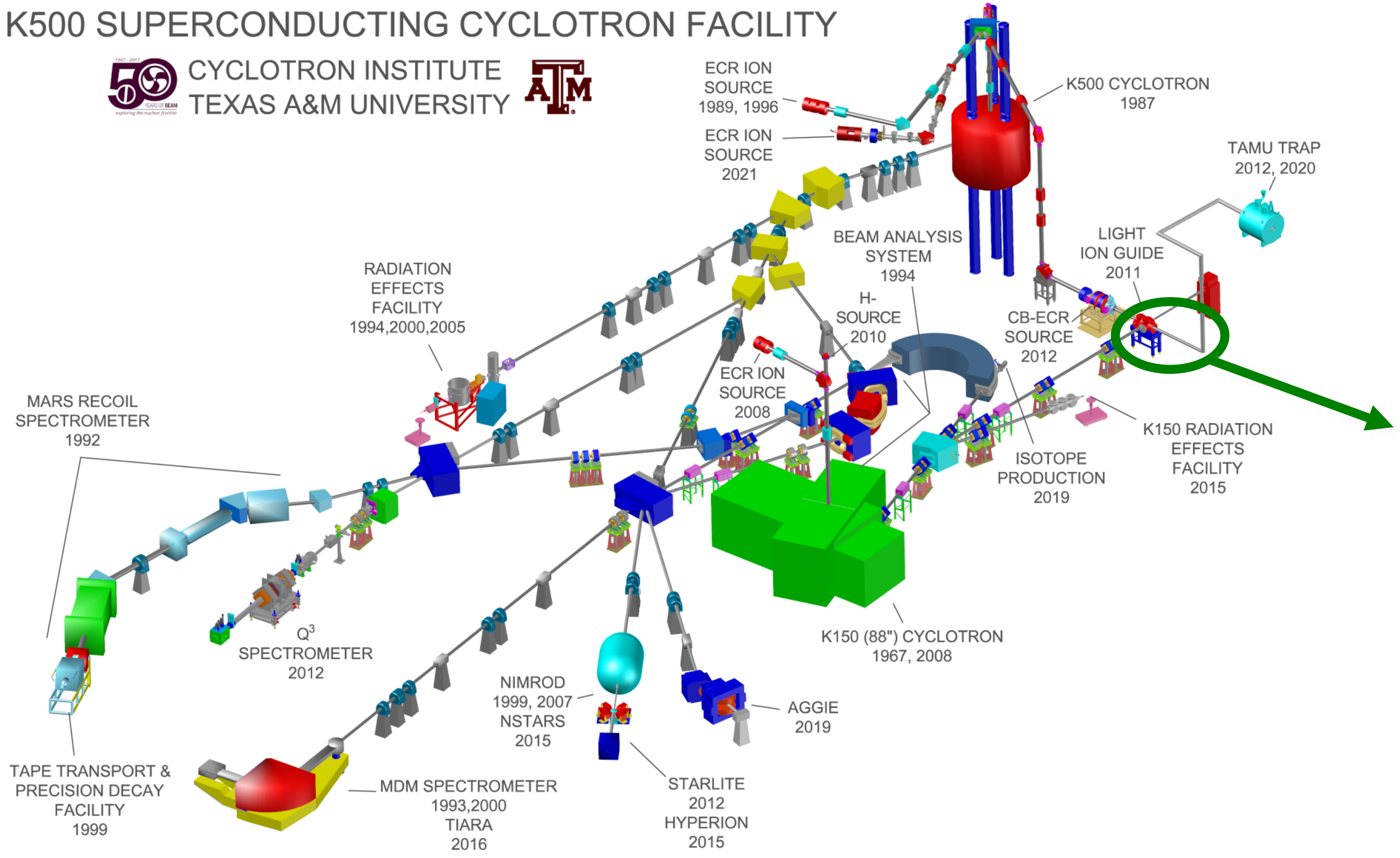
Low-energy nuclear β decay at the CI: current status and future prospects

Dan Melconian



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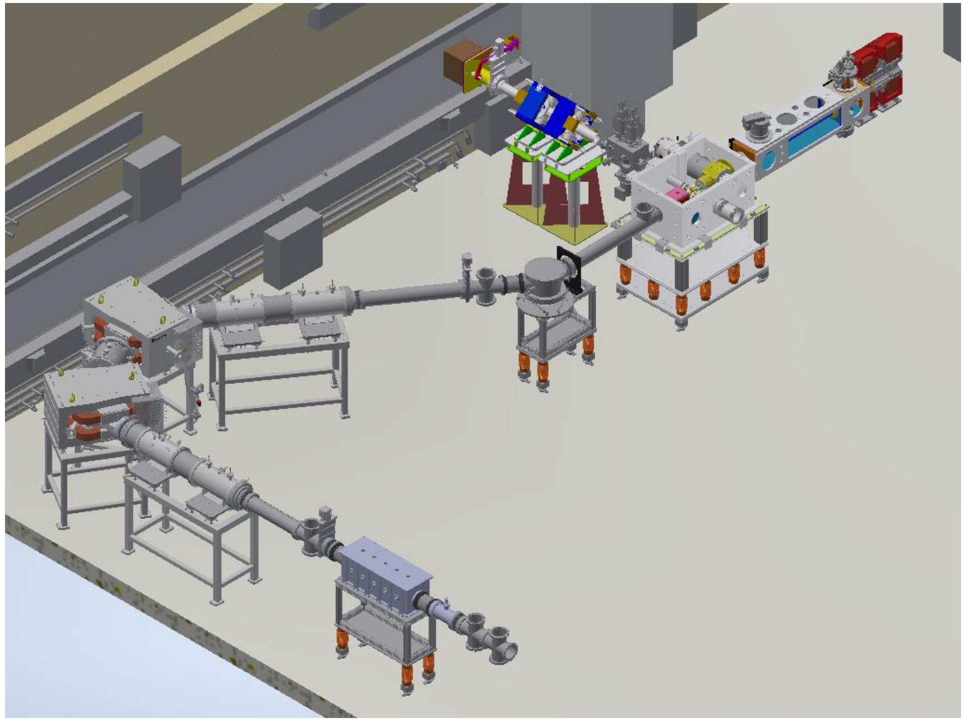


Overview

- Bird's eye view of the Cyclotron Institute
- Re-accelerated RIB with the *p*-LIG
- Lifetimes and branching ratios with the K500 and MARS
  - Fast-tape transport system and "golden" HPGe detector
  - Lifetime example: ^{29}P
  - Branching ratio example: ^{37}K
- Near future
  - ^{10}C branching ratio
  - He-LIG and LSTAR separator
  - β-delayed proton decays in TAMUTRAP
- Opportunities
  - He-LIG re-accelerated RIB? General-purpose decay station? Other ideas…?

A primer on β decay and fundamental physics

- Expand to the often-quoted angular distribution of the decay
  (Jackson, Treiman and Wyld, Phys Rev **106** and Nucl Phys **4**, 1957)

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2|V_{ud}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2}^{\text{basic decay rate}} \xi \left(1 + \overbrace{a_{\beta\nu}\frac{\vec{p}_e\cdot\vec{p}_{\nu_e}}{E_eE_{\nu_e}}}^{\beta-\nu\text{ correlation}} + \overbrace{b\frac{\Gamma m_e}{E_e}}^{\text{Fierz term}}\right) + \cdots$$

- Comparative half-life:

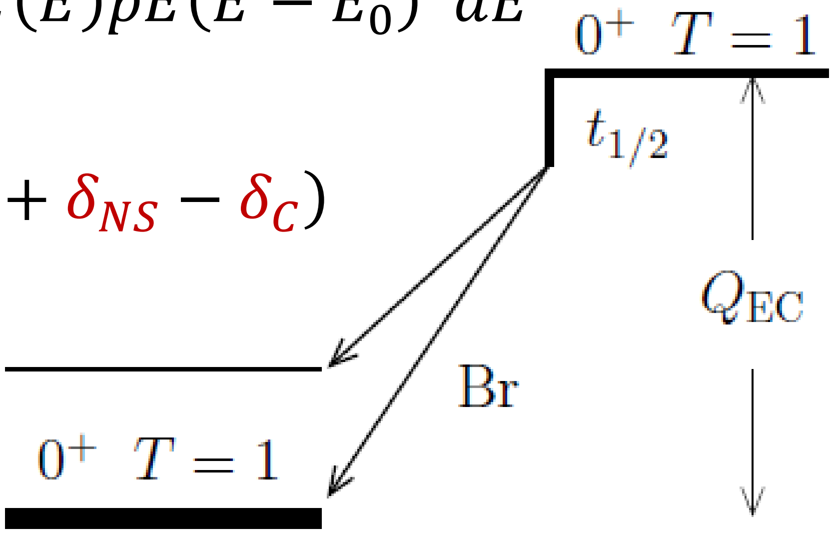
$$t = \frac{t_{1/2}}{\mathrm{Br}}(1 + P_{\mathrm{EC}})$$

and $f = \int F(Z', E)C(E)pE(E-E_0)^2 dE$

$$\sim Q^5$$

- $Ft \equiv ft(1+\delta'_R)(1+\delta_{NS}-\delta_C)$

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

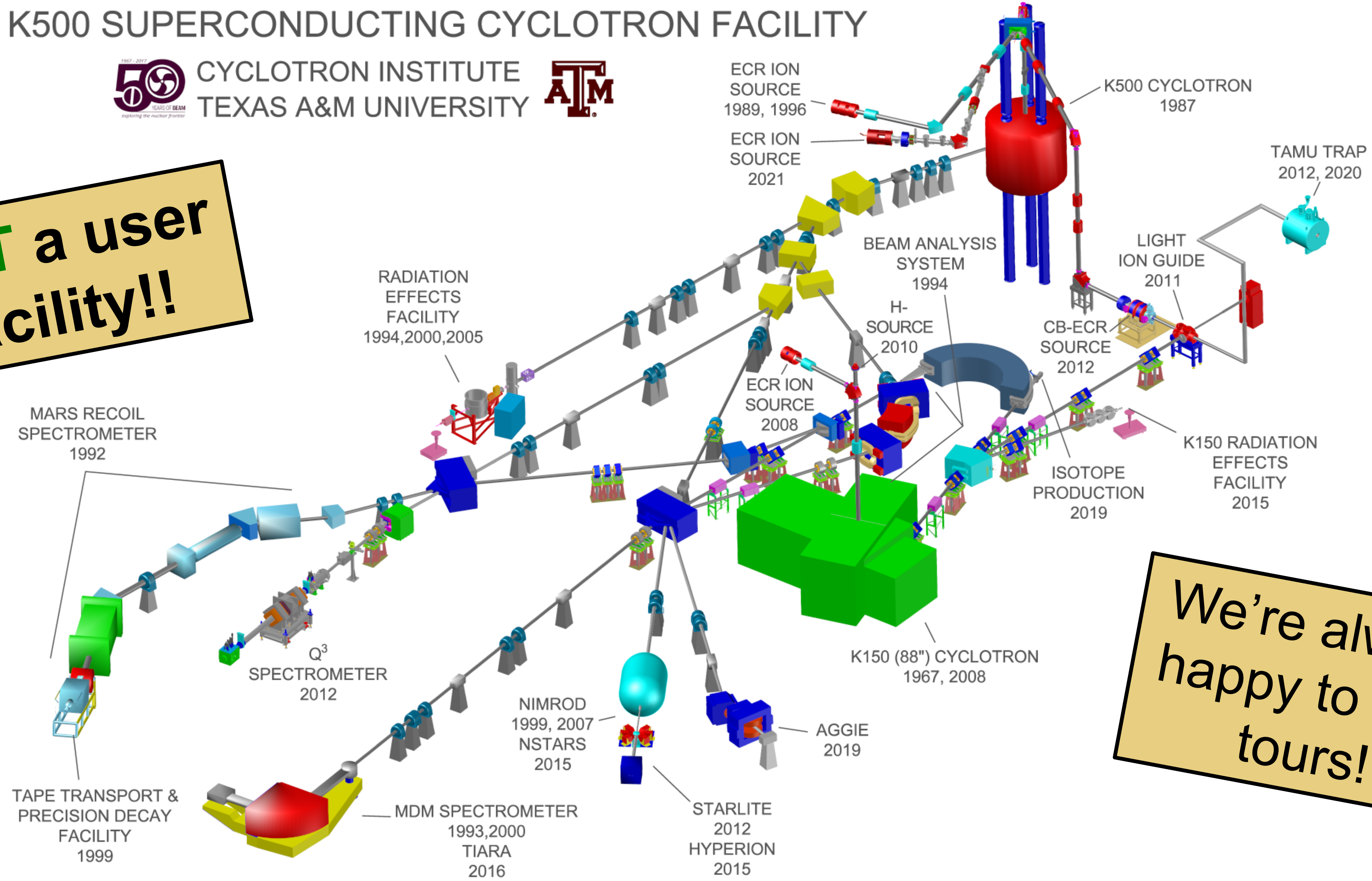


$$a_{\beta\nu} = \frac{|C_V|^2 + |C'_V|^2 - |C_S|^2 - |C'_S|^2}{|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2} = 1??$$

$$b = \frac{-2\Re e(C_S^* C_V + C_S'^* C'_V)}{|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2} = 0??$$

(thank you for covering this already, Sam!)

The Cyclotron Institute



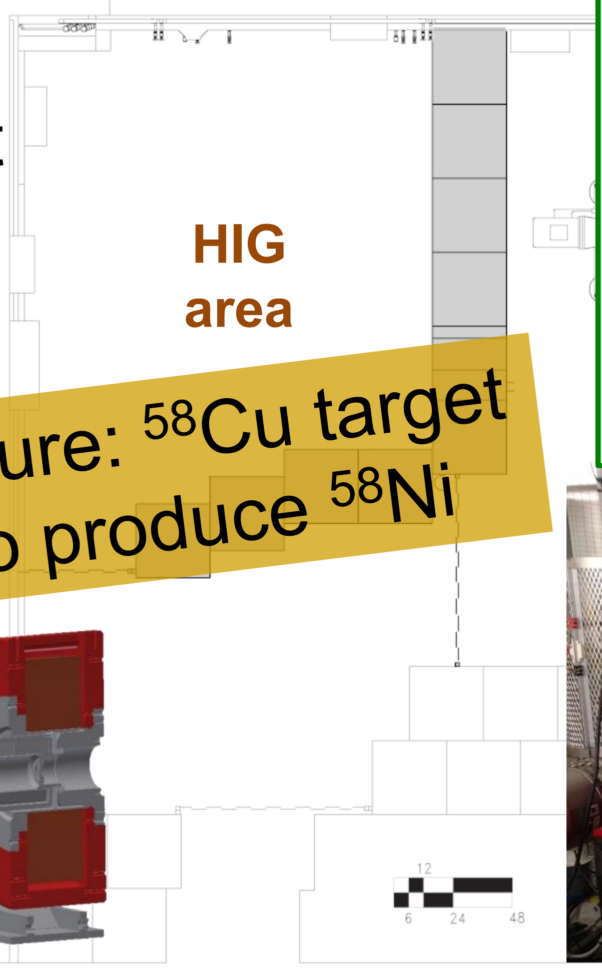
NOT a user facility!!

We're always happy to give tours!

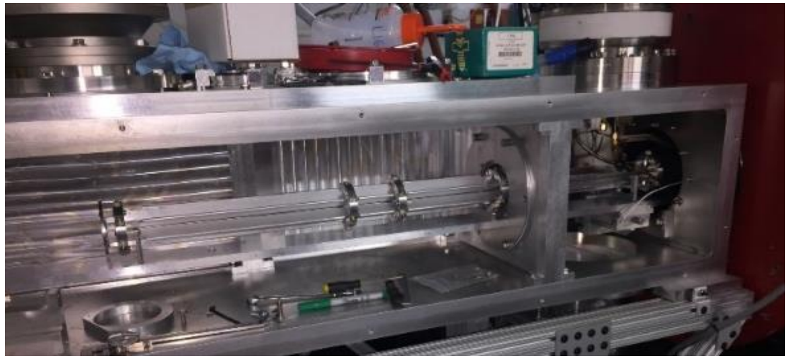
RIB production and re-acceleration: the *p*-LIG

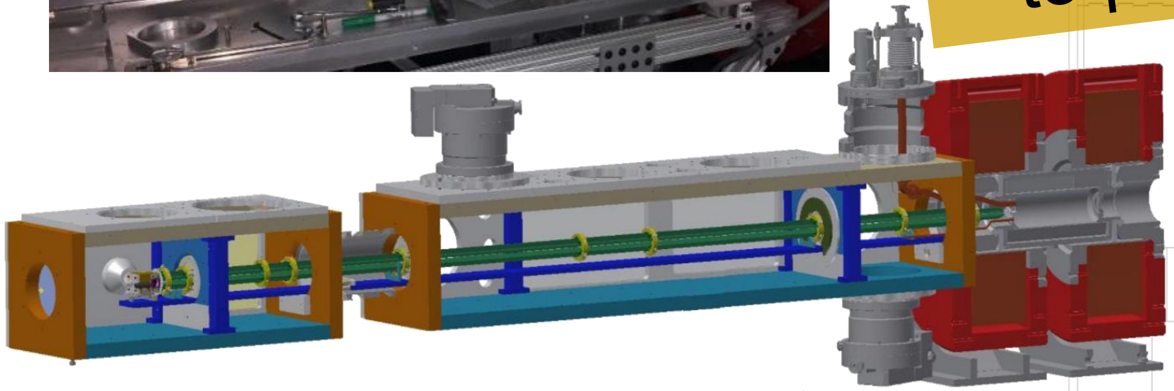
- Re-commission the K150 for high intensity beams and/or to re-accelerate RIBs in the K500
- Light Ion Guide – used for production of neutron deficient RIBs via $A(p,xn)B$ reactions

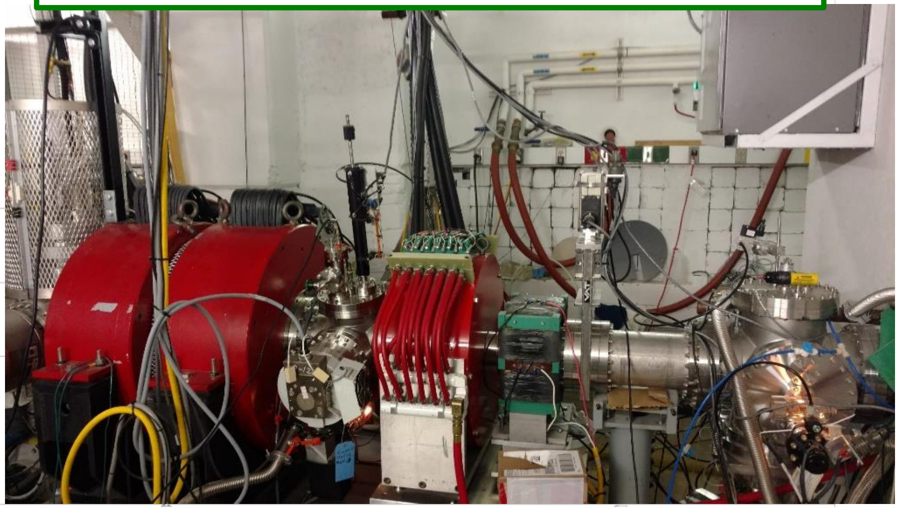
Target	RIB product	Beam energy [MeV]	Yield [ions/μA]
^{114}Cd	**^{114}In^{19+}**	10	685
^{114}Cd	**^{112}In^{21+}** ✓	28	975
^{106}Cd	**^{106}In^{20+}**	14	410
^{106}Cd	**^{105}Cd^{20+}**	24	620
^{90}Zr	**^{90}Nb^{17+}**	13	300
^{90}Zr	**^{89}Zr^{17+}** ✓	22	200
^{64}Zn	**^{64}Ga^{14+}**	14	210



Future: ^{58}Cu target to produce ^{58}Ni

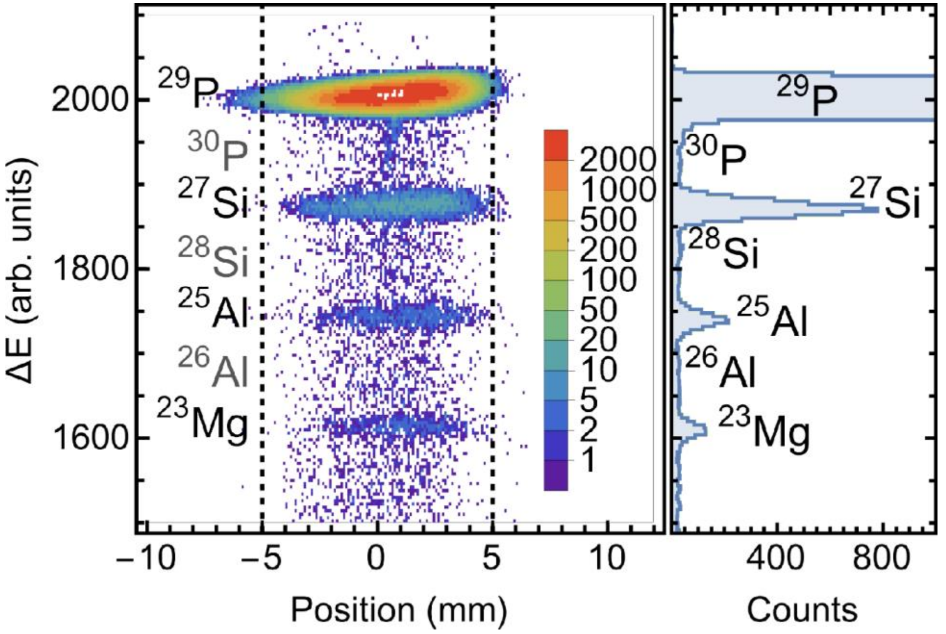


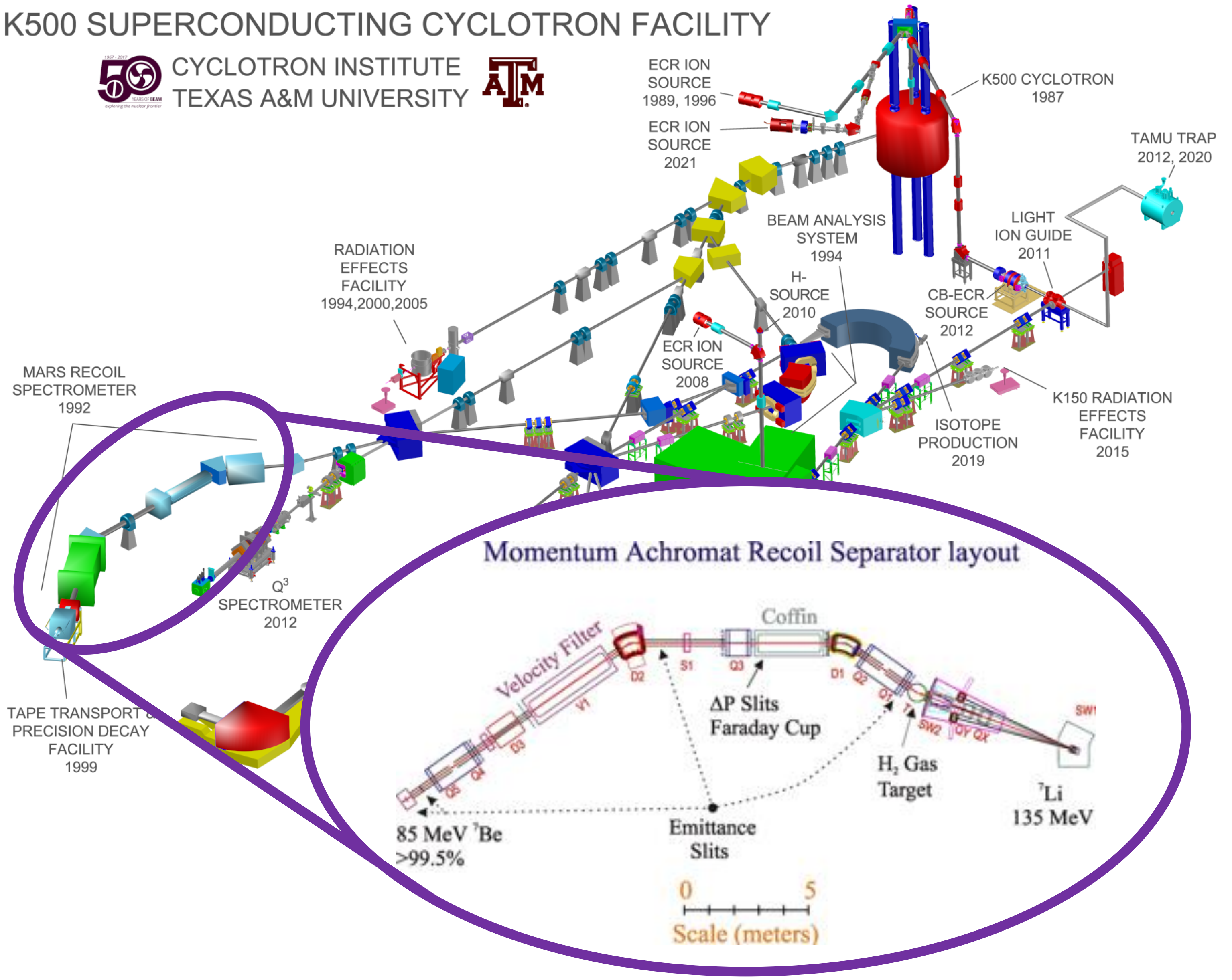




MARS: a heavily utilized spectrometer

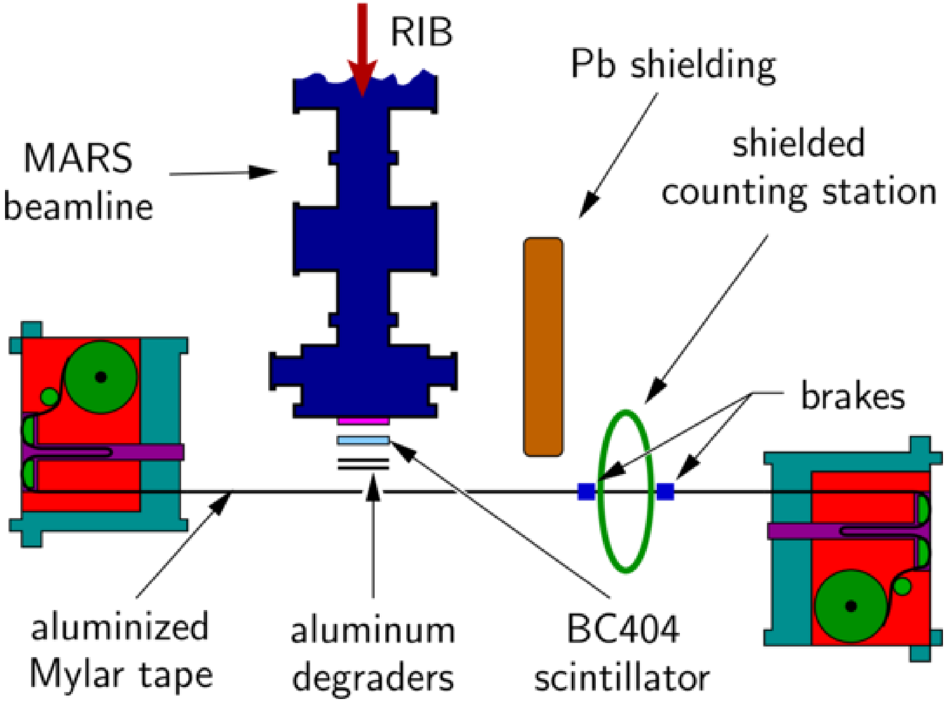
- Follows a LN_2-cooled H_2 target for inverse kinematic reactions.
- Very pure beams!
- SATURN is on the horizon (see Grisha's talk Thu)

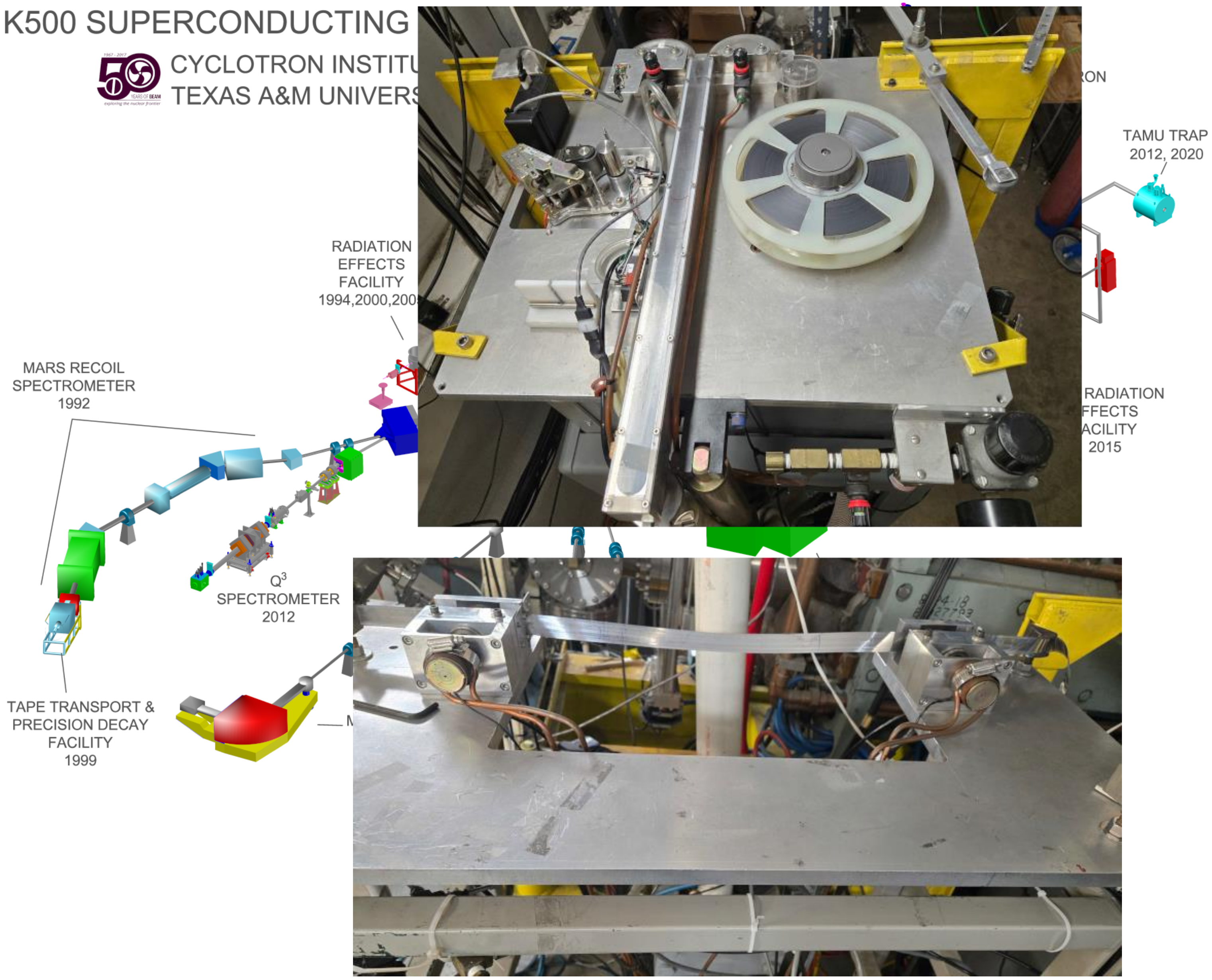




Fast-tape transport system (Hardy and Iacob)

- Fundamental symmetries: fast-tape transport system + HPGe or 4π gas counter
- Lifetimes and branching ratios (V_{ud})





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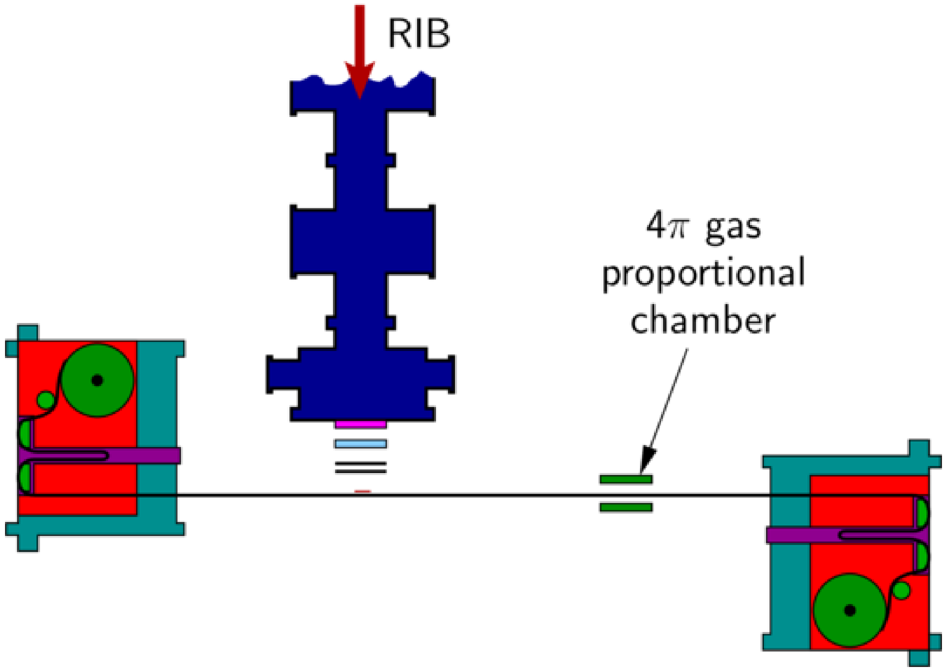
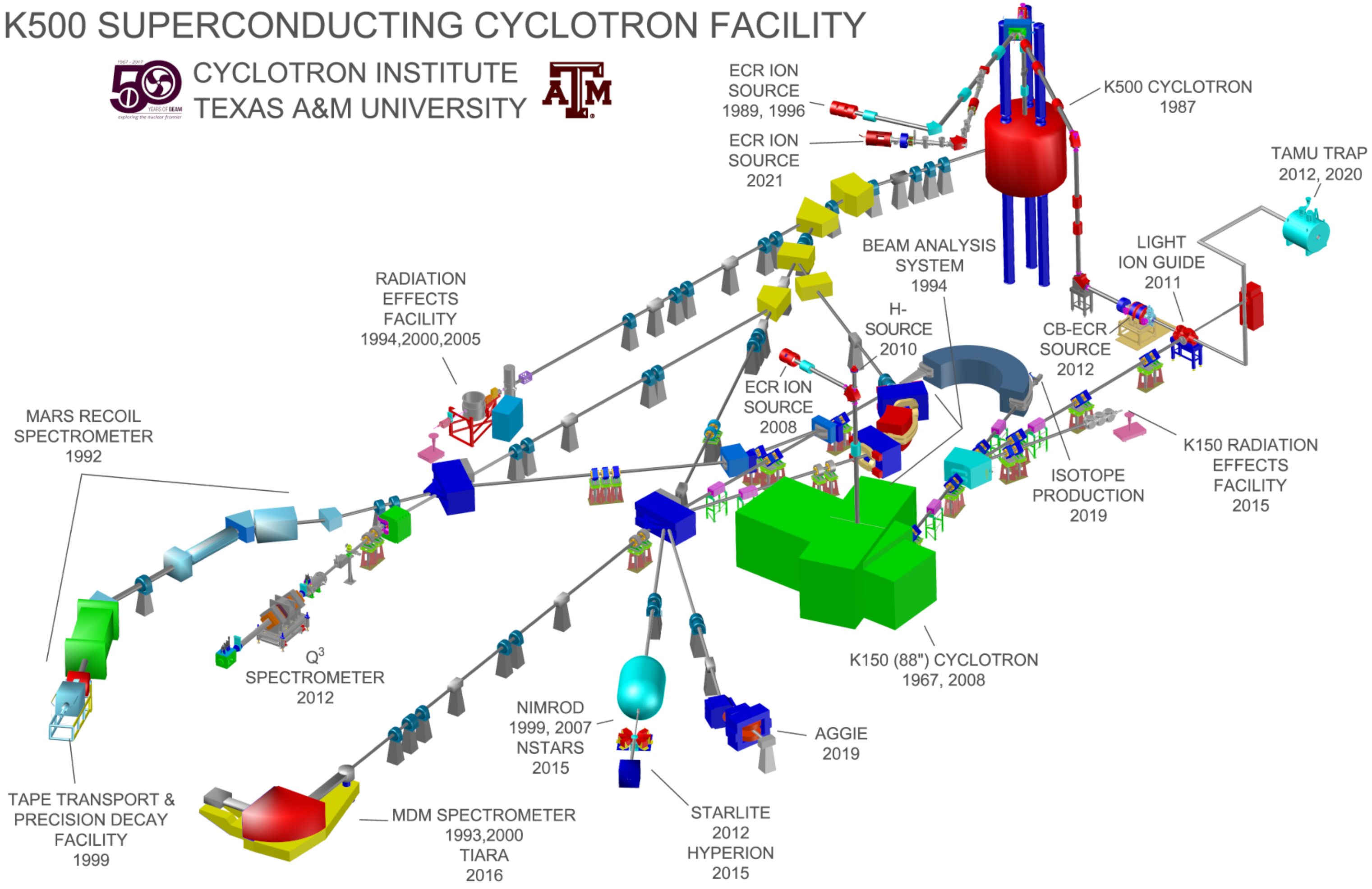
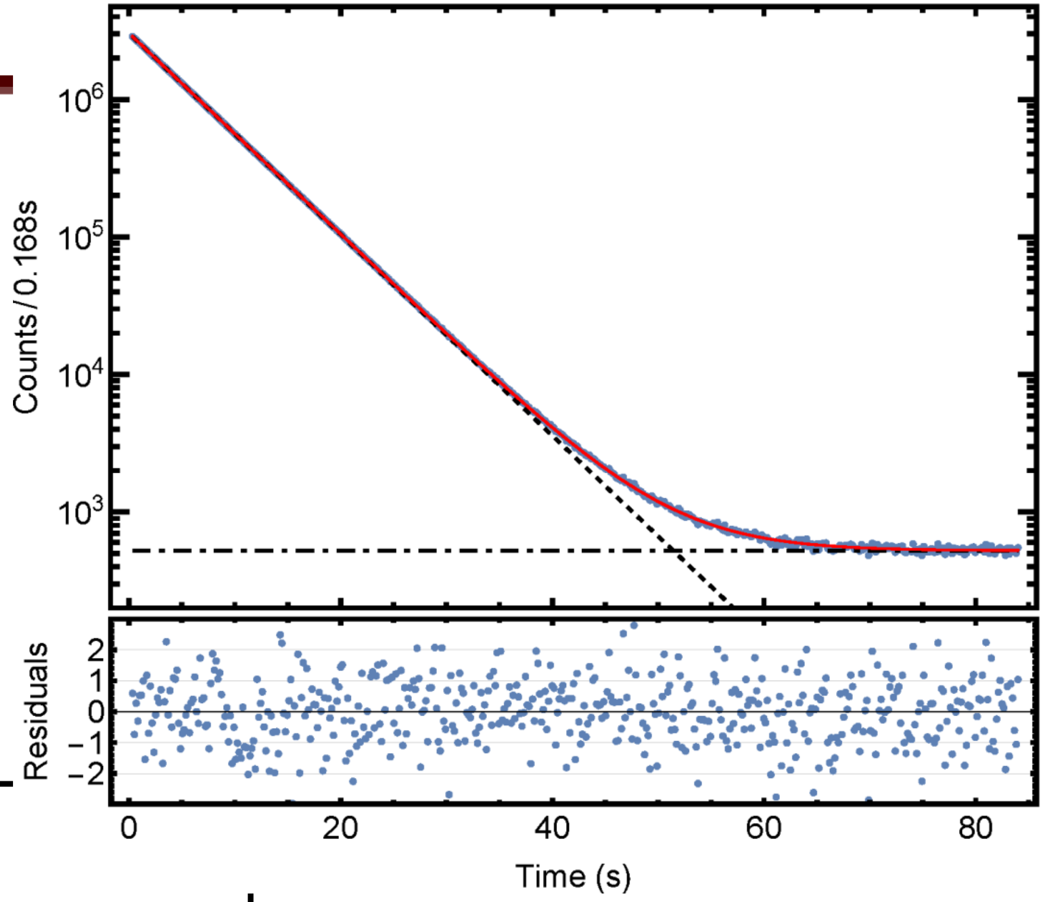


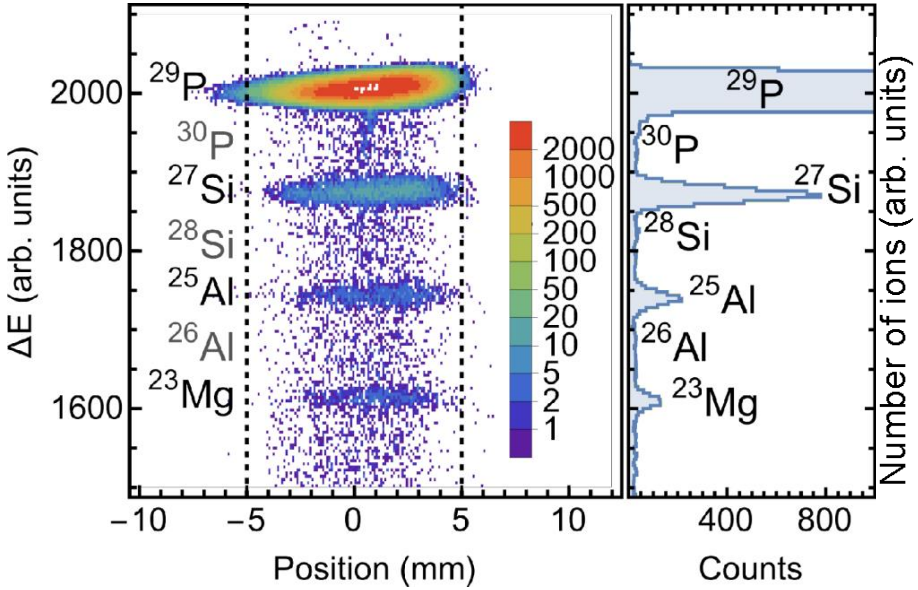


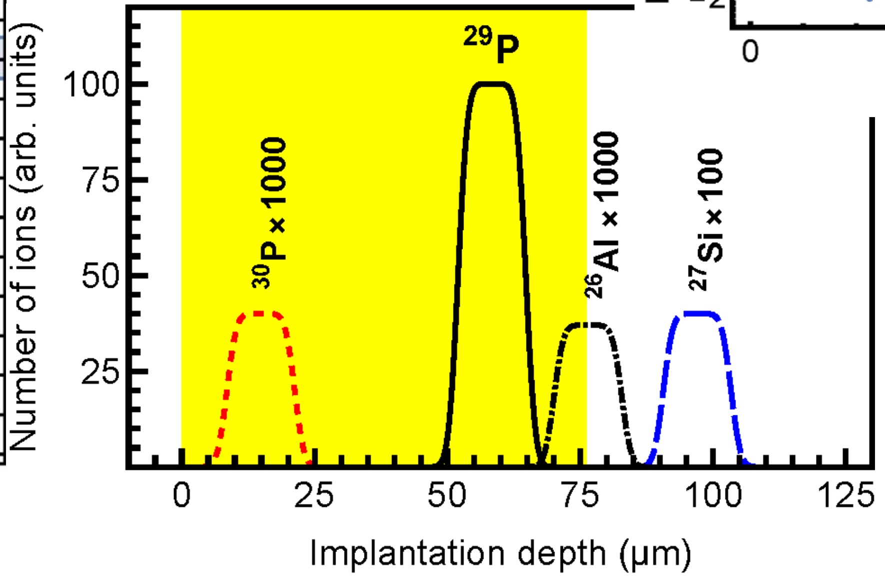
Lifetime example: ^{29}P

- Degraders let us tune where activity is implanted in the tape and further purify the beam out of MARS

Source	Uncertainty (ms))
statistics	0.6
^{30}P half-life	0
^{26}Al half-life	0.01
sample impurities (^{30}P $+^{26}$Al)	0.4
total	0.8
^{29}P half-life	4.1146(8) s







2σ tension with 2020 result of Long *et al.*:

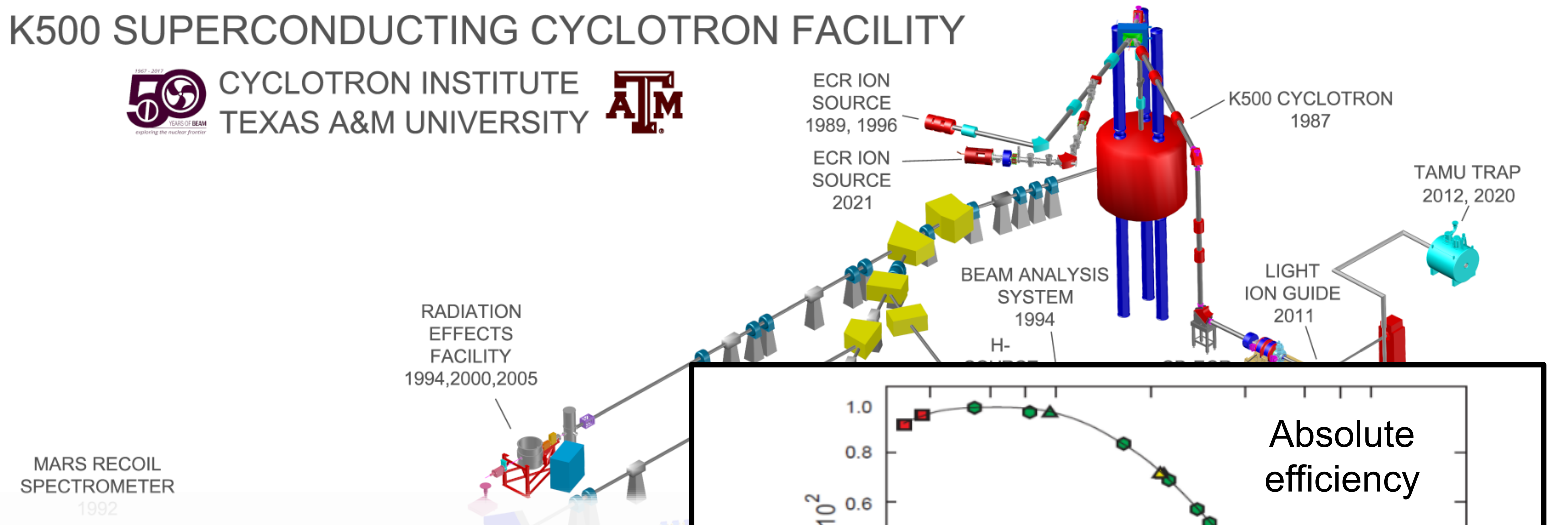
$$t_{1/2} = 4.1055(44)\ s$$

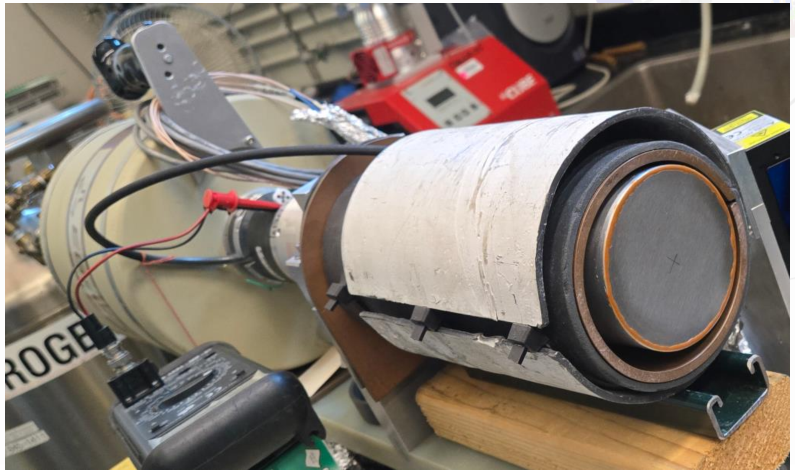
Sam

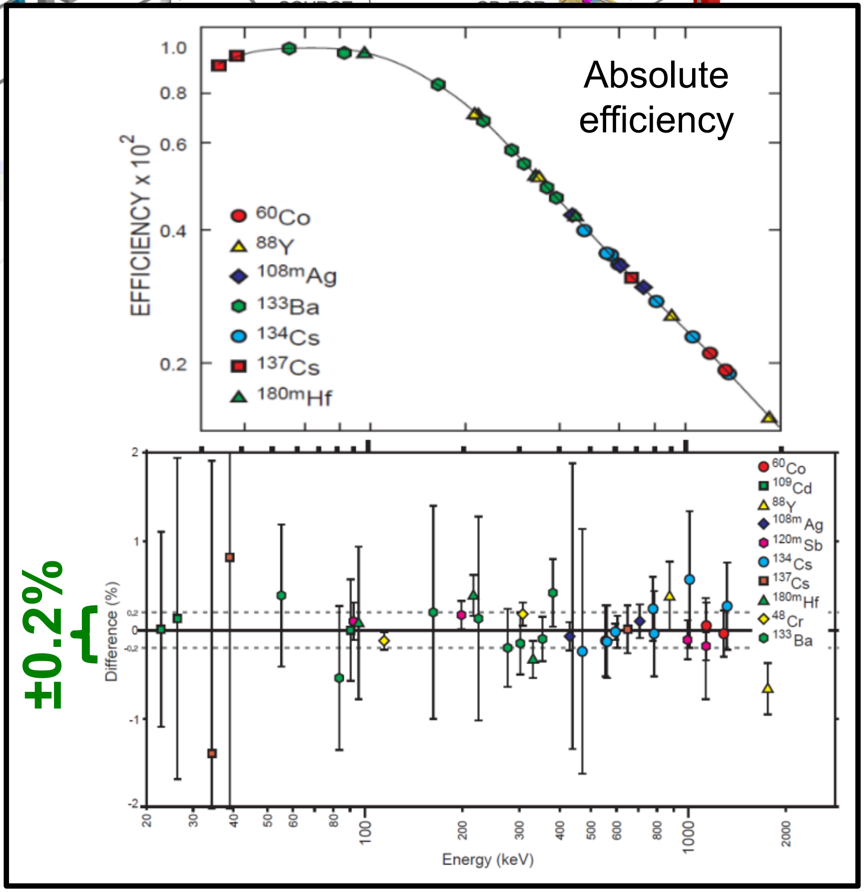
(let's talk ~~Maxime~~!)

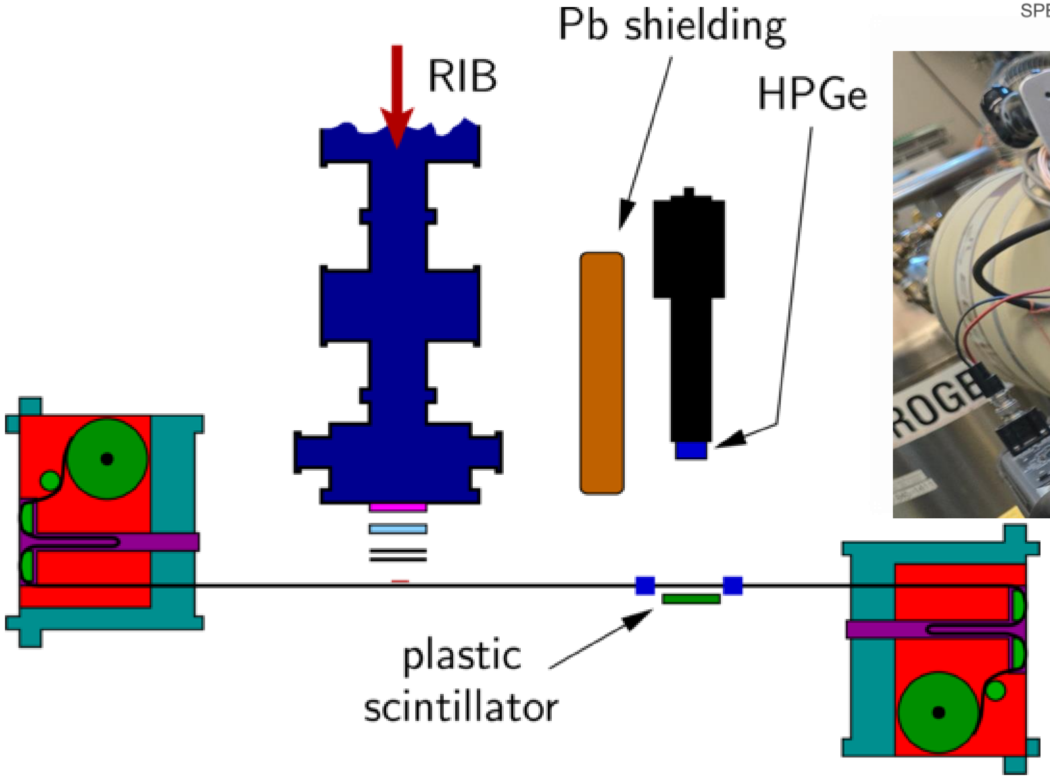
MARS: a heavily utilized spectrometer

- Fundamental symmetries: fast-tape transport system + HPGe or 4π gas counter
- Lifetimes and branching ratios (V_{ud})

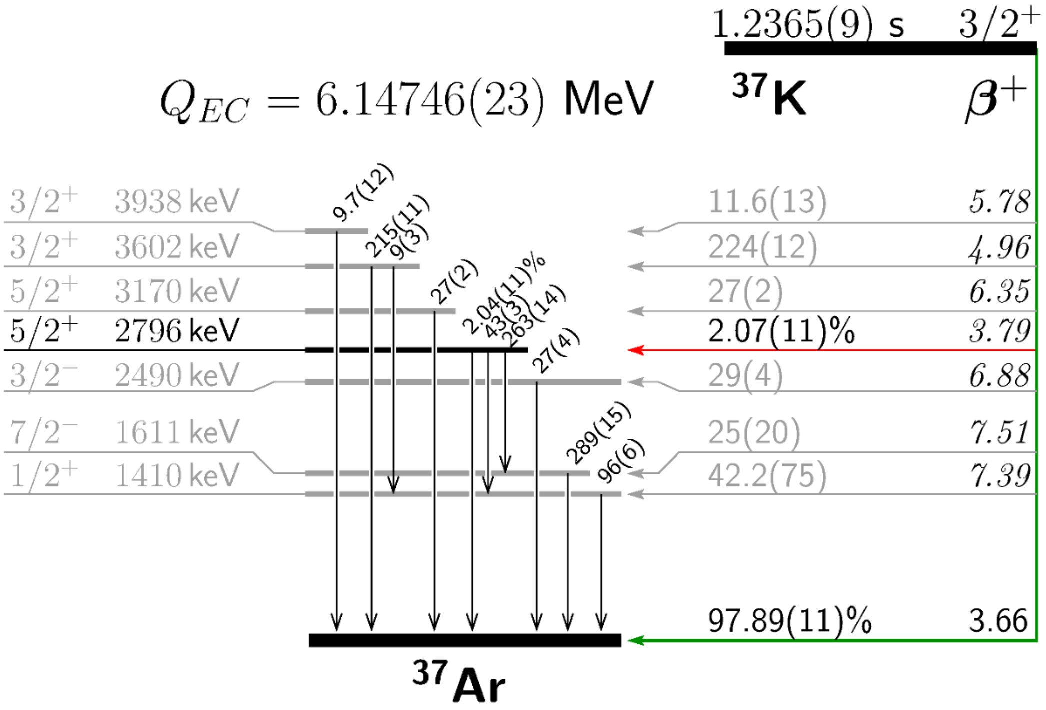


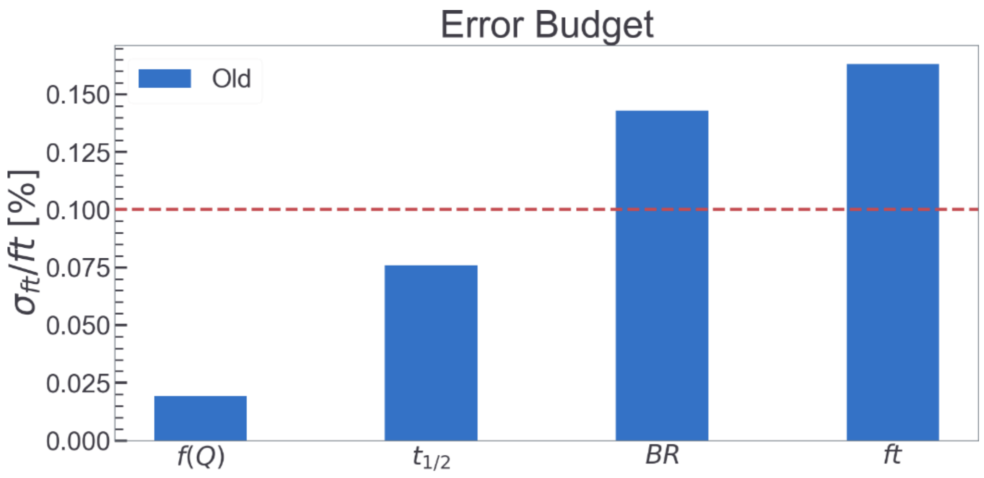


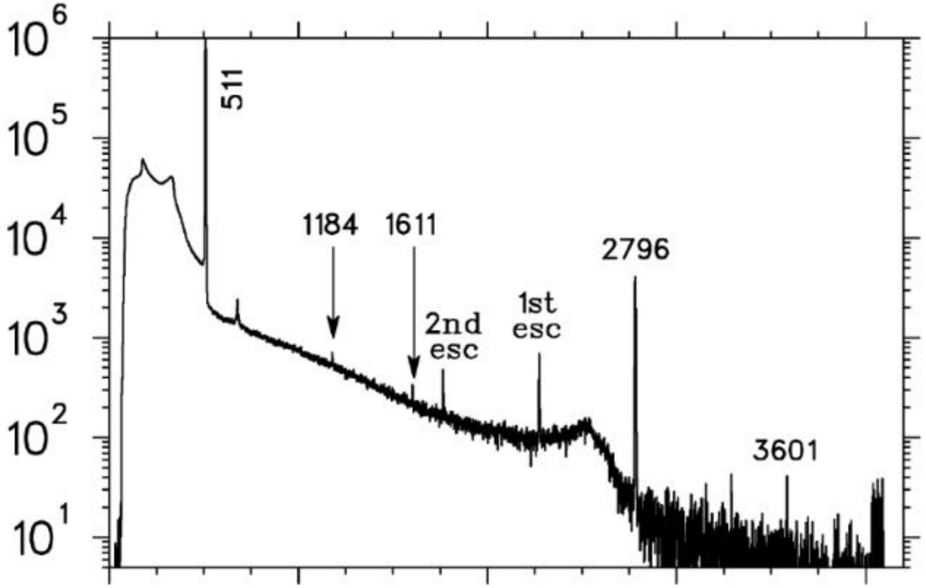


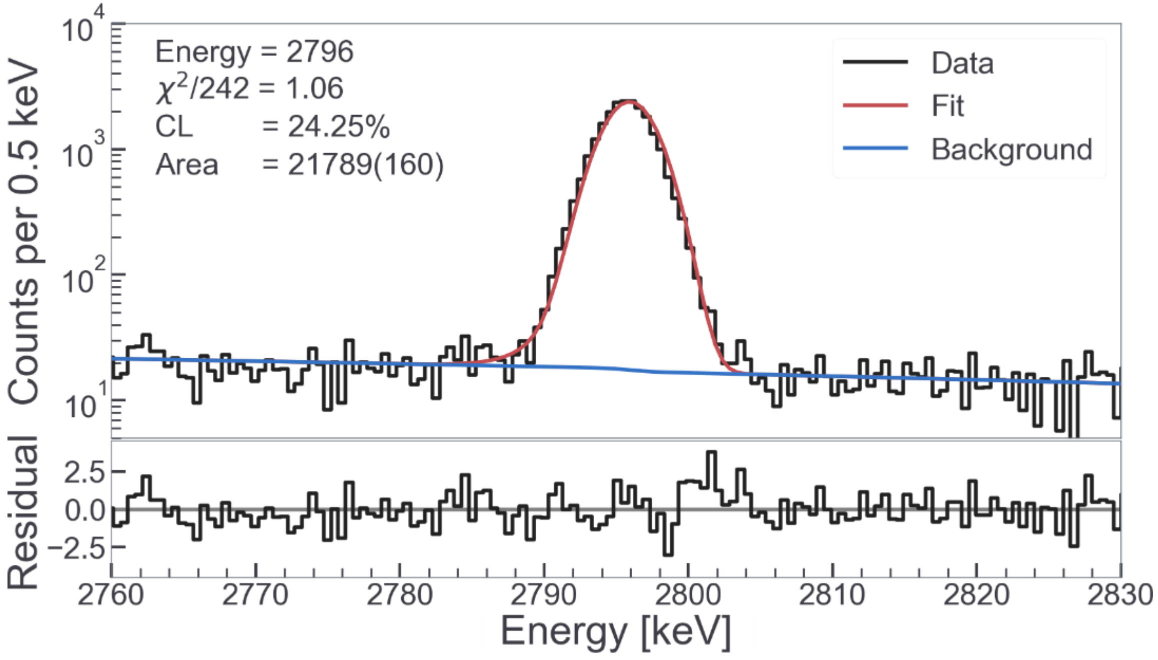


Branching ratio example: ^{37}K



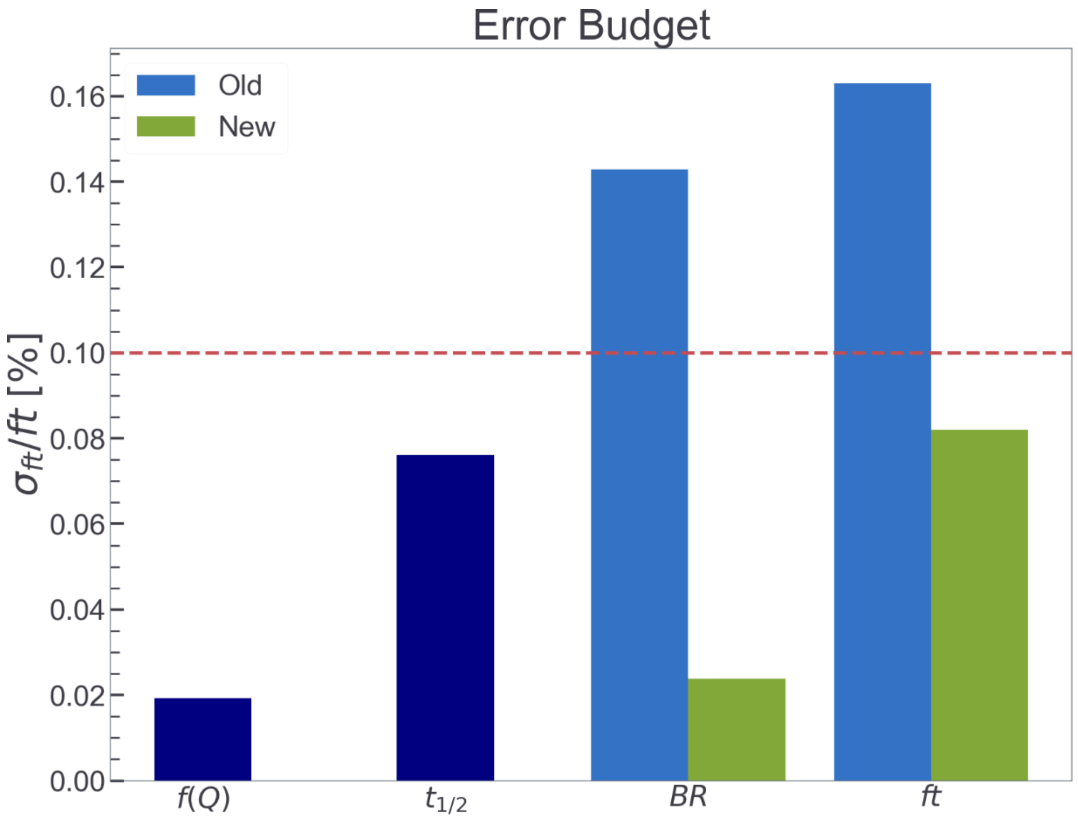






Branching ratio example: ^{37}K

Source	Uncertainty, σ_{BR} [%]			
	$E_\gamma = 1184$ keV	1611 keV	2796 keV	3601 keV
γ efficiencies	0.0001	0.0002	0.012	0.0002
$t_\beta - t_\gamma$ cuts	0.0006	0.0007	0.006	0.0012
Preemption	0.0001	0.0001	0.005	<0.0001
β/HI cuts	0.0011	0.0002	0.004	<0.0001
Fitting range	0.0002	0.0002	<0.001	<0.0001
Total systematics	0.0013	0.0008	0.015	0.0013
Statistical	0.0032	0.0030	0.017	0.0024
Total uncertainty	0.0035	0.0031	0.022	0.0027



BR: 97.99(**14**)% → 97.81(**2**)%

ft: 4576(**8**) s → 4585(**4**) s

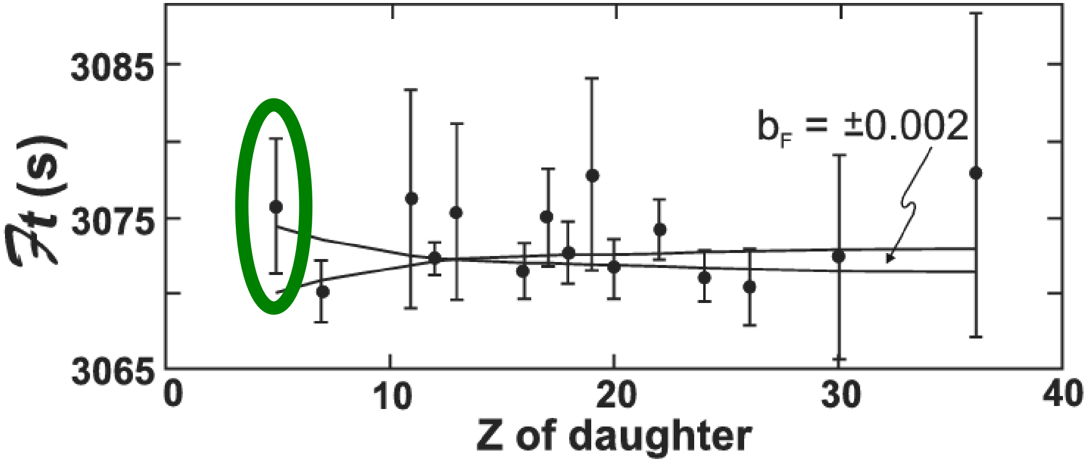
$|V_{ud}|$: stay tuned

Another branching ratio – ^{10}C

- One of if not the most important $0^+ \rightarrow 0^+$ decays to be improved
- Sometime, nature can be cruel…
- Chalk River back in 1995:

$$B = 1.4625(25)\%$$

- And a number since…none better



Superallowed beta branching-ratio measurement of ^{10}C

T. Eronen, J.C. Hardy, V. Iacob, H.I. Park, M. Bencomo, L. Chen, V. Horvat, N. Nica,
B.T. Roeder, and A. Saastamoinen

Superallowed beta decays yield the most precise value for V_{ud}, the top-left matrix element of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1,2]. The ^{10}C superallowed β-decay is one of the 14 transitions that are included in the determination. In addition to contributing to the CKM matrix, ^{10}C decay is also sensitive to the possible existence of a scalar current, the existence of which would

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https://doi.org/10.1140/epja/s10050-020-00165-1
THE EUROPEAN PHYSICAL JOURNAL A
Regular Article - Experimental Physics

Branching ratio of the super-allowed β decay of ^{10}C

B. Blank[1,a], M. Aouadi[1], P. Ascher[1], M. Gerbaux[1], J. Giovinazzo[1], S. Grévy[1], T. Kurtukian Nieto[1], M. R. Dunlop[2], R. Dunlop[2], A. T. Laffoley[2], G. F. Grinyer[3], P. Finlay[4,5]

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[3] Department of Physics, Univeristy of Regina, Regina, SK S4S 0A2, Canada
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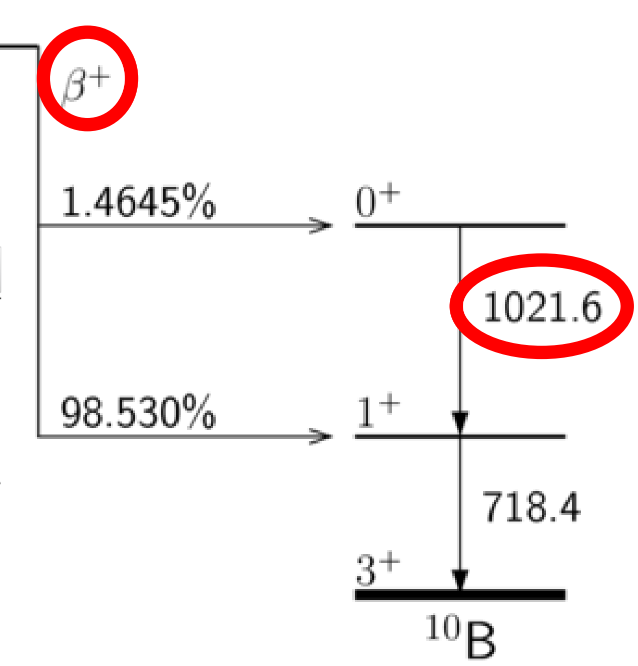
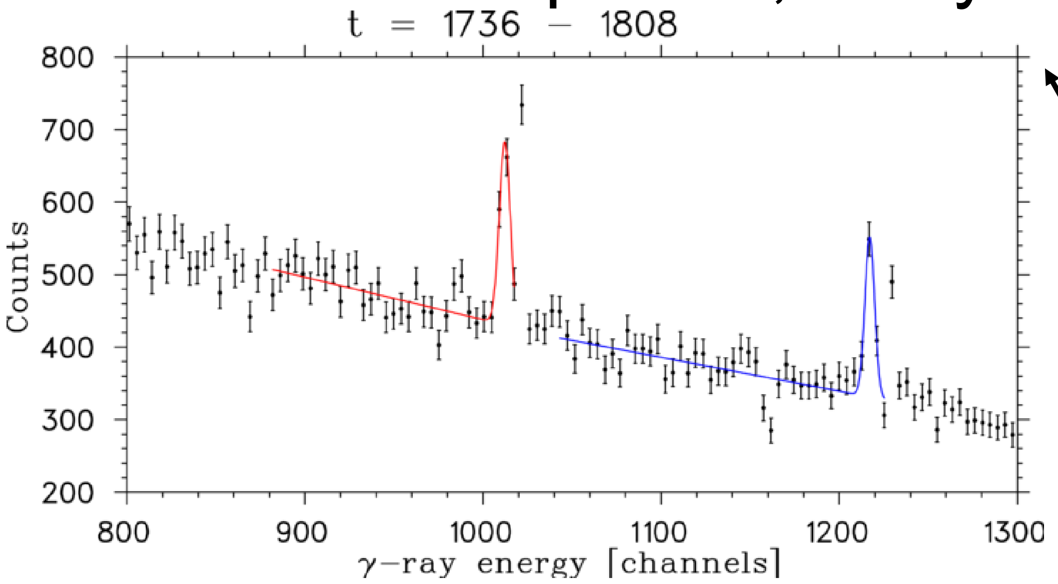
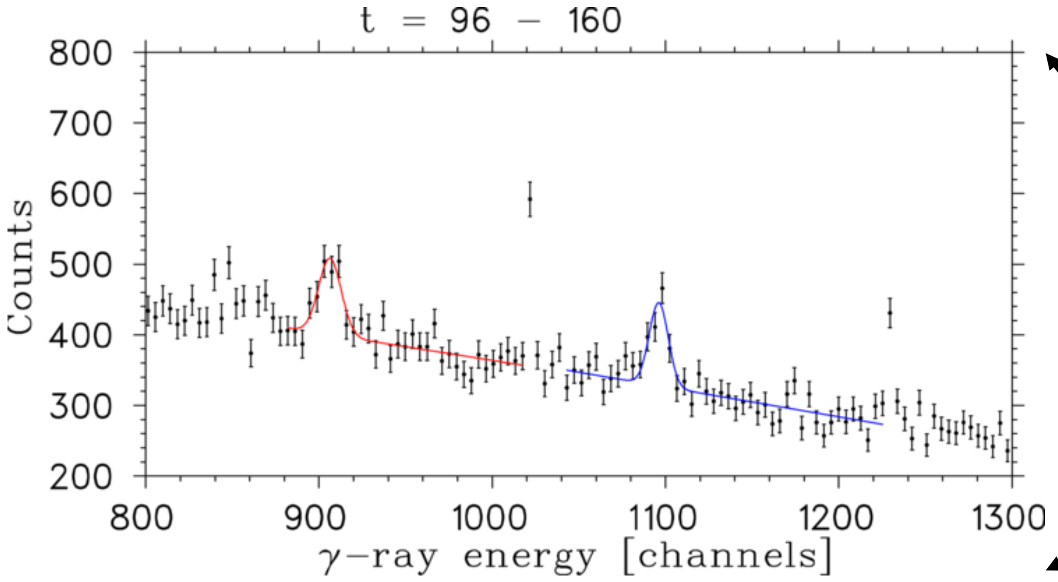
[5] *Present address:* Xanadu, 777 Bay Street, Toronto, ON M5G 2C8, Canada

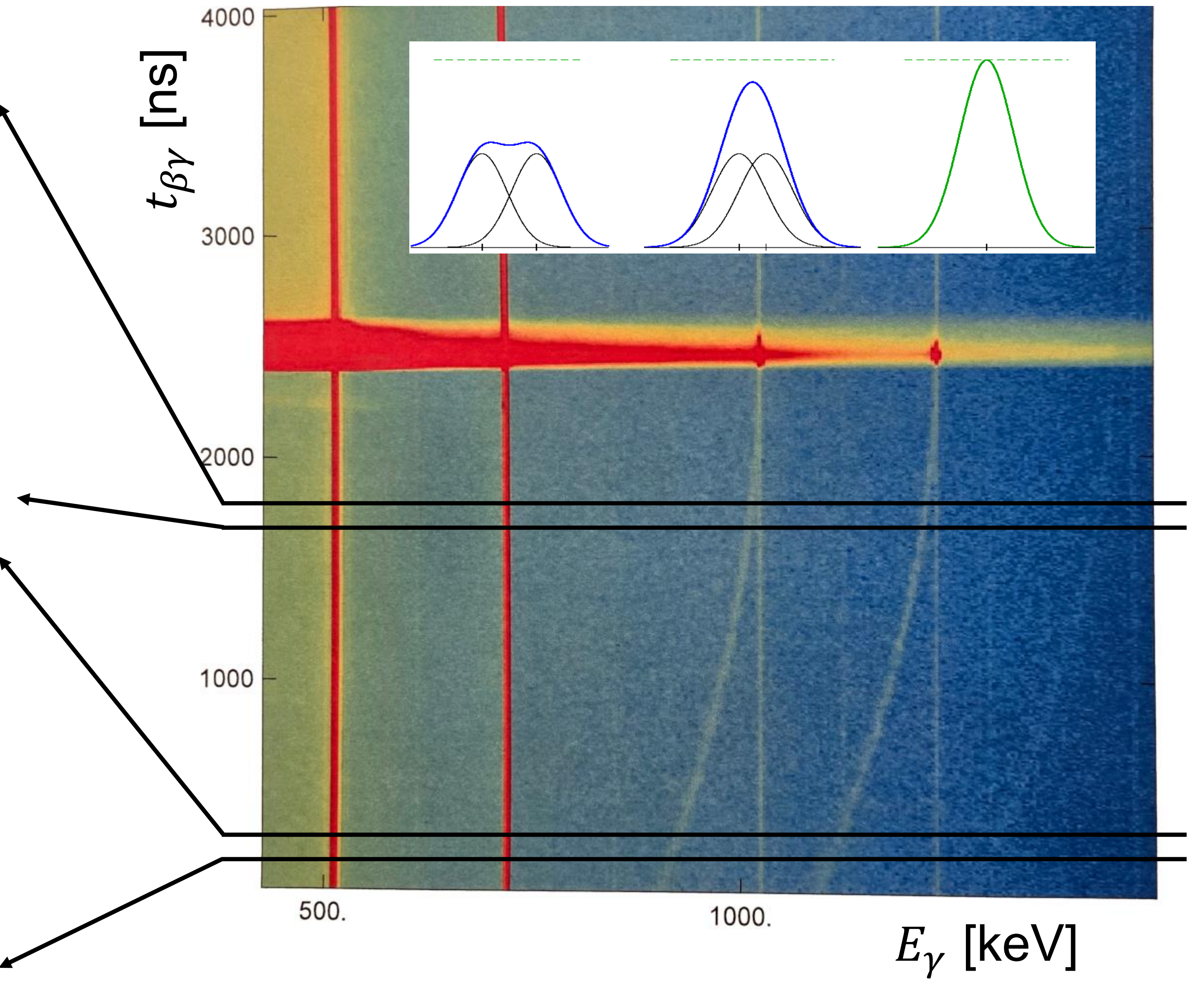


Recent ^{10}C – first test run (more data this fall)

- Better than expected, really

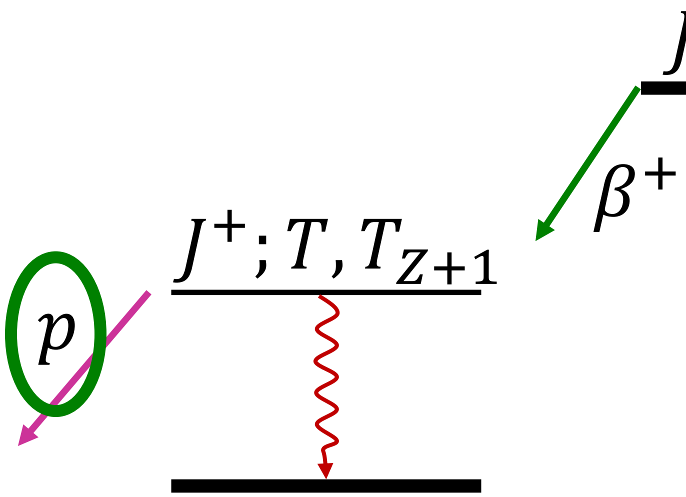


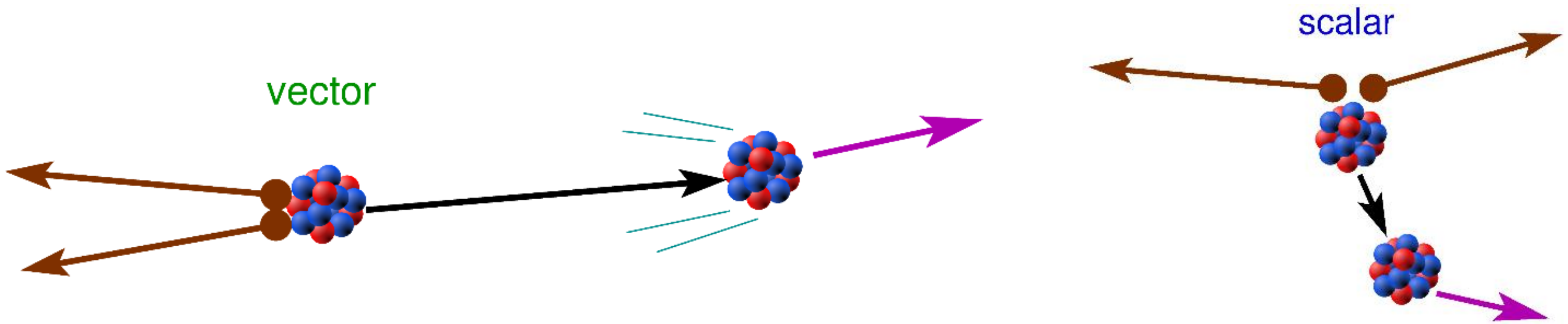




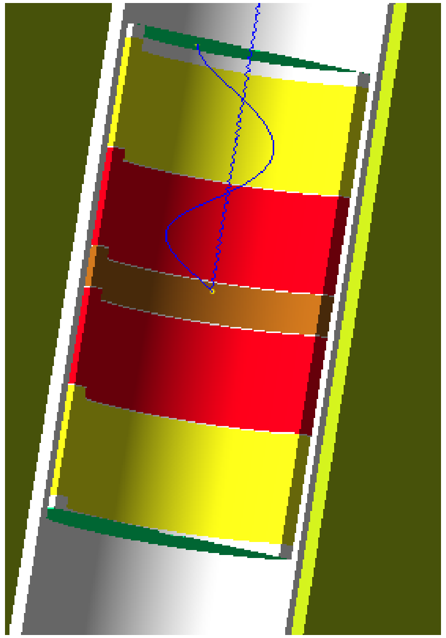
Eventually we *will* trap radioactive ions at the CI!

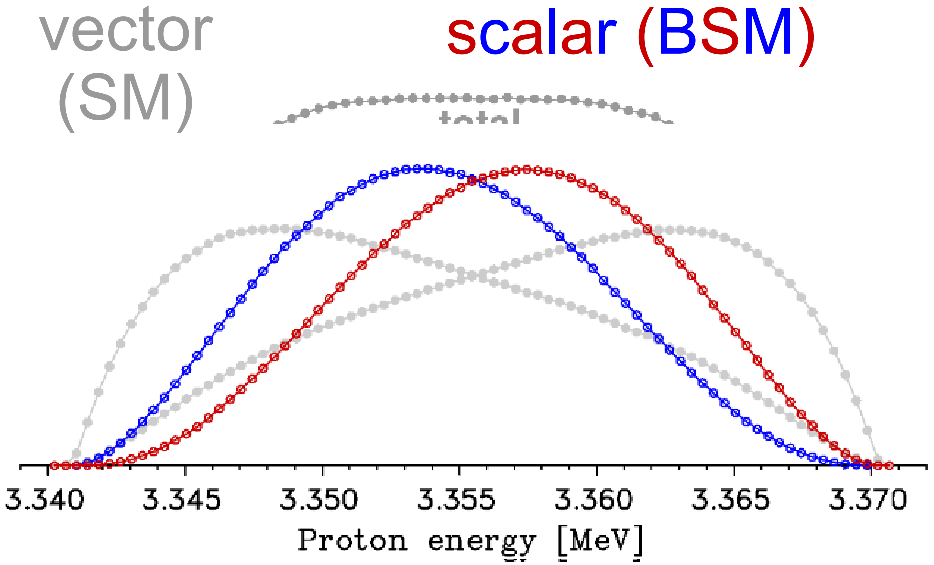
- Motivation: V_{ud} (corrections) and structure near the proton dripline

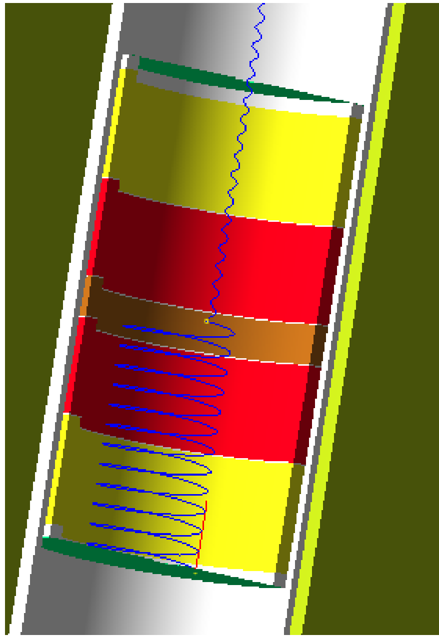




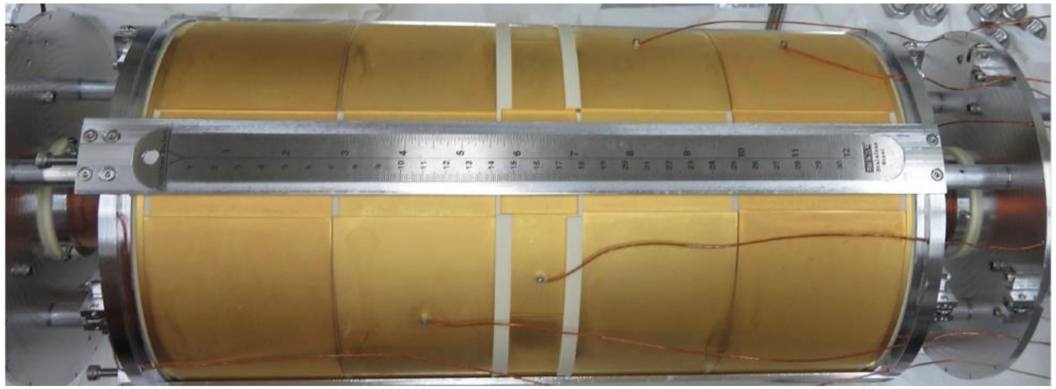
Doppler shape of proton energy depends on $\vec{p}_\beta \cdot \vec{p}_\nu$!





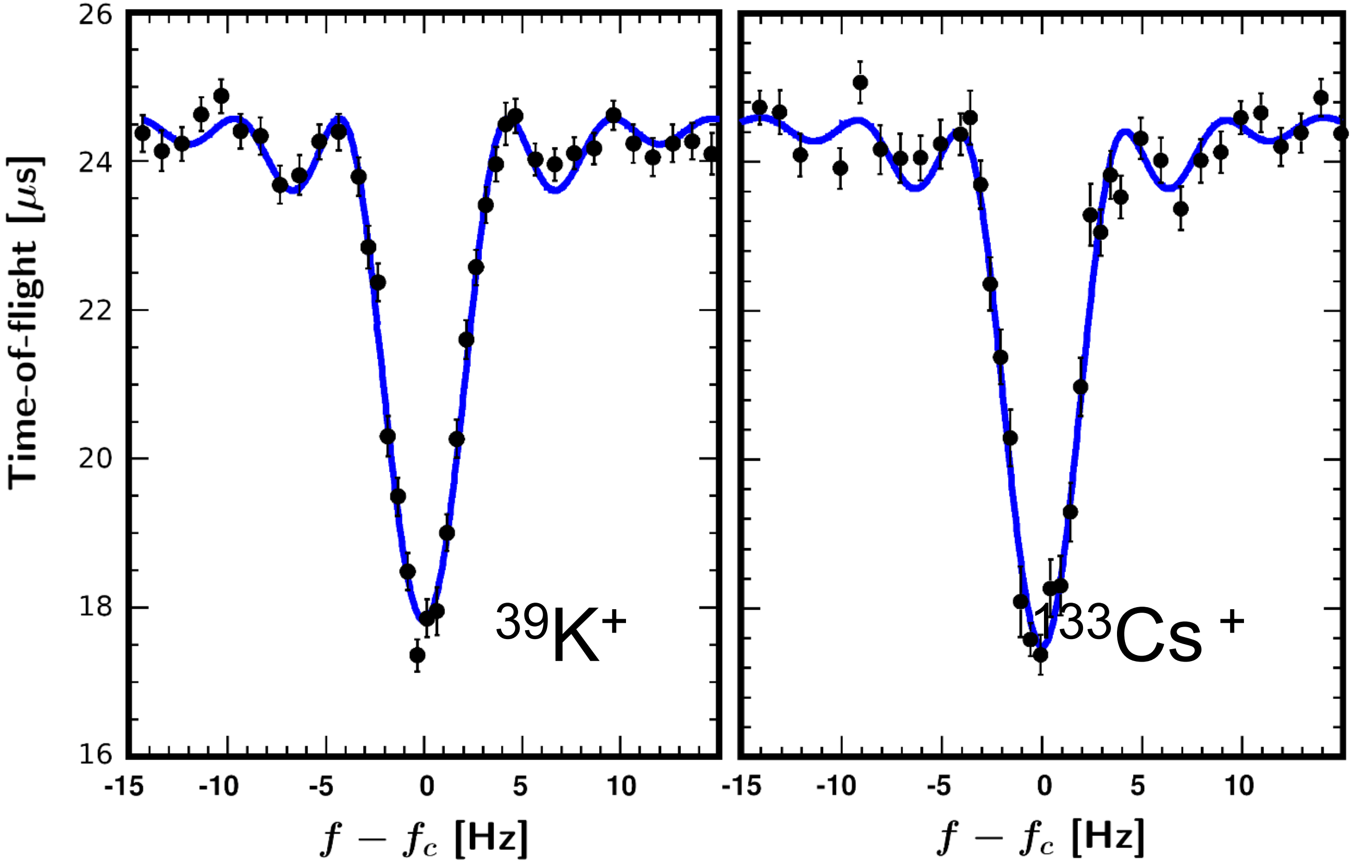


TAMUTRAP: a "new" Penning trap



- 180 mm in diameter with endcaps
- Find resonant frequencies for ^{23}Na, ^{85,87}Rb, ^{133}Cs and ^{39}K (ref). Precisions obtained (2020):
  - ^{23}Na: 400 ppb
  - ^{85}Rb: 500 ppb
  - ^{87}Rb: 500 ppb
  - ^{133}Cs: 800 ppb

TOF ICR, 200 ms excitation time



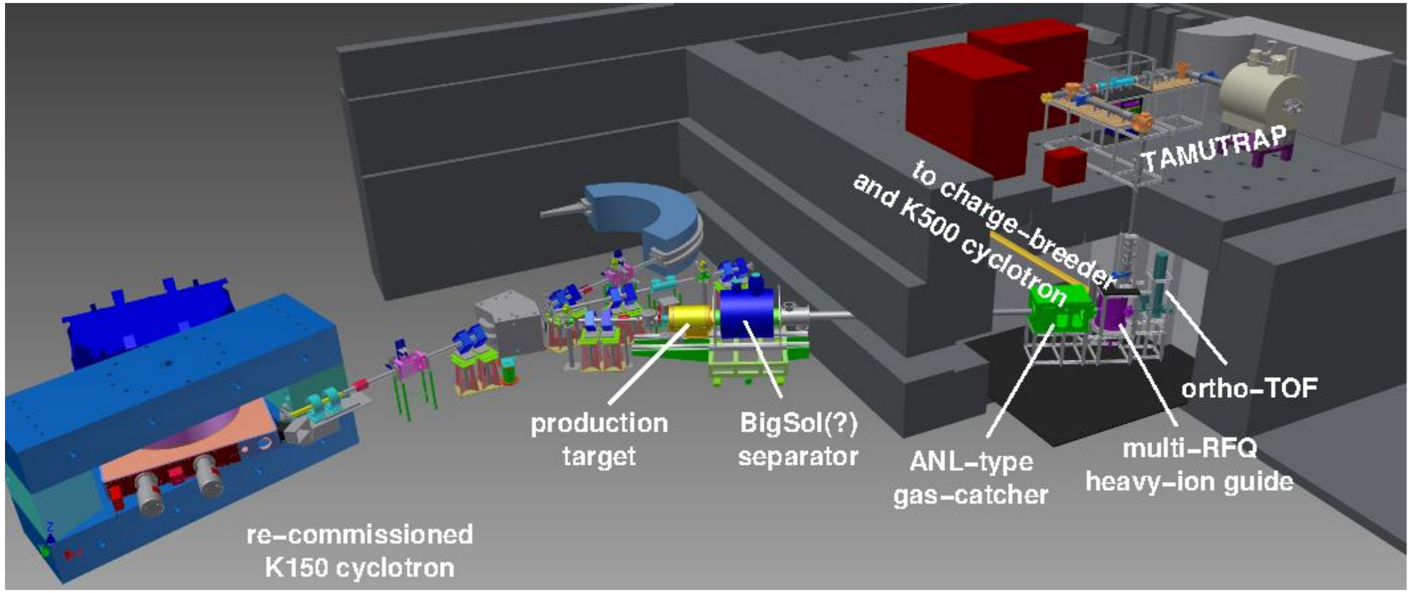
All agree with AME

P.Shidling *et al*., Hyperfine Interact. **240**, 40 (2019)
P.Shidling *et al*., Int. J. Mass Spectr. **468**, 116636 (2021)

Heavy Ion Guide for TAMUTRAP

- Primarily for β-ν correlation studies using β-delayed proton decays in a Penning trap
- Heavy ion guide approach was abandoned in favour of a LIG system and separator
  - Delays with catcher/multi-RFQ,
  - BigSol cooling issues,
  - K150 working better with low-mass beams,

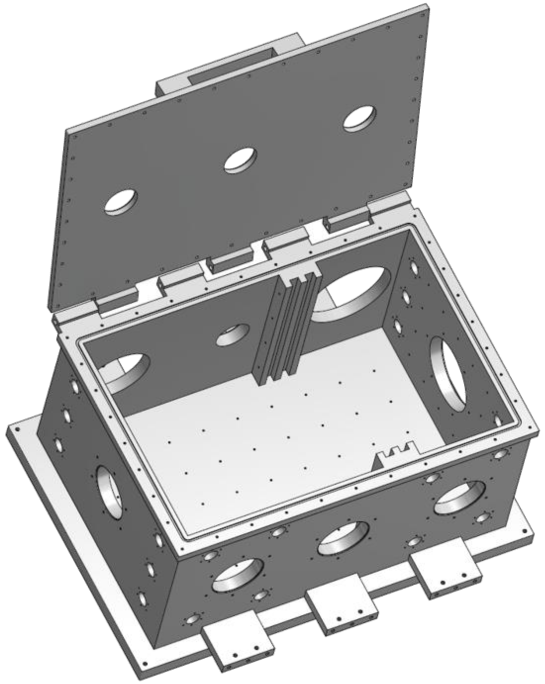
⋮

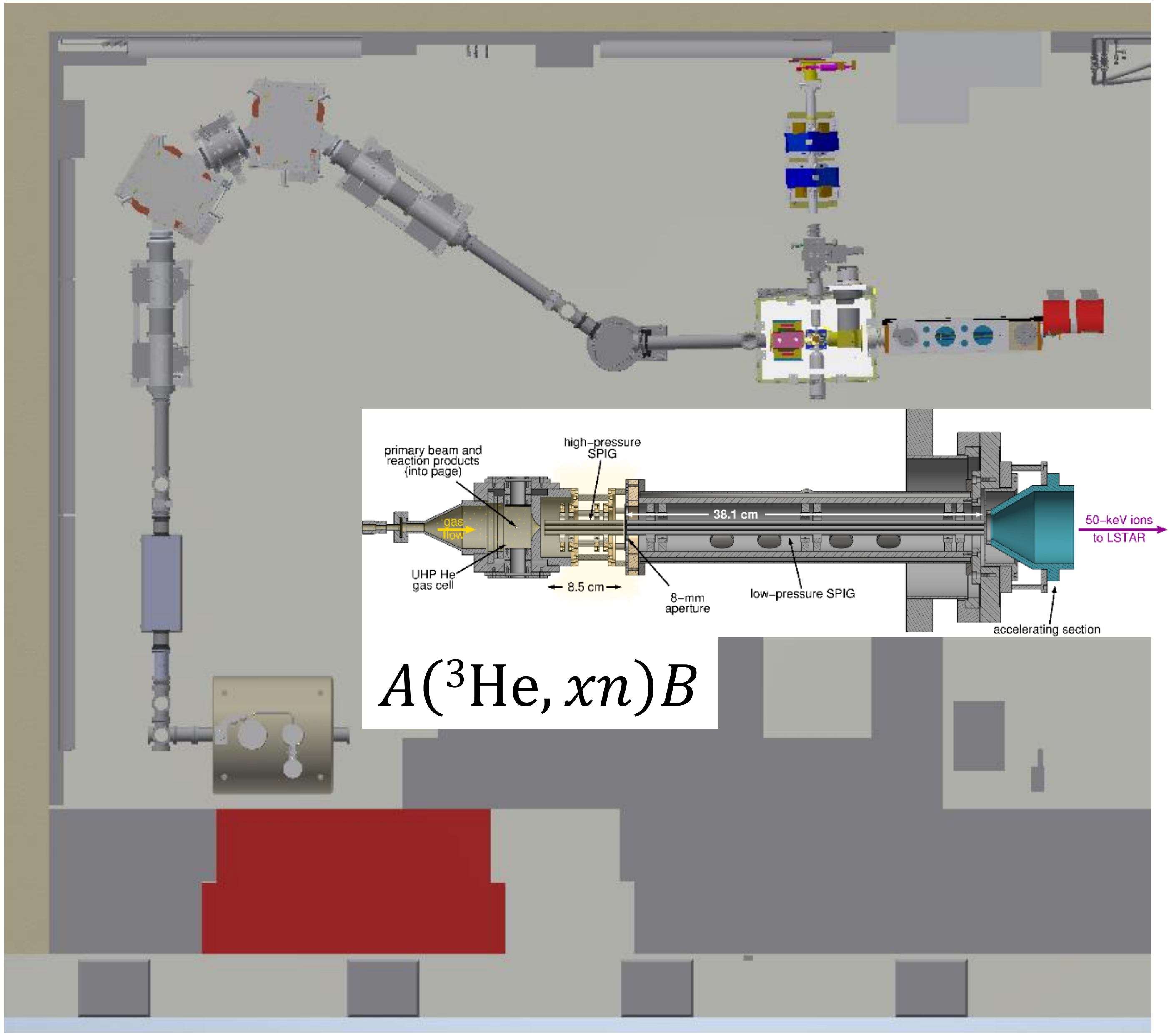


^{3}He-LIG and LSTAR for TAMUTRAP

- Primarily for β-ν correlation studies using β-delayed proton decays in a Penning trap
- *p*/He-LIG chamber ready to be installed, inside parts about to be ordered

Target	Product	Production rate
^{20}Ne	^{20}Mg	4×10^3
	^{21}Mg	3×10^5
^{24}Mg	^{24}Si	3×10^3
	^{25}Si	2×10^5
^{28}Si	^{28}S	3×10^3
	^{29}S	8×10^4
^{32}S	^{32}Ar	0.9×10^3
	^{33}Ar	0.9×10^5
^{36}Ar	^{36}Ca	0.2×10^3
	^{37}Ca	0.2×10^5

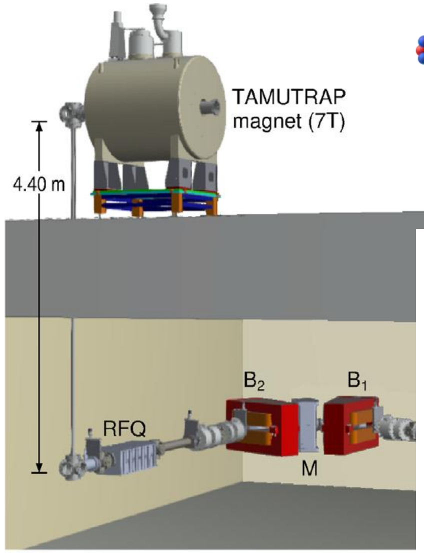


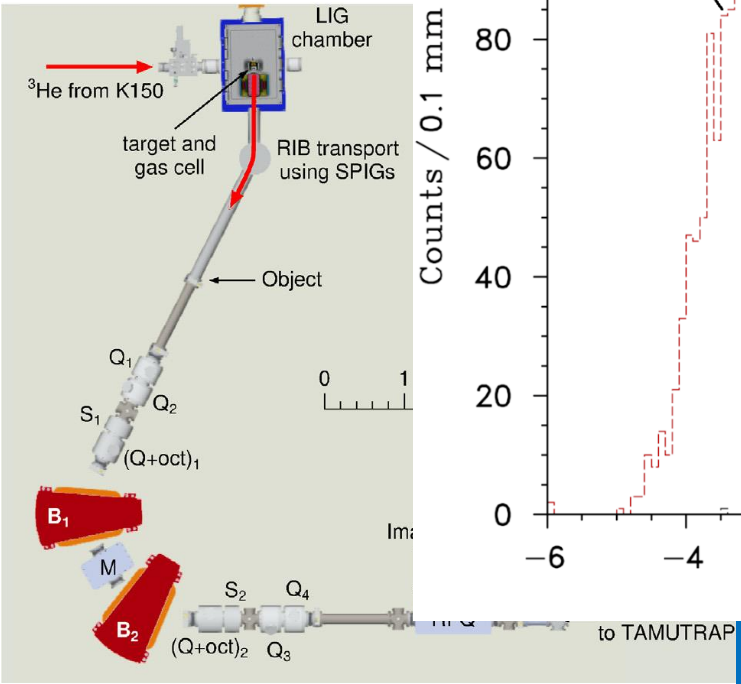


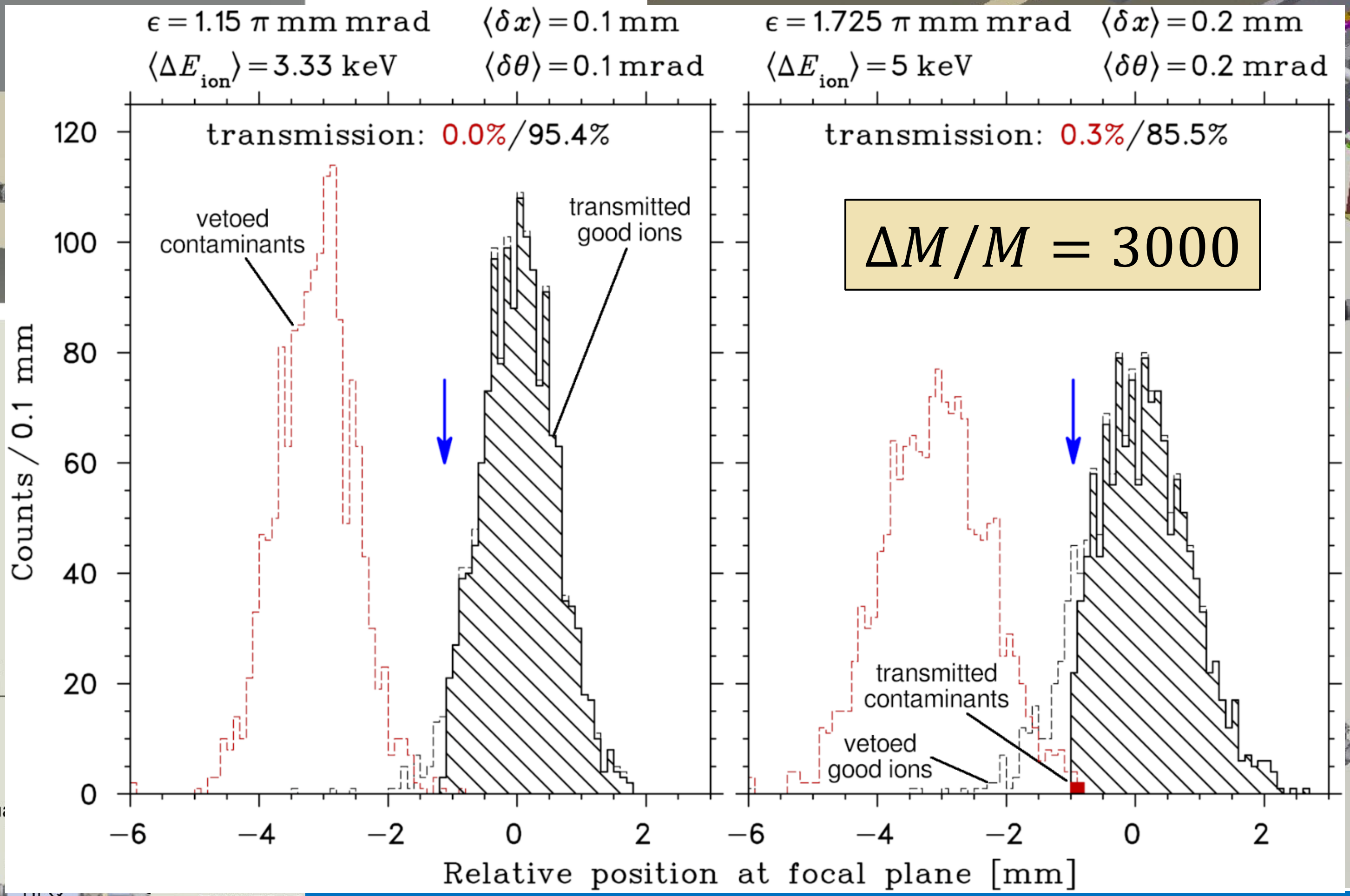
$A(^3\mathrm{He}, xn)B$

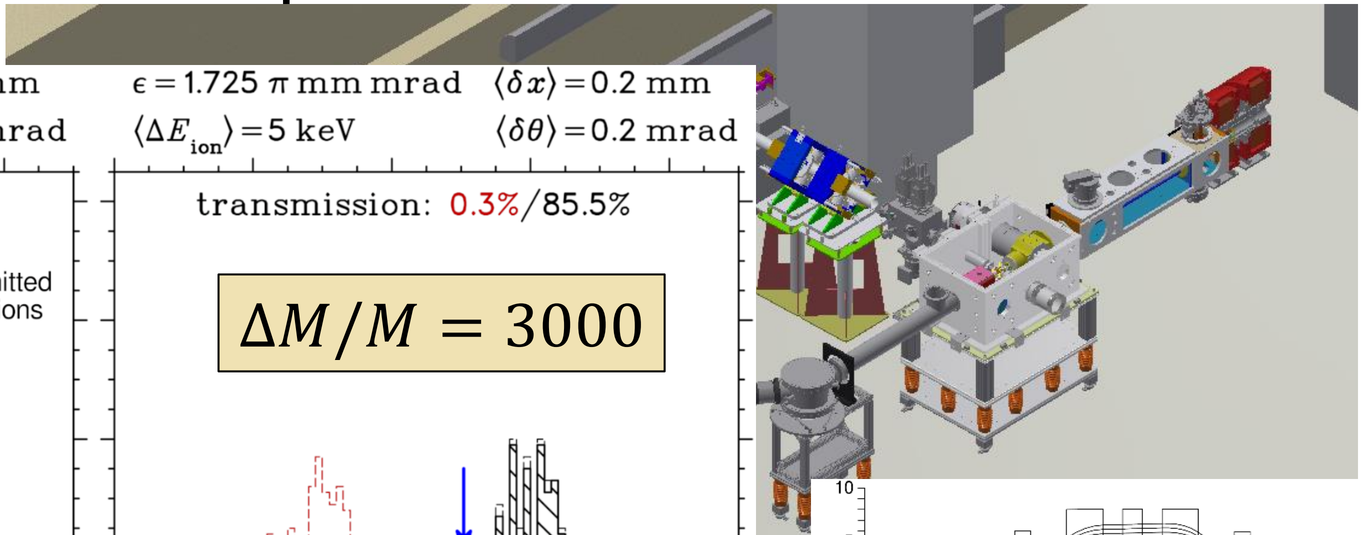
LSTAR: purify and transport up to TAMUTRAP

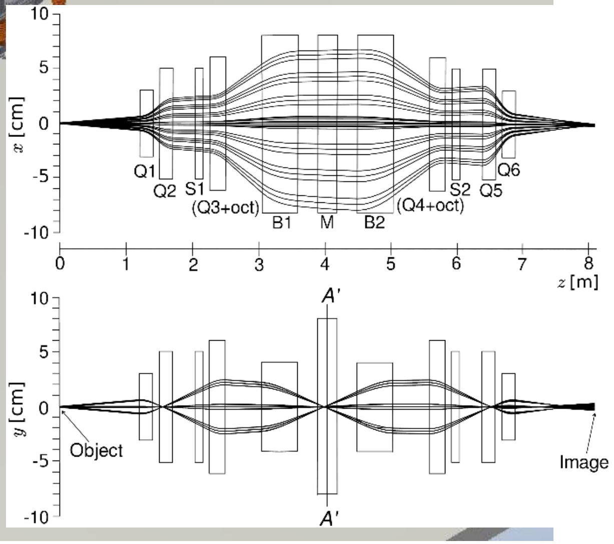
- In collaboration with Notre Dame (Berg, Couder, Brodeur), design based on $2 \times 60°$ separator at CARIBU.







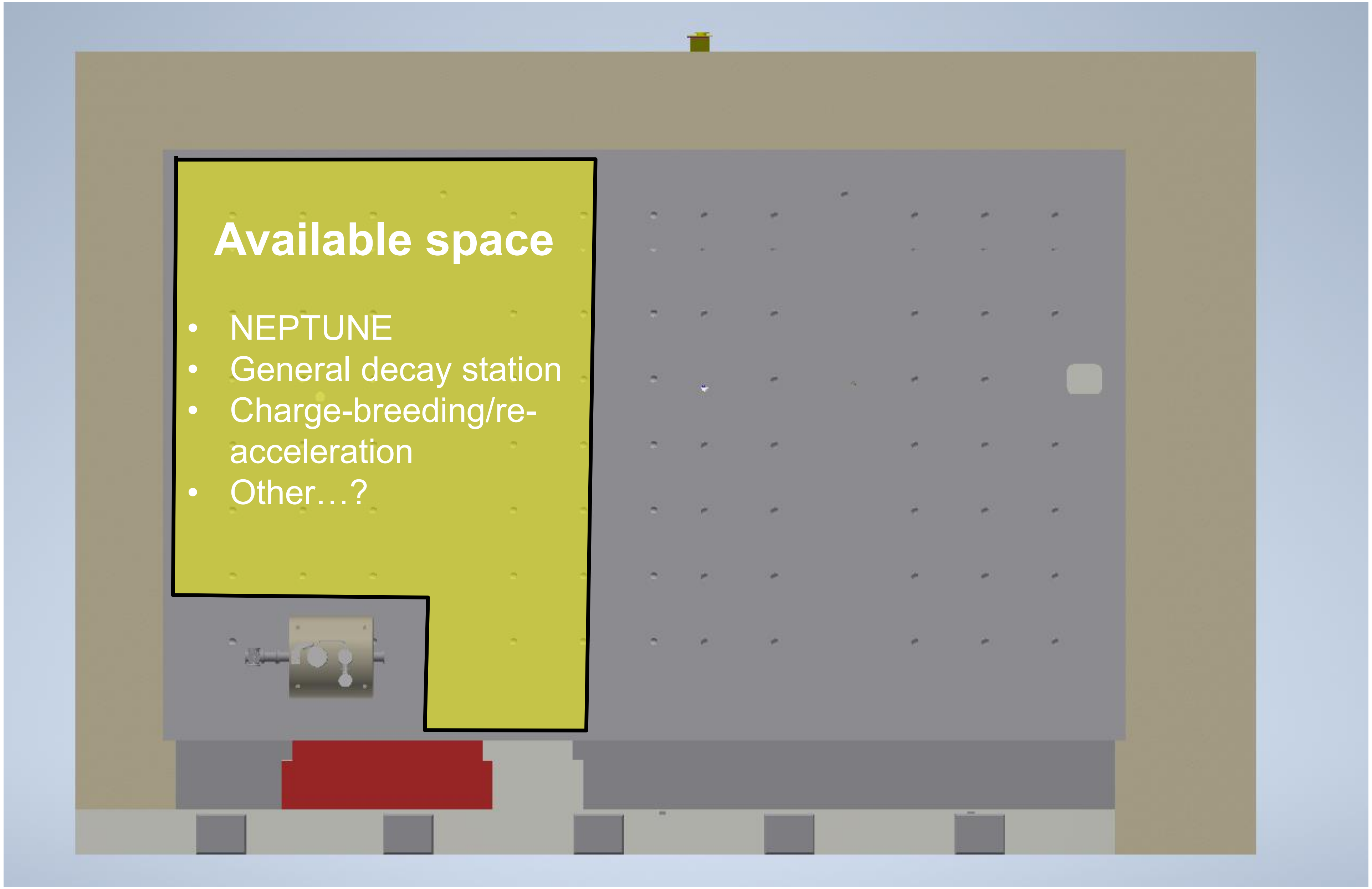




GPA Berg, D Melconian, M Couder, M Brodeur, VE Iacob, J Klimo, PD Shidling, NIMA **1069**, 169944 (2024)

Once He-LIG and LSTAR running

- There will be room on the highbay for stations to utilize RIB from the He-LIG

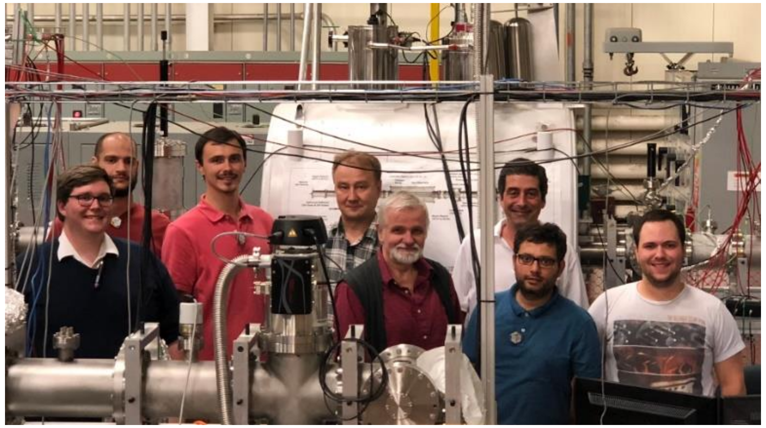


Before Jonas asks: my wishlist

- In general, more people
  - Have undergrads in abundance, but need more (good) graduate students
  - Hoping some of the facilities I described are of interest to some of you, new collaborations? Remember: we're not a user facility!
- Help setting up a HV platform to 70 kV in the tight confines of Cave 5
  - The roots blowers are very close to the roof planks (π metres high = 10′3″)
  - Keeps me up at night. Literally!
- Ideas for TAMUTRAP
  - We're not as exotic as user facilities (FRIB), but lots of beamtime available. Highly-charged ions? Laser spectroscopy of trapped ions? Aside from astrophysics, interest in re-accelerated RIB?
- Eventually, theory calculations to interpret our data
  - FRIB Theory Alliance workshop next month!

Final thoughts, collaborators and thanks

- MARS (→ SATURN) + Fast-tape transport + HPGe = precise τ + BR
- TAMUTRAP: commissioned, just need radioactive ions…
- p/He-LIG + LSTAR: (near?) future is bright!



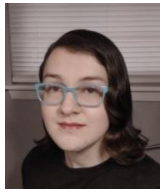
TEXAS A&M UNIVERSITY

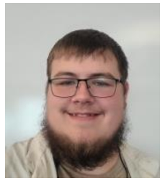
B. Fenker
B.M. Vargas-Calderon
M. Holloway
M. Mehlman
D. Melconian
P.D. Shidling

N. Morgan
A. Ozmetin
D. McClain
V. Kolhinen
V.E. Iacob
G. Morgan

UNIVERSITY OF NOTRE DAME

G. Berg
M. Brodeur
M. Couder





\+ several REUs, a few ENISCAEN interns, and TAMU undergrads

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