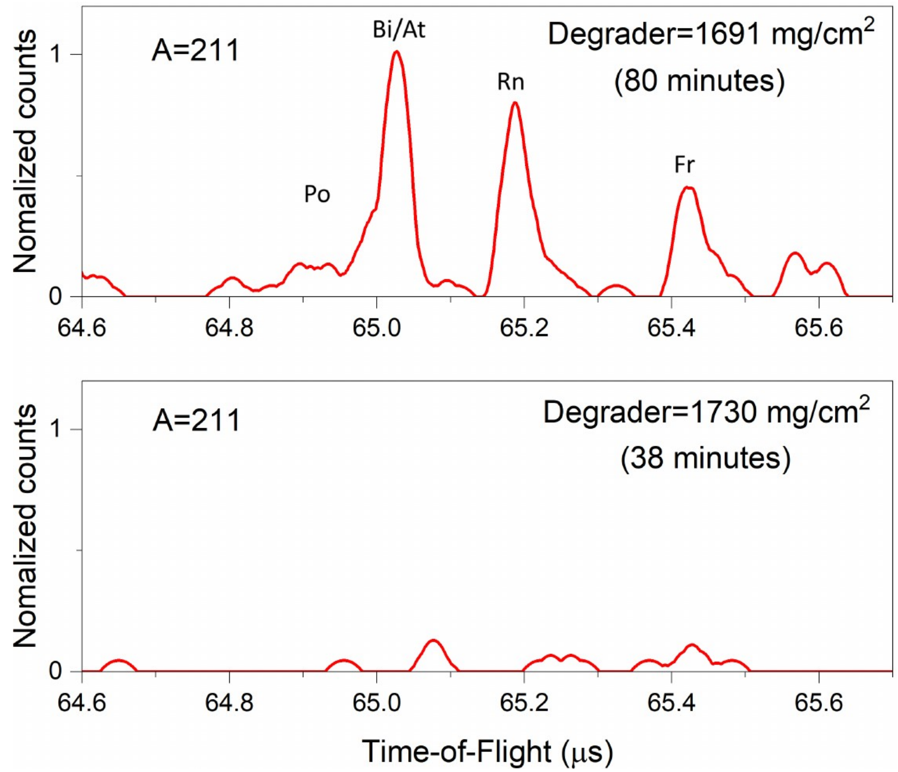
$$\sum_{Z} IFY(N,Z)_{exp}^{N+Z=A} \cdot C(Z) = frac(FY_{lit}(A)) \cdot FY_{lit}(A)$$

G-22-00117 experiment

May 24-27 (followed by Ali's MNT experiment): ^{238}U beam at 500MeV/u, slowed down by FRS to ~13MeV/u, on ^{209}Bi target inside INCREASE

– MNT TLFs recorded by the MR-ToF: **we have signal!**
– intensity on target 10^5–10^6 ions/s without efficiency decrease: **space charge contained!**

Ali Mollaebrahimi et al., submitted to Nucl. Phys. A



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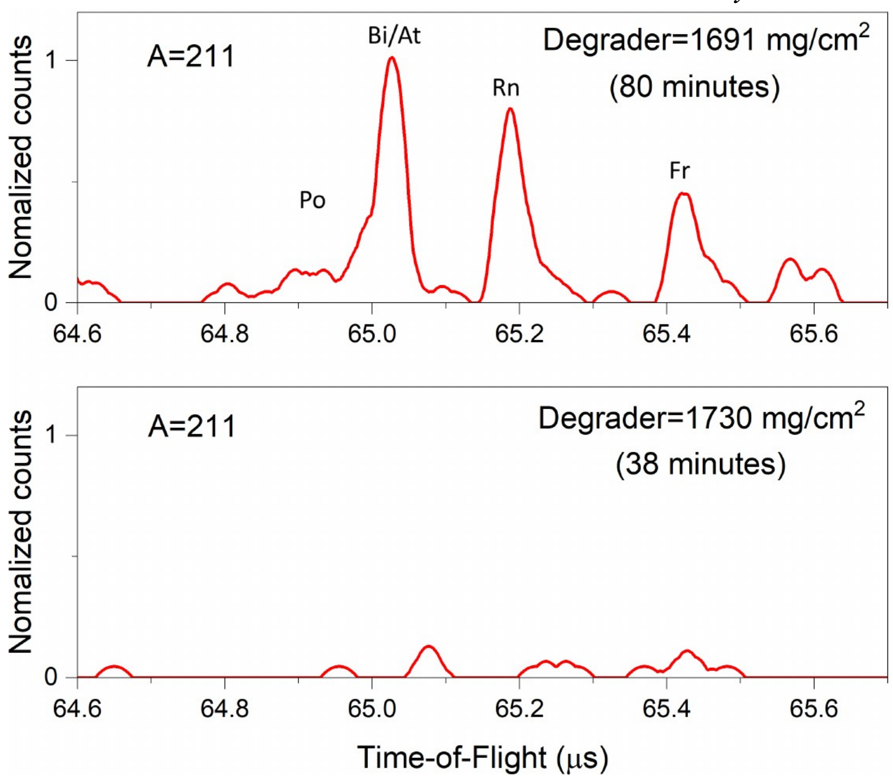
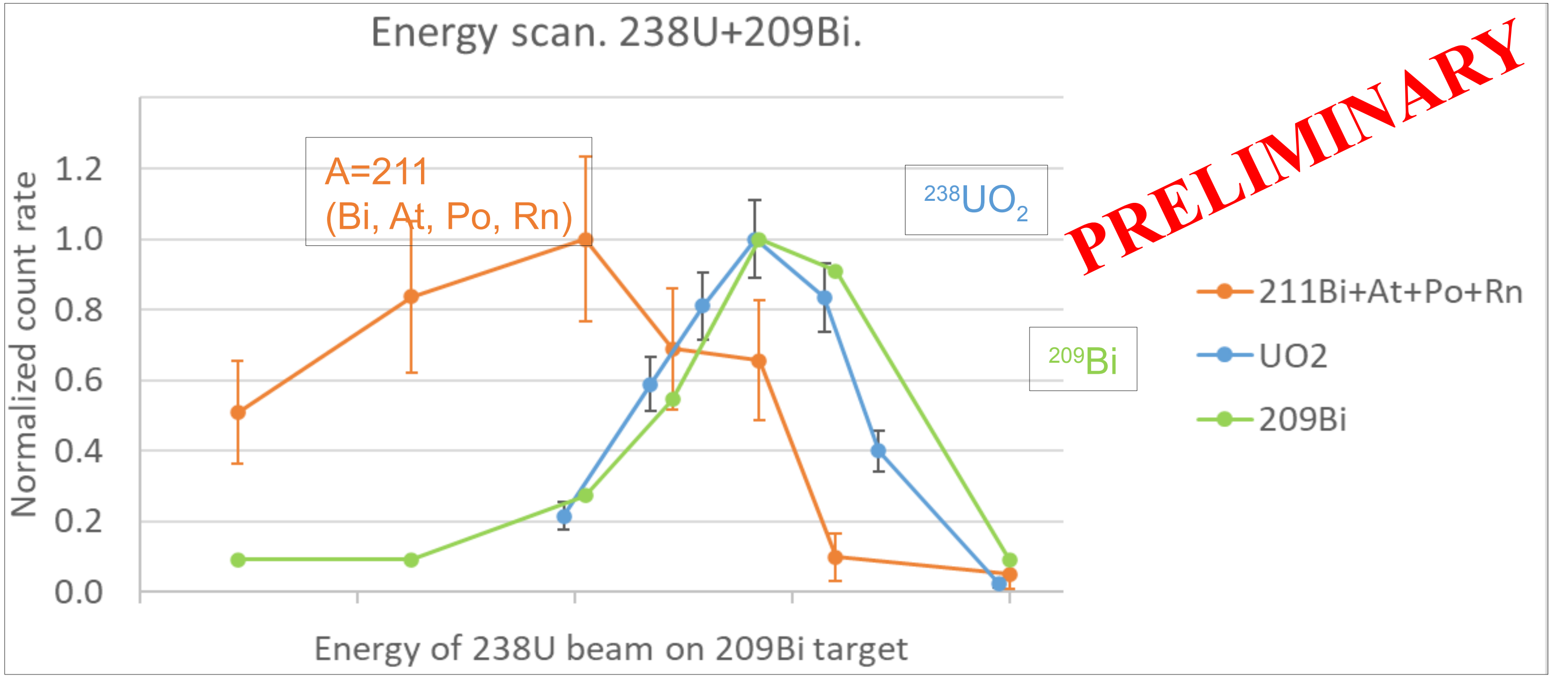
Problems:
1. Degrader drive broken, need to use another degrader 4 m upstream: non-optimal degrading system
 → broader beam spread and spot on target
2. Air leak in CSC: molecular ions, esp. actinide oxide; also, large amount of Xe extracted
 (2^+ actinide oxides A/q~127-135;1^+ Xe ions A/q~128-132)
 → actinide region more difficult to analyze
3. High radiation level in S4: electronics failure + radiation alarms
 → access during beamtime, beam intensity limitation
4. Large background in extraction Si detector
 → MNT study directly after CSC with high efficiency not possible

Ali Mollaebrahimi et al., submitted to Nucl. Phys. A



G-22-00117 experiment

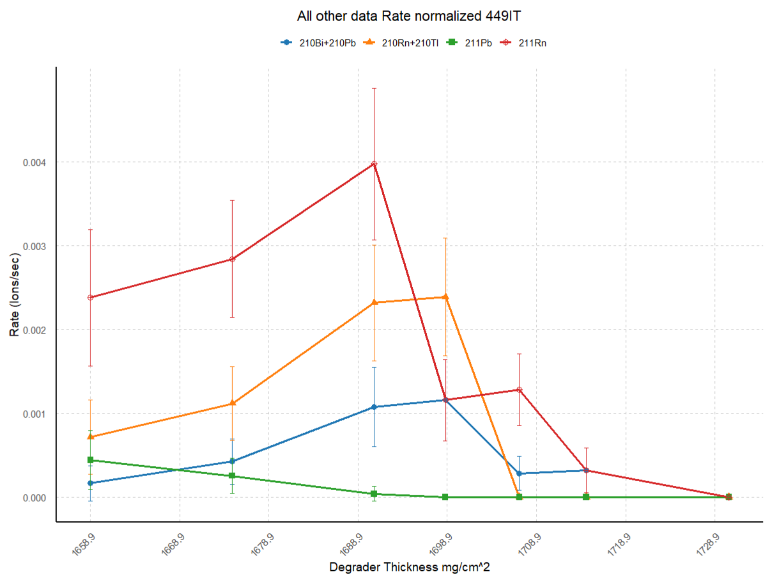
- MNT products on A=211 isobaric chain: **MNT proof-of-principle measurement!**
  - TLF signal is clearer than PLF (TLFs can be generated only in the target,while PLFs not)
  - energy scan and angular selection (by INCREASE acceptance) characteristic to MNT reactions

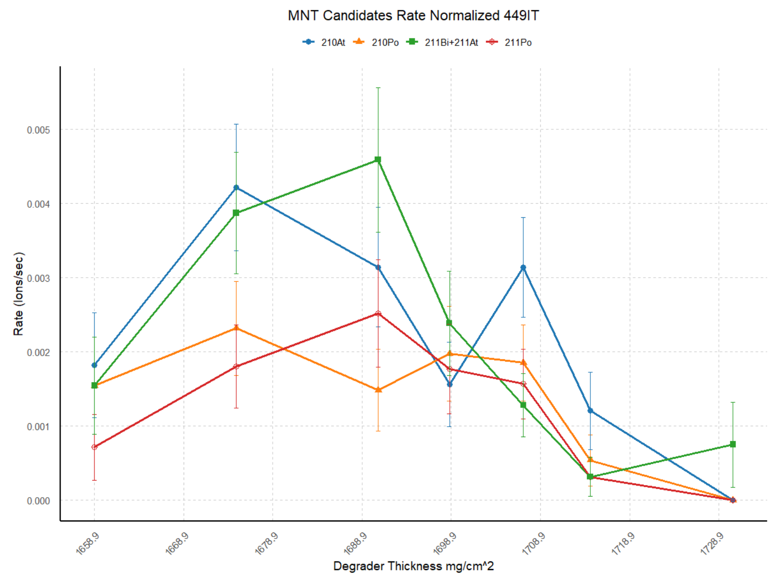


normalized count rate with the MR-TOF mass spectrometer versus beam energy (FRS degrader thickness) for: primary beam (extracted as UO_2), target ions (elastic scattering), **identified A=211 TLF isobars** (Bi, At, Po, Rn)

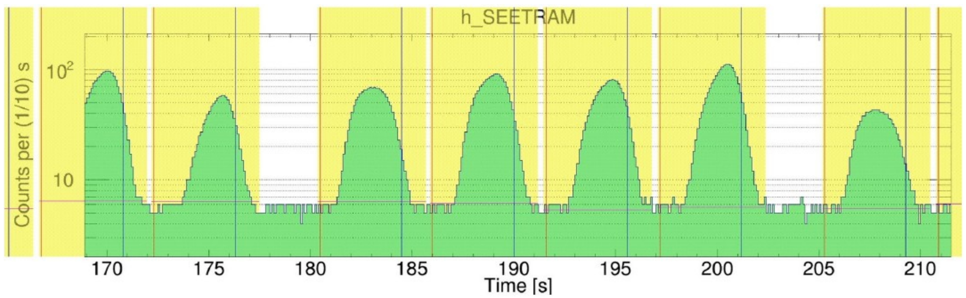
Data analysis ongoing...

Amir Shrayer / Israel Mardor
(Tel Aviv University)





Debodyuti Kar / Soumya Bagchi
(Indian Institute of Technology)



Conclusions & Outlook

– experimental setup for in-cell MNT reaction working up to ~10^6 U/s on target:
primary beam of 0.2pA is sufficient to generate secondary RIBs!

– MNT TLFs measured: *proof-of-principle done*
– n-rich actinides: seen online in ^{238}U+^{209}Bi, analysis to follow (as for the TLFs)

– expected challenges:
1) beam slow-down and focusing: OK(ish), room for improvement...
2) space charge effects on extraction: no problem at 10^6 U/s on target!
3) gas purity: TLF masses ✔, PLF masses ?, cross sections ✘

– not expected problems:
1) high radiation from beam degrading
2) extraction Si det. not usable

LoI 12:
"*Next stage of MNT driven neutron-rich isotope studies at the FRS Ion Catcher*"
Paul Constantin, Soumya Bagchi, Timo Dickel
→ presentation tomorrow afternoon

THANK YOU!

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eli

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and the ***Super-FRS Experiment Collaboration***