RIB Production at the Holifield Radioactive Ion Beam Facility

Fifth RIA Summer School on Exotic Beam Physics

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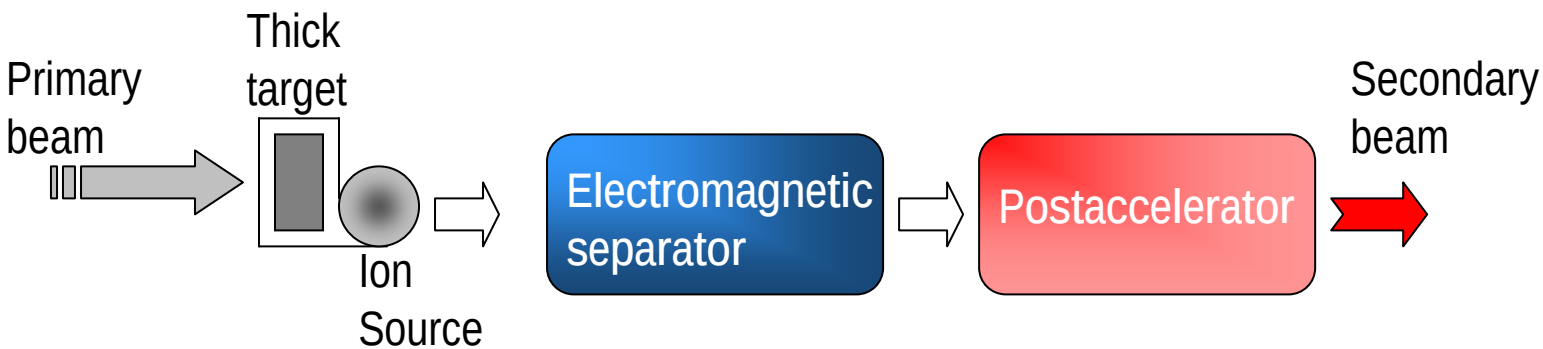
Outline

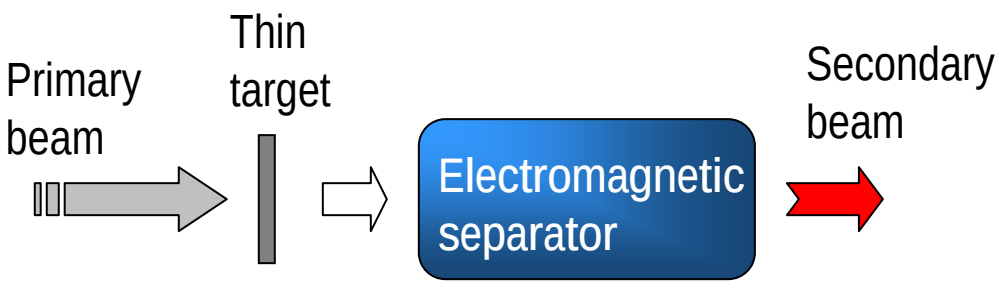
- **Introduction**
  - **Description of the ISOL technique**
  - **Facilities around the world**
- **Holifield Radioactive Ion Beam Facility (HRIBF)**
  - **Description and layout**
  - **Accelerator systems**
- **Radioactive Ion Beams**
  - **Targets and ion sources**
  - **Beam intensities**
  - **RIB purification techniques**

RIB production techniques



ISOL (Isotope Separation On-Line)

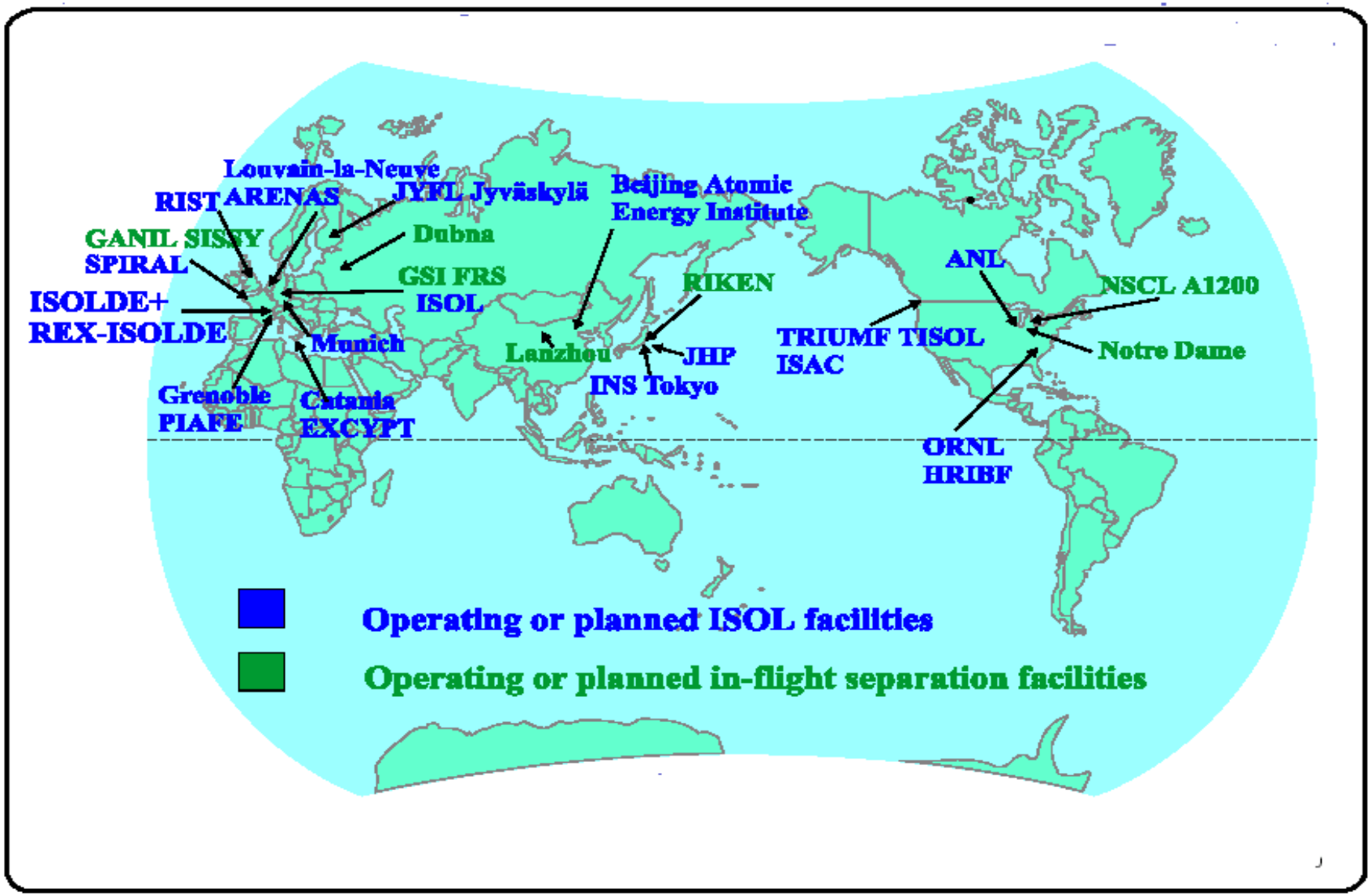
high beam intensity & quality
slow (diffusion and effusion)



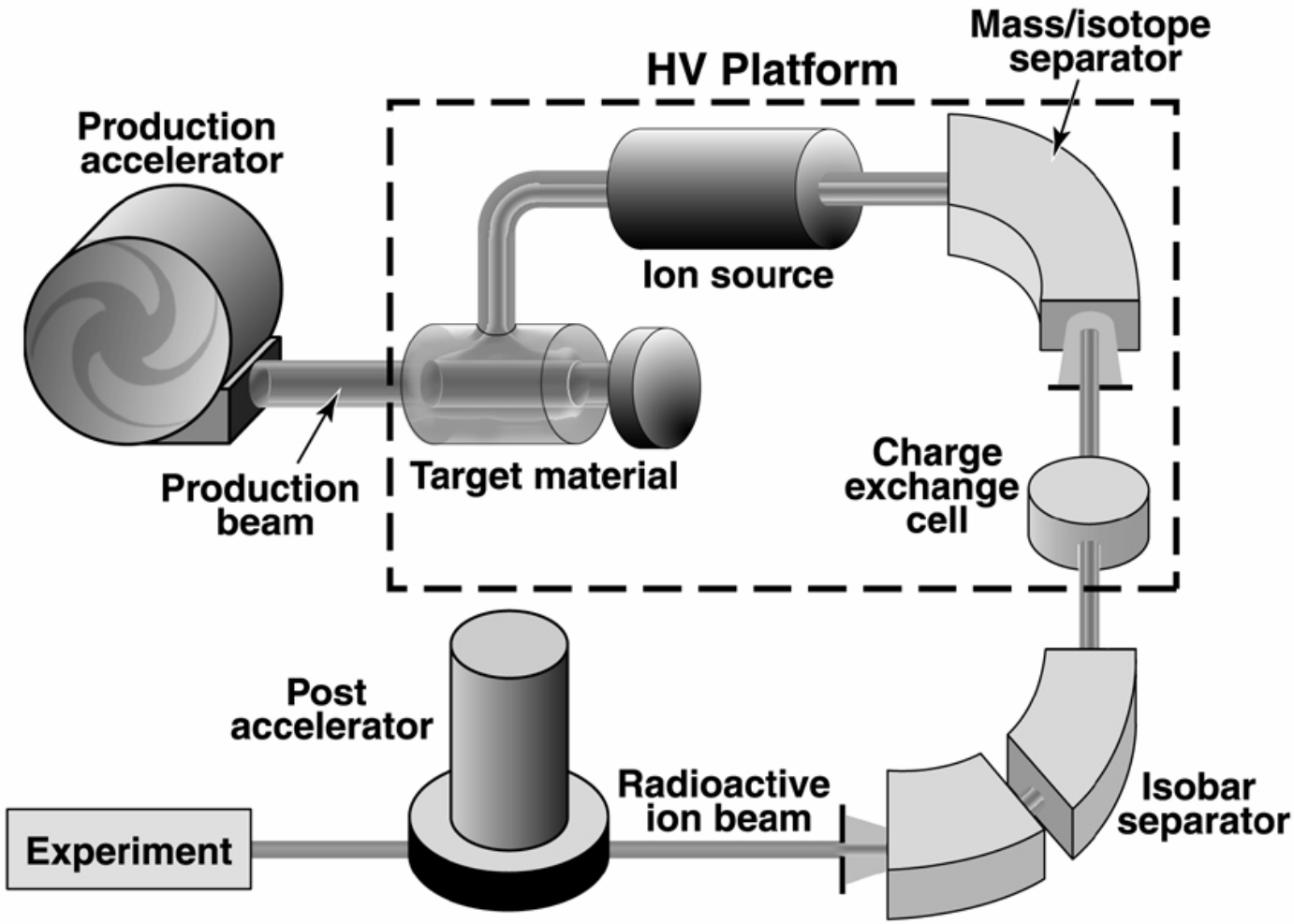
IF (In-flight fragment separator)

lower beam intensity
worse beam quality
fast

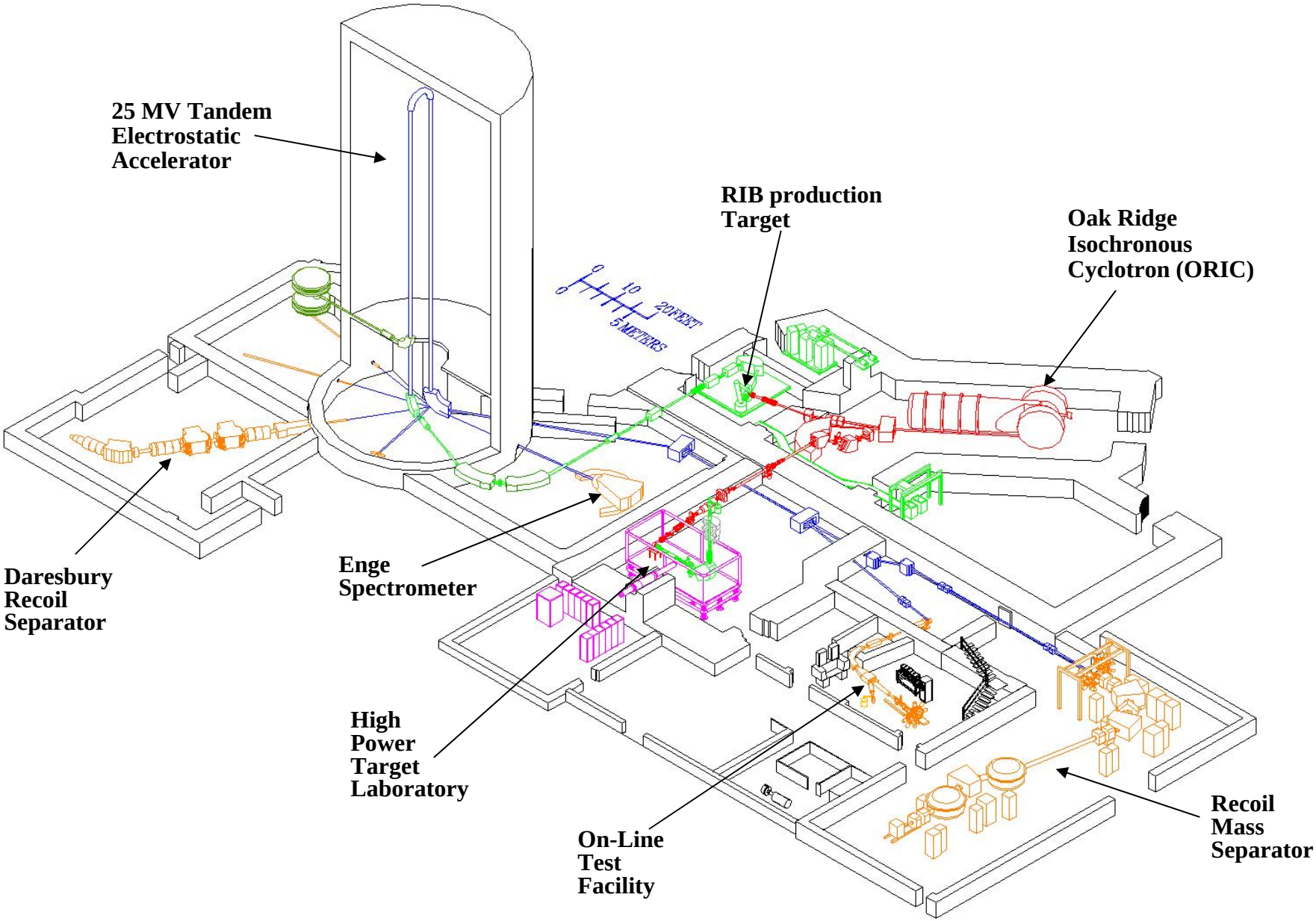
RIB production around the World



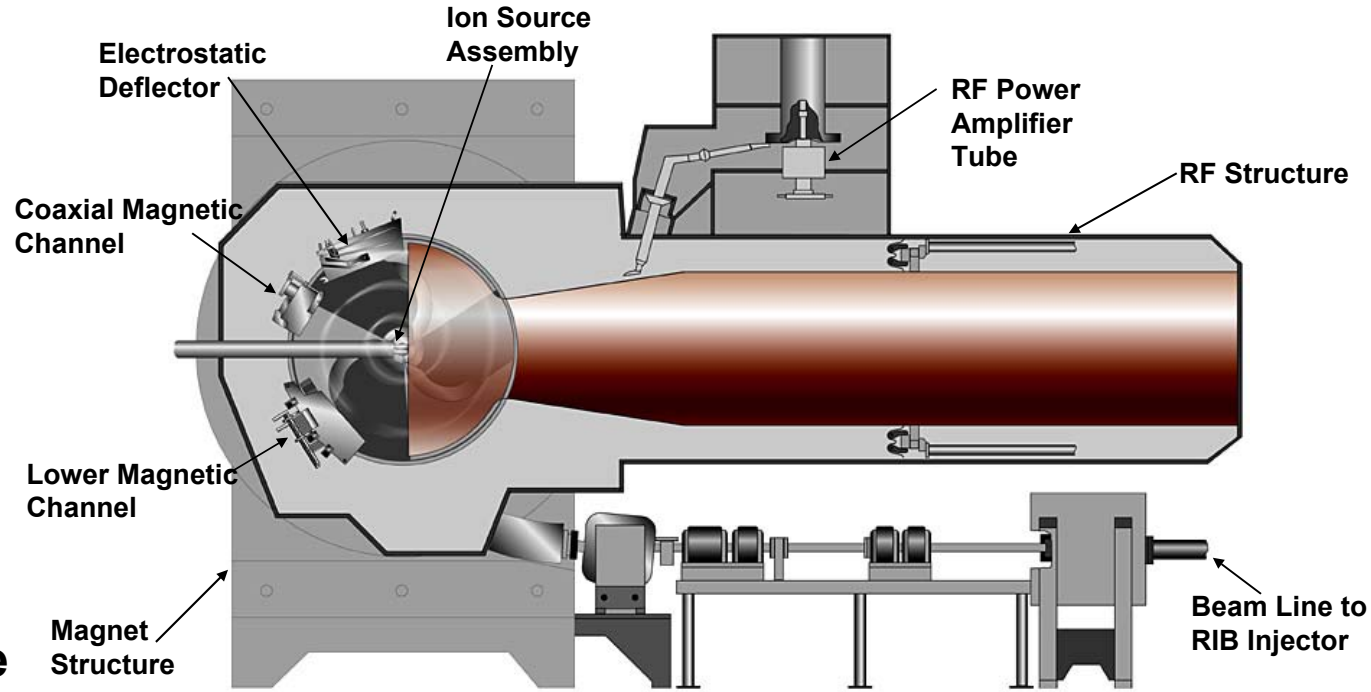
Schematic of RIB Production at the HRIBF



Holifield Radioactive Ion Beam Facility



ORIC



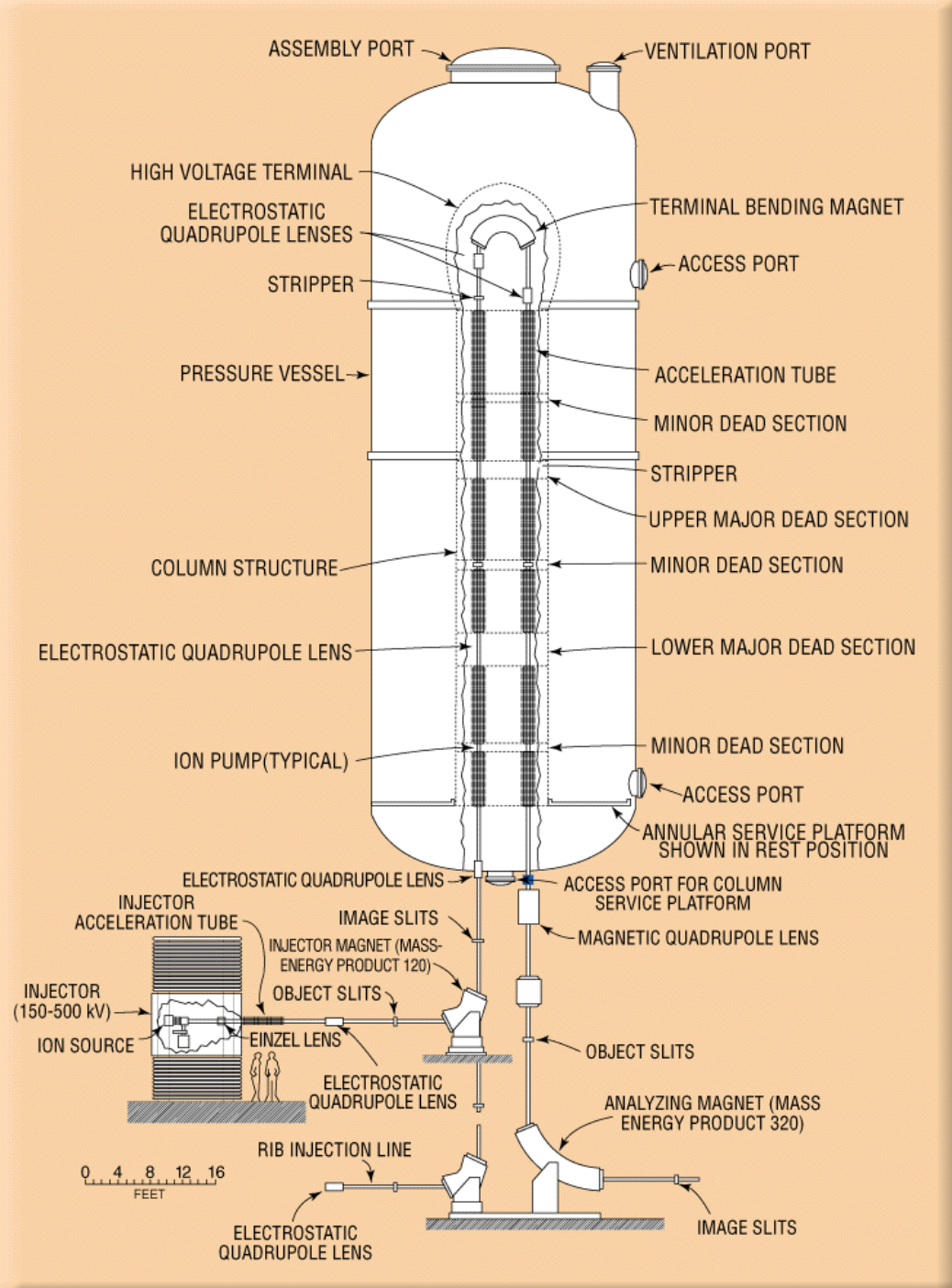
- **Provides intense light-ion beams to produce radioactive species**
- **Produced first beams in 1962**
- **1.5m, k=100, variable energy, multi-particle**
- **Proton energy presently limited by rf system**

Species	Goal	Max. E	Max. I	Max. ε
p	60 MeV @50 μ A	54 MeV	20 μ A	85%
d	50 MeV @75 μ A	49 MeV	12 μ A	75%
^{3}He	133 MeV @200 μ A	-	-	-
^{4}He	100 MeV @200 μ A	85 MeV	10 μ A	45%

Effects of using ORIC as a Driver

- **ORIC = Oak Ridge Isochronous Cyclotron**
- **Low beam energy ➔ short range in targets**
  - **less than 4 g/cm^2 for protons**
  - **for p-rich, use compound nucleus reactions**
    - **large σ (100's mb), localized in energy**
    - **limited to products close to the target nucleus**
  - **for n-rich (fission), yield proportional to target thickness**
  - **modest total beam power deposited in the target**
  - **high local power density in target**
    - **average power density for 45 MeV 1 kW p beam is similar to that for a 100 kW 1 GeV p beam**
- **Few RIBs produced from a given target**
  - **many target systems must be developed**
  - **fission is a notable exception**

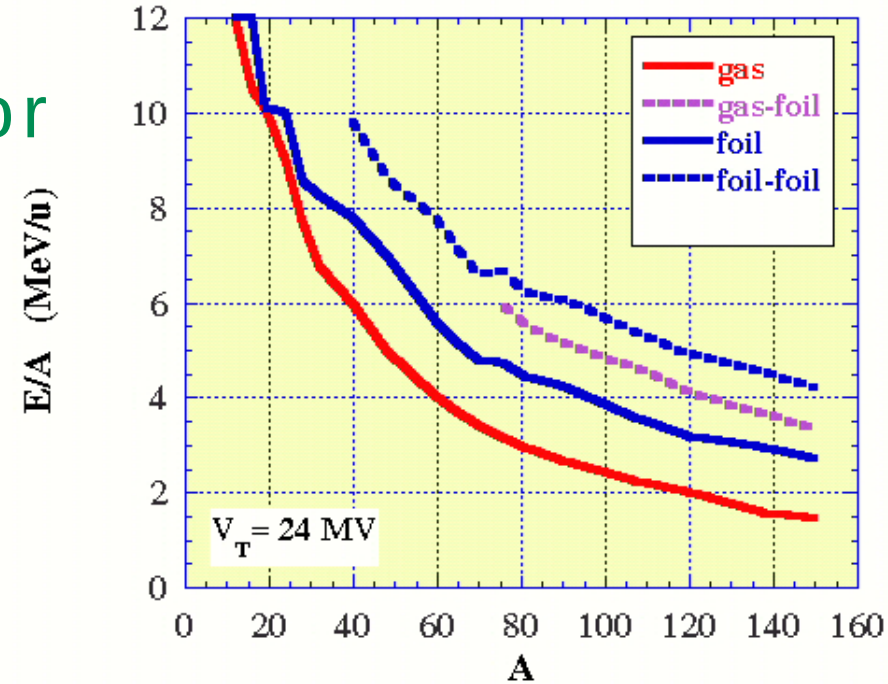
25 MV Tandem

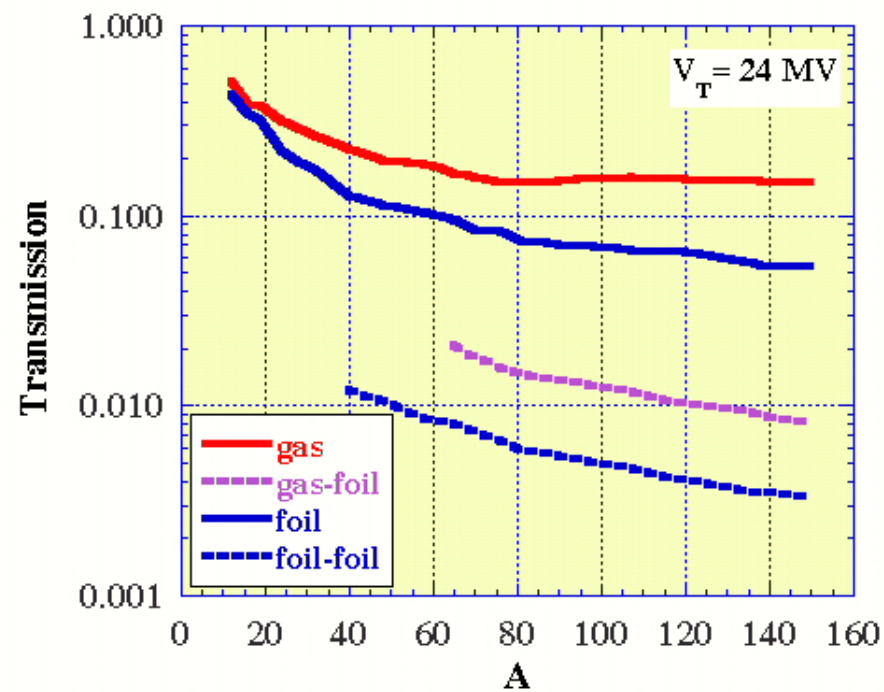

ASSEMBLY PORT
VENTILATION PORT
HIGH VOLTAGE TERMINAL
ELECTROSTATIC QUADRUPOLE LENSES
TERMINAL BENDING MAGNET
ACCESS PORT
STRIPPER
PRESSURE VESSEL
ACCELERATION TUBE
MINOR DEAD SECTION
STRIPPER
UPPER MAJOR DEAD SECTION
COLUMN STRUCTURE
MINOR DEAD SECTION
ELECTROSTATIC QUADRUPOLE LENS
LOWER MAJOR DEAD SECTION
ION PUMP(TYPICAL)
MINOR DEAD SECTION
ACCESS PORT
ANNULAR SERVICE PLATFORM SHOWN IN REST POSITION
ELECTROSTATIC QUADRUPOLE LENS
ACCESS PORT FOR COLUMN SERVICE PLATFORM
INJECTOR ACCELERATION TUBE
IMAGE SLITS
MAGNETIC QUADRUPOLE LENS
INJECTOR MAGNET (MASS-ENERGY PRODUCT 120)
INJECTOR (150-500 kV)
OBJECT SLITS
ION SOURCE
EINZEL LENS
OBJECT SLITS
ELECTROSTATIC QUADRUPOLE LENS
ANALYZING MAGNET (MASS ENERGY PRODUCT 320)
RIB INJECTION LINE
0 4 8 12 16
FEET
ELECTROSTATIC QUADRUPOLE LENS
IMAGE SLITS

Characteristics of Tandem Post-accelerator

- Simple, reliable, economical
- Wide range of operating voltage
  - 1MV - 26 MV
- Large Acceptance
  - well suited to RIB source emittance
  - weak dependence on injection E
  - trans. eff. 15%-50% for gas stripping
- Excellent beam quality
  - good energy resolution ($E/\Delta E > 10^4$)
  - low emittance (0.3-1.0 π mm mrad)
- Easy energy variation

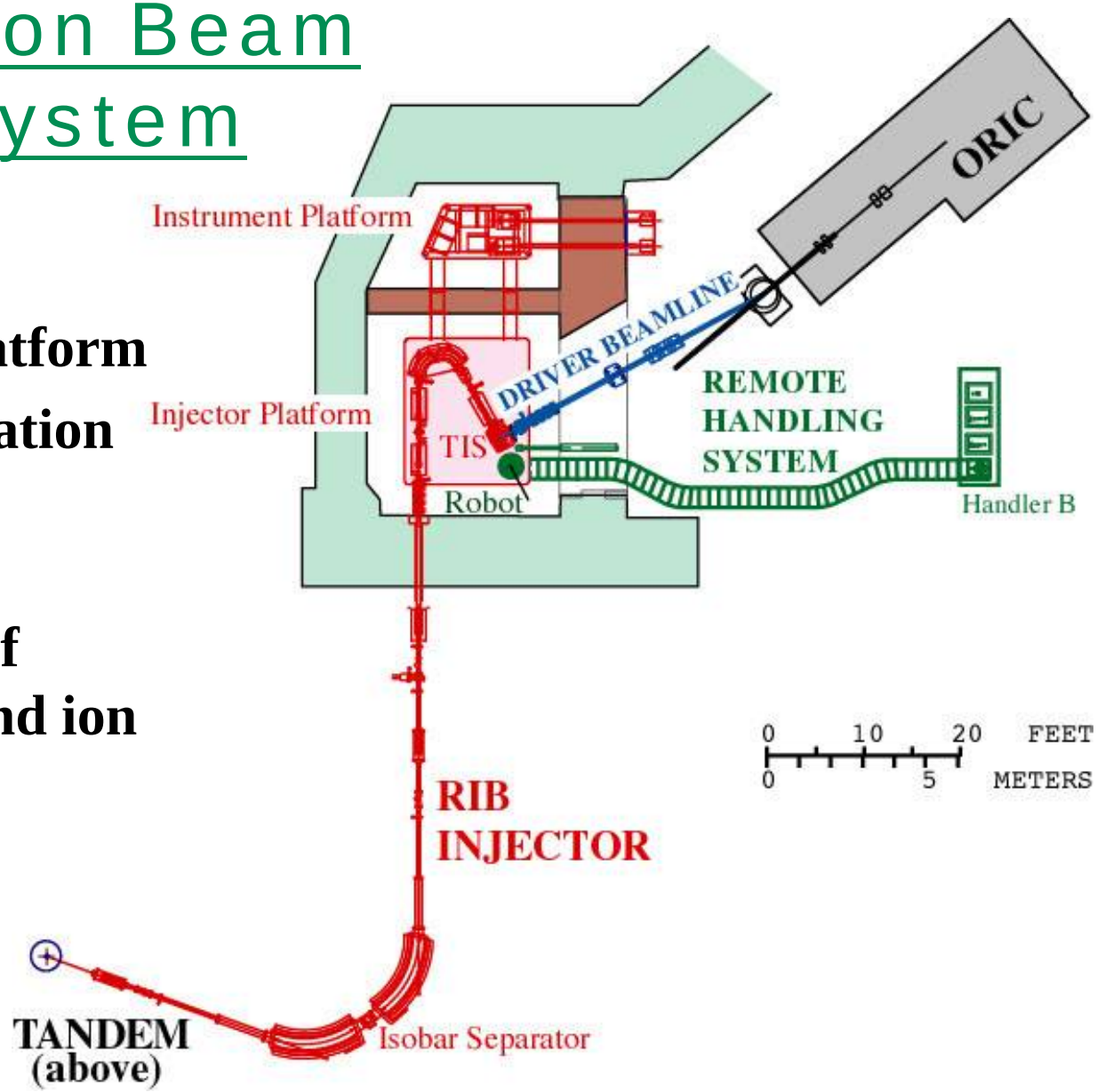
- Must double strip for A>80
  - to reach E/A~5 MeV/amu (up to A~140)
- Negative-ion accelerator



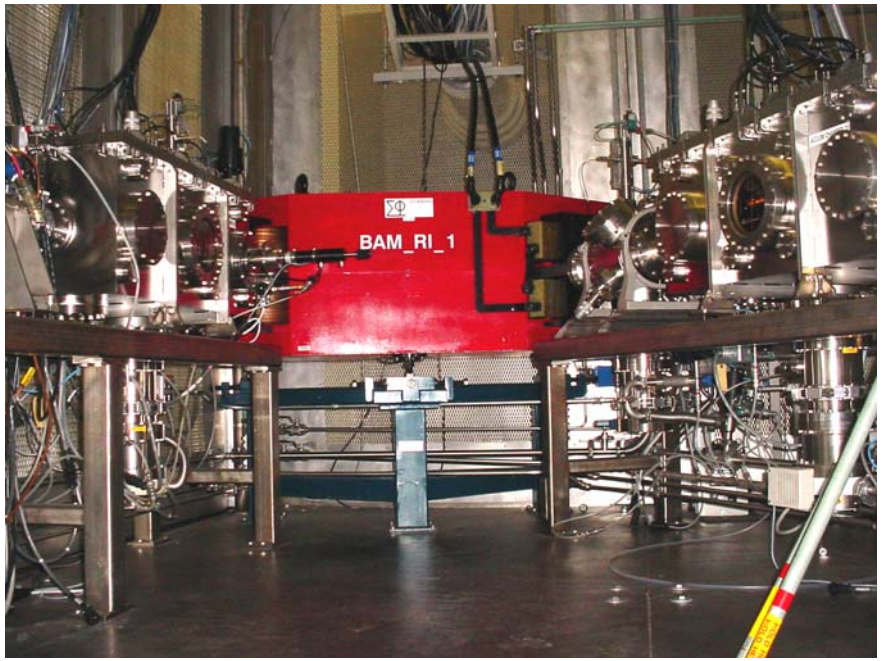


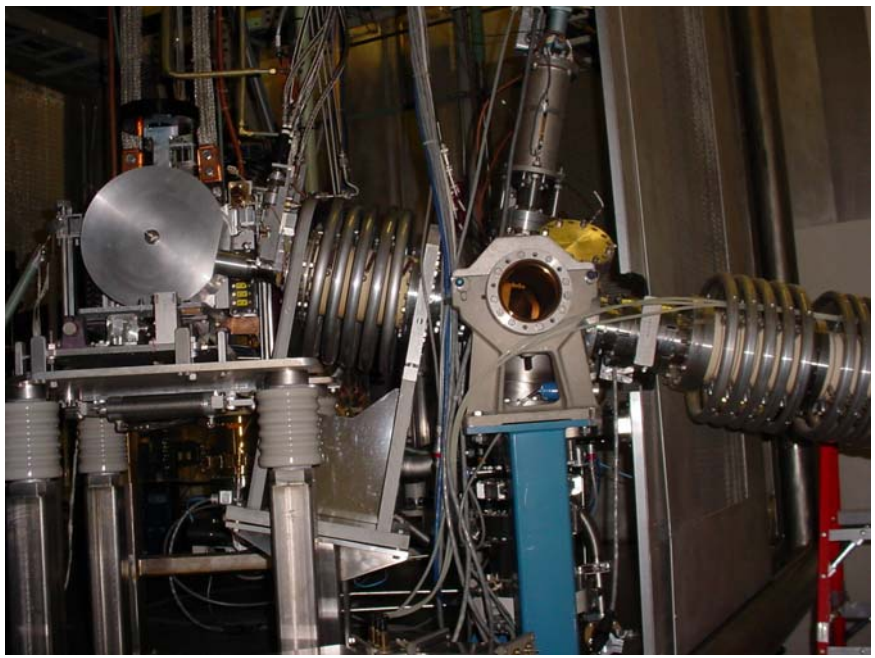
Radioactive Ion Beam Injector System

- **300 kV (design) platform**
- **2-stage mass separation**
  - **M/ΔM ~ 1000**
  - **M/ΔM ~ 20000**
- **Robotic handling of activated targets and ion sources**



RIB Platform





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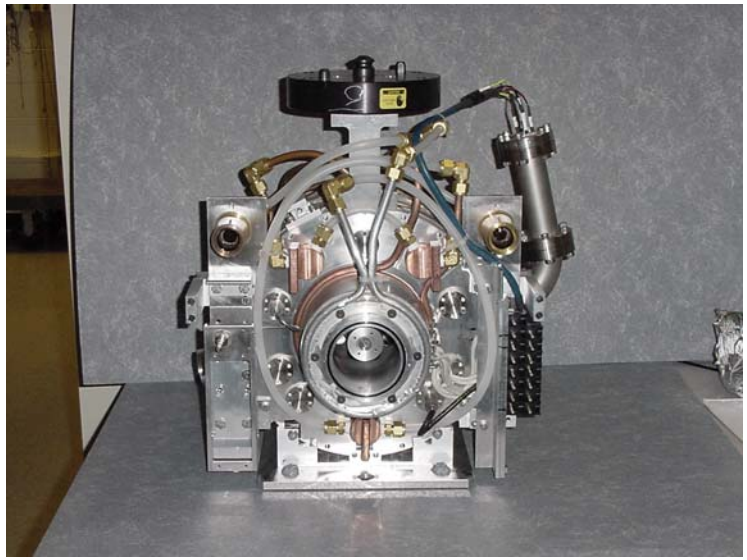
RIB Development and Testing Facilities

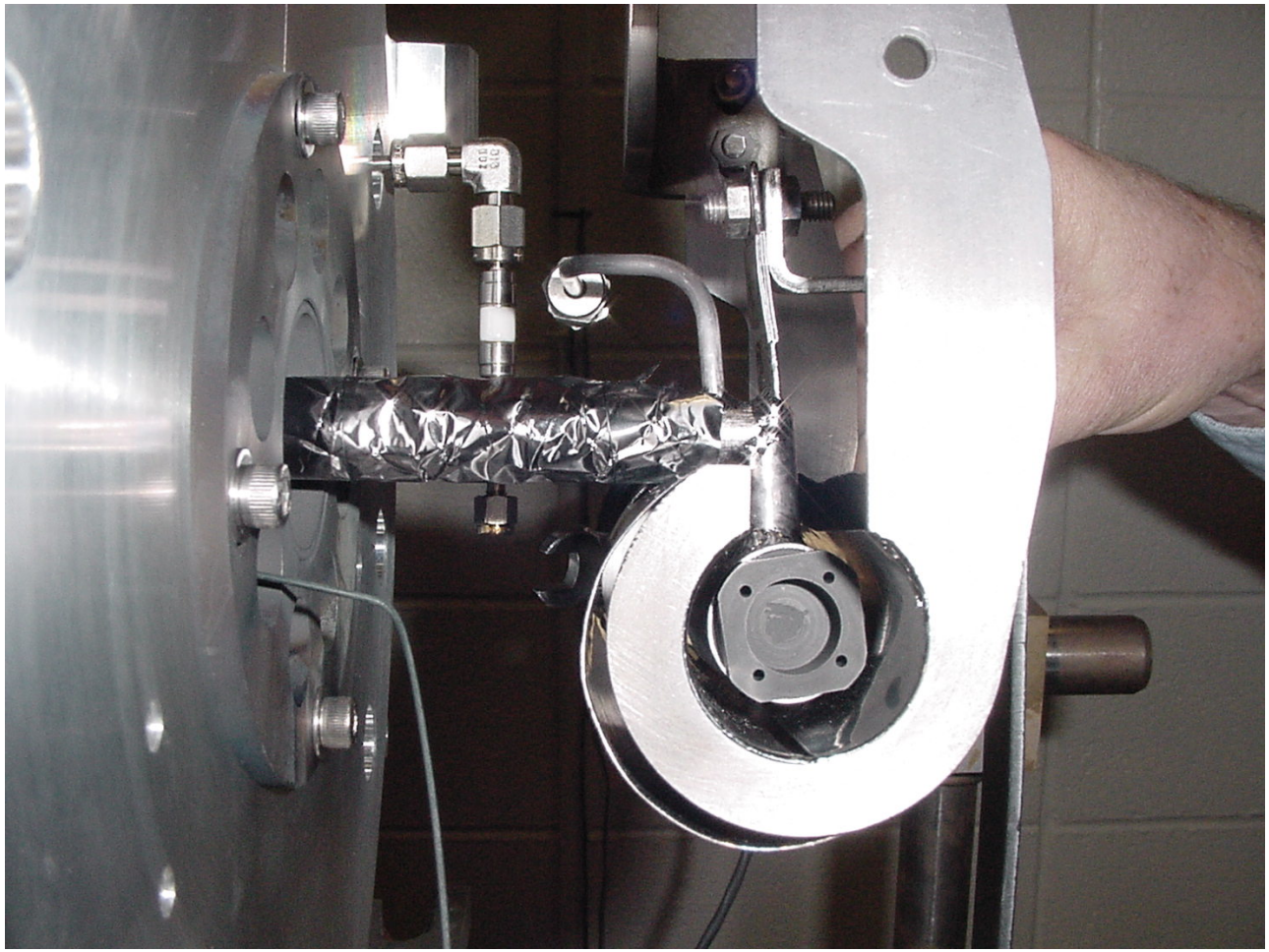
- **Ion Source Test Facility I (ISTF-1)**
  - characterize ion sources (efficiency, longevity, emittance, energy spread, effusion)
  - some target tests (e.g. effusion through matrix)
  - photodetachment tests with gas-filled RFQ ion cooler
- **Ion Source Test Facility II (ISTF-2)**
  - laser ion source
  - ion source lifetime tests
- **On-Line Test Facility (OLTF)**
  - low intensity tests of target and ion source performance (release from target, transport time to ion source, ionization efficiency)
  - compatible with the RIB Injector and results are scaleable
- **High Power Target Laboratory (HPTL)**
  - target tests with high power beams from ORIC
  - release measurements with larger target geometries
- **Facility for preparing target/ion source modules for the RIB Injector (assembly and quality assurance)**

Target and Ion Source Enclosure

- A complete assembly that can be manipulated by a remote handling system
- Assembled off-line and then moved to the RIB Injector
- Holds the target and the ion source
- The target/ion source temperatures can be varied independently
- All TIS connections must be fed through vacuum-tight fittings
- Couples to both the ORIC and the RIB Injector beam lines



Target holder and transfer line to Ion Source

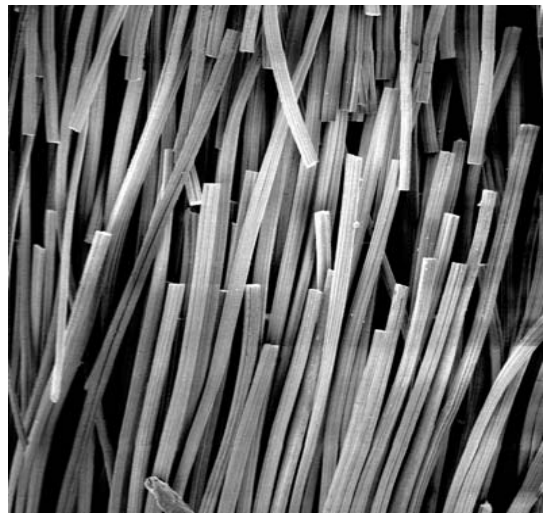


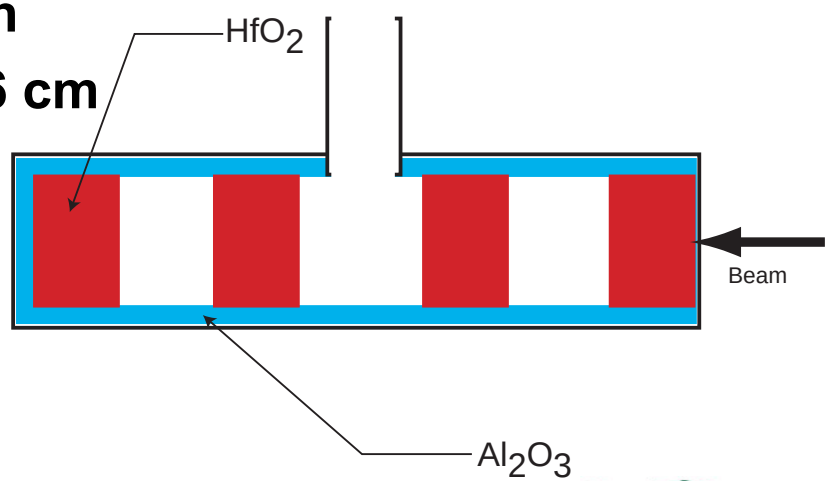
RIB Production Targets

- **HfO_2 fibers** (production of ^{17}F and ^{18}F)
- **Uranium carbide** (n-rich beams via proton-induced fission)
- **Thorium oxide** (different fission fragment distribution)
- **Molten metals**
  - germanium for production of As, Ga, and Se isotopes
  - nickel for production of Cu isotopes
- **Ni pellets** (^{56}Ni via (p,p2n) reaction – ^{56}Co contamination)
- **Cerium sulfide** (production of ^{33}Cl and ^{34}Cl)
  - thin layers deposited on W-coated carbon matrix
- **Silicon carbide** (production of ^{25}Al, ^{26}Al, and ^{29}P)
  - fibers (15 μm), powder (1 μm), thin layers on carbon matrix
- **Aluminum oxide** (production of ^{26}Si and ^{27}Si)
  - thin fibers (6μm) with sulfur added for transport
- **^{7}Be** sputter targets (mixed with copper, silver, or niobium)

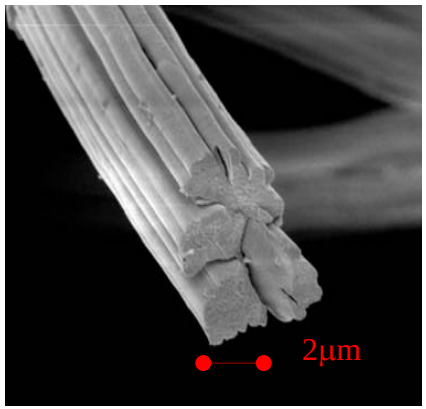
HfO_2 Fiber Target for Production of $^{17,18}F$ Beams

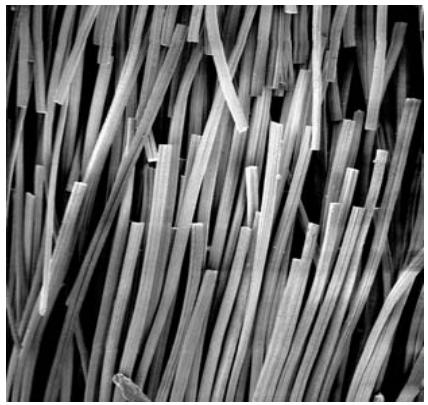
- Thin Fibers (5 μm) - fast diffusion
- High porosity (density is 1.15 g/cm^3)
- Refractory (m.p. is 2770 C)
- Free of volatile impurities
- $^{16}O(d,n)^{17}F$ & $^{16}O(\alpha,pn)^{18}F$
- 4 rolls of HfO_2 cloth used for target
  - 1.5 cm diameter x 1 cm thick each
  - Range of 42 MeV deuterons is 1.6 cm
- Al_2O_3 felt sheath
  - Provides aluminum vapor
  - Transported as AlF molecule



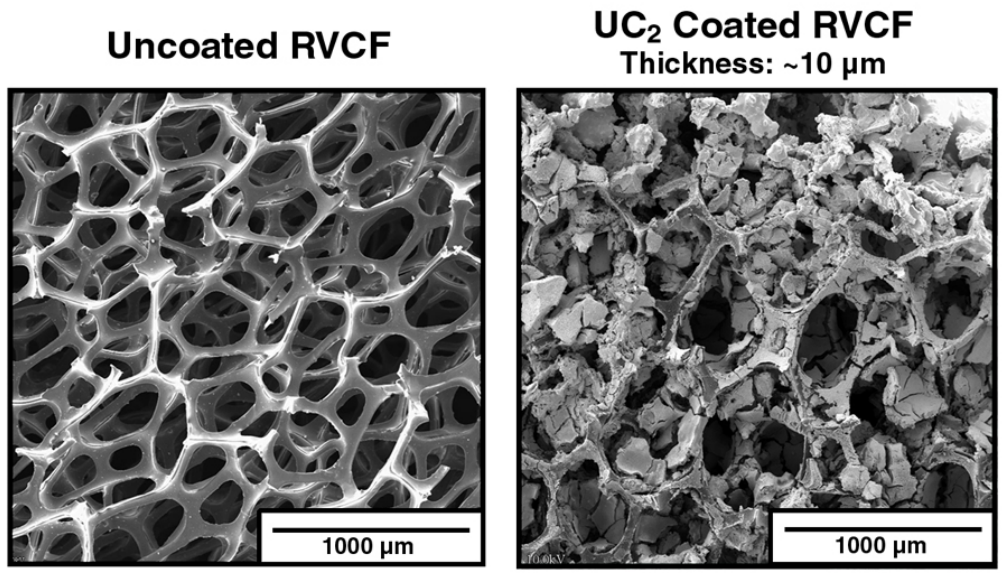


HfO_2 Target Assembly





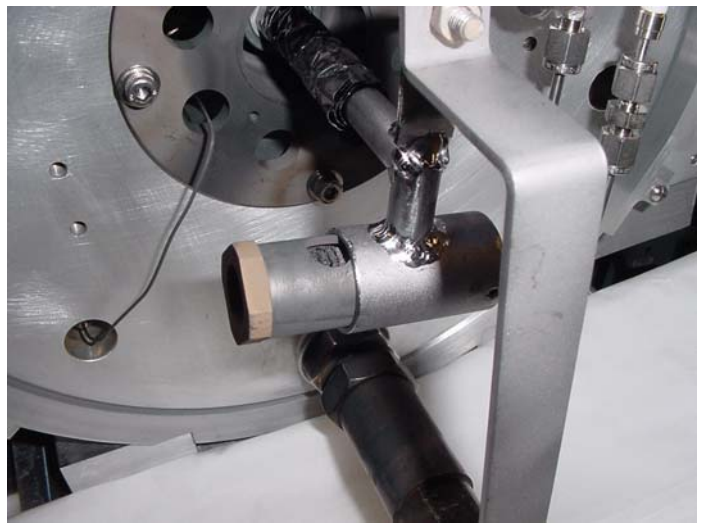
UC Targets for Production of Neutron-rich Beams



- RVC fiber diameter: 60 µm
- Matrix density: 0.06 g/cm^3
- UC coating thickness: 8 - 10 µm
- Target density: 1.2 g/cm^3
- Uranium thickness: 2.1 g/cm^2
- Mass ratio is U:C is 6:1
- Atomic ratio is UC_3

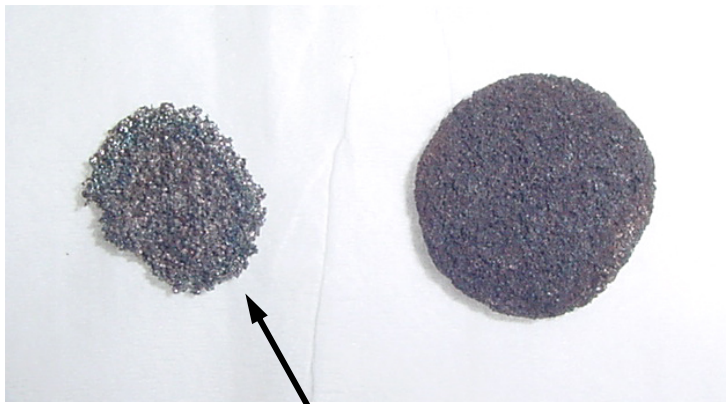
UC/RVC Target Operation

- **50 days of operation with target temperature greater than 2100 C**
- **1200 hours of 10-12 μA of 42 MeV protons**
  - **400 W deposited in target**
  - **average power density is 113 W/cc (97 W/g)**
- **More than 120 different radioactive beams extracted**



UC/RVC Fabrication Process

- Saturate RVC matrix with uranyl nitrate solution
- Heat to 300 C for a few hours (convert to uranium oxide)
- Repeat until the desired density of uranium is achieved
- Heat to 2000 C (convert to uranium carbide)
  - additional carbon must be added so that the RVC matrix is not compromised



no additional carbon added

effect of 'too much' oxygen in UC target

RIB yields from different actinide targets

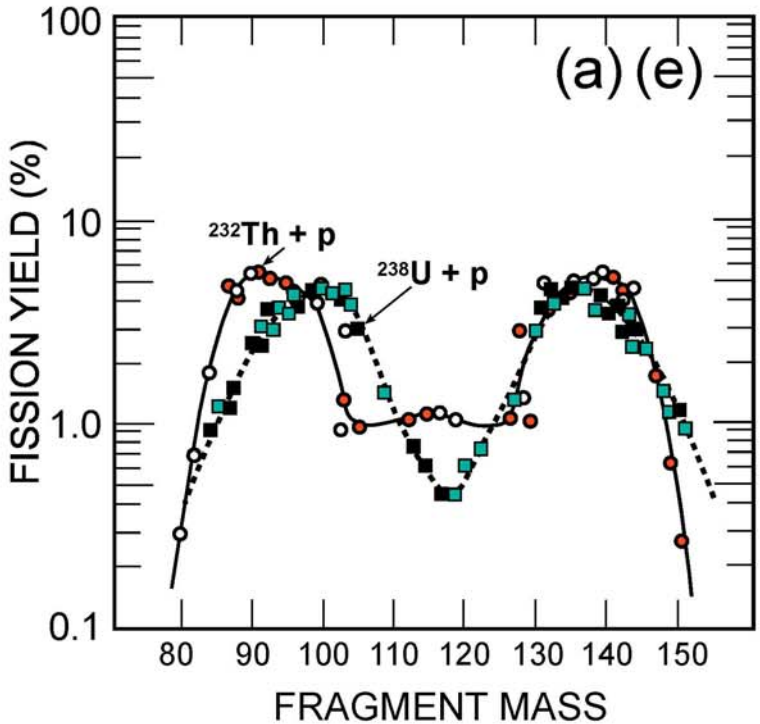
- **Five different UC_x targets and a ThO_2 target were tested**

- **UC_2-coated RVC**
  - **low-density, highly porous carbon matrix (standard for HRIBF)**
  - **density is 0.6 g/cm^3 to 1.2 g/cm^3**
- **UC_x pressed-powder targets supplied by ANL**
  - **uranium oxide powder mixed with graphite powder and converted at high temperature to UC (density is 2.5 g/cm^3)**
  - **uranium carbide powders mixed with graphite powder and pressed**
    - **-200 mesh (< 74 μm) UC powder, density is 5.2 g/cm^3**
    - **-325 mesh (< 44 μm) UC powder, density is 6.0 g/cm^3**
    - **-400 mesh (< 37 μm) UC powder, density is 5.5 g/cm^3**
- **ThO_2 pressed-powder target (density is 6.9 g/cm^3)**

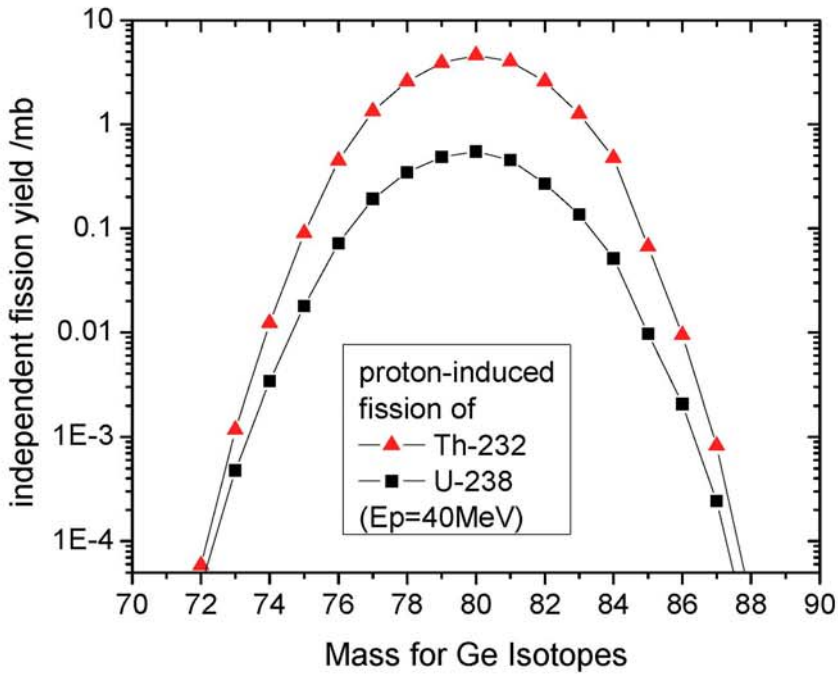
- **The pressed-powder targets**
  - **quality is more reproducible**
  - **are significantly cheaper to produce**
  - **need to be tested at high power**

Comparison of production rates in ^{238}U and ^{232}Th

(proton-induced fission with 40 MeV protons)

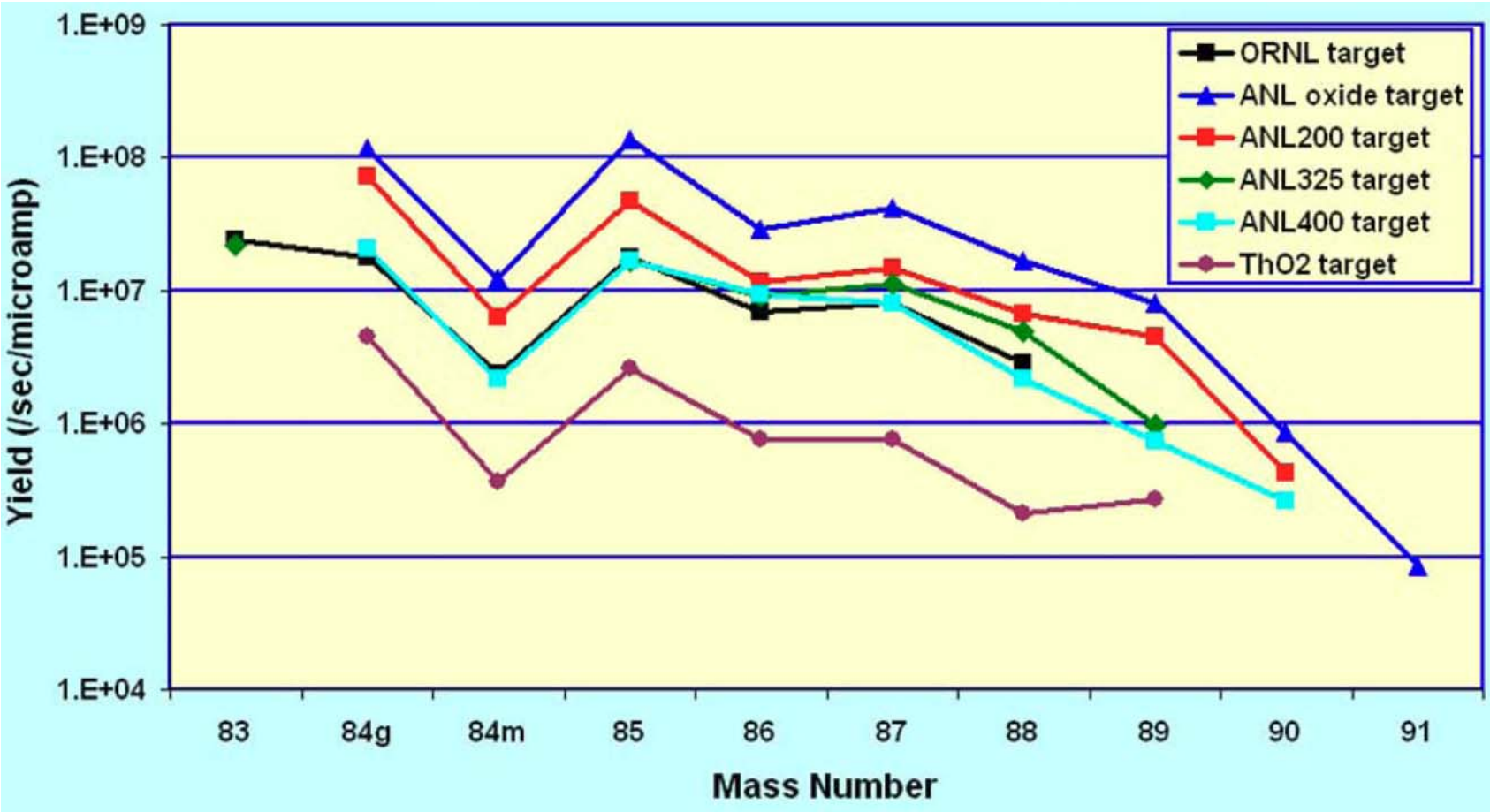


[T. Ohtsuki, et al., Phys.Rev. C40 (1989) 2144]

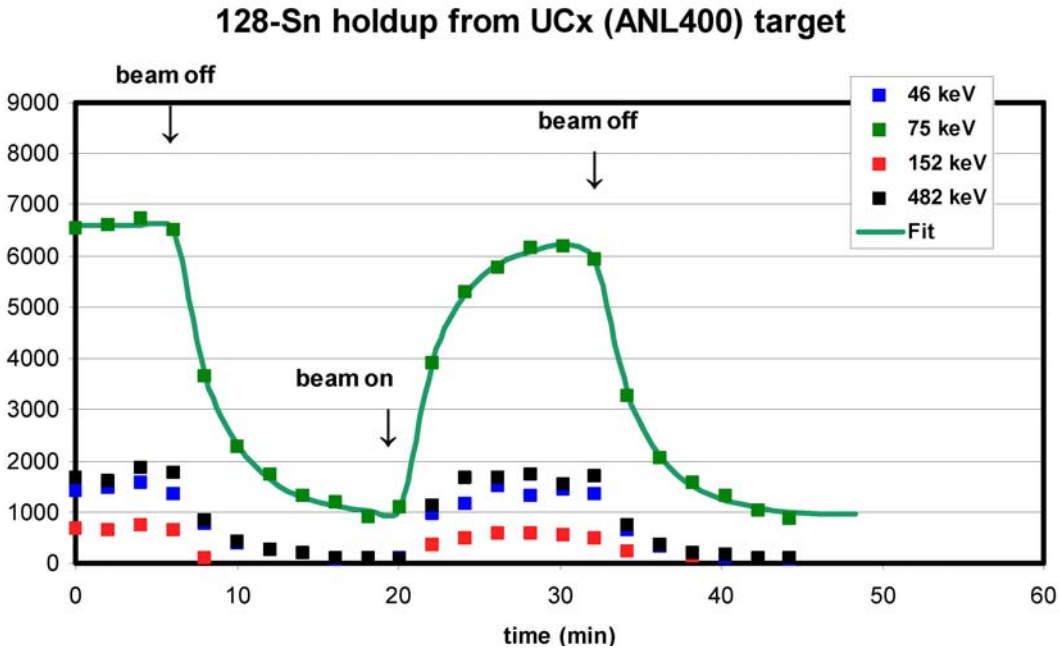


Calculation for Ge (Z=32)
by Valery Rubchenya
Jyvaskyla, Finland

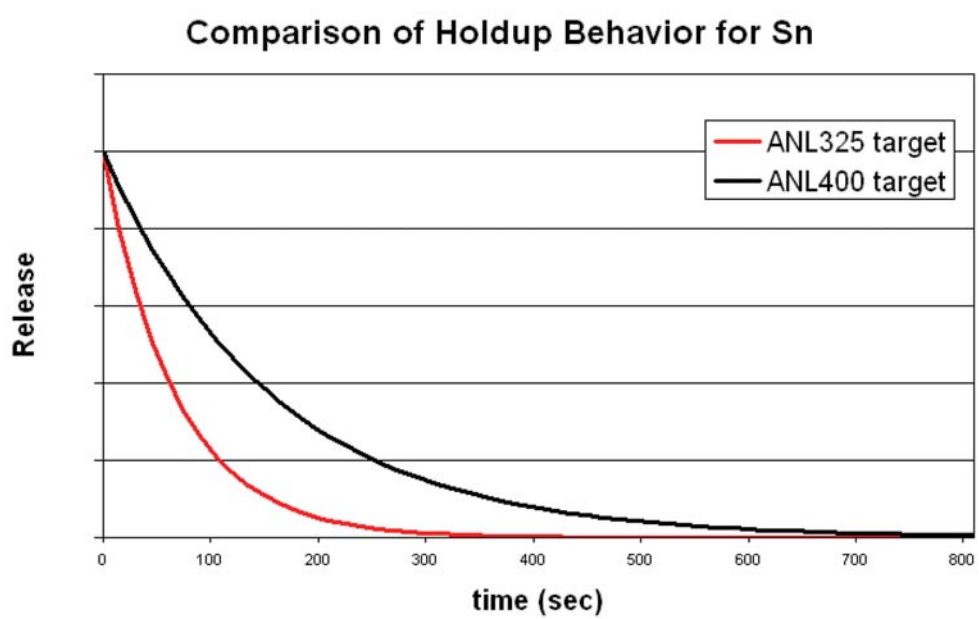
Yields of Br isotopes using 40 MeV protons



Measurements of holdup times to find fast-release targets



- **Holdup times were recently measured for several elements from several production targets**
  - **ANL-UC (-325 mesh)**
  - **ANL-UC (-400 mesh)**
  - **ORNL UC/RVC**
  - **ThO_2 (pressed powder)**
- **Data is being analyzed with the help of summer students and visitors**



Liquid Metal targets

- **Liquid Ge (for Ga, As, and Se beams)**
  - **Interacts with Ta (use graphite target holder)**
  - **Surface tension is quite high**
    - **Thin layers of Ge tend to coalesce into droplets**
    - **Ge will wet a molybdenum surface but forms a eutectic, destroys the substrate in just a few hours at ~1000° C**
  - **Efforts to make a thin layer of Ge suspended on an open matrix have failed**

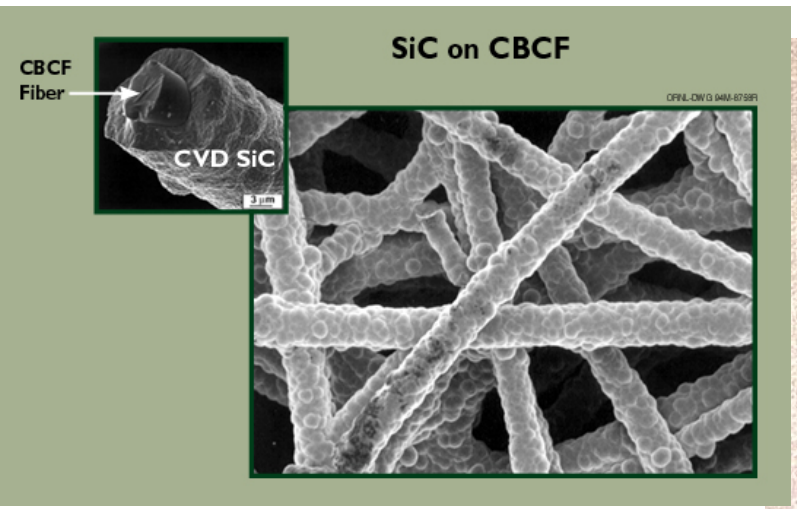
- **Liquid Ni (for Cu beams)**
  - **Reacts with most metals at relatively low temperature**
  - **Molten Ni quickly destroys a Ta target holder at the melting point (1453° C)**
  - **Even a low concentration of Ni vapor will destroy a Ta tube in a few hours at 1800° C (Ta thickness was 0.5 mm)**
  - **Need an all-graphite target holder and ion source**

On-line Tests using SiC targets
(for the production of ^{25}Al and ^{26}Al beams)

- 15 μm diameter SiC fibers
- 1 μm diameter SiC powder
- SiC does not sinter
- Maximum operating temperature is 1650 C
- ^{25}Al yields were about the same – 10^4 ions/sec/μA
- Can increase yield significantly (x10) by adding fluorine to system and extract as AlF

$$^{28}Si(p,\alpha)^{25}Al$$
$$^{28}Si(d,\alpha n)^{25}Al$$

$$^{28}Si(p,2pn)^{26}Al$$
$$^{28}Si(d,\alpha)^{26}Al$$



CeS target on RVC matrix

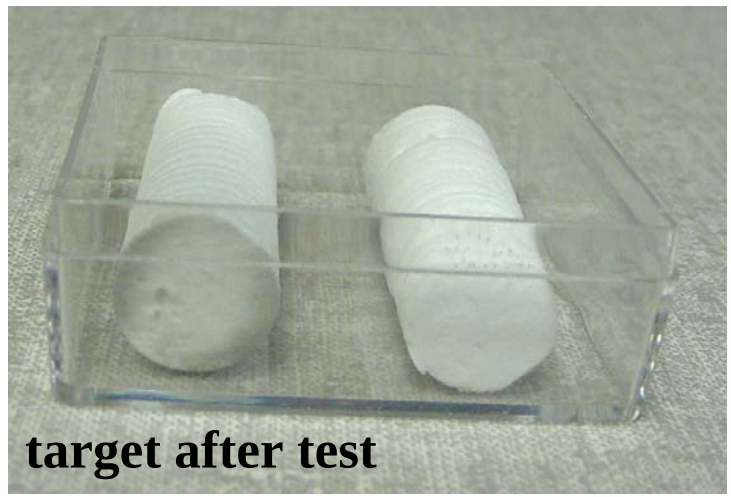
- Thin layer of CeS (5 μm thick) deposited onto a tungsten-coated carbon matrix
  - same matrix that is used for UC targets
- Maximum operating temp. is 1900 C
- Used to produce ^{33}Cl and ^{34}Cl beams
  - $^{32}S(d,n)^{33}Cl$ ($T_{1/2}$ = 2.5 sec)
  - $^{34}S(p,n)^{34}Cl$ & $^{34}S(d,2n)^{34}Cl$ ($T_{1/2}$ = 32.2 min)
- Initial on-line tests
  - measured 10^4 ions/sec/μA of ^{34}Cl
  - extracted from ion source as $AlCl^+$
  - very little Al vapor was present in the target
  - ^{nat}S used to make target (natural abundance of ^{34}S is 4.2%)
- Targets showed no change during on-line test

Al_2O_3 target for production of ^{26}Si and ^{27}Si beams

target holder (1.5 cm dia. x 7.6 cm)

$$^{27}Al(p,n)^{27}Si$$
$$^{27}Al(p,2n)^{26}Si$$

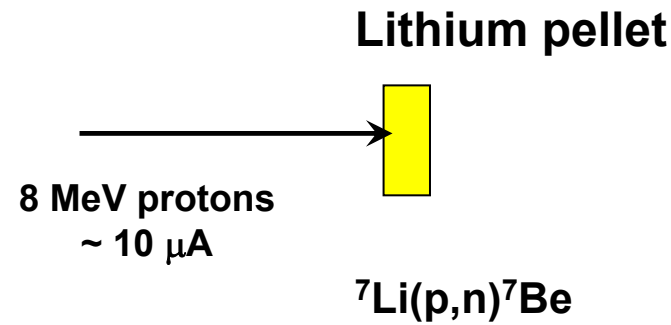
target before test



target after test

- Max. operating temp. is 1900 C
- Tested at 1750 C
- Measured yield of ^{27}Si is 2000 ions/sec/μA
- Observed as molecular ion (SiS^+)

^{7}Be Production



- $T_{1/2}$ = 53.3 days
- produced ~300 mCi of ^{7}Be at TUNL
- Be chemically separated from Li
- cathode with ~126 mCi of ^{7}Be was made and pressed with Cu powder
- two other cathodes with lower activity were also made
- negative ions produced in a Cs-sputter ion source
- ^{7}Be yields were up to 2 x 10^7 pps on target over a period of several days
- beam energies ranged from 4 MeV up to 100 MeV

RIB Production Ion Sources

- **Electron Beam Plasma Ion Source (EBPIS)**
  - presently used to produce n-rich beams from UC target
  - high positive ionization efficiency for many elements
  - followed by Cs-vapor charge exchange cell (neg. ions)
  - >1200 hours lifetime with 10 – 12 μA of 42 MeV protons on target
- **Kinetic Ejection Negative Ion Source (KENIS)**
  - produces negative ions
  - used for production of ^{17,18}F beams
  - may also be used for production of ^{33,34}Cl beams
  - >1200 hrs (3000 μAh) mean lifetime in beam (44 MeV ^{2}H)
- **Multi-sample, Cs-sputter ion source for ^{7}Be beams**
  - produces negative ions
  - useful for long-lived activity
  - the radioactive atoms are produced elsewhere, extracted from the target material, and inserted into the ion source

Laser Ion Source Experiments (Sept. 04 & Sept. 05)

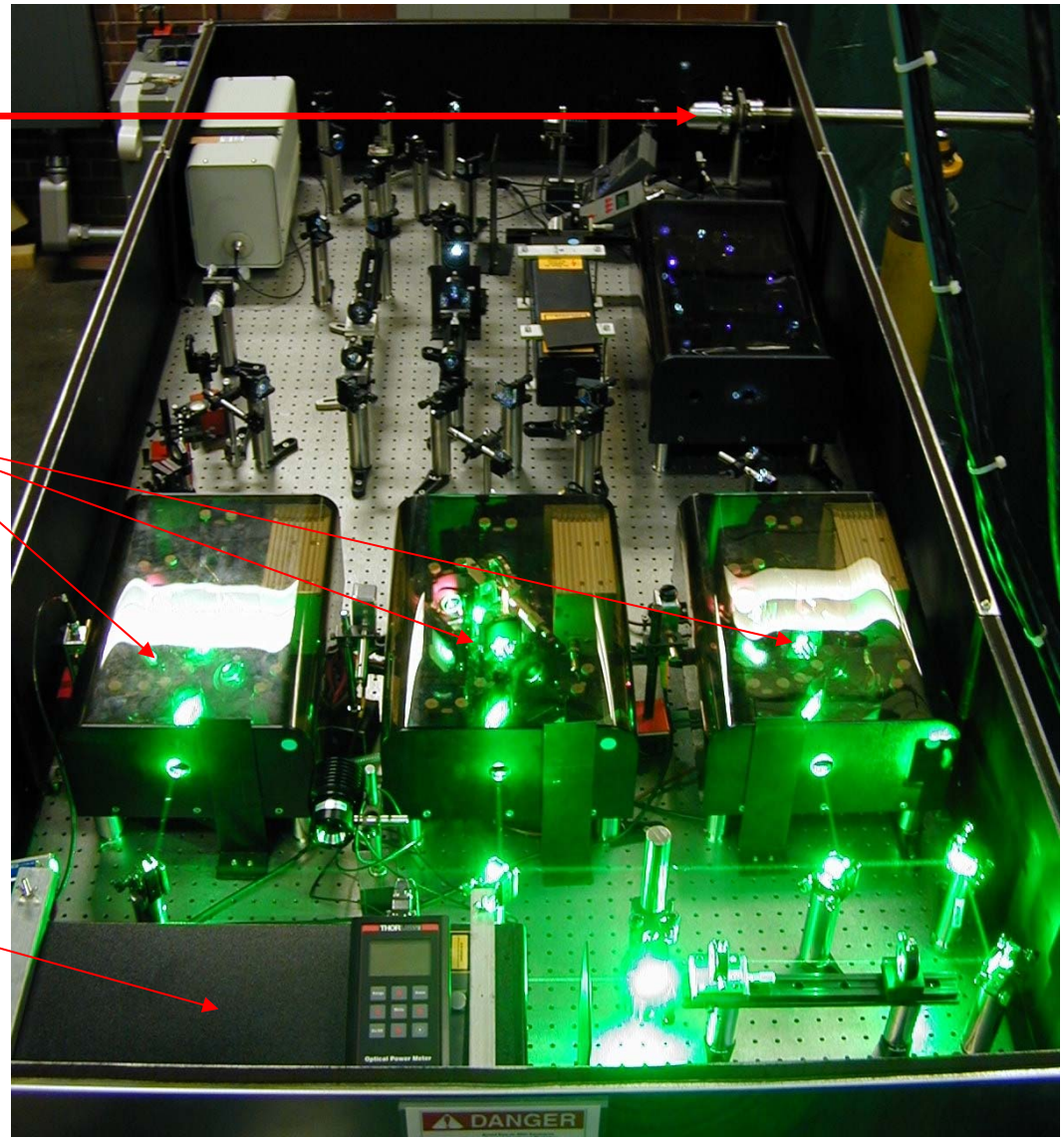
- Laser ion source set up and operated at HRIBF in collaboration with a group from Mainz
- Three-step ionization of Sn, Ge, Ni, and Cu obtained
- Autoionization states found for Sn and Ge (higher ionization efficiency)
- Frequency quadrupling of the Ti:sapphire used successfully, for the first time, to resonantly ionize Cu atoms
- Measured beam emittance of laser-ionized and surface-ionized beams
- Measured time profile of laser-ionized beams
- Overall LIS efficiencies:
  - 22% for Sn (compared to 10% reported at ISOLDE)
  - 3.3% for Ge
  - 2.7% for Ni
  - 2.4% for Cu

Laser setup for the initial test at the HRIBF

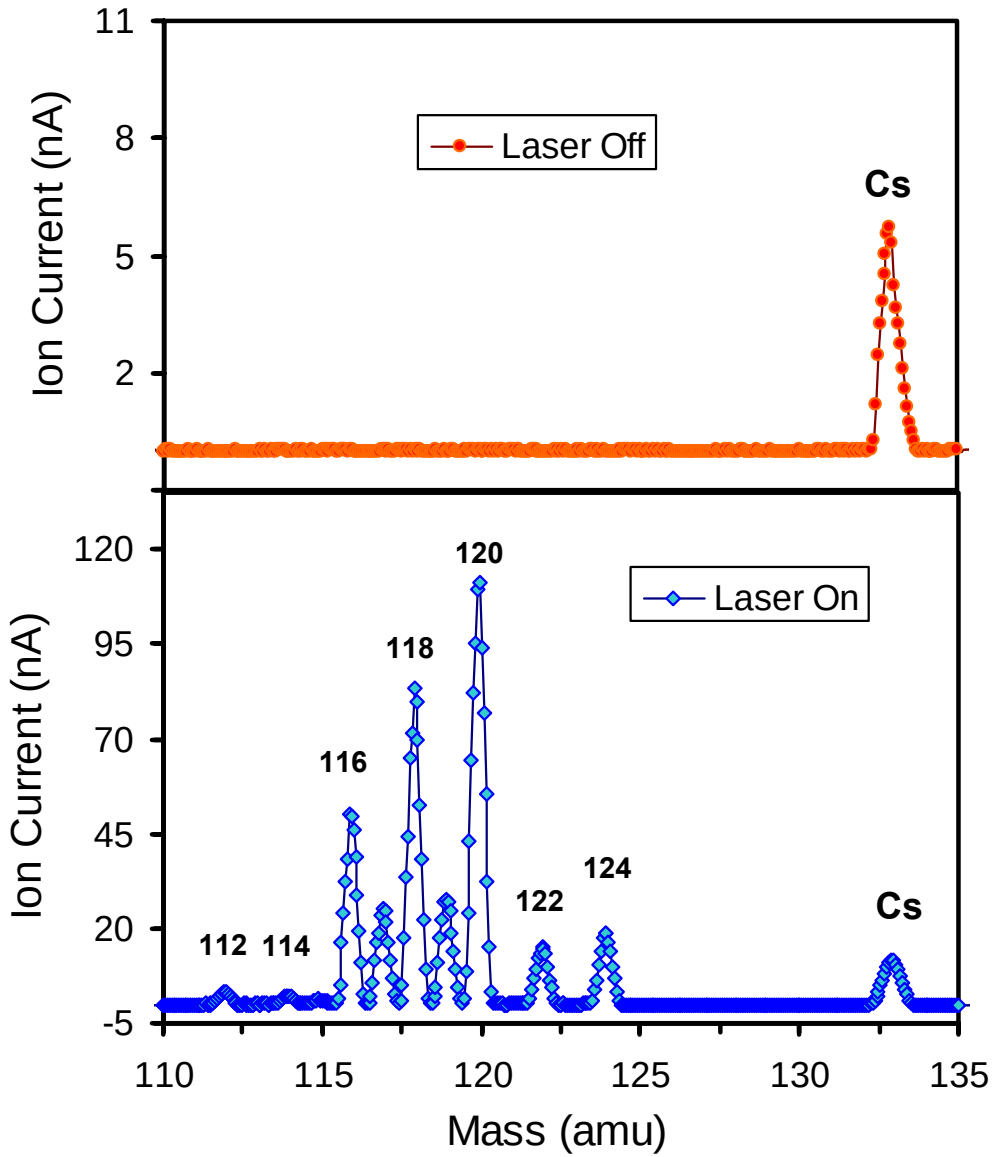
Laser beam into the hot cavity through the mass-analysis magnet

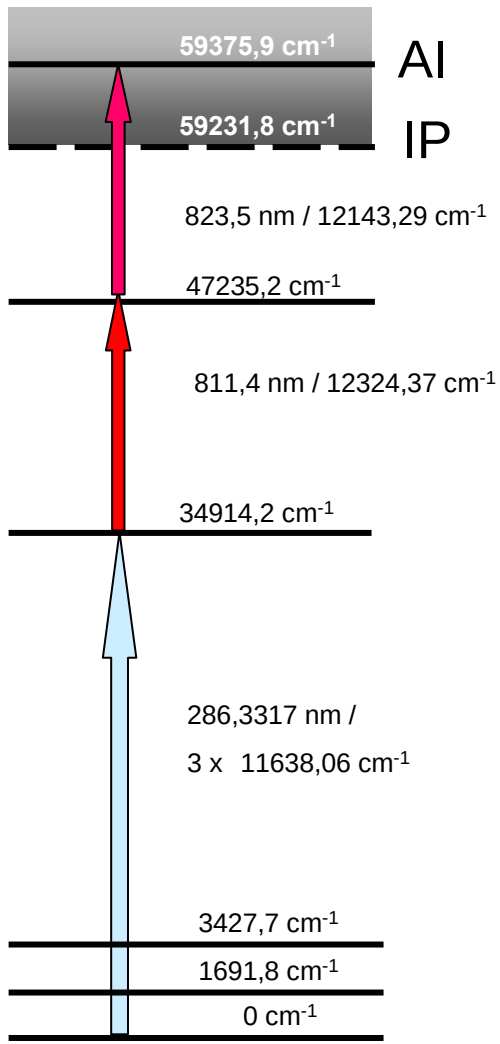
Ti:sapphire lasers (supplied by the Mainz group)

Nd:YAG Pump laser (60 W, 10 kHZ, 532 nm)



Sn Ionization Scheme

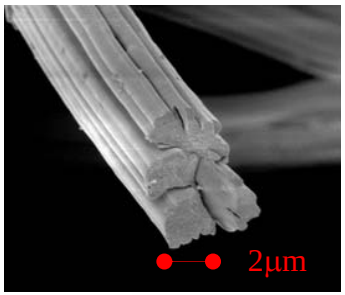


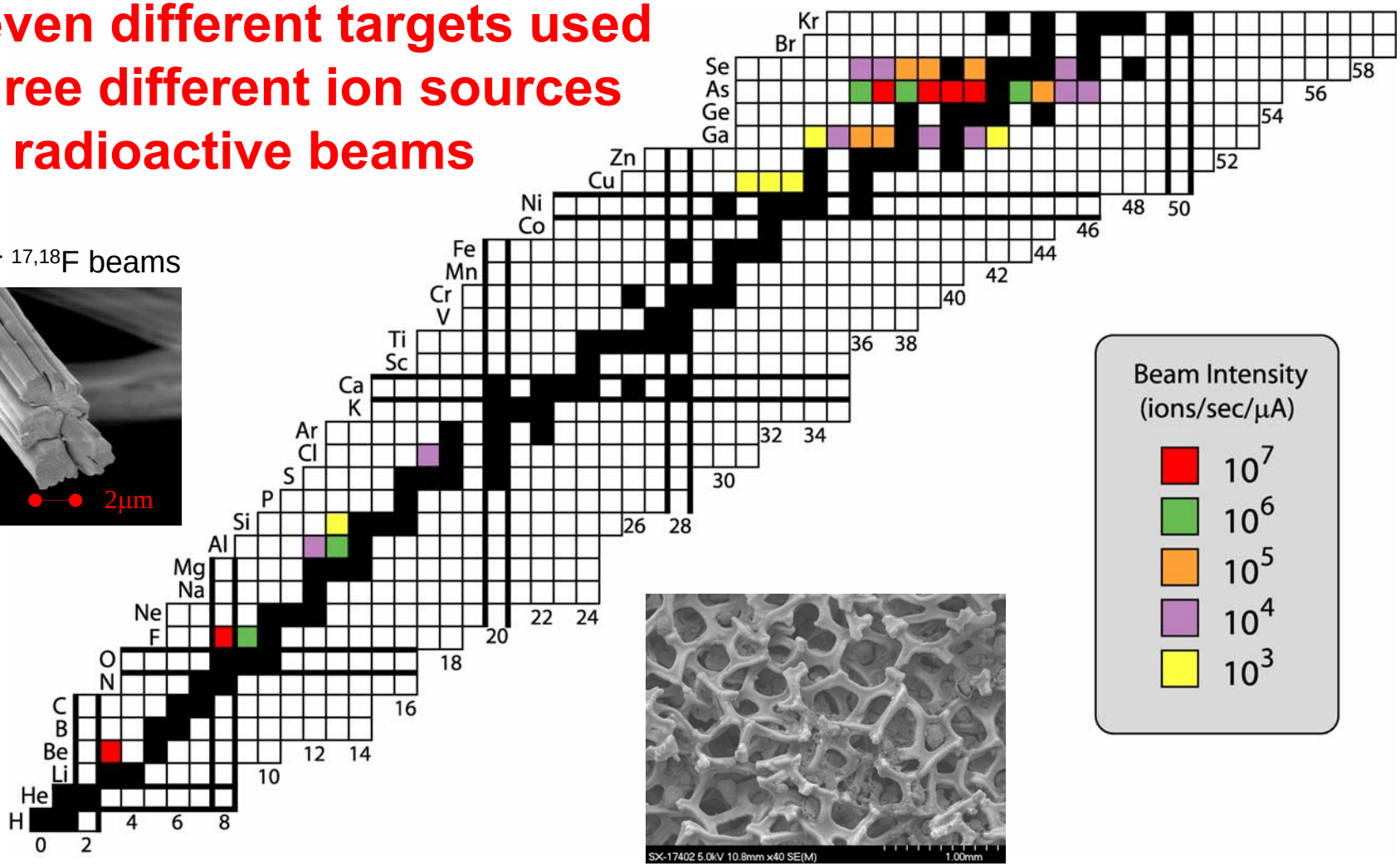


Proton-rich Radioactive Ion Beams

- **Seven different targets used**
- **Three different ion sources**
- **33 radioactive beams**

HfO_2 for $^{17,18}F$ beams



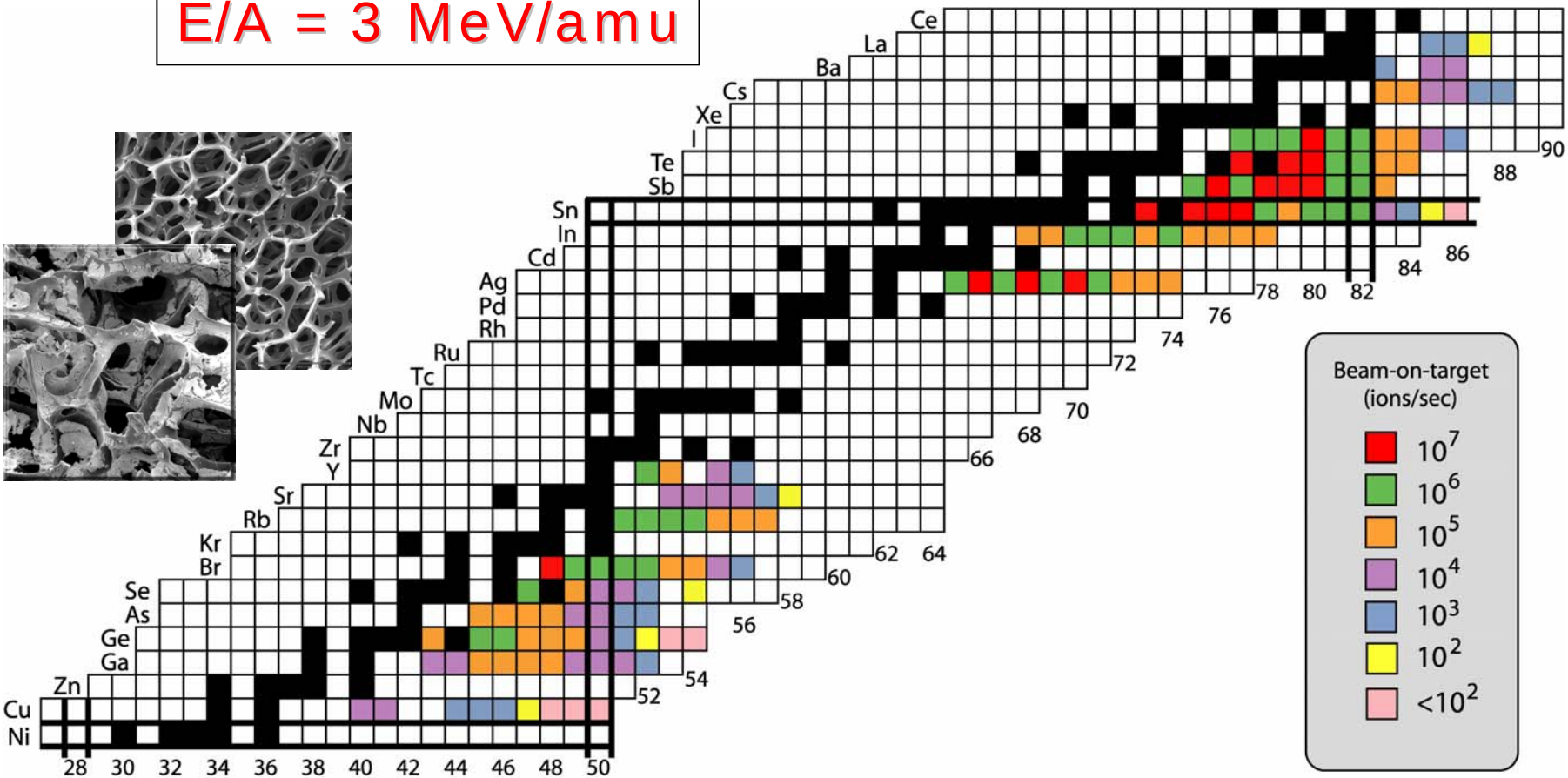


CeS on RVC matrix for ^{34}Cl

Available Neutron-rich Radioactive Ion Beams

(over 120 beams with intensities ≥10^3 ions/sec)

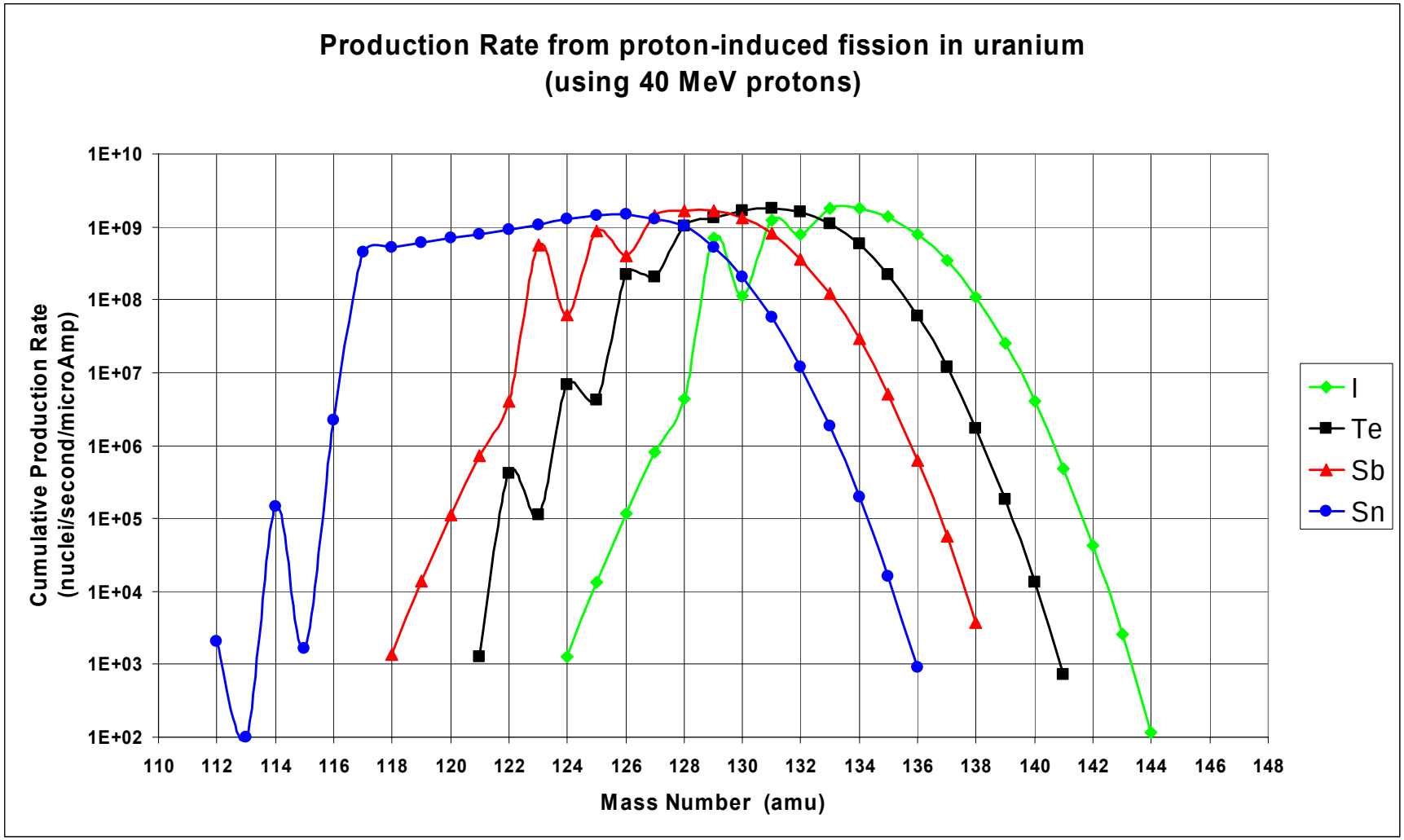
E/A = 3 MeV/amu



Radioactive Beams

- **Three factors affect the quality of the experiment**
  - **RIB intensity**
  - **purity of the beam**
  - **selectivity of the detectors**
- **The RIB intensity can be increased by**
  - **increased production in the target**
  - **faster diffusion and release from the production target**
  - **higher ionization efficiency (ion source)**
  - **better transmission (better emittance)**
- **The beam purity can be improved using**
  - **ion sourcery (selective ionization, temperatures, …)**
  - **chemistry (molecular ion transport, wall materials, …)**
  - **high-resolution mass separation**
- **Detectors must be efficient, selective, and designed for low intensities with relatively high backgrounds from decay of the beam**

Production Rates for Sn, Sb, Te, and I isotopes in a UC target

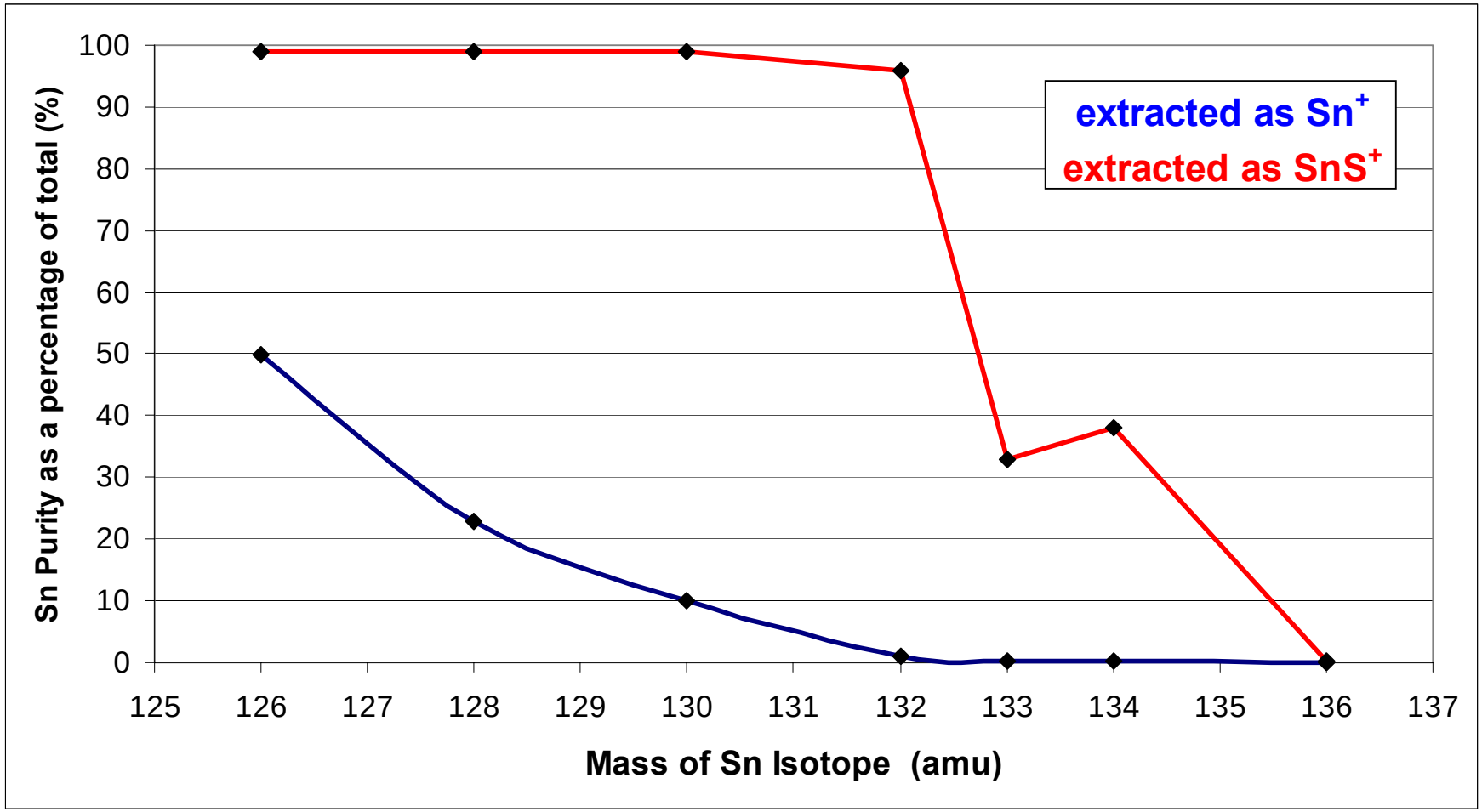


Pure Sn Beams

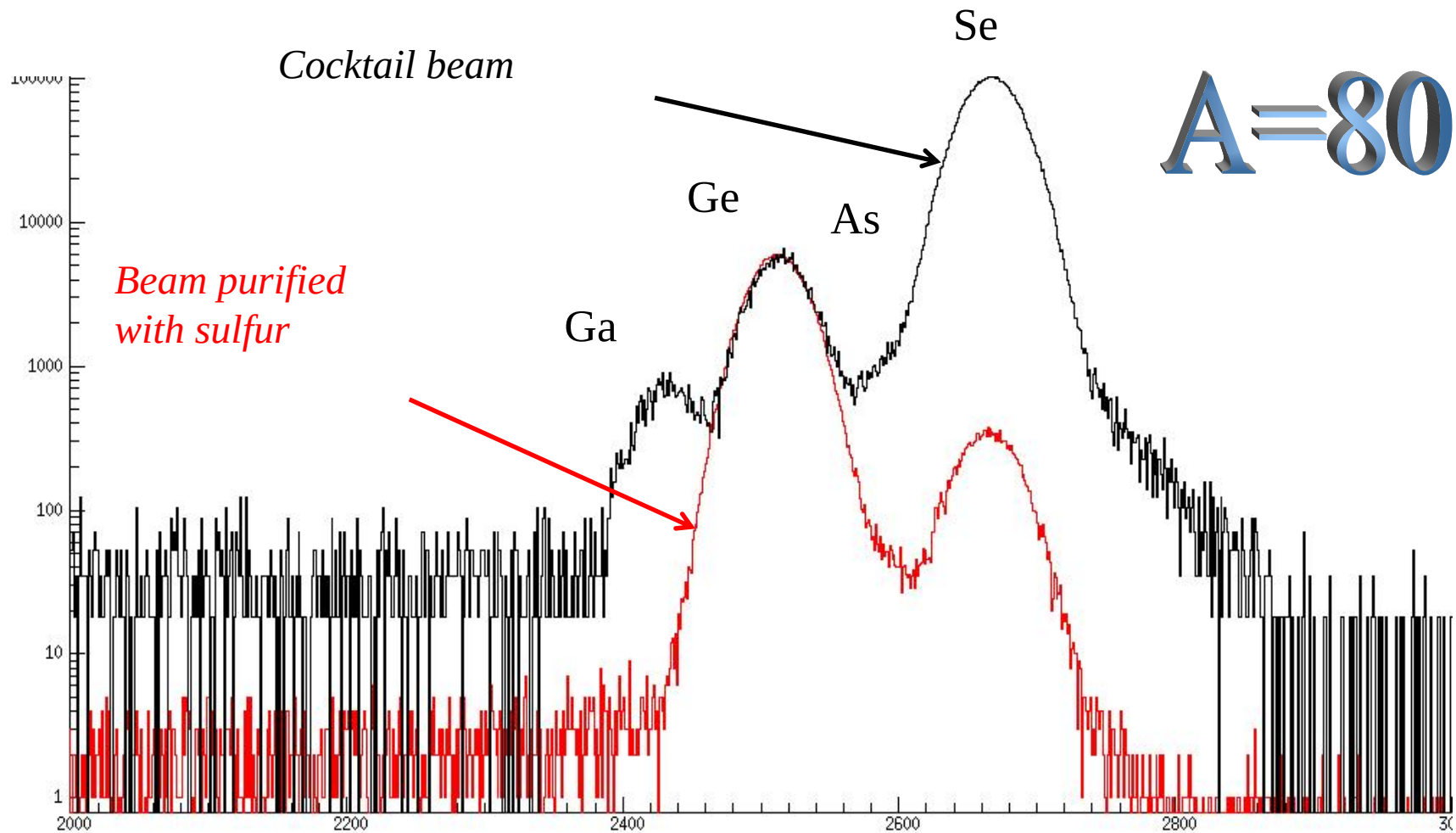
- **Most of the neutron-rich Sn beams are contaminated**
  - **A=132 beam consists of 85% Te, 14% Sb, and 1% Sn**
- **Solution: extract from EBP ion source as SnS^+**
- **Sulfur is added to the UC target via H_2S gas**
- **Yields of TeS^+ or SbS^+ ions are reduced by $>10^4$**
  - **these molecules breakup at temperatures below 1500 C**
- **Convert SnS^+ to Sn^- in a Cs-vapor cell**
- **Energy spread is ~400 eV (molecular breakup)**

- **Purified Ge beams are also provided using this technique (same chemical family)**
  - **for A=80, the Se beam was reduced by a factor of 300**
  - **^{80}Ge beam purity went from 6% up to 95%**

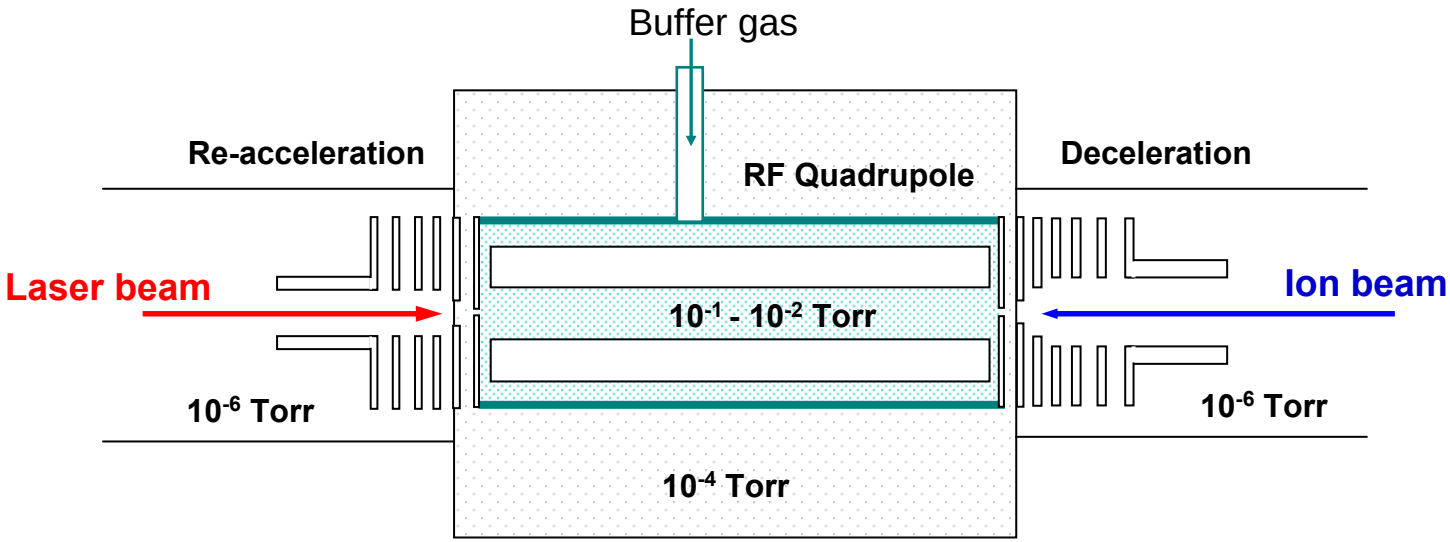
Purity of radioactive Sn Beams



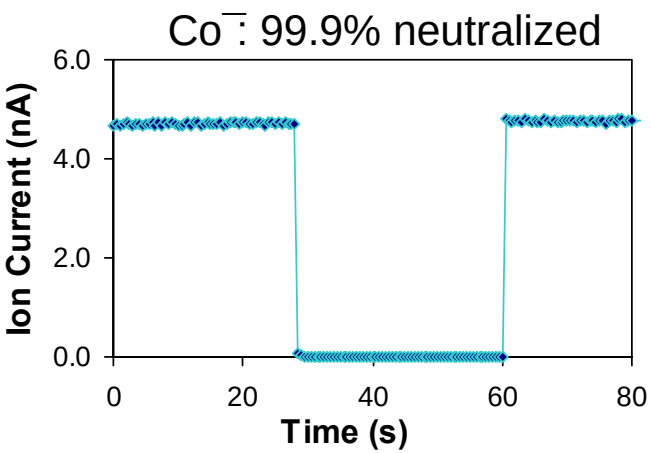
Purification of ^{80}Ge beam

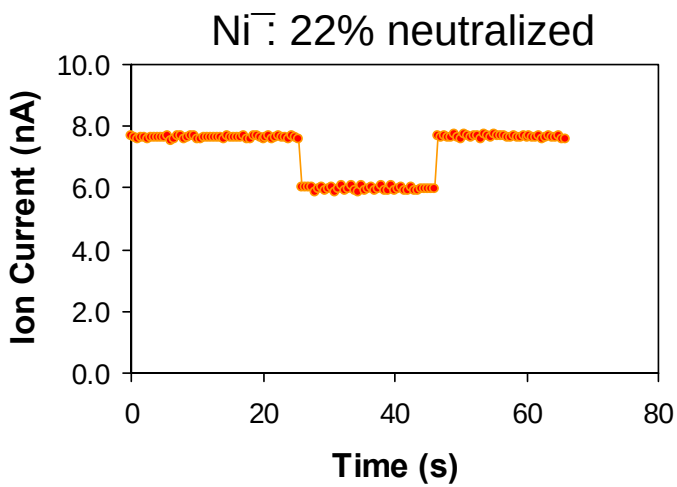


Beam purification by photodetachment in RFQ Ion Cooler

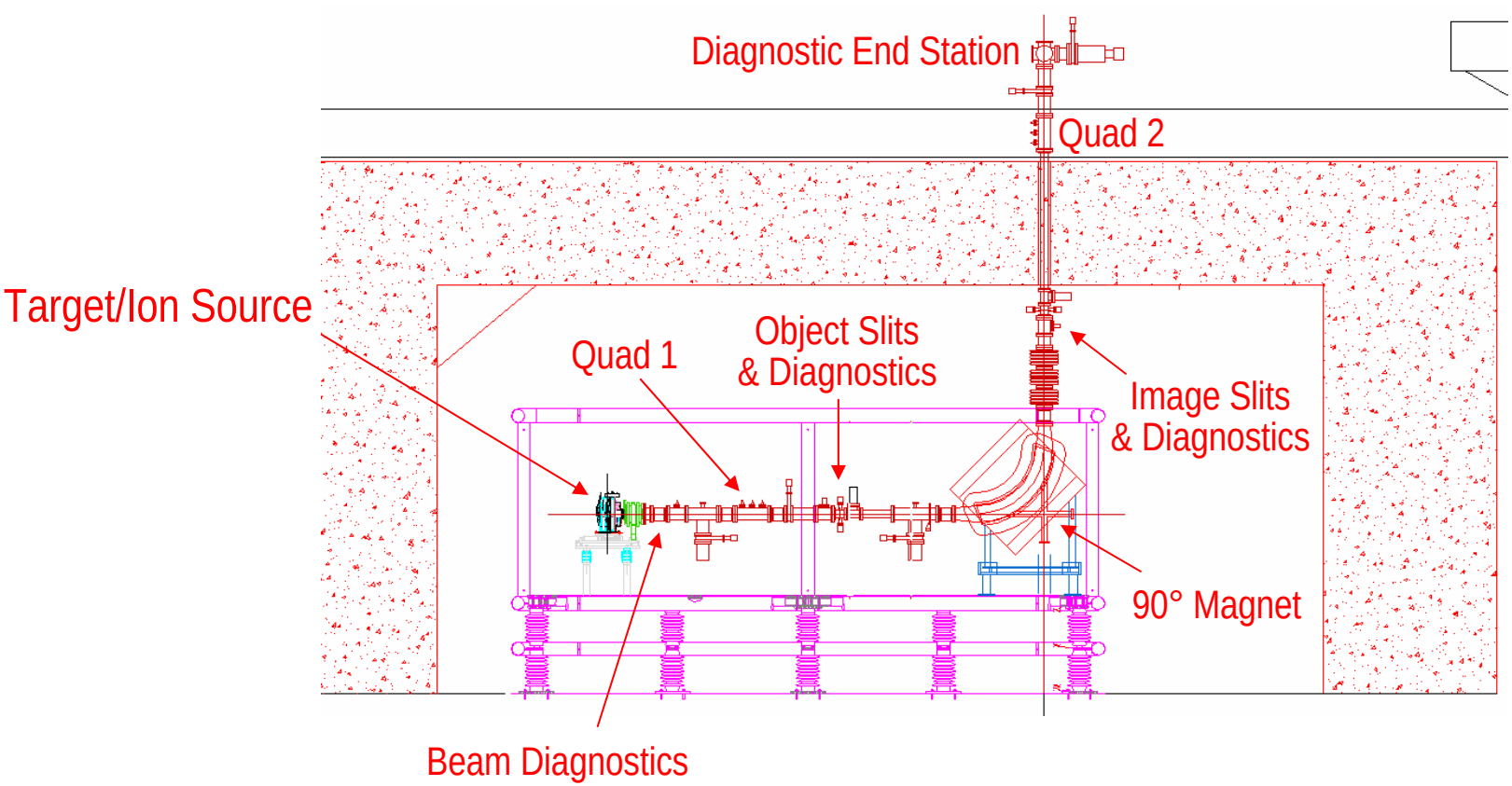


90% $^{56}Co^{-}$
10% $^{56}Ni^{-}$





RIB Analysis Beam Line at the HPTL

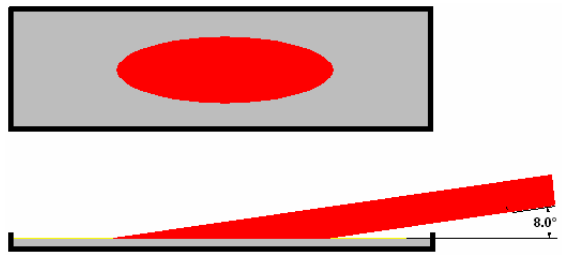


Plans for Target Development at the HPTL

We need to significantly enhance the quality (intensity and purity) of the available proton-rich radioactive beams at the HRIBF.

- **New materials tests with high beam power deposition**
  - SiC and metal silicides (e.g. Zr_5Si_3, Ta_5Si_3, Nb_5Si_3) for ^{25,26}Al beams
  - CeS for ^{33,34}Cl and ^{29,30}P beams

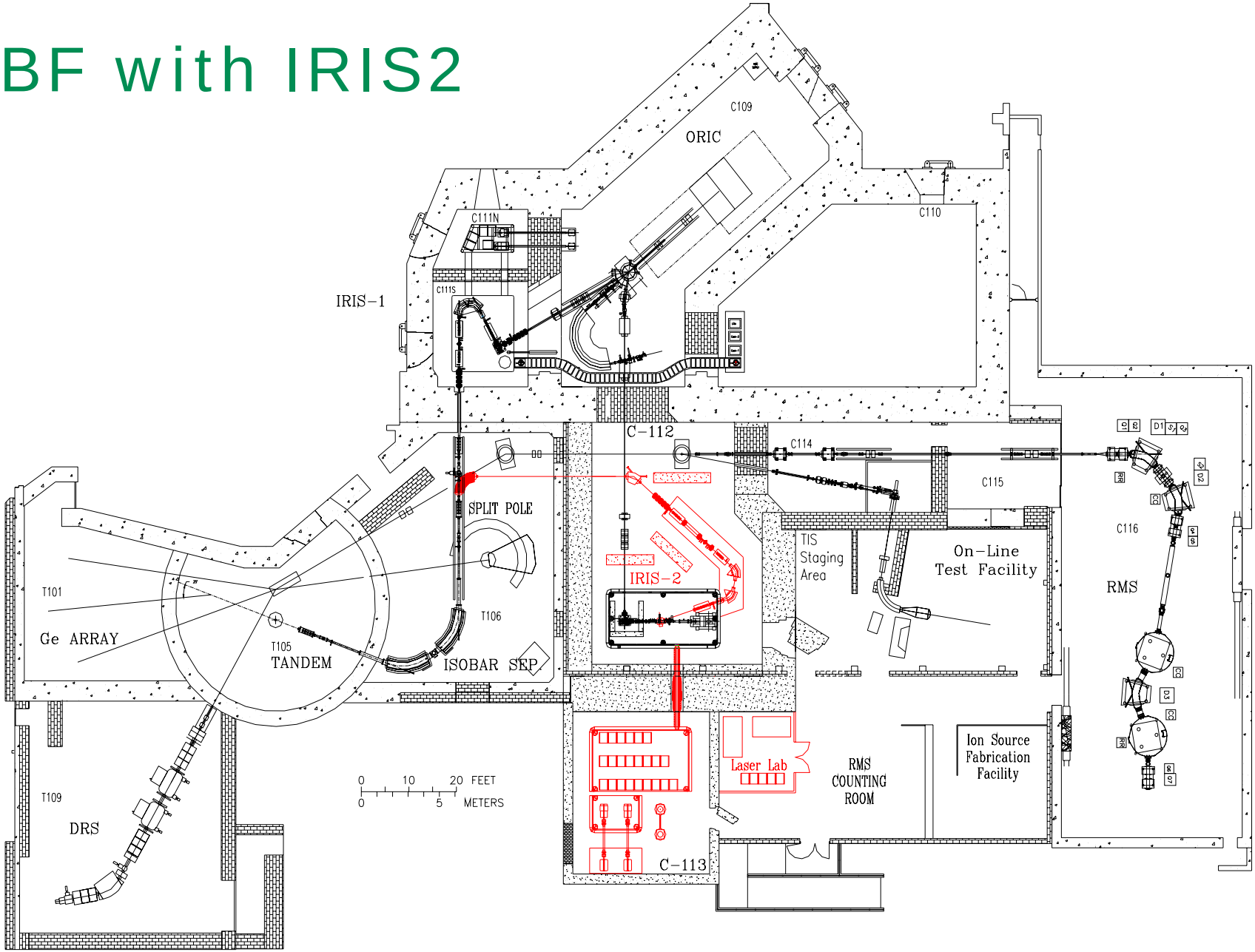
- **New target geometries**
  - Small incident angle (8 deg.)
  - Thin liquids (Ge for ^{69}As and p-rich Se beams)
  - Thin solids for use with ^{3,4}He production beams
    (Al_2O_3 → P, SiC → S, C → ^{15}O)



- **Effect of rastering the production beam**
  - Increase intensity of ^{17,18}F beams from HfO_2 (production beam presently limited to 3 μA due to target damage)
  - Important measurements to be made include ^{17}F(p,γ)^{18}Ne, ^{18}F(p,α)^{15}O
  - ^{17}F Beam-on-target is 1 x 10^7 pps – need about a factor of ten improvement

Plans for Target Development at the HPTL

Other R&D efforts will focus on improving the quality of the available n-rich beams from actinide targets.

- **UC target tests**
  - **Proton-induced fission vs. deuteron-induced fission (direct)**
  - **Investigate 2-step targets (larger volumes)**
  - **Higher density UC targets**
    - **Measure release efficiency for short-lived isotopes**
    - **Lifetime of high-density targets (e.g. pressed-powder targets)**
- **Actinide target materials (e.g. UB_4, ThC_x, low-density ThO_2)**
- **Ion sources**
  - **LaB_6 ion source to make pure Br and I beams (investigate long-term poisoning with high intensity production beams)**
  - **Close-coupled target to reduce effusion times**

HRIBF with IRIS2