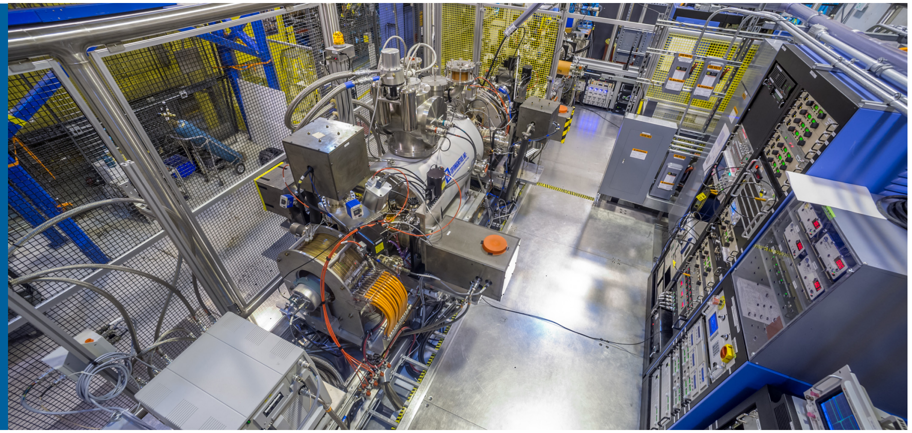
OCTOBER 23, 2018

OPERATIONAL COMPARISON OF AN ECR AND AN EBIS CHARGE BREEDER FOR CARIBU



RICHARD VONDRASEK
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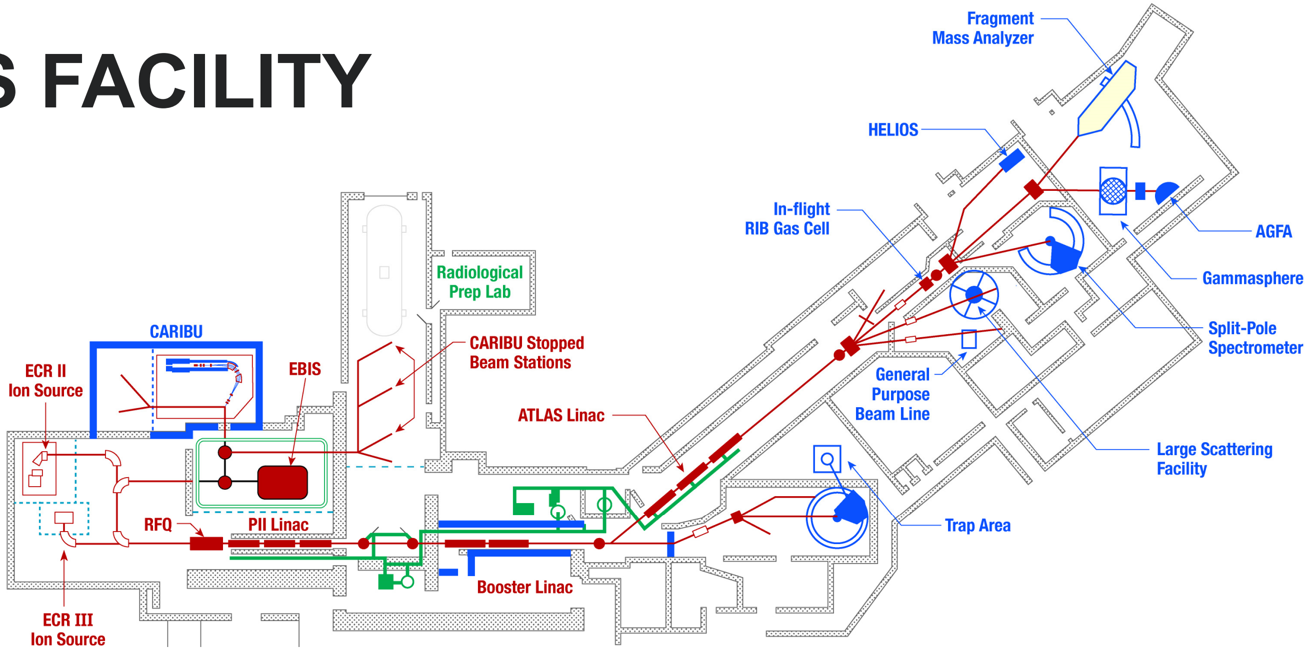
Physics Division

OUTLINE

- ATLAS and CARIBU
- Past ECR-CB performance
- On going efforts to reduce stable background
- Present EBIS-CB performance
- Comparison with ECR-CB
- Future plan

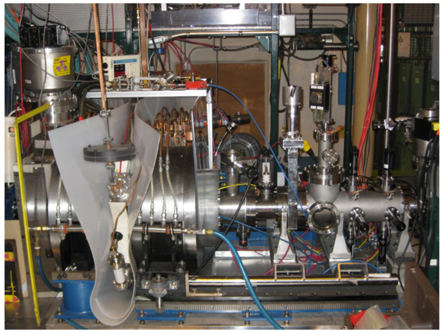
ATLAS FACILITY



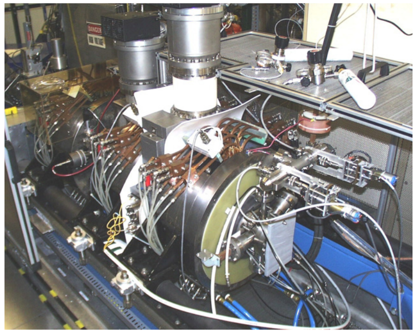
- ATLAS is a National User Facility delivering stable, low energy, ion beams with a focus on nuclear physics research
- ATLAS has a rich history of radioactive beam research
  – Irradiated source materials
  – In-flight beam production
  – CARIBU – reacceleration of Cf fission fragments

ATLAS FACILITY

Front end

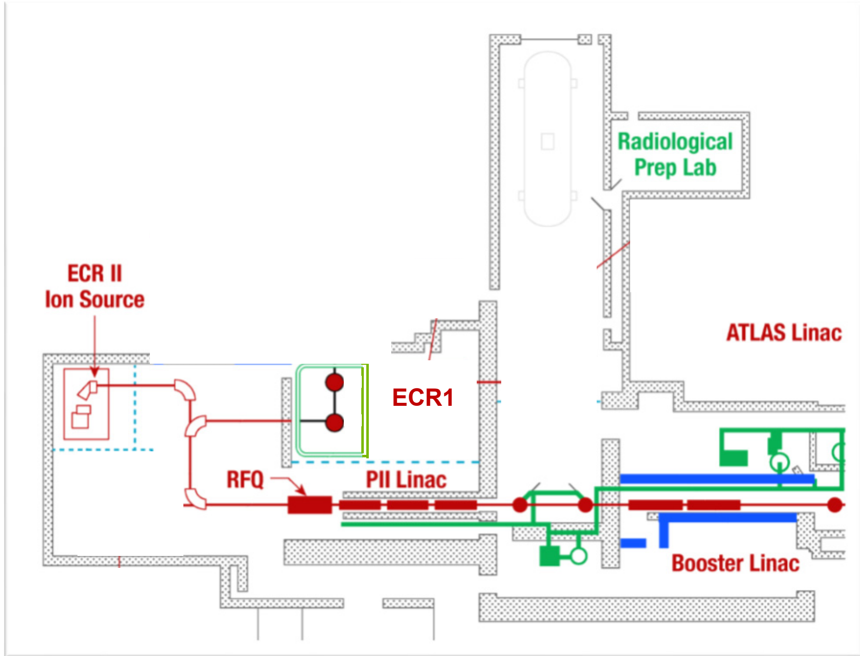


ECR1

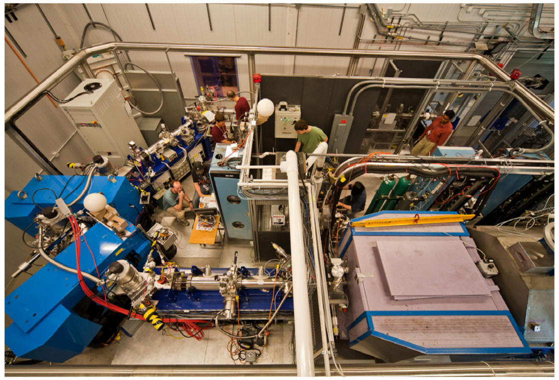


ECR2

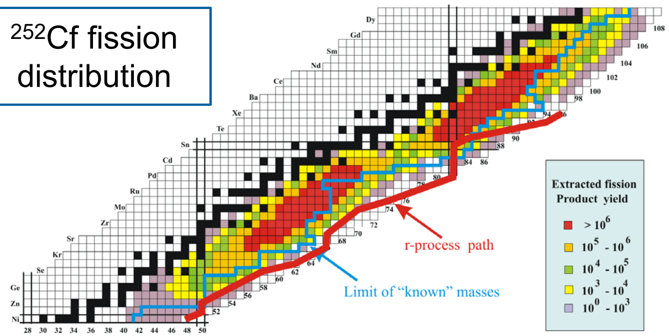
- Delivering beams for low-energy nuclear physics research for over 30 years
- In 2005 launched a project expanding our reach into radioactive nuclei near the r-process pathway



CARIBU
Californium Rare Ion Breeder Upgrade



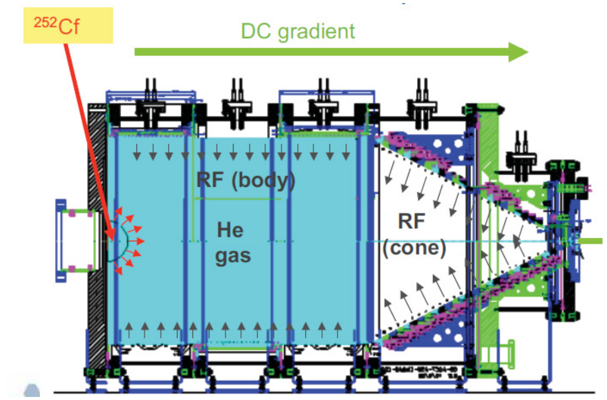
252Cf fission distribution



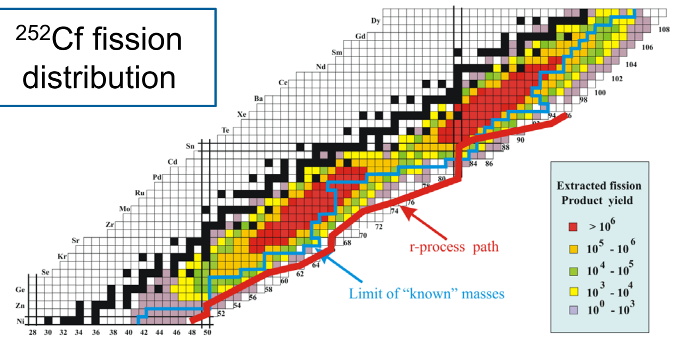
- ^{252}Cf fission source provides radioactive species
  - 500 mCi source installed 2018
  - Effectively 150 mCi due to thickness
- Fission fragments are thermalized in a large volume helium gas catcher with RF and DC carpets and extracted as 1+ or 2+ ions
- Isobar separator - 1:20,000 resolution
- For the stopped beams
  - RFQ cooler/buncher and MR-TOF
- What to use in order to raise the charge state to something the linac could accept
  - ECR or EBIS

CARIBU

Californium Rare Ion Breeder Upgrade



^{252}Cf fission distribution



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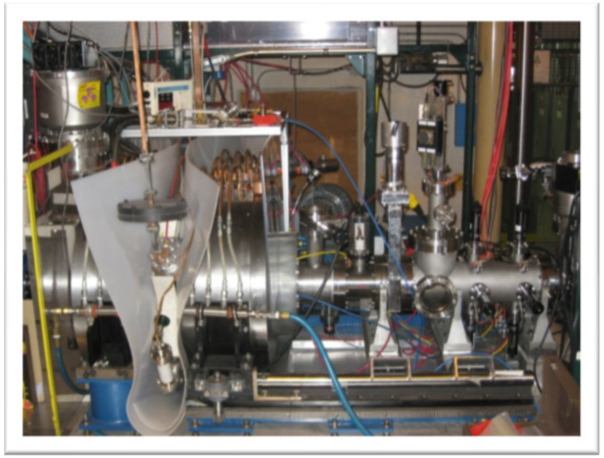
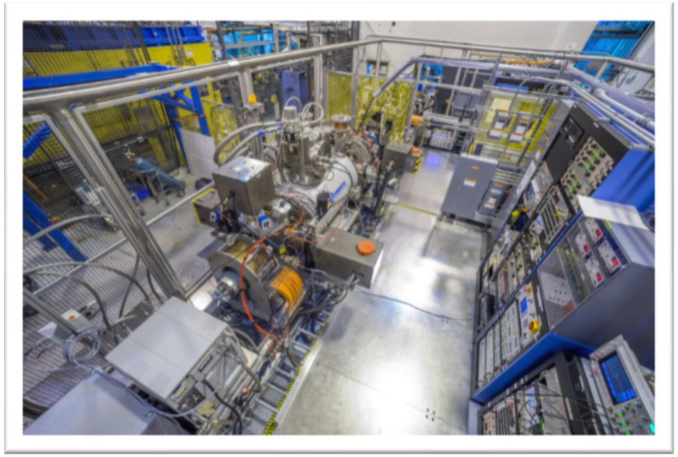
GENERAL COMPARISON – ECR vs. EBIS

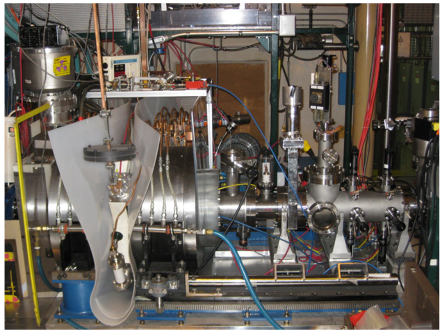




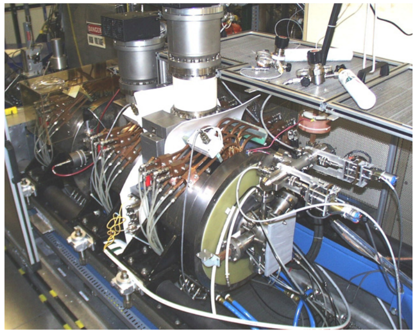
ECR		EBIS
24%	Best Efficiency	32%
4 - 8	A/Q	2.2 – 5.5
10-20 ms/q	Breeding time	10 - 100 ms (total)
> pA	Contamination	< pA
pμA (~10^{13} pps)	Maximum injected beam	pnA (~10^{10} pps)
CW or pulsed	Mode of operation	Pulsed

ATLAS FACILITY

Front end - 2008

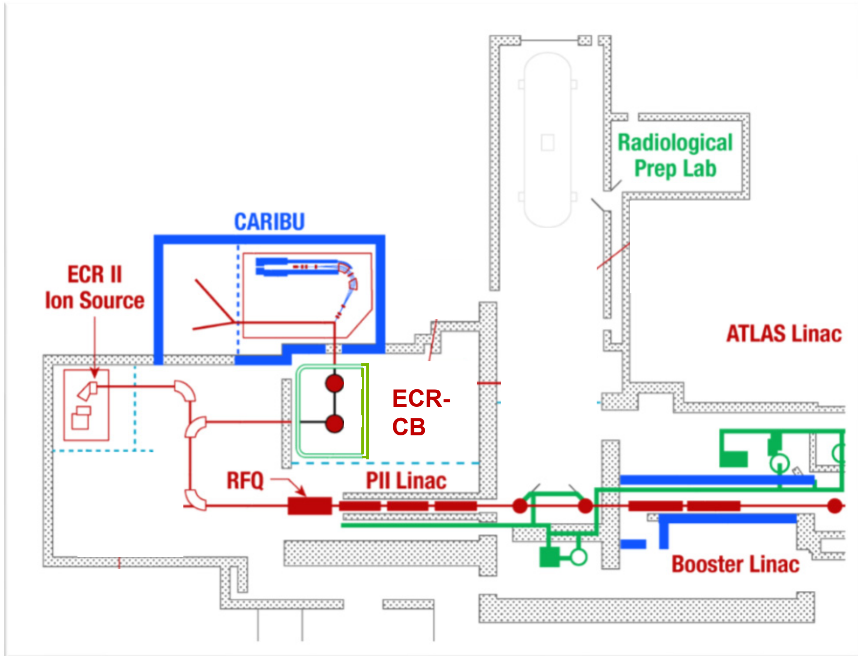


ECR-CB



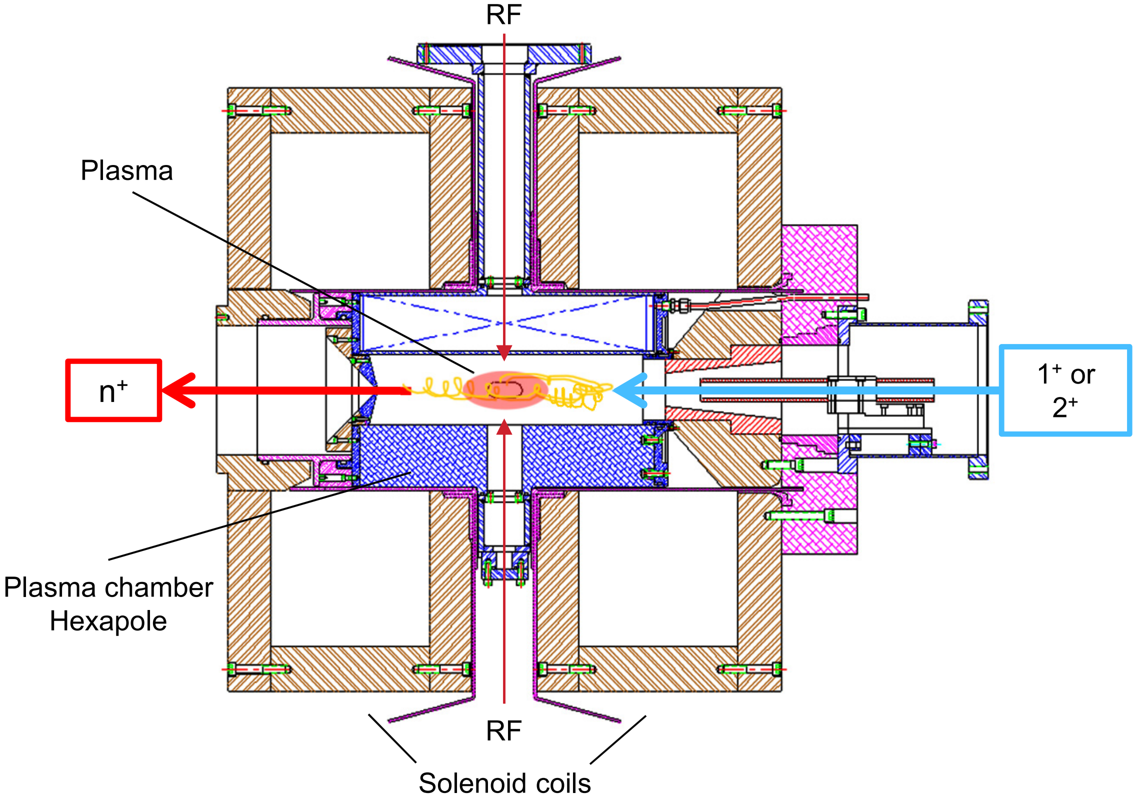
ECR2

CARIBU



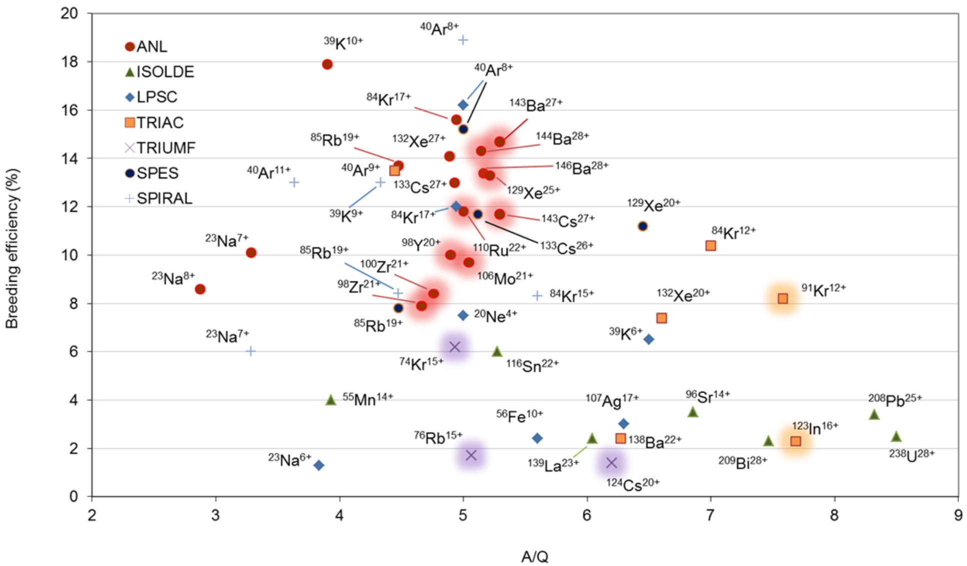
ECR CHARGE BREEDER

Operational 2008-2015



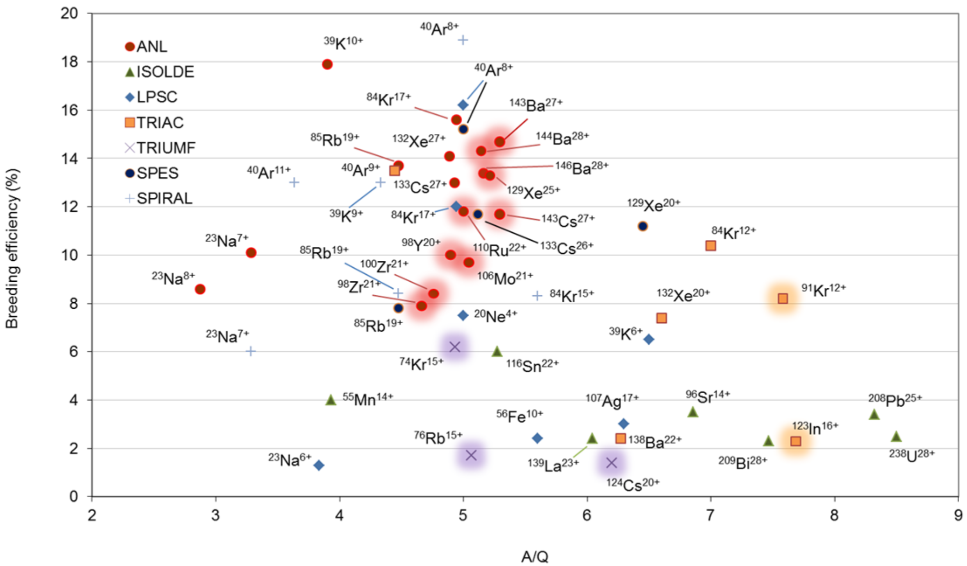
- Solenoid coils provide axial confinement
- Permanent magnet hexapole provides radial confinement
  - Open hexapole
  - Symmetric iron
  - Direct pumping of plasma chamber
- Plasma excited by multiple frequencies in the 10-14 GHz range and <500 W total power
- Step-wise ionization via collisions with energetic electrons

ECR CHARGE BREEDER PERFORMANCE



Worldwide ECR charge breeding as of 2017

ECR CHARGE BREEDER PERFORMANCE



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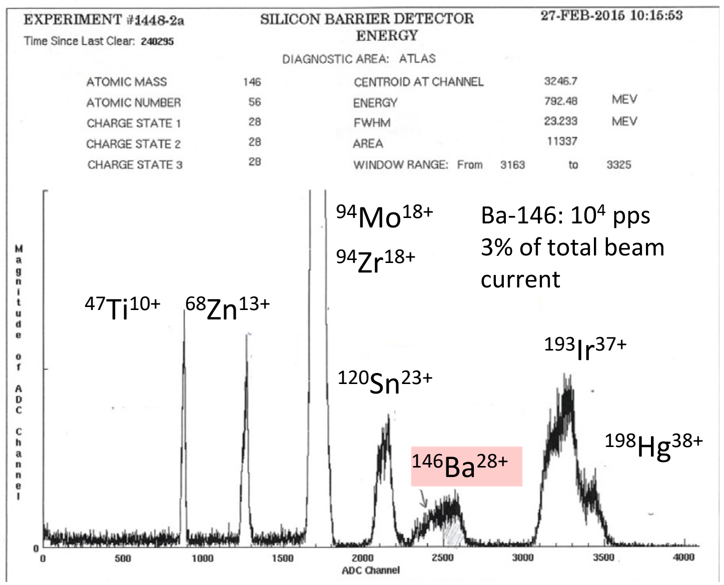
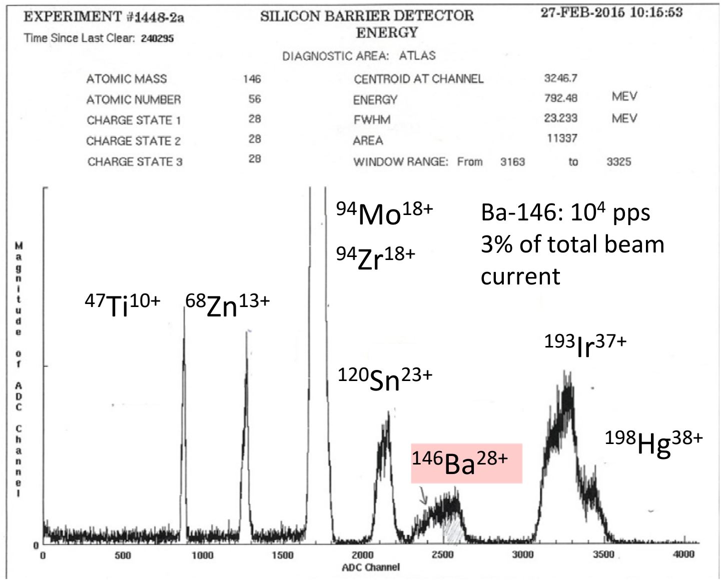


Contamination of RIB with stable background

STABLE BACKGROUND

Sources

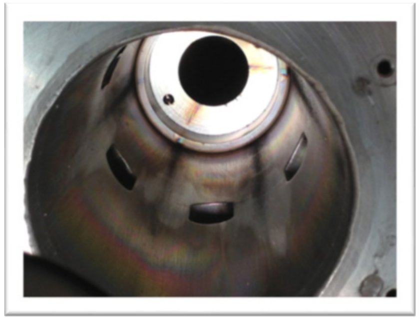
- Foremost mechanisms
  - O-ring permeation
  - Chamber surfaces
  - Bulk materials
    - Plasma chamber
    - Grounded tube
    - Extraction plate
    - RF waveguides
- LEBT discrimination is 1:400
  - Many species were closer than 1:1000
  - Only solution was to eliminate contamination at the ion source



Contamination of RIB with stable background

STABLE BACKGROUND

Mitigation - clean and cover

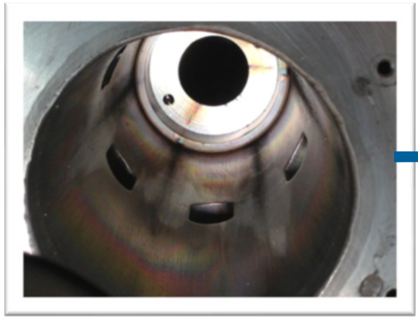


Chamber before cleaning

Established a baseline for F, Cl, Fe at ECR source as well as Mo beam on target detector

STABLE BACKGROUND

Mitigation - clean and cover



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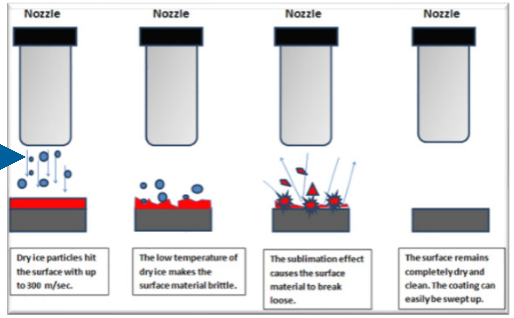


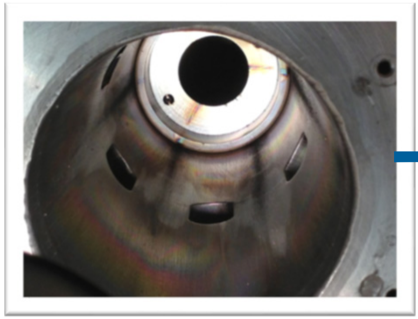
CO_2 surface cleaning

Established a baseline for F, Cl, Fe at ECR source as well as Mo beam on target detector

F: factor of 20 reduction
Cl: factor of 4 reduction
Fe: factor of 50 reduction

STABLE BACKGROUND

Mitigation - clean and cover



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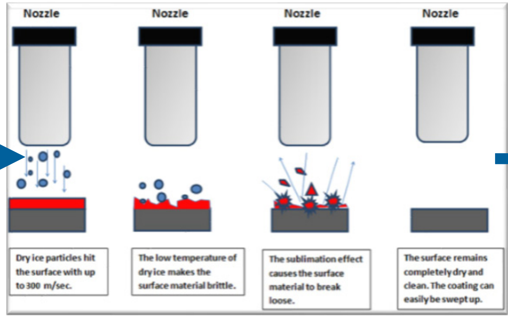


CO_2 surface cleaning

F: factor of 20 reduction
Cl: factor of 4 reduction
Fe: factor of 50 reduction

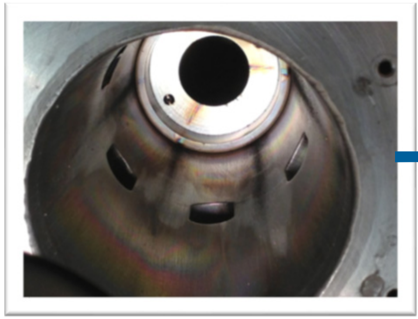
Aluminum coating

F: factor of 160 reduction
Cl: factor of 17 reduction
Fe: not detectable
Mo: factor of 5 reduction

Contaminants of Ta and W introduced by heating element

STABLE BACKGROUND

Mitigation - clean and cover



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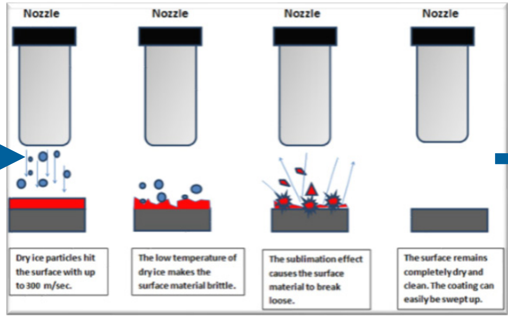

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F: factor of 20 reduction
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Aluminum coating

F: factor of 160 reduction
Cl: factor of 17 reduction
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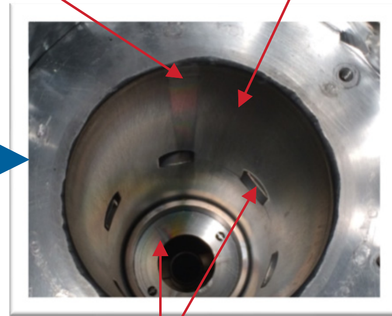
Mo: factor of 5 reduction

Contaminants of Ta and W introduced by heating element

Shadow from current lead

1 micron aluminum layer

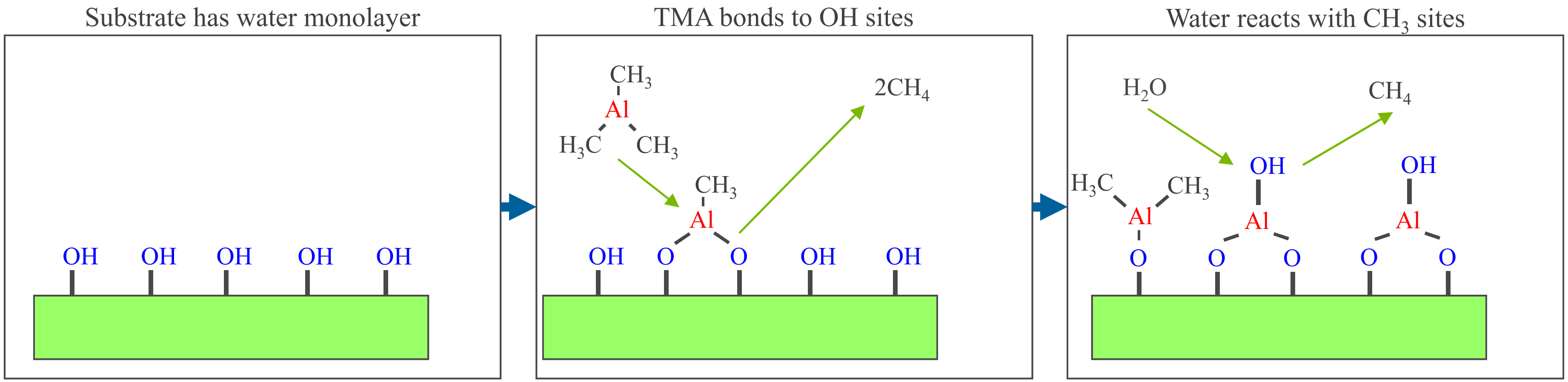


Some areas not coated

ATOMIC LAYER DEPOSITION

A better way to coat with aluminum?

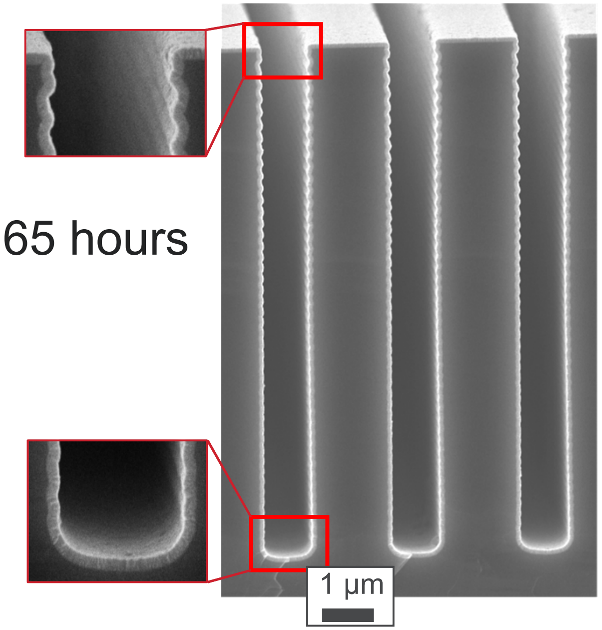
- Thin-film deposition technique based on the use of a gas-phase chemical process
- Two chemicals react with the substrate in a sequential and self-limiting fashion
- Thin film is slowly deposited over the course of successive exposures
- For Al_2O_3 the chemical precursor is trimethylaluminum $Al(CH_3)_3$ (TMA)



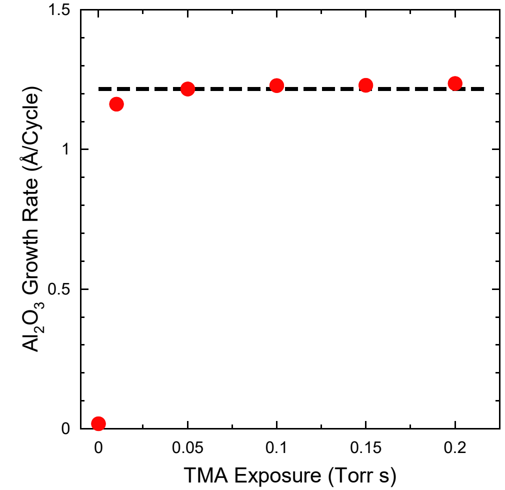
ATOMIC LAYER DEPOSITION

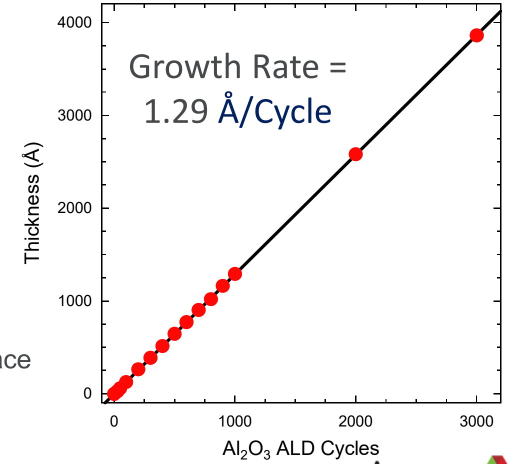
Characteristics

- Conformal
- Self-terminating
- Linear film thickness
  - 1 micron: 7752 cycles, 65 hours
- In situ
- No hot filament
- High purity materials
- Outstanding questions
  - Effectiveness
  - Longevity
  - Tests with ECR3 ion source



J. Lu, J. W. Elam, and P. C. Stair, Surface Science Reports, **71**, 410-472, (2016)



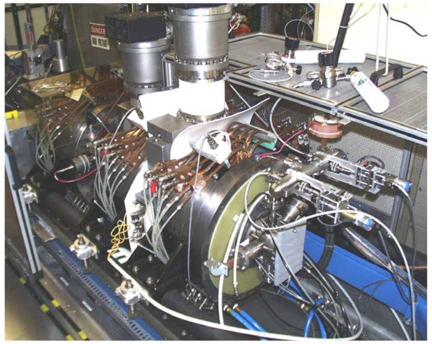


ATLAS FACILITY

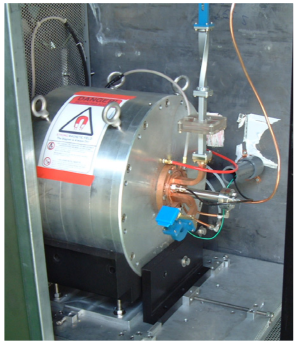
Front end – present day

CARIBU

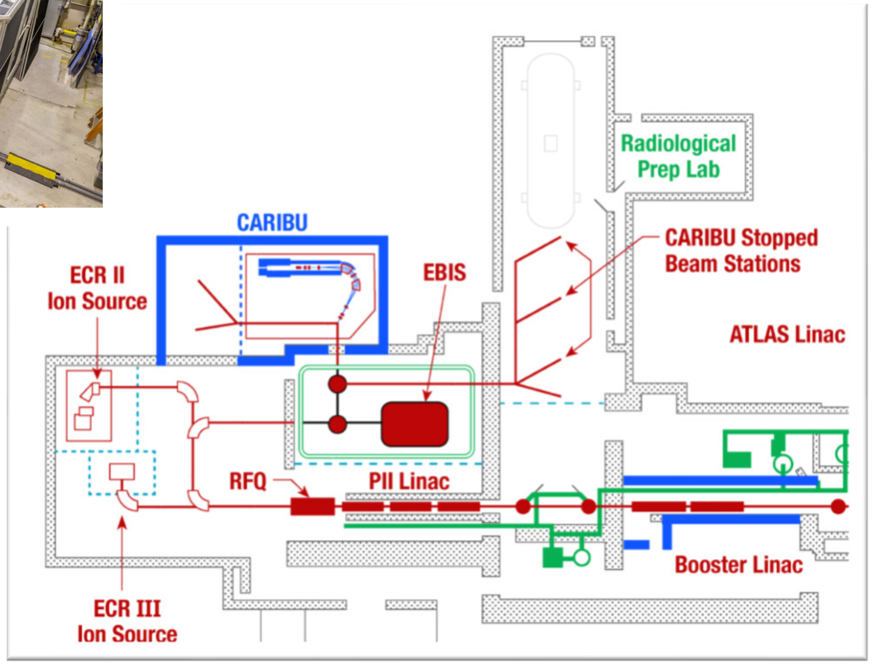
EBIS-CB



ECR2

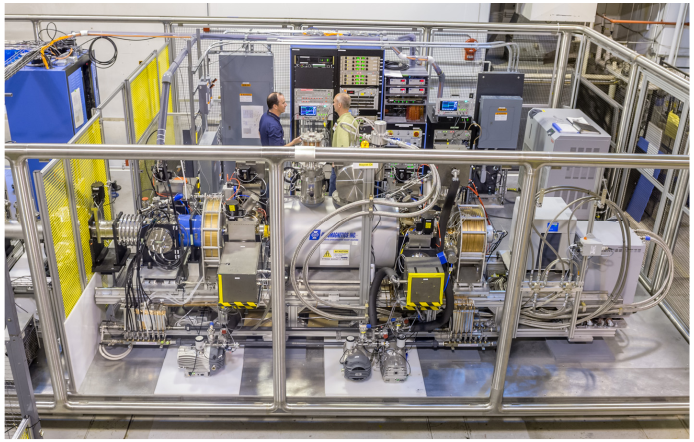


ECR3



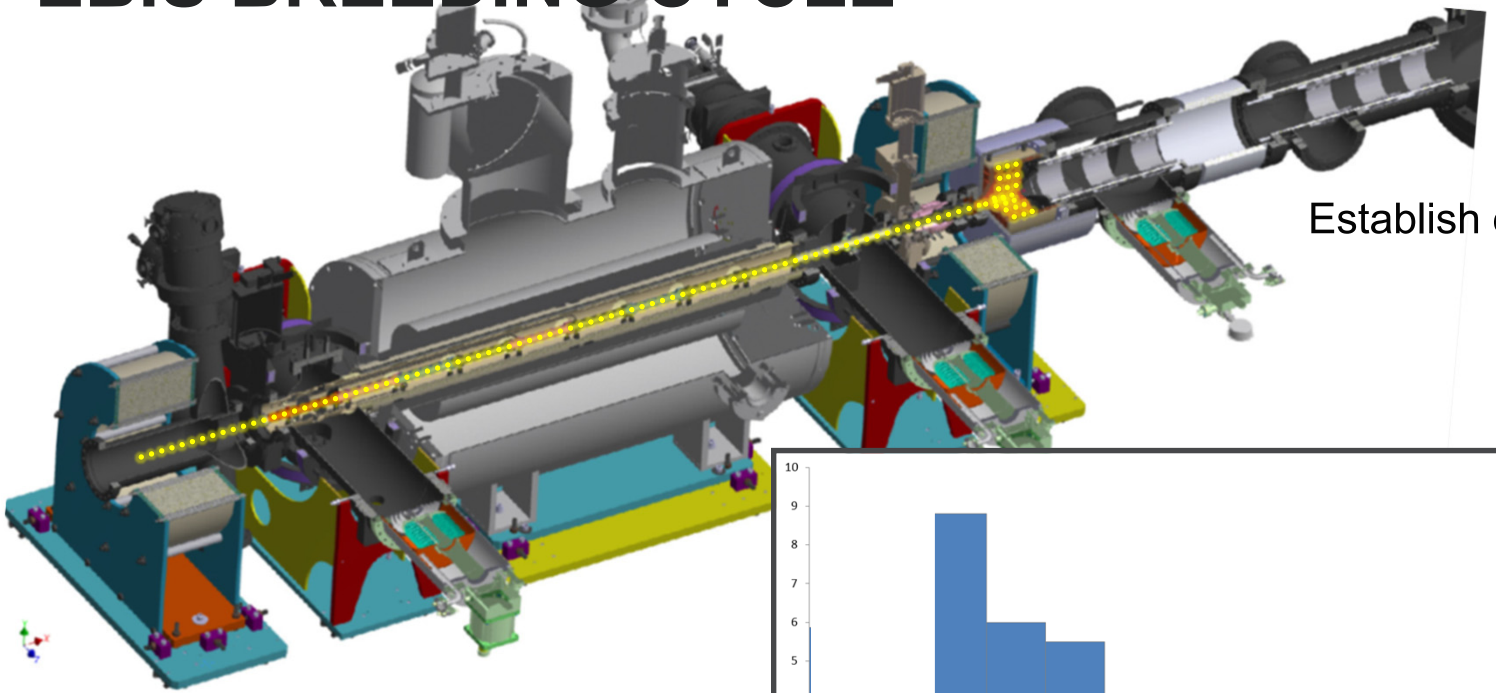
EBIS CHARGE BREEDER

- Developed in collaboration with BNL and is based upon the TestEBIS design
- October 2015 – Replaced the ECR-CB at the ATLAS front end
- September 9, 2016 - First accelerated radioactive charge bred beam (^{142}Cs)



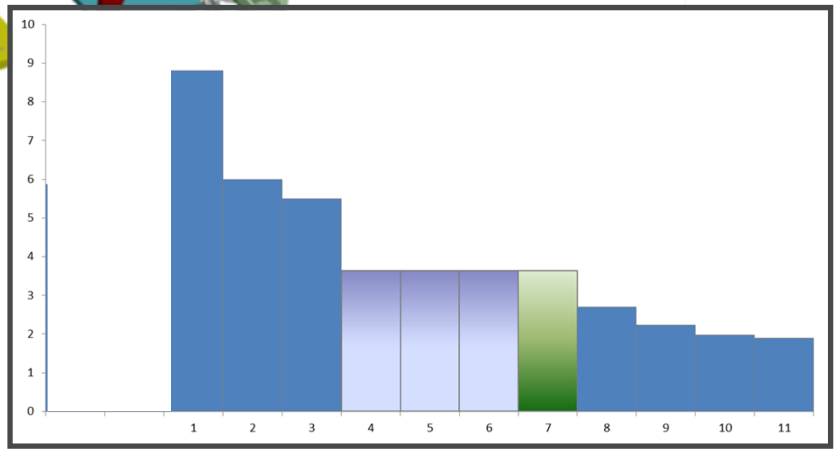
EBIS Operating Parameters	
Solenoid field	5.5 T
Magnetic field on cathode	0.15 T
IrCe cathode diameter	4.2 mm
Electron beam current	1.12 A
Electron beam diameter in trap	0.692 mm
Electron beam density in trap	296 A/cm^2
Electron beam energy in trap	8118 eV
Trap length	0.532 m
Trap capacity	11 nC
Injection time	10-40 μs
Repetition rate	10 Hz
Duty cycle	33 %
EBIS bias	20 kV
Pressure	1x10^{-10} Torr

EBIS BREEDING CYCLE



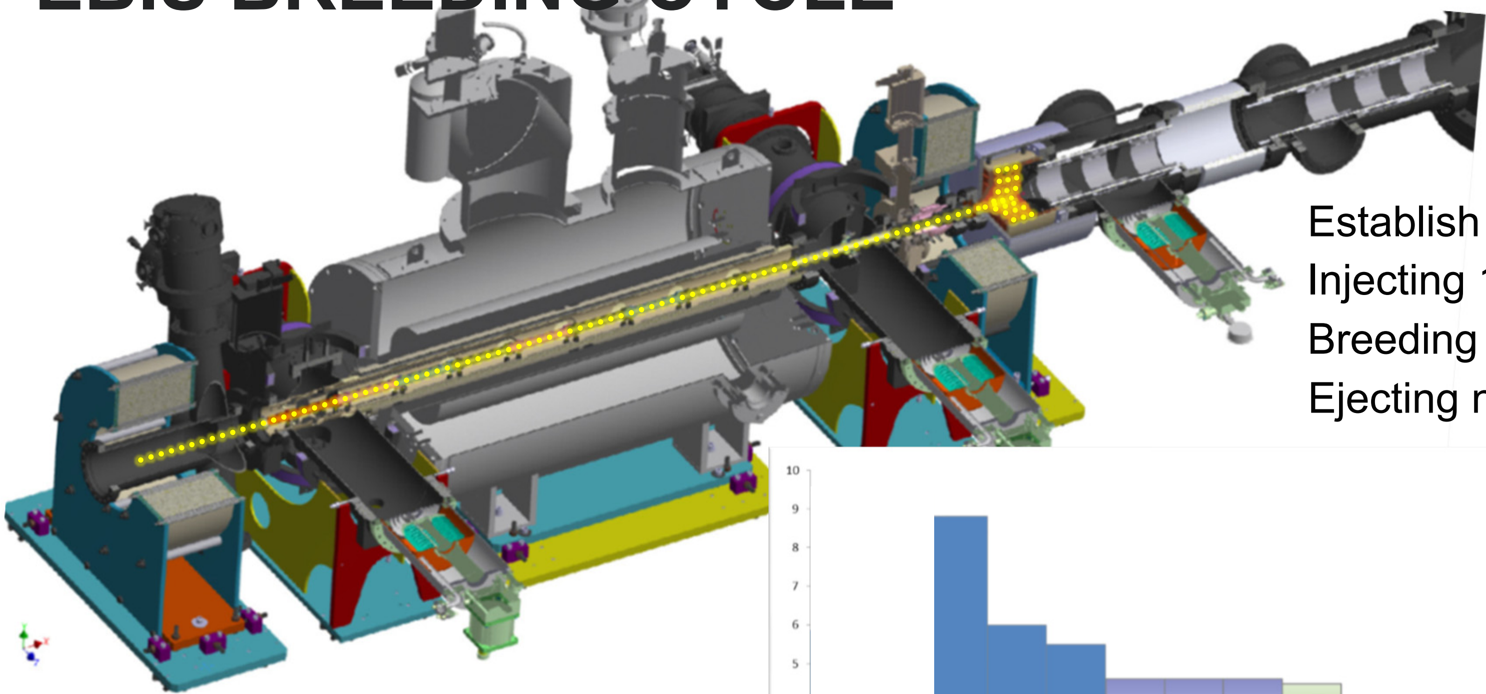
Establish e-beam: 0→1 ms

- Trap electrodes provide axial ion confinement
- Electron beam provides radial ion confinement
- Strong solenoid for electron beam compression
- Interaction with e-beam produces HCI



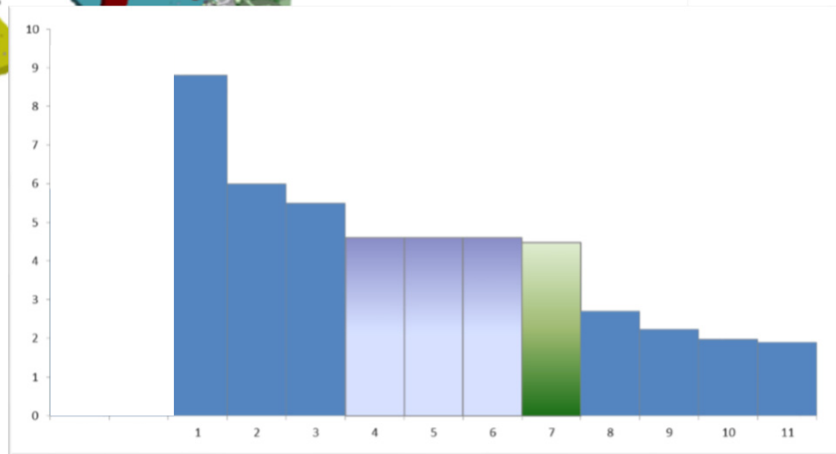
Drift tube applied voltages (kV)

EBIS BREEDING CYCLE



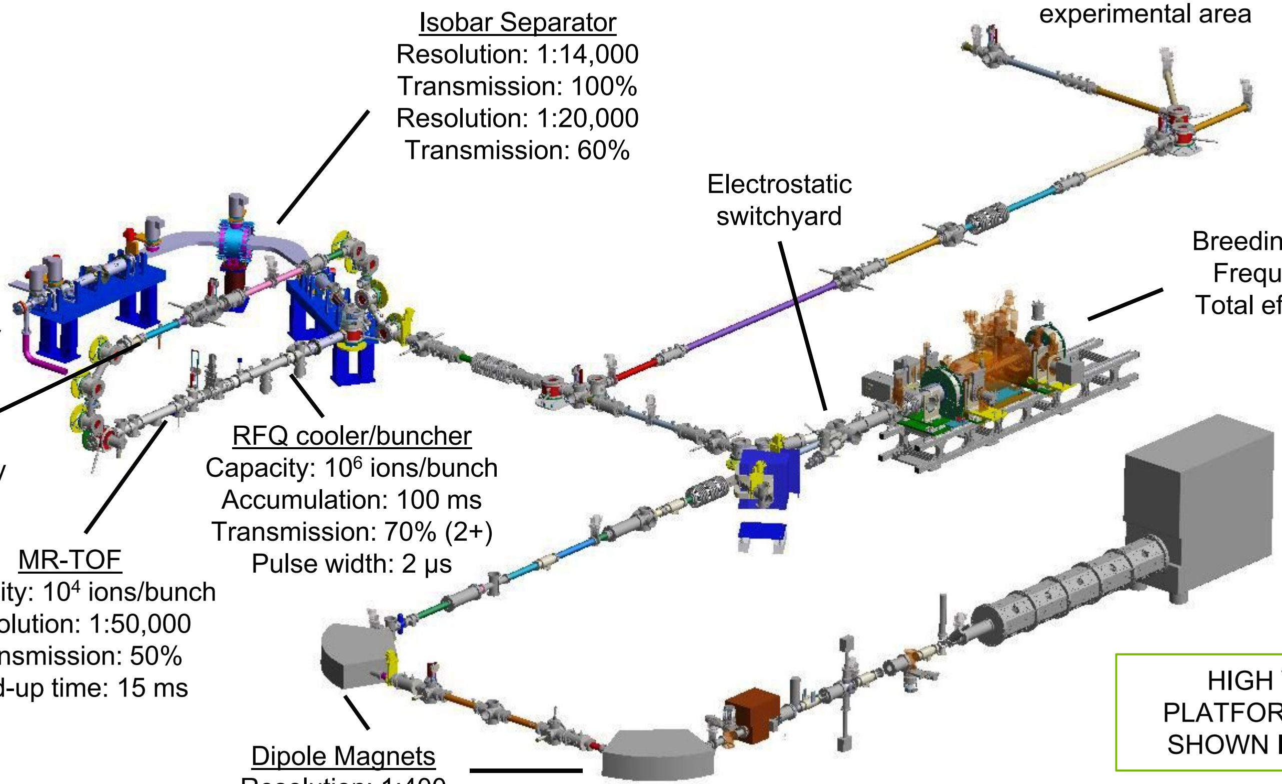
Establish e-beam: 0→1 ms
Injecting 1+ ions: 1→1.1 ms
Breeding to n+: 1.1→30 ms
Ejecting n+ ions: 30→33 ms

- Trap electrodes provide axial ion confinement
- Electron beam provides radial ion confinement
- Strong solenoid for electron beam compression
- Interaction with e-beam produces HCI

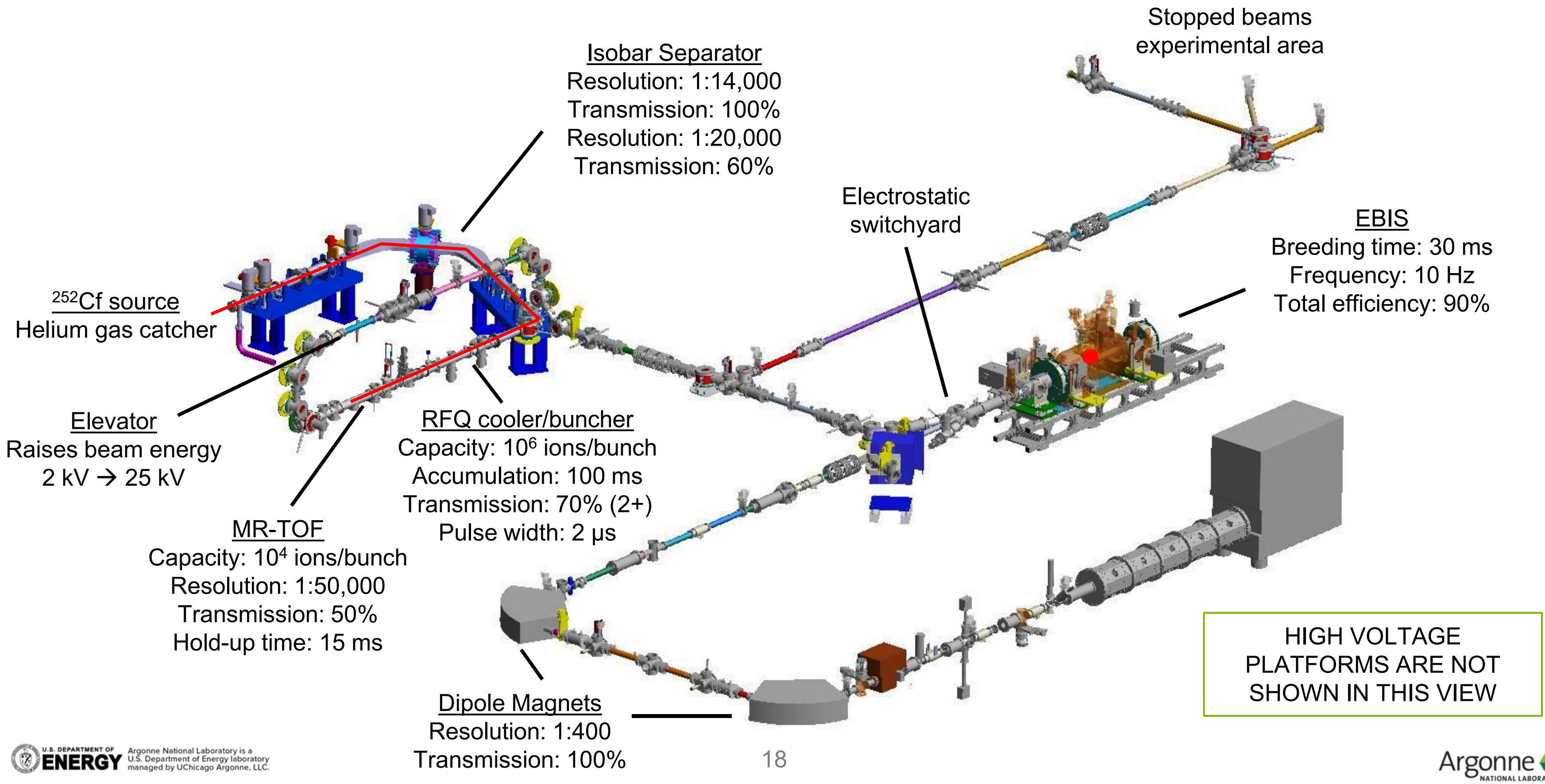


Drift tube applied voltages (kV)

EBIS CHARGE BREEDING CYCLE

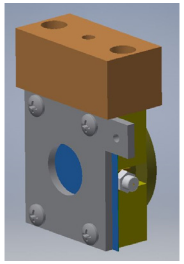


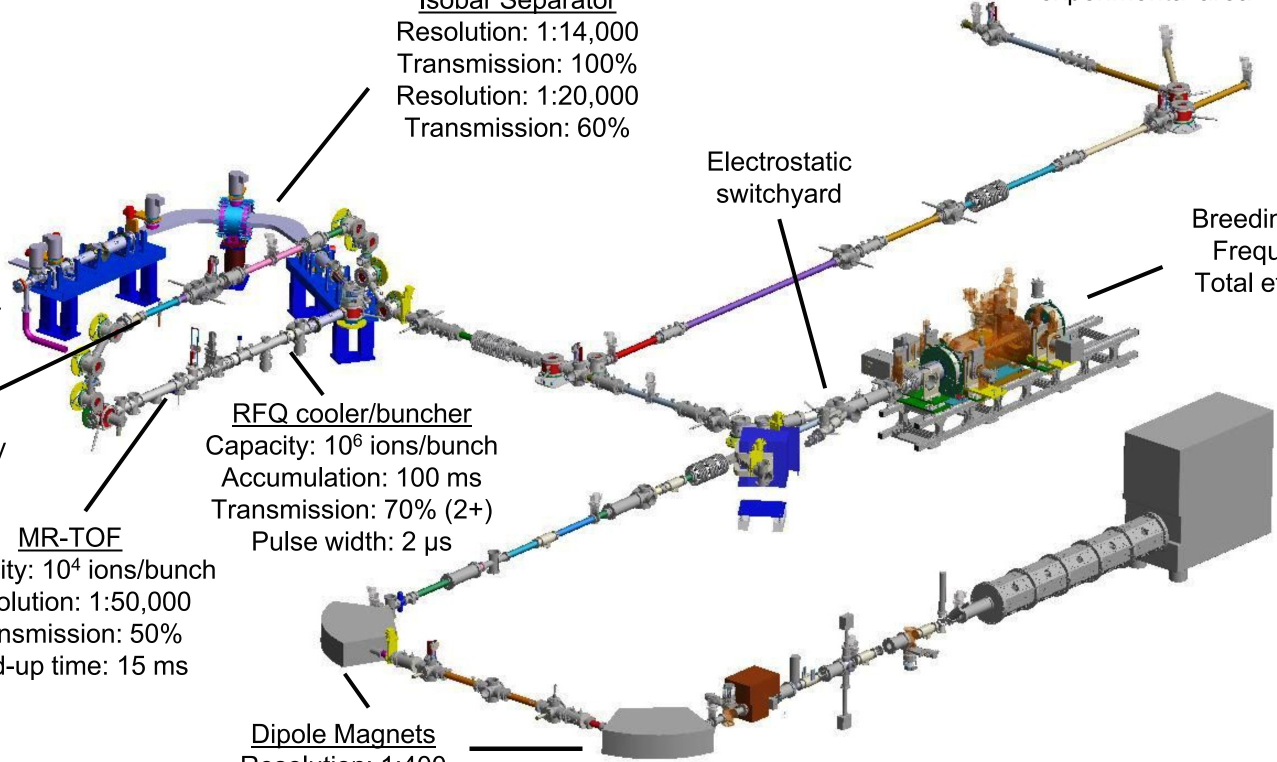
EBIS CHARGE BREEDING CYCLE



EBIS CHARGE BREEDING CYCLE

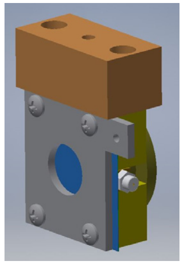
RIB detection and tuning



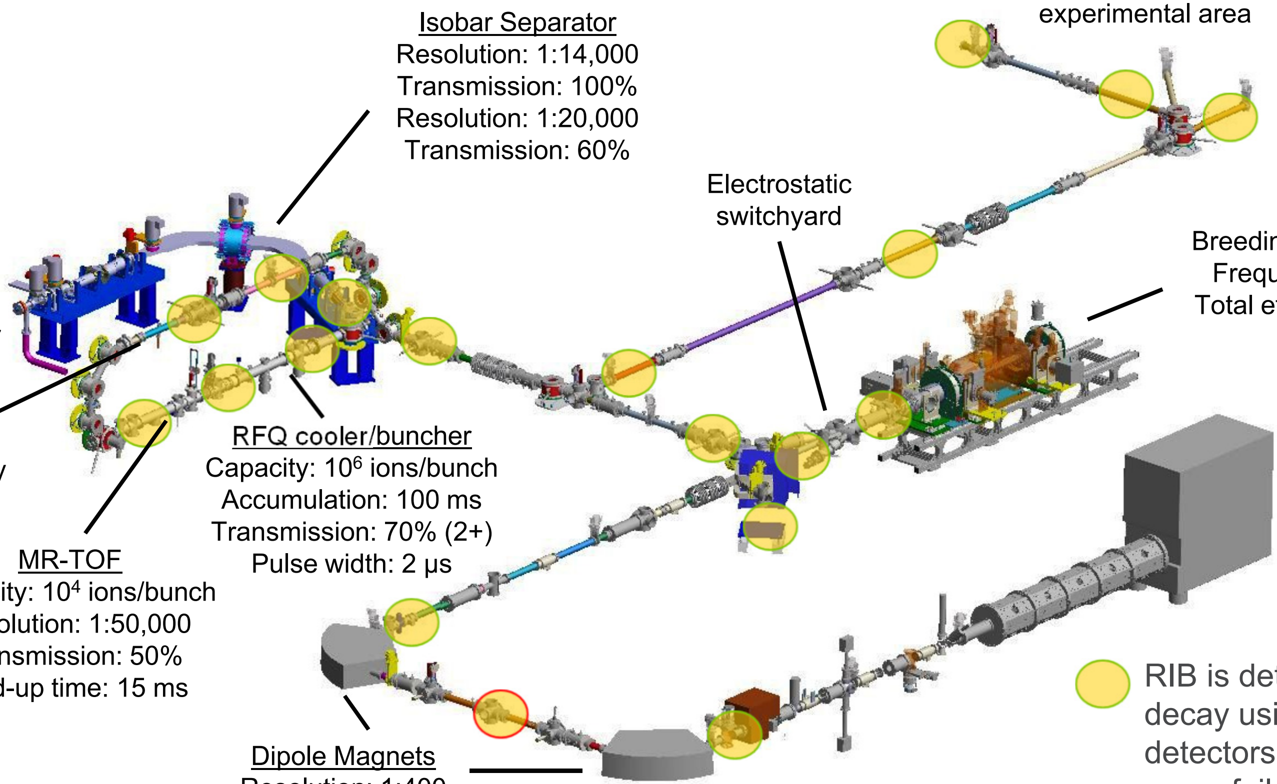


EBIS CHARGE BREEDING CYCLE

RIB detection and tuning



^{252}Cf source
Helium gas catcher



Isobar Separator
Resolution: 1:14,000
Transmission: 100%
Resolution: 1:20,000
Transmission: 60%

Stopped beams experimental area

Electrostatic switchyard

EBIS
Breeding time: 30 ms
Frequency: 10 Hz
Total efficiency: 90%

Elevator
Raises beam energy
2 kV → 25 kV

RFQ cooler/buncher
Capacity: 10^6 ions/bunch
Accumulation: 100 ms
Transmission: 70% (2+)
Pulse width: 2 μs

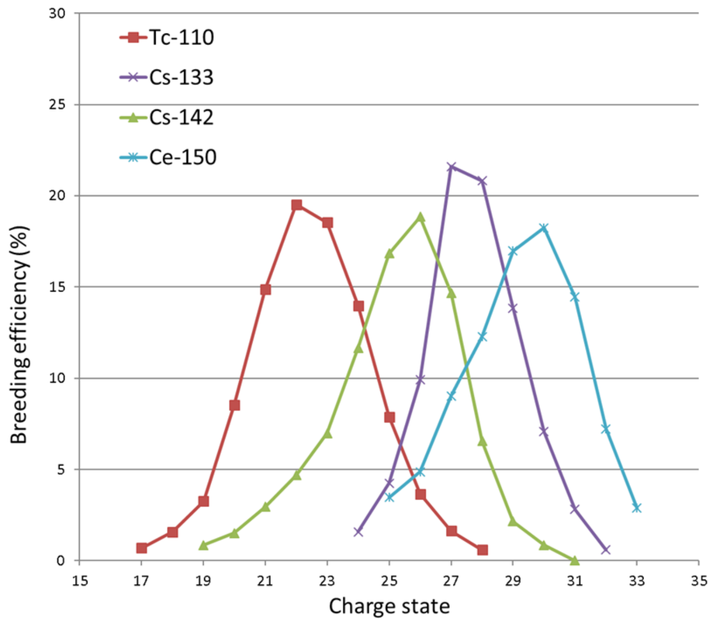
MR-TOF
Capacity: 10^4 ions/bunch
Resolution: 1:50,000
Transmission: 50%
Hold-up time: 15 ms

Dipole Magnets
Resolution: 1:400
Transmission: 100%

RIB is detected via beta decay using silicon barrier detectors with aluminum cover foil

EBIS CHARGE BREEDER PERFORMANCE

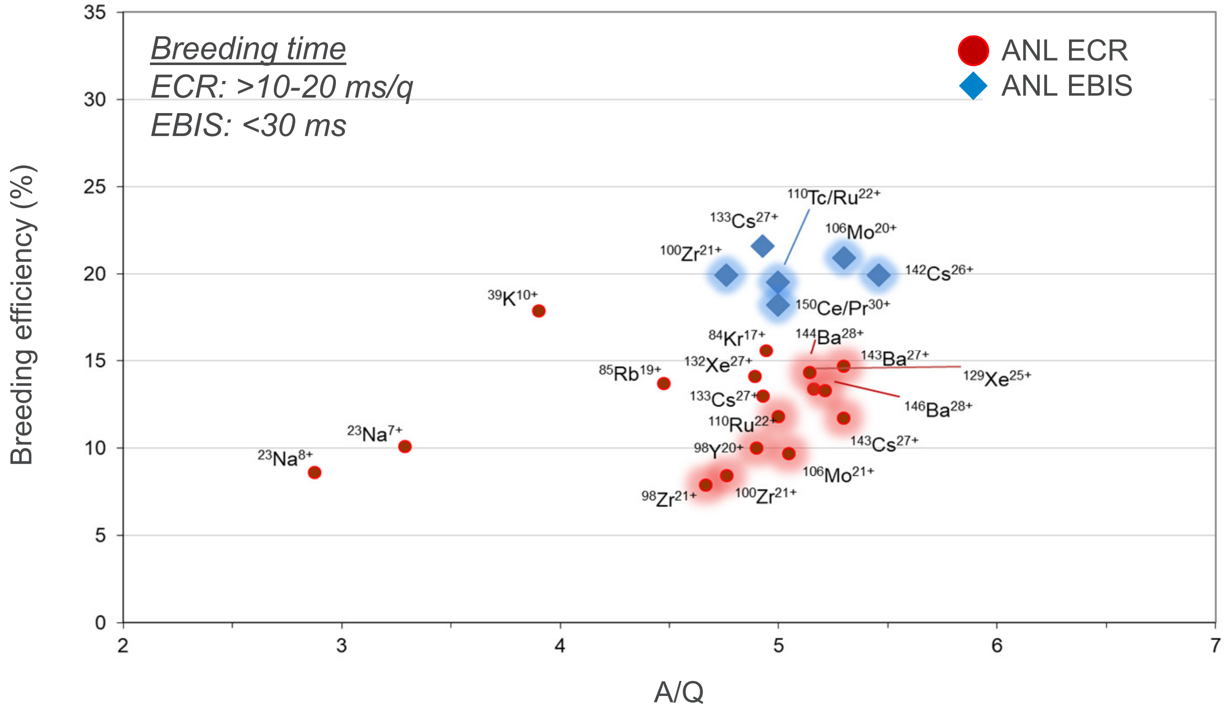
- Set up EBIS with ^{133}Cs pilot beam and adjust trap timing and injection steering for RIB
- Have produced 11 radioactive species in last six months
  - Average single charge state efficiency
    - EBIS only: 19%
    - RFQ-CB + EBIS: 13%
  - Rep rate: 10 Hz
  - Breeding time: 18-26 ms
  - Injected pulse width: 10 μs
  - Extracted pulse width: 1-3 ms



Breeding efficiency charge state distributions for selected species

EBIS CHARGE BREEDER EFFICIENCY

Compared to ANL ECR charge breeder



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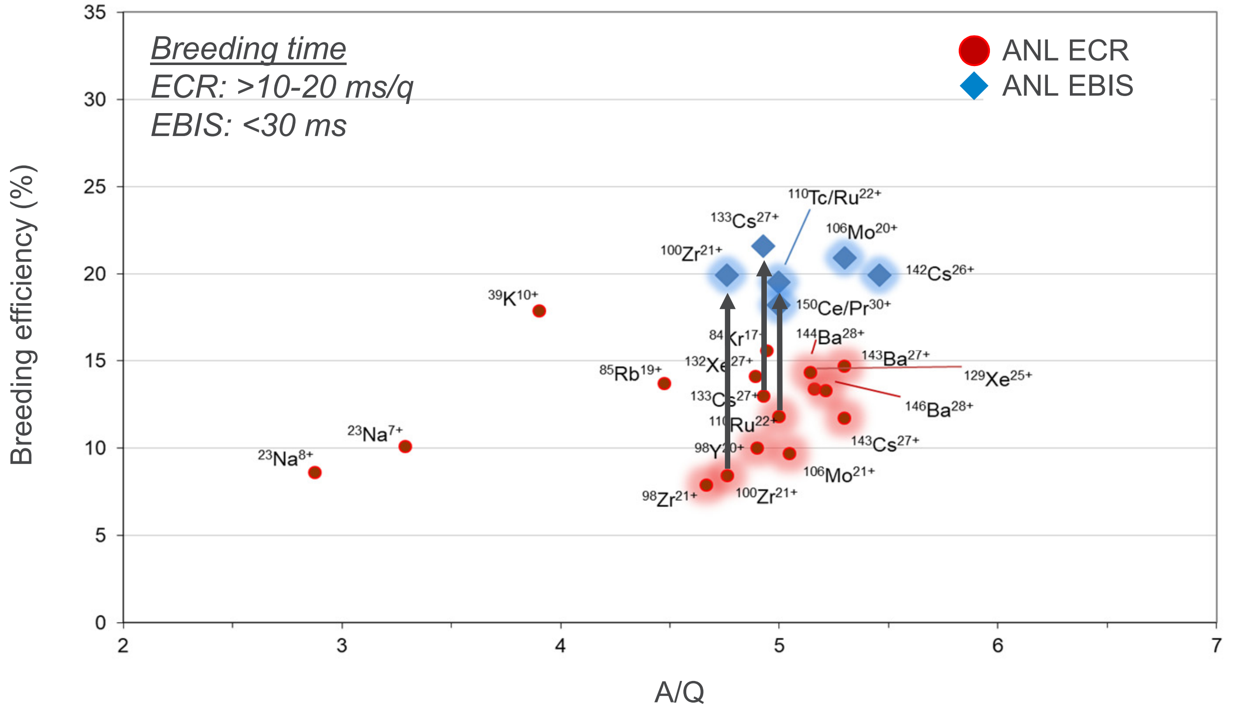
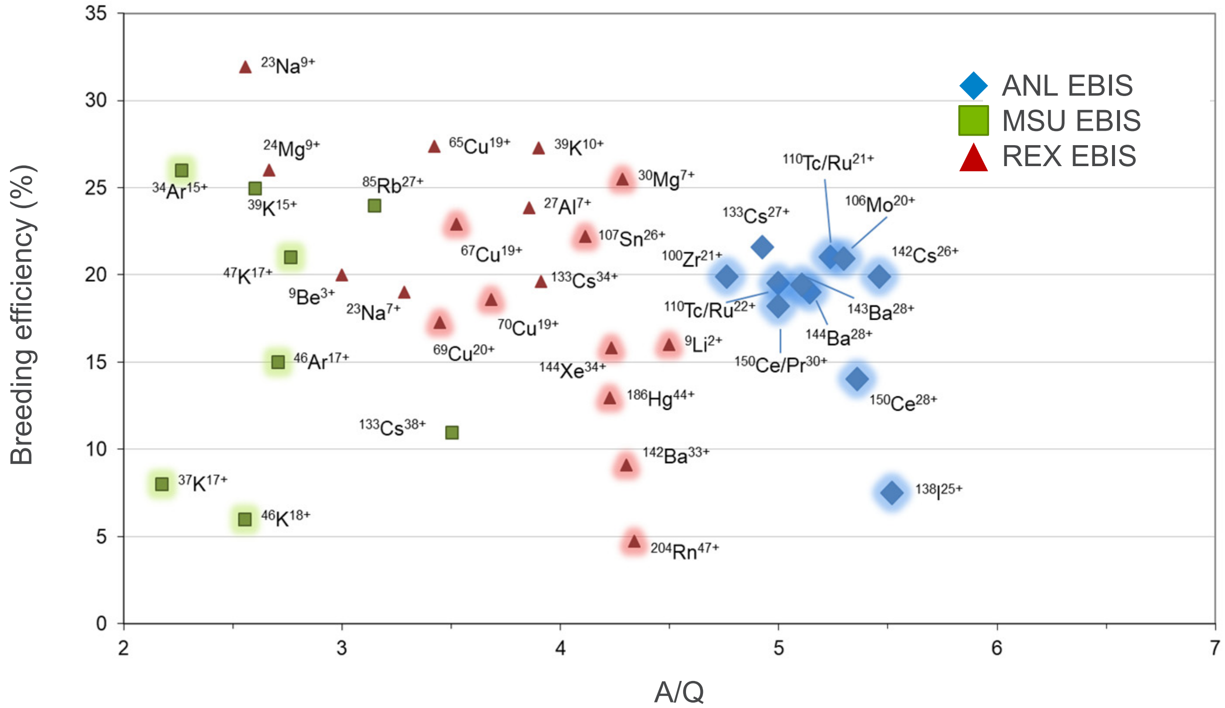


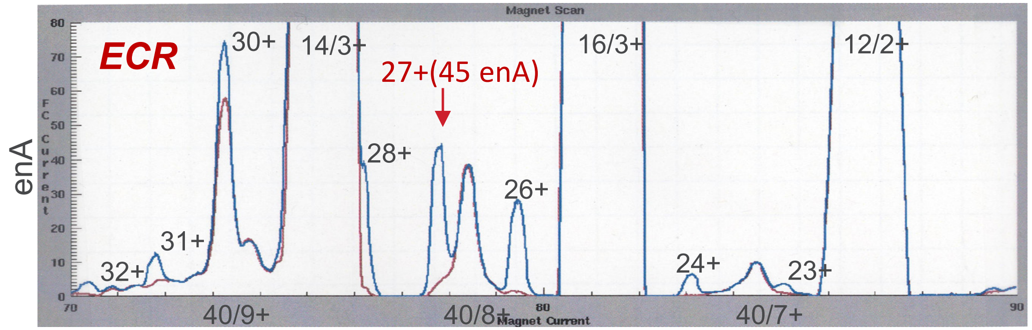
EBIS CHARGE BREEDER EFFICIENCY

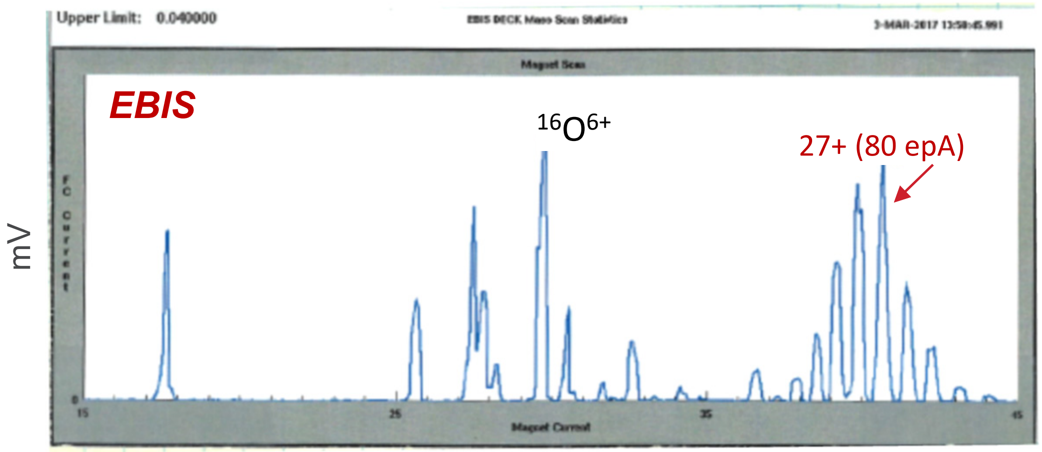
EBIS ONLY



STABLE BACKGROUND – 133Cs

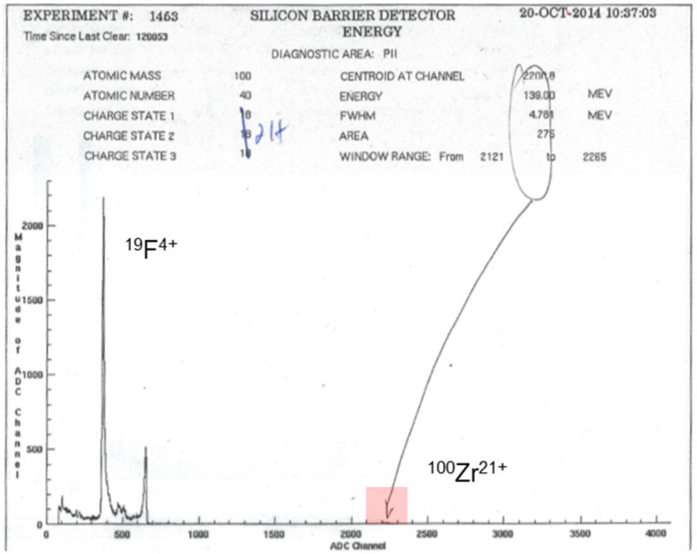
ECR vs. EBIS





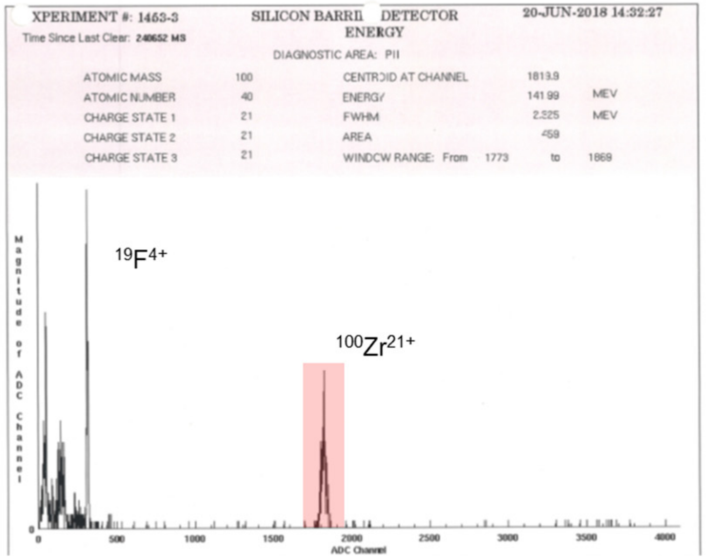
BEAM BACKGROUND – 100Zr

ECR vs. EBIS



Beam from ECR charge breeder

$^{100}Zr^{21+}$:2400 pps (beta)
Stable background rate: 2400 Hz
RIB: <0.01% of total beam current

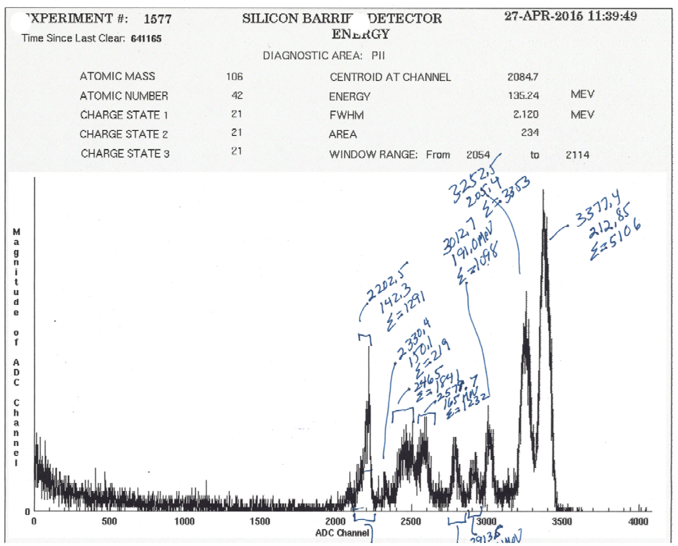


Beam from EBIS charge breeder

$^{100}Zr^{21+}$: 300 pps (beta)
Stable background rate: 1.6 Hz
RIB: 55% of total beam current

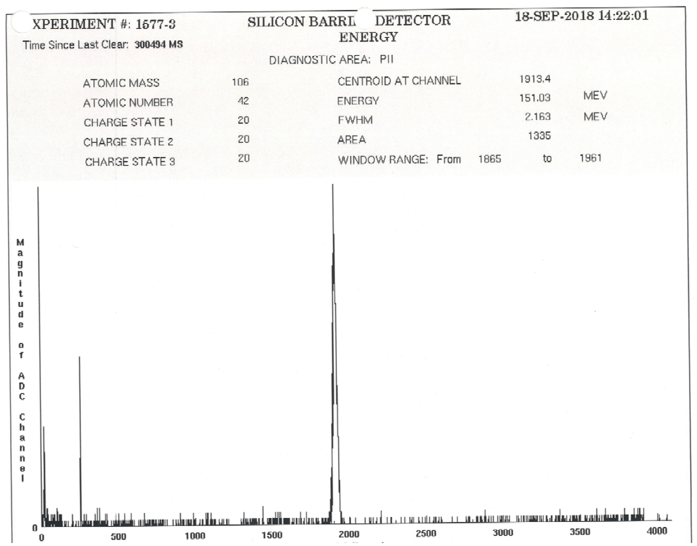
BEAM BACKGROUND – 106Mo

ECR vs. EBIS



Beam from ECR charge breeder

$^{106}Mo^{21+}$: 6000 pps (beta)
Stable background rate: 25 Hz
RIB: <0.01% of total beam current

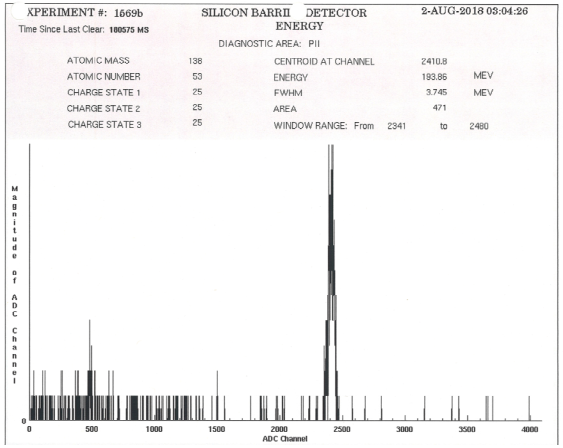


Beam from EBIS charge breeder

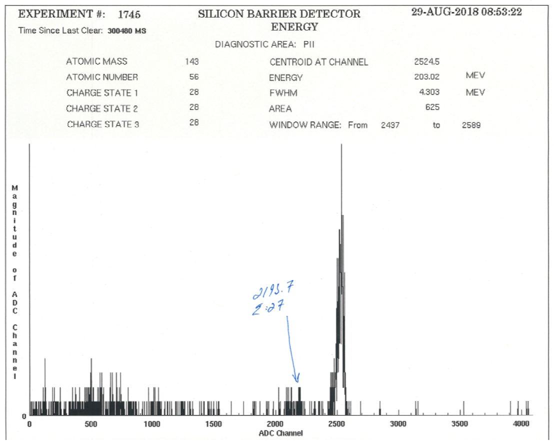
$^{106}Mo^{20+}$: 5500 pps (beta)
Stable background rate: 0.3 Hz
RIB: 94% of total beam current

BEAM BACKGROUND

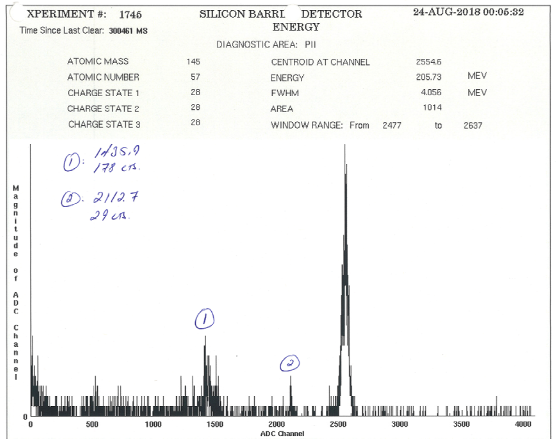
EBIS only



$^{138}I^{25+}$: *1300 pps (beta)*
Stable background rate: 0.2 Hz
RIB: 92% of total beam current



$^{143}Ba^{28+}$: *6800 pps (beta)*
Stable background rate: 0.1 Hz
RIB: 96% of total beam current

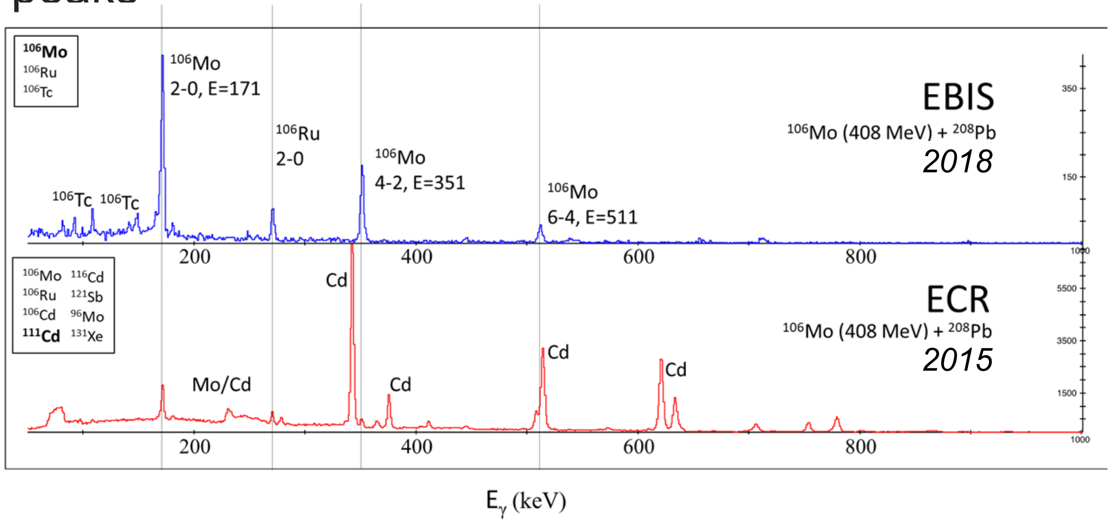


$^{145}Ba^{28+}$: *7000 pps (beta)*
Stable background rate: 0.7 Hz
RIB: 83% of total beam current

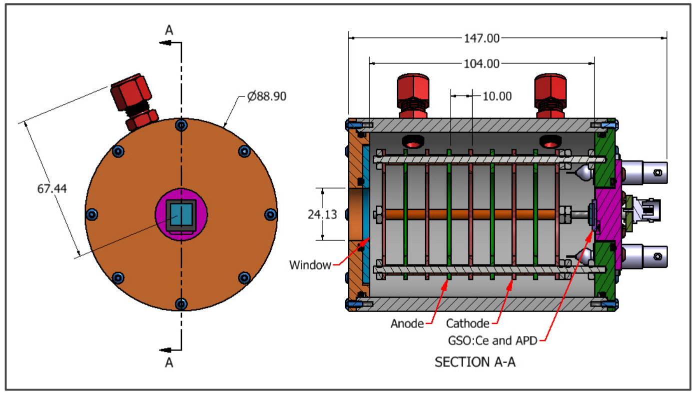
EFFECT ON EXPERIMENTAL EFFICIENCY

Quality of beam on target

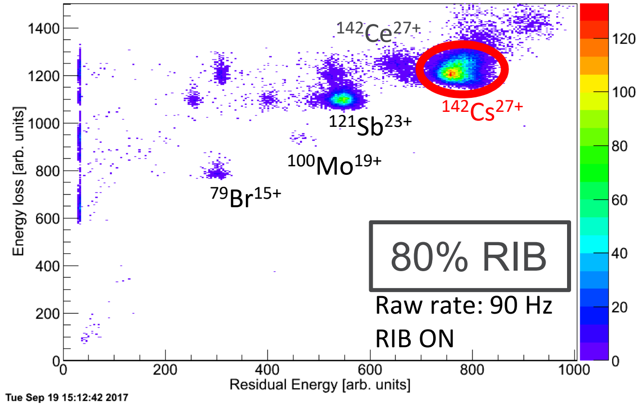
- Had performed a ^{106}Mo experiment with ECR-CB in 2015
- Repeated the same experiment with EBIS-CB in 2018
- Improved signal-to-noise ratio
- Less spurious peaks

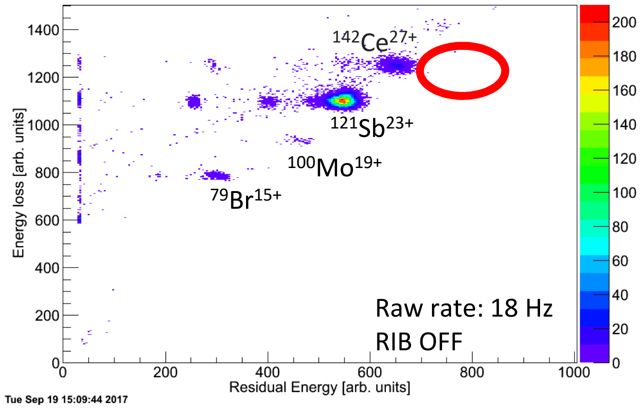


RIB DETECTION



- Fast and compact gas ionization chamber
  - Direct measurements of CARIBU RIBs for tuning and identification
  - Avoids time lag inherent to beta decay detection method
  - Can be positioned at many places along accelerator
  - Prototype performance limited at rate of 2 x 10^4 ions/sec

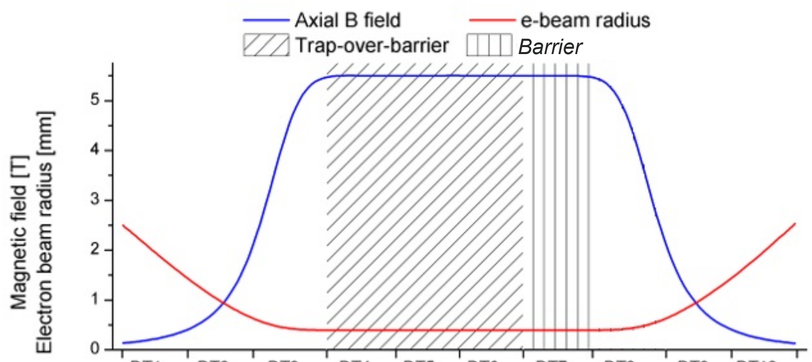




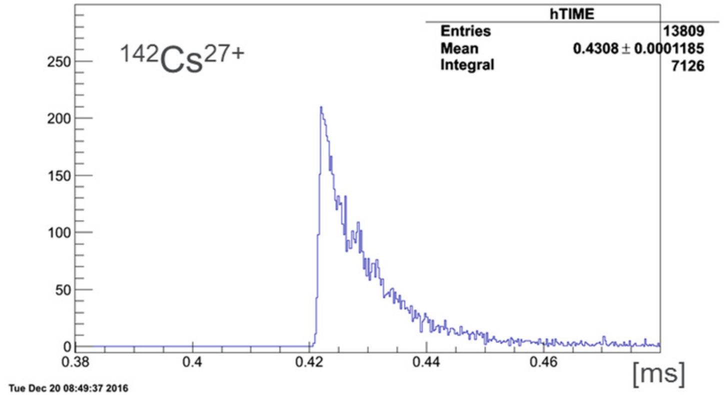
BEAM EXTRACTION

Fast and slow modes

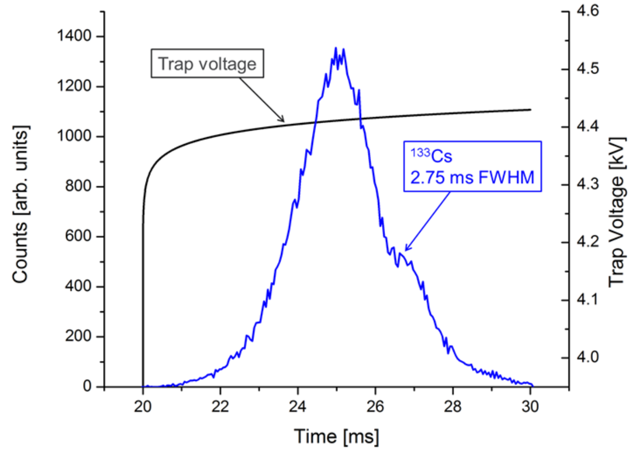
- Fast – barrier lowering
  - Drop DT7
- Slow – trap over barrier
  - DT7 stays fixed
  - Raise DTs 4, 5, 6



EBIS drift tube configuration



Fast extraction

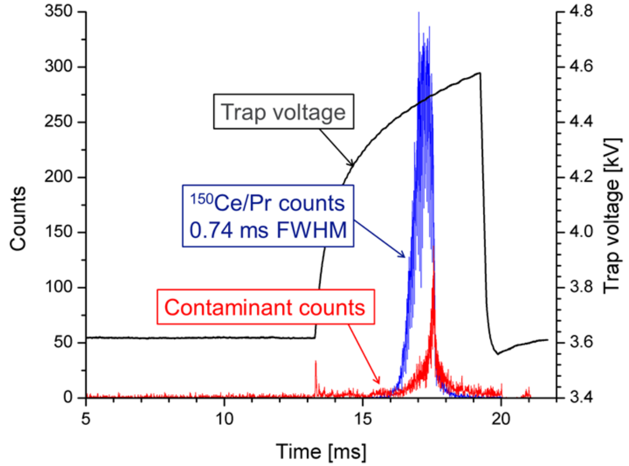


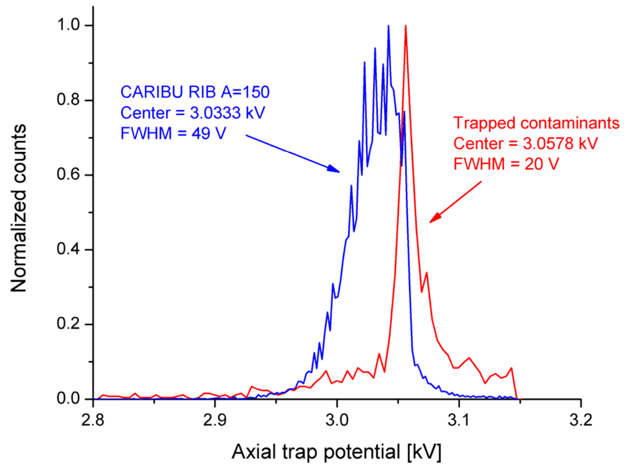
Slow extraction

BEAM EXTRACTION

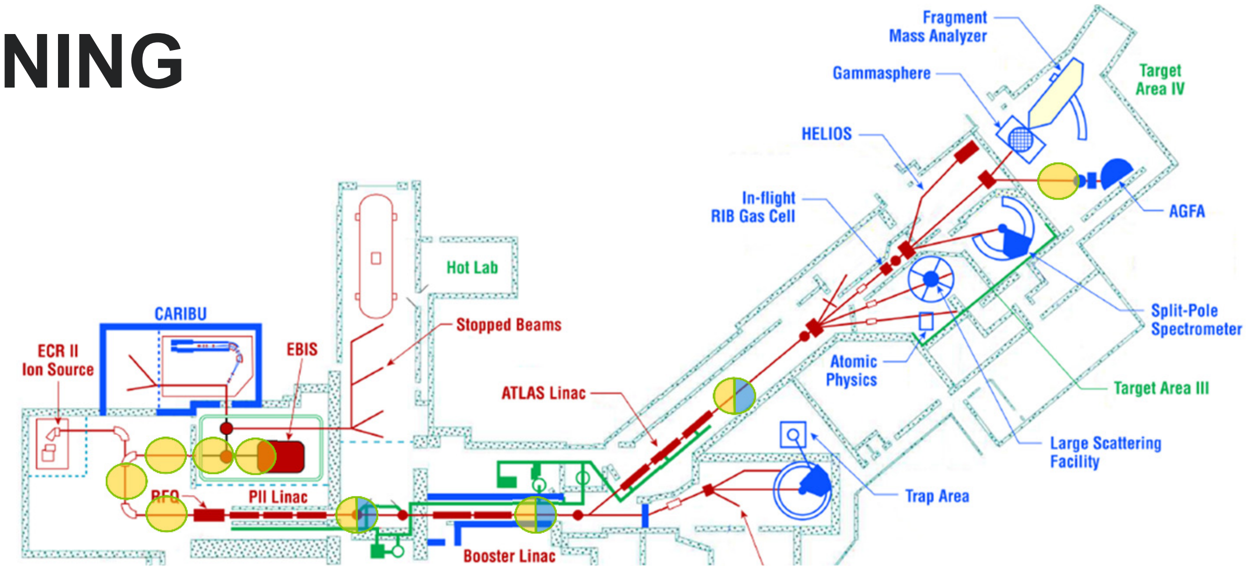
Slow mode – trap over barrier

- Observed beam with gas ionization chamber – mass and timing information
- Arrival time correlated to trap voltage ramp
- Continuous extraction of light species which are ionized outside of the trap
- Distinct energies of injected and residual ions released from the trap



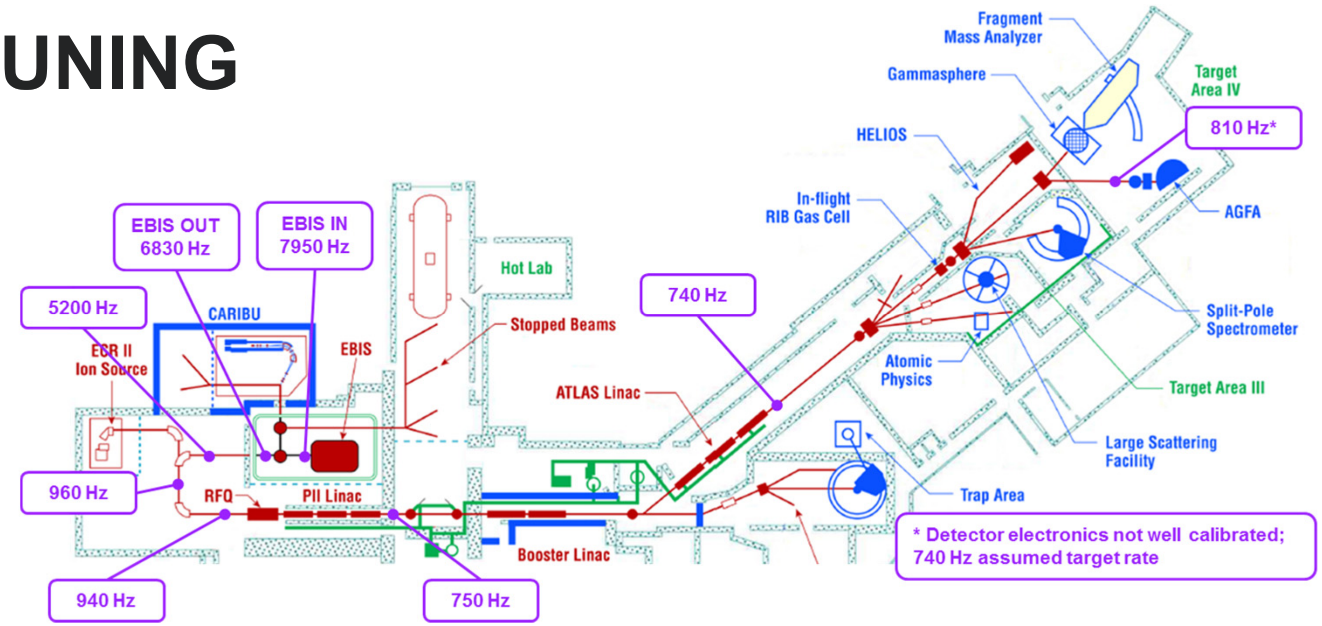


RIB TUNING



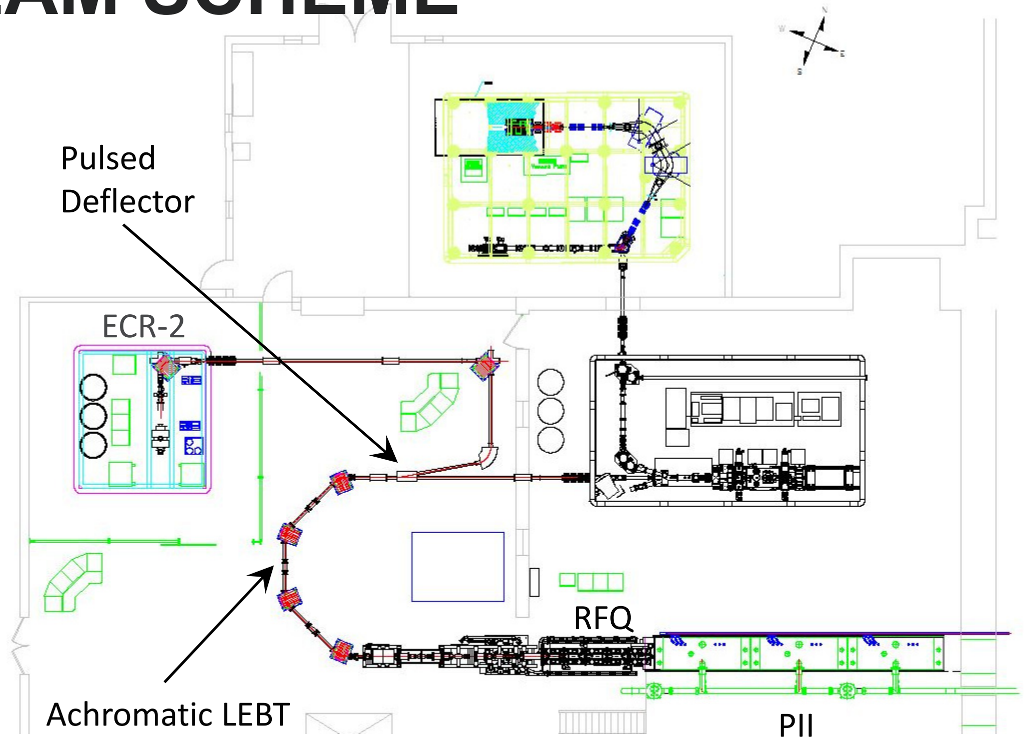
- Tune machine with stable pilot beam of $^{133}Cs^{26+}$
- Pilot beam measured on faraday cups
  - Typically 30-50 epA
- Stop Cs^{+} beam and inject low charge state RIB into EBIS
- Scale entire machine over to RIB of interest
- Beta rates measured with silicon barrier detectors with aluminum cover foils

RIB TUNING



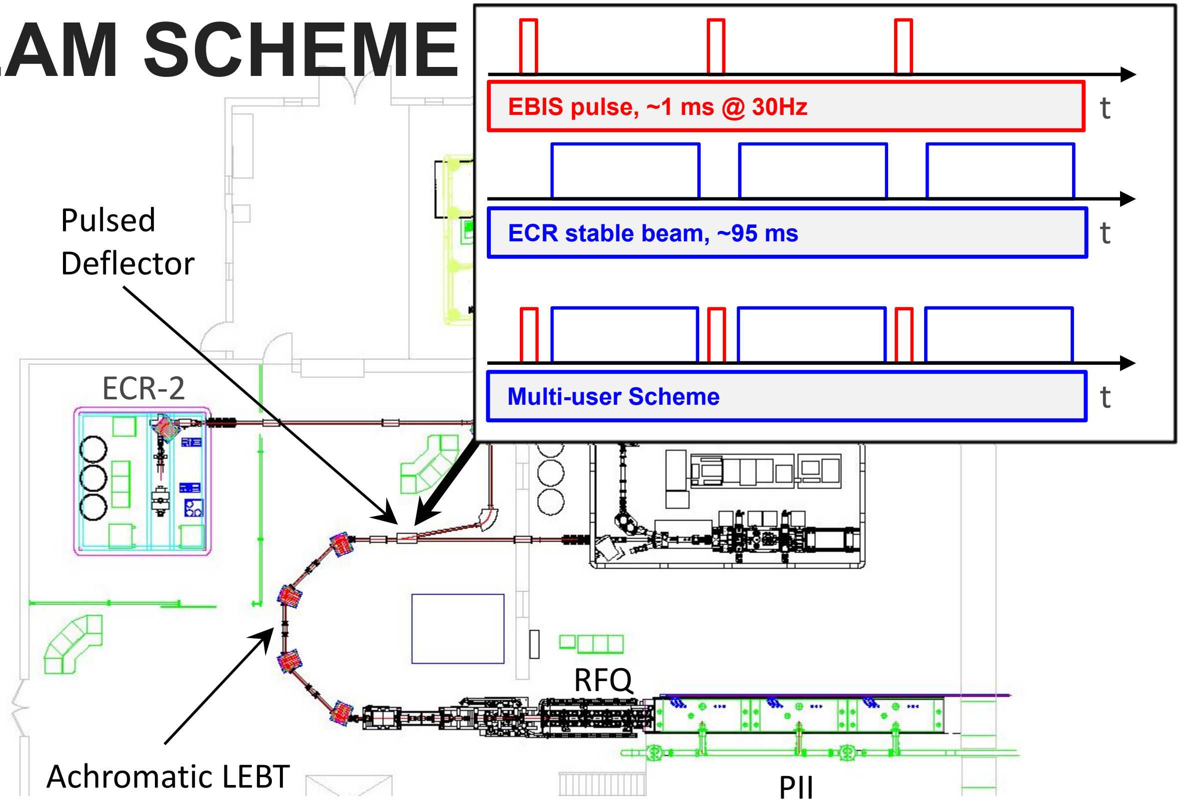
- Stable pilot beam of $^{133}Cs^{26+}$ with transmission of 73%
- Transmission with $^{150}Ce/Pr^{29+}$ was 77%
- EBIS IN-to-target efficiency: 740/7950 = 9.3%

MULTI-BEAM SCHEME



- The simultaneous acceleration of two beam species
  - One stable from the ECR and one radioactive from CARIBU-EBIS
  - A/q required to be within 1% of each other

MULTI-BEAM SCHEME



- The simultaneous acceleration of two beam species
  - One stable from the ECR and one radioactive from CARIBU-EBIS
  - A/q required to be within 1% of each other

ACKNOWLEDGEMENTS

This is the work of many people…

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