Stable & Radioactive Ion Beams
at the Texas A&M University
Cyclotron Institute

S. Yennello

LECM 2015

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Scientific priorities

- What is the origin of the elements?
  - ANC measurements of critical (p,γ) and (α,γ) reactions
  - Understanding the structure of light exotic nuclei
- What is the equation of state (EOS) of nuclear (including stellar) matter?
  - Studies of the nuclear compressibility through measurement of the GMR
  - Measurements of the asymmetry dependence of the EOS and the caloric curve
  - Effects of clusterization on the low-density EOS, important to nucleosynthesis in the neutrino wind
- Is there physics beyond the standard model?
  - Testing CVC and CKM unitarity via superallowed $\mathbf{0^+} \rightarrow \mathbf{0^+}$ beta decay
  - Test of isospin symmetry breaking with ^{38}Ca
  - Precision determination of correlations in beta-delayed proton decays
- What are the limits of nuclear stability?
  - Prospects for discovering new super-heavy elements
  - Resonances in exotic neutron-rich nuclei

CI Facts & Figures

$7 M/yr Research and Operations budget

5735 hrs/yr beam on target (3yr ave)

> 100 publications/yr

19

16 Faculty

32 students

14 Postdocs

26 Staff (Research + Ops)

6 TAMU undergraduates

13 REU students

44 collaborating institutions

~100 Radiation effects line users

Aldo Bonasera
PHYSICS
Theoretical Nuclear Physics
- Visiting dist. scientist JAERI-Japan
- Honorary professor Three Gorges University-China
- Full professor - Italy

Cody Folden
CHEMISTRY
Chemistry, Physics and Nuclear Forensics of the heaviest elements
- DOE Early Career Award

Rainer Fries
PHYSICS
Theory of nuclear collisions, quark gluon plasma and hadrons
- NSF Career Award
- IUPAP Young Scientist Prize

Carl A. Gagliardi
PHYSICS
Fundamental interactions and nuclear astrophysics
- Fellow, American Physical Society
- Distinguished Achievement Award in Teaching, AFS, - Texas A&M

John C. Hardy
PHYSICS
Fundamental interactions and exotic nuclei
- Fellow, Royal Society of Canada
- Fellow, American Physical Society
- 2006 Bonner Prize, Nuclear Physics

Dan Melconian
PHYSICS
Fundamental interactions using trapped ion atoms
- Canadian Division of Nuclear Physics PhD thesis award
- DOE Early Career Award

Che Ming Ko
PHYSICS
Theoretical nuclear physics
- Fellow, American Physical Society
- Humboldt Research Award
- Distinguished Achievement, Research AFS, - Texas A&M

Saskia Mioduszewski
PHYSICS
Experimental, high-energy nuclear physics
- Presidential Early Career Award for Scientists and Engineers
- Alfred P. Sloan Foundation Fellowship
- Maria Goeppert Mayer Award

Joseph B. Natowitz
CHEMISTRY
Heavy-ion reaction dynamics and thermodynamics
- ACS Award in Nuclear Chemistry
- Fellow, American Physical Society
- Fellow, American Chemical Society

Ralf Rapp
PHYSICS
Theoretical Nuclear Physics
- Humboldt Bessel Research Award
- NSF CAREER Award
- Texas APS Hyer Award

Grigory Rogachev
PHYSICS
Nuclear Structure, nuclear reactions and nuclear astrophysics
- 1998 Kurchatov Prize
- Russian Research Center Fellowship for Young Researchers

Shalom Shlomo
PHYSICS
Theoretical Nuclear Physics
- RIKEN Eminent Scientist Award
- Fellow, Institute of Physics
- Fellow, American Physical Society

Robert E. Tribble
PHYSICS
Fundamental interactions and nuclear astrophysics
- Alfred P. Sloan Foundation Fellowship
- Fellow, American Physical Society
- Distinguished Achievement, Research AFS, - Texas A&M

Sherry J. Yennello
CHEMISTRY
Heavy-ion reactions and isospin studies
- NSF National Young Investigator
- ACS Garvin-Olin award
- Fellow, APS, ACS and AAAS

Dave H. Youngblood
PHYSICS
Giant resonances and nuclear matter
- Fellow, American Physical Society
- Distinguished Achievement Award in Research, AFS - Texas A&M

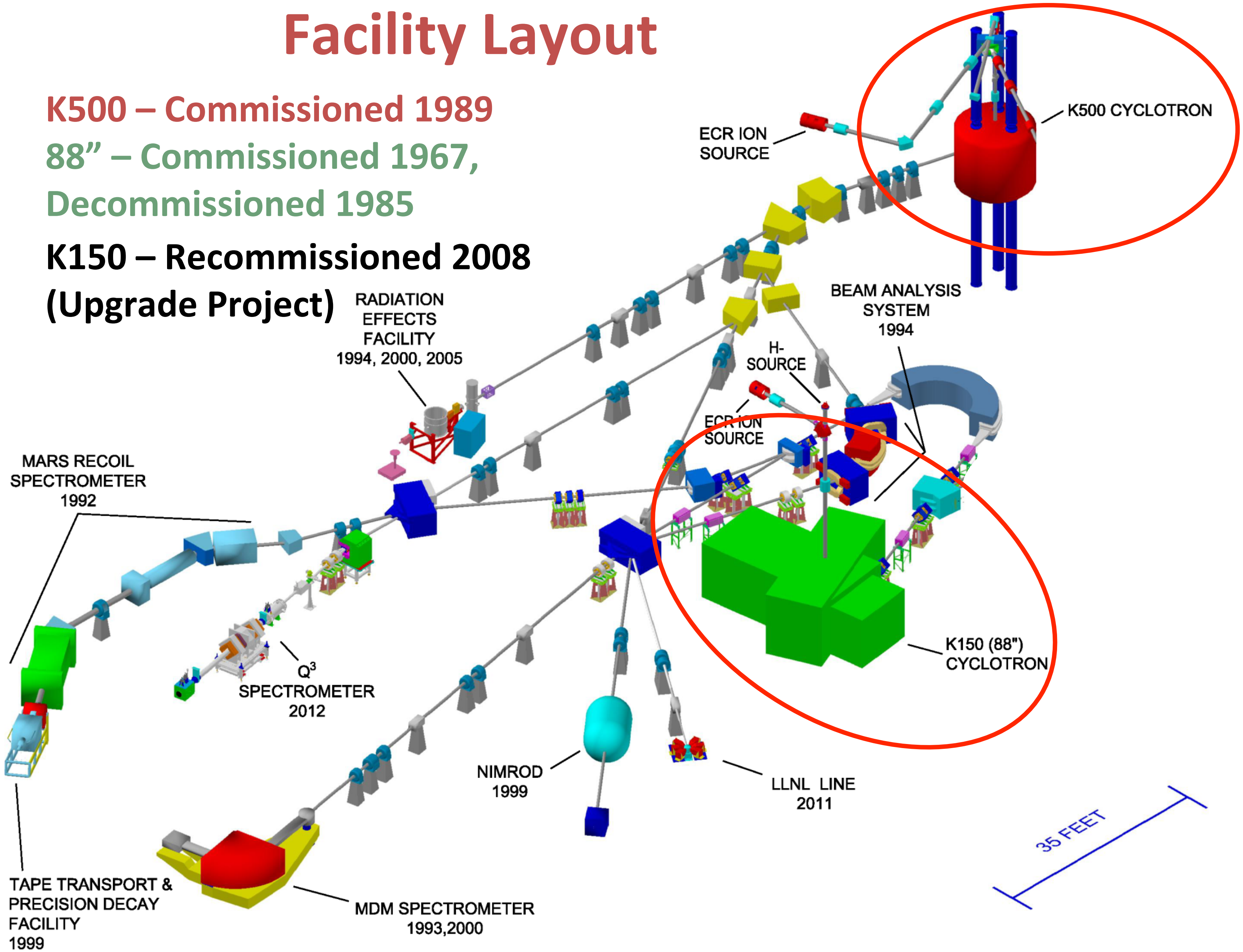
Akram Zhanov
PHYSICS
Theoretical nuclear astrophysics and nuclear reaction theory

Facility Layout

K500 – Commissioned 1989

88" – Commissioned 1967, Decommissioned 1985

K150 – Recommissioned 2008 (Upgrade Project)



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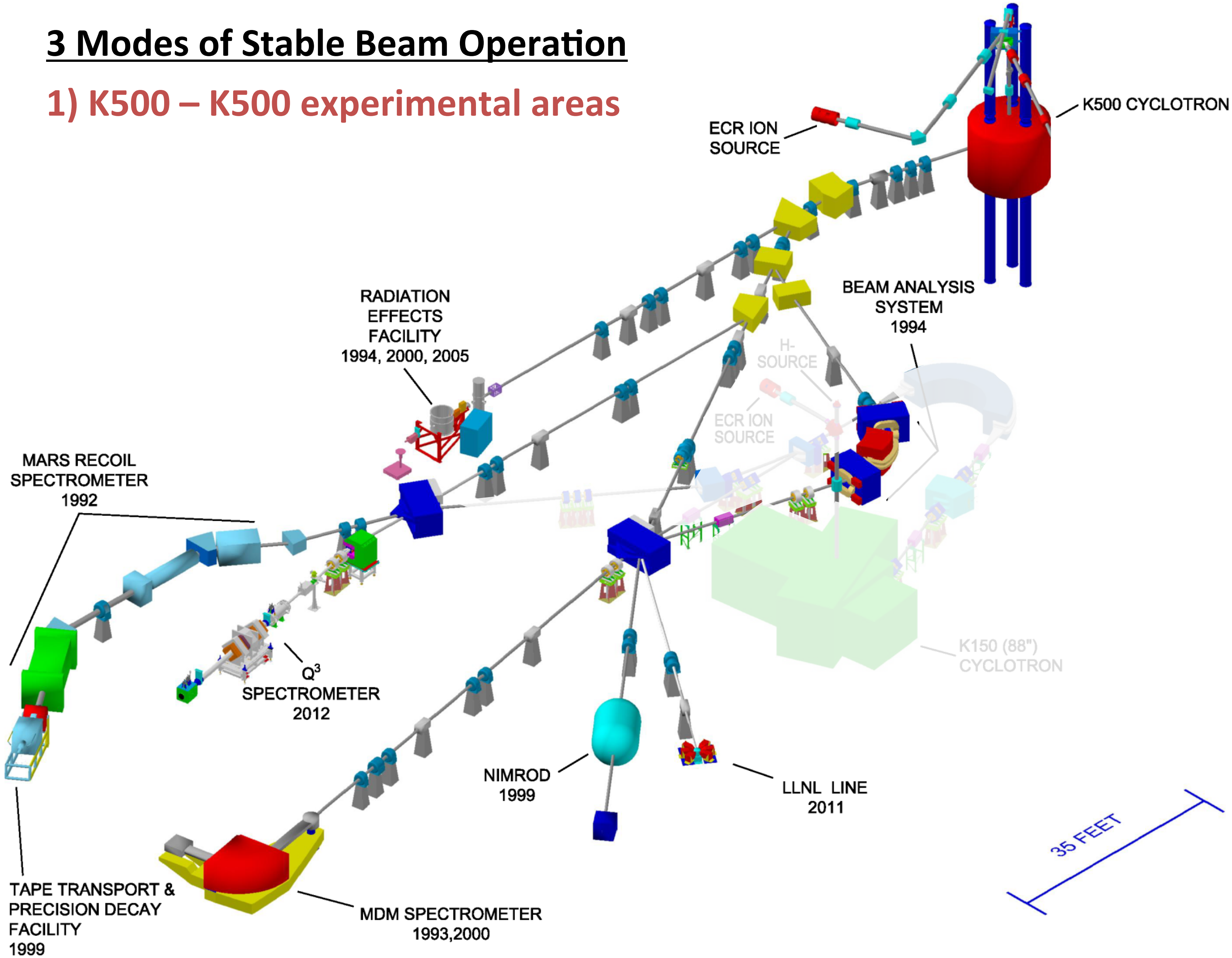
3 Modes of Stable Beam Operation

1) K500 – K500 experimental areas



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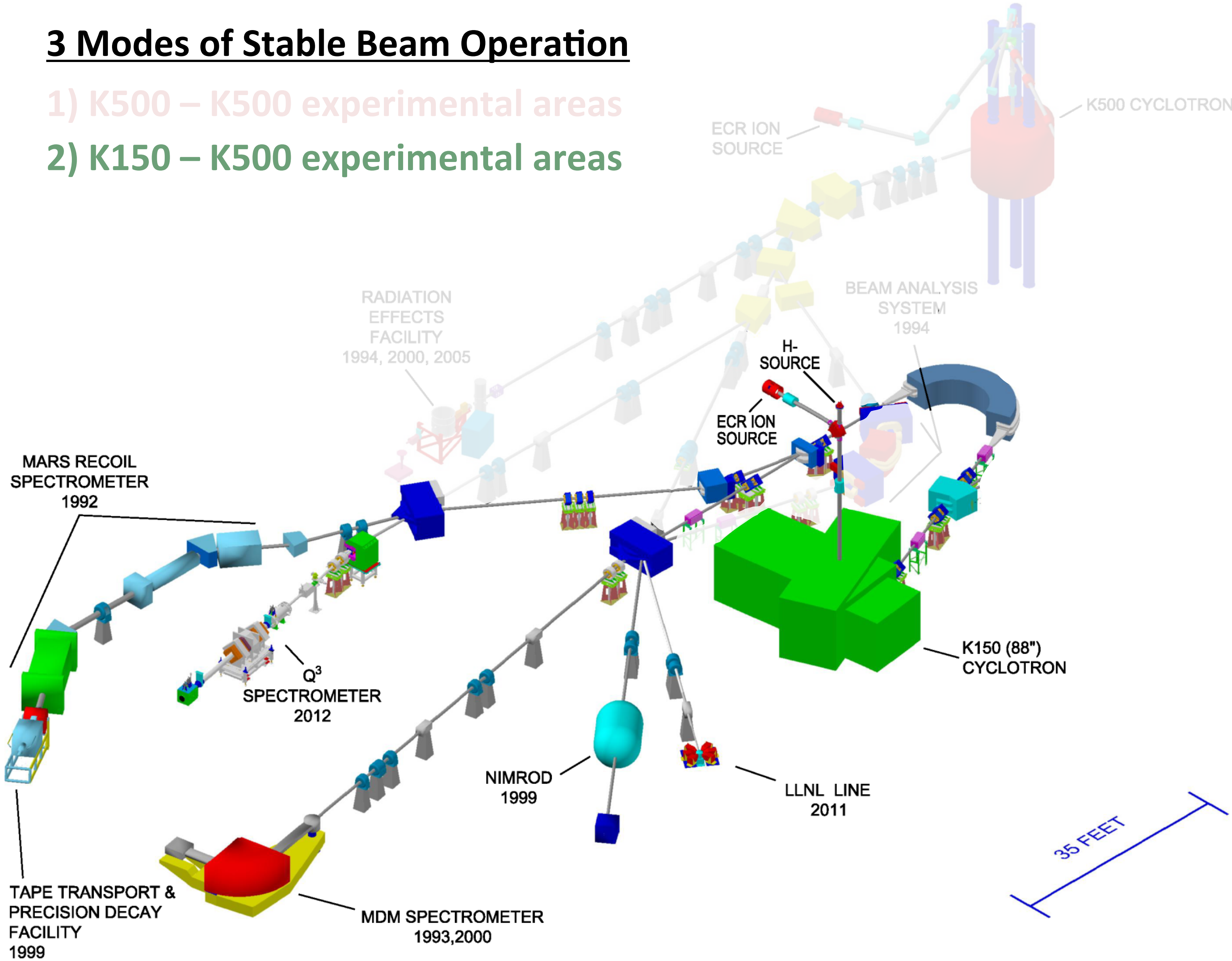
3 Modes of Stable Beam Operation

1) K500 – K500 experimental areas

2) K150 – K500 experimental areas



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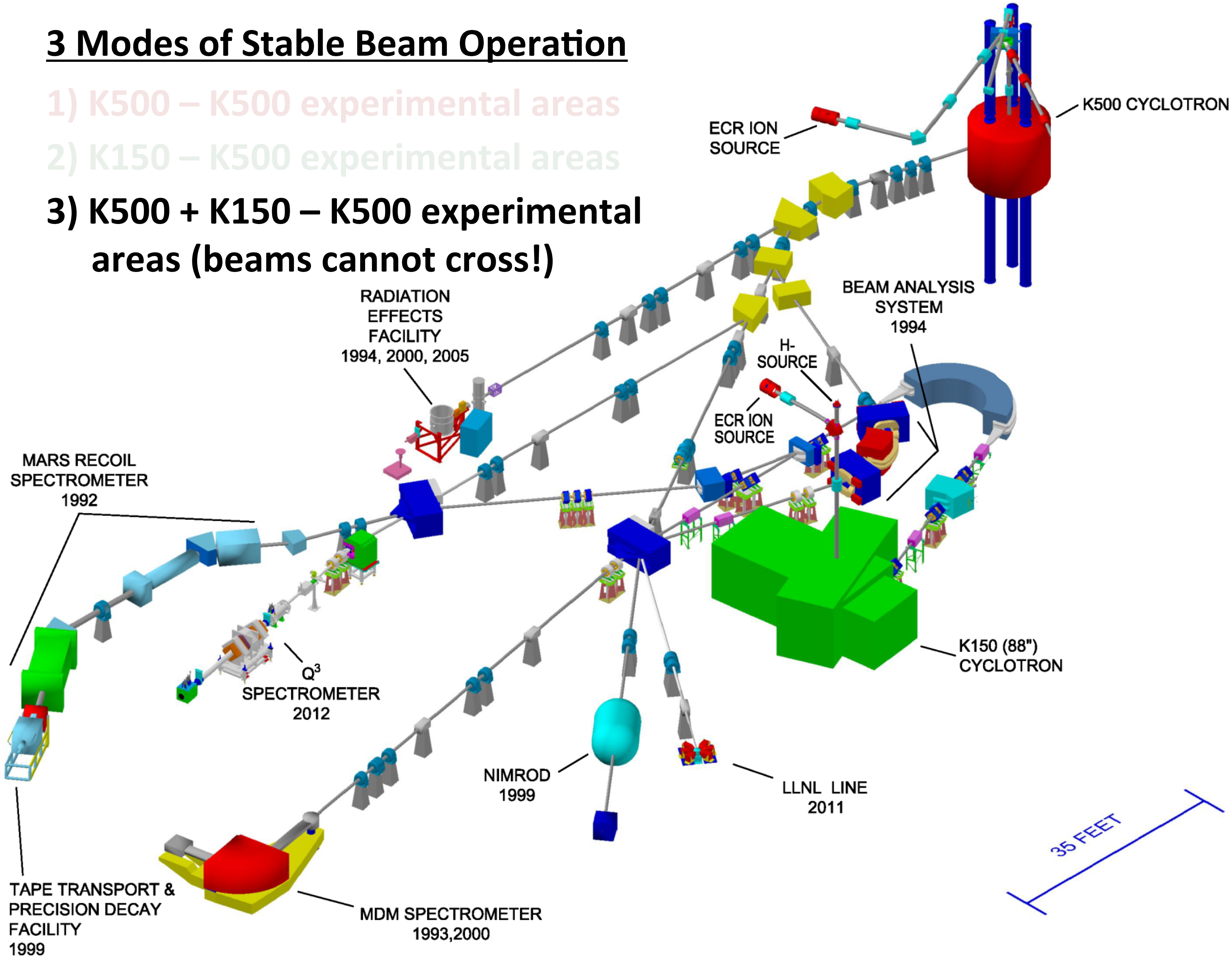
3 Modes of Stable Beam Operation

1) K500 – K500 experimental areas

2) K150 – K500 experimental areas

3) K500 + K150 – K500 experimental areas (beams cannot cross!)



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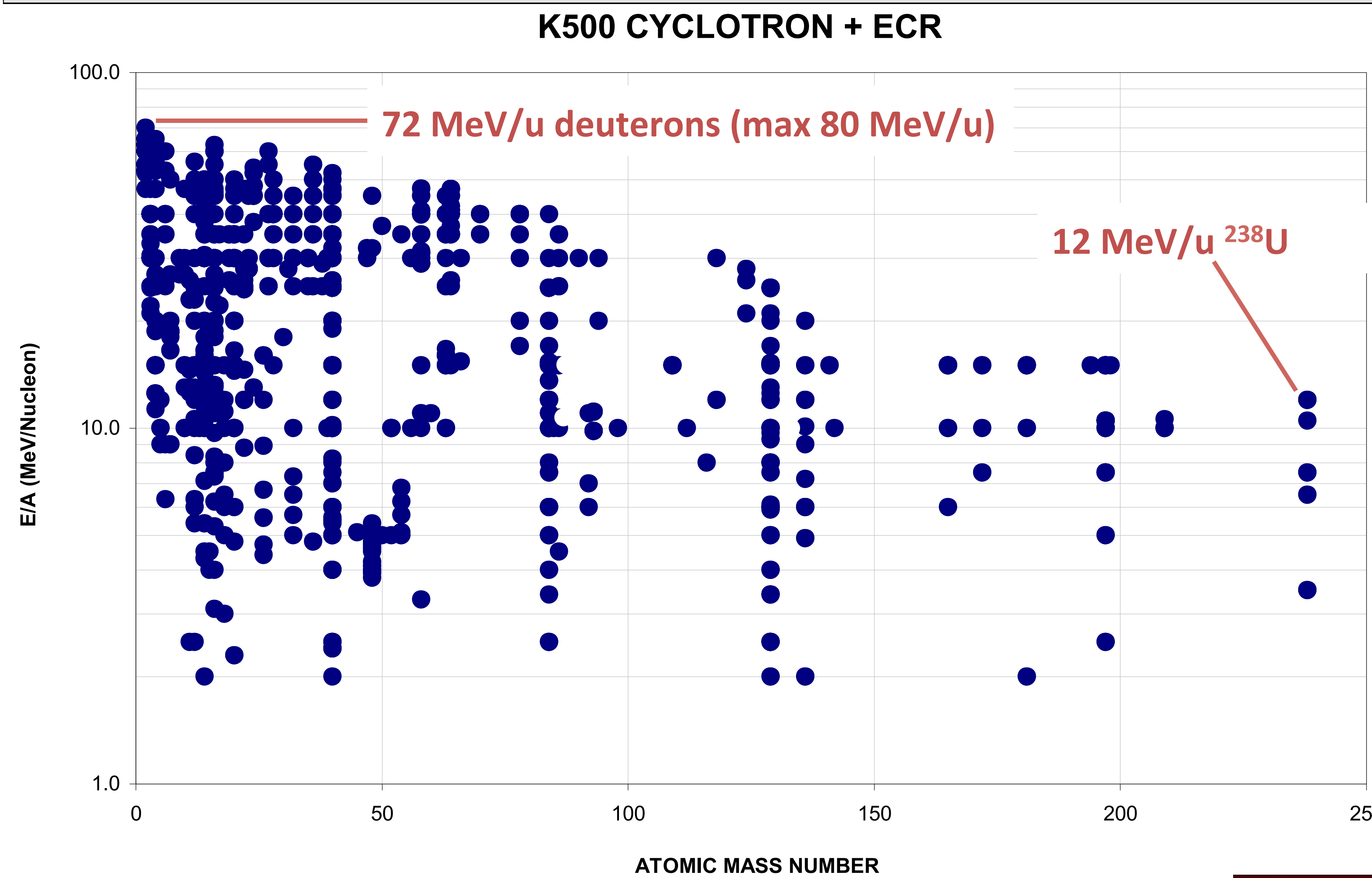
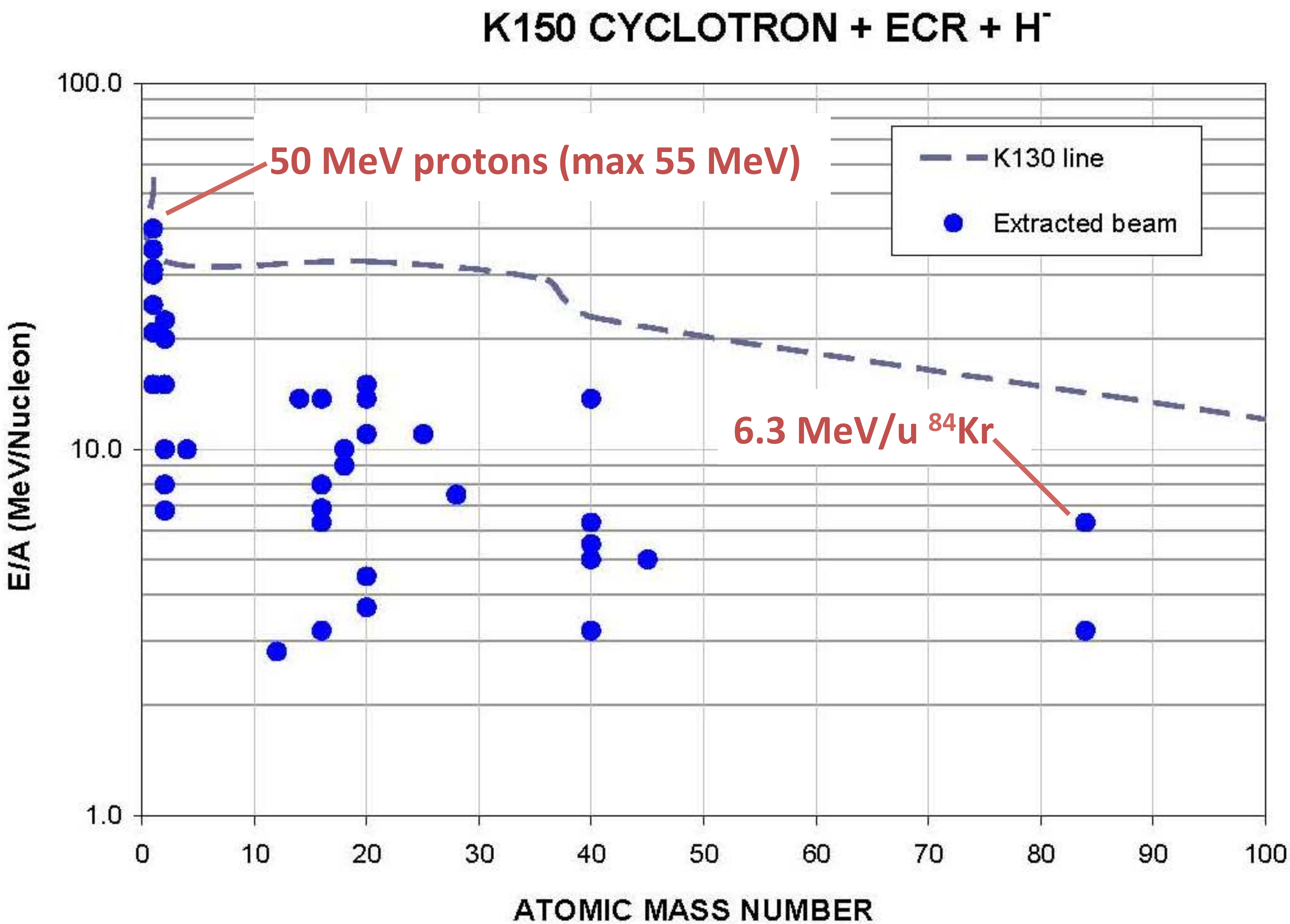
K500 SUPERCONDUCTING CYCLOTRON



K150 CYCLOTRON



Nuclear Science Programs at TAMU

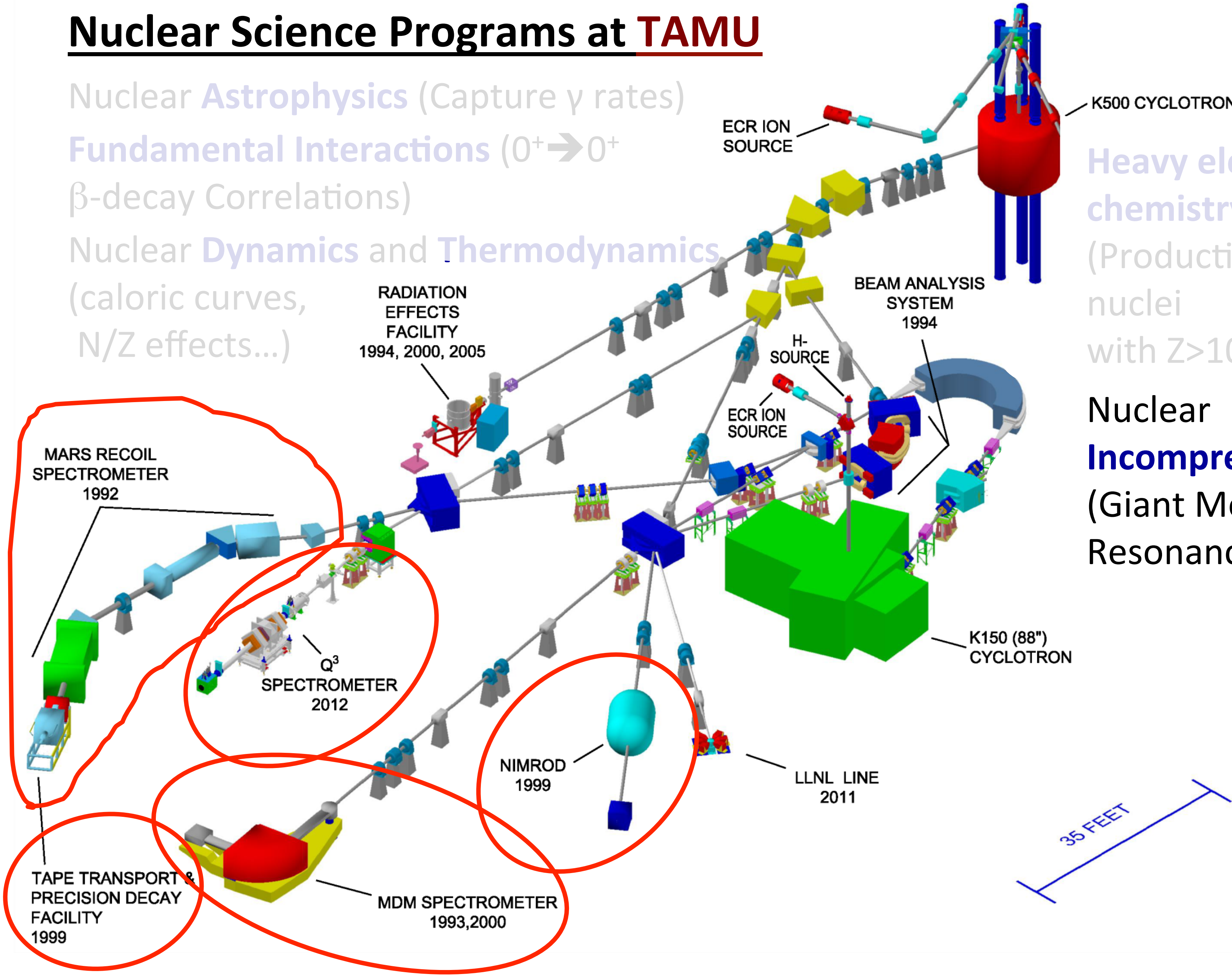
Nuclear **Astrophysics** (Capture γ rates)

Fundamental Interactions ($0^+ \rightarrow 0^+$ β-decay Correlations)

Nuclear **Dynamics** and **Thermodynamics** (caloric curves, N/Z effects...)

Heavy element chemistry (Production of nuclei with Z>100. . .)

Nuclear **Incompressibility** (Giant Monopole Resonance)



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Present Research Program

Program	Project	Leaders
Nuclear Incompressibility	Giant Resonances	Youngblood
Fundamental Interactions	$0^+ \rightarrow 0^+$ β decay	Hardy, Melconian (Gagliardi, Tribble)
Astrophysics	Capture γ rates	Rogechev, Tribble (Gagliardi)
RHI	STAR	Mioduszewski, Gagliardi (Tribble)
Nuclear Dynamics and Thermodynamics	Reactions with exotic beams Properties of hot nuclei	Natowitz, Yennello
Nuclear Structure	Resonances in light exotic nuclei	Rogechev
Heavy elements	Production of nuclei with Z>100	Folden
Theory	Reaction Dynamics	Bonasera
	Nuclear Response	Shlomo
	Few-body systems Nuclear astrophysics	Zhanov
	Relativistic Heavy Ion Reactions	Fries, Ko, Rapp

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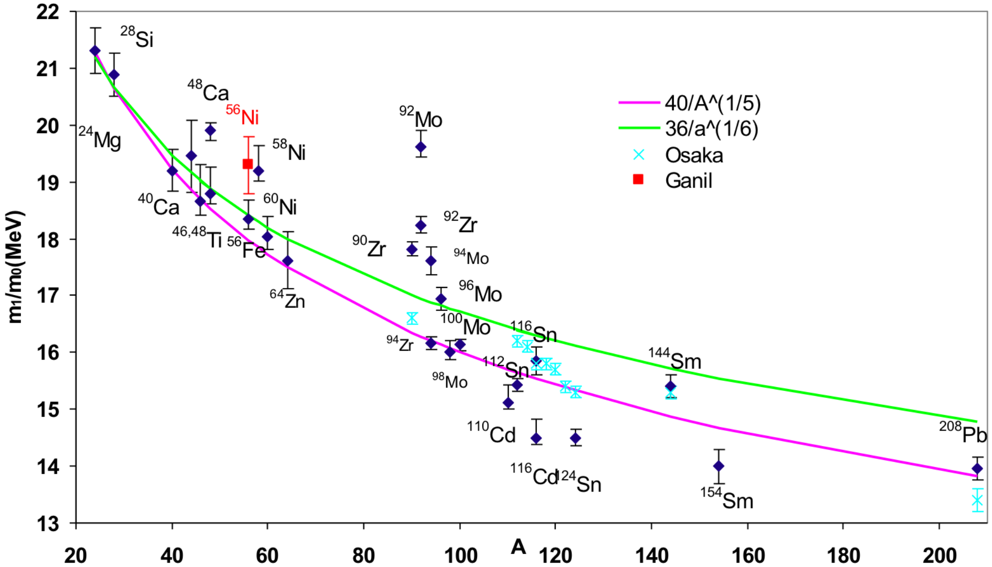
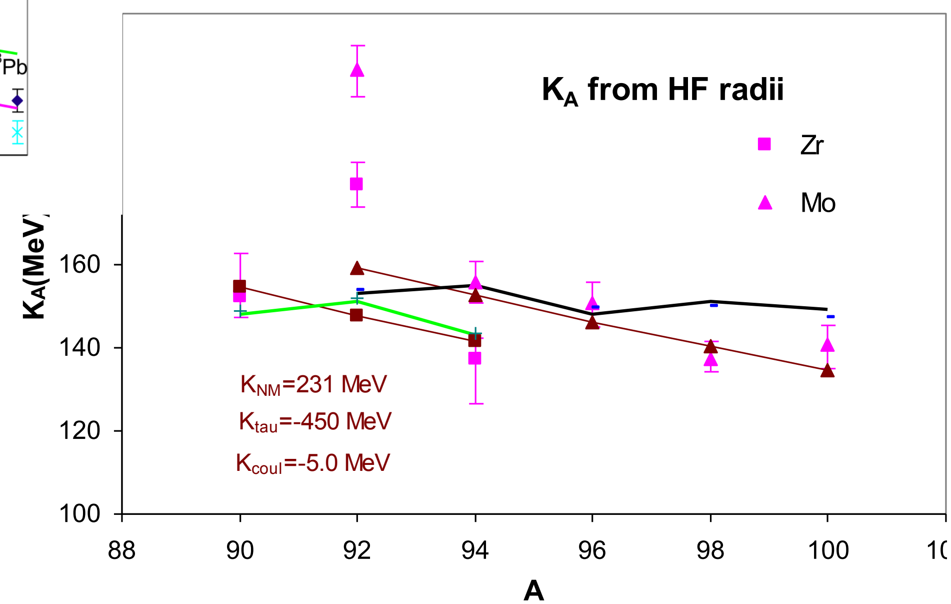
Current State of Published E_{GMR}



Lots of Variation in energy of GMR: Ca Isotopes; Ni isotopes; Zr-Sn isotopes; (^{154}Sm is deformed)

Mass 92 Issue

Unexpected characteristics of the isoscalar monopole resonance in the $A \approx 90$ region: Implications for nuclear incompressibility



Green Line-Zr isotopes HF-RPA KDE0v1(K_{NM}=227.5 MeV).

Black Line-Mo isotopes HF-RPA KDE0v1(K_{NM}=227.5 MeV).

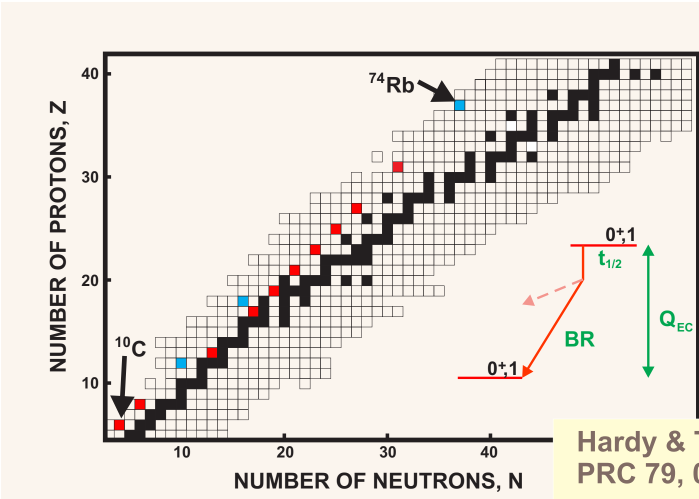
Brown Line-Leptodermous Expansion

K_A for ^{92}Mo 8 σ above Calculation

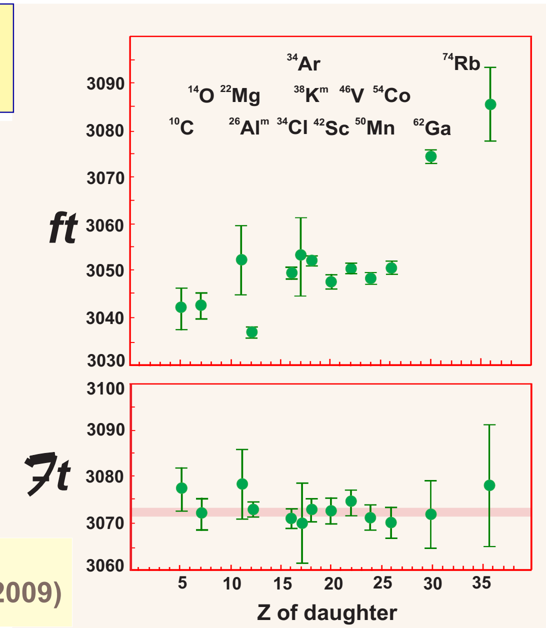
K_A for ^{92}Zr 4 σ above Calculation

SUPERALLOWED $0^+ \rightarrow 0^+$ BETA DECAY

$$\mathcal{F}t = ft\,(1 + \delta'_R)[1 - (\delta_C - \delta_{NS})] = \frac{K}{2G_V^2\,(1 + \Delta_R)}$$



Hardy & Towner
PRC 79, 055502 (2009)



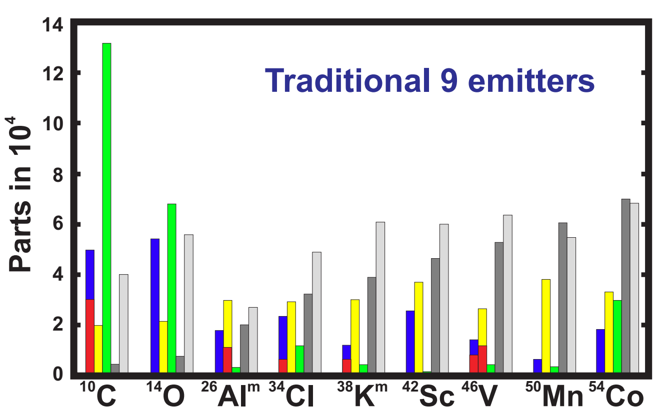
- CVC verified
- V_{ud} = 0.97425(22)

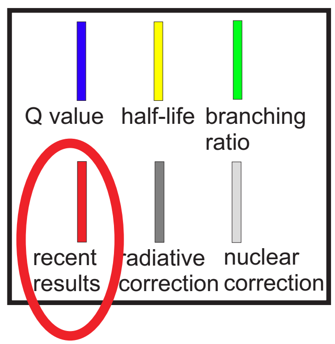
CKM unitarity test:

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9999(6)$$

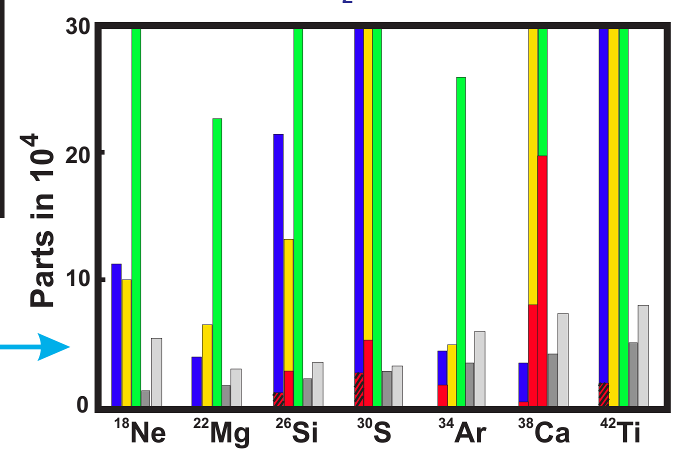
Improvements since 2009

(Most done at, or in collaboration with TAMU)



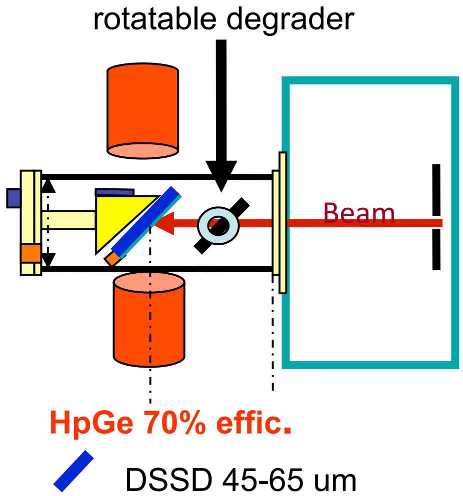


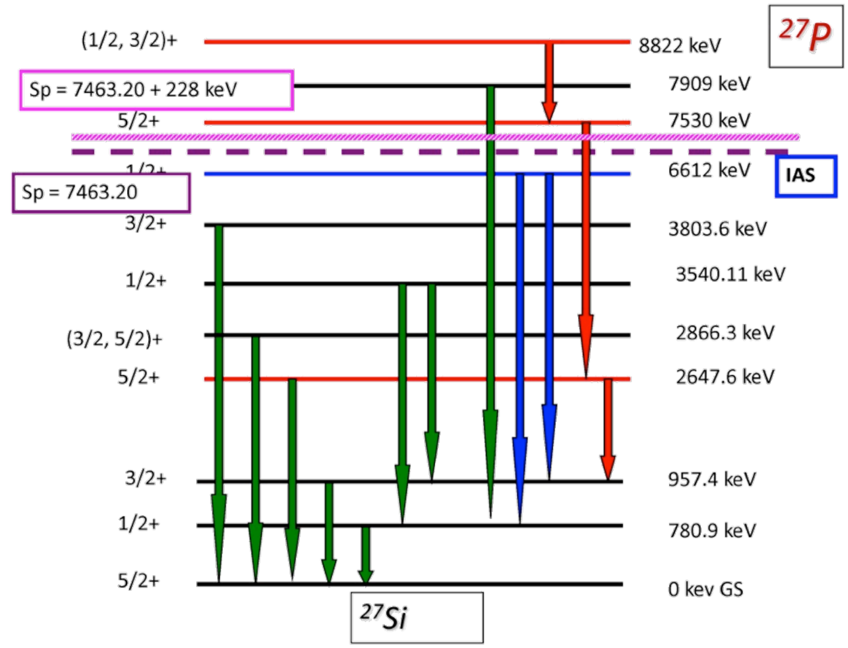
Uncertainty budgets

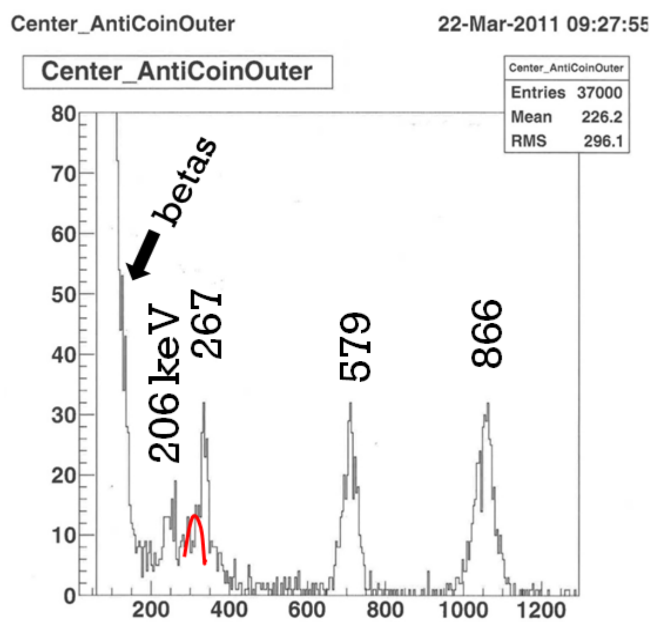


MARS Implantation-Decays for Nuclear Astrophysics

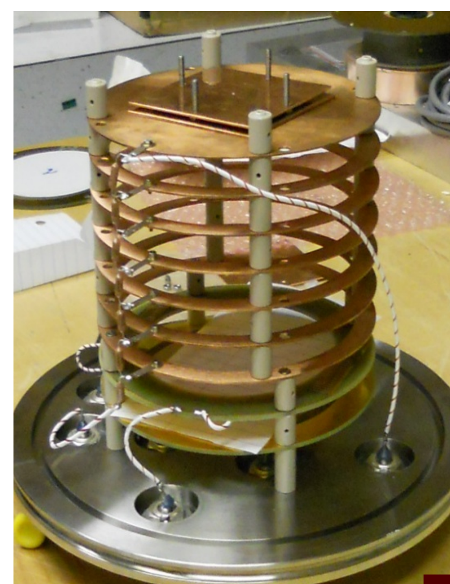
β-delayed γ spectroscopy







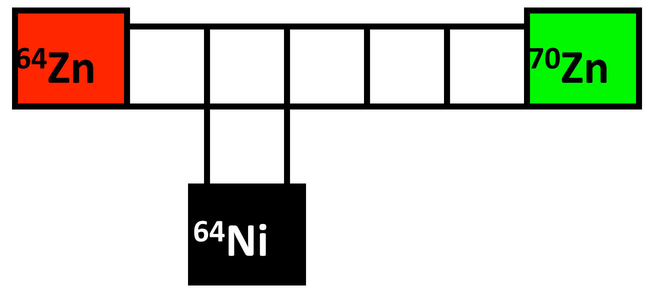
β-delayed p-decay of ^{23}Al with GEM detector



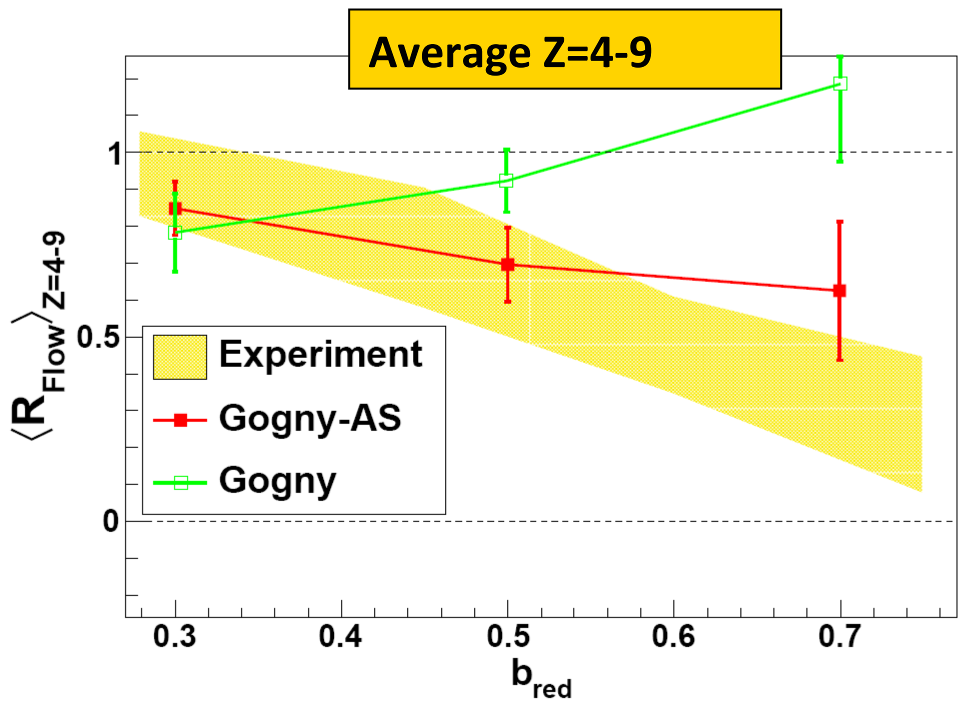
Transverse Collective Flow Sensitivity to $E_{asym}(\rho)$

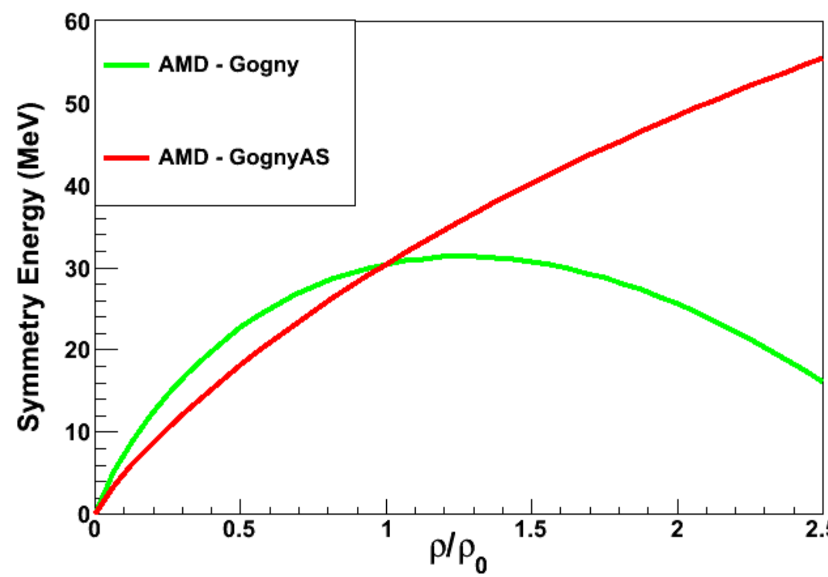
The transverse collective flow of intermediate mass fragments from the reactions of ^{64}Zn + ^{64}Zn, ^{70}Zn + ^{70}Zn, and of ^{64}Ni + ^{64}Ni at 35 MeV/nucleon are consistent with predictions from the ASY-Stiff, Gogny-AS interaction in AMD and inconsistent with the ASY-Soft Gogny interaction.

Comparison to AMD-GEMINI Model



$$R_{Flow} = \frac{\overline{\langle Px/A\rangle}_{^{64}Zn} - \overline{\langle Px/A\rangle}_{^{70}Zn}}{\overline{\langle Px/A\rangle}_{^{64}Ni} - \overline{\langle Px/A\rangle}_{^{70}Zn}}$$





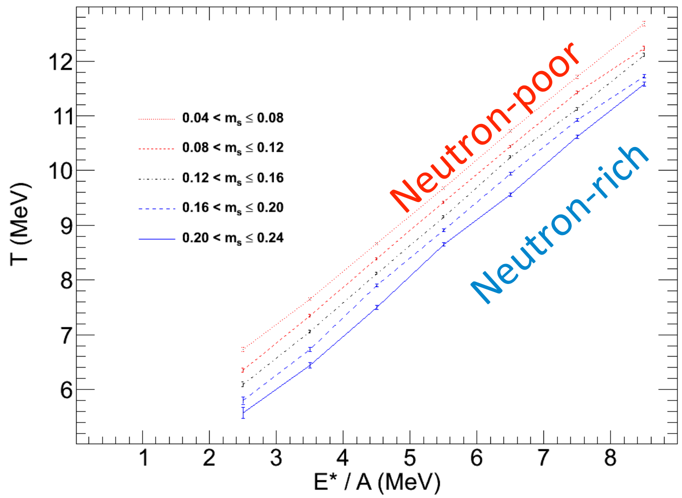
Kohley, PRC 2011

Asymmetry Dependence of Thermodynamic Properties

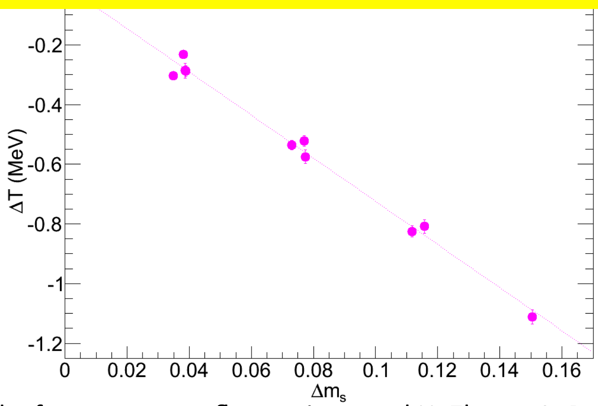
$m_s = N - Z/A$

Heavy-Ion collisions around the Fermi energy.
Measure charged particles & neutrons in NIMROD-ISiS.

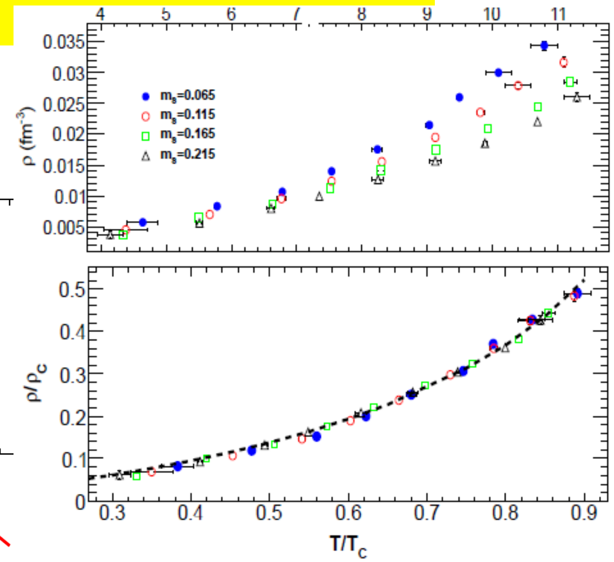
Caloric curves observed to depend on asymmetry of the emitting source

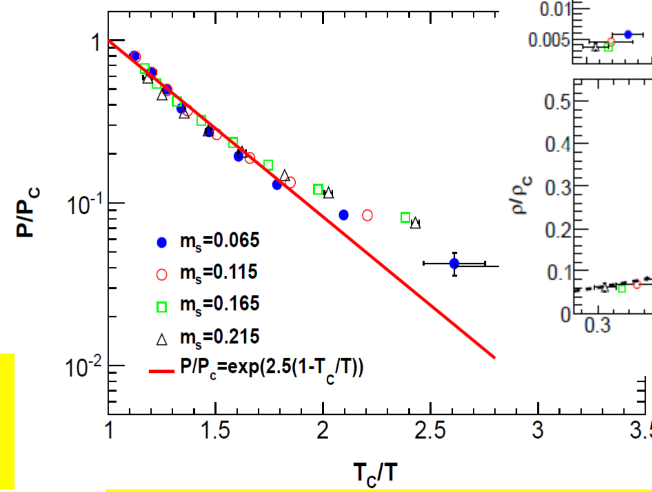


The shift in temperature is linear with the change in asymmetry



Extraction of critical parameters T_c, ρ_c, P_c using scaling laws





Critical point: depends on asymmetry

Table 1: Critical values and thermodynamic quantities for the four m_s bins.

m_s	T_c (MeV)	ρ_c (fm^{-3})	P_c (MeV/fm^3)	$P_c/\rho_c T_c$	ΔH (MeV)
0.065	12.12 ± 0.39	0.070 ± 0.006	0.211 ± 0.002	0.25 ± 0.02	31.50 ± 1.01
0.115	12.51 ± 0.35	0.066 ± 0.005	0.209 ± 0.001	0.25 ± 0.02	32.53 ± 0.90
0.165	13.11 ± 0.30	0.064 ± 0.004	0.232 ± 0.001	0.27 ± 0.02	31.46 ± 0.71
0.215	13.39 ± 0.21	0.061 ± 0.002	0.258 ± 0.002	0.31 ± 0.01	32.13 ± 0.50

T and ρ from quantum fluctuations, a al H. Zheng, A. Bonasera, nucl-th/1112.4098 (2011)

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Test of Astrophysical Equations of State Equilibrium Constant, K_α

- Many tests of EOS are done using mass fractions. Various calculations include various different competing species., if all relevant species are not included, mass fractions are not accurate.

- Equilibrium constants, e.g.,

$$K_c = \frac{\rho(A,Z)}{\rho_p^Z \rho_n^{(A-Z)}}$$

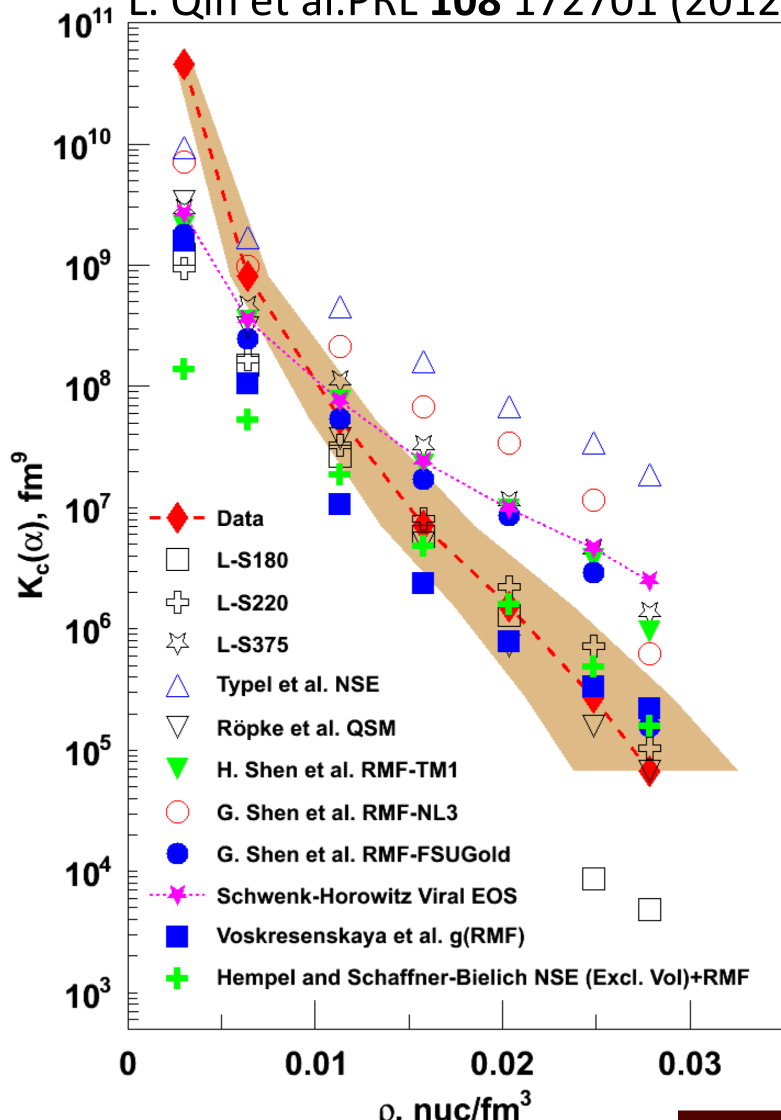
should be independent of proton fraction and choice of competing species.

- Models converge at lowest densities, but many are significantly above data at higher density

- Lattimer & Swesty with K=180, 220 show reasonable agreement with data

- QSM with in-medium binding energy shifts works well

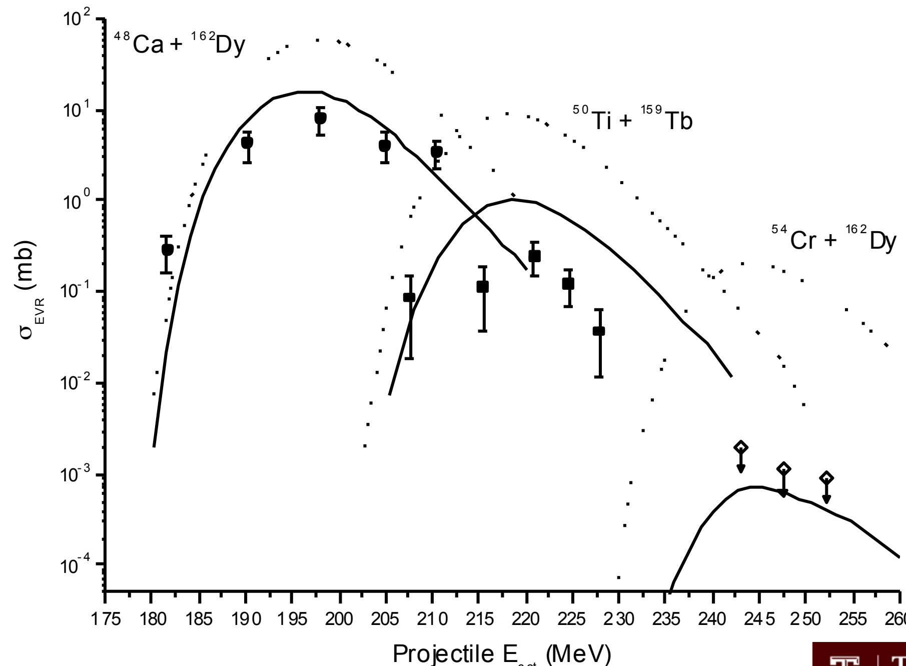
L. Qin et al.PRL **108** 172701 (2012).



Heavy Element Reaction Studies at the Cyclotron Institute

- We are working to better understand the mechanism of the “warm fusion” reaction, which was used to discovered elements 113-118.
- Our focus has been on determining which projectile is most likely to lead to the next new element.

- Preliminary results (right) suggest a substantial drop in cross section for proj. above ^{48}Ca.
- $^{45}Sc + {}^{159}Tb$, ^{162}Dy data analysis in progress.



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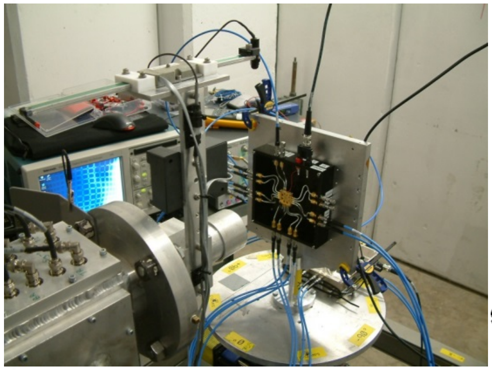
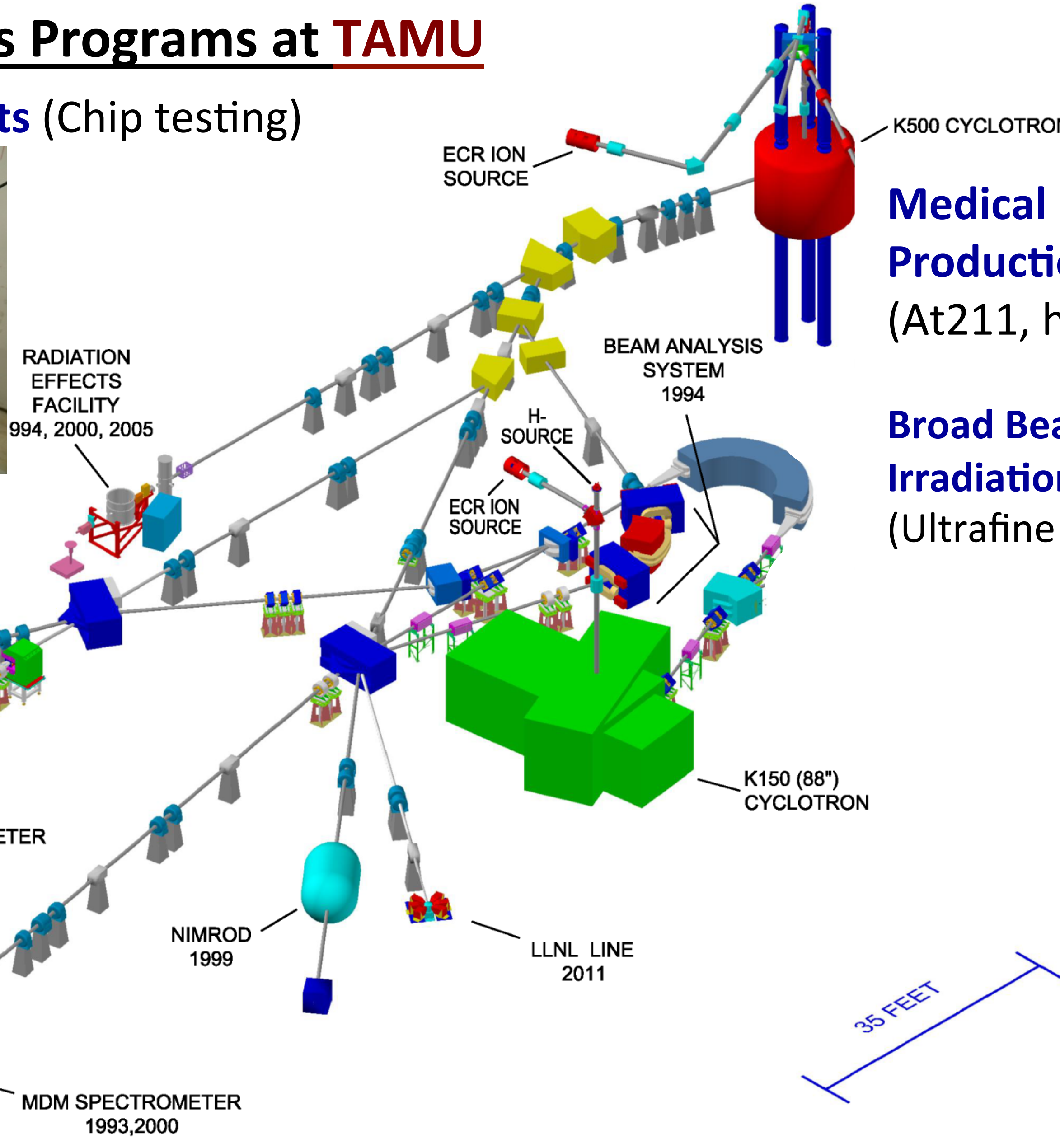
Applied Physics Programs at TAMU

Single Event Effects (Chip testing)





Medical Isotope Production
(At211, high E - α)

Broad Beam Irradiation
(Ultrafine filters)

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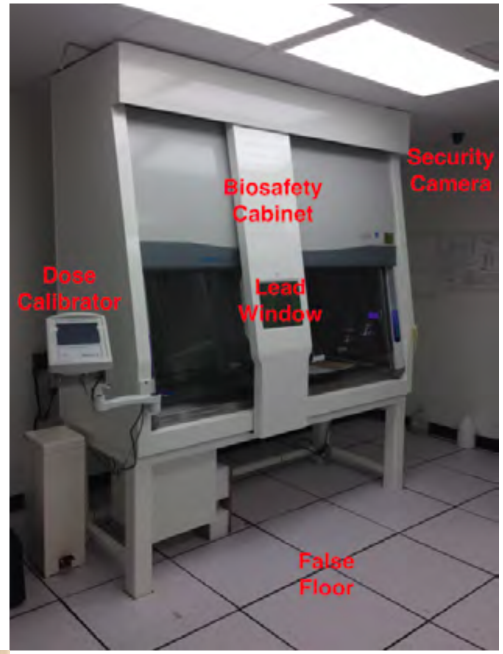
Isotope production and research activities

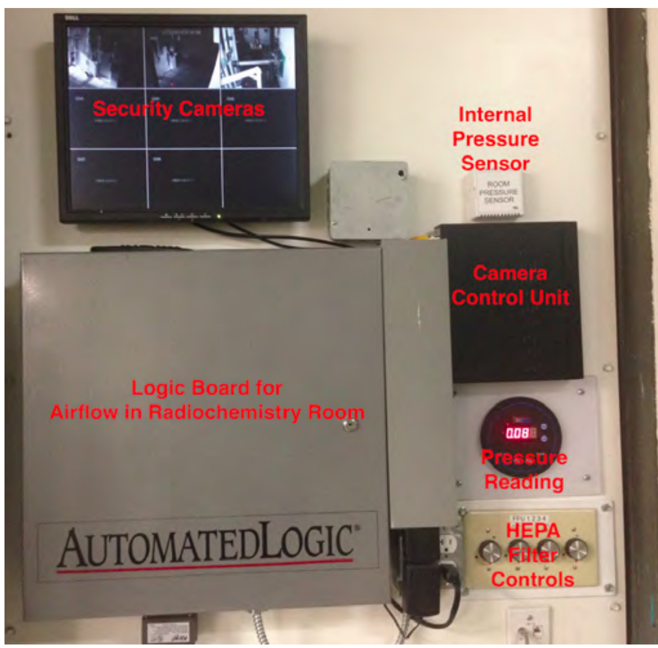
Successful proof of principle for 211At

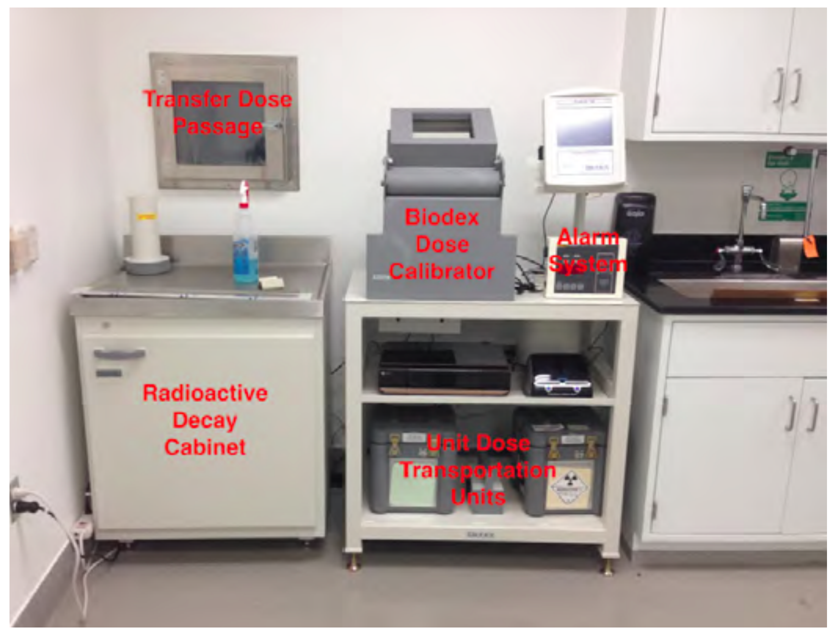
“Preliminary Production of ^{211}At at the Texas A&M University Cyclotron Institute”, T. Martin et al, Health Physics 107, 1 (2014)

Next steps

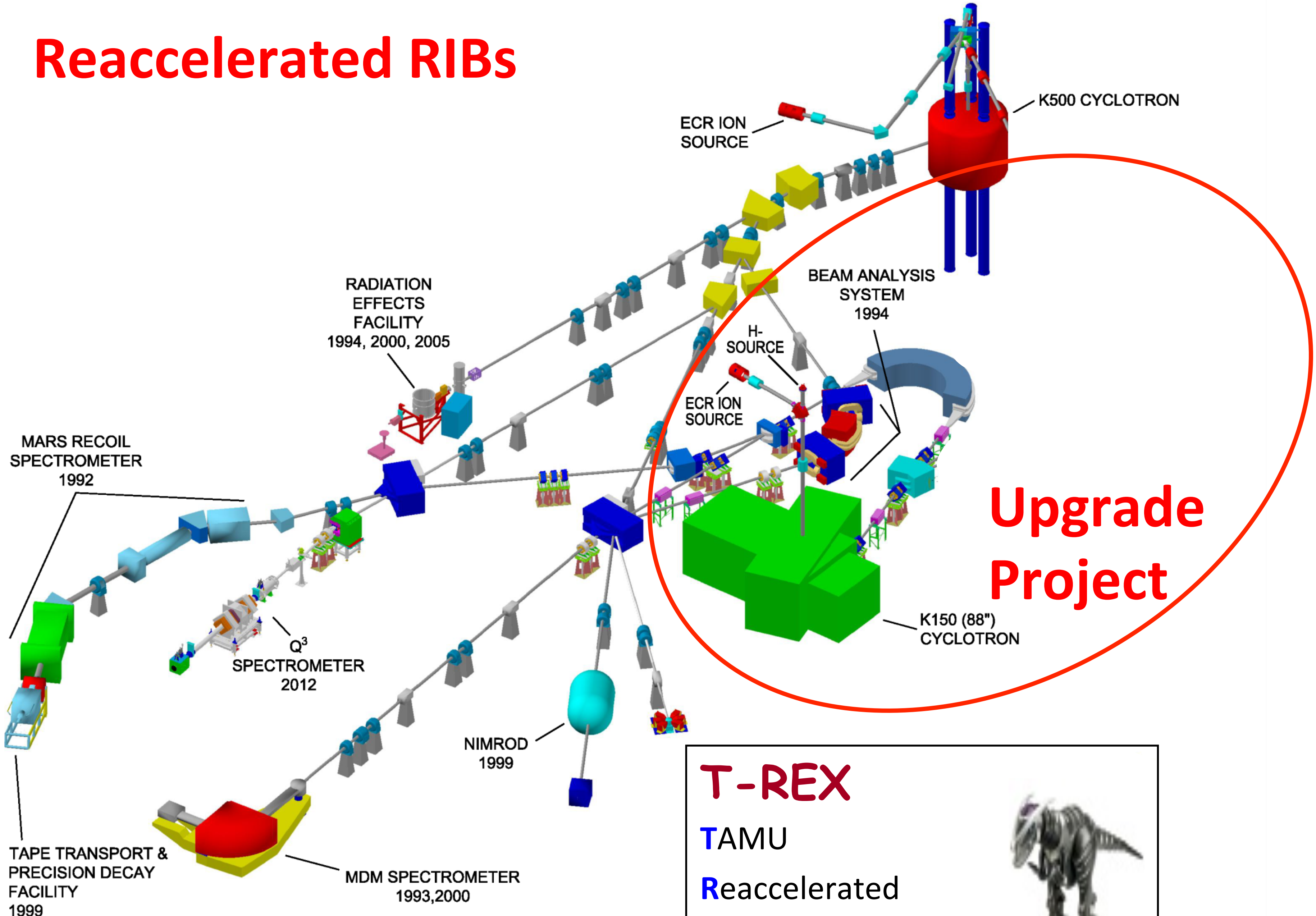
- Production target
- Separation procedure







Reaccelerated RIBs



T-REX

TAMU

Reaccelerated

Exotics

The Upgrade Project

- Production of reaccelerated ion beams (RIBs): two cyclotrons – K500 (superconducting) and 88” (K150)

- 88” (K150) – used as driver for acceleration of high intensity primary beams: proton, heavy ions

- K500 – used for re-acceleration

- Light Ion Guide – used for production of neutron deficient RIBs A(p,xn)B reactions

- Heavy Ion Guide – used for both neutron deficient and proton deficient RIBs (deep inelastic and nuclear fragmentation reactions)

Two Methods for making RIBs

<u>1- Heavy Ion Guide</u>

•Deep inelastic scattering of intense heavy ion beams at 12-15 MeV/u on neutron rich targets

•Big Sol used as front end (clean up) separator

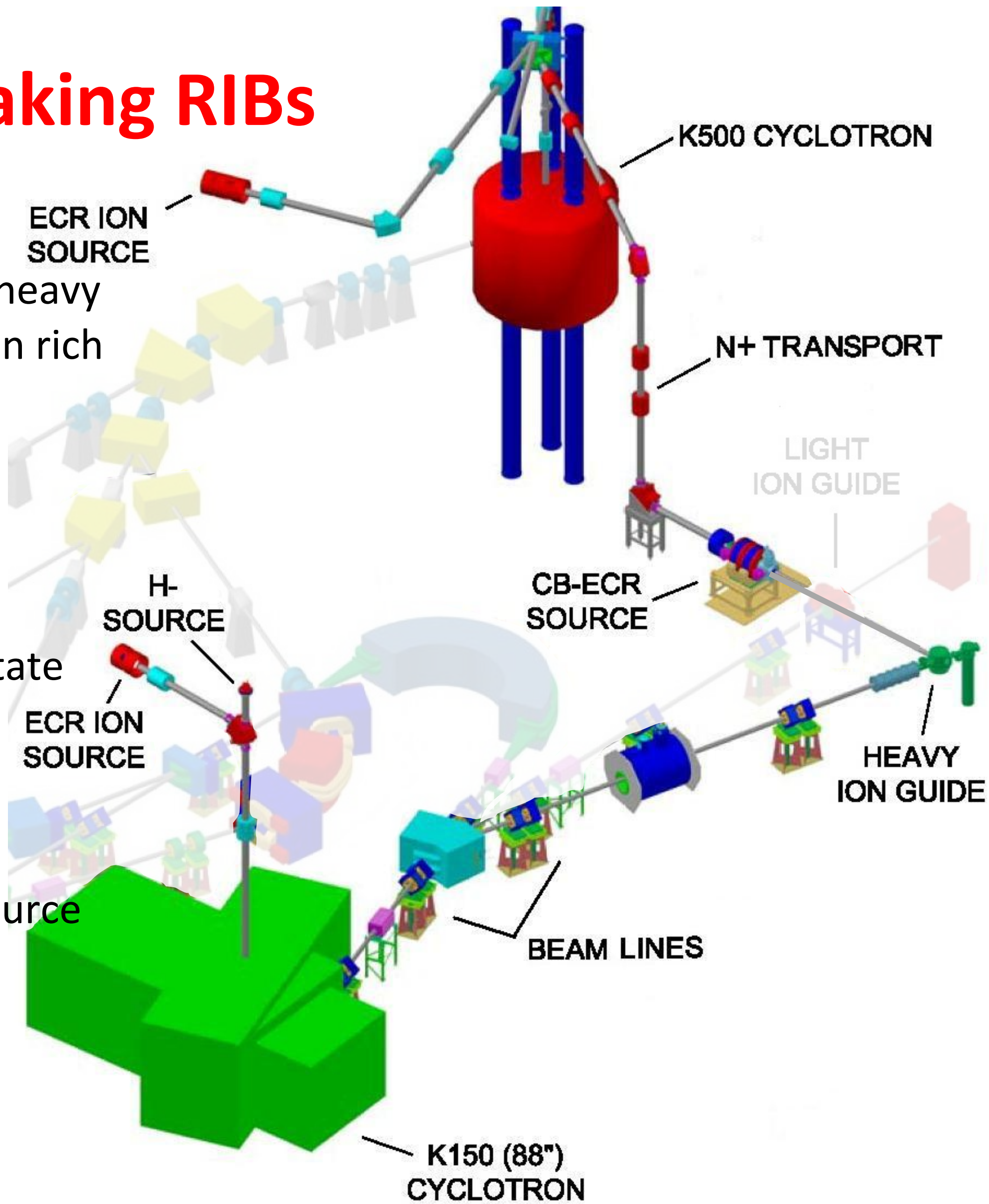
•Degrader system and ANL (He) gas catcher, thermalize RIBs, charge 1+ state

•Ortho-TOF used for diagnostics and

beam tuning

•LEBT transport RIBS to CBECR ion source

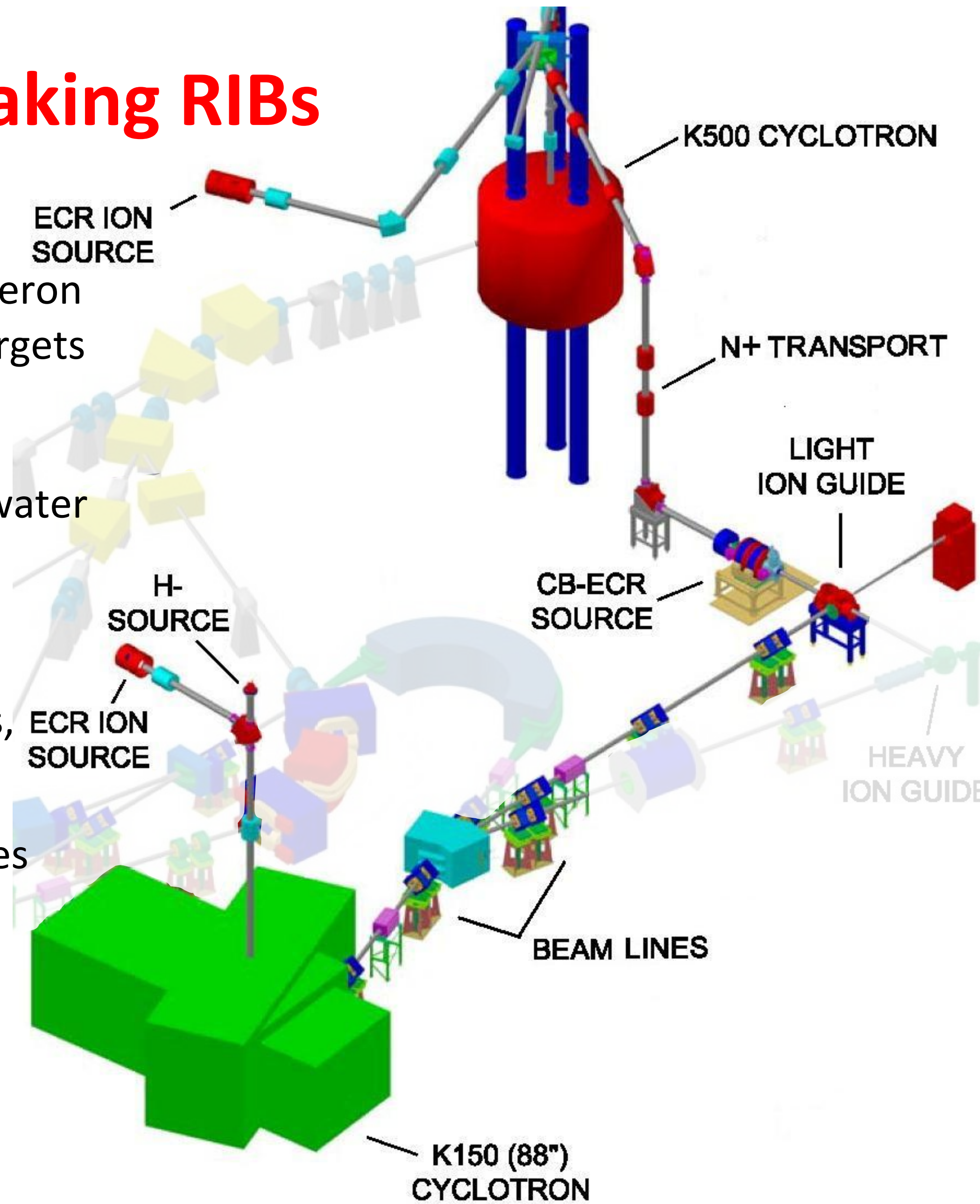
•First RIB: ^{38}S via $^{40}Ar \rightarrow {}^{64}Ni$



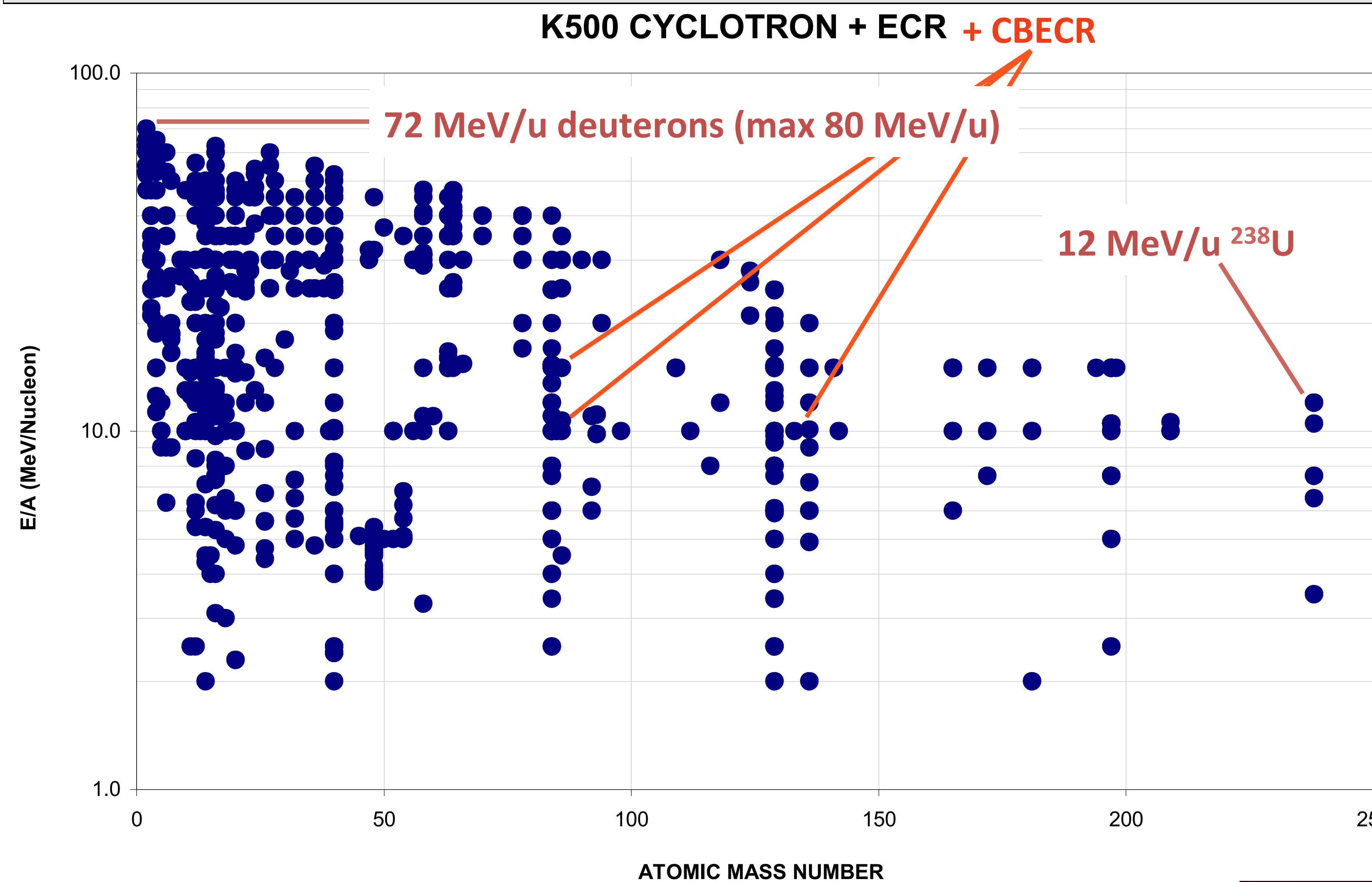
Two Methods for making RIBs

<u>2- Light Ion Guide</u>

- Intense (10-20 μA) proton and deuteron beams at 30-50 MeV/u on various targets
- Beams created negative ion source
- Primary beam stopped aluminum, water cooled beam dump
- p,n reactions create RIBs
- Dense (He) gas cell thermalizes RIBs, charge 1+ state
- Differential pumping and SPIG moves RIBs to CBECR ion source
- First RIB: ^{27}Si : ^{27}Al(p,n) ^{27}Si



K500 SUPERCONDUCTING CYCLOTRON



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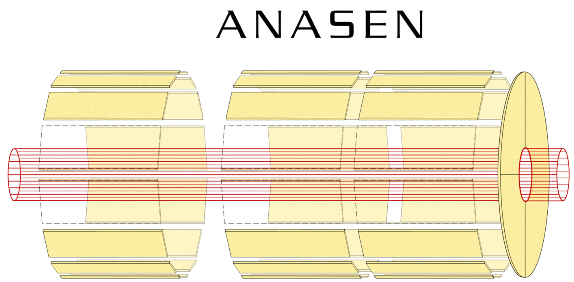
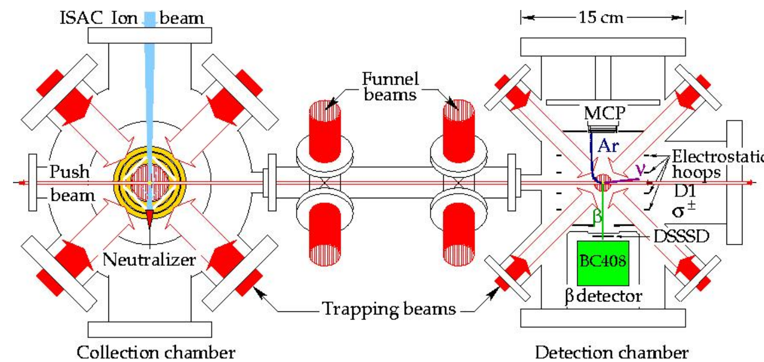
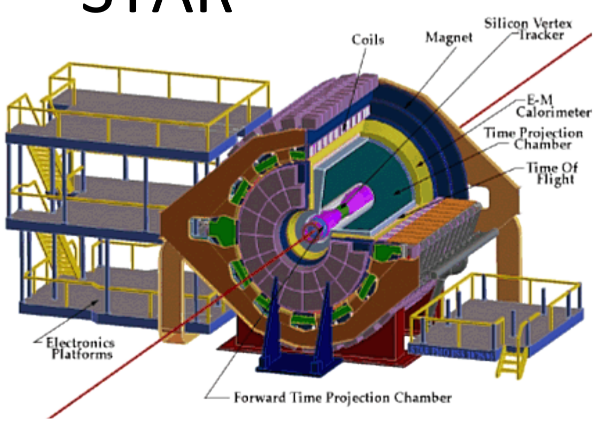
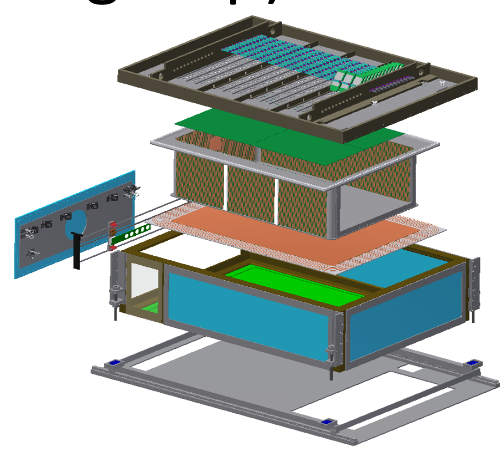
External collaborations





- NSCL - ANASEN
- TRINET collaboration @TRIUMF(beta decays)
- SAMURAI collaboration at RIKEN
- Jyvaskyla (mass measurements w/ penning trap)
- STAR

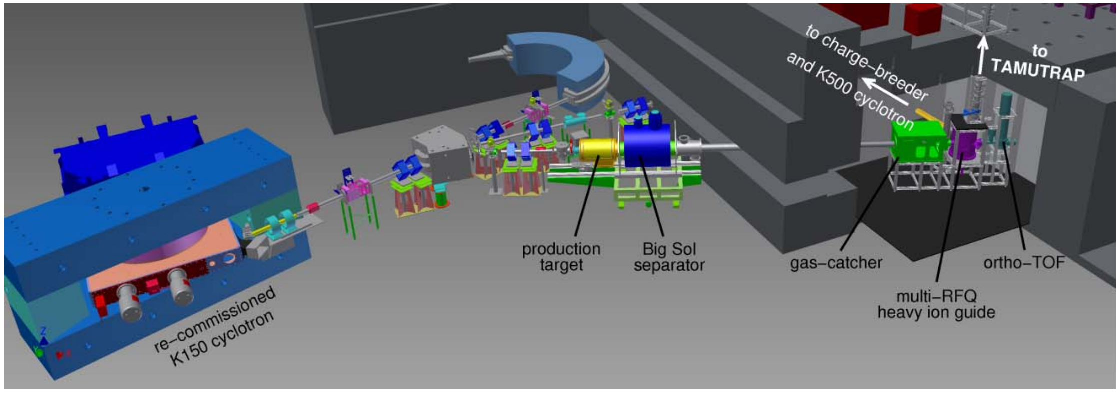


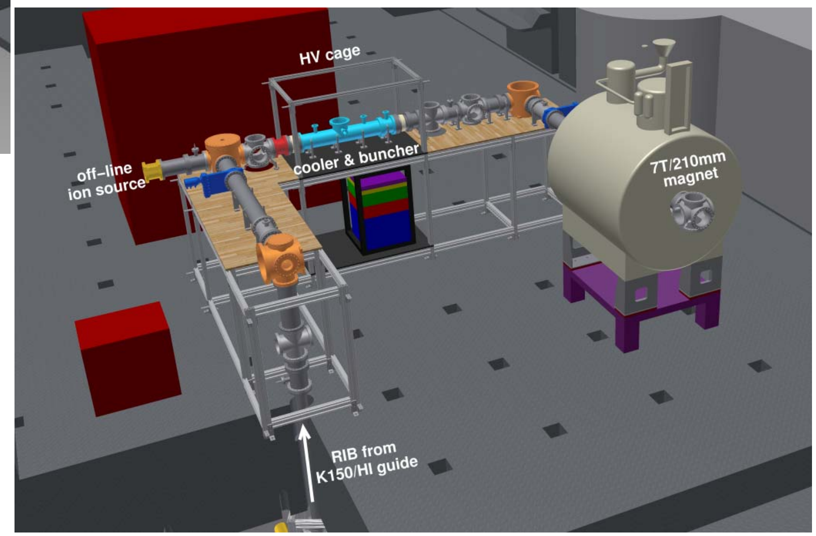


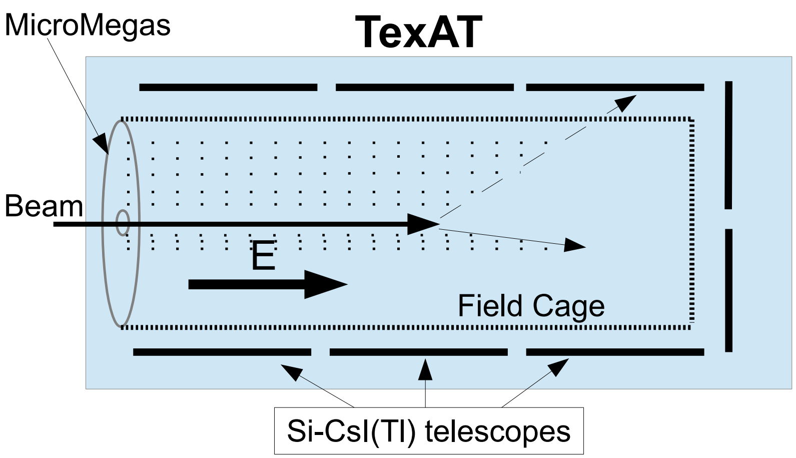
Future research directions

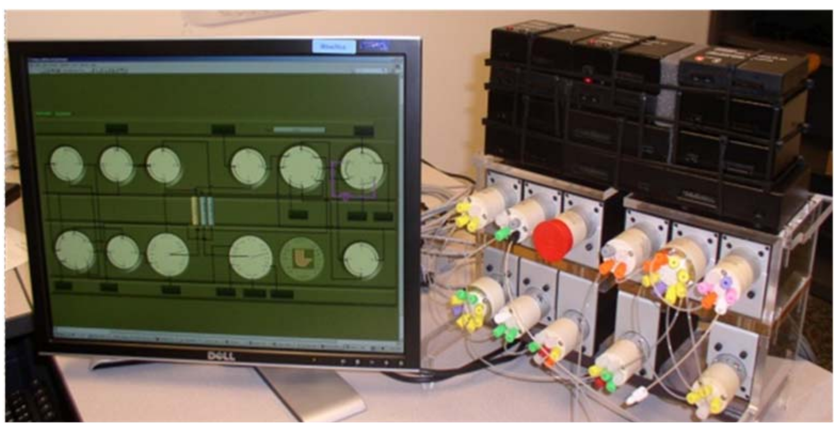
- Studies of survival of excited nuclei in the actinide region with SaSSYER.
- Study the chemistry of transactinide homologs in "online" experiments
- Studying beta-delayed proton decays of pure Fermi transitions with TAMUTrap
- Nuclear astrophysics with stable and rare isotope beams using Astrobox and TIARA.
- Structure of light exotic nuclei with TexATP / TexAT.
- Clustering phenomena in light and medium mass nuclei.
- Studies of the EOS and Esym with FAUST-QTS
- Pionic Fusion
- Superallowed β decay studies on Tz=-1 nuclei
- GMR as probe of structure and asymmetry

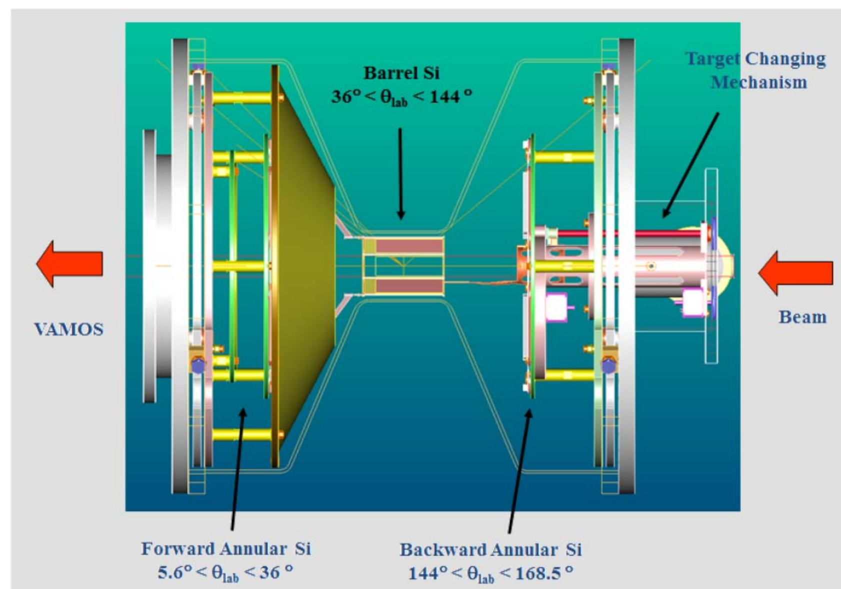
Future Equipment











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Summary

- Texas A&M Cyclotron Institute is able to deliver a wide variety of stable and radioactive beams
- MARS currently produces inflight RIBs
- T-REX will deliver
  - reaccelerated RIBs to all current (and future) experimental equipment
  - stopped RIB to TAMU Trap