NEUTRON-RICH BEAMS FROM ^{252}CF FISSION AT ATLAS – THE CARIBU PROJECT

Argonne NATIONAL LABORATORY

... for a brighter future

The 2009 Particle Accelerator Conference

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Richard Pardo, Project Manager
for the CARIBU Team

Argonne National Laboratory

U.S. Department of Energy

UChicago Argonne LLC

Office of Science
U.S. DEPARTMENT OF ENERGY

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

A U.S. Department of Energy laboratory managed by UChicago Argonne, LLC

Outline

CARIBU - CAlifornium Rare Ion Breeder Upgrade

- CARIBU in the context of low-energy nuclear physics research
- Project Description & Expected Performance
  - Technical approach
    - *Source and radiological issues*
    - *Gas catcher/RFQ cooler*
    - *ECR Charge-breeder*
    - *Isobar separator - beam purity*
    - *Low-Intensity Diagnostics*
- Status and Commissioning Plans

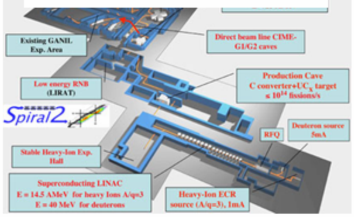
Low-energy nuclear physics research

Continued progress in nuclear physics and associated fields needs radioactive beams

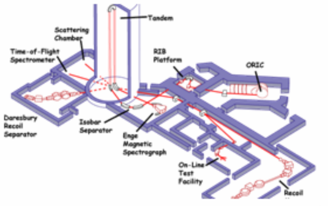
Proton-rich side reached by existing facilities

Neutron-rich side will be the focus of new facilities

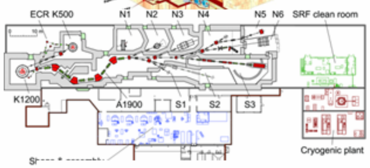
GANIL - SPIRAL



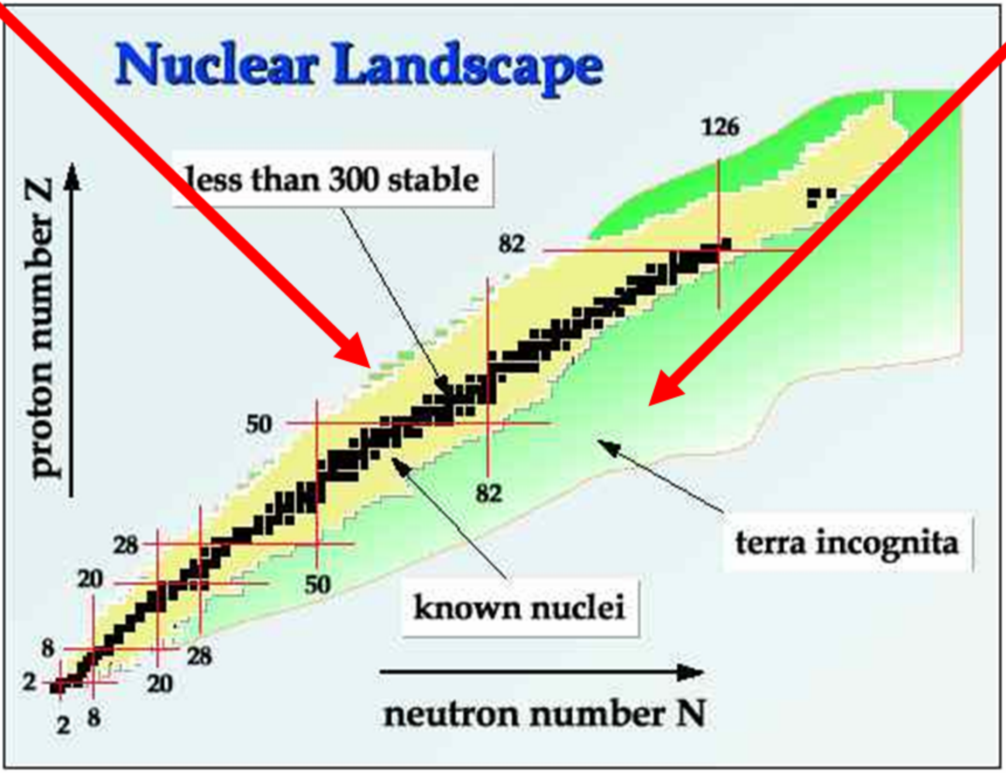
ORNL - Holifield



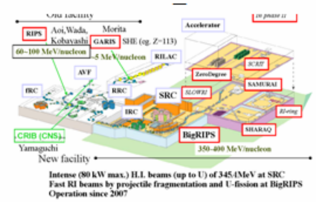
TRIUMF - ISAC



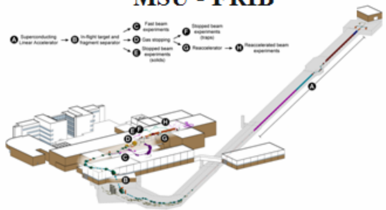
MSU - NSCL



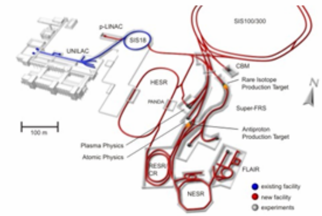
RIKEN _ RIBF



MSU - FRIB



GSI - FAIR



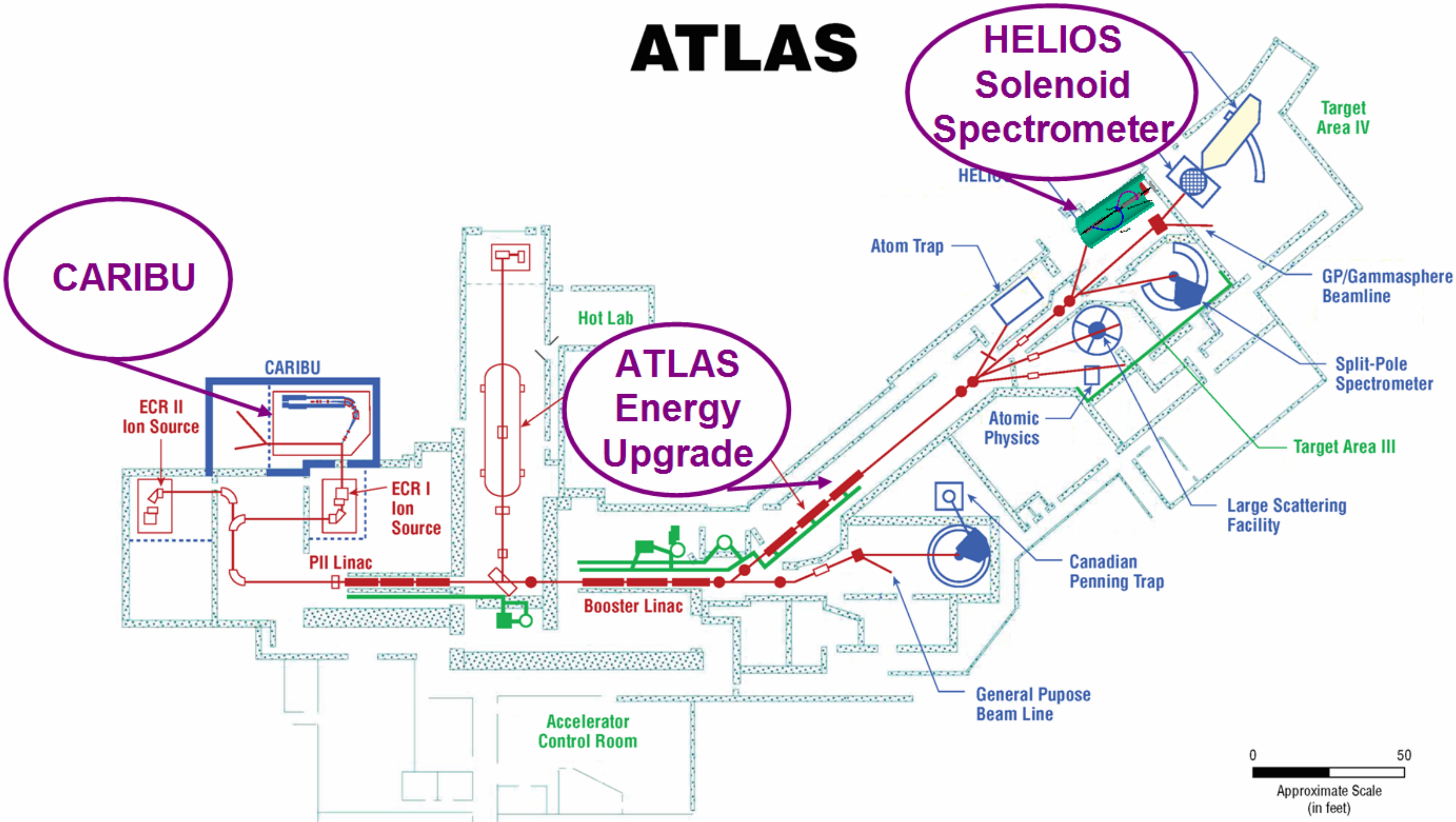
n-rich region is the next frontier

CARIBU - CAlifornium Rare Ion Breeder Upgrade

A neutron-rich ion source for ATLAS

CARIBU + Energy Upgrade Project + Solenoid Spectrometer: Unique Synergy

These three projects combine to form a truly forefront facility for neutron-rich beams that complements the capabilities of other world facilities in the era leading to FRIB.

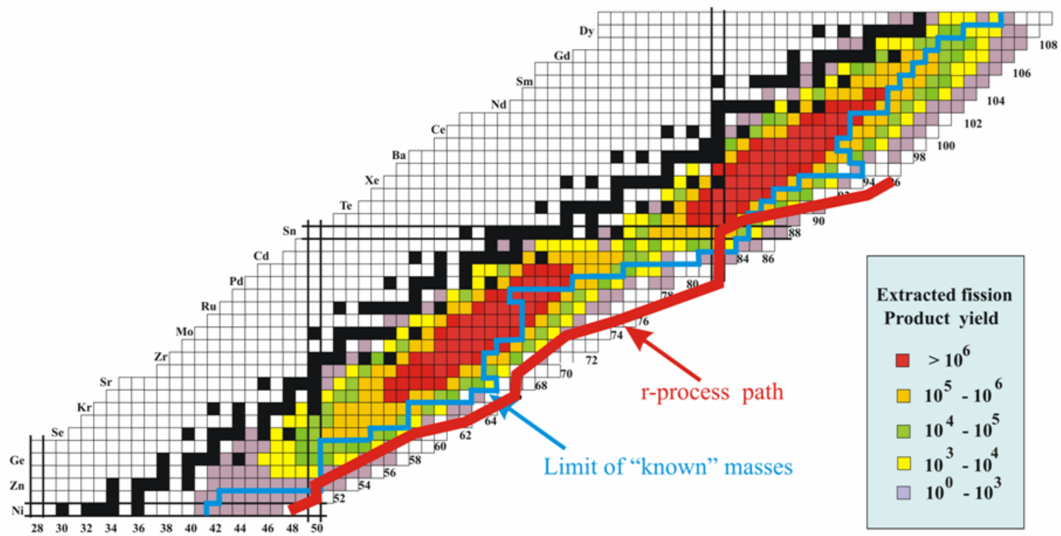


A Californium Fission Source for ATLAS

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

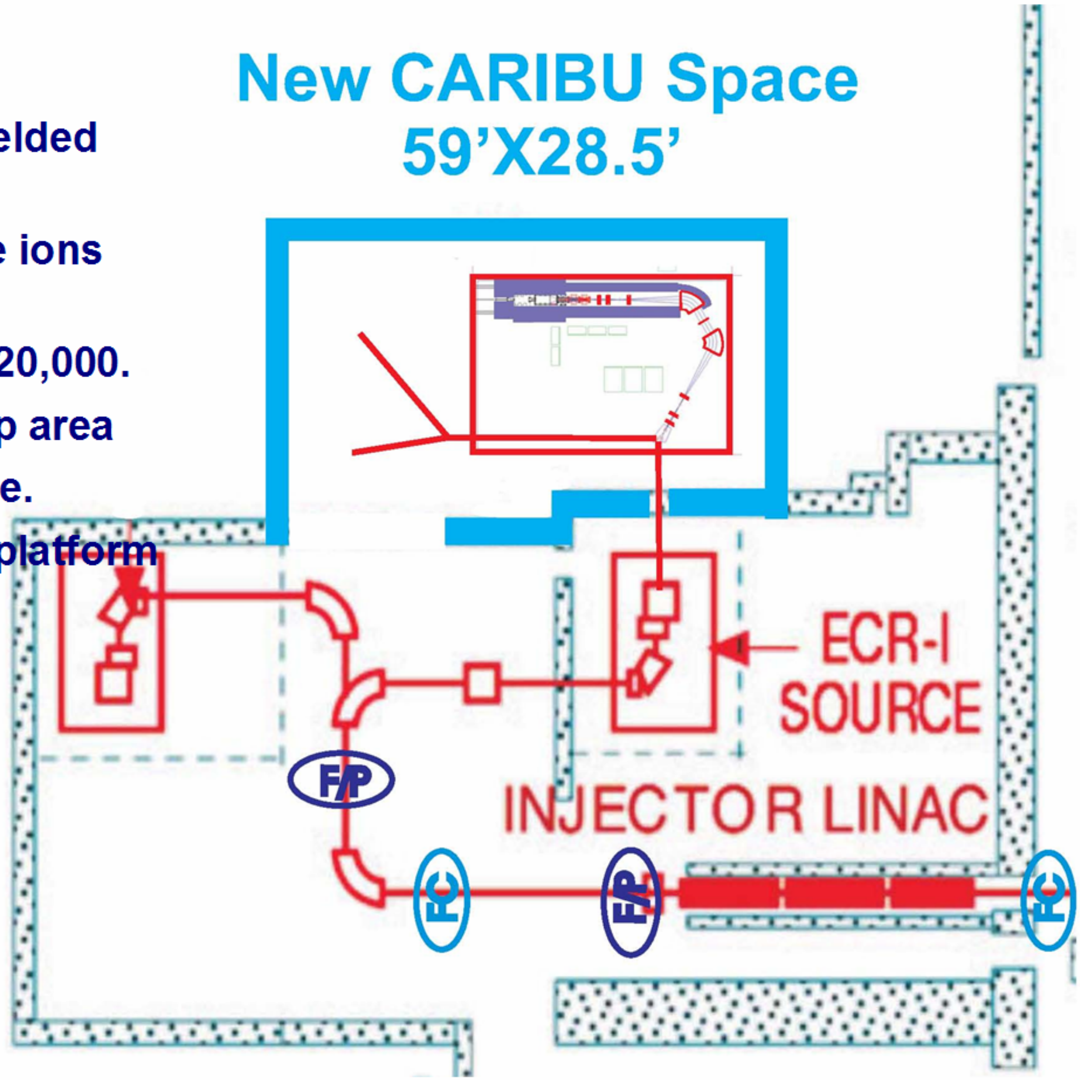
^{252}Cf spontaneous fission yield

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



^{252}Cf Fission Source System

- New ~1600 ft^2 building.
- 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 ion & atom trap area
- ECR charge breeder ion source.
- Mounted on HV (up to 200kV) platform
- Weak beam diagnostics.



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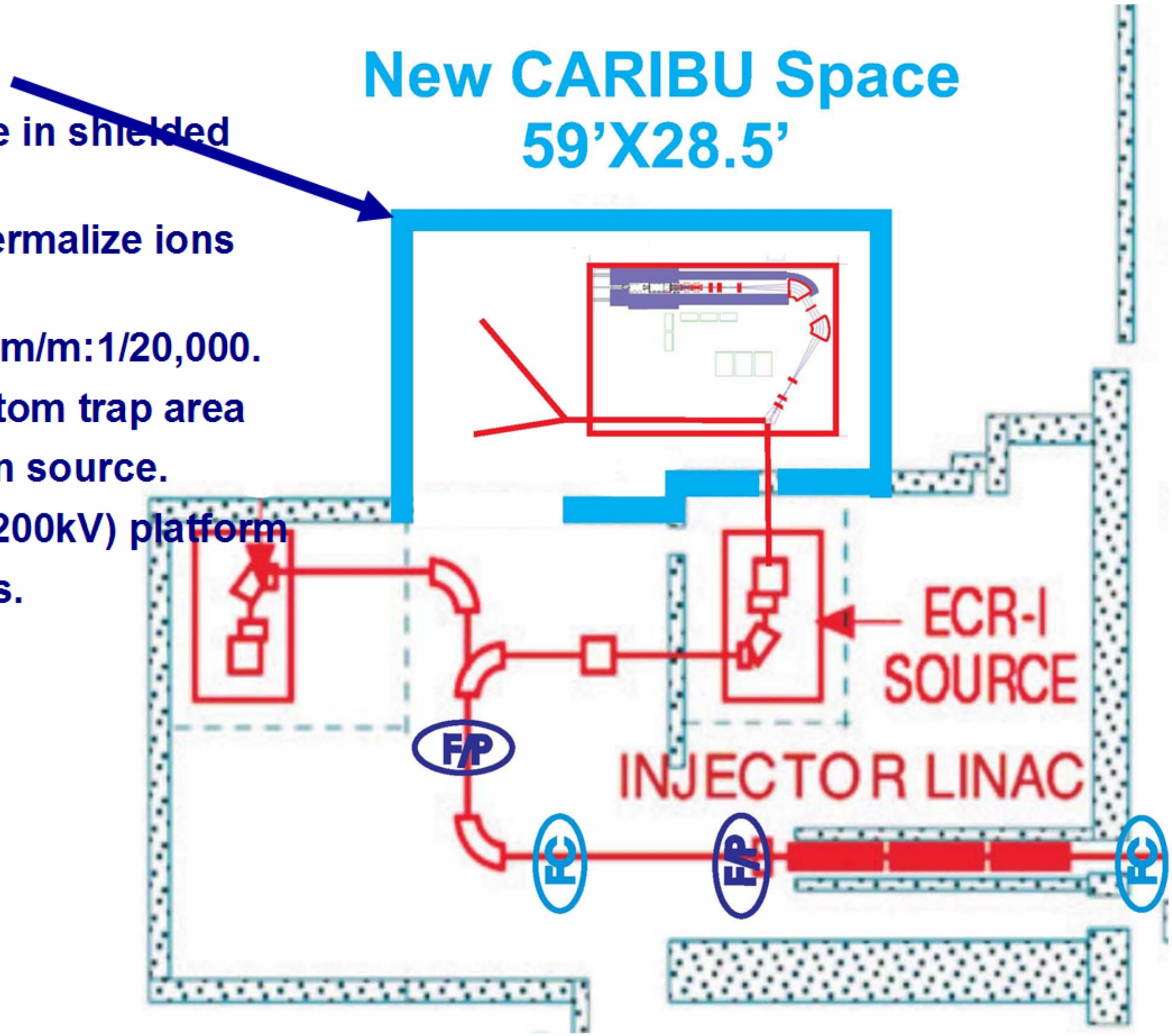

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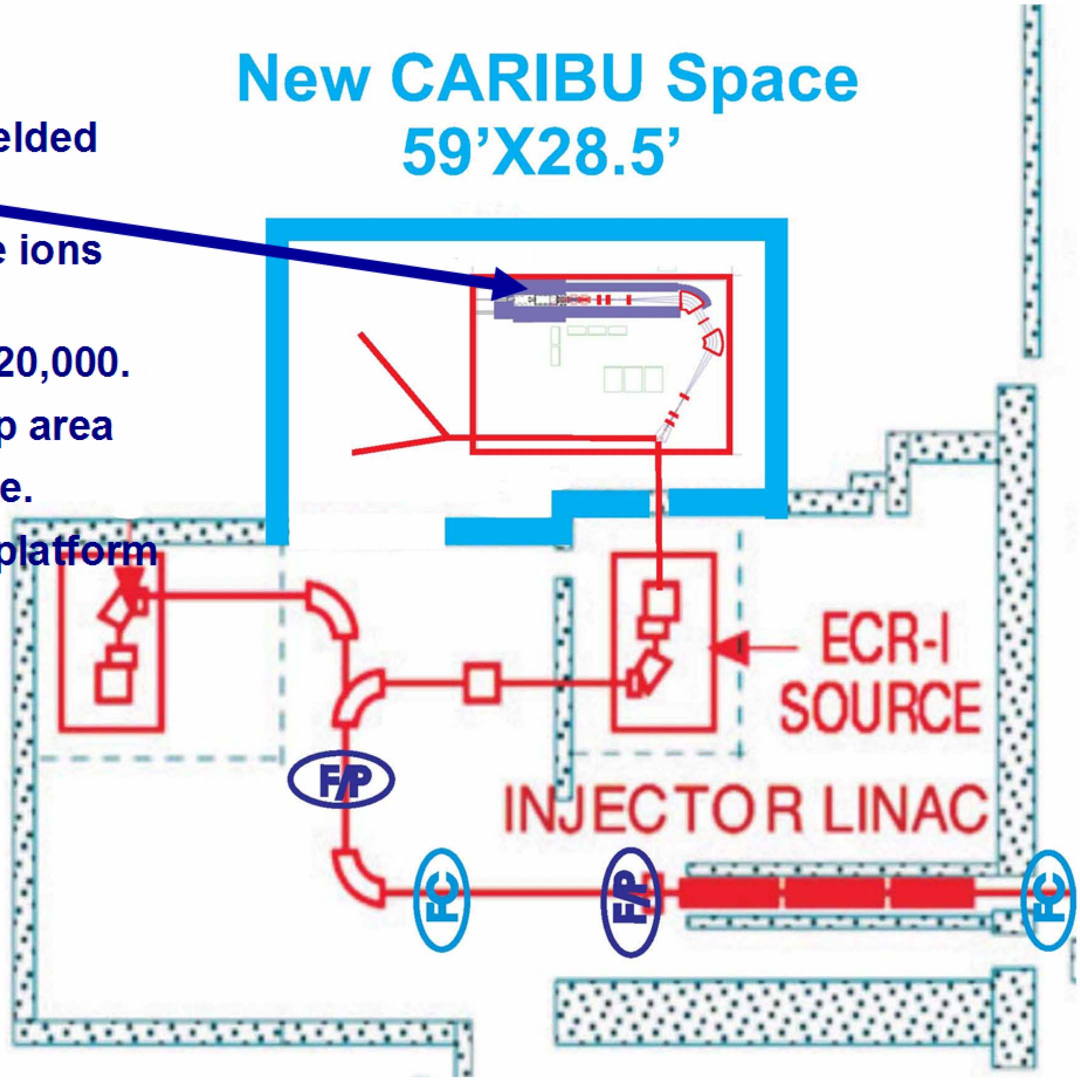

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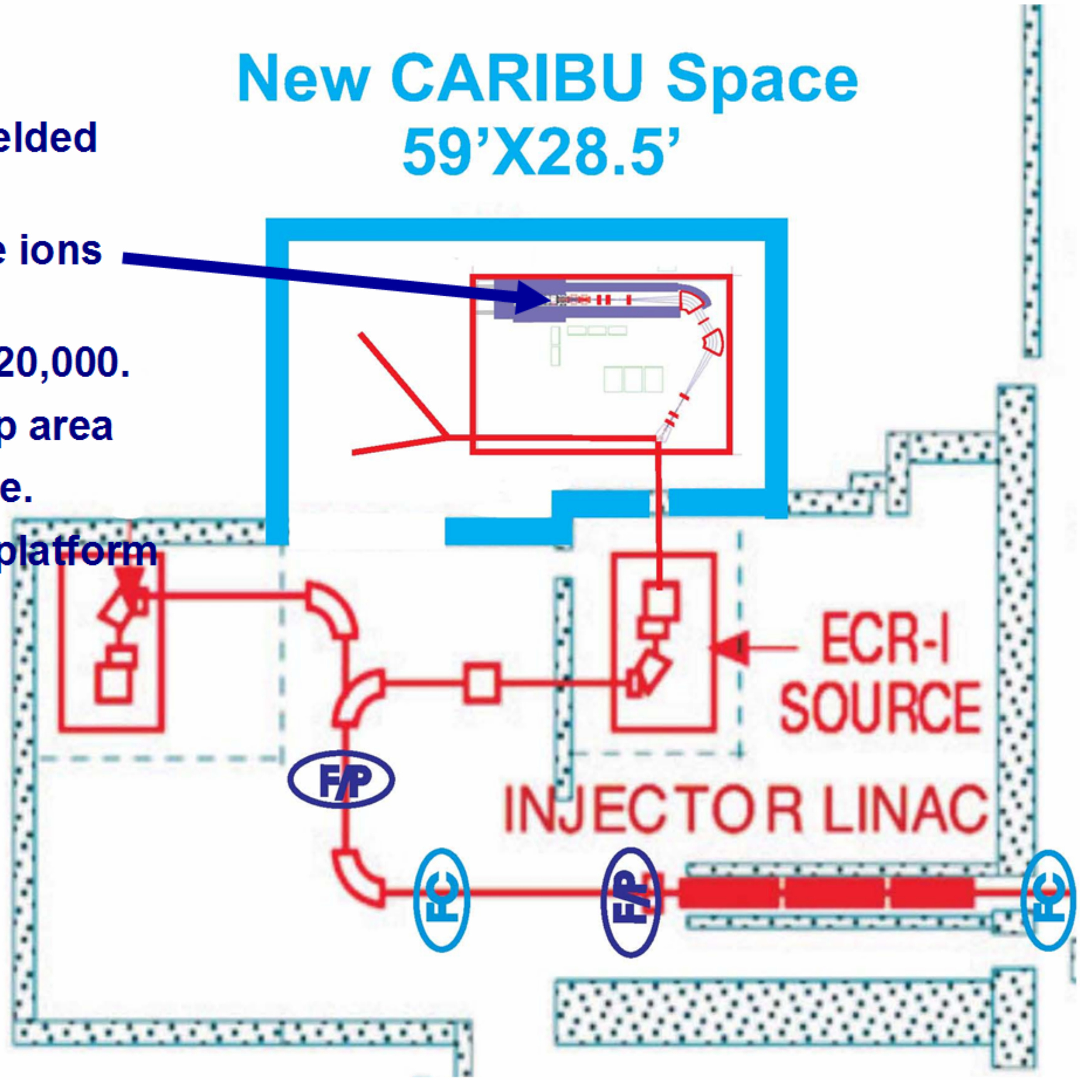

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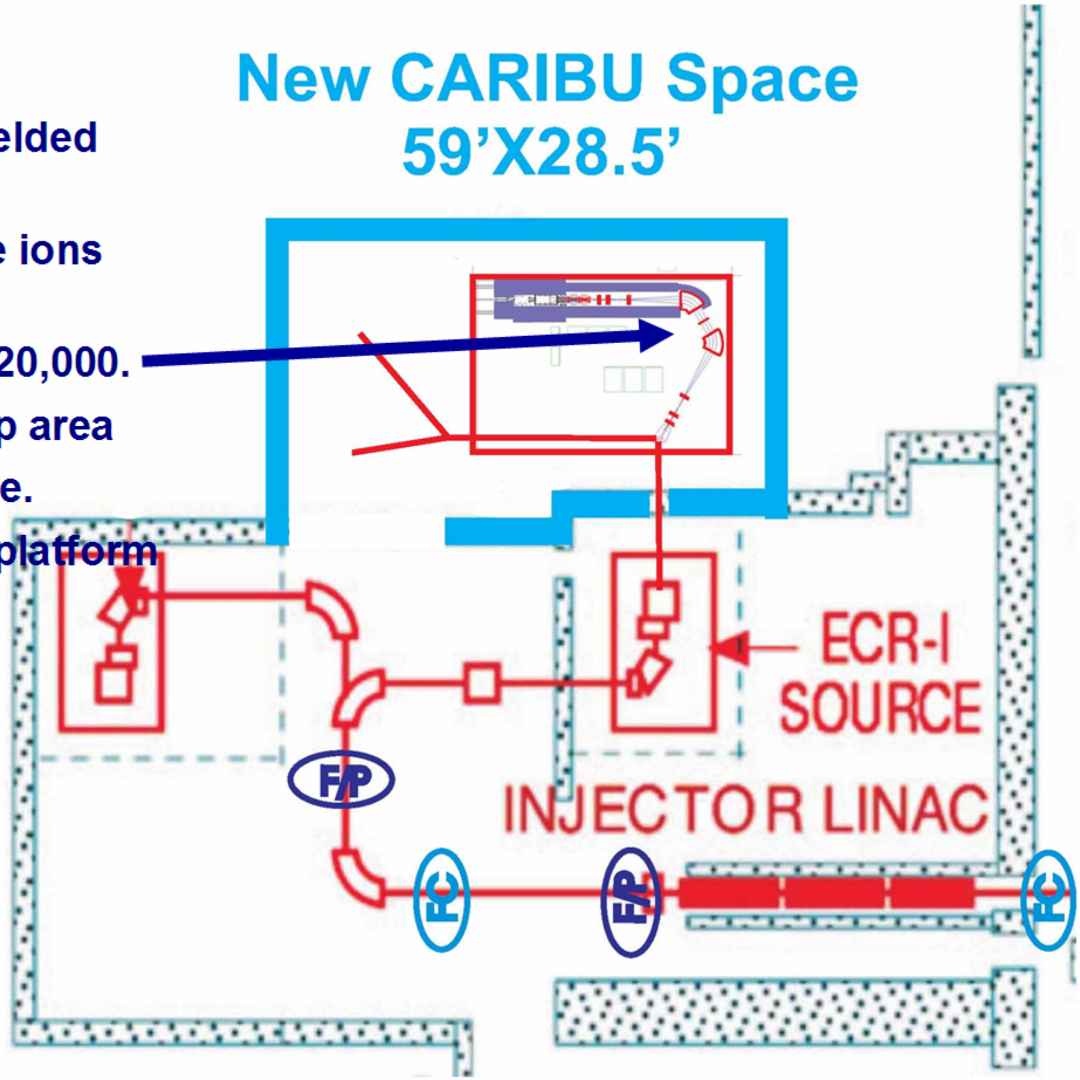

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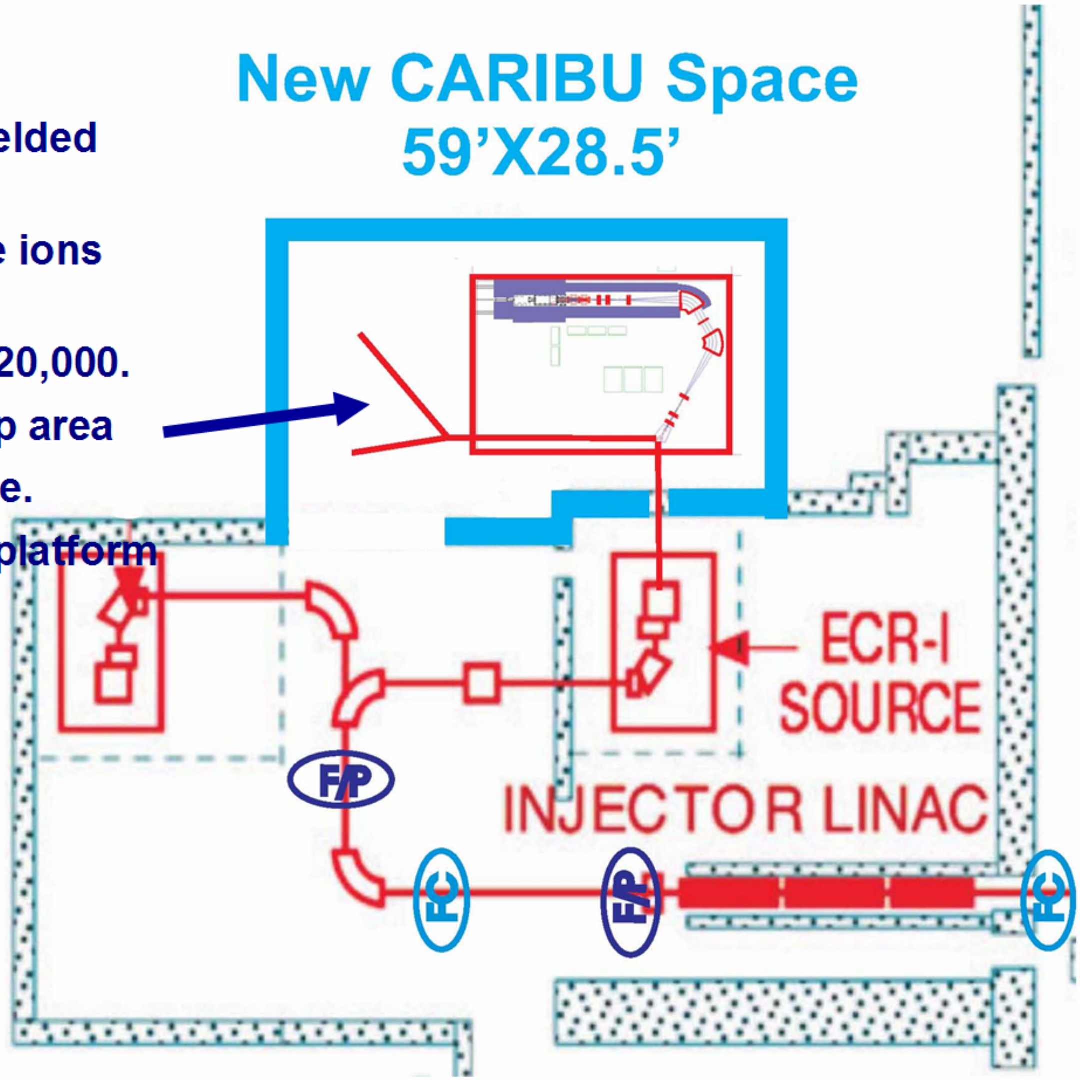

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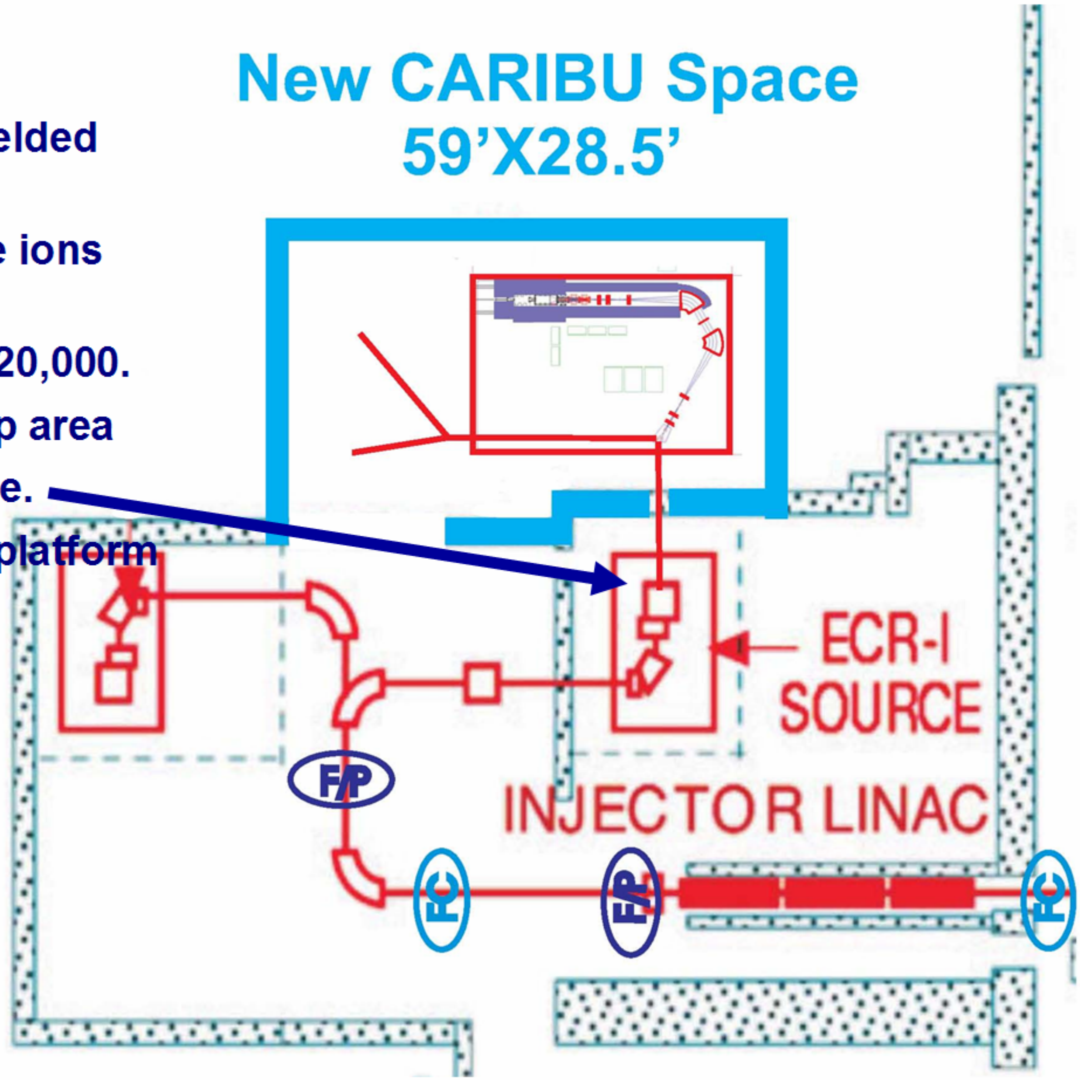

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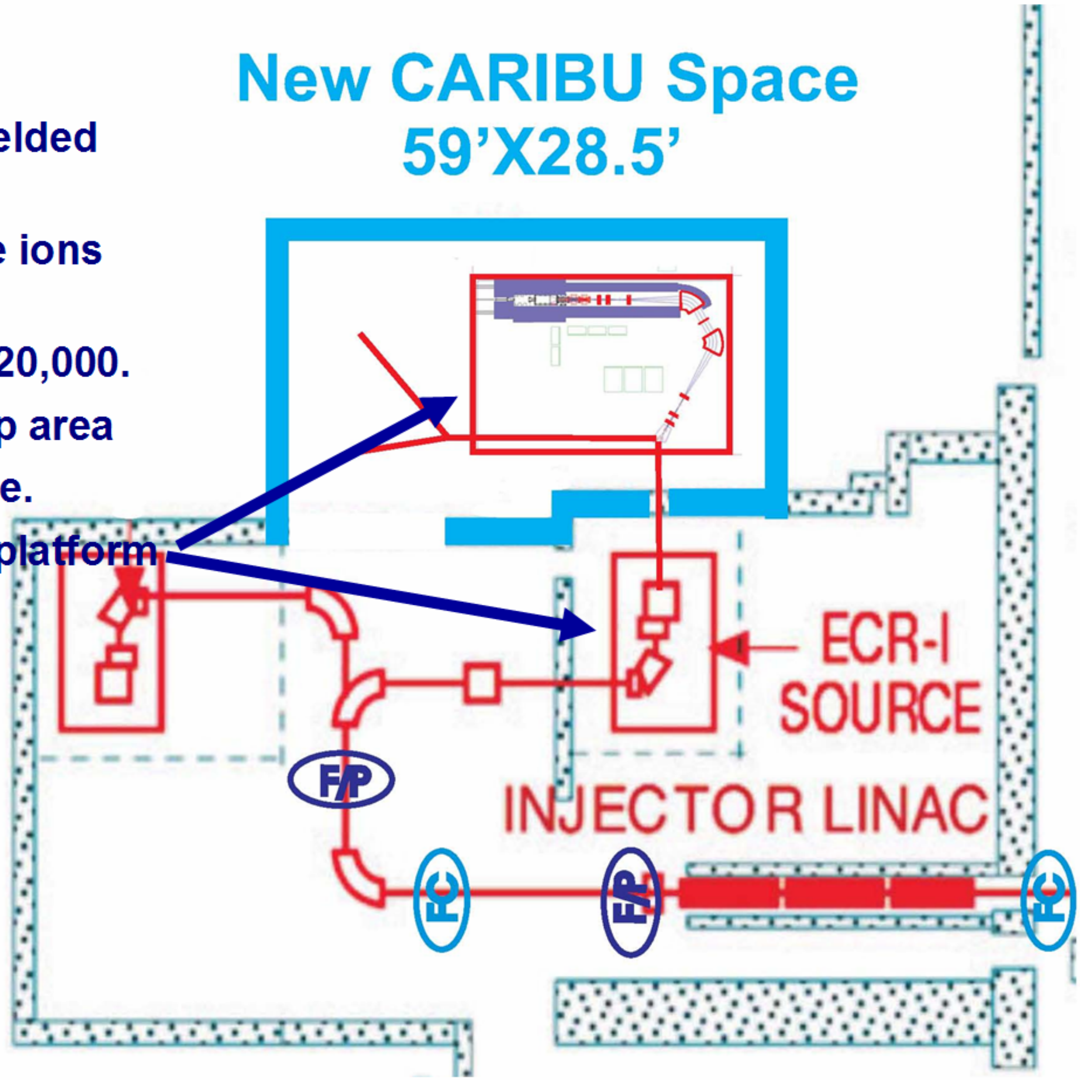

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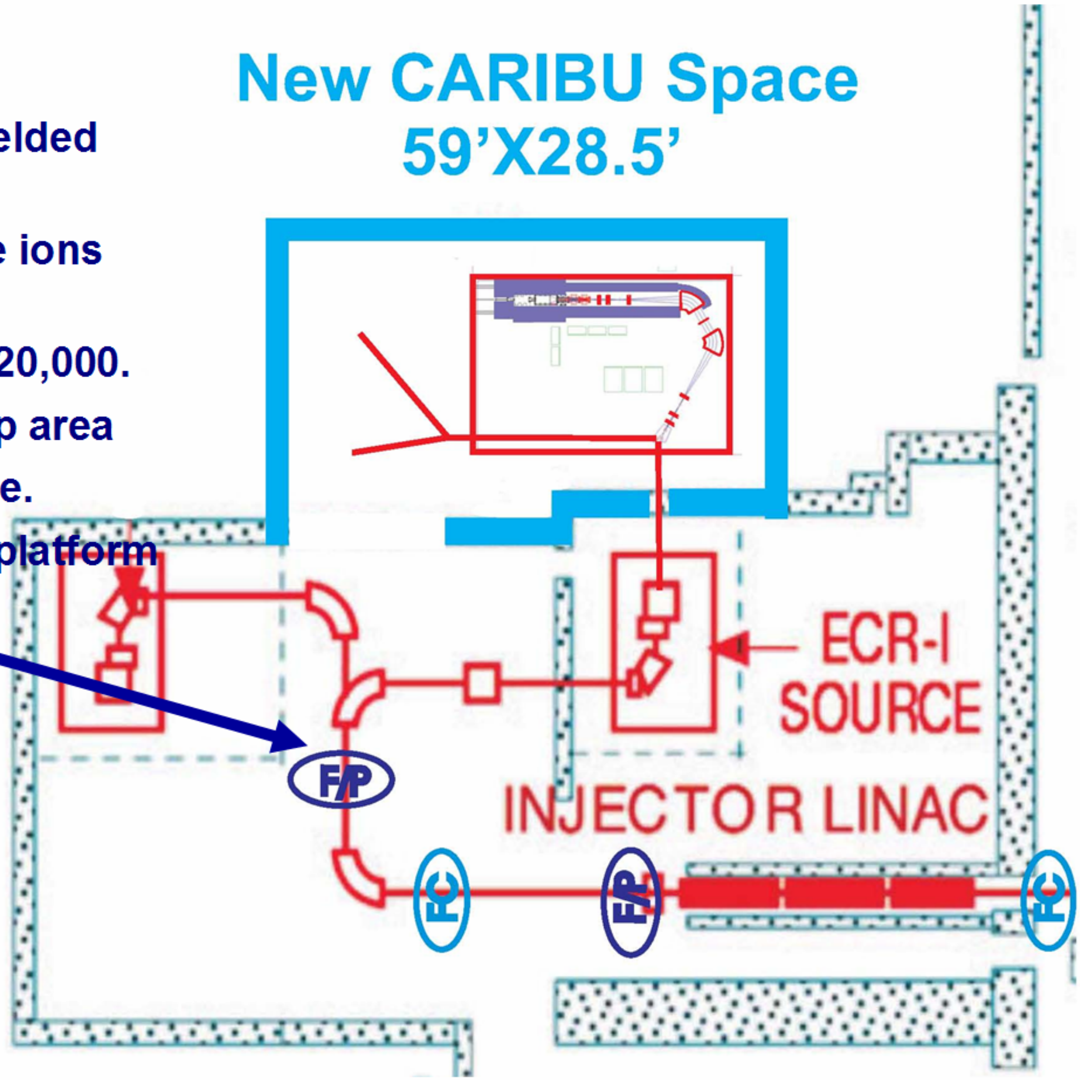


Examples of Yields for Representative Species

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

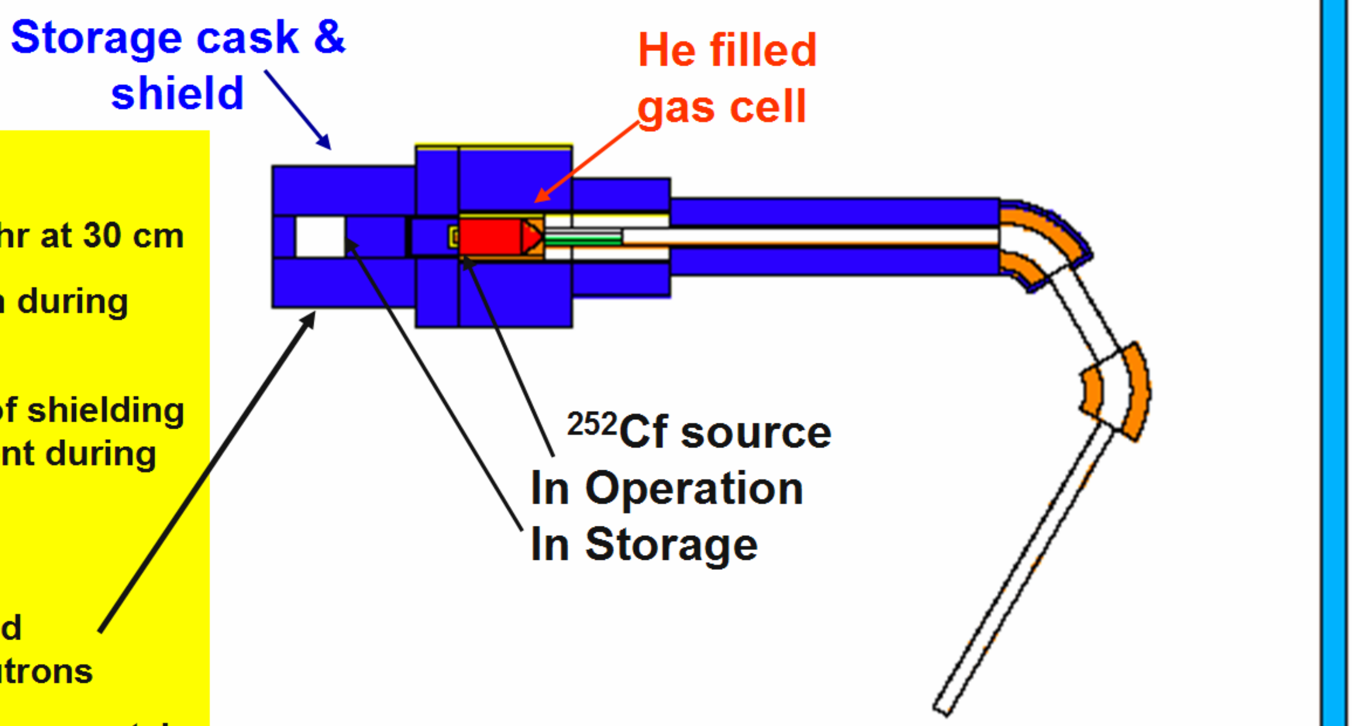
Californium source characteristics

- CARIBU will (eventually) use fission fragments from a 1 Ci source of ^{252}Cf.
  - Start with two weaker sources – ~2 mCi and ~80 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.
- ^{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 1.9 cm diameter circle this yields a density of ~660 $\mu g/cm^2$
- A 1 Ci source has significant radiation and radioactivity emissions
  - 46 rem/hr neutrons at 30 cm
  - 5 rem/hr γ-rays at 30 cm
  - Radioactive and noble gas emissions must be trapped or exhausted

CARIBU Shielding

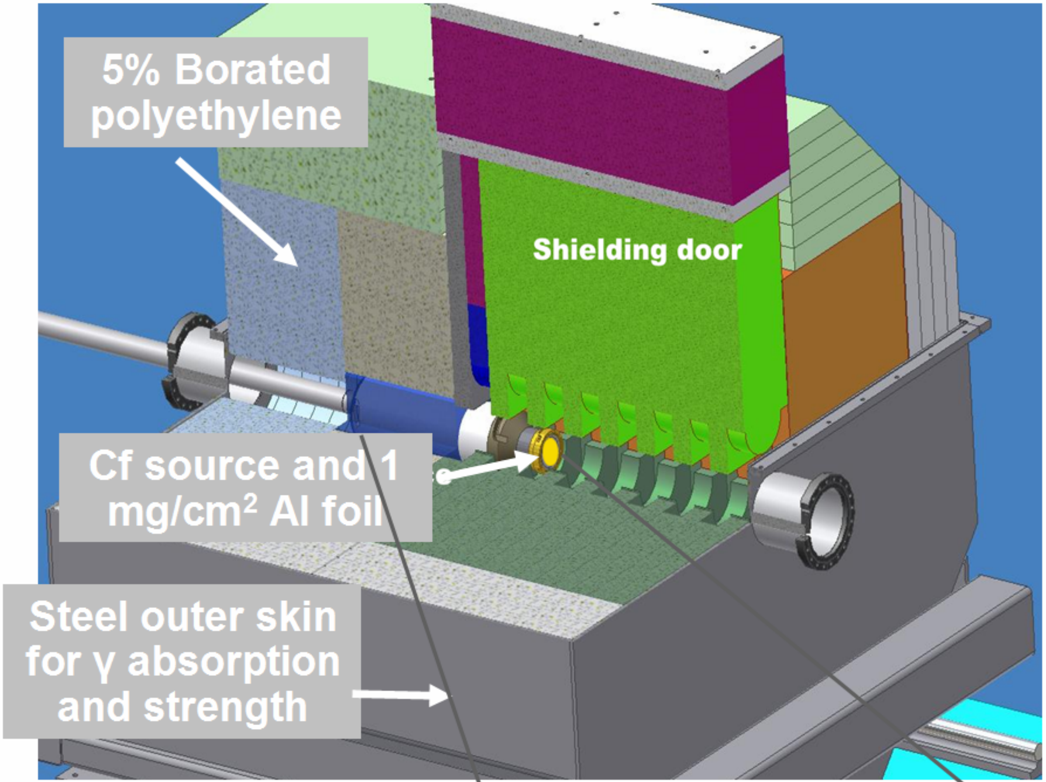
Required: Access to equipment near source for extended periods.

- Shielding Design Goals
  - Less than 1 mrem/hr at 30 cm
  - Fully shielded even during source installation
  - Manual operation of shielding and source movement during installation
- Shield requirements:
  - ~0.65 m. 5% borated polyethylene for neutrons
  - Additional 5 cm. heavy metal shielding for γ-rays
- Exhausting system through HEPA filters for volatile species.



CARIBU Shield Cask

- The CARIBU source is installed in a shielded storage cask
- Shields, stores and transports ^{252}Cf source
  - Tungsten for γ absorption
  - borated polyethylene for neutrons
  - Outer steel for
    - secondary γ
    - fire suppression
    - strength for transport



- The source is mounted on a shielded plug which provides shielding for unplanned emergency work.

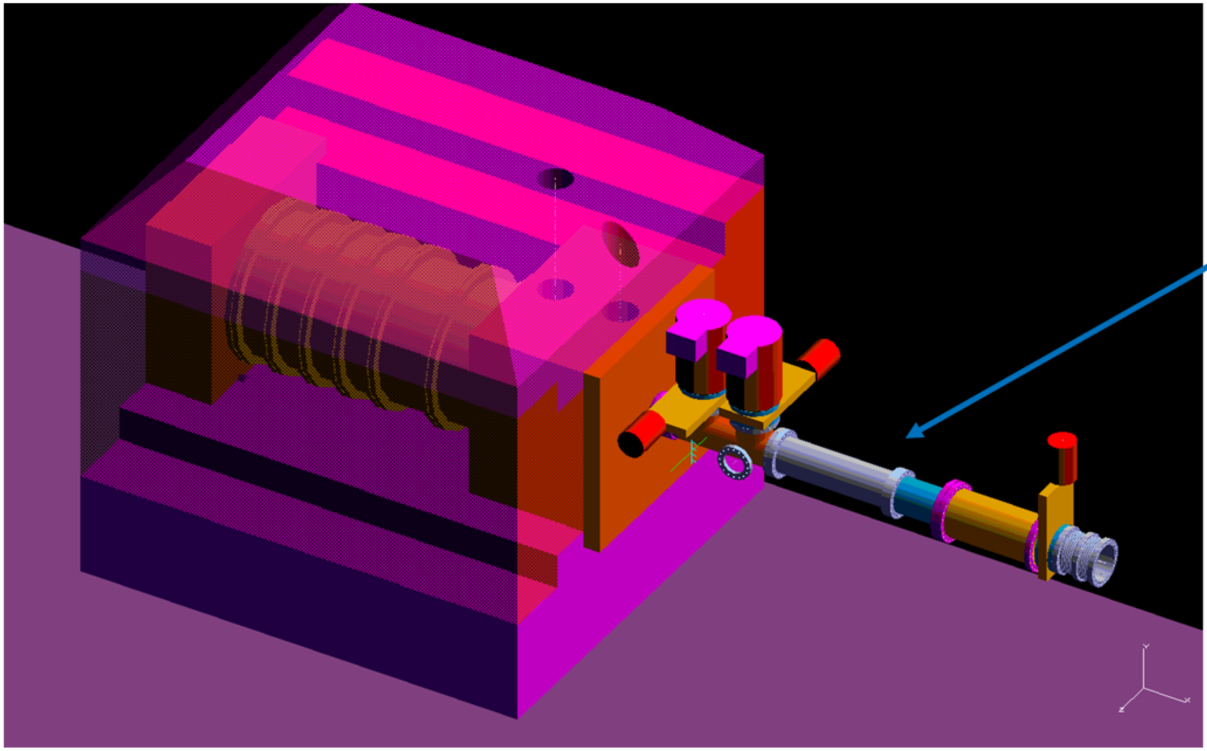
Californium source and gas catcher relationship

- For installation in the gas catcher, the source and shielding plug are pushed from the storage location into position at the end of the helium gas catcher.
- The assembly is sealed to the gas catcher, the source being inside the gas catcher.

Gas catcher shielding

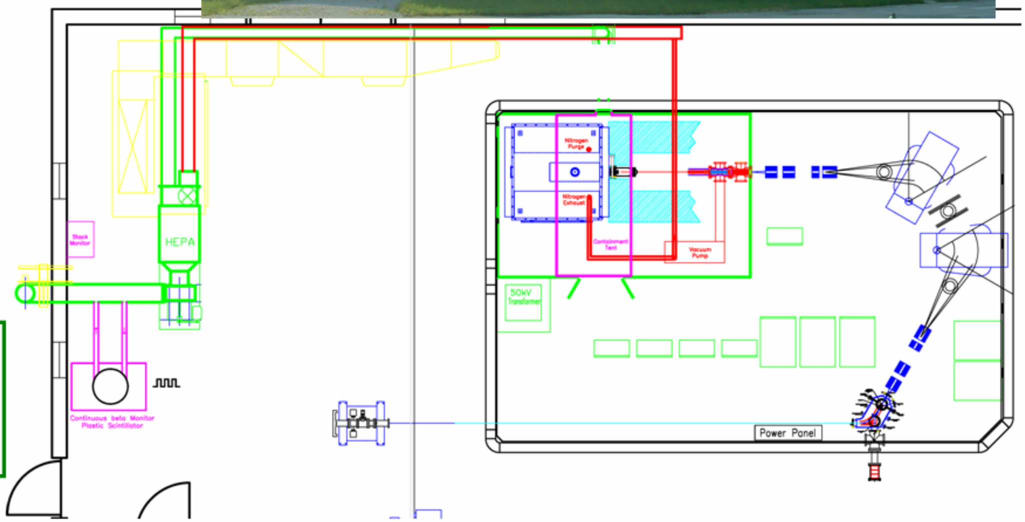
- Gas catcher shielding
  - *Interlocked pieces to remove line of sights*
  - *Removable to provide access for maintenance*
  - *Leave ports for pumping and RF feeding access*
  - *Polyethylene enclosed in metal shield to minimize fire hazard*
  - *Whole shielding assembly sitting at 50 kV above platform*

Additional shielding will be installed around beamline



Monitoring and exhausting radioactive volatiles

- CARIBU building is kept at negative pressure by HEPA exhaust system
  - Contains any spill/leakage
- Cask storage space purged by N_2 flow
- Combined with gas catcher exhaust
  - 100 second holdup time
  - Charcoal traps for iodine
  - Additional small HEPA
    - *Particulate trap*
- Continuous exhaust monitor
  - Exhaust ß activity logged
- Work area n/γ monitored

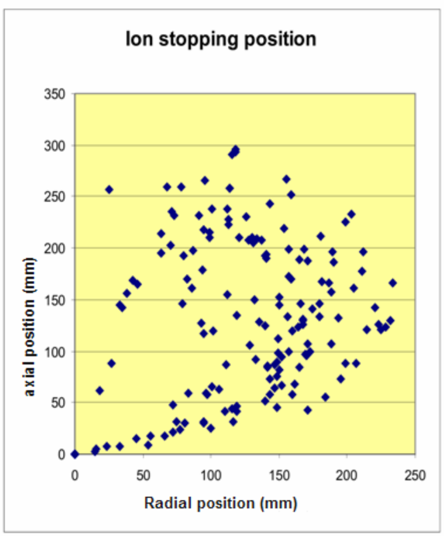


See: TH5RFP093 "Fission Fragment Ion Source Radiation Protection", Samuel I. Baker, et al for more information.

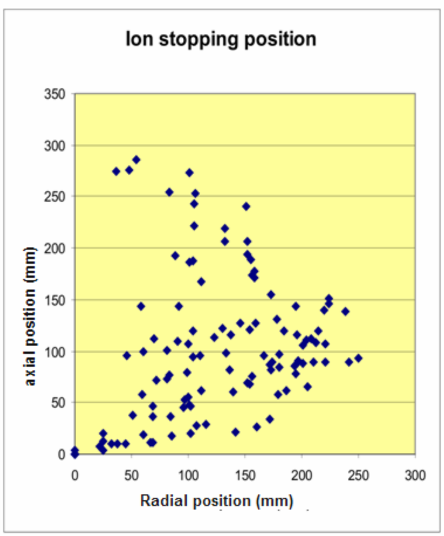
CARIBU gas catcher requirements (1)

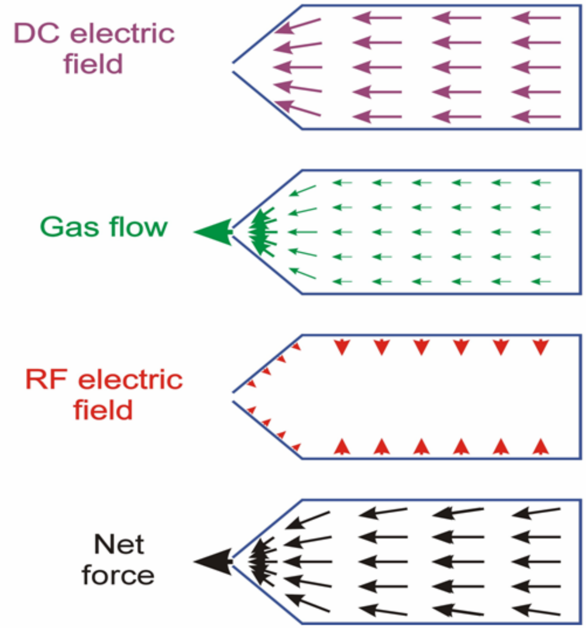
- **Detailed simulations of fission fragment stopping in the gas catcher, incorporating contaminants in the californium source, source size, protective foil, spherical degrader thickness and size, and proper energy-mass distribution for different fragments indicate that**
  - **a 50 cm gas catcher diameter 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***

^{104}Mo



^{144}Xe





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*

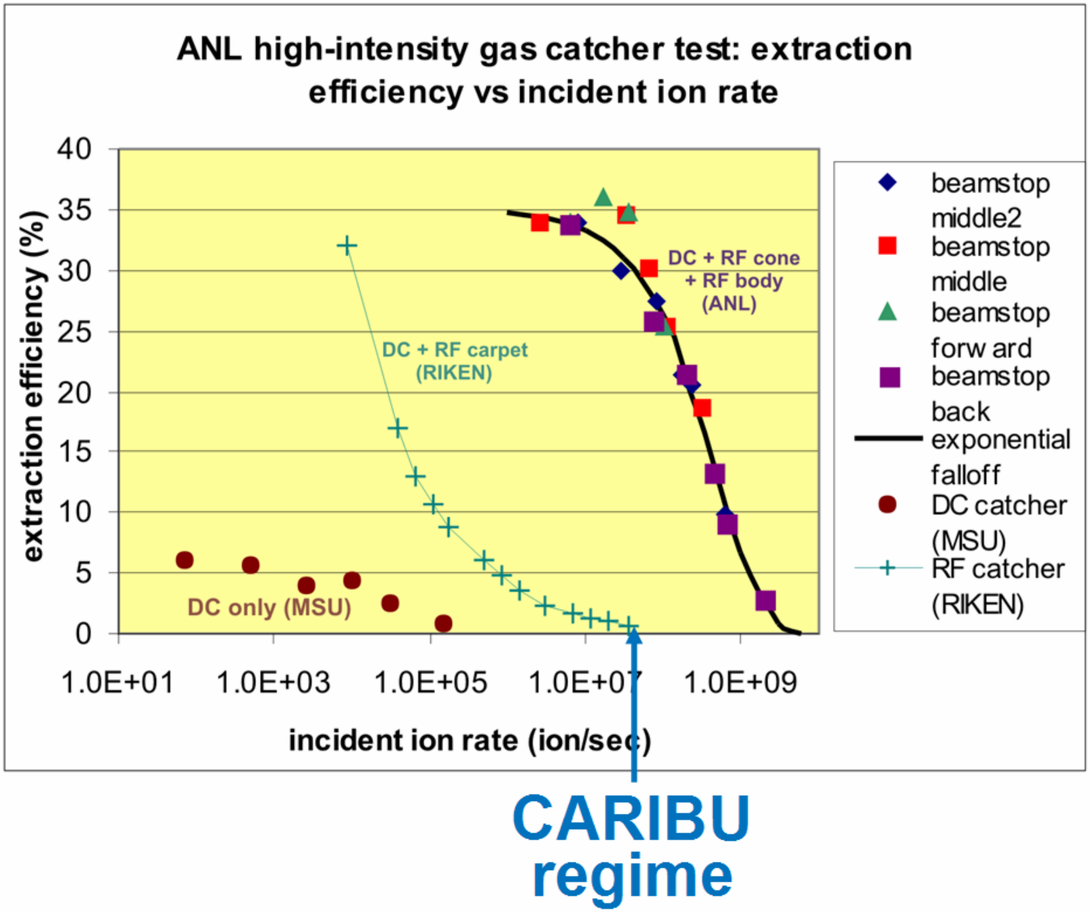
~ 10-100 times higher ionization than normal CPT operation

~ 10 times below FRIB-like ionization density

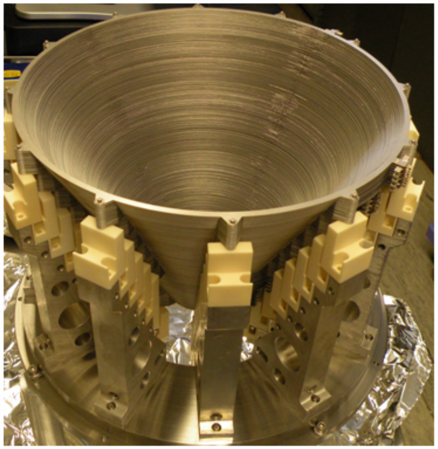
Gas catcher operation at FRIB/CARIBU intensity

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

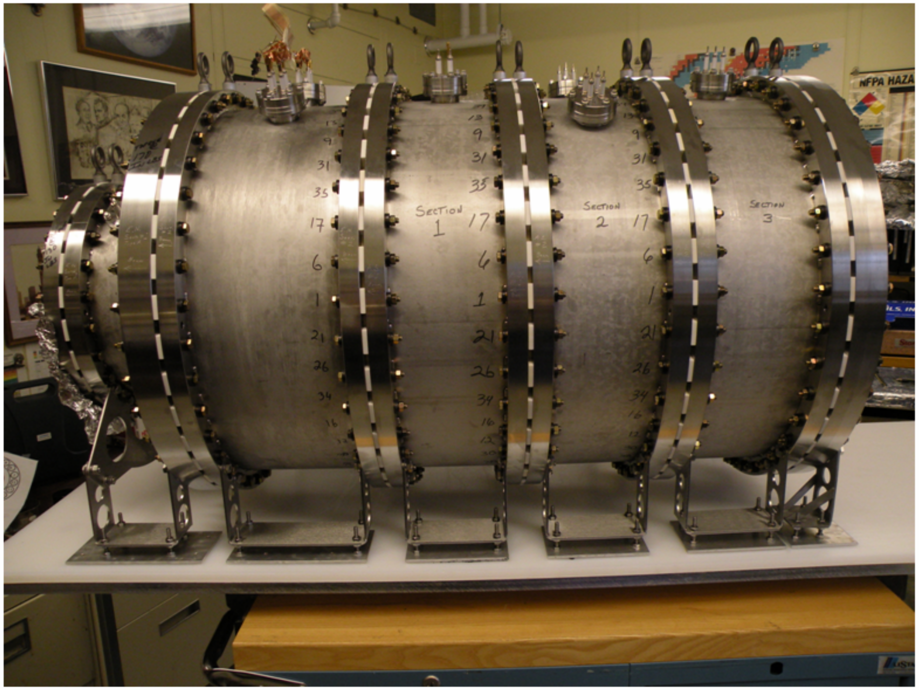
- **High efficiency obtained at up to 10^9 incoming particles per second**
- **Extracted ions identified as ions, not molecular ions**
- **All modifications had a clearly identifiable positive effect**



CARIBU gas catcher

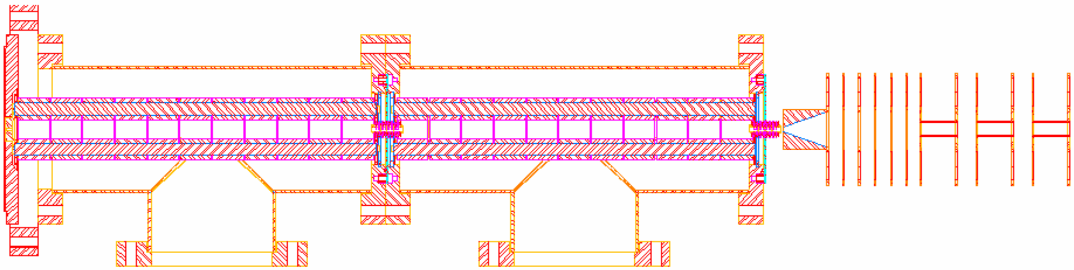


- Device similar to ANL-proposed FRIB gas catcher
  - Same operating principle (RF + DC + gas flow)
  - Similar construction
  - Similar length
  - Twice the diameter (50 cm inner diameter)



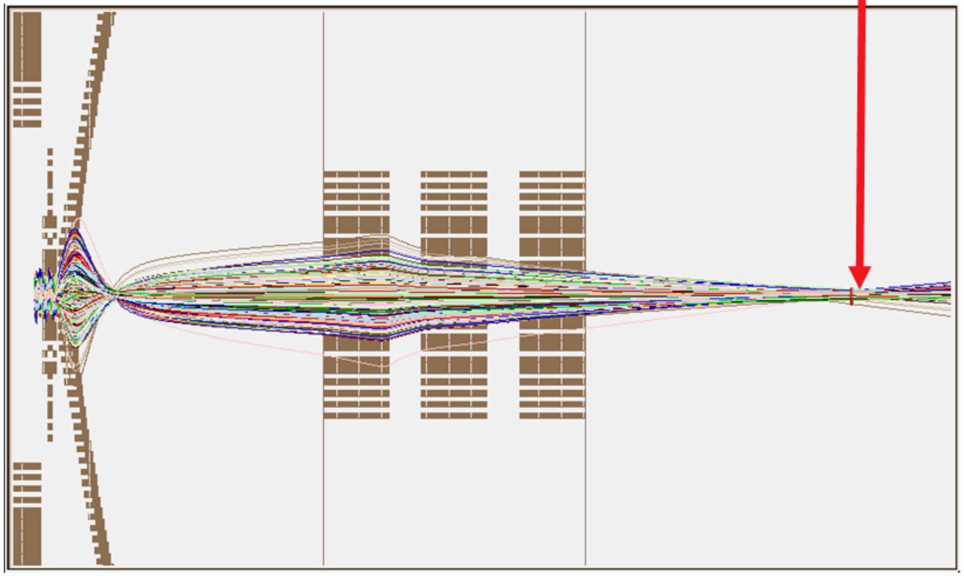
RFQs for gas cooler

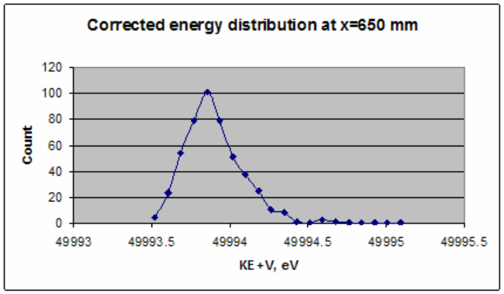
- Design criteria
  - Accept and transport all heavy-ions from gas catcher
    - *Large initial RFQ aperture of 15 mm*
  - Pressure in the acceleration region (at the end of the cooler) must be <10^{-5} mbar
    - *Two large sections of RFQ cooler and two μRFQs for differential pumping*
  - Minimal final emittance and energy spread < 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: Less than 1 meter

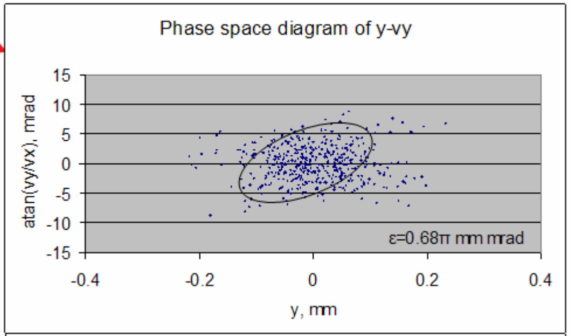


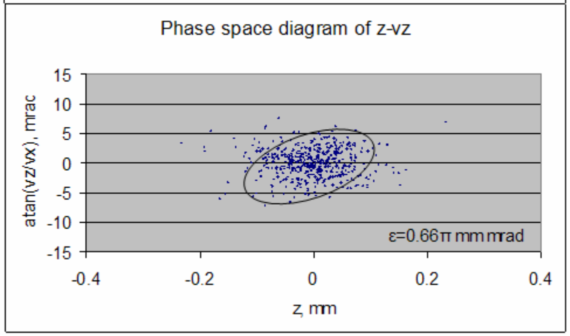
RFQ cooler simulations

- 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









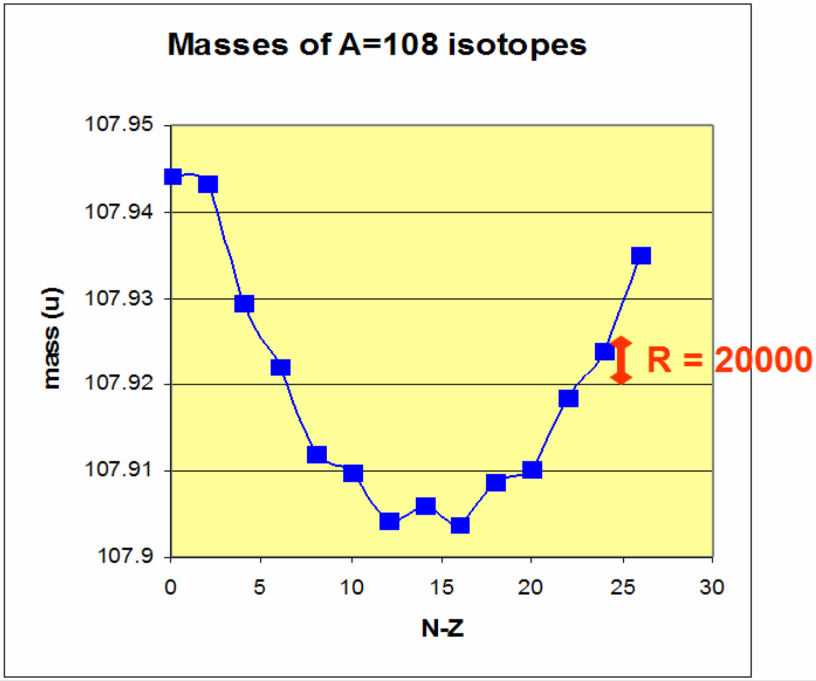
Calculations by Tao Sun using SIMION

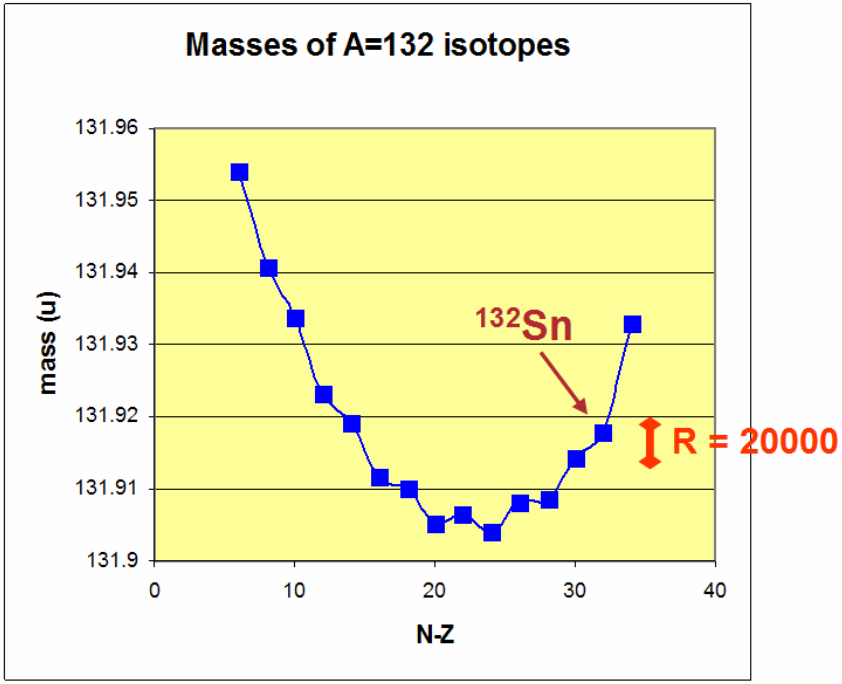
CARIBU gas catcher status

- **Gas Catcher/RFQ cooler installation on platform underway**
  - **Vacuum systems in place**
  - **RF tank circuits being tuned**
  - **First ions (stable) late May 2009**

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

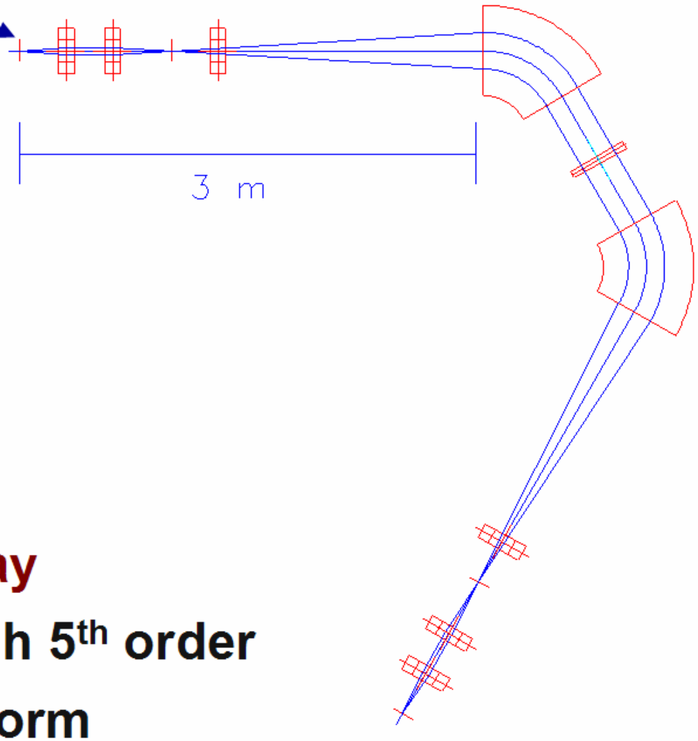




"Compact" isobar separator

- Takes advantage of low emittance and energy spread of extracted beams:

Beam Properties from gas catcher:
$\varepsilon \approx 3\ \pi$ mm•mr $\delta E \approx$ 1eV
1 mm dia. (circular) beam
$\theta_{max}, \varphi_{max} = \pm 6$ 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: 1/20,000
- Magnet delivery 1 year late, expect in May
- 3 electrostatic multipoles correct through 5th order
- Small enough footprint to fit on HV platform

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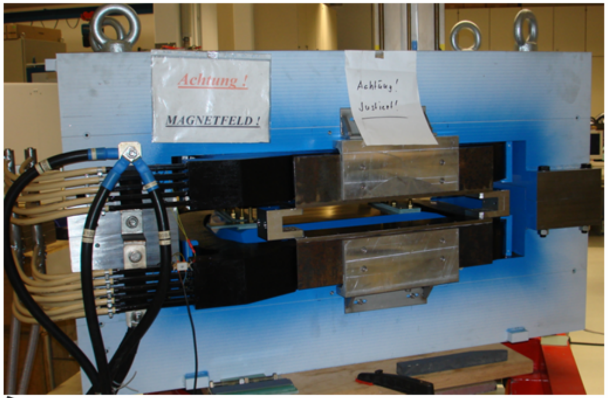

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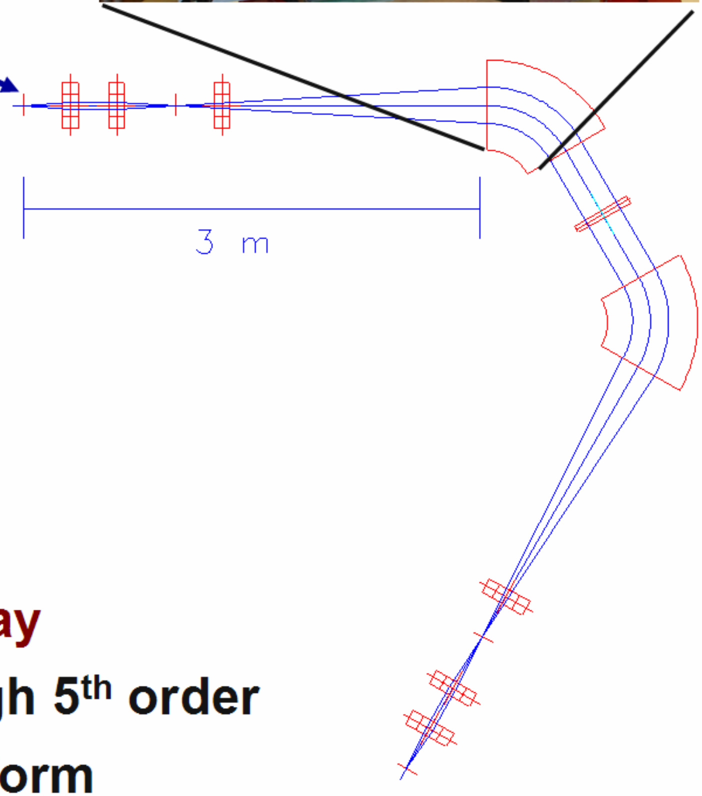

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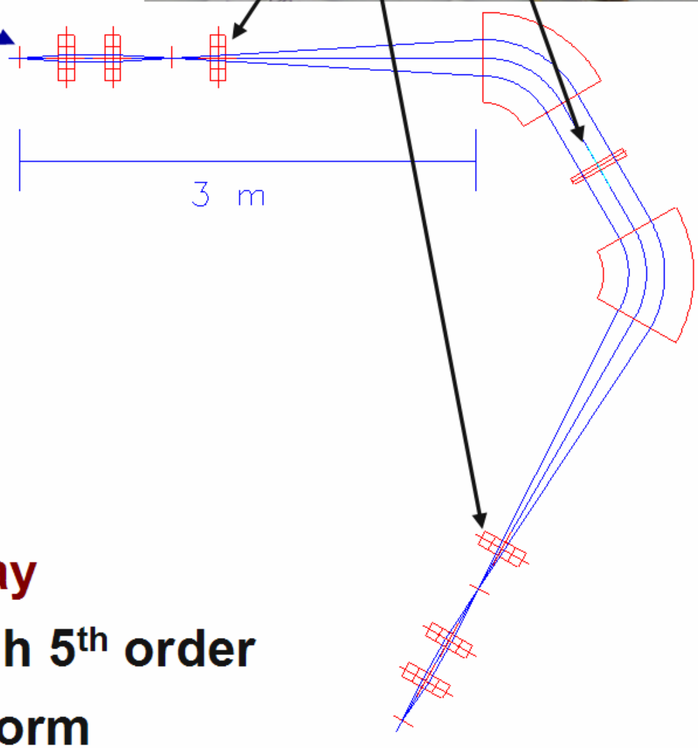
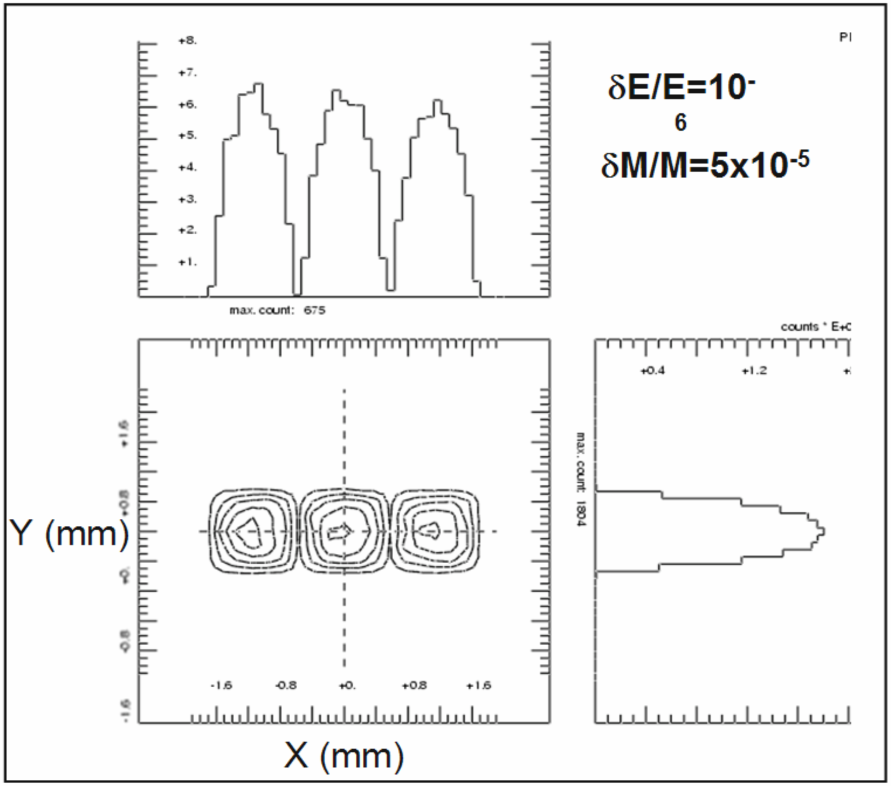
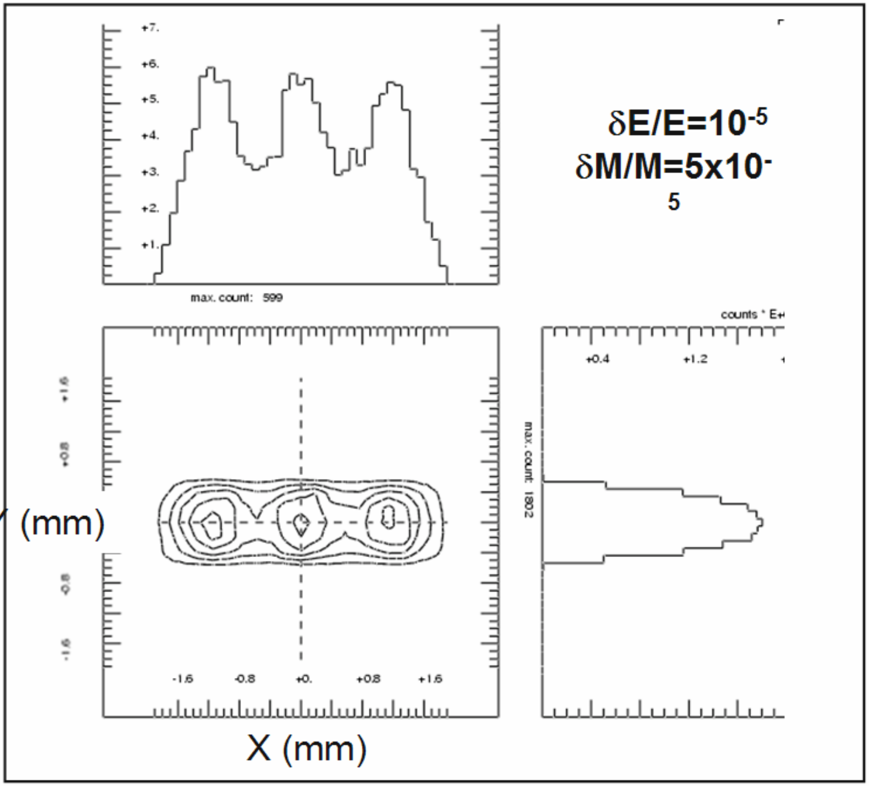


- Matching sections at entrance and exit transform beam to a ribbon beam.
- 2 x 60 degree bends
- R = 50 cm
- Dispersion 22.8 meters
- First order mass resolution: 1/20,000
- Magnet delivery 1 year late, expect in May
- 3 electrostatic multipoles correct through 5th order
- Small enough footprint to fit on HV platform

X and Y Projections at Focal Plane



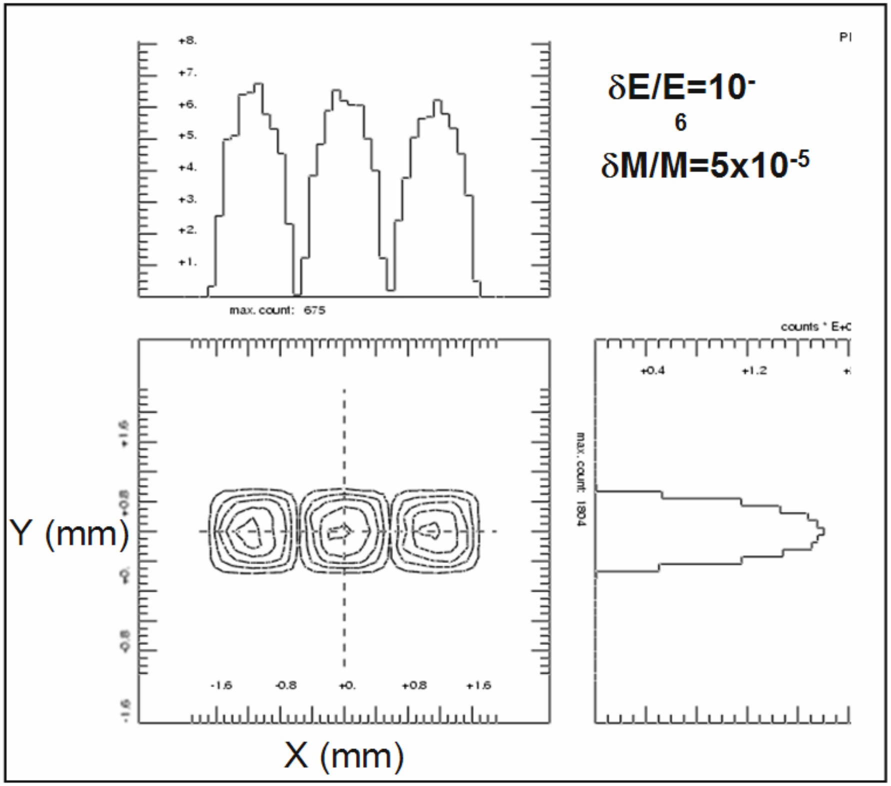


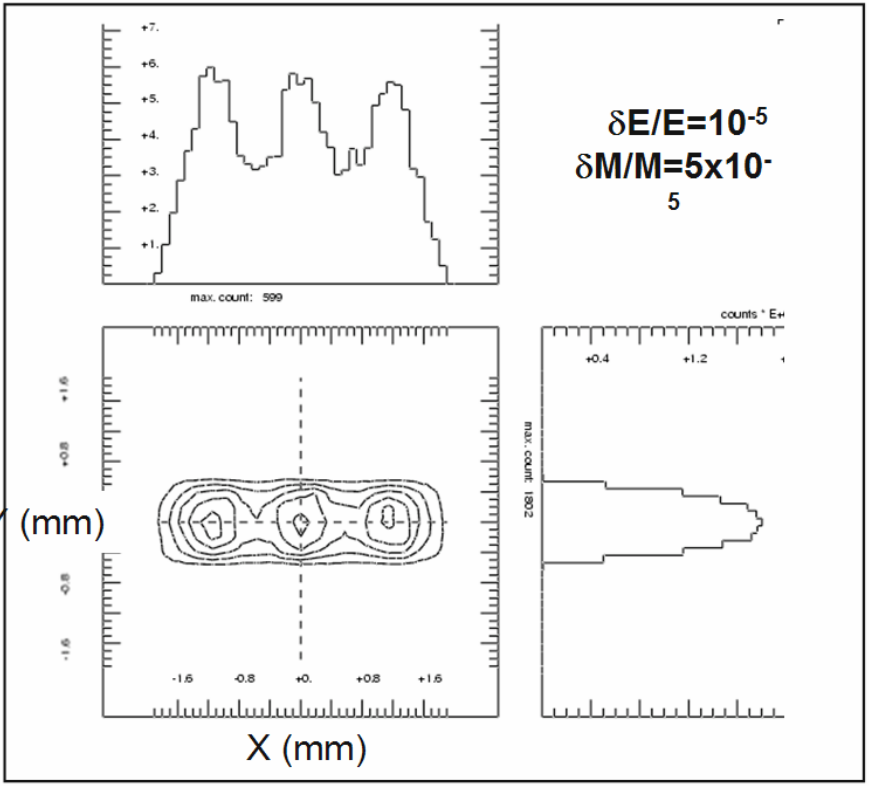
@50keV: $\delta E = 0.05$ eV

@50keV: $\delta E = 0.5$ eV

- Separator has no energy compensation.
- Relies on very low energy spread from gas catcher

X and Y Projections at Focal Plane





@50keV: δ E = 0.05 eV

@50keV: δ E = 0.5 eV

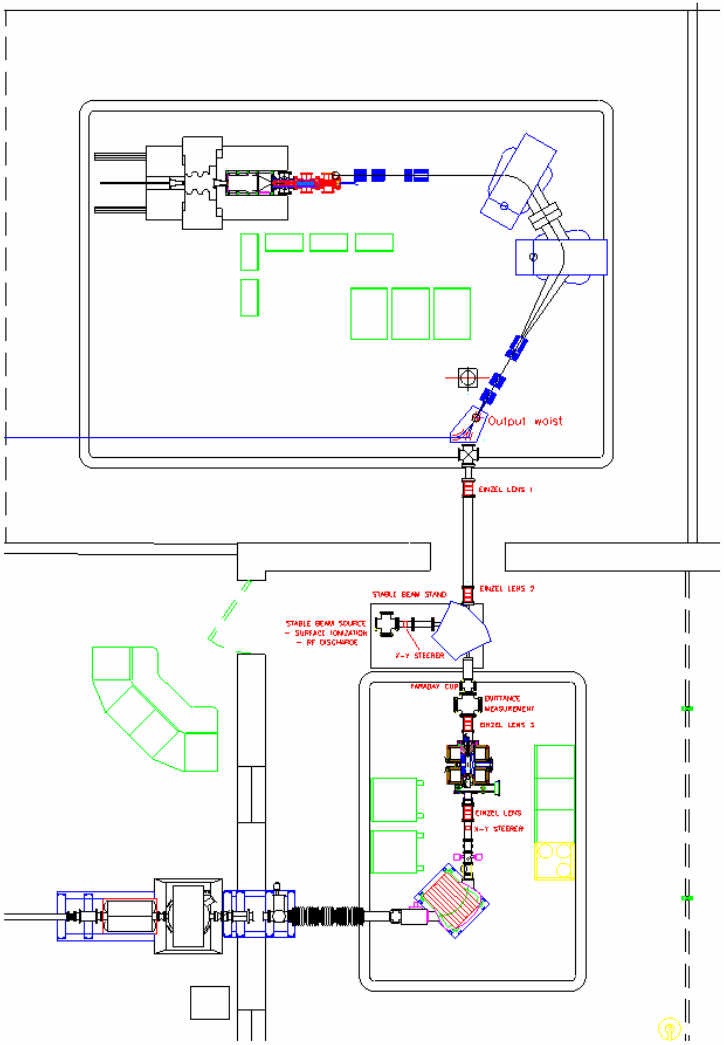
- Separator has no energy compensation.
- Relies on very low energy spread from g

See: FR5REP116, "A Compact High-Resolution Isobar Separator for the CARIBU Project", C. Davids & D. Peterson for more information.

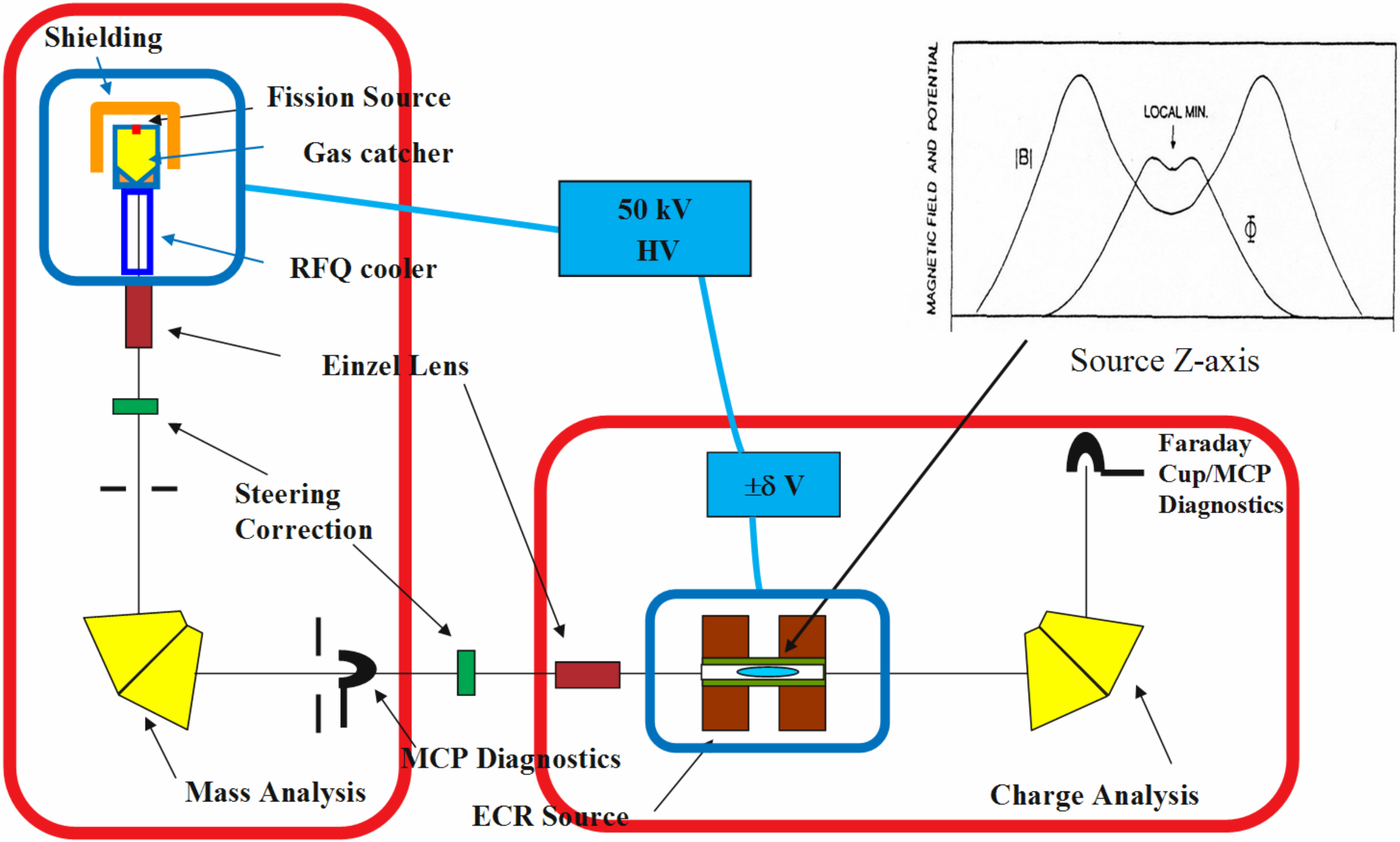
1+ → n+ *Implementation with ECR-I – CARIBU*

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

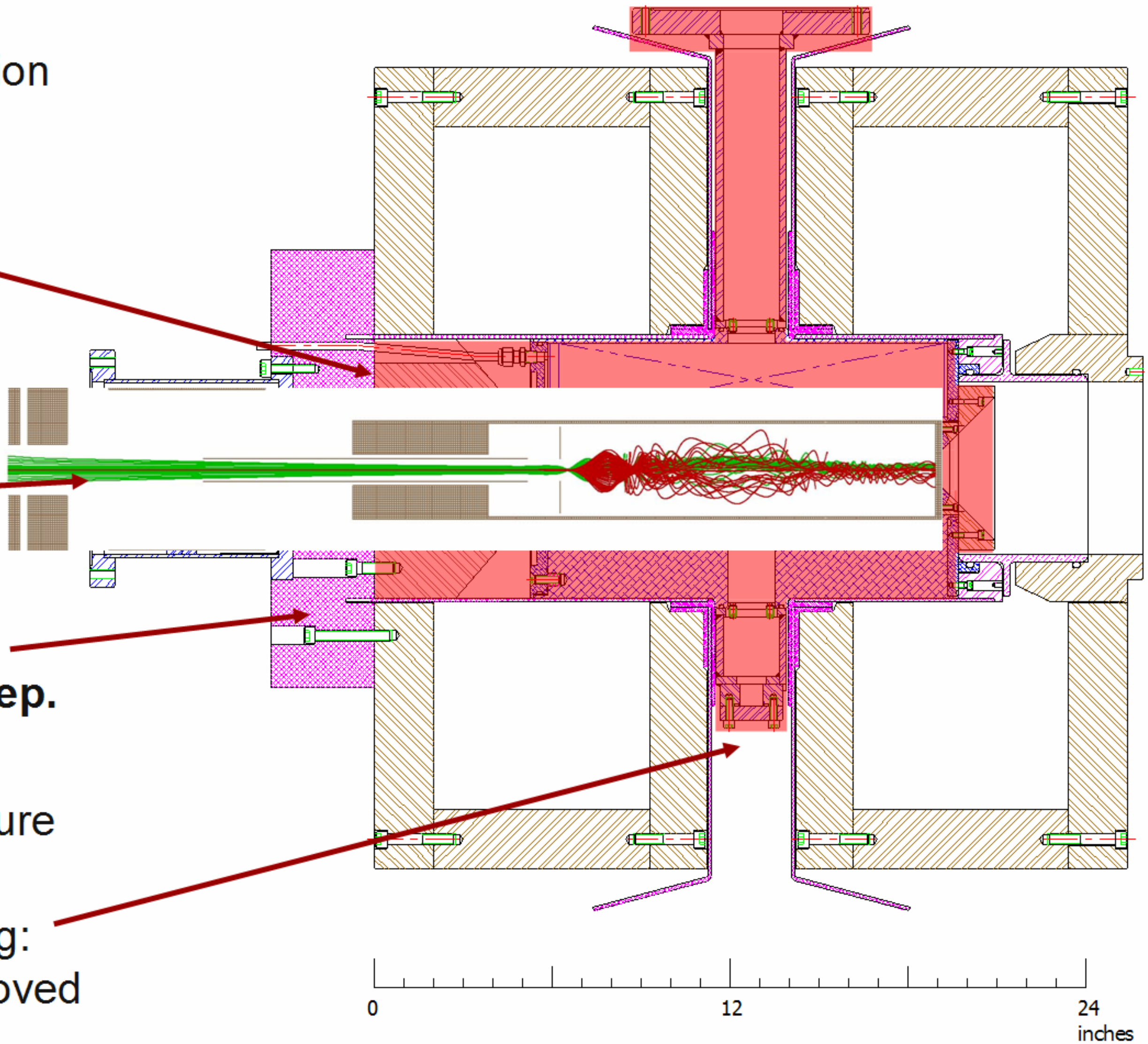


CARIBU ECR Charge-Breeder System



ANL ECR-I modified to function as a Charge Breeder

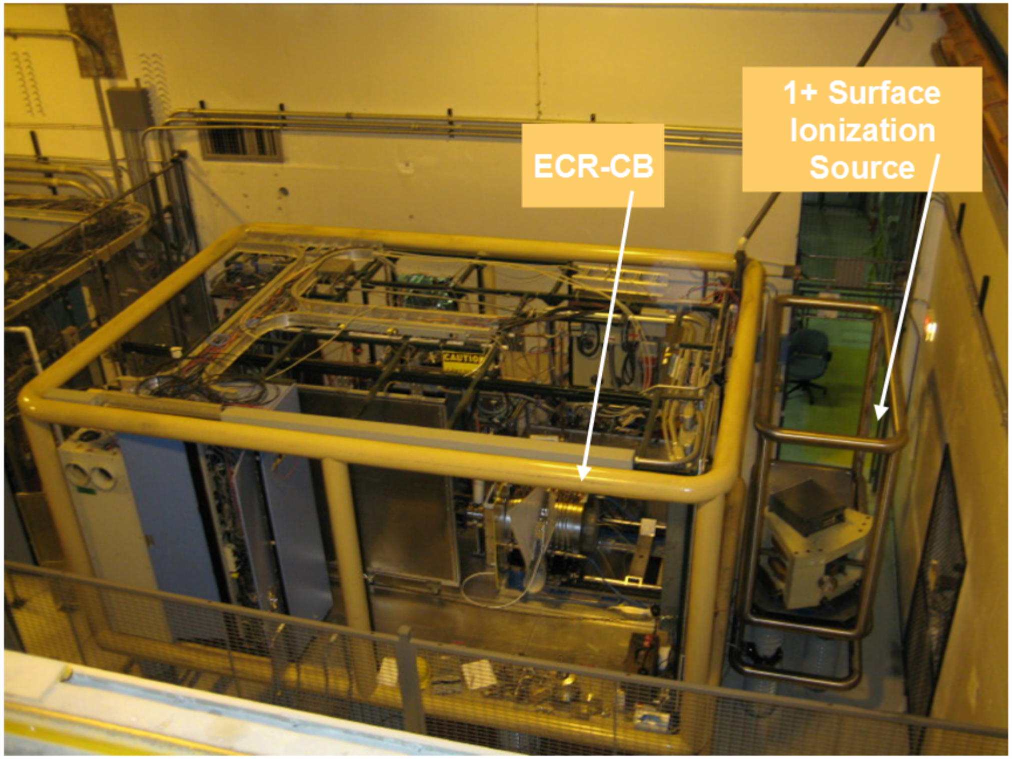
- Necessary to increase ion charge state for acceleration in ATLAS. (q/m > 0.15)
- Injection side iron modifications to allow injection tube and optics
- Injection capture optics modeled with SIMION & GEM codes of Far-Tech, Inc.
- High voltage isolation
  - **Increase to 50 kV as required by isobar sep.**
- RF injection
  - Open hexapole structure allows radial injection
  - Two frequency heating: 10 & 14 GHz for improved efficiency



ECR Charge Breeder Status

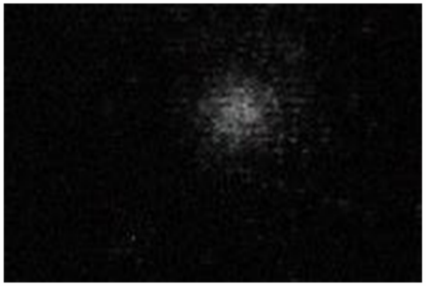
- Initial operation of rebuilt source: January 2008
- Charge Breeding Studies with alkali metal began in May 2008
- Long-term charge breeding efficiency goal:
  - 5% solid materials
  - 10% gases

Ion Species	Efficiency Single/Two Freq.
$^{85}Rb^{11+}$	0.8%/ -
$^{85}Rb^{113+}$	1.8%/ -
$^{85}Rb^{15+}$	3.8%/ -
$^{85}Rb^{17+}$	0.8%/ -
$^{133}Cs^{16+}$	0.9%/1.4%
$^{133}Cs^{18+}$	1.0%/1.5%
$^{133}Cs^{20+}$	2.4%/2.9%
$^{133}Cs^{23+}$	0.5%/1.1%

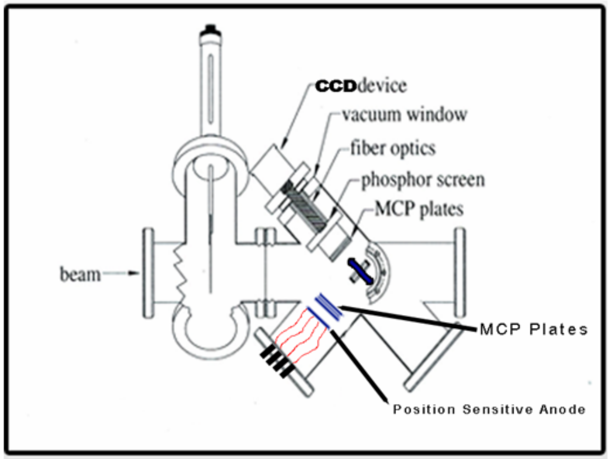


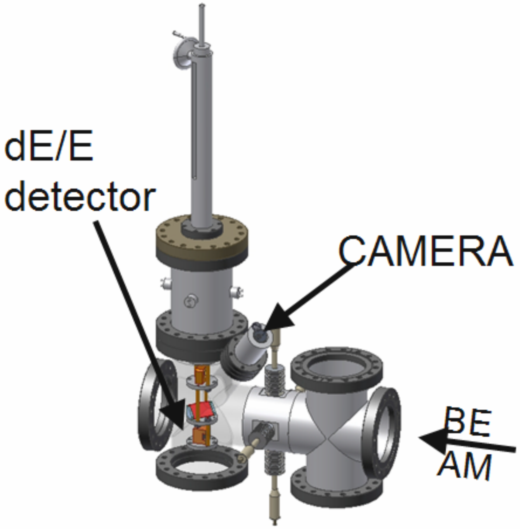
Weak Beam Diagnostics

- **Beam Profile & Current integration**
  - ANL-designed Beam Profile Monitoring Device
    - *Secondary electrons → MCP → phosphor screen →CCD image*
  - Commercial (Quantar Technologies) position sensitive device
    - *Secondary electrons → MCP using a 2D charge division anode*
  - Phosphor surface → high sensitivity CCD camera (profile only)
    - *Gd_2O_2S:Tb and Y_2O_2S:Tb*
- **Longitudinal beam quality and mass determination/beam contamination**
  - Silicon detectors in dE/E format
- **Tape station: ß counting**
  - Decay constant and istope identification



1000 ions/s
Single frame capture





CARIBU Project Status

- ECR Charge Breeder commissioned
  - Charge state distributions are as expected
  - Minimum efficiency goals met (with stable beams)
  - Within 30% of long term goals
- Installation of Gas Catcher/RFQ underway
  - First stable ion extraction, late May
- Dipole magnets shipment now (May 2009)
  - Commissioning and calibration in June 2009
- Weak beam diagnostics available for commissioning
  - Four of six stations in place.
  - First radioactive beam using 2.2 mCi source ~July 2009.
- Commissioning goals met: September 2009.

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 in Fall 2009 with an 80 mCi source.***
- ***1 Ci source not available until near end of calendar 2009.***
- ***Total project cost: $4.6M***