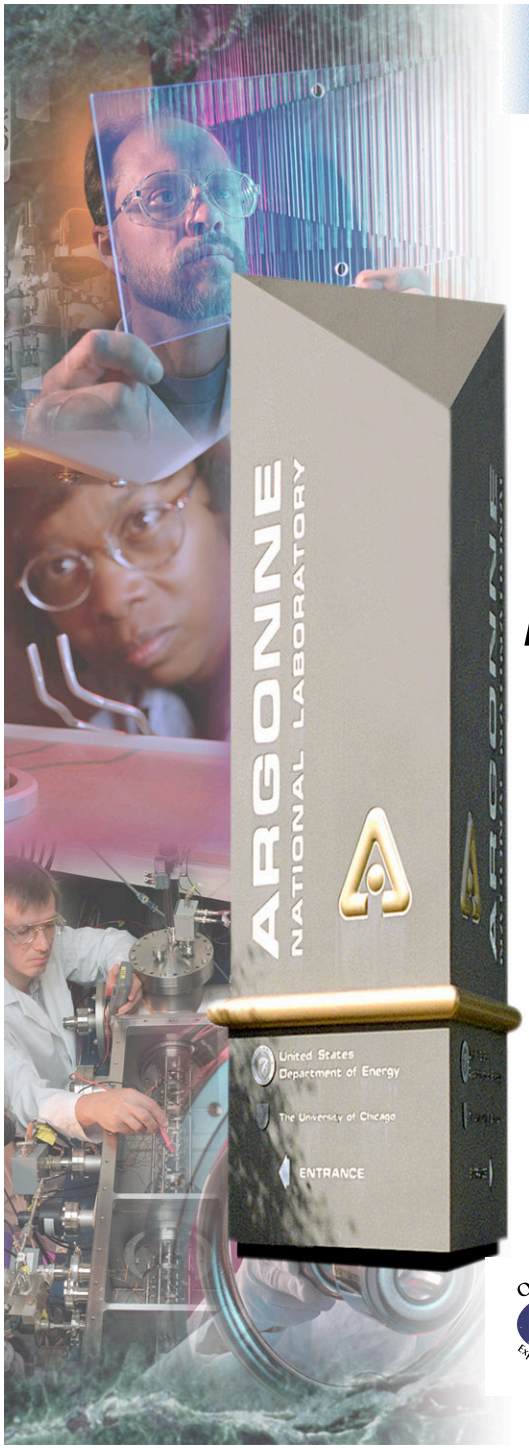

CARIBU - Radioactive Beams from ^{252}Cf fission

using a Gas Catcher and an ECR Charge Breeder at ATLAS

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For the CARIBU Team

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Argonne National Laboratory & The University of Chicago

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

Argonne National Laboratory is managed by The University of Chicago for the U.S. Department of Energy

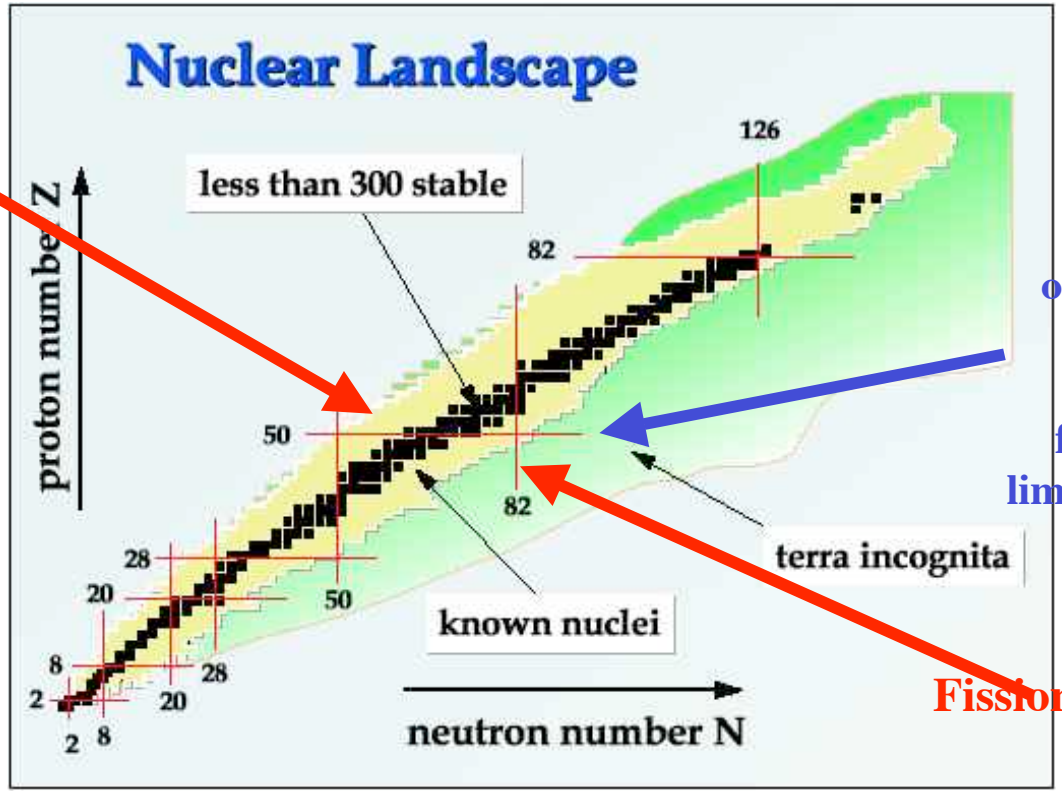
Outline

CARIBU - CAlifornium Rare Ion Beam Upgrade

- **Scientific Justification**
  - Nuclear structure
  - Nuclear astrophysics
- **Why is ^{252}Cf fission interesting?**
- **Project Description**
  - Technical approach
    - *Gas catcher*
    - *ECR Charge-breeder*
    - *Beam purity issues*
    - *Radiological issues*
  - Cost, Manpower, Schedule
- **Status**

Low-energy nuclear physics … big picture

Fusion-evaporation & fragmentation



If changes are to occur, they will take place here. Most existing facilities have very limited capabilities here.

Fission + Fragmentation

n-rich region is the next frontier

Important physics questions

I. **modification of nuclear structure in neutron rich systems**
   - *shell-structure quenching*
   - *single particle structure near n-rich magic nuclei*
   - *pairing interaction in weakly bound systems*

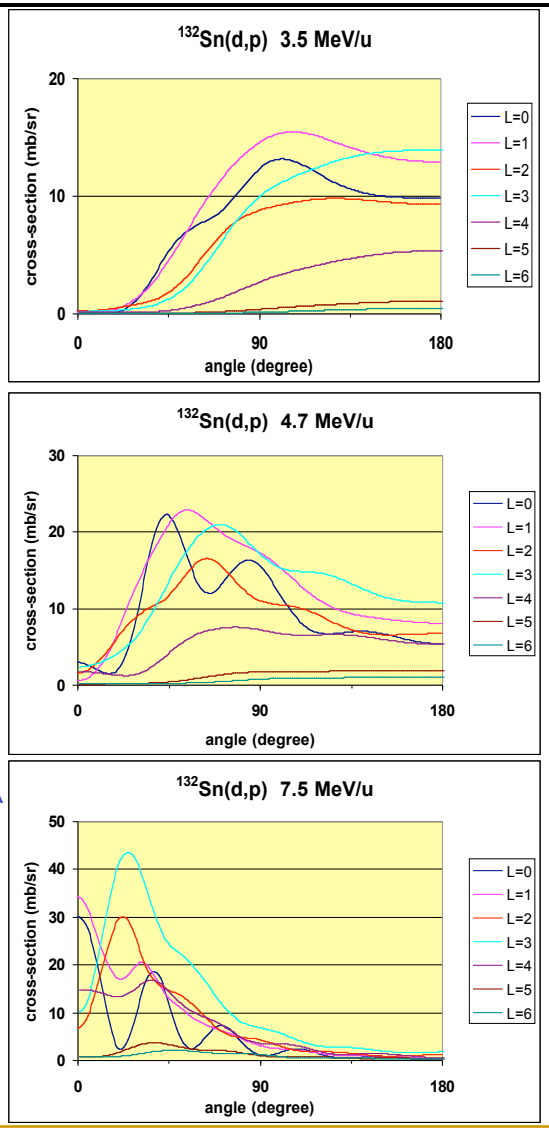
II. **collective behavior in neutron-rich systems**

III. **r-process path**
   - *ground-state information*
     - mass
     - lifetime
     - beta-delayed neutron branching ratio
   - *neutron capture rate*
   - *fissionability of very heavy n-rich isotopes*

Nucleon transfer reaction … single particle state

- **Single particle/hole states around magic nuclei**
  - ^{132}Sn
  - ^{78}Ni
- **(d,p) reactions**
  - needs to be well above Coulomb barrier in both entrance and exit channels … i.e. about 7.5 MeV/u around ^{132}Sn
  - requires 10^4 per second to get information on angular distribution
- **(^{3}He, α), (α,t) reactions**
  - similar requirements

(d,p) reactions can also be important to determine (n,γ) rates close to r-process path.



Multinucleon transfer … pairing interaction

- **(p,t) and (t,p) reactions … 2-neutron pairing in weakly bound n-rich nuclei**
- **energy and strength of excited 0+ states (paired neutron particles/holes)**
- **Q-value and Coulomb barrier set required energy**
  - (t,p) reactions can be done with energies available at ATLAS, some (p,t) require on-going energy upgrade

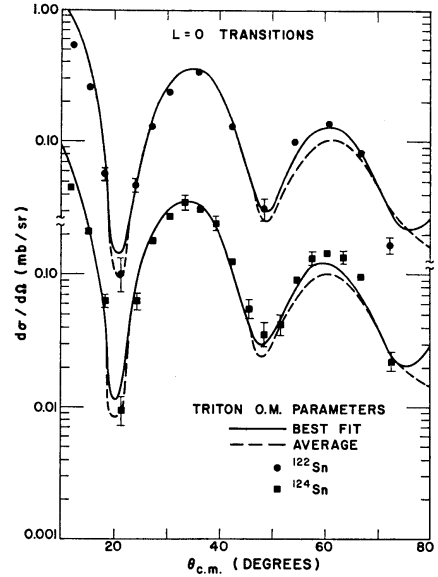
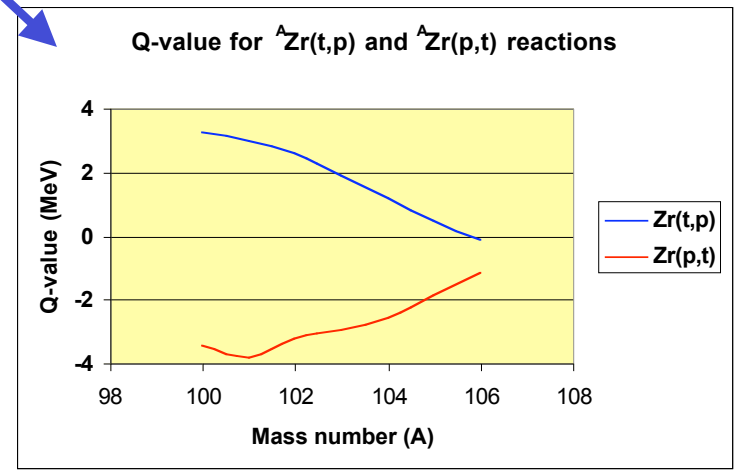


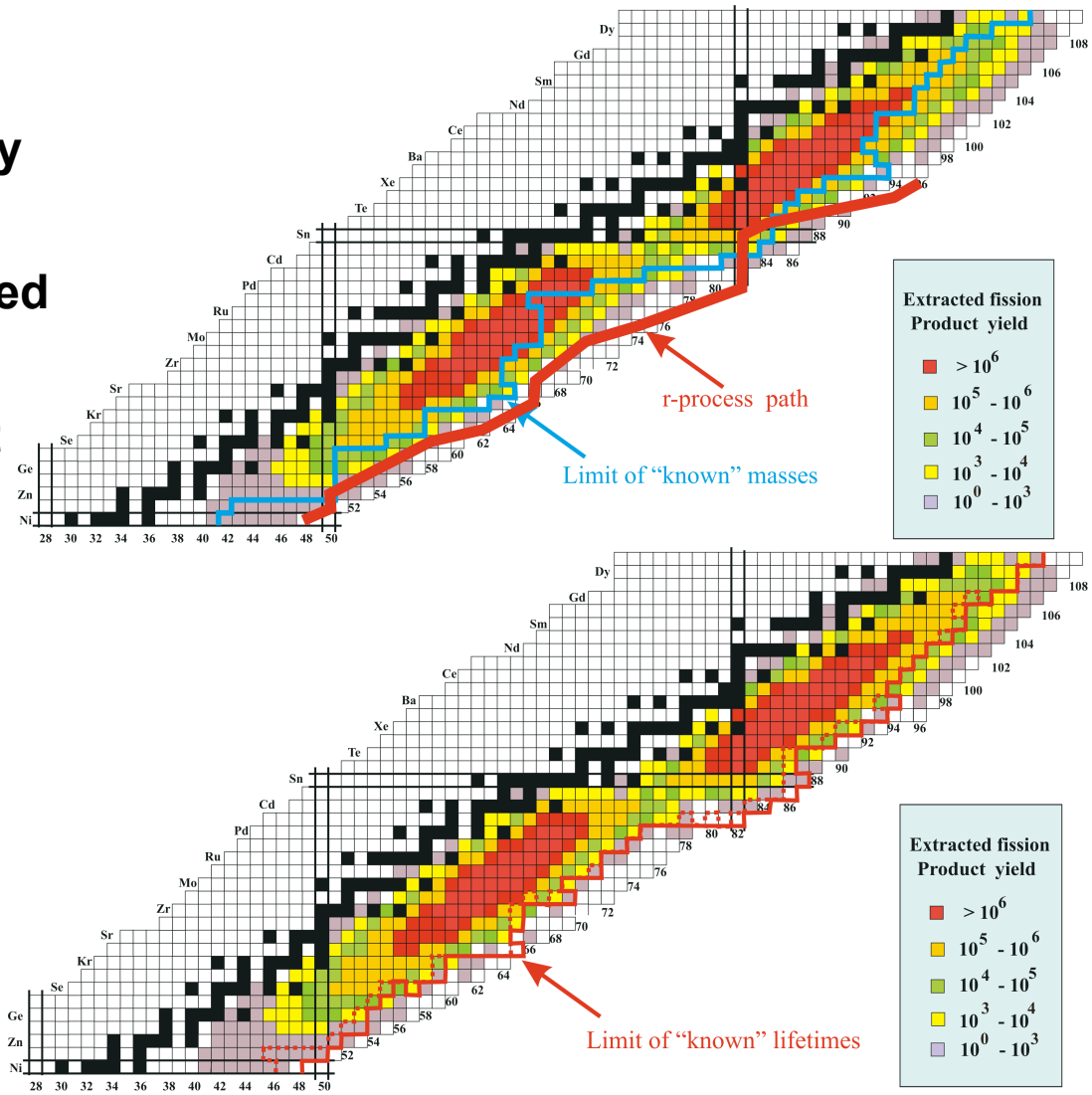
Fig. 1. $L = 0$ transitions. Distorted wave calculations are shown for two cases of optical-model potentials, the best fit parameters, and the average geometry parameters.

	Current ATLAS		ATLAS Upgrade	
	(MeV/u)	(MeV/u)	(MeV/u)	(MeV/u)
A	No Strip	Strip	No Strip	Strip
16	13.0	15.7	18.5	21.5
40	12.4	13.4	17.5	19.9
58	9.9	11.8	13.5	17.9
78	9.5	11.2	12.8	16.7
132	8.0	9.3	10.4	13.4
197	6.6	7.9	8.4	10.9
238	6.4	7.4	7.9	10.0



Ground state properties close to r-process path

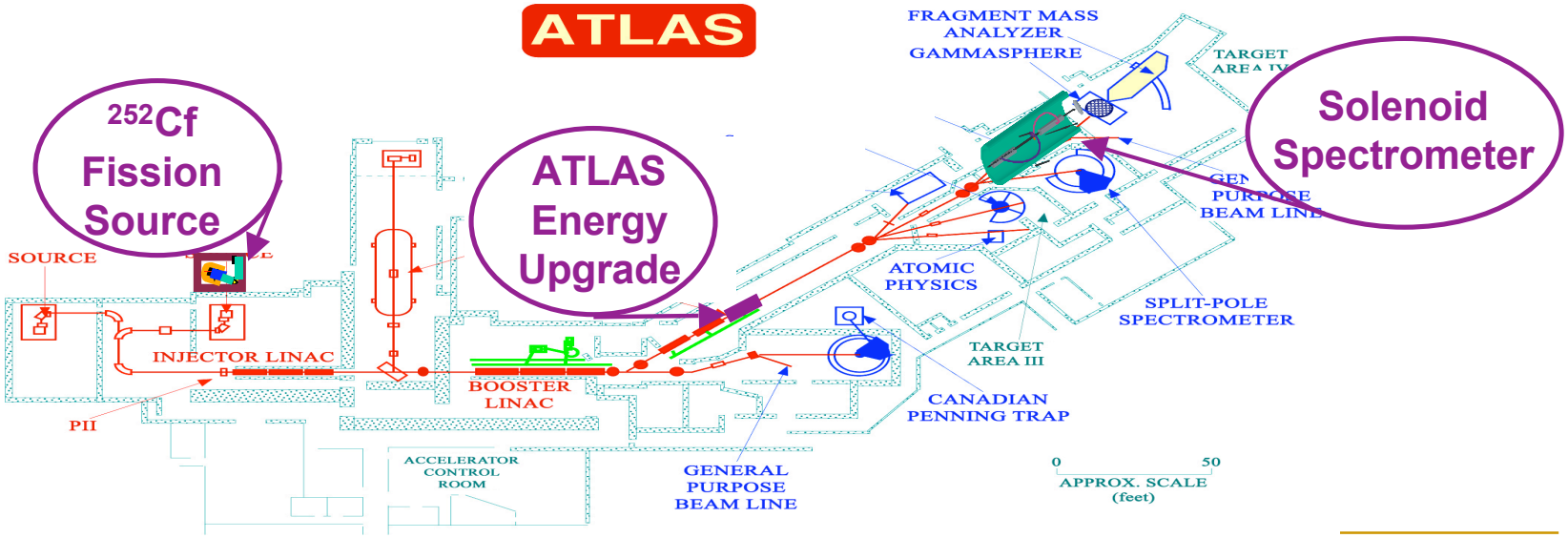
- r-process path determined by nuclear masses
- r-process evolution dominated by nuclear lifetimes
- beta-delayed neutrons affect final isotope distribution
- very little information in the refractory element region around Mo, Zr, Tc, …
- need element independent technique to access these regions



CARIBU + Energy Upgrade+ Solenoid Spectrometer

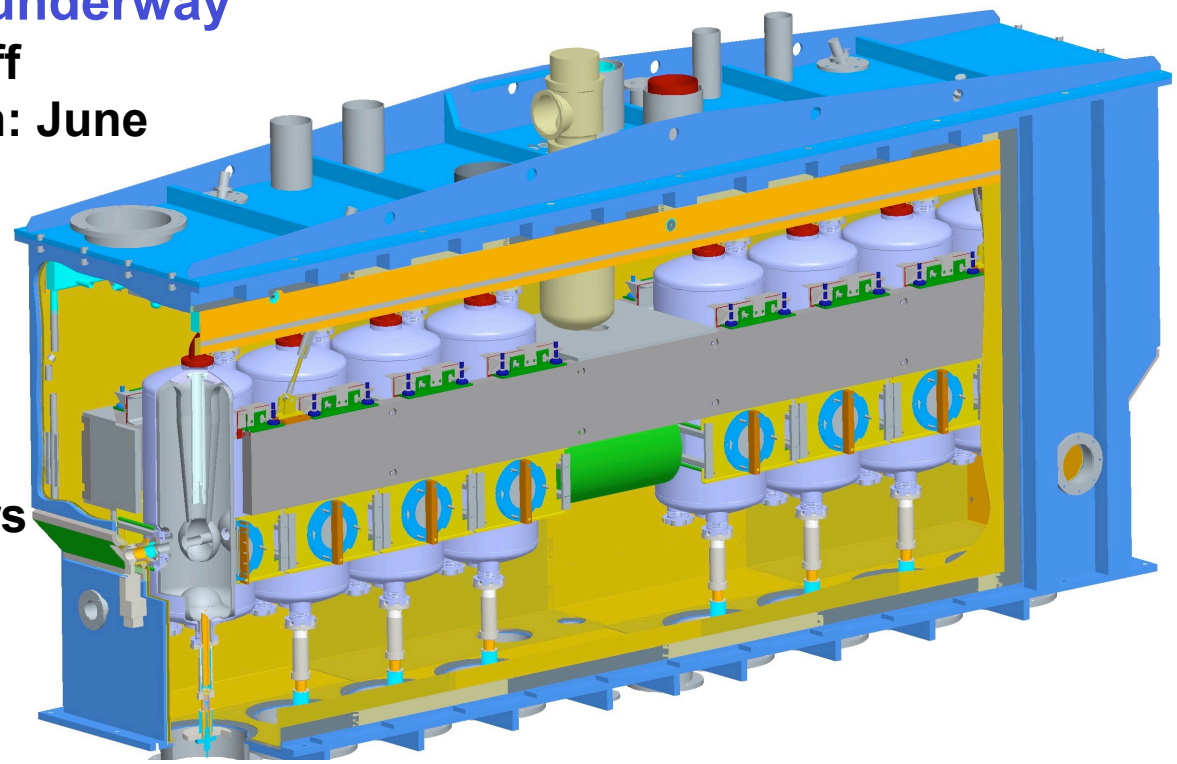
Unique Synergy

- Important physics planned using beams from the ^{252}Cf project need the new energy regime opened by Energy Upgrade Project.
- Solenoid Spectrometer will greatly expand the effectiveness of both the fission fragment beams at these higher energies.
- The three projects will combine to form a truly unique facility which complements the capabilities of other world facilities in the era leading to RIA.



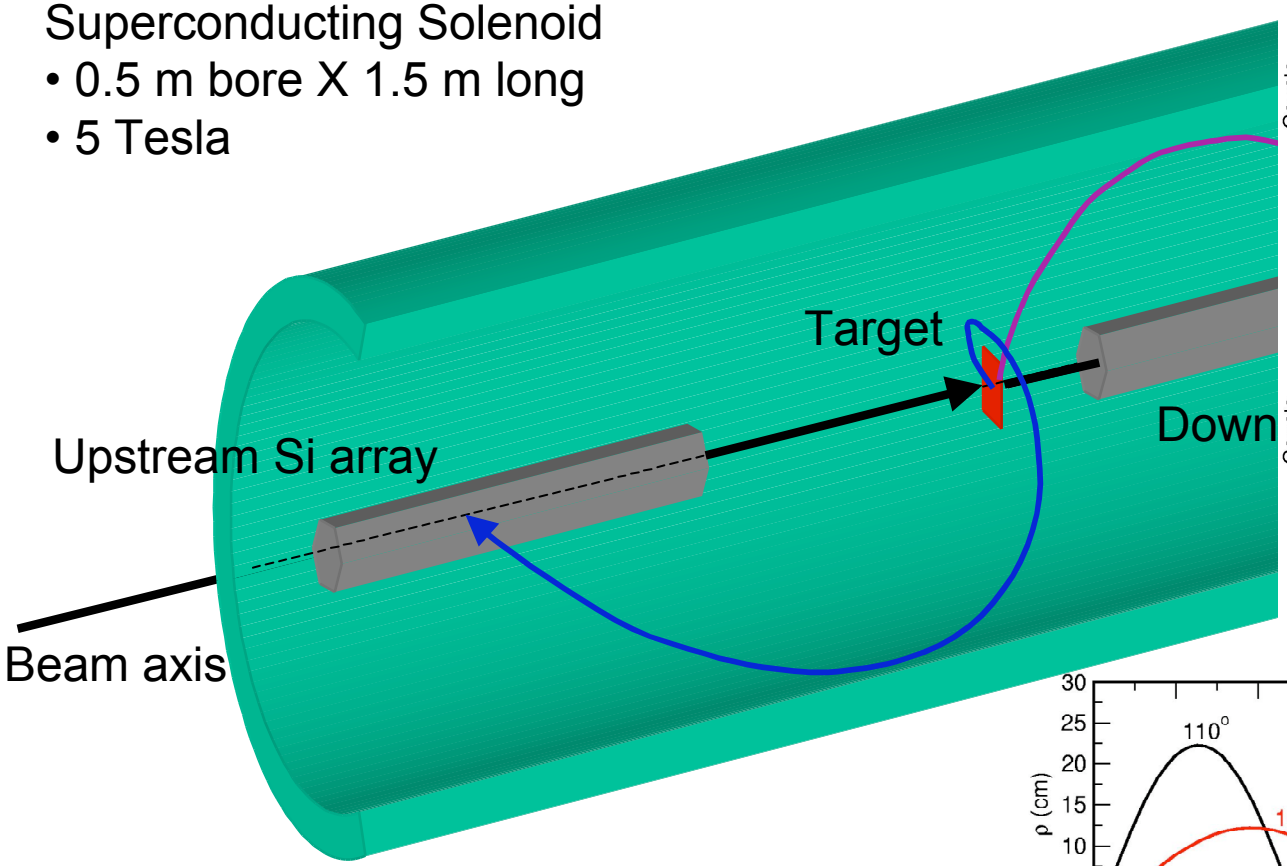
ATLAS Energy Upgrade Project

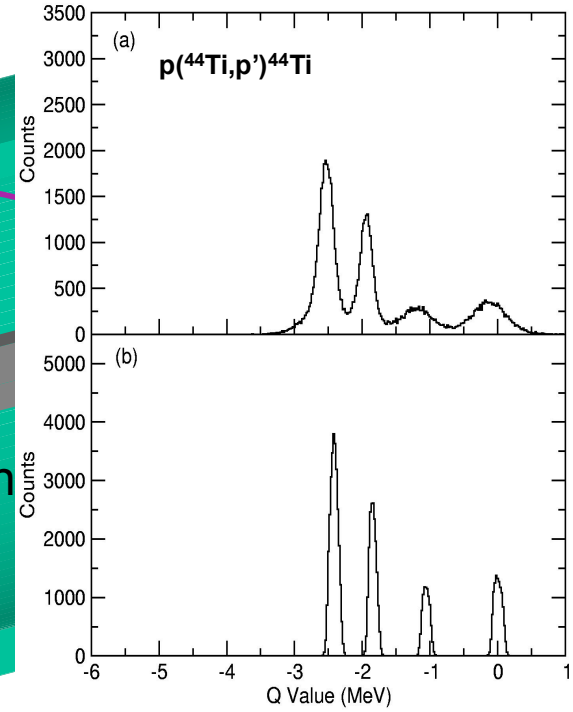
- **Cryostat component construction complete**
  - ✓ Design builds on PII cryostat design & is RIA prototype
  - ✓ New: Separate resonator & insulating vacuum
    - Cleaner resonator surfaces _ higher operating fields
- **Cryostat assembly is now underway**
  - ✓ Assembly by ATLAS staff
  - ✓Empty Cryostat cooldown: June
- **End of calendar 2005:**
  - ✓ Initial cooldown offline
  - ✓ 2-prototype resonators
  - ✓ RF tests
- **End of calendar 2006:**
  - ✓ Final 6 new _/4 resonators complete and online
  - ✓ First beam acceleration

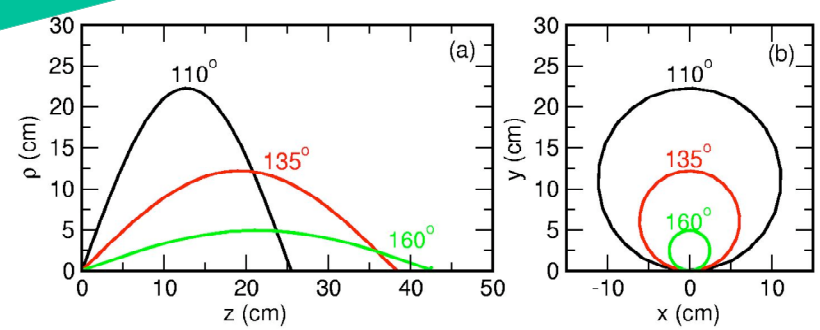


Solenoid Spectrometer Schematic design

Superconducting Solenoid
- 0.5 m bore X 1.5 m long
- 5 Tesla

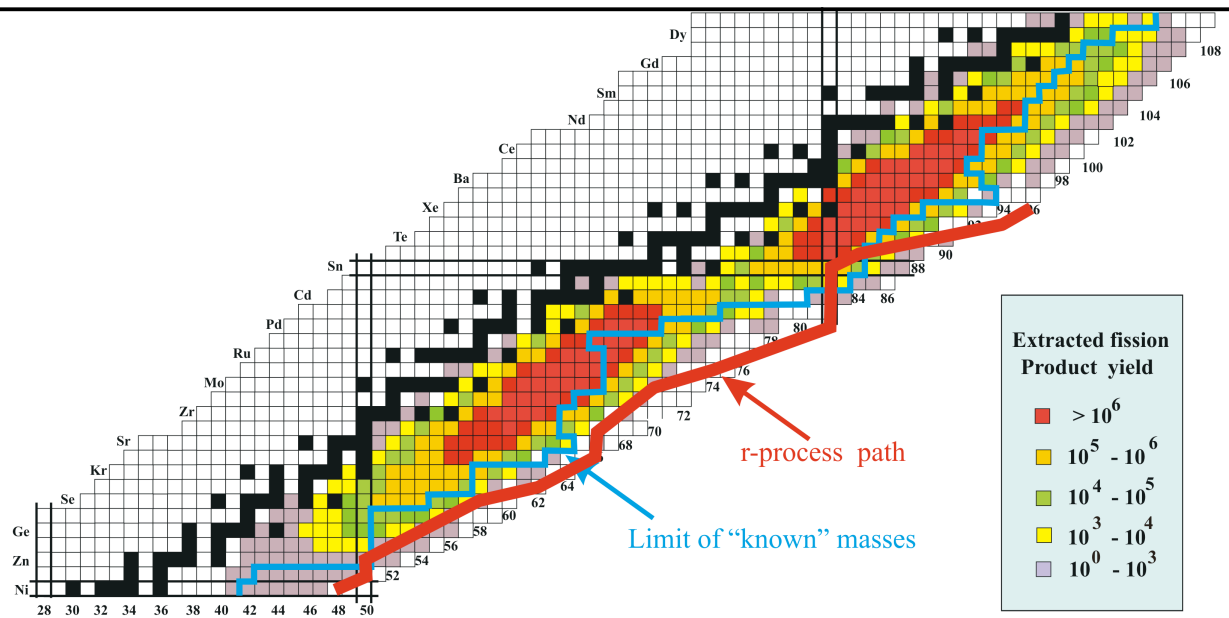




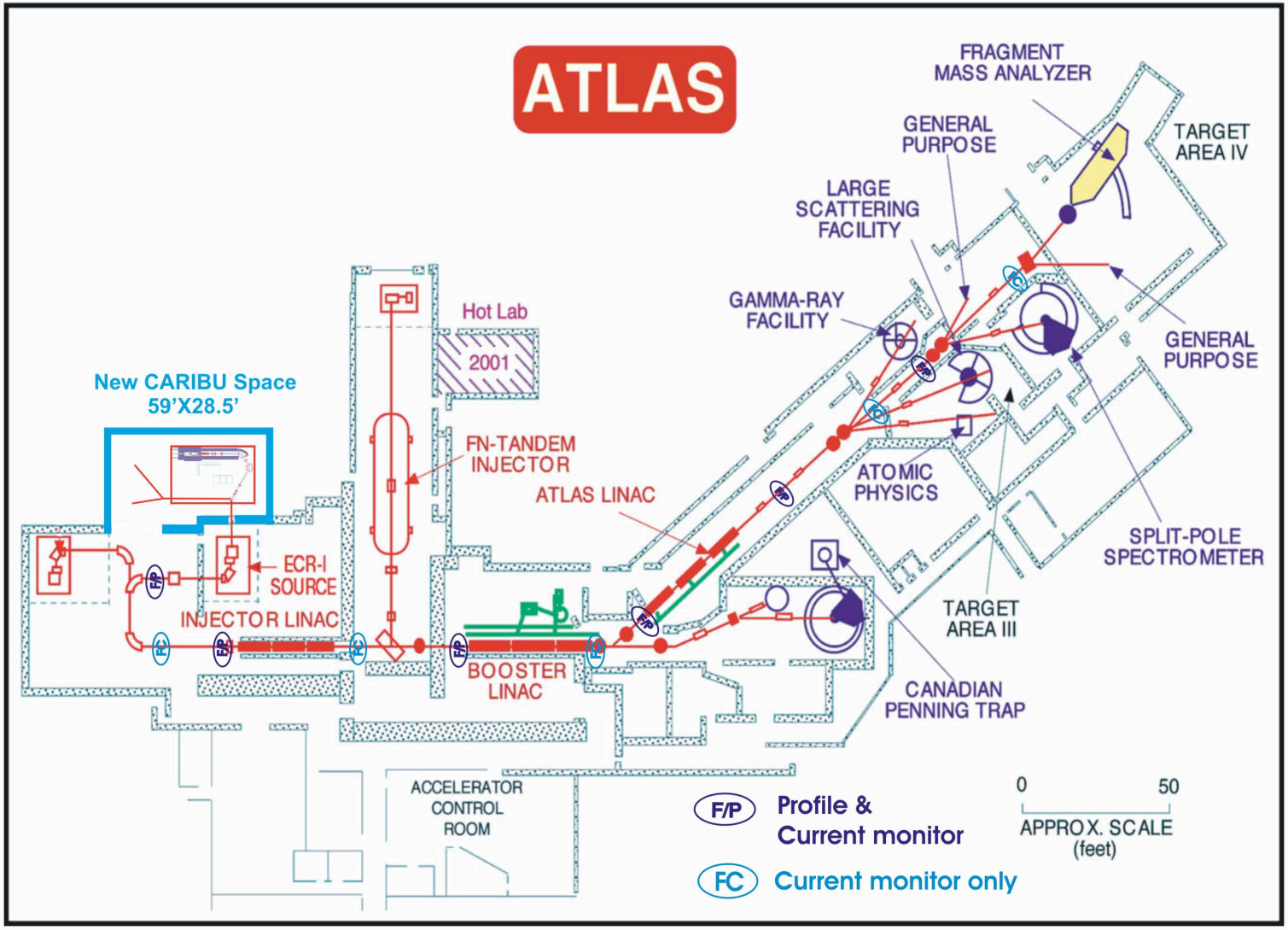


^{252}Cf Fission Source Project for ATLAS

- 1 Ci ^{252}Cf fission source + gas catcher/RF cooler
- Injects ECR-I modified to a 'charge breeder'
- Yields from source of up to 10^7 ions/s
- On-target, accelerated beam, rates of ≤ 5×10^5 ions/s
- Builds on extensive ATLAS weak beam experience
- Technology and experience useful for RIA



Planned layout for ^{252}Cf fission source system



Floor plan ^{252}Cf fission source system

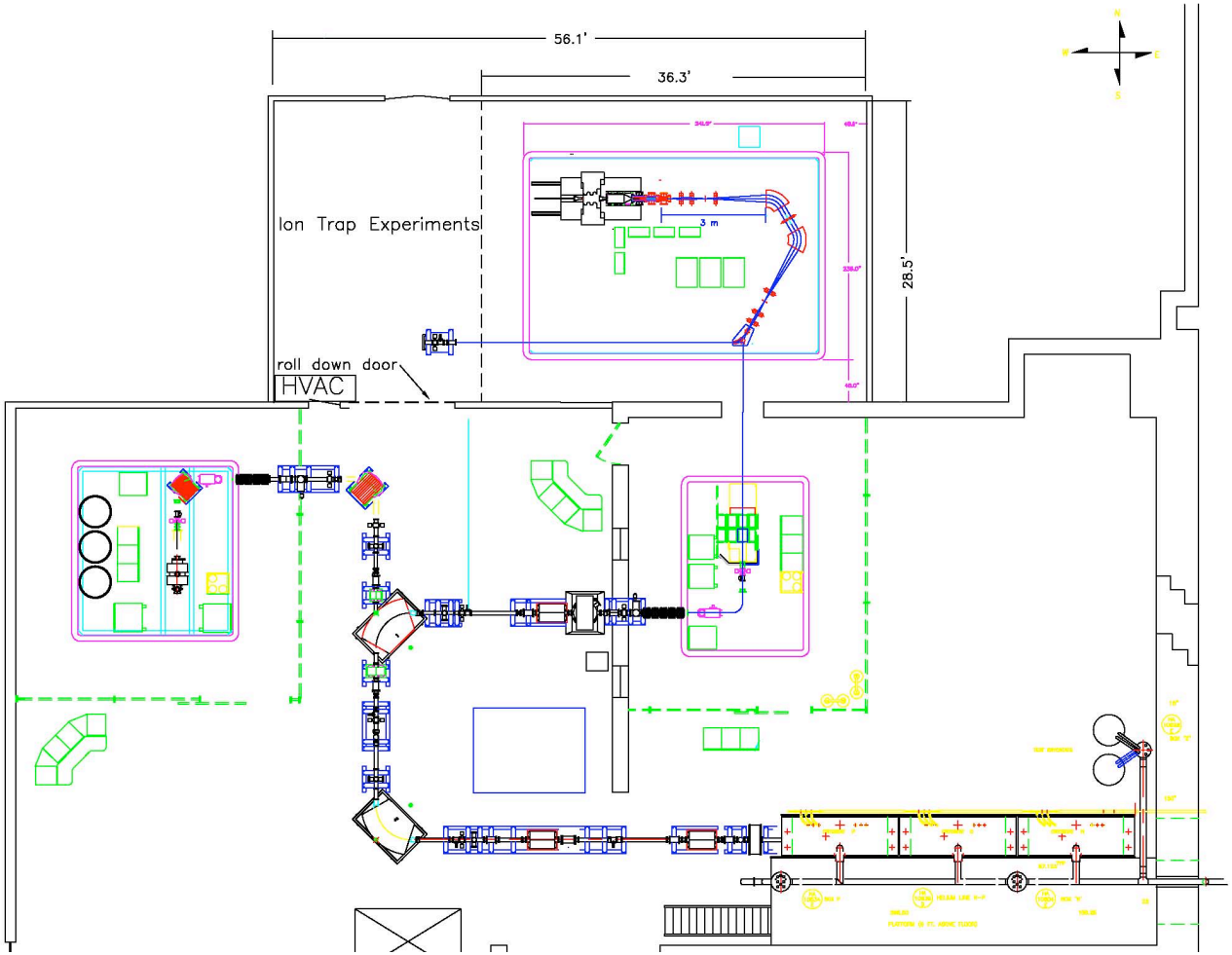
New ~1600 ft^2 building

Isolation of source and other high-activity components

Building is a separate project with separate funding:

CARIBU contribution will provide
Facility Space Enhancements:

- **2-ton Crane**
- **beamline hole in wall**
- **HEPA exhaust system for room and pumps**
- **Isolation door**
- **Utilities for CARIBU & Experiments**

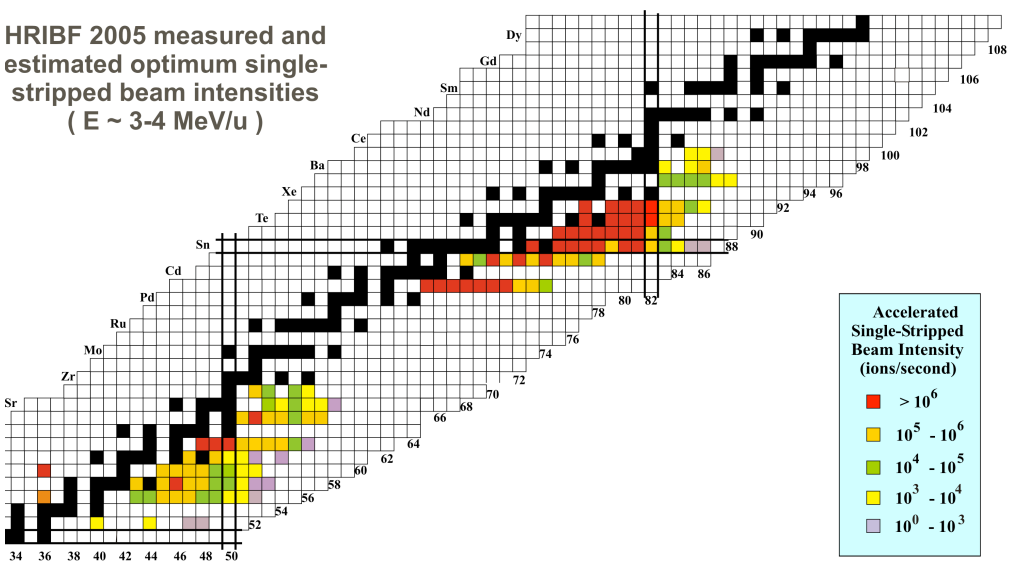


A Californium Fission Source for ATLAS

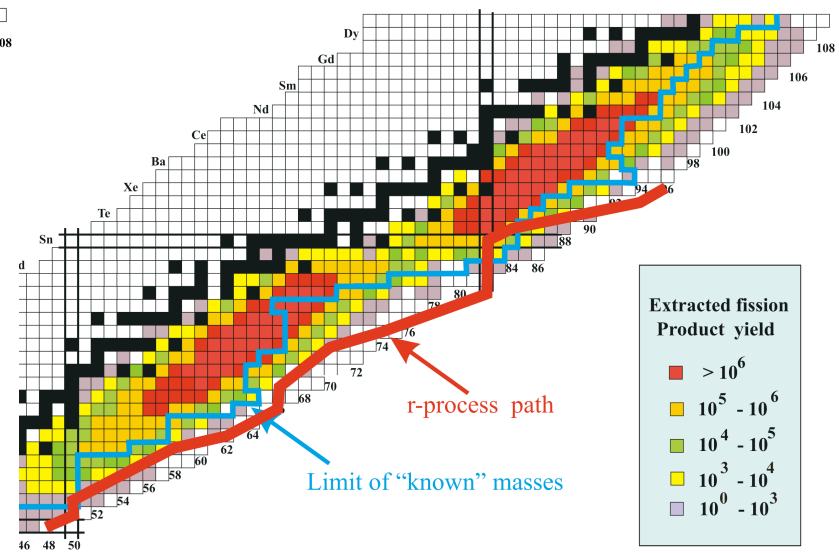
- ^{252}Cf fission yield is complementary to uranium fission
- Provides access to unique, important areas of the N/Z plane
- Significant yield extends into r-process region
- Available energy exceeds that from HRIBF and ISAC

HRIBF yields from ^{238}U

HRIBF 2005 measured and estimated optimum single-stripped beam intensities (E ~ 3-4 MeV/u)



^{252}Cf spontaneous fission yield



Californium source characteristics

- **Use of a 1 Ci source of ^{252}Cf is proposed for CARIBU.**
- **^{252}Cf is produced at the High Flux Reactor at Oak Ridge and sources are available in various forms. The most sturdy open source form is electroplated on a metal disk. Such sources are in use at ATLAS.**
- **Transport of the source from Oak Ridge in a readily available certified cask limits the size of the source to less than 10 cm.**
- **To minimize the possibility of flaking, the thickness of the deposit is kept to a practical minimum. A half mm thick, 8 cm diameter tantalum disk is planned as the backing support.**
- **^{252}Cf has a fairly short lifetime of 2.645 yrs so that source thickness is small**
  - *1 Ci of ^{252}Cf is 1.9 mg; over an 8 cm diameter area this yields a density of 38 μg/cm^2*

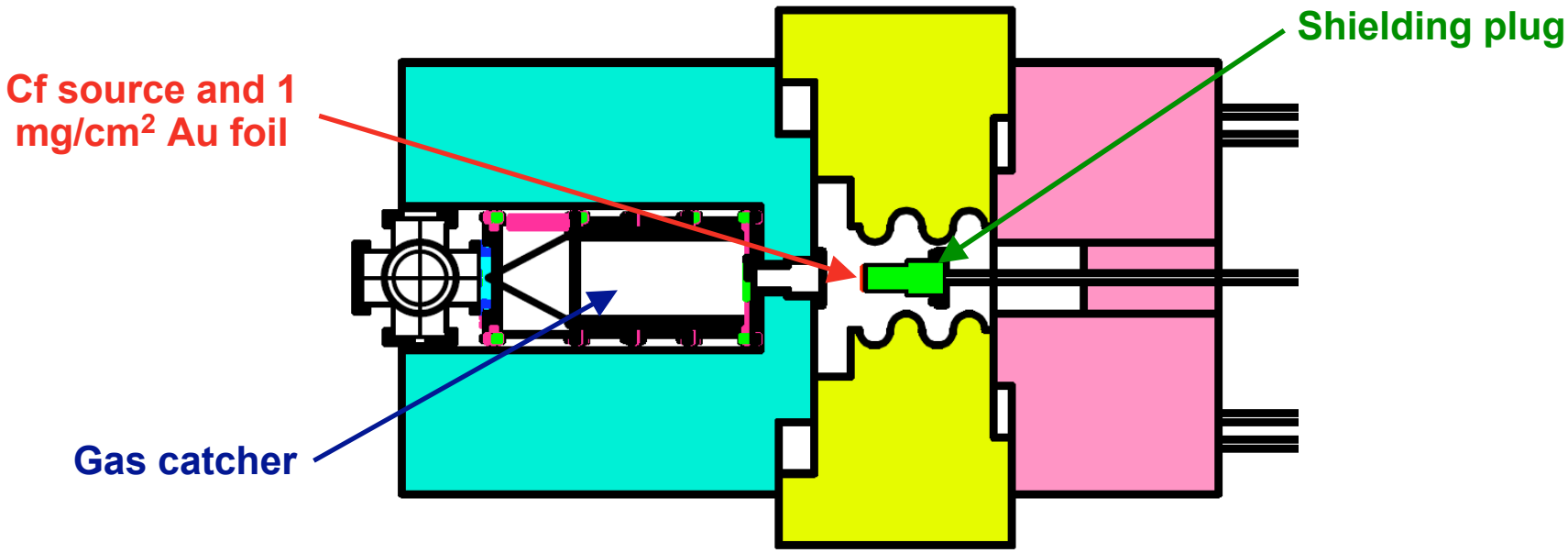
Energy loss in the source is negligible.

Handling activity: ^{252}Cf Ion Source Preparation

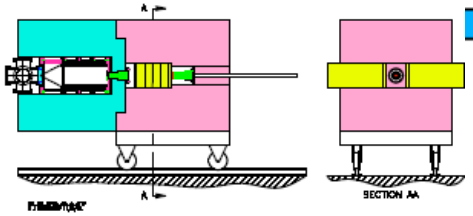
- **Source Handling at ANL**
  - Mounting of Source in Source Holder in Hot Cell
  - Transfer of Source Holder to Special Purpose Cask
  - On-Site Transport of Cask to ATLAS Accelerator
  - Elevation of Cask to High Voltage Platform
  - Opening of Cask and Mating of Source Holder with Gas Catcher using Metal Vacuum Seal

Californium source characteristics(2)

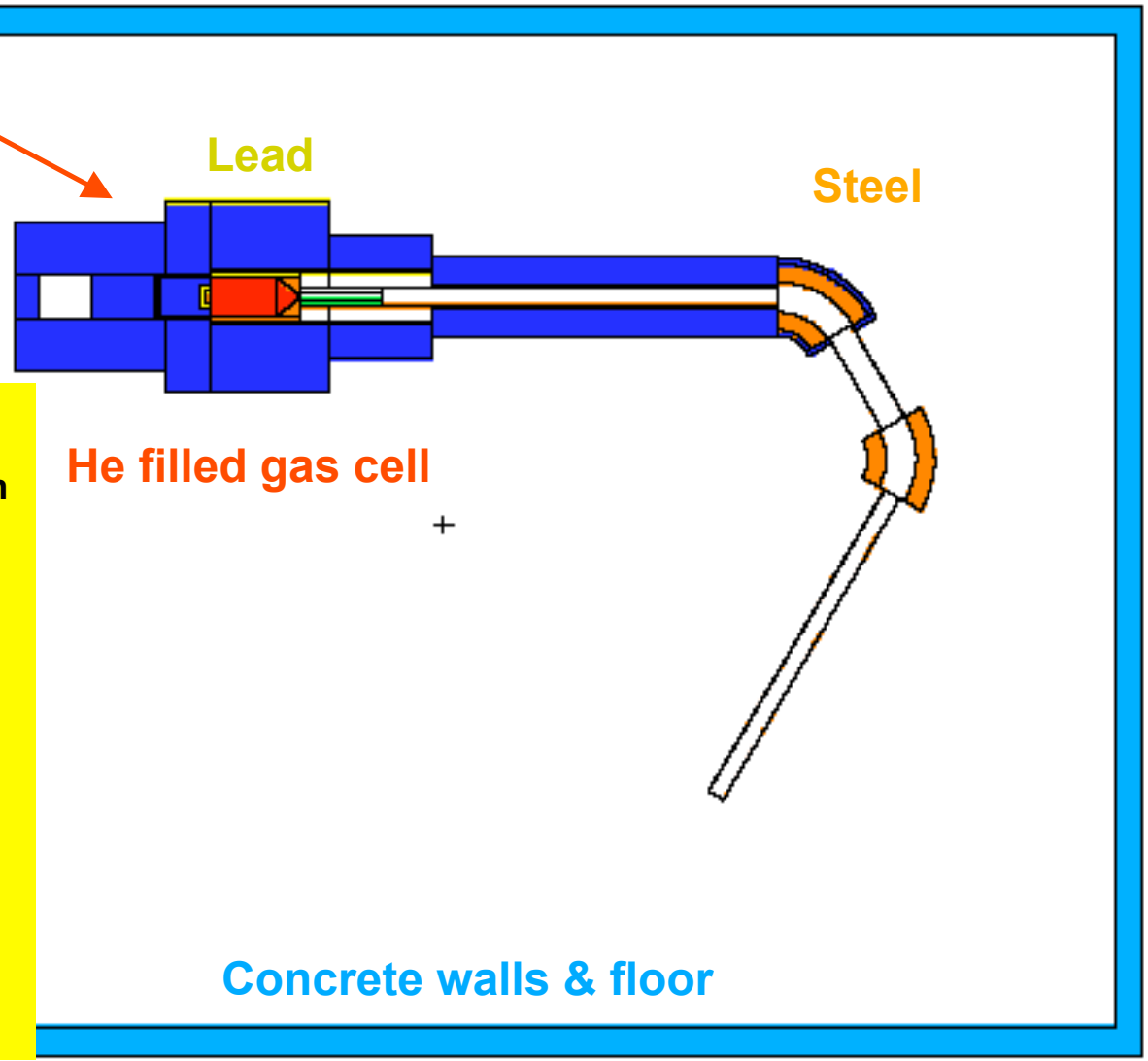
- For installation in the gas catcher, the source is installed on a shielding plug and covered by a 1 mg/cm^2 Au foil for protection (with a pumping hole for pressure equilibration) and containment of the fissionable material in case of flaking.
- The assembly is sealed to the gas catcher, the source being inside the gas catcher.



Shielding Geometry



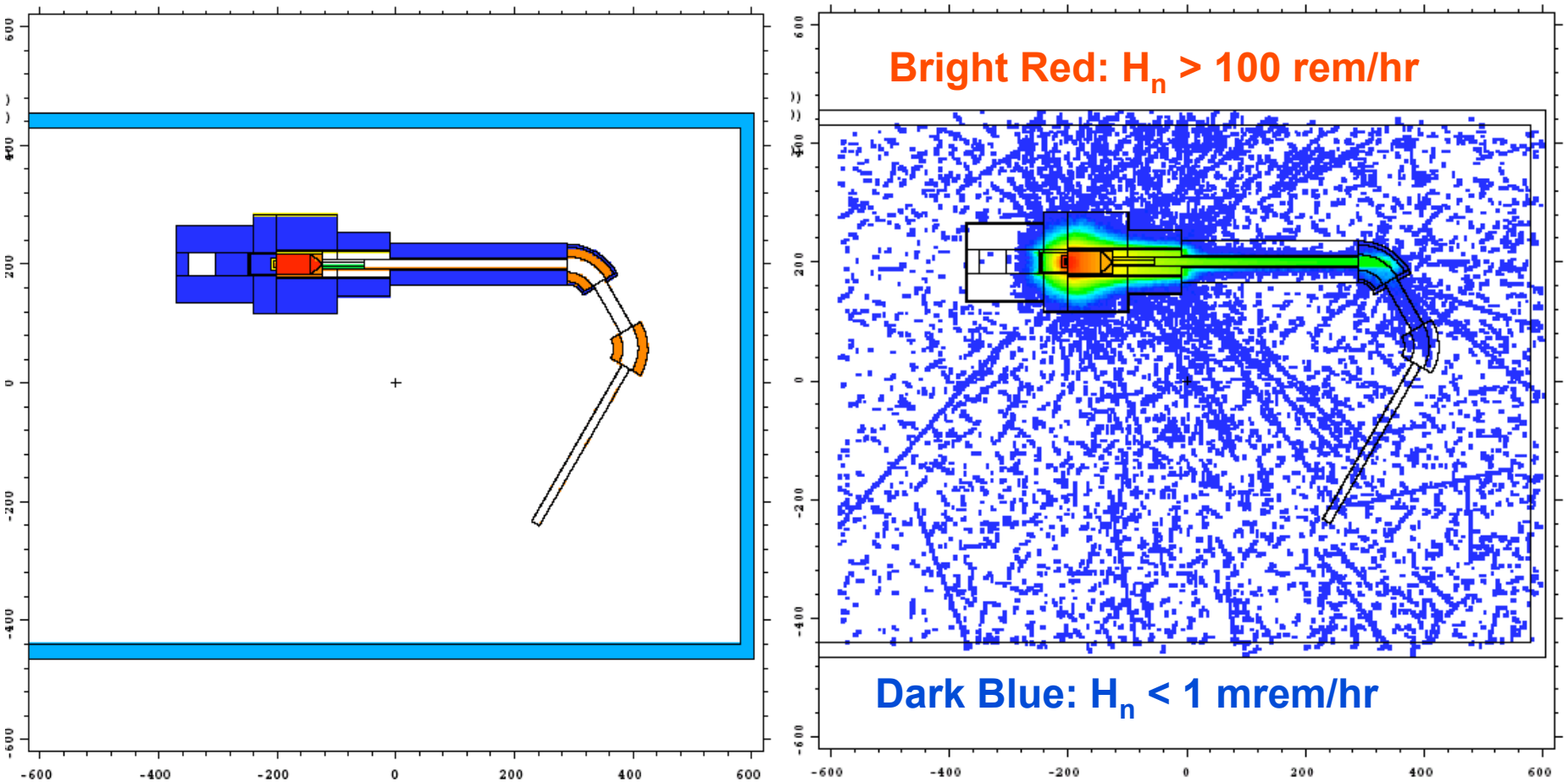
5% Borated Polyethylene (BPE)



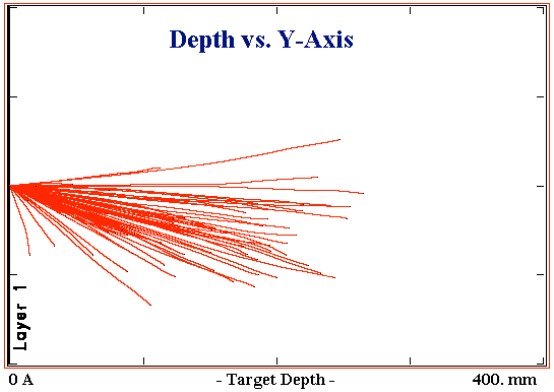
- Shielding Design Goals
  - Less than 1 mrem/hr at 30 cm
  - Fully shielded even during source installation
  - Remote operation of shielding and source movement during installation
- Shield requirements:
  - ~0.75 m, mostly polyethylene for neutrons
  - Additional 5 cm. lead shielding for γ-rays

Neutron Dose Rate Calculated with MCNPX

60 cm Borated Polyethylene around cell, 30 cm around pipe + 5cm lead and steel for γ-rays

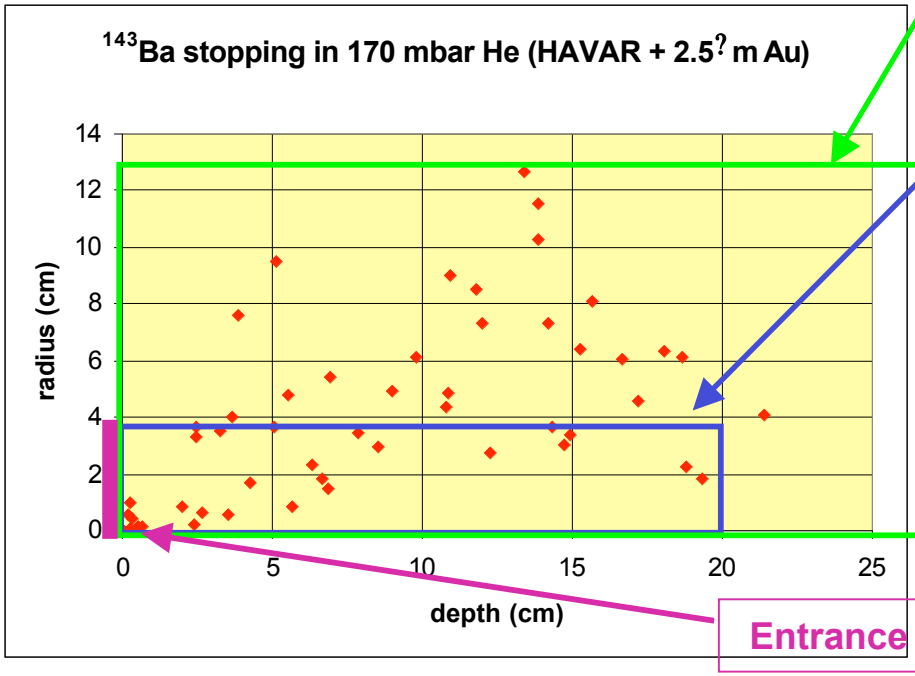


Stopping of fission fragments in gas catchers



RIA-type gas catcher

- 25-30 cm inside diameter
- ~60 cm total length
- Pressure 150-200 mbar for final thermalization.

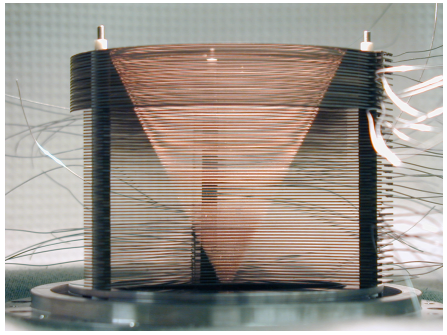


CPT gas catcher

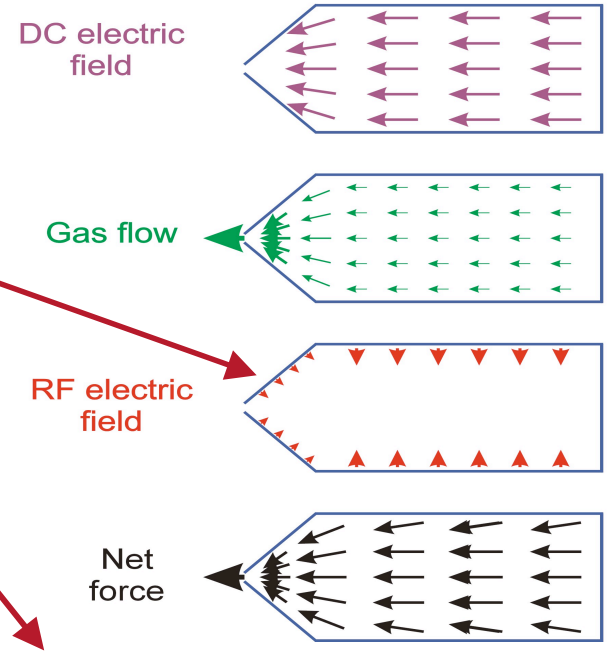
Entrance degrader foil slows ions

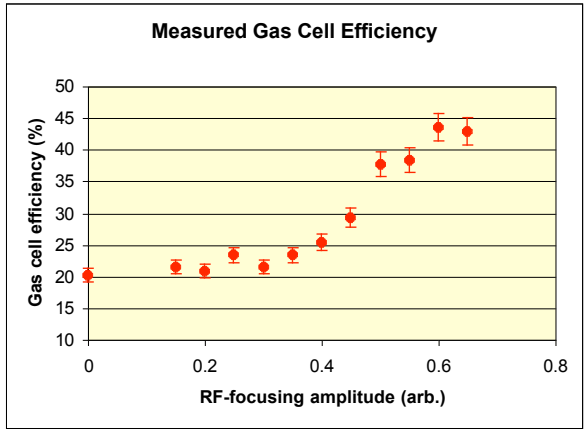
Gas catcher developed at the Canadian Penning Trap (CPT) at ATLAS

- 20 cm long gas cell with second generation RF cone



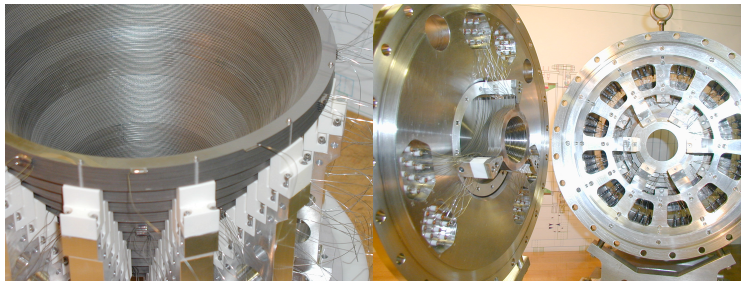
- ε ~ 45%
- mean delay time below 10 ms
- demonstrated off-line with fission products and on-line with fusion–evaporation reactions
- years of operating experience accumulated





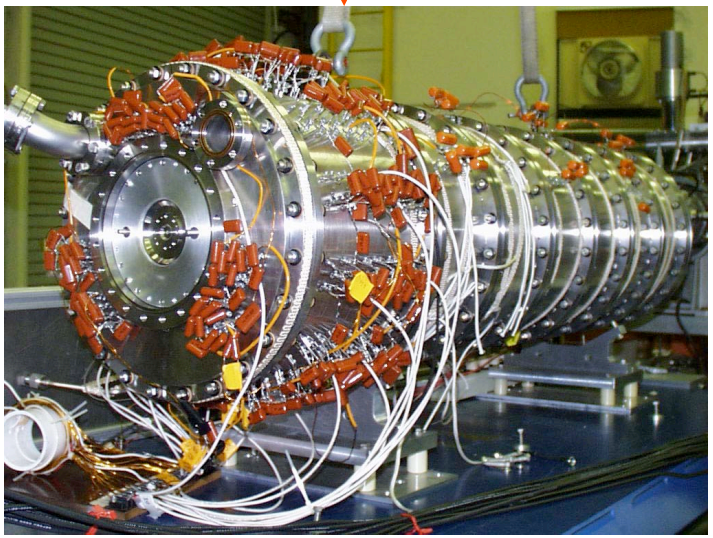
Large fission fragment gas catcher

- **Shortened version of RIA gas catcher can efficiently stop fission products from a fission source.**
  - **~ 50% stopped in gas for backed source**
- **About 45% of those can be extracted as charged ions.**
- **Very efficient and fast source, provides cooled bunched beams for post-acceleration.**
- **Production peaks in new regions and extraction is element independent … new isotopes available**



Gas catcher technology developed, tested and now routinely used at ATLAS for CPT.

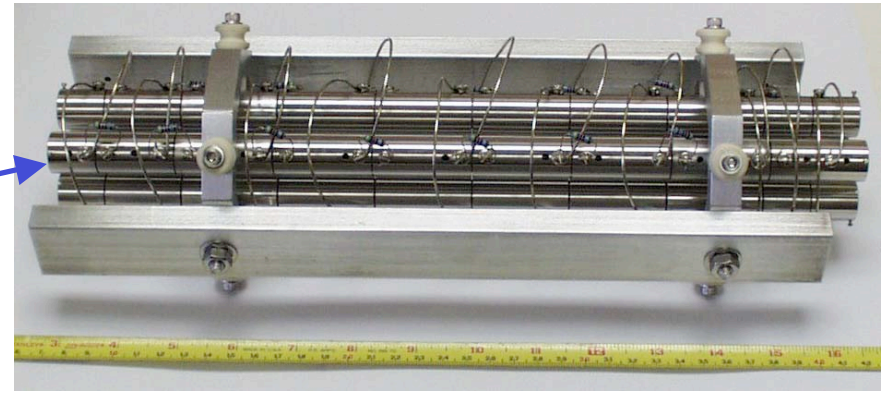
GC for RIA built and in tests at GSI.



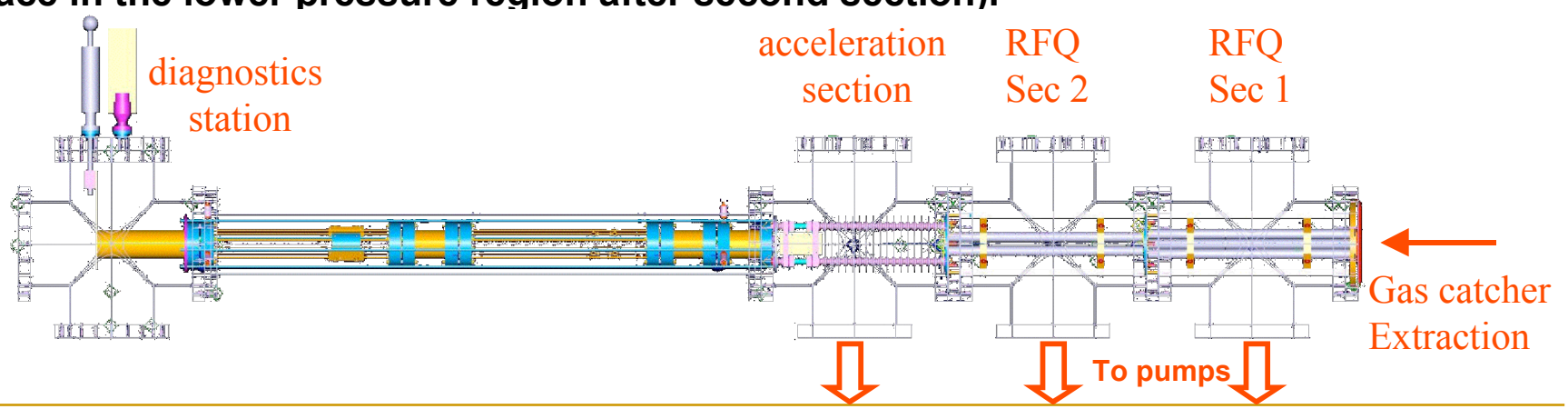
Extraction in the presence of large gas flow

Transport ions to lower pressure region via open structures that guide ions while letting the gas escape and be pumped away.

Section of segmented RFQ for ion transport and differential pumping

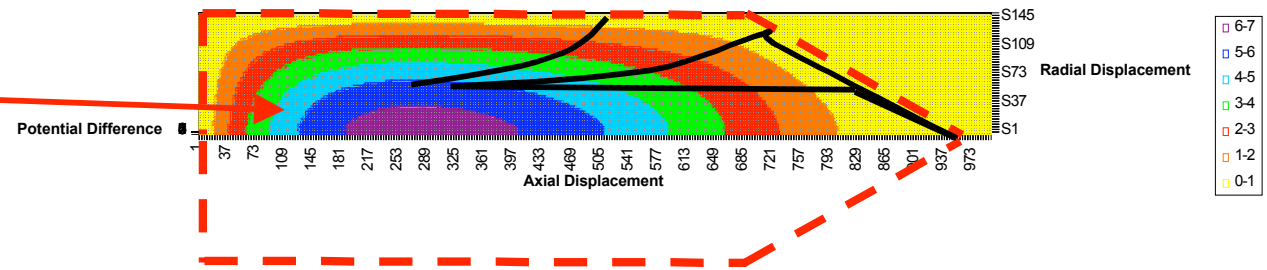


In DC mode, a limiting emittance (corresponding to roughly the gas temperature) is obtained after two such sections separated by small apertures (acceleration takes place in the lower pressure region after second section).



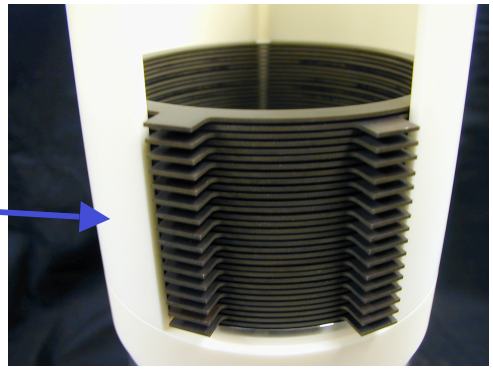
Dealing with high space charge density

Potential from space charge



Ions are lost radially, can be corrected by:

- **Larger DC field**
- **RF focusing on gas catcher body, not just cone**
- **Improved gas purity**



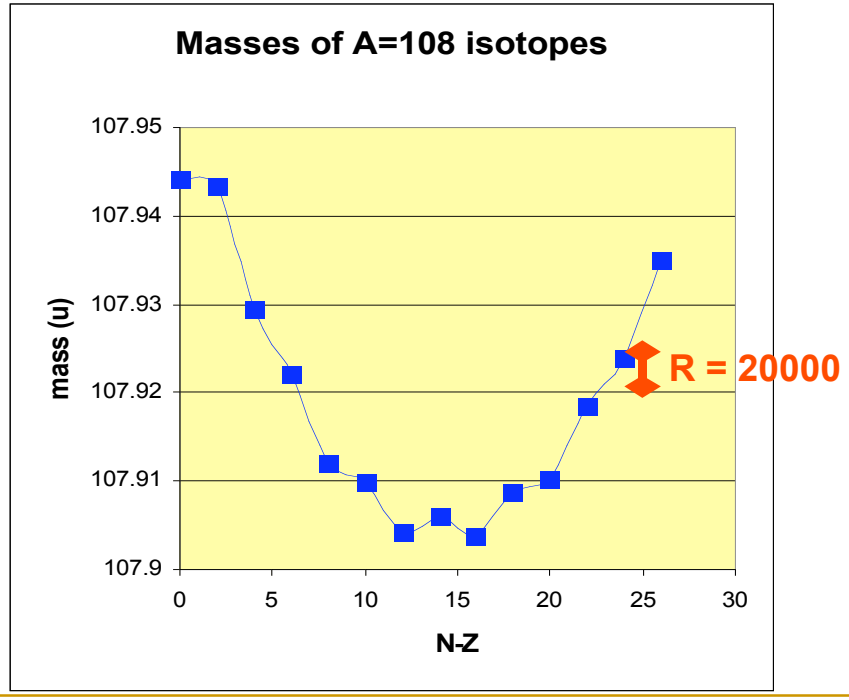
This approach can handle the space charge from:

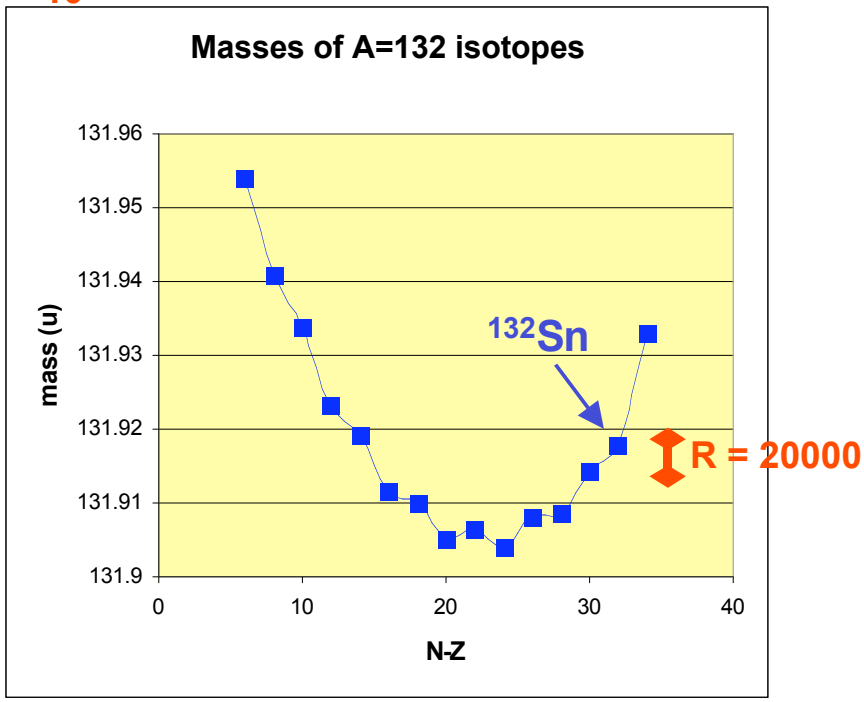
- **the 50 millions Cs ions incident in the ~ 600 cm^3 volume of the CPT catcher (previous slide)**
- **the similar conditions from the roughly 1 billion fission fragments entering the ~ 30000 cm^3 volume of the gas catcher in the CARIBU application.**

Purification of radioactive ion beam

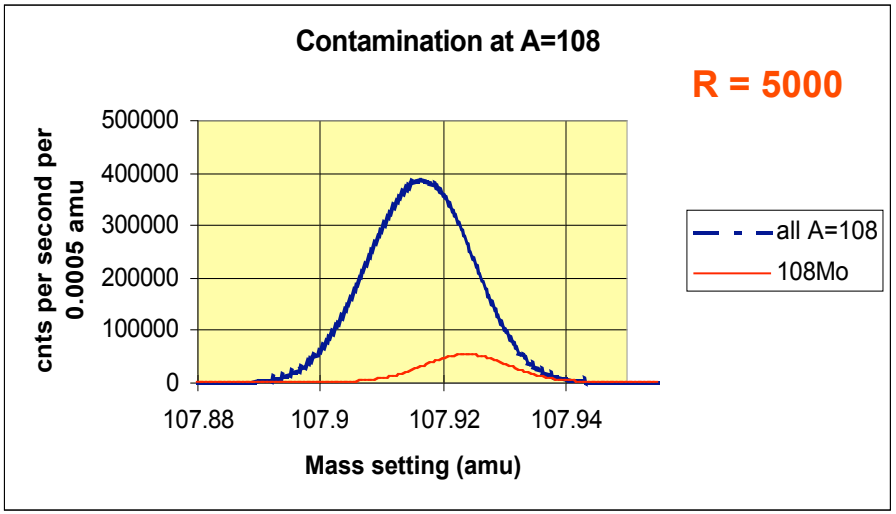
•Contaminant of neighboring masses are handled easily by most experiments. Same mass contaminants are more difficult. The resolution required to remove contamination is:

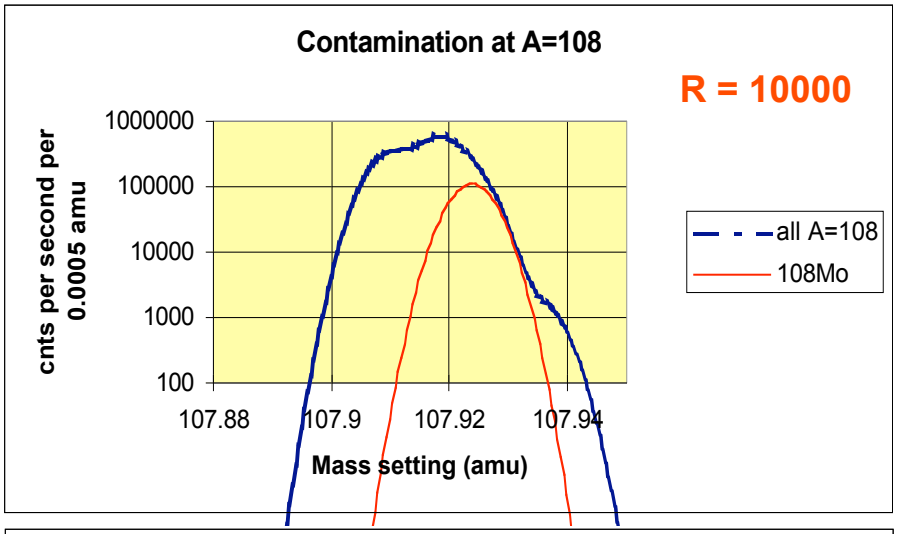
- neighboring masses — R = 250
- molecular ions — R = 500 - 1000
- isobars — R = 5000 – 50000 (far/close to stability)
- isomers — R = 10^5 - 10^6

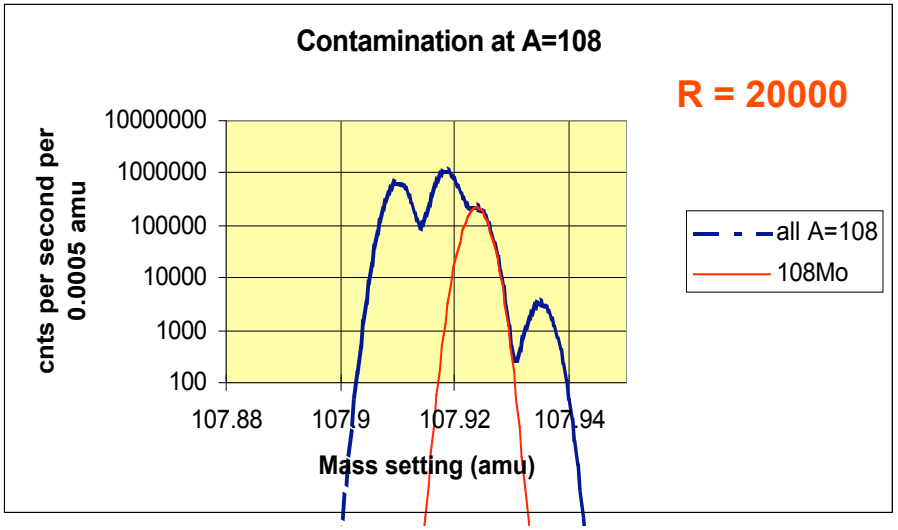


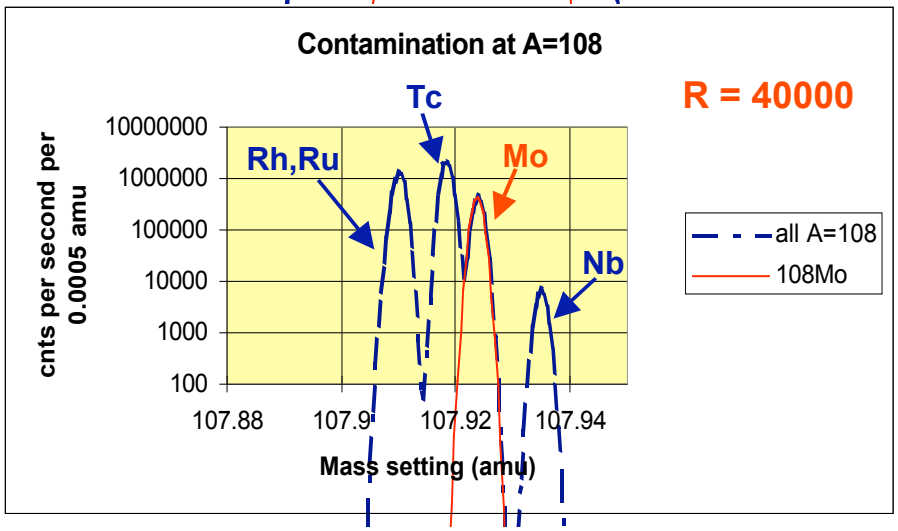


A=108 Contamination versus separator resolution



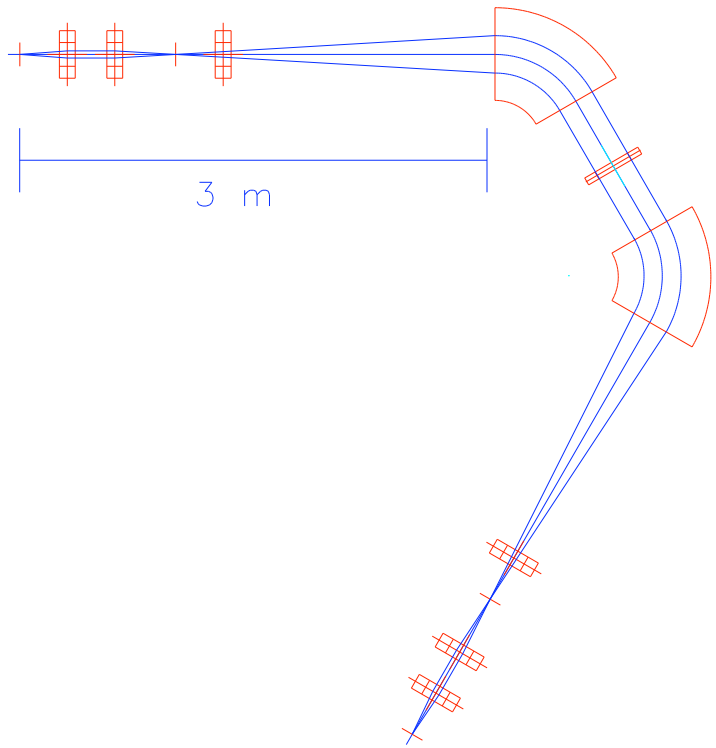




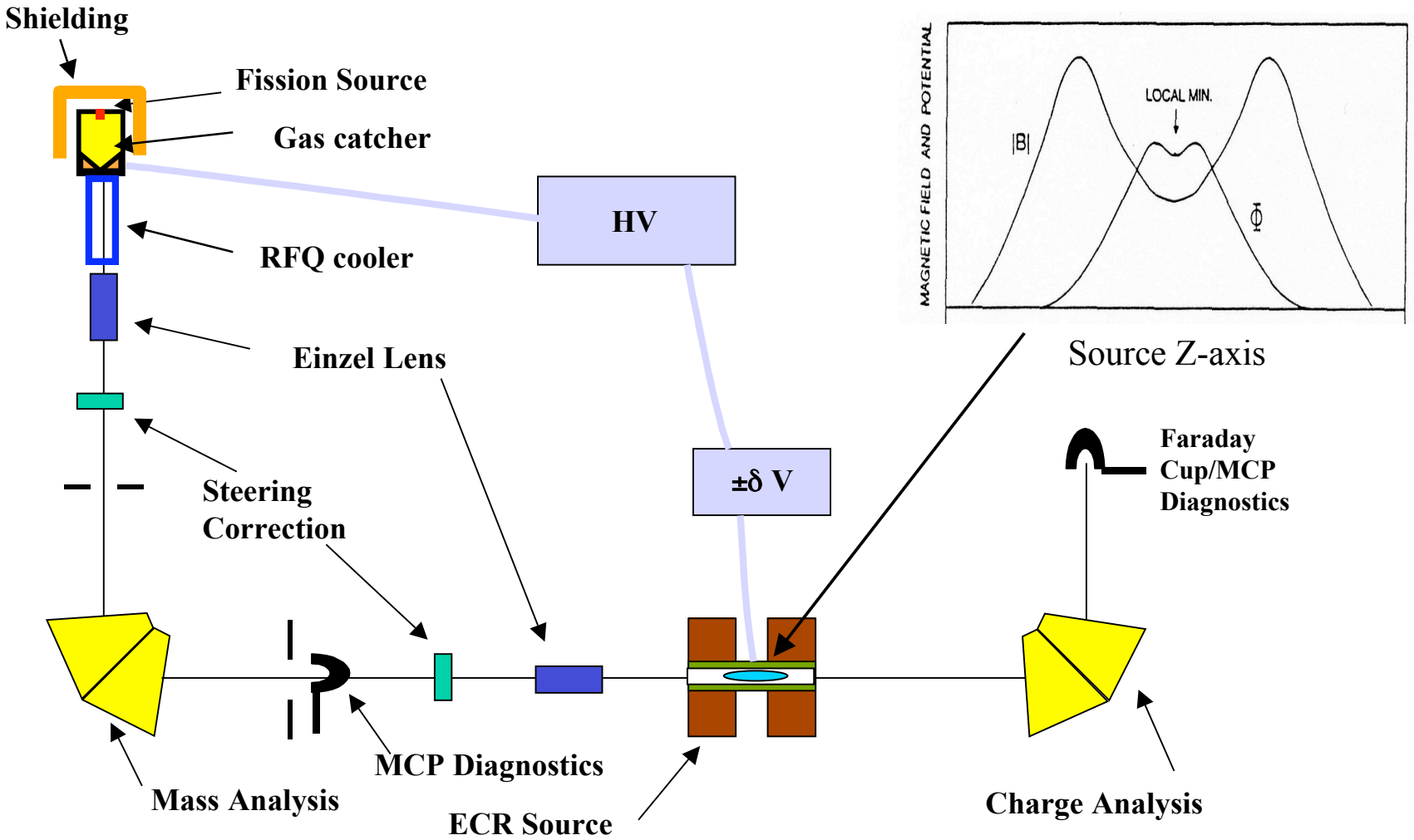


"Compact" isobar separator

- Modified scaled down version of first half of RIA mass separator … taking advantage of low emittance and energy spread of extracted beams
- Matching sections at entrance and exit
- 120 degrees total bend
- R = 50 cm
- Dispersion 21.6 meters
- First order mass resolution: 1/20000
- 3 multipoles correct through 5th order
- Small enough footprint to fit on HV platform

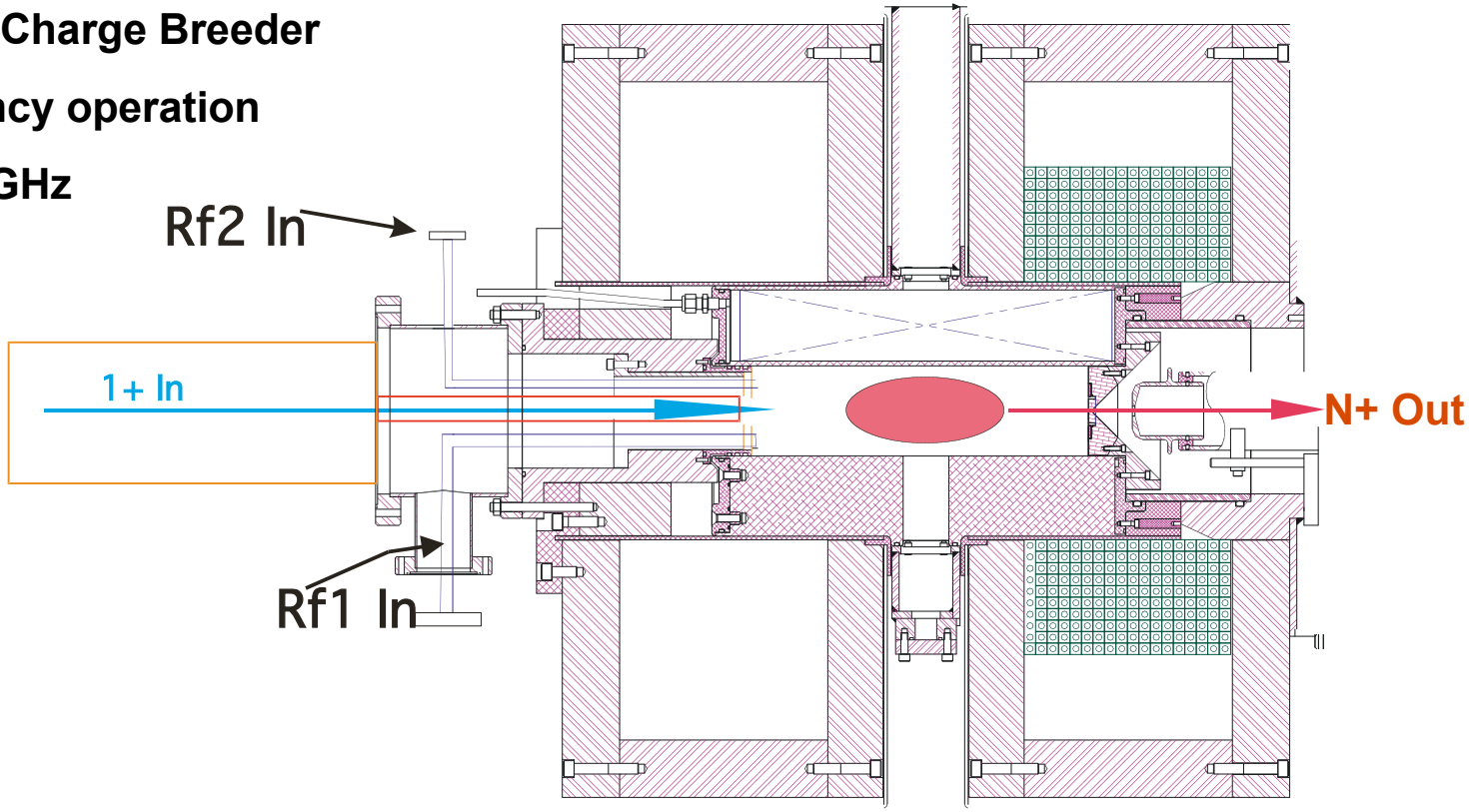


ECR Charge-Breeder Scheme



ANL ECR-I Modified as a Charge Breeder

- Existing ECR-I
- Modified as Charge Breeder
- Two frequency operation
  - 10 & 14 GHz



Phenix Charge Breeder Ionization Efficiency

- **Gases**

	Efficiency	A/Q	Time(ms)
- $^{40}Ar^{9+}$:	11.9%	4.4	25
- $^{84}Kr^{14+}$:	10.3%	6.0	60

- **Solids**

- $^{115}In^{18+}$:	4.6%	5.8	
- $^{109}Ag^{19+}$:	3.9%	5.7	25
- $^{120}Sn^{22+}$:	4.0%	5.5	20(19+)

- **1+ beam emittance used: 55π mm•mr**

ISN/TRIUMF

Emittance extracted from gas catcher system is ~ 3π mm mr so one may expect even higher charge breeding efficiency.

Examples of Yields for Representative Species

Calculated maximum beam intensities for a 1 Ci ^{252}Cf fission source using expected efficiencies.

Isotope	Half-life (s)	Low-Energy Beam Yield (s^{-1})	Accelerated Beam Yield (s^{-1})
^{104}Zr	1.2	6.0×10^5	2.1×10^4
^{143}Ba	14.3	1.2×10^7	4.3×10^5
^{145}Ba	4.0	5.5×10^6	2.0×10^5
^{130}Sn	222.	9.8×10^5	3.6×10^4
^{132}Sn	40.	3.7×10^5	1.4×10^4
^{110}Mo	2.8	6.2×10^4	2.3×10^3
^{111}Mo	0.5	3.3×10^3	1.2×10^2

Schedule for project

	FY2006				FY2007				FY2008			
Component	FQ1	FQ2	FQ3	FQ4	FQ1	FQ2	FQ3	FQ4	FQ1	FQ2	FQ3	FQ4
ATLAS Facility Space	Construct/ Enhance											
ECR Charge Breeder	Design	Fabricate/Procure			Install	Commission				Pre-Operations		
HV Platform	Design		Fab./Procure		Install	Comm.						
HV Transformer									Procure		Comm.	
Gas Catcher/Gas Cooler	Design		Fabrication/Procurement				Install		Commission			PreOp
Isobar Separator	Design		Fabrication/Procurement					Install		Comm.		PreOp
Source, Cask, & Transport	Design				Fabrication/Procurement				Install		Comm.	PreOp
Phase I (1 mCi Source)									Proc/Ins			
PhaseII (30 mCi Source)										Proc	Ins	
PhaseIII (1Ci activity)												Ins
ATLAS Diagnostics			Design						Fabric.	Install	Comm.	PreOp
Low-Energy Beamline					Design				Fabric.	Install	Comm.	

Schedule is determined by funding profile.

Cost and Manpower Requirements

- **Total Project Cost: $4.9 M**
  - Including 21% contingency
  - Funding over a three year period: FY06 – FY08
  - $3450k new AIP funds + ANL Physics Division manpower
- **Staffing requirements**
  - Permanent new additions (included in costs through FY08)
    - *Postdoctoral position*
    - *Technician/source operator*
  - Temporary additions during construction (included in costs)
    - *Designer*
    - *Engineer*
  - Existing Division staff effort
    - *~ 4 man-years spread over 2 year period*
- **Impact on ongoing operations**
  - Minimal impact during construction
  - ~10% reduction in available hours during commissioning

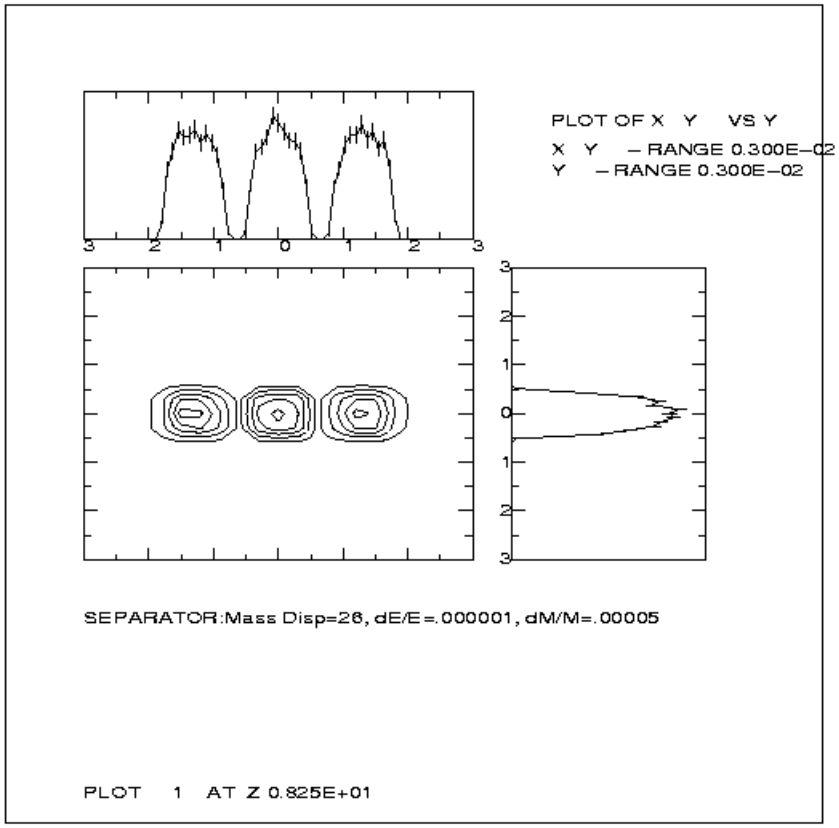
Summary

ATLAS must continue to develop new capabilities in order to provide the tools necessary for cutting edge science.

- ***The ^{252}Cf fission source proposal compliments other facilities.***
  - **Provides tools to address an important class of physics questions during the era leading up to RIA**
  - **Unique array of radioactive beams**
  - **Energy regime not generally available at other RIB facilities**
  - **Leverages the expertise and technologies available at ATLAS**
  - **The proposed upgrade has great synergy with RIA on both the technical and physics fronts.**

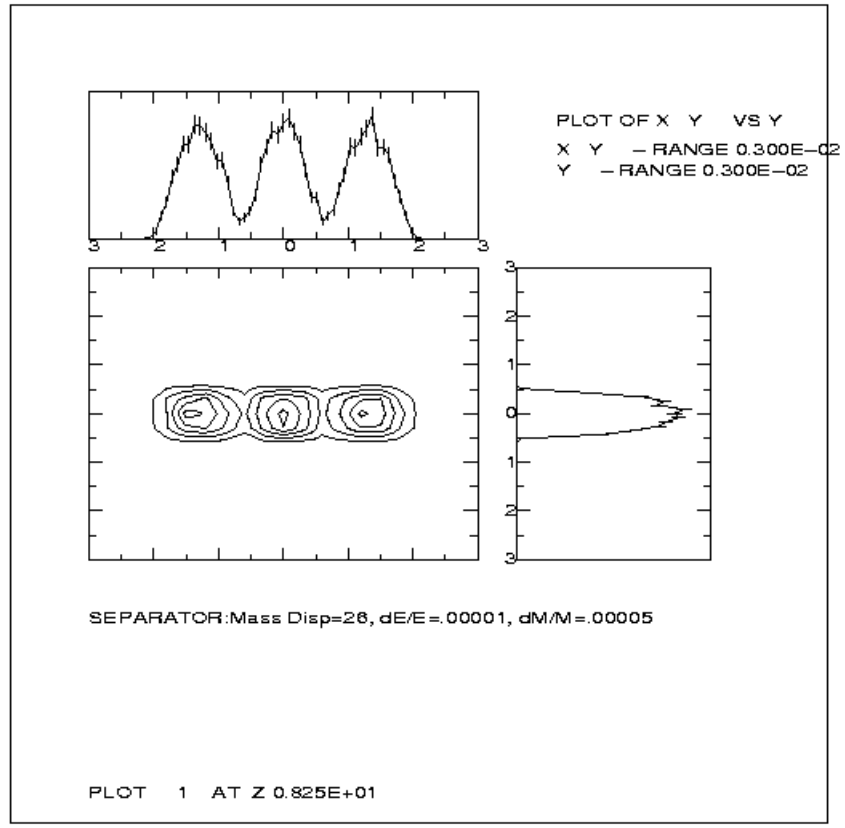
- ***Major Technical, Cost, Management, Schedule Project Review***
  - **Very positive result**
  - **Project will formally begin before end of year**

Resolution of compact isobar separator



Energy spread of 0.05 eV

R ~ 26000



Energy spread of 0.5 eV

R > 20000

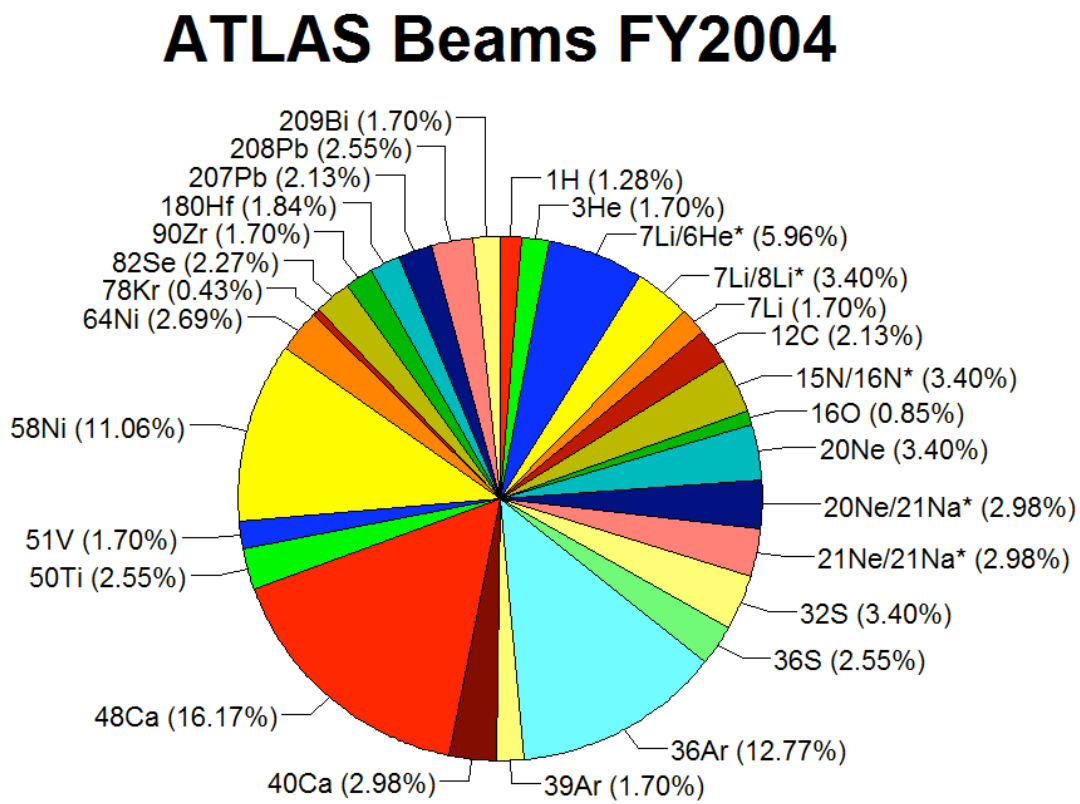
Calculations by C.N. Davids

ATLAS Performance

Beams Provided

Variety, type and beam properties of beams driven by the experimental program.

- **3-4 new beam each year.**
- **Continued push to higher beam current**
- **Medium mass has been recent focus**



28 different isotopes
***18.7% beam time (1040 hours) for exotic beams**

Measures of ATLAS Performance

Operating Statistics

Machine Operation	FY1999	FY2000	FY2001	FY2002	FY2003	FY2004
Scheduled Research Hours	6096	5496	5576	4586	5500	5623
Research Hours (on Target)	5998	5384	5619	4311	5468	5512
Accelerator Devel. Hours	48	76	97	105	22	47
Total R & D Hou rs	**6046**	**5460**	**5716**	**4416**	**5490**	**5559**
Scheduled Maintenance	300	597	465	665	333	437
Experimental Downtime	440	296	300	242	256	230
Availability (%)	93.2	94.9	95.5	95.1	96.1	96.4
Num. of Experiments	56	51	42	37	46	41

Recent budget constraints have forced a reduction in running time

- **5.3-day operation started in June 2001**
- **7-day operation resumed in April, 2003 to May, 2004**
- **5.3-day operation now in effect**

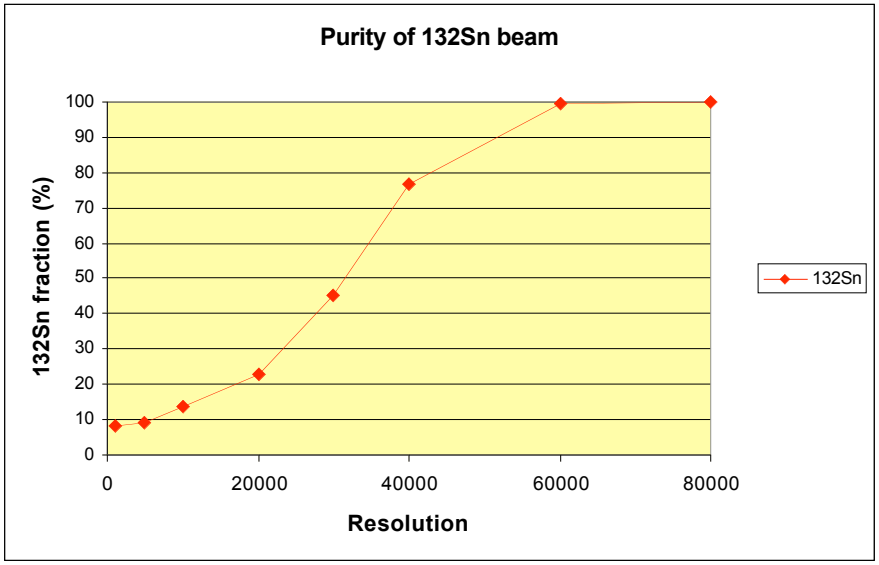
Summary

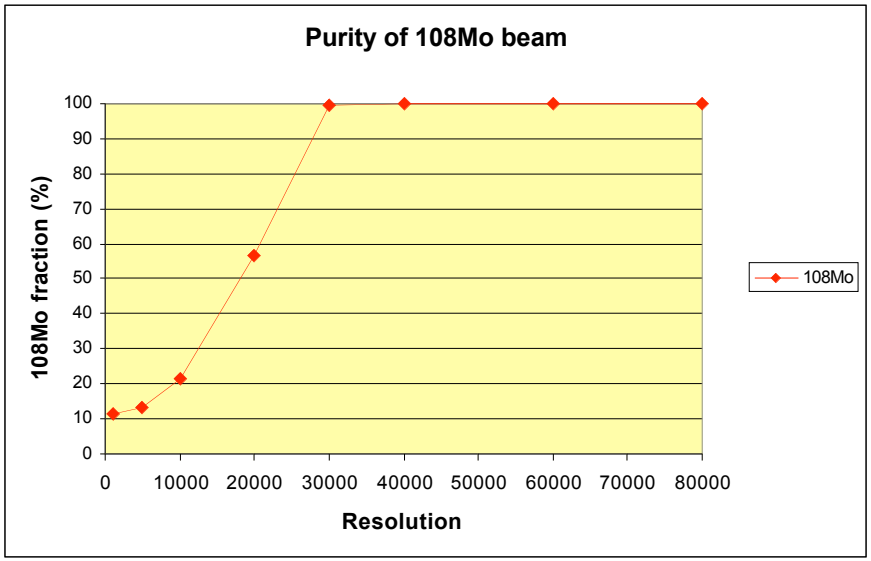
- A ^{252}Cf fission source delivers a unique and complimentary group of radioactive beams that can provide tools to address an important class of physics questions during the era leading up to RIA.
- Makes use of unique technologies and expertise available at ATLAS.
- The proposed upgrade has great synergy to RIA on both the technical and physics fronts.

Purification of beams with isobar separator

•resolution used is width at 1/10 amplitude (→ 90-95% of total intensity within slits acceptance, ~ 30% higher requirement than what some magnetic spectrometer people quote, agrees roughly with FWHM in Penning trap separator case)

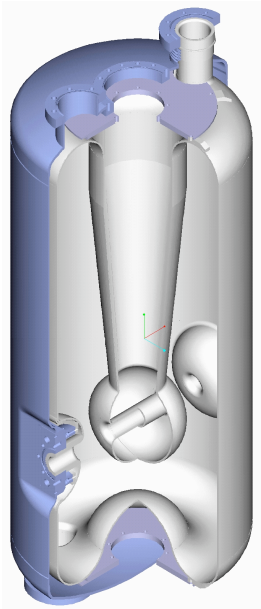
•ran some representative cases with correct relative intensities to determine what resolution is really needed





•if you want high transmission (and we want that!) … reduction in beam contamination by isobars require 10000 resolution at the very least, more like 20000 to 40000 if beam purity is critical

ATLAS Energy Upgrade Project



Prototype resonators successfully demonstrated the design to be used for ATLAS and RIA.

109 MHz
QWR Cavity

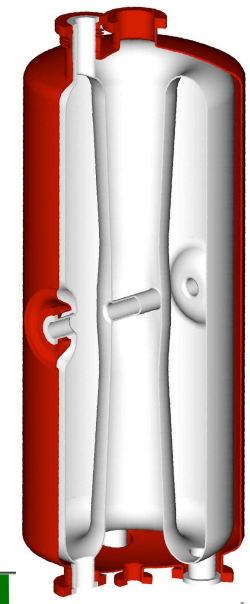
$ß_s$ = 0.144
Length = 25cm

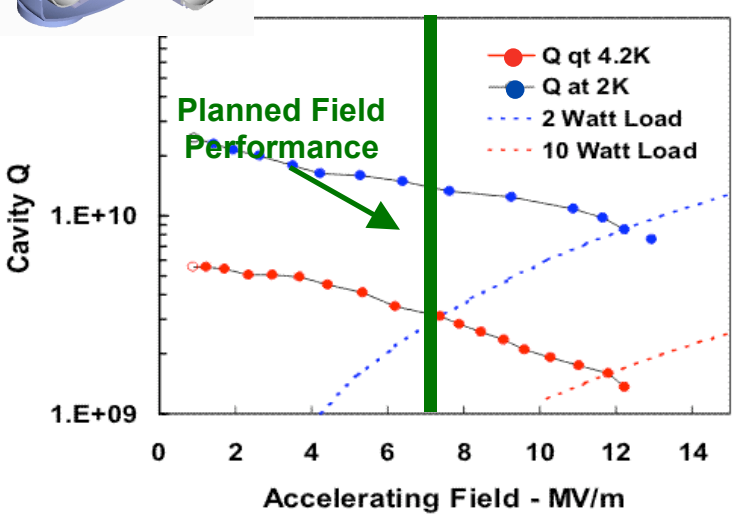
7 Resonators

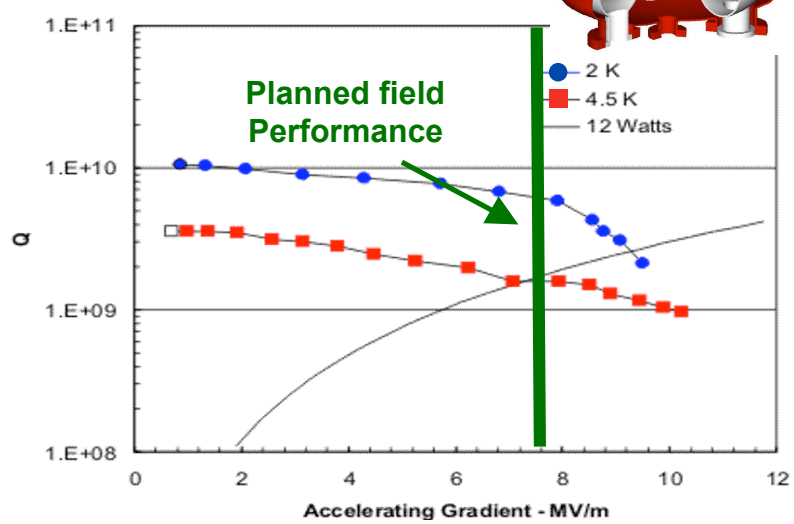
170 MHz
HWR Cavity

$ß_s$ = 0.26
Length = 30cm

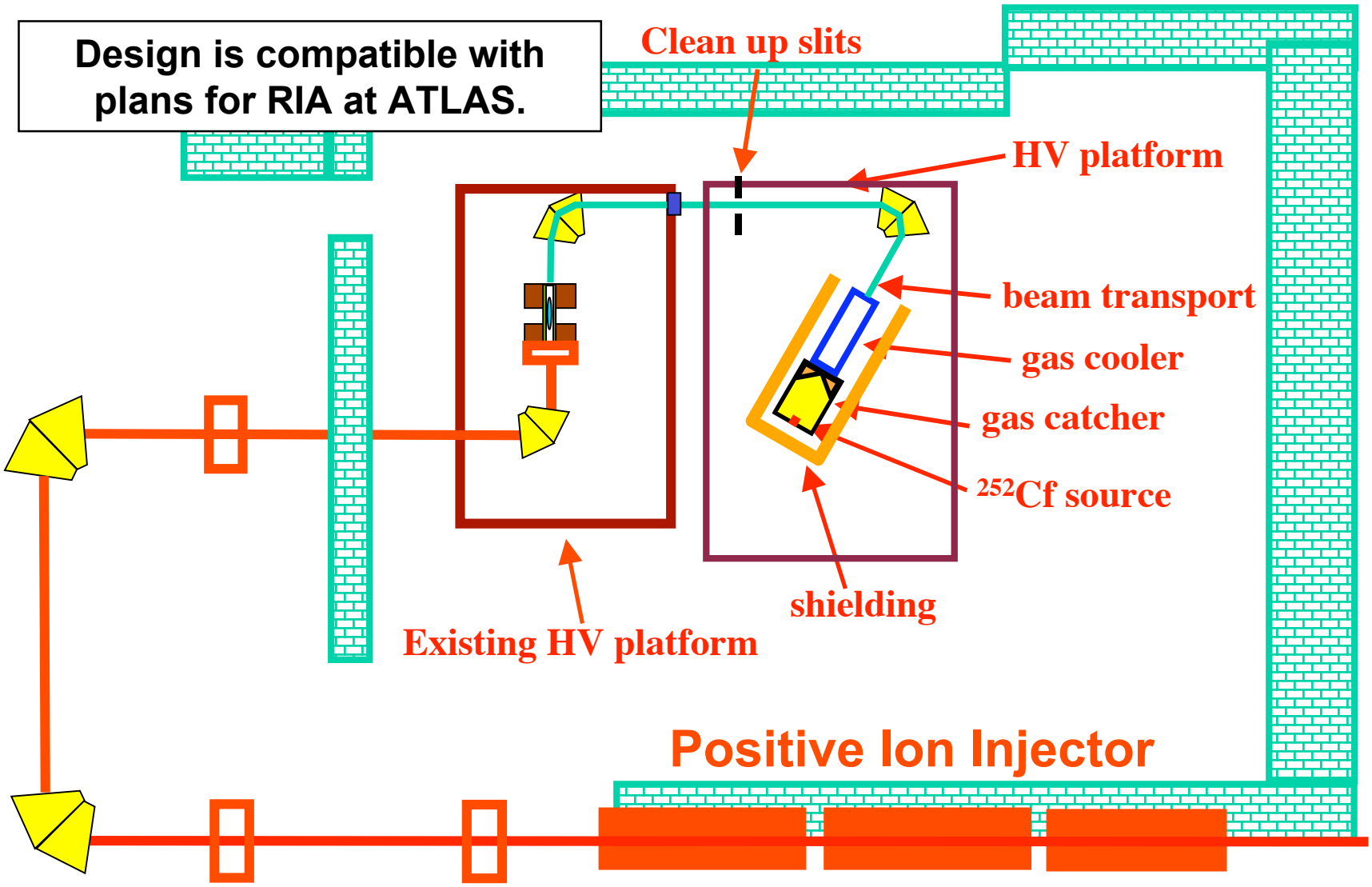
1 Resonator





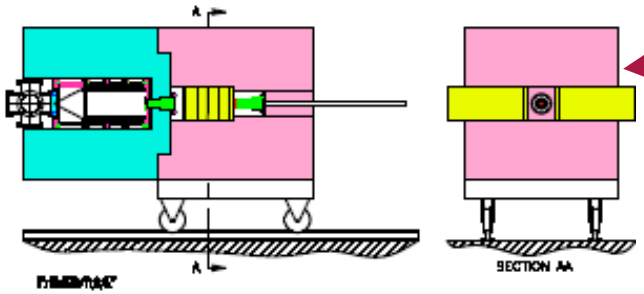


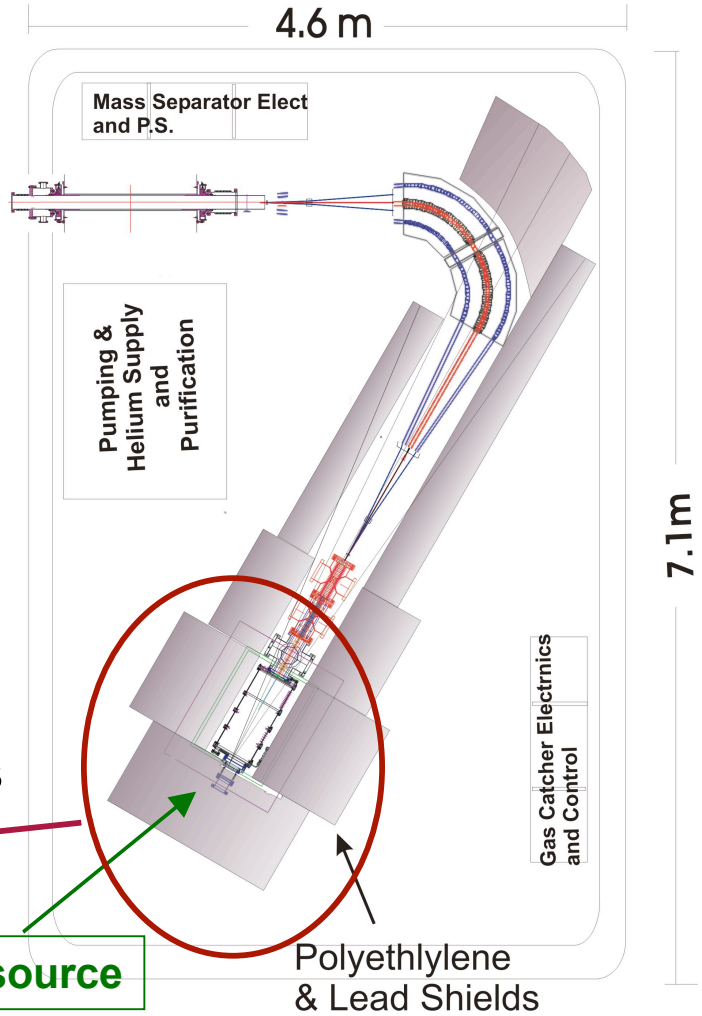
Schematic layout for fission source and breeder upgrade



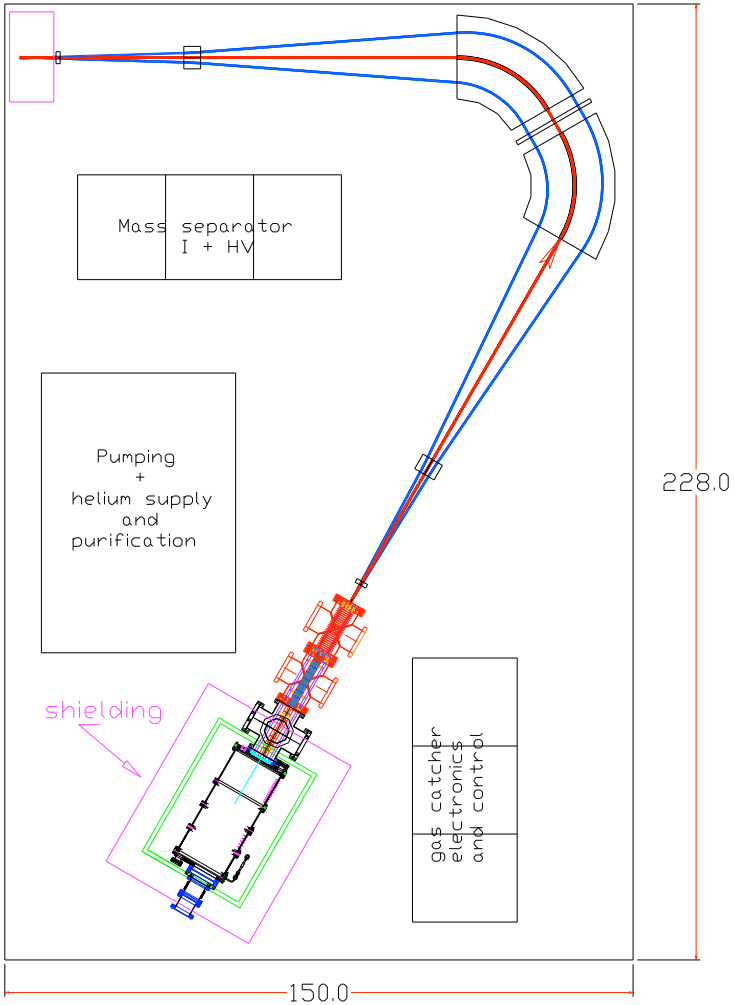
Shielding Considerations

- **Shielding Design Goals**
  - **Less than 1 mrem/hr on contact**
  - **Fully shielded even during source installation**
  - **Remote operation of shielding and source movement during installation**
- **Shield requirements:**
  - **~0.60 m polyethylene for neutrons**
  - **Additional 5 cm. lead shielding for γ-rays**





Shielding mid-plane view

Platform layout with scaled down RIA separator

- platform of same size as existing ECR 1 platform
- beam from gas catcher cooled by 2 sections of RFQ (at ECR source voltage)
- isobar separation based on one stage of two-stage RIA isobar separator
    - floated to 50 kV
    - gas catcher provides 3π mm mrad at 50 keV and energy spread below 1 eV
    - scale down by factor of 4 and use one stage
- mass resolution of 20000
- emittance great for injection into charge-breeder
- no rate limitation
- no delay
- high stability (<1 in 50000) requirements on HV and magnet current