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CARIBU - Radioactive Beams from ^{252}Cf fission

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for the CARIBU Team

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Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

Outline

CARIBU - CAlifornium Rare Ion Breeder Upgrade

- Scientific Justification
    - Nuclear structure
    - Nuclear astrophysics
- Why is ^{252}Cf fission interesting?
- Project Description & Status
    - Technical approach
        - *Gas catcher/RFQ cooler*
        - *ECR Charge-breeder*
        - *Isobar separator - beam purity*
        - *Radiological issues*
    - Performance
    - Cost & Schedule

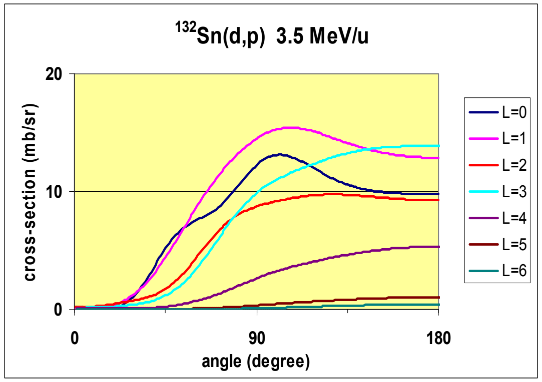
Important physics questions

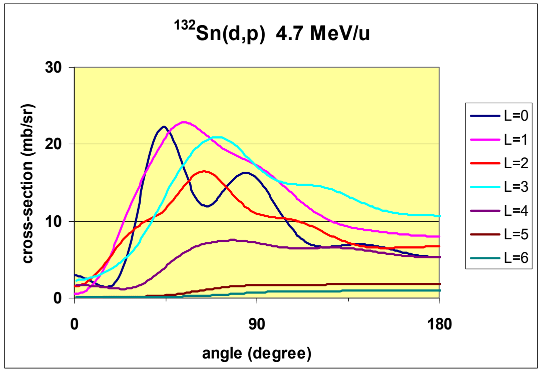
- Modification of nuclear structure in neutron-rich systems
    - *shell-structure quenching*
    - *single particle structure near neutron-rich magic nuclei*
    - *pairing interaction in weakly-bound systems*
- Collective behavior in neutron-rich systems
- R-process path
    - *ground-state information*
        - *mass*
        - *lifetime*
        - *beta-delayed neutron branching ratio*
    - *neutron capture rate*
    - *fissionability of very heavy neutron-rich isotopes*

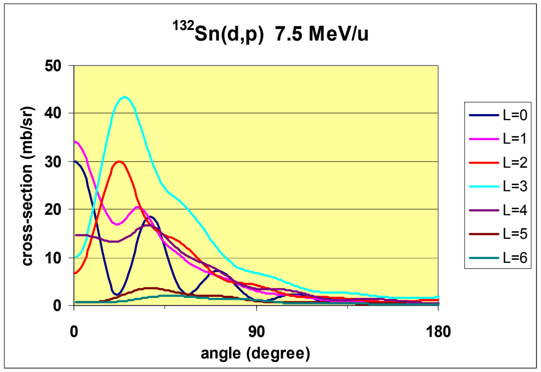
I. Nucleon transfer reaction … single particle state

- Single particle/hole states around magic nuclei
  - *^{132}Sn*
  - *^{78}Ni*
- (d,p) reactions (inverse)
  - 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.







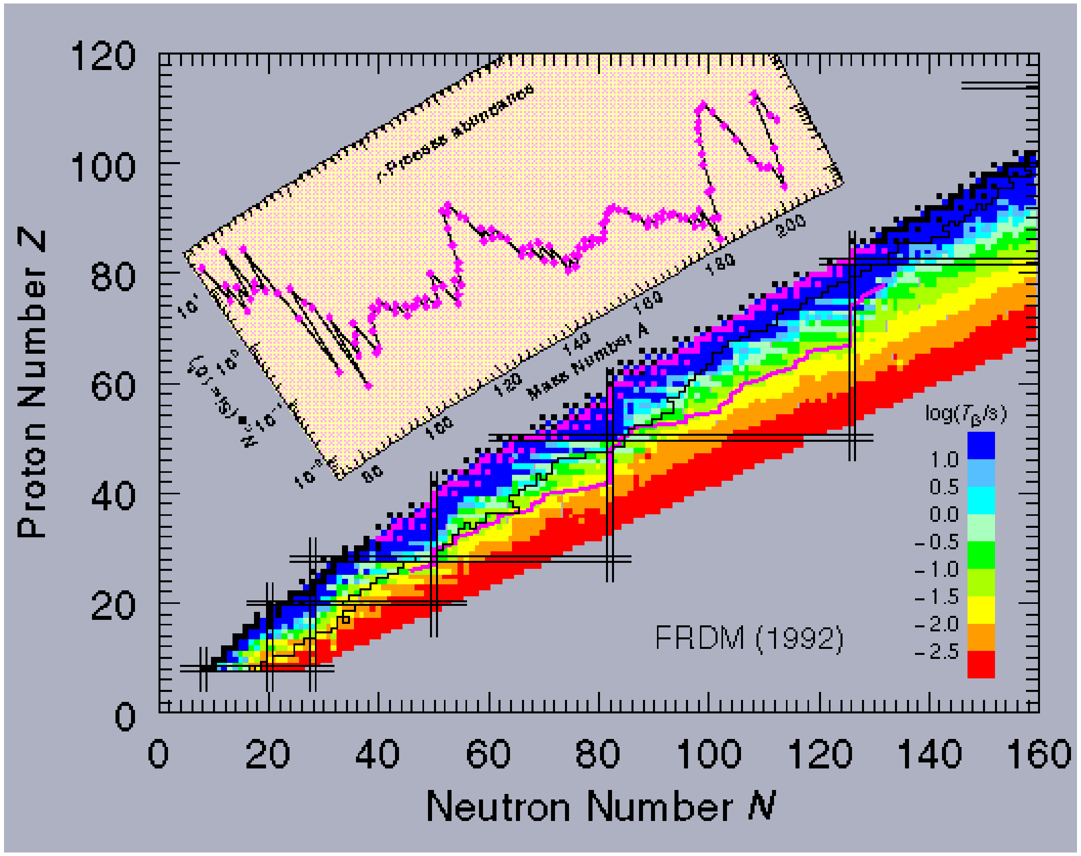
III. BE(2) strength in neutron-rich nuclei

- Fission products have been studied with fission sources working off-line inside spectrometers like Gammasphere
  - Gamma ray energies measured
  - Low-energy levels determined
  - Little additional information except for most intense fragments
- Coulomb excitation of beams of these fission fragments would yield precision BE(2)'s and other information via multiple Coulomb excitation
- Gammasphere is an ideal instrument for these studies

IV. 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**

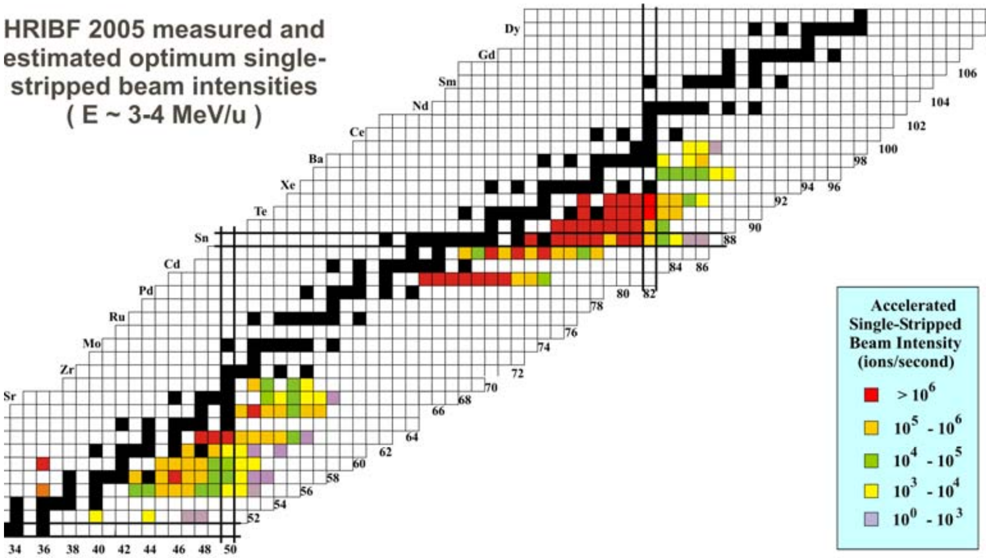
These measurements are done with unaccelerated beams.



A Californium Fission Source for ATLAS

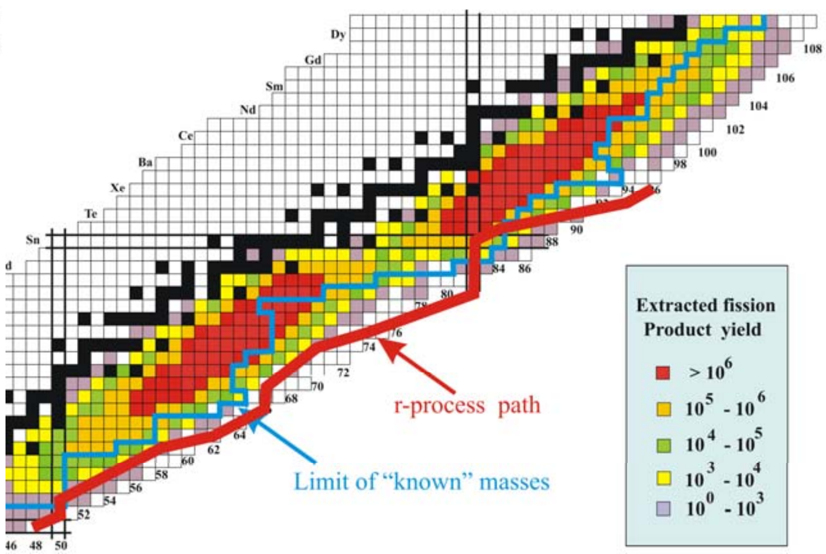
- ^{252}Cf fission yield is complementary to uranium fission
- Provides access to unique, important areas of the N/Z plane
- Significant yield extends into r-process region
- Available energy exceeds that from HRIBF and ISAC
- Builds on extensive ATLAS weak beam experience
- Technology and experience useful for a future exotic beam facility

HRIBF yields from ^{238}U



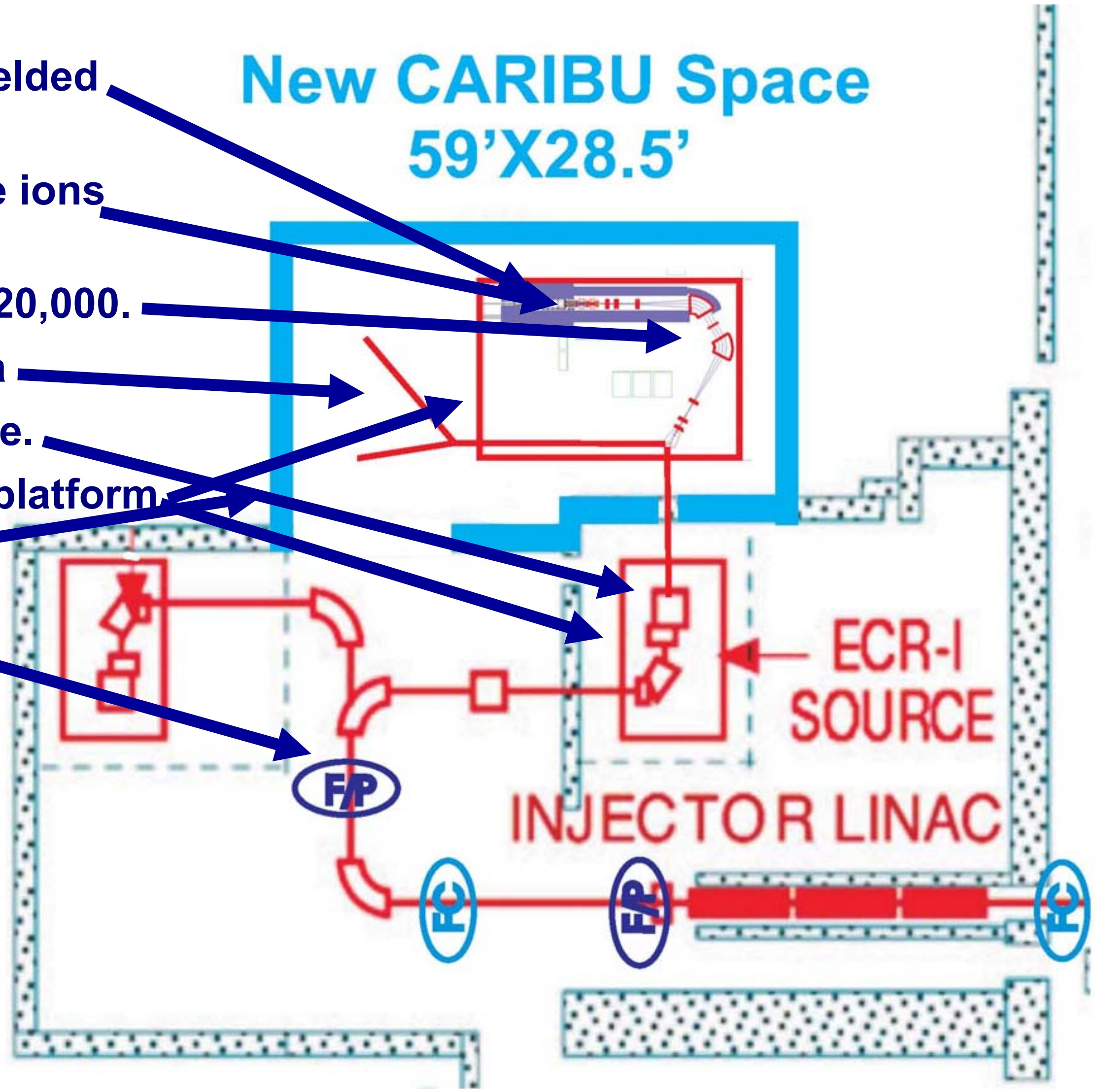
^{252}Cf spontaneous fission yield

$T_{1/2}$=2.6 a   3+% fission branch

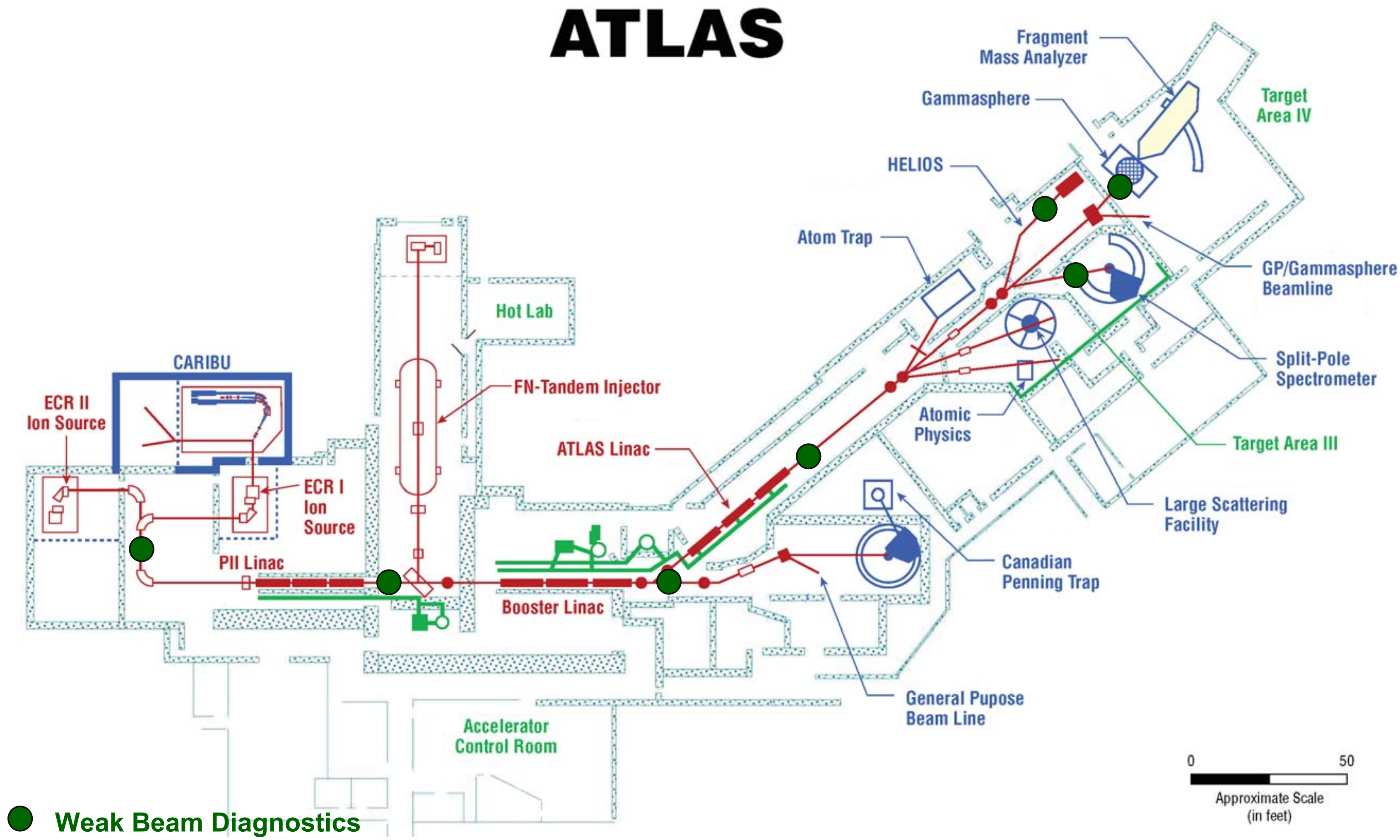


^{252}Cf Fission Source System

- 1 Ci ^{252}Cf fission source in shielded cask.
- Gas catcher/RFQ to thermalize ions and create beam.
- Isobar separator with δm/m:1/20,000.
- Un-accelerated beam trap area
- ECR charge breeder ion source.
- Mounted on HV (up to 200kV) platform.
- New ~1600 ft^2 building.
- Weak beam diagnostics.



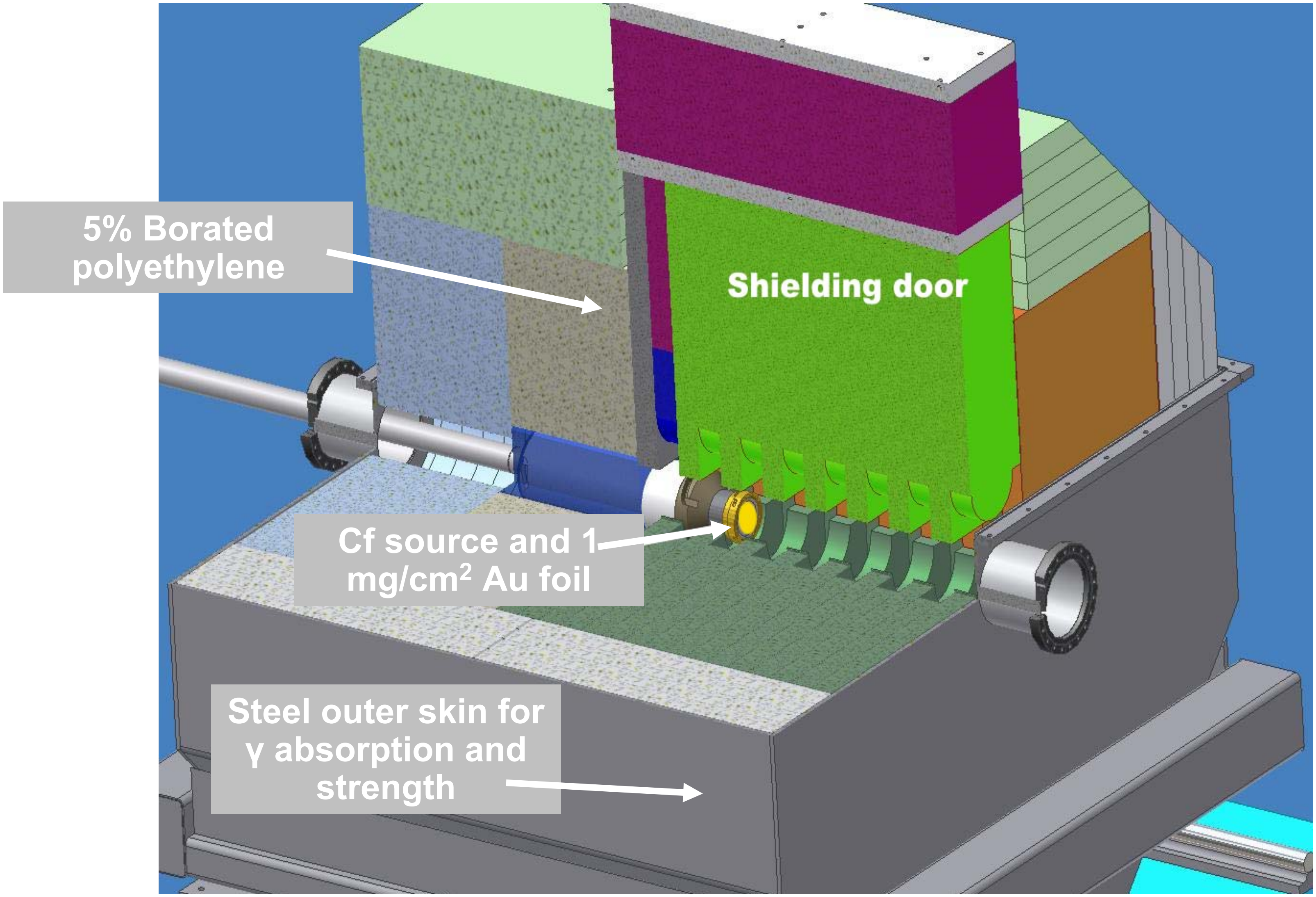
Layout for ^{252}Cf fission source system at ATLAS



Californium source characteristics

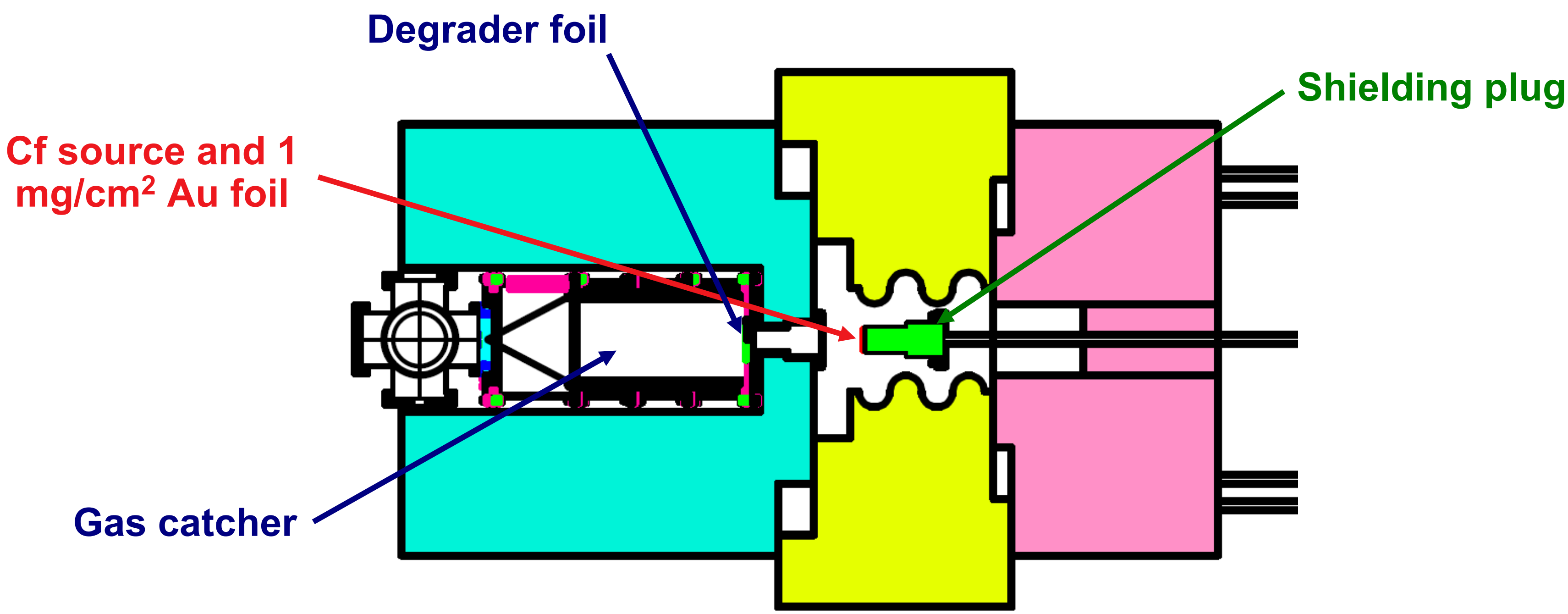
- CARIBU will (eventually) use fission fragments from a 1 Ci source of ^{252}Cf.
  - Start with two weaker sources – ~3 mCi and ~30 mCi
- ^{252}Cf is produced at the High Flux Reactor at Oak Ridge and will be produced by ORNL as an open source electroplated on a polished SS plate. Similar sources are in use at ATLAS & INEL.
- Source will be sealed in a welded double container.
- Transport of the source from Oak Ridge will use a DOT certified cask.
- To minimize the possibility of flaking, the thickness of the deposit is kept to a practical minimum.
- ^{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 3X6 cm ellipse area this yields a density of ~150 μg/cm^2*

CARIBU Cask Cutaway View from Front Side

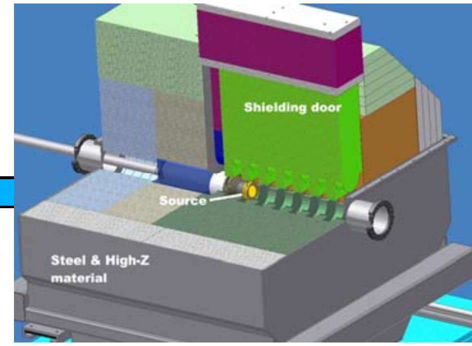


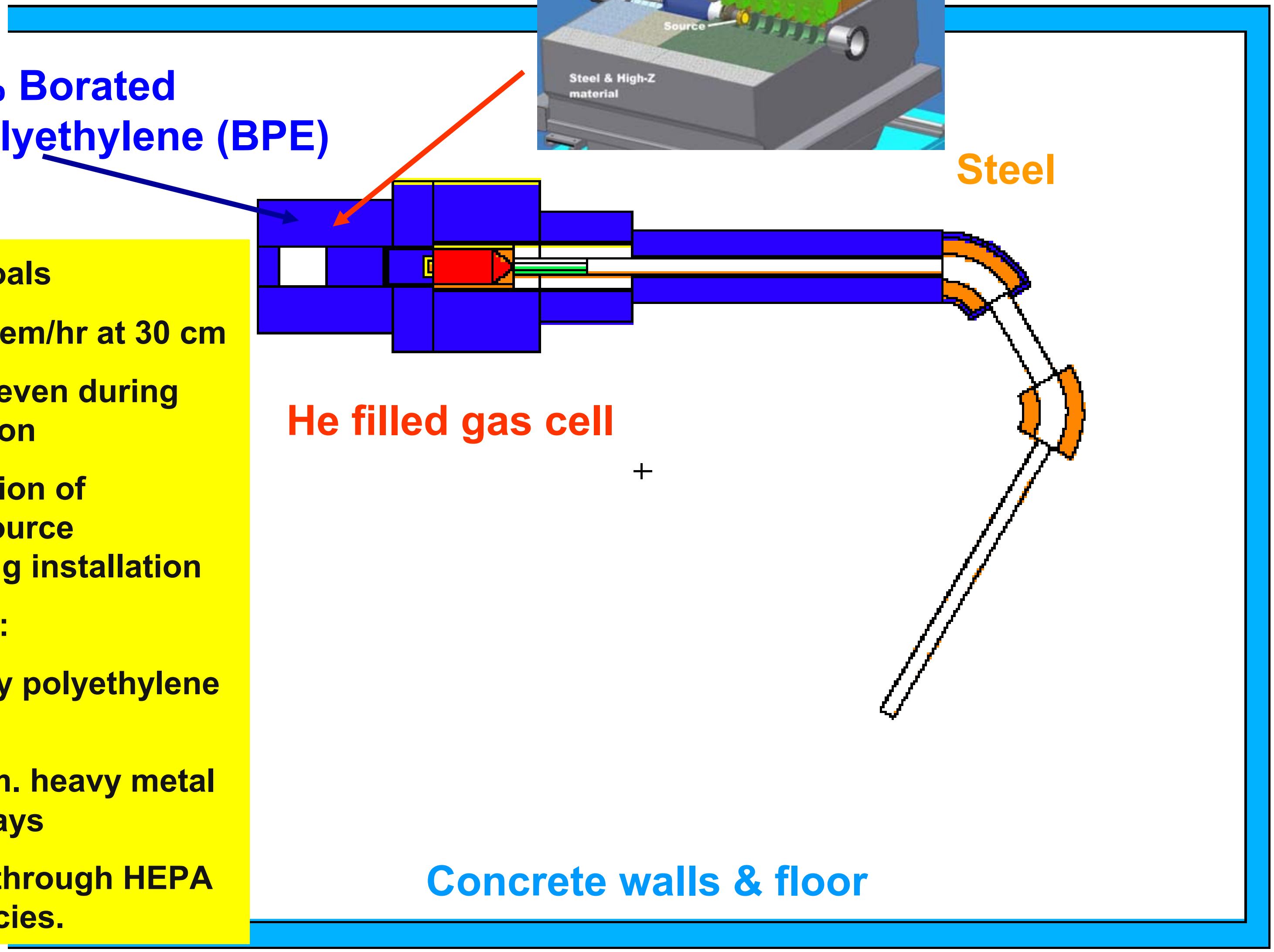
Californium source and gas catcher relationship

- For installation in the gas catcher, the source is installed on a shielding plug, 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, and followed by an energy degrader foil.
- The assembly is sealed to the gas catcher, the source being inside the gas catcher.



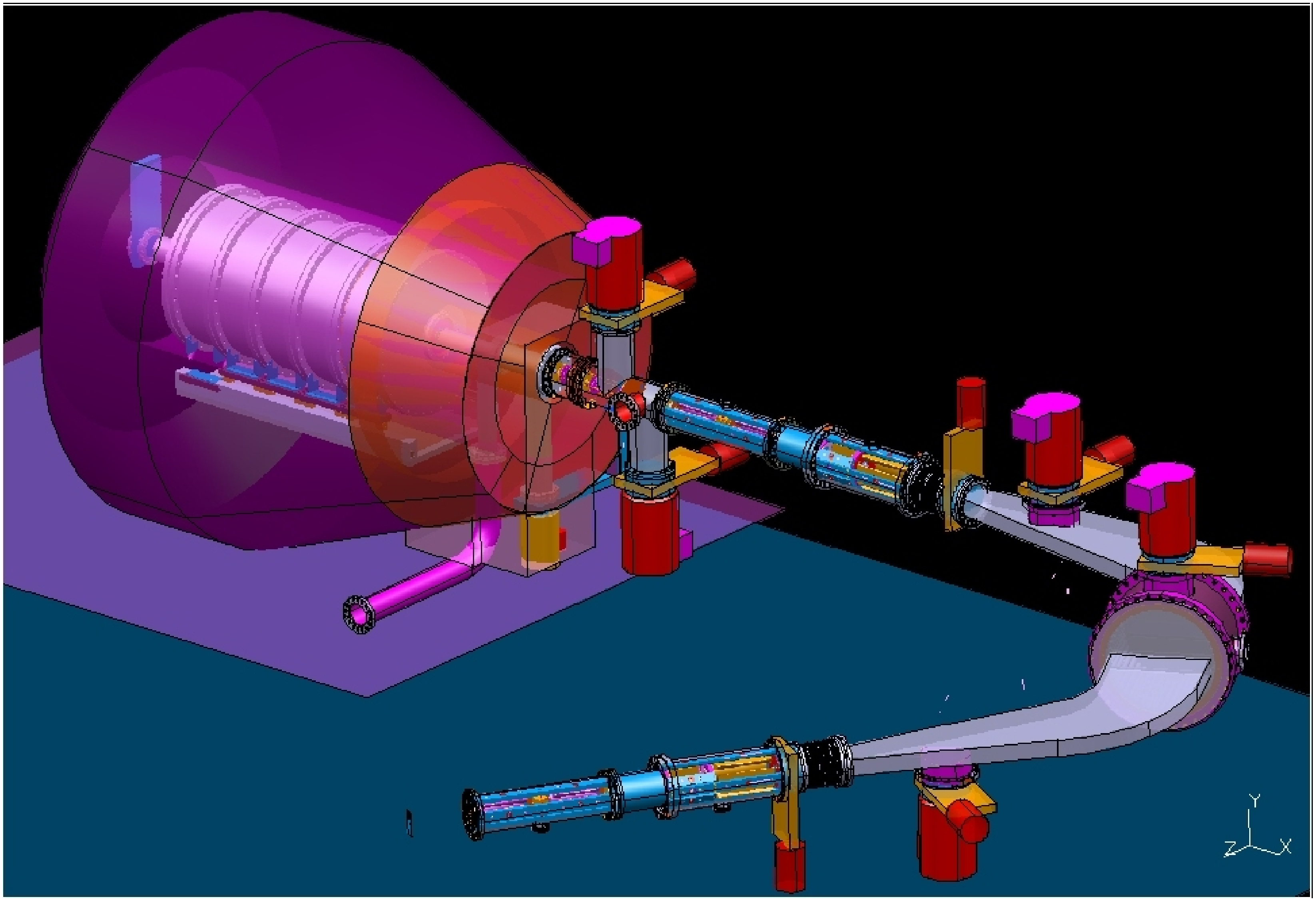
Shielding Geometry





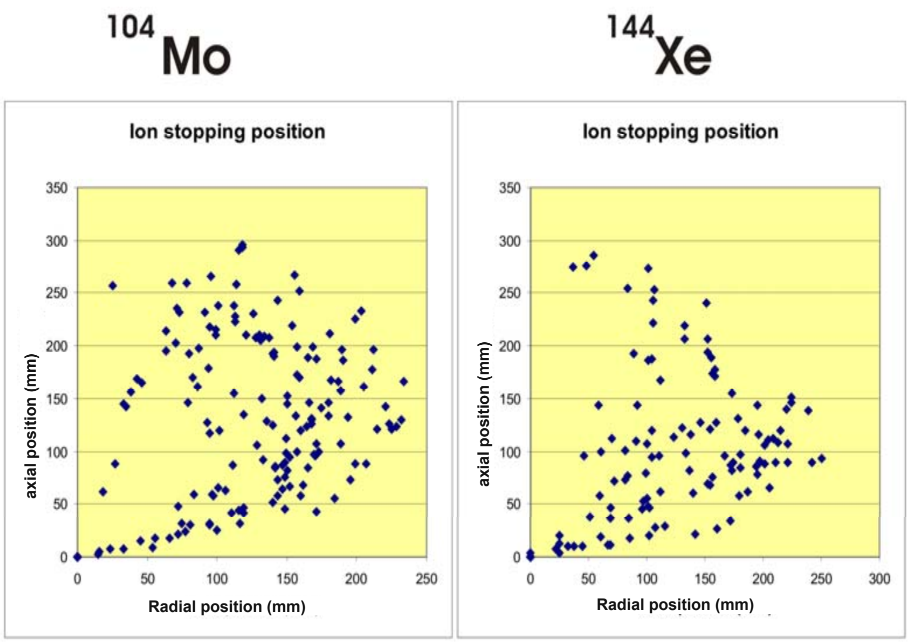
- Shielding Design Goals
  - Less than 1 mrem/hr at 30 cm
  - Fully shielded even during source installation
  - Remote operation of shielding and source movement during installation
- Shield requirements:
  - ~0.75 m, mostly polyethylene for neutrons
  - Additional 5 cm. heavy metal shielding for γ-rays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

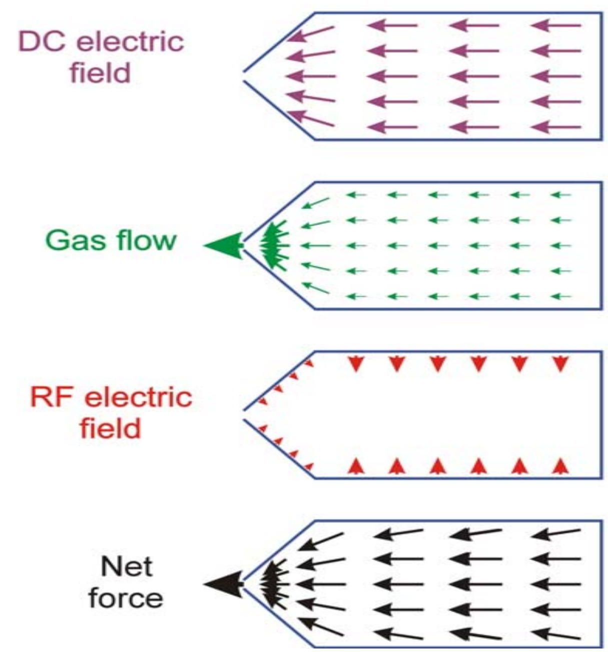
Gas Catcher-Isobar Separator Relationship Including gas catcher shielding



CARIBU gas catcher requirements (1)

- **Detailed simulations of fission fragment stopping in the gas catcher, incorporating contaminants in the californium source, source size, protective foil, spherical degrader thickness and size, and proper energy-mass distribution for different fragments indicate that**
  - **a 50 cm gas catcher diameter is required**
  - **3 different degraders can cover the full fission fragment mass range**
    - ***degrader is a half sphere of 4 cm radius (~11 mg/cm^2 Al thickness)***
    - ***degrader will be removable locally***





CARIBU gas catcher requirements (2)

- **The 1 Ci ^{252}Cf source will generate significant ionization in the gas catcher:**
  - **~ 10^9 fission per second with two fission fragments per fission (one emitted towards the gas catcher volume)**
    - **Fission fragments lose roughly 5 MeV in gas volume (most energy lost in degrader)**
  - **~ 4 X 10^{10} alpha particles per second, half of which go through the gas catcher**
    - **Alphas lose roughly 0.5 MeV in gas volume (most go through the gas and hit the enclosure where they deposit the rest of their energy)**
  - **Both sources contribute almost equally to ionization density**
  - **Build up of beta decaying activity has a negligible effect**
  - **Total ionization density ~ 1.5 X 10^{16} eV/s over a 160,000 cm^3**
    - ***~ 9 X 10^{10} eV/cm^3.s → high intensity operation***

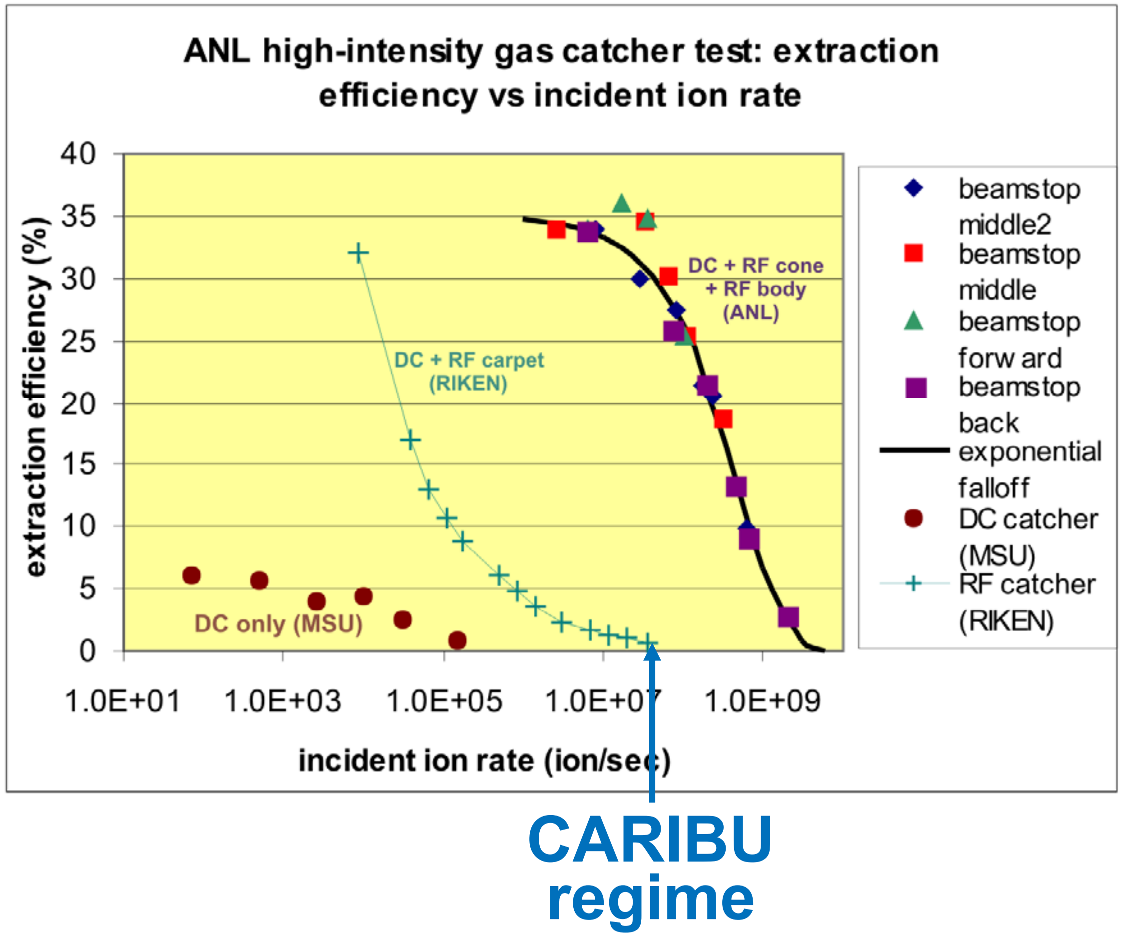
~ 10-100 times higher ionization than normal CPT operation

~ 10 times below RIA-like ionization density

Gas catcher operation at AEBL/CARIBU intensity

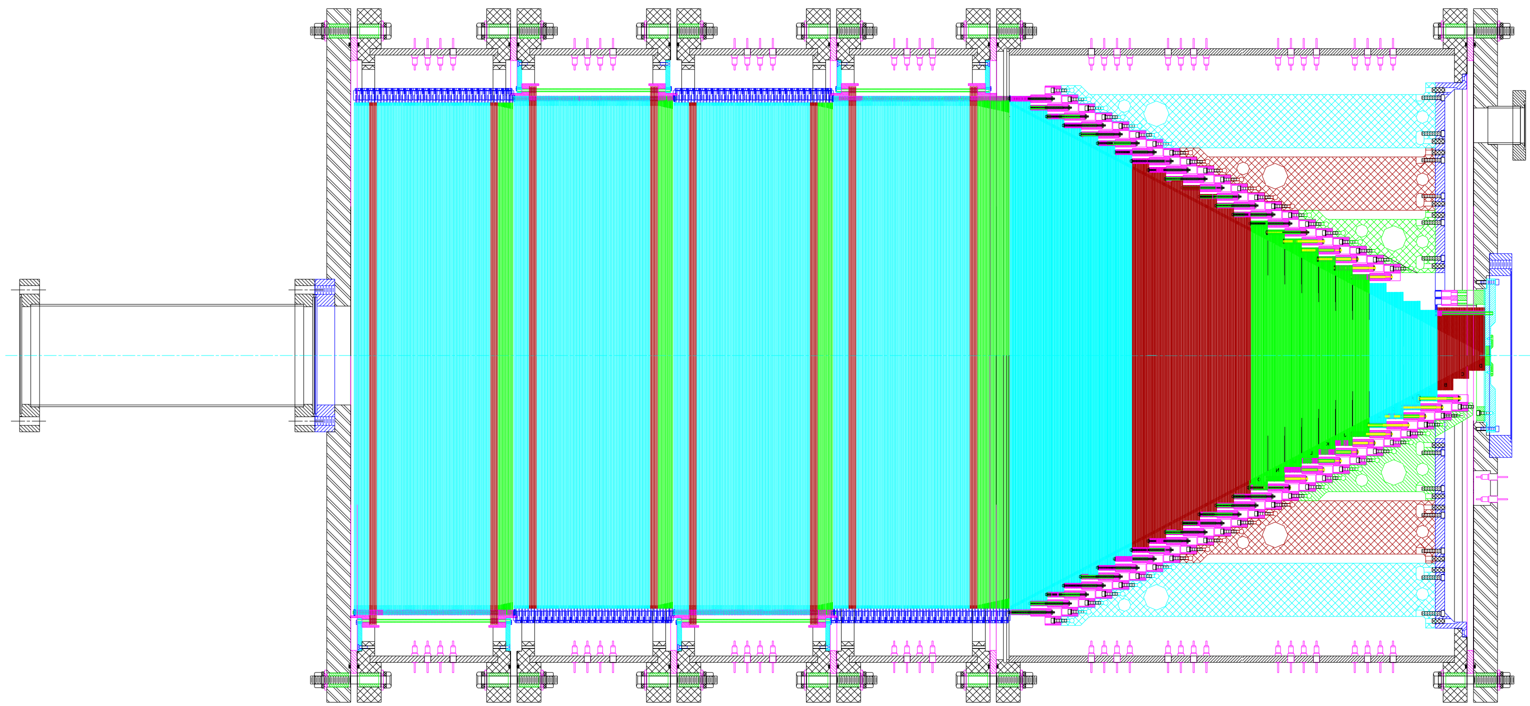
Series of high intensity tests at ATLAS in late 2006 confirmed redesigned gas catcher.

- **High efficiency obtained at up to 10^9 incoming particles per second**
- **Extracted ions identified as ions, not molecular ions**
- **All modifications have a clearly identifiable positive effect**



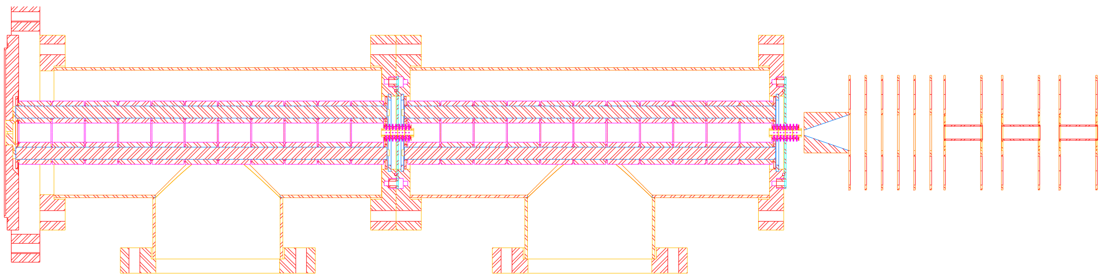
CARIBU gas catcher design

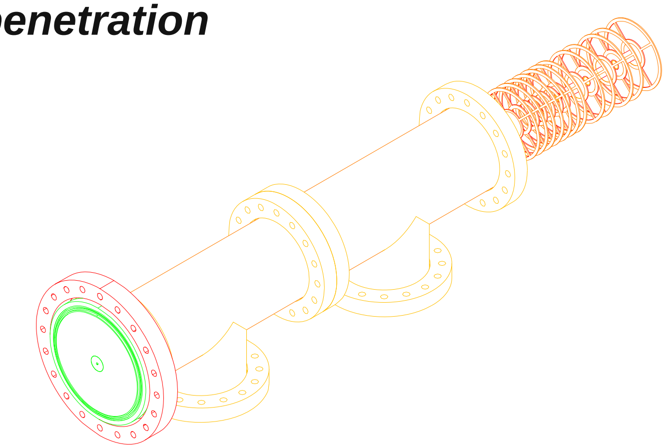
- Device similar to RIA gas catcher
  - Same operating principle (RF +DC + gas flow)
  - Similar construction
  - Similar length
  - Twice the diameter (50 cm inner diameter)



RFQs for gas cooler

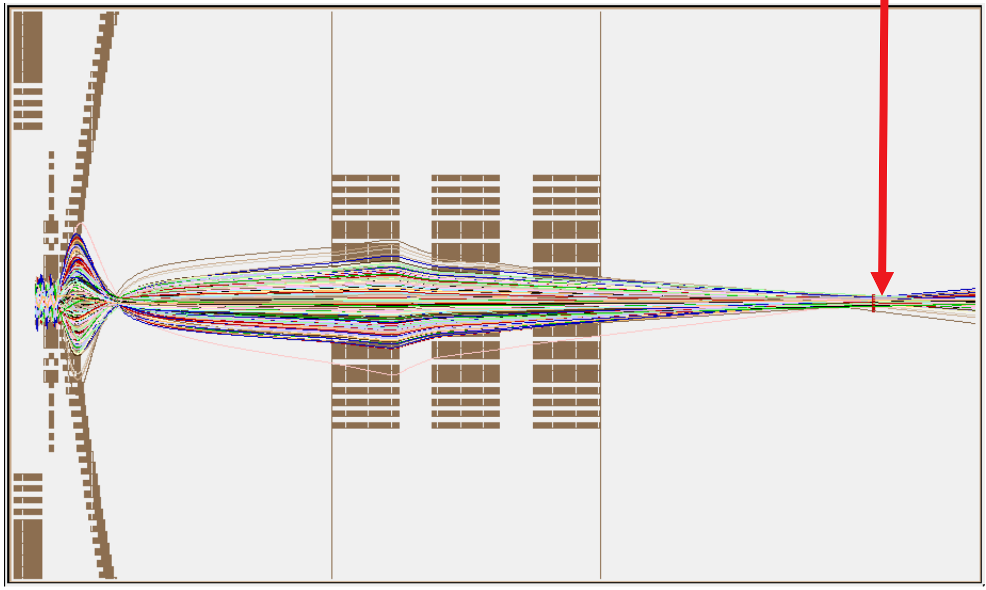
- Design criteria
  - Accept and transport all heavy-ions extracted from gas catcher
    - *Large initial RFQ aperture of 15 mm*
  - Pressure in the acceleration region (at the end of the cooler) must be $<10^{-5}$ mbar
    - *Two large sections of RFQ cooler and two μRFQs for differential pumping*
  - Minimal final emittance and energy spread below 1 eV
    - *Matching of RFQs (and μRFQs) sections to minimize reheating during transitions*
    - *Individual lengths tuned to assure thermalization*
    - *Conical extraction structure to minimize field penetration*
  - Total length should be as small as possible
    - *Less than 1 meter*

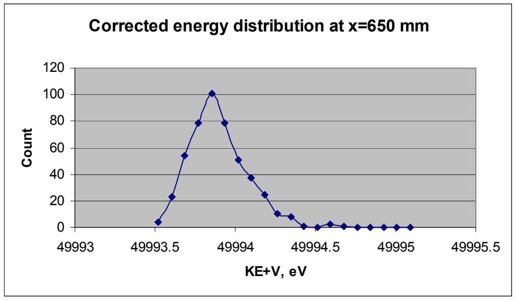


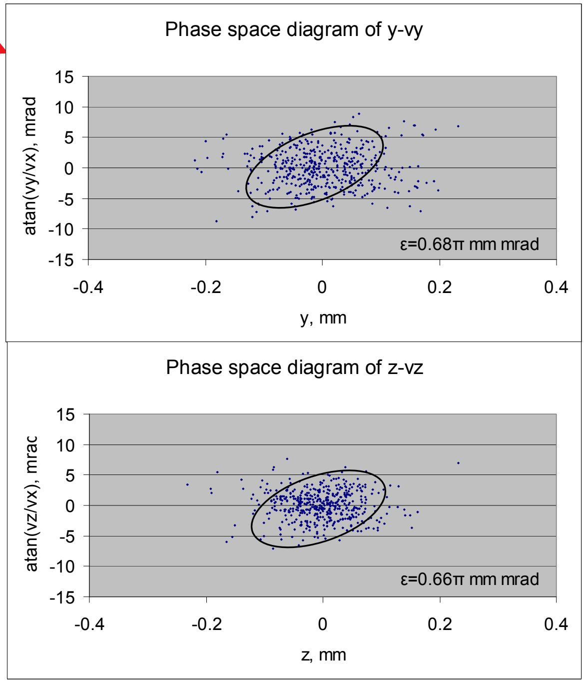


RFQ cooler simulations result (2)

- **Energy spread ~ 0.5 eV**
- **Emittance ~ 1π mm•mrad**
- **Differential pumping sufficient**
- **Acceleration by 50 kV DC potential yields spot size diameter below 1 mm**
- **Total length just below 1 m**





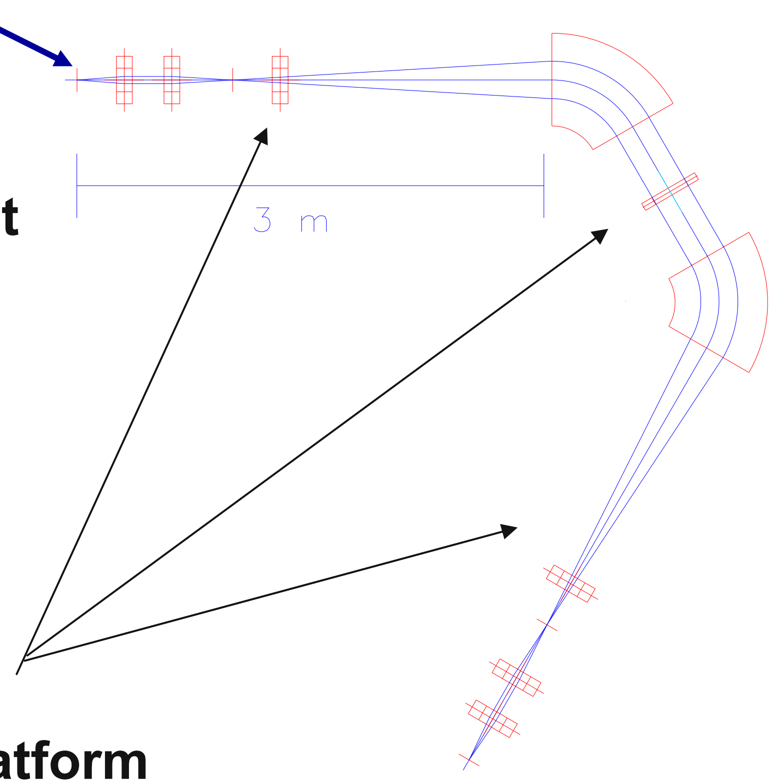


Calculations by Tao Sun using SIMION

“Compact” isobar separator

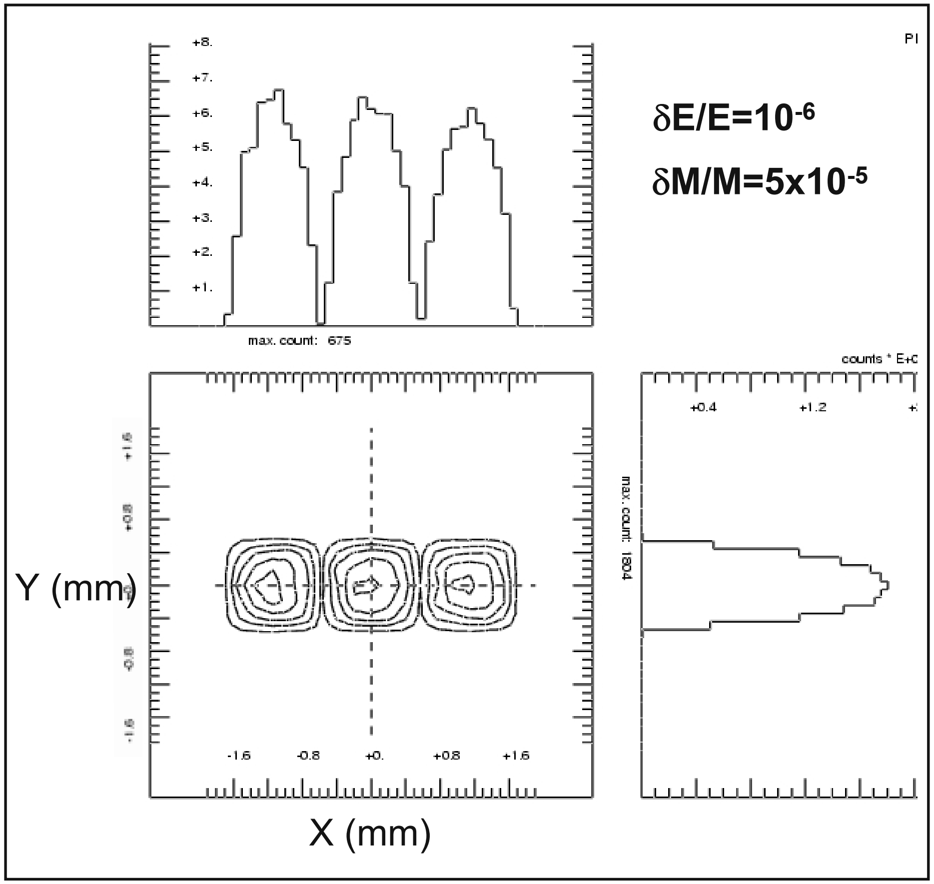
- **Modified scaled down version of first half of RIA mass separator, taking advantage of low emittance and energy spread of extracted beams:**

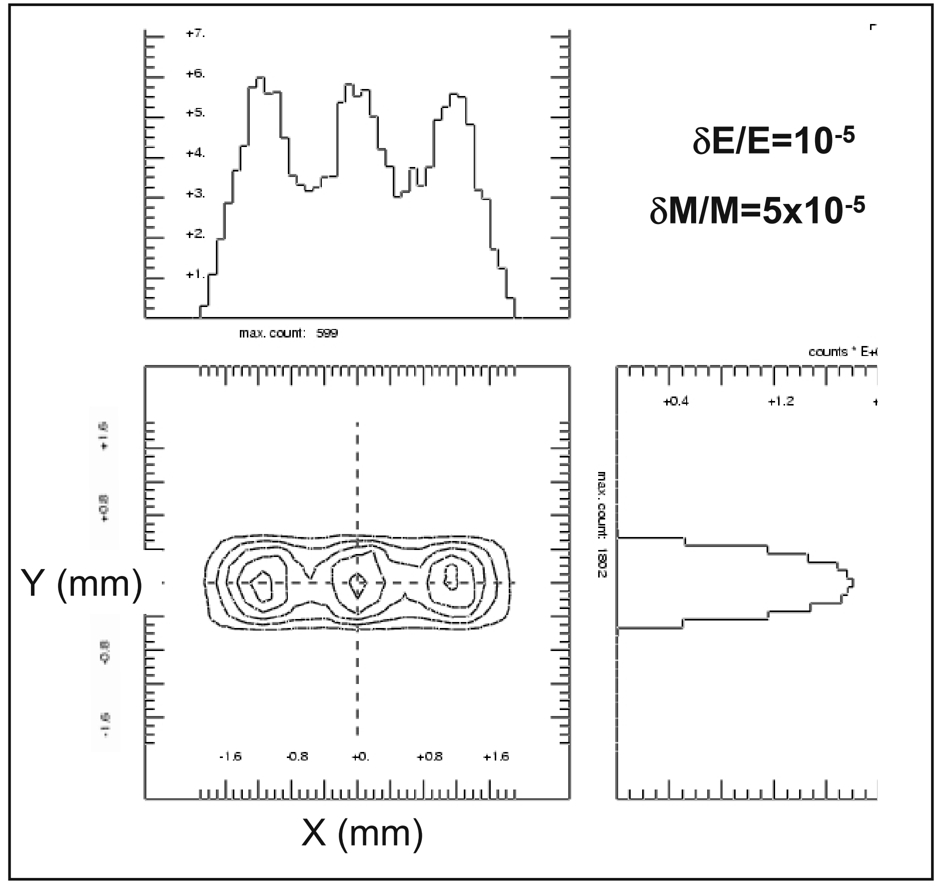
Beam Properties from gas catcher:
$\varepsilon \approx 3\,\pi$ mm•mr $\delta E \approx 1$eV
1 mm dia. (circular) beam
θ_{max}, φ_{max}= ±6 mr



- **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: 1/20000**
- **3 multipoles correct through 5th order**
- **Small enough footprint to fit on HV platform**

X and Y Projections at Focal Plane





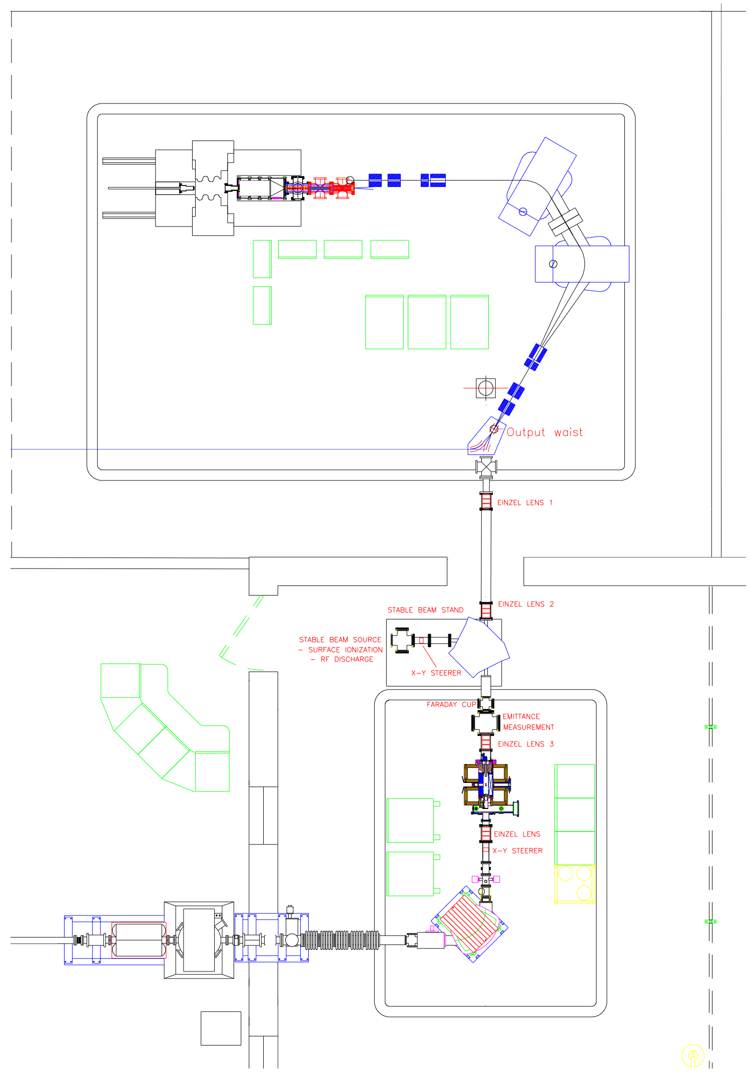
@50keV: δE = 0.05 eV

@50keV: δE = 0.5 eV

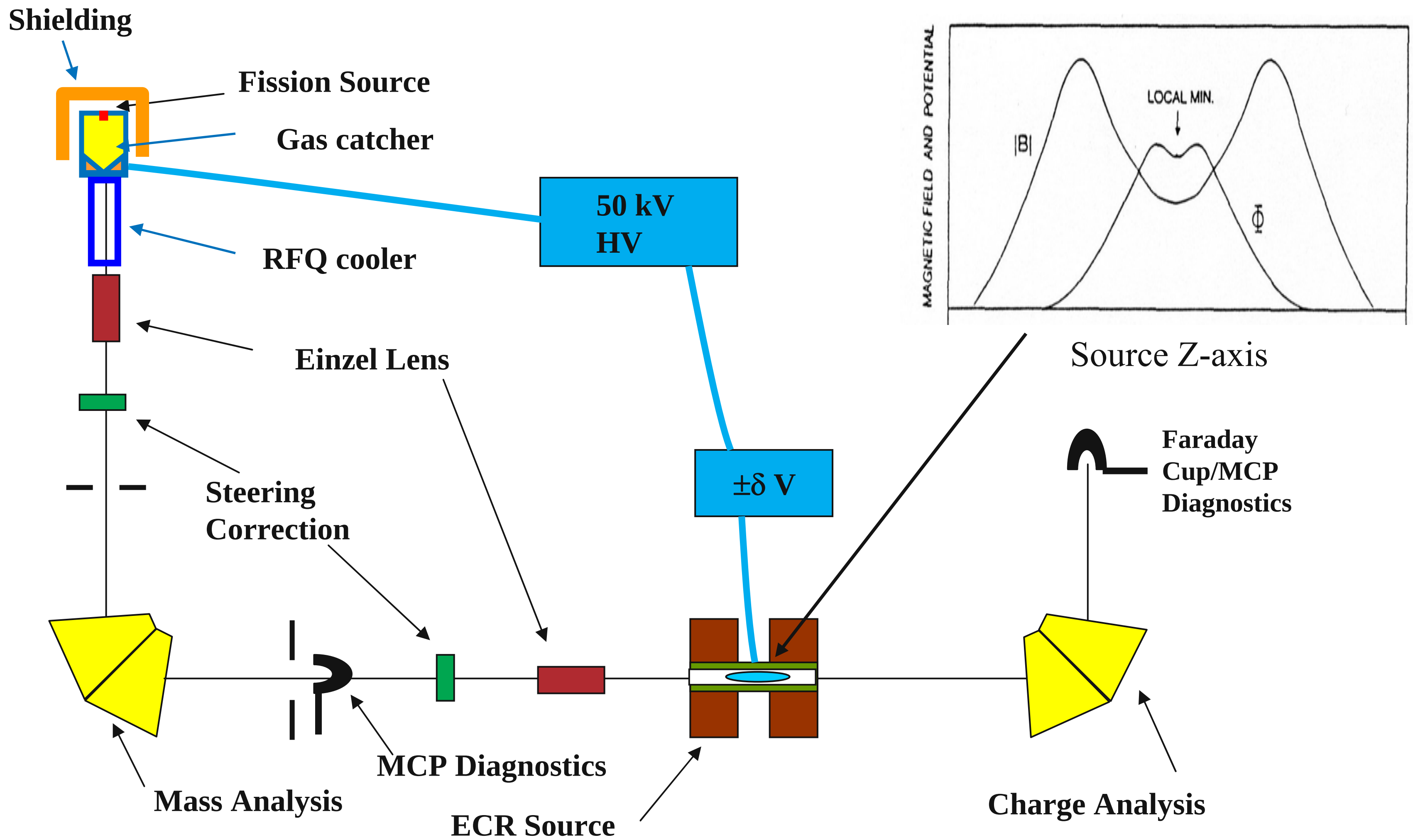
1+ → n+ Implementation with ECR-I – CARIBU

Acceleration in ATLAS requires the ion's q/m ≥ 0.15

- Radioactive beams from a 1.0 Ci ^{252}Cf fission source
  - Fission products are collected and thermalized in a helium gas catcher
- High resolution mass analysis (1:20,000) limits the number of isobars in the 1+ beam
- Transported to the ECR charge breeder source and stopped in plasma.
  - To achieve required mass resolution, source must operate at 50 kV (0.5 V stability)
  - High efficiency into one charge

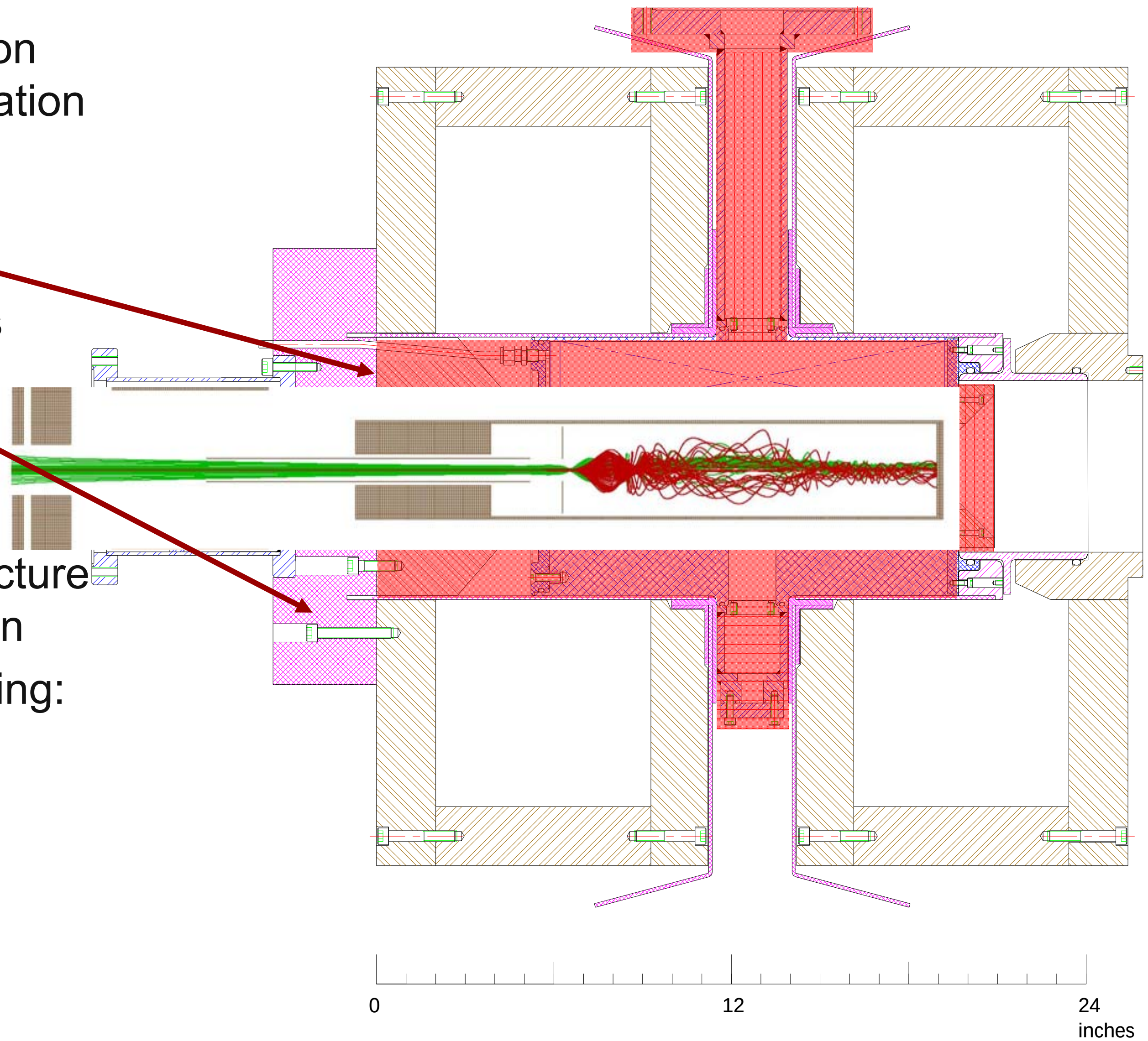


CARIBU ECR Charge-Breeder System



ANL ECR-I Modified to function as a Charge Breeder

- Necessary to increase ion charge state for acceleration in ATLAS. (q/m > 0.15)
- Injection side iron modifications to allow injection tube and optics
- High voltage isolation
  - **Increase to 50 kV**
- RF injection
  - Open hexapole structure allows radial injection
  - Two frequency heating: 10 & 14 GHz may improve efficiency



Phoenix 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
- CARIBU Efficiency assumed: 10% for gases and 5% for solids

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}

~75 species have accelerated intensities of over 10^{5}

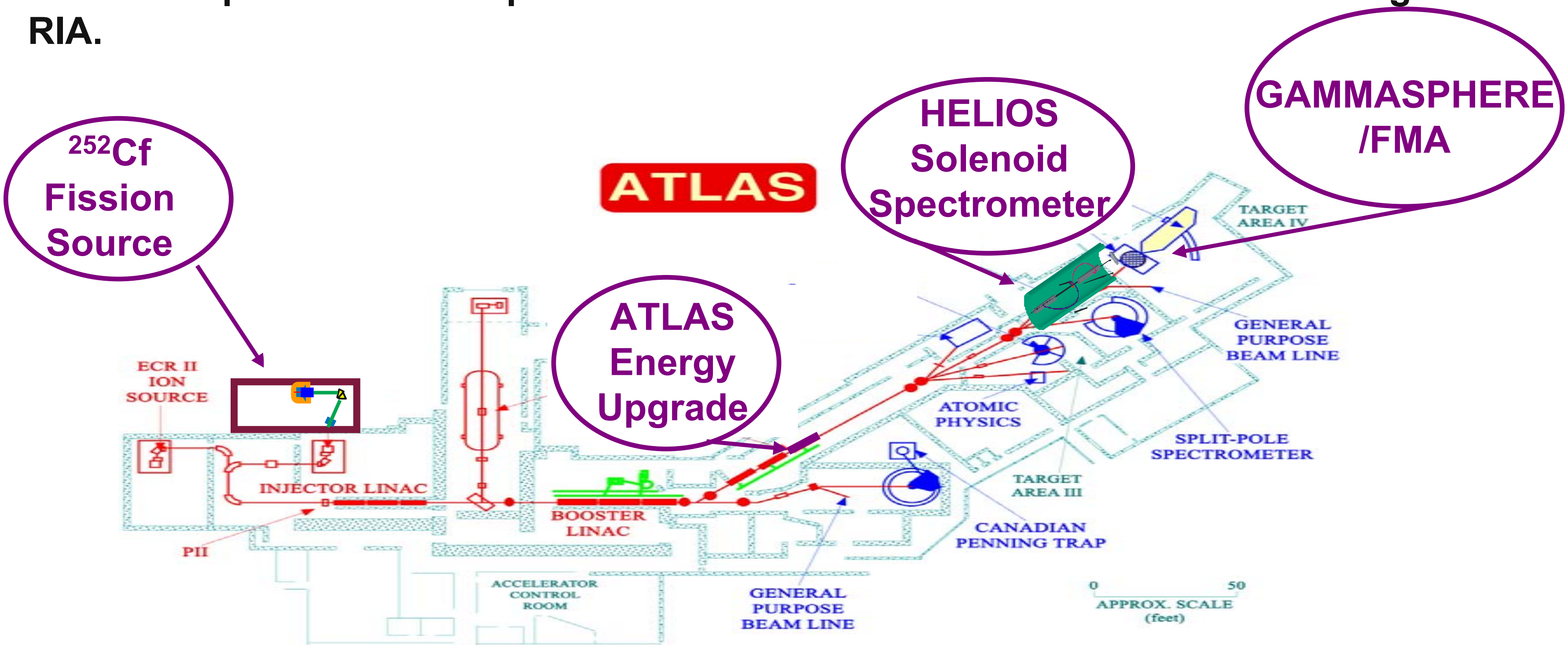
>125 species have accelerated intensities of over 10^{4}

Project Status

- Building and associated services complete.
- HV Platform construction complete.
- ECR Charge Breeder mods complete. 1+ stable beam system installation in progress. First charge bred beams before end of 2008.
- Construction and procurement of all other major components in progress.
- First tests with 3 mCi source by late spring 2008.
- Isobar separator installation Fall 2008.
- First charge bred beams late Fall 2008.

CARIBU + Energy Upgrade Project + Solenoid Spectrometer: Unique Synergy to address these issues

- **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 and the existing in-flight RIB program at these higher energies.**
- **These three projects, plus γ-sphere/FMA, will combine to form a unique facility which complements the capabilities of other world facilities in the era leading to RIA.**



Summary

CARIBU is an exciting, cost effective enhancement to the capabilities of the ATLAS facility that provides the tools necessary for cutting-edge nuclear physics research.

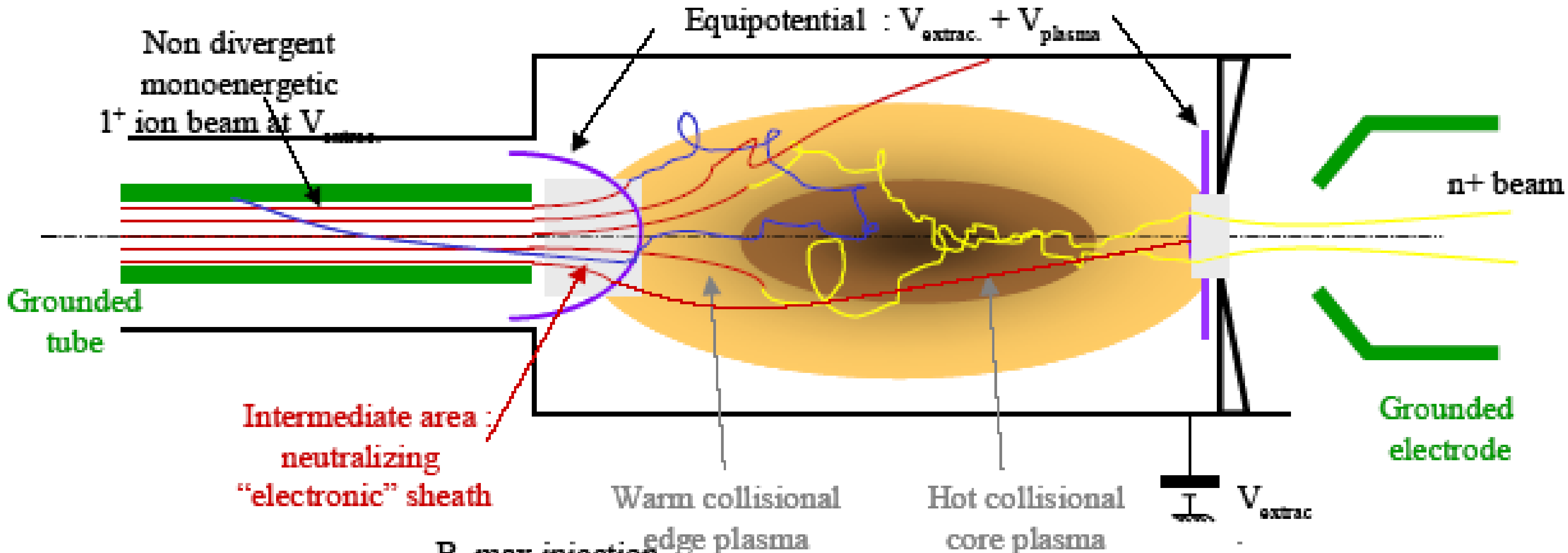
- ***The ^{252}Cf fission source project compliments other existing facilities.***
  - **Provides tools to address an important class of physics questions during the era leading up to a national exotic beam facility.**
  - **Interesting array of radioactive beams.**
  - **Energy regime not generally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

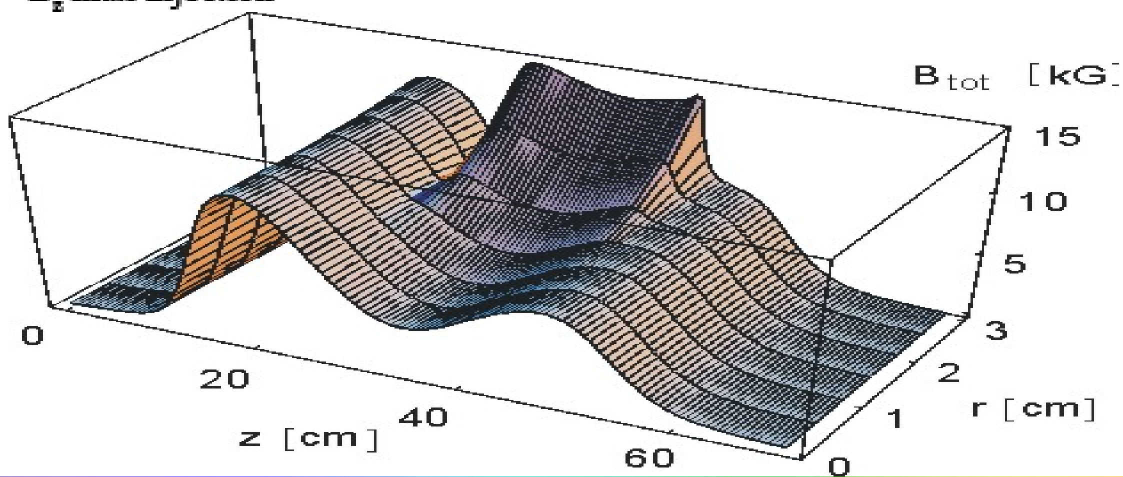
- ***Serves as a bridge to higher intensity facilities.***

- ***First beams are planned by the end of March 2009.***

- ***Total project cost: $4.6M***

Charge breeding concept – 1+n⁺

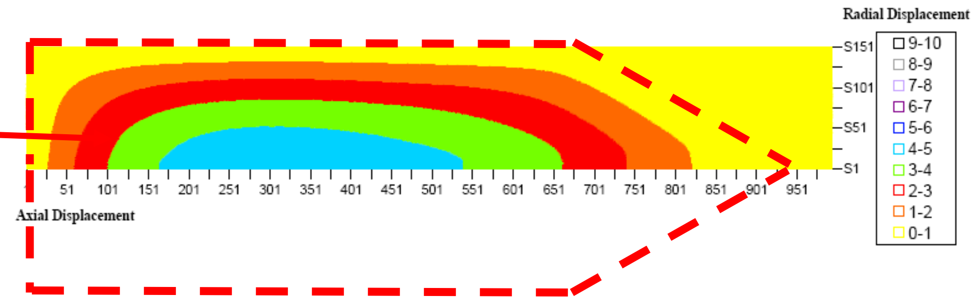




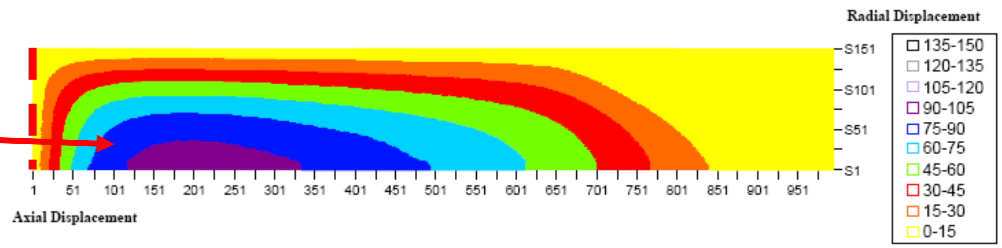
Space charge is the critical effect in the CARIBU gas catcher: Study of space-charge saturation in gas catcher

- **Space-charge effect is modeled:**
  - **by determining the time-averaged space-charge density in catcher by an iterative procedure**
  - **determining the resulting electric potential buildup**
  - **running ions of interest under the influence of the combined static and RF fields from the electrodes, DC potential from the space-charge and the gas flow**

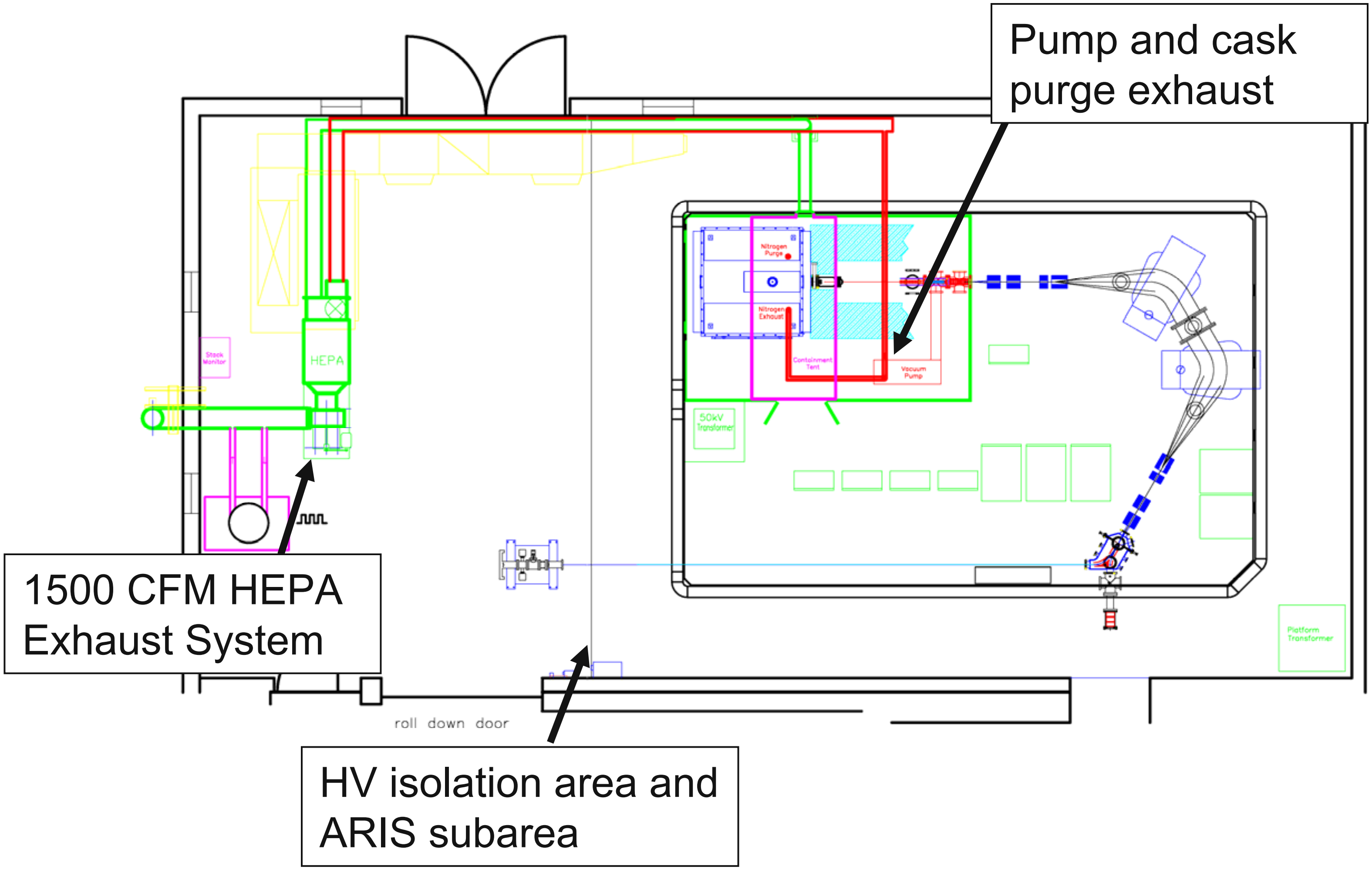
Potential buildup due to 200,000 incident Cs ions per second in CPT gas catcher at 9 V/cm DC gradient.



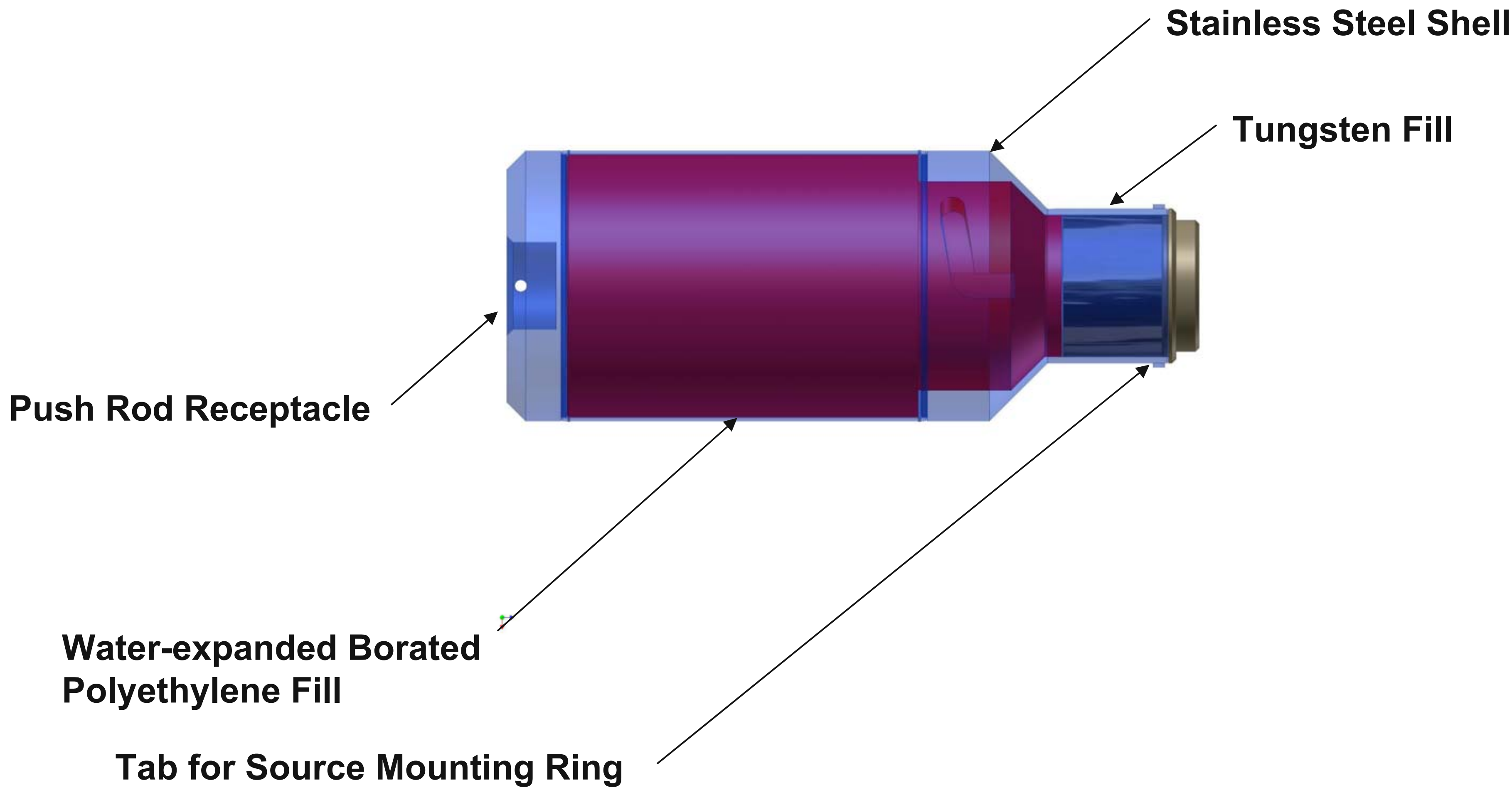
Potential buildup due to 50 million incident Cs ions per second in CPT gas catcher at 50 V/cm DC gradient.



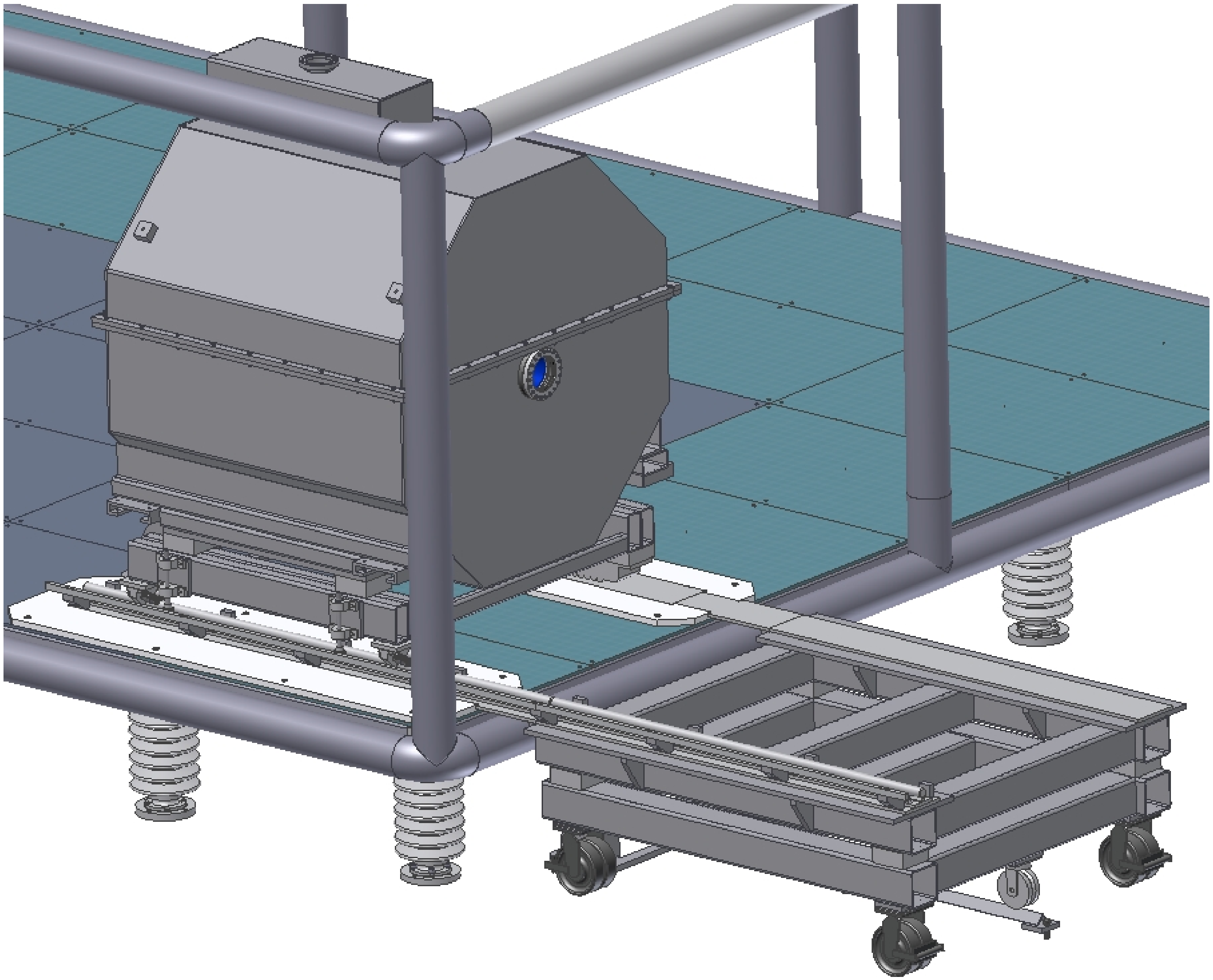
CARIBU Room, High Voltage Platform, and Equipment



Source Holder ("Milk Jug")



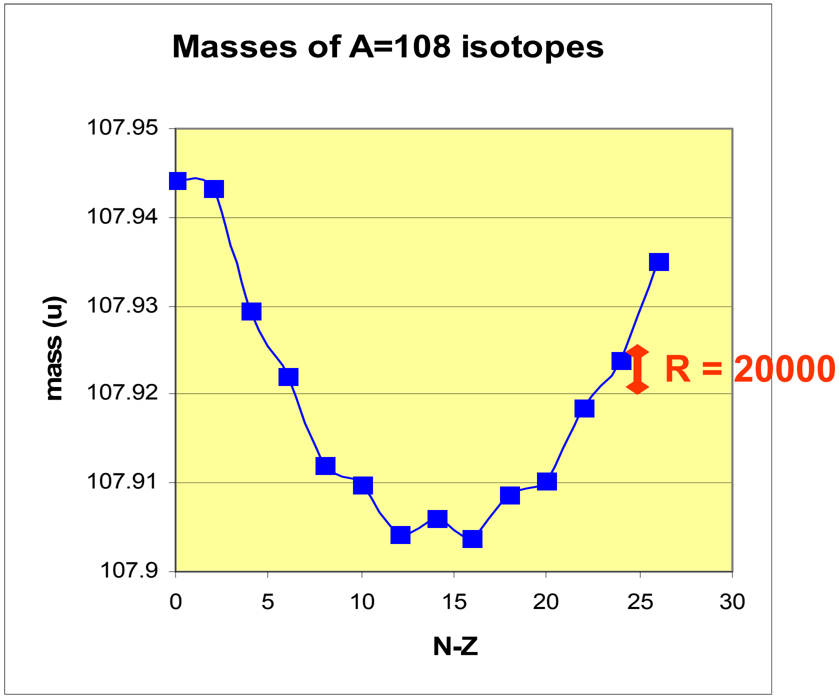
CARIBU Cask on HV Platform

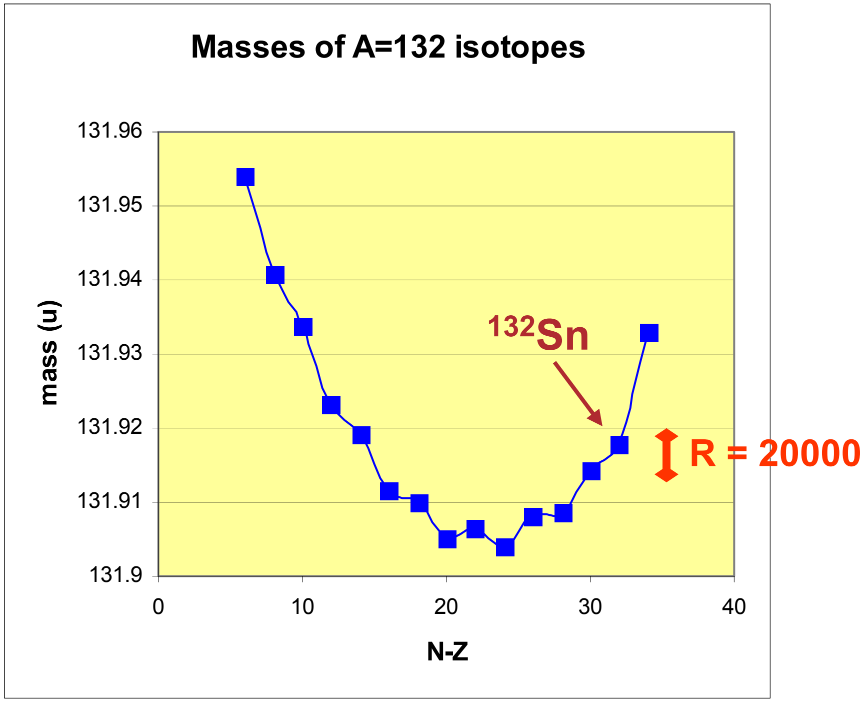


Purification of radioactive ion beam

•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





II. Two-nucleon 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

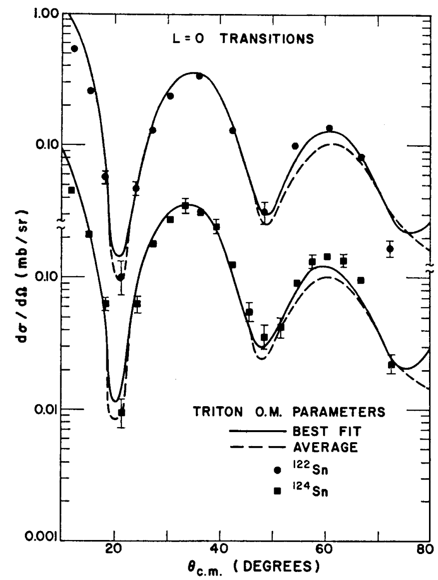


Fig. 1. $L = 0$ transitions. Distorted wave calculations are shown for two cases of optical-model potentials, the best fit parameters, and the average geometry parameters.

	Current ATLAS		ATLAS Upgrade	
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