Probing the Standard Model via Mixed Mirror Transitions with St. Benedict

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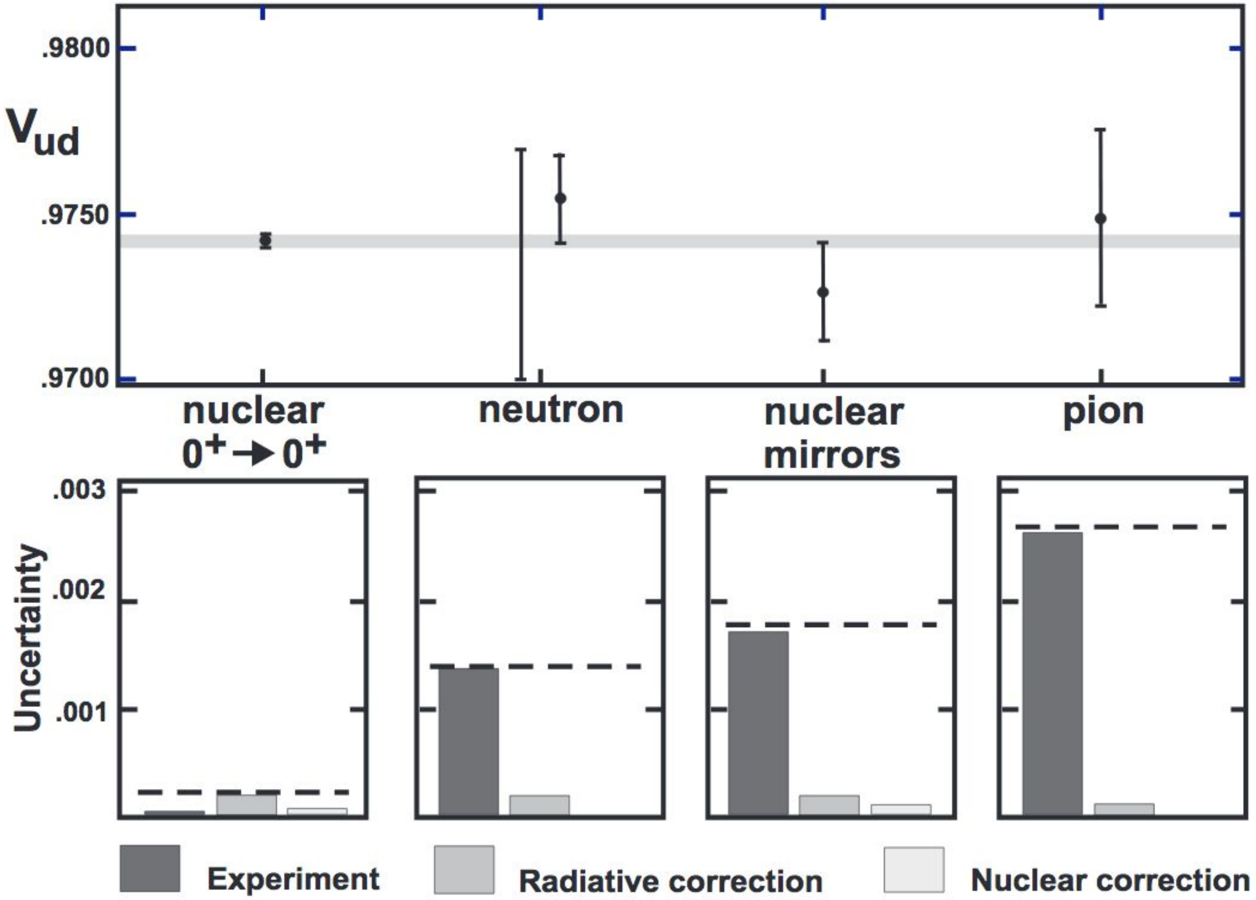
University of Notre Dame

INT Workshop: *Testing the Standard Model in Charged-Weak Decays*
January 14, 2026

Outline

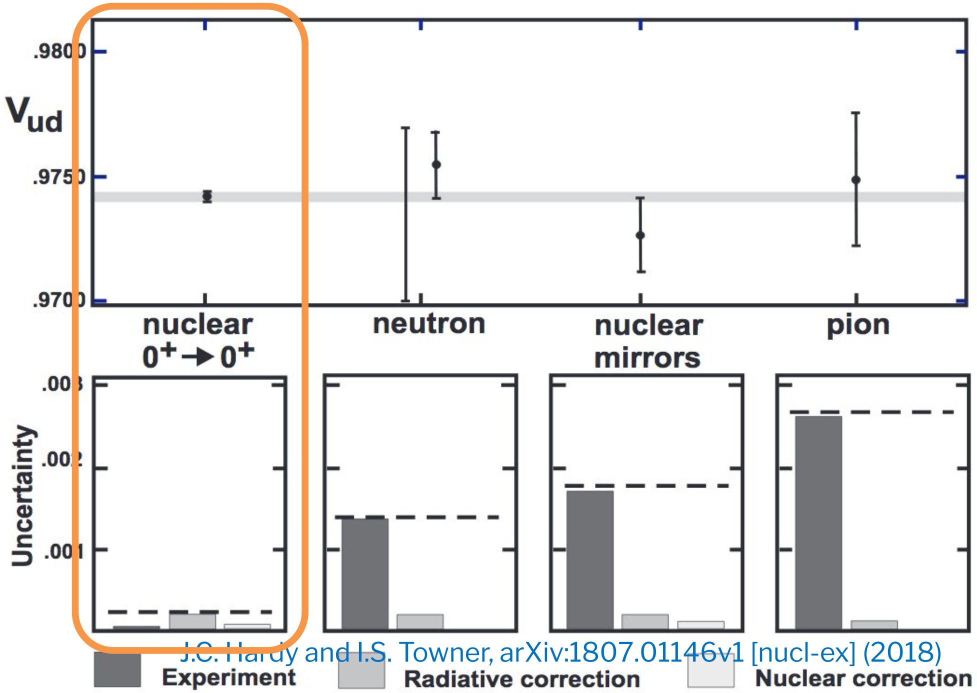
- V_{ud} from mixed mirror transitions
- Producing RIBs at the Nuclear Science Lab
- St. Benedict, overview and experimental results
- Half-life campaign at Notre Dame

Extracting V_{ud}



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

V_{ud} from Ft Values



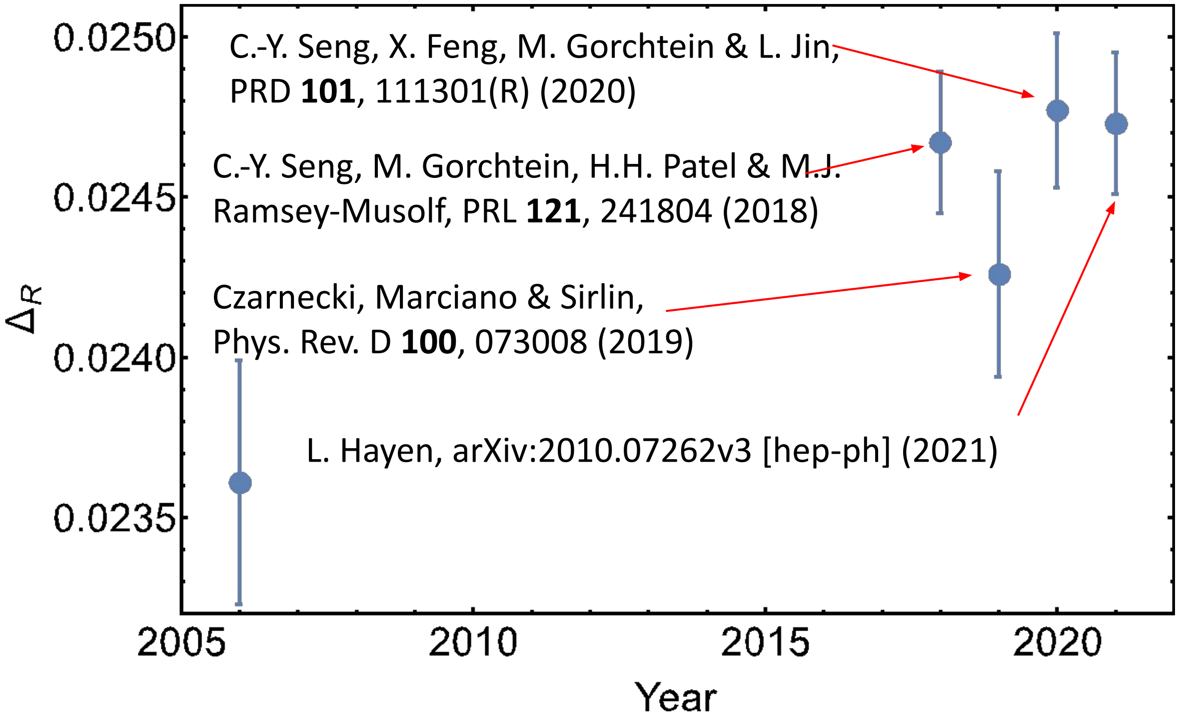
J.C. Hardy and I.S. Towner, arXiv:1807.01146v1 [nucl-ex] (2018)

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

Theoretical Correction Terms

Recent values for nuclear radiative corrections have routinely measured higher

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



$V_{ud} = 0.97370(25)$ → 2020 H&T

$V_{us} = 0.2245(8)$

$V_{ub} = 0.00382(24)$

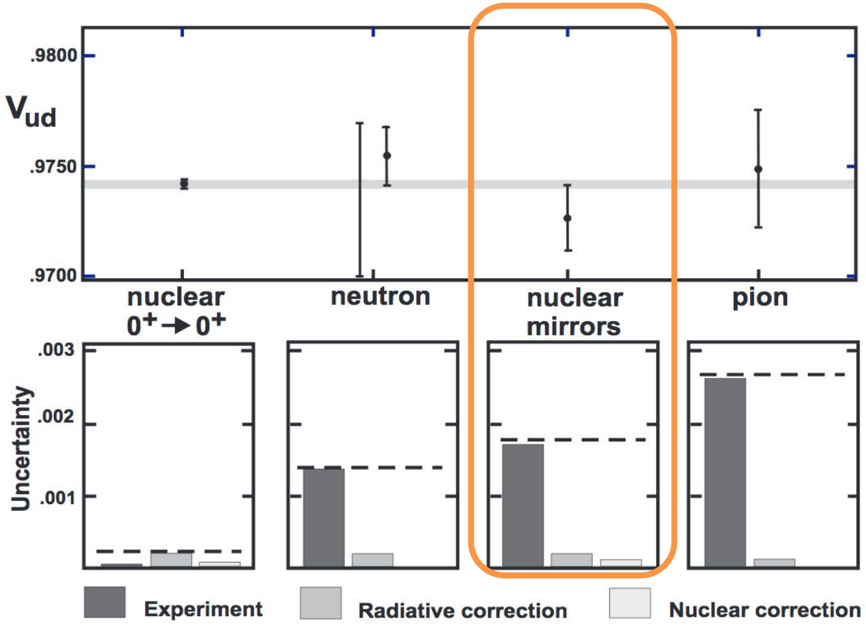
} 2020 PDG

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

= 0.9985(6)

~2.5σ tension with unitarity

V_{ud} from Nuclear Mirrors



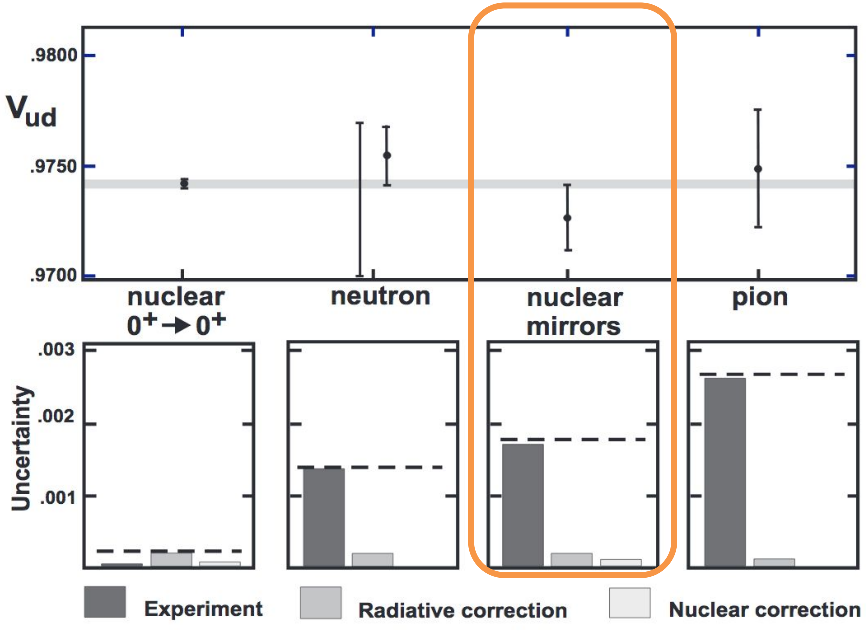
J.C. Hardy and I.S. Towner, arXiv:1807.01146v1 [nucl-ex] (2018)

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

Requires many of the same values as their pure Fermi counterparts

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

V_{ud} from Nuclear Mirrors



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

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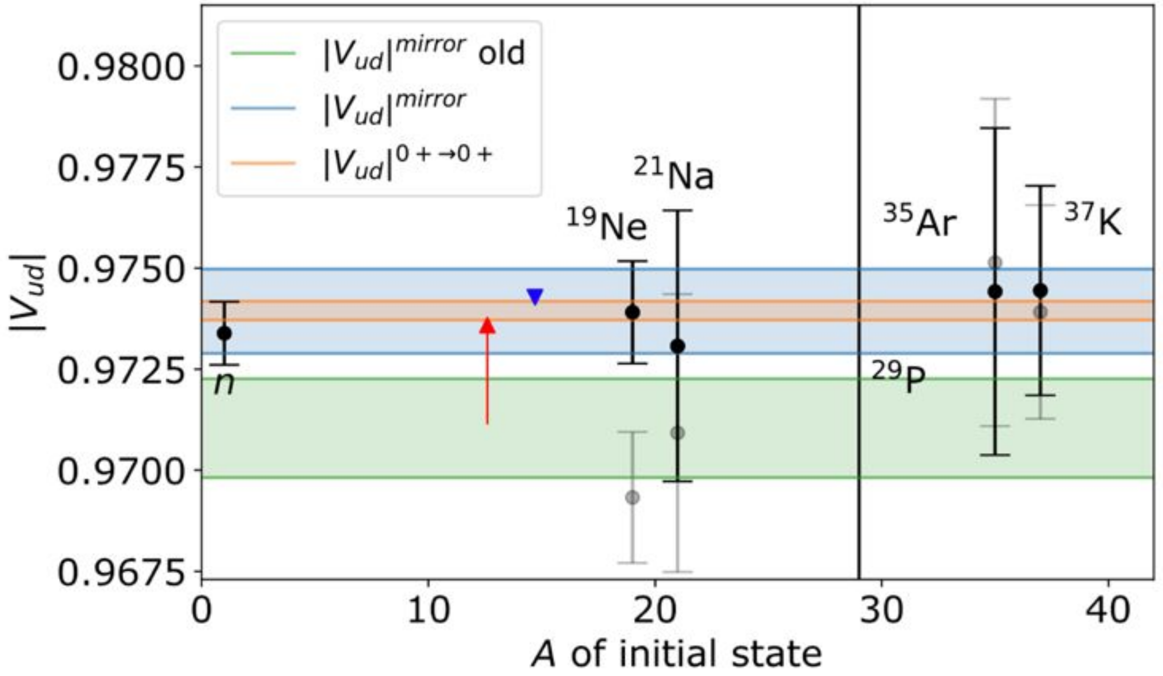
V_{ud} from Nuclear Mirrors

V_{ud} from mirror transitions is currently 6x less precise than $0^+ \rightarrow 0^+$



L. Hayen, PRD **103**, 113001 (2021)

- ϱ is only known for 5 nuclei, can been determined via:
  - β asymmetry parameter A_β
  - ν asymmetry parameter B_ν
  - β-ν angular correlation $a_{\beta\nu}$

V_{ud} from Nuclear Mirrors

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

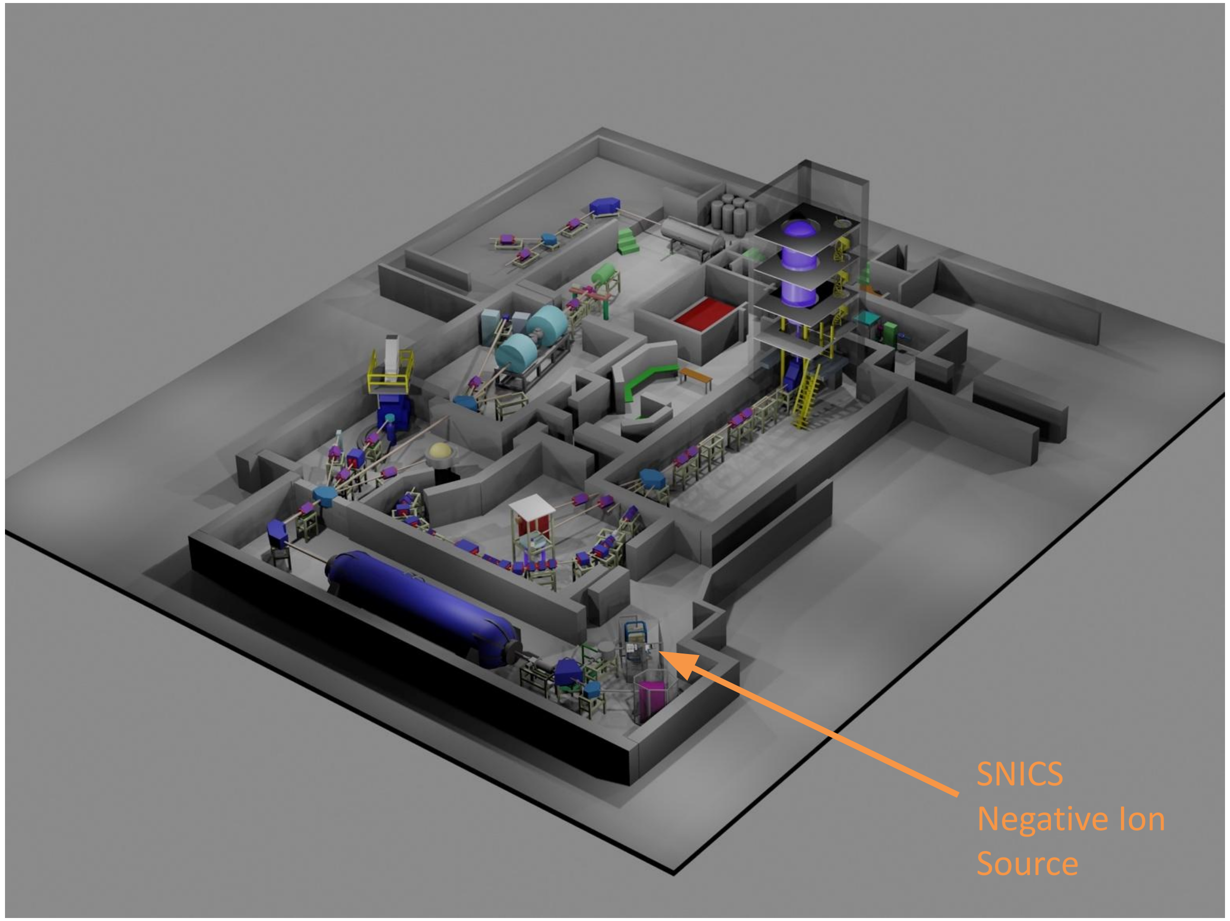
Table I. Calculated sensitivities to $\delta\rho/\rho$ for the lowest mass mirrors, with approximate ρ values taken from [10] and the leading order expressions.

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

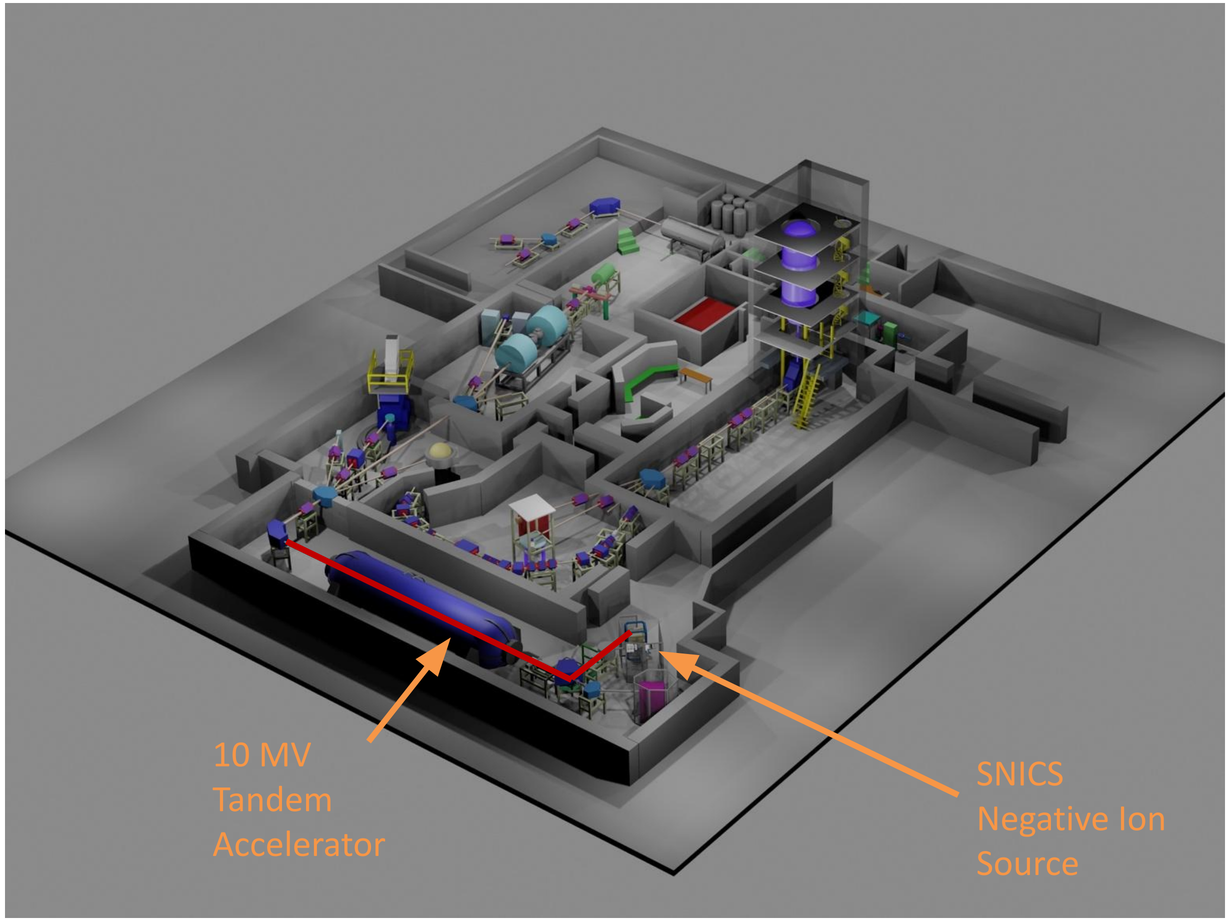
$$a_{\beta\nu} = \frac{1}{3}\left(\frac{3-\rho^2}{1+\rho^2}\right)$$

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

Producing RIBs at ND



Producing RIBs at ND



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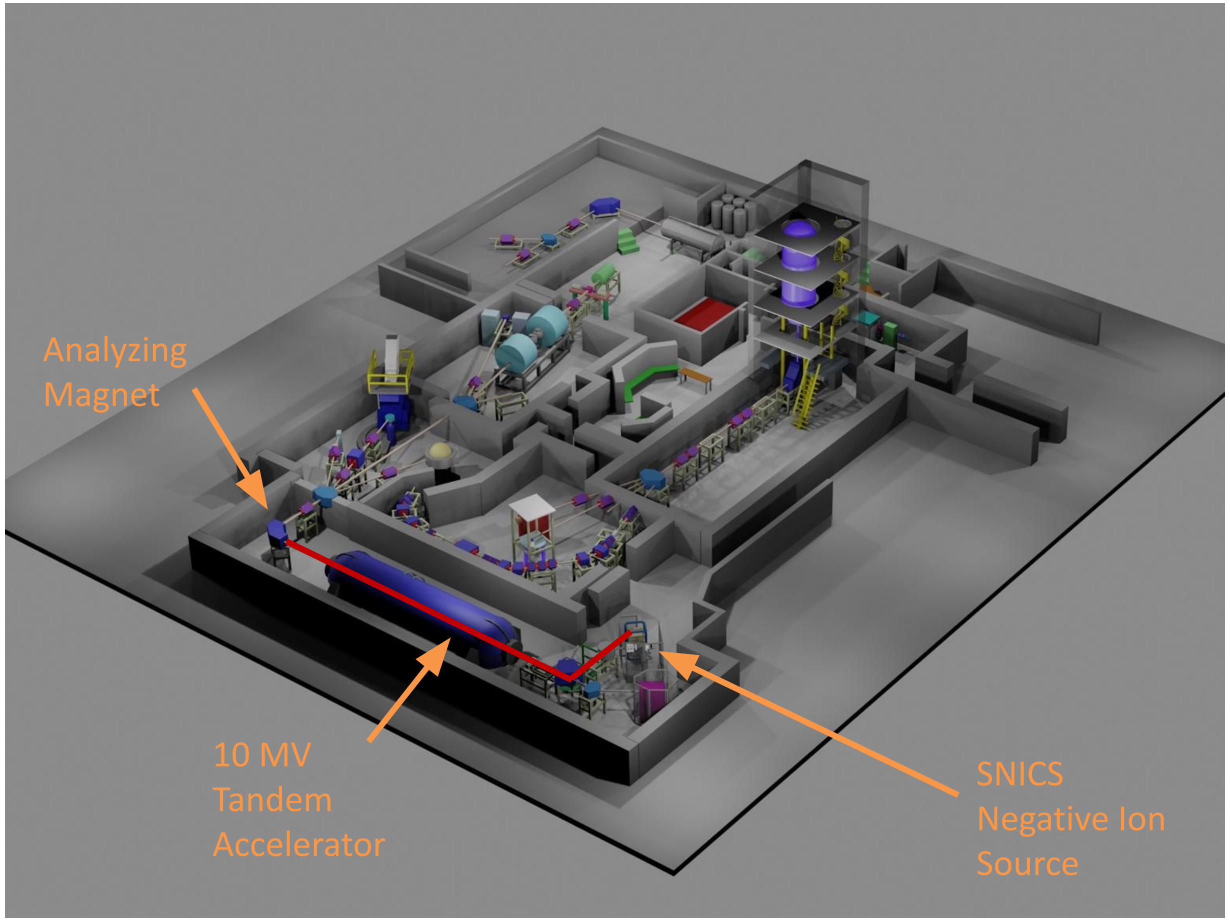

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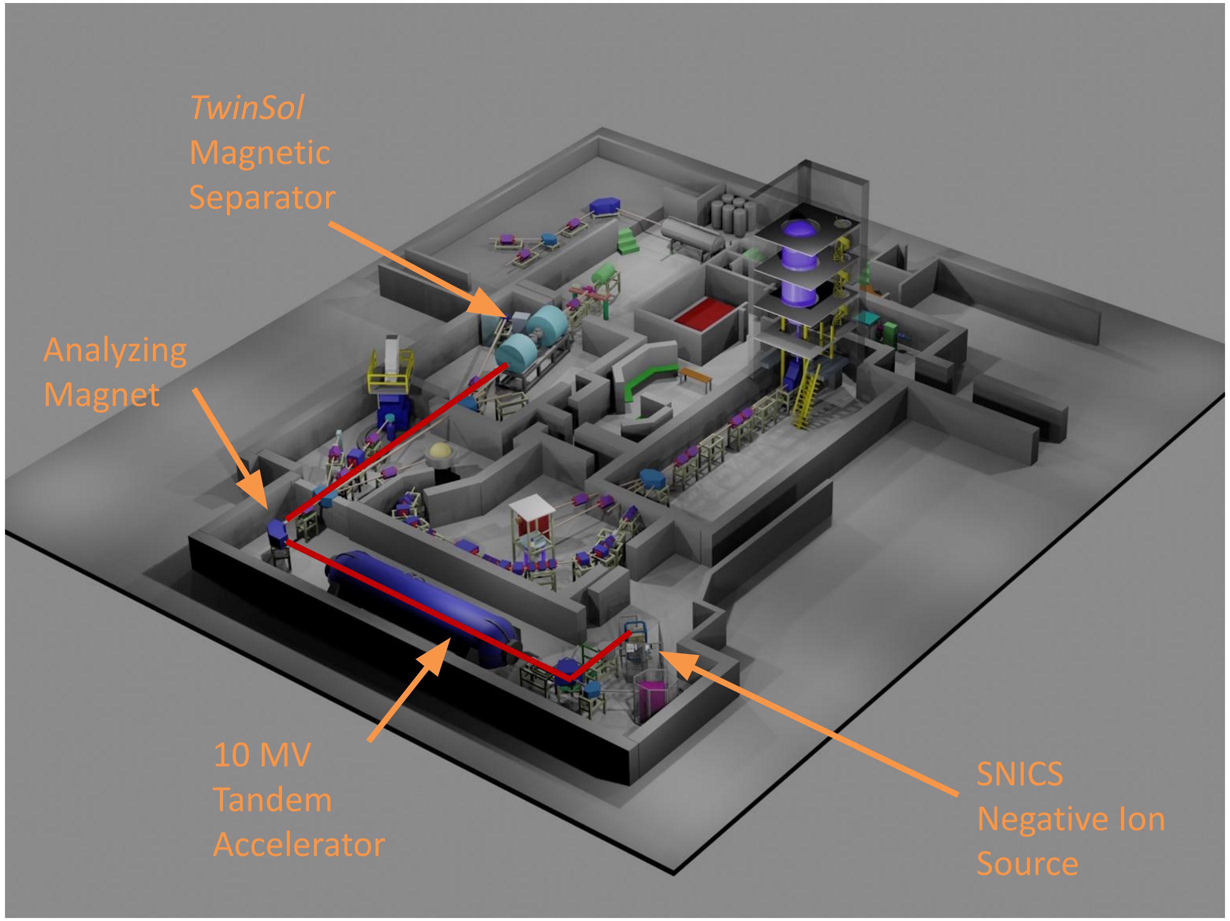
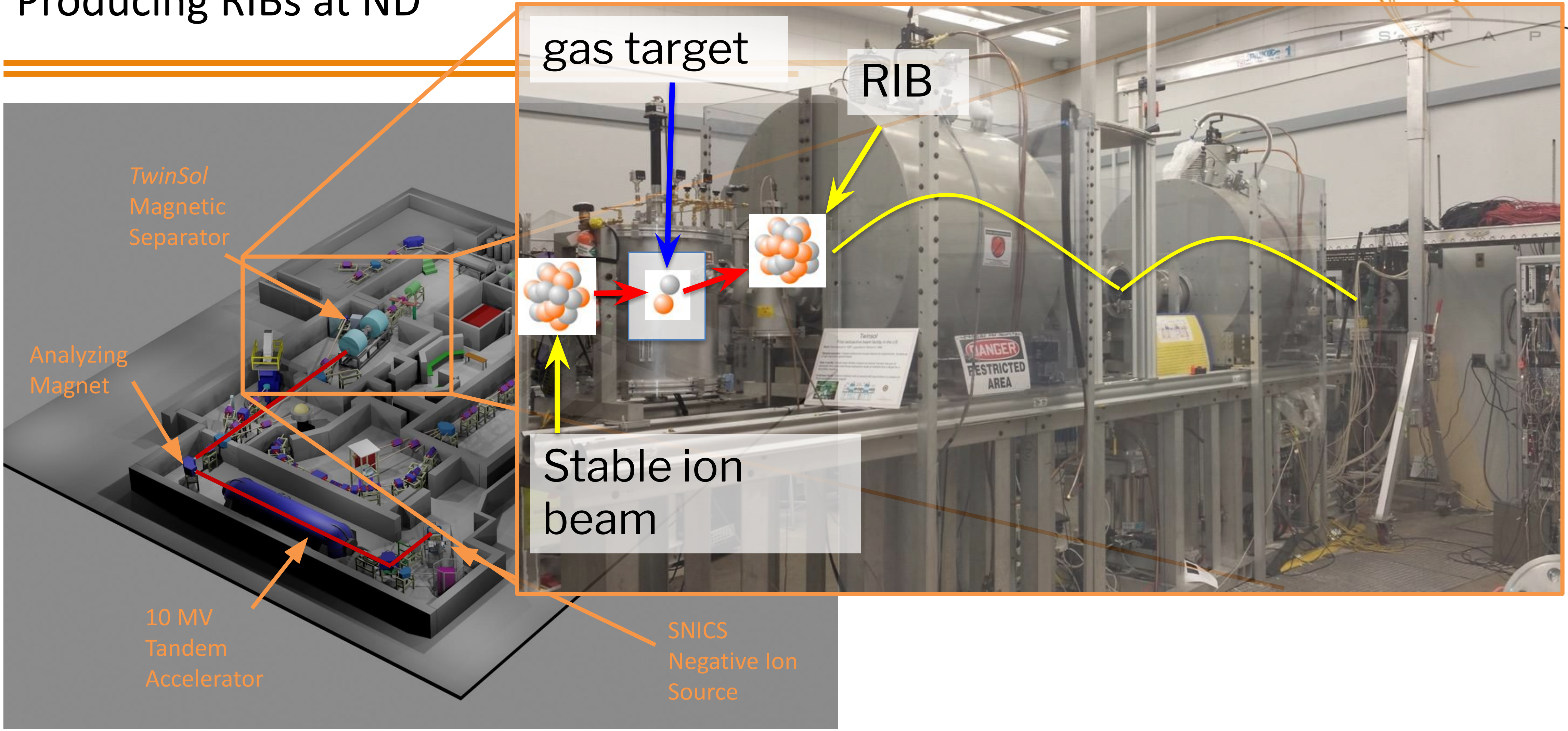
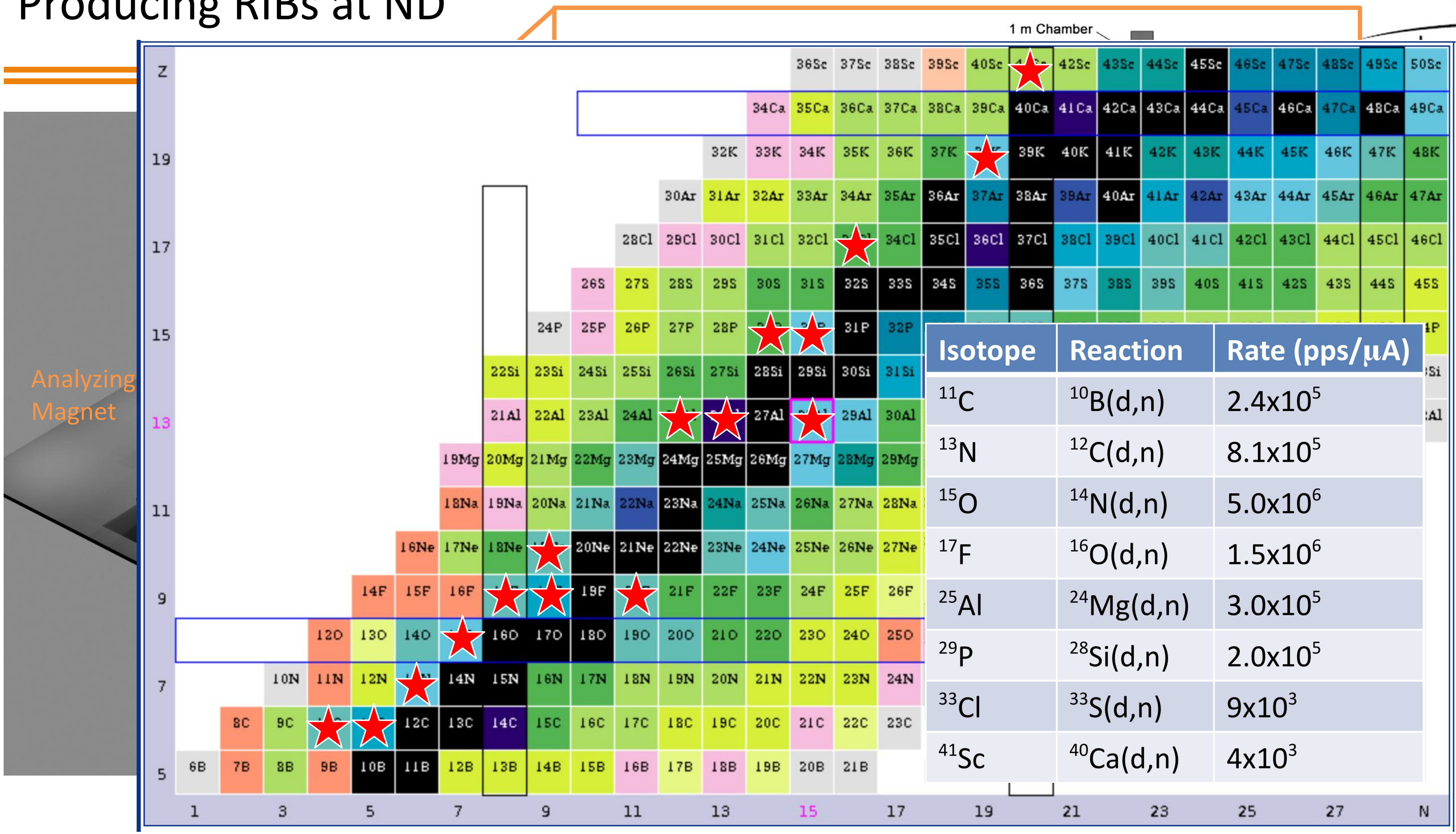


Producing RIBs at ND

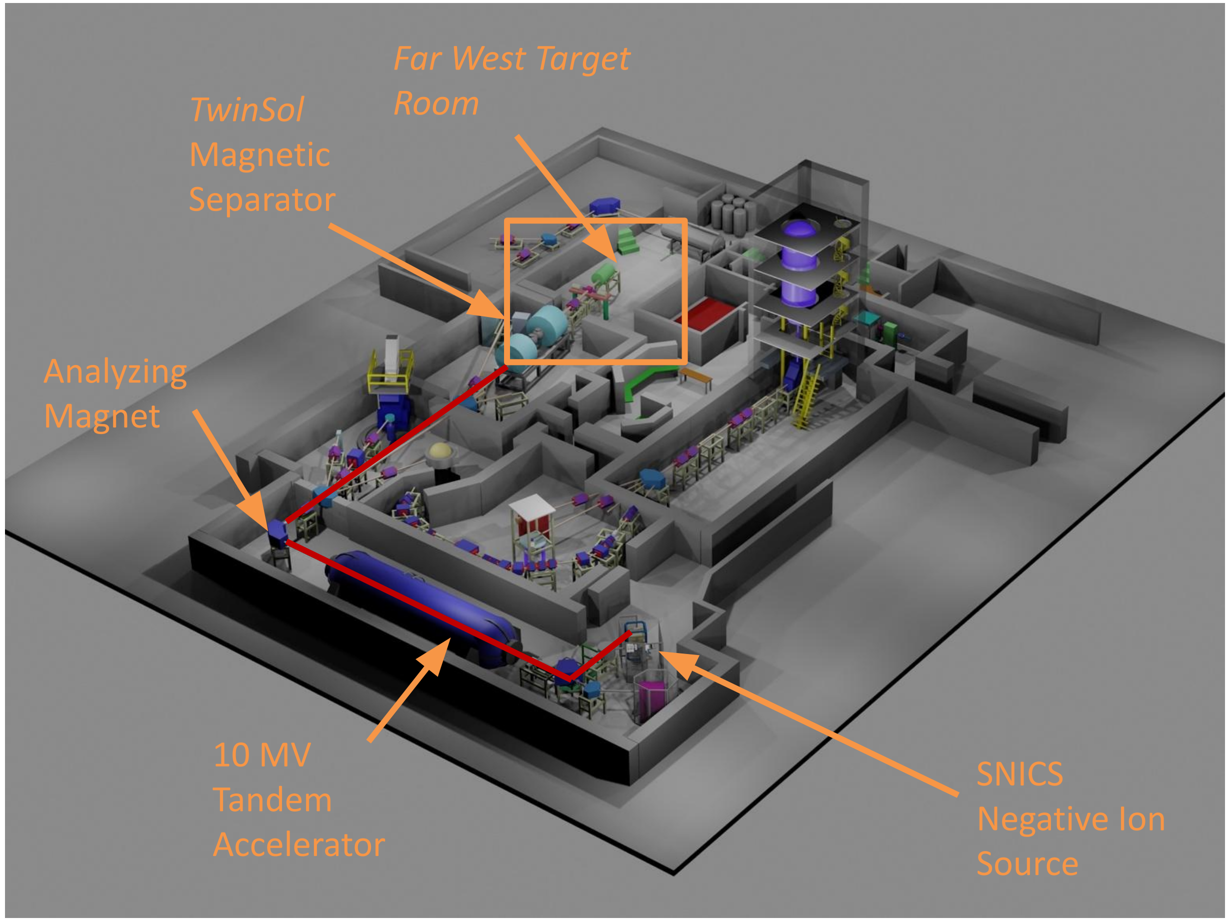


Producing RIBs at ND



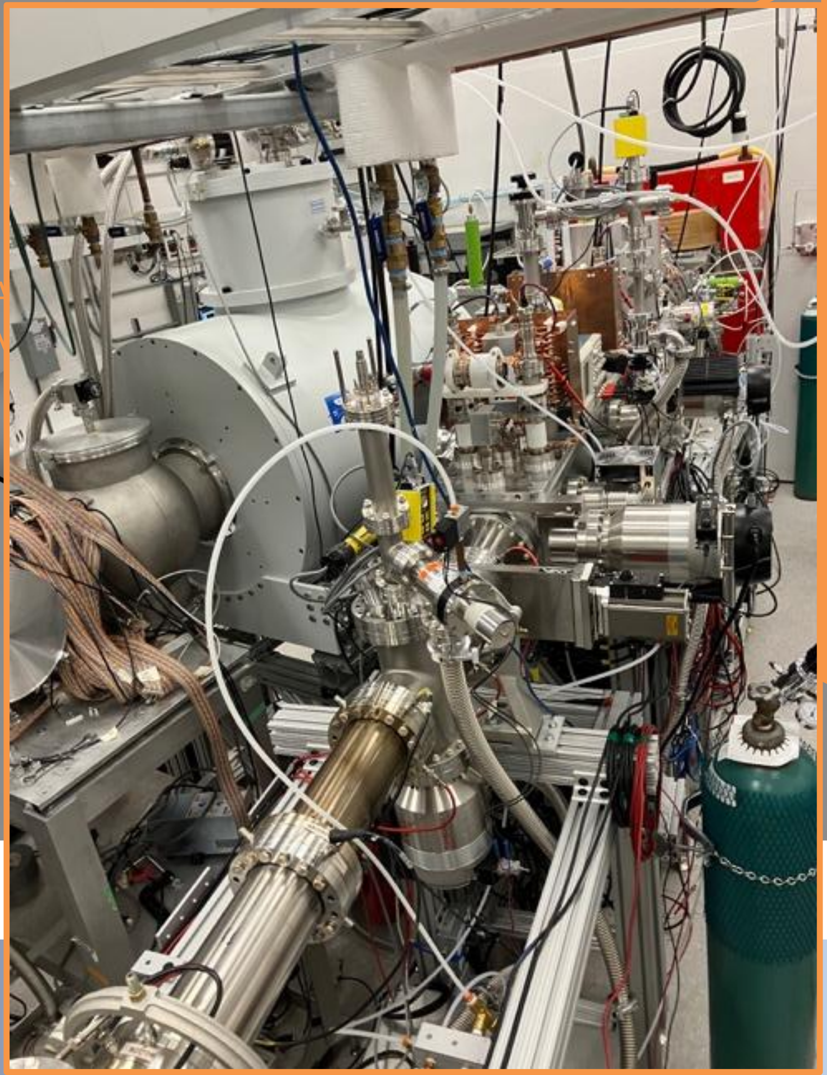
Isotope	Reaction	Rate (pps/μA)
^{11}C	^{10}B(d,n)	2.4×10^{5}
^{13}N	^{12}C(d,n)	8.1×10^{5}
^{15}O	^{14}N(d,n)	5.0×10^{6}
^{17}F	^{16}O(d,n)	1.5×10^{6}
^{25}Al	^{24}Mg(d,n)	3.0×10^{5}
^{29}P	^{28}Si(d,n)	2.0×10^{5}
^{33}Cl	^{33}S(d,n)	9×10^{3}
^{41}Sc	^{40}Ca(d,n)	4×10^{3}

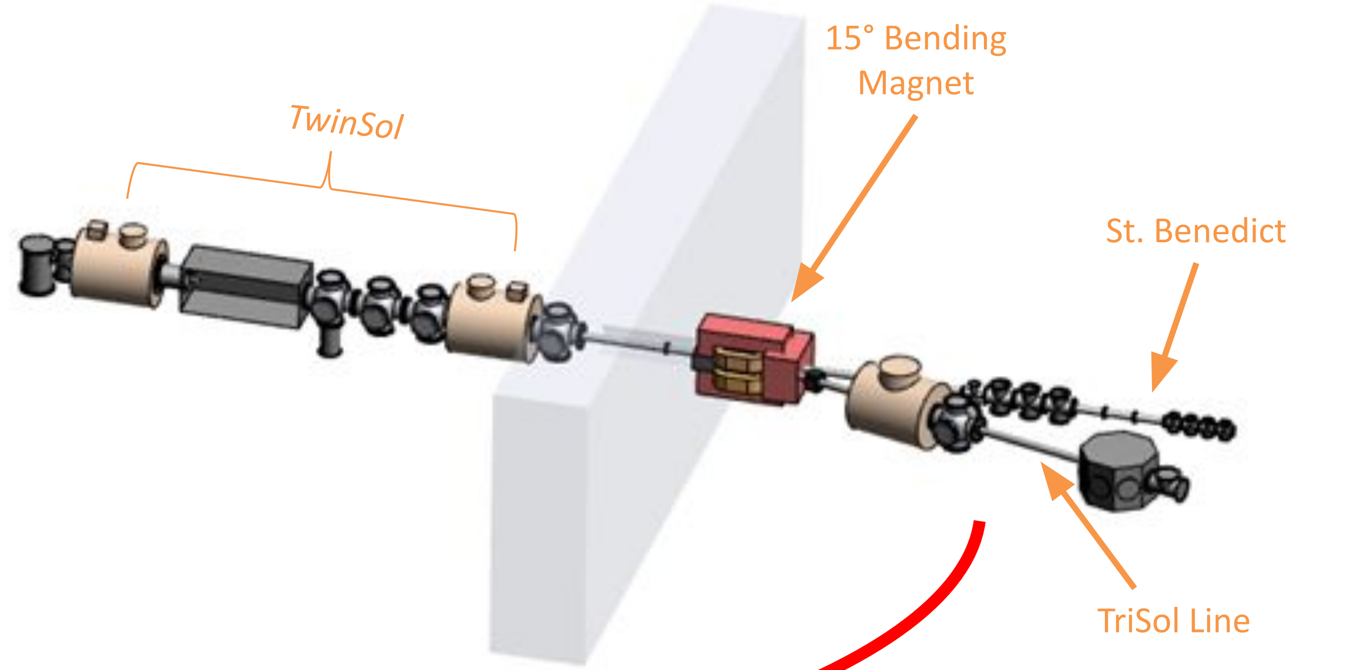
Producing RIBs at ND



Producing RIBs at ND

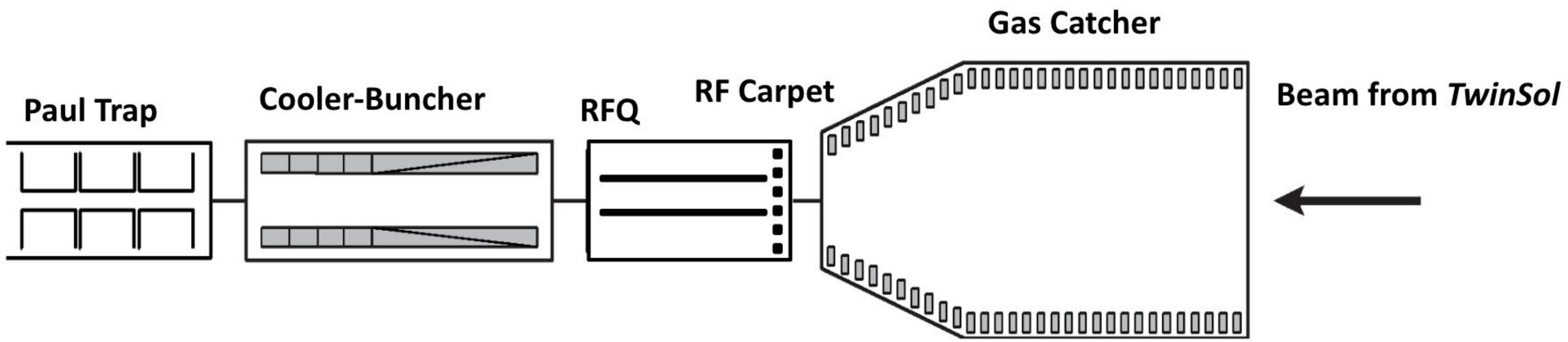
Far West Target

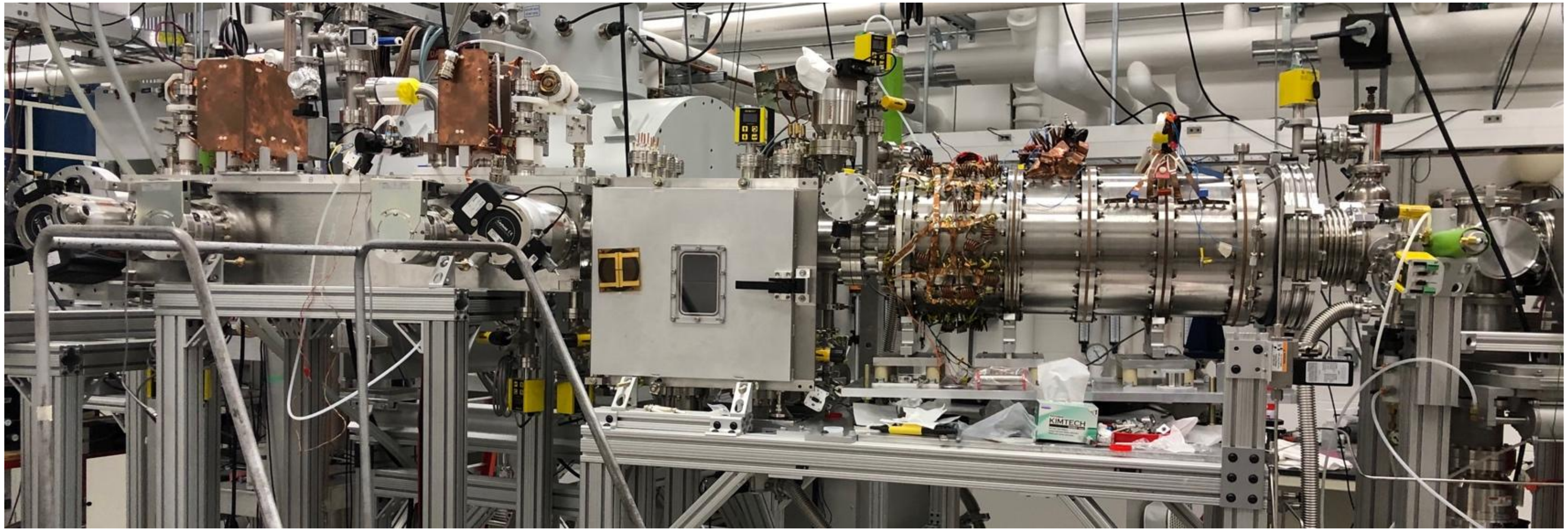




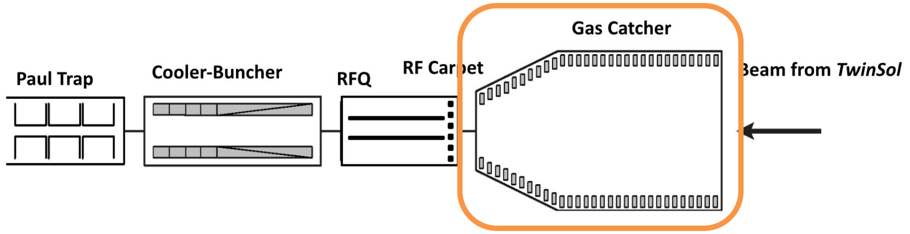
SNICS Negative Ion Source

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

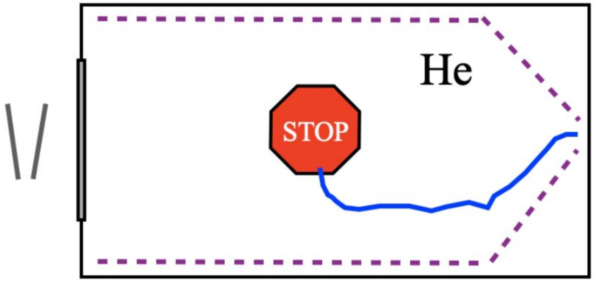




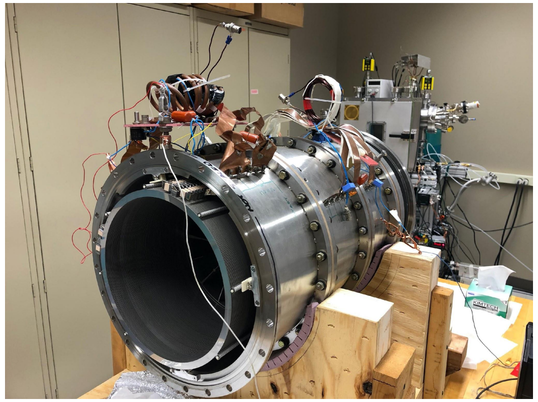
Gas Catcher

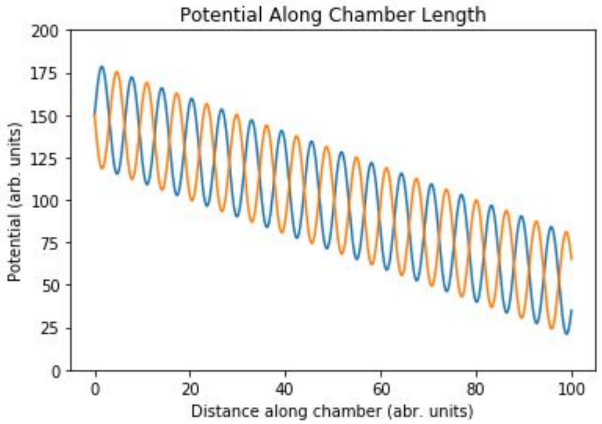


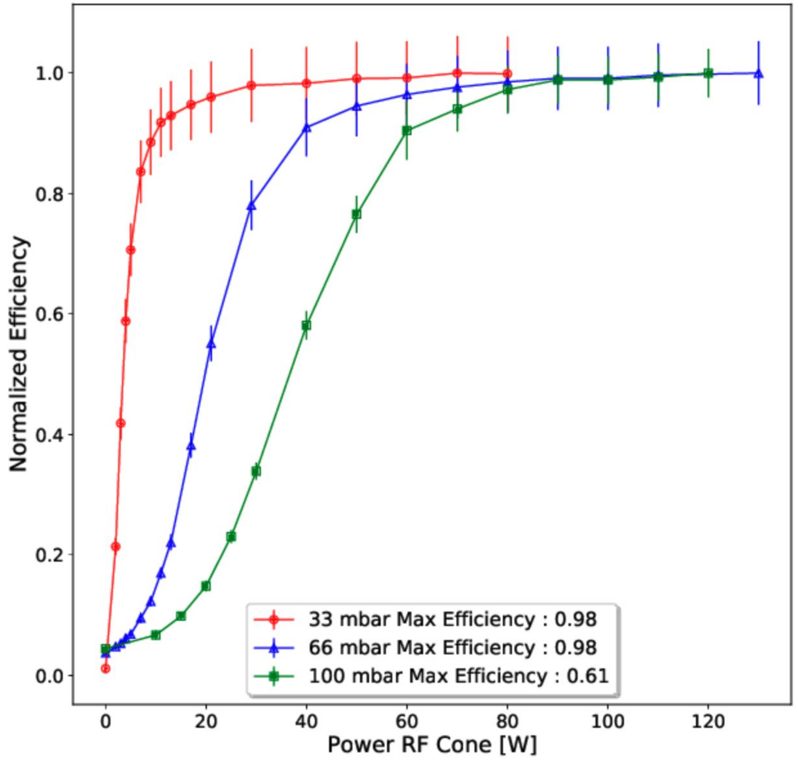
TwinSol beam
E = 10-40 MeV



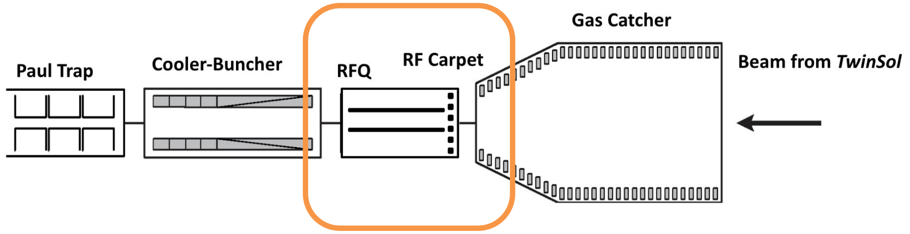
100 eV
beam

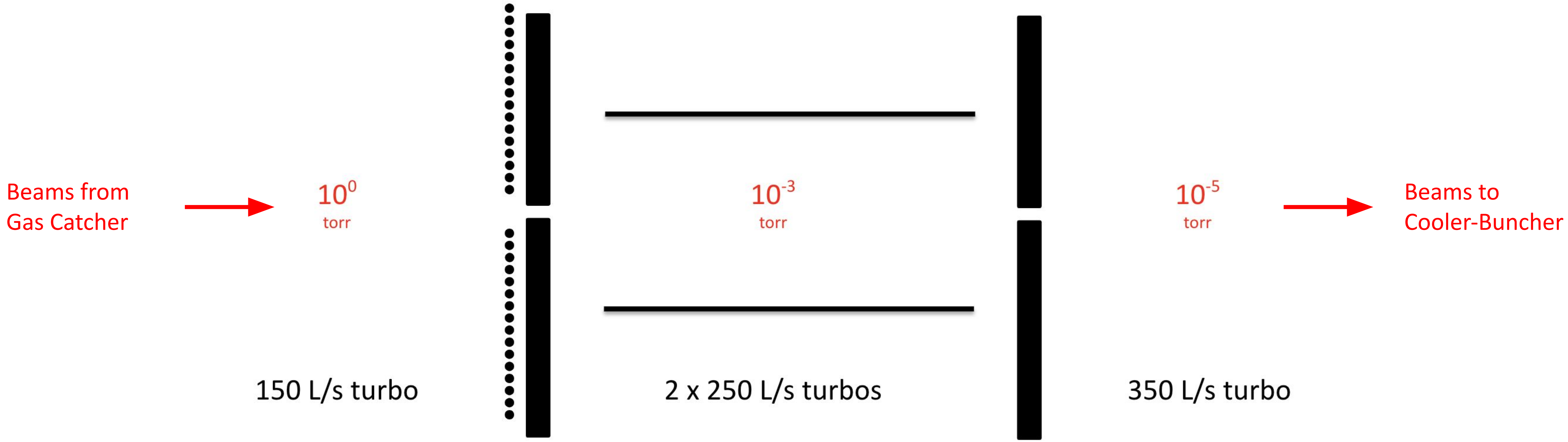






Differential Pumping





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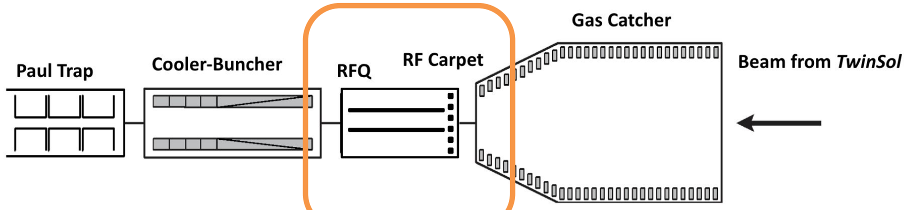
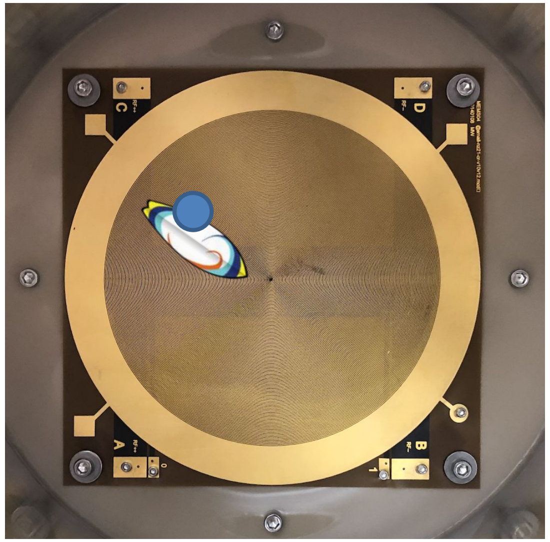
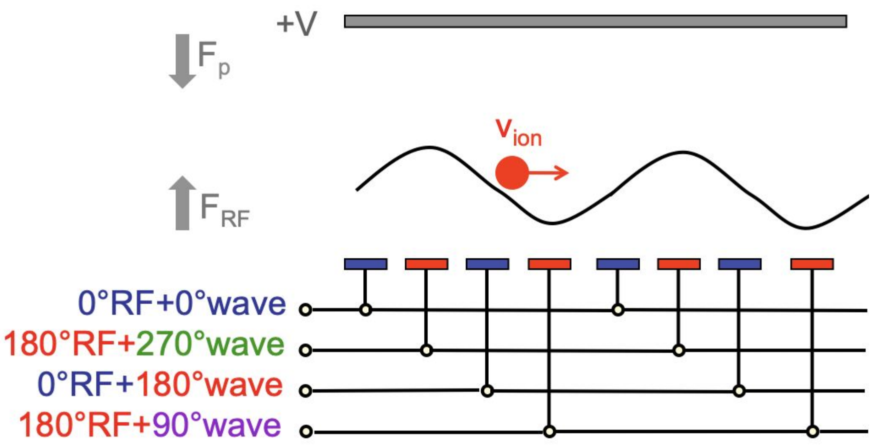
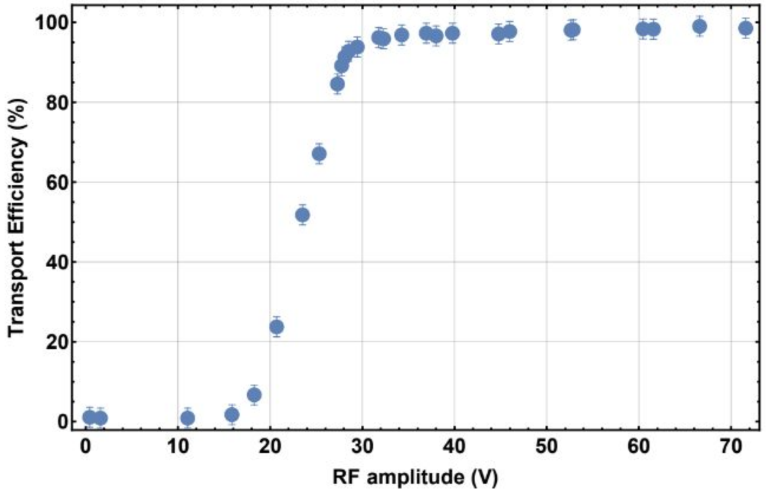
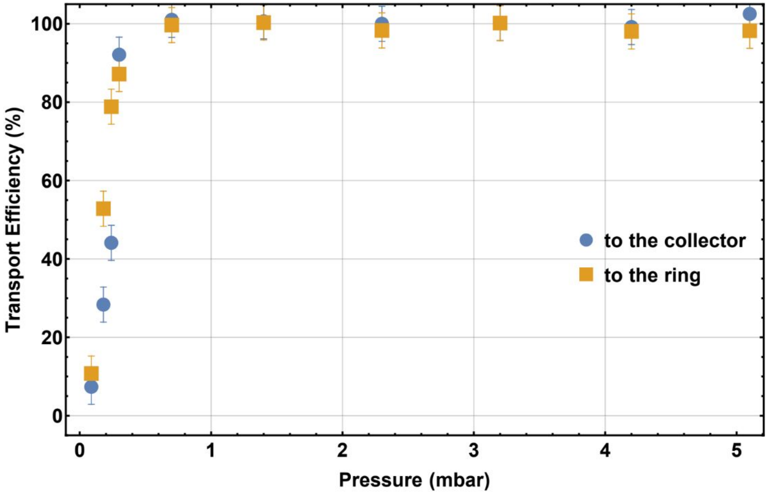




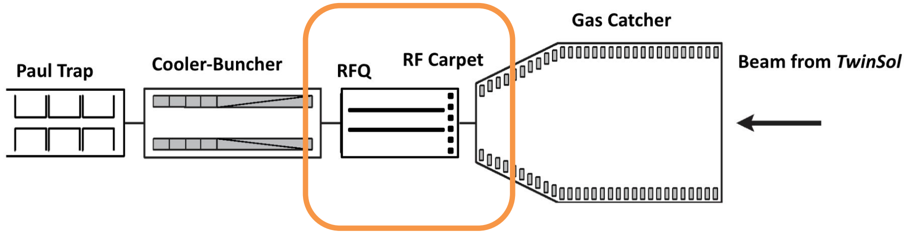


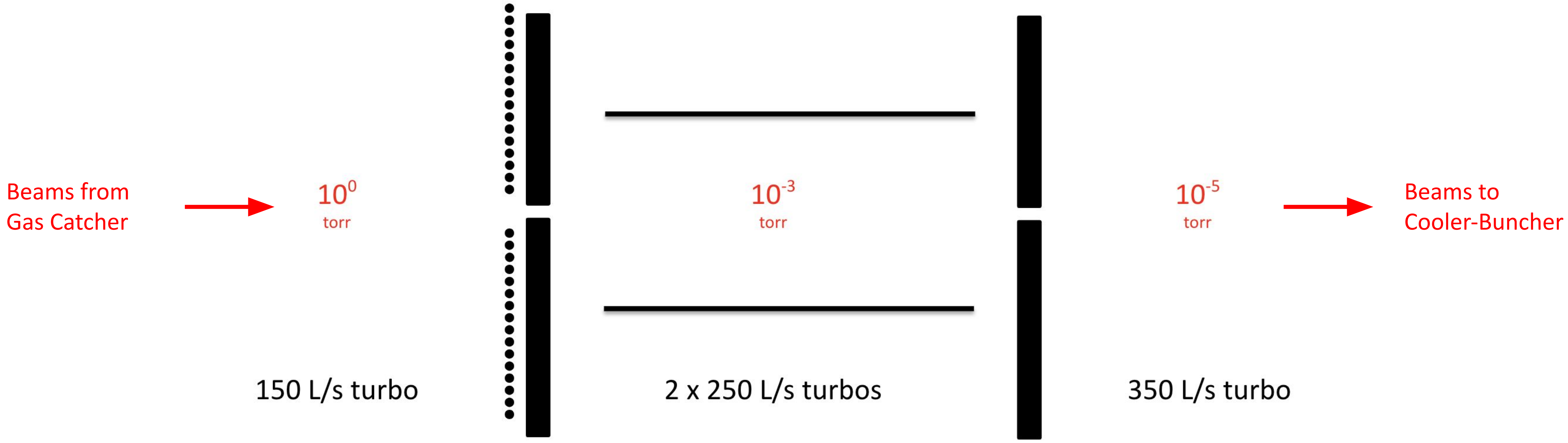




Commissioning of the St. Benedict RF Carpet: C. Davis *et. al.*, NIM A **1042**, 167422 (2022)

Differential Pumping





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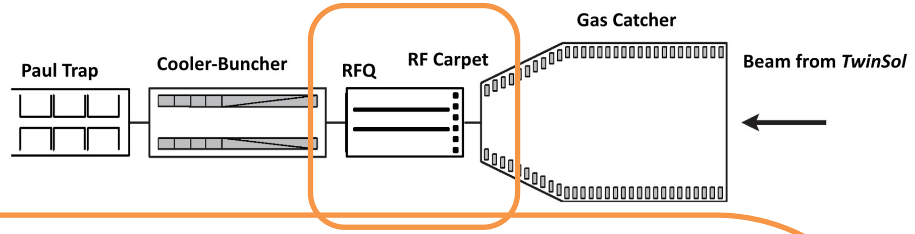

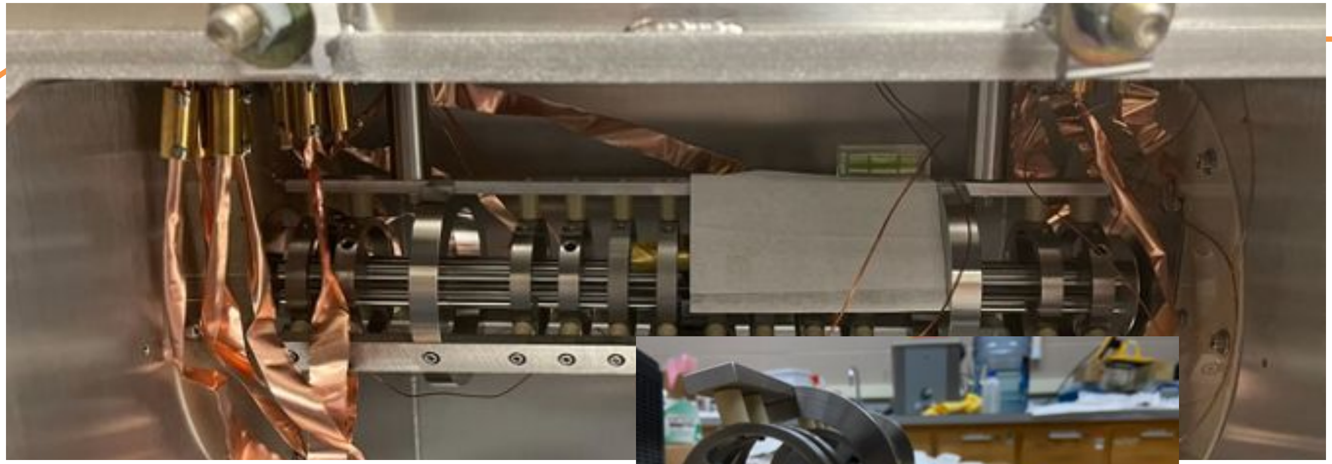

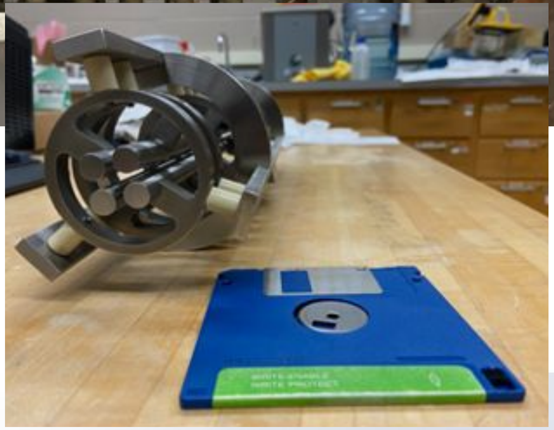

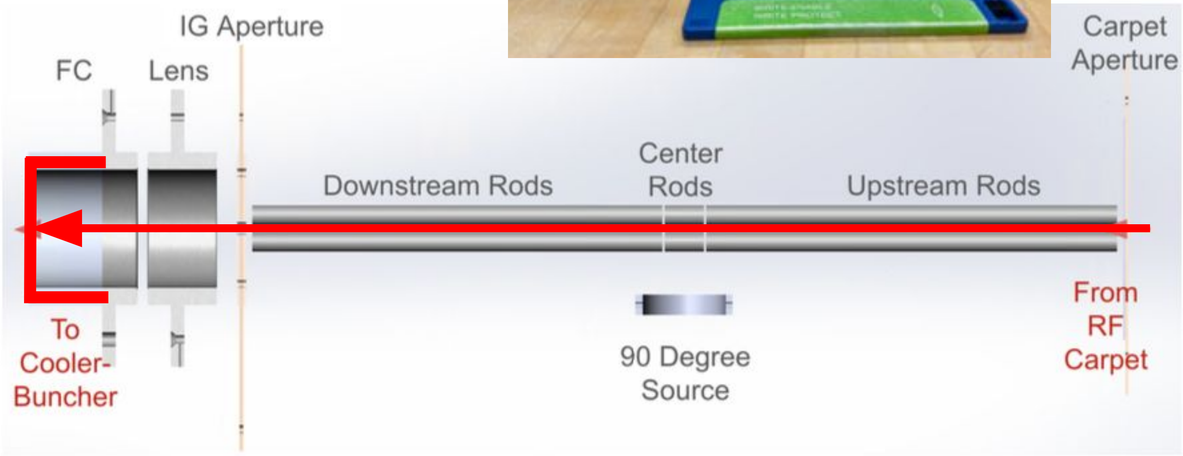

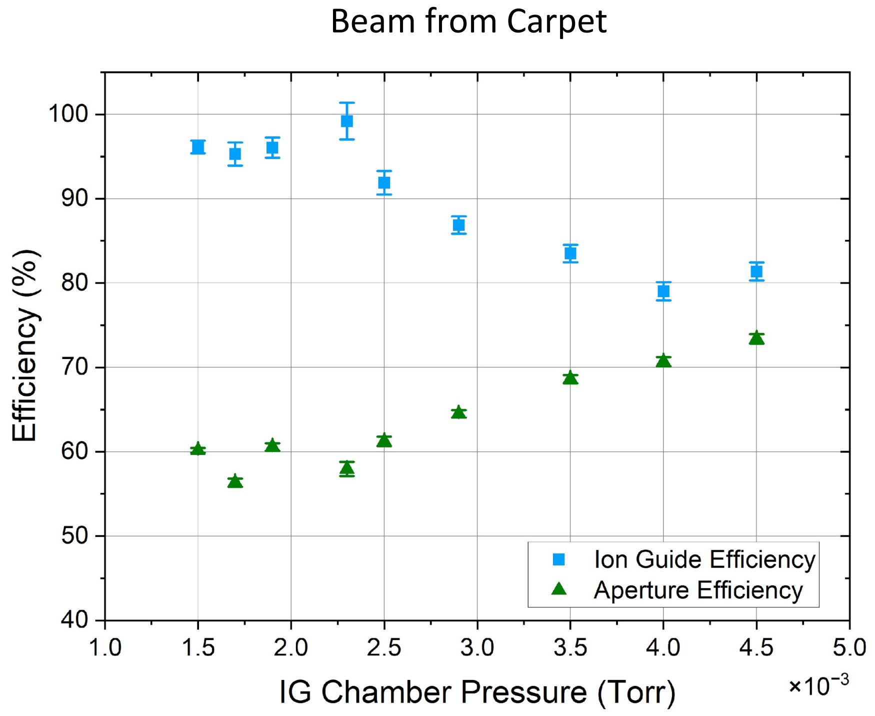

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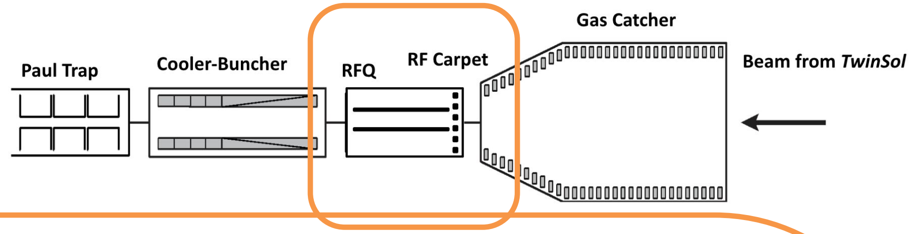
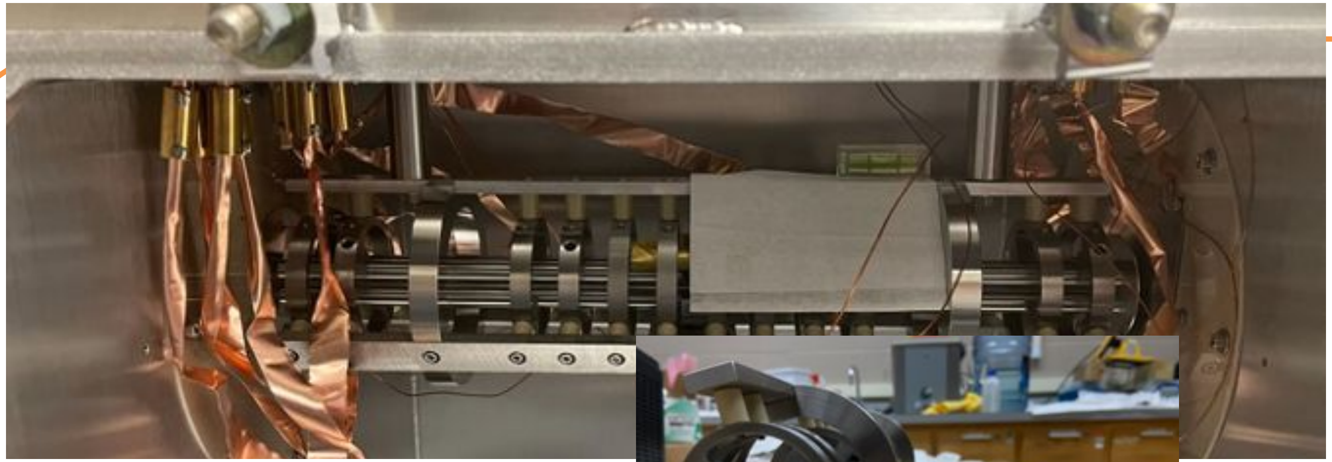
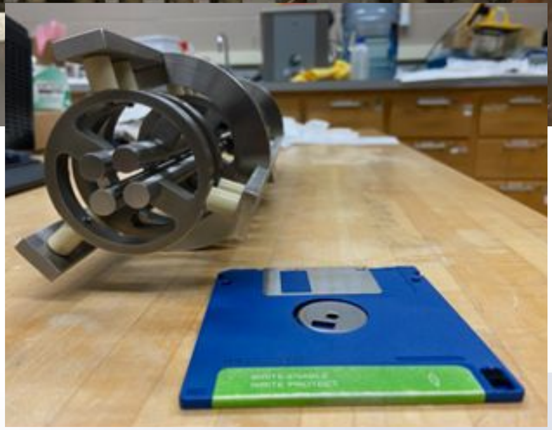
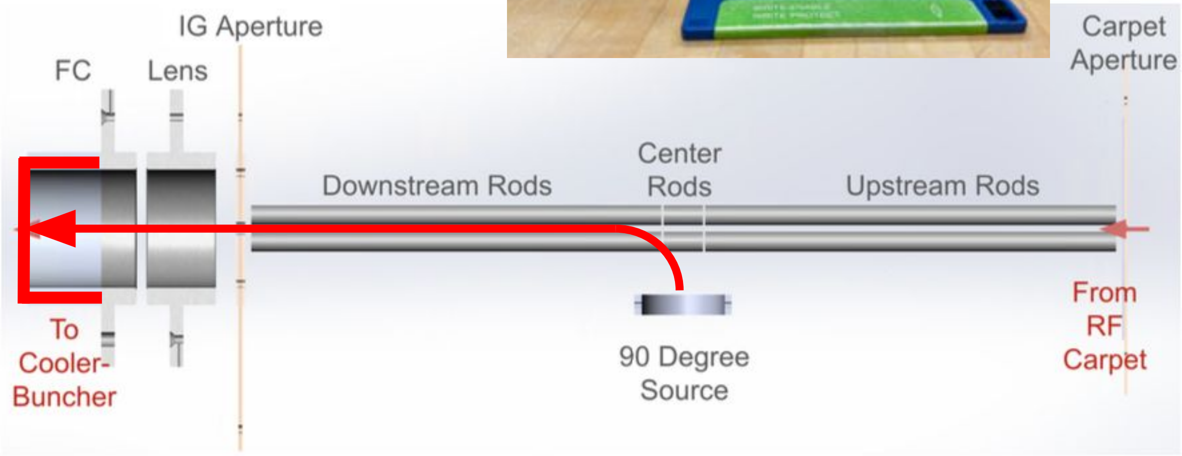
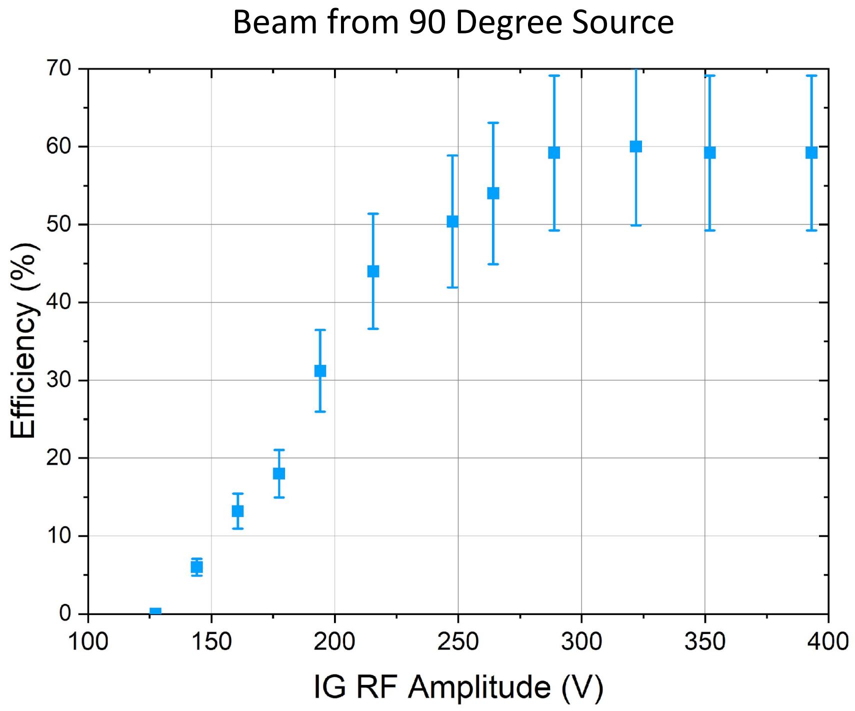


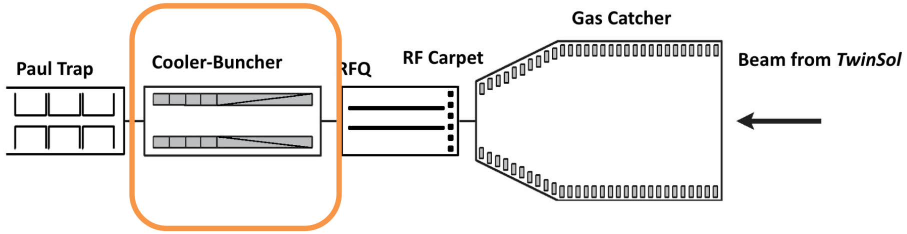


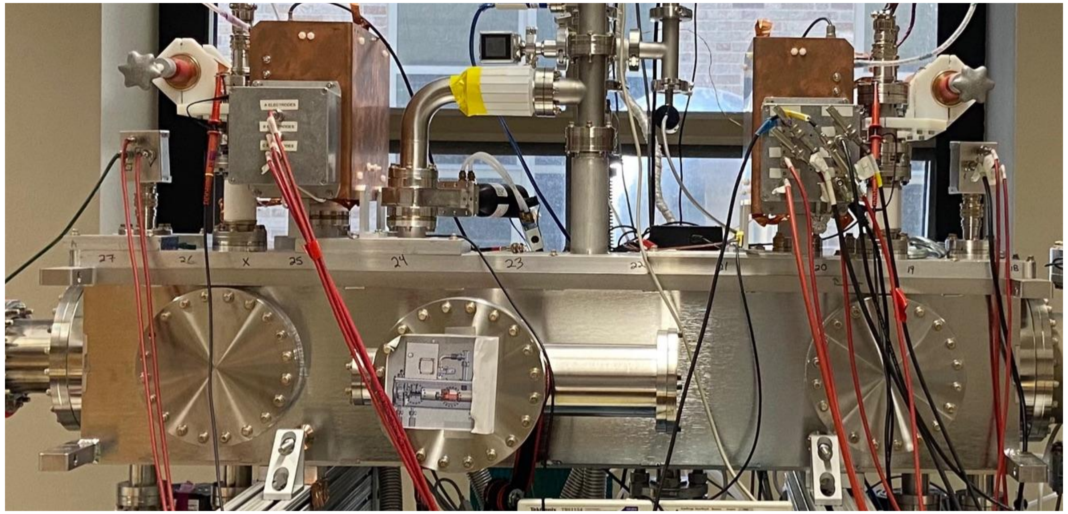


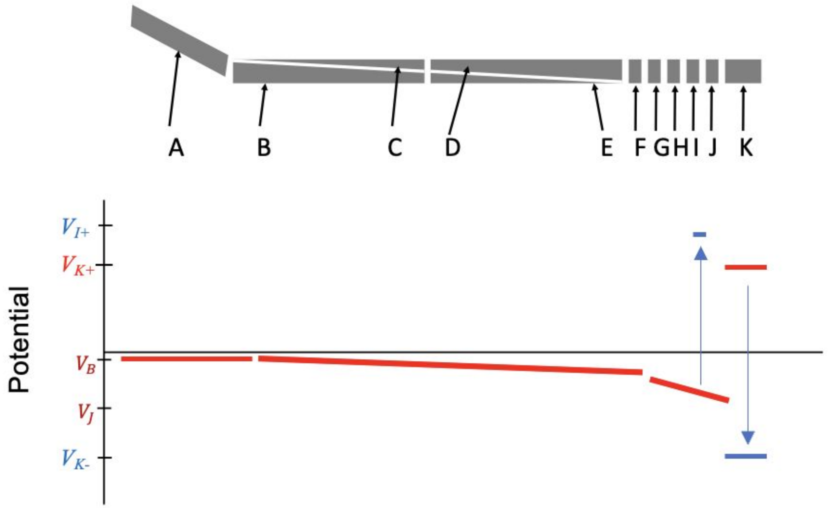




Cooler Buncher







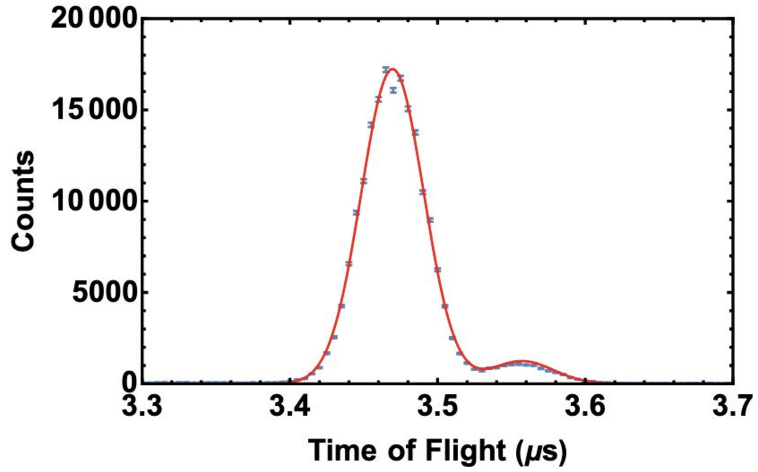
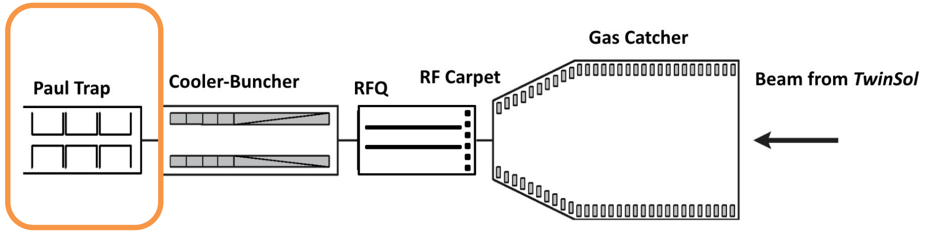


Figure 18: The sum of 10,000 consecutive bunches ejected from the cooler-buncher obtained by the MCP detector directly downstream of the chamber. The fit, given in red, shows the two peak Gaussian fit matching the two masses coming from the ion source, $^{39}K^+$ and $^{41}K^+$, based on their separation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

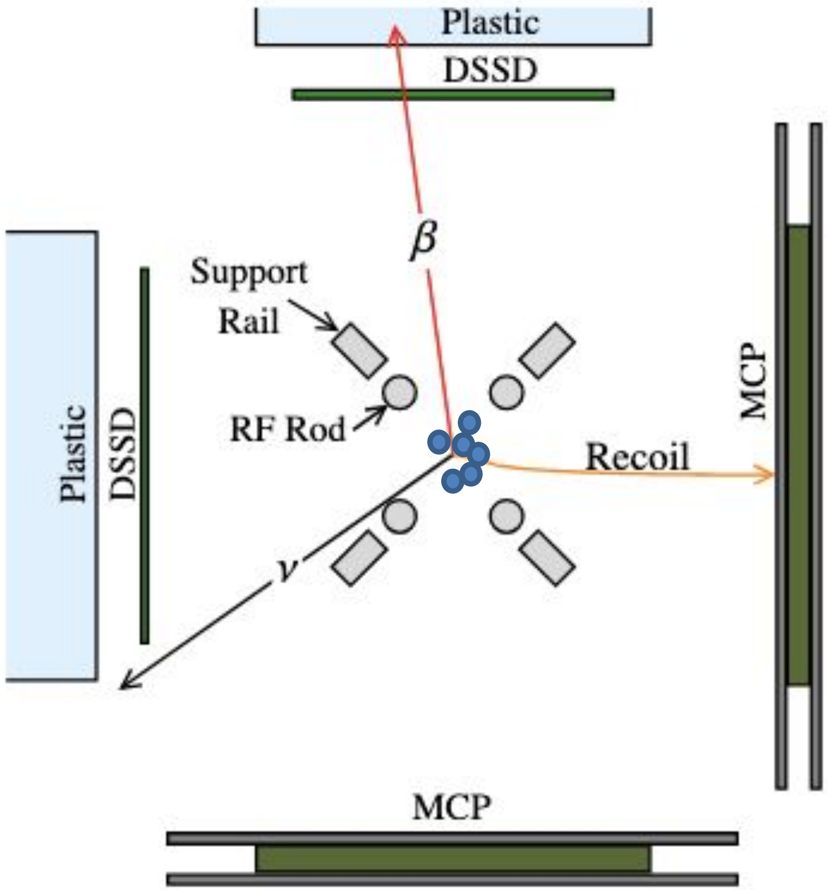
Trapping Efficiency: 93(1)%
FWHM: 50 ns

Off-line Commissioning of the St. Benedict Radiofrequency Quadrupole Cooler-Buncher, D. P. Burdette, *et. al.*, NIMA: Vol 1084, 171187, 2026

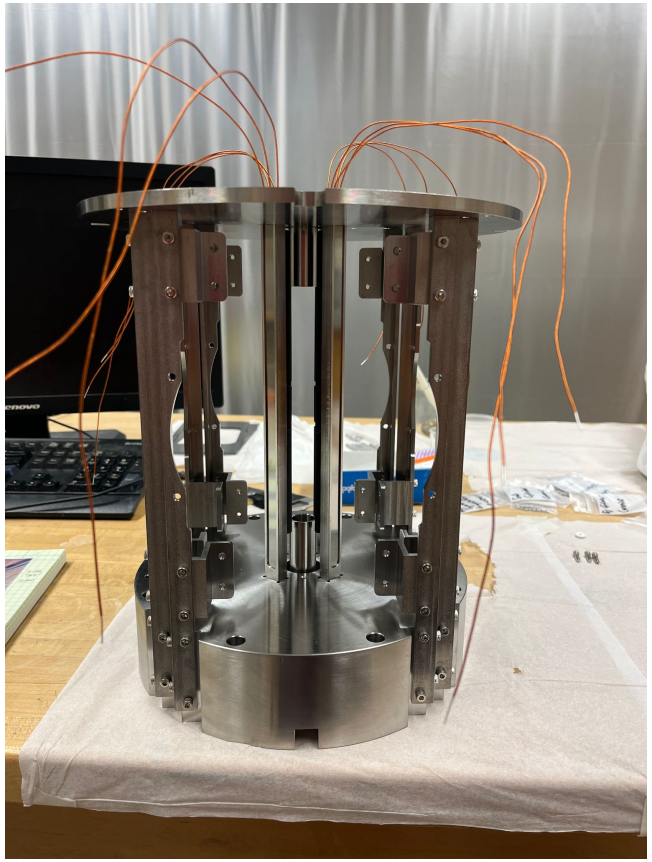
Paul Trap

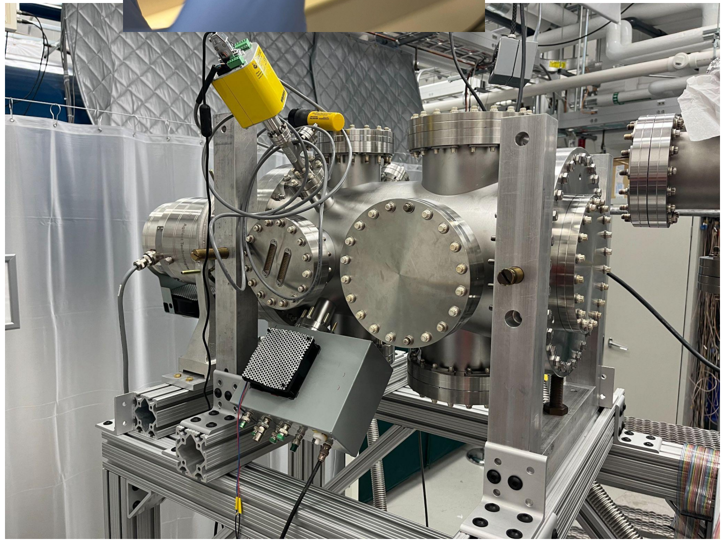


Paul Trap
Cooler-Buncher
RFQ
RF Carpet
Gas Catcher
Beam from *TwinSol*

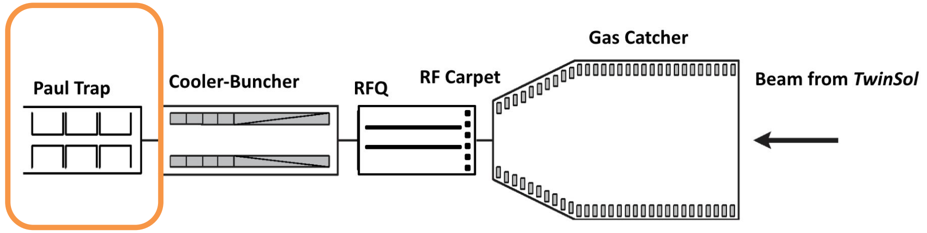


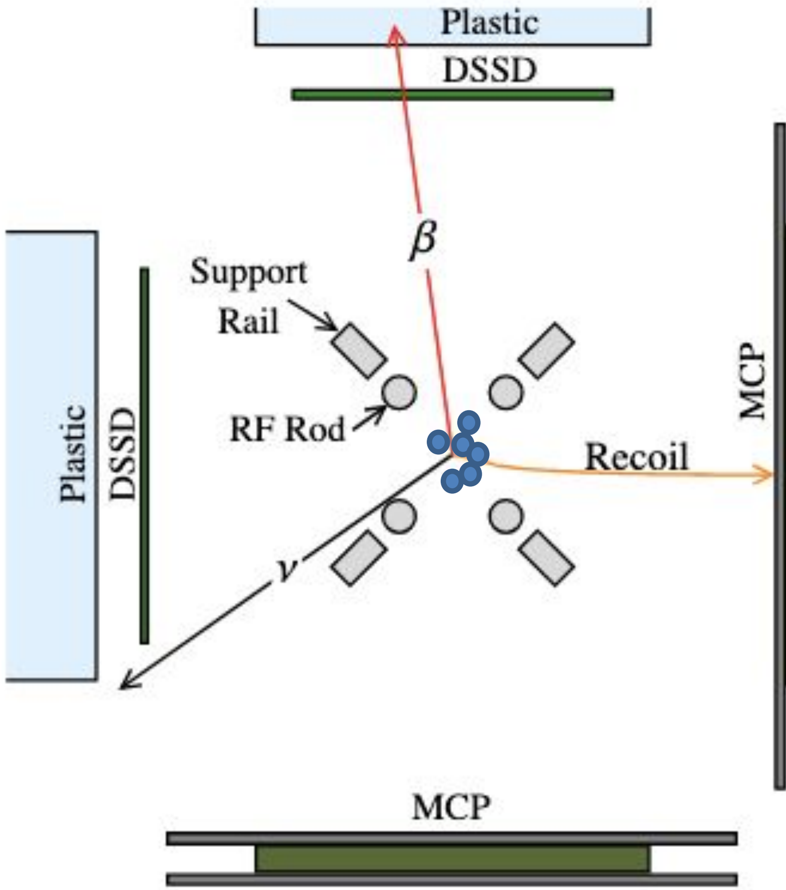
Plastic
DSSD
Plastic
DSSD
Support Rail
RF Rod
β
ν
Recoil
MCP
MCP



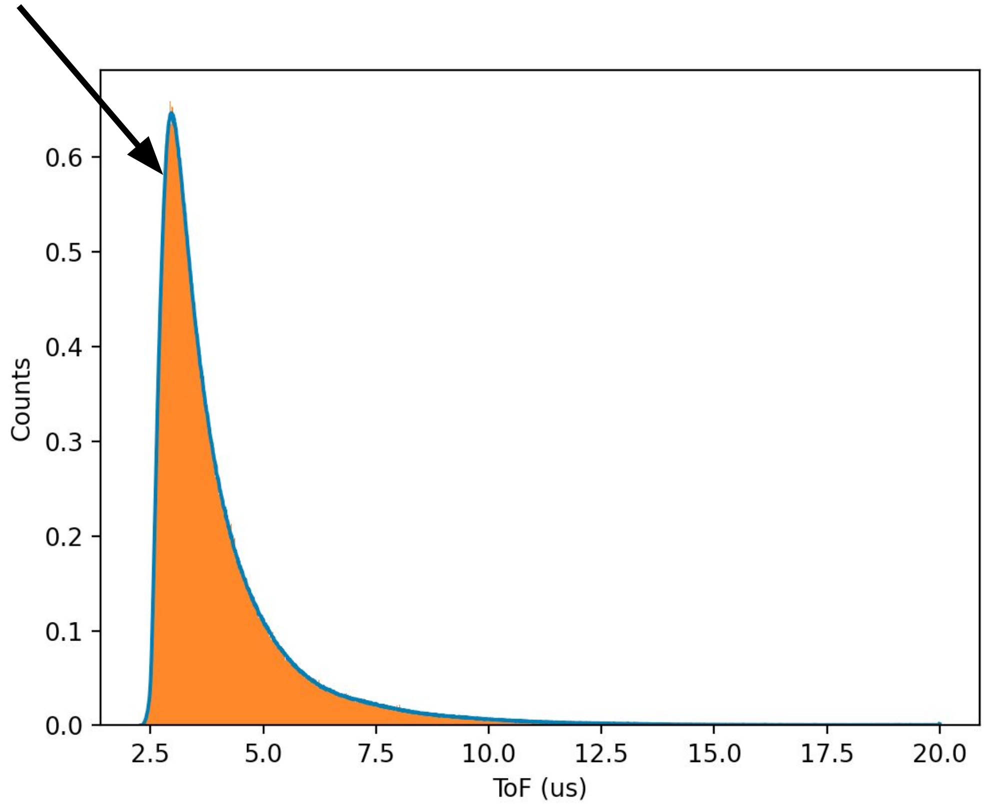


Paul Trap

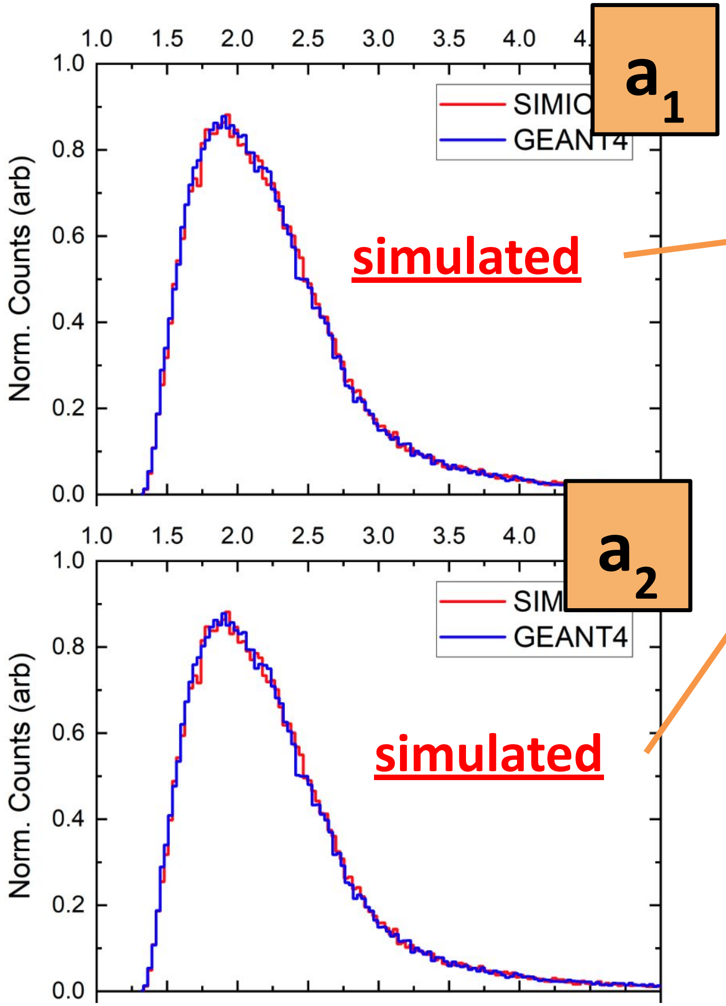




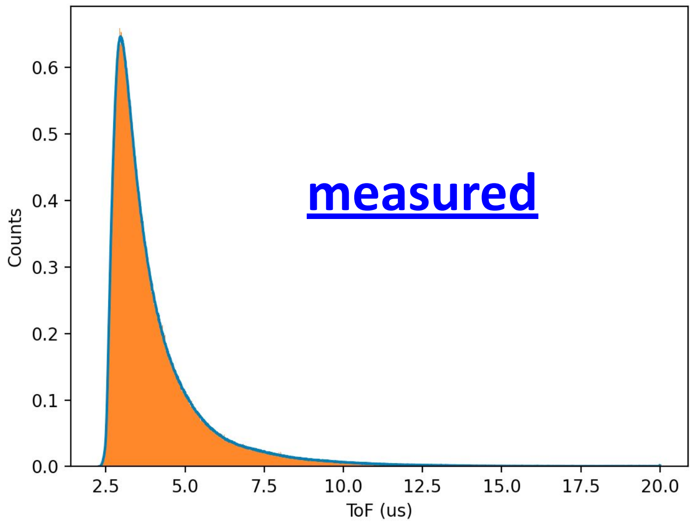
$t_1 - t_2 = \Delta t$



Fitting $a_{\beta\nu}$

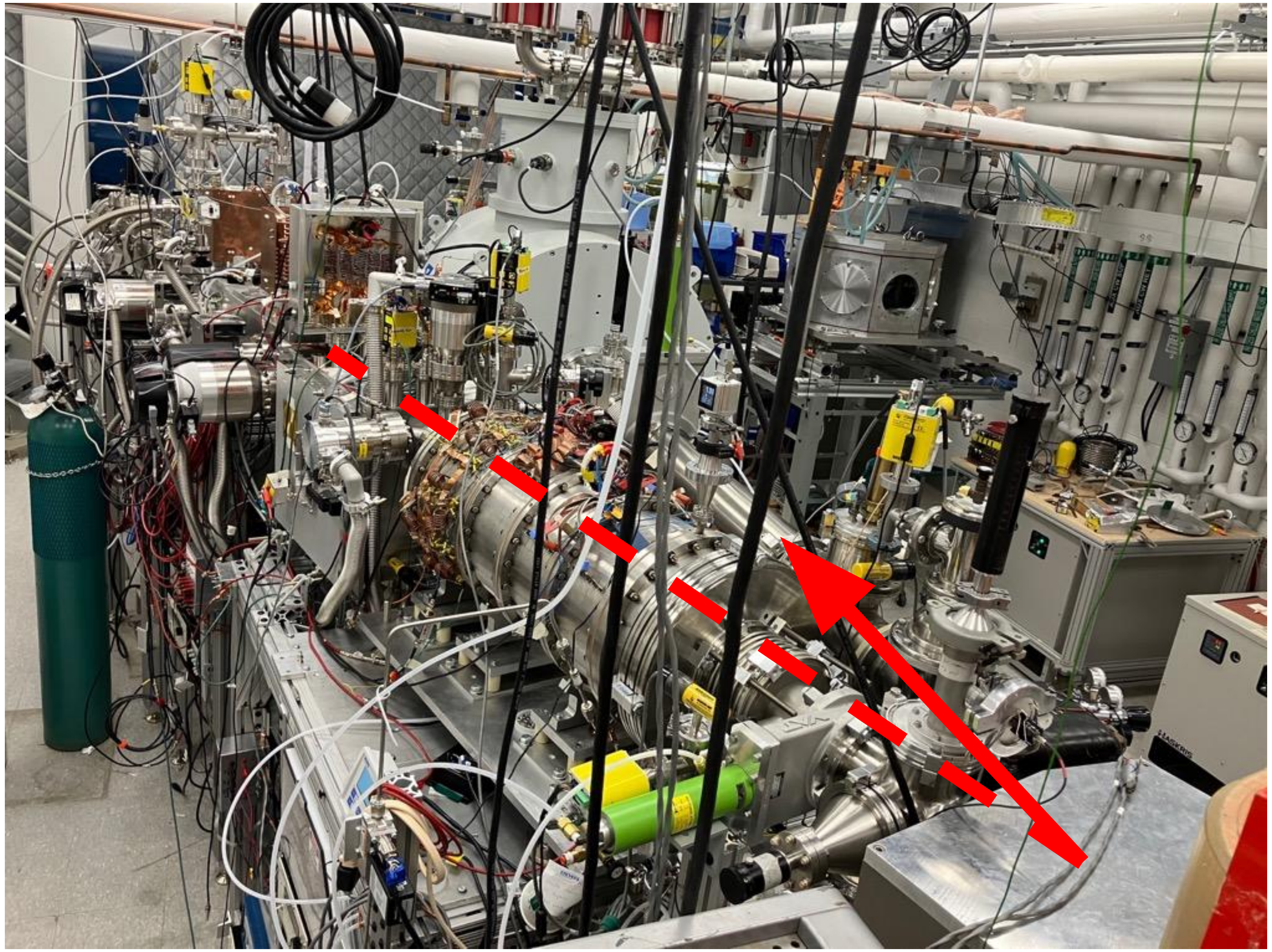


$$\beta(\alpha F_{a1}(t) + (1 - \alpha) F_{a2}(t))$$

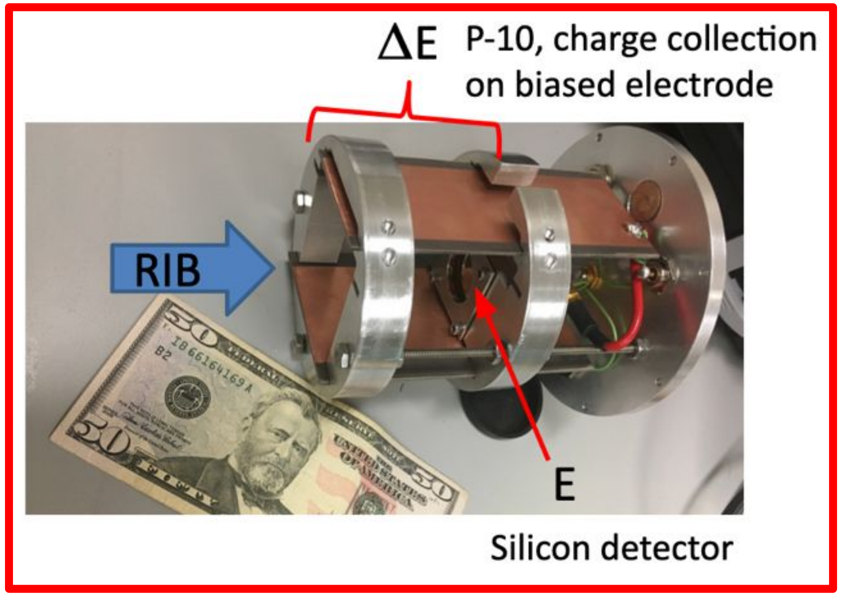


$$a_{\beta\nu} = \alpha a_1 + (1 - \alpha) a_2$$

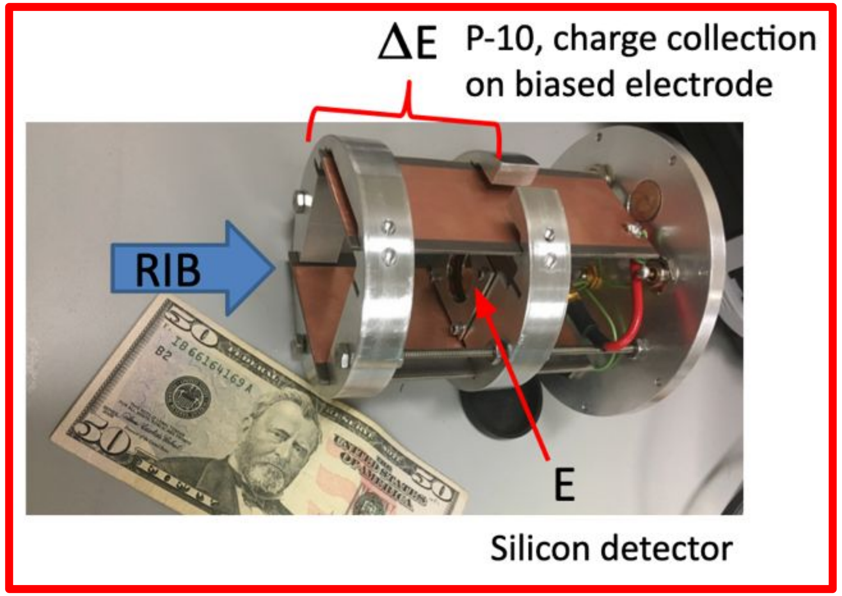
On-line Results

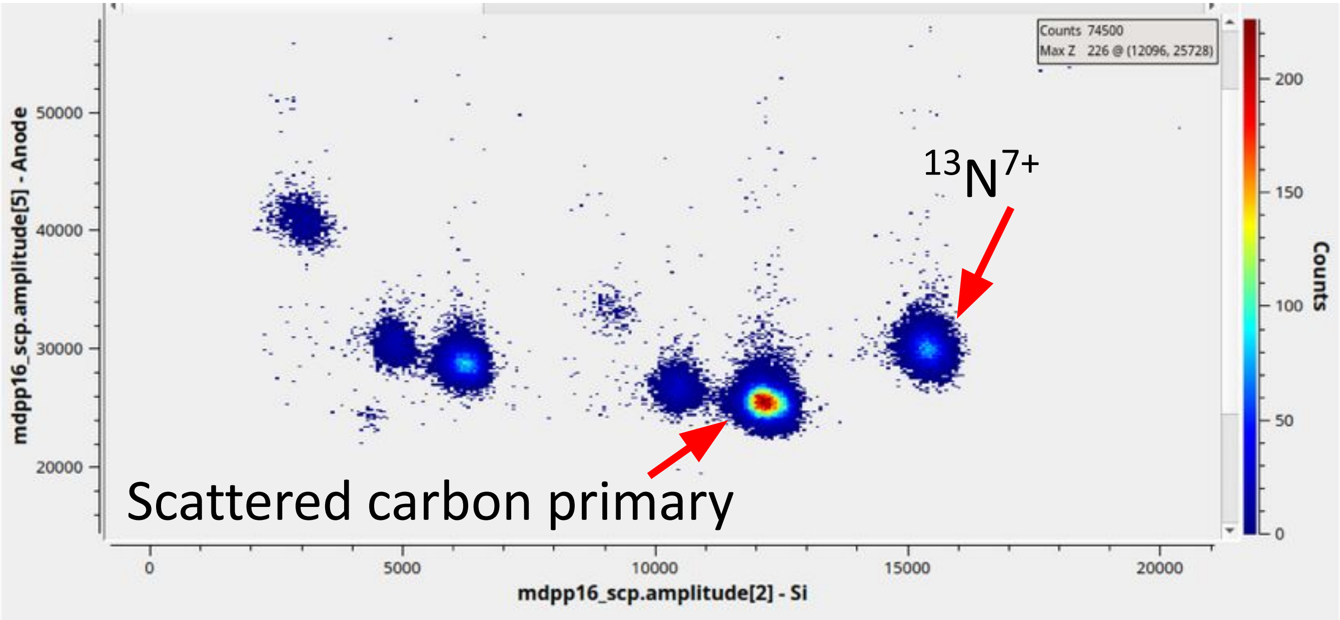


RIB is tuned on Ackbar our PID. Located at the 15° TriSol beam line at a similar distance from magnet than gas catcher entrance.

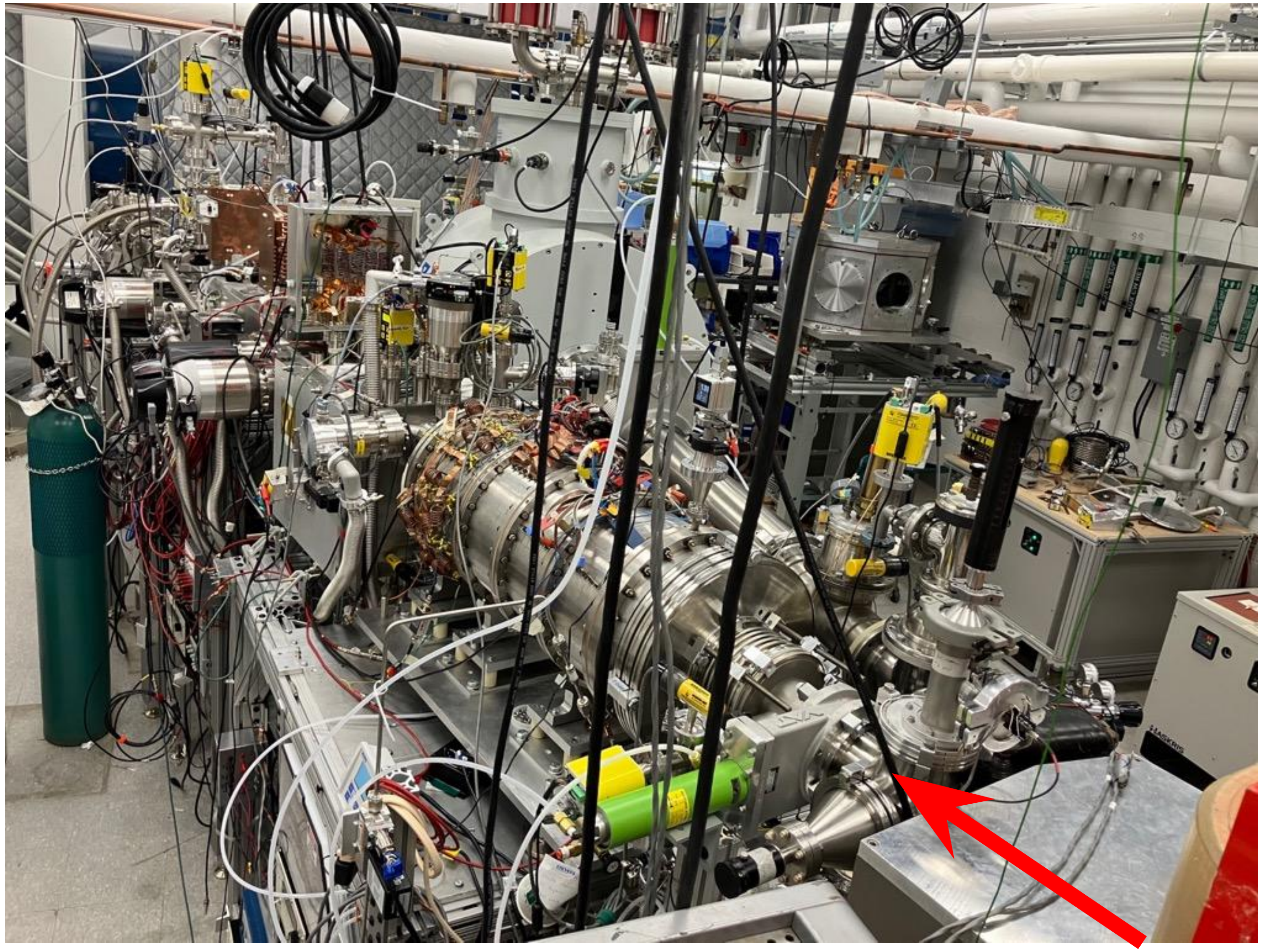


On-line Results





On-line Results

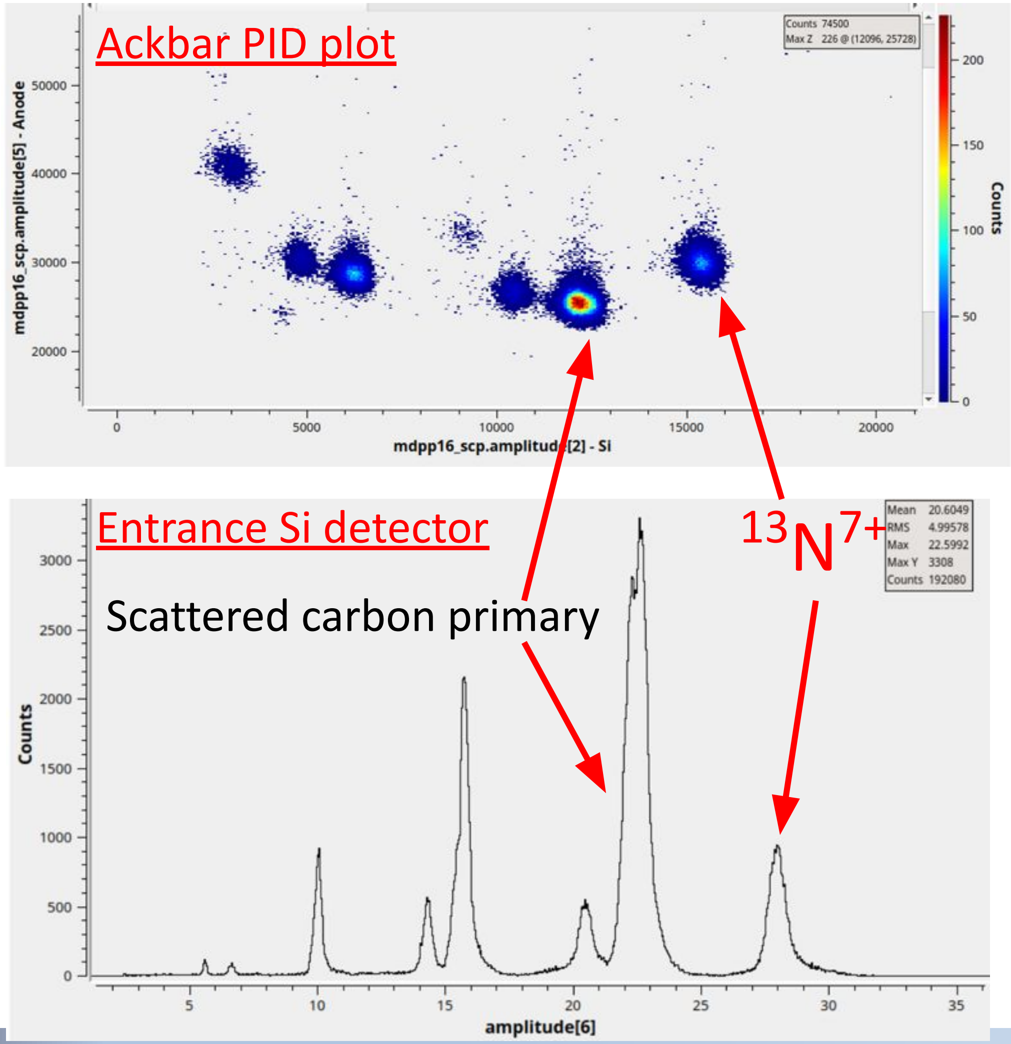


RIB is sent to a Si surface barrier detector. Located just before the degrader on the St. Benedict line.

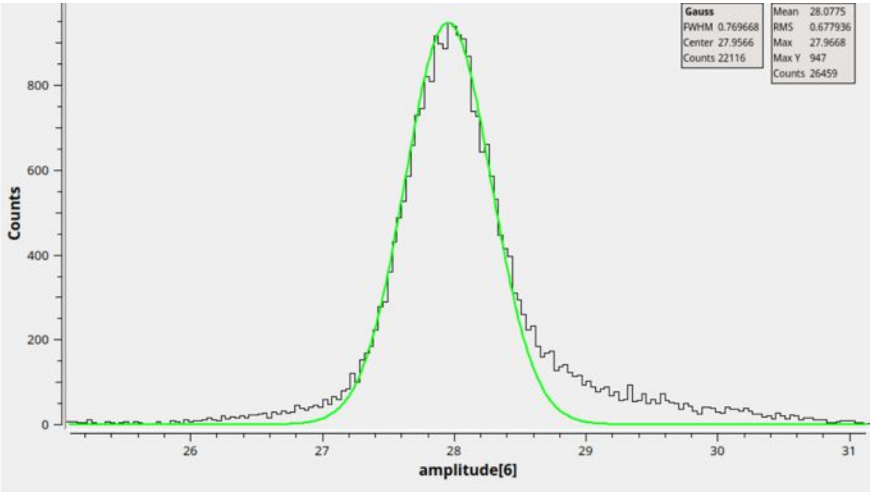
X-Y steerers adjusted to maximize ^{13}N vs C.

Energy of $^{13}N^{7+}$ cross-check with LISE++ prediction.

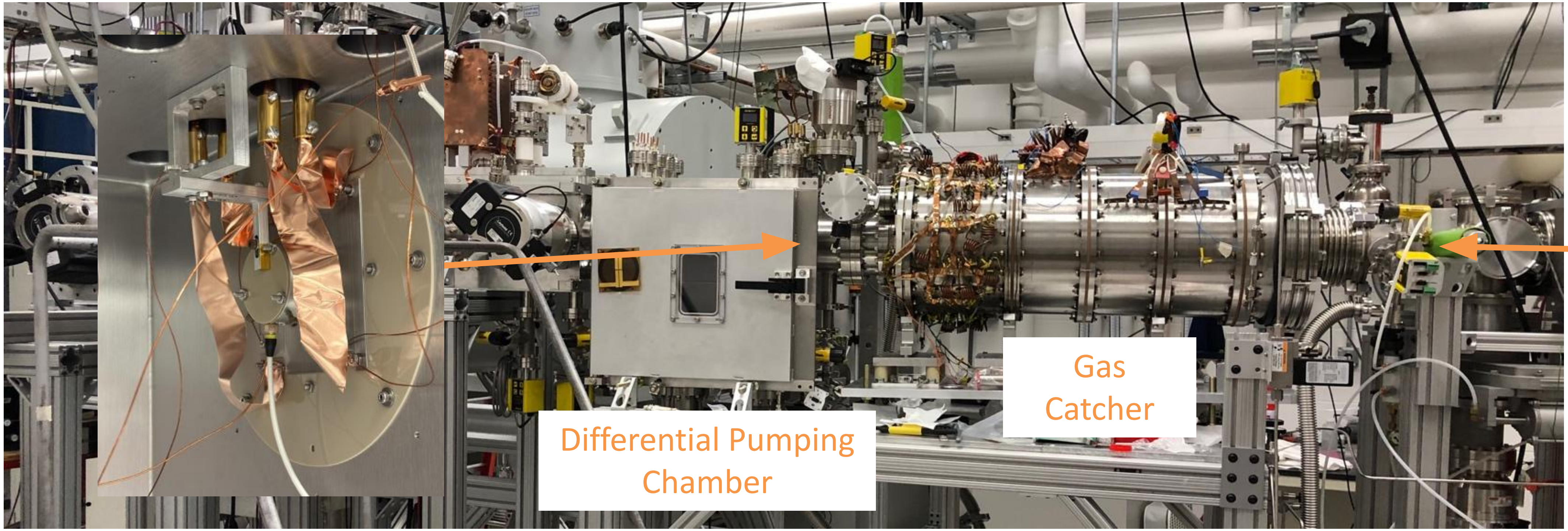
On-line Results



LISE++ calculation: 28.4 MeV
Measured: 28.0 MeV

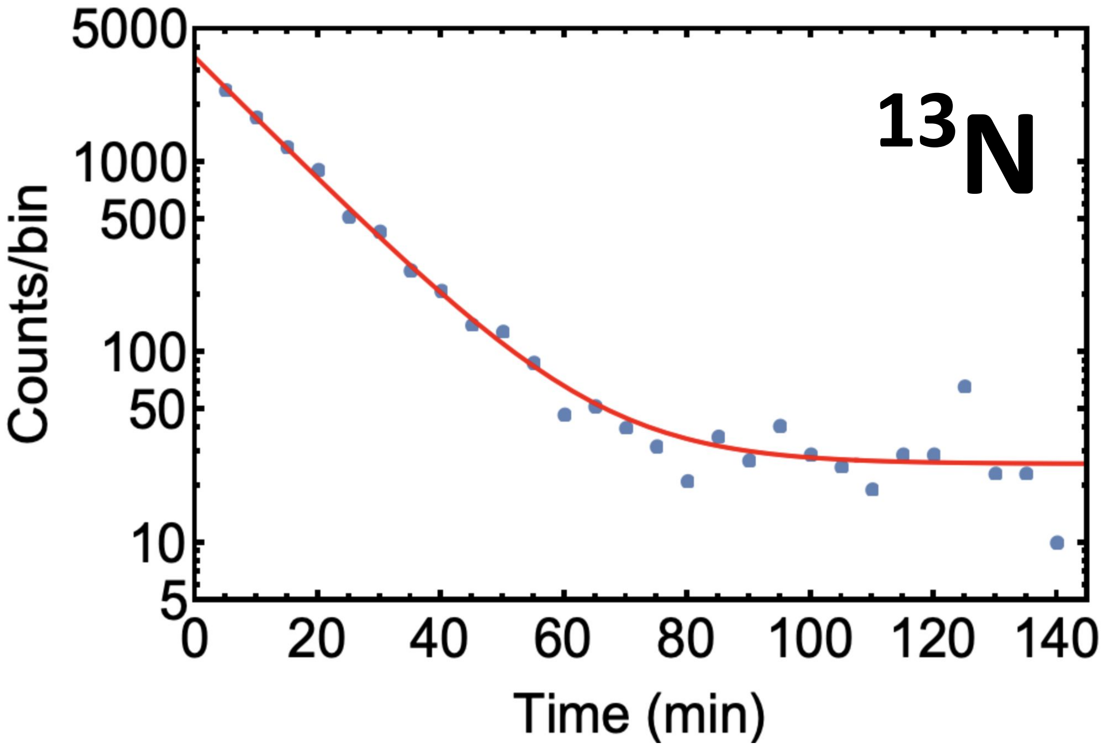


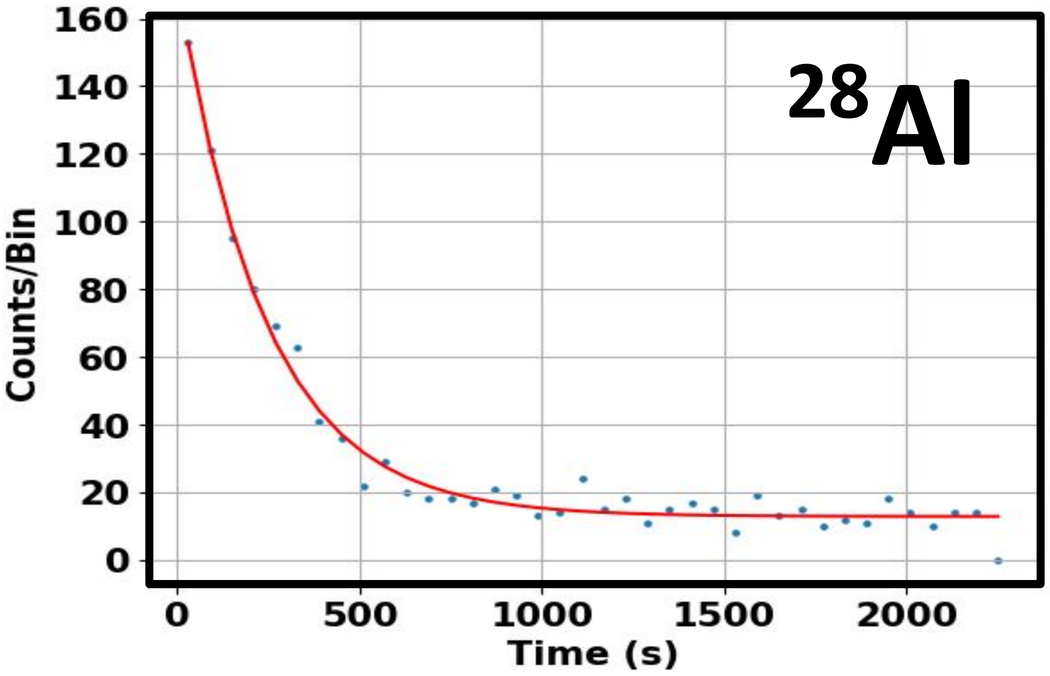
First Stopped and Extracted RIBs with St. Benedict:



- Ion guide has been removed and replaced by a foil backed by a Si detector.
- Implant ^{13}N ions transported by the RF carpet on the foil.
- Positron from the ^{13}N decay are recorded by the Si detector.

First Stopped and Extracted RIBs with St. Benedict:

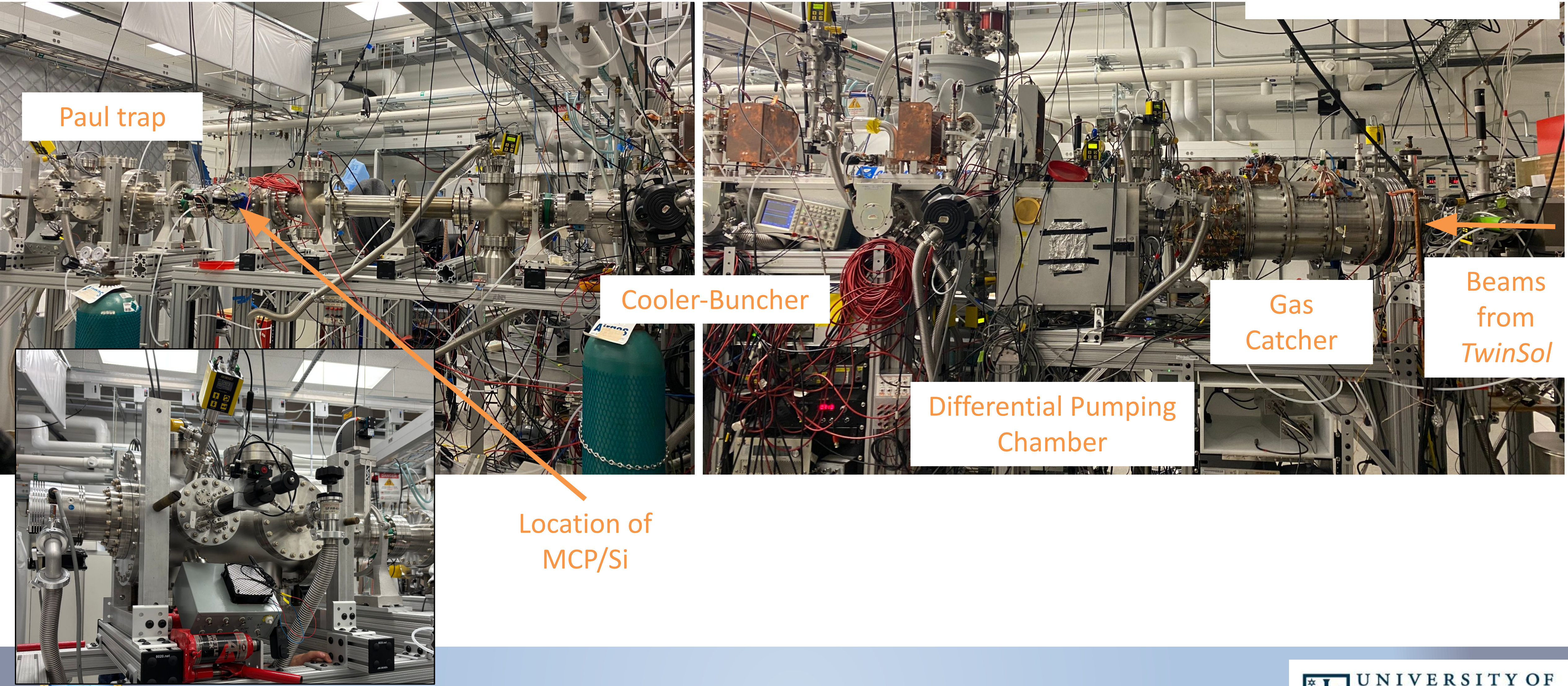




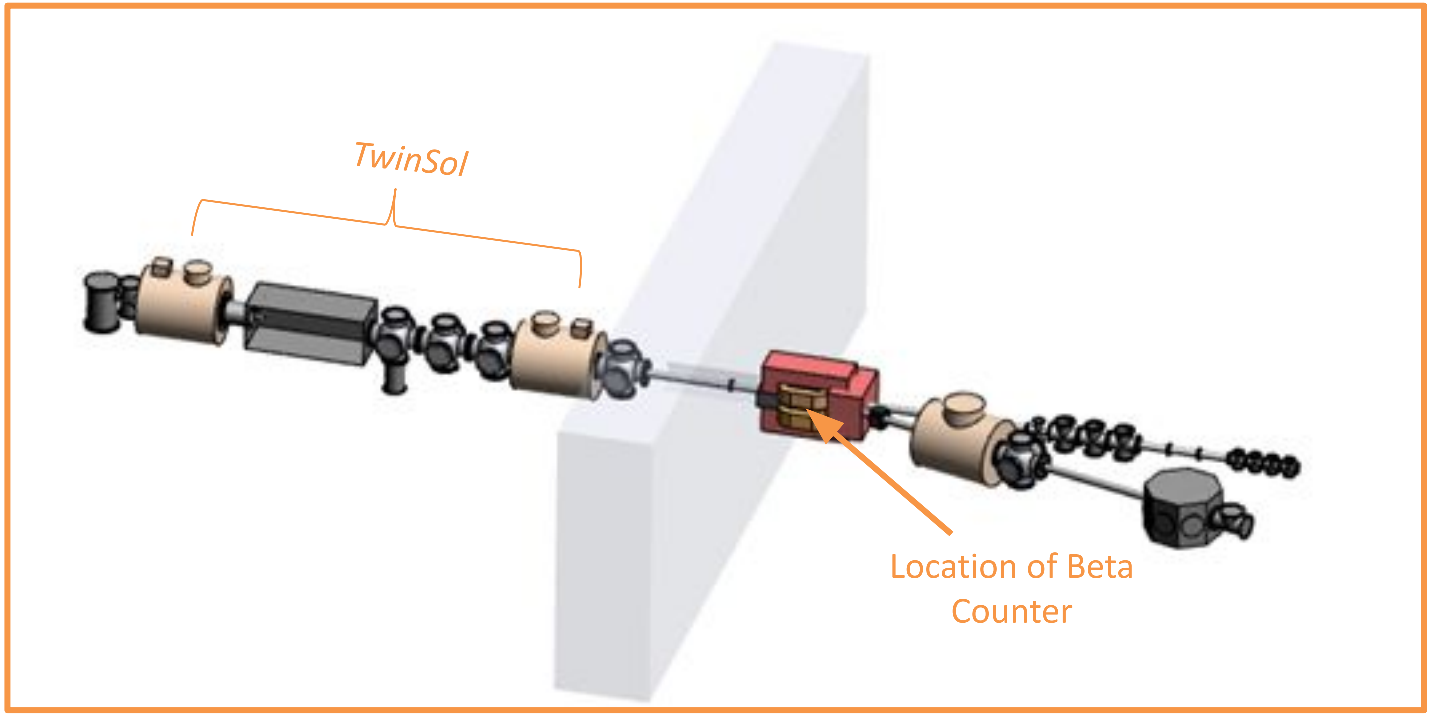
~ 1-2% transport efficiency with current online setup

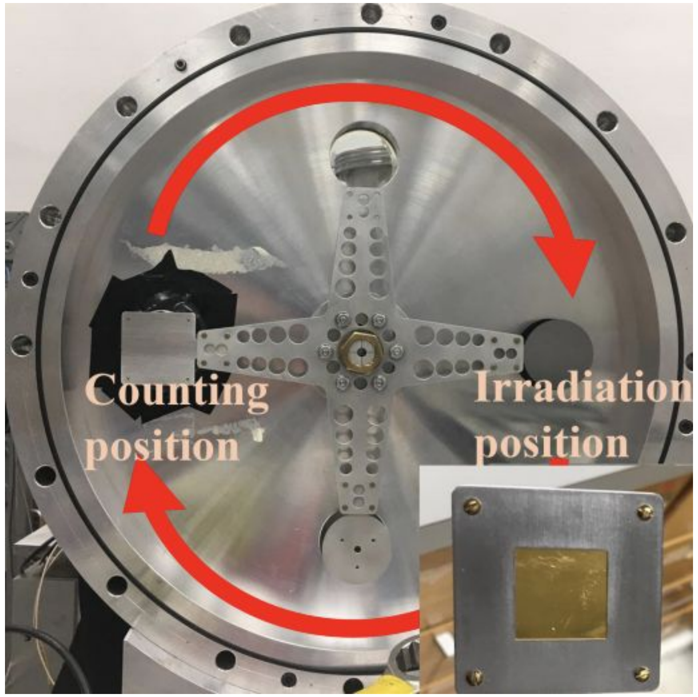
Also tried to extract ^{17}F, ^{15}O, ^{11}C without succeses

Moving Forward with St. Benedict:

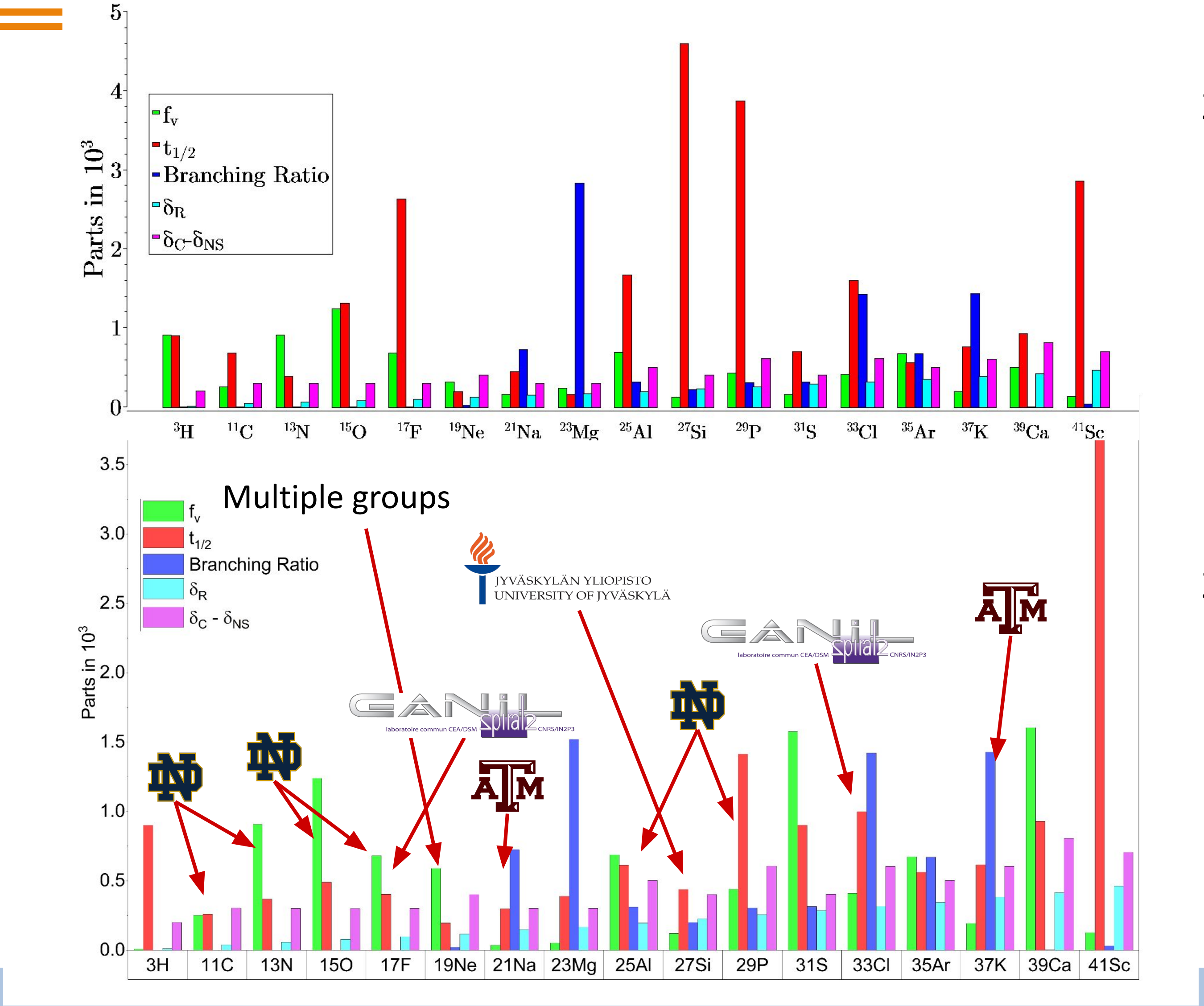


Half Life Measurements at Notre Dame





Half Life Measurements at Notre Dame

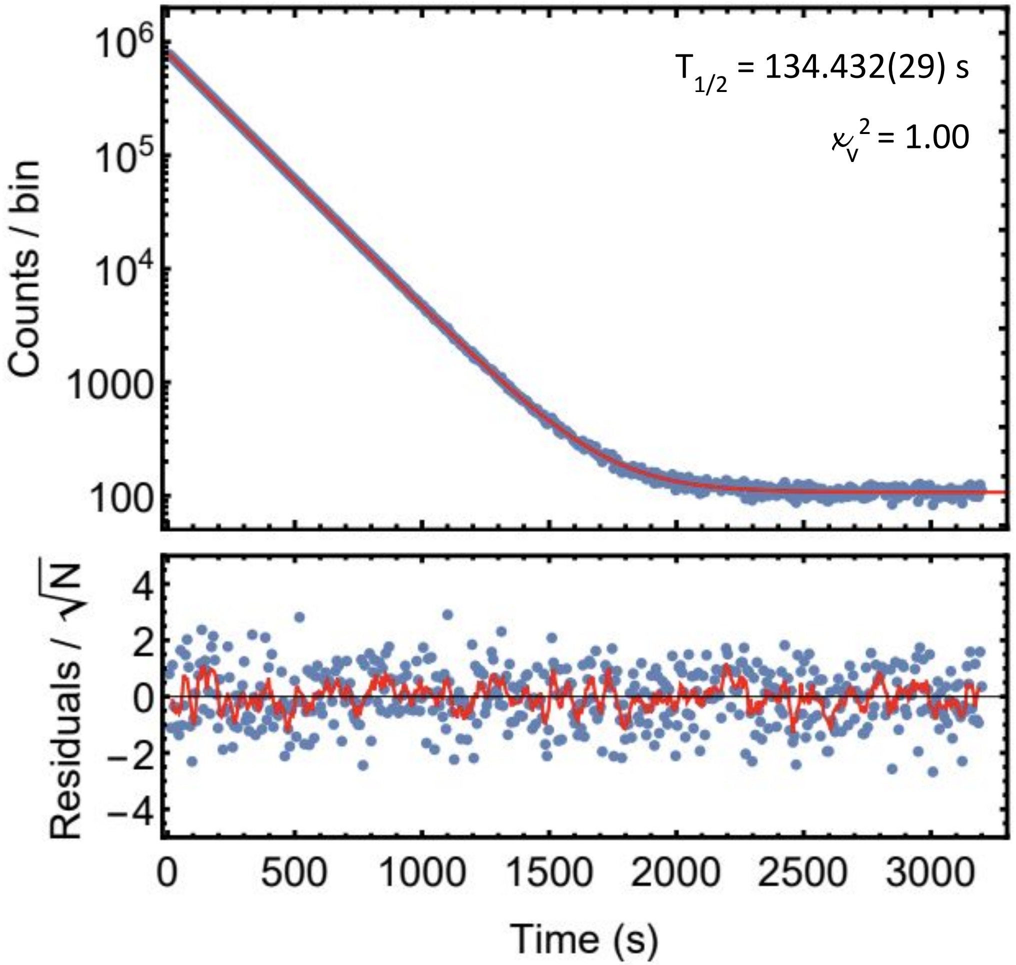


2015 relative uncertainties

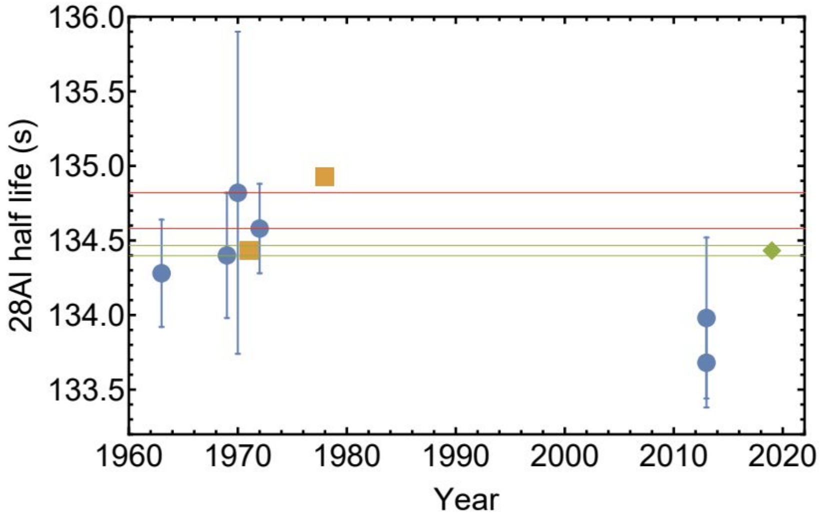
2023 relative uncertainties

N. Severijns, et. al., PHYSICAL REVIEW C 107, 015502 (2023)

^{28}Al Half Life Measurement

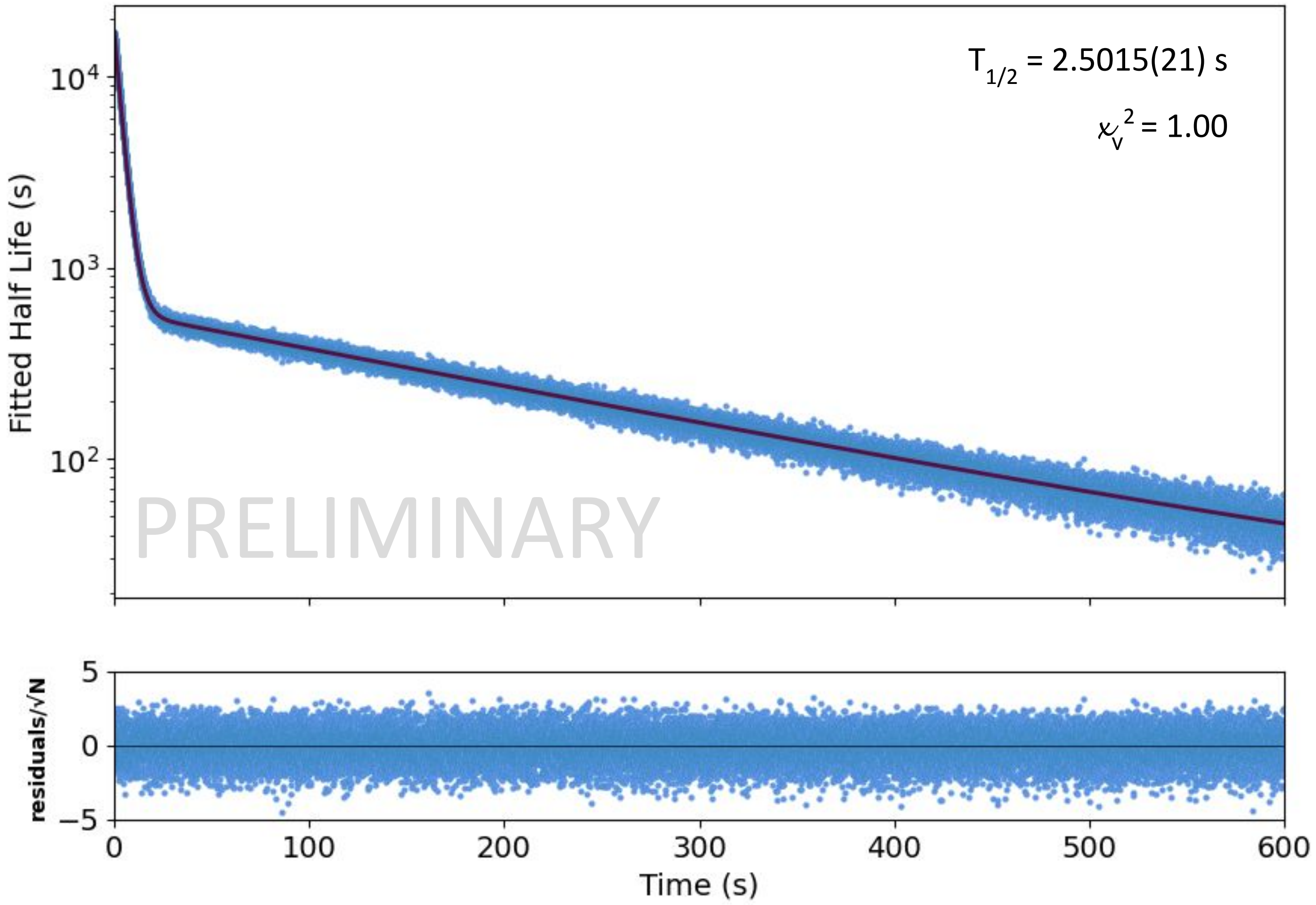


Fitting techniques used from:
V.T. Koslowsky *et al.*, NIM A **401**, 289 (1997)



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.,* Phys. Rev. C 112, 045504

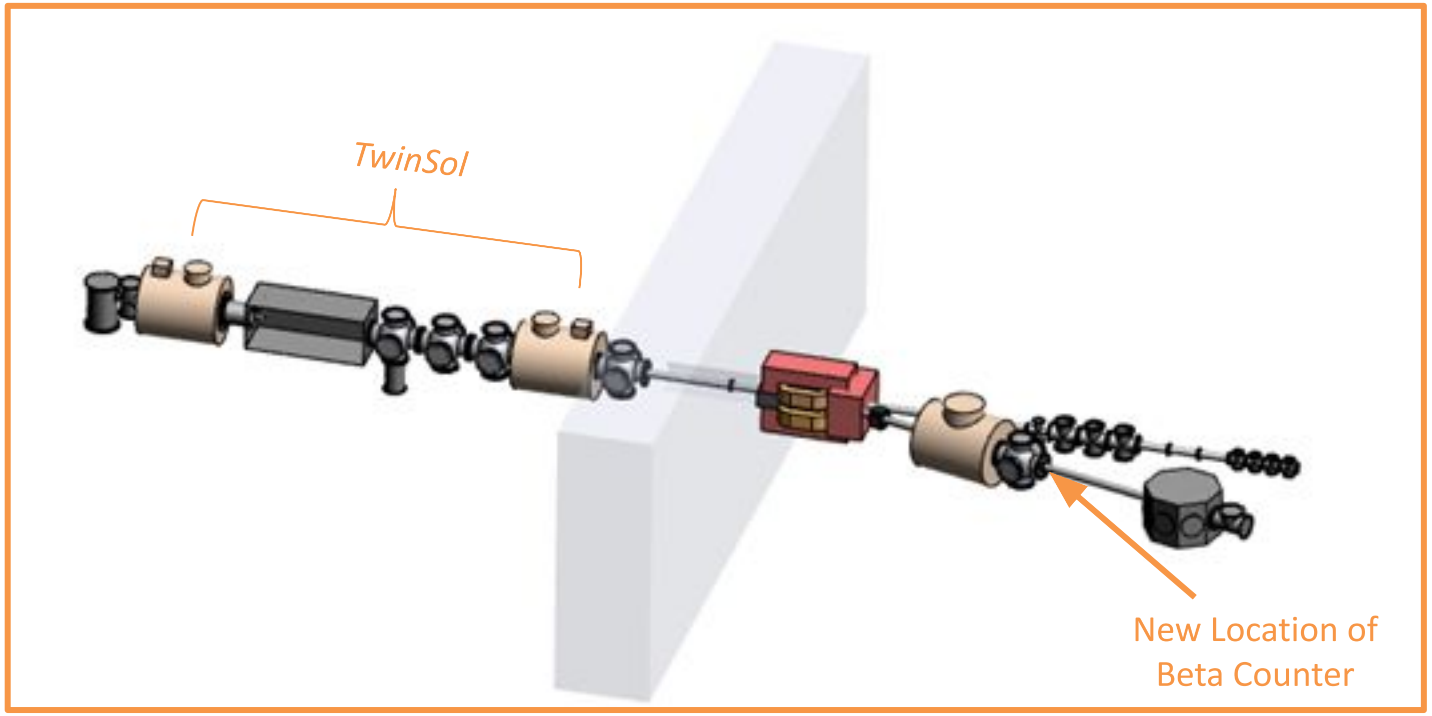
^{33}Cl Half Life Measurement



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

Fit with ^{30}P as a contaminant

Half Life Measurements at Notre Dame

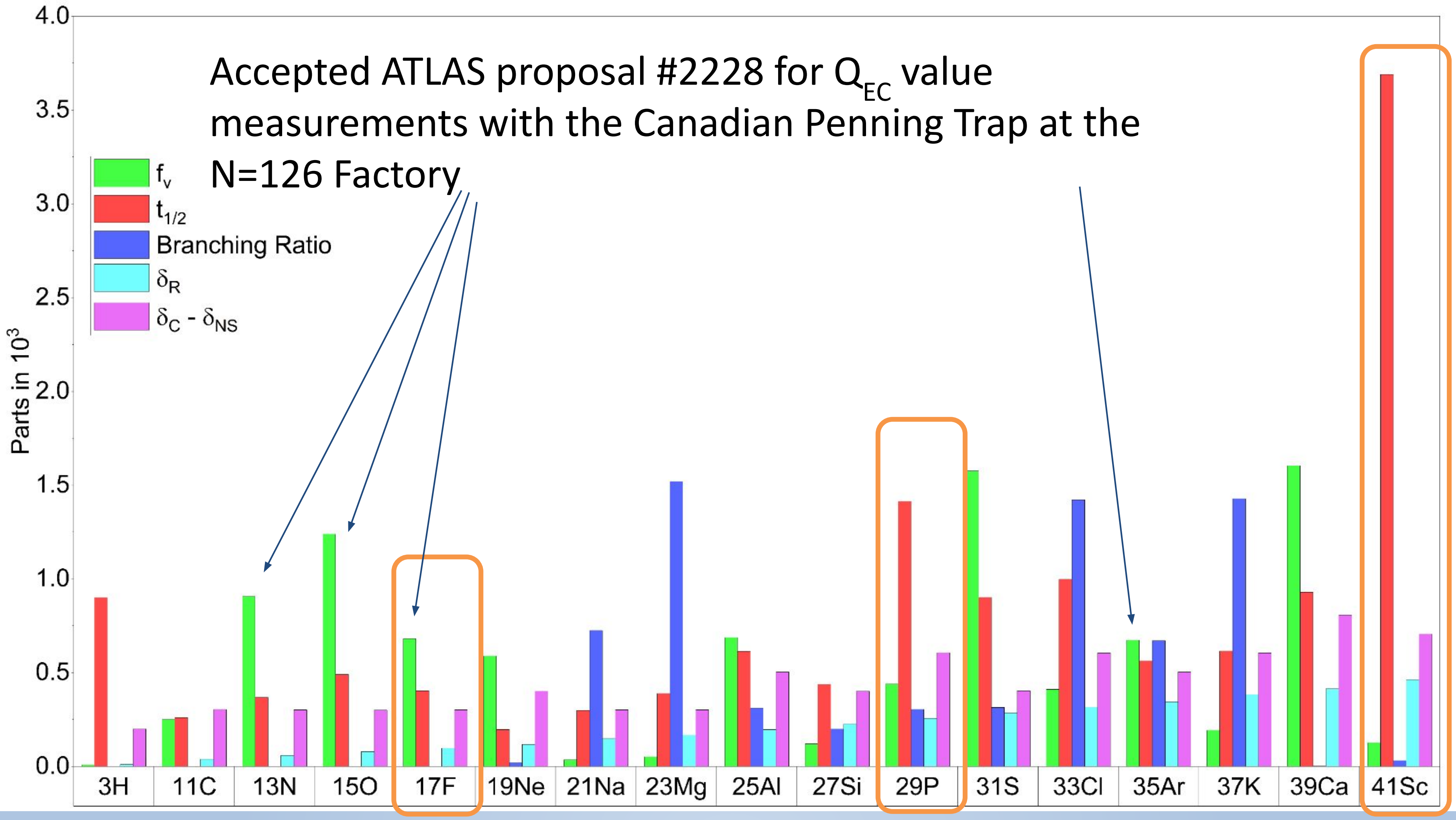


Use of the 15° switching magnet and the third solenoid allows us to better select our isotope of interest and focus it on the target

Transitioning to a Mesyteq DAC

Future Half Life and Q_{EC} Measurements

Accepted ATLAS proposal #2228 for Q_{EC} value measurements with the Canadian Penning Trap at the N=126 Factory



N. Severijns, et. al., PHYSICAL REVIEW C 107, 015502 (2023)

In Summary

- Extracting V_{ud} from mirror transitions will allow us to probe the tension with unitarity of the CKM matrix
- St. Benedict aims to measure $a_{\beta\nu}$ for a range 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: ^{17}F, ^{41}Sc, ^{29}P
- St. Benedict has successfully extracted ^{13}N and ^{25}Al from the gas catcher
- Next steps include commissioning the rest of St. Benedict with an offline source before RIBs

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+ rest of *twinsol* collaboration

UG students
G students
Former G students