Precision Measurements of Mixed Mirror Transitions for St. Benedict

St. Benedict
TRAPPISTES DE PAUL

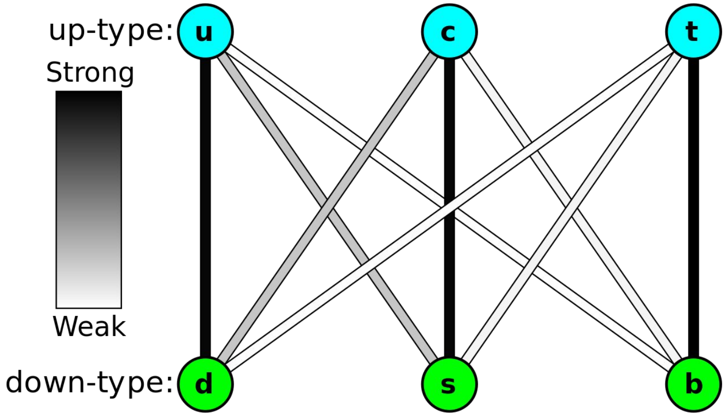
Rey Zite
University of Notre Dame

INPC, May 27 2025

BSM Physics

The Standard Model can be tested via unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix

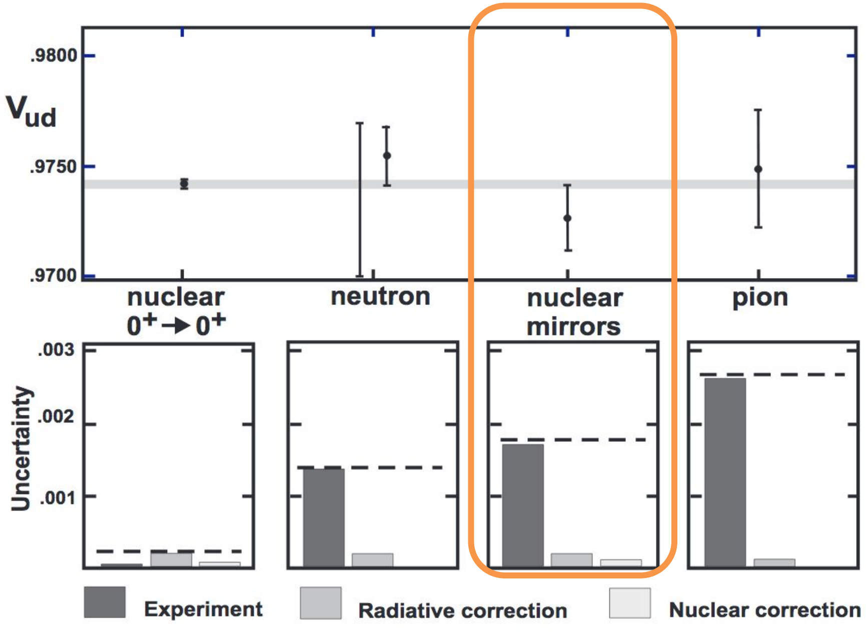
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



The top row test:

$$\sum_i |V_{ui}|^2 = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

V_{ud} from Ft Values



J.C. Hardy and I.S. Towner, arXiv:1807.01146v1 [nucl-ex] (2018)

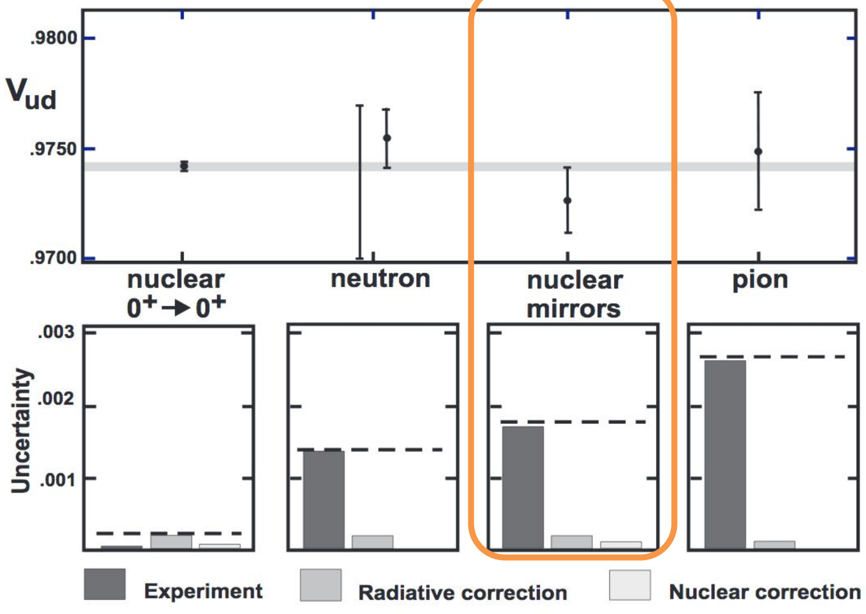
$$\mathcal{F}t^{(mirrors)} = ft(1+\delta_R)(1+\delta_{NS}-\delta_C) = \frac{K}{2G_F^2 V_{ud}^2 (1+\Delta_R^v)(1+\frac{f_A}{f_V}\rho^2)}$$

Requires many of the same values as their pure Fermi counterparts

- Branching ratios
- Q values
- Half life
- Fermi to Gamow Teller Mixing Ratio (ρ)

$$a_{\beta\nu} = \frac{1}{3}\left(\frac{3-\rho^2}{1+\rho^2}\right)$$

V_{ud} from Ft Values



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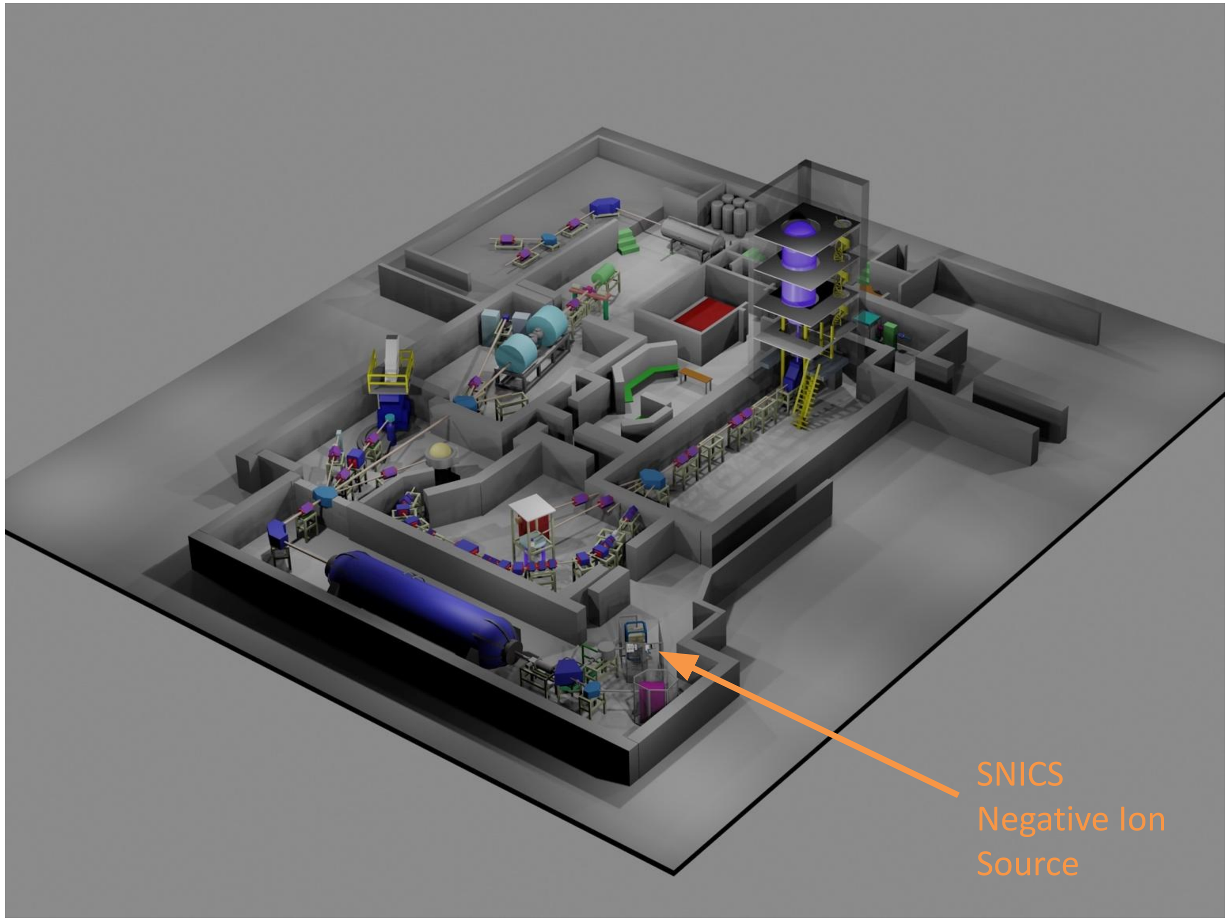
Producing RIBs at ND



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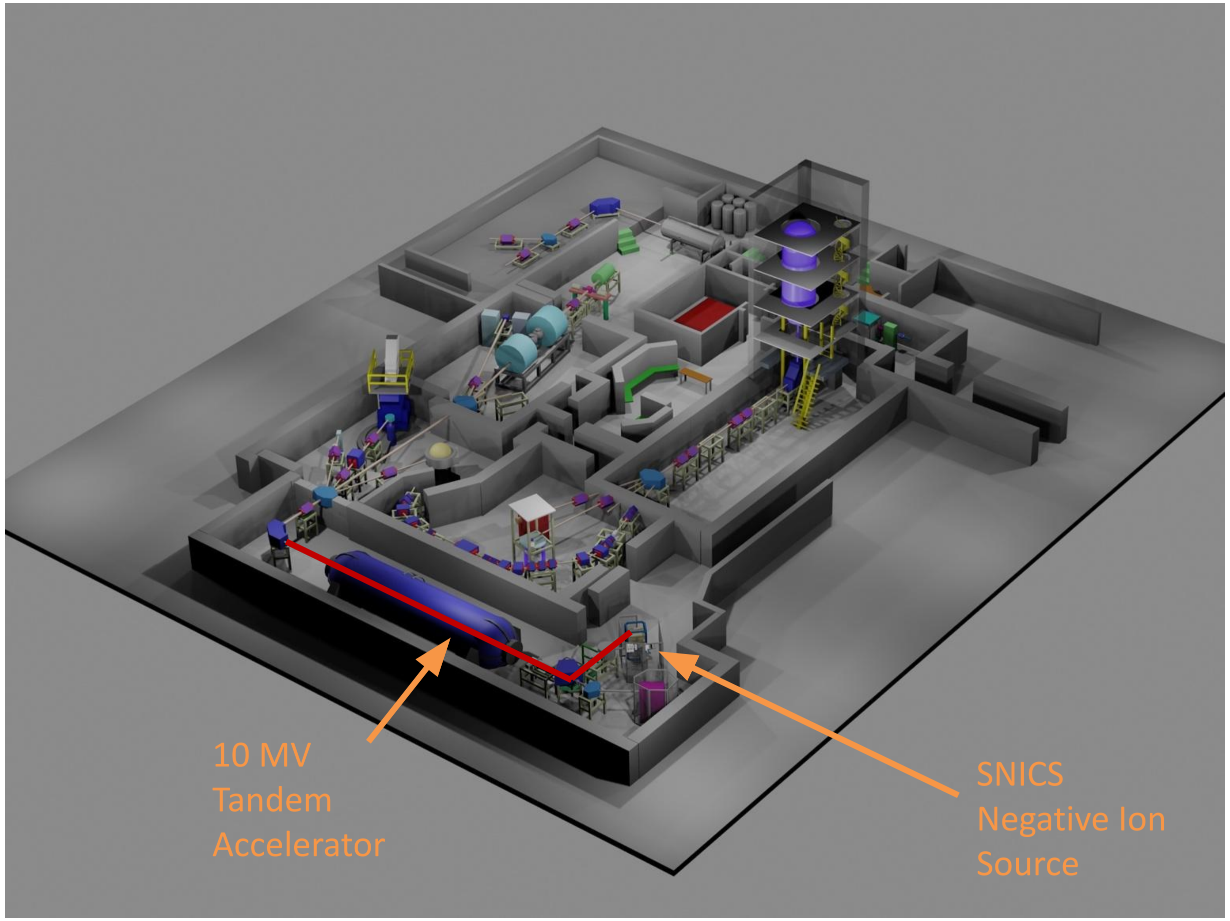

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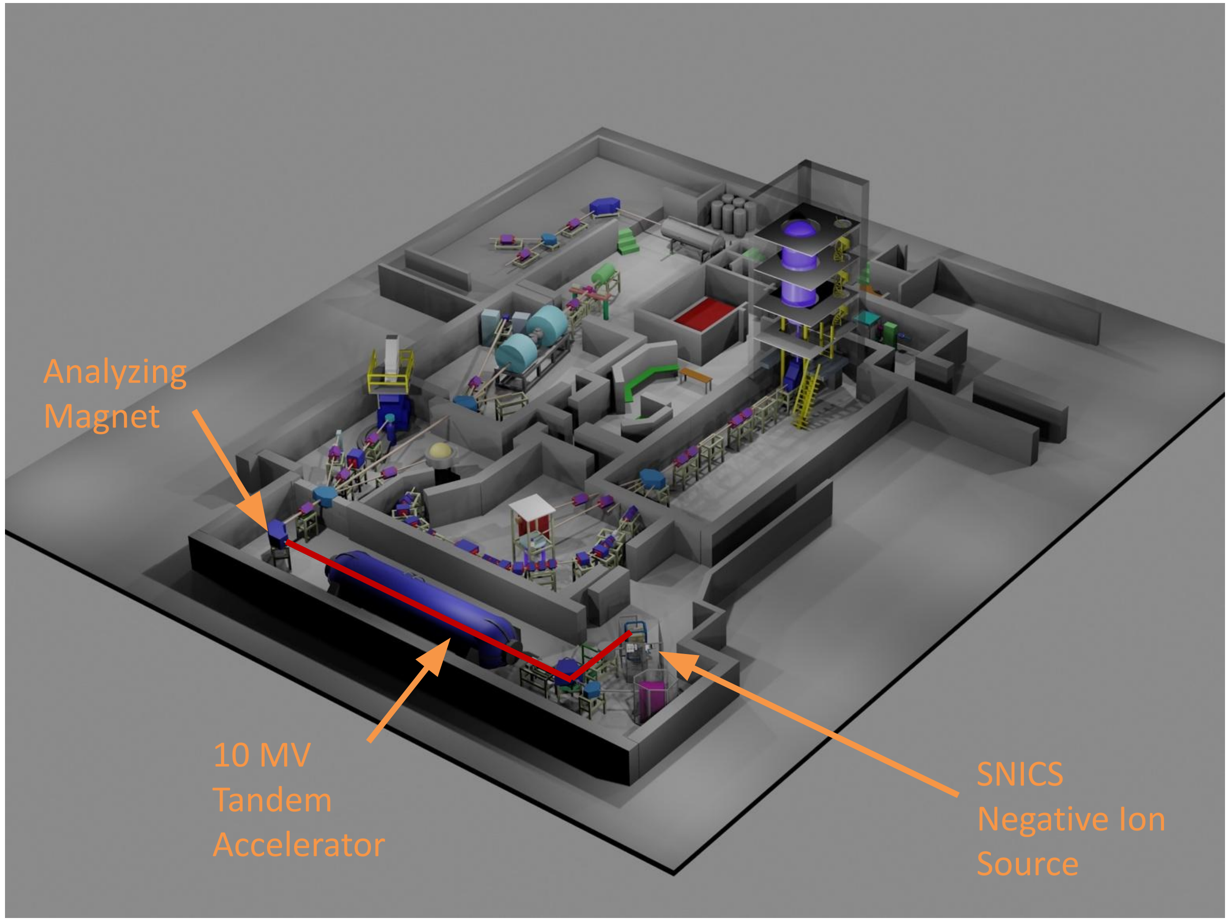

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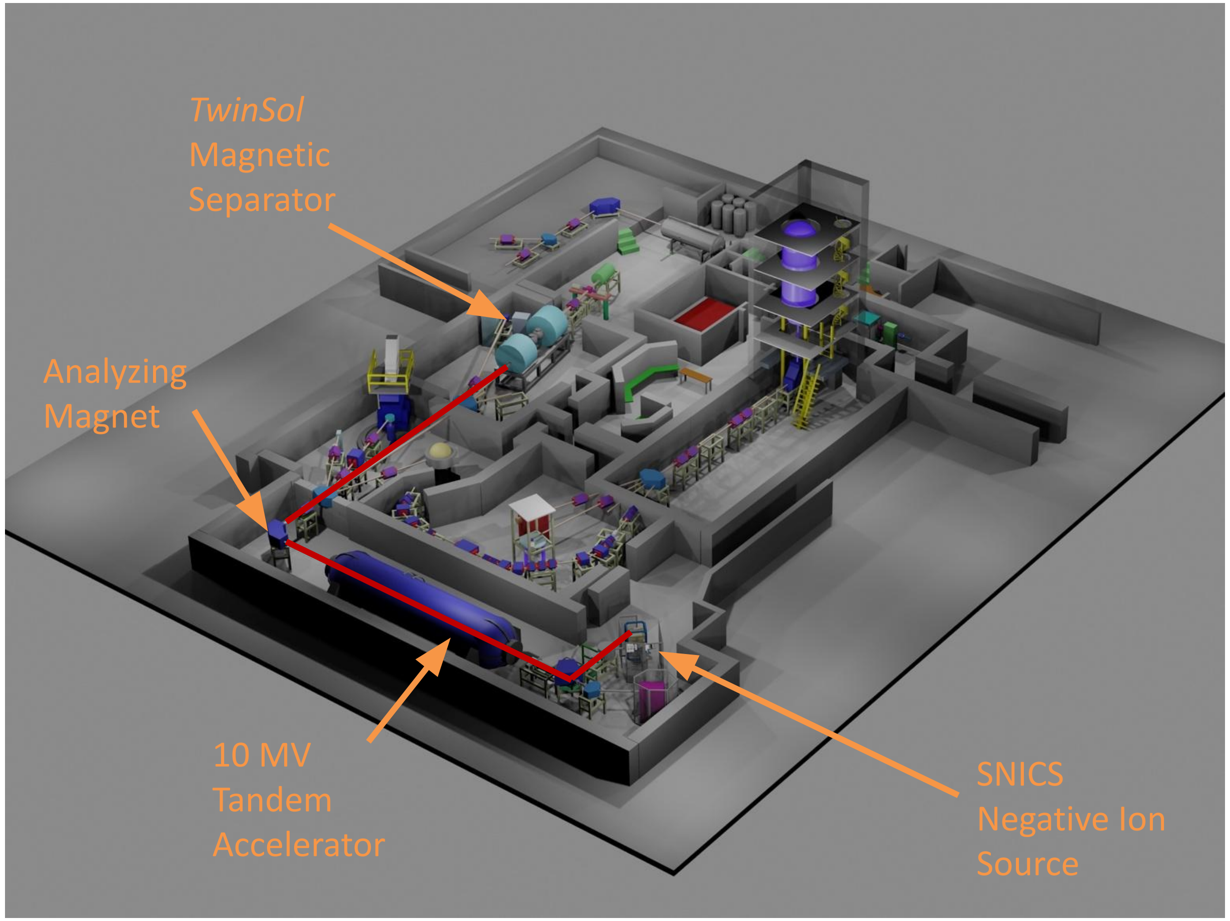
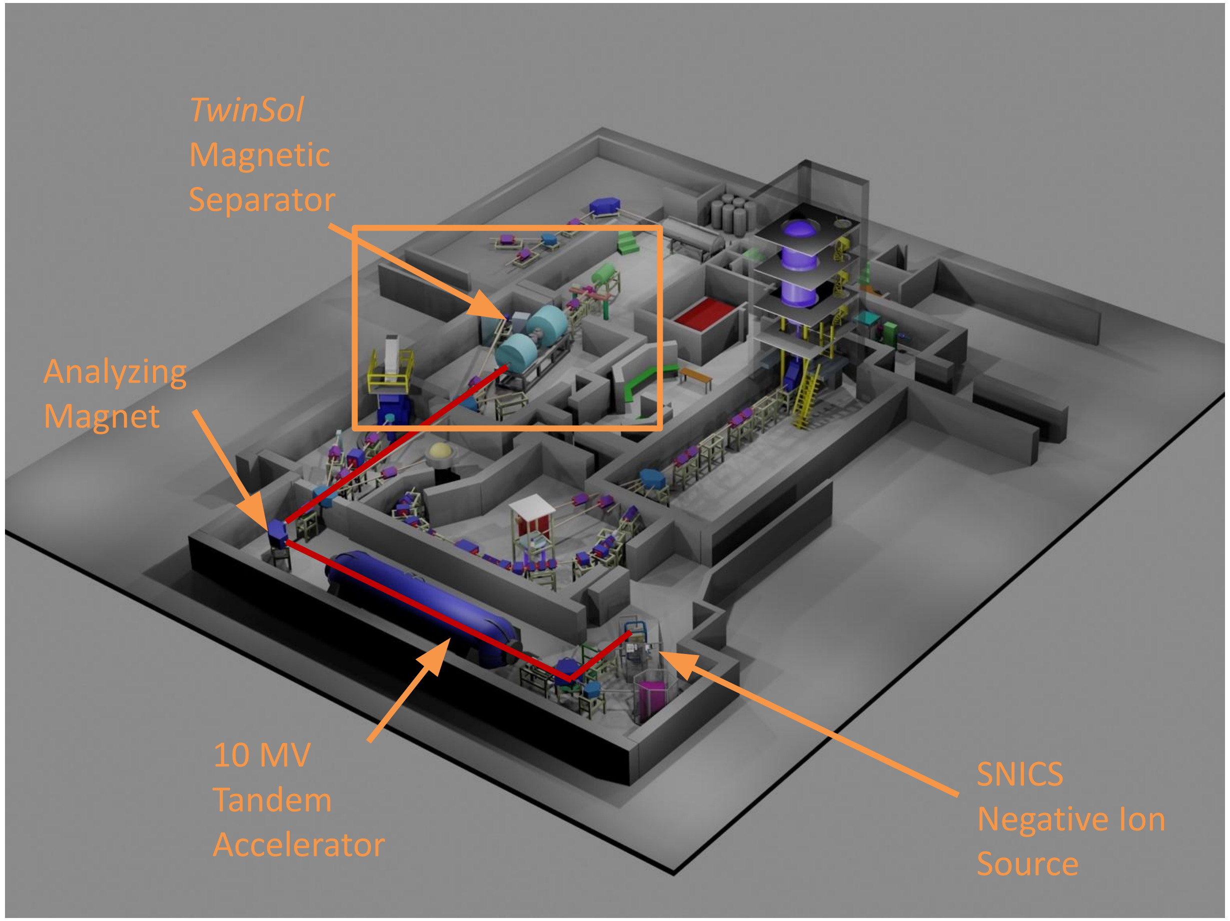
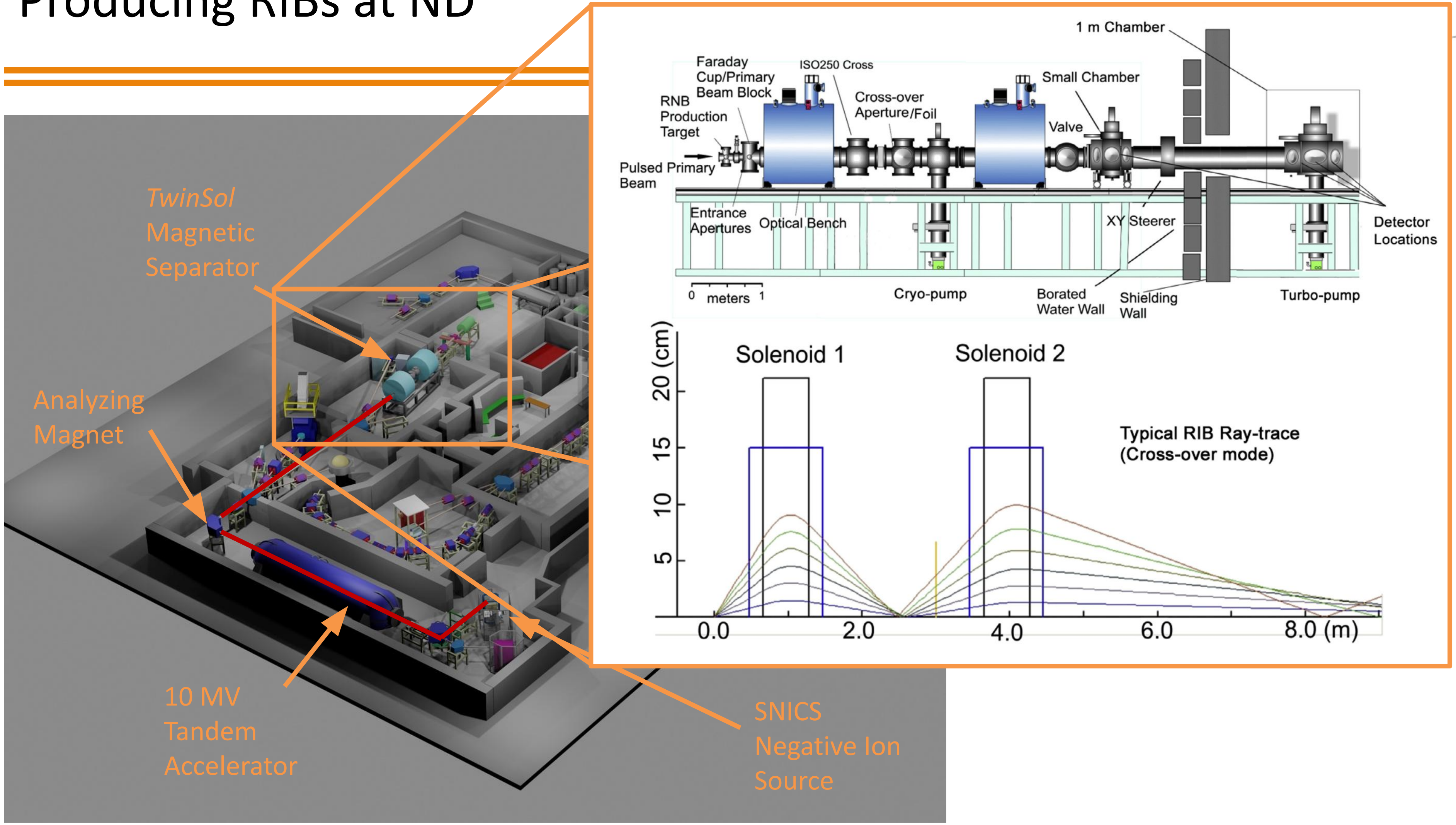


Producing RIBs at ND



Producing RIBs at ND



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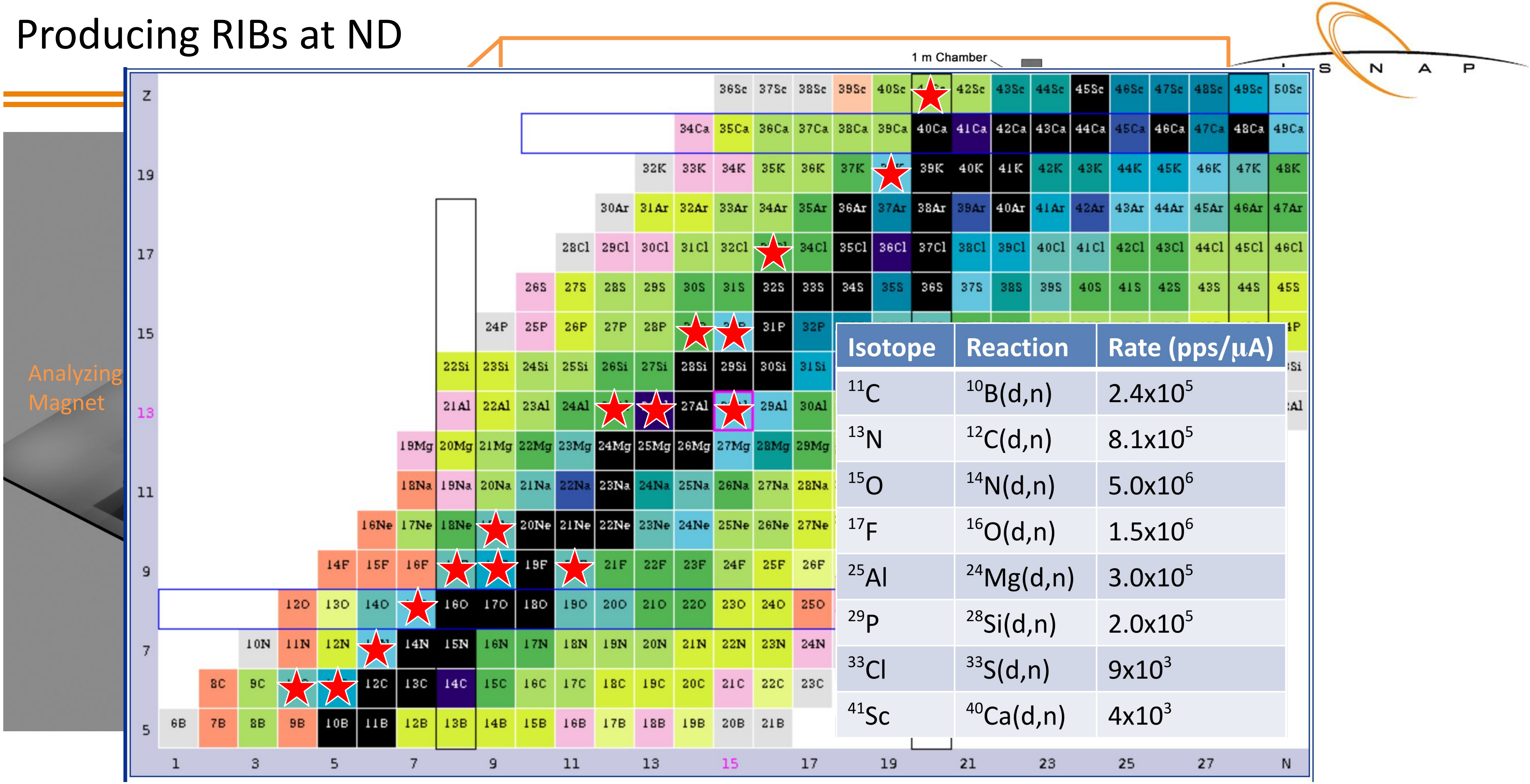

Isotope	Reaction	Rate (pps/μA)
^{11}C	^{10}B(d,n)	2.4×10^{5}
^{13}N	^{12}C(d,n)	8.1×10^{5}
^{15}O	^{14}N(d,n)	5.0×10^{6}
^{17}F	^{16}O(d,n)	1.5×10^{6}
^{25}Al	^{24}Mg(d,n)	3.0×10^{5}
^{29}P	^{28}Si(d,n)	2.0×10^{5}
^{33}Cl	^{33}S(d,n)	9×10^{3}
^{41}Sc	^{40}Ca(d,n)	4×10^{3}

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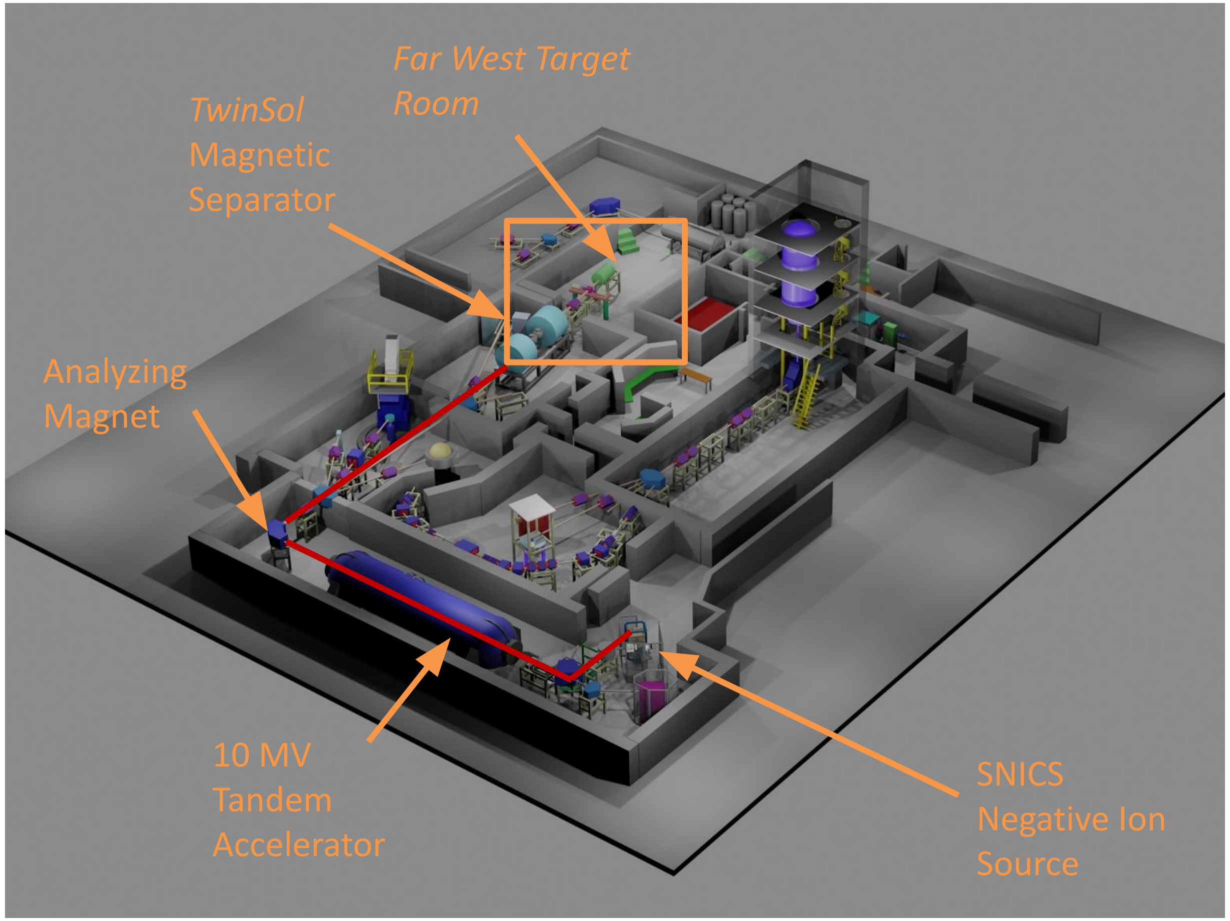
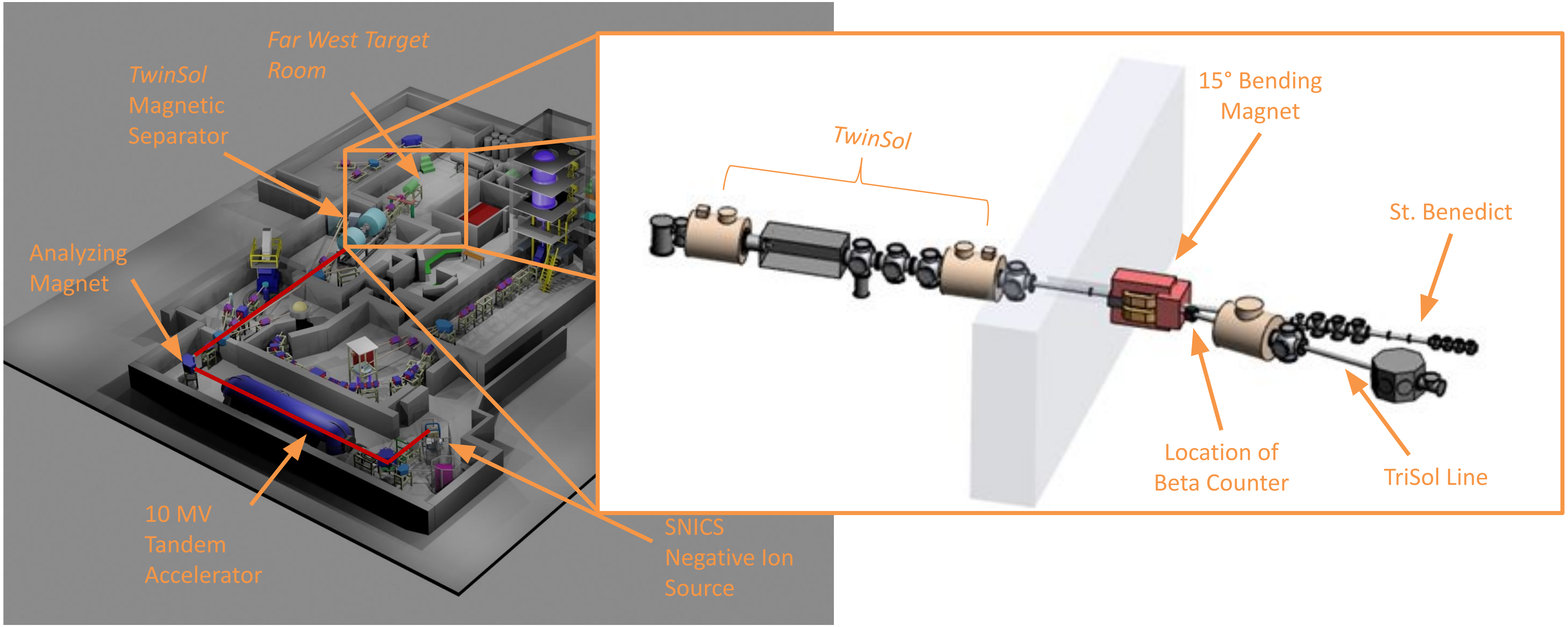
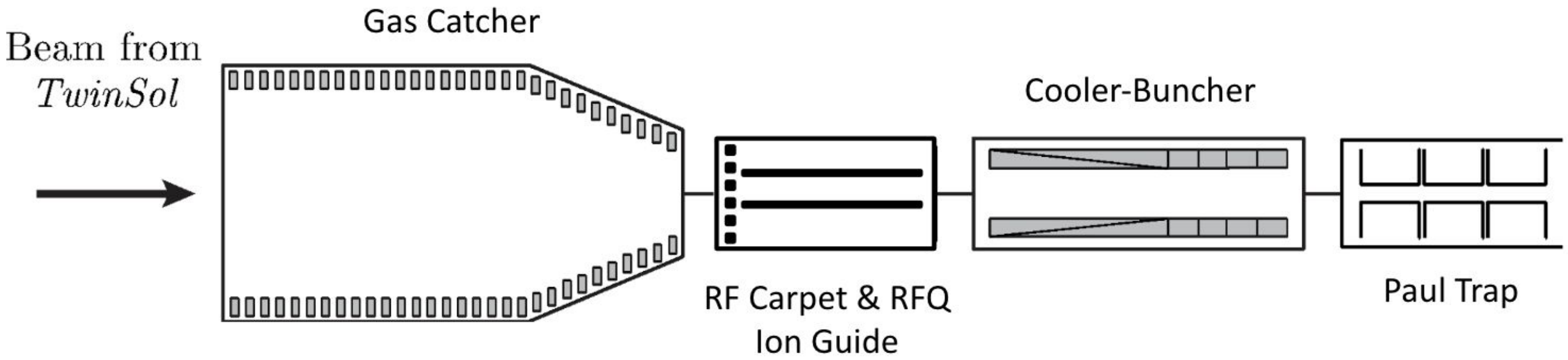
Producing RIBs at ND

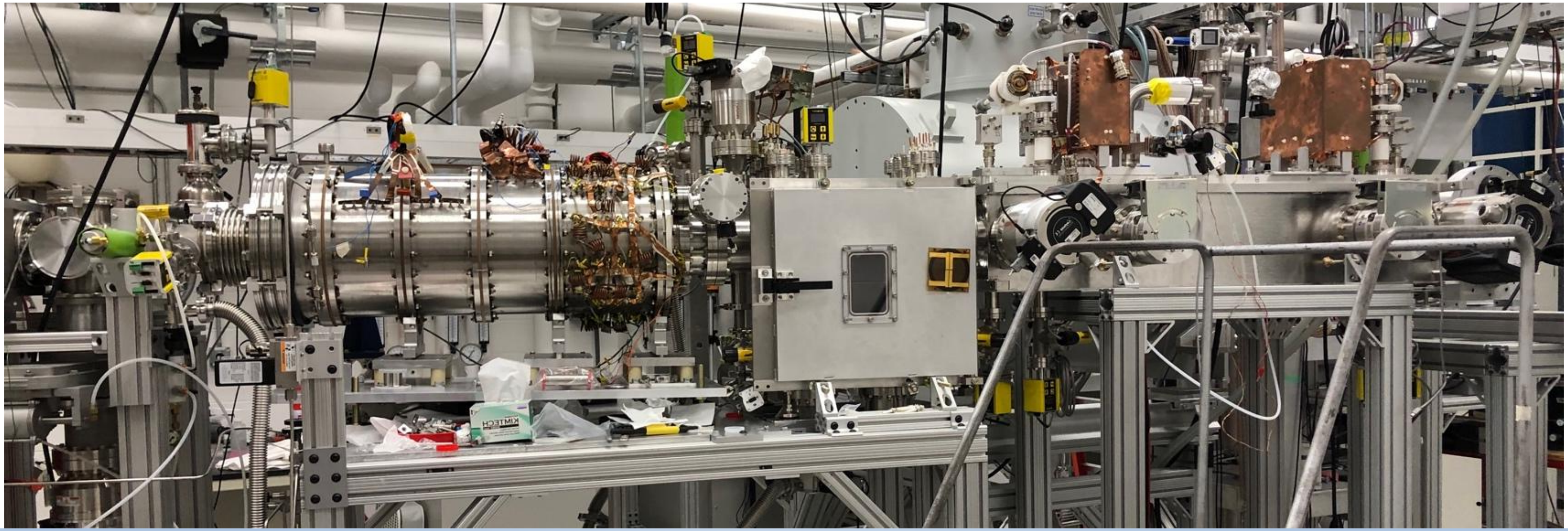


Producing RIBs at ND

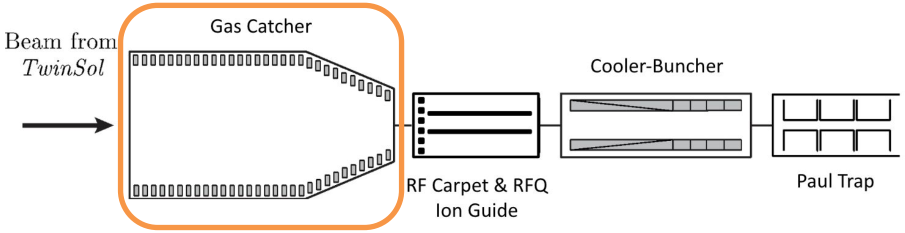


Superallowed Transition Beta-Neutrino Decay Ion Coincidence Trap (St. Benedict)

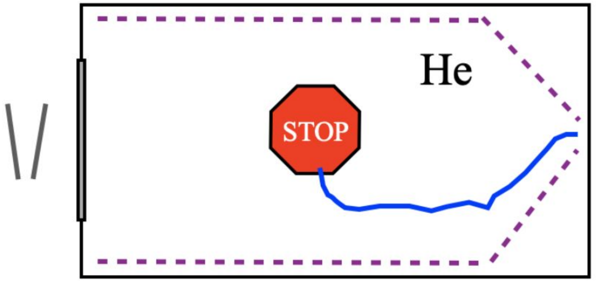




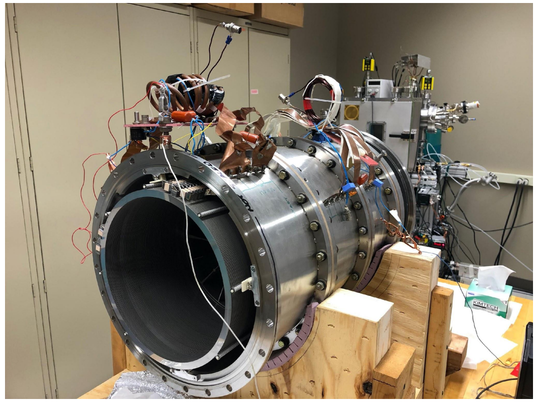
Gas Catcher

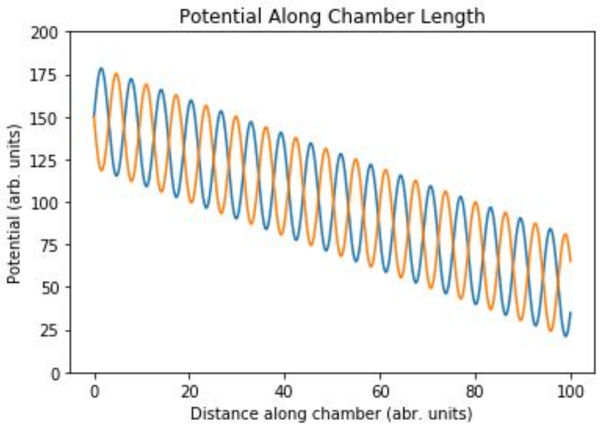


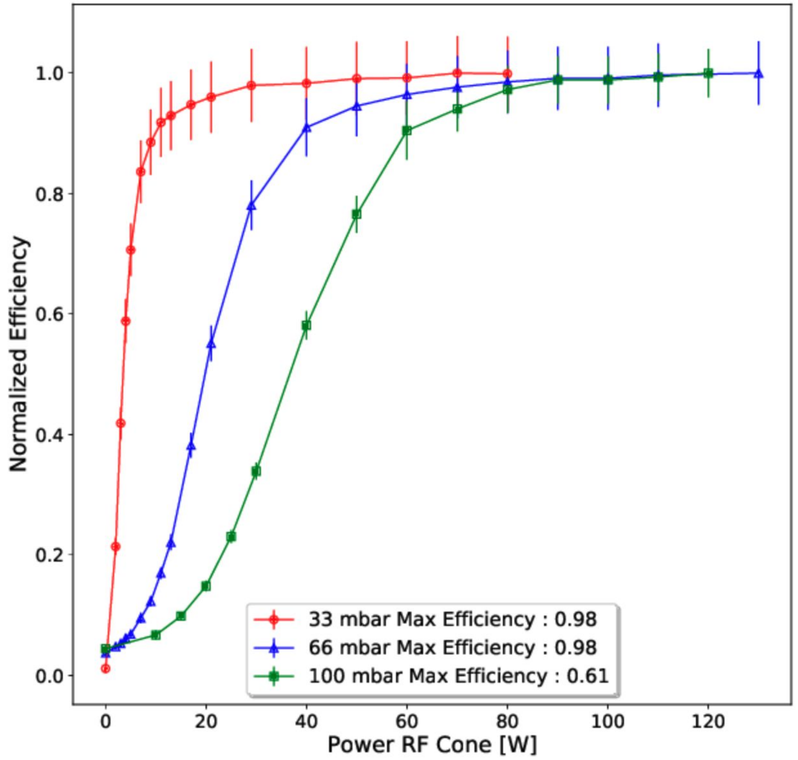
TwinSol beam
E = 10-40 MeV



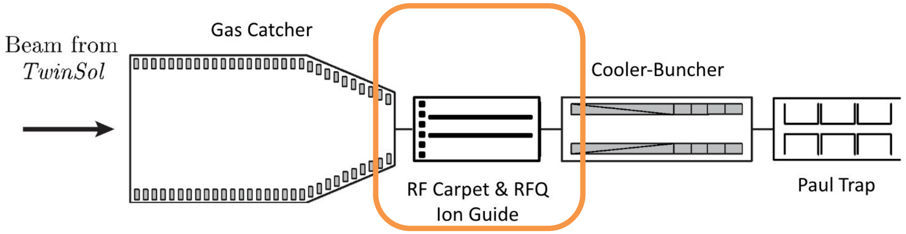
100 eV
beam

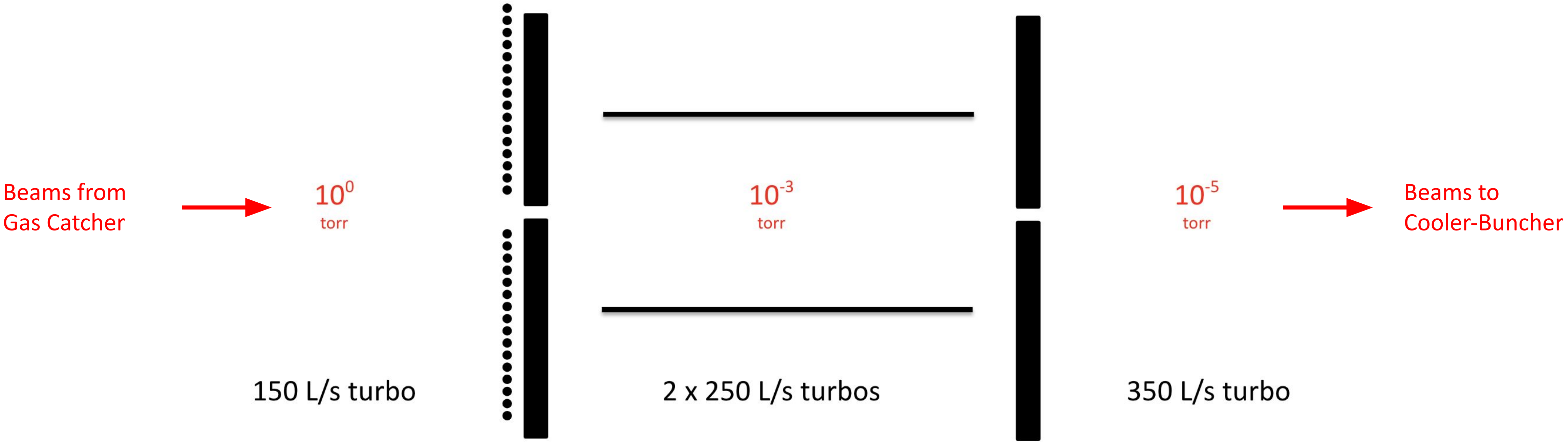




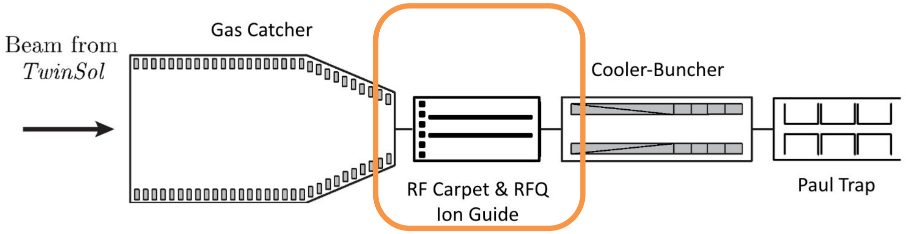


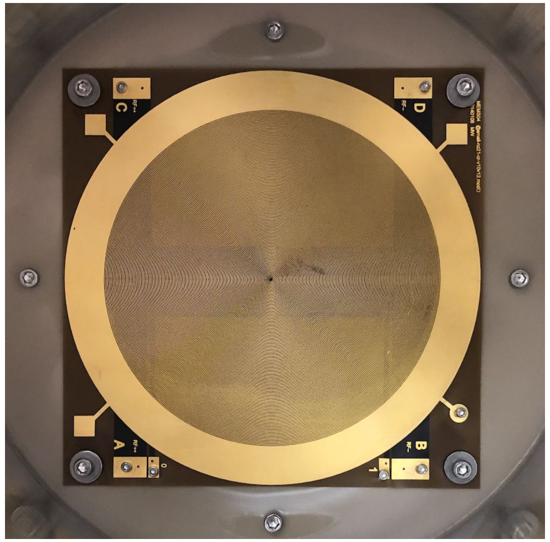
Differential Pumping

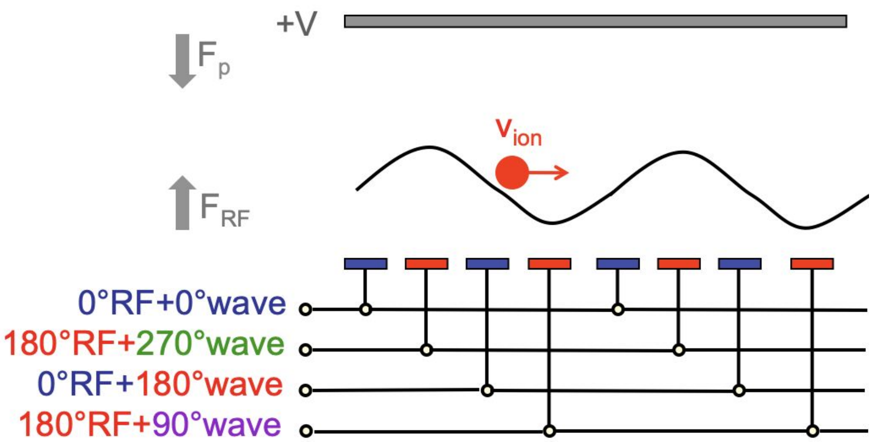


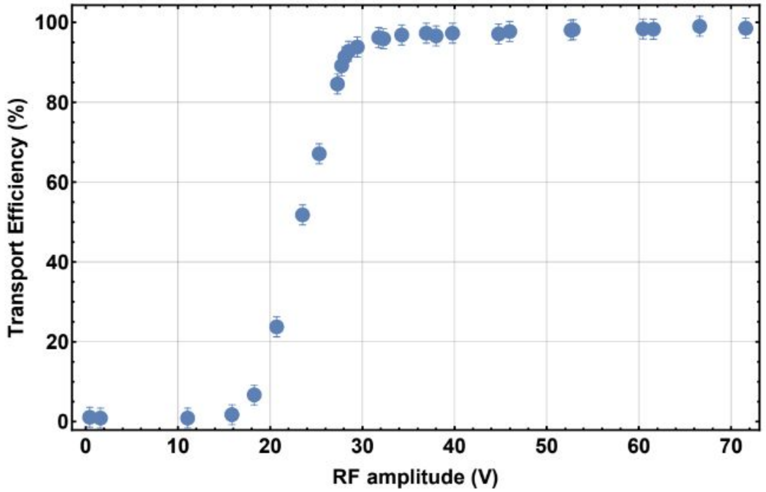


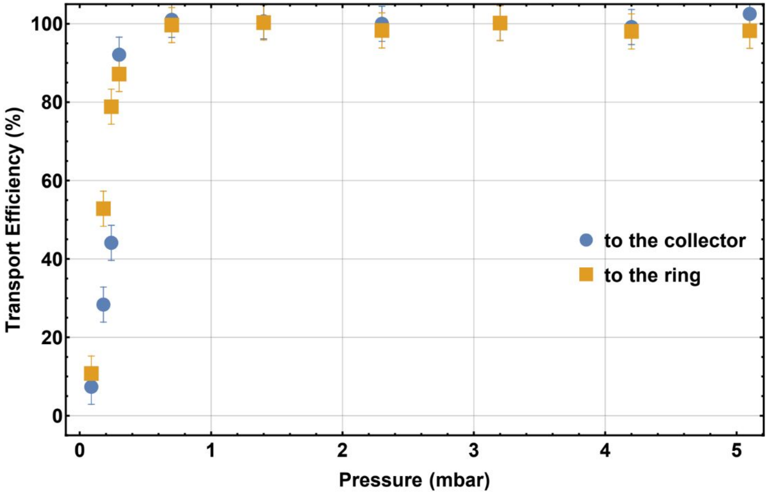
Differential Pumping





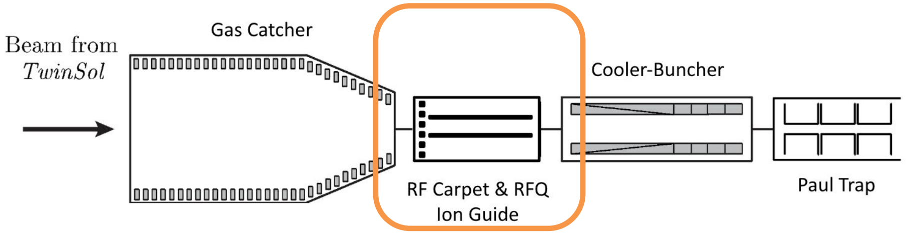


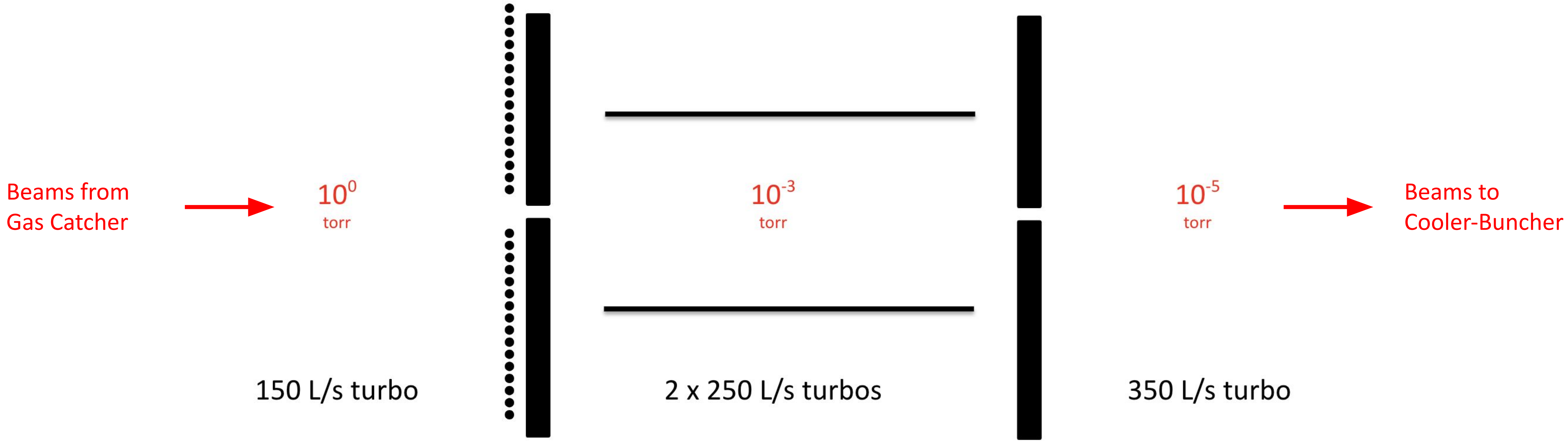




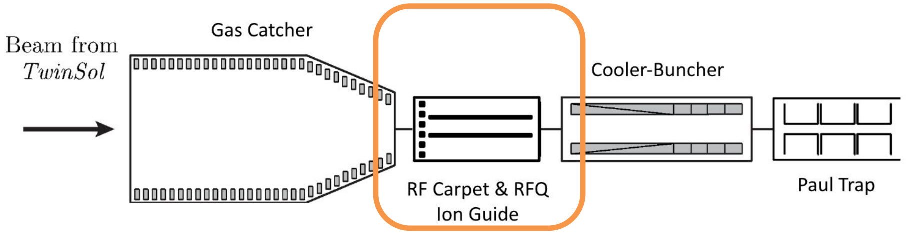
Commissioning of the St. Benedict RF Carpet: C. Davis *et. al.*, NIM A **1042**, 167422 (2022)

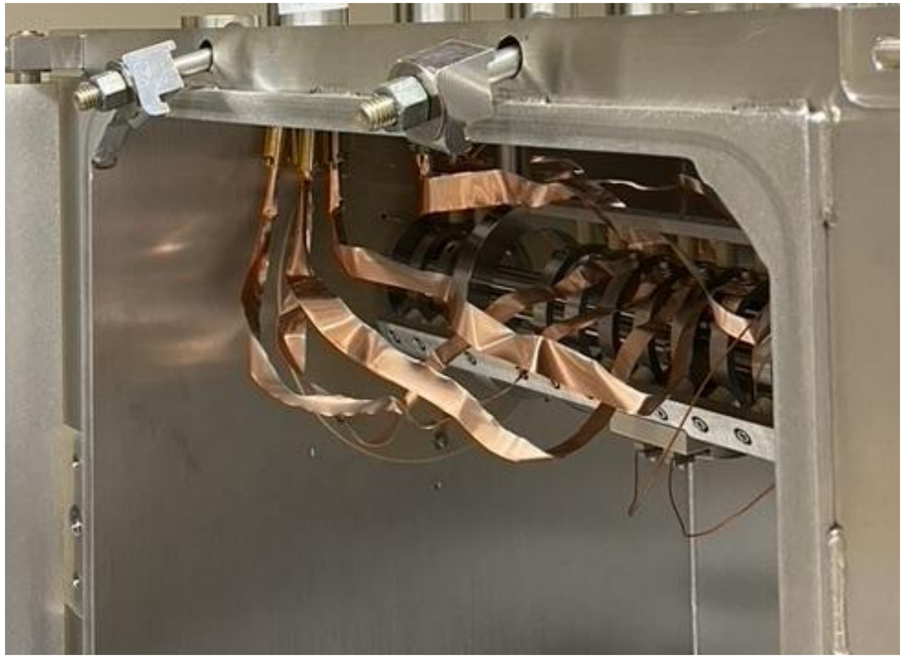
Differential Pumping

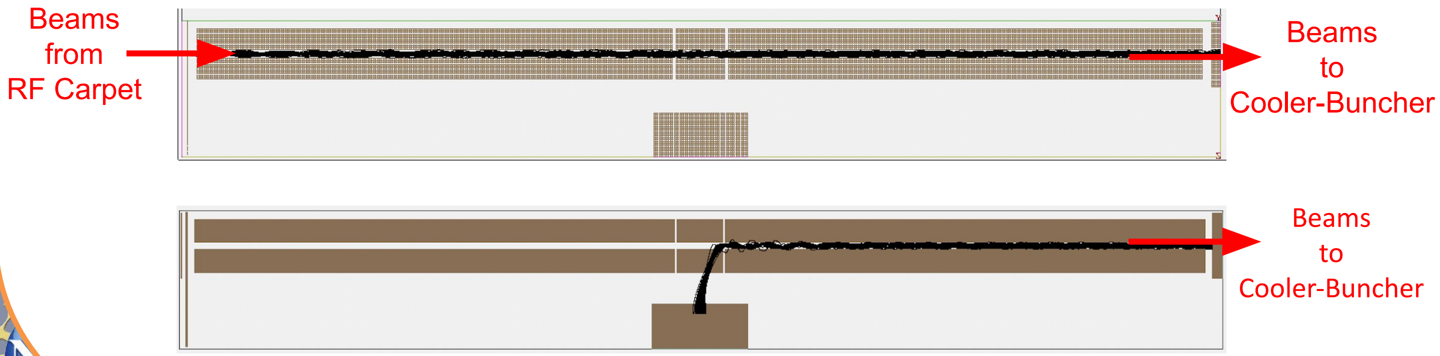


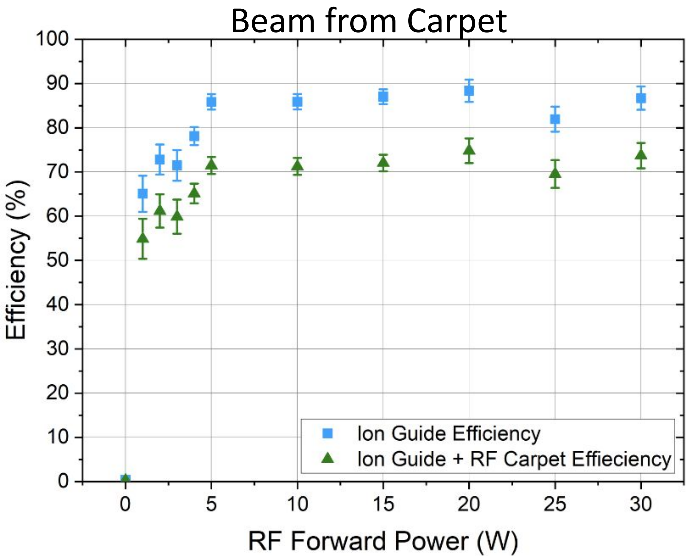


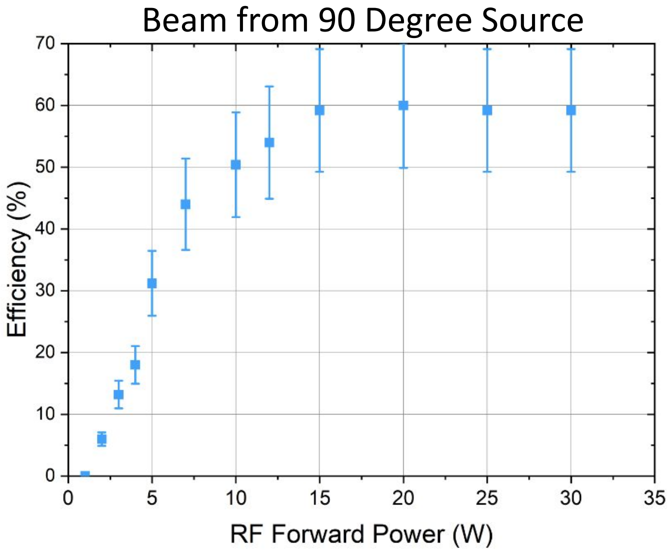
Differential Pumping



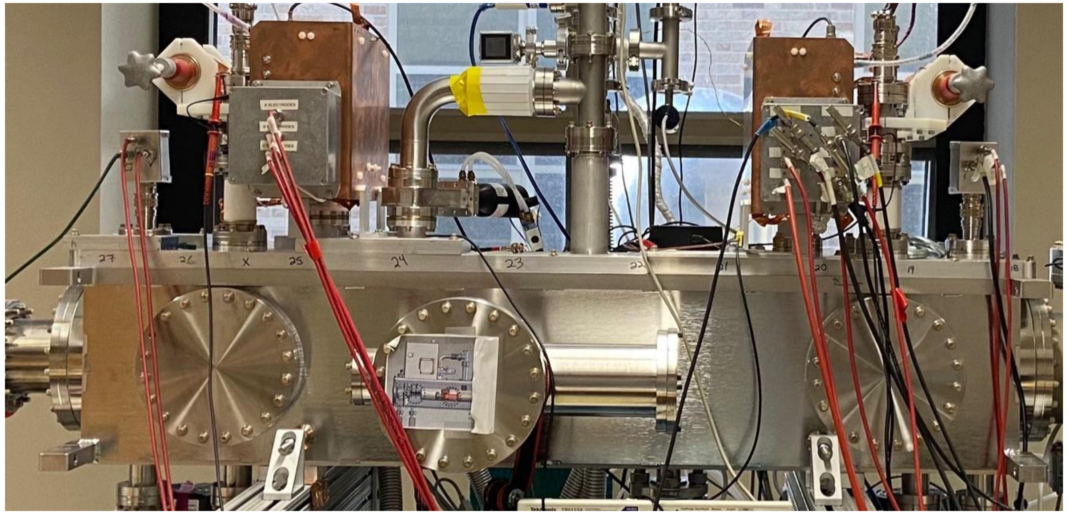


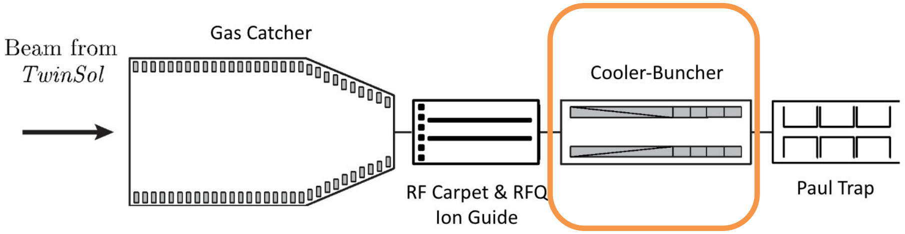


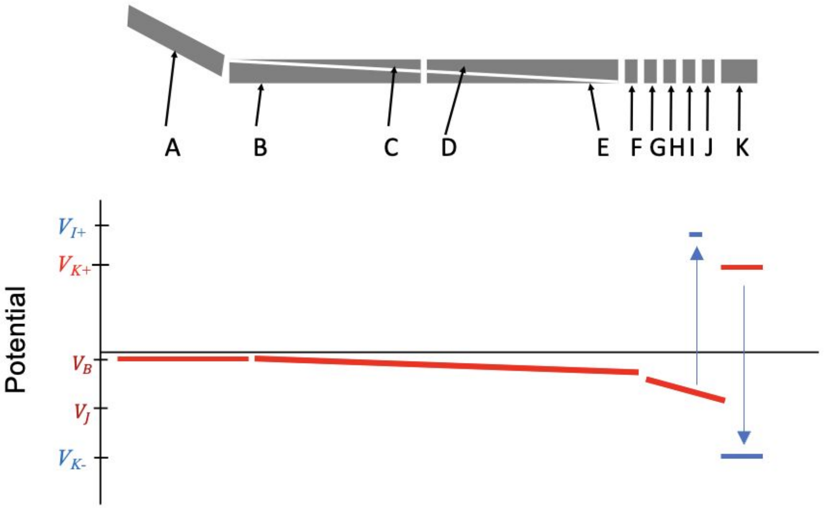




Cooler Buncher







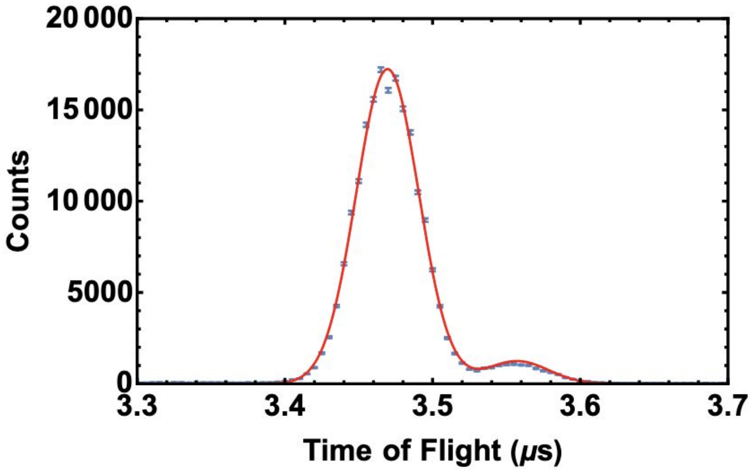
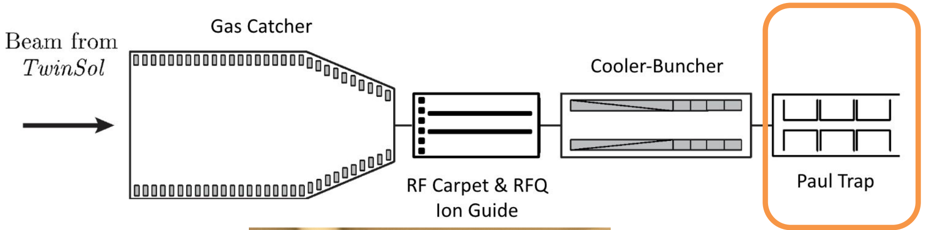


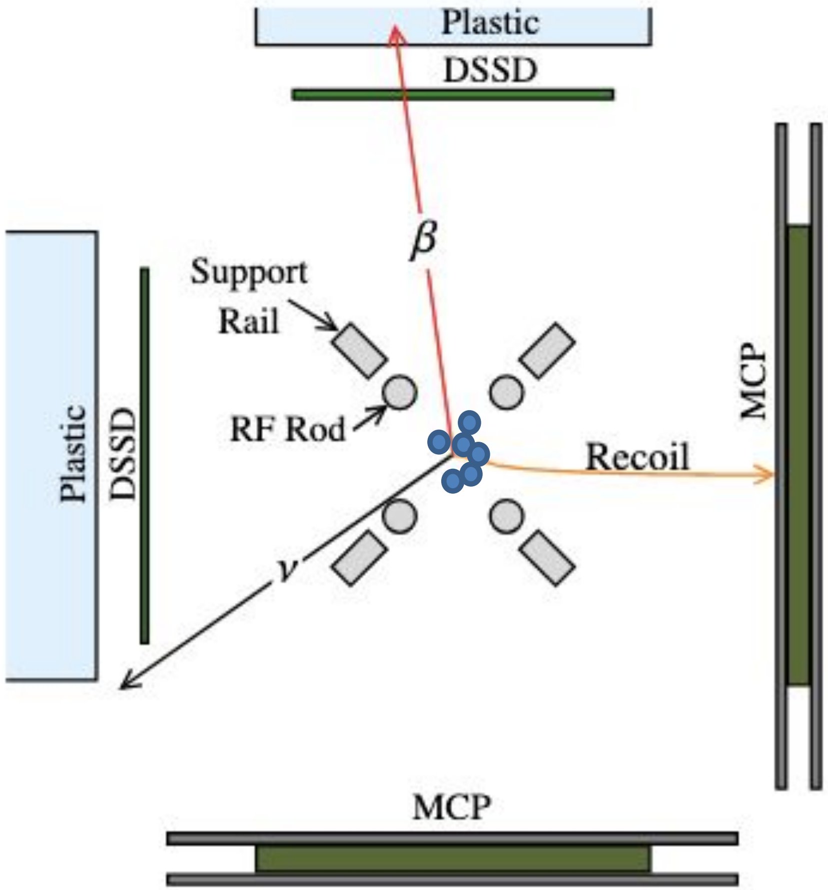
Figure 18: The sum of 10,000 consecutive bunches ejected from the cooler-buncher obtained by the MCP detector directly downstream of the chamber. The fit, given in red, shows the two peak Gaussian fit matching the two masses coming from the ion source, $^{39}K^+$ and $^{41}K^+$, based on their separation and natural abundance.

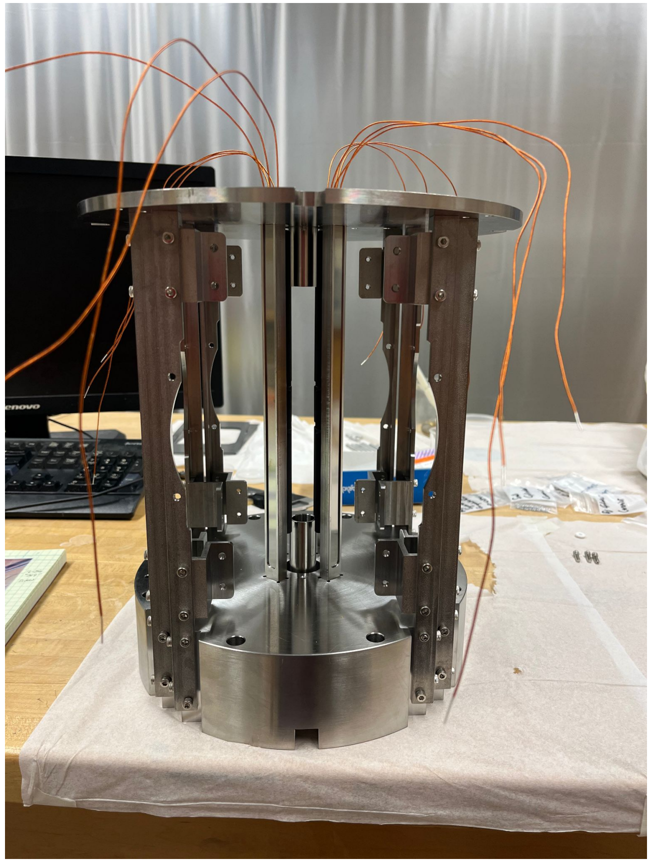
Trapping Efficiency: 93(1)%
FWHM: 50 ns

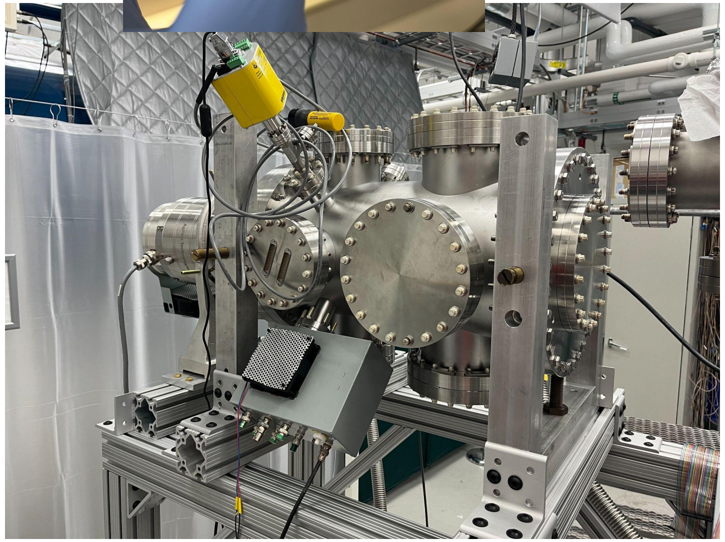
Off-line Commissioning of the St. Benedict Radiofrequency Quadrupole Cooler-Buncher, D. P. Burdette, *et. al.*, arXiv:2504.08021, 2025

Paul Trap


Beam from
TwinSol
Gas Catcher
RF Carpet & RFQ
Ion Guide
Cooler-Buncher
Paul Trap


Plastic
DSSD
β
Support
Rail
RF Rod
Recoil
MCP
Plastic
DSSD
ν
MCP





First Stopped RIBs with St. Benedict:
March - July 2024

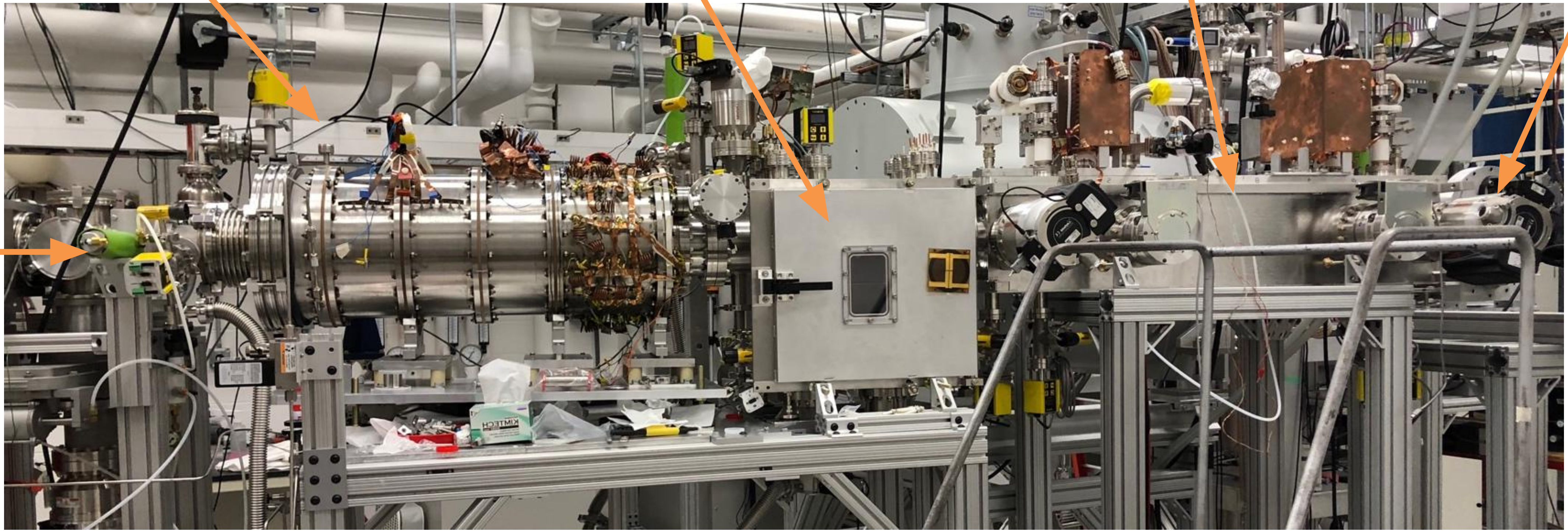
Gas Catcher

Differential Pumping Chamber

Cooler-Buncher

Location of MCP/Si

Beams from *TwinSol*



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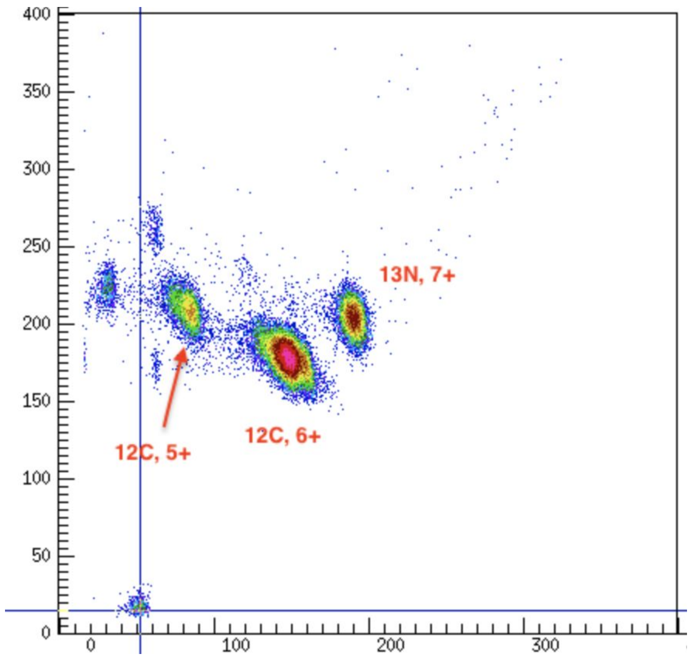
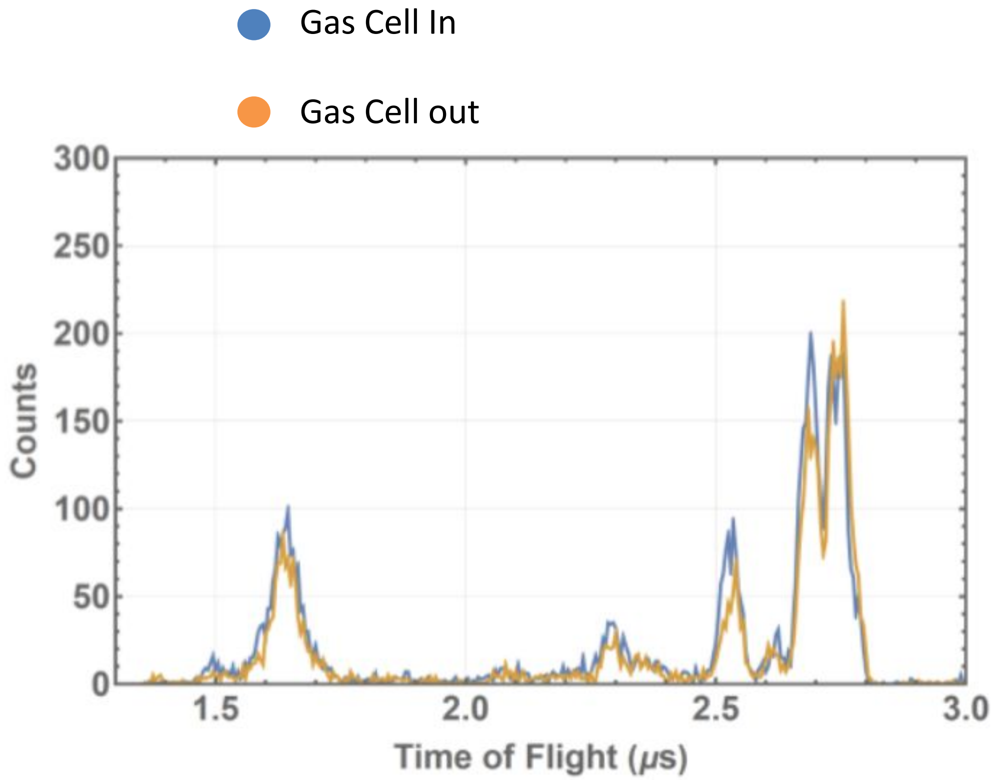
First Stopped RIBs with St. Benedict: March - July 2024

13N



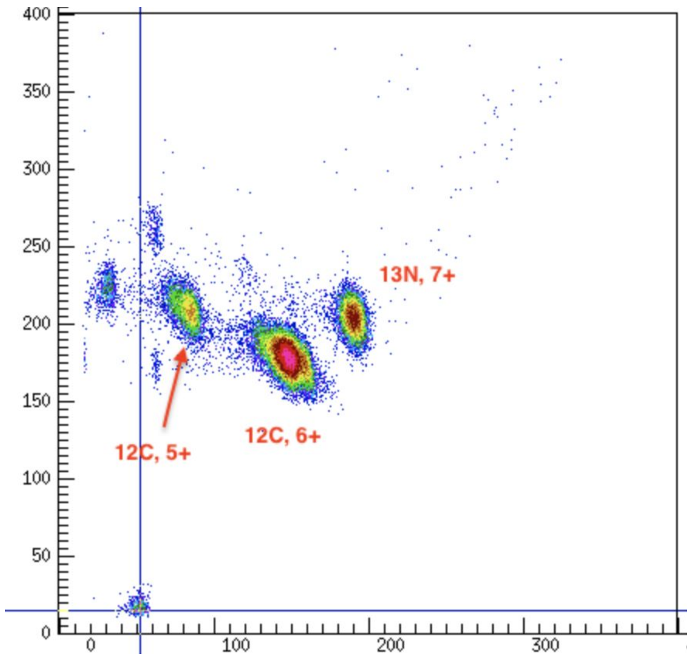
PID for 13N



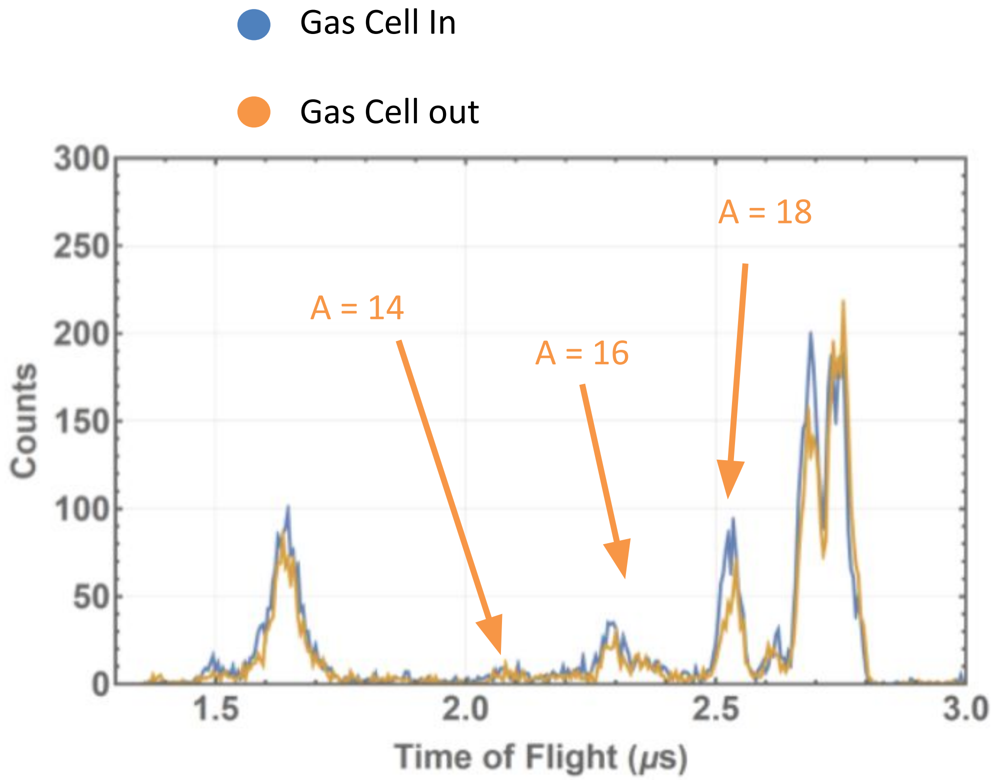
Can transport these beams through the cooler-buncher

First Stopped RIBs with St. Benedict: March - July 2024

13N



PID for 13N



Can transport these beams through the cooler-buncher

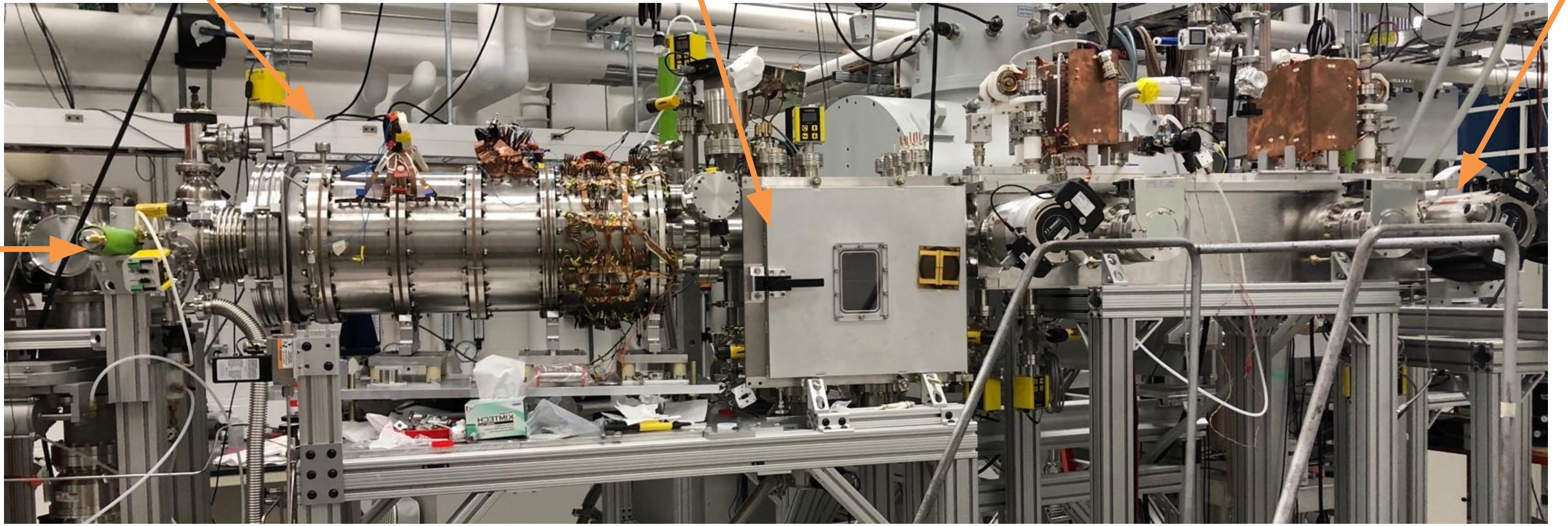
Where is the RIB?

Gas Catcher

New Location of Si

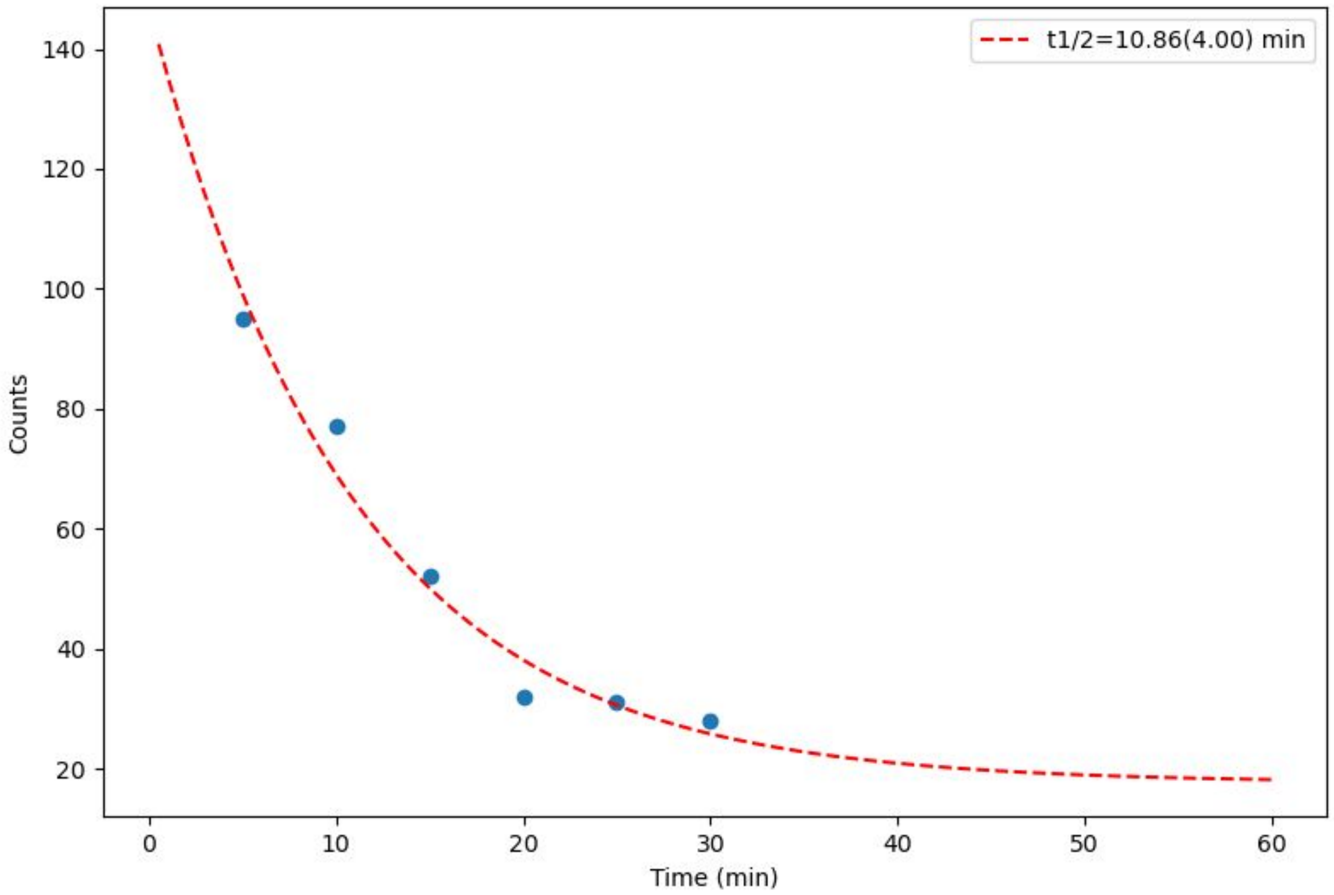
Location of MCP/Si

Beams from *TwinSol*



First Extracted RIB with St. Benedict Gas Catcher

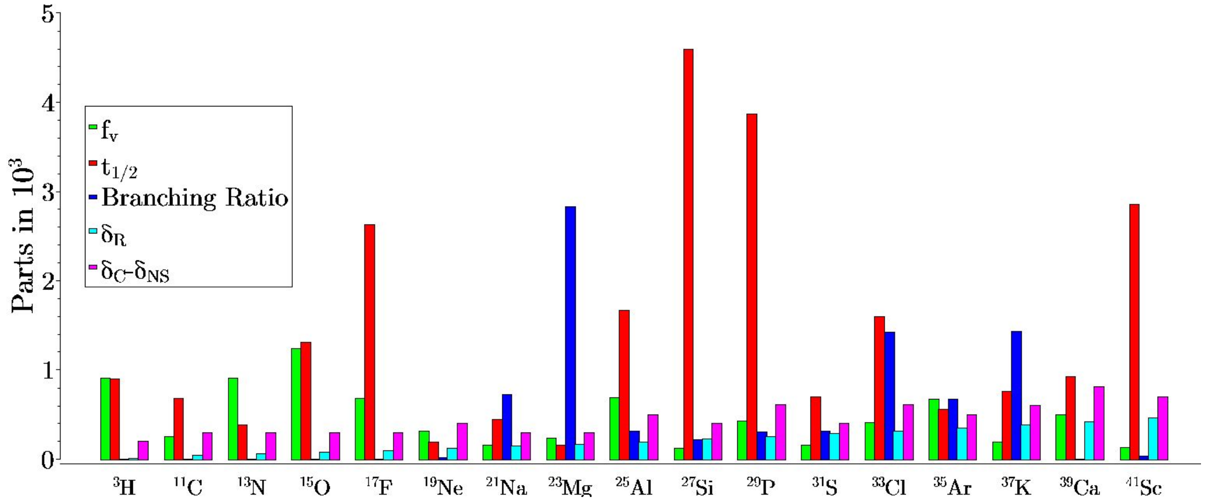
^{13}N: NNDC $t_{1/2}$ = 9.967 min



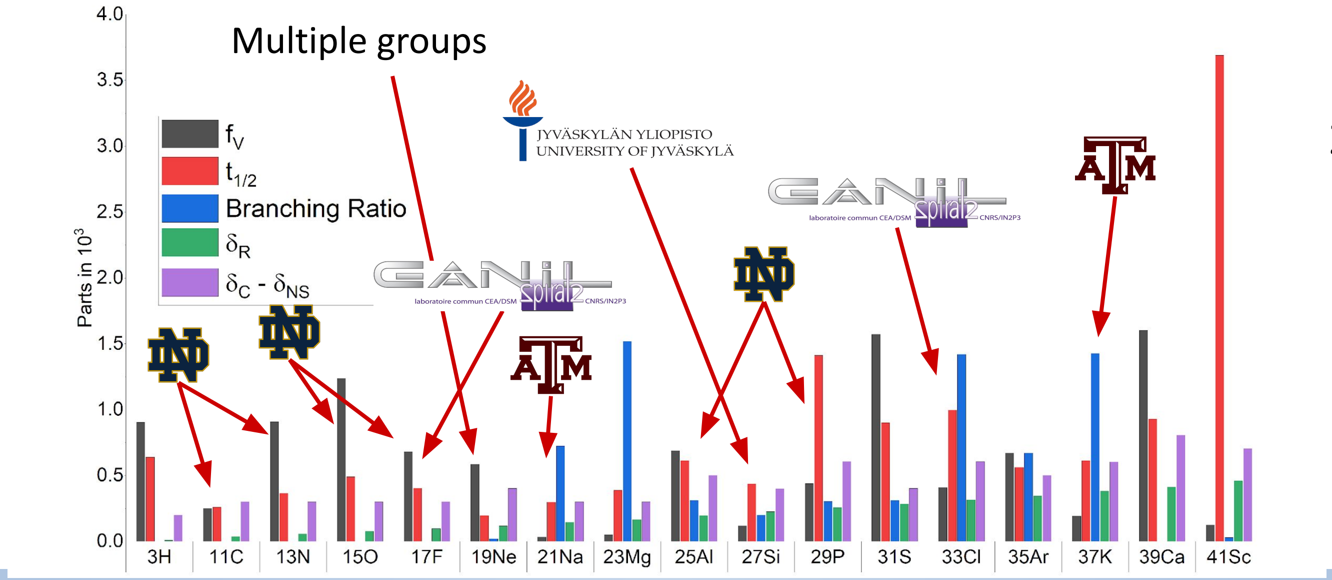
- Very low count rate, at about 0.2 counts/s
- Hard to tune system with a 10 minute half life
- Next steps: Stop and extract more isotopes!

Half Life Campaign at Notre Dame

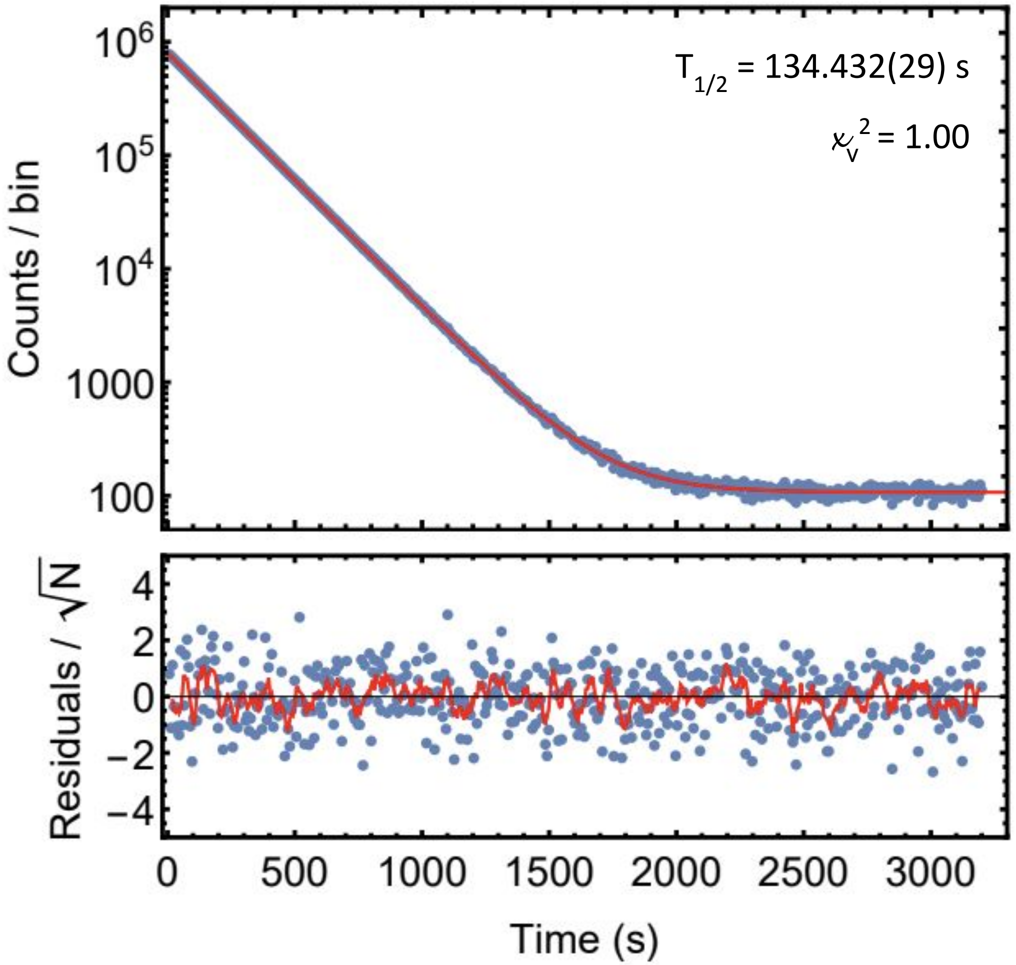
2015 relative uncertainties



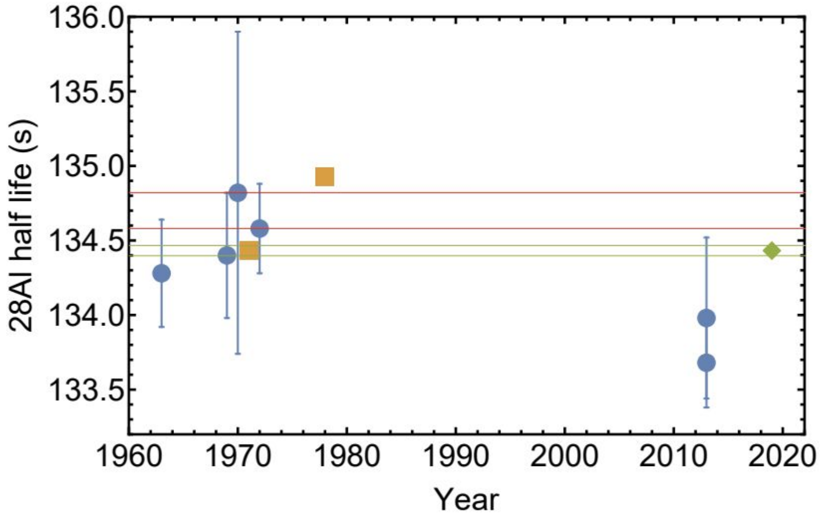
2023 relative uncertainties



^{28}Al Half Life Measurement

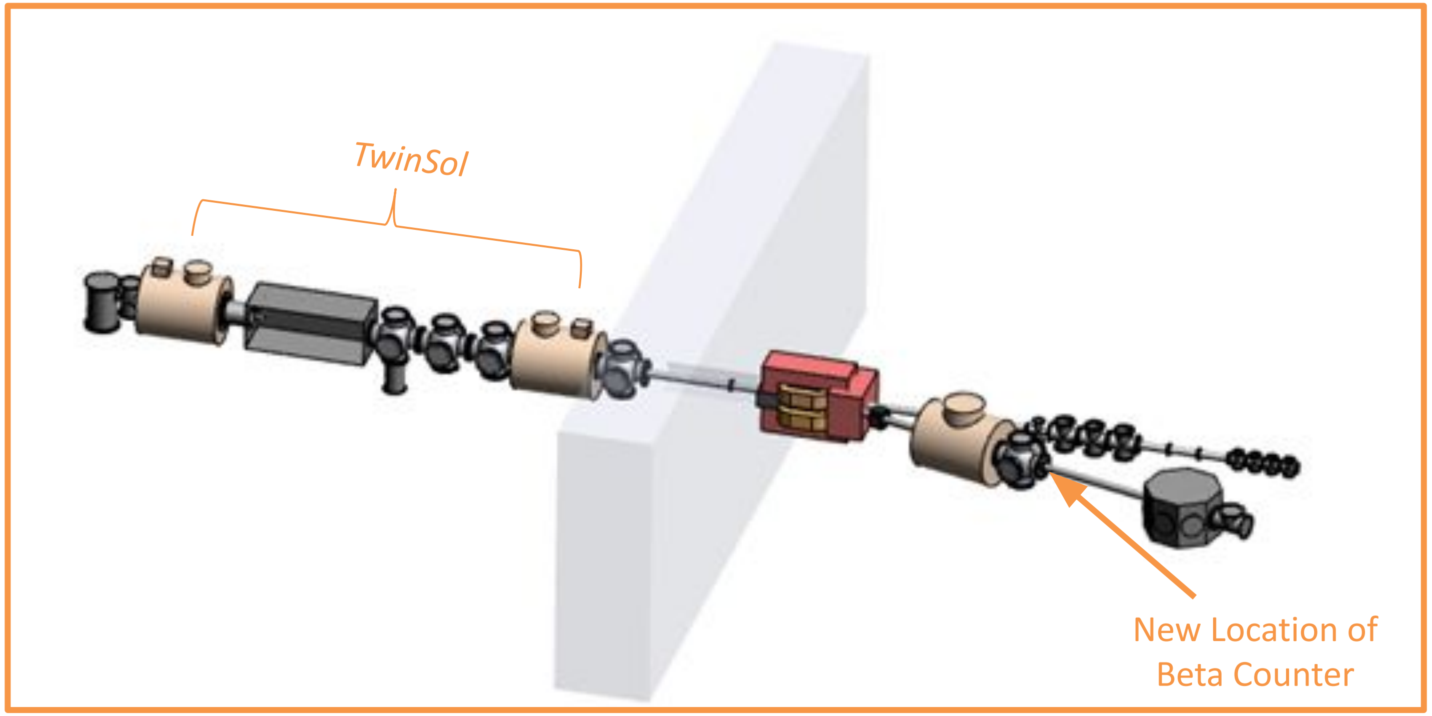


Fitting techniques used from:
V.T. Koslowsky *et al.*, NIM A **401**, 289 (1997)



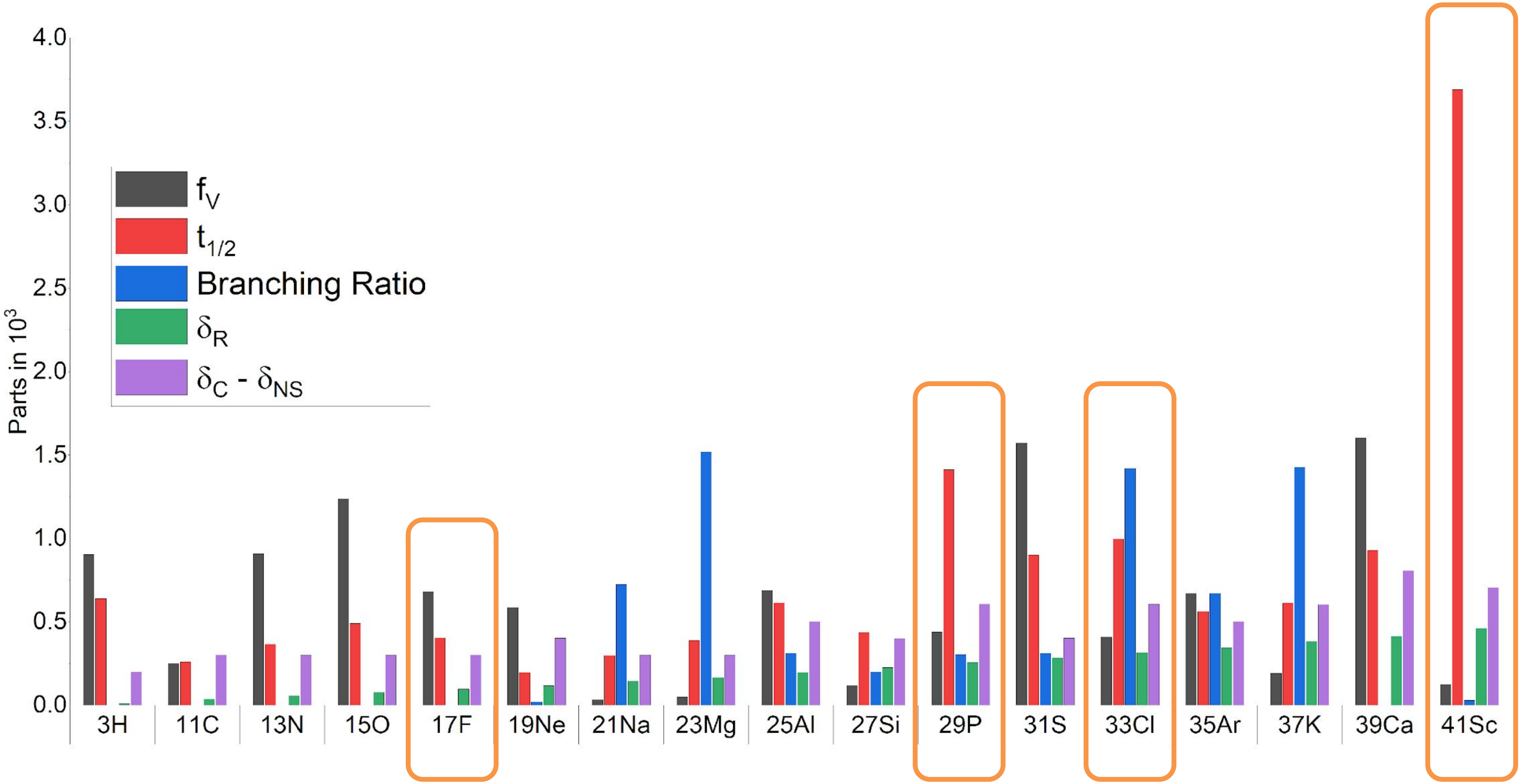
28Al Half-life Measurement and the negative mirror asymmetry between the ^{28}Al(β−)^{28m}Si and ^{28}P(β+)^{28m}Si decays, B. Liu, *et. al.,* arXiv:2505.01722

The Next Year of Half Life Measurements



Use of the 15° switching magnet and the third solenoid allows us to better select our isotope of interest and focus it on the target

The Next Year of Half Life Measurements



In Summary

- Extracting V_{ud} from mirror transitions will allow us to test the tension with unitarity of the CKM matrix
- St. Benedict aims to measure $a_{\beta\nu}$ for a suite of nuclear mirrors ranging from ^{11}C to ^{41}Sc
- A half-life campaign at Notre Dame has been ongoing to reduce uncertainties that contribute to the extraction of V_{ud} from these isotopes
- Expected half-life measurements in the next year: ^{33}Cl, ^{41}Sc, ^{17}F, ^{29}P
- St. Benedict is expected to take its first measurement by summer 2026

Acknowledgements

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Aaron Gallant
Alicen Houff

Jim Kolata
Biying Liu
Jacob Long
Jakob McRea
Patrick O'Malley
Sam Porter

Caleb Quick
Ryan Ringle
Fabio Rivero
Guy Savard
Adrian Valverde
Abe Yeck

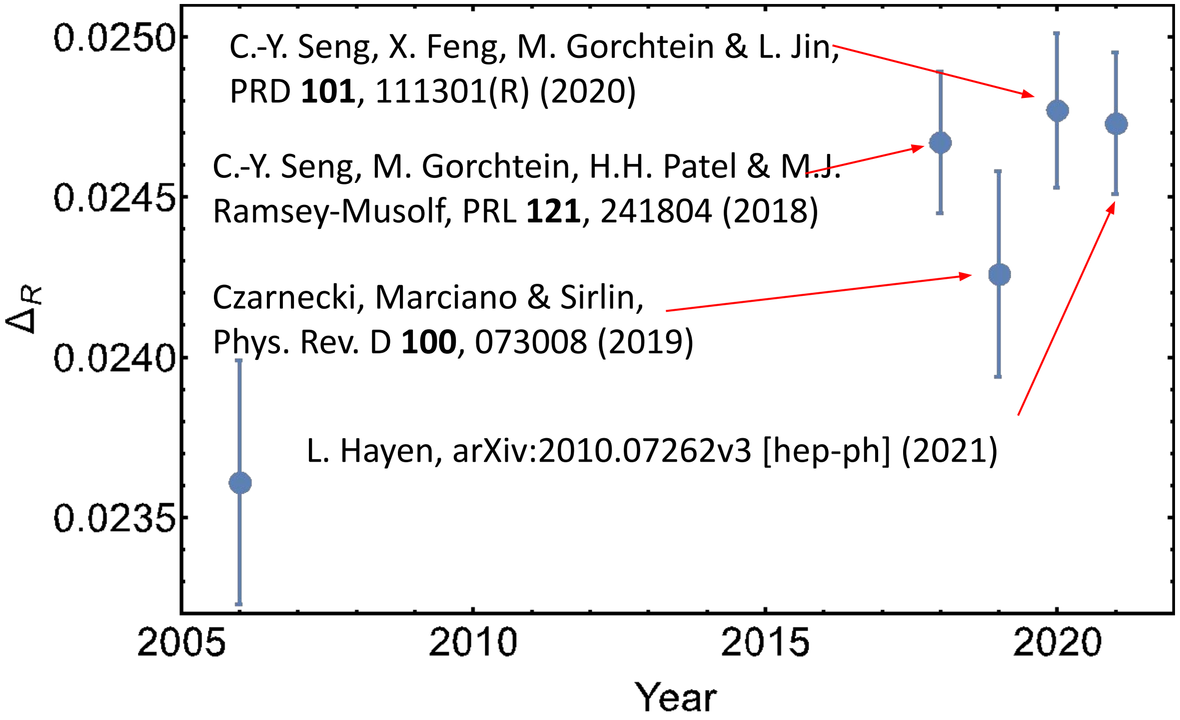
+ rest of *twinsol* collaboration

UG students
G students
Former G students

Backup Slides

Recent values for nuclear radiative corrections have routinely measured higher than previous measurements

$$\mathcal{F}t^{(0^+\to 0^+)} \equiv ft(1+\delta_R)(1+\delta_{NS}-\delta_C) = \frac{K}{2G_F^2 V_{ud}^2(1+\Delta_R^v)}$$



$V_{ud} = 0.97370(25)$ → 2020 H&T

$V_{us} = 0.2245(8)$

$V_{ub} = 0.00382(24)$

} 2020 PDG

$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2$

= 0.9985(6)

2.5σ tension with unitarity

Backup Slides

Nucleus	n	^{3}H	^{11}C	^{13}N	^{15}O	^{17}F	^{19}Ne
ρ	-2.20	-2.10	0.75	0.56	-0.63	-1.28	1.60
J	1/2	1/2	3/2	1/2	1/2	5/2	1/2
$\delta A_\beta/A_\beta$	4.0	5.1	0.04	0.04	0.7	-0.06	-12.6
$\delta a_{\beta\nu}/a_{\beta\nu}$	3.6	4.6	-1.2	-0.7	-0.9	-3.6	-13.1

Table I. Calculated sensitivities to $\delta\rho/\rho$ for the lowest mass mirrors, with approximate ρ values taken from [10] and the leading order expressions.

L. Hayen & A.R. Young, arXiv:2009.11364 (2020)

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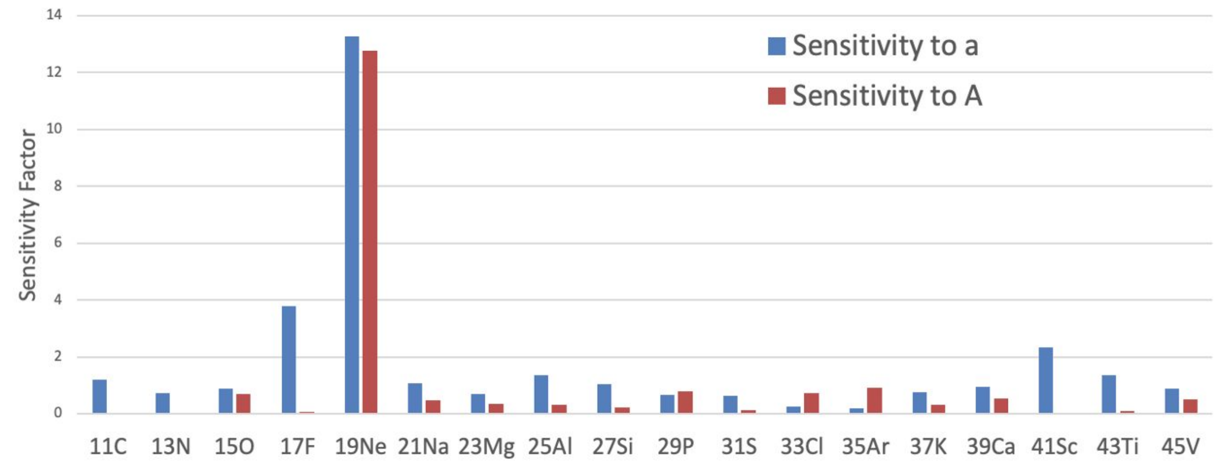
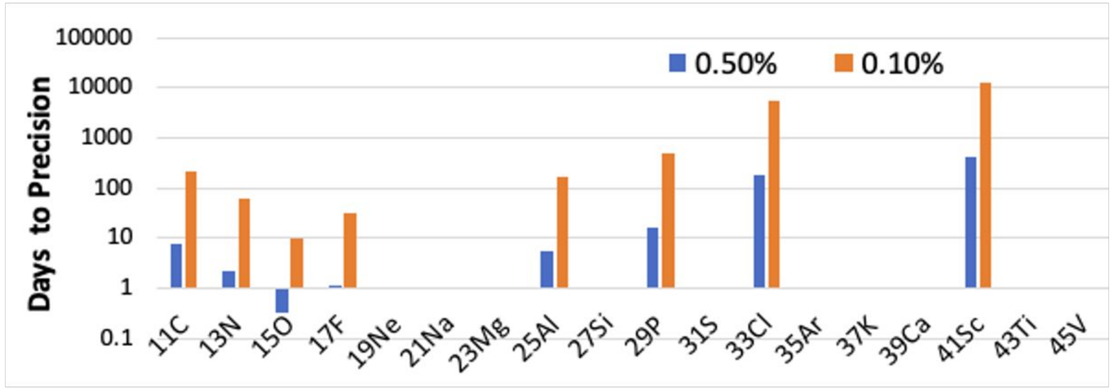
Established *TwinSol* production rates

Isotope	Half-life (s)	Rate (pps/pμA)
^{11}C	1221.8(8)	2.4×10^5
^{13}N	597.9(2.4)	8.1×10^5
^{15}O	122.24(12)	5.0×10^6
^{17}F	64.49(16)	1.5×10^6
^{25}Al	7.183(12)	3.0×10^5
^{29}P	4.142(15)	1.0×10^5
^{33}Cl	2.511(4)	9.0×10^3
^{41}Sc	0.5963(17)	4.0×10^3



Sensitivity of ρ to measurable quantities



TwinSol beam days to given δa/a

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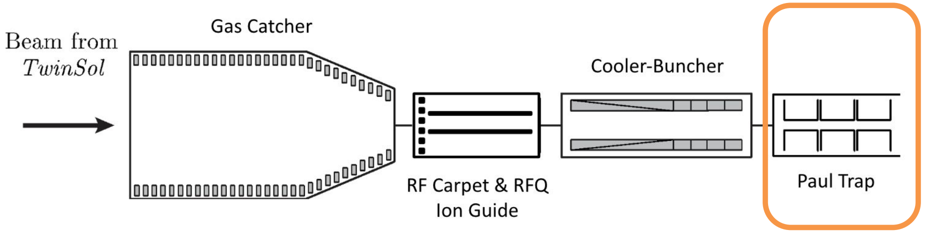
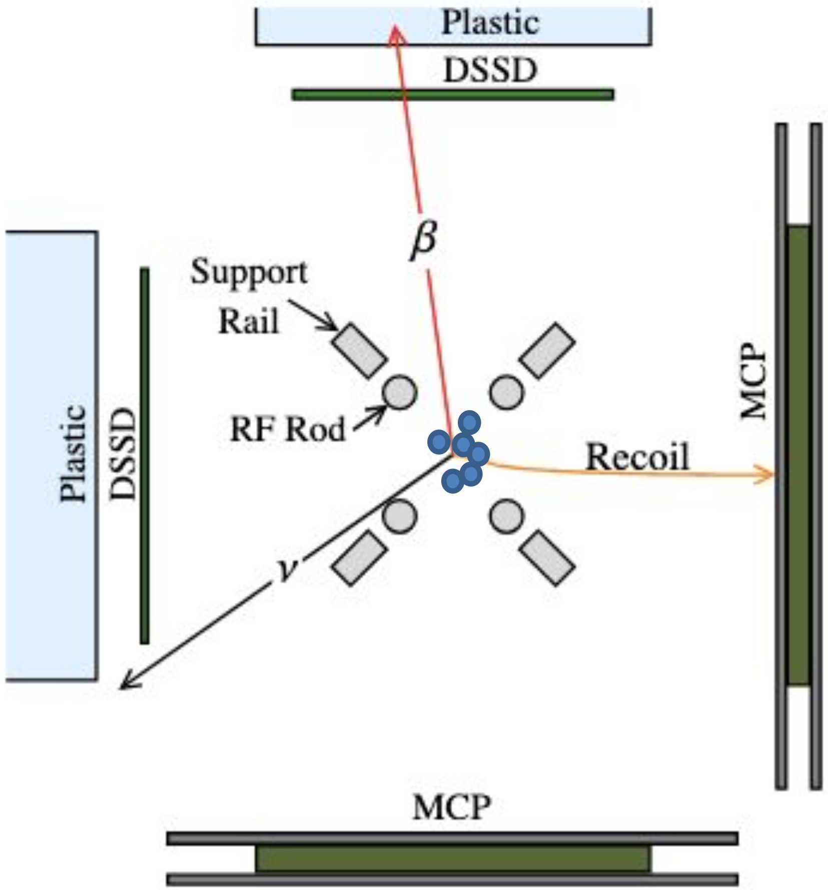
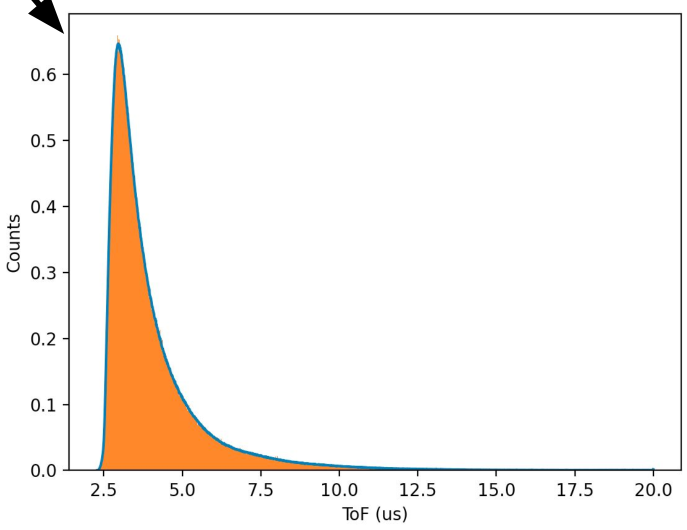




$t_1 - t_2 = \Delta t$



$$W \propto F(Z,E_e)p_eE_e(E_0-E_e)^2[1+a_{\beta\nu}\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_eE_\nu}+b\frac{m_e}{E_e}]$$

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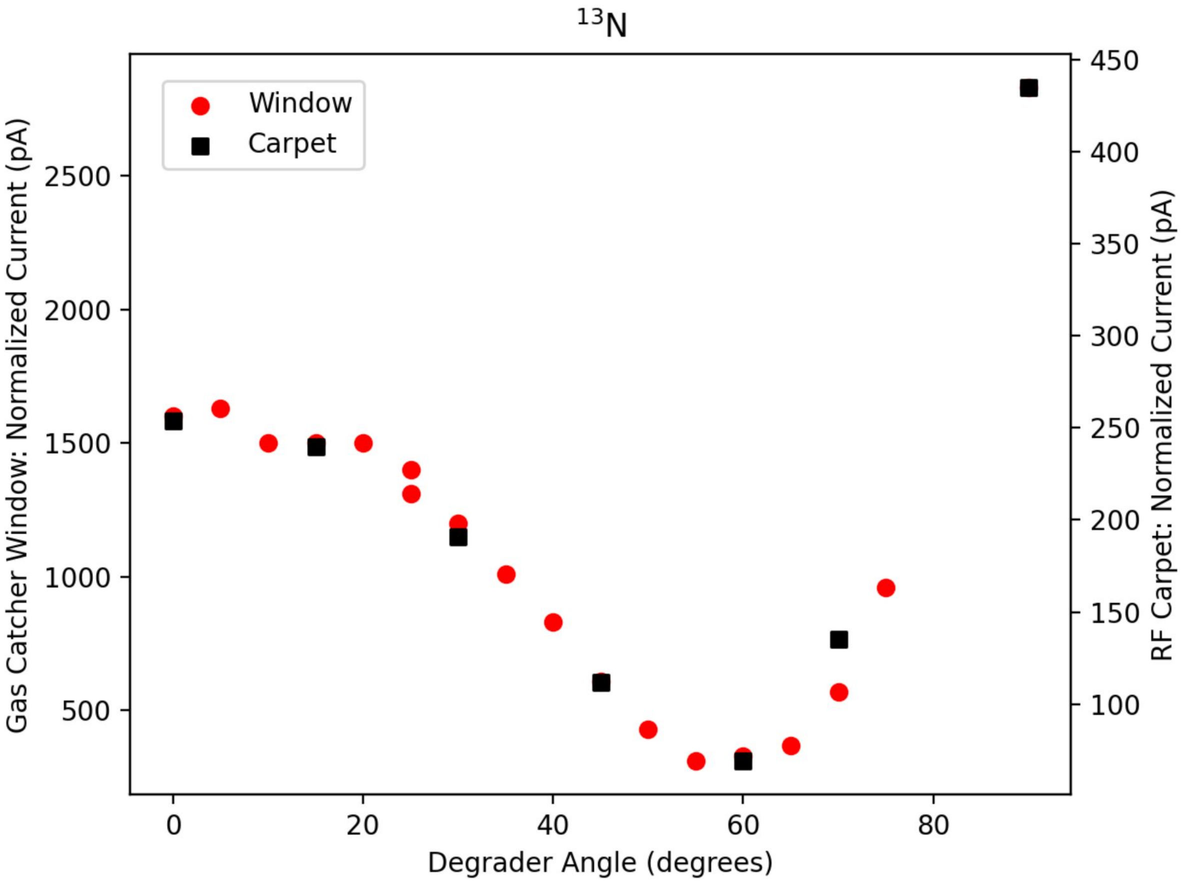

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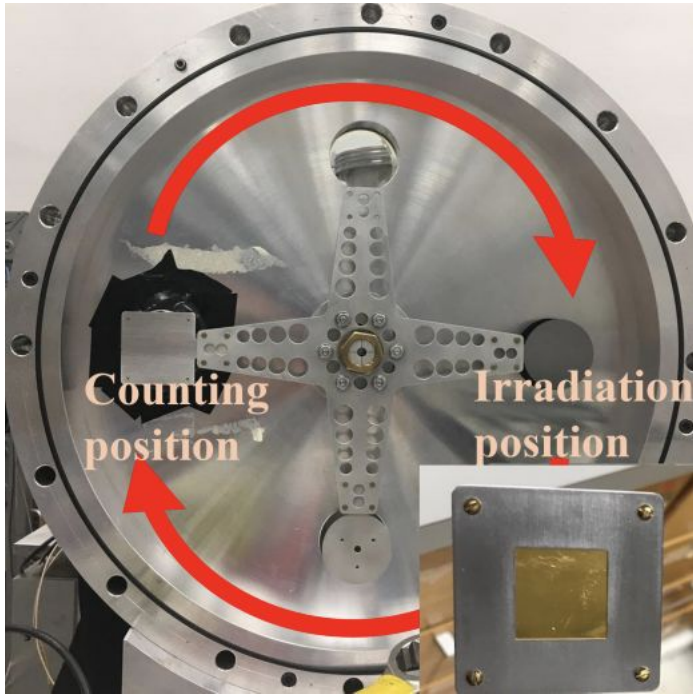

Typical procedure:

1. Implant ion beam on a Au foil for ~3 $t_{1/2}$.
2. Deflect beam entering tandem.
3. Rotate foil in front of 1 mm plastic scintillator coupled to a PMT.
4. Count for ~25 $t_{1/2}$.
5. Rotate back to implant position, turn on the beam and repeat.