Mass measurements of neutron-rich isotopes at the CARIBU facility

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RIBF-ULIC Symposium on Physics of Rare-RI Ring

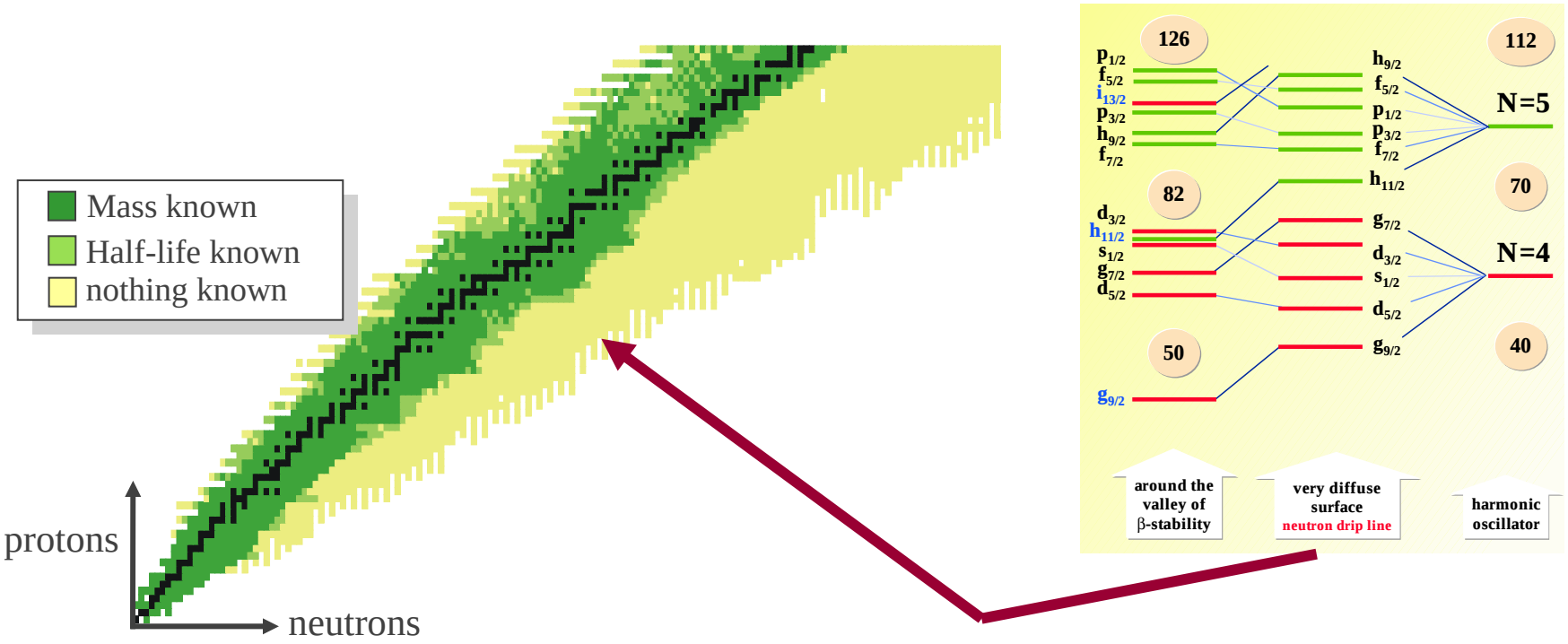
Riken Nishina Center, November 10-12 2011

Outline

- Why neutron rich nuclei?
- Description of CARIBU
- First mass measurement results
- Current efforts

Nuclear structure of neutron-rich nuclei

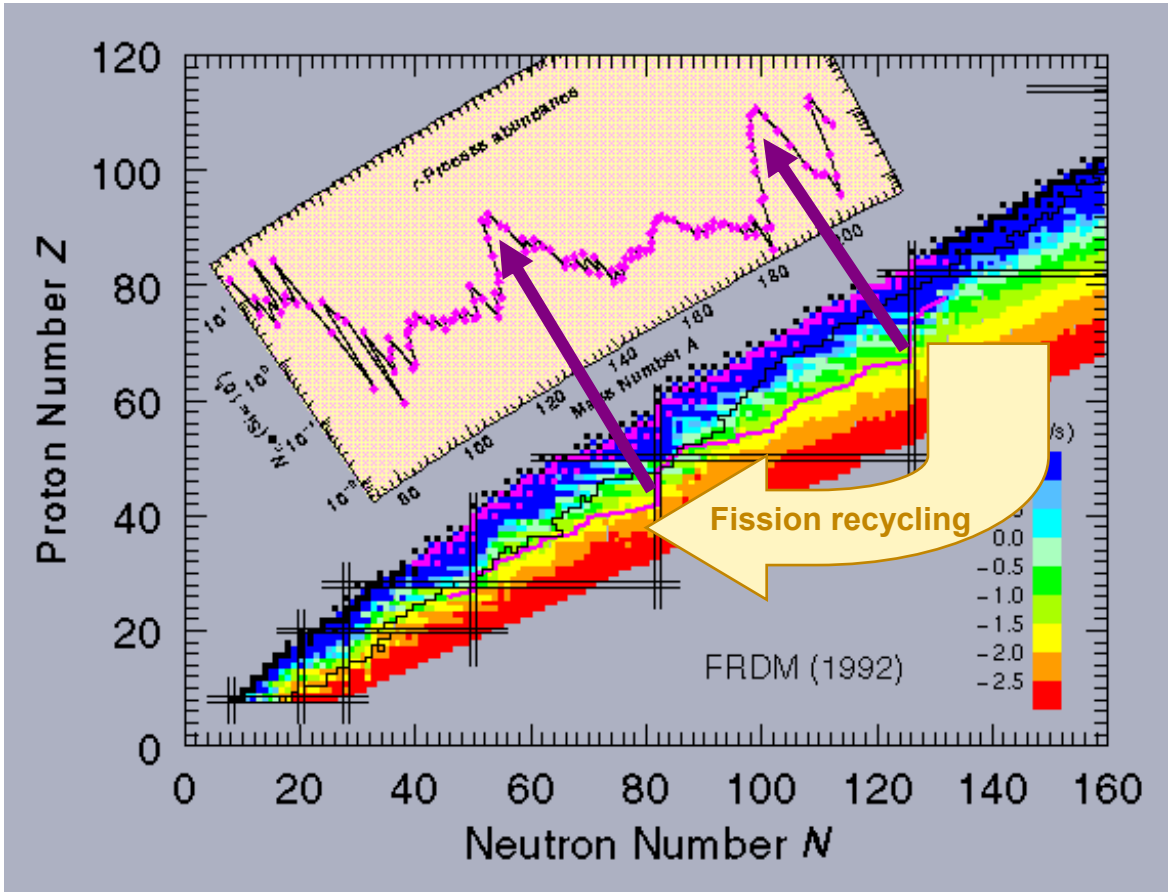
- **Heavy neutron-rich nuclei region:**
  - region mostly unexplored even for the most basic properties
  - weakly bound with diffuse surface … reduced spin-orbit coupling, shell model possibly modified
  - signature can take many forms: single particle structure, ground state properties, etc …



The r-process path

r-process:

- Process known to exist
- Exact site unknown
- Path critically depends on nuclear properties of neutron-rich nuclei:
  - mass
  - lifetime
  - β-delayed neutrons
  - fissionability



Efficient techniques exist to obtain this information but the required beams are missing in most of this region of the chart of nuclides.

CARIBU – Californium Rare Ion Breeder Upgrade

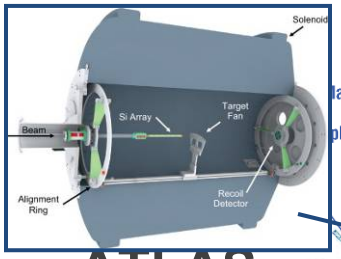
Access to n-rich region obtained at ATLAS via fission of the most neutron-rich "available" very heavy nuclei (e.g. ^{252}Cf)

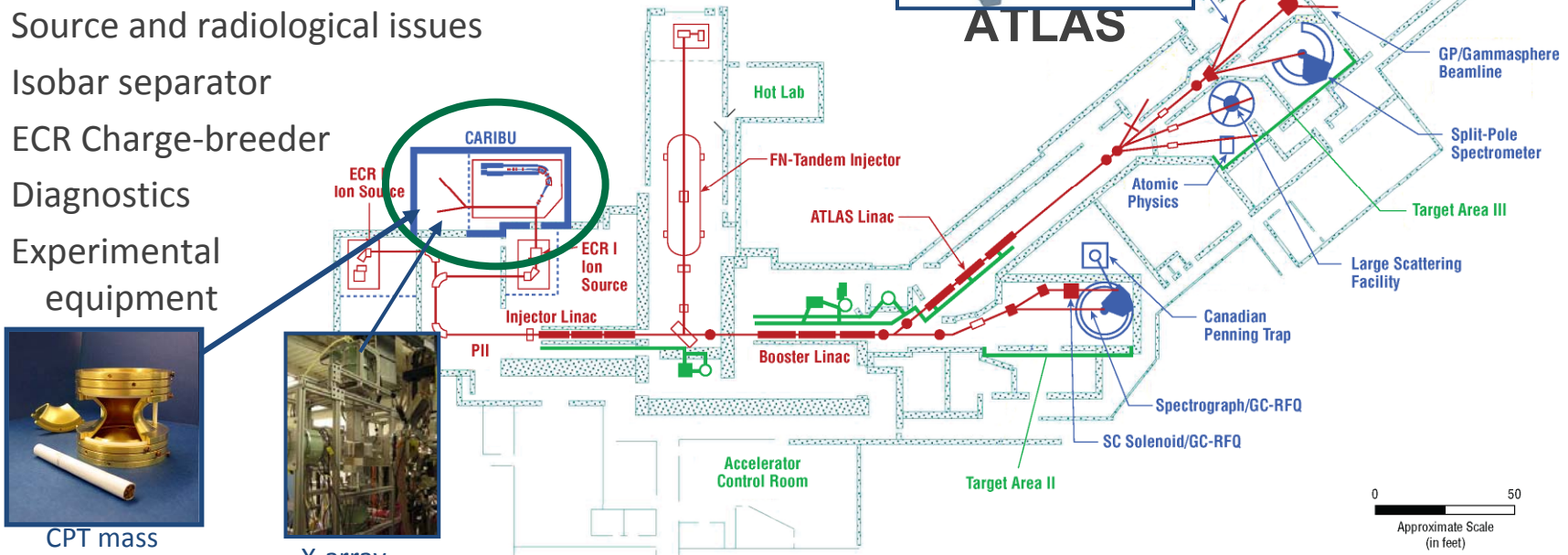
- Project goal: Provide neutron-rich radioactive beams to user community
  - Low-energy
    - Masses, decay spectroscopy, laser spectroscopy, …
  - Reaccelerated through ATLAS at up to 15 MeV/u
    - Single particle structure, gamma-ray spectroscopy, …

- Project Description
  - Gas catcher/RFQ cooler
  - Source and radiological issues
  - Isobar separator
  - ECR Charge-breeder
  - Diagnostics
  - Experimental equipment

Gammasphere

HELIOS spectrometer





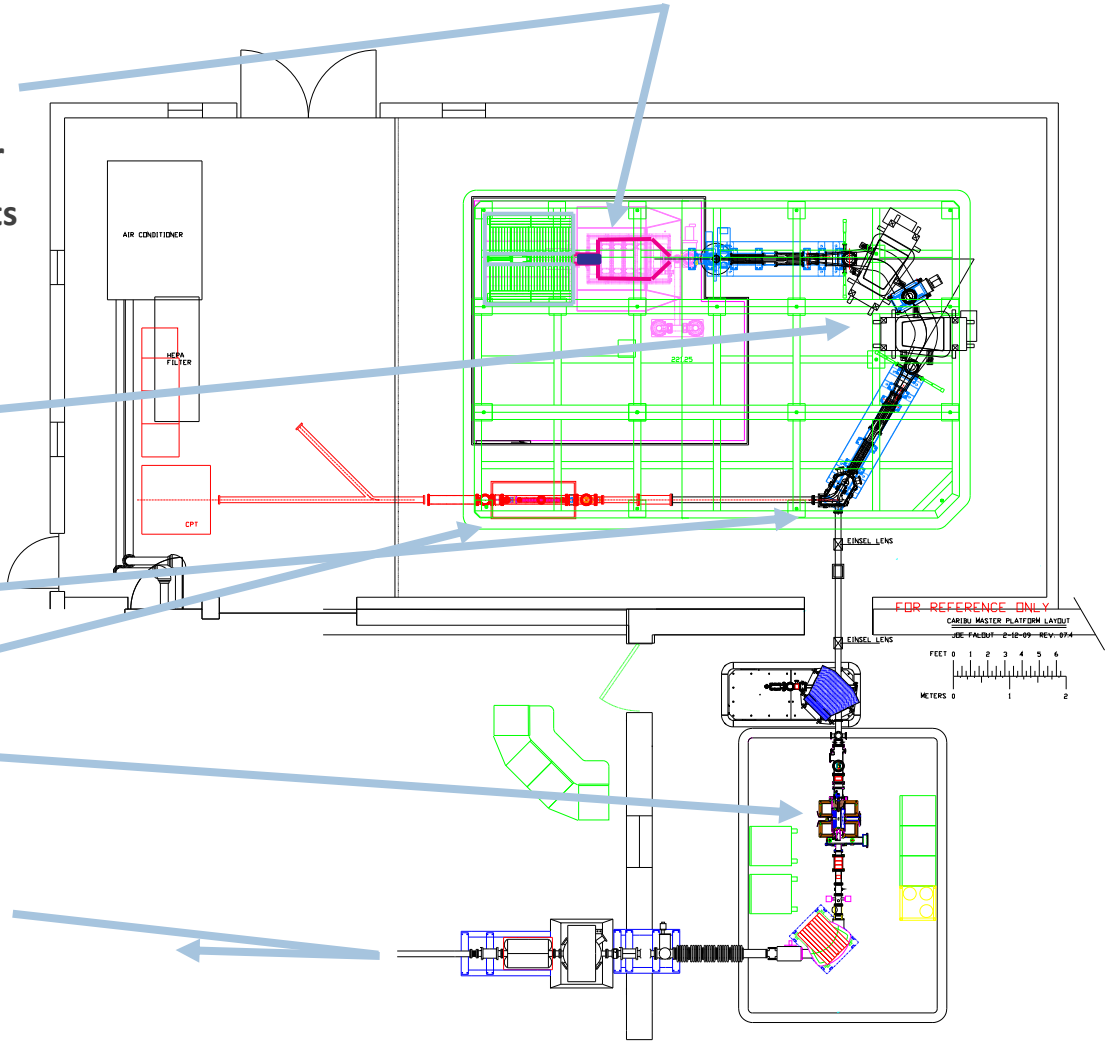
CPT mass spectrometer

X-array

Neutron-rich beam source: CARIBU “front end” layout

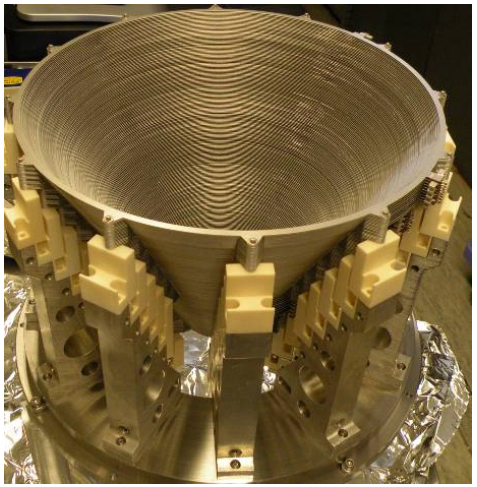
Main components of CARIBU

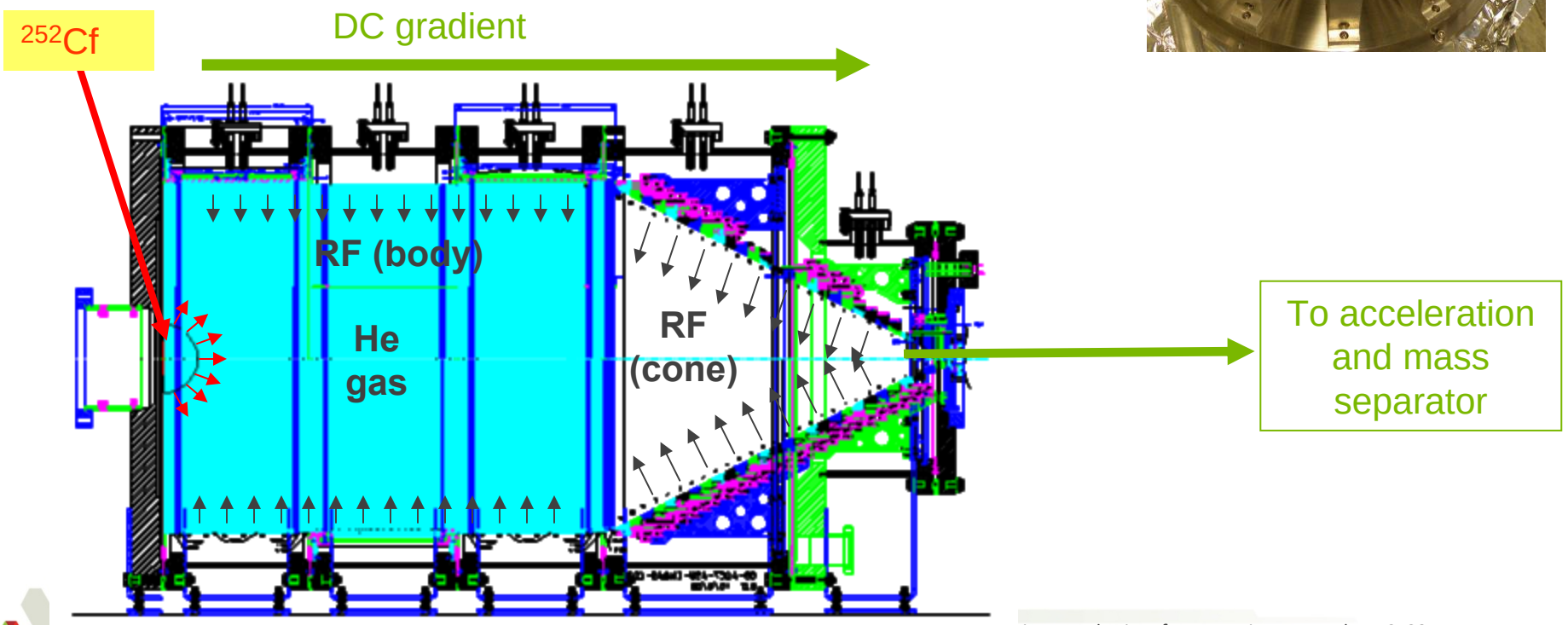
- **PRODUCTION**: “ion source” is ^{252}Cf source inside gas catcher
  - Thermalizes fission fragments
  - Extracts all species quickly
  - Forms low emittance beam
- **SELECTION**: Isobar separator
  - Purifies beam
- **DELIVERY**: beamlines and preparation
  - Switchyard
  - Low-energy buncher and beamlines
  - Charge breeder to Increase charge state for post-acceleration
  - Post-accelerator ATLAS and weak-beam diagnostics



CARIBU gas catcher: transforms fission recoils into a beam with good optical properties

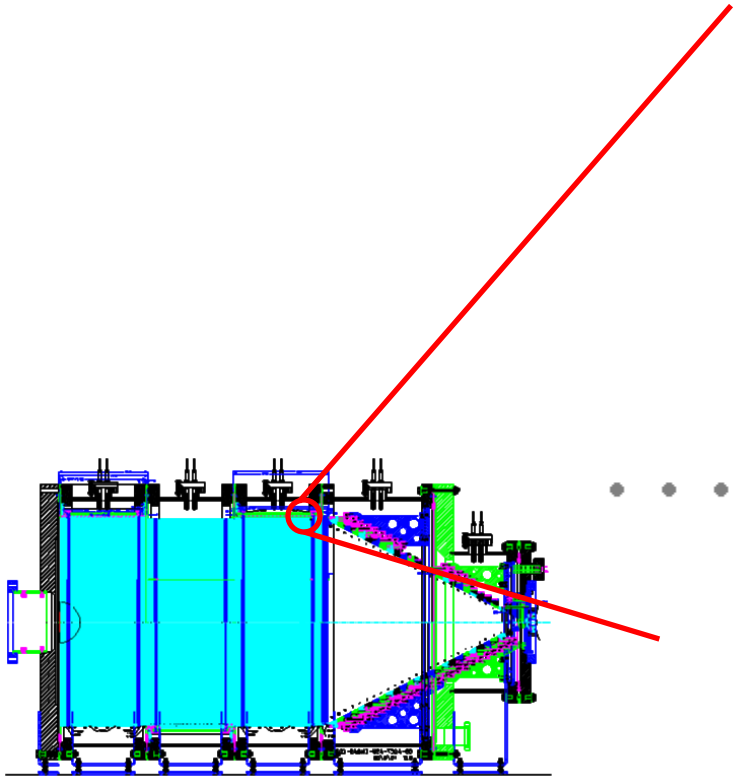
- Based on smaller devices developed at ANL
  - Radioactive recoils stop in sub-ppb level impurity Helium gas
  - Radioactive ion transport by RF field + DC field + gas flow
  - Stainless steel and ceramics construction (1.2 m length, 50 cm inner diameter)
  - Fast and essentially universally applicable
  - Extraction in 2 RFQ sections with µRFQs for differential pumping

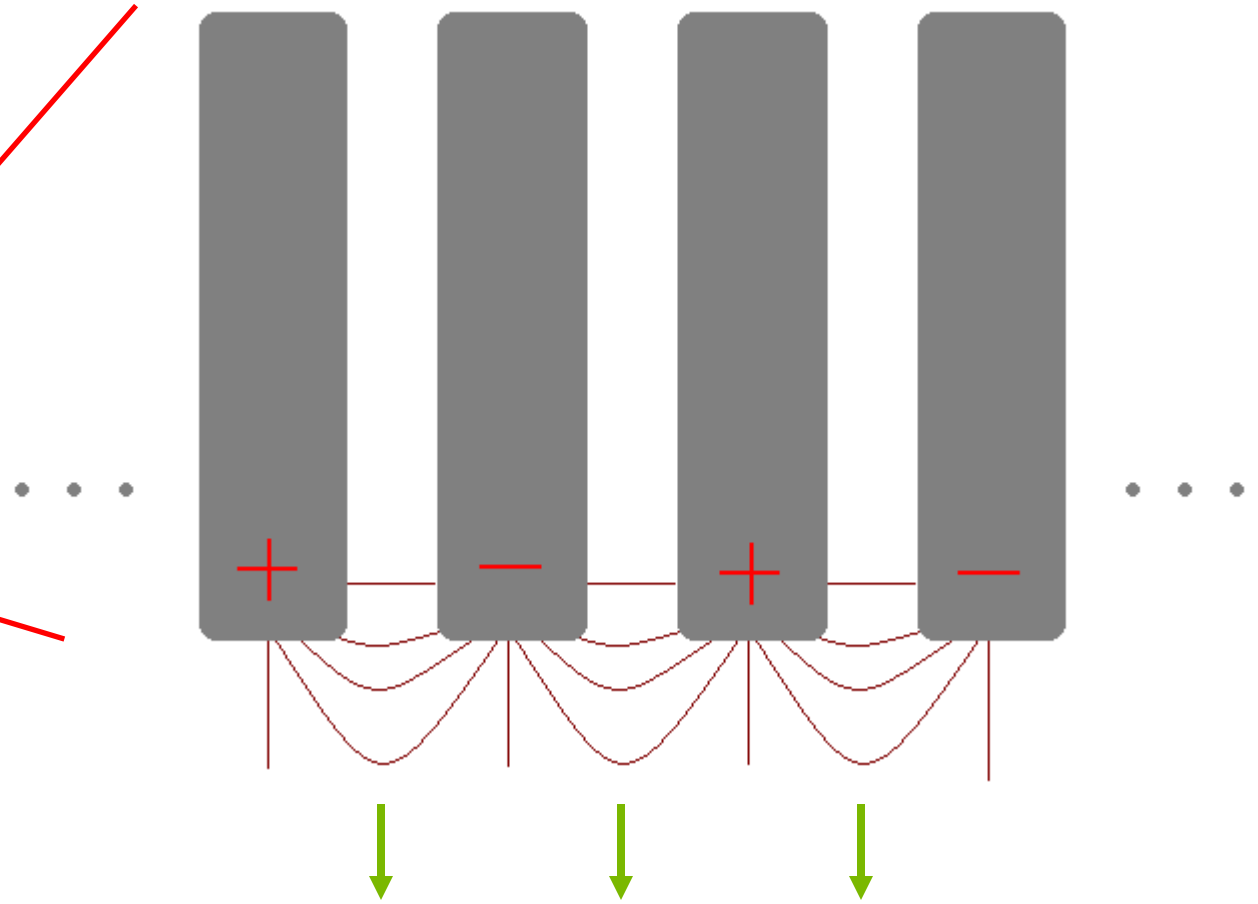




RF cone and walls

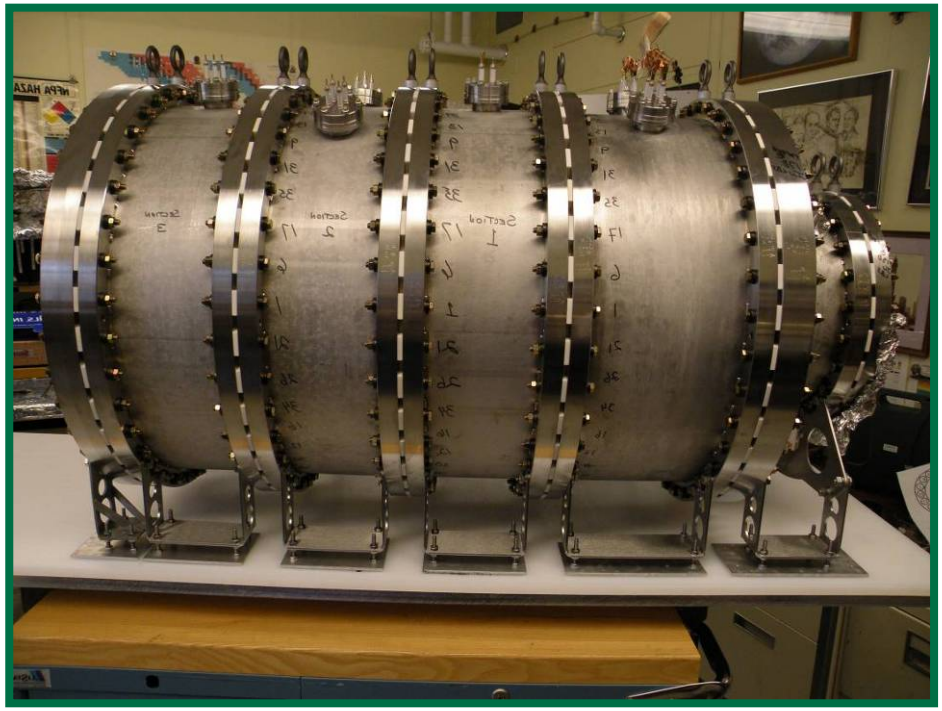
RF applied to ring electrodes in alternating phases @ ~ MHz





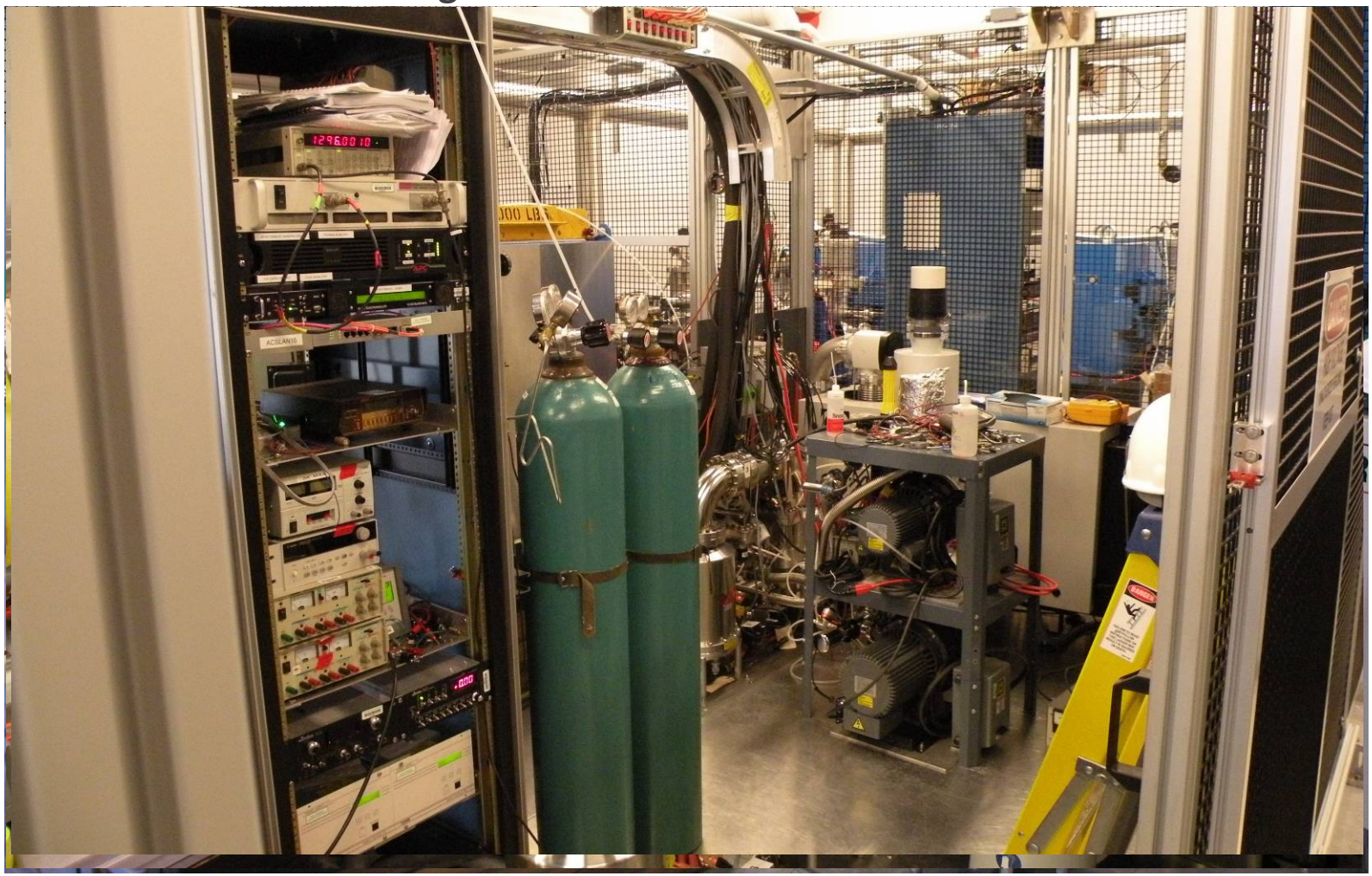
Average force is toward weaker field - IN

Ion extraction and beam formation: CARIBU gas catcher, RFQs and acceleration section



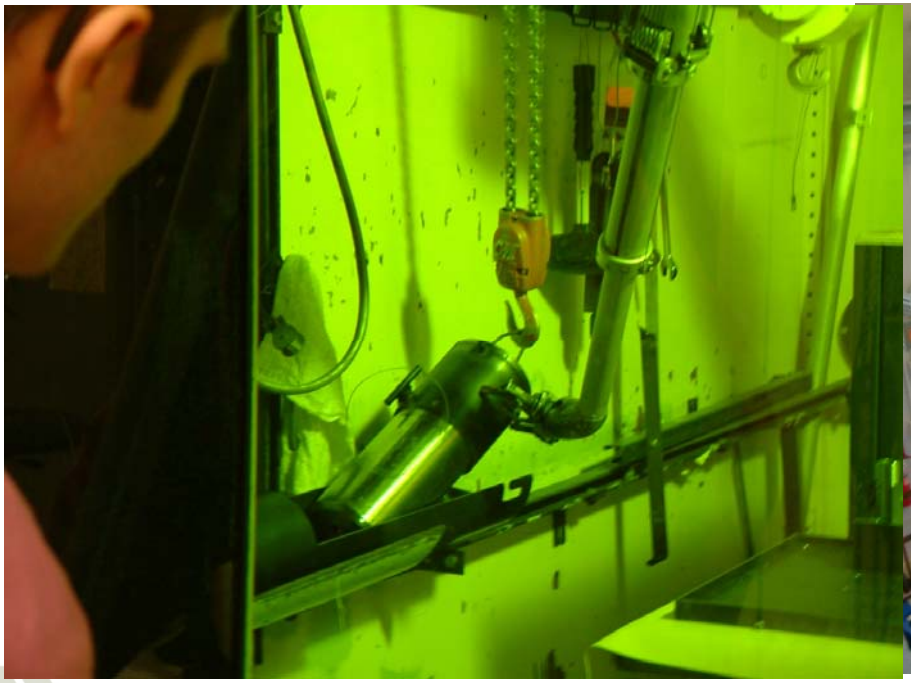
The very large high-intensity gas catcher for CARIBU

- Gas Catcher/RFQ cooler isolated from main platform and biased to 50 kV.
- Installed inside secondary enclosure with pumping, cooling and gas distribution
- Under 12000 lbs of shielding



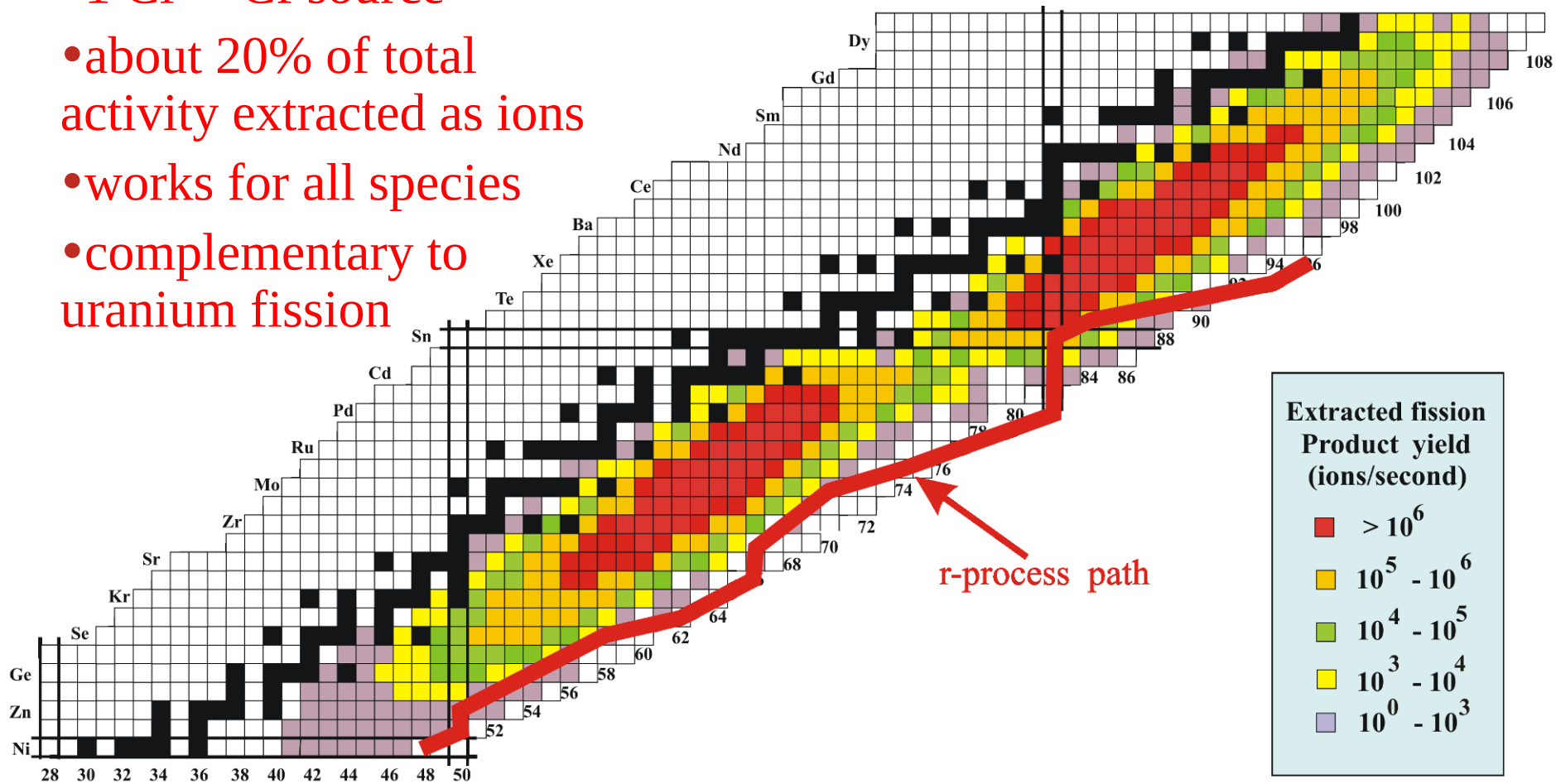
Californium source and transport cask

- Cf source is made at the HIFR high-flux reactor in Oak Ridge (~50 rem/hr unshielded)
  - Progression of 3 sources … 2 mCi, 80 mCi, 1 Ci
- Transported in a steel/cement cask to Argonne
- Installed in the CARIBU transport cask using manipulators in hot cells at Argonne
- Move in the cask on site at Argonne
- For installation in the gas catcher, the source and shielding plug are pushed from the storage location into position at the end of the gas catcher.
- The assembly is sealed to the gas catcher, the source being inside the gas catcher.



Extracted isotope yield at low energy (50 keV)

- 1 Ci ^{252}Cf source
- about 20% of total activity extracted as ions
- works for all species
- complementary to uranium fission



“Compact” isobar separator

- Need to select specific activity

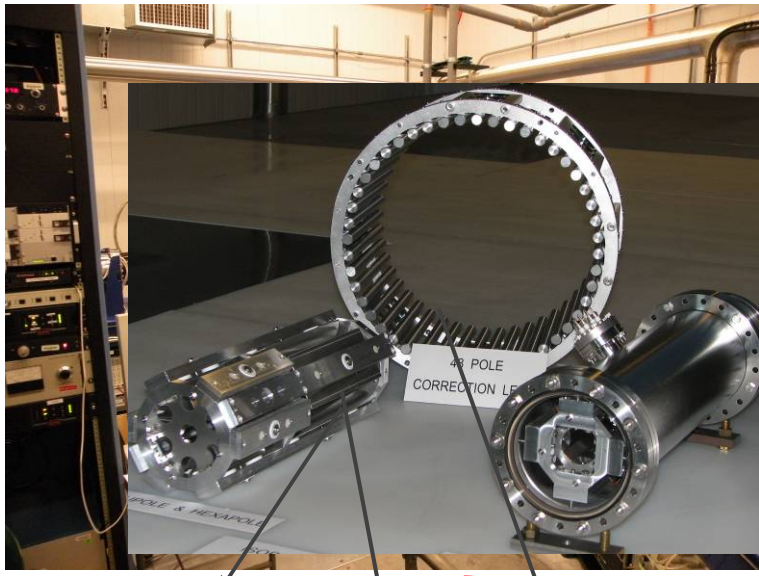
- Take advantage of low emittance and energy spread of extracted beams:

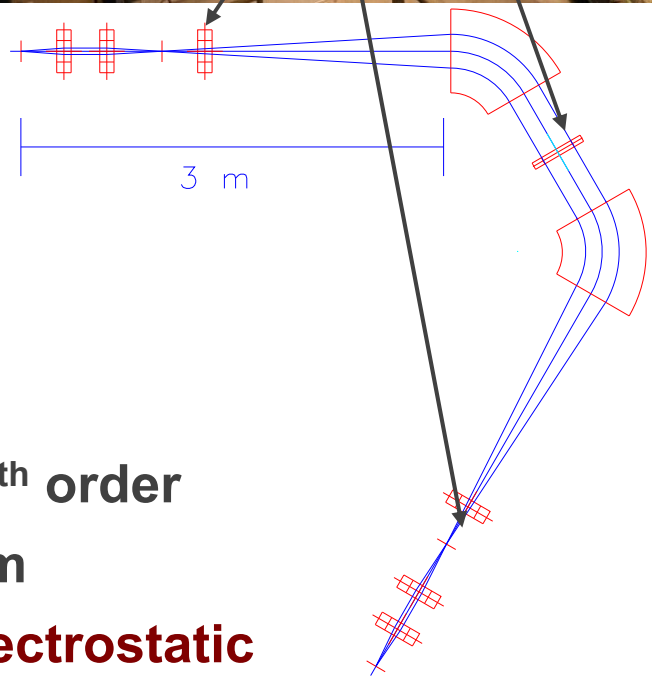
Beam Properties from gas catcher:

$\varepsilon \approx 3\ \pi$ mm•mr $\delta E \approx 1$eV

1 mm dia. (circular) beam

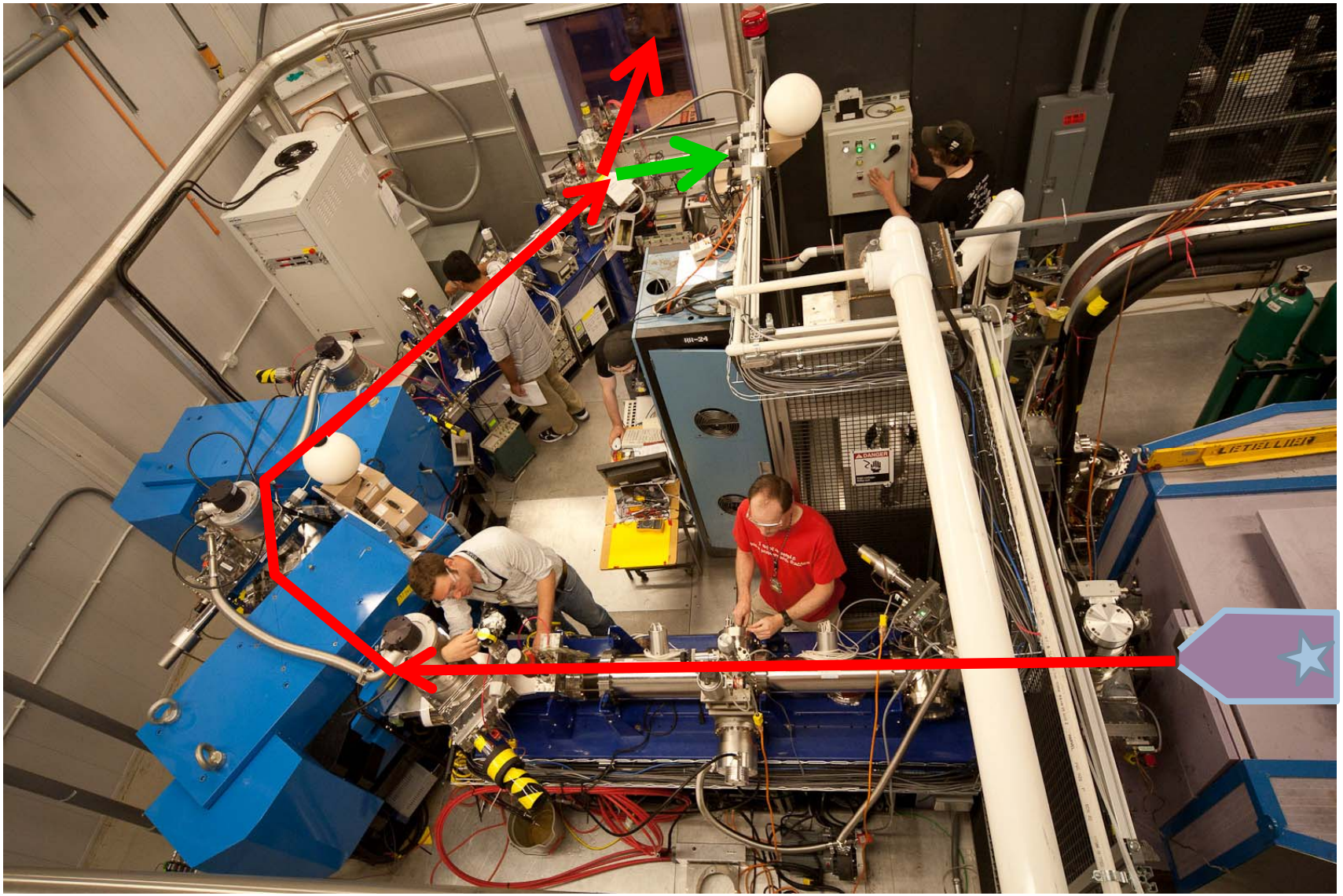
$\theta_{max}, \varphi_{max} = \pm 6$ mr



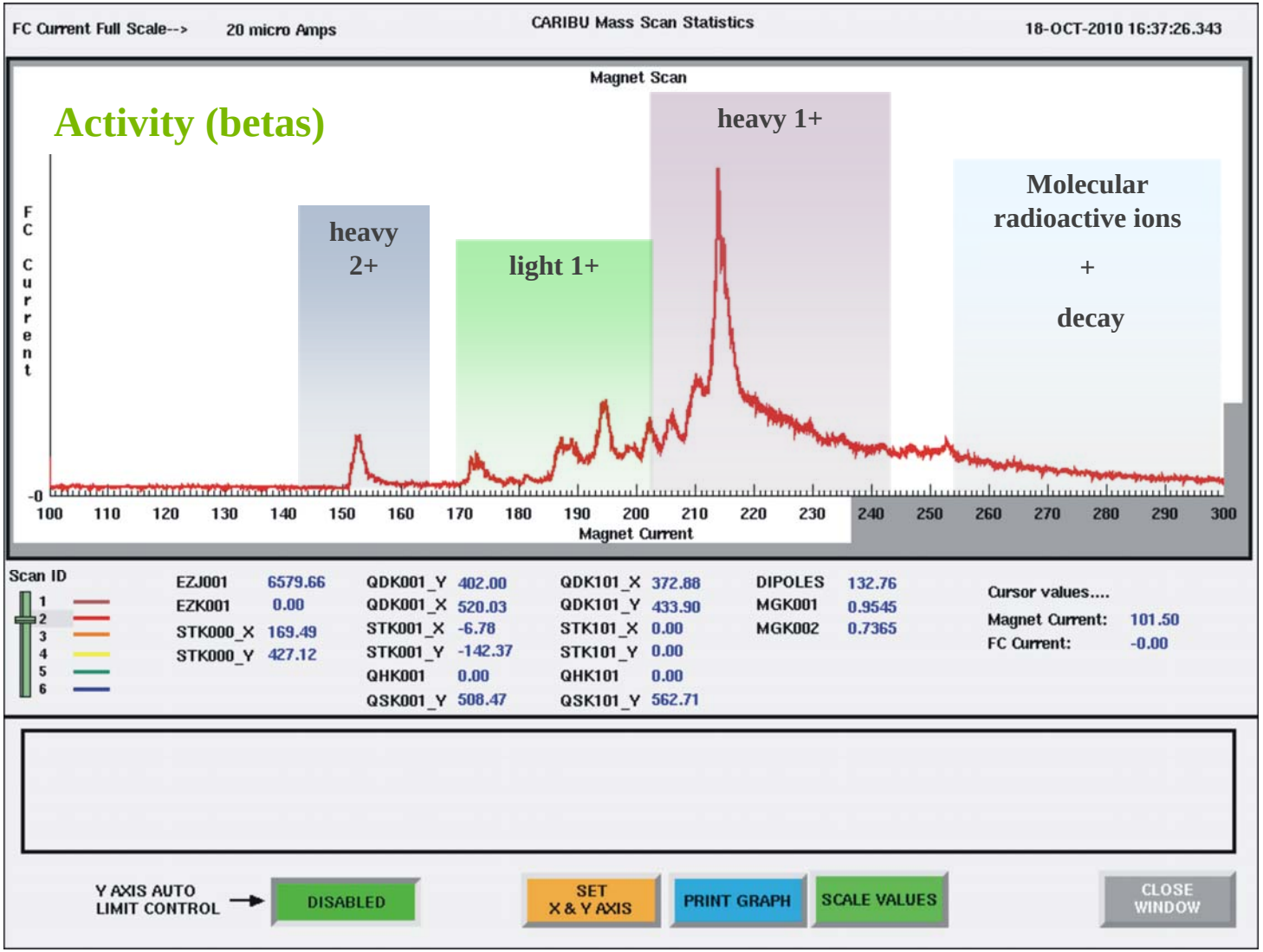


- Matching sections at entrance and exit transform beam to a ribbon beam.
- 2 x 60 degree bends, R = 50 cm
- Dispersion 22.8 meters
- First order mass resolution: 1/20,000
- 3 electrostatic multipoles correct through 5th order
- Small enough footprint to fit on HV platform
- All optics, except for bending magnet, is electrostatic so that tune is essentially mass independent

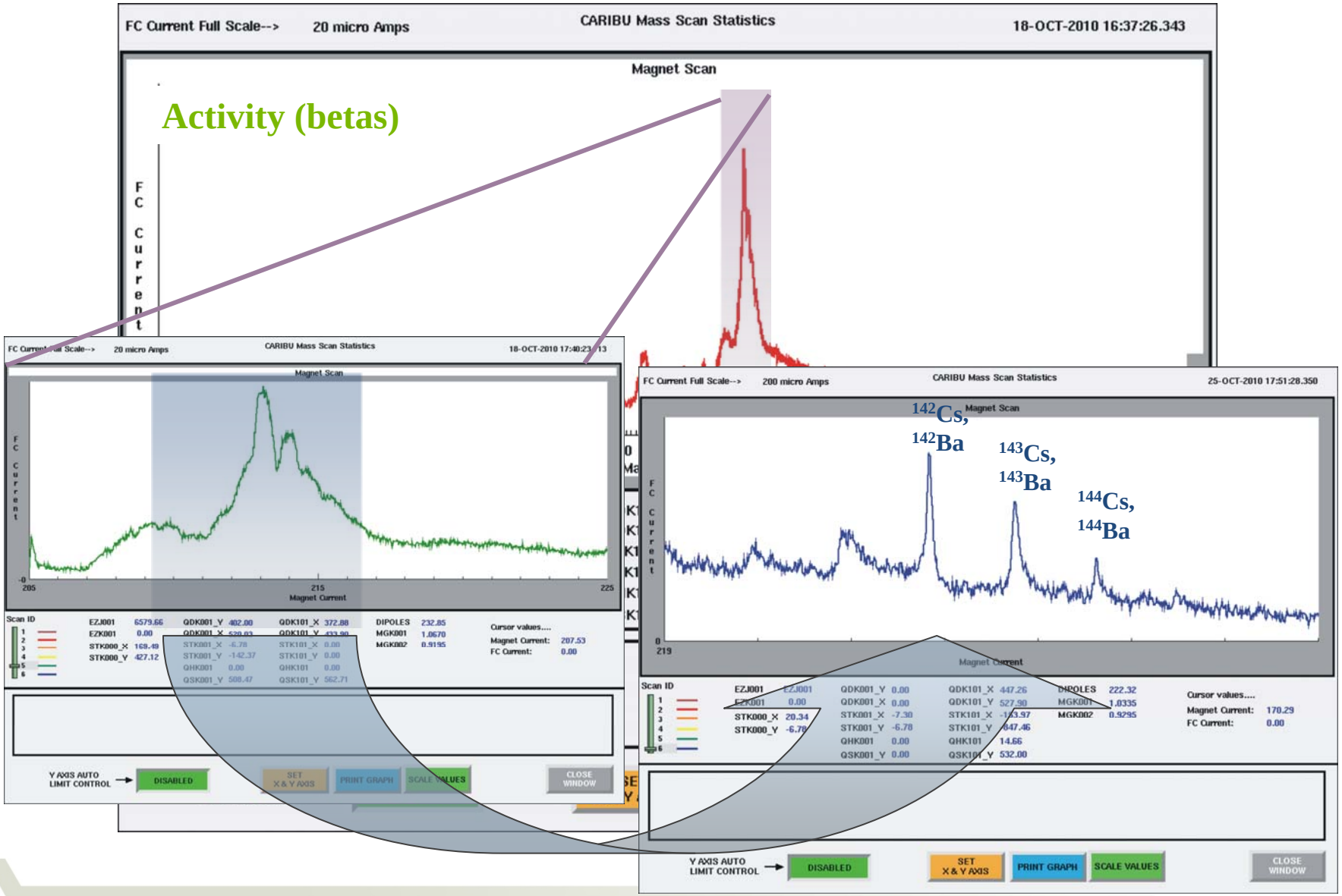
Photo of CARIBU w/ beam paths overlay to ECRCB & Trap



Going from mass to specific activity

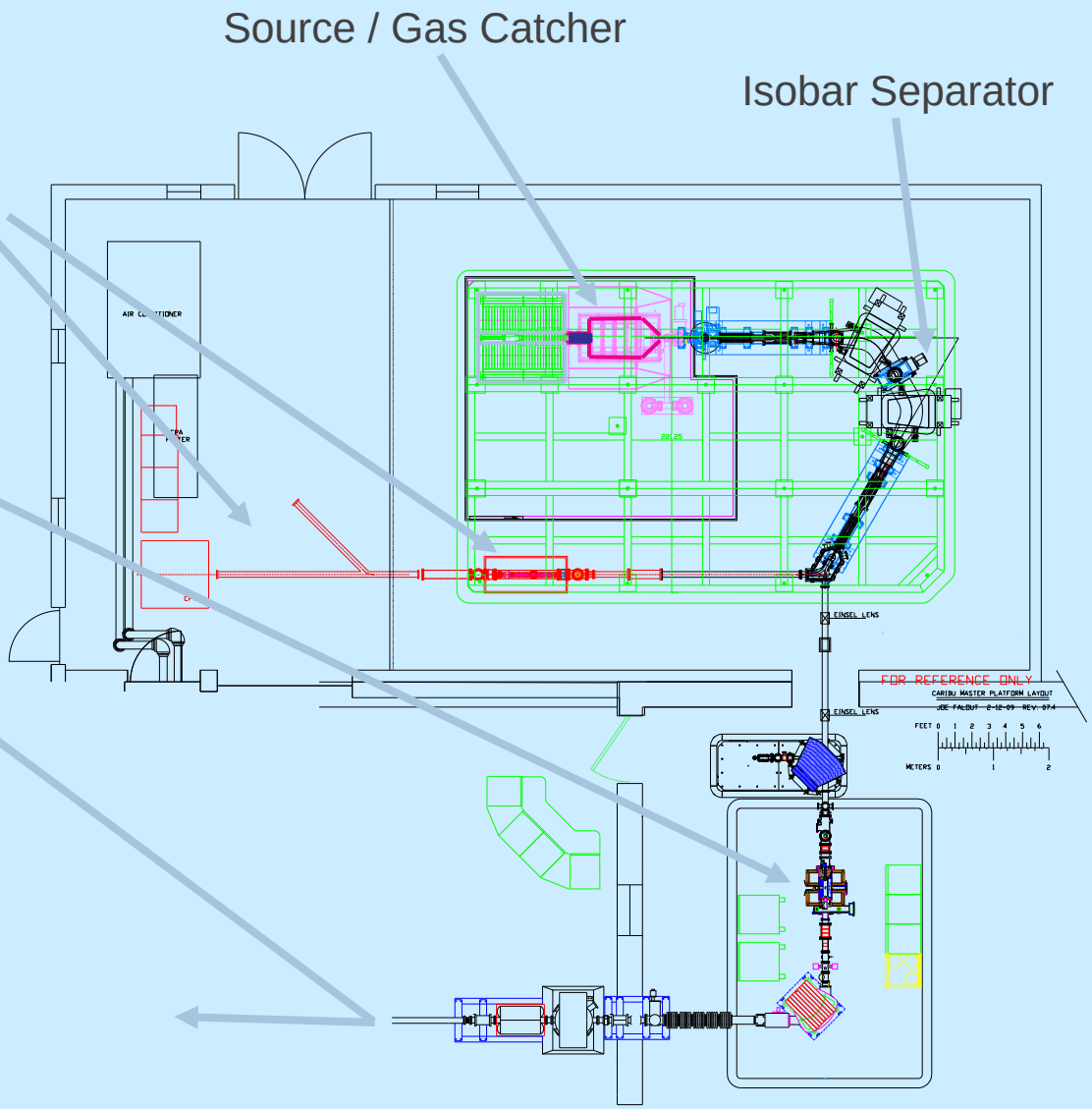


Zooming in on specific activity

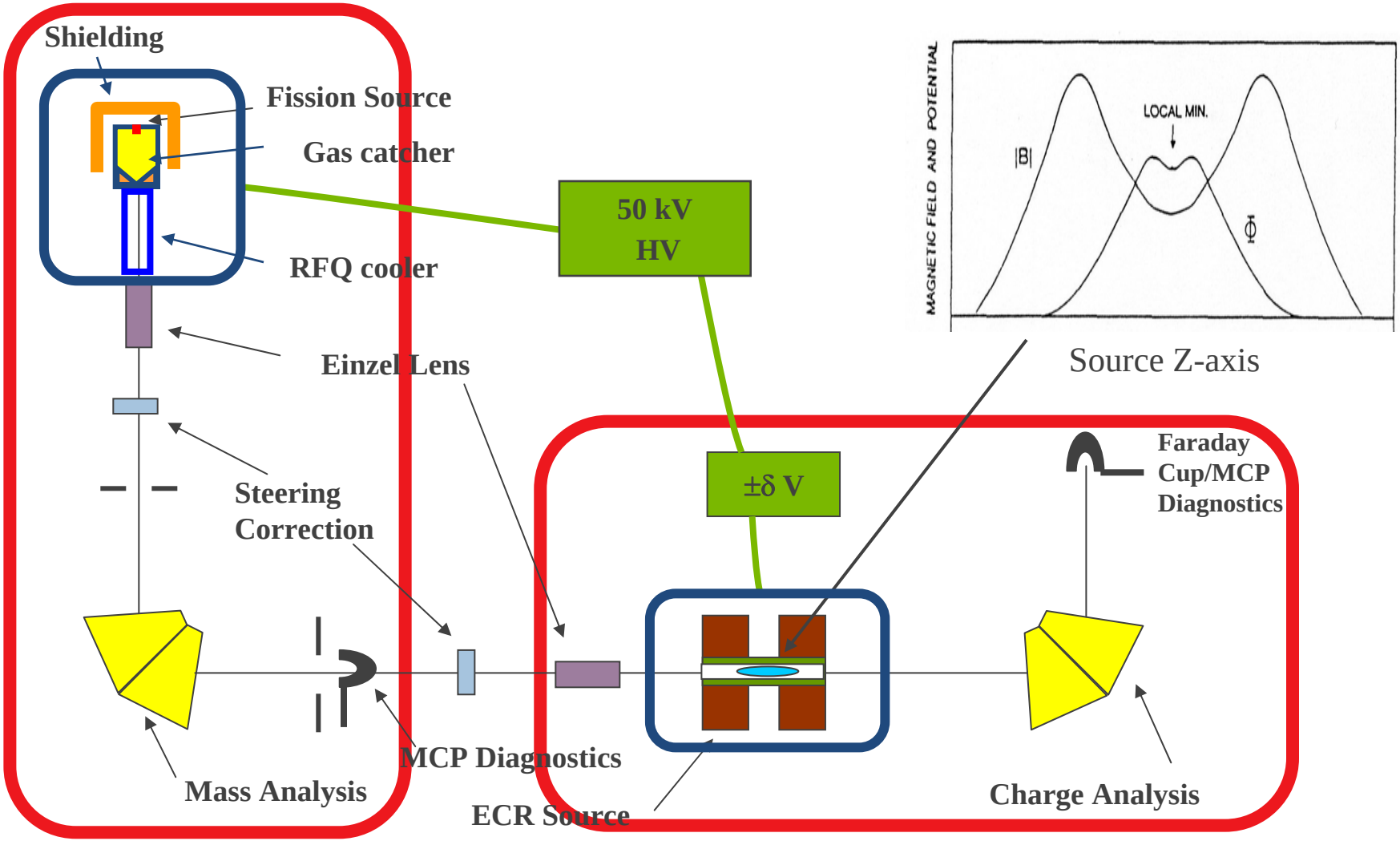


Beam Delivery

- After isobar separation, two options for beam use
- Low energy experiments after beam bunching
  - Mass measurement
  - Laser Spectroscopy
  - Beta decay studies
- Reaccelerated Beams
  - Use ECR-1 as charge breeder
  - Inject ions into ATLAS in high charge state (q/m > 0.15) and energy (~100-200 keV)

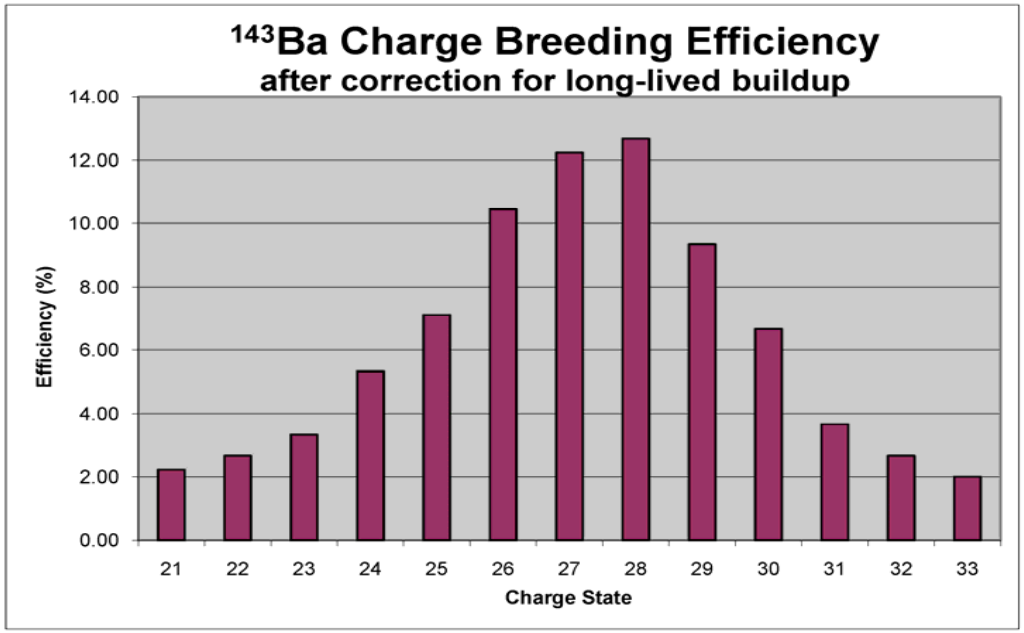


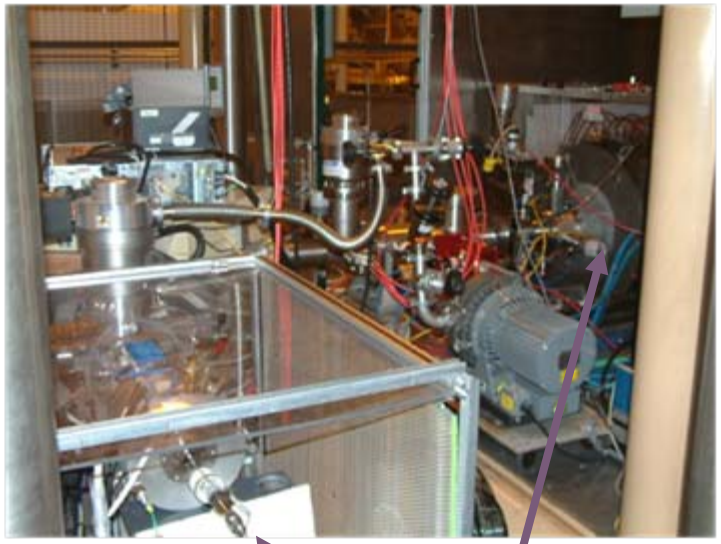
CARIBU ECR Charge-Breeder System

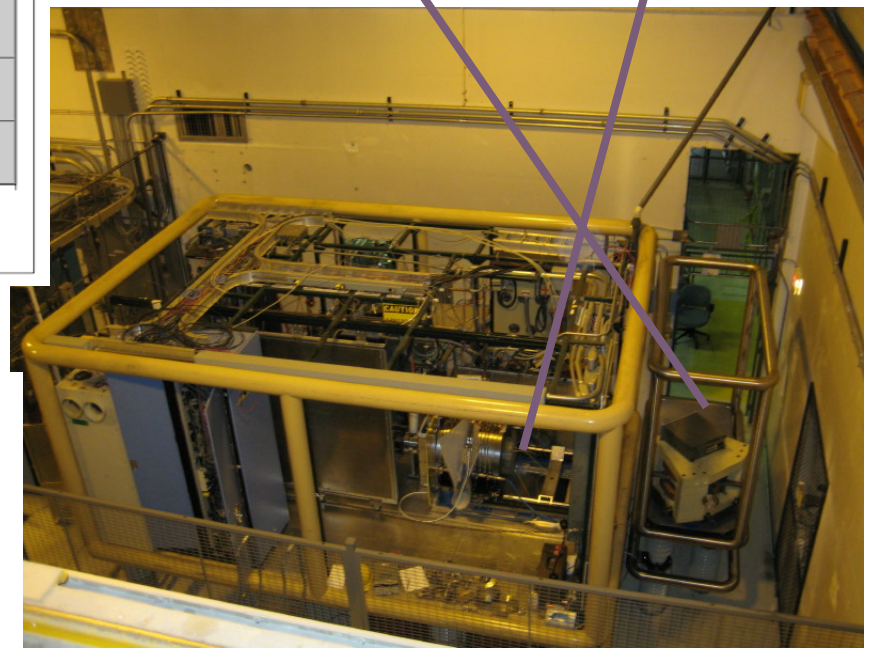


ECR Charge Breeder Results

In order to accelerate beams in ATLAS the charge-to-mass ration (q/m) must be raised to >1/8 (depending on the desired energy).

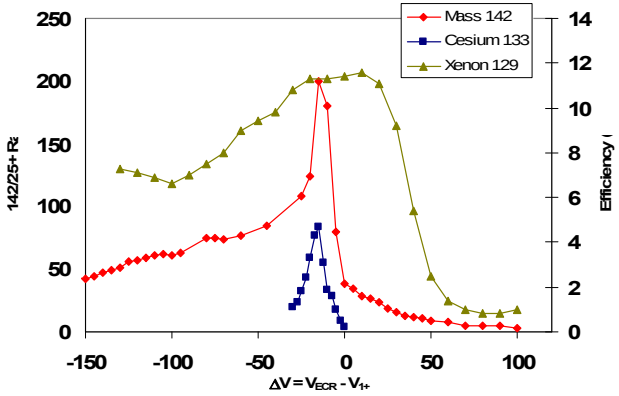






Best breeding efficiencies: 11-16% for all gases, solid, & RIBs.

Rate and Efficiency for Mass 142/25+, $^{129}Xe^{25+}$ and $^{133}Cs^{26+}$ as function of Voltage difference between ECRCB & 1+ source



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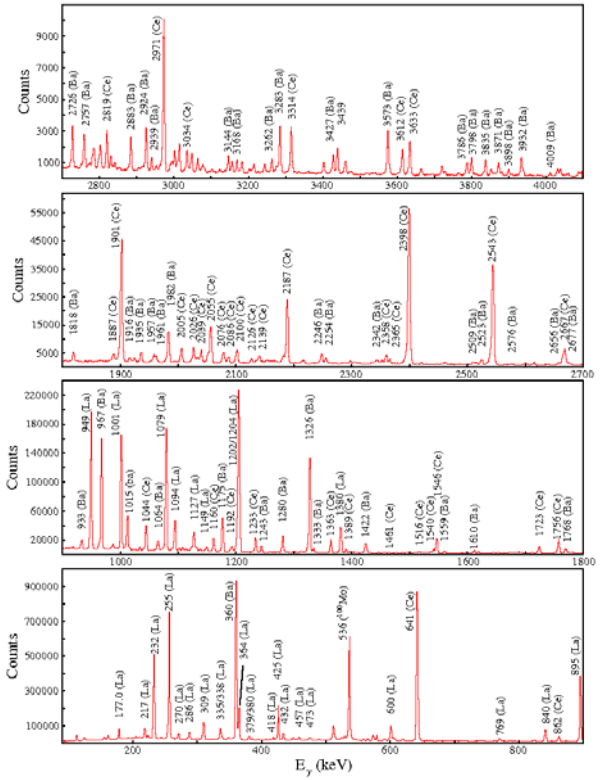
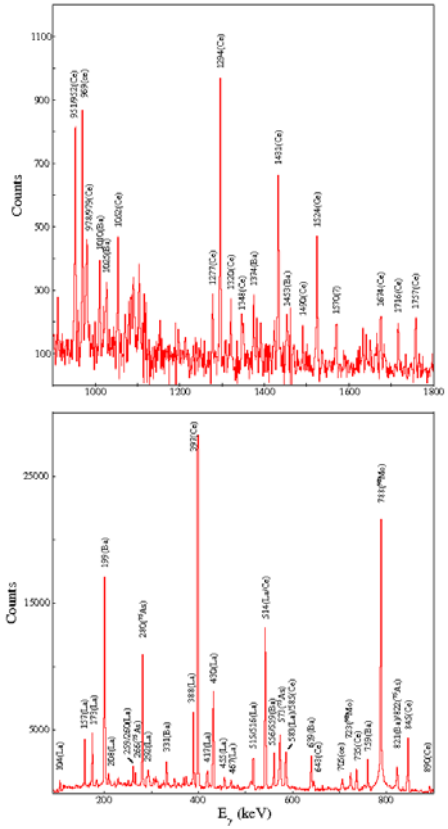
CARIBU beams delivered to Gammasphere

- CARIBU beams reaccelerated to Coulomb barrier and delivered to Gammasphere





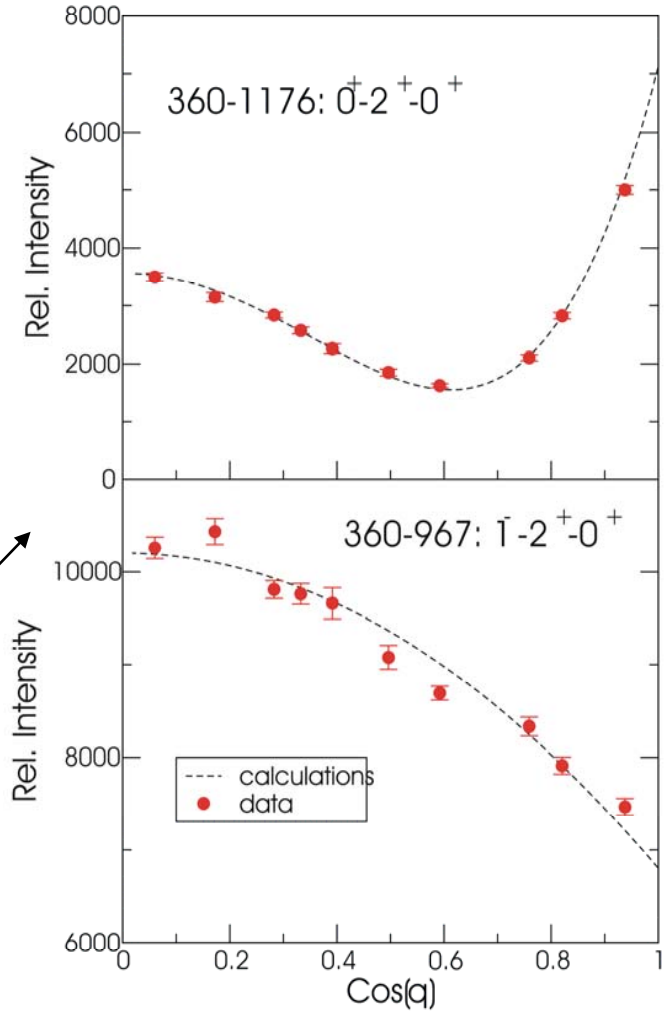
^{142}Cs in Gammasphere

^{144}Cs in Gammasphere

The power of Gammasphere : γ–γ correlations

- High efficiency, granularity, symmetry and angular coverage of Gammasphere allows
  - detailed decay spectroscopy to be performed
    - GS → beating down the pandemonium effect
  - γ–γ angular correlations
    - fix spin sequences

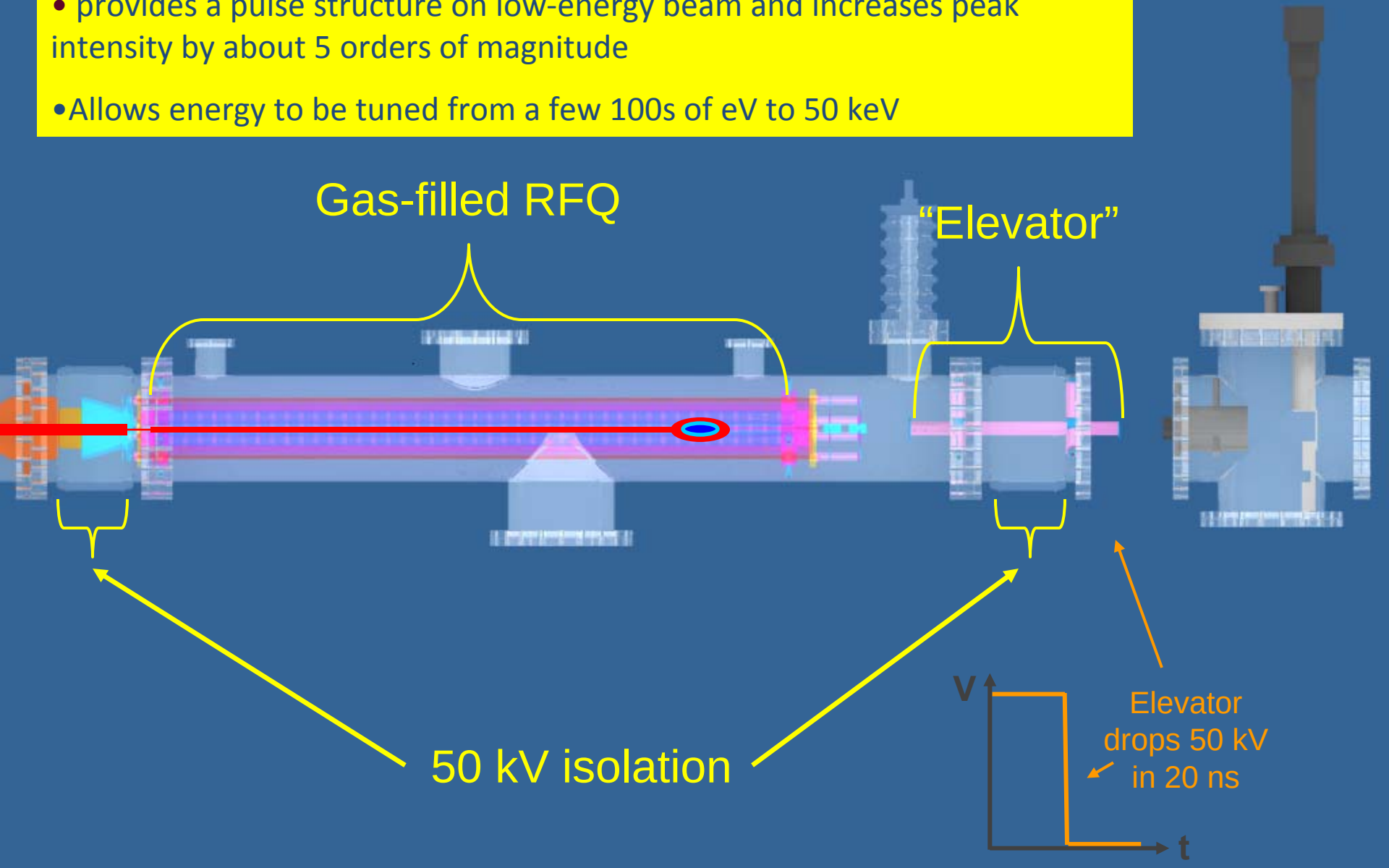
γ–γ correlation between states in ^{142}Ba populated in the decay of ^{142}Cs



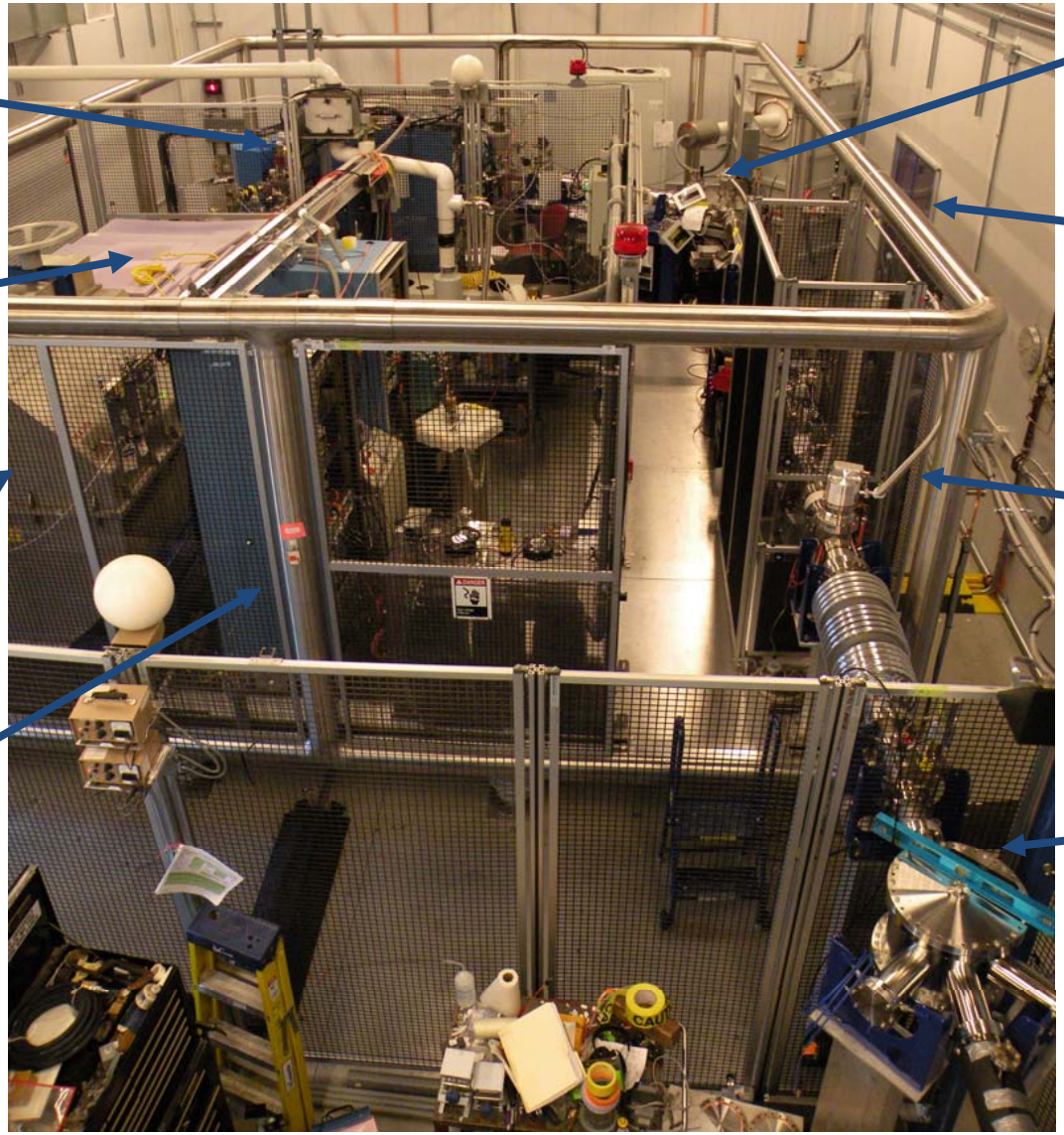
Courtesy of Shaofei Zhu

Low-energy buncher

- provides a pulse structure on low-energy beam and increases peak intensity by about 5 orders of magnitude
- Allows energy to be tuned from a few 100s of eV to 50 keV



CARIBU and low-energy beamline



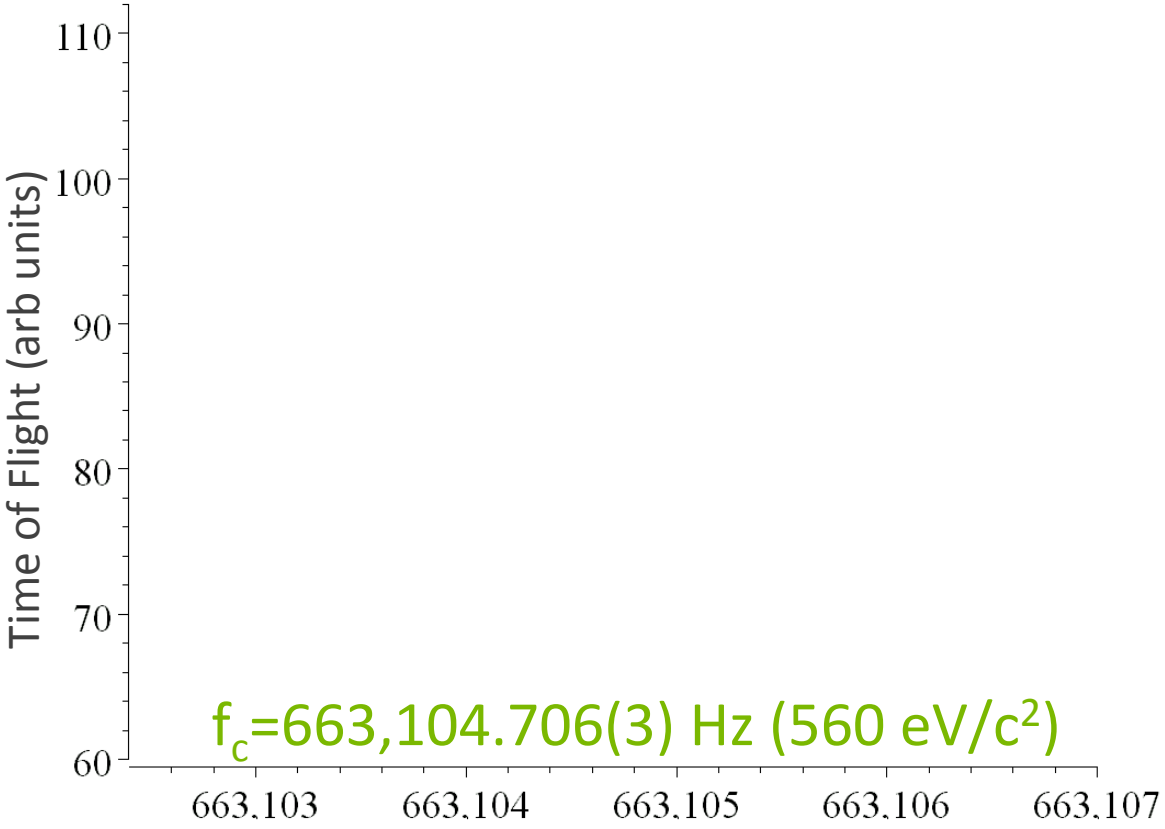
The CPT apparatus at CARIBU

Penning Trap

2 kV pulsed beam

cryogenic linear ion trap

Sample time-of-flight (TOF) spectrum



$$\omega_c = \frac{q_c B_c}{m_c}$$

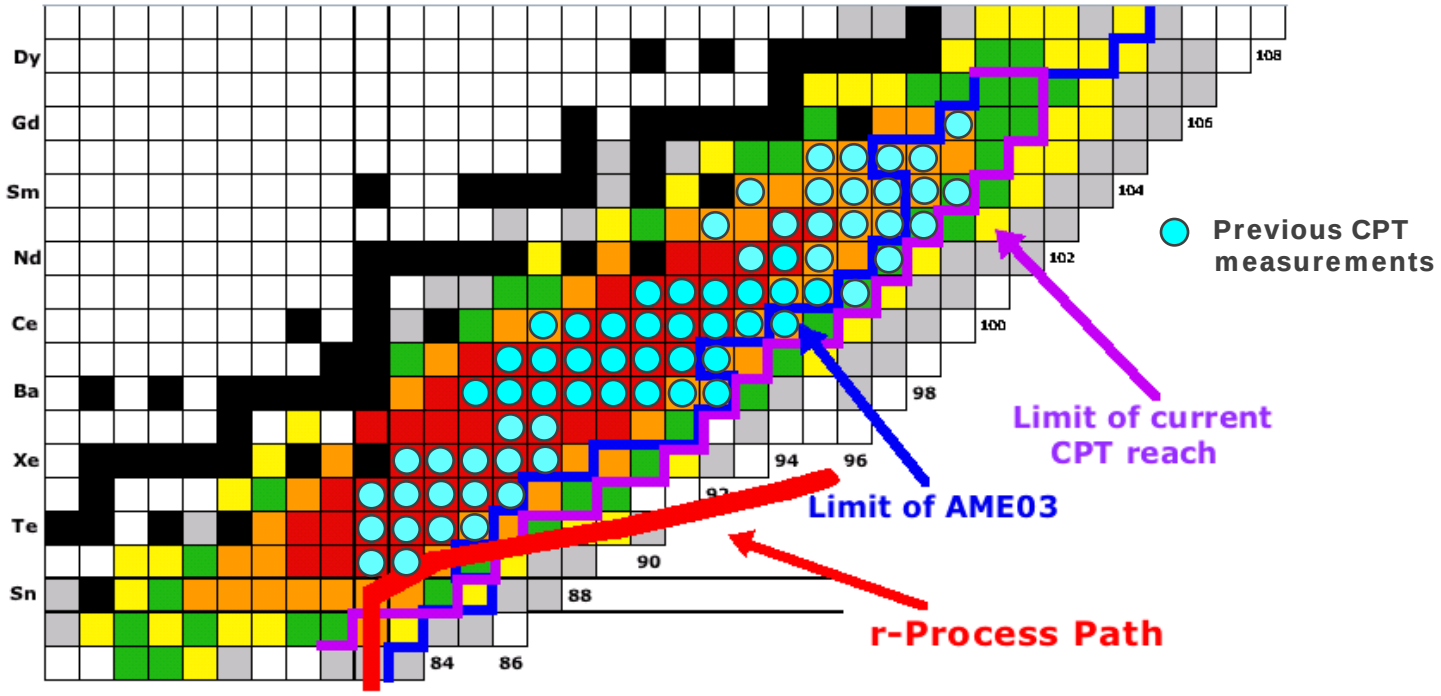
Unknown: $\omega_? = \frac{q_? B_c}{m_?}$

$$\frac{Unknown}{Calibration} \Rightarrow m_? = \frac{q_?}{q_c}\frac{\omega_c}{\omega_?} m_c$$

Well-known calibrant mass is a requirement for accurate measurements, use ^{133}Cs (known to ~ 0.01 keV) in this region.

CPT Fission Fragment Measurements in Triangle Room

^{252}Cf Heavy Fission Peak

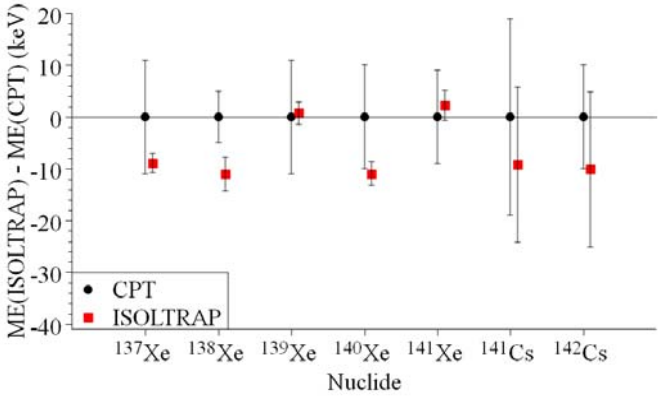


- ^{252}Cf fission fragments from gas catchers in ATLAS target area II.
- 70 measurements near target 15 keV precision ($\delta m/m \sim 10^{-7}$)
- Need more production farther from stability to get on *r*-process path
  - Final CARIBU source will be 10000 times stronger

Enough data to compare to other techniques

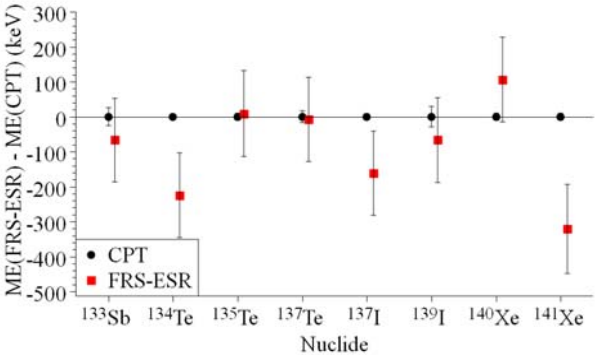
- CPT vs ISOLTRAP

$\chi^2/n = 0.9$



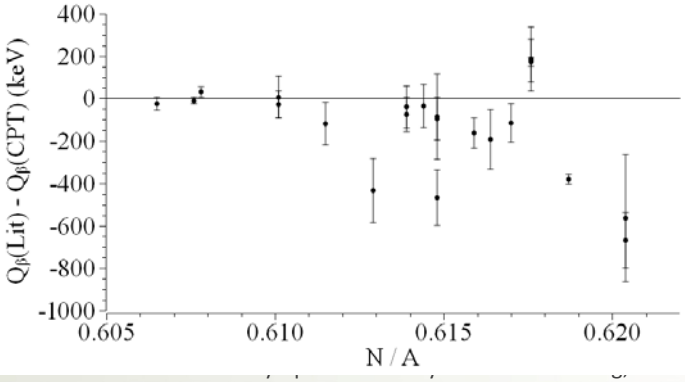
- CPT vs FRS-ESR

$\chi^2/n = 1.8$

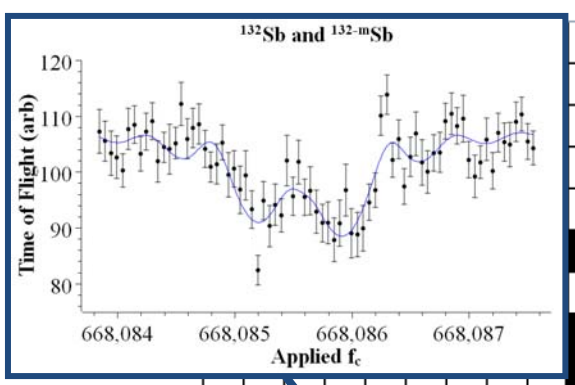


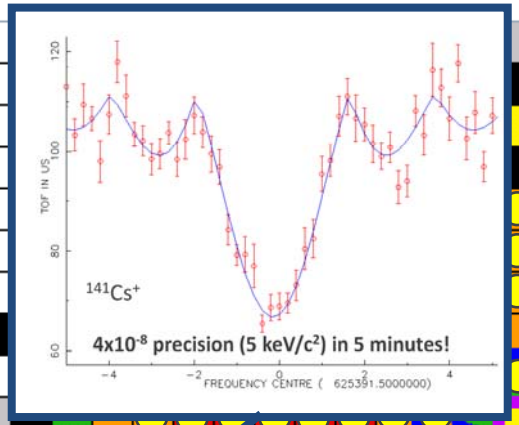
- CPT vs beta endpoint

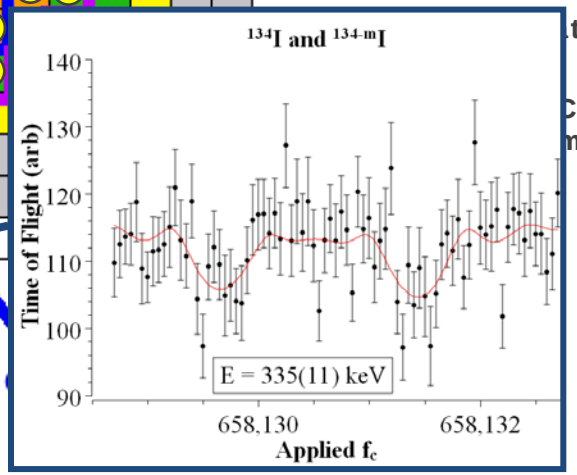
$\chi^2/n = 10.7$



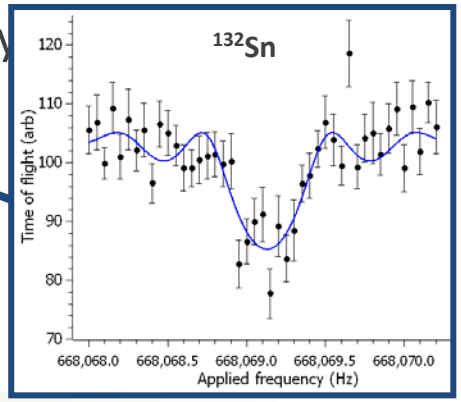
First CARIBU measurements: n-rich isotope masses



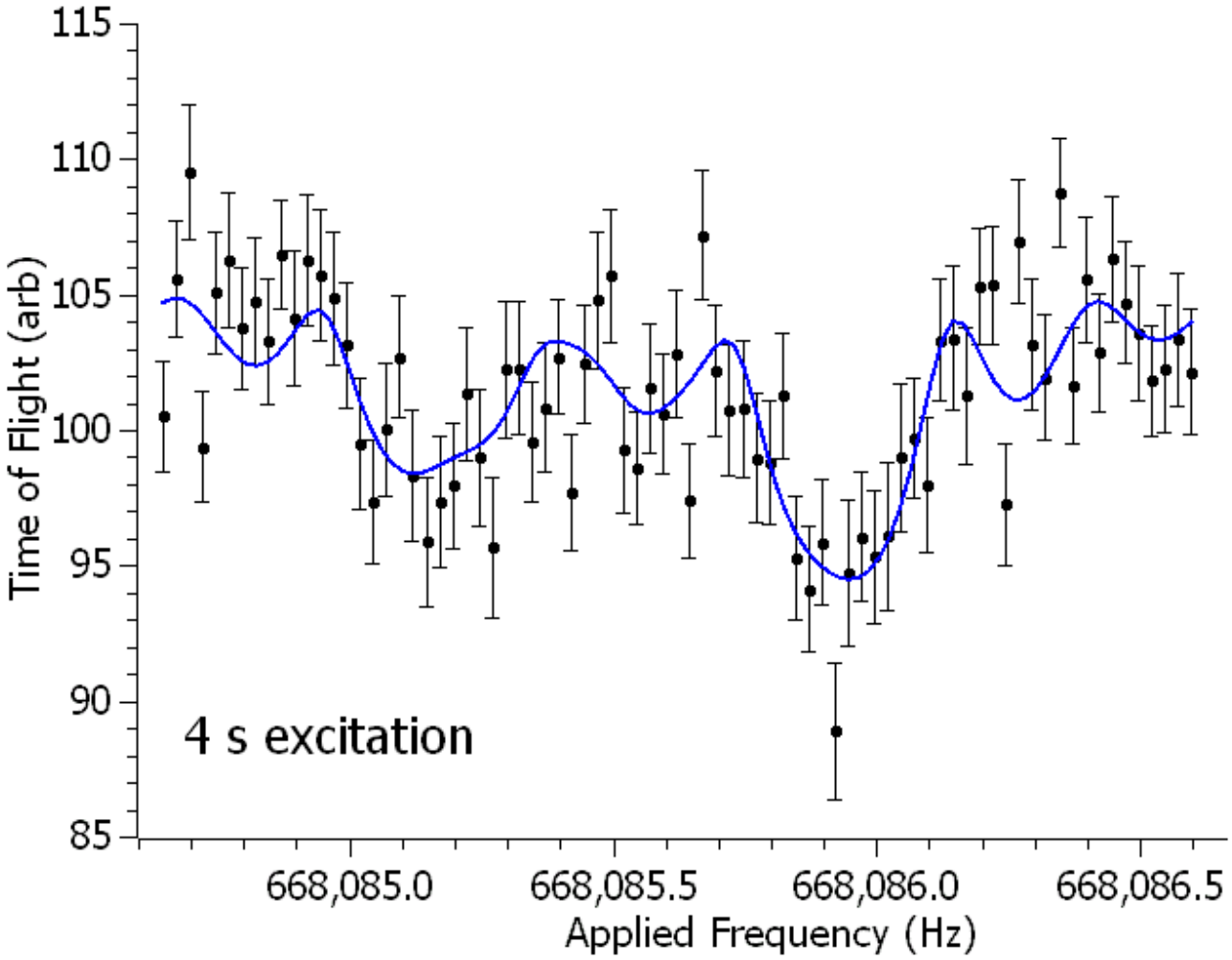




- First physics measurements and yield mapping at low energy
  - 25(+2) radioactive nuclides identified and measured at CPT
- Combined (Area II + CARIBU) work already covers most elements in heavy peak
  - universal
  - changing mass is turning one knob



^{132}Sb and $^{132-m}$Sb

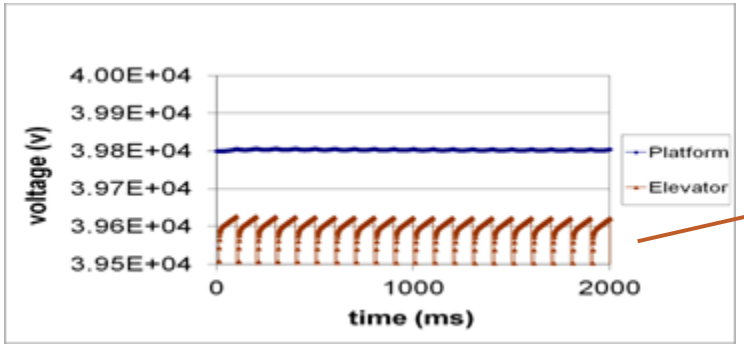


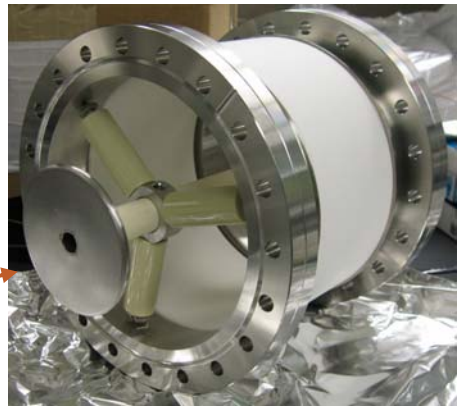
Measurement of isomer excitation energy to 4 keV

No direct measurement, lit: 150-250 keV estimate based on possible level schemes

Current efforts

- Facility works.
  - Next ATLAS PAC just announced on Monday with CARIBU beams available. Proposals due on Dec. 12 2011. PAC meeting on Jan. 13-14 2012.
- Efforts ongoing to reach full intensity and improve on limitations observed in first round of experiments:
  - Isobaric contamination at low energy
  - Stable beam contaminants in reaccelerated beams
  - Installing the full intensity 1 Ci source
- Currently working on improving isobar separation at low energy
  - New ejection pulsing circuitry to improve stability of beam energy and therefore mass selection
  - Improve control and locking of isobar separator magnet





Current efforts

- Preparing for 1Ci source installation
  - New micro-RFQ's in ion cooler to increase transmission efficiency at large intensity
  - Modify flow pattern and increase helium gas flow in gas catcher to keep gas cleaner—fewer contaminant molecules
  - Installation of new cover foil on source in hot cells
  - Characterize thickness of current 60 mCi source
  - Additional diagnostics for yield identification
  - Tests ongoing at ORNL in preparation for 1Ci source deposition in December 2011.

Status

- CARIBU is the first RIB facility based on the gas catcher system. It has met its commissioning goals.

- CARIBU is delivering low-energy beams for physics experiments and reaccelerated beams for developments
  - Open to community in current PAC proposal cycle → proposals due Dec. 12 2011

- All components work essentially as expected … lots of work to optimize and map yield and beam purity

- Mass measurement campaign on n-rich isotopes started
  - All colored isotopes are accessible to high-precision measurements
  - Will provide excellent calibration in the region for indirect measurements on more exotic isotopes