Superheavy Element Studies at LBNL

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Outline

- Superheavy Elements
- Introduction to FIONA
- Results from FIONA commissioning
- Results from first FIONA scientific campaign

BERKELEY, CALIFORNIA

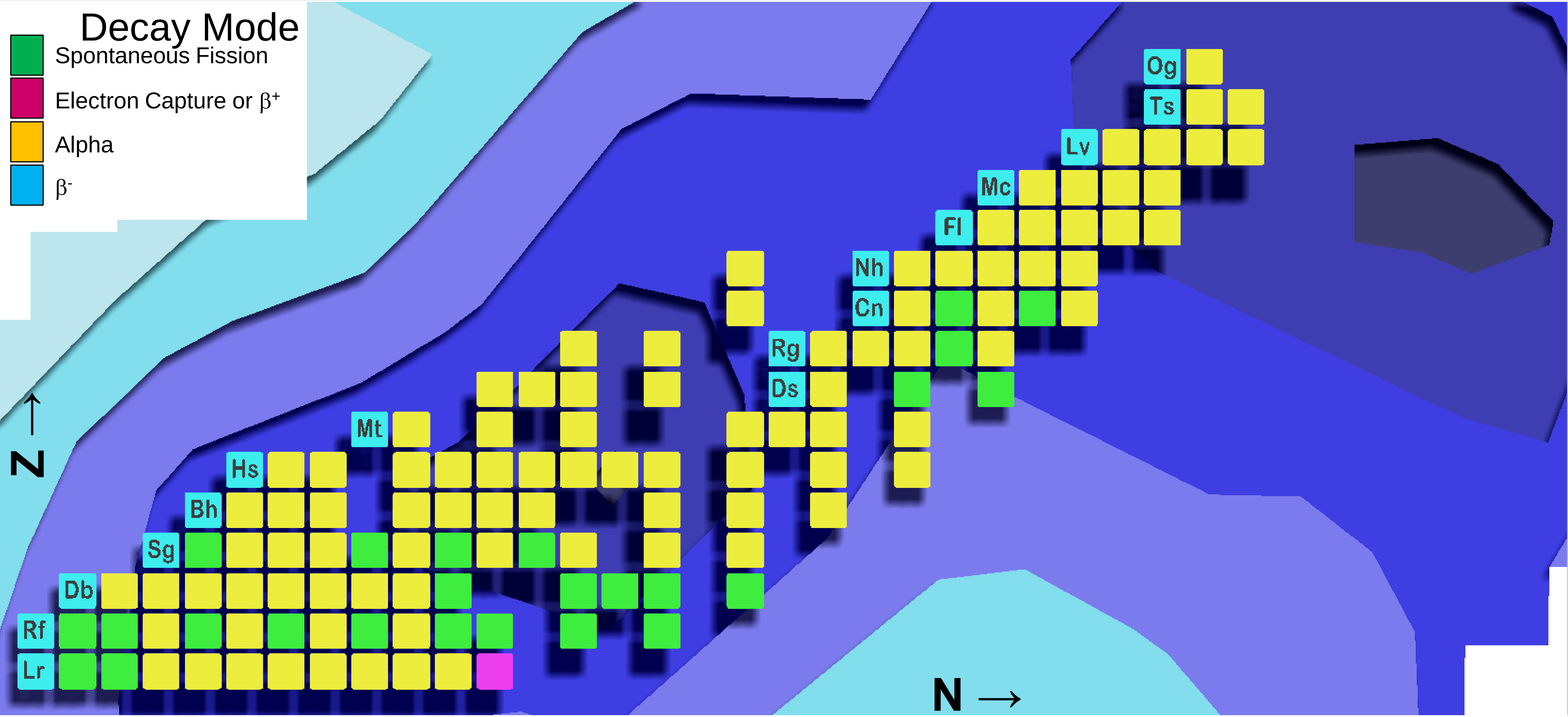
FIONA People

Ken Gregorich (PI, retired)
Jeff Kwarsick (grad student)
Michel Kireeff Covo (staff)
Rodney Orford (Postdoc)
Greg Pang (Project Scientist)
Jenn Pore (Postdoc)
Guy Savard (ANL)

Lawrence Berkeley National Laboratory
University of California, Berkeley
Argonne National Laboratory
University of Chicago
TRIUMF
Lawrence Livermore National Laboratory
McGill University

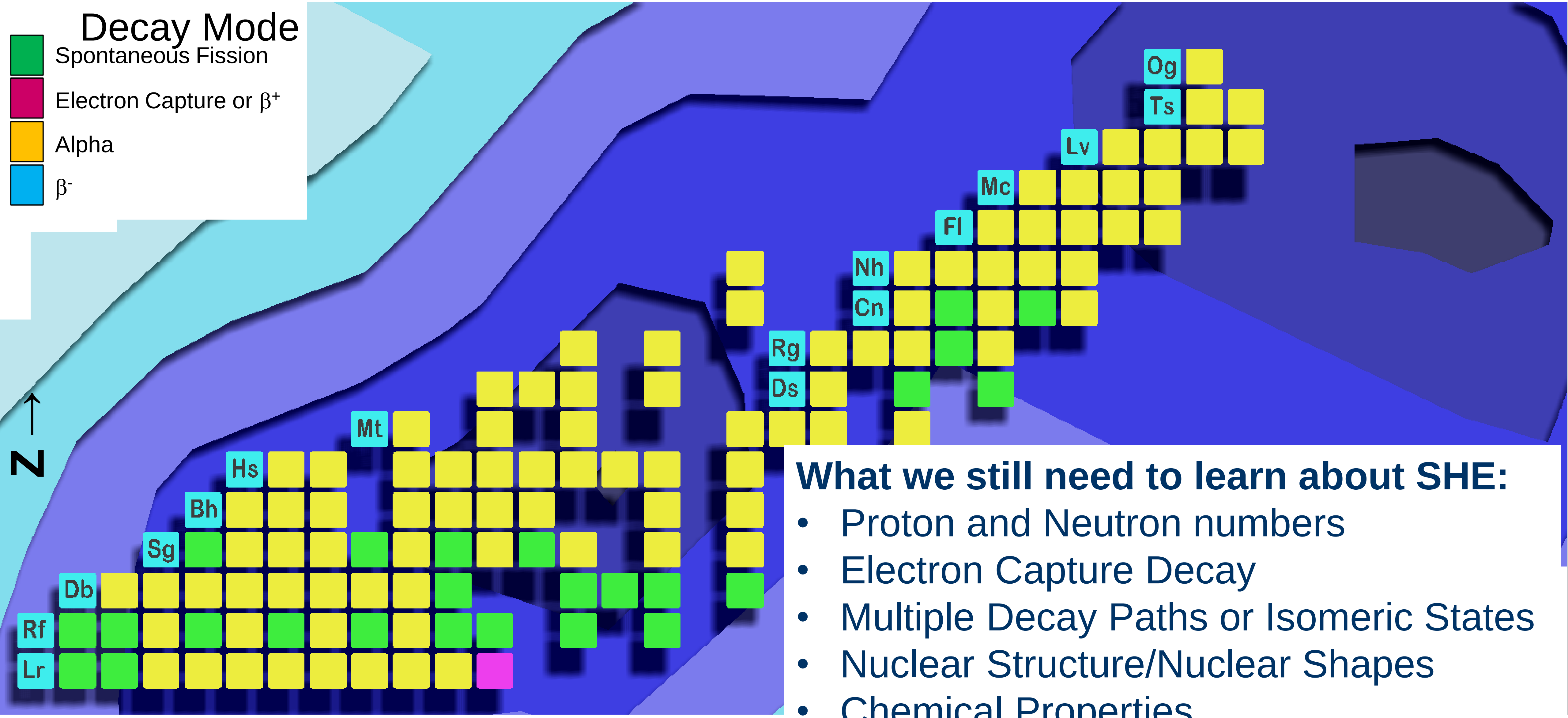
Nick Esker
Mejdi Mogannam
Jon Batchelder
Darren Bleuel
Rod Clark
Heather Crawford
Paul Fallon
Klaire Hubbard
Aaron Hurst
Ian Kolaja
Augusto Macchiavelli
Chris Morse
Larry Phair
Mark Stoyer

Chart of the Nuclides



Shell effects from Sobiczewski et al: Phys. Rev. C 63 (2001) 034306

Chart of the Nuclides



What we still need to learn about SHE:

- Proton and Neutron numbers
- Electron Capture Decay
- Multiple Decay Paths or Isomeric States
- Nuclear Structure/Nuclear Shapes
- Chemical Properties

Shell effects from Sobiczewski et al: Phys. Rev. C 63 (2001) 034306

Multiprong approach towards investigating SHE

Mass number identifications

- Neutron numbers
- Ambiguities in isotope assignments
- Multiple decay paths

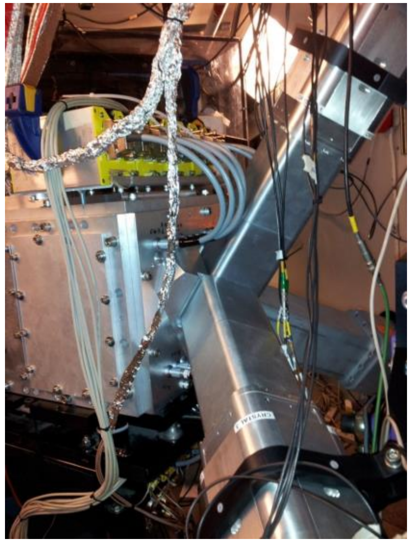
Spectroscopy in low α-, γ- background

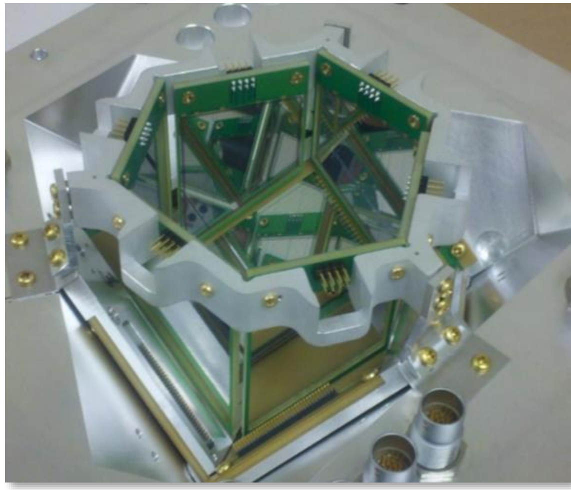
- Electron capture decay

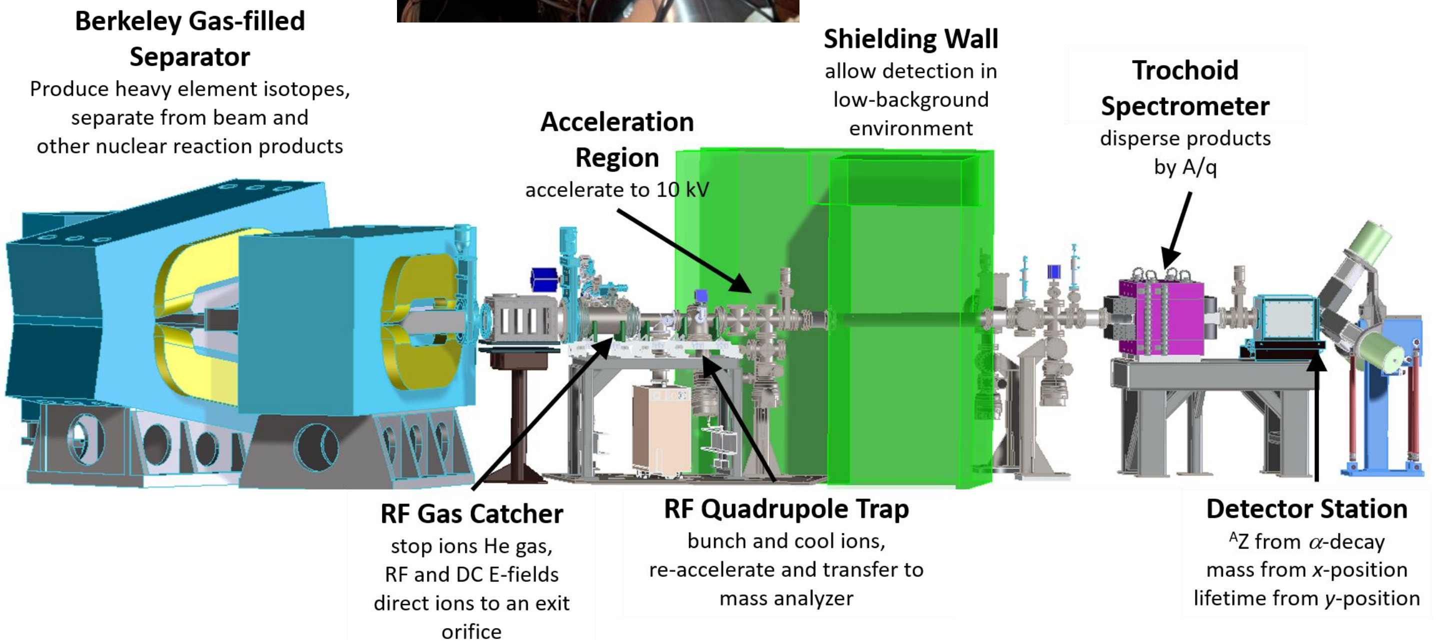
Chemistry

α-γ Spectroscopy

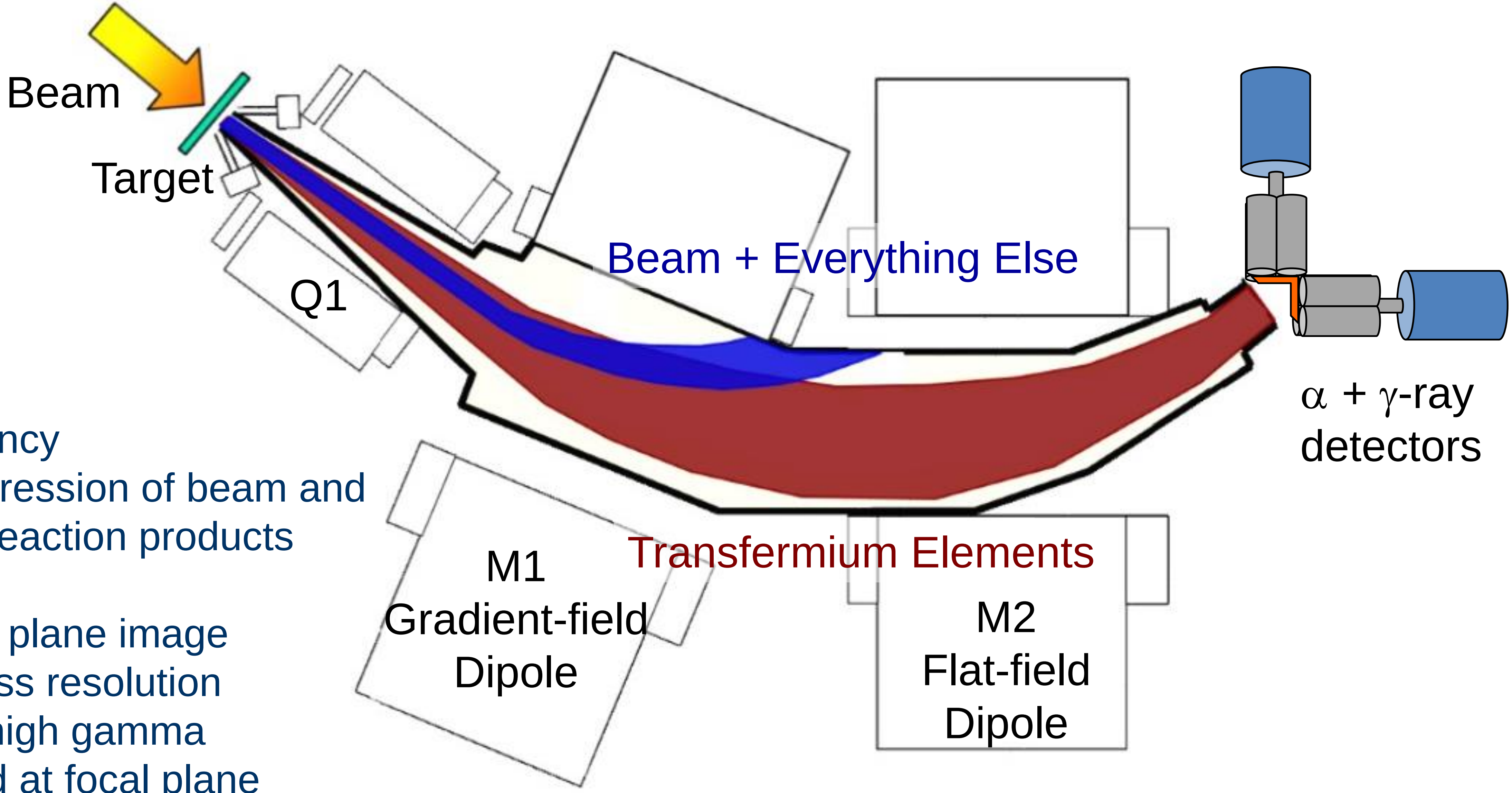
- Nuclear Structure
- Proton numbers
- Shapes







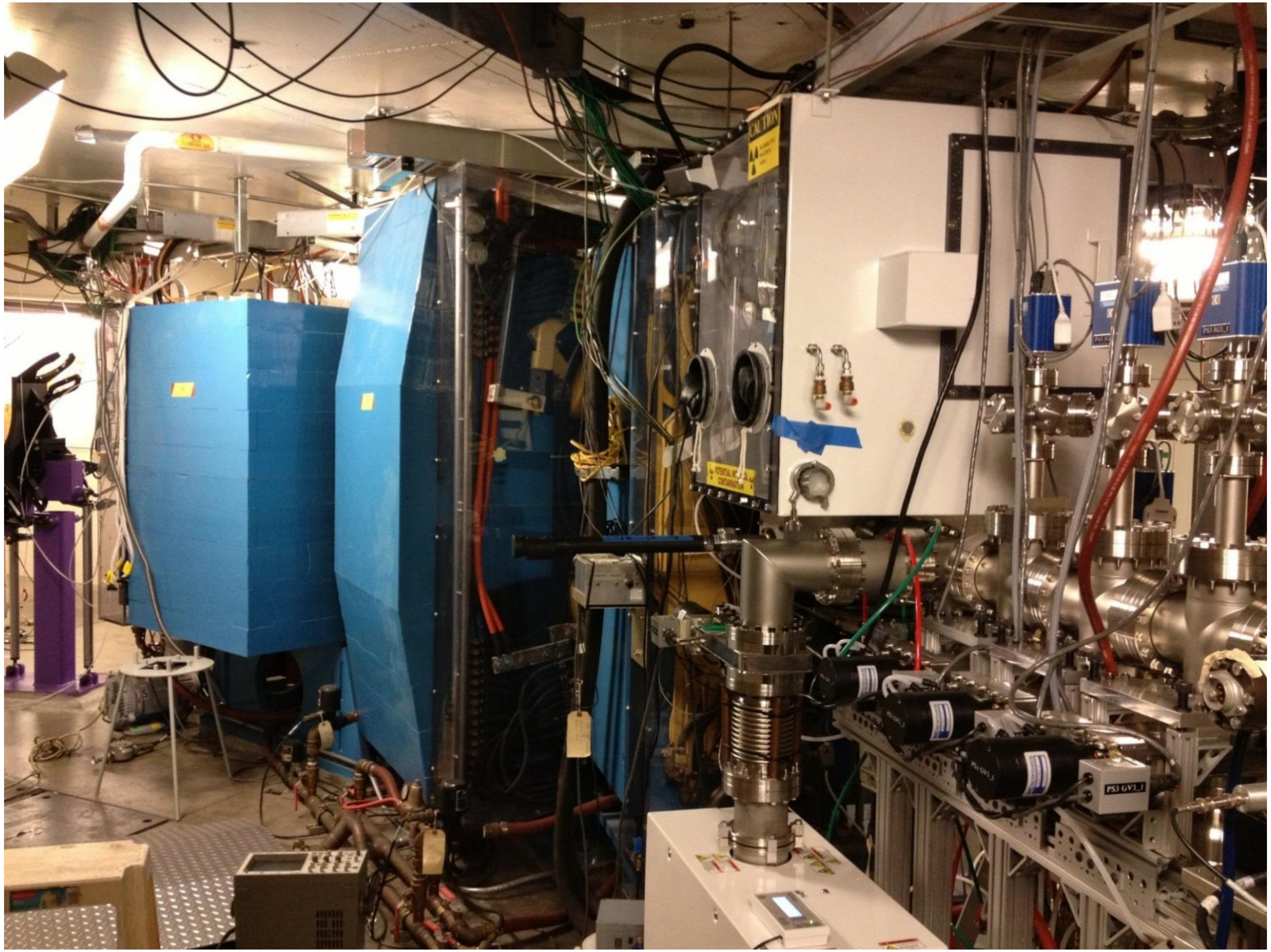
Berkeley Gas-filled Separator (BGS)



Positives:
- High efficiency
- Large suppression of beam and unwanted reaction products

Challenges:
- Large focal plane image
- Limited mass resolution
- Relatively high gamma background at focal plane

Berkeley Gas-filled Separator (BGS)



Ions at end of BGS are:

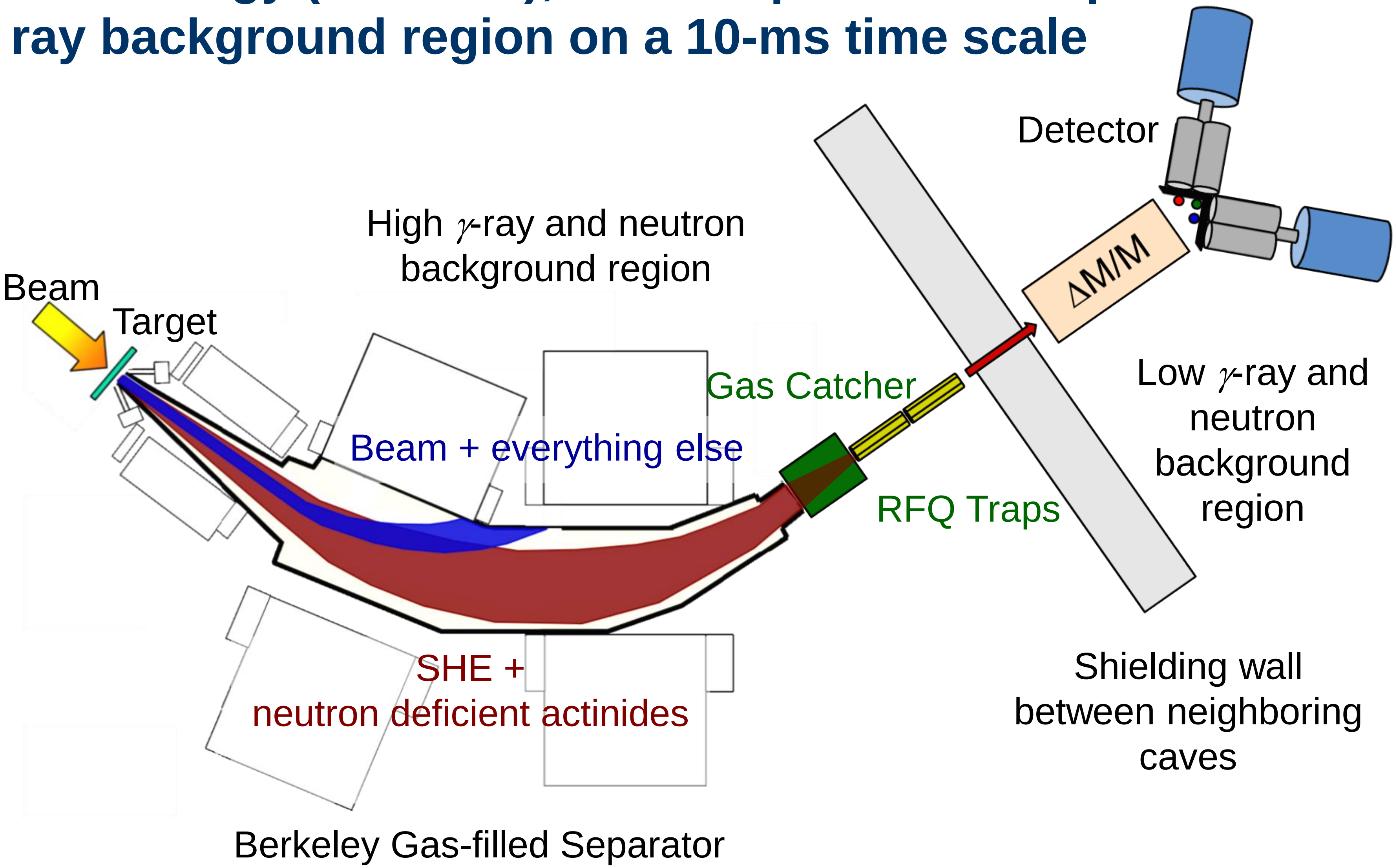
- Separated from the beam and unwanted reaction products
- Traveling at 10-45 MeV
- Beamspot is 2x3 cm FWHM

What we want after that:

- Low energy (5-10 keV), mass-separated isotopes delivered to a low neutron and γ-ray background region on a 10-ms time scale

BGS+FIONA - Overview

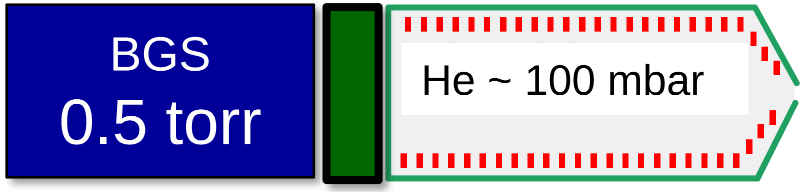
Low energy (5-10 keV), mass-separated isotopes delivered to a low neutron and γ-ray background region on a 10-ms time scale



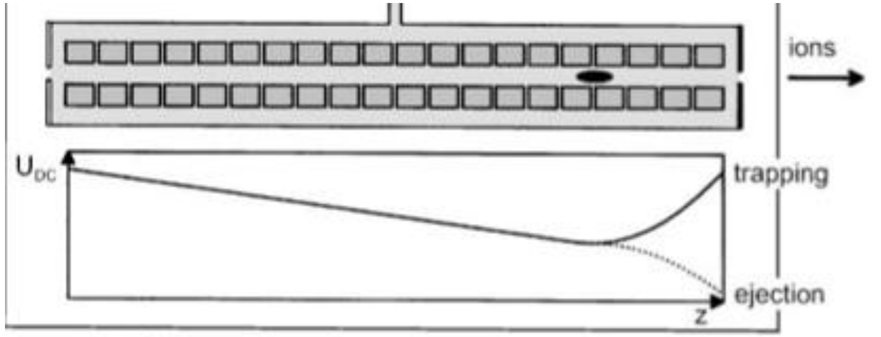
The Plan:

- Collect recoils at BGS focal plane
- Stop, cool and bunch
- Reaccelerate
- Separate by mass
- Send to detector station

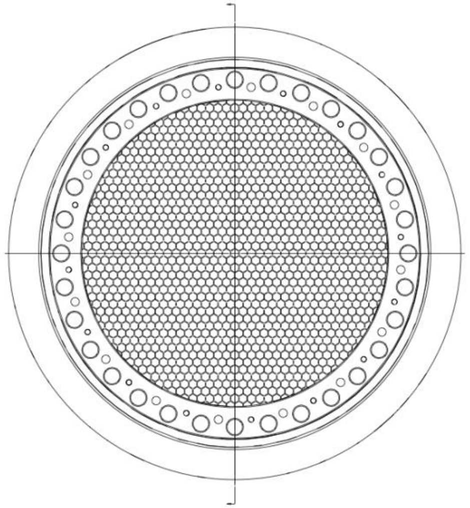
Interface between BGS and Mass Analyzer



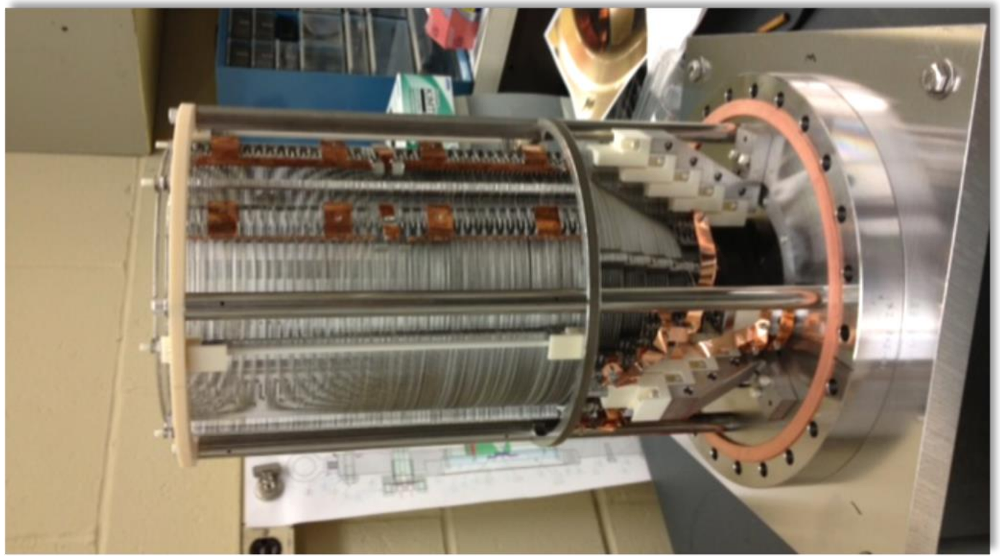
RF + DC



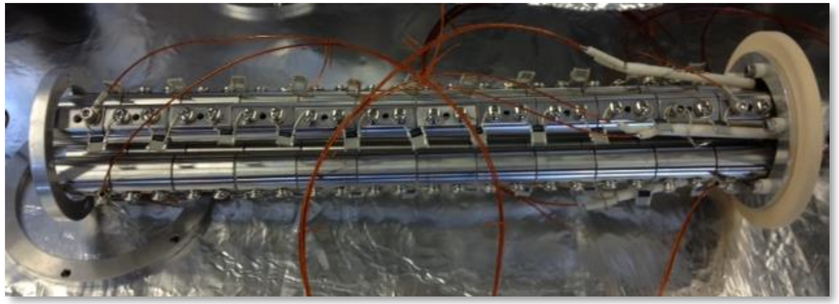
Acceleration across 5-10 kV gap



> 2 µm metal foil with support grid

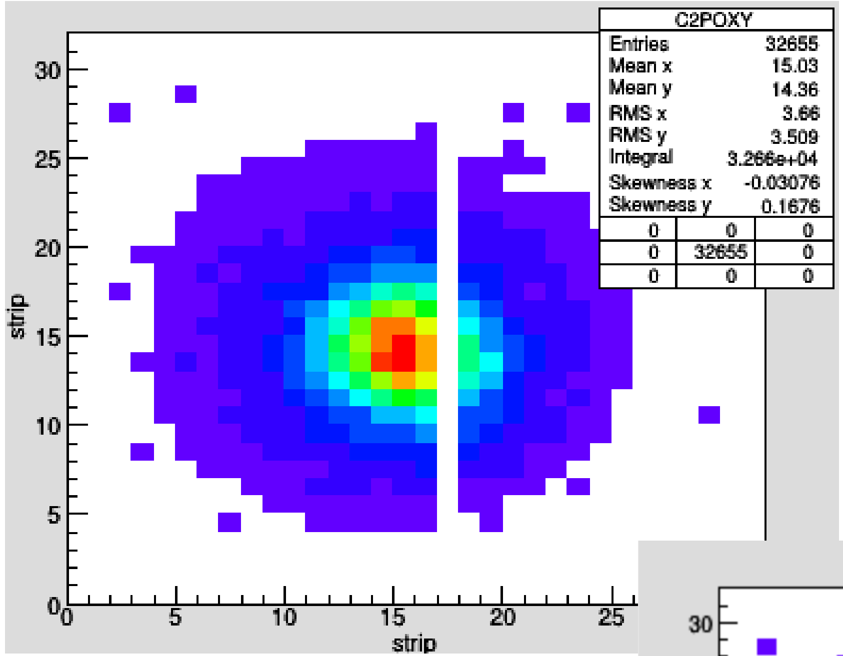


Gas Catcher

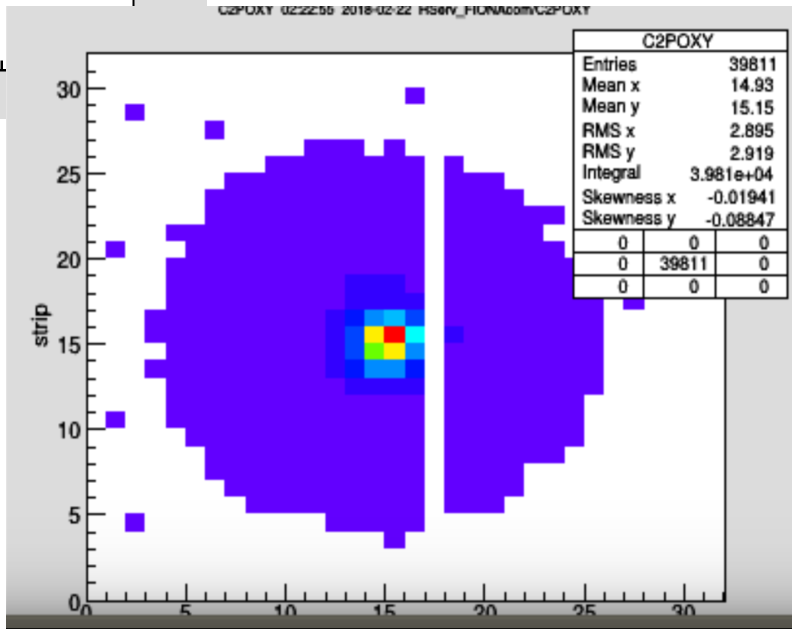


RFQ Trap

Built by Guy Savard et al. at ANL



No Focus

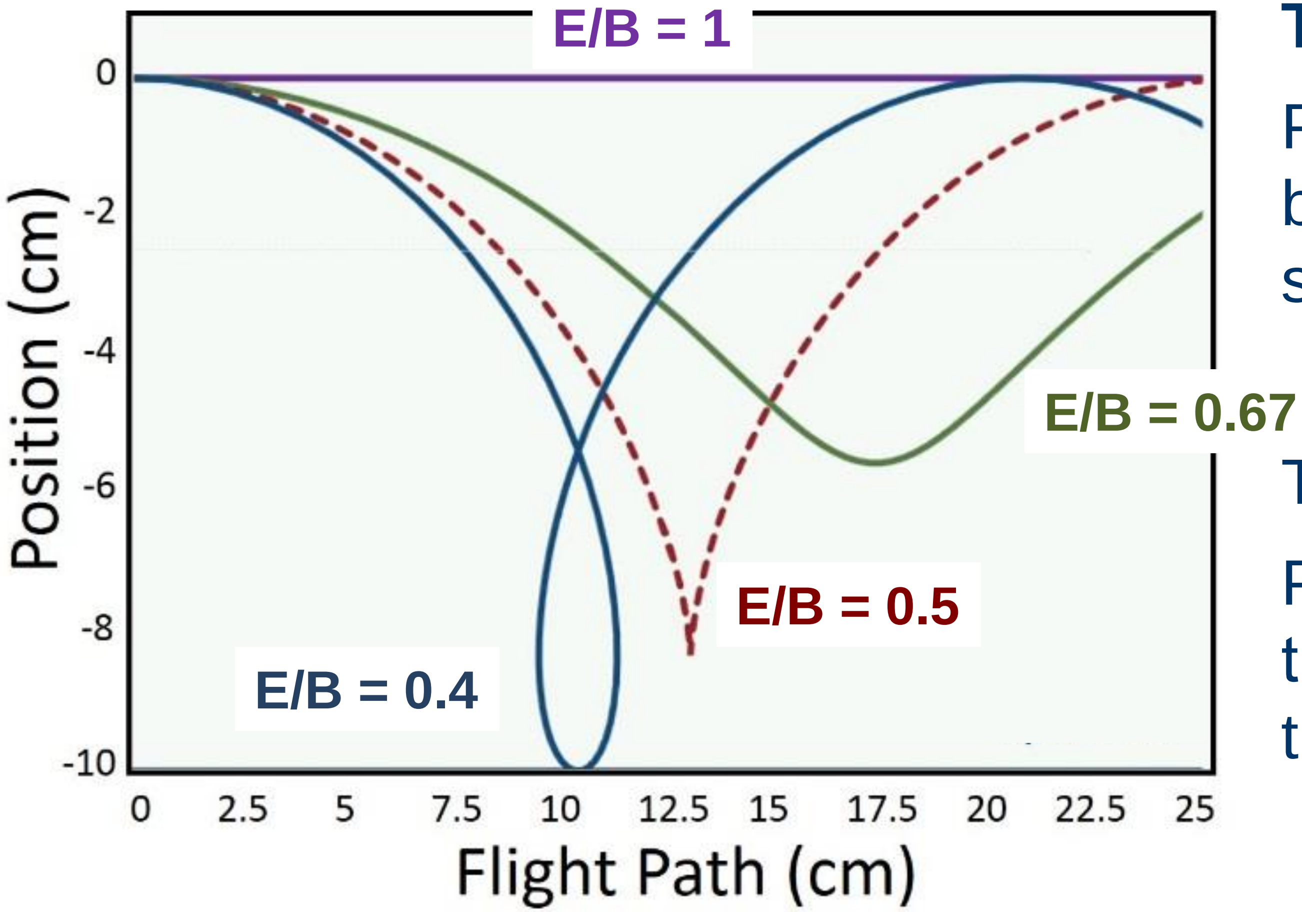


Max Focus

Requirements for mass analyzer:

1. Mass determination from ≤3 atoms
   Fit at least 6 masses on detector
2. High dispersion
3. Masses separated by >4 σ
4. Low extraction voltage from RFQ
5. High efficiency >50%
6. Fit within existing space

ExB Mass Analyzer – The Idea



Traditional wien filter:

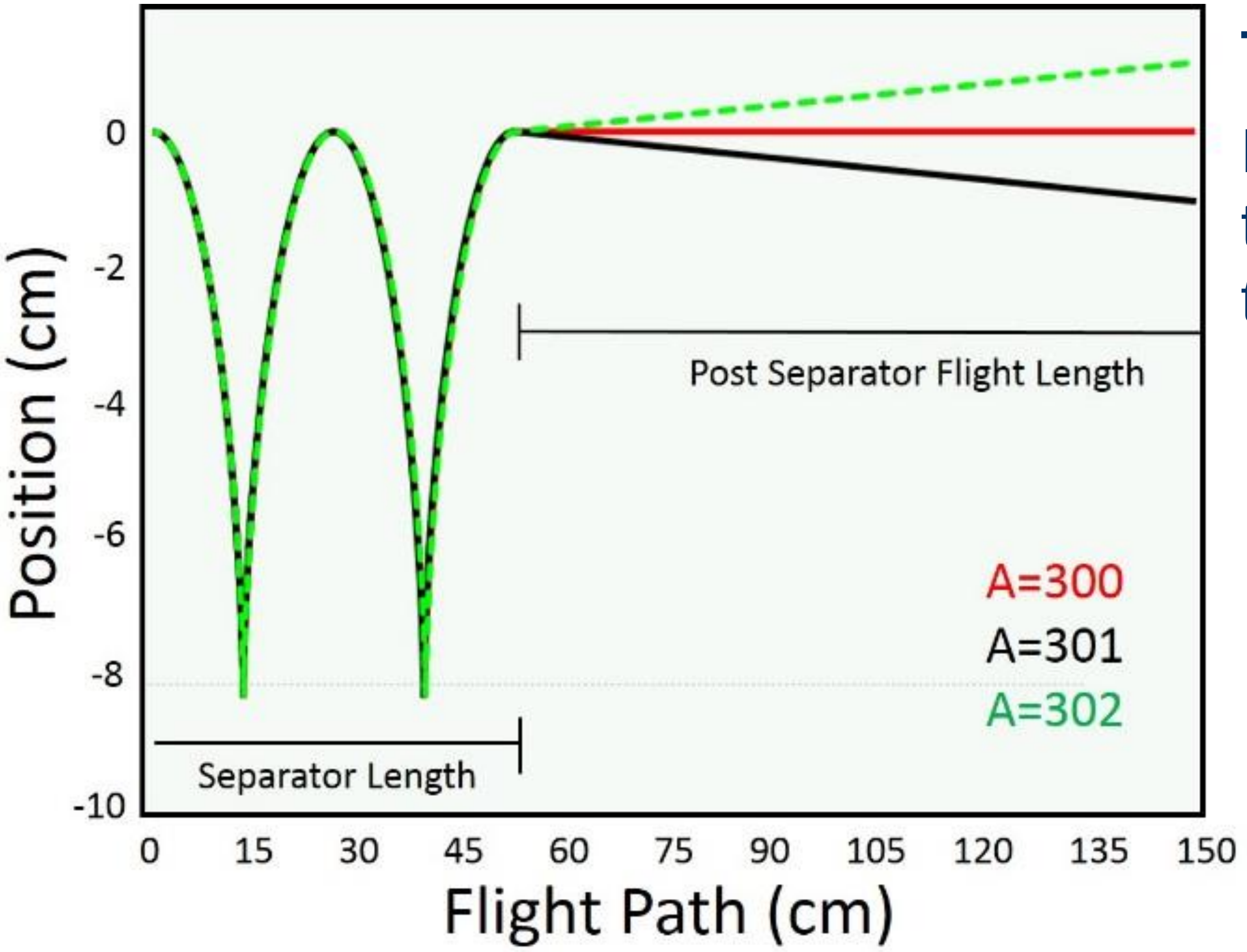
Perpendicular electric and magnetic fields, balanced such that ions with V=E/B travel straight through separator

Trochoid spectrometer:

Perpendicular electric and magnetic fields that are unbalanced → ions take trochoidal trajectories

BGS	Window	Gas Catcher	RFQ Trap 1	RFQ Trap 2	Extr. Accel.	Mass Anal.	Det. Box

ExB Mass Analyzer – The Idea

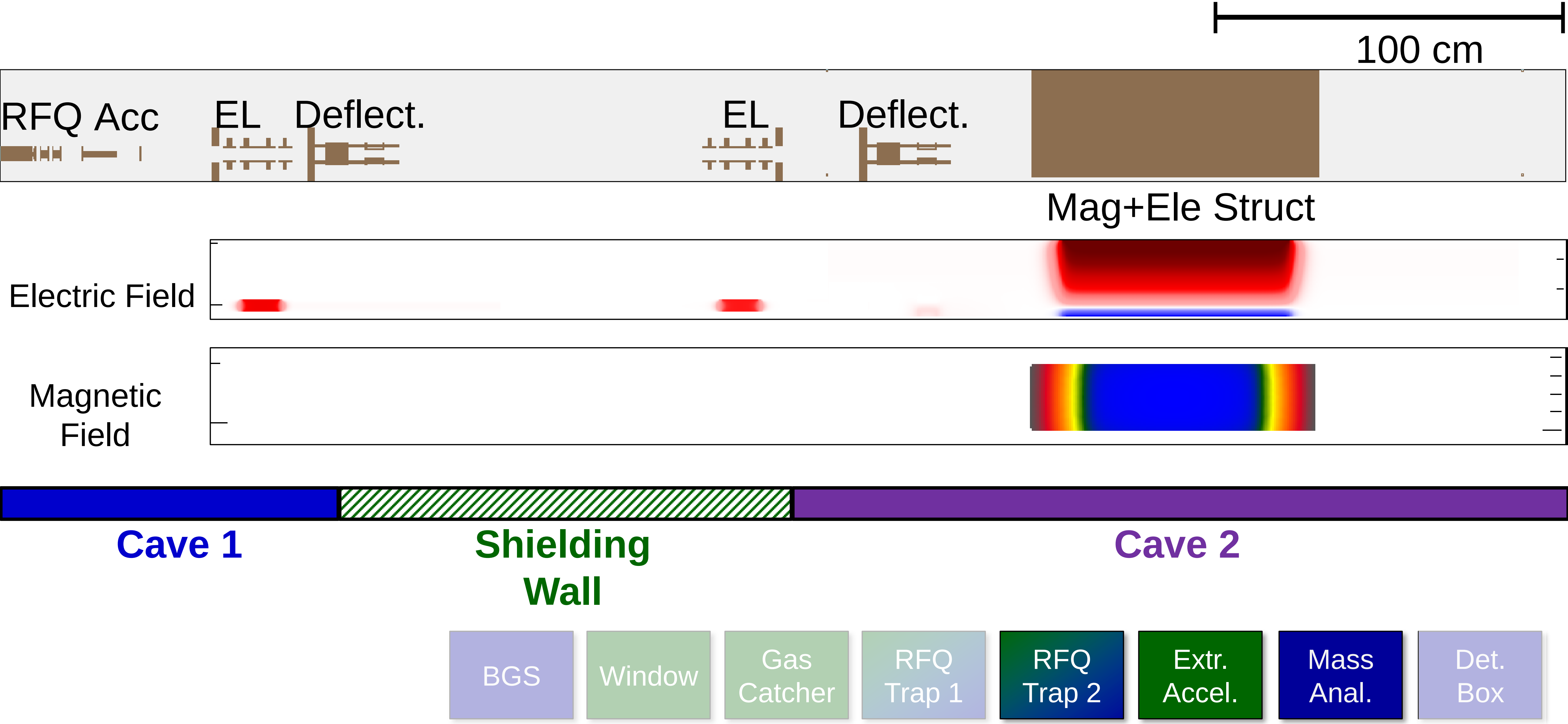


Trochoid spectrometer:

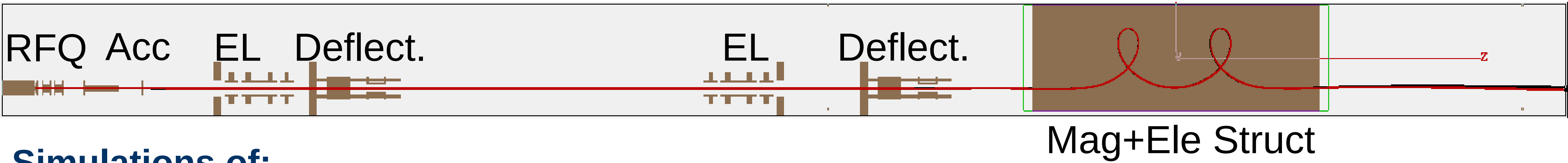
Perpendicular electric and magnetic fields that are unbalanced → ions take trochoidal trajectories

BGS	Window	Gas Catcher	RFQ Trap 1	RFQ Trap 2	Extr. Accel.	Mass Anal.	Det. Box

Mass Analyzer: Simulations w/ SIMION



Simulations of ^{288}115 and ^{289}115



Simulations of:

^{288}115 and ^{289}115

Charge state: 2+

Accelerated across 5 kV gap

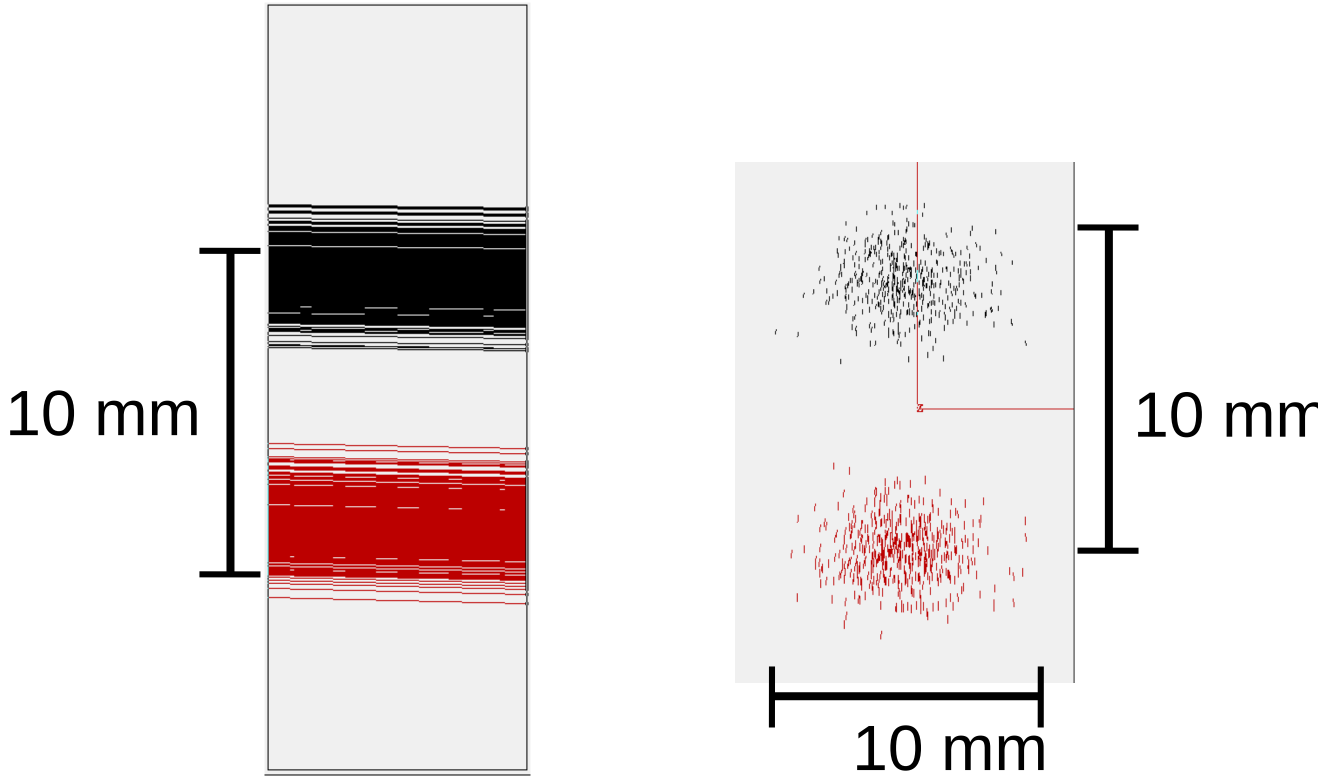
Simulations assumed:

Magnetic field: 0.95 T

Electric field: 250 V/cm

Einzel lenses: 1000-1500 V

Deflector: 100 V



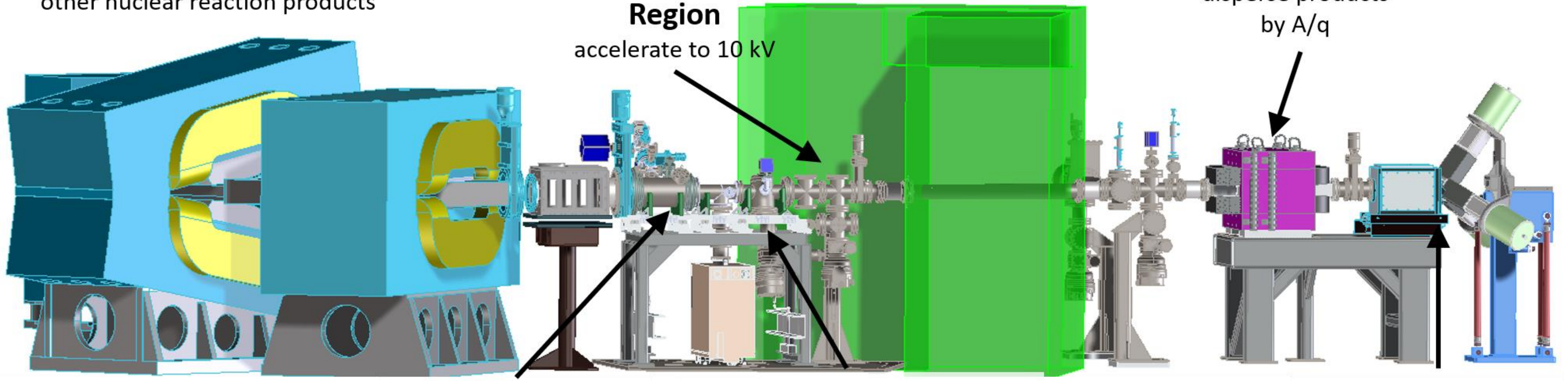
BGS+FIONA - Overview

Berkeley Gas-filled Separator
Produce heavy element isotopes, separate from beam and other nuclear reaction products

Acceleration Region
accelerate to 10 kV

Shielding Wall
allow detection in low-background environment

Trochoid Spectrometer
disperse products by A/q

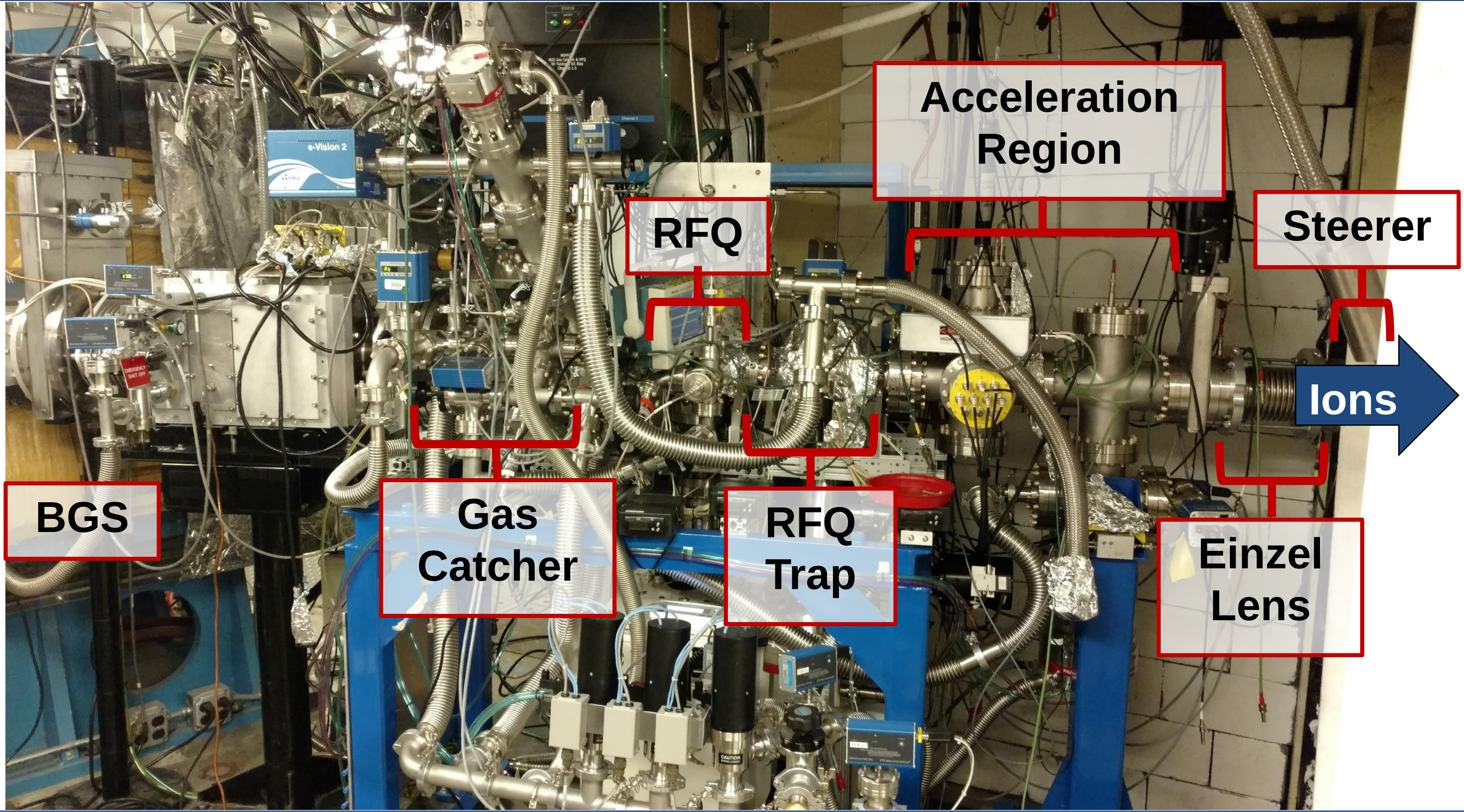


RF Gas Catcher
stop ions He gas, RF and DC E-fields direct ions to an exit orifice

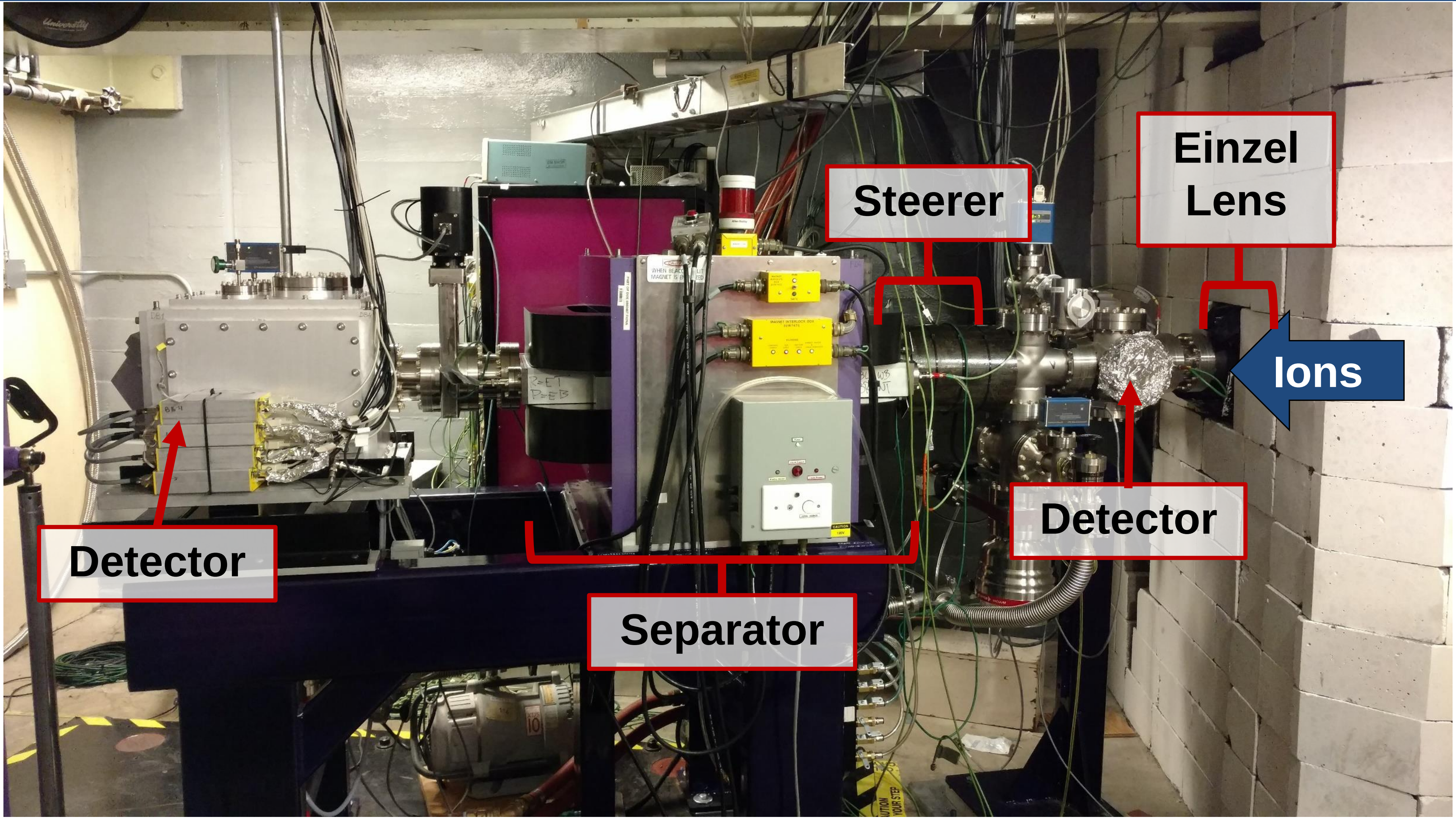
RF Quadrupole Trap
bunch and cool ions, re-accelerate and transfer to mass analyzer

Detector Station
^{A}Z from α-decay
mass from x-position
lifetime from y-position

Cave 1: BGS → Gas Catcher → RFQ Trap → Acceleration Region



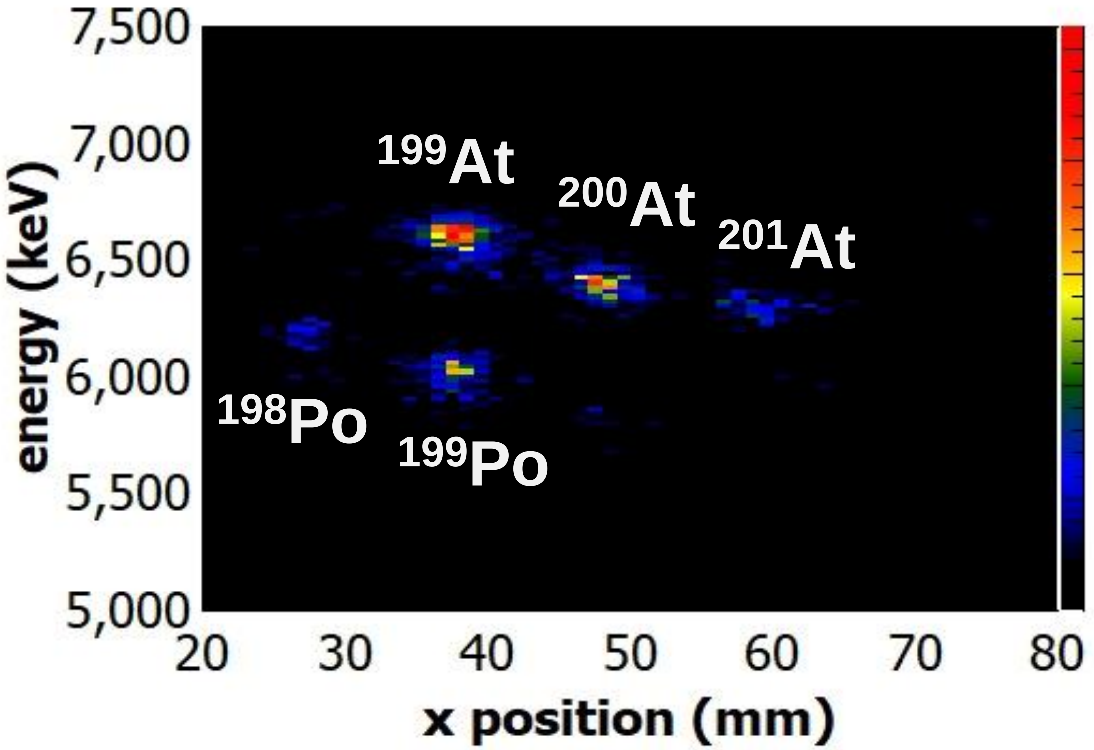
Cave 2: Diagnostics → Separator → Detector

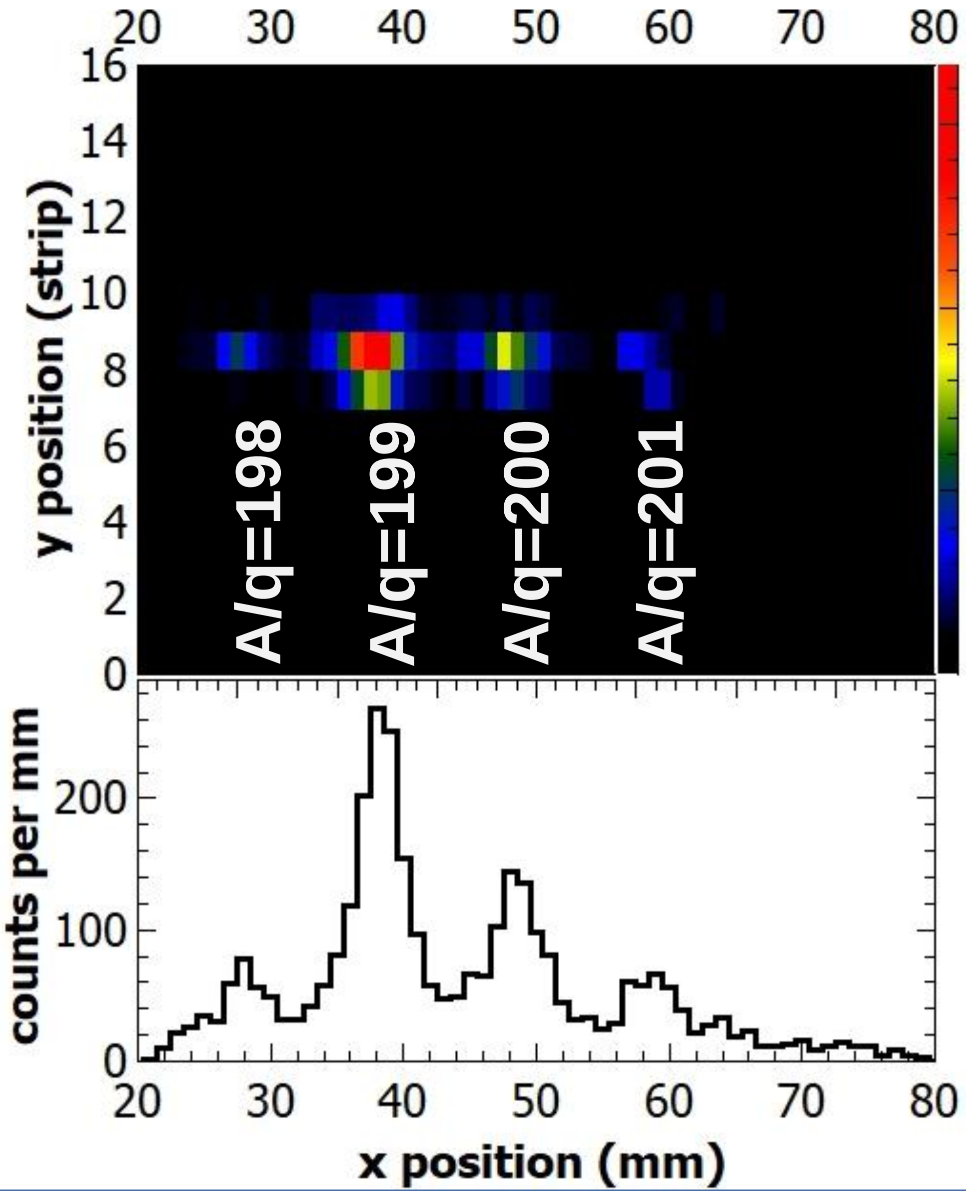


FIONA Commissioning: *A/q* separation

Experiment:

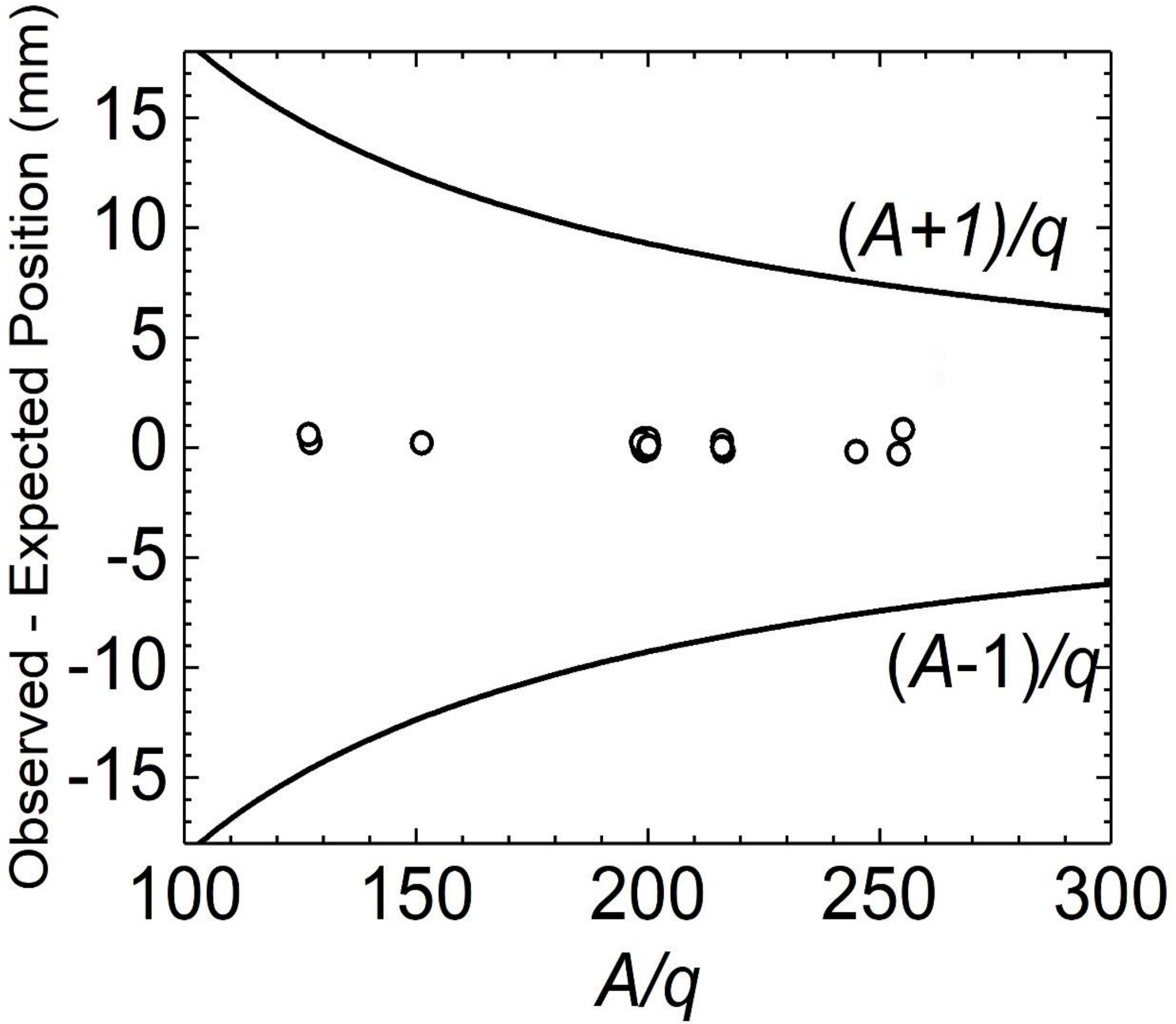
- At and Po isotopes produced at the 88” Cyclotron using the reaction:
- $^{nat}Tb + ^{48}Ca \rightarrow ^{199-201}At, ^{198,199}Po$
- Separated by Mass/charge in FIONA





FIONA Calibration and Scaling to a New Mass

1. Scale new mass acceleration potential by mass/charge ratio of ion
   - same magnetic rigidity
2. Scale all electric elements to account for new electric rigidity
   - new mass should exact same trajectories through FIONA as old mass ➔ show up in same position in focal plane detector
3. Tested by scaling between $^{254}No^{2+}$, $^{255}Lr^{2+}$, $^{151}Ho^{1+}$, $^{200}At^{1+}$, $^{208}Fr^{1+}$, $^{216}Po^{1+}$, $^{245}Fm^{1+}$, $^{254}No^{1+}$ and $^{255}Lr^{1+}$



What to do for *Proof-of-Principle* Chemistry with FIONA?

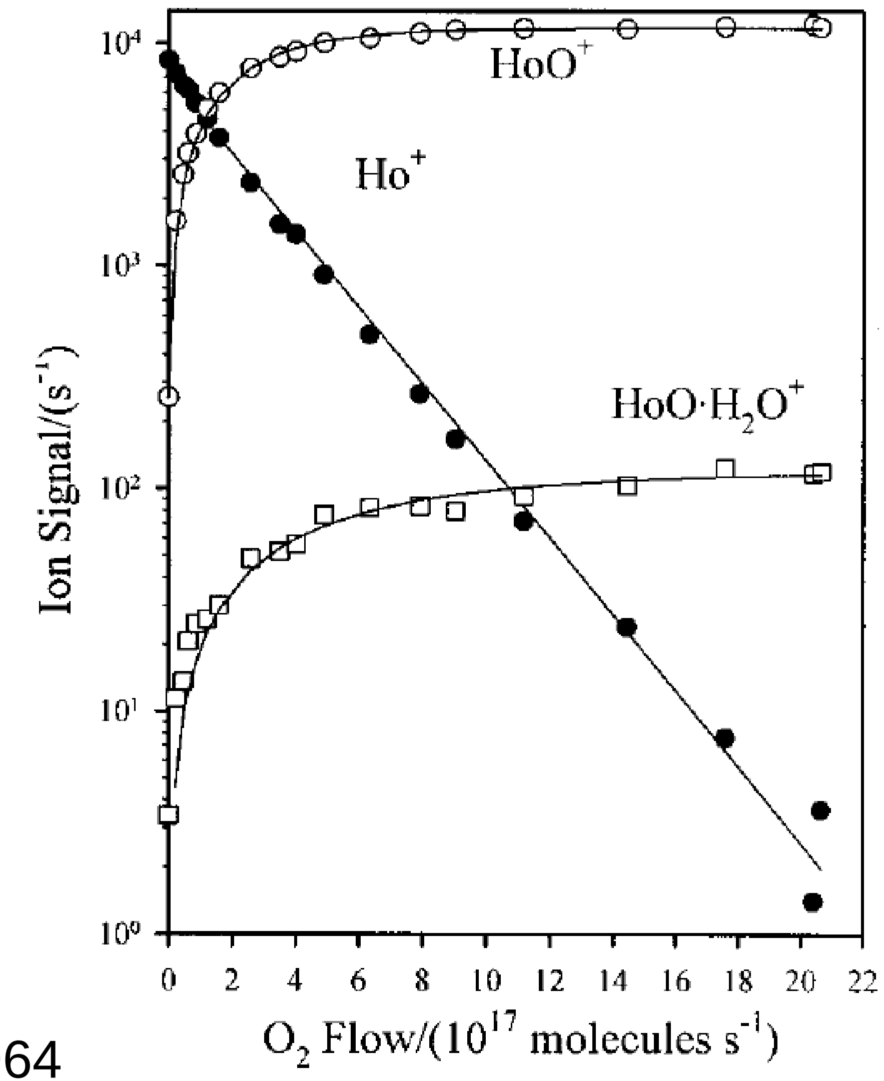
We do not have a good way to measure (partial) pressure inside the trap ➔ do calibration measurement!

Requirements:

- Well-defined reaction constant
- Fast kinetics
- Easily-made, short-lived, alpha-decaying isotope
- Proceeds at room temperature, in low pressures

Holmium!

- Forms HoO^+ in the presence of O_2
- Measured reaction rate coefficients:
  - 2.4×10^{-10} (O_2)
  - 1.7×10^{-11} (N_2O)

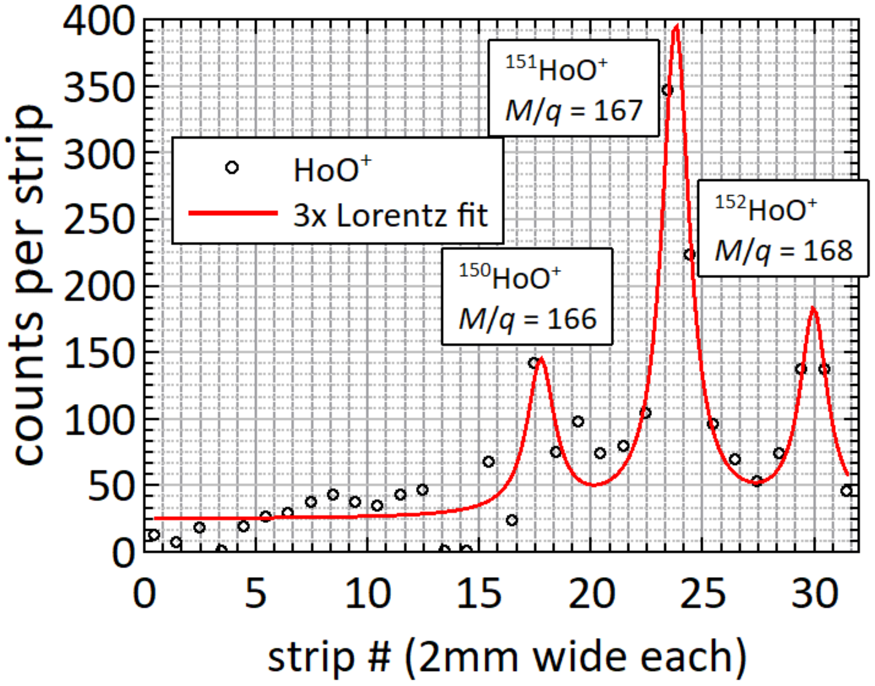


J. Phys. Chem A, **2001**, 8964

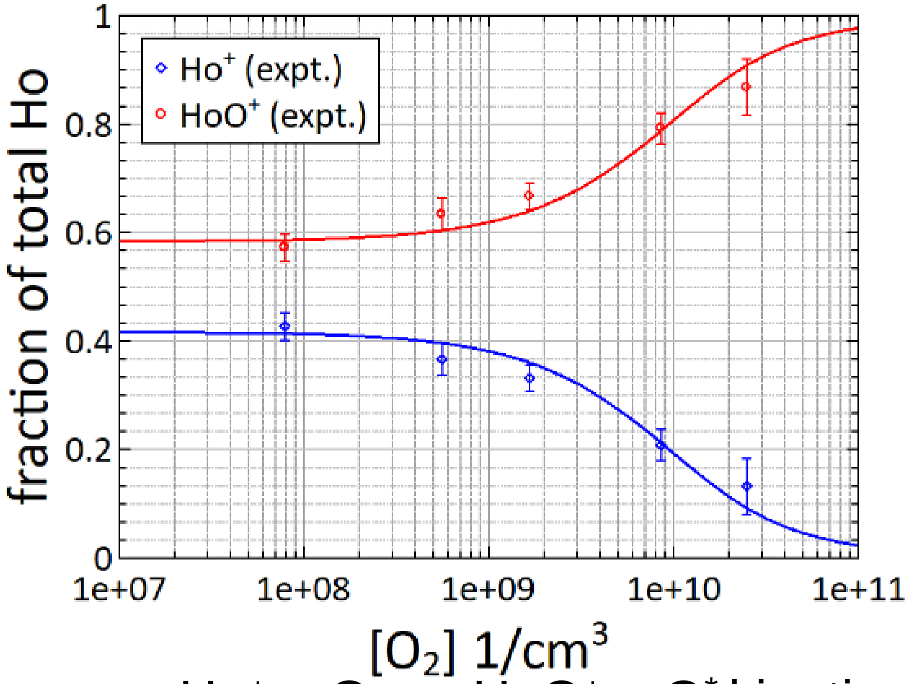
Proof-of-Principle experiment for gas-phase ion chemistry: Ho + O_2

1) **Produced and separated Ho at the 88**
2) **Ho^{1+} ions were captured and cooled in a RFQ trap containing a small partial pressure of O_2**
3) **Relative amounts of Ho^+ and HoO^+ were measured with a mass separator**

Reaction kinetics: change in $[Ho^+]/[HoO^+]$ with $[O_2]$ was measured, and used to calibrate $[O_2]$



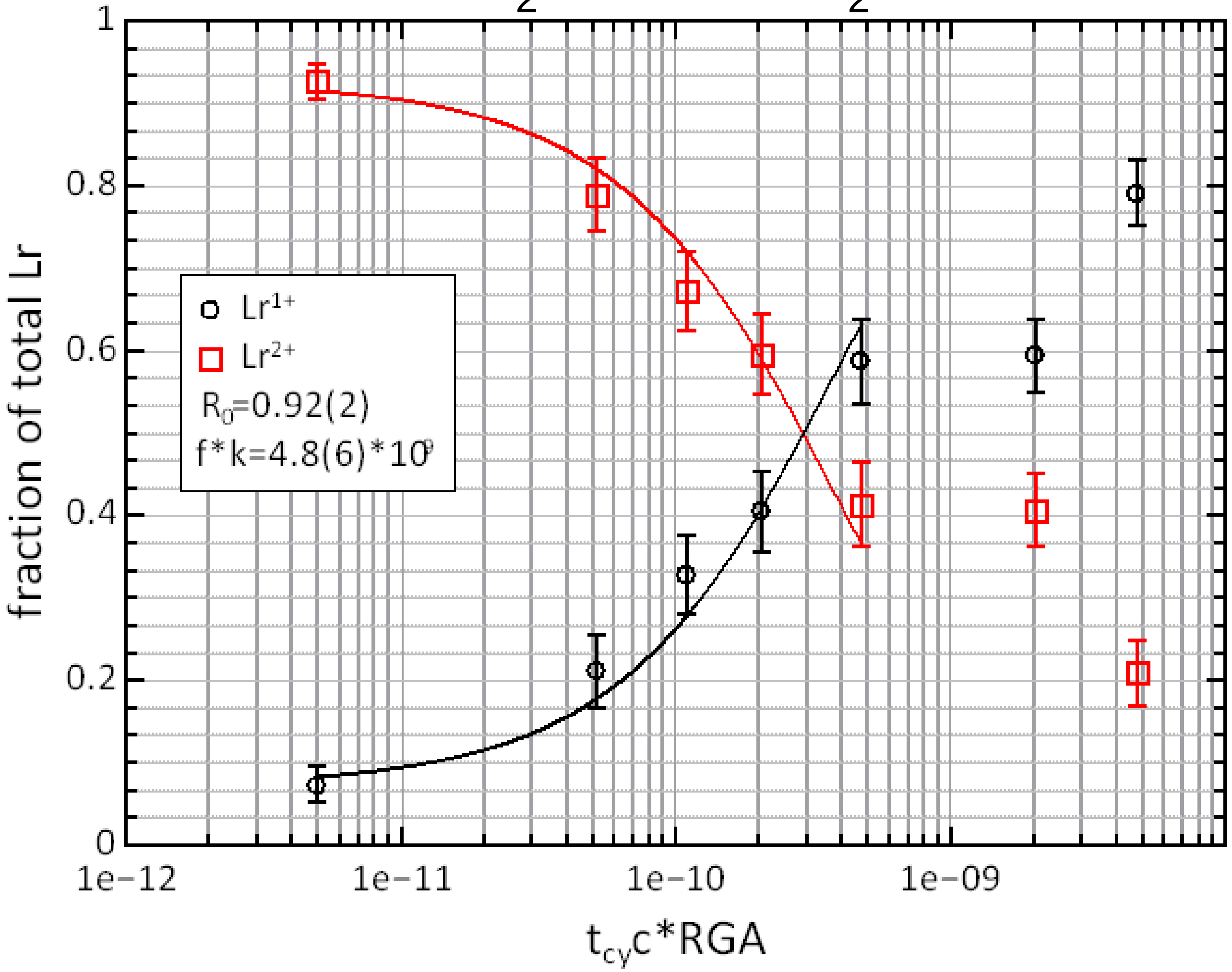
$^{150,-152}HoO^+$ mass spectrum



$Ho^+ + O_2 \rightarrow HoO^+ + O^*$ kinetics

First Chemistry with FIONA: Reduction of Lr^{2+} by O_2

$Lr^{2+} + O_2 \rightarrow Lr^{1+} + O_2^{+}$



If the electron affinity of M^{2+} is sufficiently greater than the ionization potential of O_2, reduction of M^{2+} by electron transfer can occur.

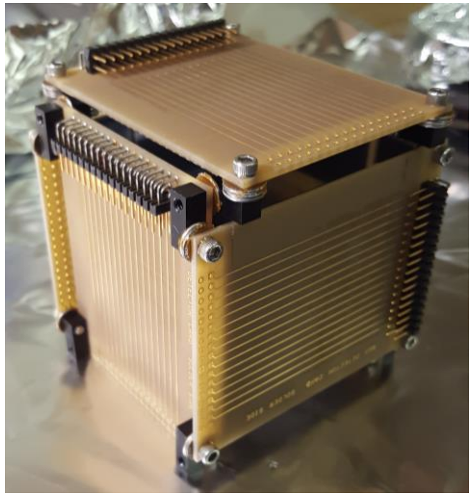
$IP(O_{2+})$ = 12.07 eV
EA Lr^{2+} = IP Lr^{1+} = 14.54 eV
Reaction rate is near the O_2 collision rate

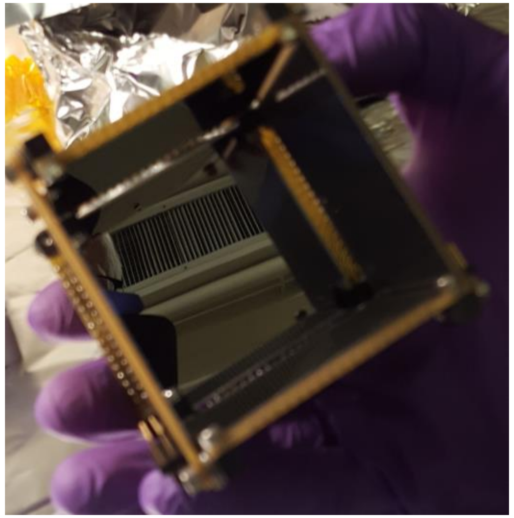
Other Results:
Reduction of No^{2+} by O_2 not observed
(IP No^{1+} = 12.93)
(not “sufficiently greater”)

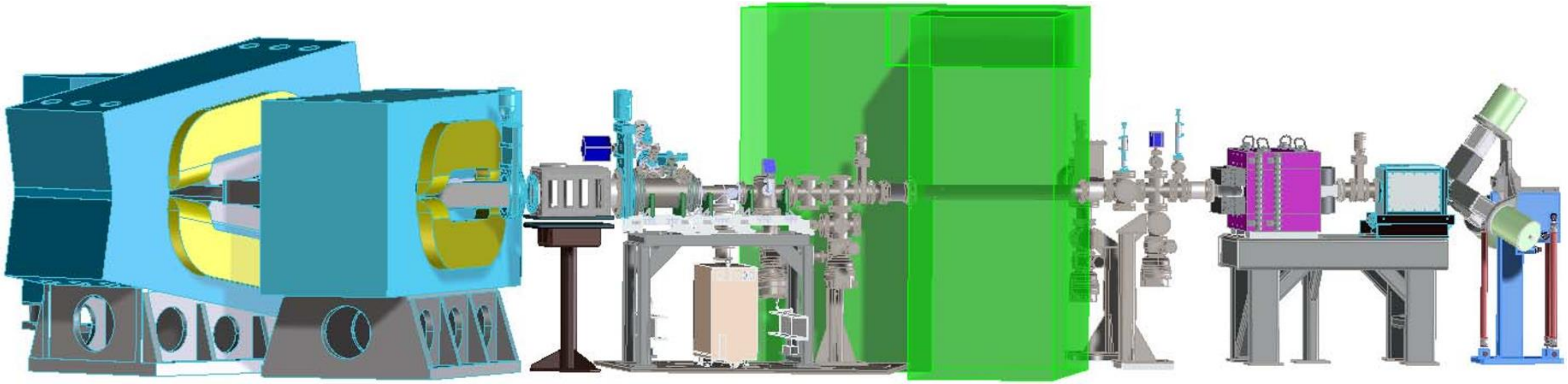
First Scientific Experiments with FIONA

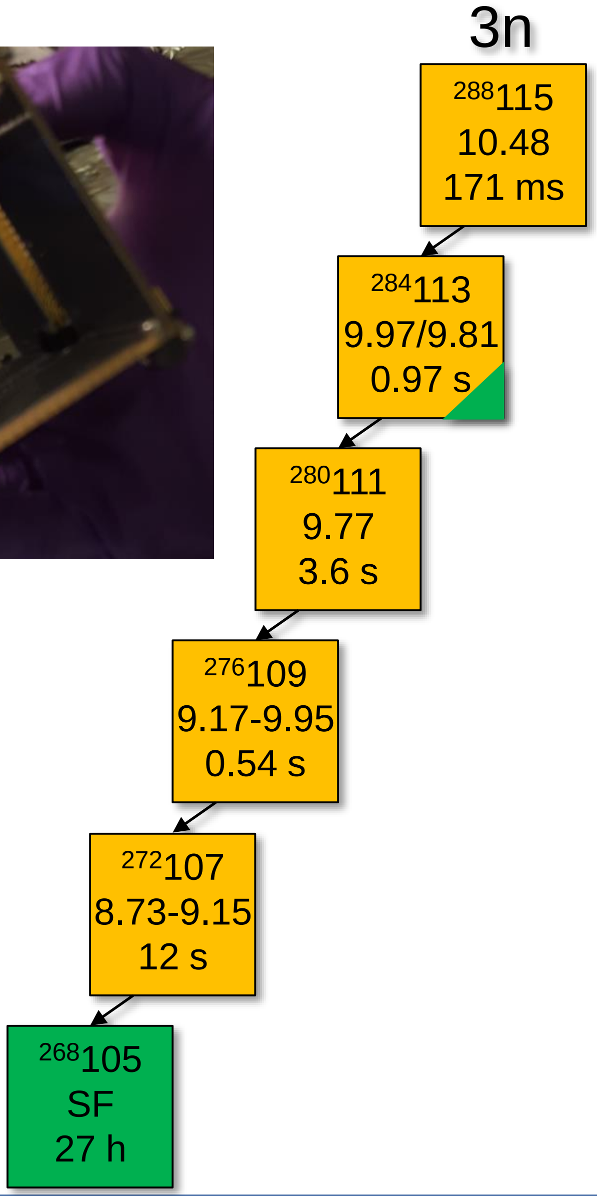
GOAL: Mass Number Measurement of E115

- Produced E115 using the ^{48}Ca + ^{243}Am reaction at the LBNL 88" cyclotron
- First scientific result from FIONA using 30 days of beam time with an average intensity of 1 puA ^{48}Ca beam



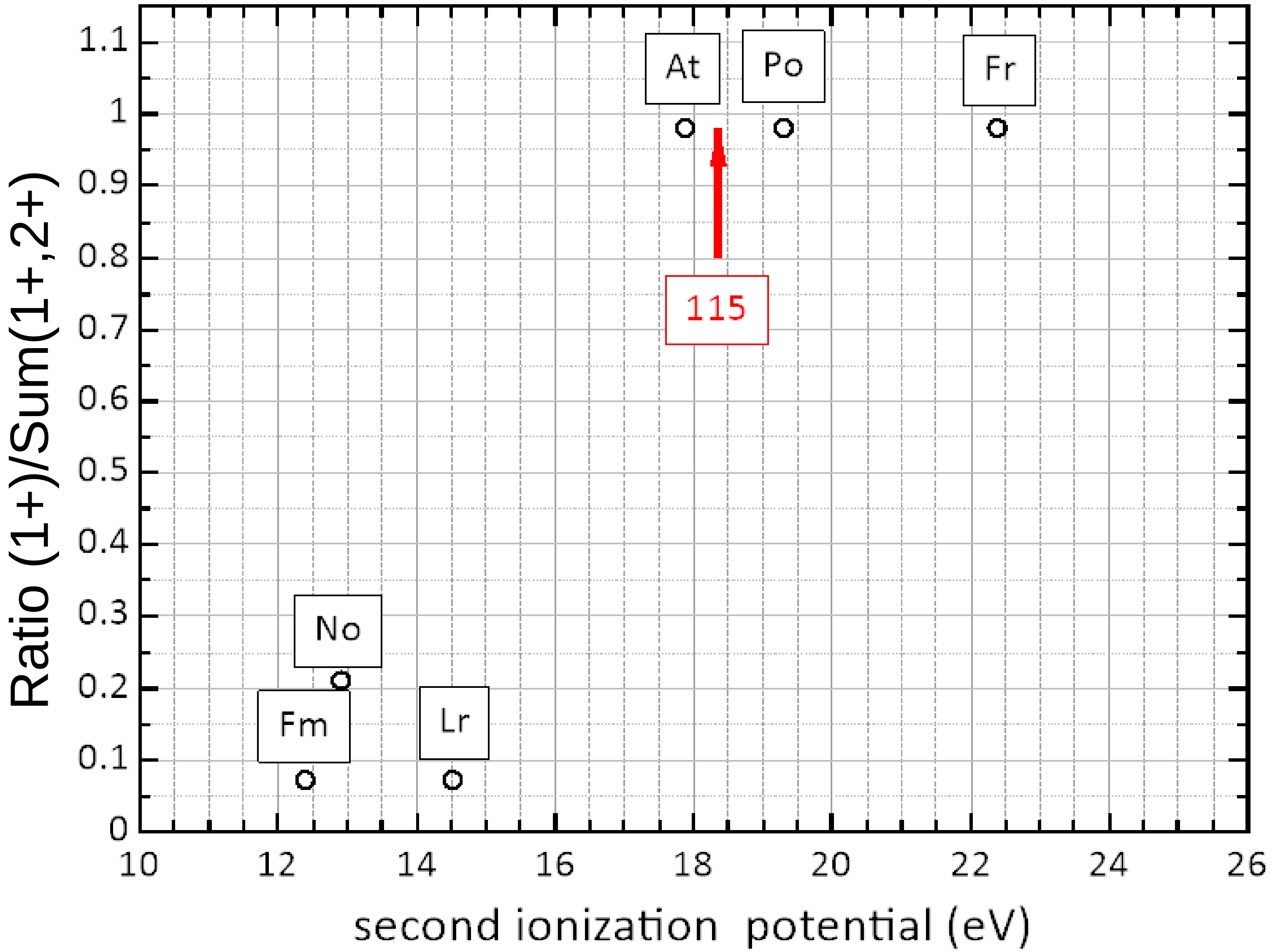






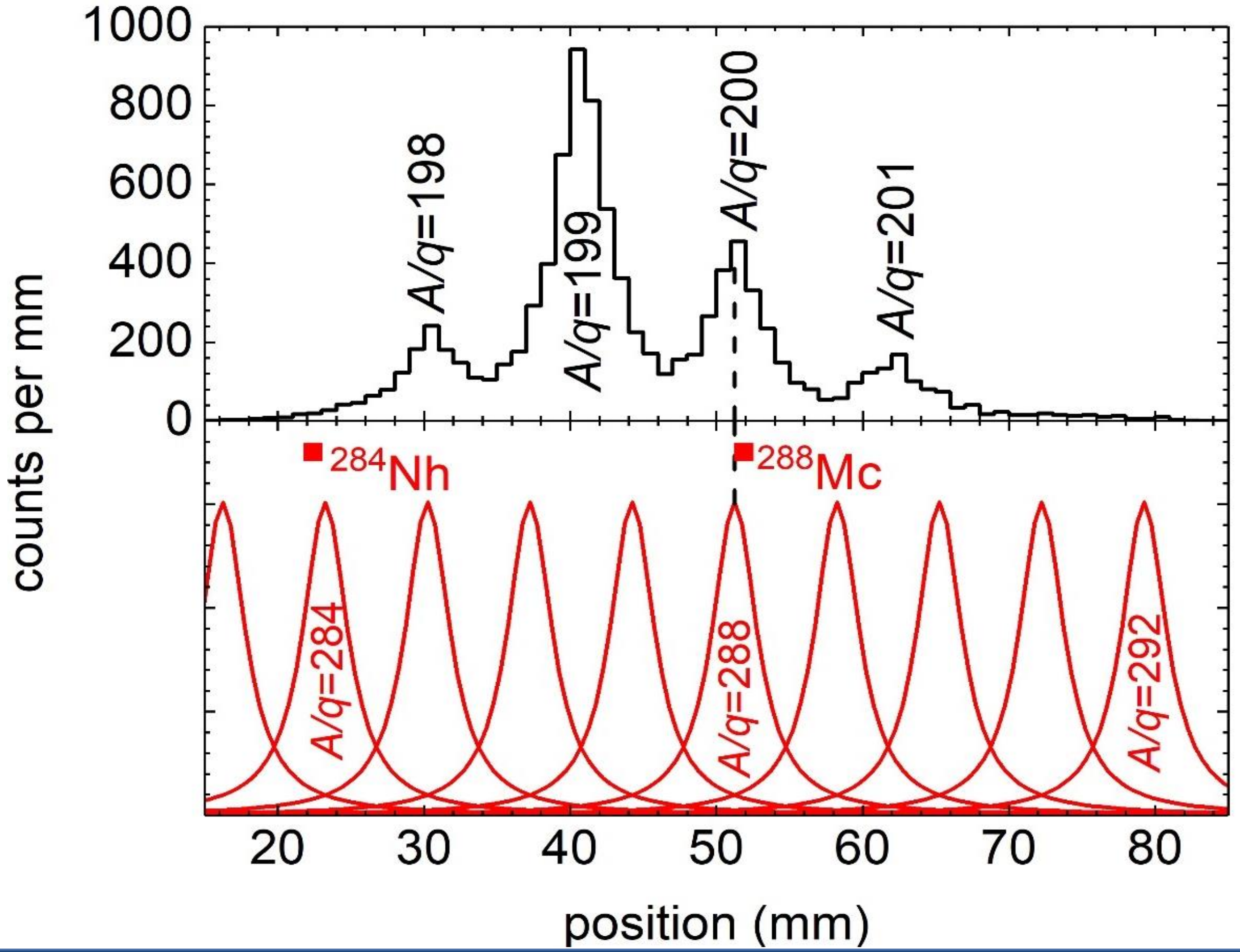
Guessing E115 Charge State

- Measured 1+/2+ ratio at exit of acceleration region for Fm, No, Lr, At, Po and Fr
- Second IP of E115 estimated to be ~18.3 eV – Table II in Borschevsky et al, Phys. Rev. A 91, 020501(R) (2015)
- Expect most E115 to be extracted as 1+ ions



First direct determination of a SHE mass number

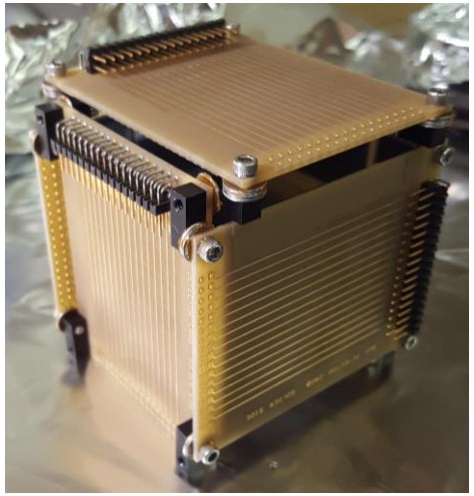
- Observed two alpha decay chains
- One chain beginning with a ^{288}115 alpha was observed at A/q=288
- One chain beginning with a ^{248}113 alpha was observed at A/q=284

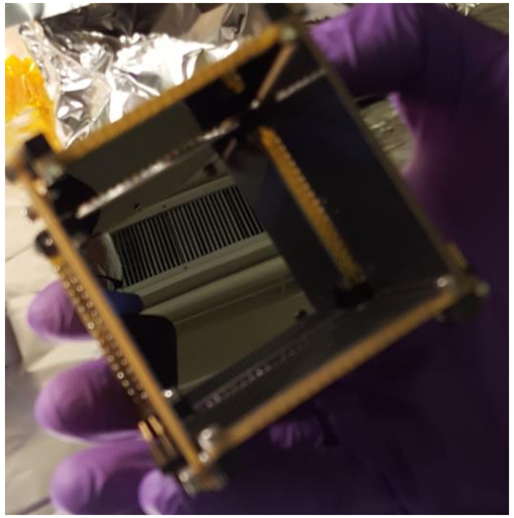


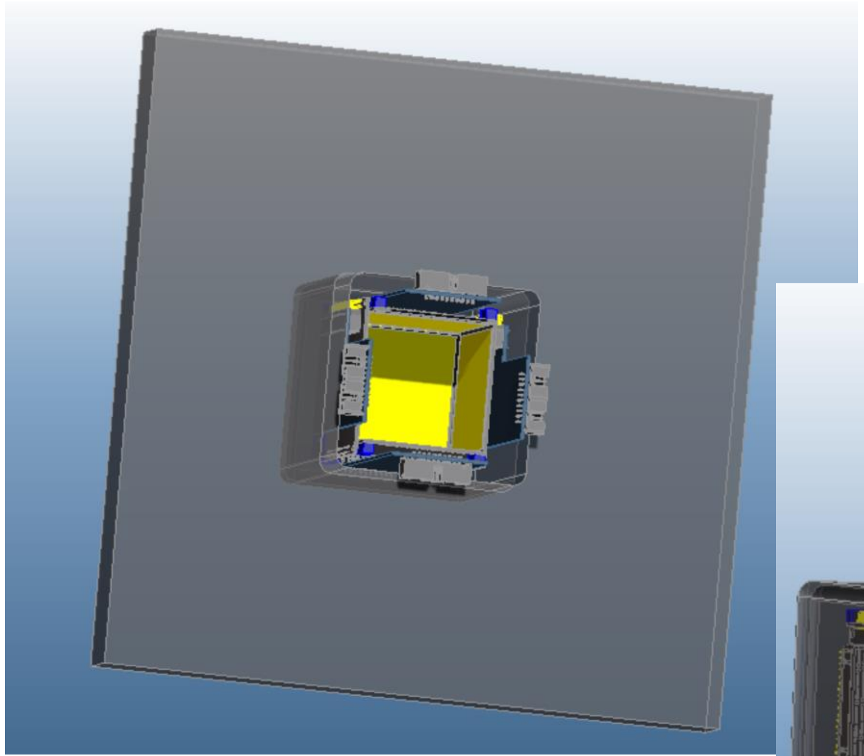
Average Decay Properties from [5][11][26]		Event Chain 1		Event Chain 2	
10.2-10.6 MeV 159 ms	^{288}Mc			^{288}Mc	10.29 MeV
9.98 MeV 0.94 s	^{284}Nh	^{284}Nh	9.93 MeV	^{284}Nh	unobserved
9.78 MeV 4.14 s	^{280}Rg	^{280}Rg	unobserved	^{280}Rg	9.70 MeV 9.998 s
9.10-10.0 MeV 0.63 s	^{276}Mt	^{276}Mt	unobserved	^{276}Mt	9.30 MeV 4.384 s
9.08 MeV 11.0 s	^{272}Bh	^{272}Bh	9.08 MeV 34.376 s *x*=22.4 mm	^{272}Bh	9.02 MeV 2.324 s *x*=51.9 mm

Next Step: BANSHE

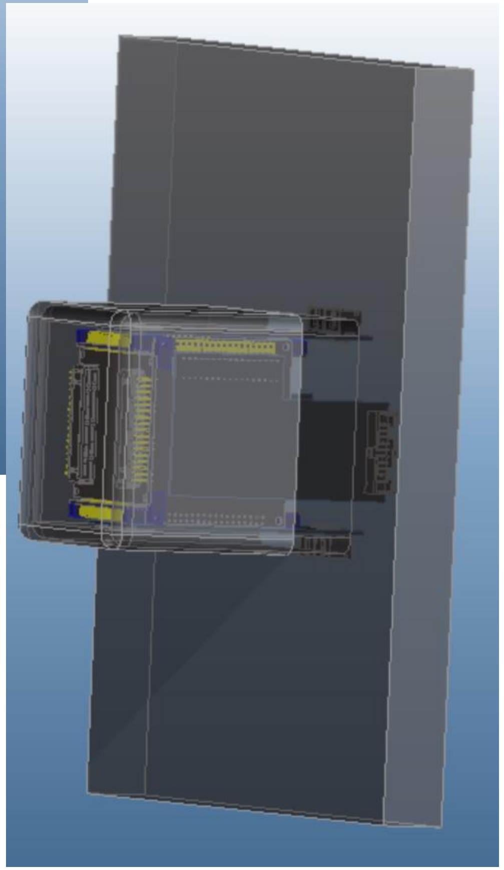
- Have:
  - focal plane detector
  - Clover detectors
  - LEGe
- Want: high-resolution α-γ- or e-γ spectroscopy on mass-separated isotopes







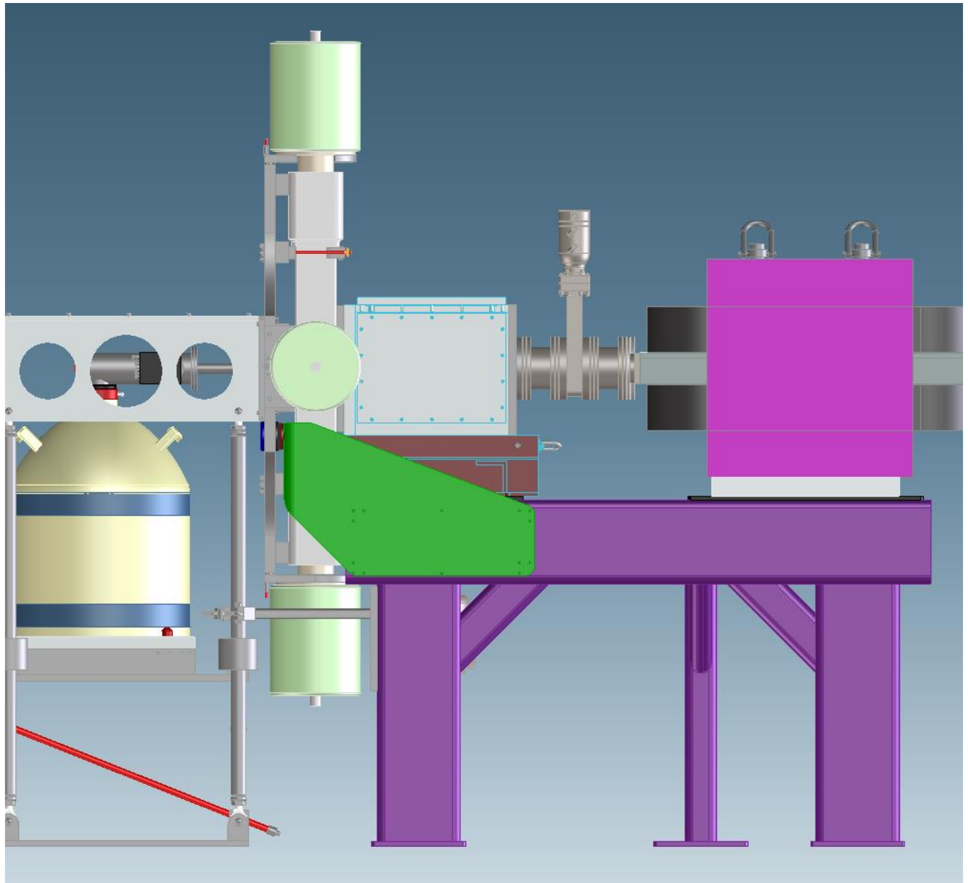
- Building BANSHE
  - Vacuum chamber
  - Cube out the back
  - 1-mm thick walls

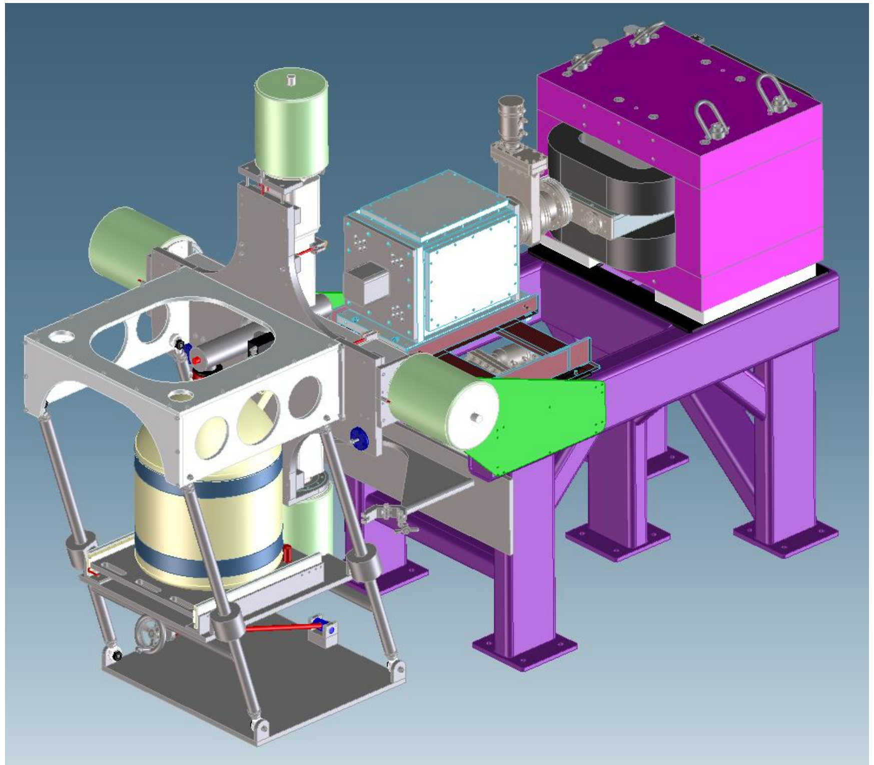


Next Step: BANSHE

Step 1: Modify detector position of FIONA with updated vacuum chamber and detector

Step 2: Surround the chamber with four clover detectors and one LEGe detector

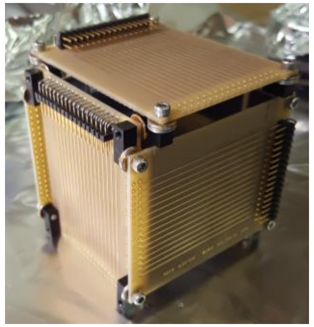


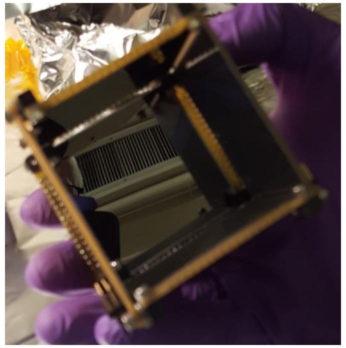


Future Science Program

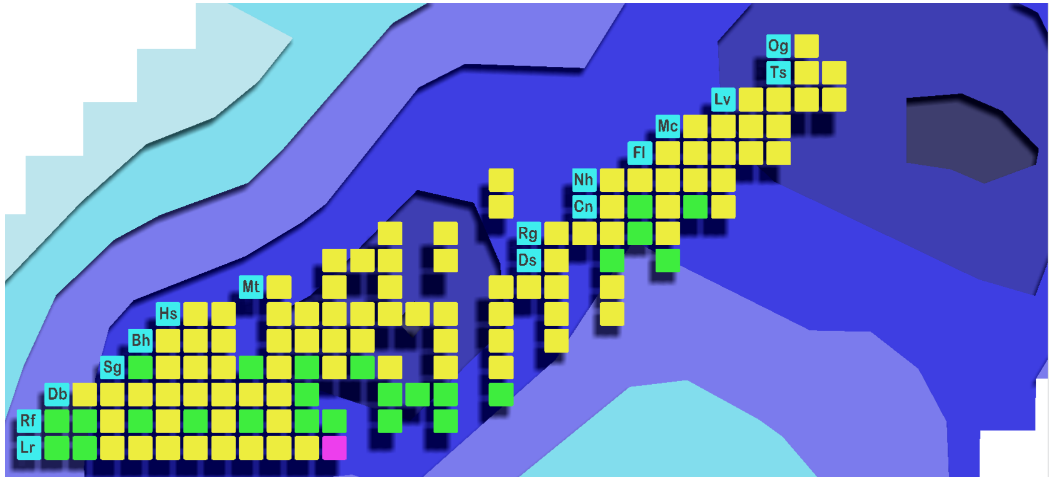
Mass separation and delivery to a low α-, γ-, n-background counting facility on a 10-ms timescale

Lr^{2+} O=O → Lr^{+} $O=O^{+}$





- Mass number measurements of SHE ➔
  - E114, E116, E115 short chains
  - Search for multiple decay paths
- Spectroscopy on mass-separated isotopes ➔ BANSHE
  - Search for electron-capture decay
  - Determination of single-particle energies
  - Nuclear structure and nuclear shapes



- Chemistry inside the RFQ trap ➔
  - A/q of reaction products
  - reaction times
  - limits on ionization potentials and bond dissociation energies

Lr^{2+} SO_2 → Lr^{+} SO_2^{+}

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