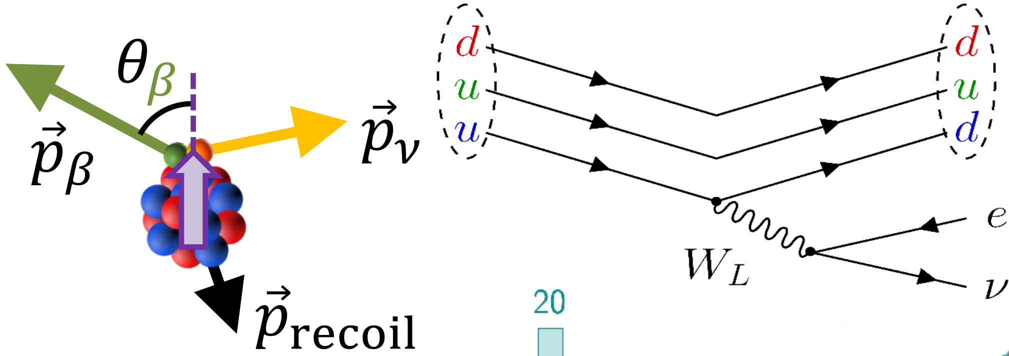
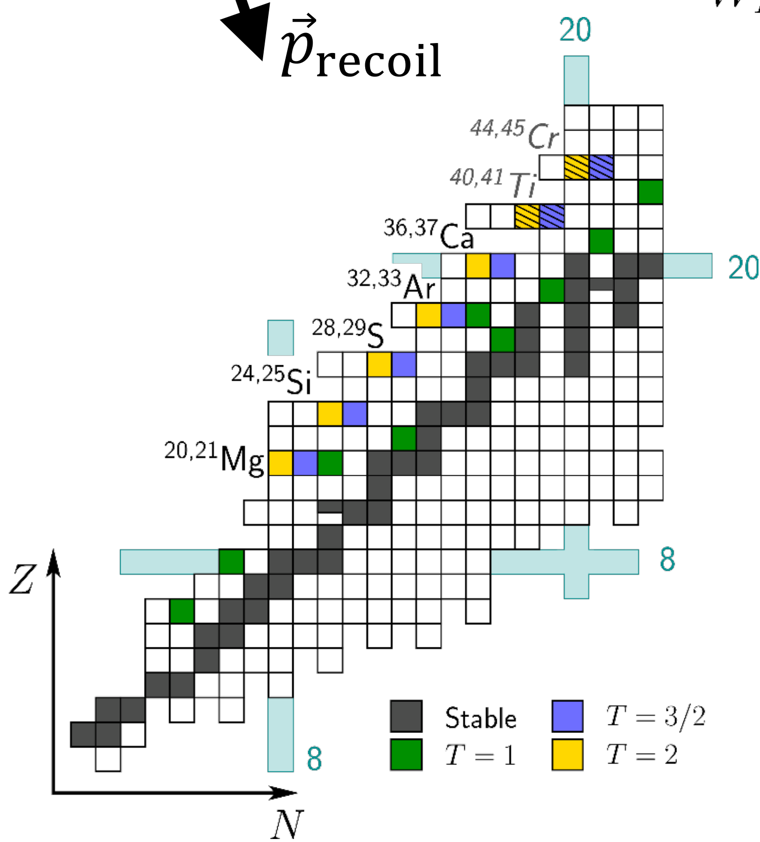
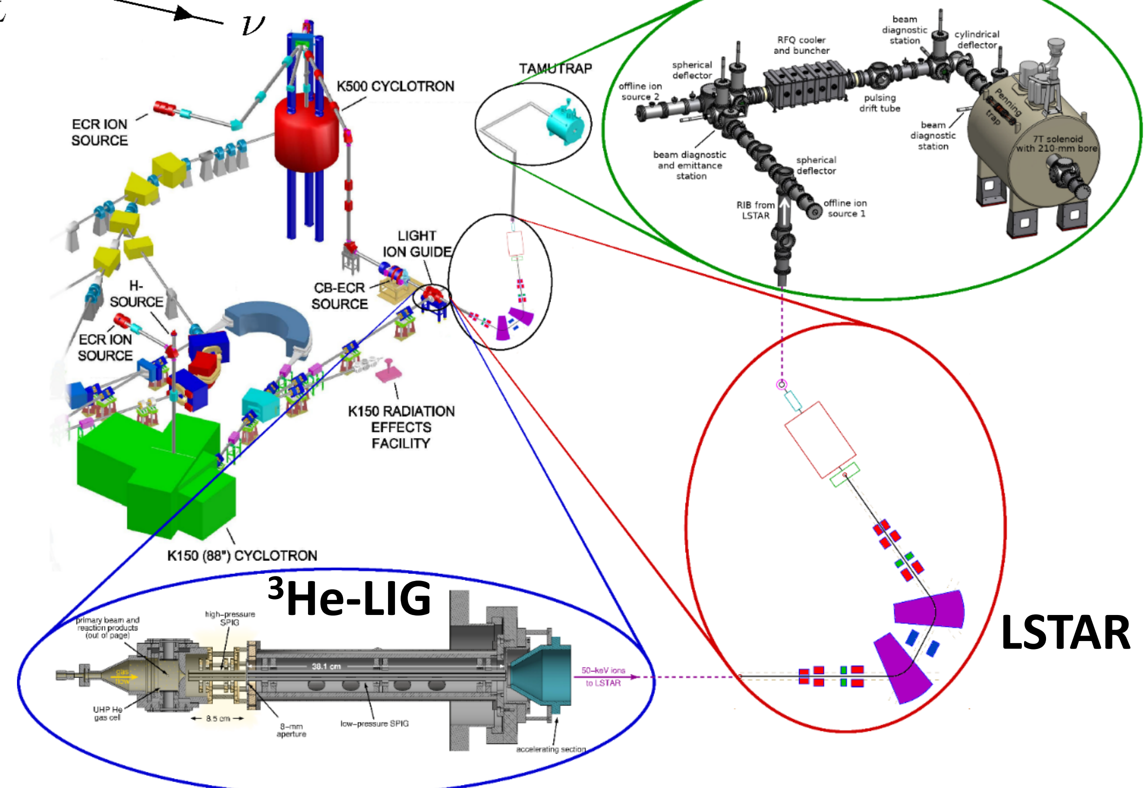
Expanding RIB Capabilities at the Cyclotron Institute: ^{3}He-LIG production with an Isobar Separator LSTAR







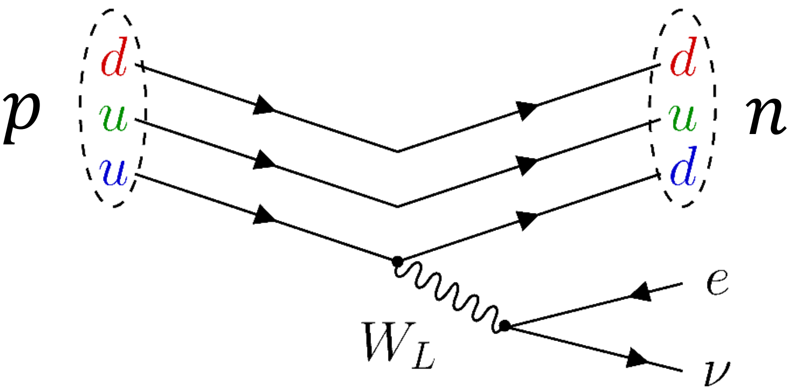
Dan Melconian – DNP, Oct 2022

Outline

- Motivation
  - Testing the standard model via the precision frontier
  - TAMUTRAP: Penning trap for β-delayed proton decay studies
- ^{3}He-driven light-ion guide
  - Initial tests with a prototype gas cell
- Transporting the beam to TAMUTRAP
  - Design of the **L**ight-ion guide **S**eparator for **TA**MU's K150 **R**IBs (LSTAR)
  - Expected performance of LSTAR
  - Looking forward

The standard model and beyond

- This is the standard model: pure $V - A$ interaction



$$H_\beta = \bar{p}\gamma_\mu n(C_V \bar{e}\gamma^\mu \nu + C_V' \bar{e}\gamma^\mu\gamma_5 \nu) - \bar{p}\gamma_\mu\gamma_5 n(C_A \bar{e}\gamma^\mu\gamma_5 \nu + C_A' \bar{e}\gamma^\mu \nu)$$

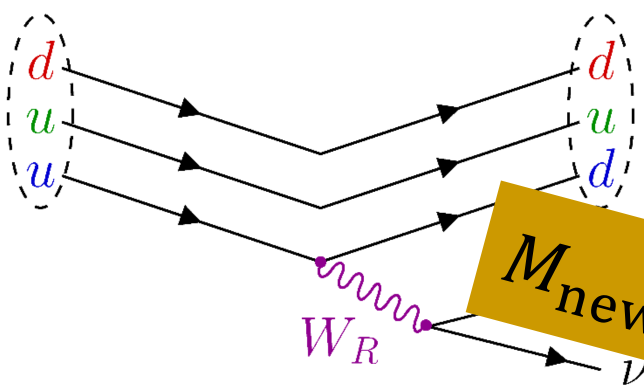
$$C_V = C_V' = 1$$

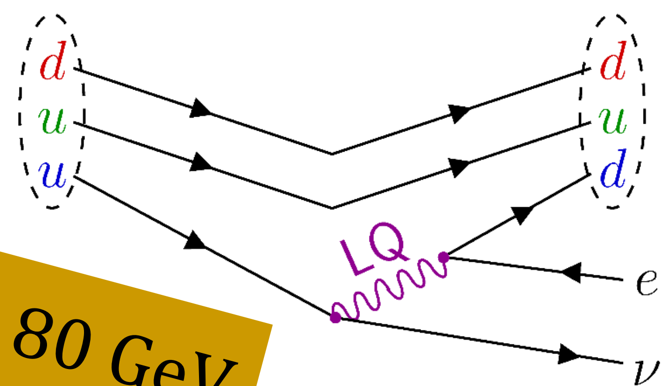
$$C_A = C_A' \approx 1.27$$

$$M_W = 80.385\ \text{GeV}$$

- These are not:

Right-handed bosons, or scalar/tensor leptoquarks, or SUSY, or…





$M_{new} \gg 80$ GeV

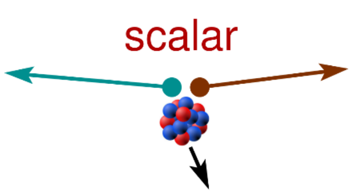
$C_i \neq C_i'$ $C_S, C_T \neq 0$

β decay and fundamental physics

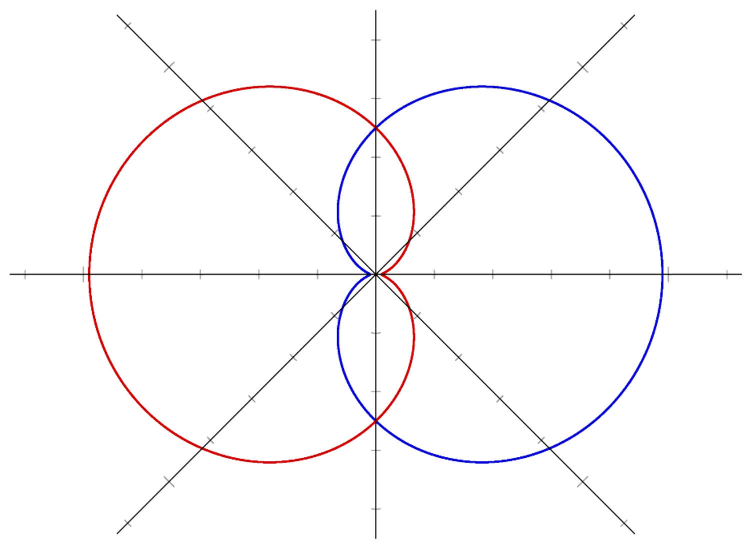
- The often-quoted angular distribution of β decay
  (Jackson, Treiman and Wyld, Phys Rev **106** and Nucl Phys **4**, 1957)

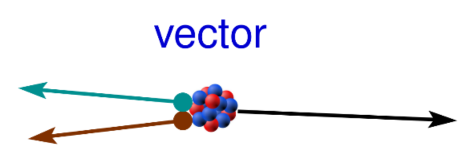
$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2|\boldsymbol{V_{ud}}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2}^{\text{basic decay rate}} \xi \left(1 + \overbrace{\boldsymbol{a_{\beta\nu}} \frac{\vec{p_e}\cdot\vec{p}_{\nu_e}}{E_e E_{\nu_e}}}^{\beta-\nu \text{ correlation}} + \overbrace{\boldsymbol{b}\frac{\Gamma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

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



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





$$a_{\beta\nu} = \frac{|C_V|^2+|C'_V|^2}{|C_V|^2+|C'_V|^2}$$

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

- Not as sensitive as the Fierz parameter, which is linear in the new couplings:

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

(see Falkowski, González-Alonso and Naviliat-Čunčić, JHEP **4**, 126 (2021))

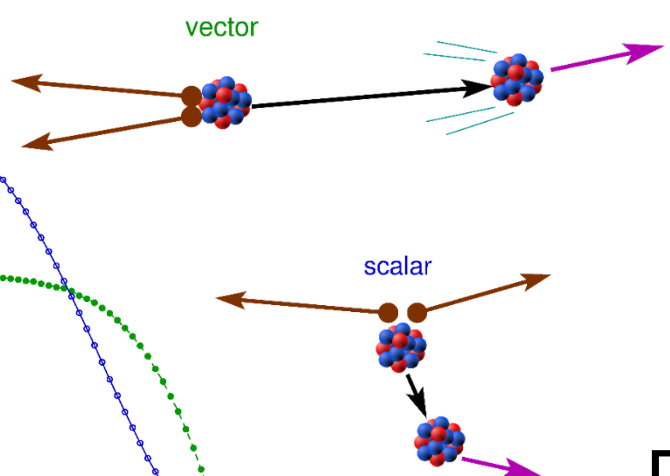
β-ν correlation via β-delayed p decay

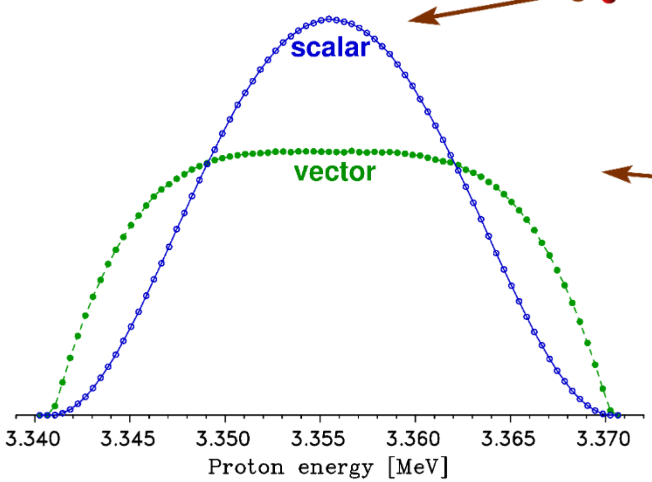
VOLUME 83, NUMBER 7 PHYSICAL REVIEW LETTERS 16 AUGUST 1999

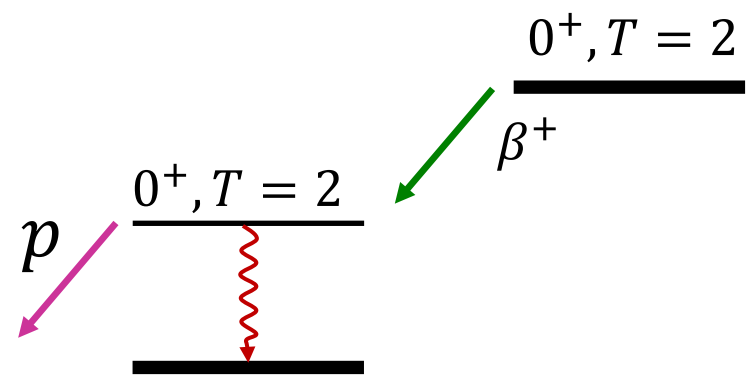
Positron-Neutrino Correlation in the $0^+ \rightarrow 0^+$ Decay of ^{32}Ar

E. G. Adelberger,[1] C. Ortiz,[2] A. García,[2] H. E. Swanson,[1] M. Beck,[1] O. Tengblad,[3] M. J. G. Borge,[3] I. Martel,[4]
H. Bichsel,[1] and the ISOLDE Collaboration[4]
[1] *Department of Physics, University of Washington, Seattle, Washington 98195-1560*
[2] *Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556*
[3] *Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain*
[4] *EP Division, CERN, Geneva, Switzerland CH-1211*
(Received 24 February 1999)

The positron-neutrino correlation in the $0^+ \rightarrow 0^+$ β decay of ^{32}Ar was measured at ISOLDE by analyzing the effect of lepton recoil on the shape of the narrow proton group following the superallowed decay. Our result is consistent with the standard model prediction. For vanishing Fierz interference we find $a = 0.9989 \pm 0.0052 \pm 0.0039$, which yields improved constraints on scalar weak interactions.

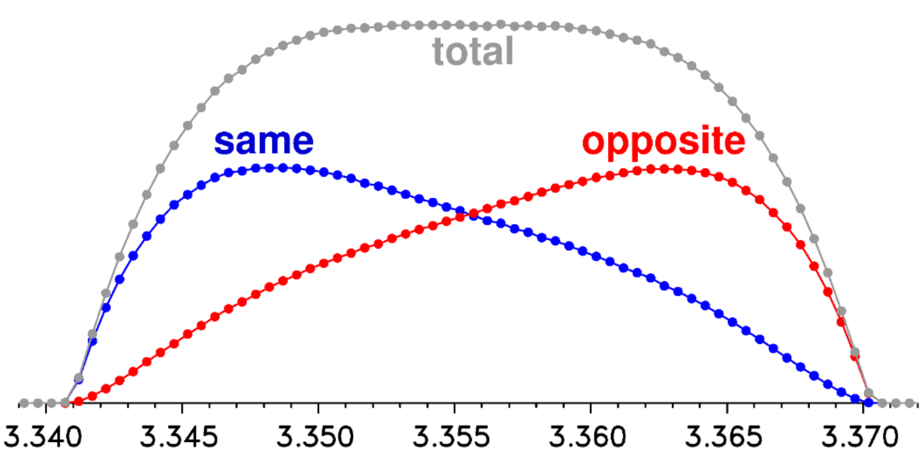


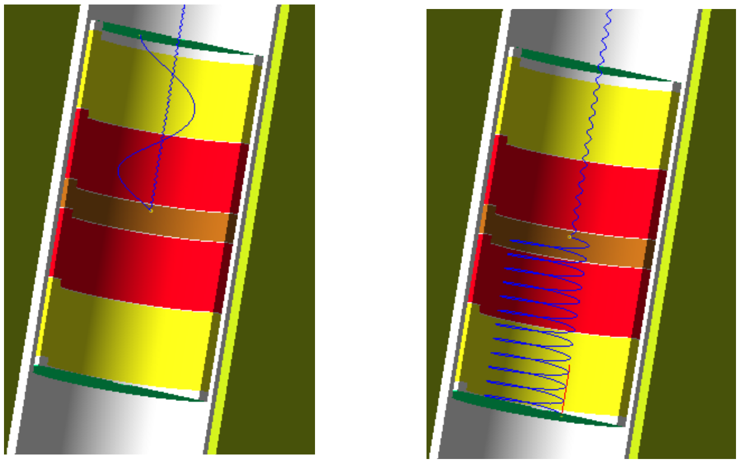


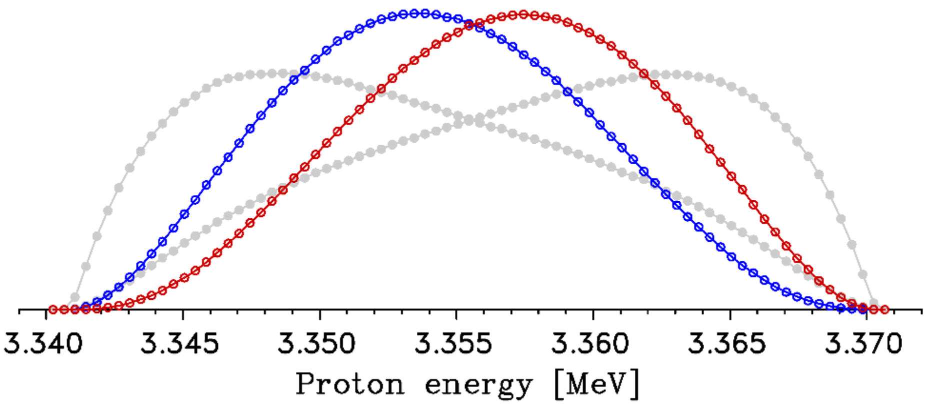


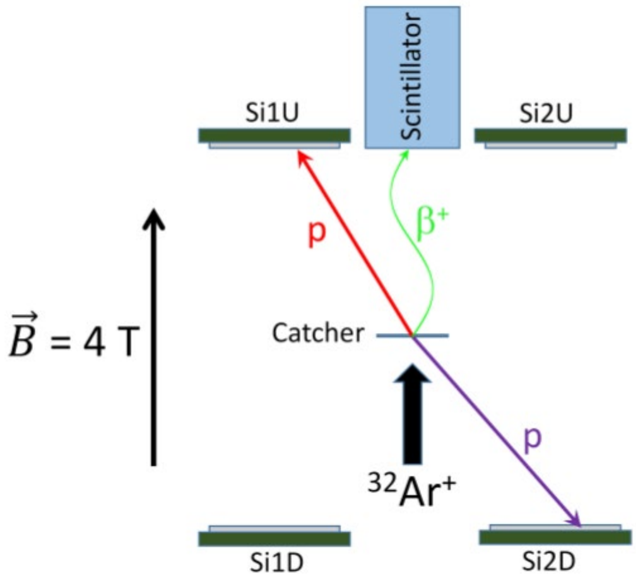
Doppler shape of proton energy depends on $\vec{p}_\beta \cdot \vec{p}_\nu$!

Measure means instead of 2^{nd} moments







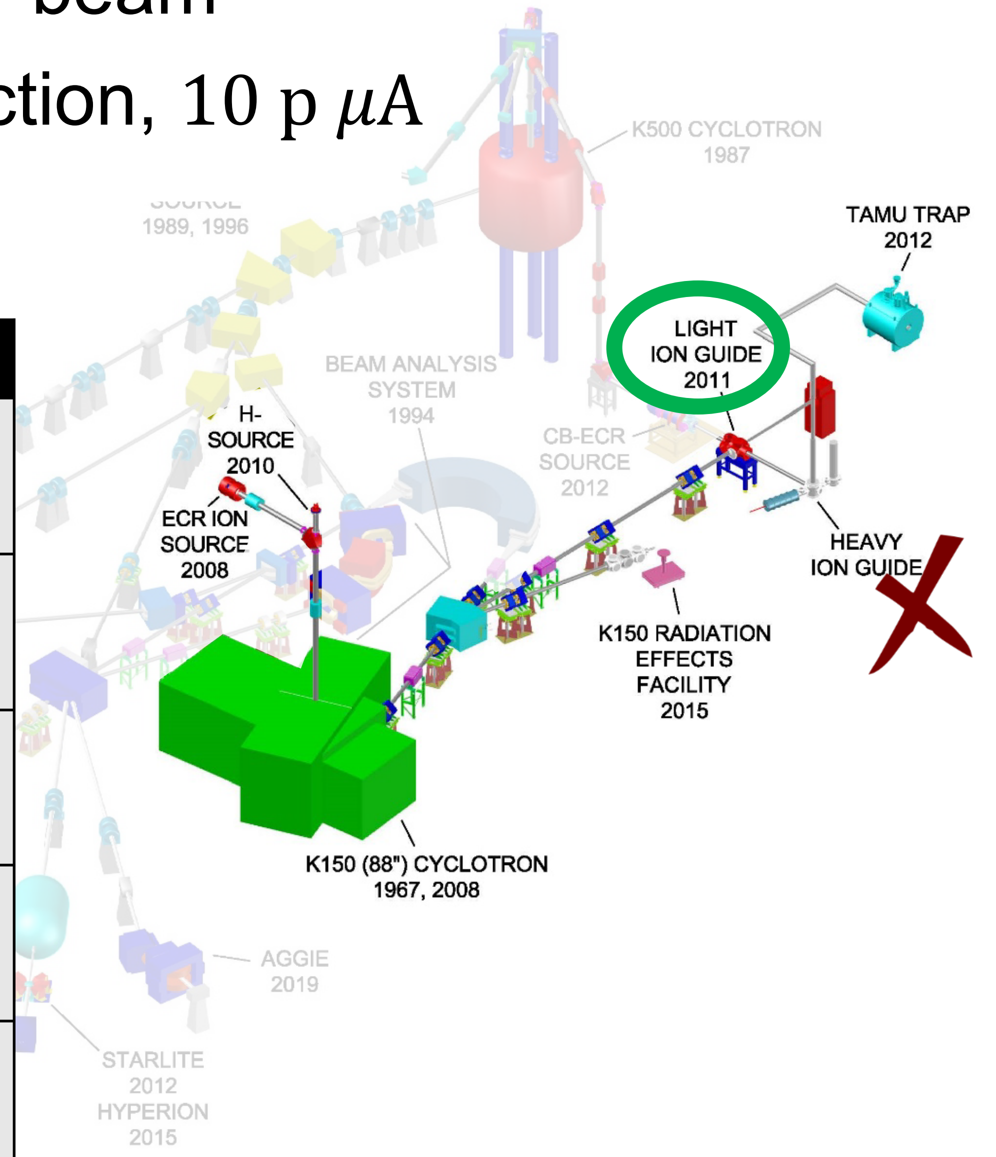


WISArD collab, PRC **101**, 055501 (2020)

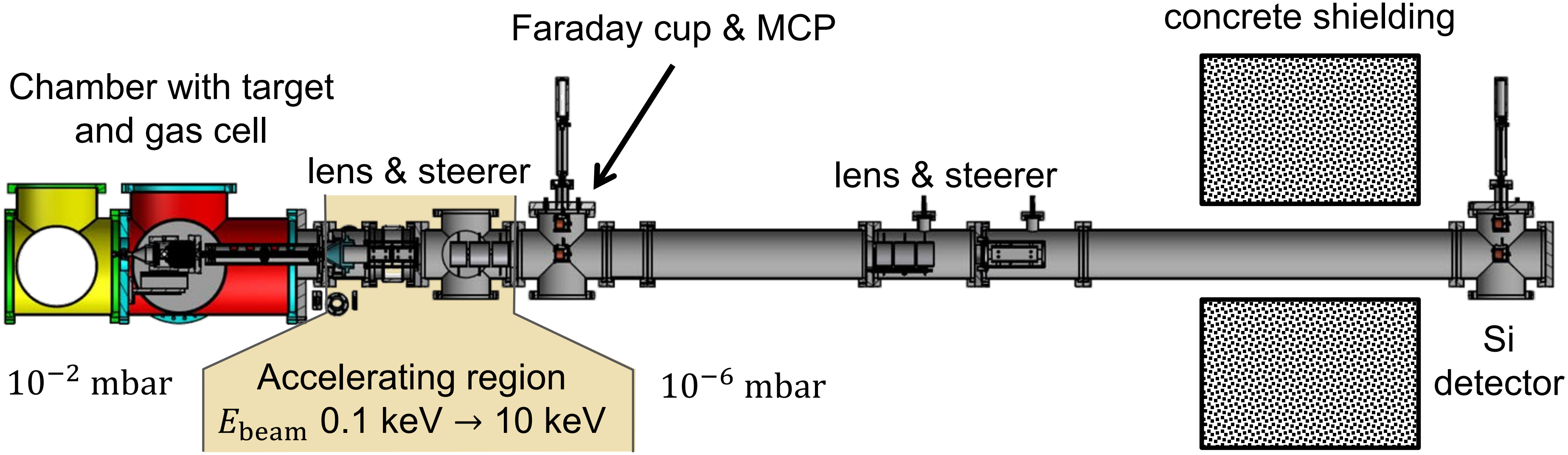
The proton-rich nuclei of interest

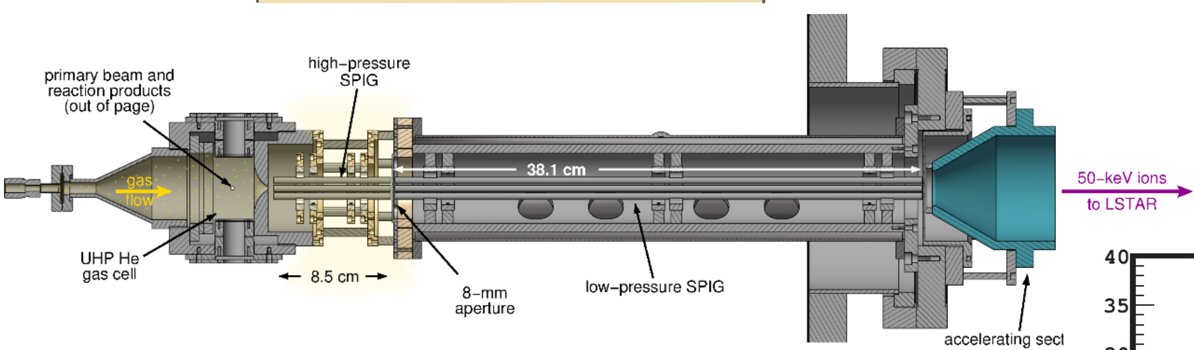
- 10-25 MeV/u ^{3}He primary beam
- Fusion-evapouration reaction, $10\ \mathrm{p}\ \mu A$

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



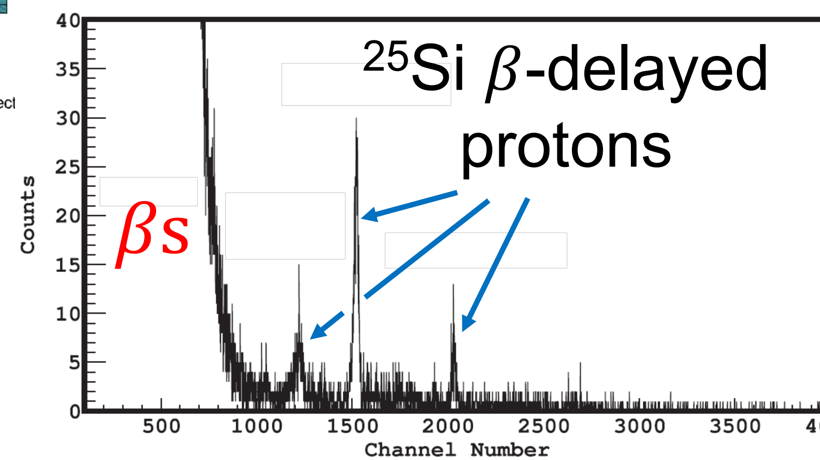
Tested prototype gas cell for ^{3}He LIG





- Efficiency ~0.1%
- Improved design to be commissioned next year

10 MeV/u ^{3}He on $^{24(nat)}$Mg



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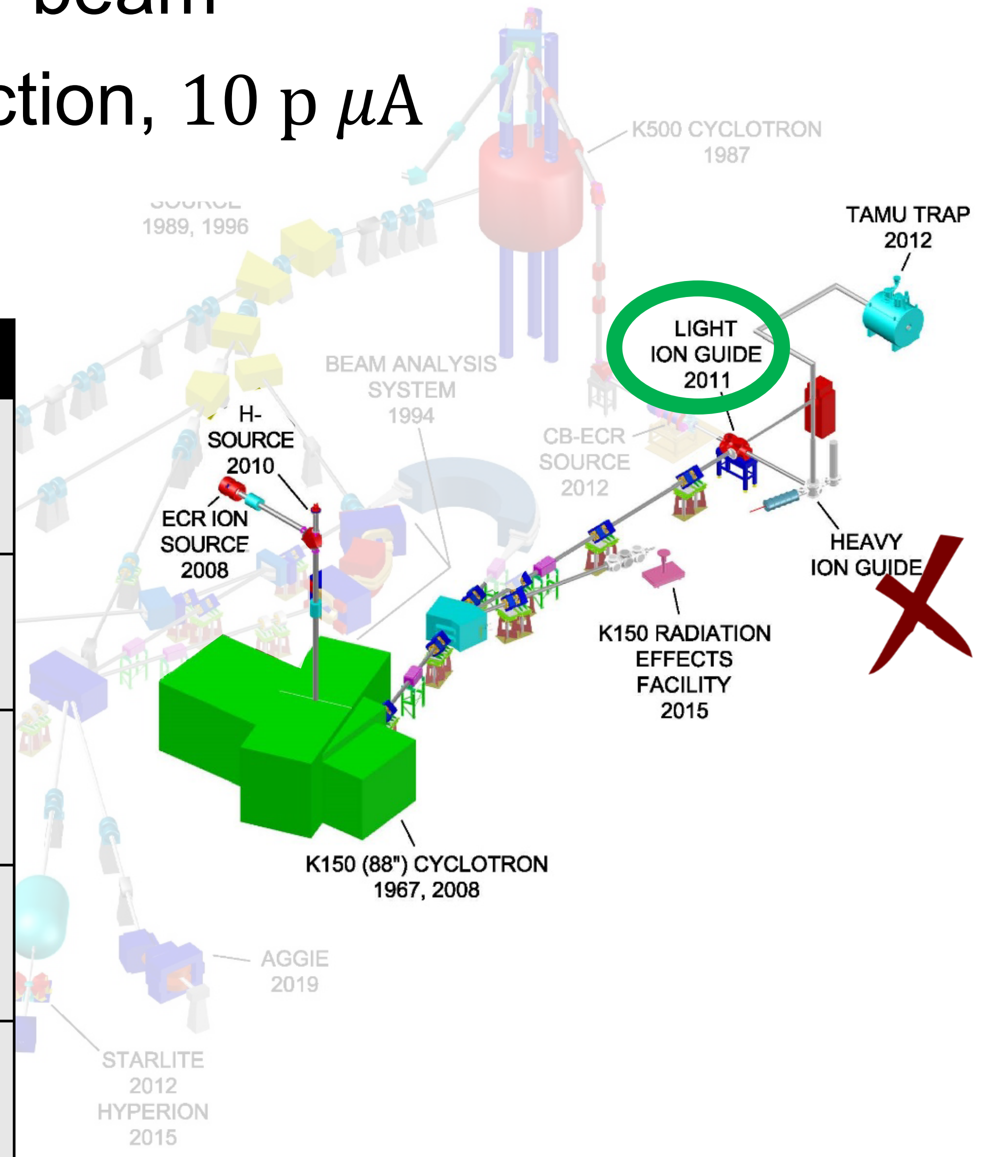
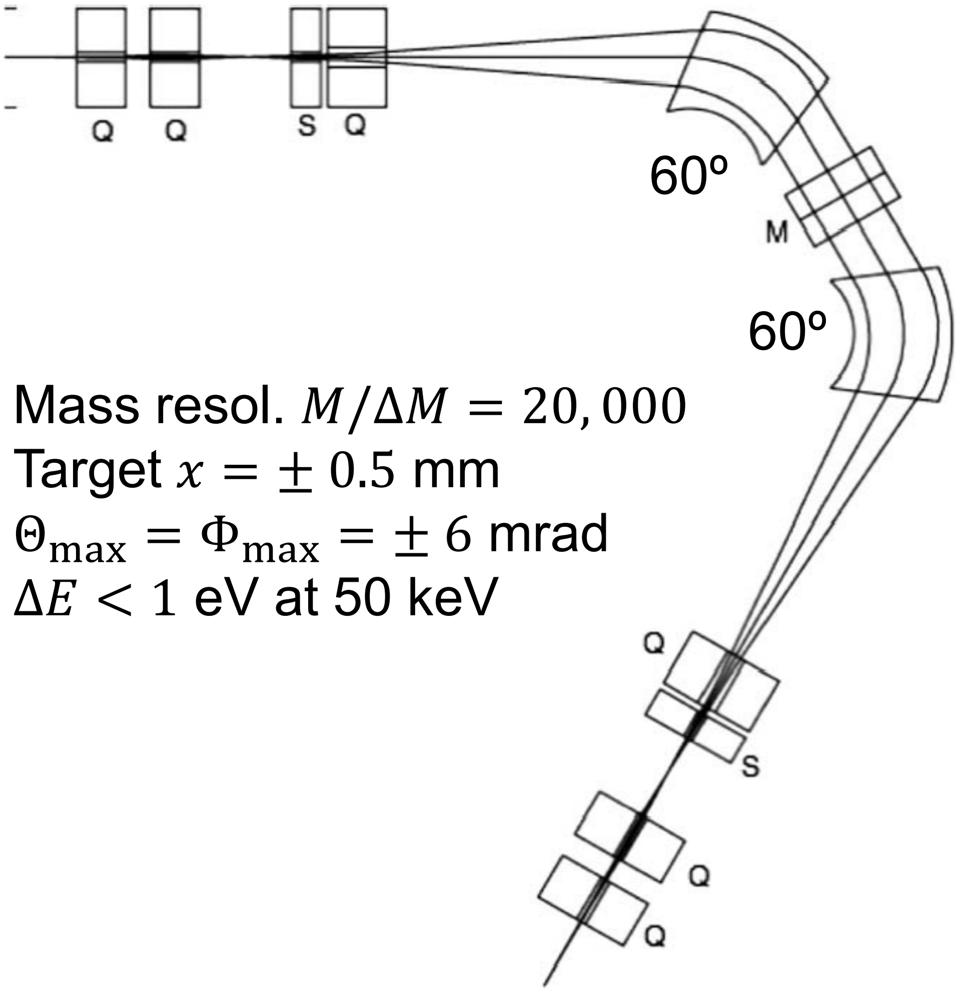
	^{33}Ar	0.9×10^5
^{36}Ar	^{36}Ca	0.2×10^3
	^{37}Ca	0.2×10^5

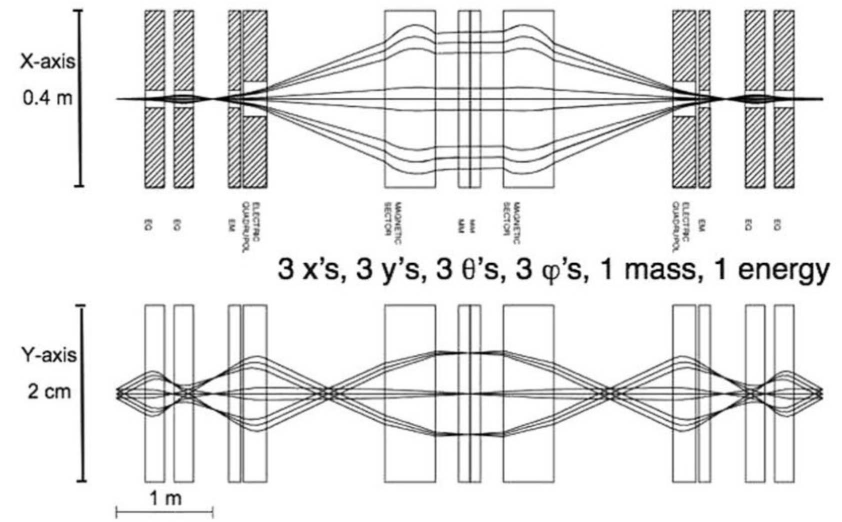


Concept for mass separator: CARIBU (ANL)



- Mass resol. $M/\Delta M = 20,000$
- Target $x = \pm\, 0.5$ mm
- $\Theta_{\text{max}} = \Phi_{\text{max}} = \pm\, 6$ mrad
- $\Delta E < 1$ eV at 50 keV

Fig. 1. Layout of the isobar separator, showing the two 60° bending magnets with $\rho = 0.5$ m, two quadrupole (Q) doublets, two quadrupole singlets, two sextupole (S) singlets and an electrostatic multipole (M).

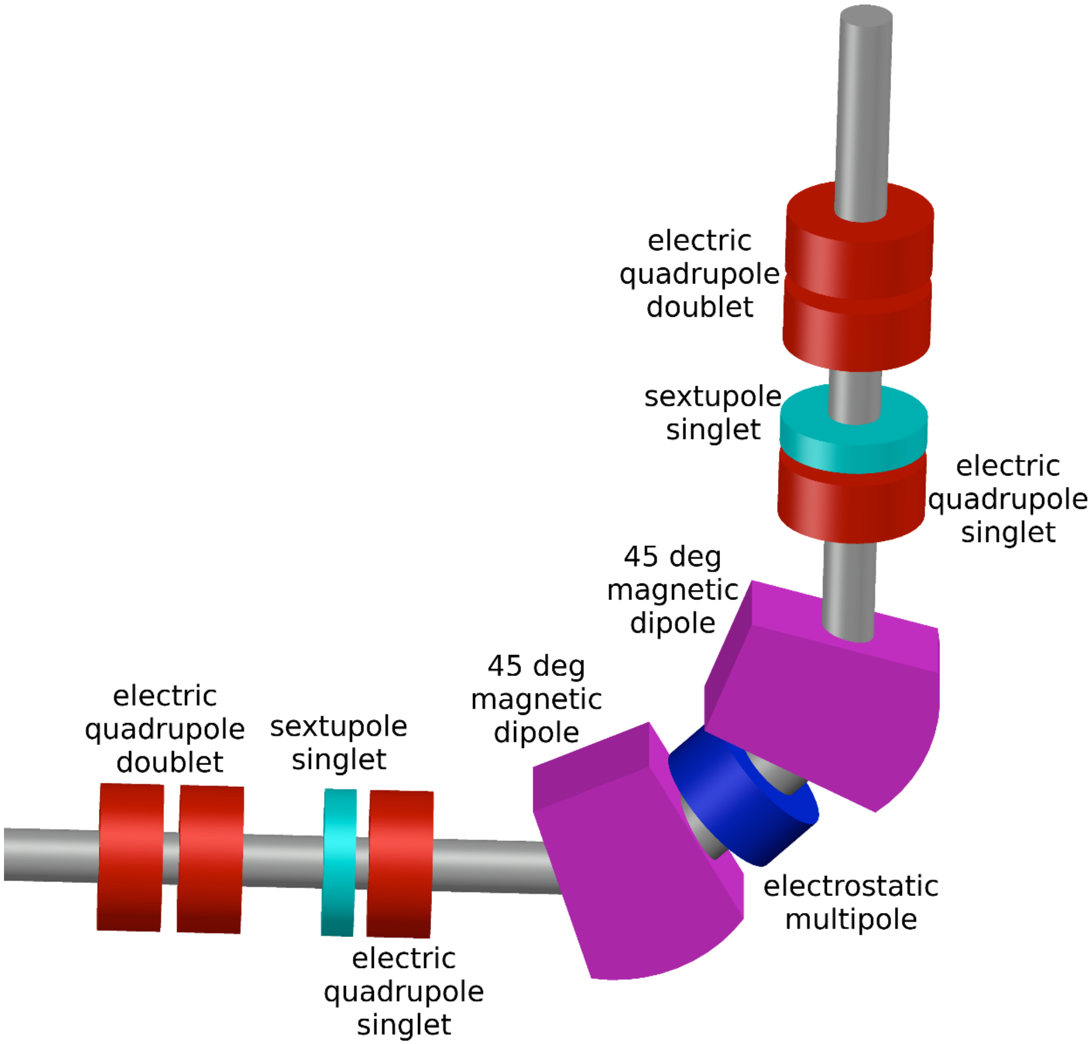


f the isobar separator in the x- (dispersive) and y- (non-dispersive) planes. Note the different scales

Davids and Peterson, NIMB **266**, 4449 (2008)

Our design

- Georg Berg has come up with two designs:
  - $2 \times 45°$ in a vertical direction



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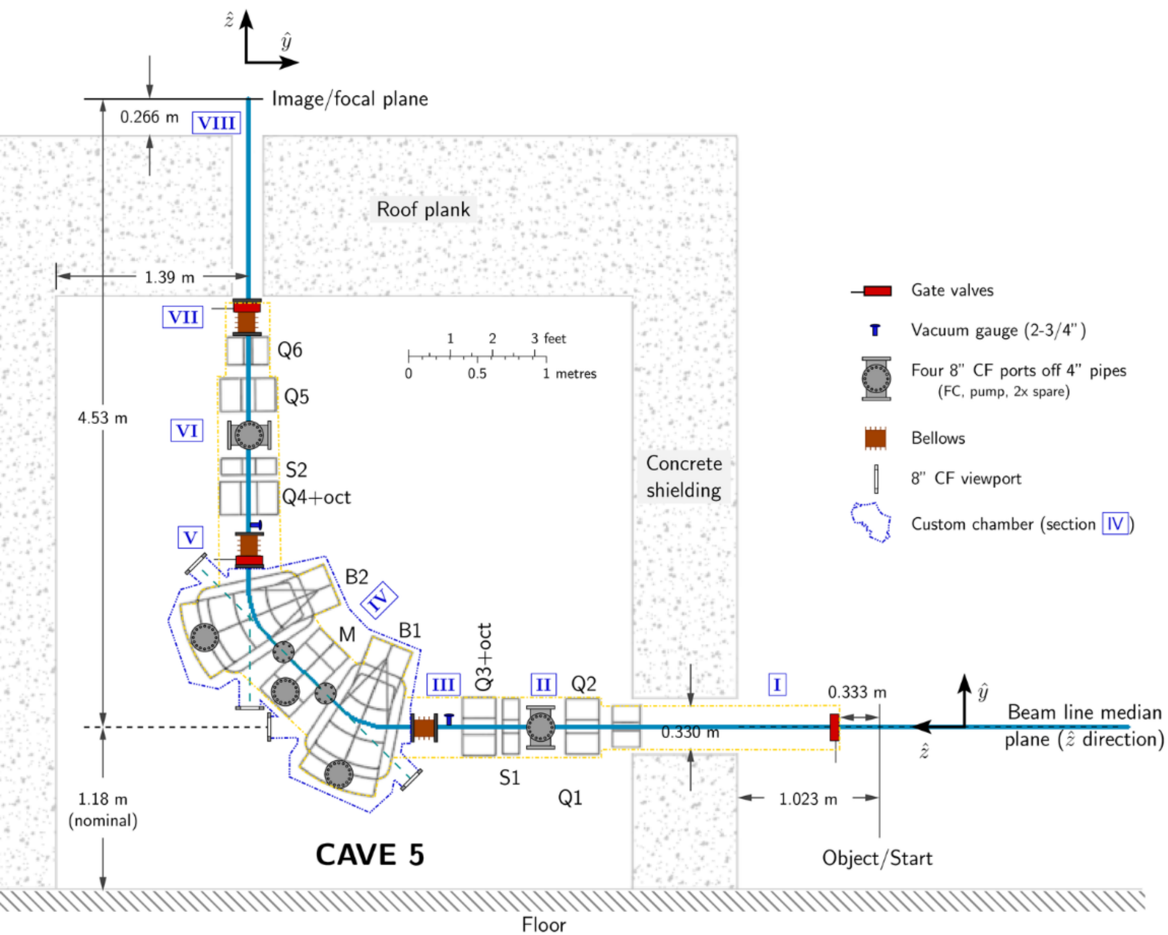
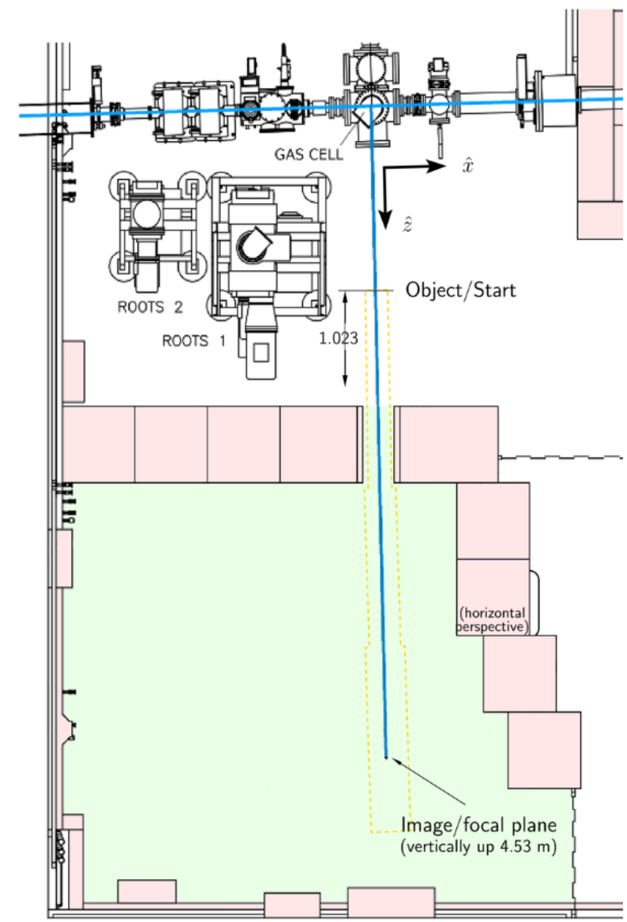
Horizontal View

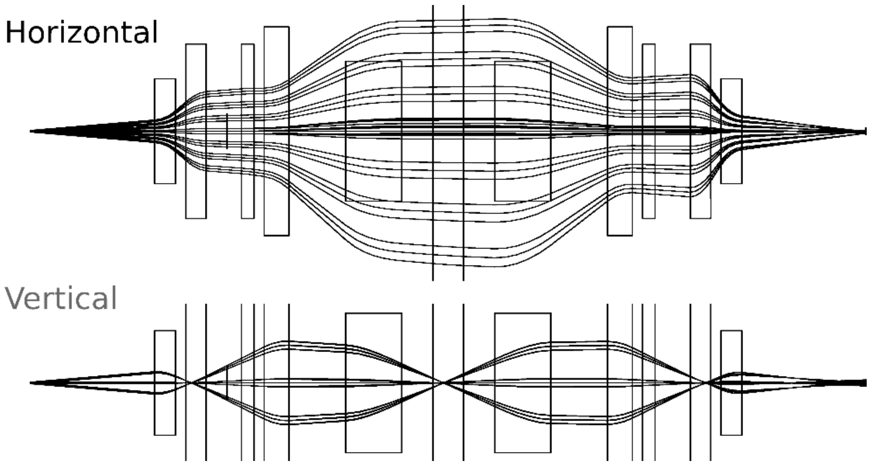


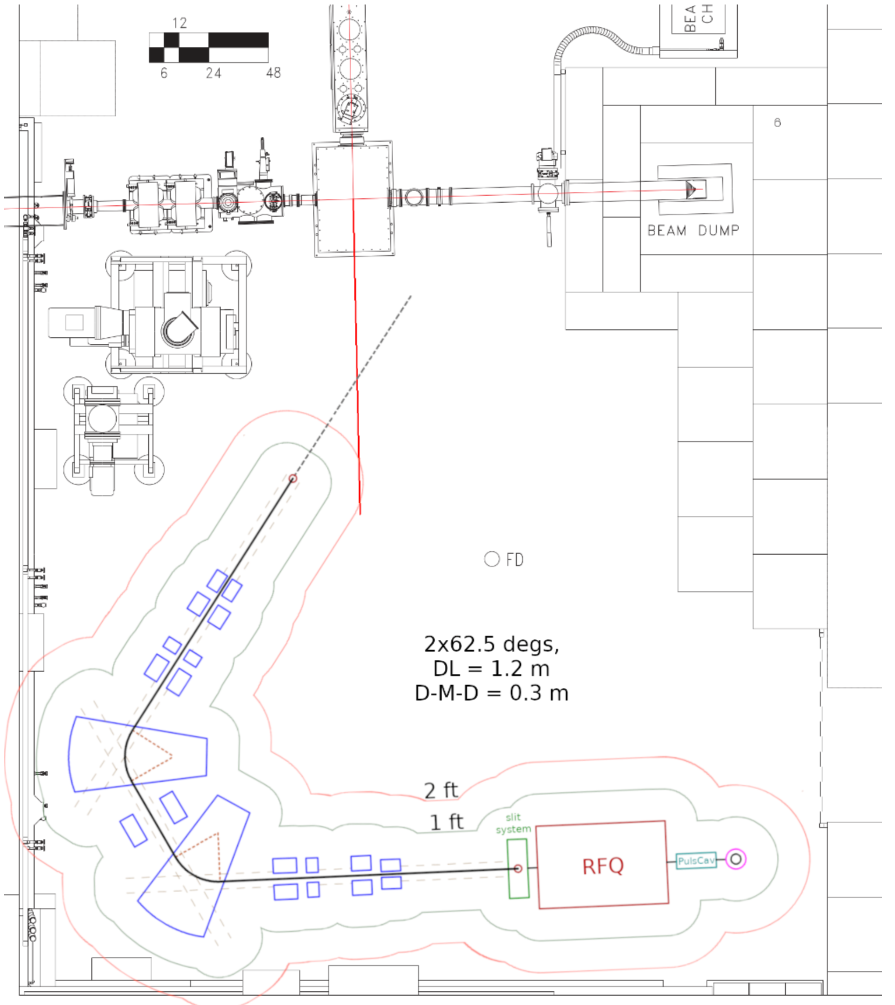
Top View



Our design

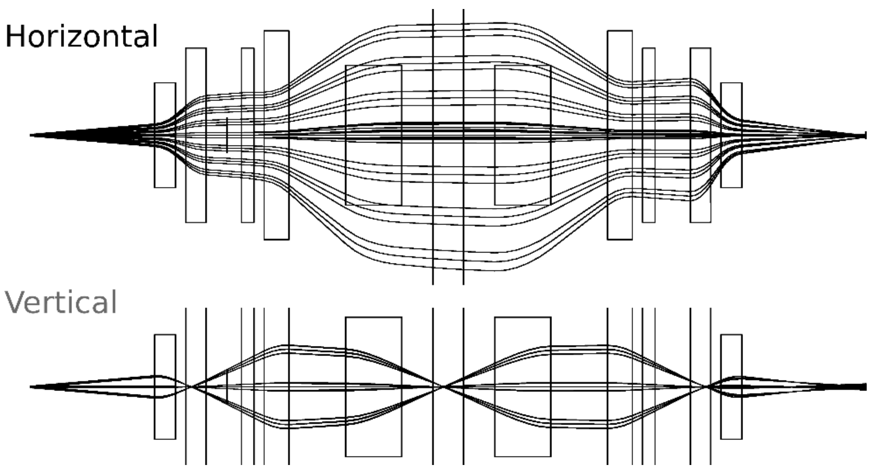
- Georg Berg has come up with two designs:
  - $2 \times 45°$ in a vertical direction
  - $2 \times 62.5°$ in a horizontal plane

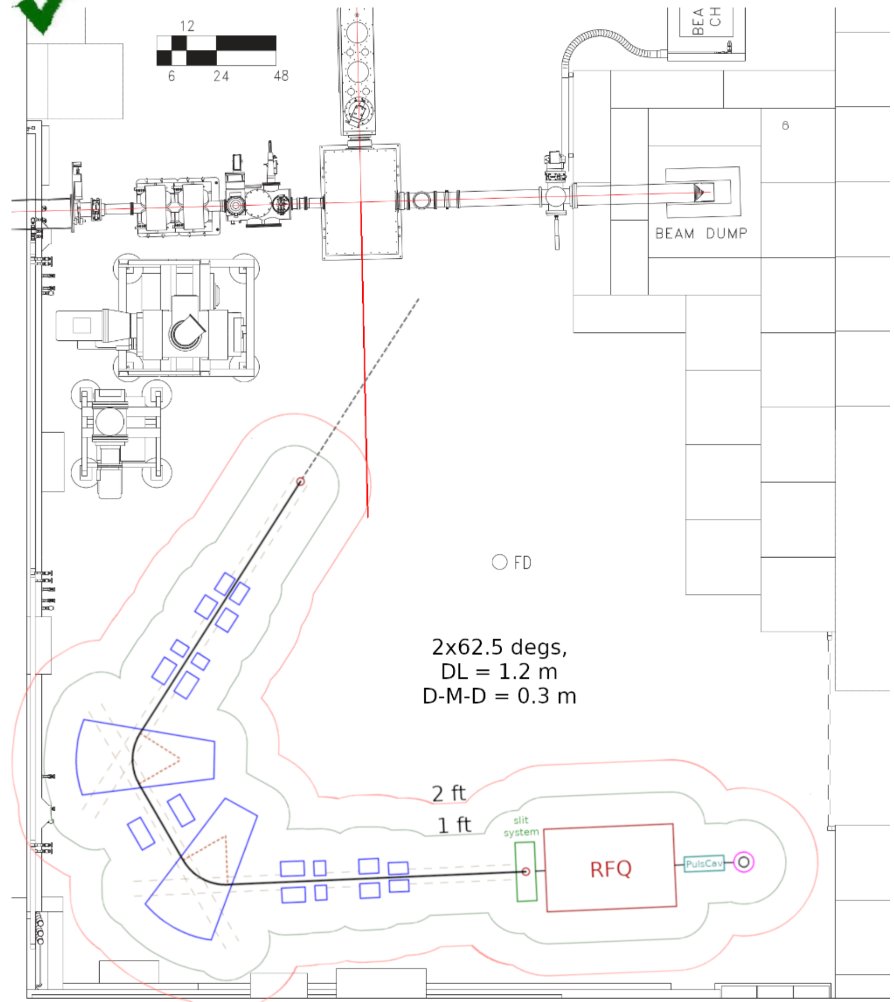




Our design

- Georg Berg has come up with two designs:
  - $2 \times 45°$ in a vertical direction ✗
  - $2 \times 62.5°$ in a horizontal plane ✓

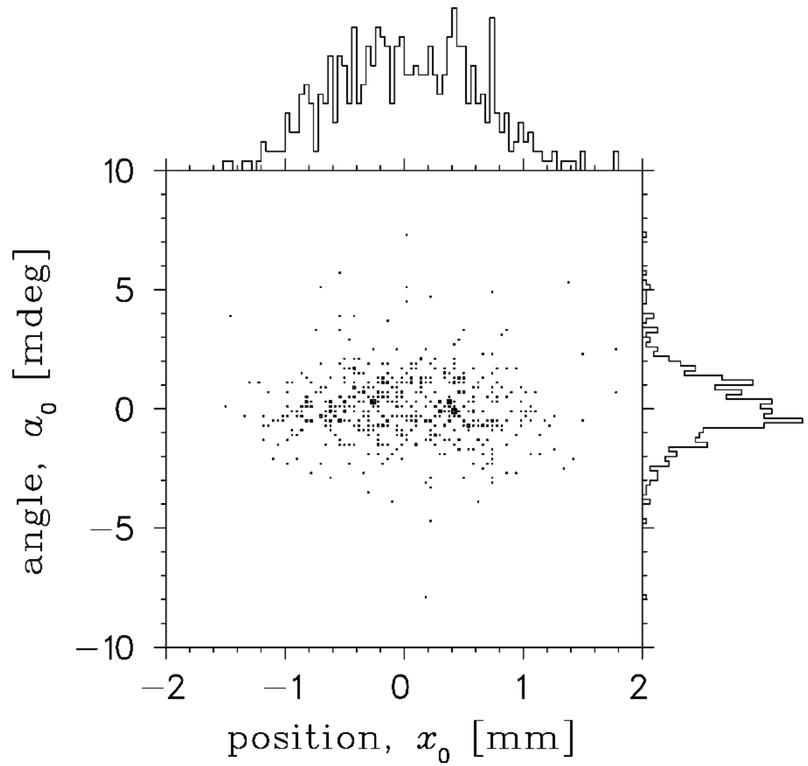




- Calculated mass resolution:
  - For a 1-mm object beam,
    1st order: $M/\Delta M = 13\,000$
    3rd order: 5 850
    7th order: 5 480

Since we know what we want…

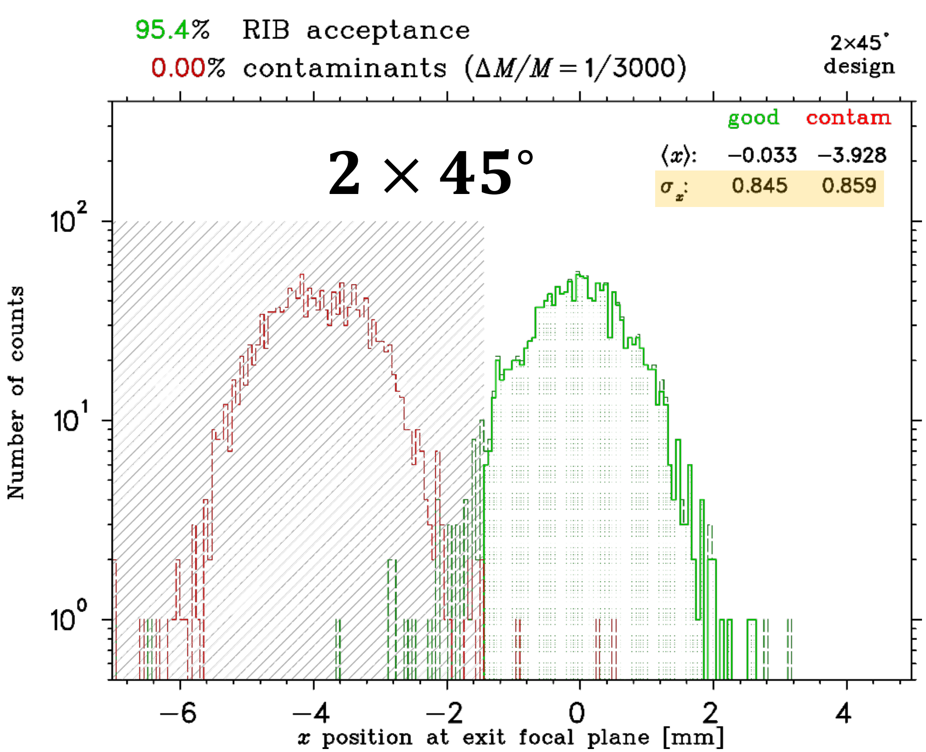
- Simulate ion position and velocities from the He-LIG to the entrance of LSTAR
- With Einzel/steerers, can minimize either the spatial or the angular spreads
- Combined 0.65π mm mrad overall emittance is constant

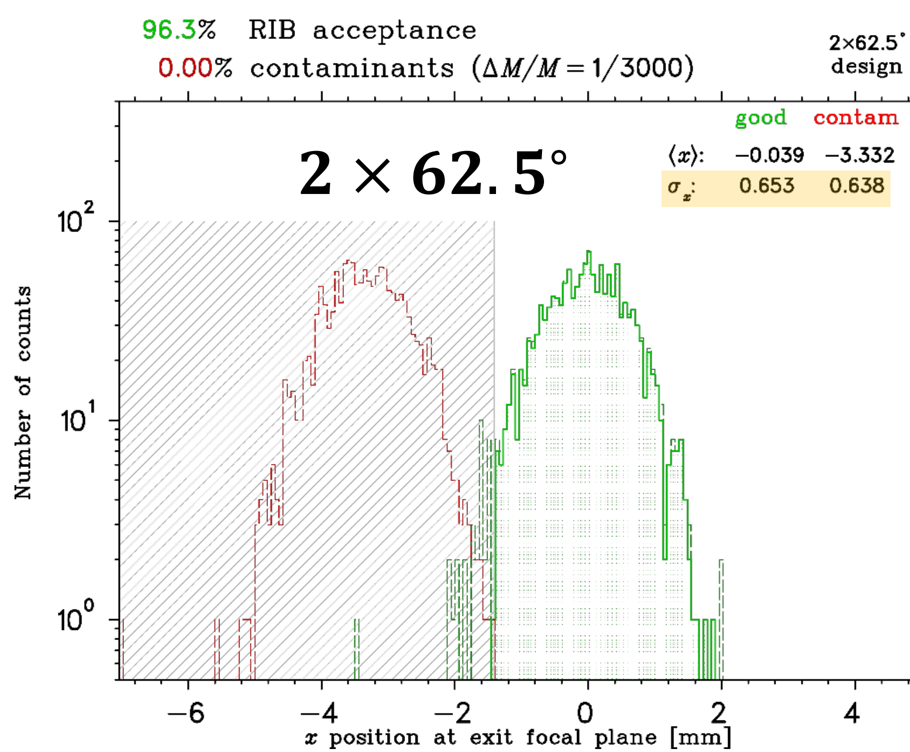


- Use this as input for COSY ray tracing for a realistic estimation of the performance

First, let's compare $2 \times 45°$ with $2 \times 62.5°$

- Green curve: ion of interest (^{36}Ca, 65 keV, $\Delta E = 3.3$ eV)
- Red curve: nearest contaminant (^{36}K, $\Delta M/M = 3\,057$)
- Solid/dashed: accepted/vetoed by separator
- New design has 30% smaller widths

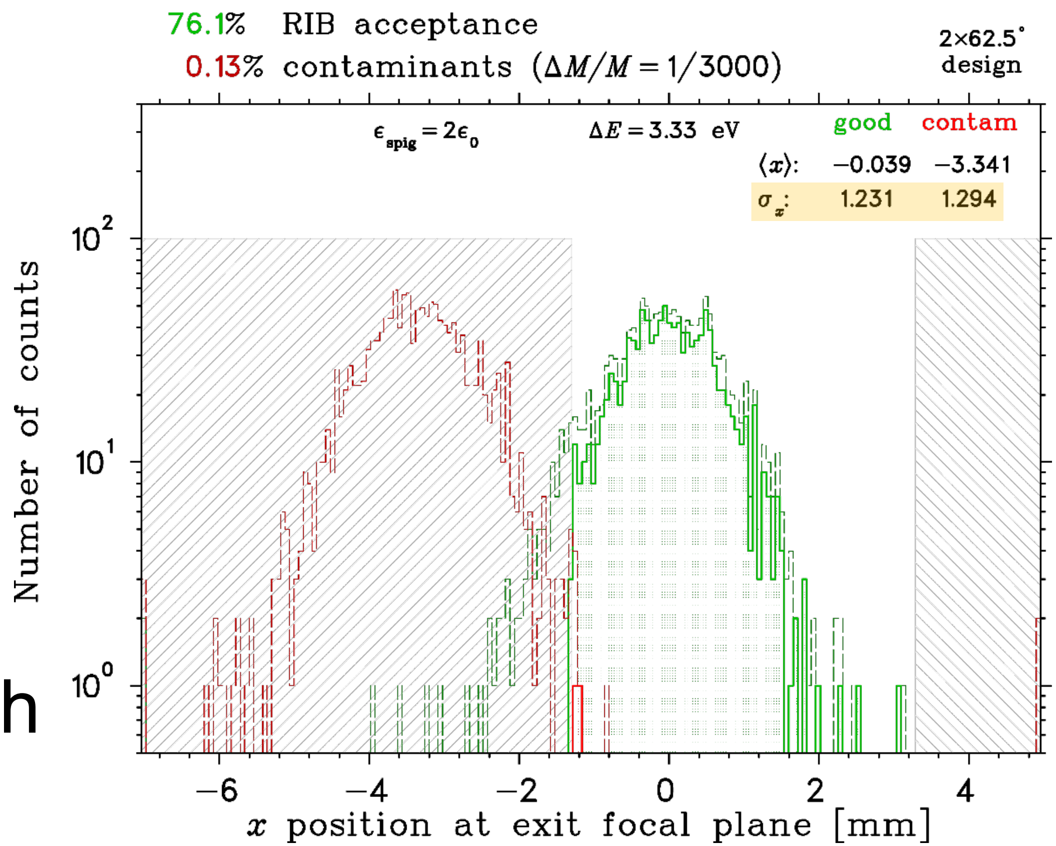




Let's get real…

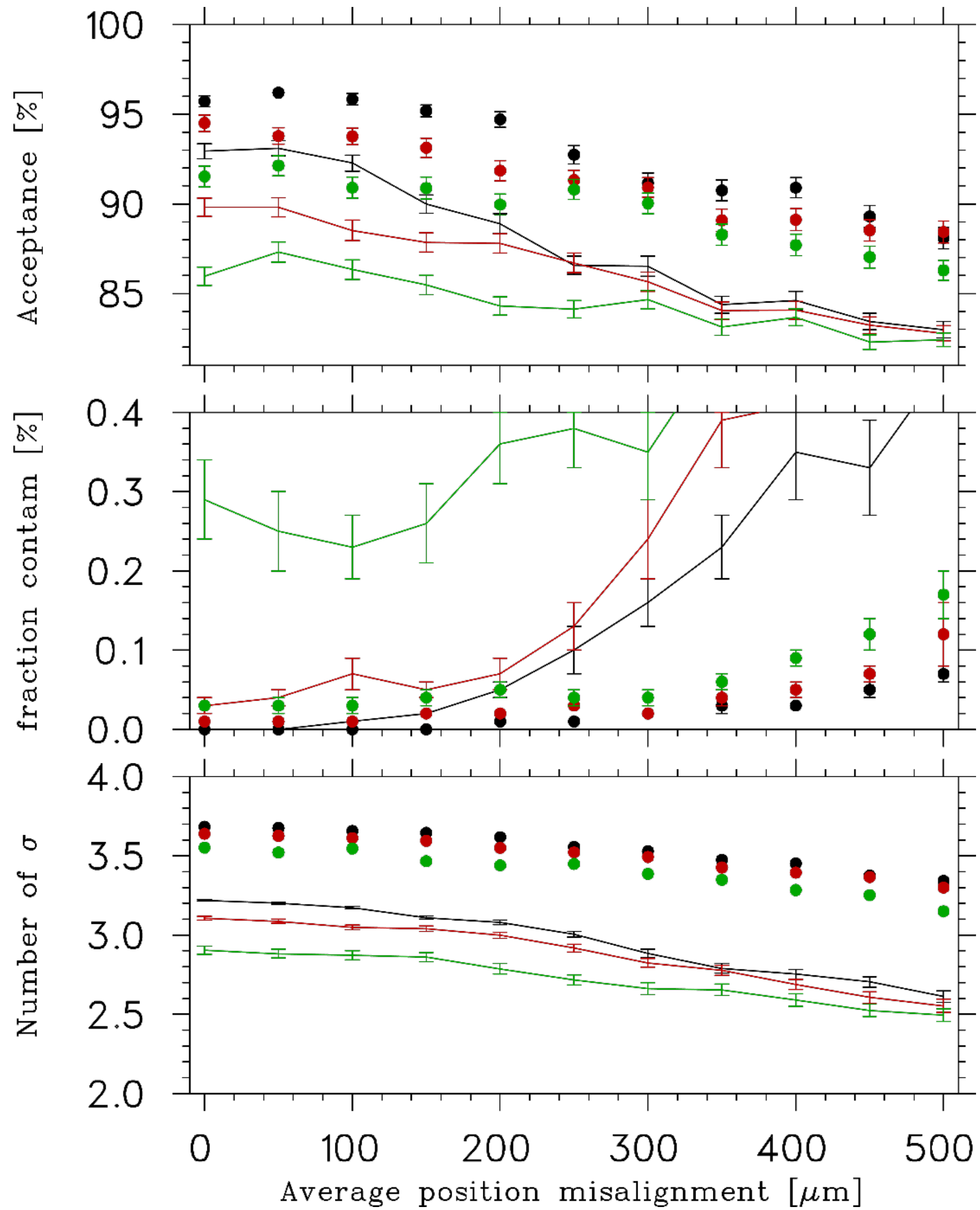
- How well can we trust SIMION?
  - Image of ion positions downstream of TAMUTRAP's RFQ was almost 2 × larger than predicted
- If we increase emittance by 2 ×, widths increase by the same factor
- Though we'd take a hit in efficiency, we can still remove nearby contaminants

(molecules produced in the He-LIG might be much closer in mass…)



Position/angular misalignments?

- Randomly move elements according to a Gaussian distr'n of width 0, 50, 100, …, 500 μm, and tilts of 0 (black), 10 (red) and 20 mdegs (green)
- $2 \times 45^{\circ}$ design (lines) is *much* more susceptible to misalignments than $2 \times 62.5^{\circ}$ (esp rotations)
- Should have >90% acceptance with ± 0.25 mm and ± 15 mdeg tolerances



Looking forward

- Working in concert with the *p*-LIG group to utilize the K150 cyclotron for RIB production
- ^{3}He-LIG system should be commissioned next year
- It will probably take ~3 years to commission LSTAR
  - Supply-chain issues? Cost increase?
- Once commissioned for TAMUTRAP, the Cyclotron Institute will also have a new beamline providing cooled and bunched proton-rich RIBs at low energy
  - Decay spectroscopy
  - p decays for astrophysics? In TAMUTRAP?
- Looking only a little farther, it wouldn't be hard to charge-breed the ions and inject them in the K500 for reaccelerated RIBs (complementing the *p*-LIG effort)

Final thoughts, collaborators and thanks

- TAMUTRAP: commissioned with offline sources, just need radioactive ions…
- ^{3}He-LIG: Initial tests were promising; commission new system early next year, measure emittance
- LSTAR: Design is finalized, specification document being written; bid request will be out before Christmas

TEXAS A&M UNIVERSITY

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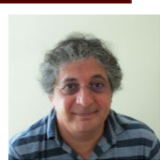
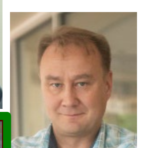
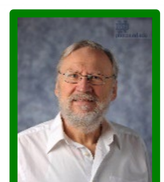
V. Kolhinen
D. Melconian
P.D. Shidling
Gabriel Tabacaru
Operations group

UNIVERSITY OF NOTRE DAME

G. Berg
M. Brodeur
M. Couder



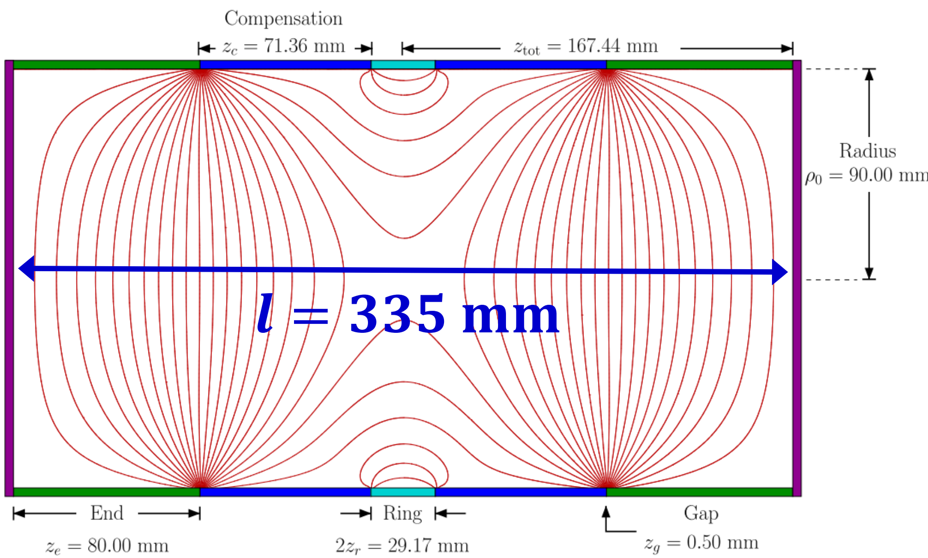

Funded by

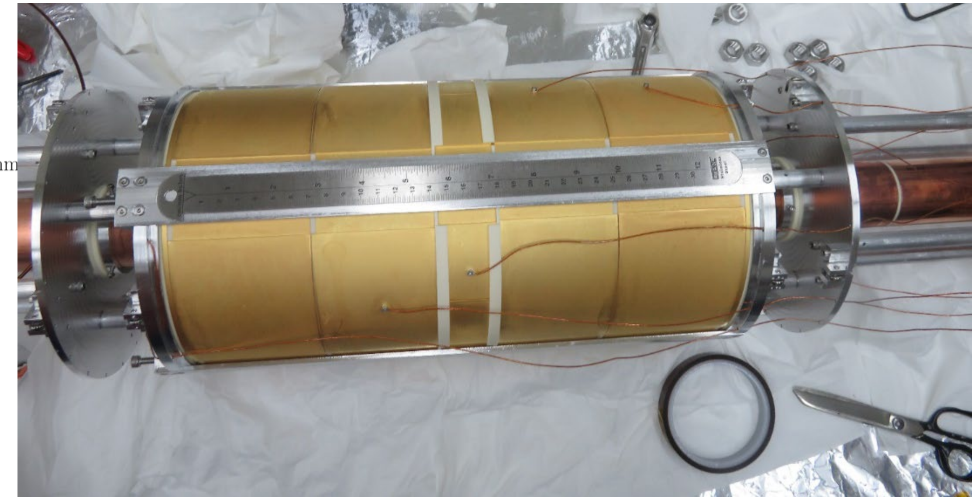
U.S. DEPARTMENT OF ENERGY | Office of Science

The State of Texas

World's largest Penning trap commissioned

- Most cylindrical Penning traps have a length-to-radius ratio of $l/r = 11.75$
- To confine the protons from $T = 2$ decays, need $r = 90\text{ mm}$
  - Needed a new design to make it fit in the 7T magnet





$l/r = 3.72$

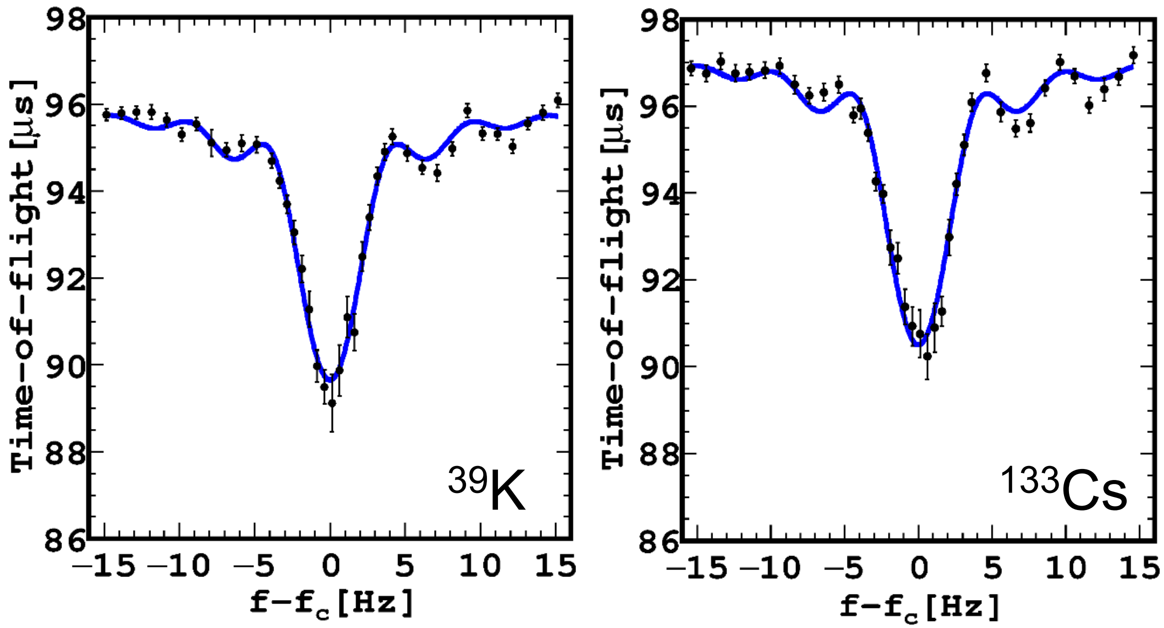
M.Mehlman *et al.*, NIMA **712**, 9 (2013)
P.Shidling *et al.*, Hyperfine Interact **240**, 40 (2019)

Mass measurement of stable ions

- Find resonant frequencies for ^{23}Na, ^{85,87}Rb, ^{133}Cs & ^{39}K
- Use AME value for ^{39}K, and calculate other masses
- Good agreement with AME values (within uncertainties)

- Precision
  - ^{23}Na: 240 ppb
  - ^{85}Rb: 5 ppb
  - ^{87}Rb: 6 ppb
  - ^{133}Cs: 7 ppb

200 ms excitation time



P.Shidling *et al.*, Int J Mass Spectr **468** (2021) 116636

Why did we change our design?

- As we were generating the specification document, we found a very significant discrepancy b/n AutoCAD and reality….