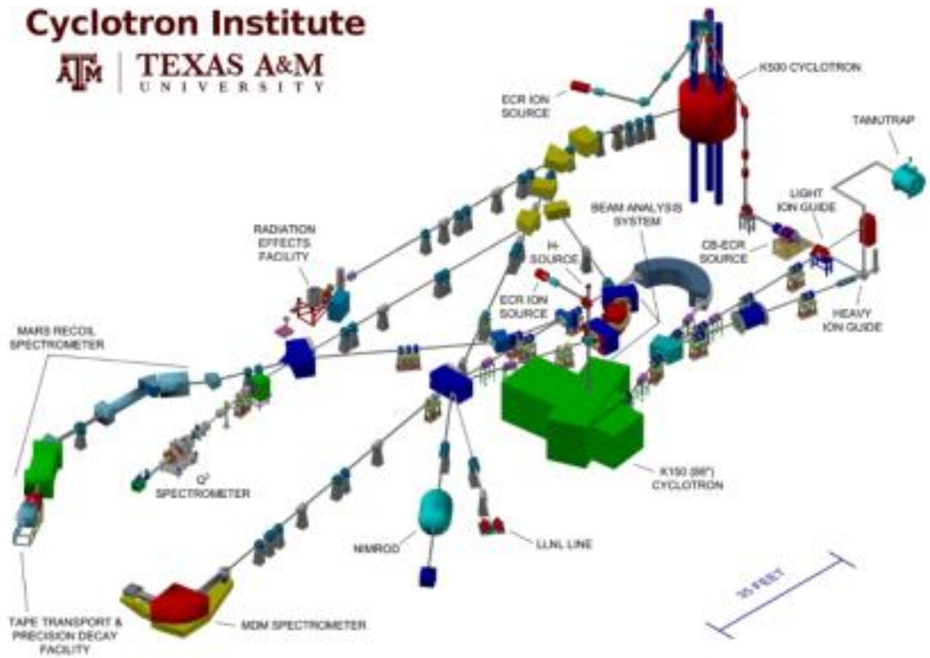
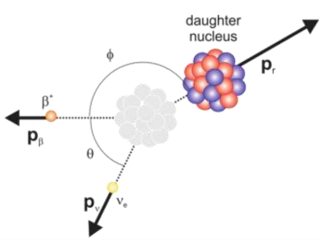
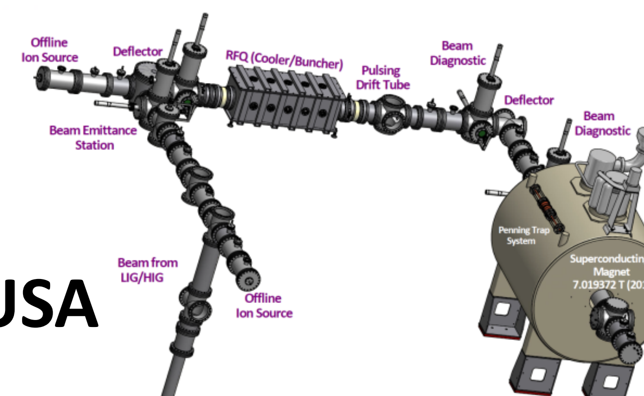
TAMUTRAP facility:
Penning trap facility for weak interaction studies





P.D. Shidling
Cyclotron Institute,
Texas A&M University, USA



TCP 2018

Outline

- Scientific Motivation
  - Low energy test of Standard Model.
  - Superallowed transition (T = 2).
- Production of T =2 proton rich nuclei
  - Heavy Ion Guide/Light Ion Guide
  - Current Status
- TAMUTRAP Facility
  - Facility overview
  - Current Status

Standard Model

- **3 Fundamental forces**
  Electromagnetic, Weak, Strong
- **12 Fundamental Fermions**
  Quarks (u, d, c, s, t, b)
  Leptons $(e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau)$
- **Force carriers (Gauge Bosons)**
  (g, γ, Z, W)
- **Scalar Bosons (Higgs)**
  $(H, \dots)$

Standard Model

- 3 Fundamental forces
  Electromagnetic, Weak, Strong
- 12 Fundamental Fermions
  Quarks (u, d, c, s, t, b)
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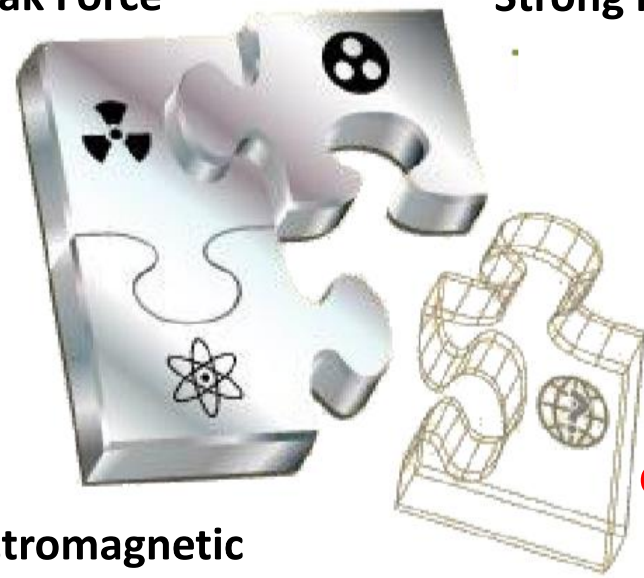
- Force carriers (Gauge Bosons)
  (g, γ, Z, W)
- Scalar Bosons (Higgs)
  $(H, \ldots)$



Standard Model
may require extension ⇒

- Why three families of Fermions
- Origin of parity violation
- Baryon asymmetry
- ....

How do we test the standard model

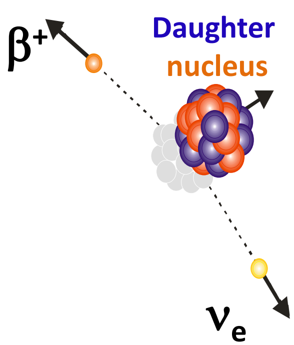
Nuclear β-decay = Governed by Weak force

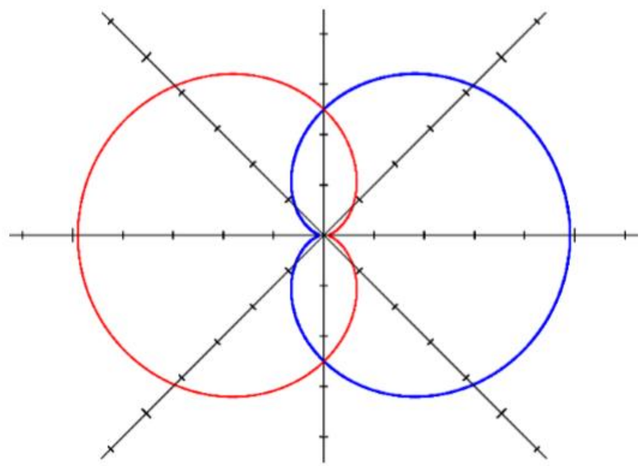
$$W(E_e,\Omega_e,\Omega_\nu) \propto \frac{F(\pm Z,E_e)}{(2\pi)^5} p_e E_e (A_o - E_e)^2 dE_e d\Omega_e d\Omega_\nu \xi \left(\mathbf{1} + \boldsymbol{a_{\beta\nu}} \frac{\boldsymbol{p_e}\cdot\boldsymbol{p_\nu}}{E_e E_\nu} + \boldsymbol{b}\frac{m_e}{E_e} + \dots\right)$$

Pure Fermi Transition:

Beyond Standard Model

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

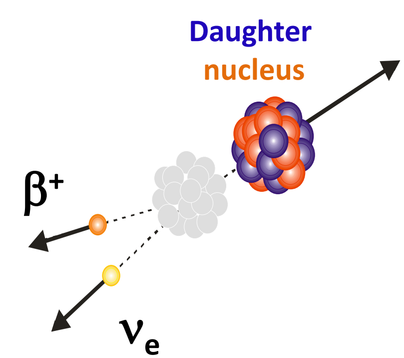




$$a_{\beta\nu} \overset{?}{=} 1$$

Standard Model

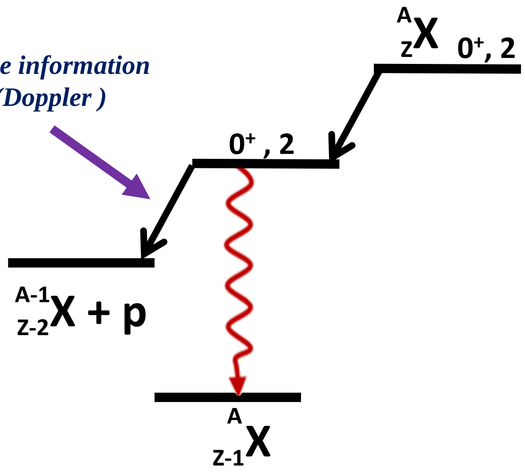
$$a_{\beta\nu} = \frac{|C_V|^2 + |C_V'|^2}{|C_V|^2 + |C_V'|^2}$$

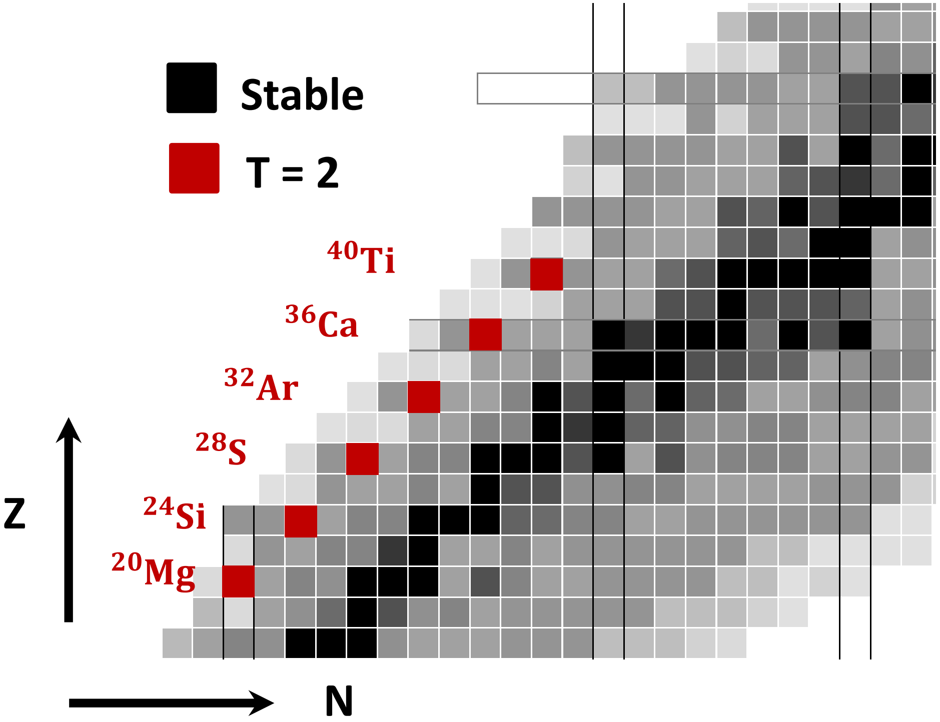


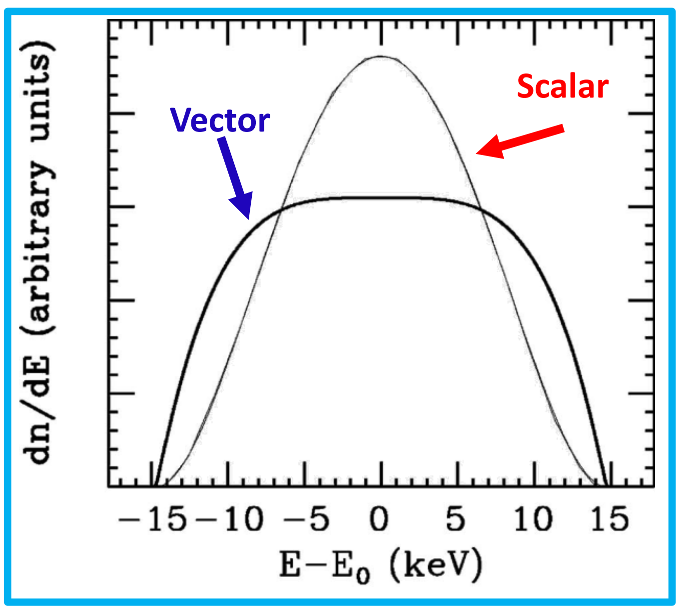
Superallowed Transition

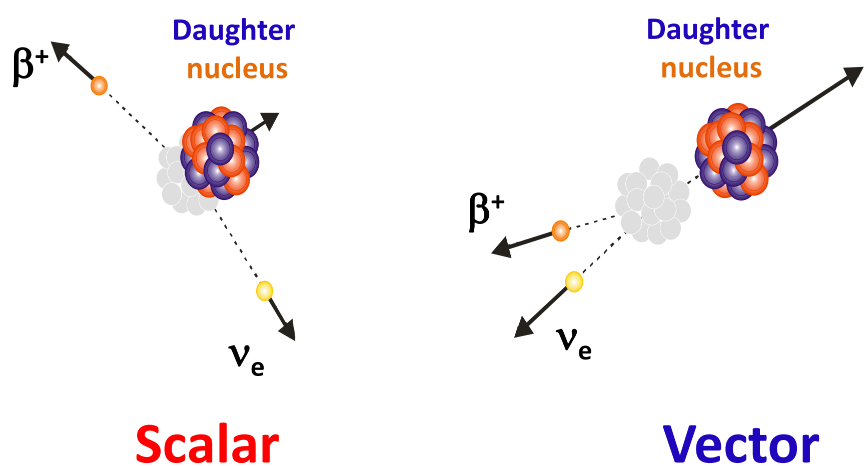
Beta delayed proton decay

Proton contain the information about ^{32}Cl recoil (Doppler)



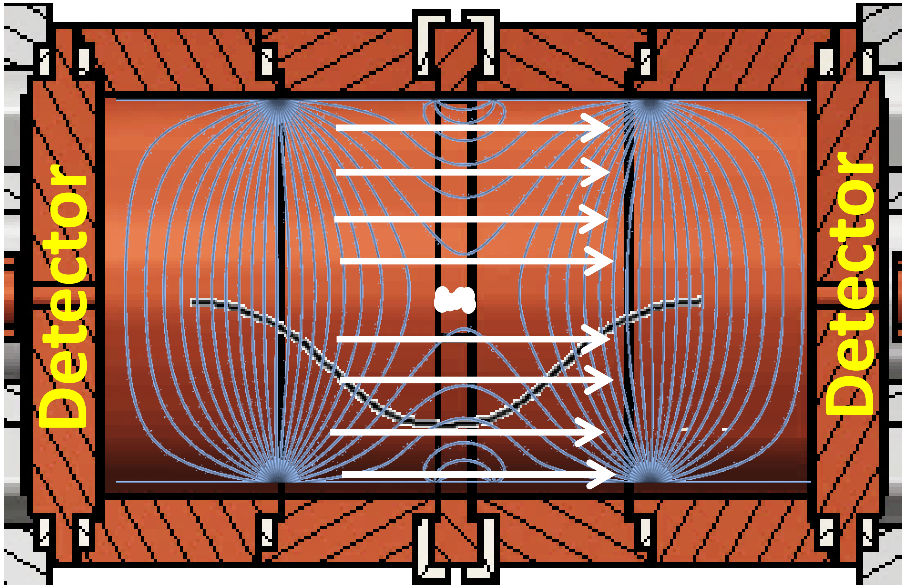






Adelberger E.G. et al. Phys. Rev. Lett. 1299 ***83*** *(1999)*

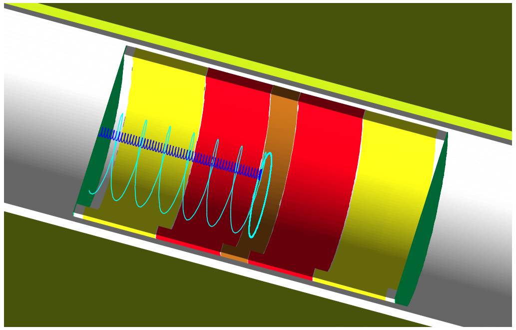
Penning trap for
$\beta - \nu$ correlation parameter

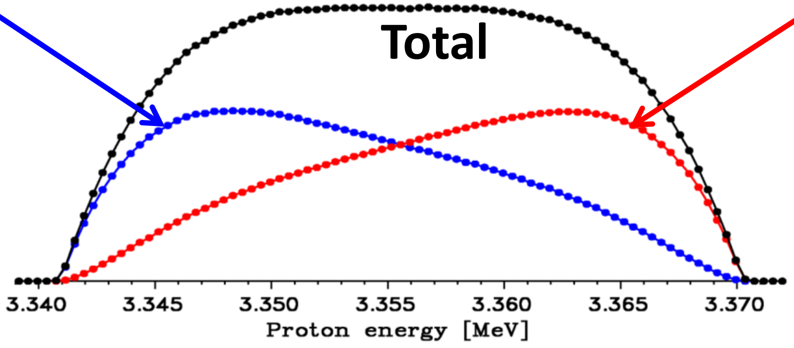


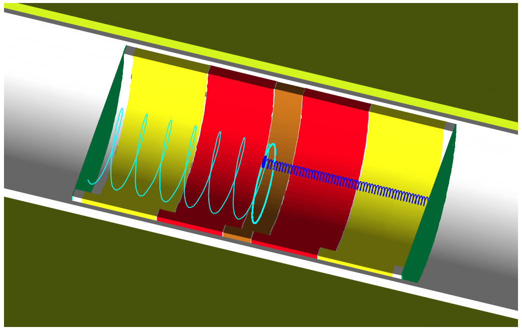
- Increase solid angle.
- Increase sensitivity.
- Allows to detect e along with p

Beta & Proton in same hemisphere

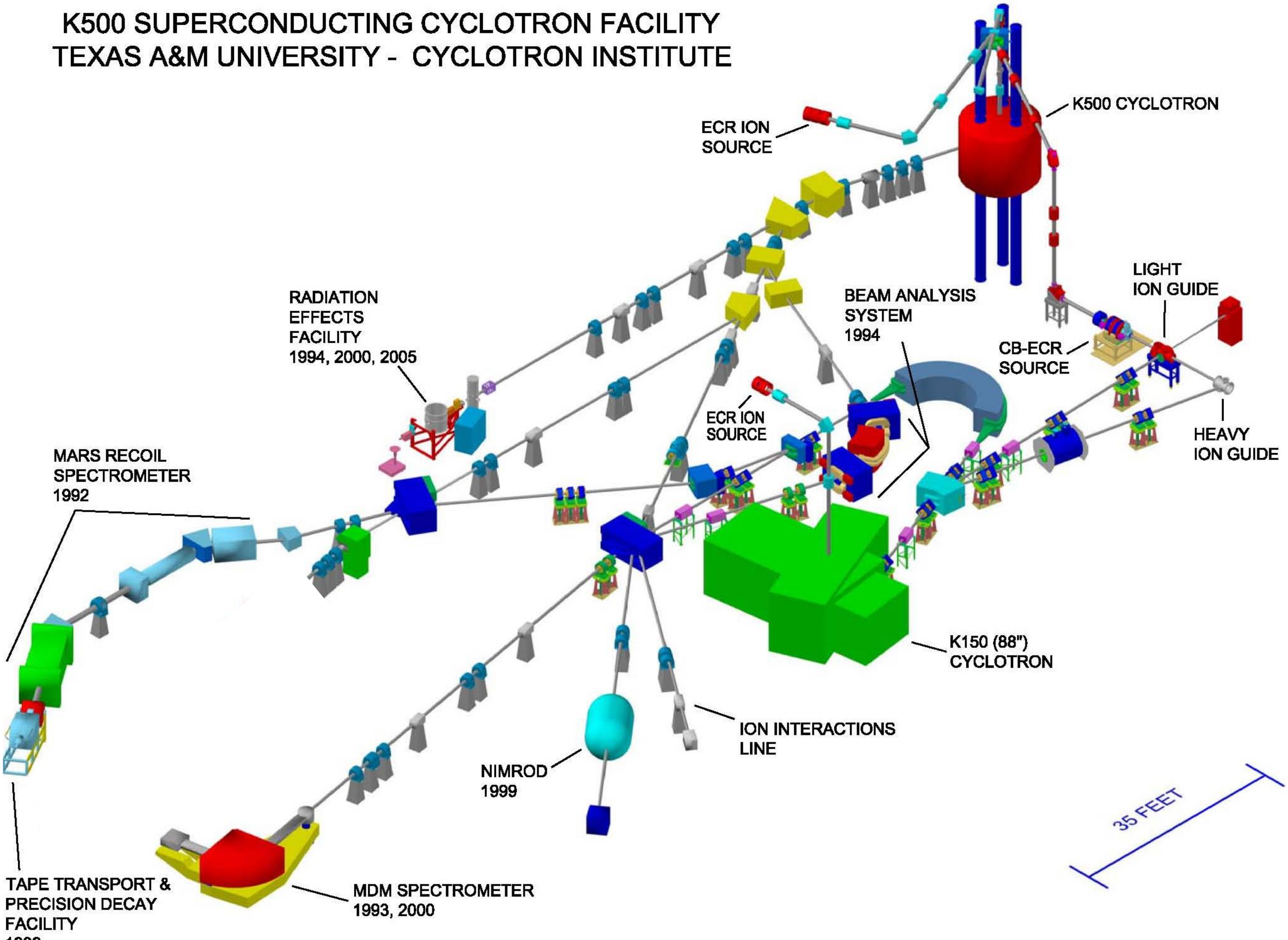
Beta & Proton in different hemisphere







K500 SUPERCONDUCTING CYCLOTRON FACILITY
TEXAS A&M UNIVERSITY - CYCLOTRON INSTITUTE



K500 SUPERCONDUCTING CYCLOTRON FACILITY
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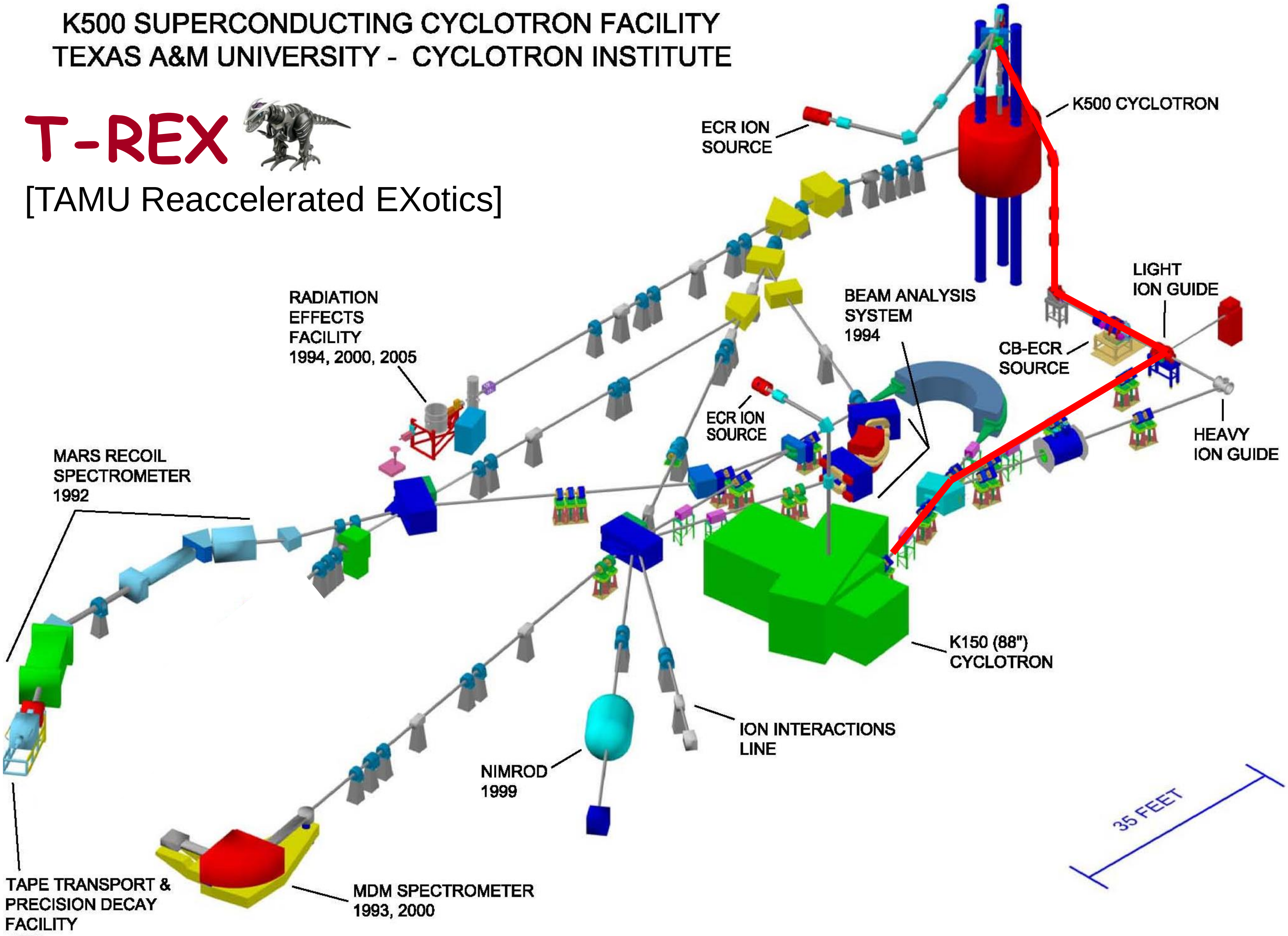
T-REX

[TAMU Reaccelerated EXotics]



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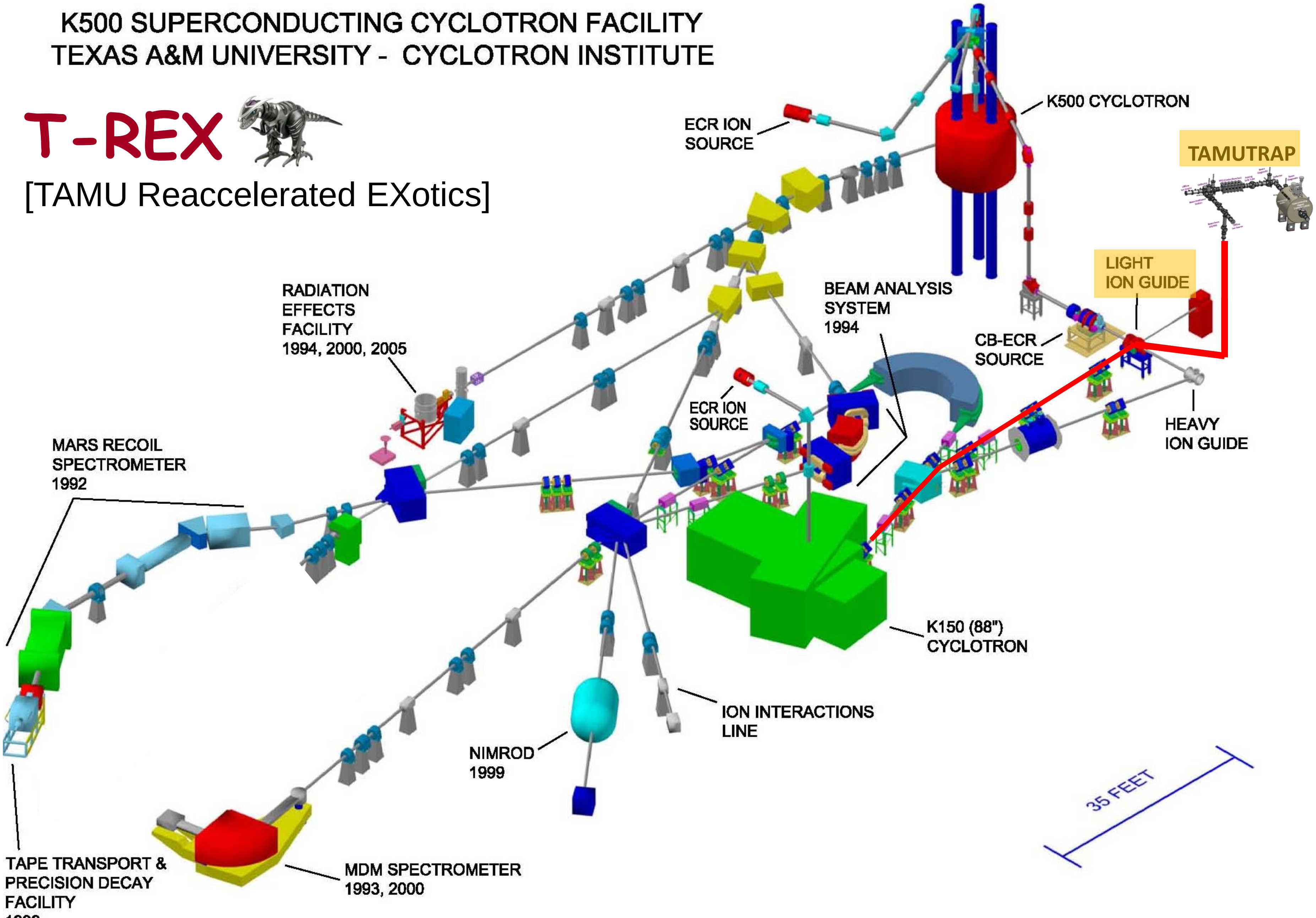
T-REX

[TAMU Reaccelerated EXotics]



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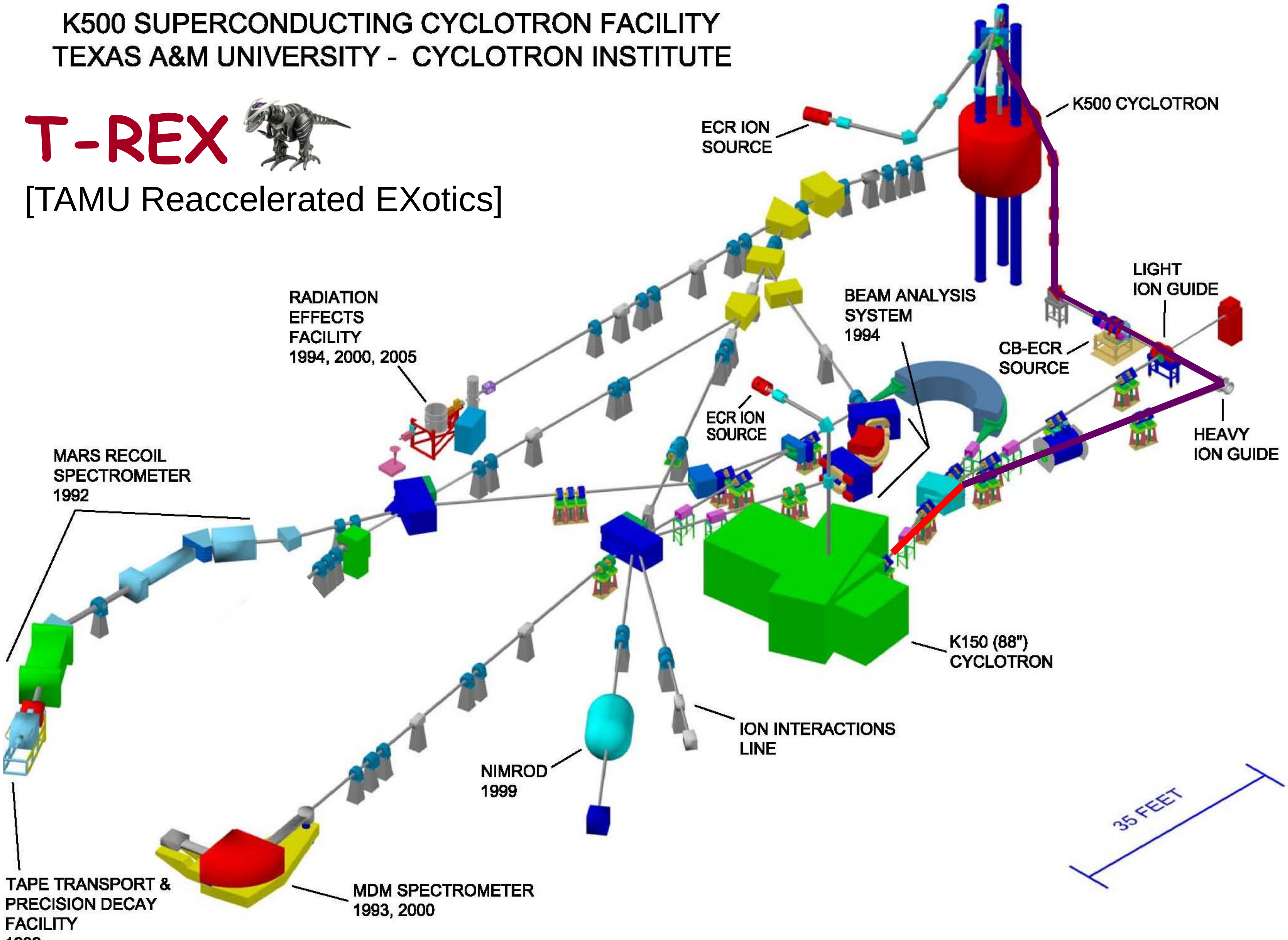

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T-REX

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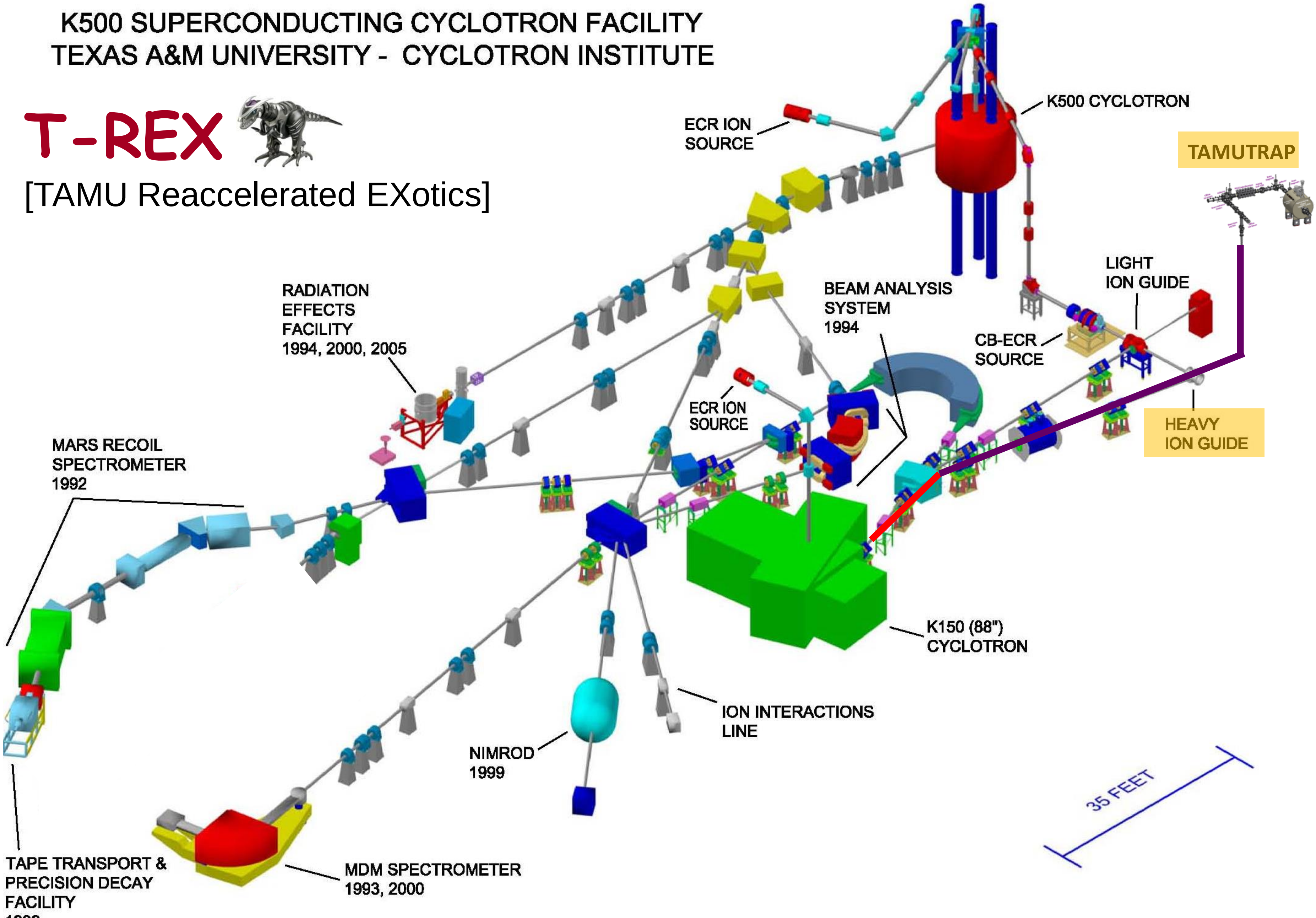
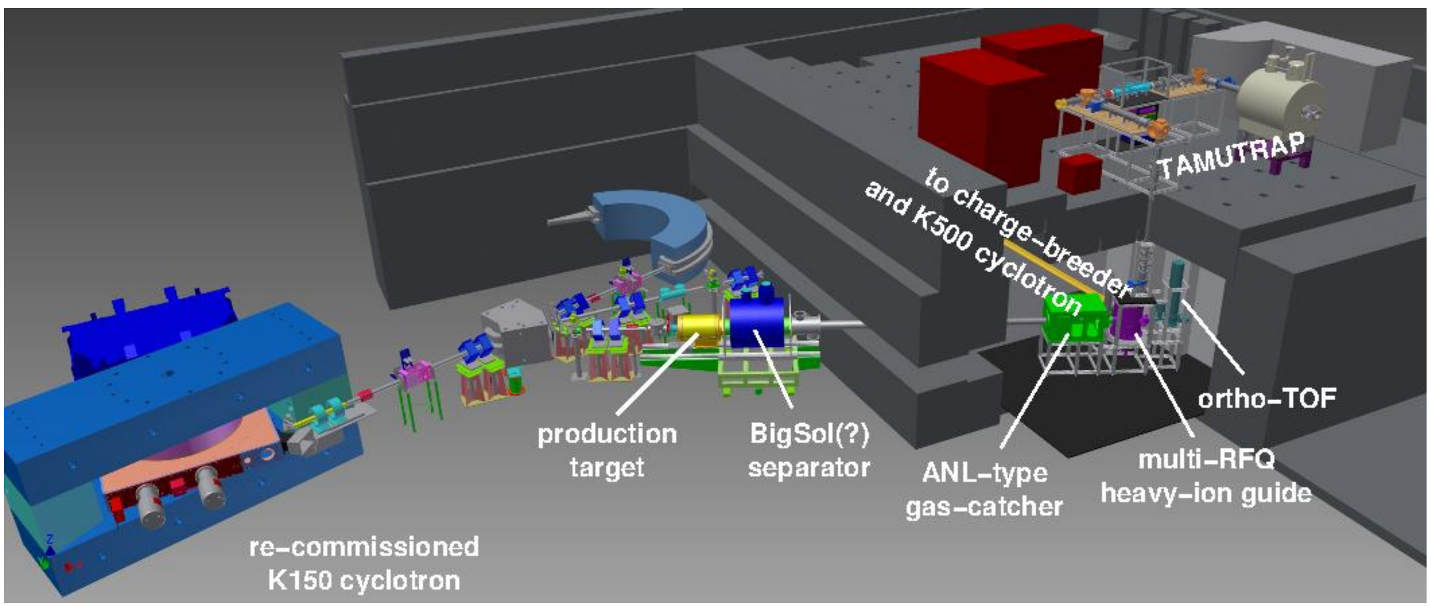


Heavy Ion Guide

Production of RIB (inverse kinematic mode):

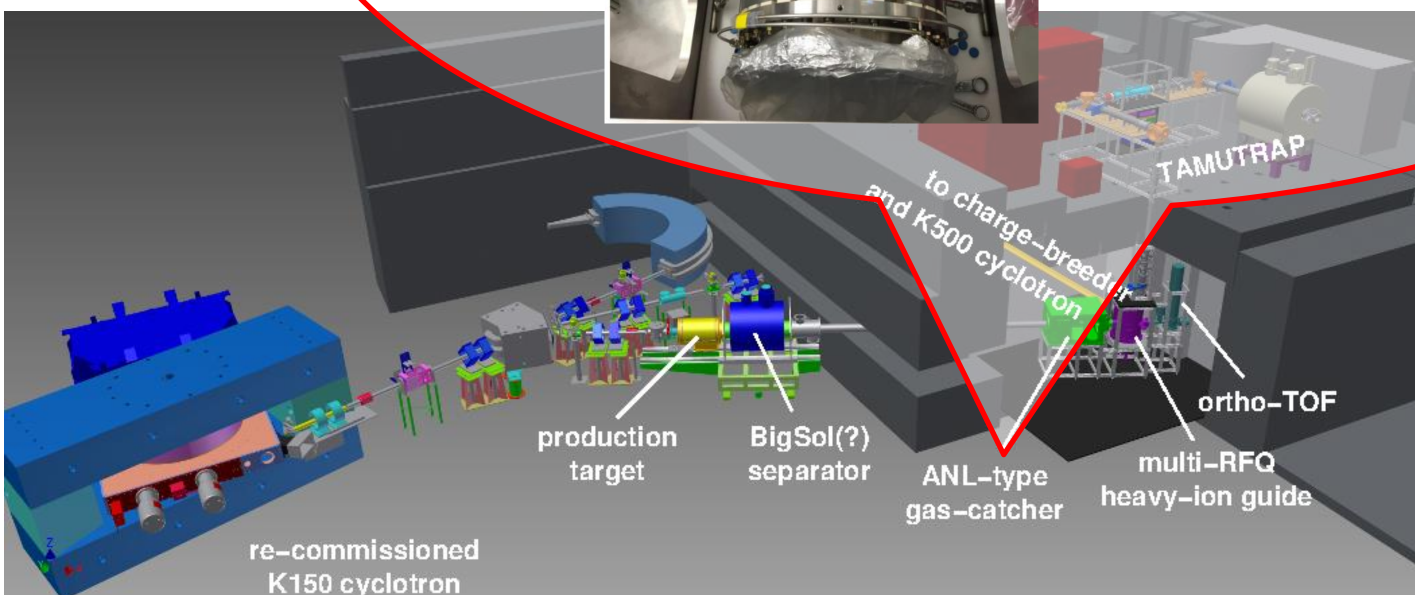
I. **Deep inelastic collision**
II. **Nuclear Fragmentation**
III. **Fusion Evaporation Reaction**



Heavy Ion Guide

Production of RIB (inv… …node):

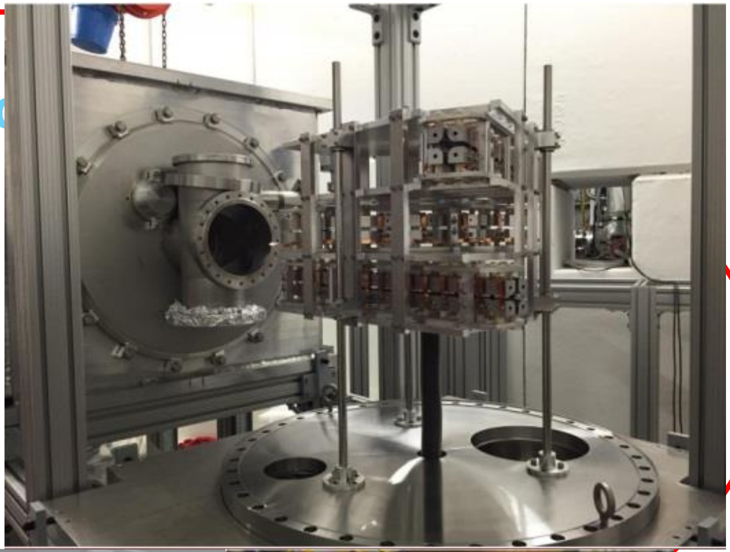
I. Deep inelastic collis…
II. Nuclear F…
III. Fusion Ev…

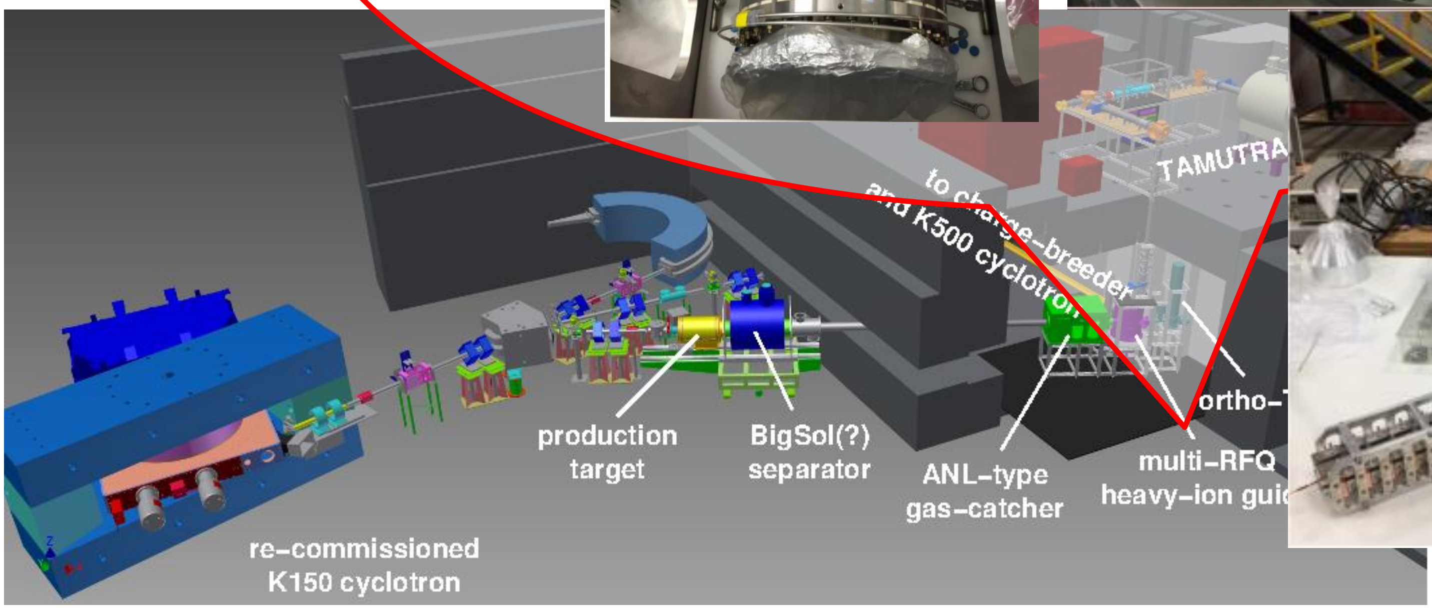


Heavy Ion Guide

Production of RIB (inv

- I. Deep inelastic collis
- II. Nuclear F
- III. Fusion Ev





Test Runs for producing proton rich nuclei

Production Mechanism:

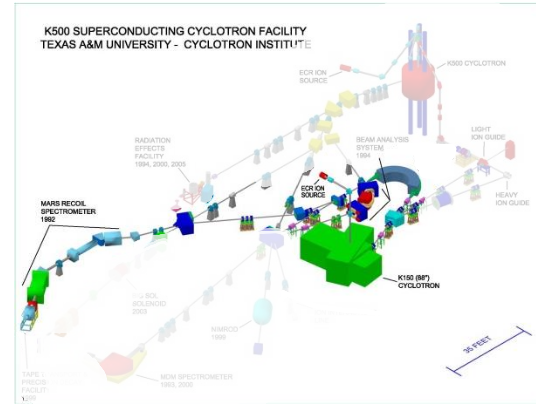
Fusion Evaporation reaction using ^{3}He gas target.

RIB	$t_{1/2}$ [ms]	Projectile	Energy [MeV/u]
^{20}Mg	90	^{20}Ne	23-30
^{24}Si	140	^{24}Mg	22-30
^{28}S	125	^{28}Si	22-30
^{32}Ar	98	^{32}S	20-24
^{36}Ca	102	^{36}Ar	23-30
^{40}Ti	53	^{40}Ca	23-30

Test Runs for producing proton rich nuclei

Production Mechanism:

Fusion Evaporating reaction using ^{3}He gas target.
Performed test run using MARS Spectrometer.



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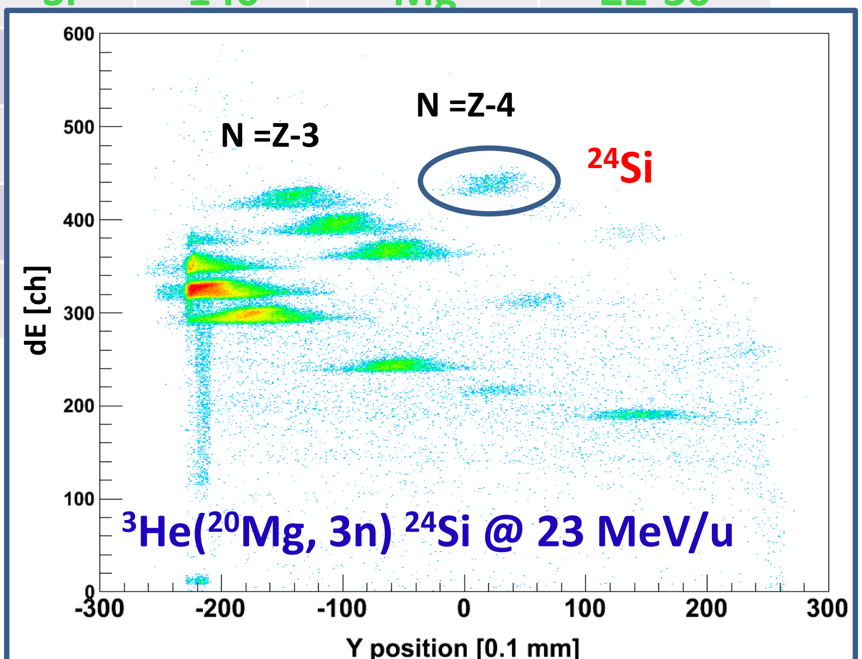

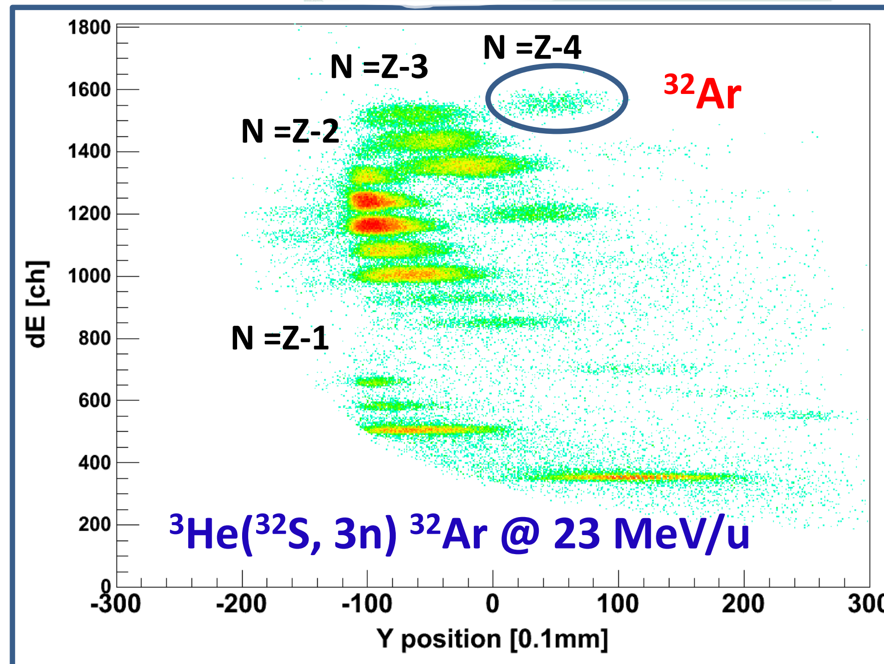

Test Runs for producing proton rich nuclei

RIB	$t_{1/2}$ [ms]	Projectile	Energy [MeV/u]	Target thickness [mg/cm²]	Expected rate @ target chamber [pps]
^{20}Mg	90	^{20}Ne	23-30	22.5 (66)	$68\ (400) \times 10^4$
^{24}Si	140	^{24}Mg	22-30	22.5 (70)	$26\ (160) \times 10^4$
^{28}S	125	^{28}Si	22-30	22.5 (60)	$7\ (40) \times 10^4$
^{32}Ar	98	^{32}S	20-24	22.5 (42)	$5\ (17) \times 10^4$
^{36}Ca	102	^{36}Ar	23-30	22.5 (28)	$12\ (31) \times 10^4$
^{40}Ti	53	^{40}Ca	23-30	22.5 (26)	$4\ (8) \times 10^4$

Test Runs for producing proton rich nuclei

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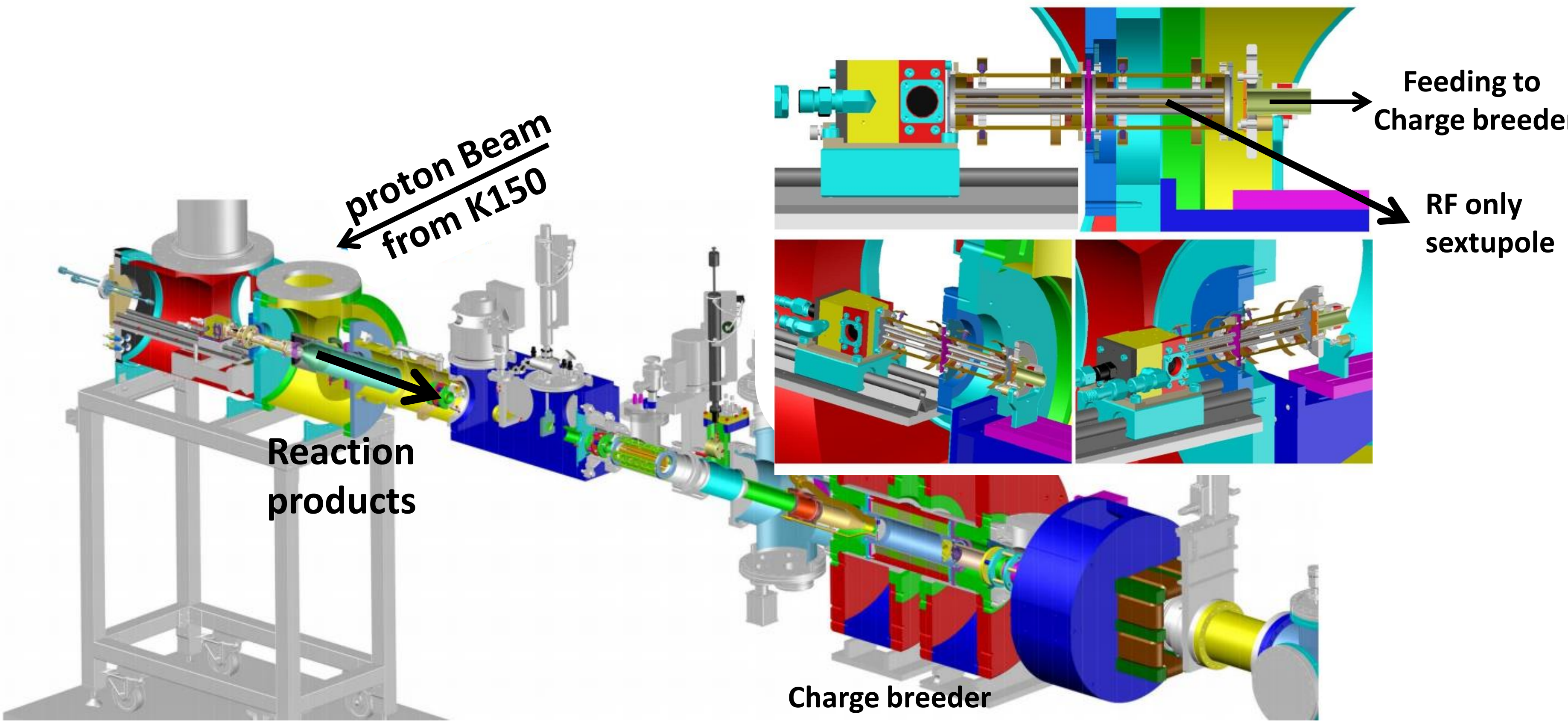
- **Lighter beam from K150 are currently being delivered with very high beam intensity (for e.g., p, ^{3}He,^{4}He ; close to 5 pμA).**
- **Gas catcher, multi-RFQ is yet to be tested.**

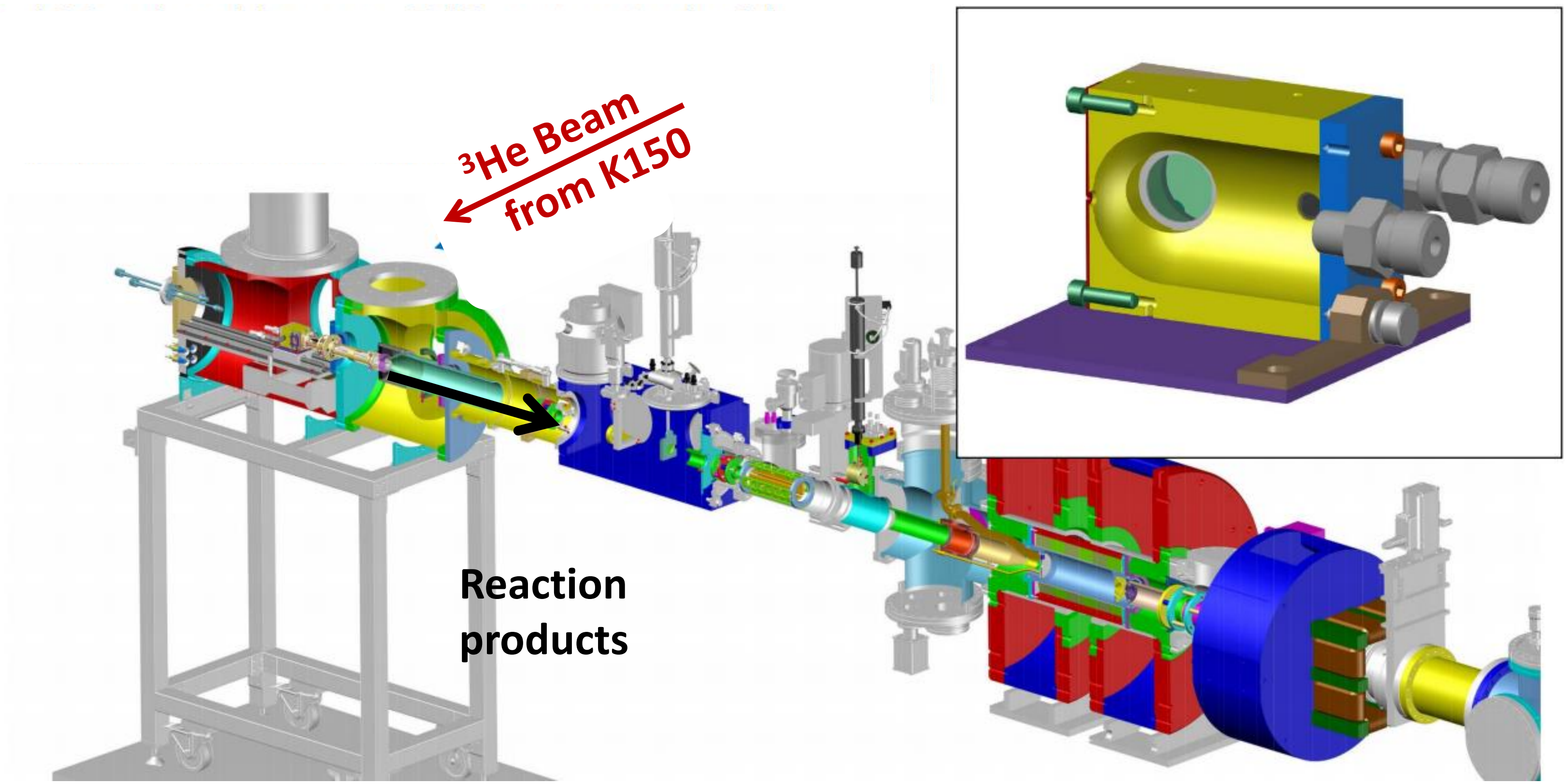
Alternative Approach: Light Ion Guide

- (p,n), (d,p) and (He,n) reaction.
- Light ion induced fission.
- Current operating pressure 100-130 mbar.

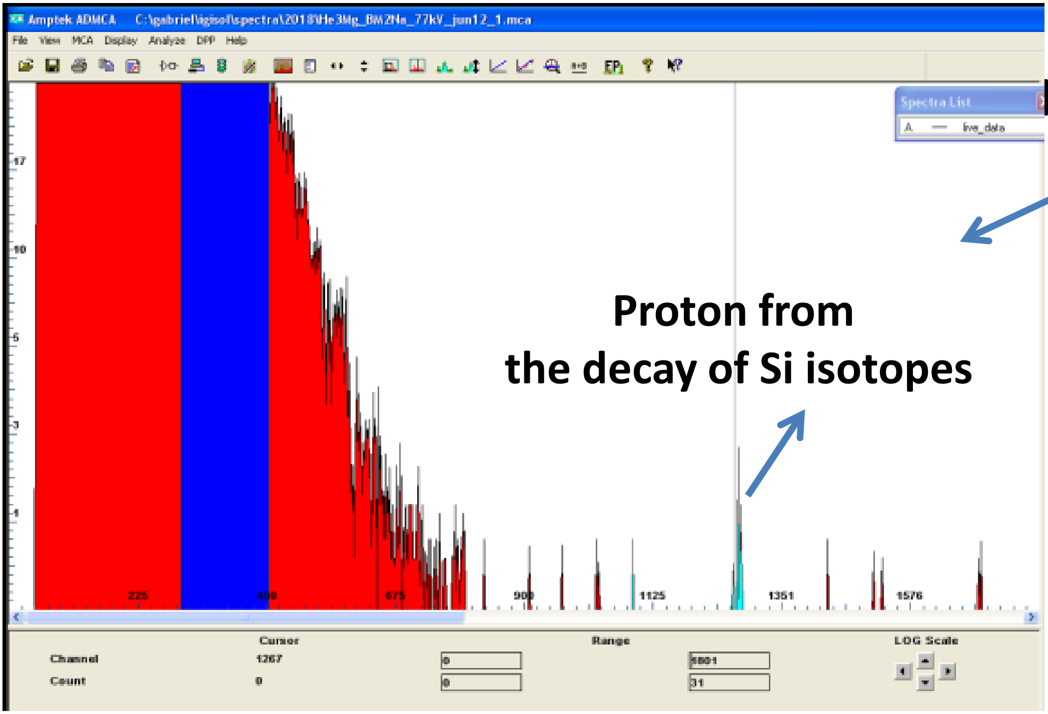


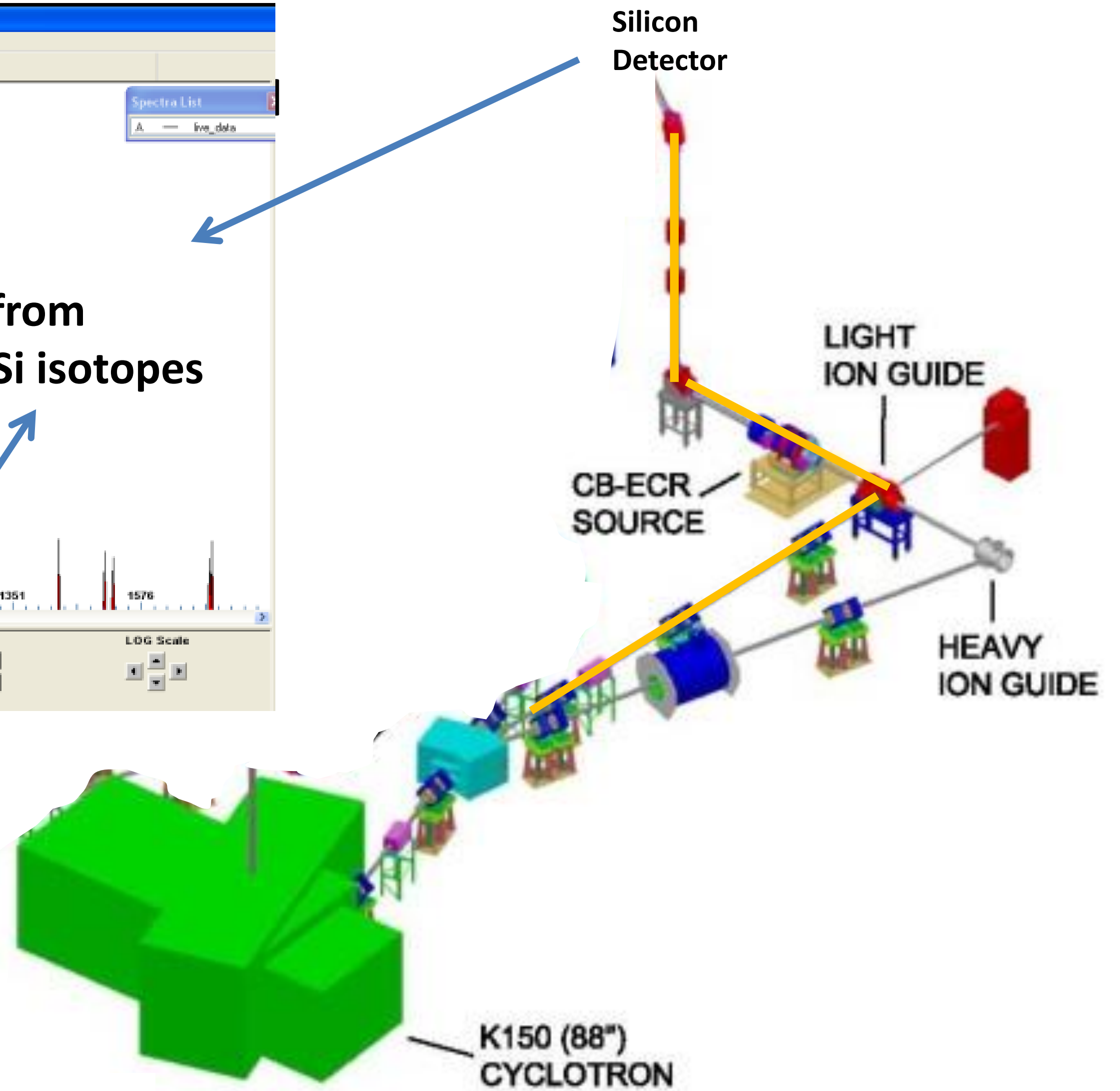
LIG for producing proton rich nuclei

- Test run for producing ^{24}Si using existing gas cell ($^{nat}Mg(^{3}He, 3n)^{24}Si$ @ 20 MeV/u).
- Observed proton peak from the decay of Silicon isotopes.



LIG for producing proton rich nuclei

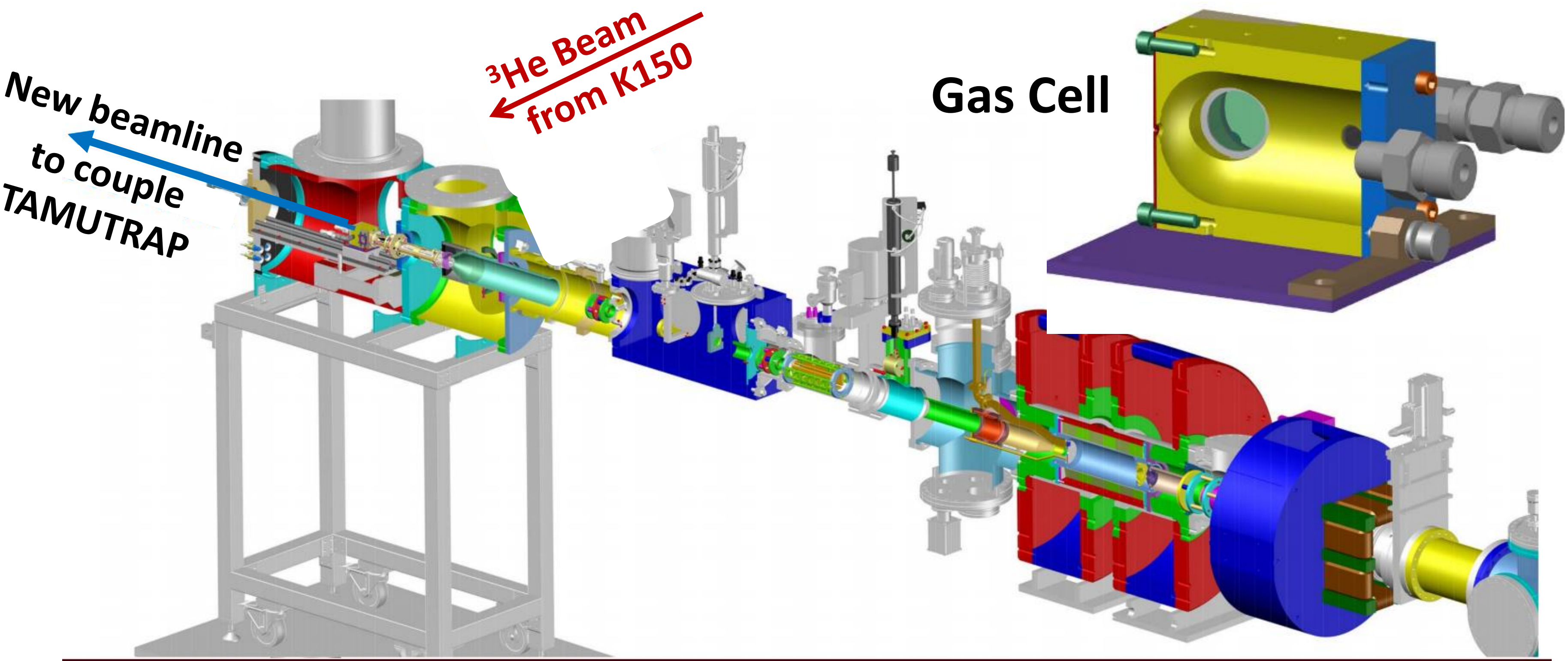




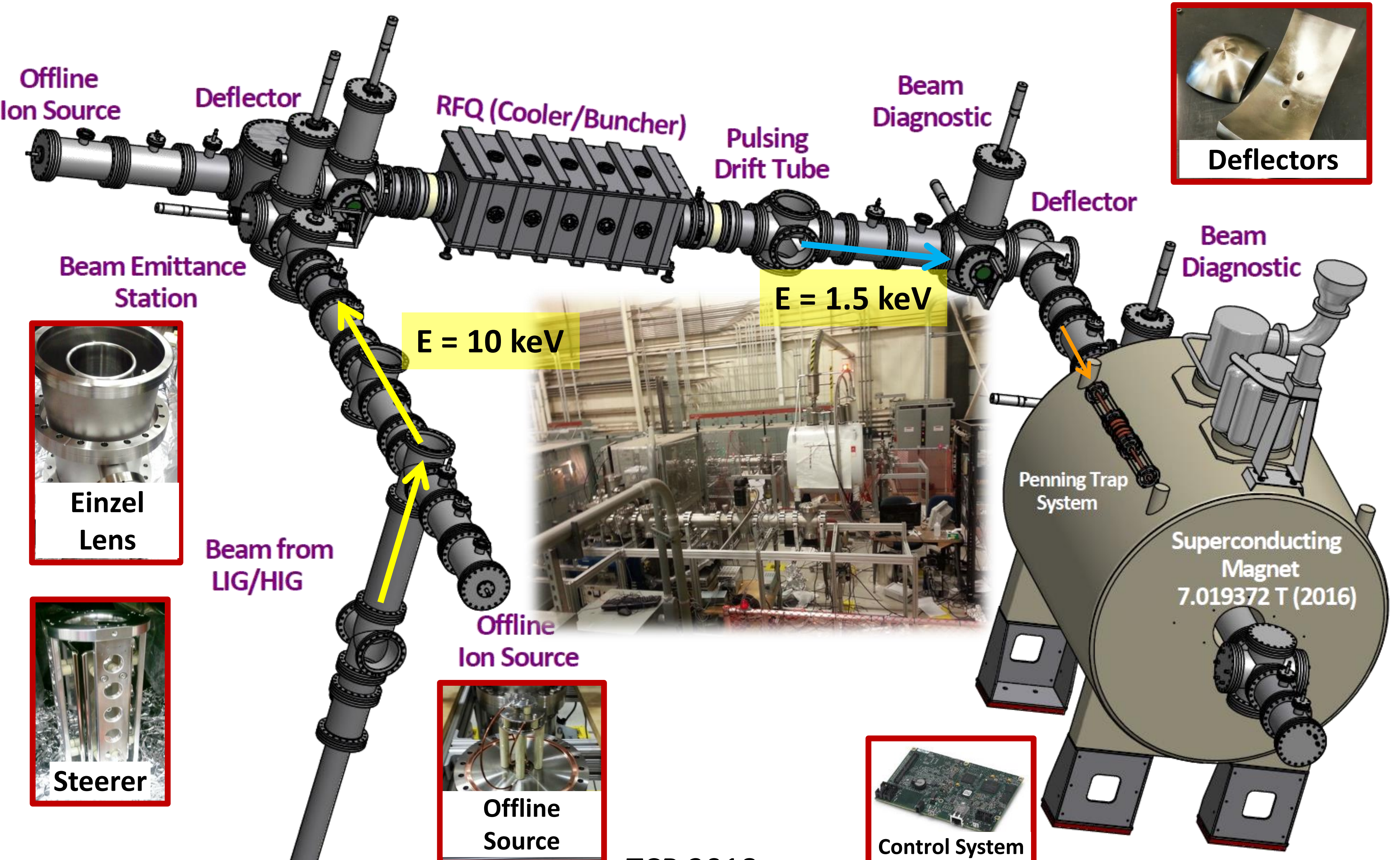
Proton from the decay of Si isotopes

LIG for producing proton rich nuclei

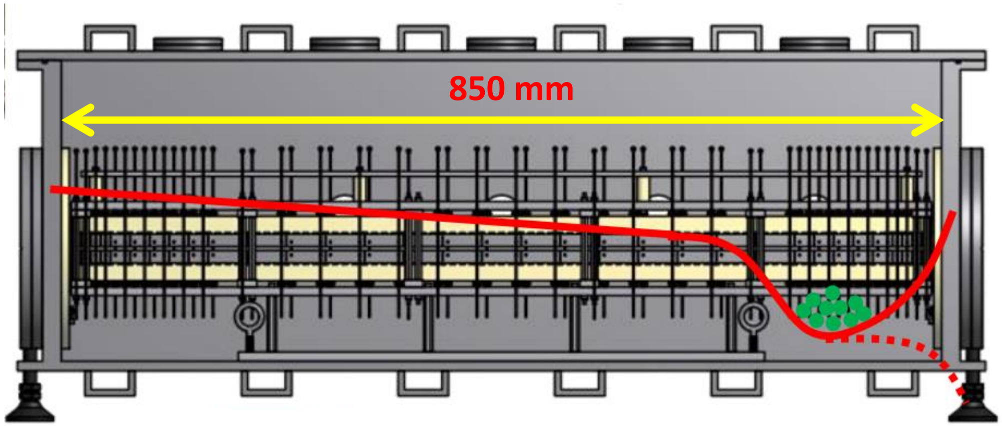
- New gas cell suitable for ^{3}He induced reaction is currently being designed.
- New detector setup and new beamline to couple TAMUTRAP facility.
- RF + Pushing electrode & pulsing primary beam might help in improving extraction efficiency.

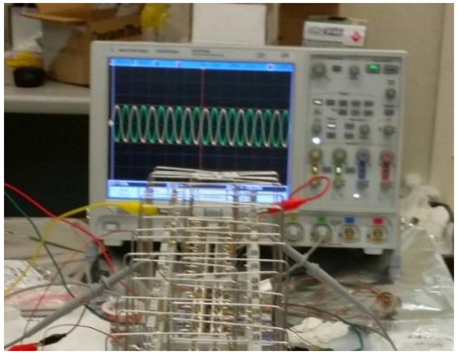


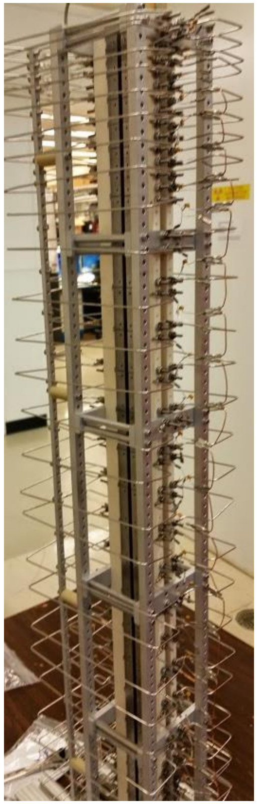
TAMUTRAP facility



TAMUTRAP facility: Cooler/Buncher

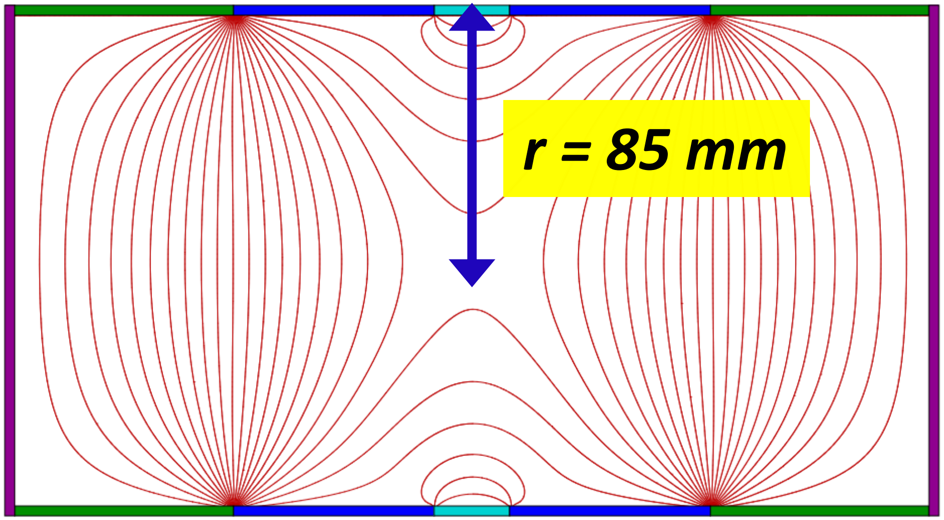




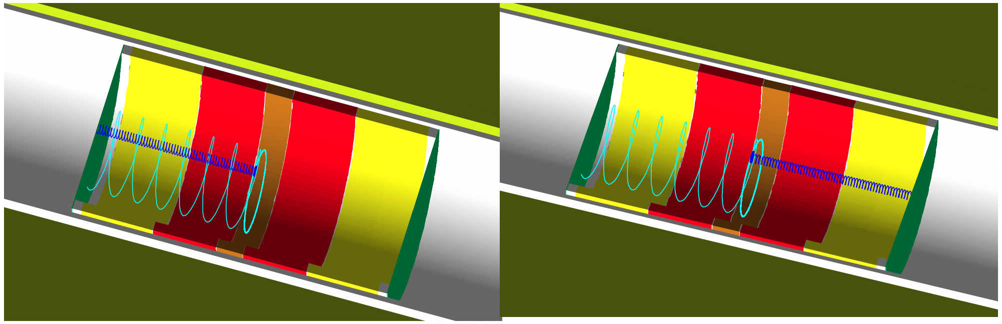


Operating Pressure : 10^{-2} – 10^{-4} mbar.
Cooling time : 2 – 20 ms.
FWHM: 1 to 1.5 μ s.

TAMUTRAP: Penning Trap

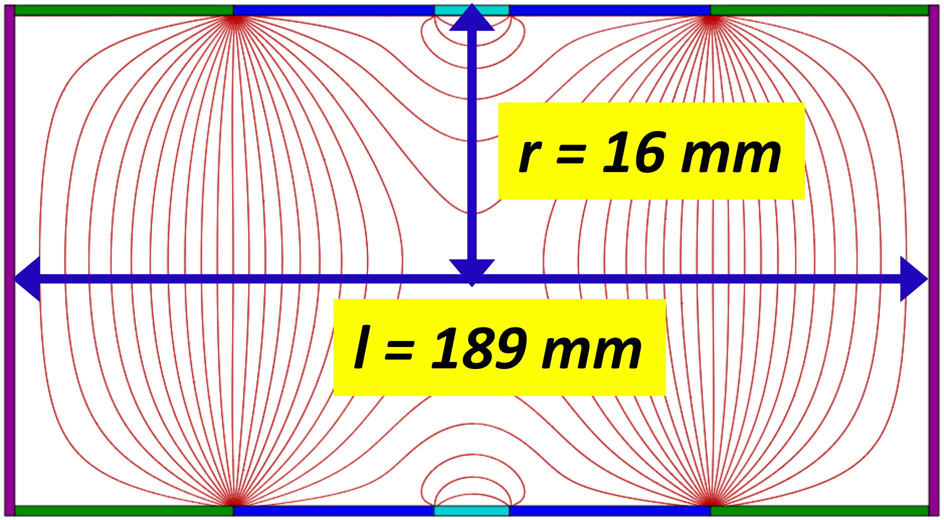


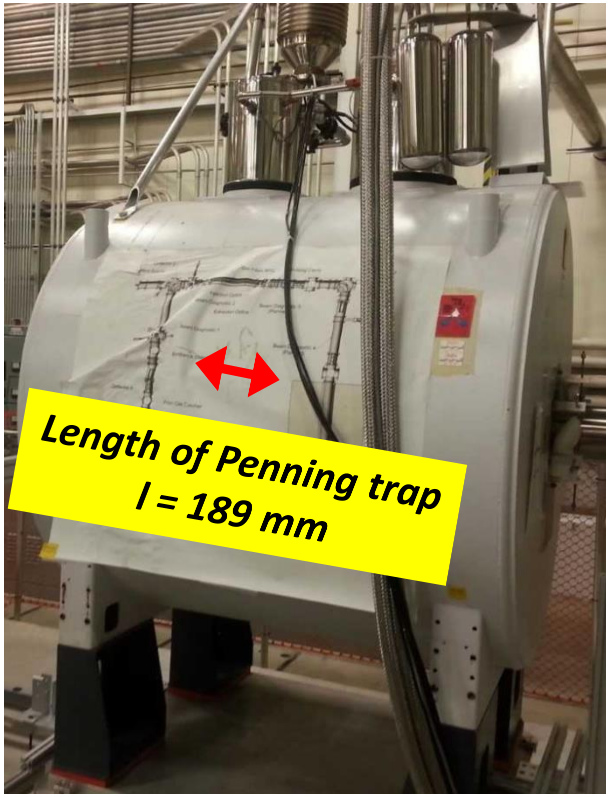
Inner diameter of the trap to contain decay products (protons, electrons):
Diameter = 170 mm.



Nuclide	Proton Energy (MeV)	Larmour radii (mm)
^{20}Mg	4.28	42.7
^{24}Si	3.91	40.8
^{28}S	3.70	39.7
^{32}Ar	3.36	37.8
^{36}Ca	2.55	33.0
^{40}Ti	3.73	39.9
^{48}Fe	1.23	22.9

Other Cylindrical Penning Trap



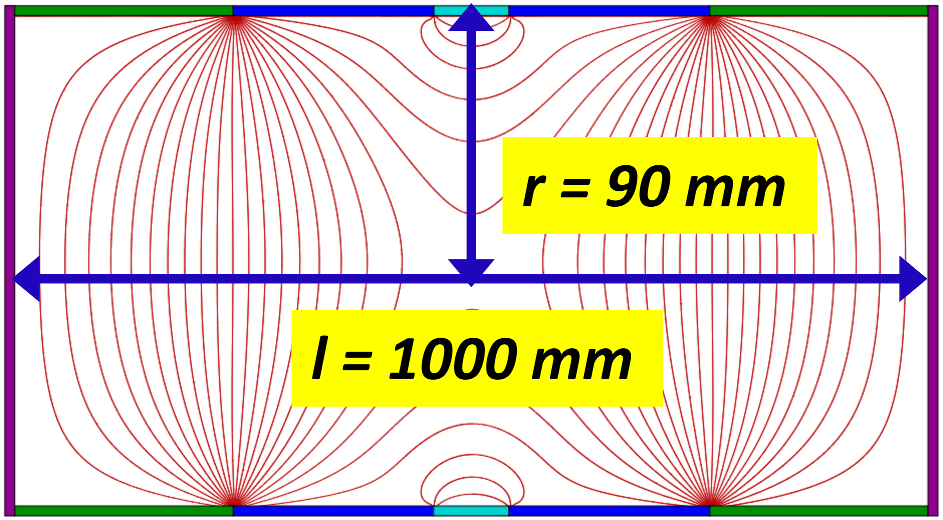


Other existing Cylindrical Penning Trap:

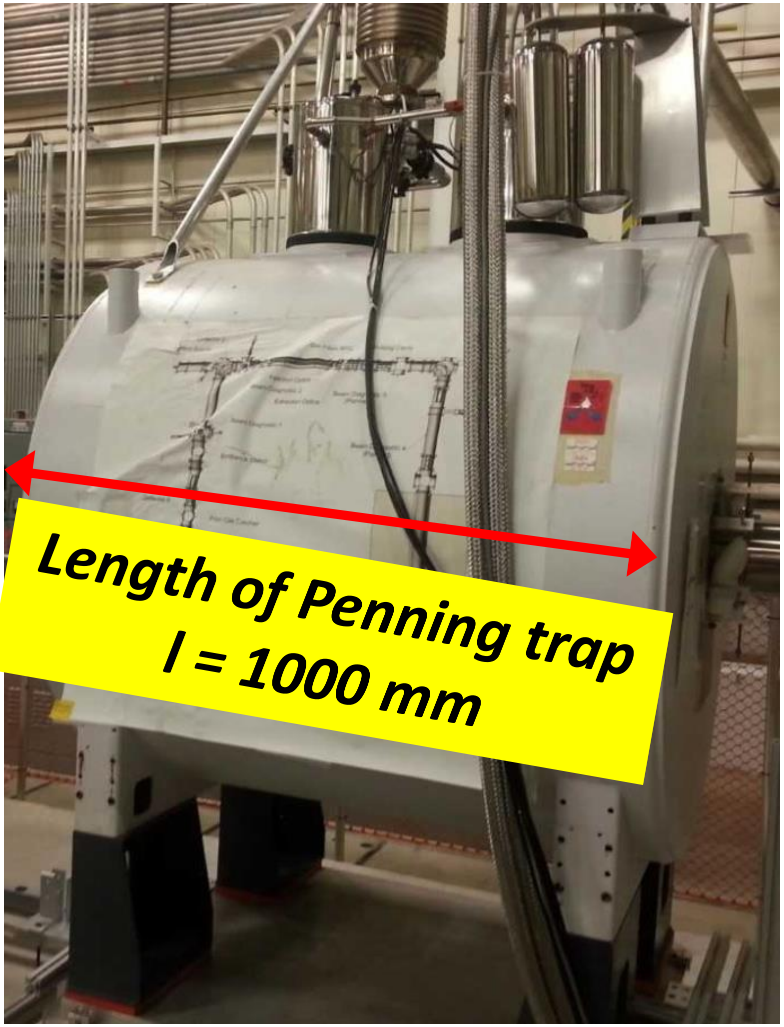
***l/r* = 11.75.**

(JYFLTRAP, ISOLTRAP, SHIPTRAP)

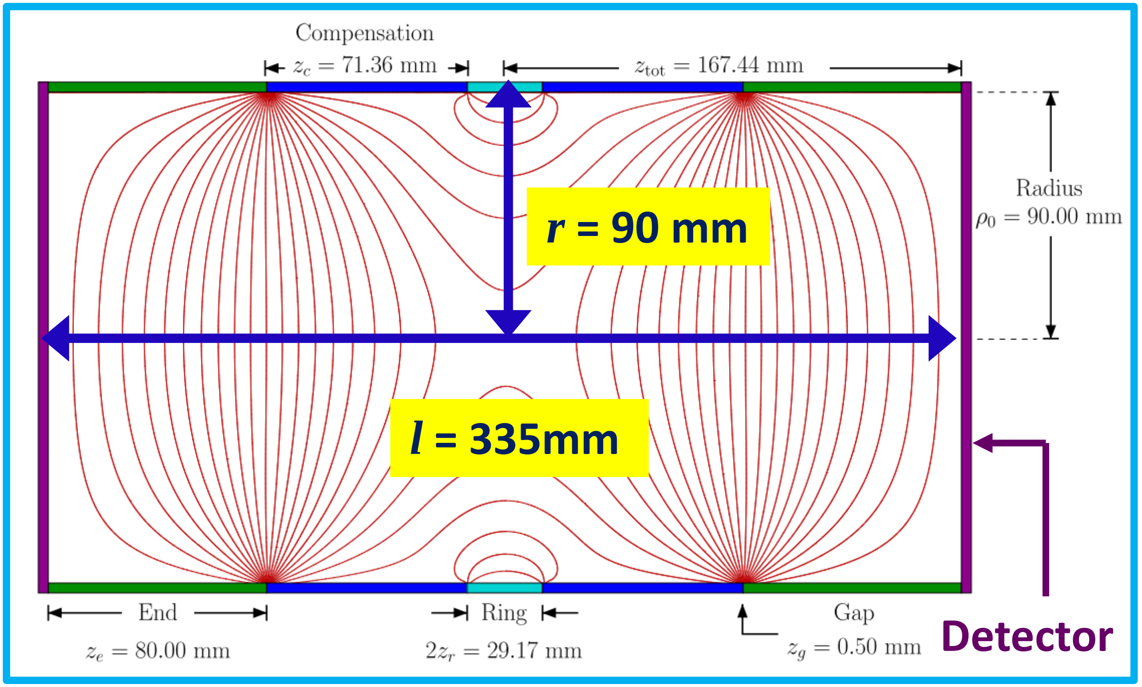
Penning Trap to confine protons (*l* /*r* = 11.75)



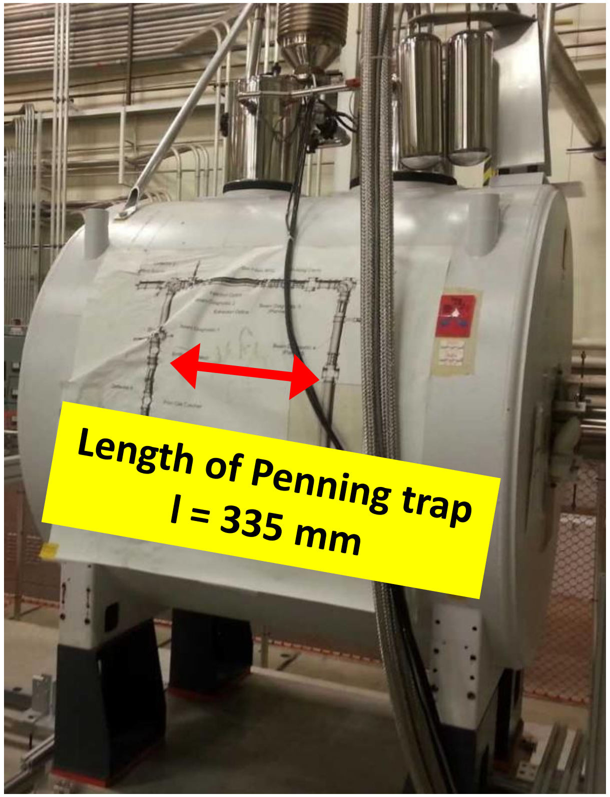
Needed a new design to make it fit in 7T magnet



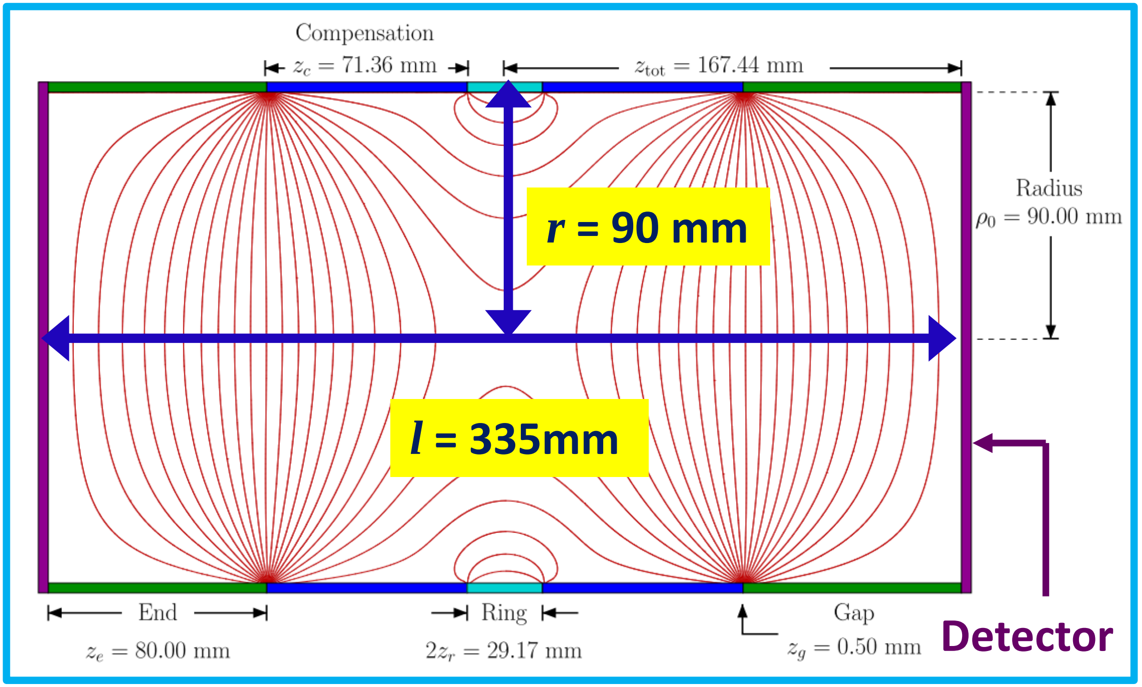
TAMUTRAP: Penning Trap (*l /r = 3.72*)



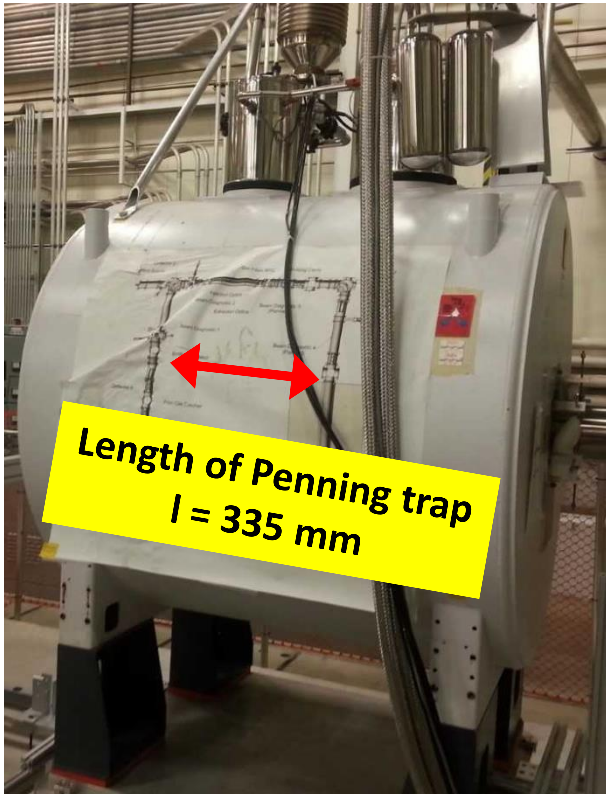
*M. Mehlman et al. NIMA **712** (2013) 9*



TAMUTRAP: Penning Trap (*l* /*r* = 3.72)



M. Mehlman et al. NIMA ***712*** *(2013) 9*



Dimension optimized to perform high precision mass measurement.

Commissioning of TAMUTRAP facility

Mass measurement of ^{23}Na

Time-of-flight cyclotron resonance technique:

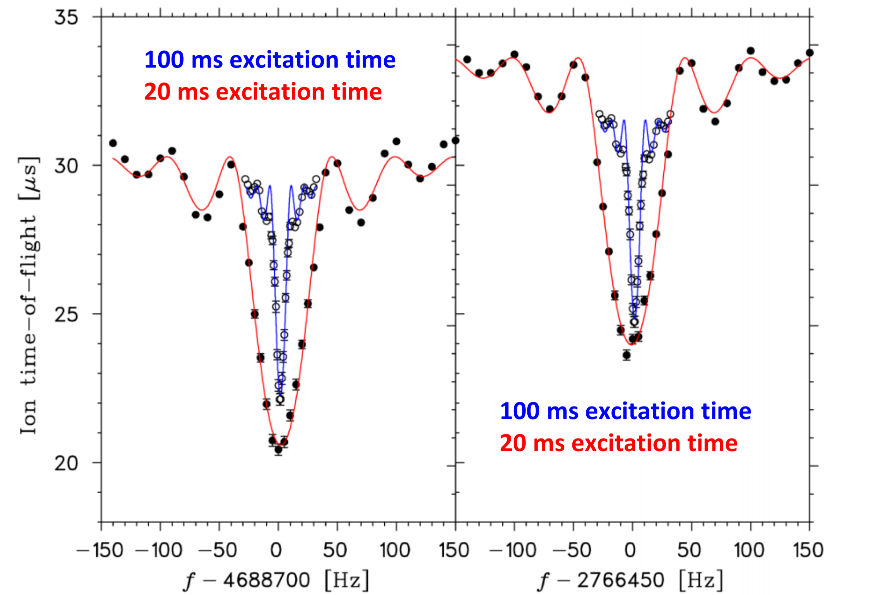
- Dipole excitation for 10 ms.
- Quadrupole excitation for 100 ms.
- Reference mass : ^{39}K

20 ms excitation (solid points, red curve)

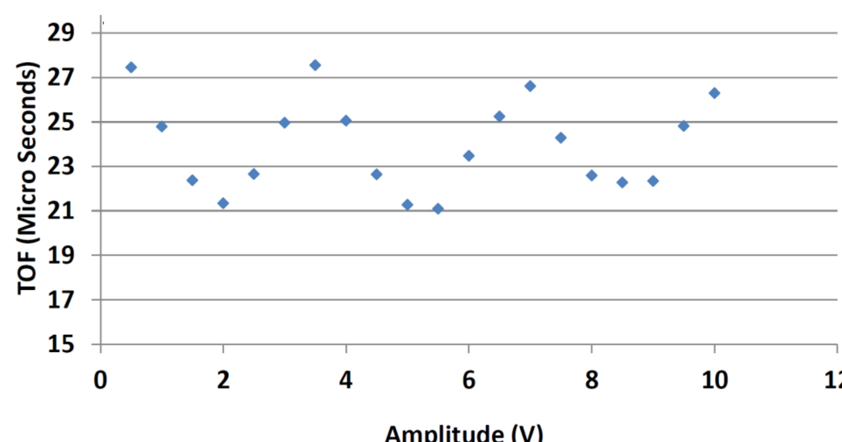
$M_{diff} = \text{calc} - \text{AME}$
$= 2.8 \pm 2.5$ keV (0.13 ppm measurement)

100 ms (open points, blue curve)

$M_{diff} = \text{calc} - \text{AME}$
$= -0.3 \pm 1.3$ keV (0.06 ppm measurement)



Amplitude scan @ 100 ms excitation time



Prototype Penning Trap
With l/r = 3.72 ; ID: 45 mm

Commissioning of TAMUTRAP facility

Mass measurement of ^{23}Na

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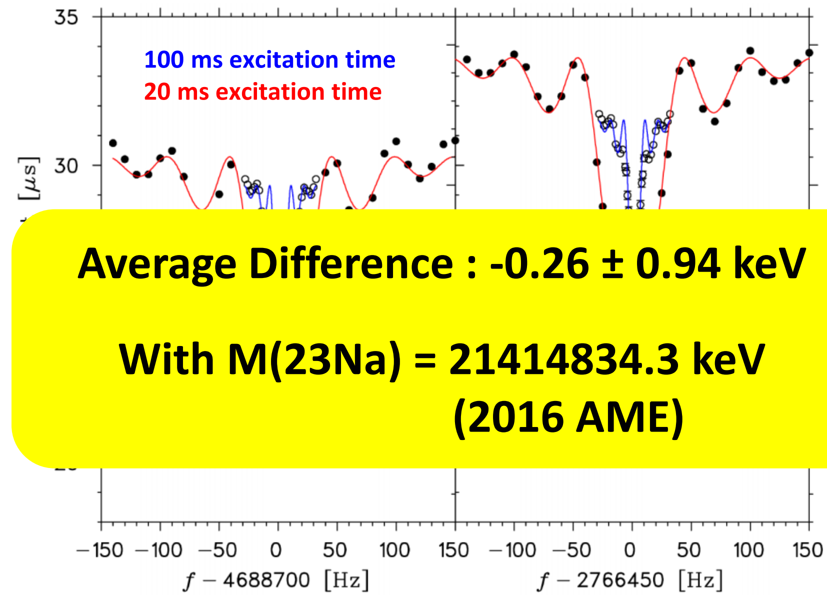
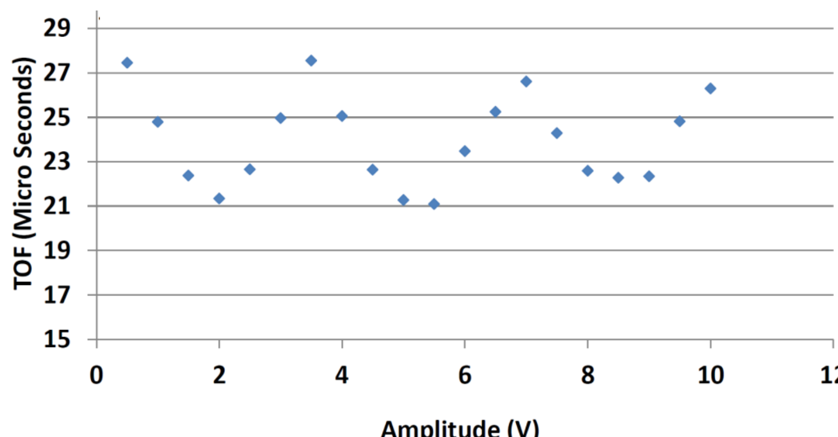


Average Difference : -0.26 ± 0.94 keV

With M(23Na) = 21414834.3 keV (2016 AME)

Amplitude scan@ 100 ms excitation time

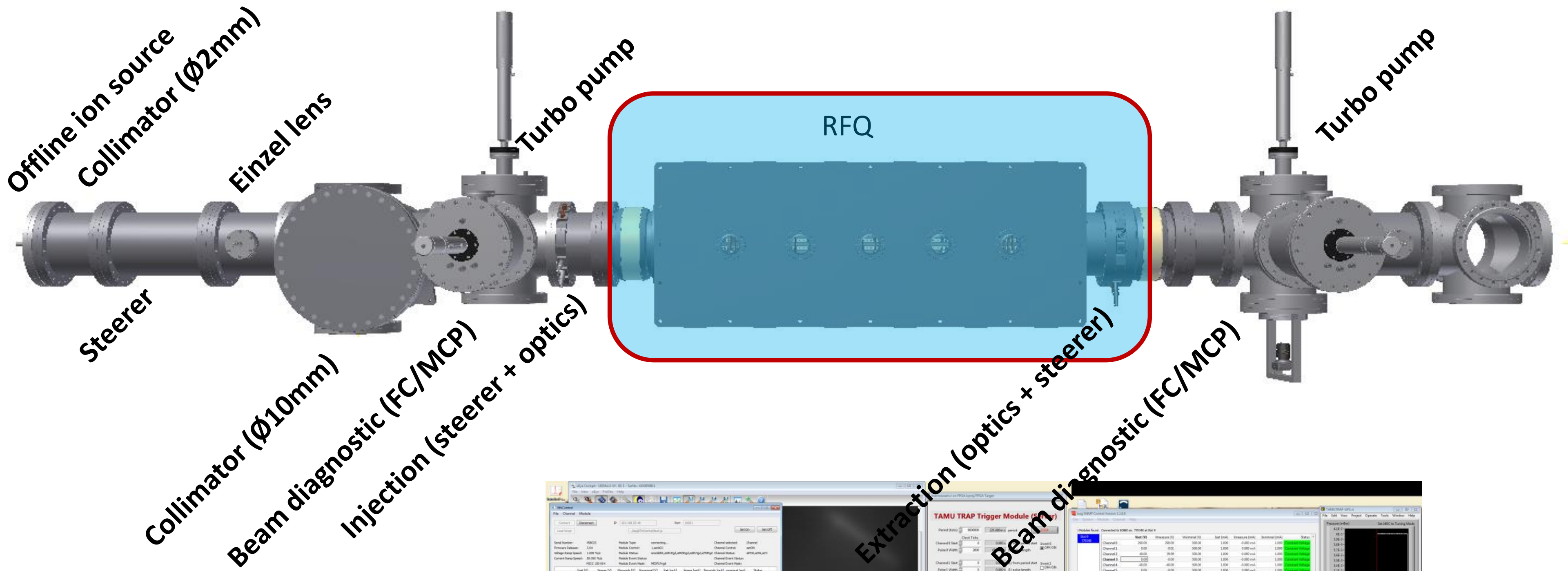


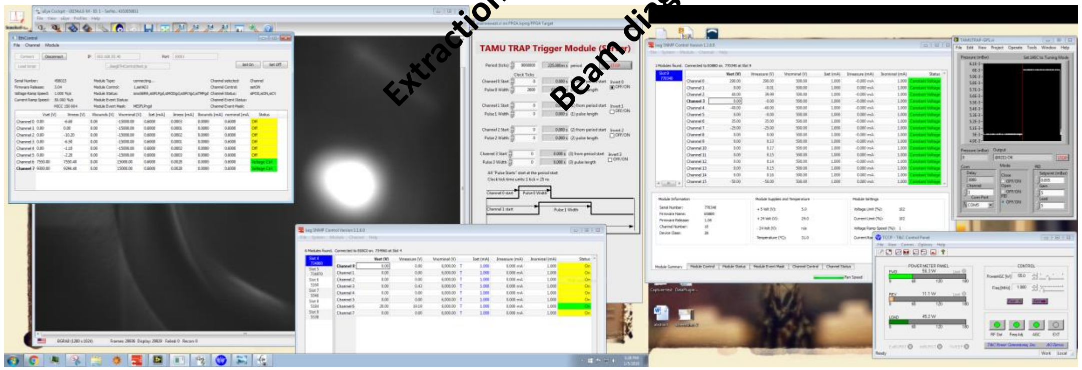
Prototype Penning Trap
With l/r = 3.72 ; ID: 45 mm

TCP 2018

Transport Efficiency

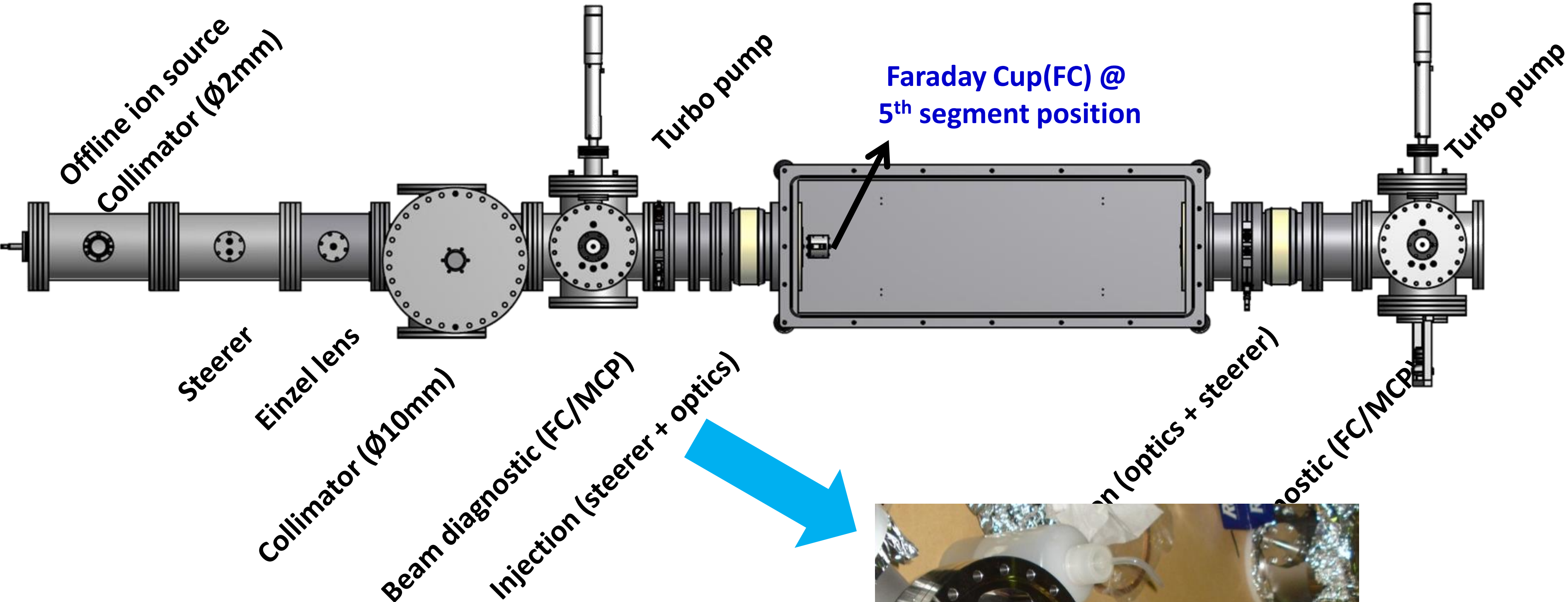
➢ **RFQ efficiency ≈ 70% - 80 % (Continuous Mode)**



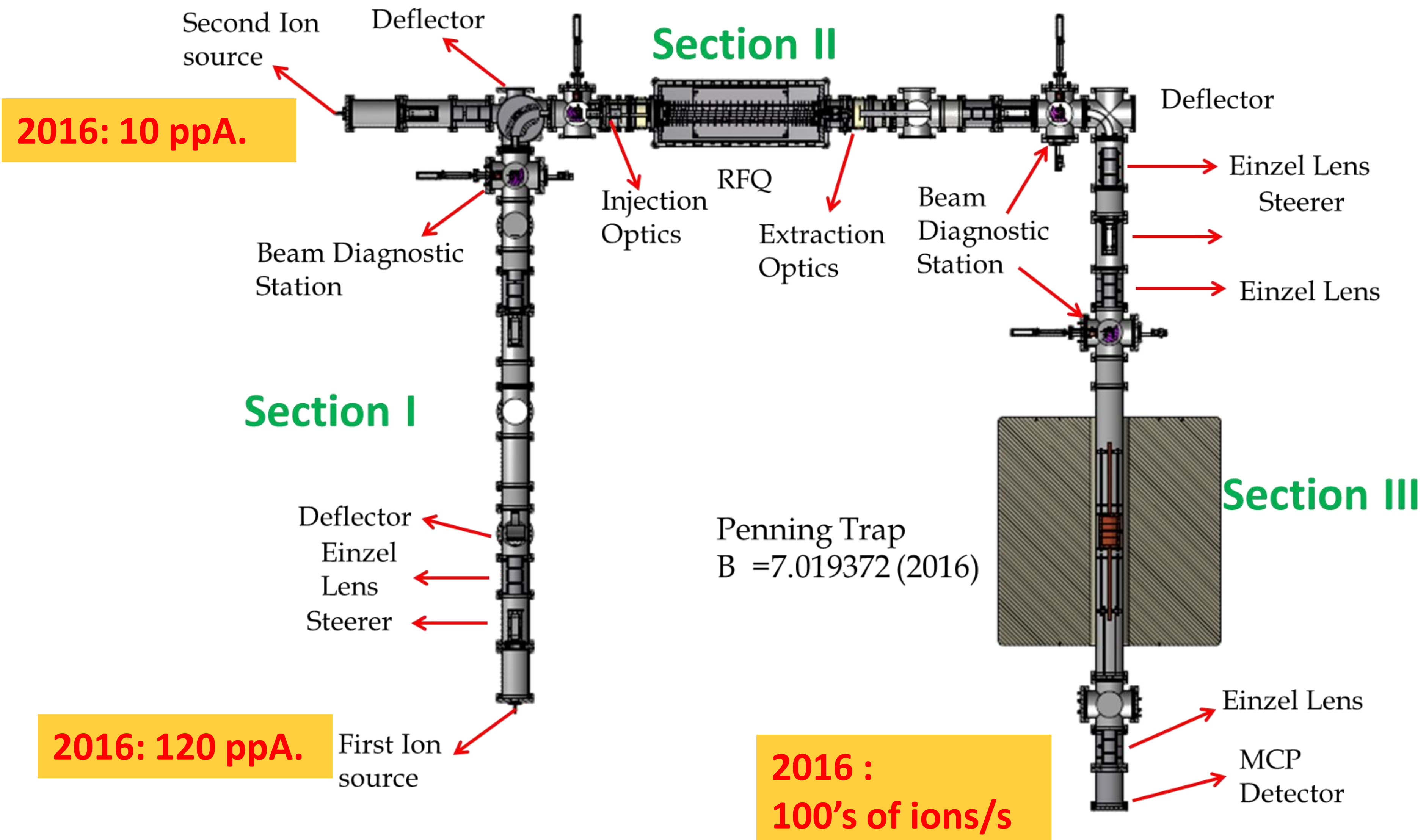


Transport Efficiency

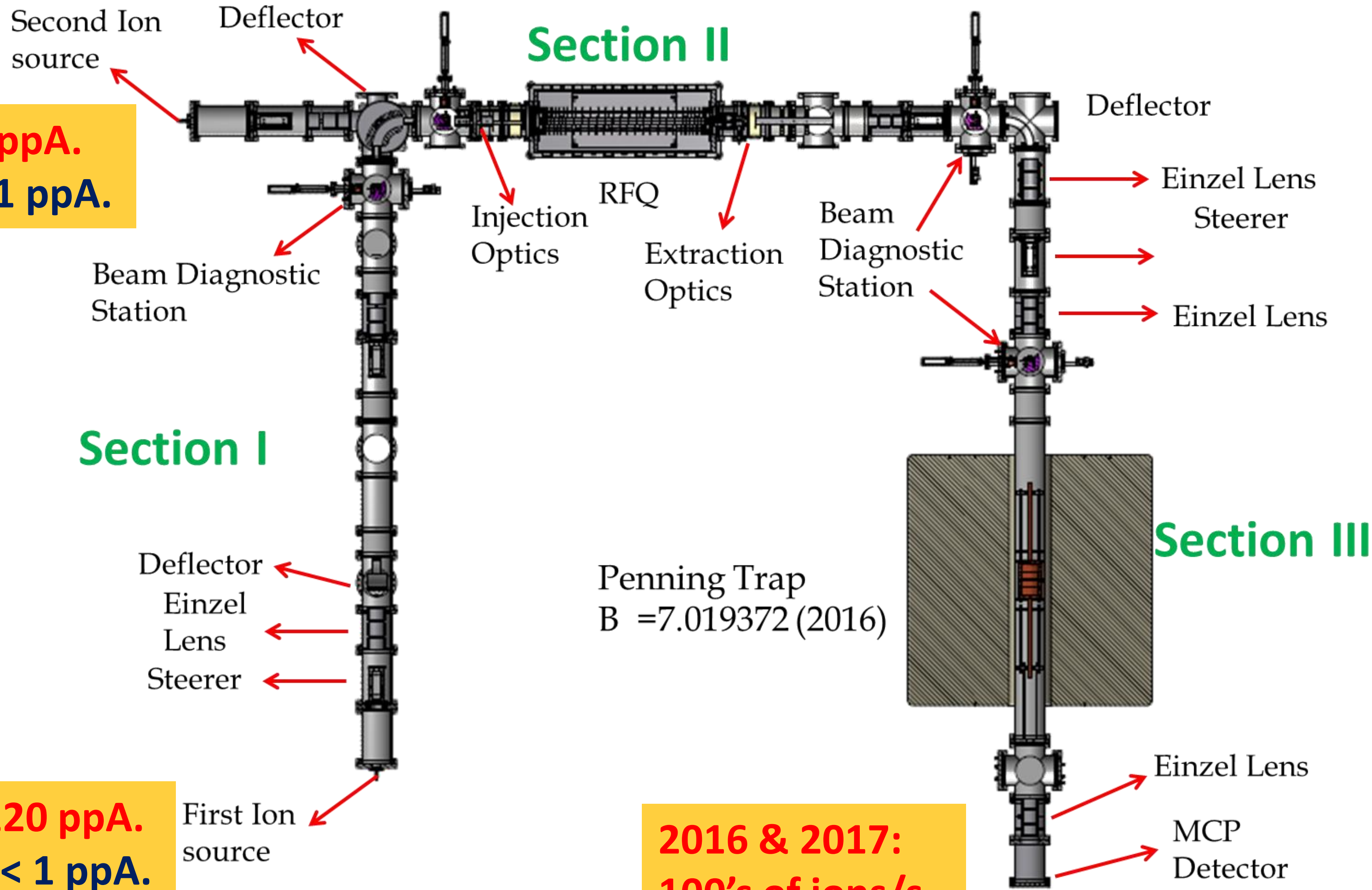
- **Injection optics efficiency : 80% -85 %**



Transport Efficiency



Transport Efficiency



2016: 10 ppA.
2017 : < 1 ppA.

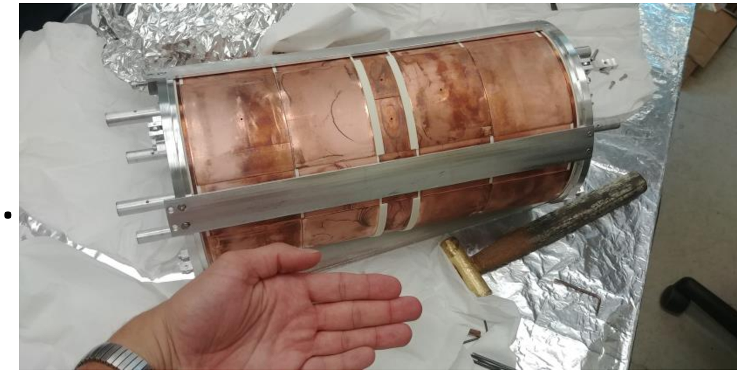
2016: 120 ppA.
2017 : < 1 ppA.

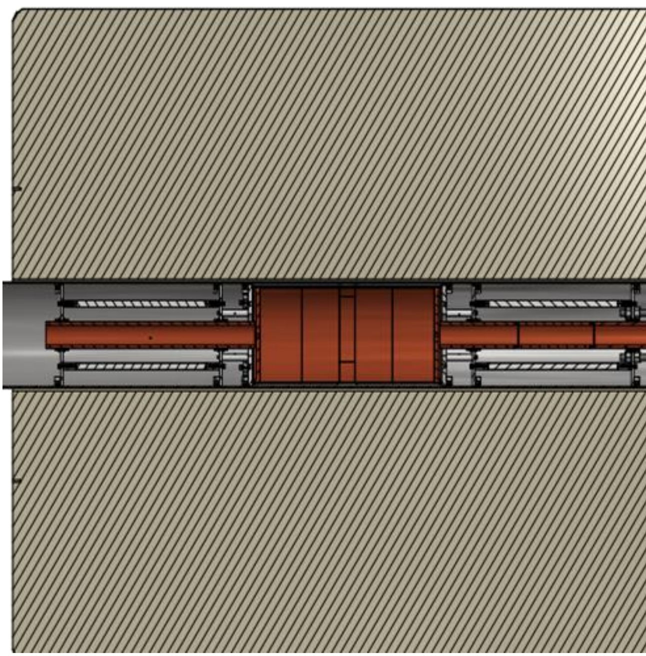
2016 & 2017:
100's of ions/s

TAMUTRAP: Penning trap

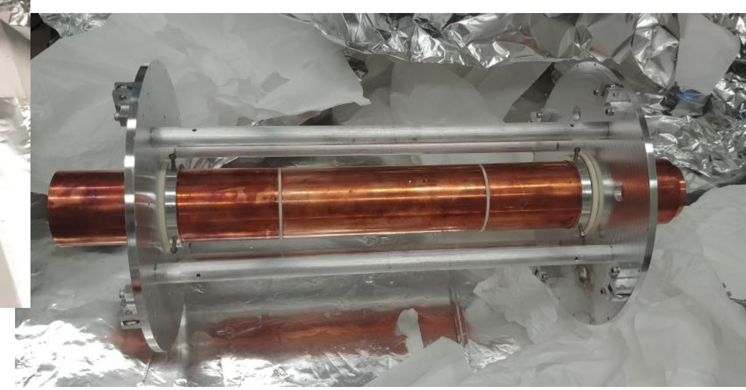
Installation in November 2018.

Inner Diameter of Penning Trap: 7.087 in (180mm).
Outer Diameter of Penning Trap system: 7.68 in (196 mm).
Magnet Bore : 8.27 in (210 mm).
Beam pipe Outer Diameter: 8 inch (203.2 mm).
Beam Pipe ID : 7.75 inch (197 mm).

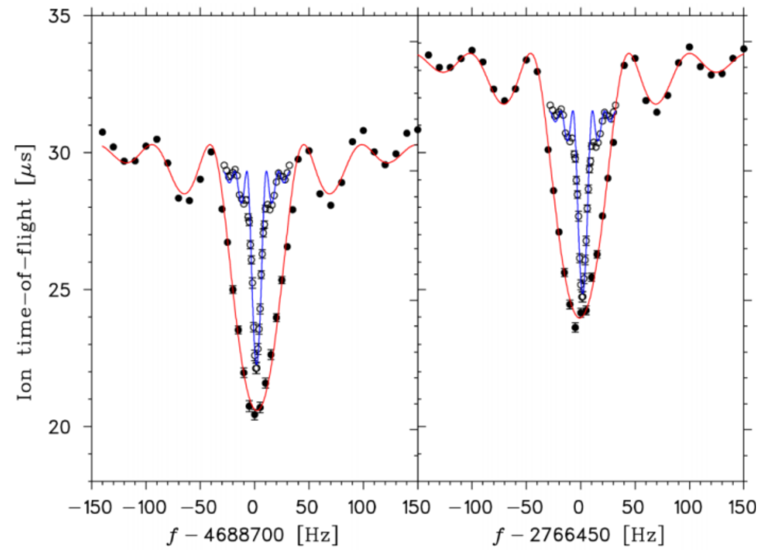




Extraction Section

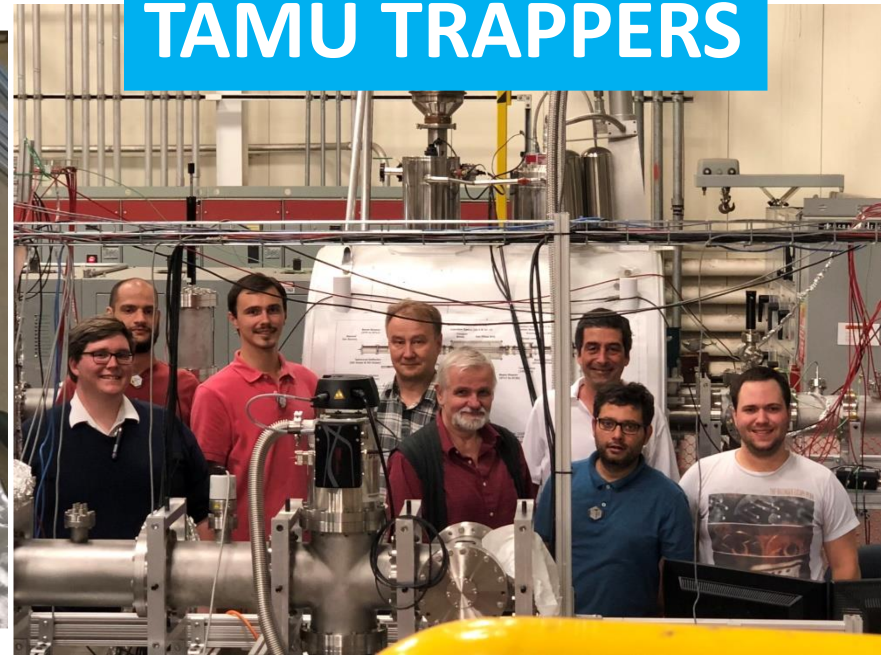


Conclusion & Future plan



- Commissioned TAMUTRAP facility.
- Complete the GEANT4 Simulation.
- Finalize the design of p/β detectors.
- Couple LIG/HIG to TAMUTRAP facility.

TAMU TRAPPERS



Many thanks to all who have helped:

R. Ringle, G. Bollen (LEBIT) , T. Eronen (JYFLTRAP)
J. Clark, G. Savard (CPT), A. Kwiatkowski, J. Dilling(TITAN)

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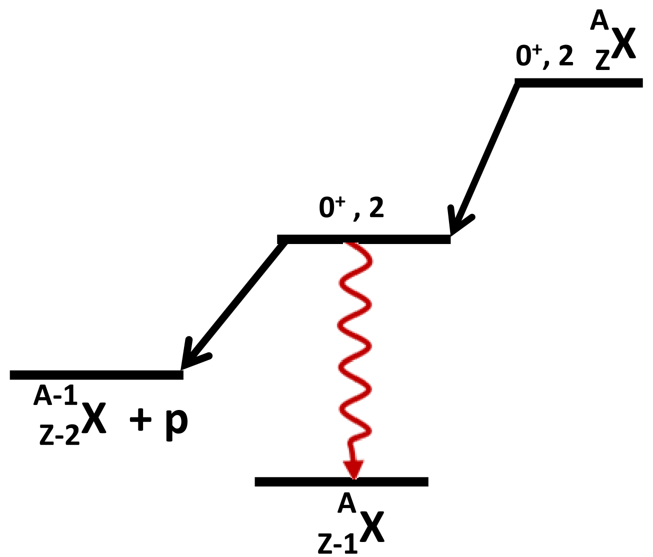
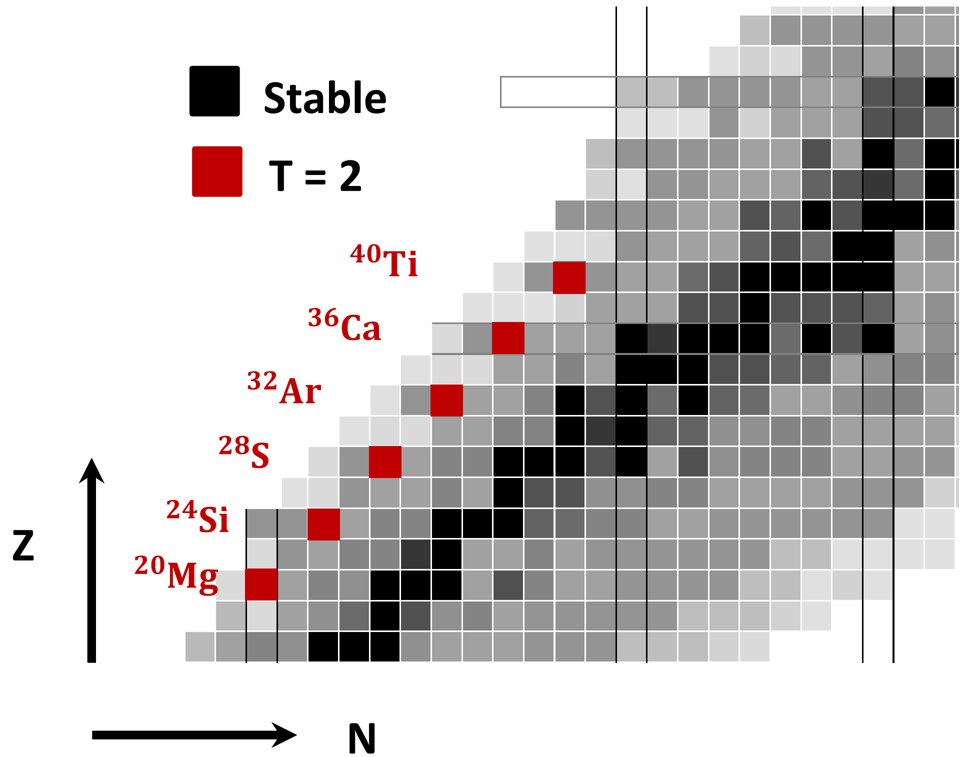
State of Texas

U.S. DEPARTMENT OF ENERGY

Superallowed Transitions

Beta delayed proton decay





- New cases to test the CVC Theory.
- δ_c calculations seems to depend on T.
- New cases for V_{ud}.

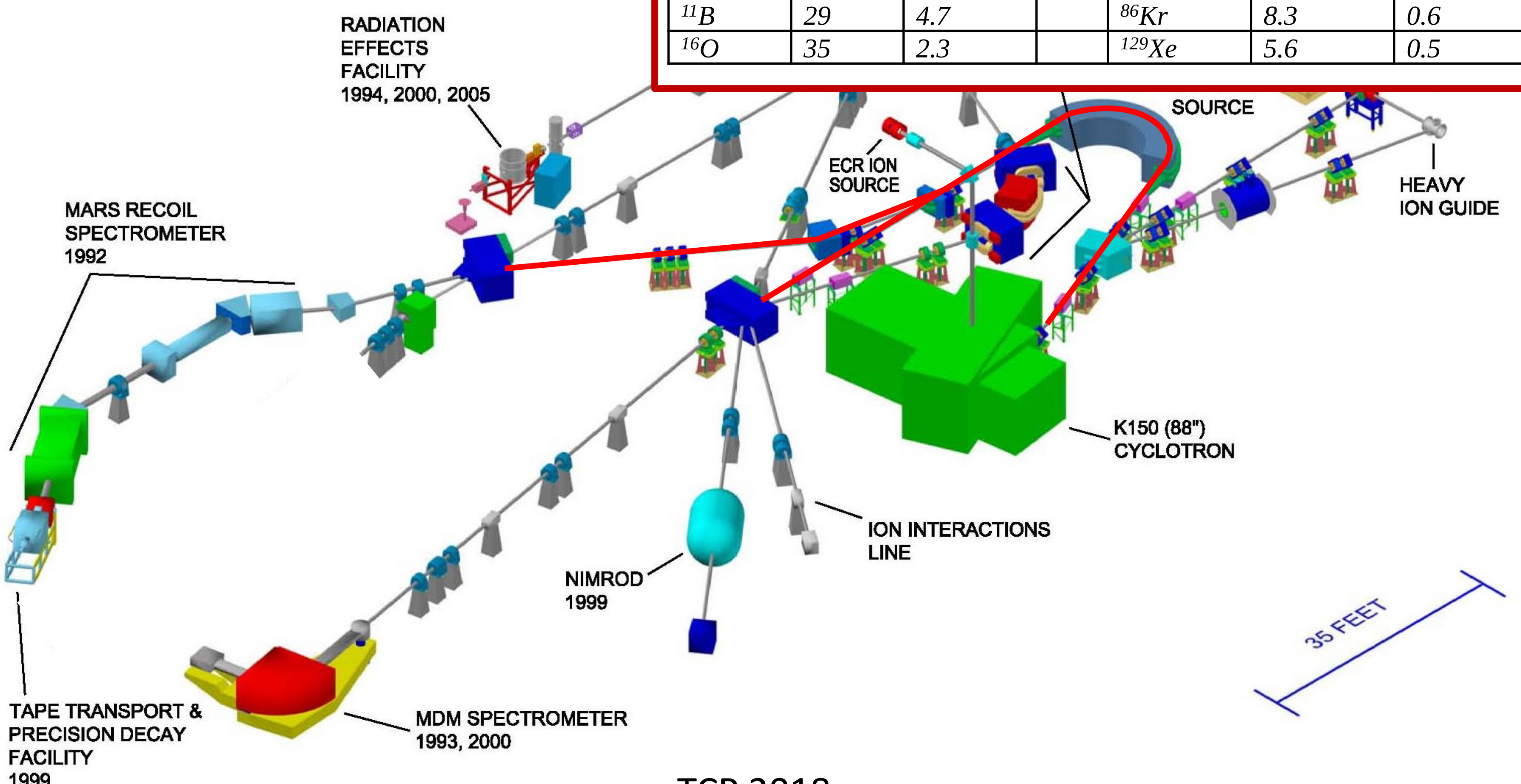
K500 SUPERCONDUCTING CYCLOTR
TEXAS A&M UNIVERSITY - CYCLOTRO

T-REX

[TAMU Reaccelerated EXotics]

Expected 88” beam intensities and energies

Isotope	*Energy* ***MeV/u***	*Intensity* ***pμA***		*Isotope*	*Energy* ***MeV/u***	*Intensity* ***pμA***
p	55	27		^{20}Ne	28	3.0
d	35	21		^{22}Ne	29	0.5
^{3}He	45	11		^{34}S	20	0.7
^{4}He	35	10		^{40}Ar	17	1.4
^{6}Li	35	7		^{40}Ca	17	1.5
^{7}Li	25	8		^{59}Co	11	0.9
^{10}B	35	4		^{78}Kr	10	0.6
^{11}B	29	4.7		^{86}Kr	8.3	0.6
^{16}O	35	2.3		^{129}Xe	5.6	0.5

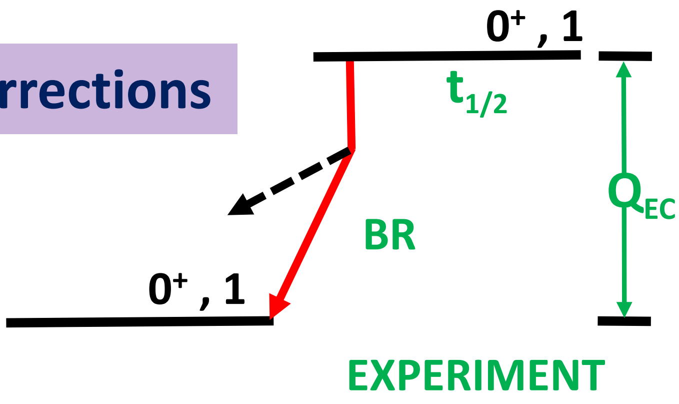


Test of Conserved Vector Current

Pure Fermi transitions

Theory corrections

$$\mathcal{F}t^{0^+\to 0^+} \equiv ft^{0^+\to 0^+}(1+\delta_R')(1+\delta_{NS}^V-\delta_C^V) = \frac{K}{2\,G_F^2 V_{ud}^2 C_V^2 (1+\Delta_R^V)}$$



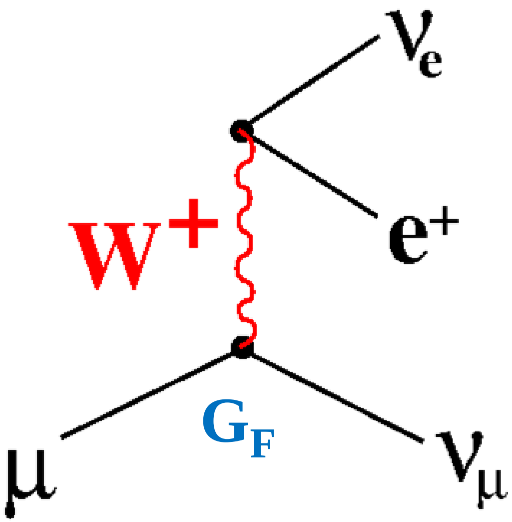
$$t = \ln 2\,\tau\left(\frac{1+\ P_{EC}}{BR}\right)$$

Q_{EC} - Decay Energy ⟺ **mass m (Q^5 dependence; goes into statistical rate calculation (f_V))**

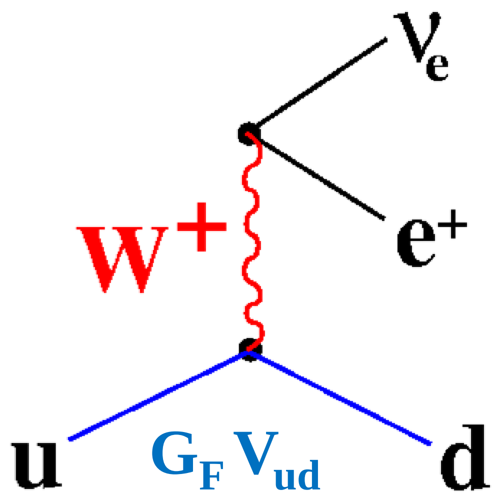
δ_R', δ_{NS}^V, Δ_R^V ⟹ **Radiative Corrections**

δ_C^V ⟹ **Isospin symmetry breaking correction**

Unitarity of CKM Matrix



Leptonic



Semi Leptonic

Cabbibo

Mass Eigen states ≠ Weak Eigen states

(u,d,c,s,t,b) (u′,d′,c′,s′,t′,b′)

Kobayashi and Maskawa: Generalized to 3 quark families

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

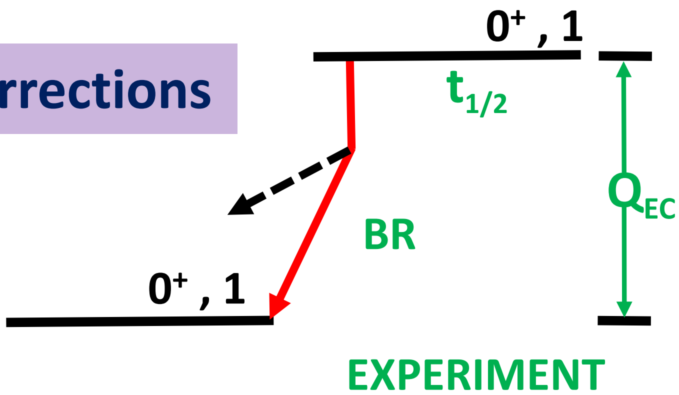
$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 \stackrel{?}{=} 1$$

Research program at TAMUTRAP facility

Pure Fermi transitions

Theory corrections

$$\mathcal{F}t^{0^+\to 0^+} \equiv ft^{0^+\to 0^+}(1+\delta'_R)(1+\delta^V_{NS}-\delta^V_C) = \frac{K}{2\,G_F^2 V_{ud}^2 C_V^2 (1+\Delta^V_R)}$$



$$t = \ln 2\,\tau\left(\frac{1+\ P_{EC}}{BR}\right)$$

Isospin symmetry breaking correction (δ^V_C)

- Mixing of states of same spin
- Difference in *n* and *p* radial wave functions

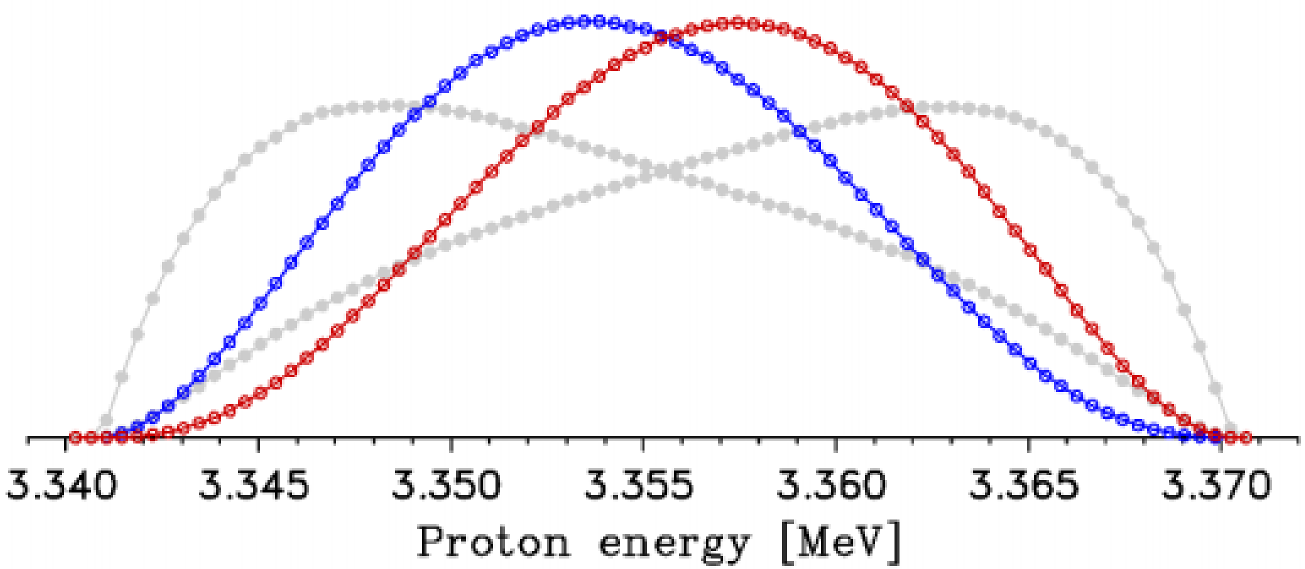
$$\delta_C = \delta_{c1} + \delta_{c2}$$

- Model dependence

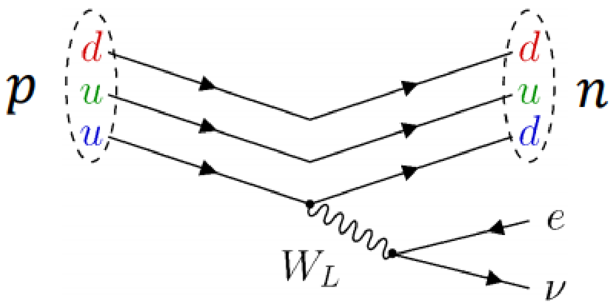
Needs experimental verification for large corrections

Fierz Interference Term

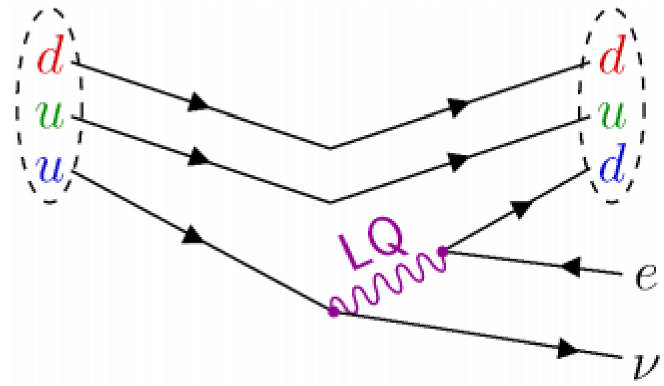
$$\tilde{a} = \frac{a_{\beta\nu}}{1 + 0.1913b}$$



Standard Model



Beyond Standard Model

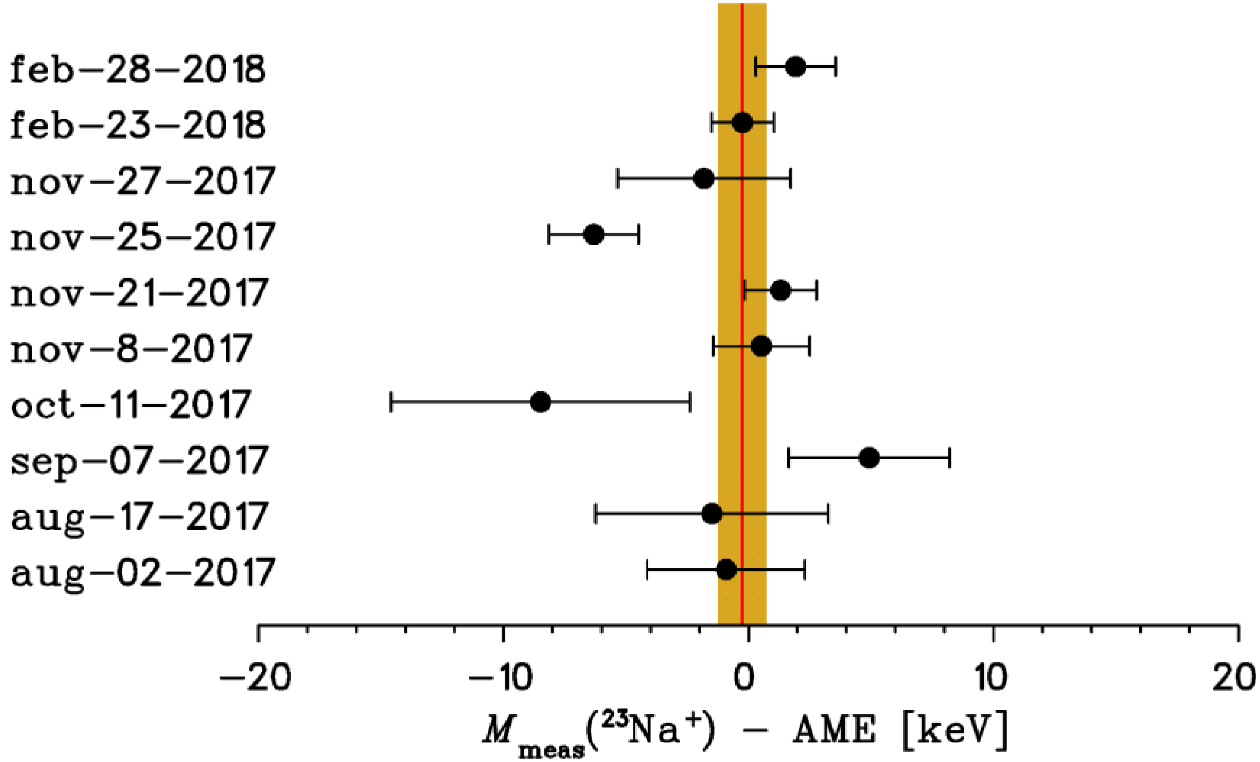


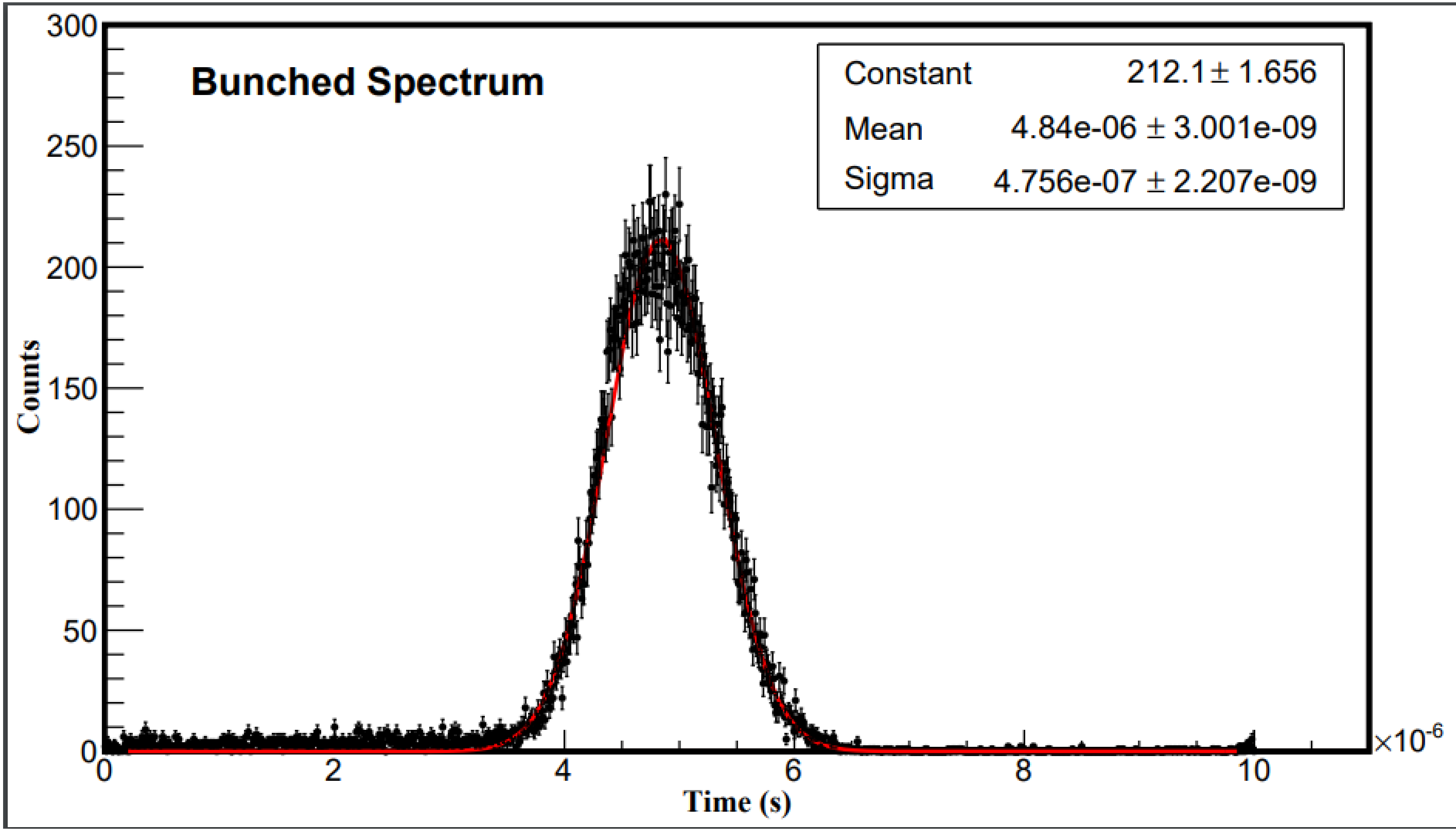
$C_S, C_T \neq 0$

Average difference: −0.26±0.94 keV

with $M(^{23}Na)$ = 21414834.3 keV (2016 AME)

⇒ a 44 ppb measurement




Bunched Spectrum
Constant 212.1 ± 1.656
Mean 4.84e-06 ± 3.001e-09
Sigma 4.756e-07 ± 2.207e-09
Counts
Time (s)
×10-6
0
50
100
150
200
250
300
2
4
6
8
10

C_i	TAMU Analytic	TAMU Simulated	TITAN Analytic	PENTATRAP Analytic	LEBIT Simulated
C_0	$-5e-1$	$-5e-1$	–	–	$8e-1$
C_2	$+5e-1$	$+6e-1$	–	$-2e-2$	$1e0$
C_4	$-7e-6$	$+9e-4$	$-7e-6$	$4e-6$	$2e-3$
C_6	$+6e-6$	$-3e-3$	$+5e-5$	$2e-7$	$-4e-3$
C_8	$-4e-2$	$-4e-2$	–	$-1e-1$	$3e-3$