Recent Results from the FIONA Separator at LBNL

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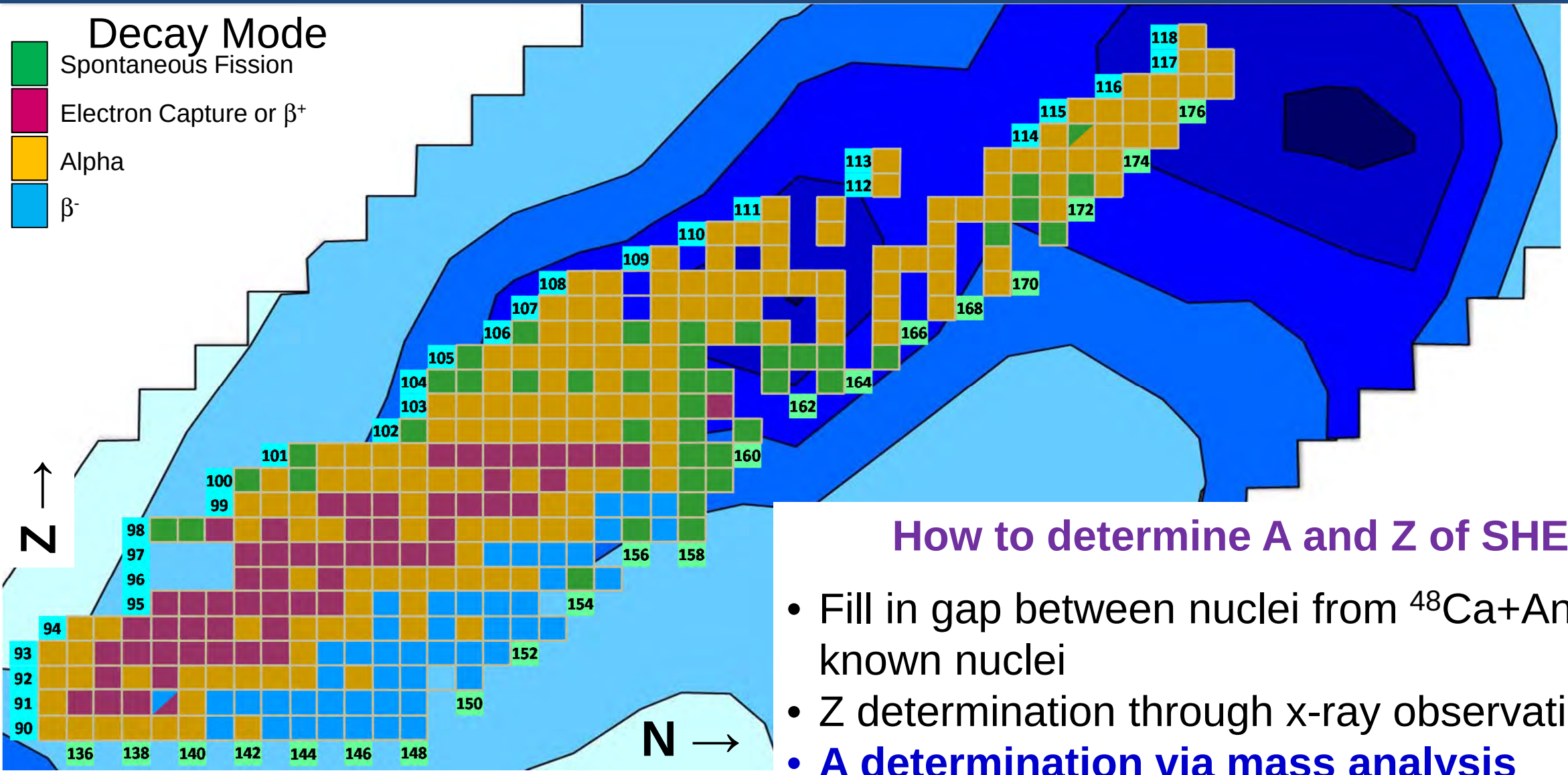
Outline

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

Chart of the Nuclides

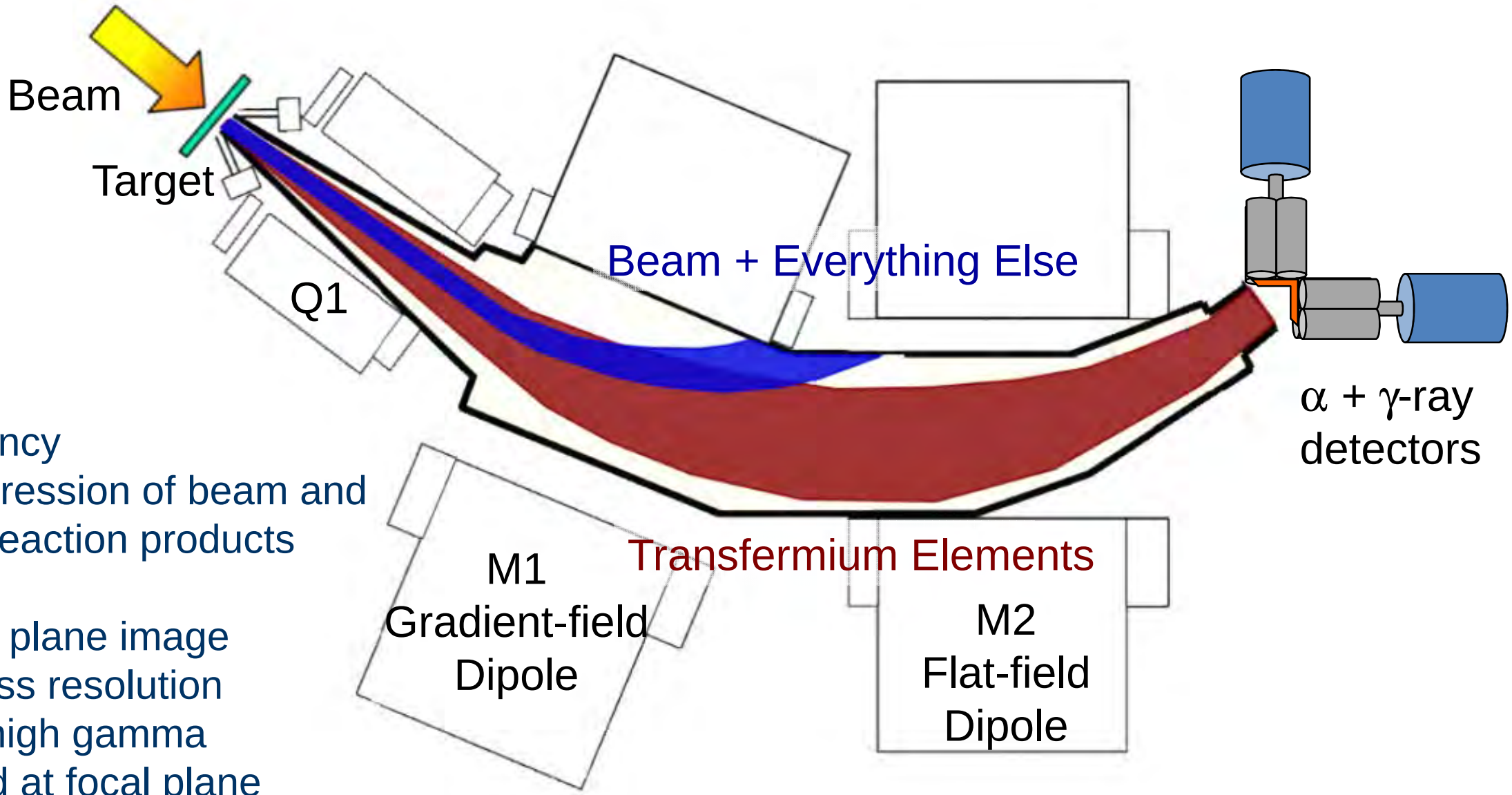


How to determine A and Z of SHE?

- Fill in gap between nuclei from ^{48}Ca+An and known nuclei
- Z determination through x-ray observation
- **A determination via mass analysis**

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

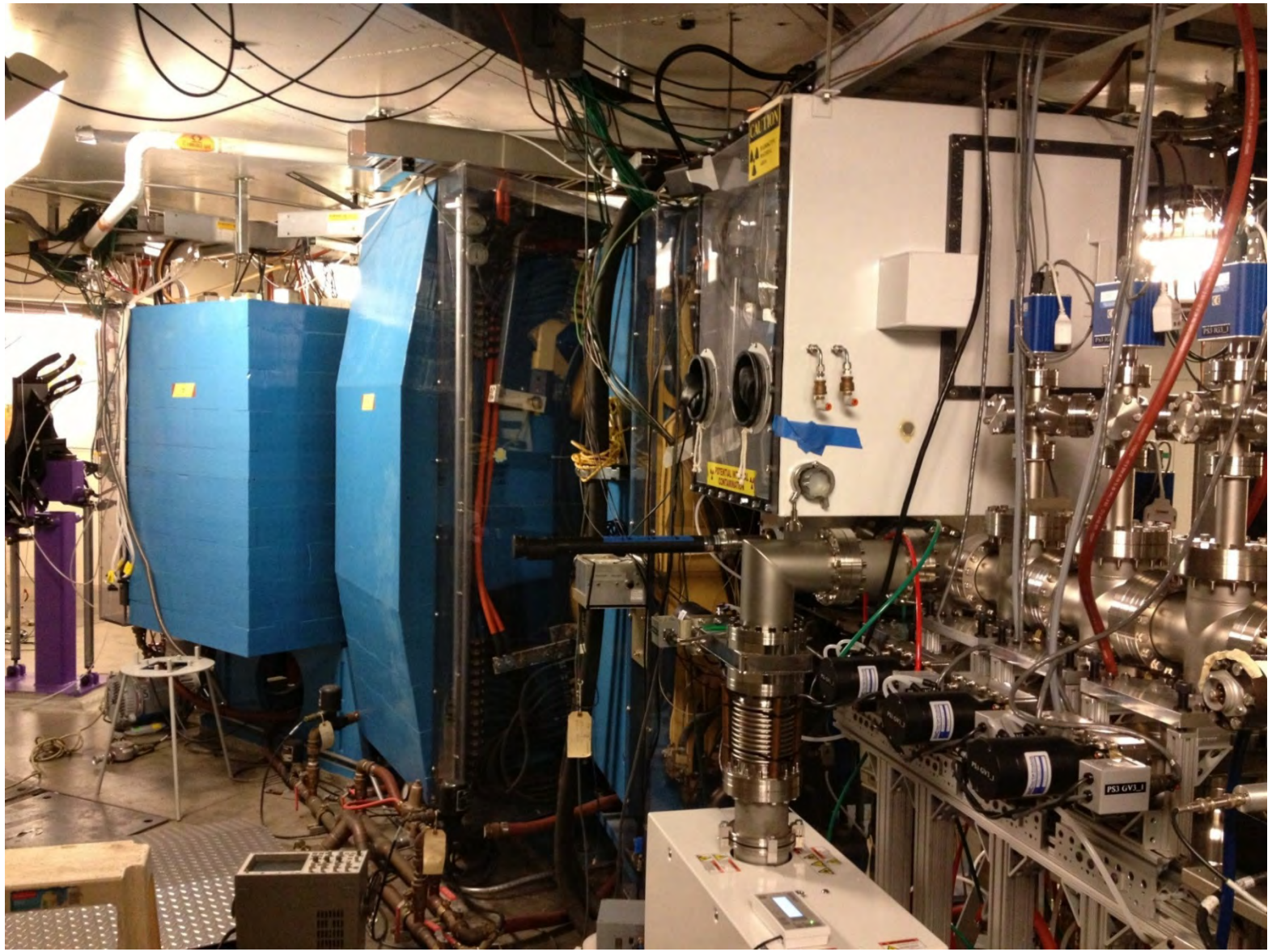
Berkeley Gas-filled Separator (BGS)



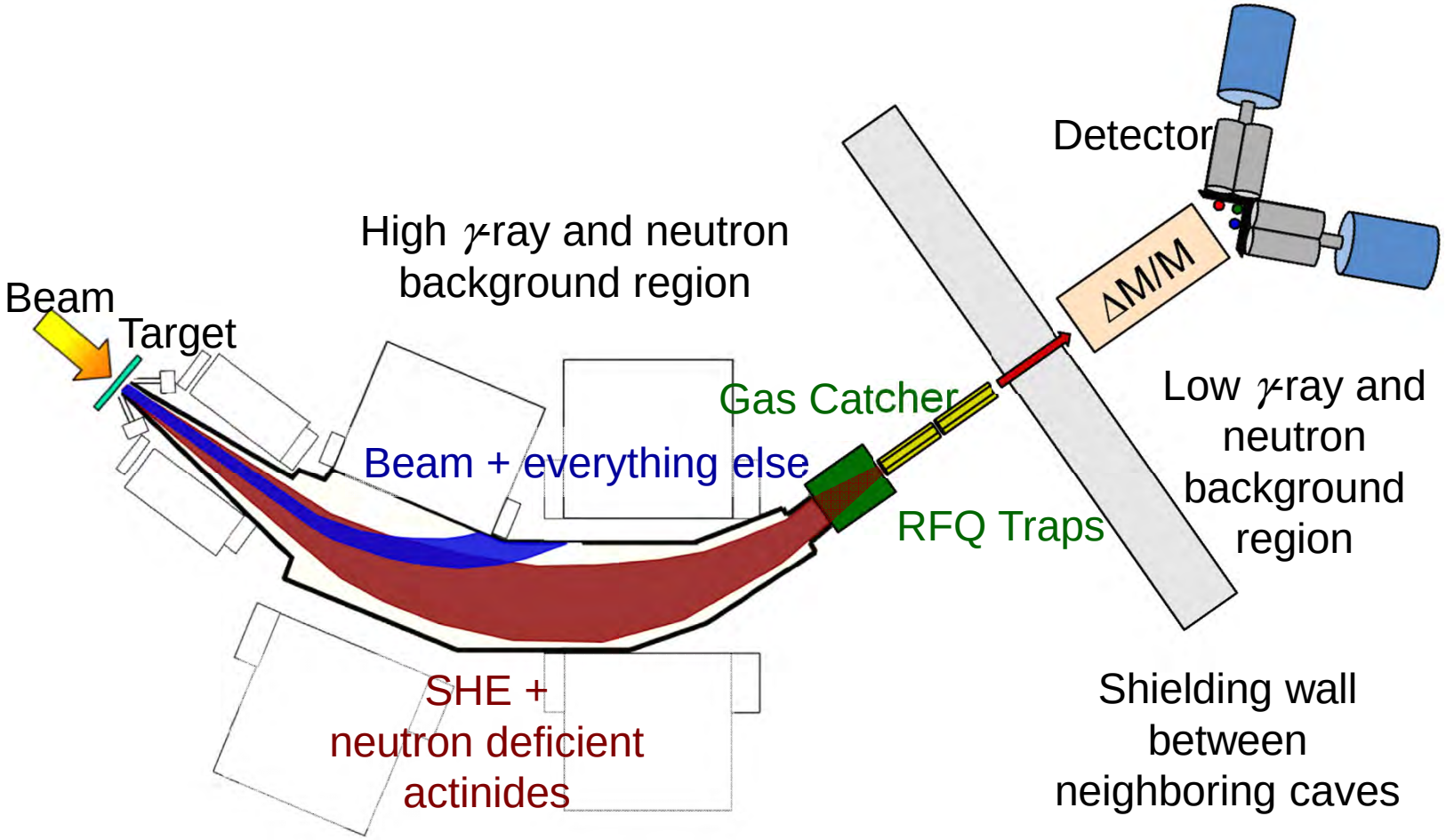
Positives:
- High efficiency
- Large suppression of beam and unwanted reaction products

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

Berkeley Gas-filled Separator (BGS)



BGS+FIONA - Overview



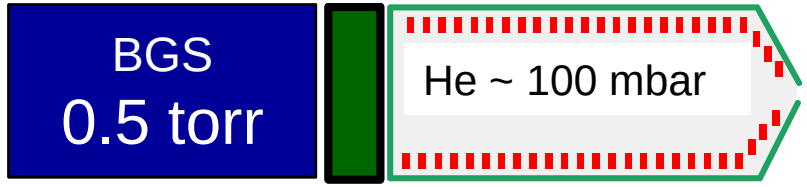
Low energy (5-10 keV), mass-separated isotopes delivered to a low neutron and γ-ray background region on a 10-ms time scale

1. Collect recoils at BGS focal plane
2. Stop, cool and bunch
3. Reaccelerate
4. Separate by mass
5. Send to detector station

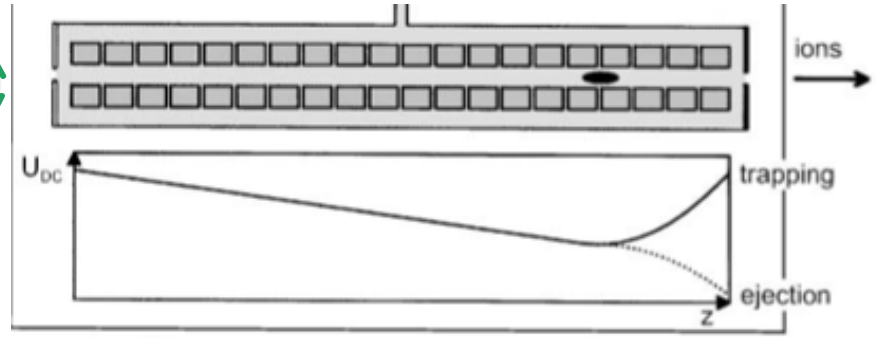
ANL Built | Berk. Built

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

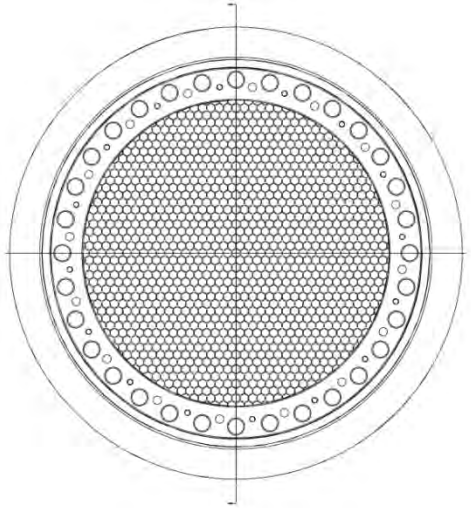
Interface between BGS and Mass Analyzer



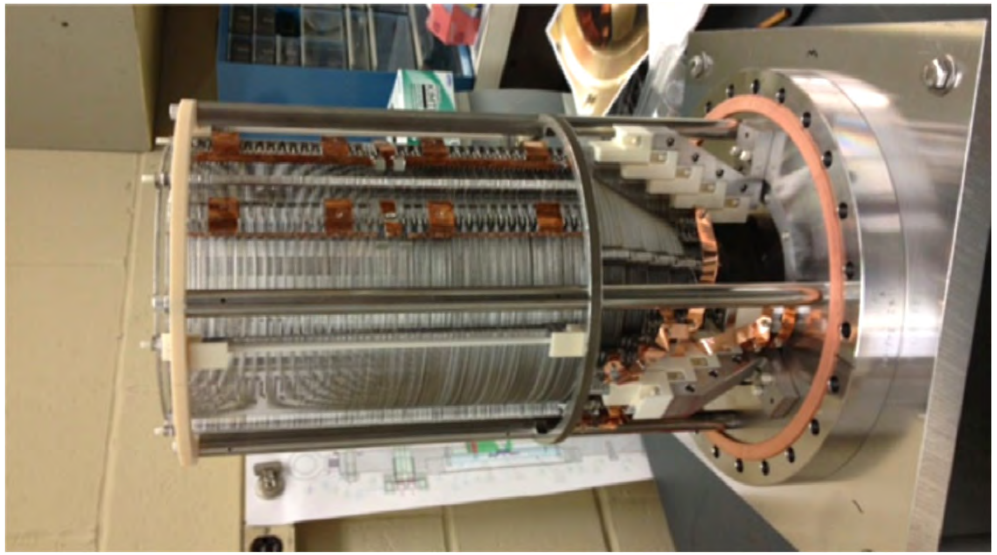
RF + DC



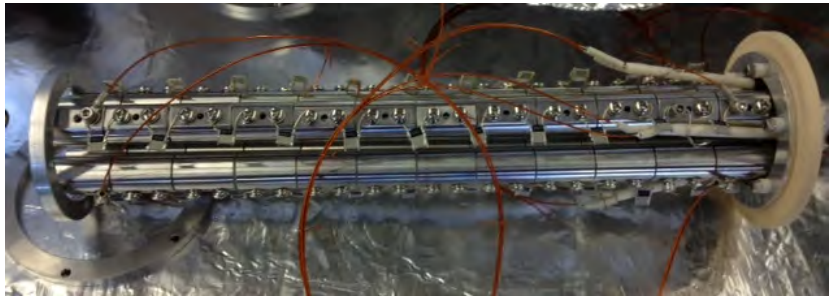
Acceleration across 5-10 kV gap



> 2 μm metal foil with support grid

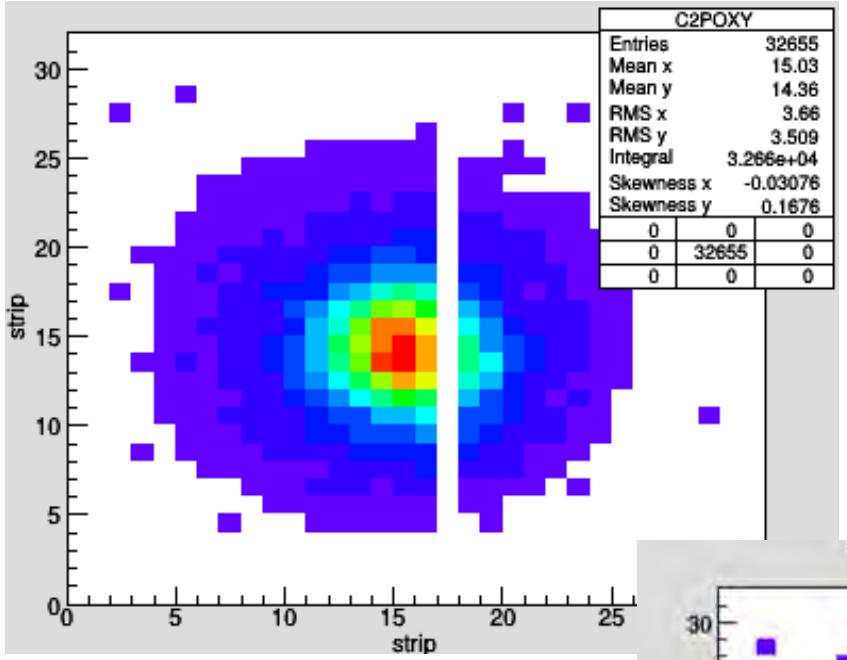


Gas Catcher

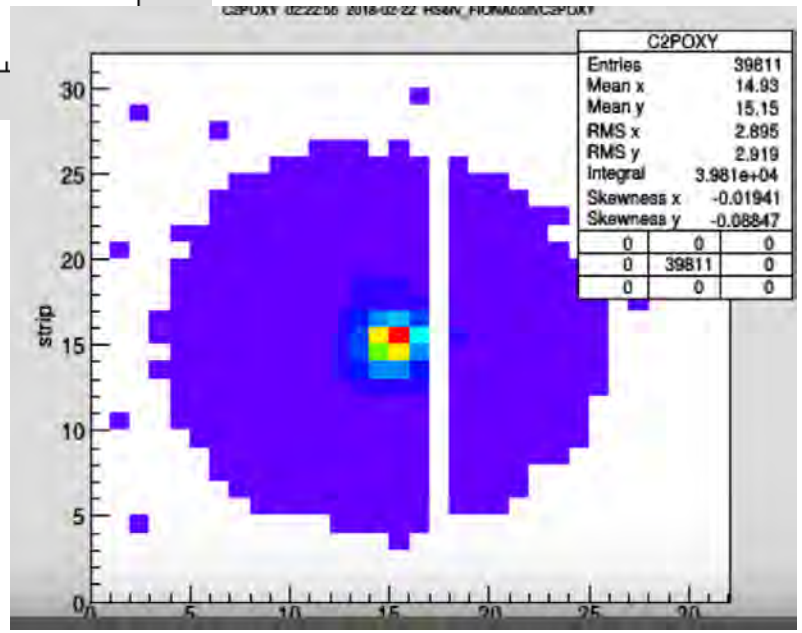


RFQ Trap

What we get at the end



No Focus

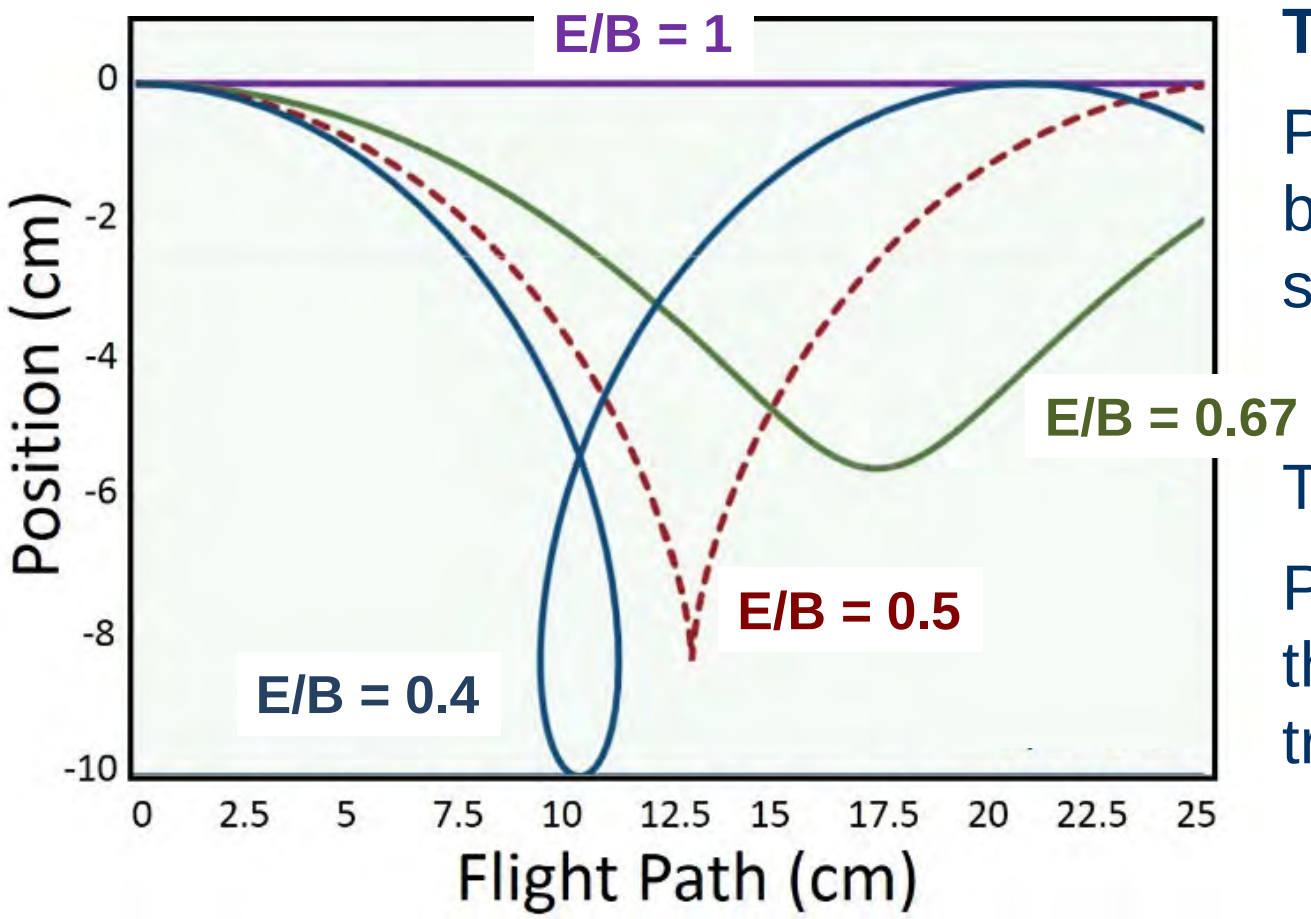


Max Focus

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

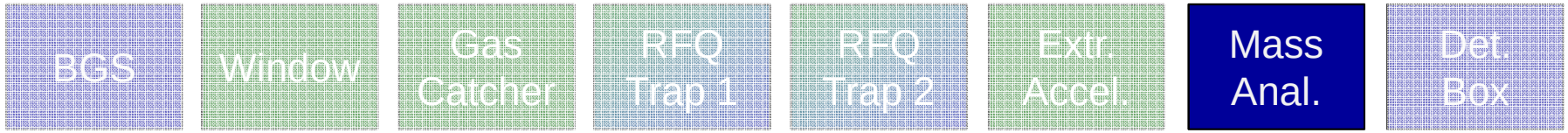


Traditional wien filter:

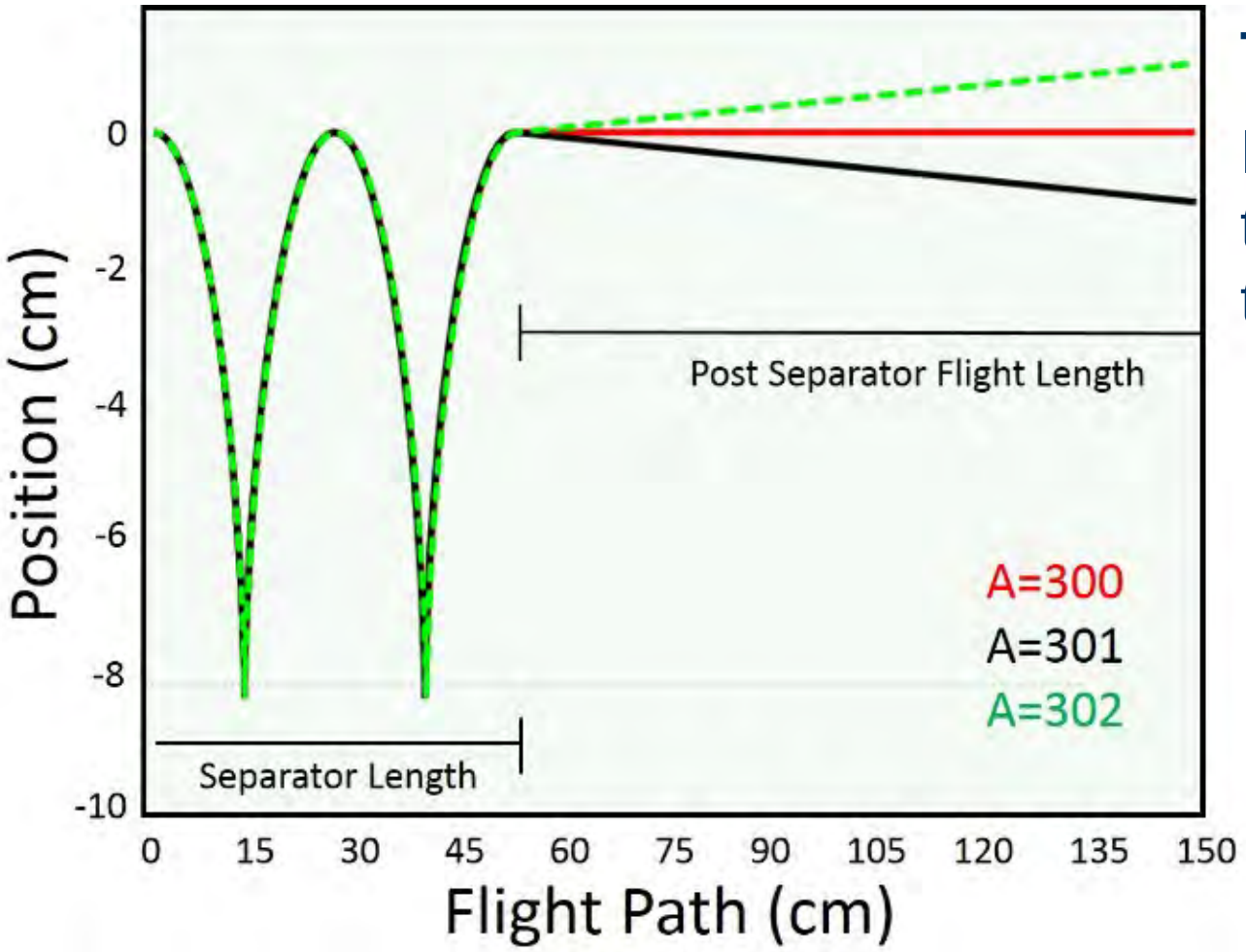
Perpendicular electric and magnetic fields, balanced such that ions with V=E/B travel straight through separator

Trochoid spectrometer:

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

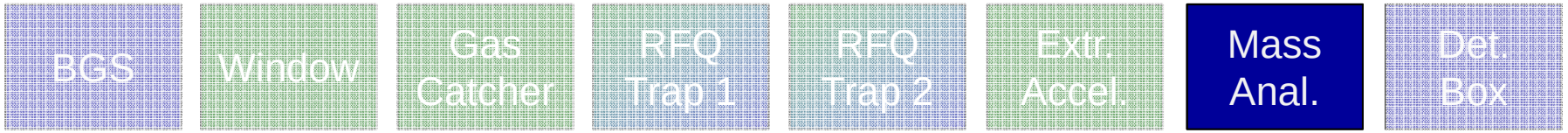


ExB Mass Analyzer – The Idea

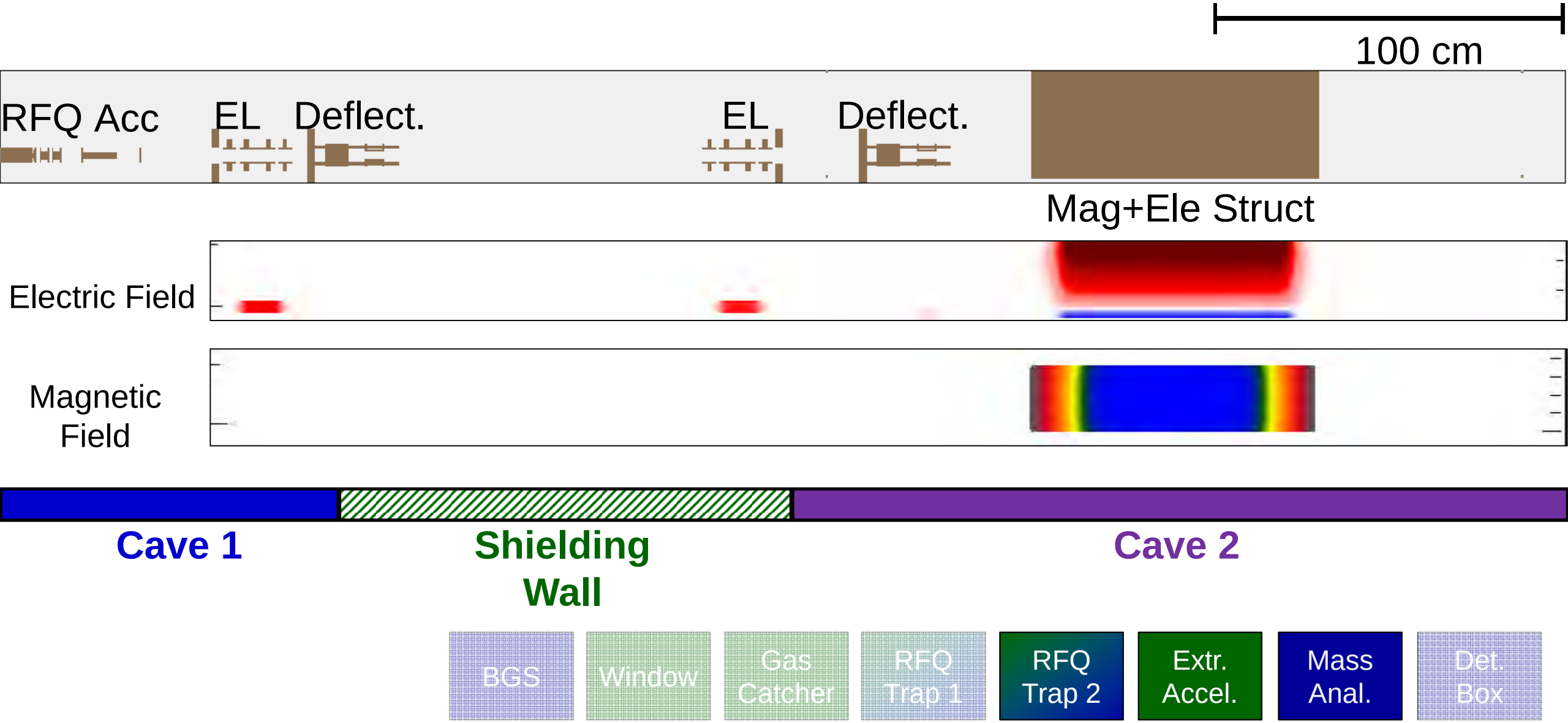


Trochoid spectrometer:

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



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

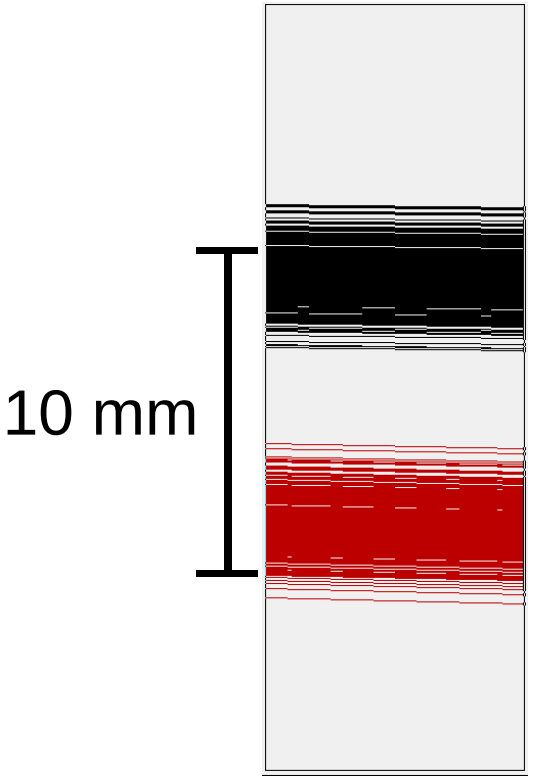
Simulations assumed:

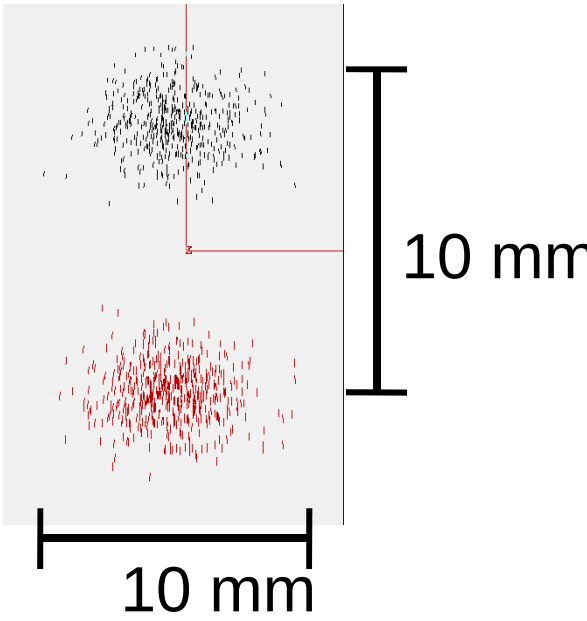
Magnetic field: 0.95 T

Electric field: 250 V/cm

Einzel lenses: 1000-1500 V

Deflector: 100 V





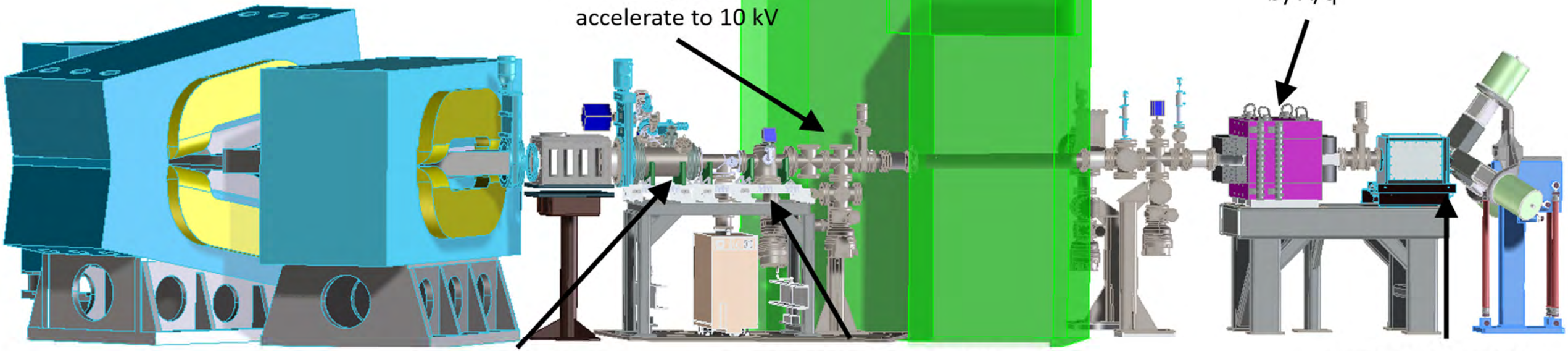
BGS+FIONA - Overview

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

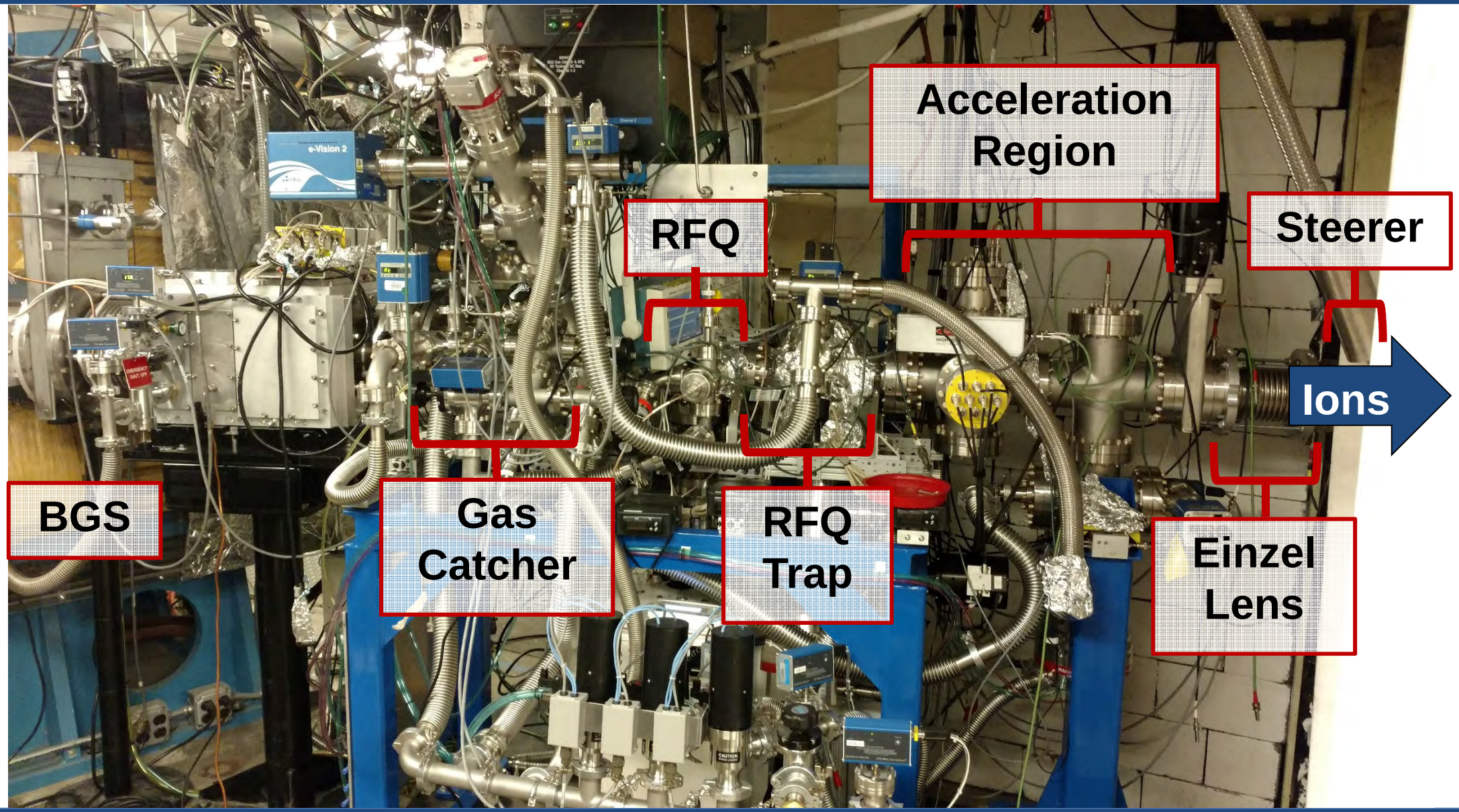


RF Gas Catcher
stop ions He gas, RF and DC E-fields direct ions to an exit orifice

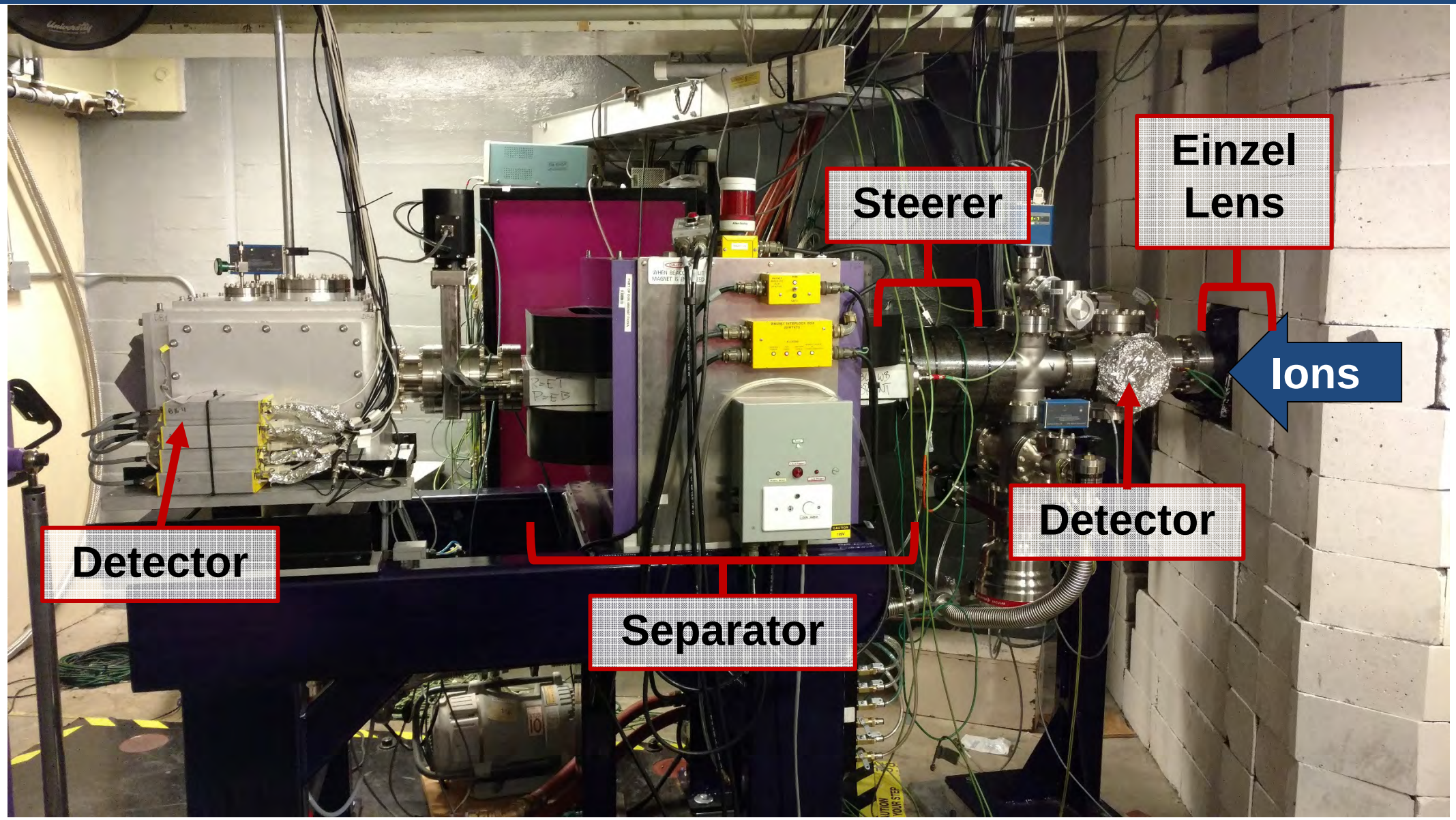
RF Quadrupole Trap
bunch and cool ions, re-accelerate and transfer to mass analyzer

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

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



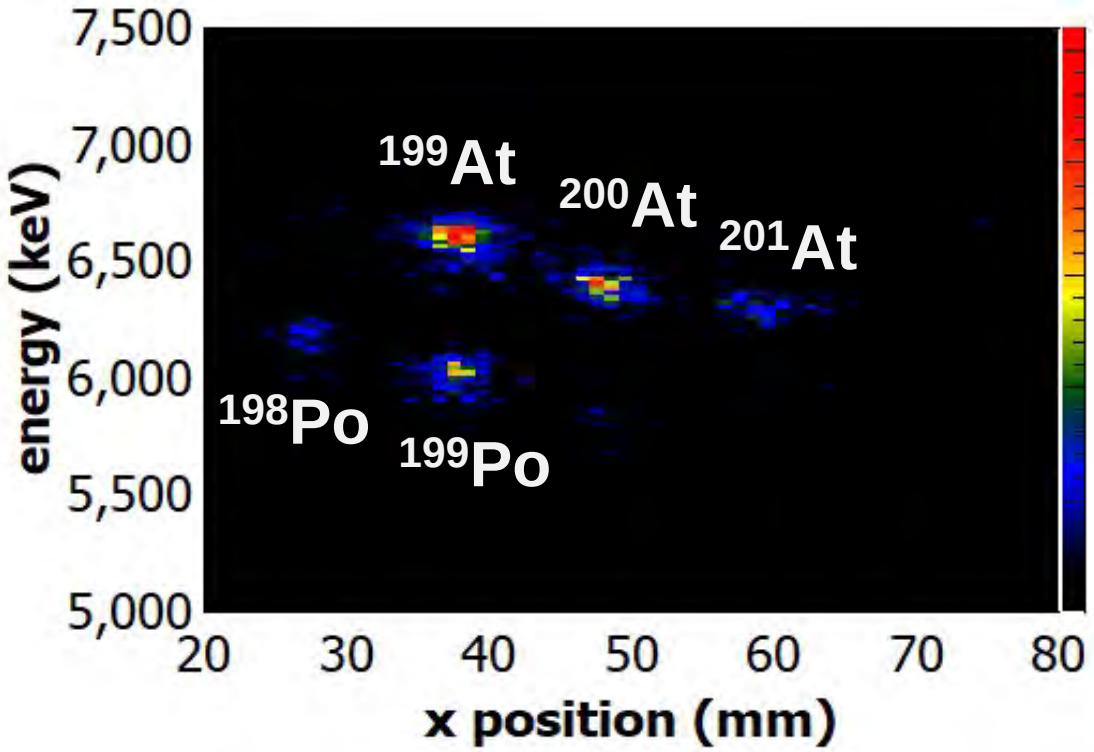
Cave 2: Diagnostics → Separator → Detector

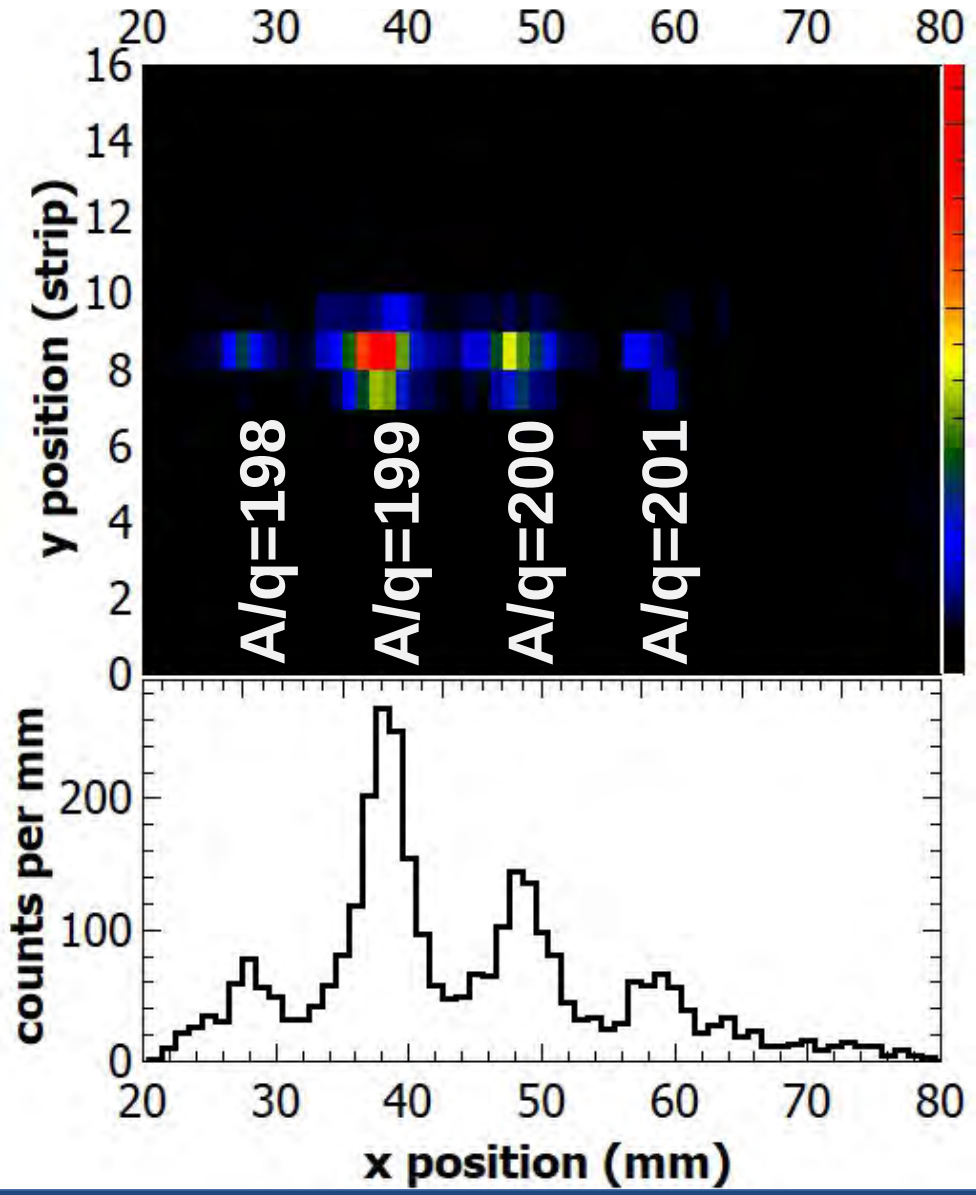


FIONA Commissioning: *A/q* separation

Experiment:

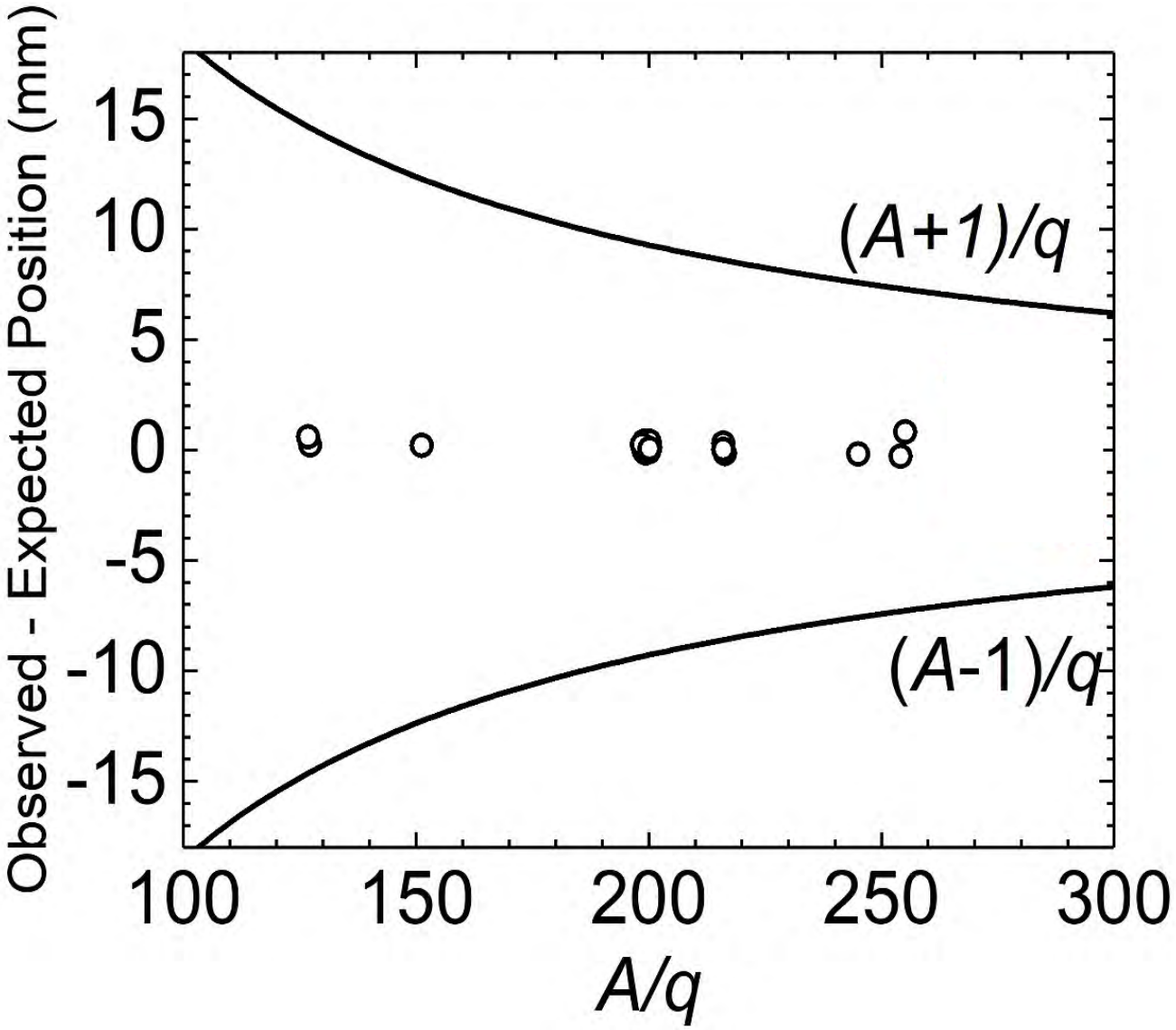
- At and Po isotopes produced at the 88” Cyclotron using the reaction:
- $^{nat}Tb + ^{48}Ca \rightarrow ^{199\text{-}201}At, ^{198,199}Po$
- Separated by Mass/charge in FIONA





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 $^{255}Lr^{1+}$



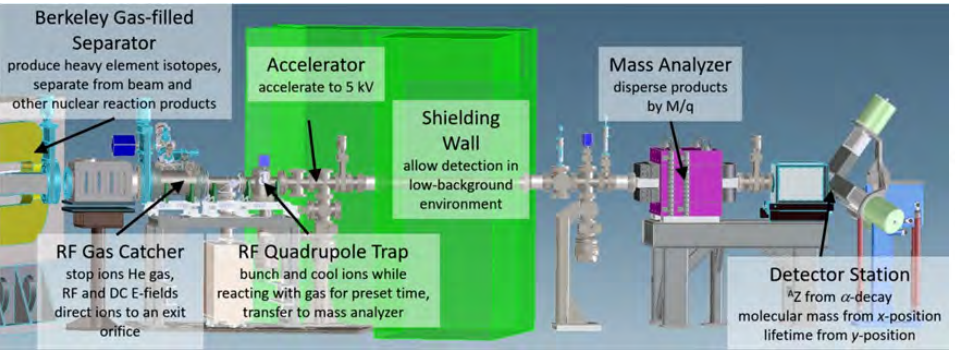
Proof-of-Principle experiment for gas-phase ion chemistry: $Ho + O_2$

1) $^{150\text{-}152}Ho$ were produced at the LBNL 88" Cyclotron and separated with the Berkeley Gas-filled Separator
2) Ho^{1+} ions were captured and cooled in a RFQ trap containing a small partial pressure of O_2
3) The $Ho^+ + O_2 \rightarrow HoO^+ + O^*$ reaction was allowed to proceed for a fixed time
4) Relative amounts of Ho^+ and HoO^+ were measured with a mass separator

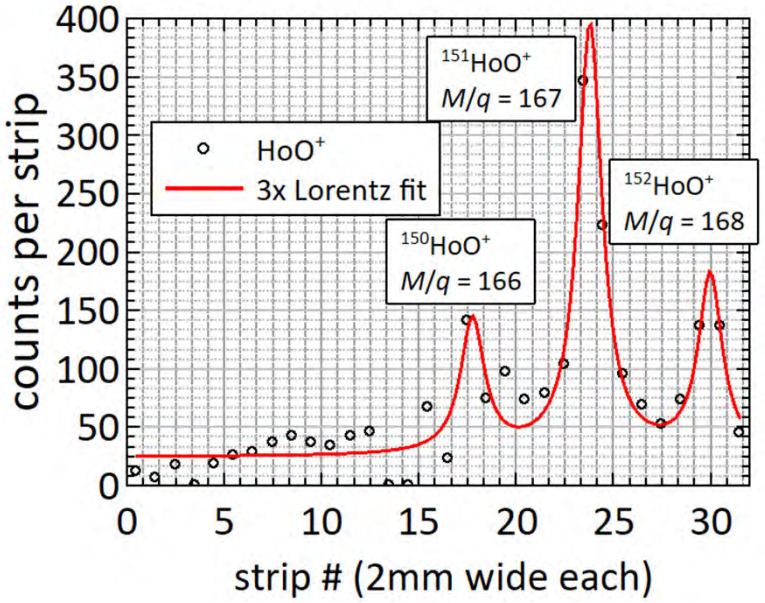
Production of HoO^+ was observed, confirming that the bond strength of HoO^+ is greater than that for O_2
Reaction kinetics: change in $[Ho^+]/[HoO^+]$ with $[O_2]$ was measured, and will be used to calibrate $[O_2]$

Future Work: Use this technique to study the chemistry of ions of Fm through Sg (*Z*=100-106)

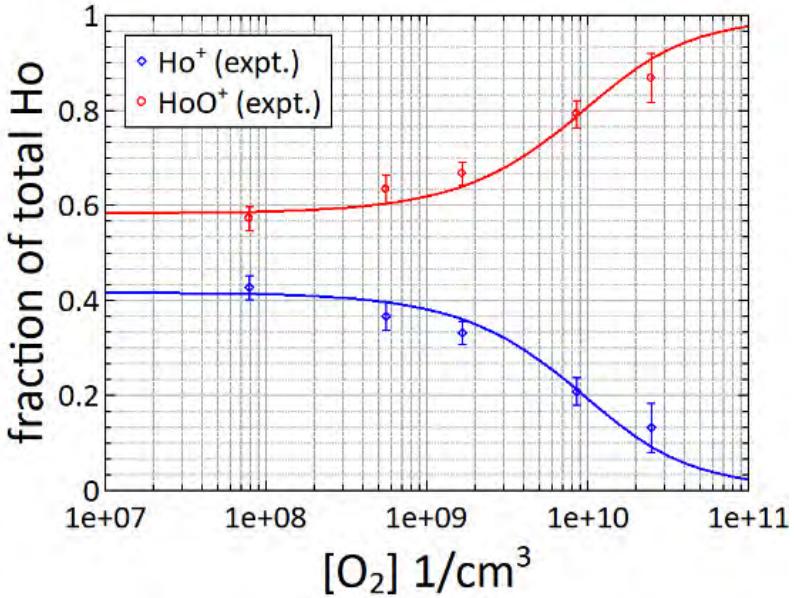
- Determination of bond dissociation energies
- Measurement of ionization potentials



Schematic of the apparatus used for heavy element gas-phase ion chemistry



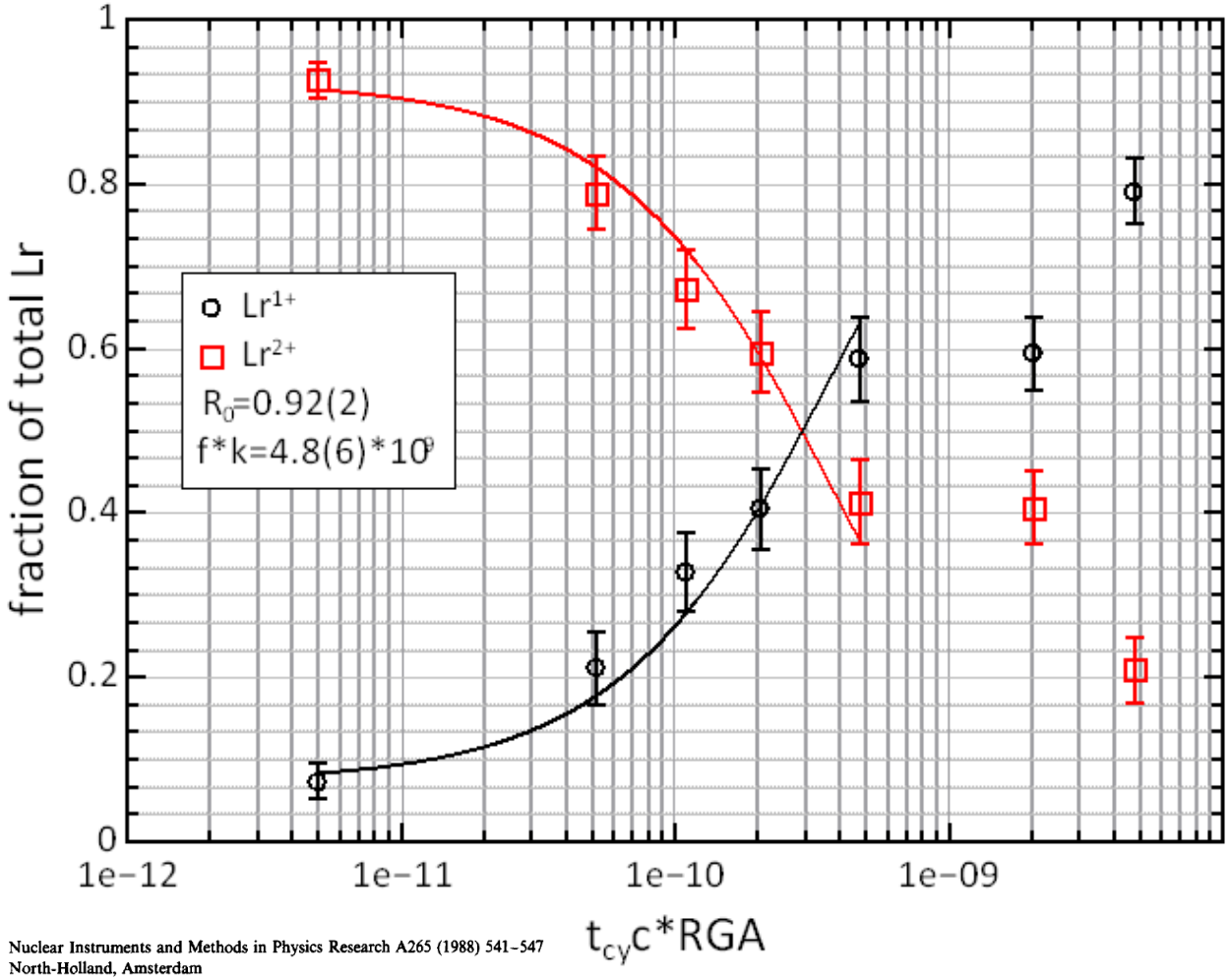
$^{150,\text{-}152}HoO^+$ mass spectrum



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

Reduction of Lr^{2+} by O_2

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



Nuclear Instruments and Methods in Physics Research A265 (1988) 541–547
North-Holland, Amsterdam

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 (haven't really calculated that yet)

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

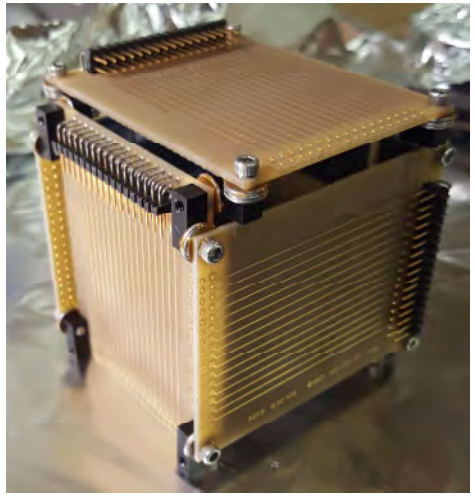
Calculating uncertainty on a fraction of a total is non-trivial, but we have the nuclear data group at the 88" cyclotron.

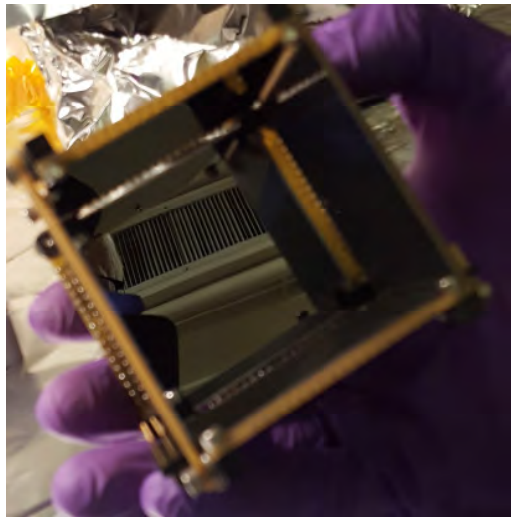
$$\frac{\mathrm{d}p_i(\%)}{p_i(\%)} = \left(\left(\frac{\mathrm{d}I_i}{I_i}\right)^2 \left(1 - \frac{2I_i}{\sum_k I_k}\right) + \frac{\sum_k \mathrm{d}I_k^2}{\left(\sum_k I_k\right)^2} + \left(\frac{\mathrm{d}B}{B}\right)^2 \right)^{1/2}$$

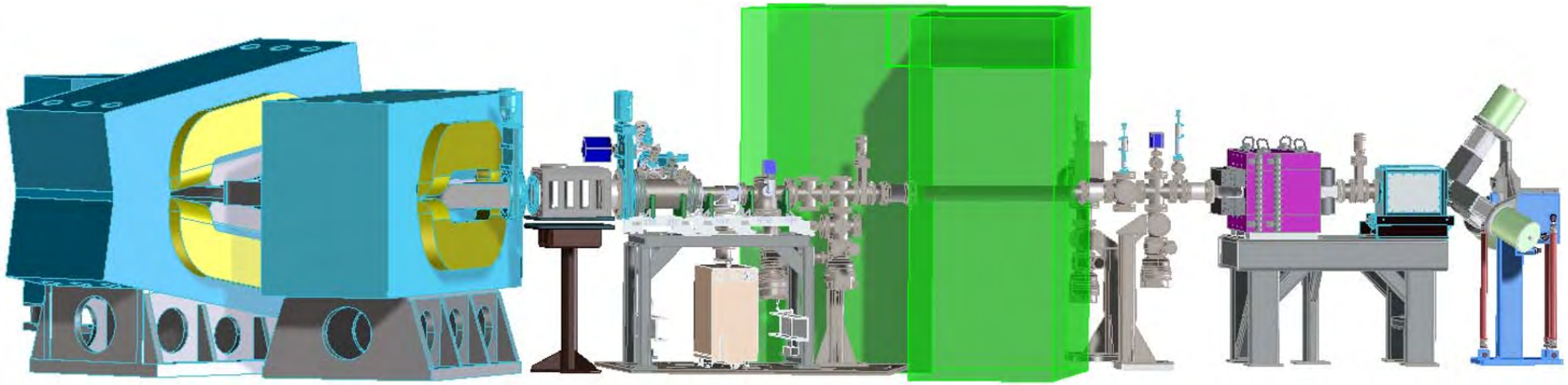
Finally, something different is happening with the longest Trapping times. That is not yet understood.

First Scientific Campaign: Mass Number ID 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







3n

$^{288}115$
10.48
171 ms

$^{284}113$
9.97/9.81
0.97 s

$^{280}111$
9.77
3.6 s

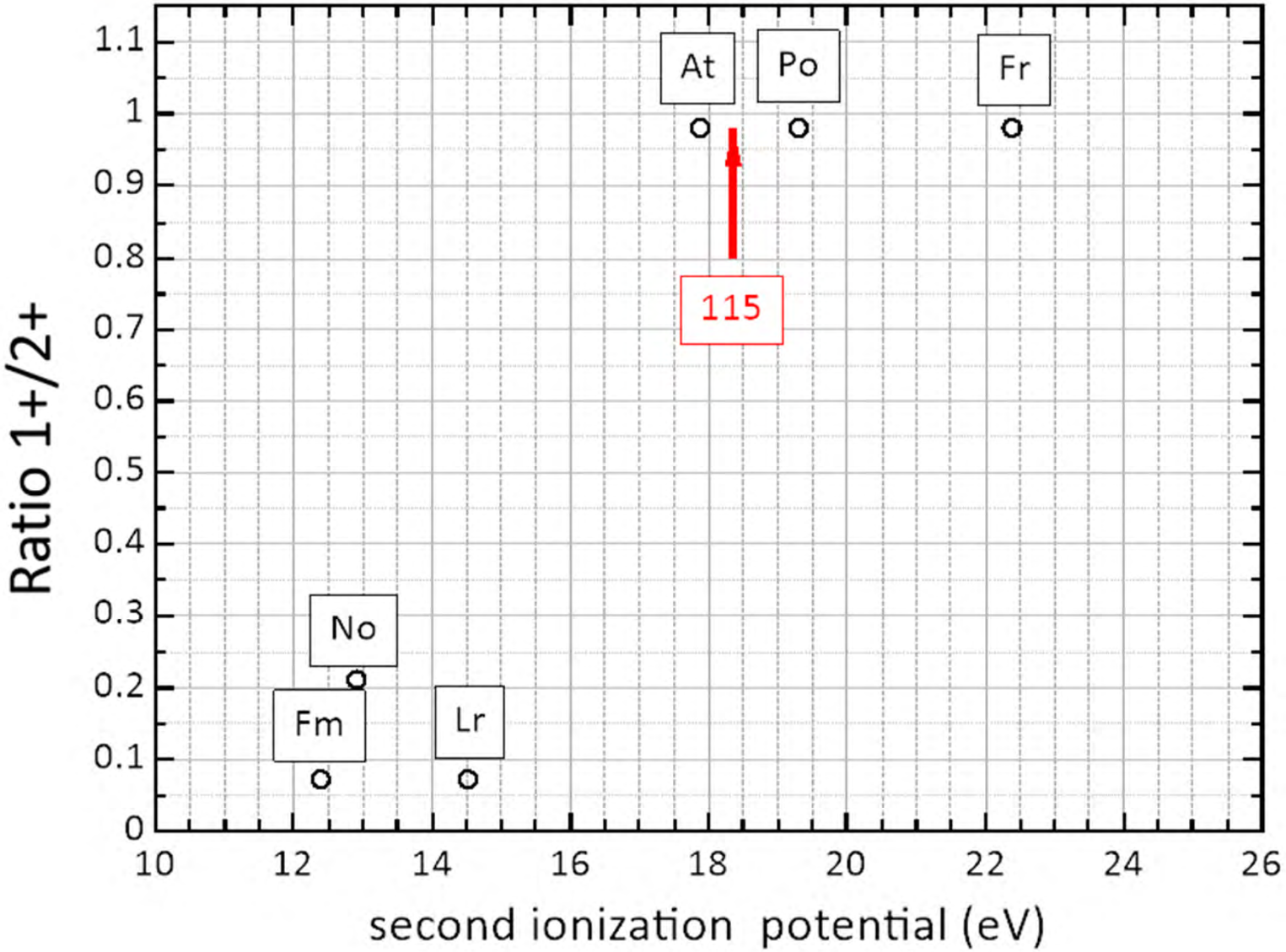
$^{276}109$
9.17-9.95
0.54 s

$^{272}107$
8.73-9.15
12 s

$^{268}105$
SF
27 h

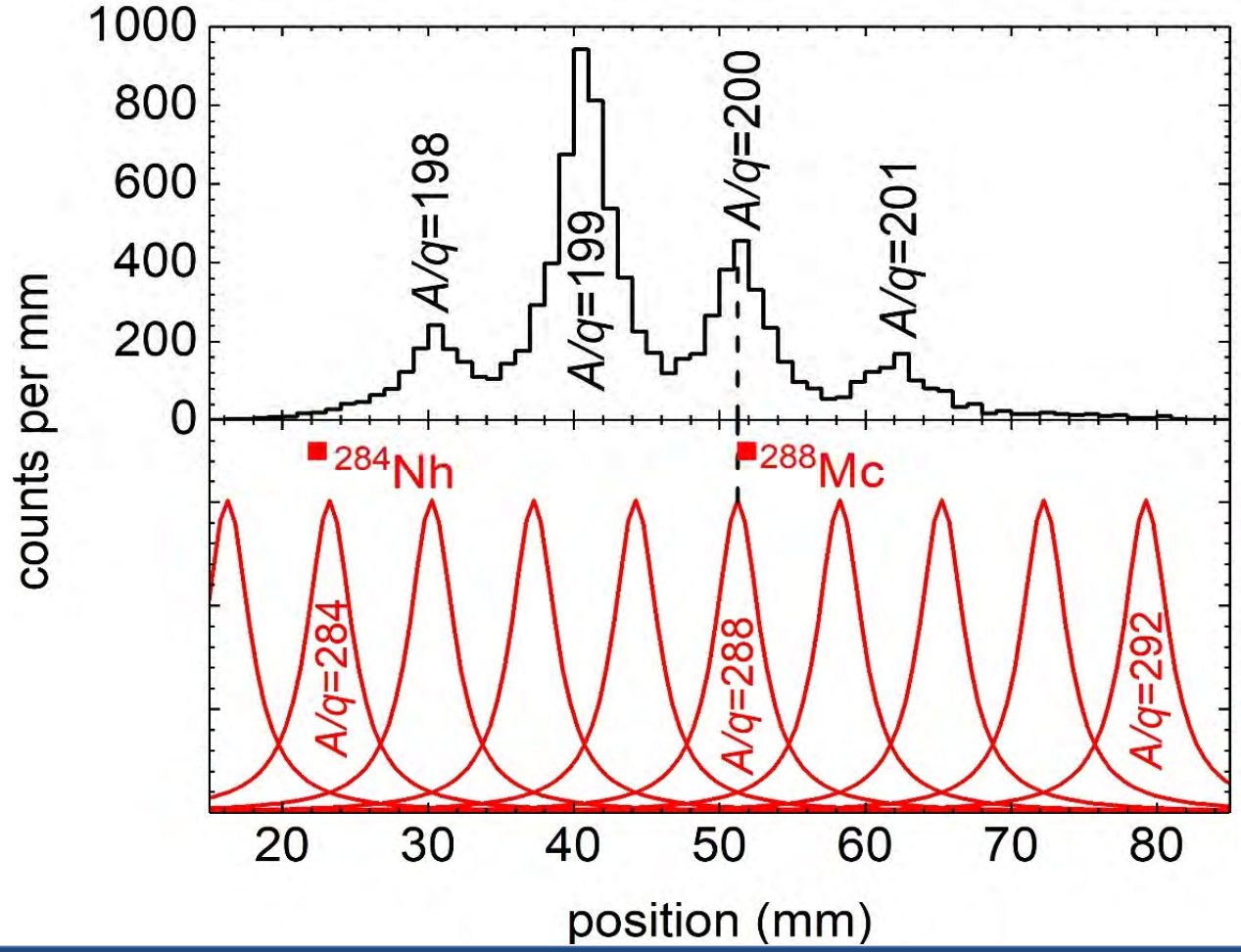
Guessing E115 Charge State

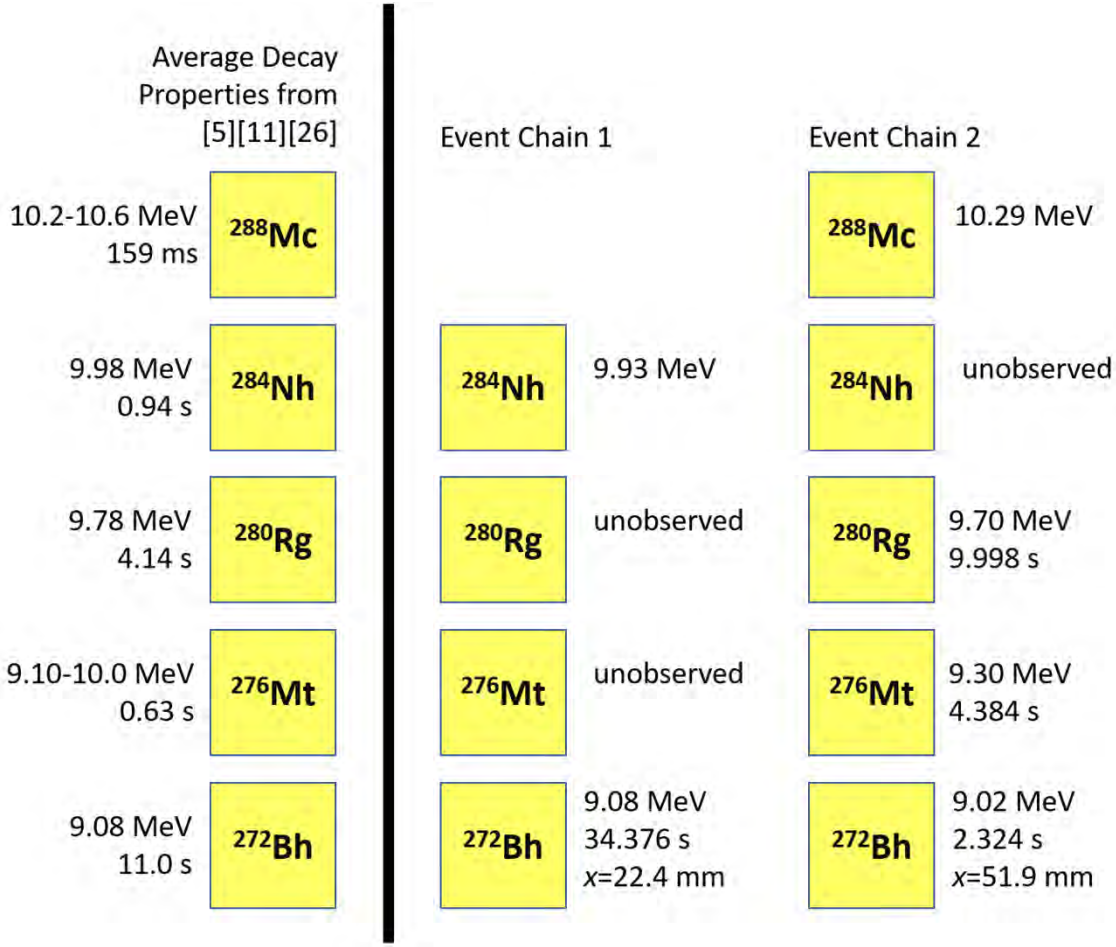
- Measured 1+/2+ ratio at exit of acceleration region for Fm, No, Lr, At, Po and Fr
- Second IP of E115 estimated to be ~18.3 eV – Table II in Borschevsky et al, Phys. Rev. A 91, 020501(R) (2015)
- Expect most E115 to be extracted as 1+ ions



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

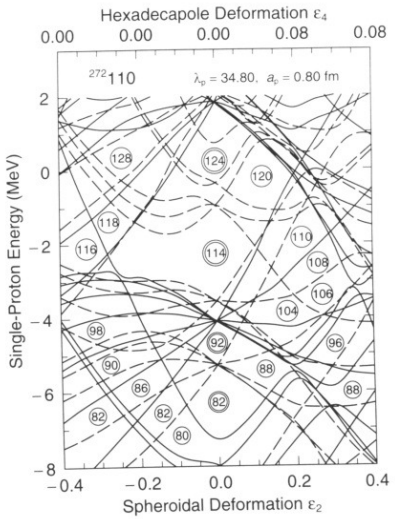


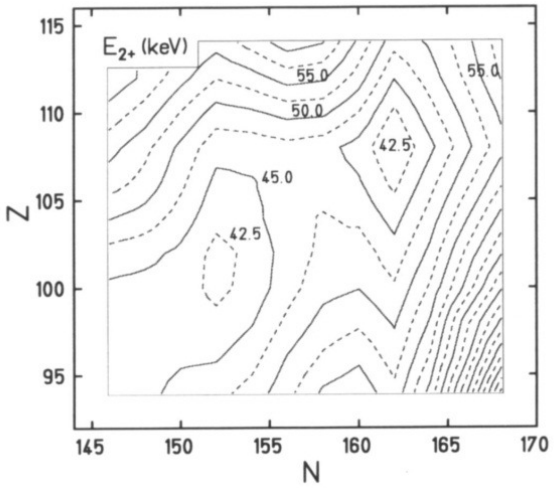


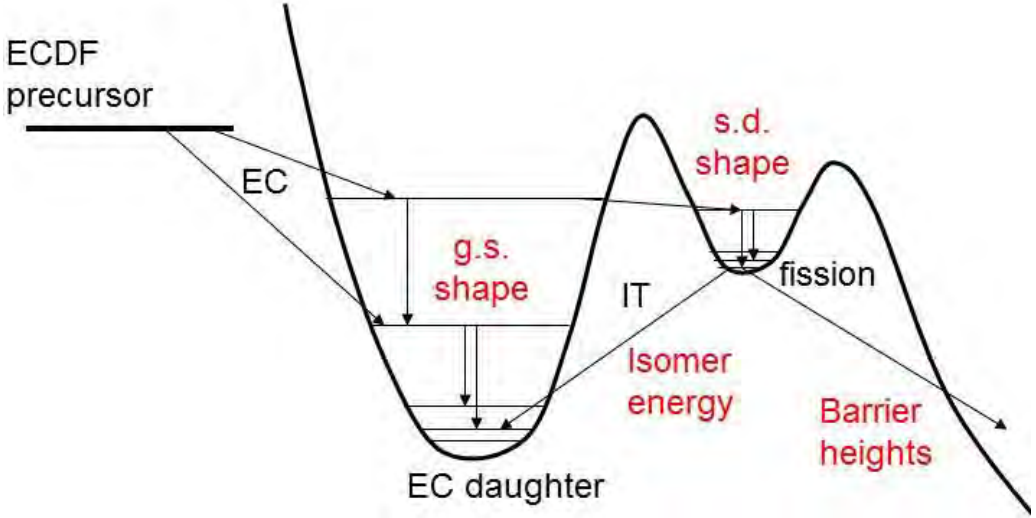
Future Science Program

Mass separation and delivery to a low-background counting facility on a 10-ms timescale

- Determination of single-particle states in heavy and superheavy element isotopes
- Identification of spontaneous fission activities in Z>90
  - Clean up many of the questionable Z and A assignments
  - Provide a more solid foundation for understanding SF systematics.
- Measure nuclear structure and nuclear shapes using α-γ coincidence measurements
- X-ray – γ coincidence measurements of electron-capture decay
  - provides information on fission barriers, fission isomers, and continuum states.







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