



Beta decay recoil time-of-flight measurements with St. Benedict



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Nuclear structure with beta-decay (II), Sept 21, 2026



Unitarity test of the SM



- The Standard Model (SM) can be tested via the CKM matrix unitarity.
- CKM matrix: relates the quark weak and regular eigenstates.

$$\begin{pmatrix} |d_w\rangle \\ |s_w\rangle \\ |b_w\rangle \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} |d_s\rangle \\ |s_s\rangle \\ |b_s\rangle \end{pmatrix}$$

- SM: CKM matrix should be unitary $\sum_i |V_{ui}|^2 = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$
- Non-unitarity could lead to new physics:
 - Extra quark generation
 - Extra Z boson
 - Supersymmetry
 - ... Or erroneous experimental data or theoretical corrections...

$$+ |V_{ux}|^2$$



Status of the Unitarity test



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

$$|V_{ud}| = 0.97367 \pm 0.00032$$

$$|V_{us}| = 0.22431 \pm 0.00085$$

$$|V_{ub}| = (3.89 \pm 0.16) \times 10^{-3}$$

PDG 2026: F. Takahashi *et al.*, Int. J. Mod. Phys. A **41**, 2630011 (2026)

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9984 \pm 0.0007$$

2.3 σ tension with unitarity

V_{ud} : obtained from β -decays



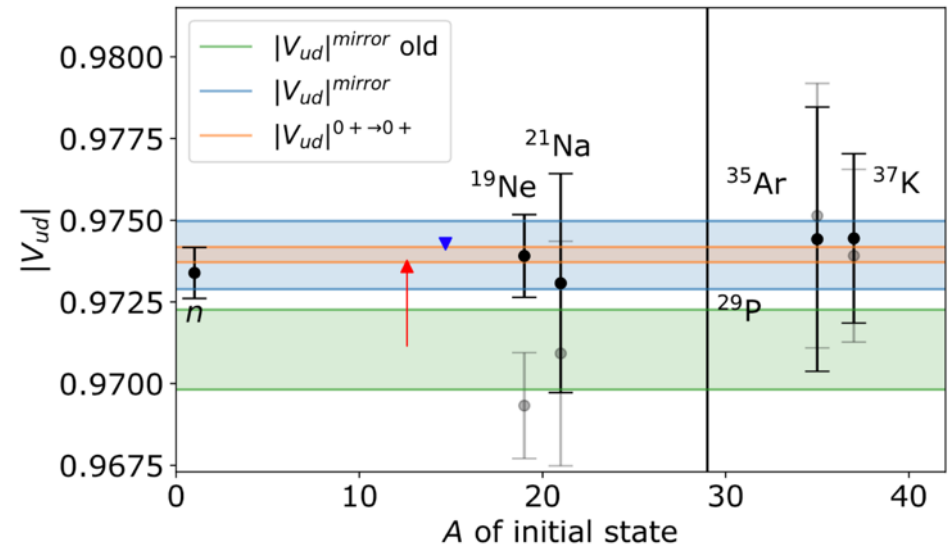
V_{ud} from mixed transitions



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

- Only 5 nuclei
- One more parameter needed than pure Fermi:

- ✓ Half-life 
 - ✓ Branching ratios
 - ✓ Q-values
 - ✓ Fermi-to-Gamow Teller mixing ratio ρ 
- } ft-value



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

$$\mathcal{F}t_0 = ft(1 + \delta'_R)(1 + \delta_{NS} - \delta_C) \left[1 + (f_A/f_V)\rho^2 \right]$$

$$= \frac{K}{G_F^2 V_{ud}^2 (1 + \Delta_R^V)},$$

ρ determined by measuring either:

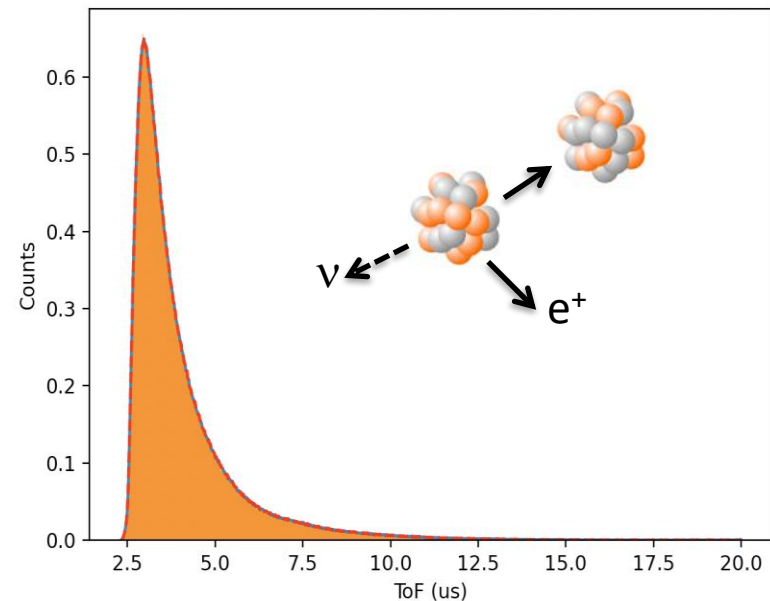
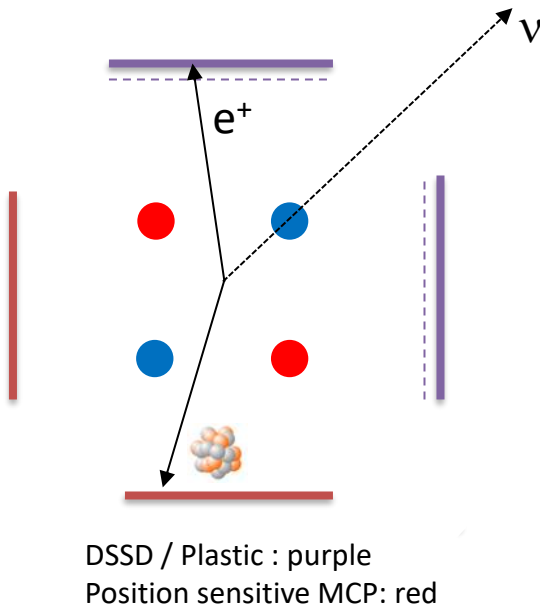
- β asymmetry parameter A_β
- ν asymmetry parameter B_ν
- β - ν angular correlation $a_{\beta\nu}$



Measuring $a_{\beta\nu}$ using a Paul trap



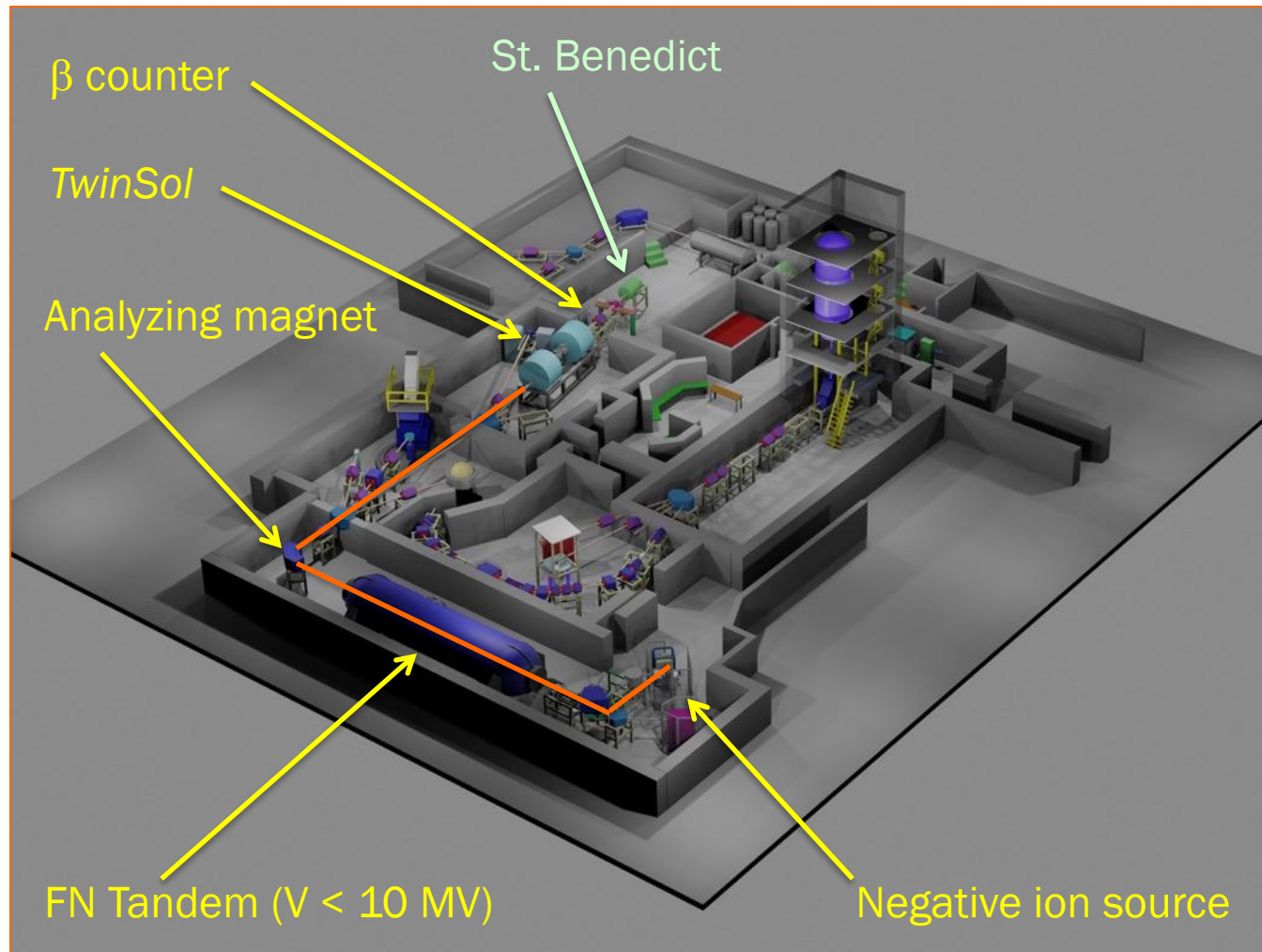
- $a_{\beta\nu}$ can be inferred from shape of energy spectra of positron and the TOF of recoil after decay of trapped nuclei.
- A Paul trap holds any kind of ions in well-defined region of space.



Superalloyed Transition Beta-Neutrino Decay Ion Coincidence Trap (St. Benedict)
At the University of Notre Dame Nuclear Science Laboratory



Nuclear Science Laboratory



Nuclear structure with beta-decay (II), Sept 21, 2026

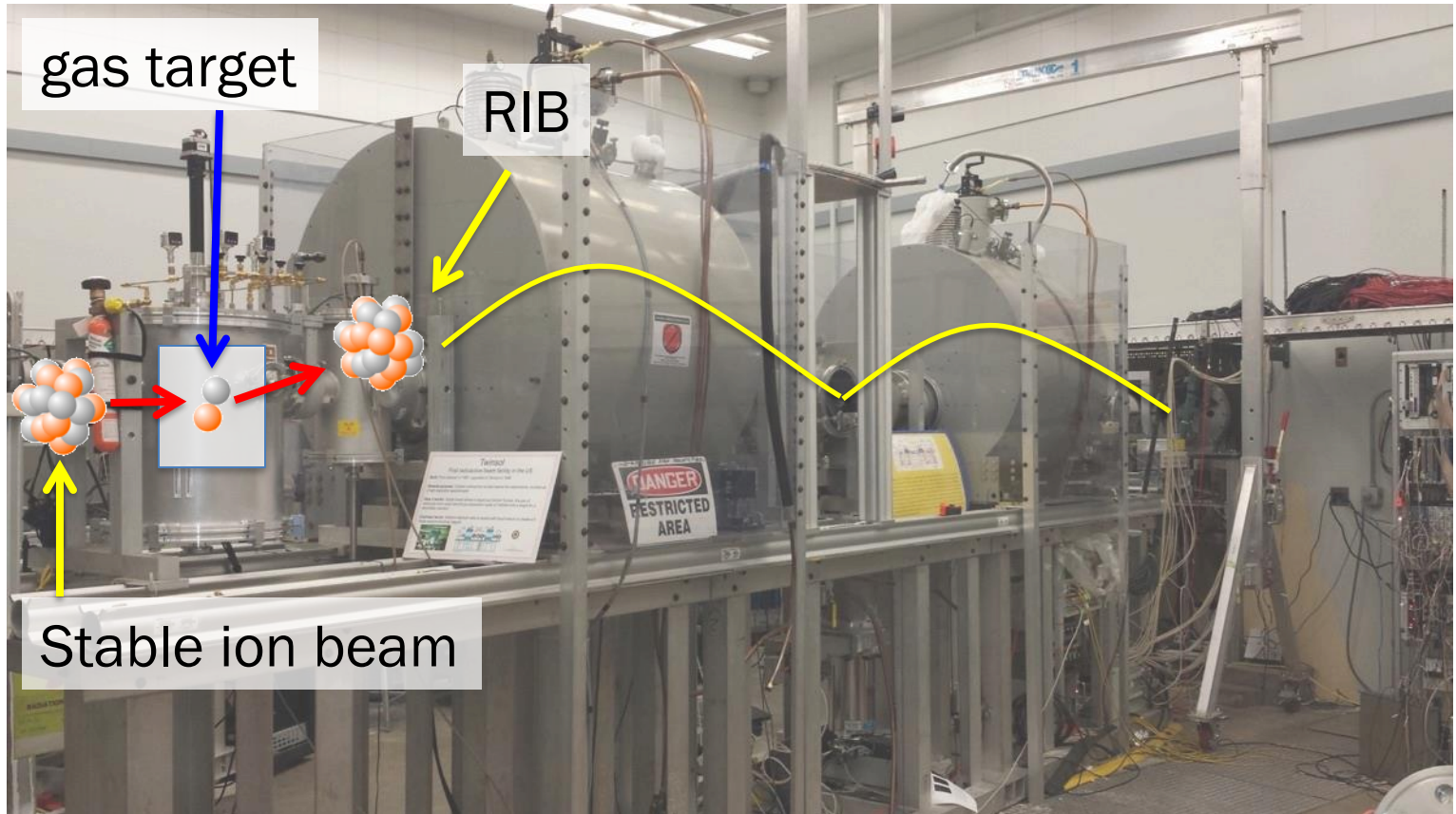


TwinSol facility



One of the oldest RIB facility still operational

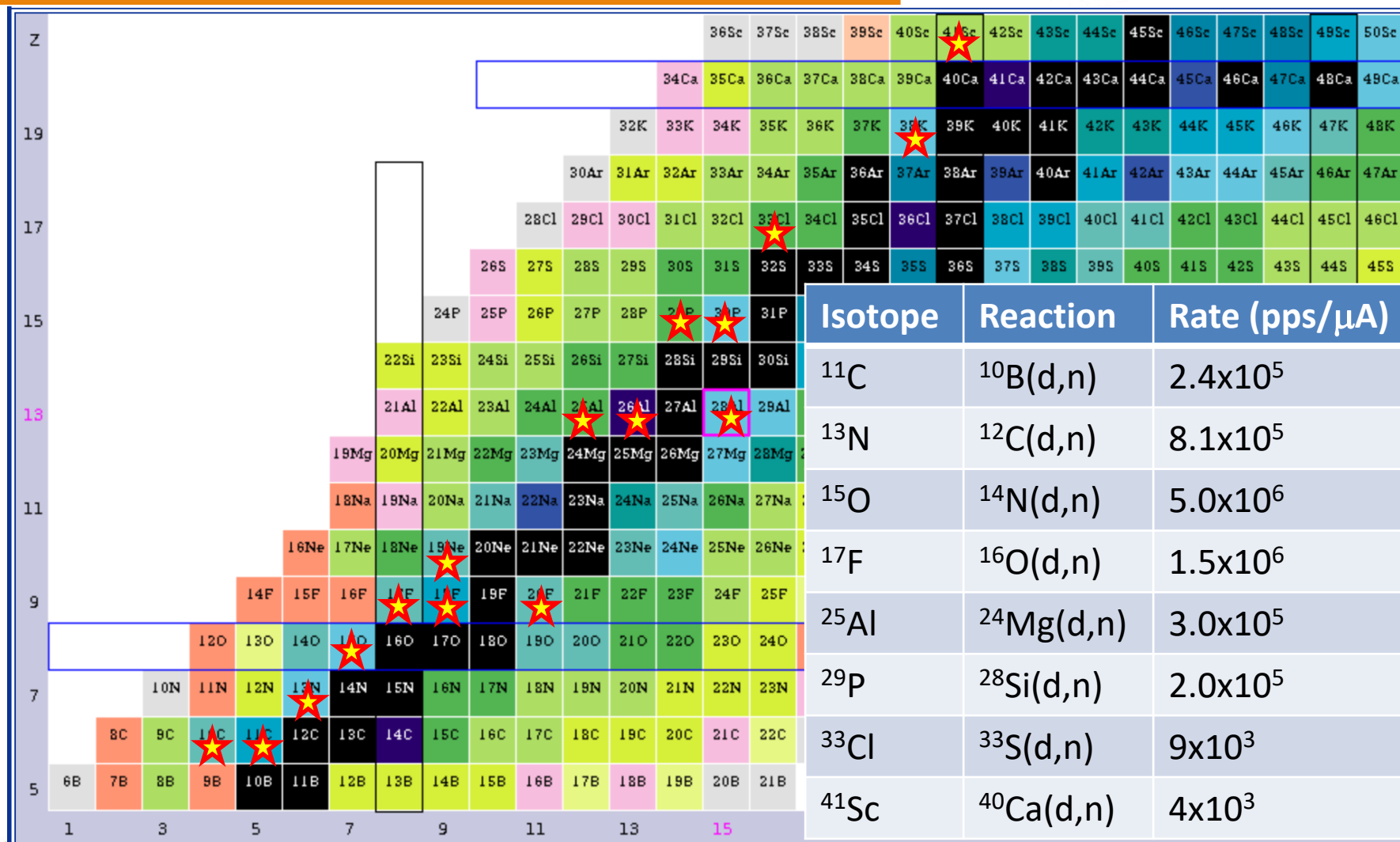
F.D. Becchetti *et al.*, NIM A **505**, 377 (2003)



Nuclear structure with beta-decay (II), Sept 21, 2026



RIB produced at *TwinSol*



Nuclear structure with beta-decay (II), Sept 21, 2026



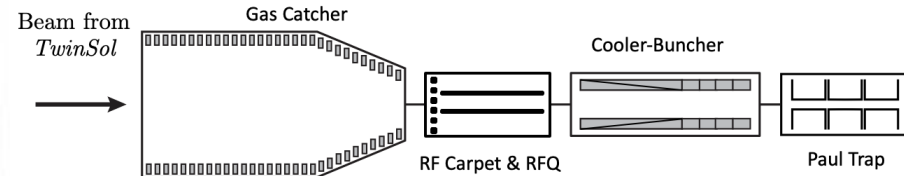
Mirror decays at the NSL



Stable
primary
beam

TwinSol

St. Benedict for determination of ρ



TriSol

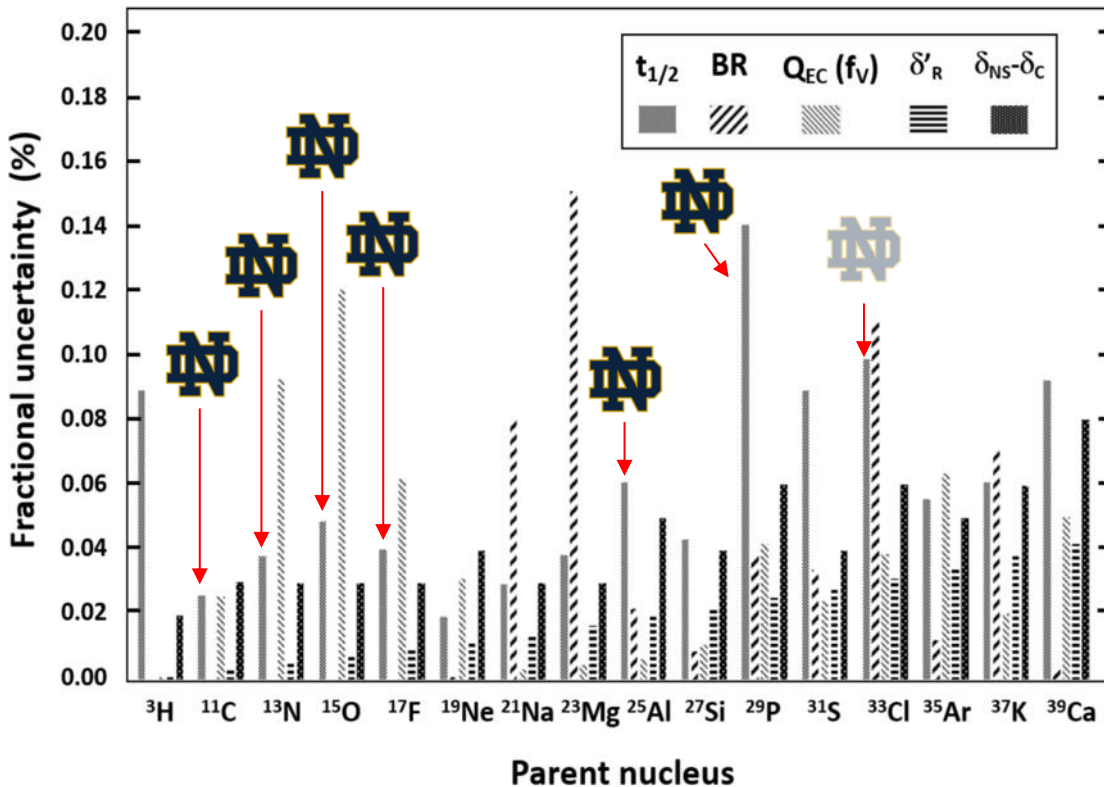
PMT

RIB

ND beta counter for
 $t_{1/2}$ measurements

beta-decay (II), Sept 21, 202

Half-life measurements after TwinSol



Measurements performed after TwinSol using the ORNL analogue DAC.

- ^{17}F : M. Brodeur *et al.* PRC **93** 025503 (2016).
- ^{25}Al : J. Long *et al.* PRC **96**, 015502 (2017) .
- ^{11}C : A. Valverde *et al.* PRC **97**, 035503 (2018).
- ^{20}F : D.P. Burdette *et al.* PRC **99**, 015501 (2019).
- ^{15}O : D.P. Burdette *et al.* PRC **101** 055504 (2020).
- ^{29}P : J. Long *et al.* PRC **101**, 015501 (2020).
- ^{13}N : J. Long *et al.* PRC **106**, 045501 (2022).
- ^{28}Al : B. Liu *et al.* PRC **112**, 045504 (2025).
- ^{33}Cl : R. Zite *et al.* under preparation.

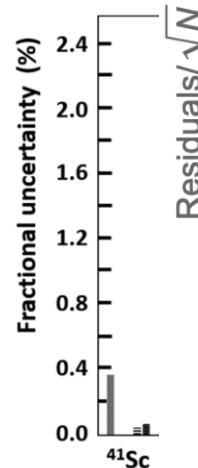
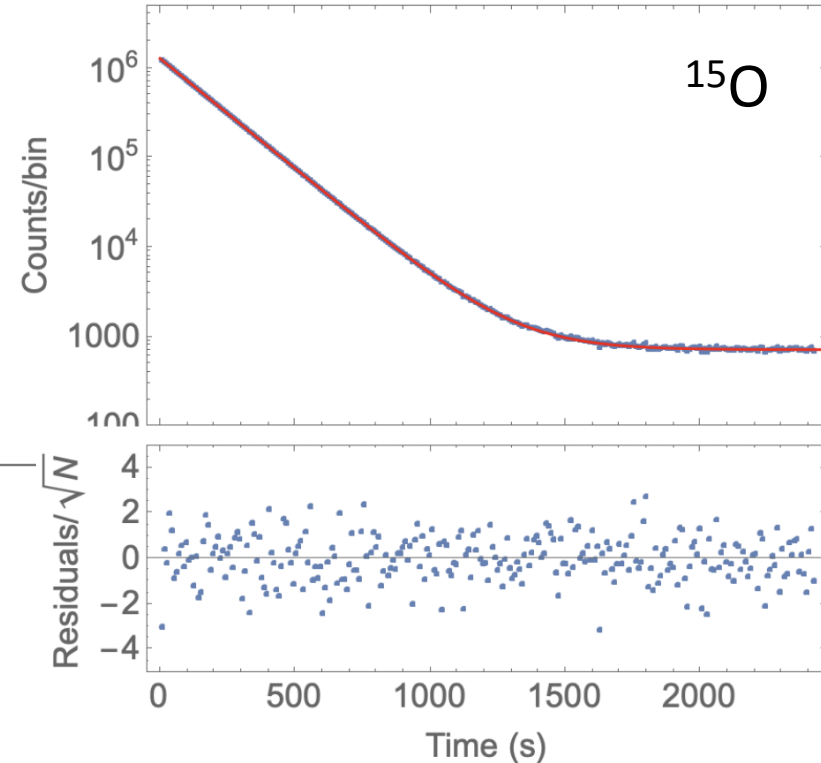
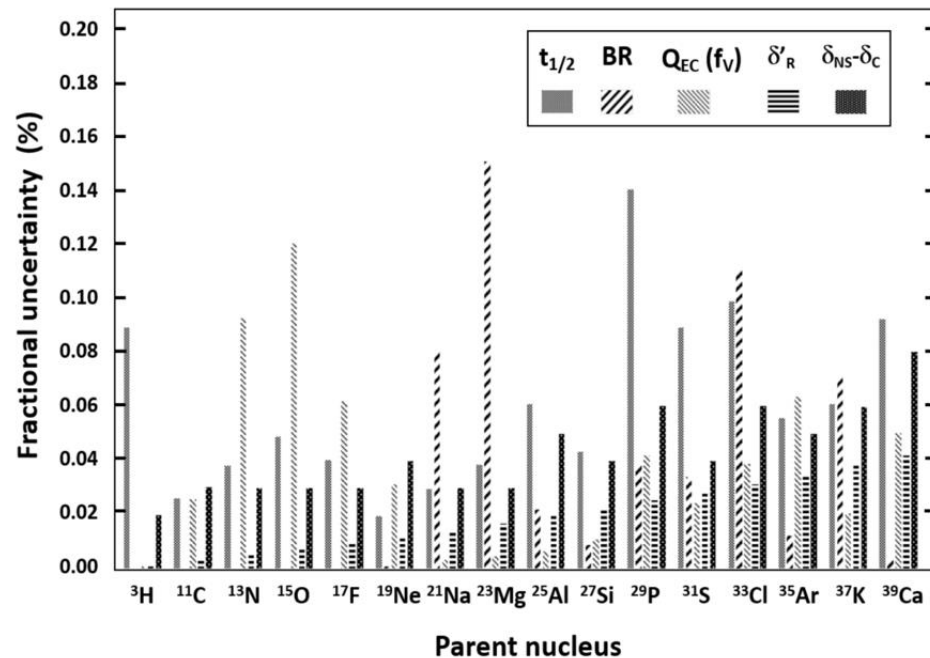
N. Severjins *et al.*, PRC **107**, 015502 (2023)



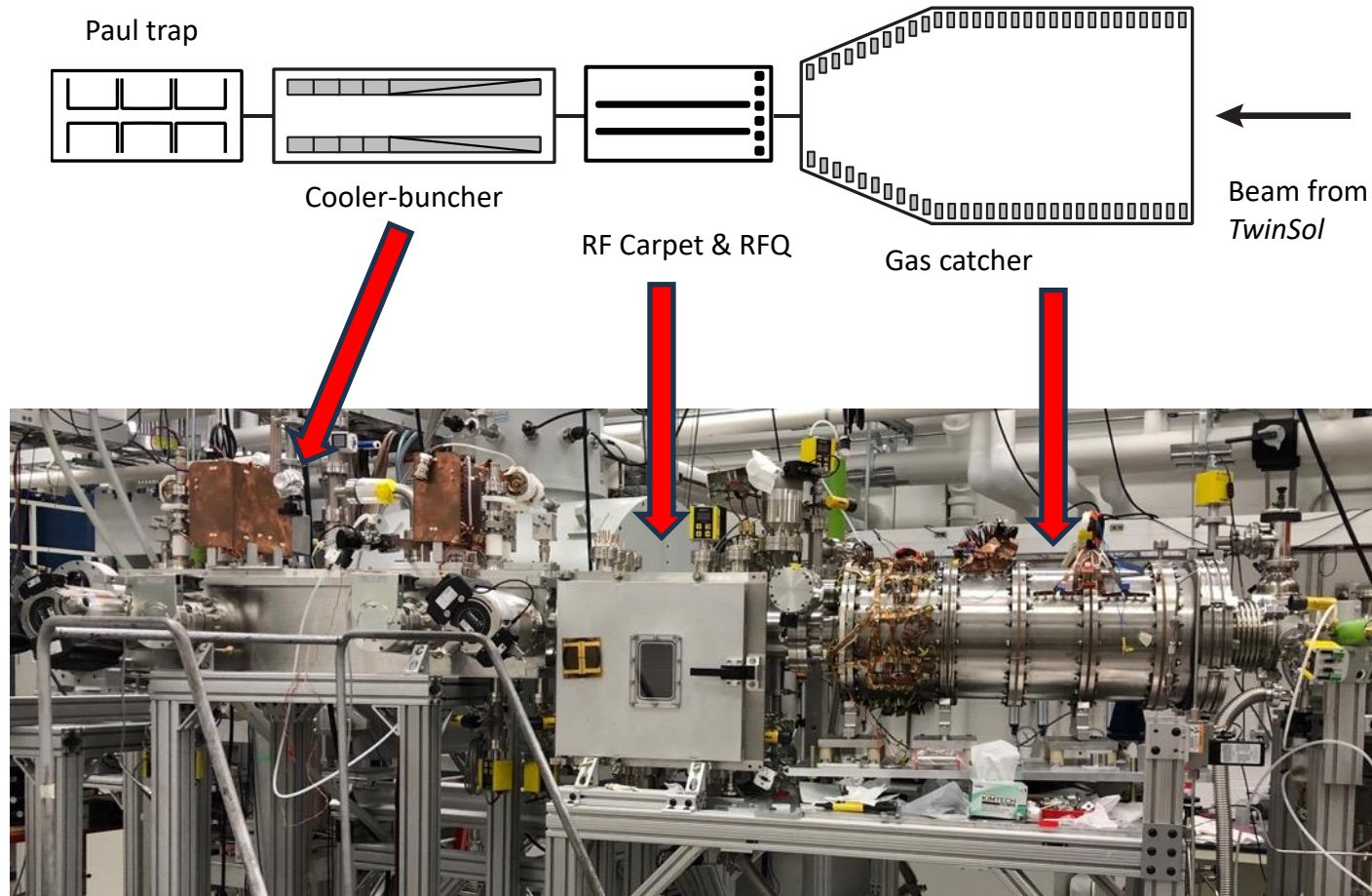
Half-life measurements @ TriSol



- Recently moved the beta counter after TriSol.
- Will allow better contaminant separation.
- Also use the Mesytec digital DAC.
- Commissioned by measuring ^{15}O and others.
- In future, plan on measuring ^{41}Sc and others.



Superalloyed Transistion Beta-Neutrino Decay Ion Coincidence Trap

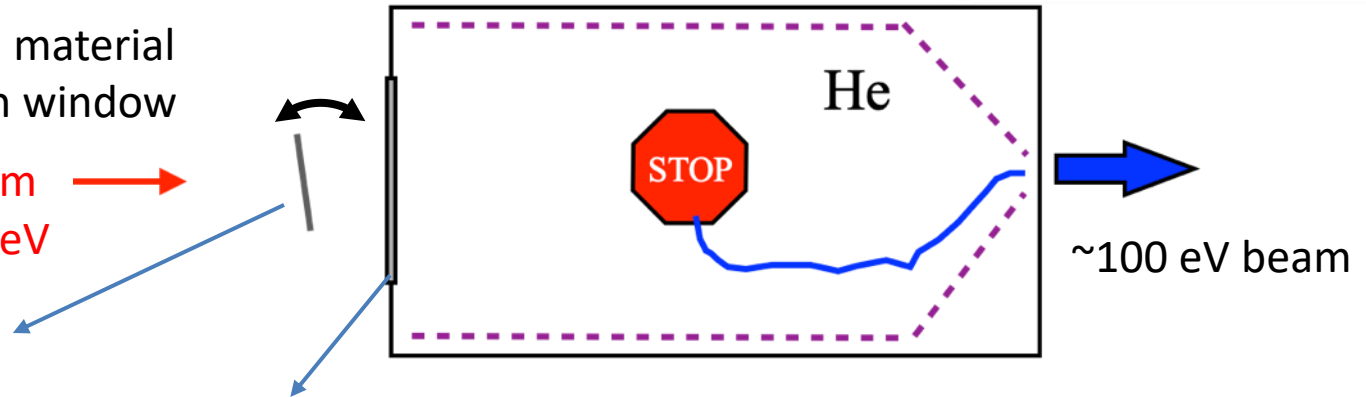


Gas catcher degrader and window



- 1) Loses energy in solid material
- 2) Punch through a thin window

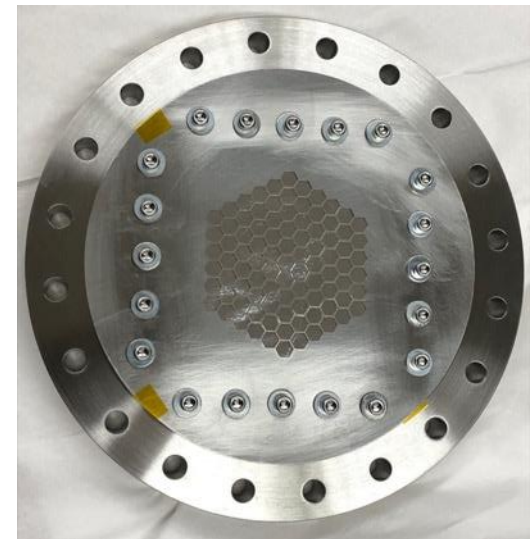
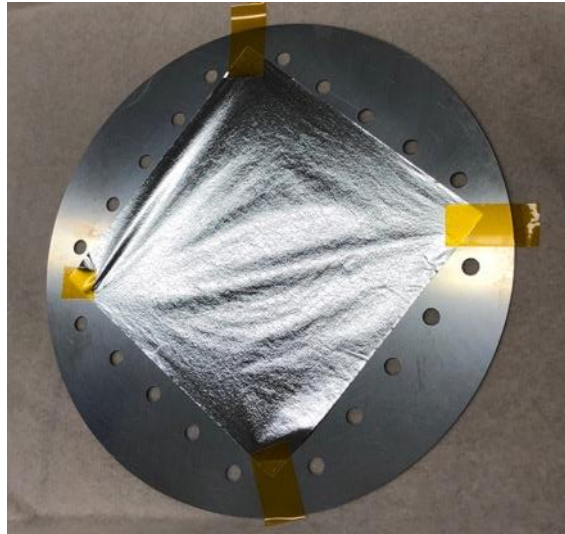
TwinSol beam
 $E = 10\text{-}40\text{ MeV}$



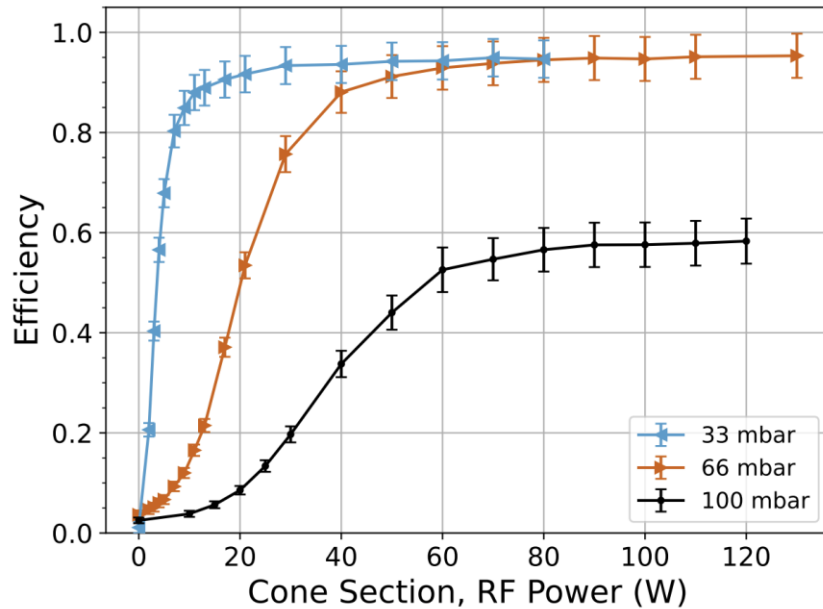
7 μm Al degrader on
rotating actuator



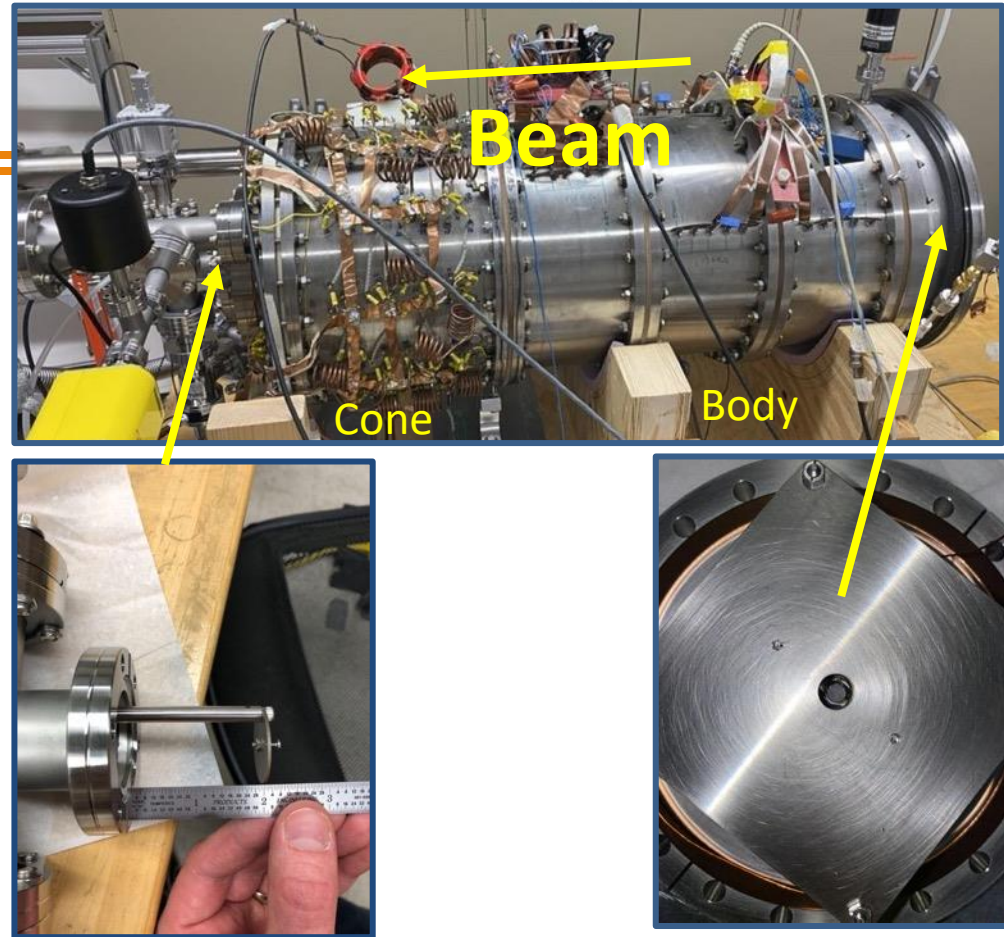
10 μm light-tight Al window from Goodfellow on a
photo-etched honey-comb supporting mesh.



Transport tests

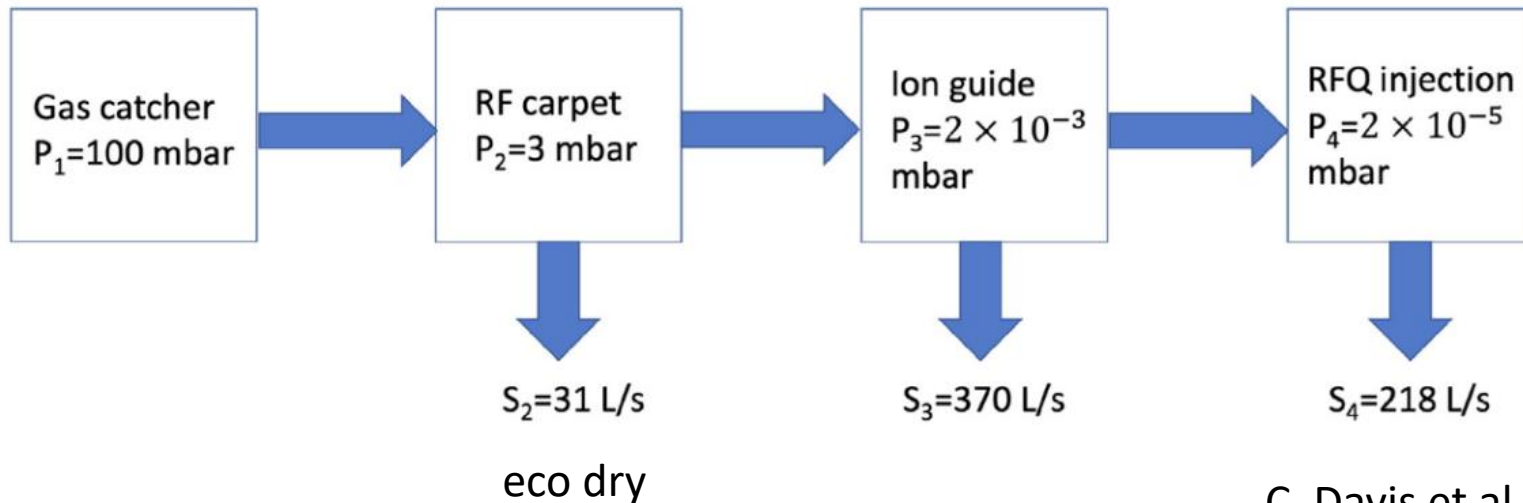


F. Rivero et al., NIMA **1092**, 171771 (2026)



- Previously used at Argonne National Lab
- Transport tests using K⁺ source in gas catcher.
- Collected transported ions on a plate after the exit nozzle.
- **>95% transport efficiency at 33, 66 mbar**
- 60% at 100 mbar (losses occurring in the body section).

Extraction system

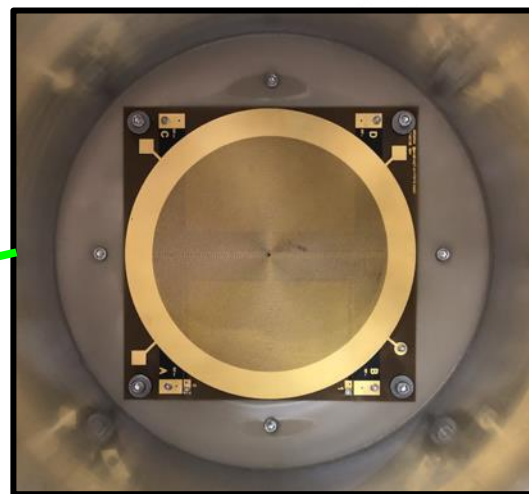
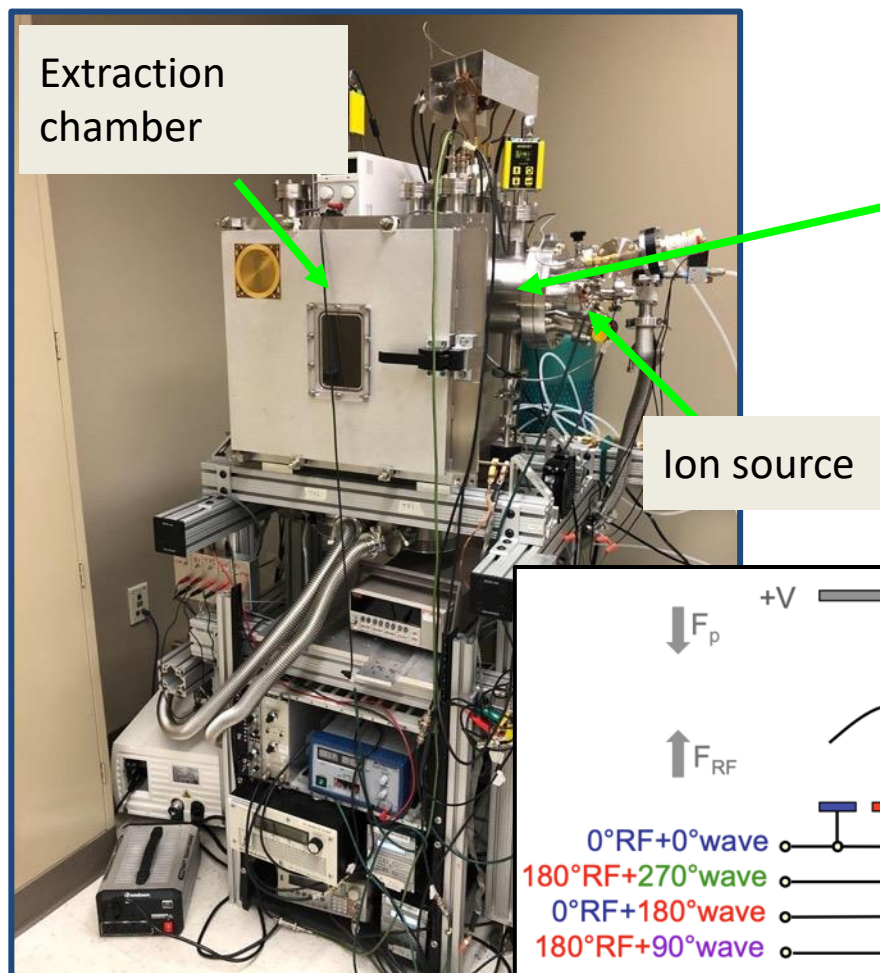


C. Davis et al, NIM A, 2022

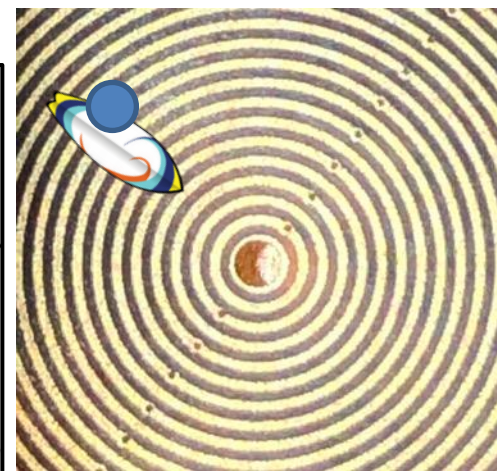
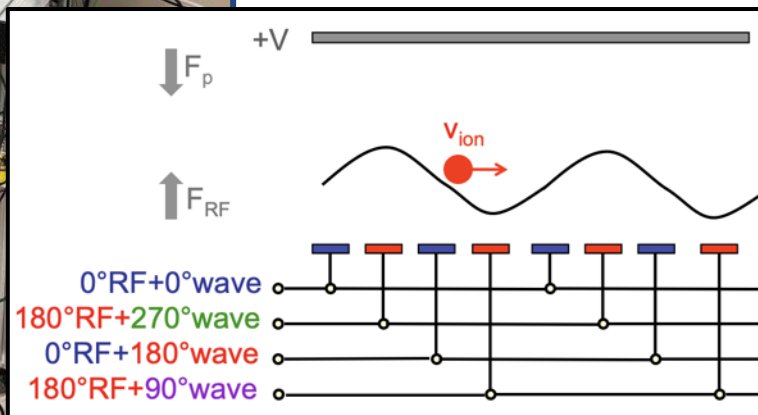
- RF Carpet and lon guide will transport ions through a differentially pumped region
- This allows for the pumping down of the region between the gas catcher and cooler-buncher to adequate pressures, using standard vacuum pumps



RF carpet transport test setup



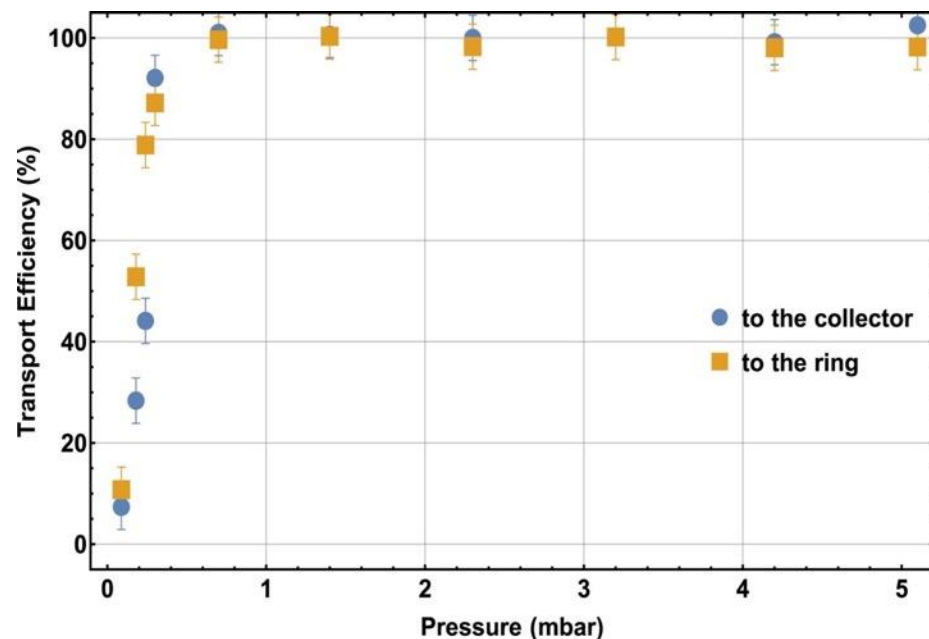
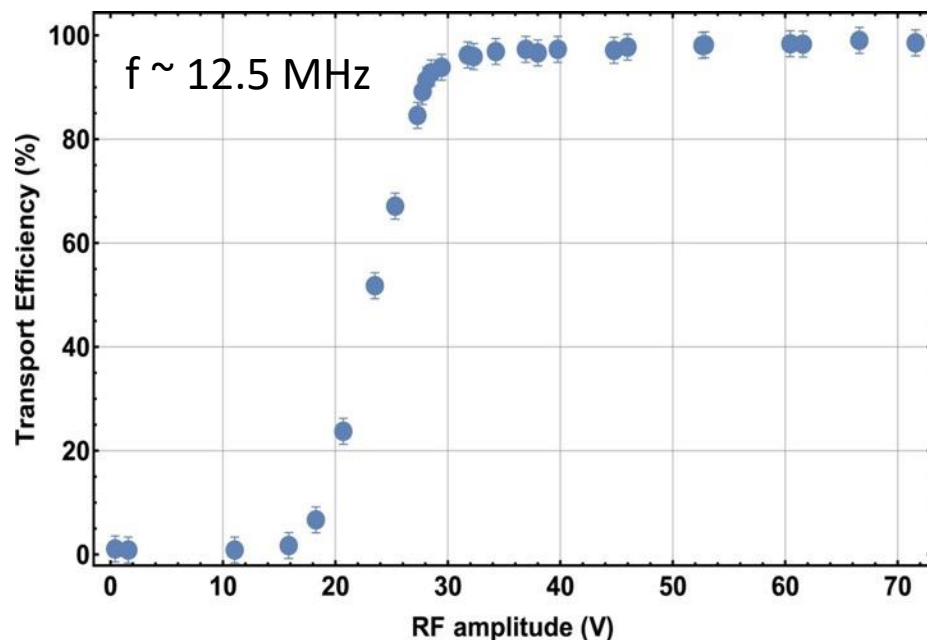
RF Carpet
Front view



RF carpet off-line commissioning



- Used same ion source mounting as gas catcher
- Compared current on entire carpet to that on the collector plate (immediately after the RF carpet aperture)/ring electrode
- Achieve ~100% transport efficiency down to 0.75 mbar pressure



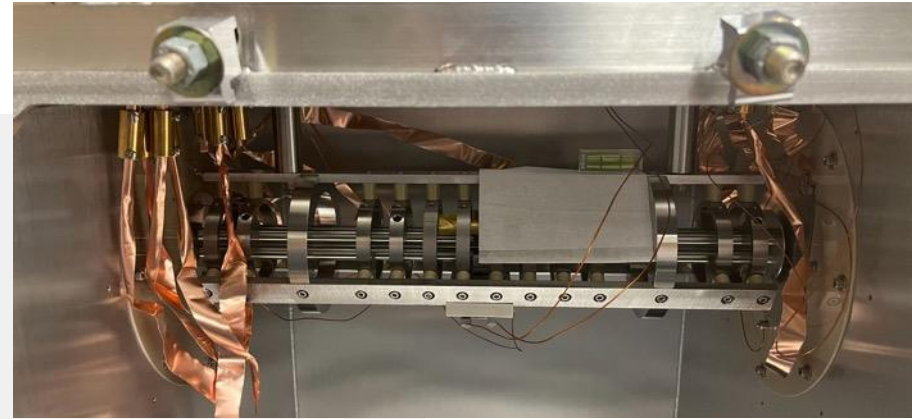
C. Davis et al. in NIM A 1042 (2022) 167422



RFQ ion guide



To cooler-
buncher

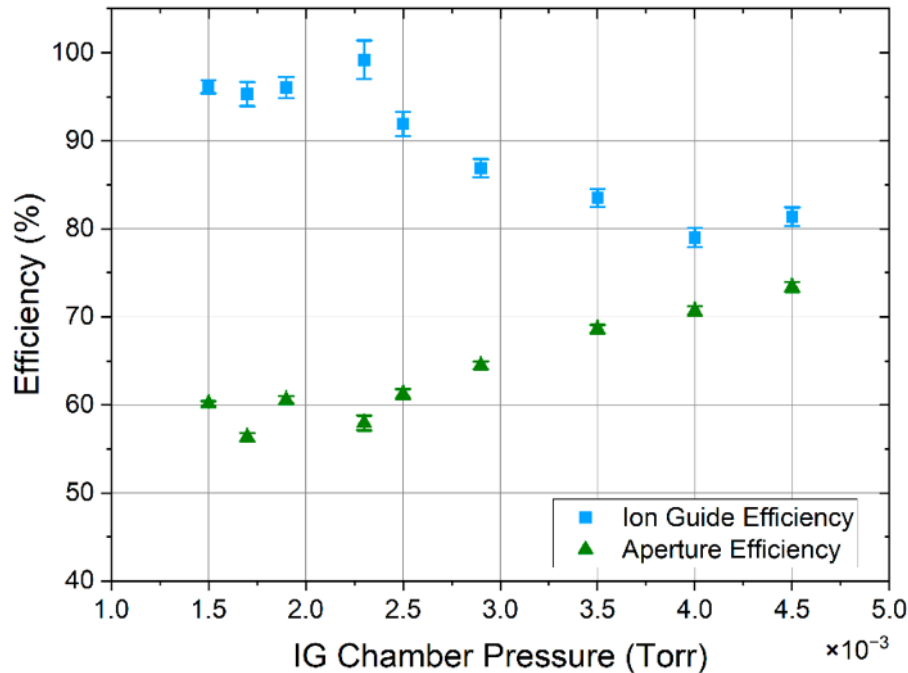


90° angle
off-line ion
source

Beam from
RF carpet

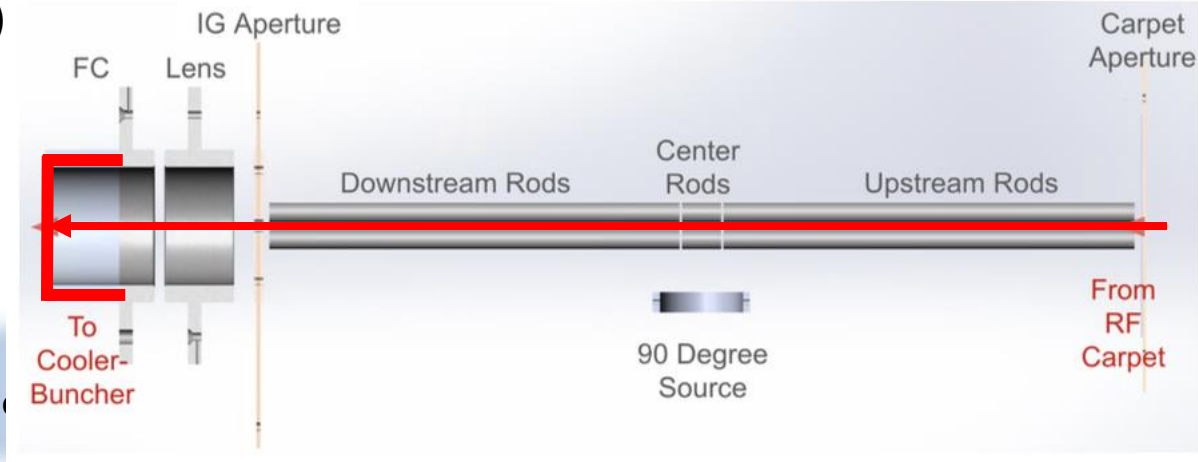


Transport tests from RF carpet



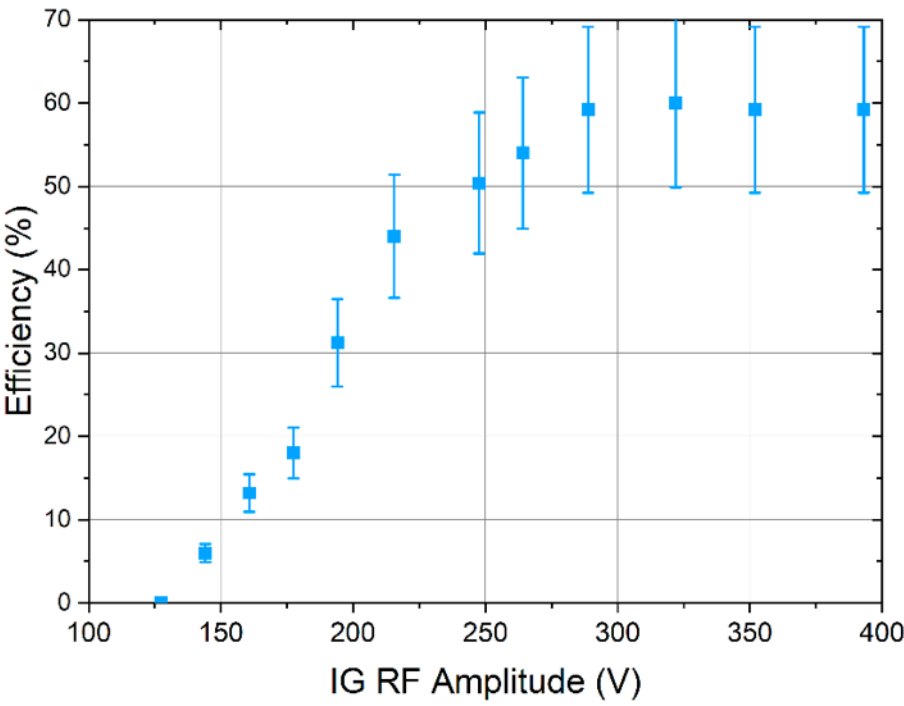
- Around 95% transport efficiency for the ion guide for $P < 2.5 \times 10^{-3}$ torr.
- A lower transport efficiency of 60% is however achieved through the RF carpet aperture at these pressures.
- Simulations underway to understand and find a way to mitigate these small transport losses.

R. Zite *et al*, NIM A **1088**, 171483 (2026)



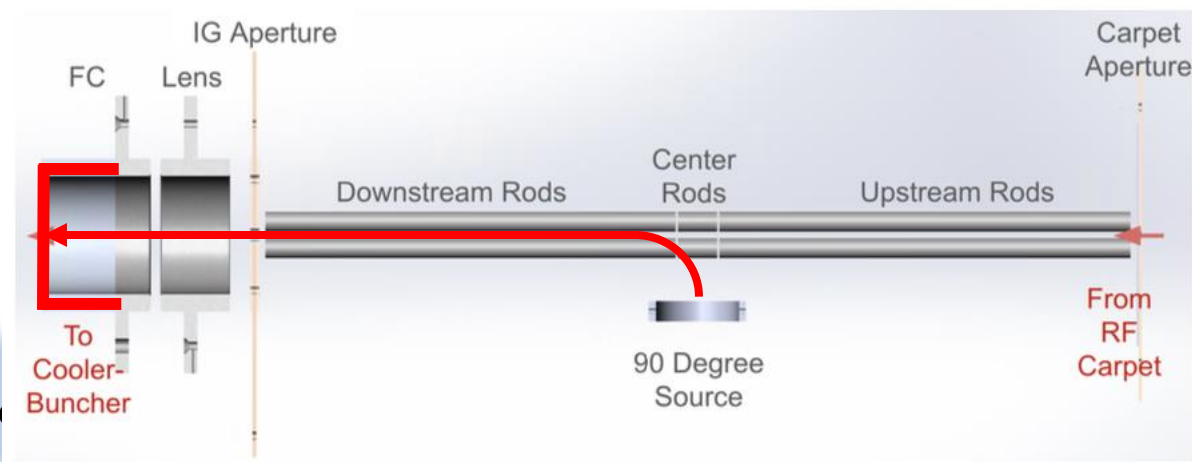
Nuclear structure with beta-decay

Transport tests from 90° ion source



- Around 60% transport efficiency from the 90 degrees ion source.
- Sufficient transport efficiency from that source.

R. Zite *et al*, NIM A **1088**, 171483 (2026)

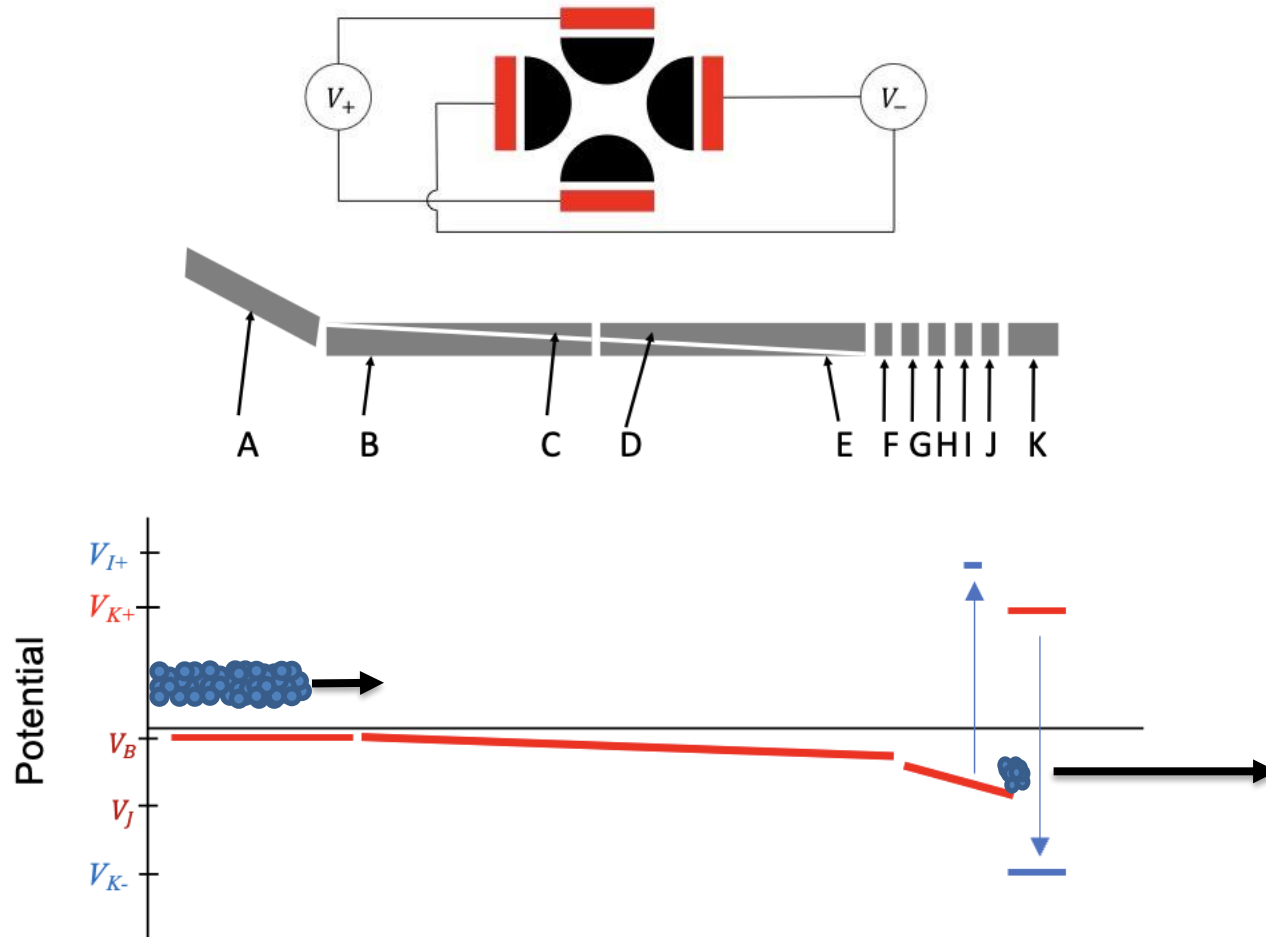


Nuclear structure with beta-decay

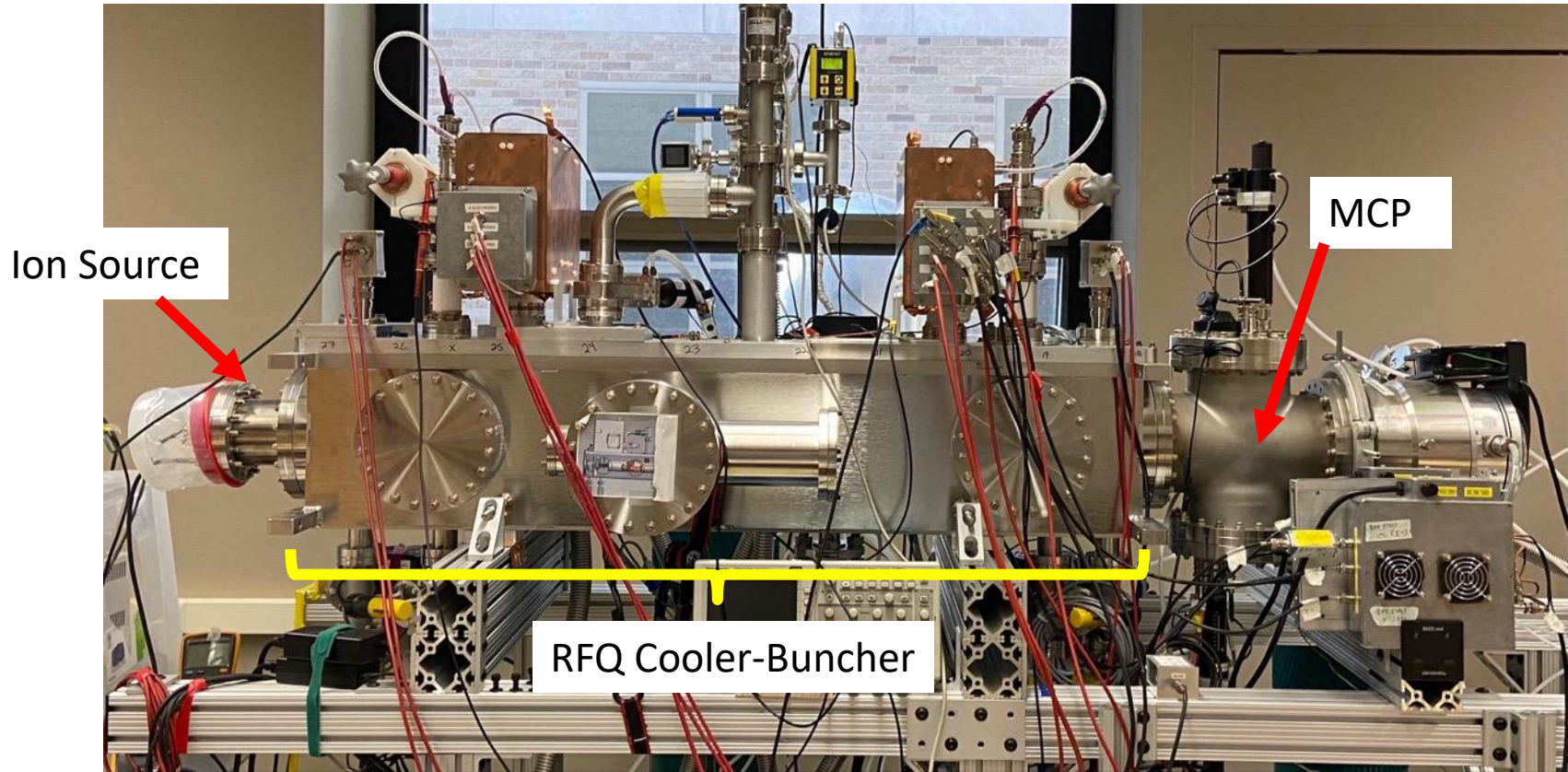
RFQ cooler-buncher



Takes continuous beam and bunch it.



RFQ cooler-buncher



NSCL EBIT cooler-buncher design.



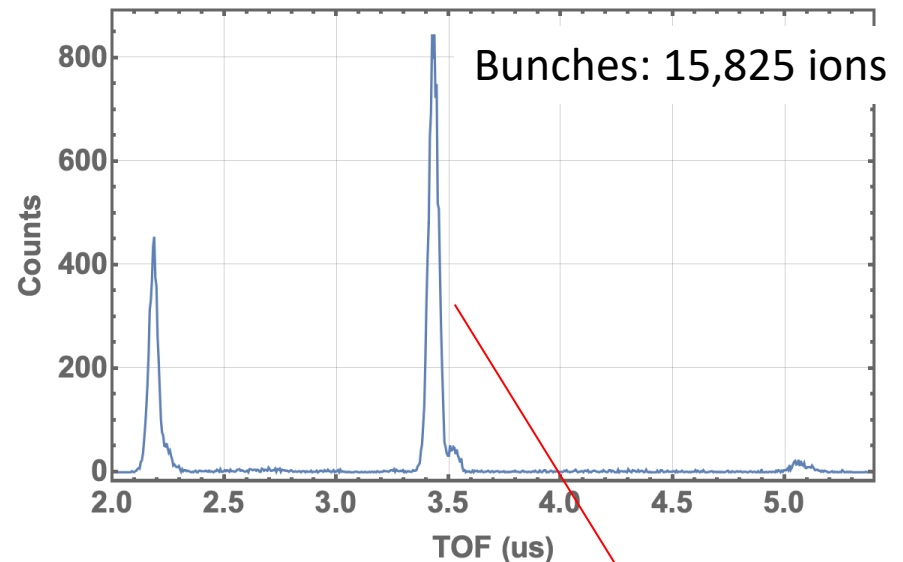
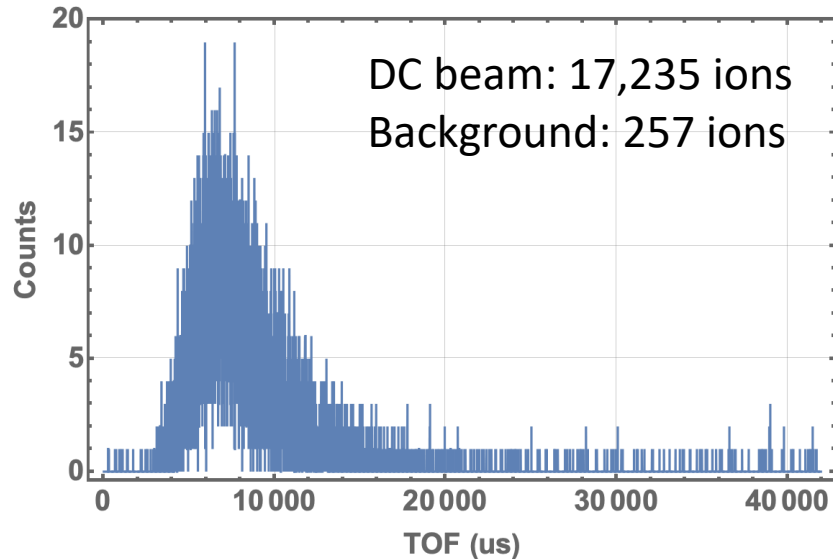
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Bunching efficiency

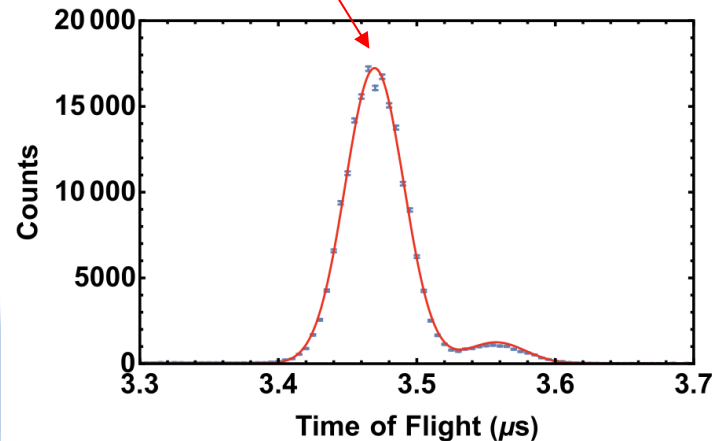


- 10,000 cycles of 10 μs gated beam sent to cooler-buncher
- Same settings for DC and bunched beams (except I & K electrodes kept low for DC)

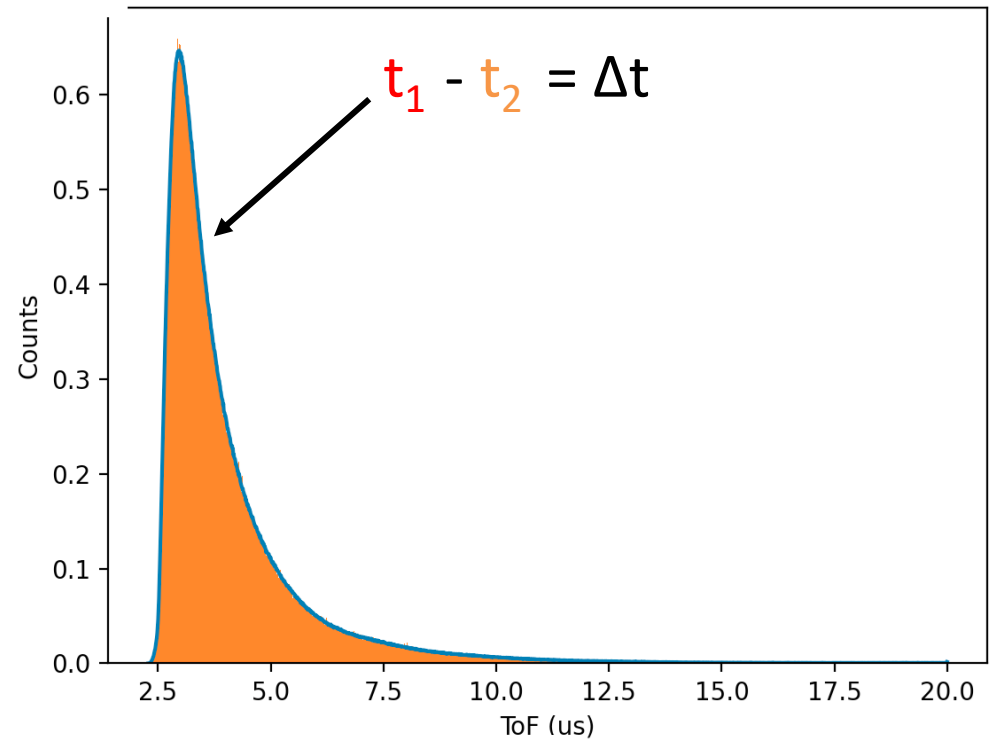
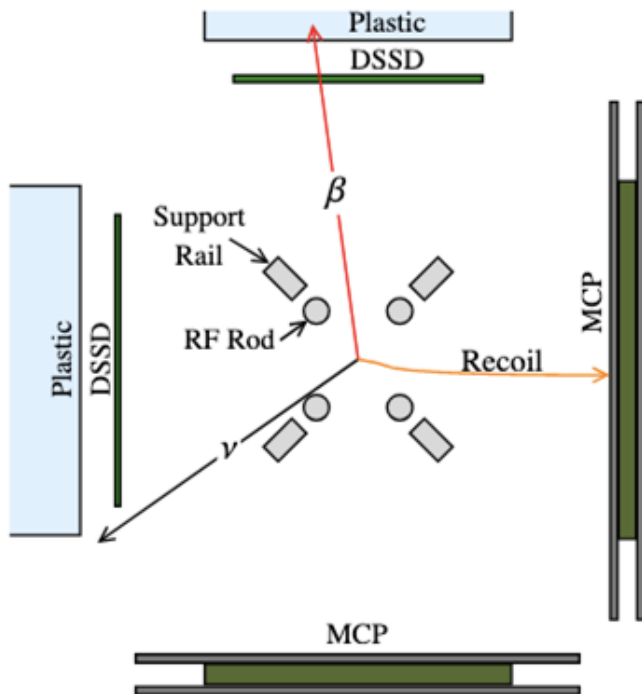
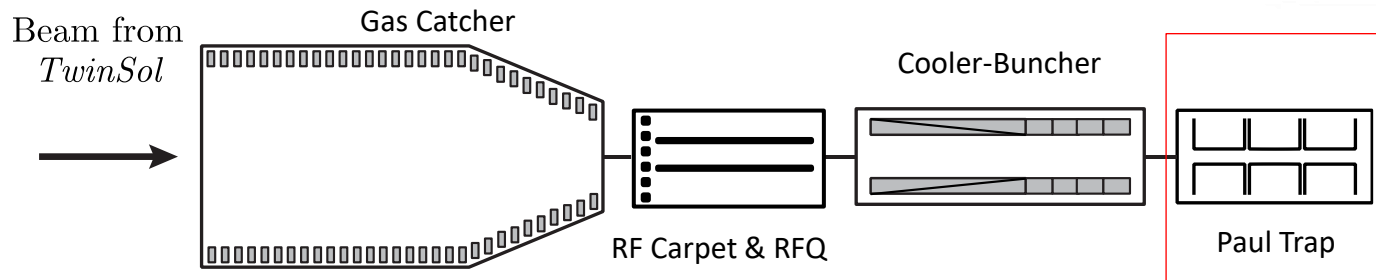


- “Bunching efficiency”: Bunch/DC = 93%

D.P. Burdette *et al*, NIM A **1084**, 171187 (2026)



Paul trap



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



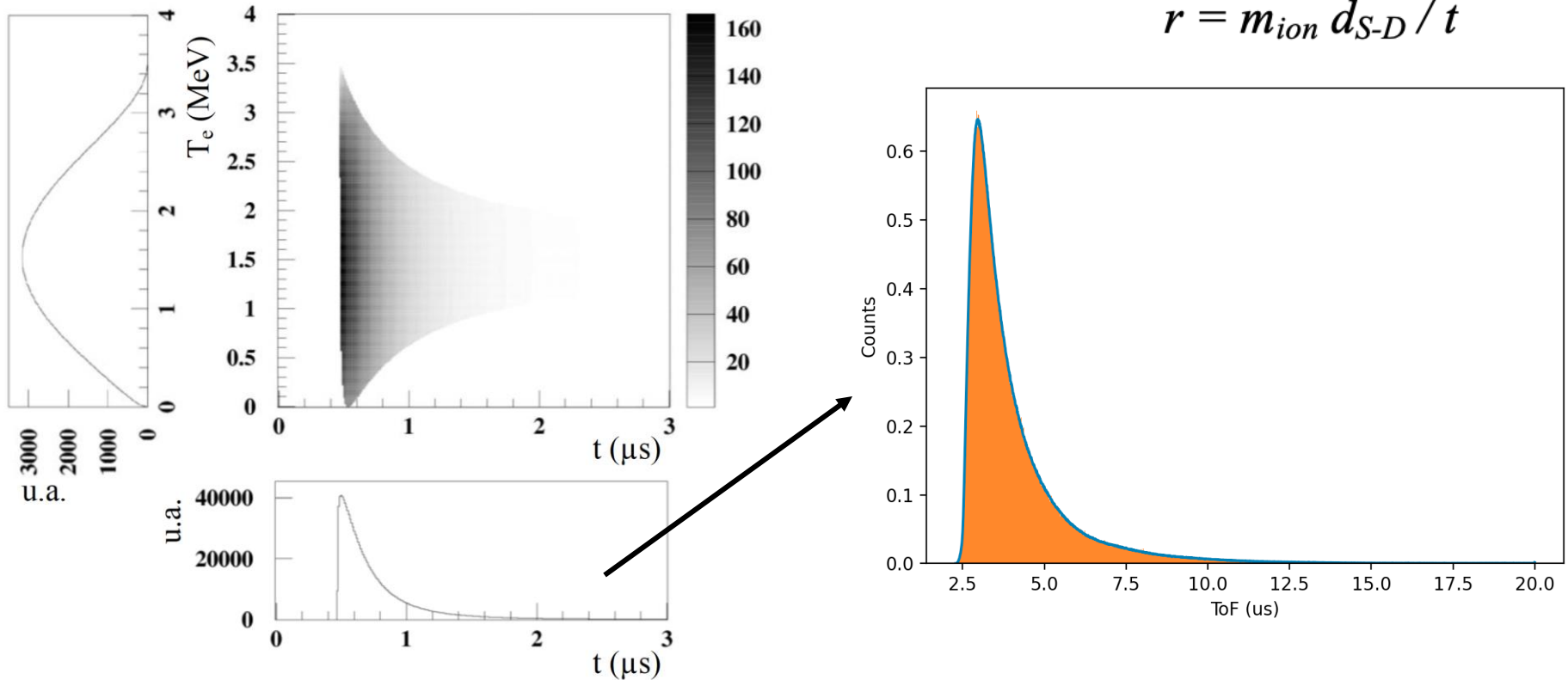
UNIVERSITY OF
NOTRE DAME

$a_{\beta\nu}$ from TOF



$$N(T_e, t) dT_e dt = C' (T_e + m_e c^2) r^3 (Q - T_e) \xi \left(1 + a \frac{(r^2 - p_e^2 - p_\nu^2) c}{2 E_e p_\nu} \right) dT_e dt$$

$$r = m_{ion} d_{S-D} / t$$



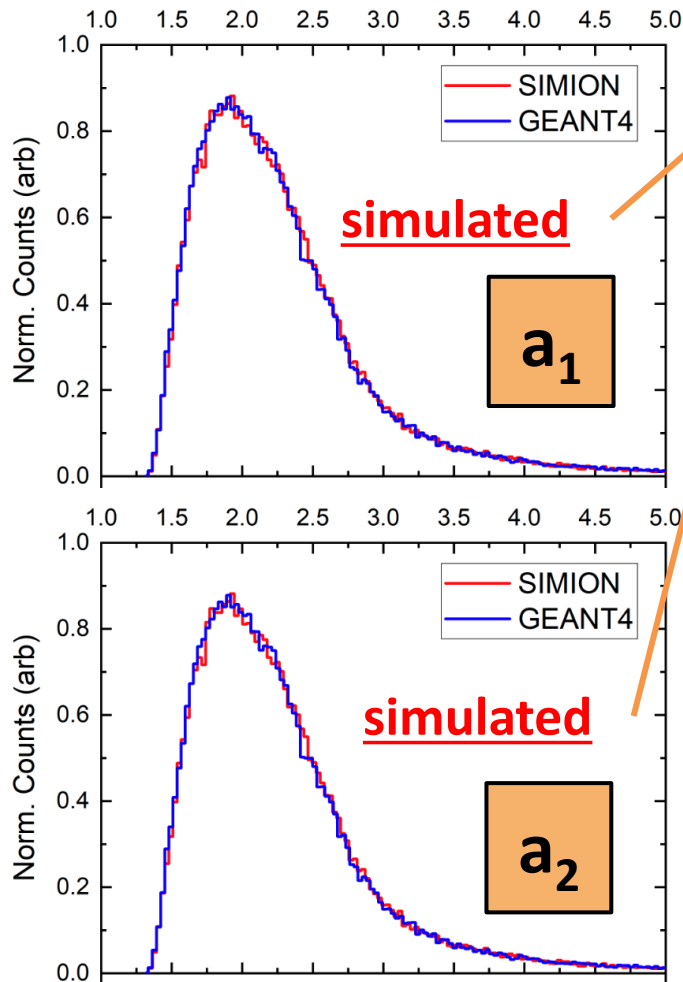
É. Linéard, Habil. Thesis (2010)



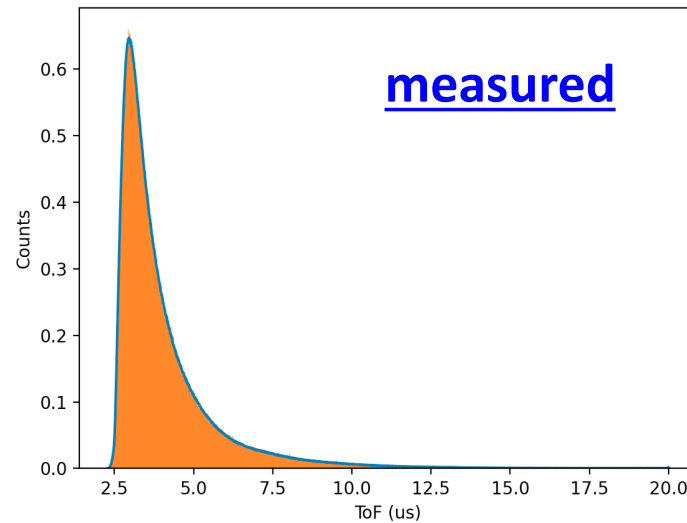
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Fitting $a_{\beta\nu}$



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



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



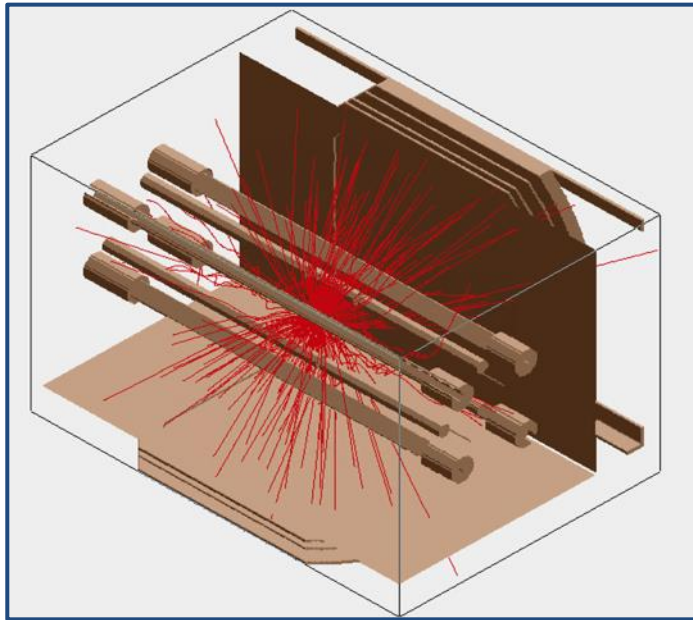
$$W \propto F(Z, E_e) p_e E_e (E_0 - E_e)^2 \left[1 + a_{\beta\nu} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} \right]$$



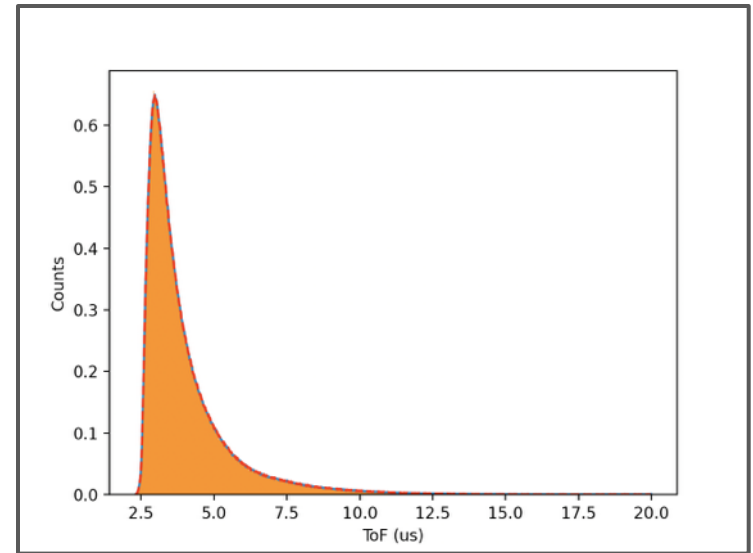
Paul Trap Simulations



- Created expected SM distribution of ^{17}O recoils from ^{17}F decay at center of trap.



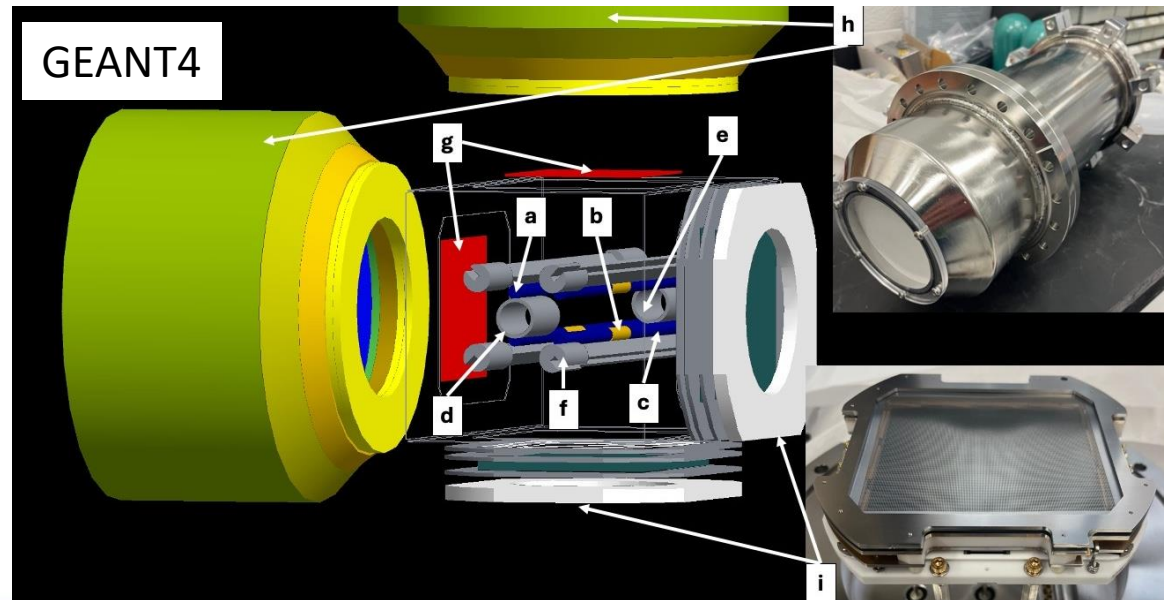
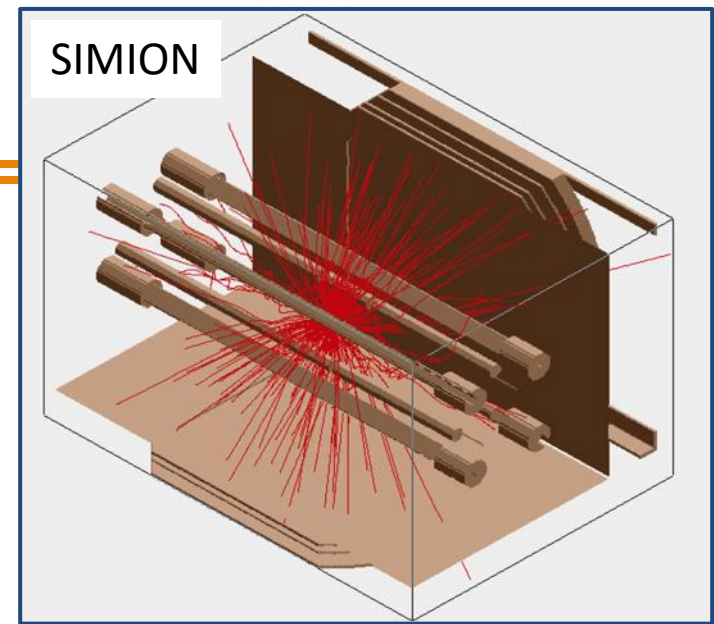
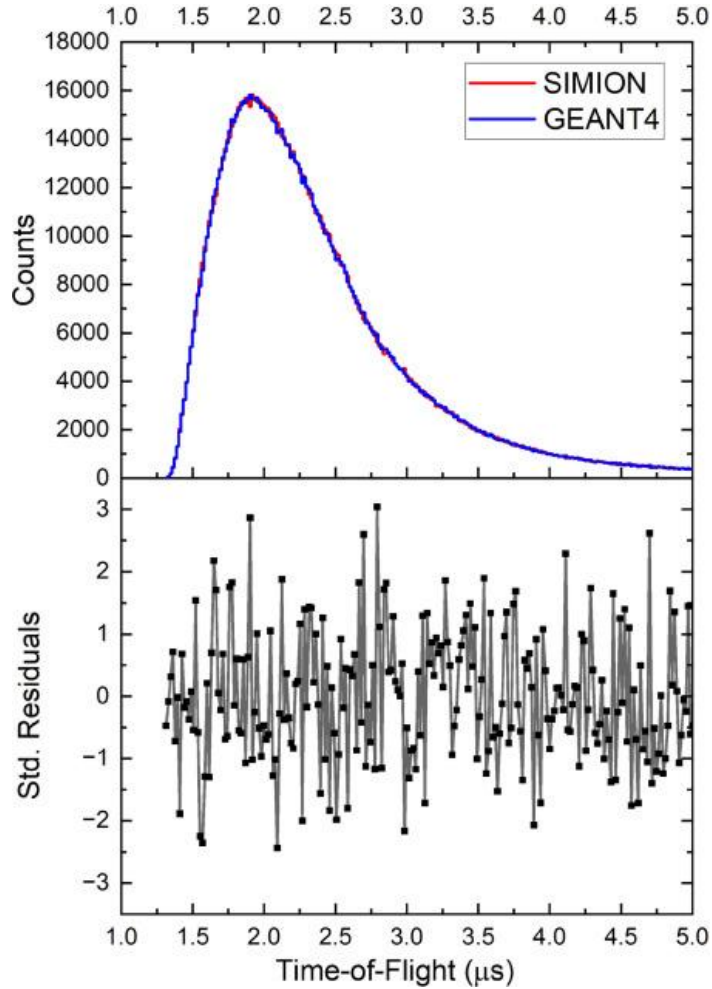
- Recorded TOF spectra of recoils to MCP.
- Fitted spectra to extract $a_{\beta\nu}$.



W.S. Porter et al., NIMB **569**, 165893 (2025)



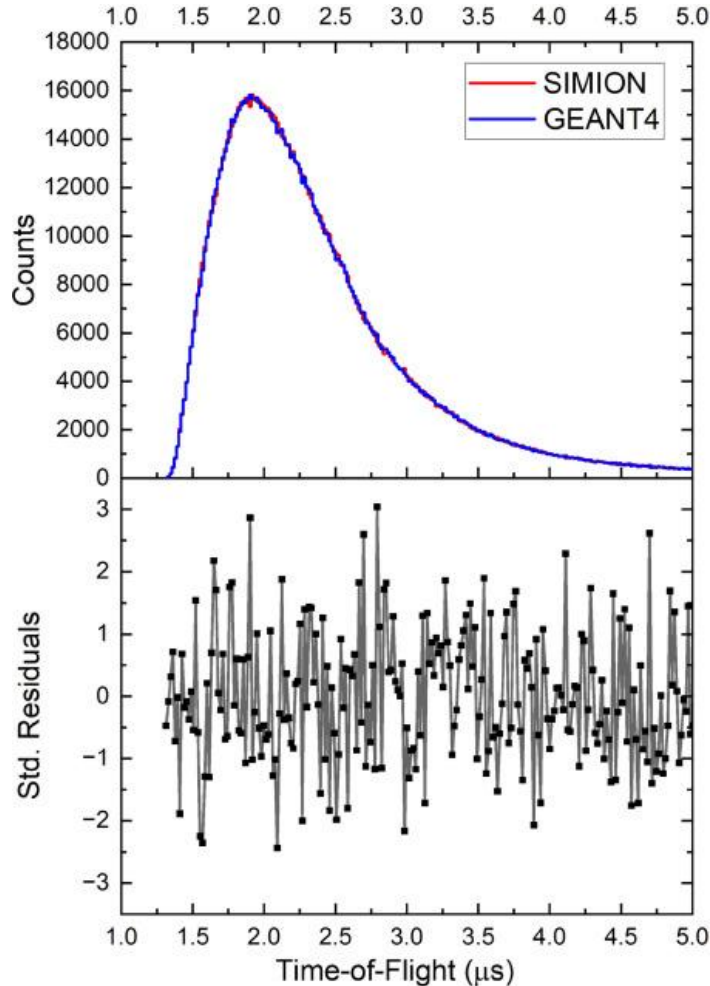
SIMION & GEANT4



W.S. Porter et al., NIMB **569**, 165893 (2025)

Nuclear structure with beta-decay (II), Sept 21, 2026

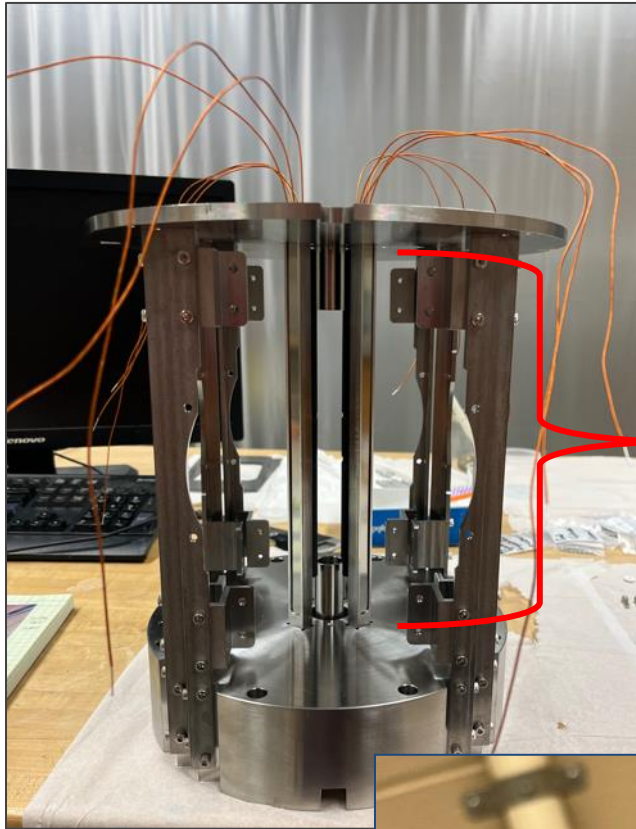




GEANT4 implementation advantages:

- Parallelizable
 - 10 million counts in SIMION: 1 day of runtime
 - 10 million counts in G4: 80 minutes of runtime
- Physics-based detector response functions are natural to implement
 - Built-in material physics, scattering processes, etc.
- Field calculations done from C-implementation of SIMION PAs

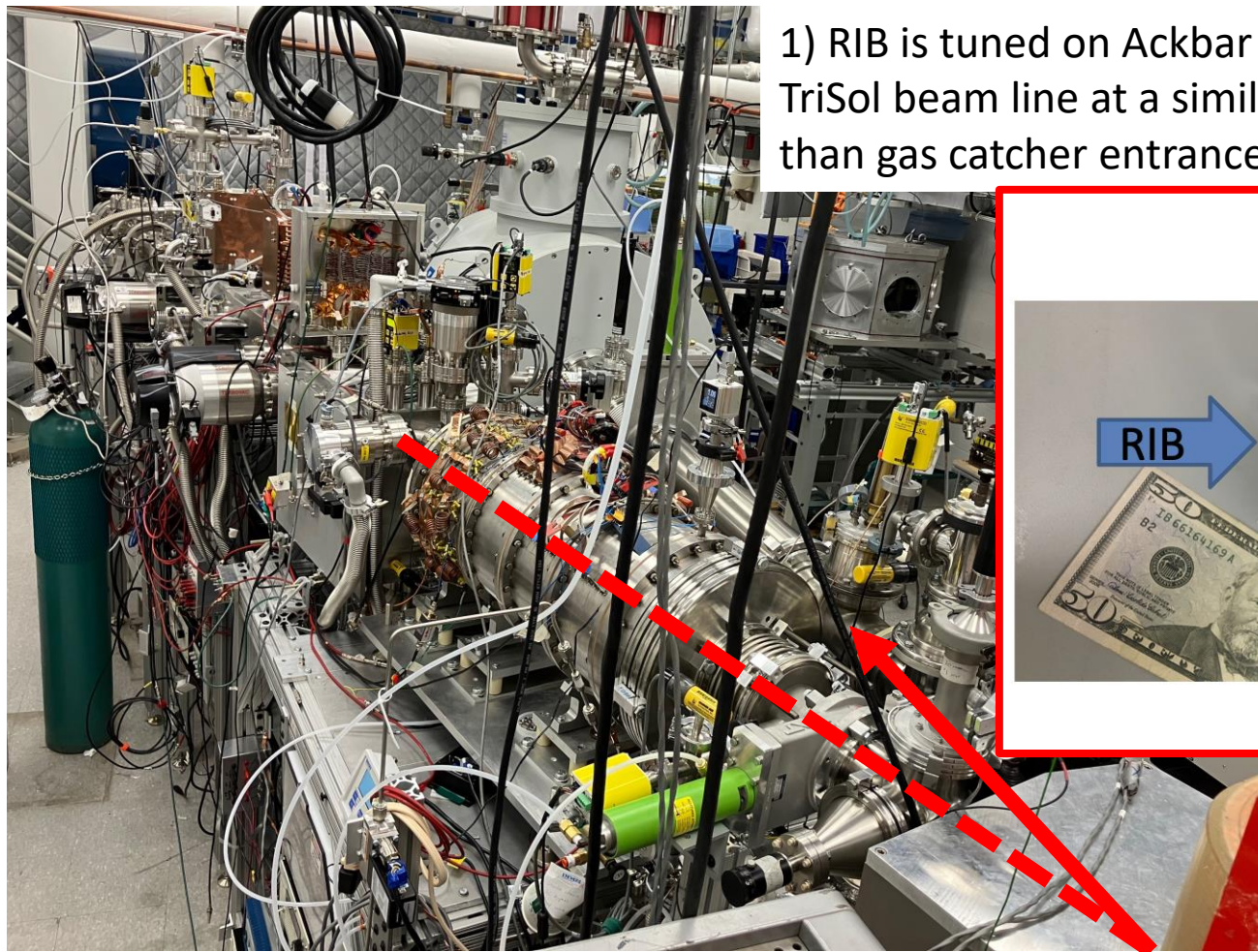
Paul trap



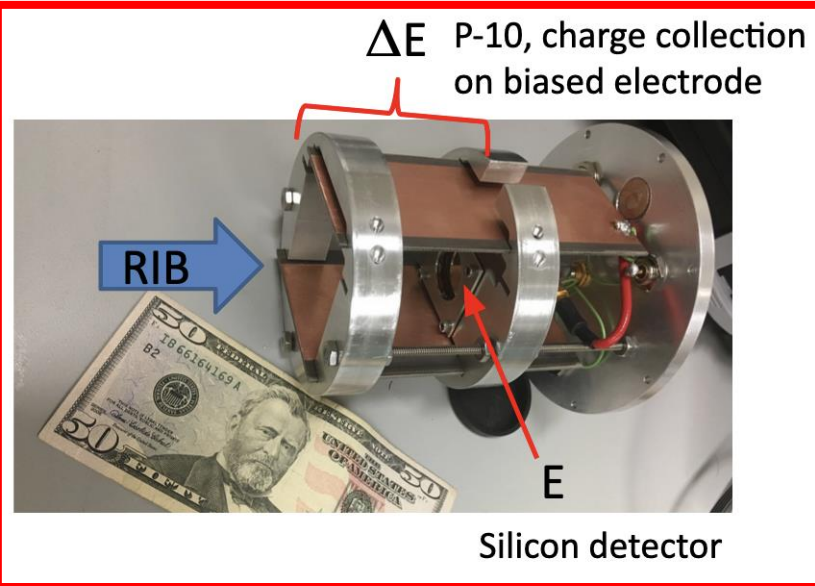
- From LLNL
- Trap is assembled, under vacuum, and connected to the rest of St. Benedict
- RF circuit built and tested



Beam tuning on Ackbar



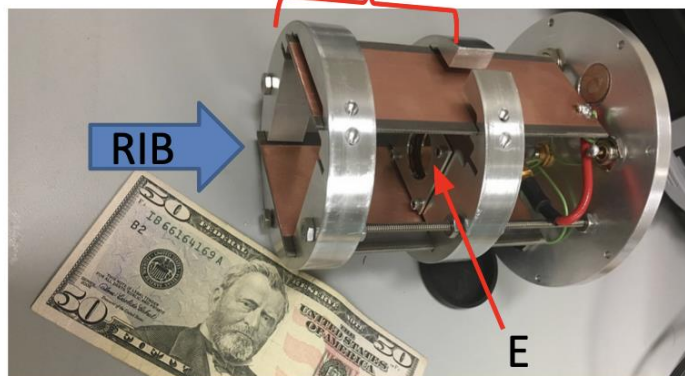
1) RIB is tuned on Ackbar our PID. Located at the 15° TriSol beam line at a similar distance from magnet than gas catcher entrance.



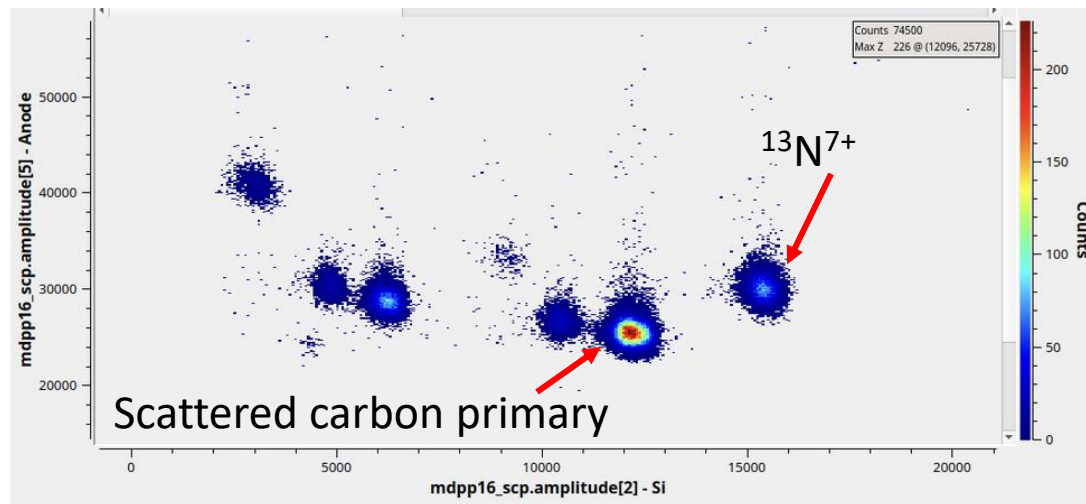
PID with Ackbar



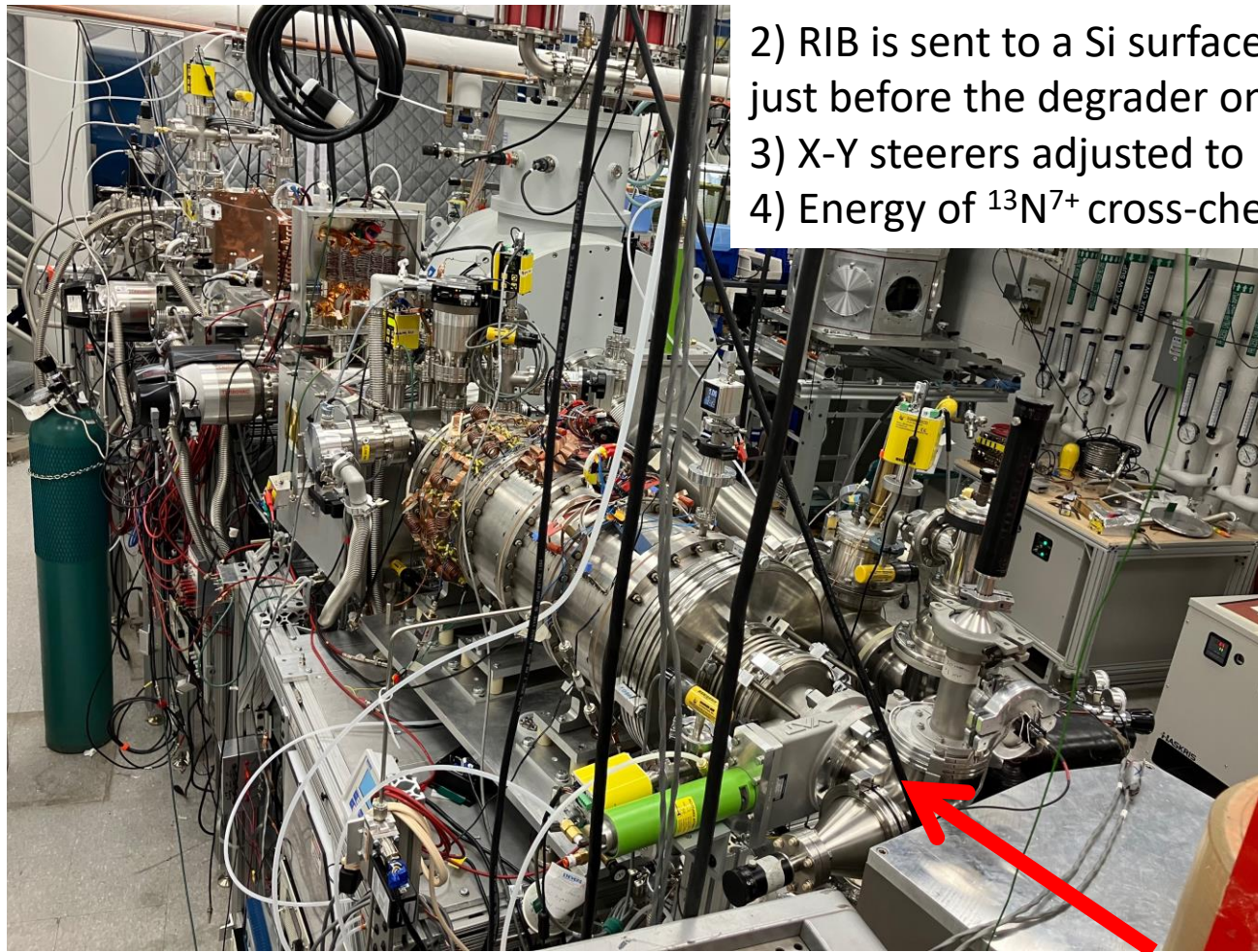
ΔE P-10, charge collection
on biased electrode



Silicon detector



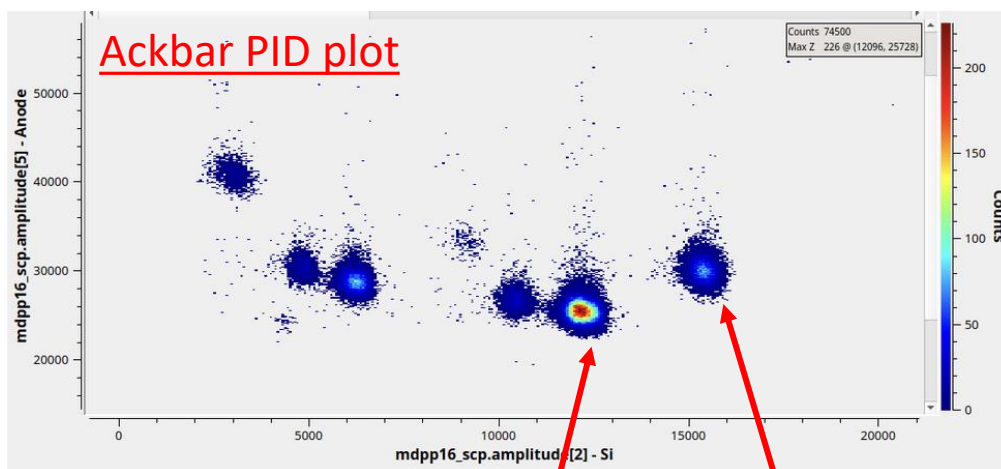
Beam tuning on Si detector



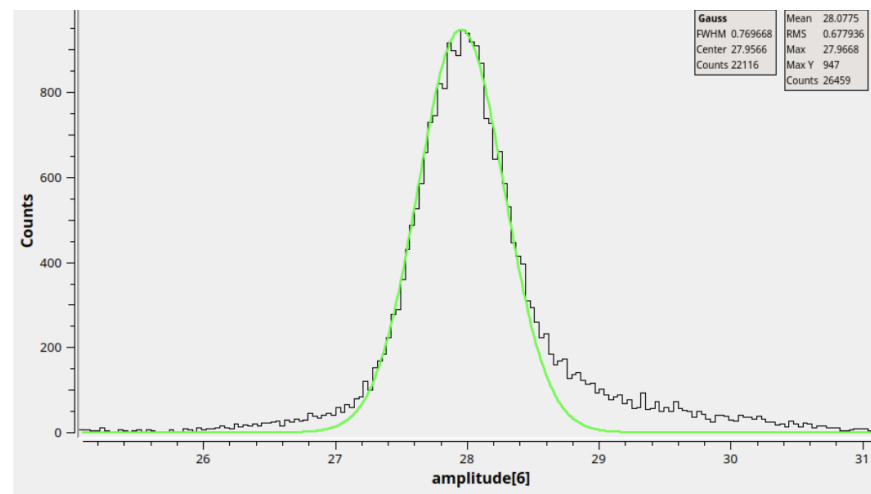
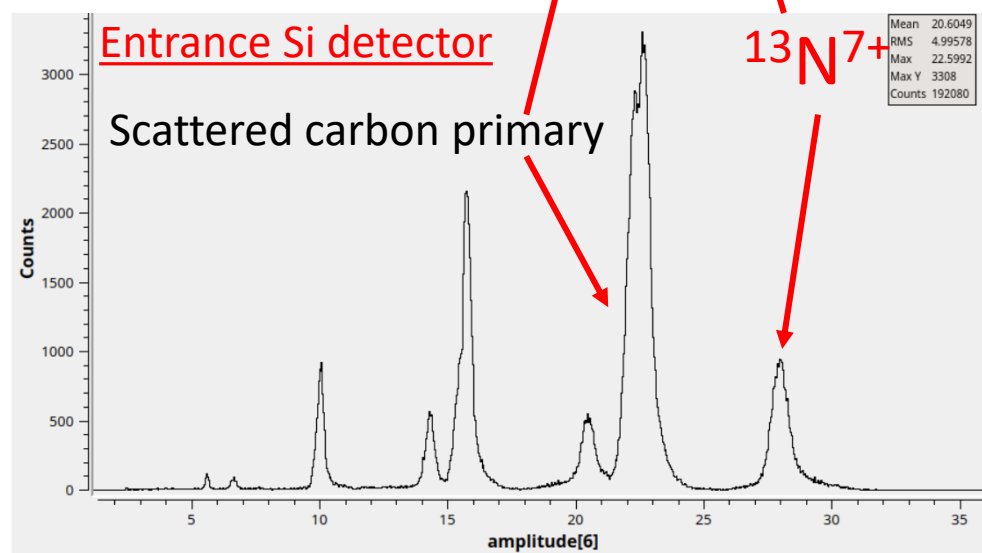
- 2) RIB is sent to a Si surface barrier detector. Located just before the degrader on the St. Benedict line.
- 3) X-Y steerers adjusted to maximize ^{13}N vs C.
- 4) Energy of $^{13}\text{N}^{7+}$ cross-check with LISE++ prediction.



Energy determination with Si detector



LISE++ calculation: 28.4 MeV
Measured: 28.0 MeV



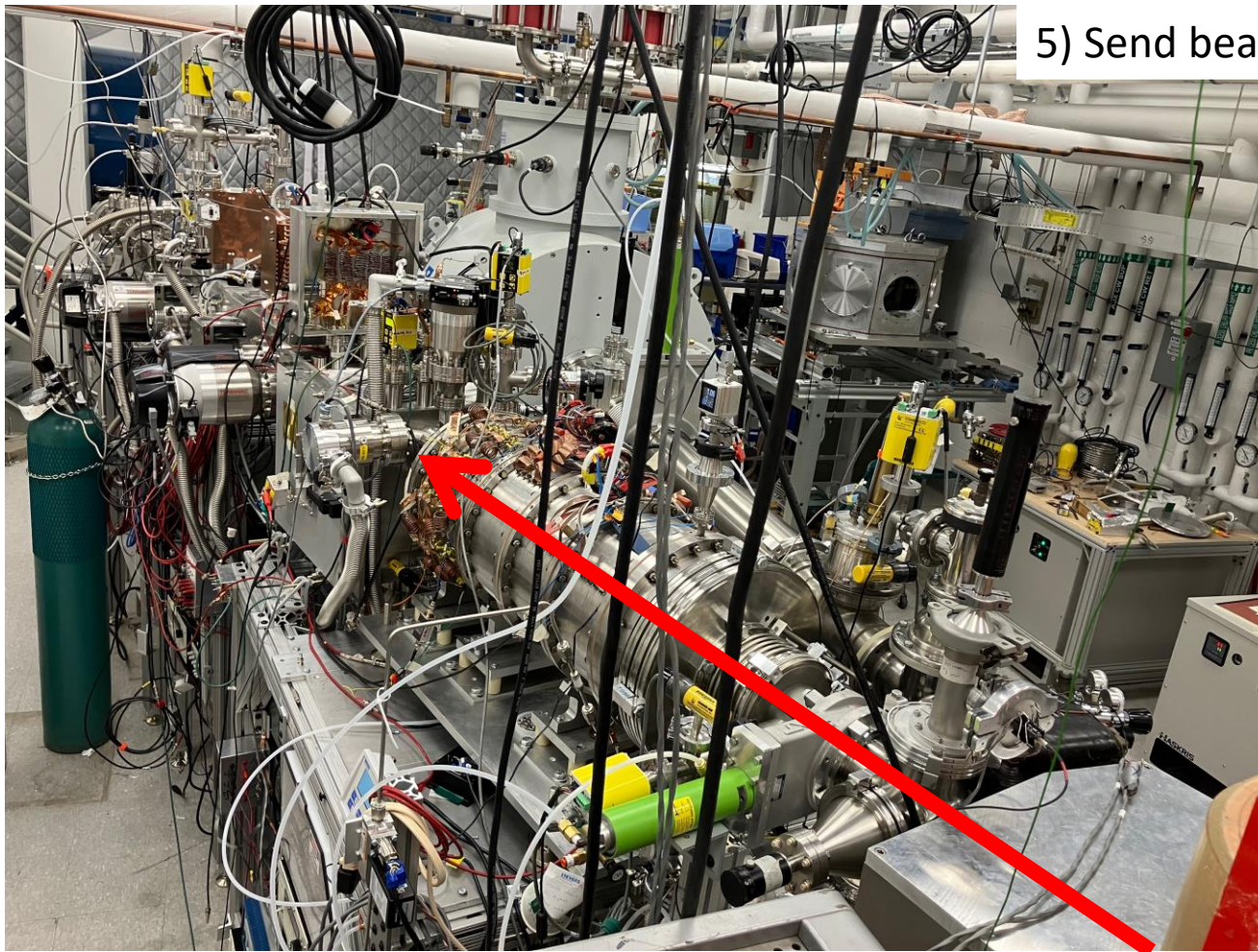
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Beam tuning on Si detector



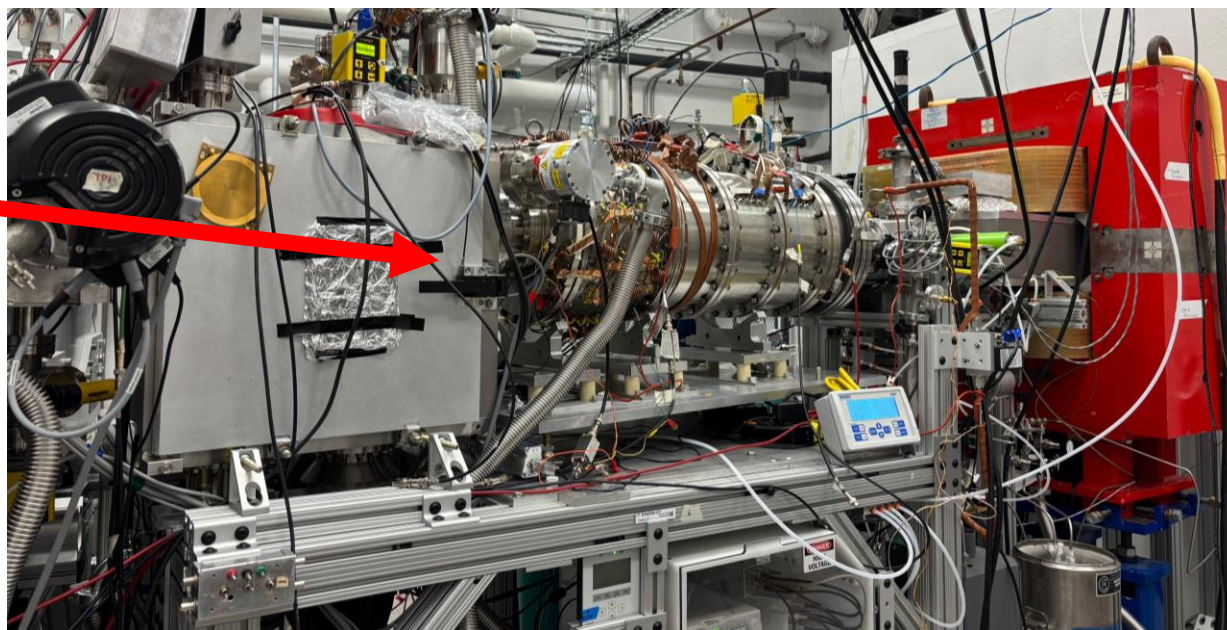
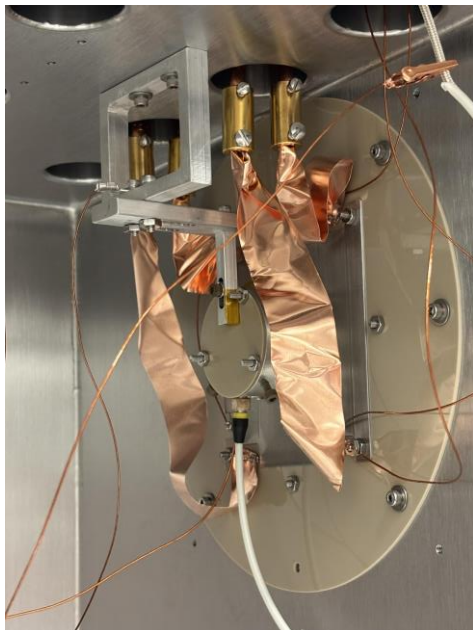
5) Send beam through the gas catcher.



Nuclear structure with beta-decay (II), Sept 21, 2026



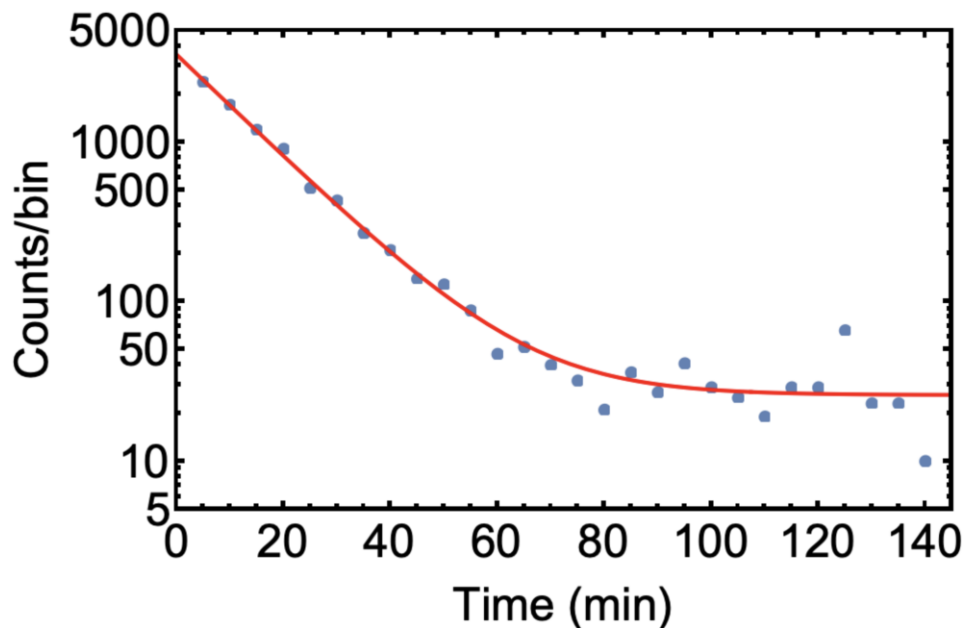
Recent On-line results



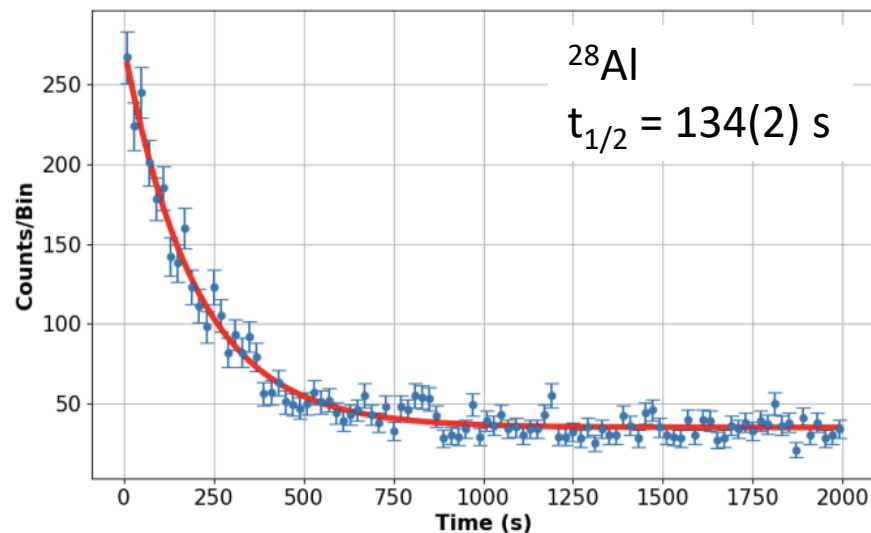
- Ion guide has been removed and replaced by a foil backed by a Si detector.
- Implant ^{13}N ions transported by the RF carpet on the foil.
- Positron from the ^{13}N decay are recorded by the Si detector.



Activity from ^{13}N decay



- Observed activity with activity with a half-life of 9.42(14) min.
- Close enough to the ^{13}N half-life.
- Also managed to stop and extract ^{28}Al .
- Stopping and transport efficiency to the foil of 1%.
- The stopping and extraction of ^{11}C , ^{15}O , and ^{17}F have proven to be more

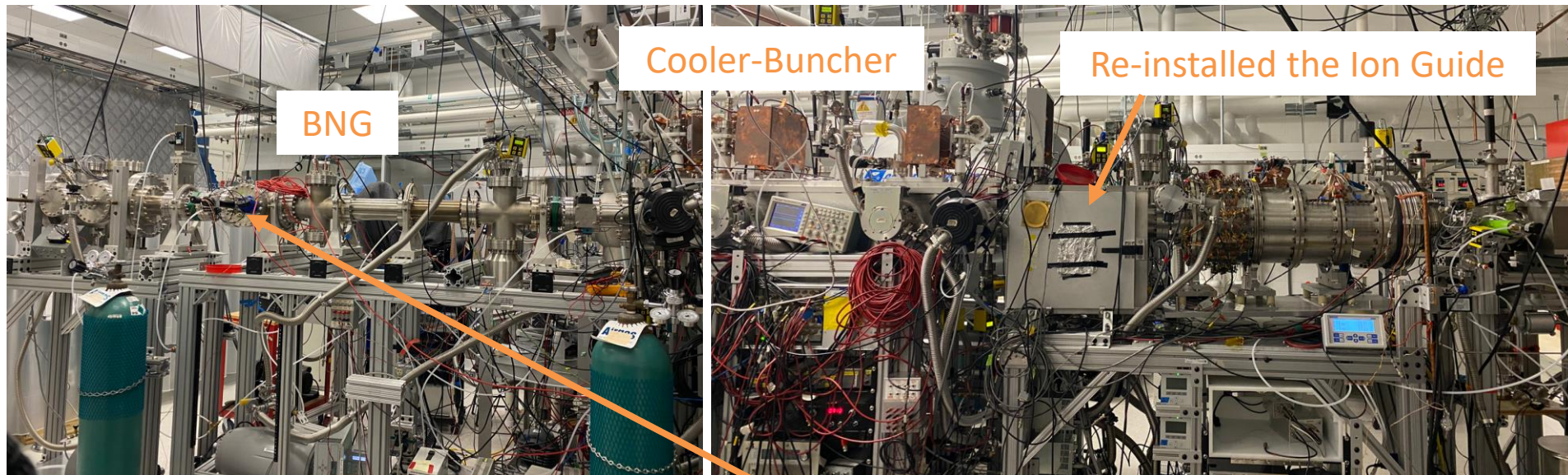


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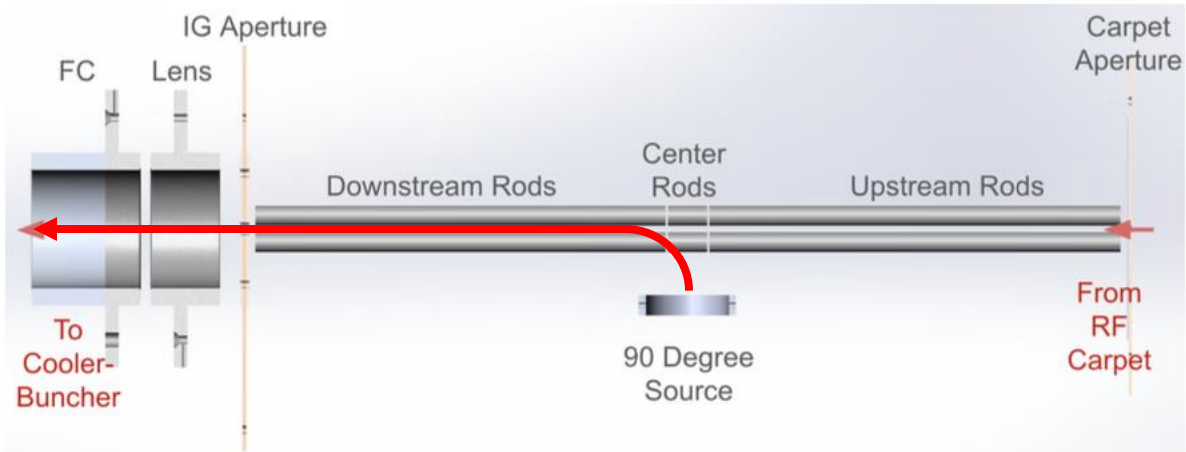


Nuclear structure with beta-decay (II), Sept 21, 20

Testing with K source

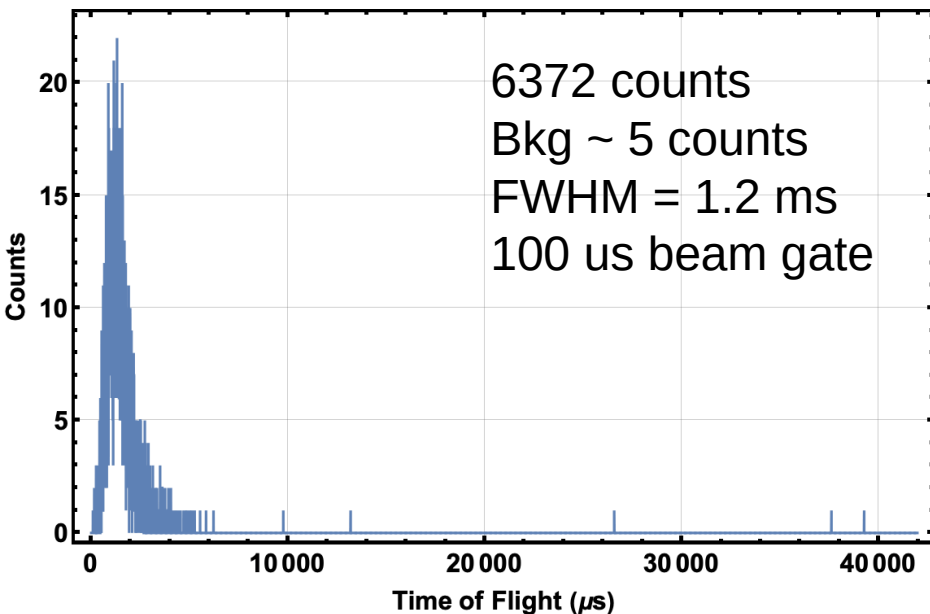


Location of
MCP/Si



Nuclear structure with beta-decay

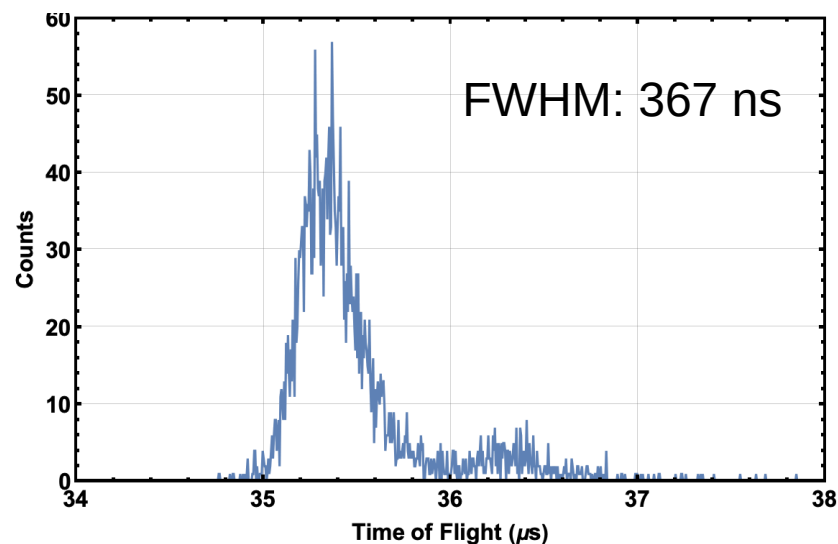
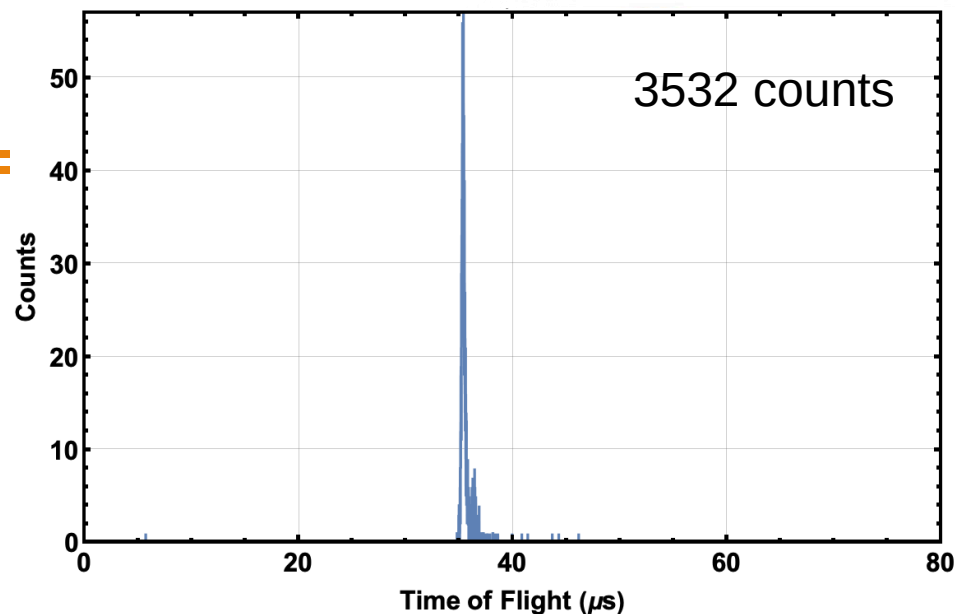
Testing with K source



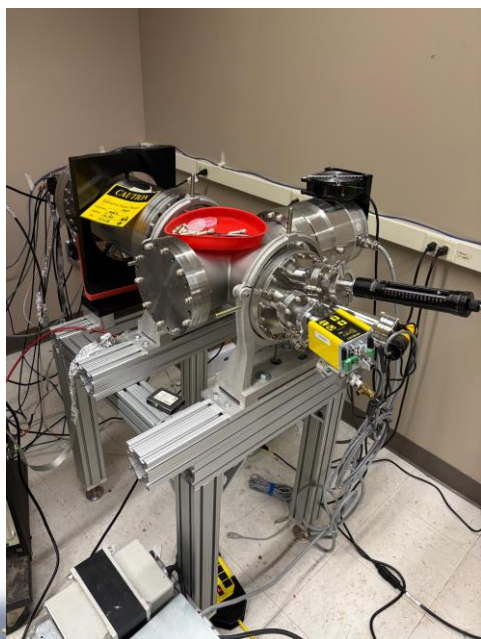
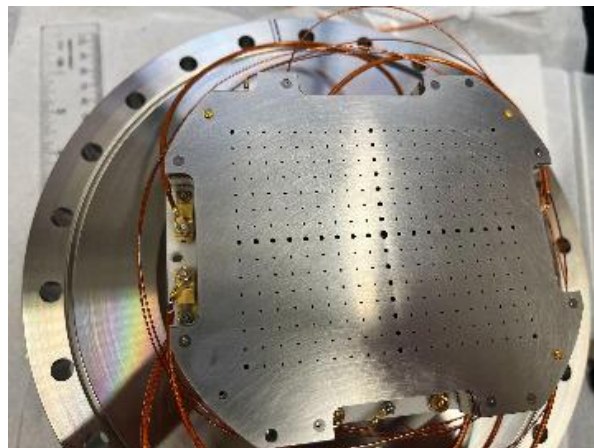
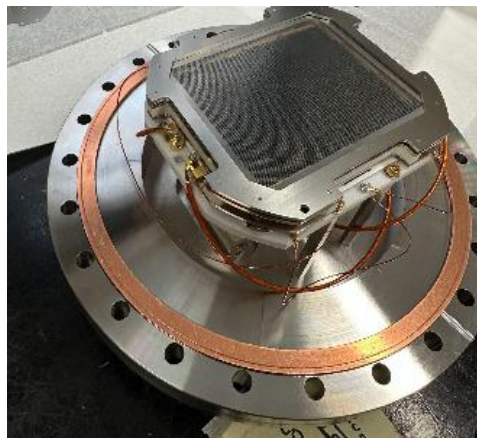
Bunching efficiency: 55%.

DC efficiency: 10%.

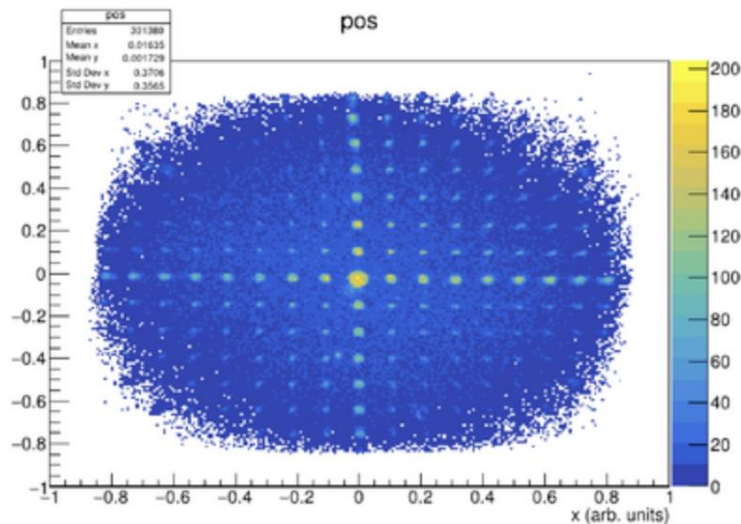
Not horrible, but room for improvement.



Paul trap MCP testings



- Testing done with an alpha source.
- Large volume plates (z-stack) and resistive anode.
- Surprising <1 mm resolution has been achieved.



Summary



- Superaligned pure Fermi transitions are currently the most precise mean to extract V_{ud} . Limited by theoretical corrections.
- The ft-value from superallowed mirror decay transitions can be used to extract a value of V_{ud} that complement the value from pure Fermi decays.
- The half-life of several nuclei undergoing a superallowed transition to their mirror partner has been measured at Notre Dame.
- St. Benedict currently being commissioned at ND. Aim to measure a_{bn} in many superallowed mixed transition for the first time to test theoretical corrections used to determine V_{ud} .
- System will be comprised of a gas catcher, an extraction systems (that includes a RF carpet and ion guide), a cooler-buncher, and a linear Paul trap.
- Each component except the Paul trap have been commissioned using an off-line ion source.
- ^{13}N and ^{28}Al ions have been stopped and extracted from the gas catcher with a total efficiency of around 1%.
- Next: send RIB of N and Al through the cooler-buncher and identify at which mass the activity is coming out.
- Next: trap K ions and RIBs in the Paul trap.

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Thank you!



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