Radioactive Beams at the HRIBF

- **Introduction to HRIBF and layout**
- **Radioactive Ion Beams**
  - **RIB production targets**
  - **Beams available**
  - **Purification techniques**
- **Facility upgrades**
- **Recent physics highlights**

HRIBF

Dan Stracener

SPES2010 International Workshop

November 15 - 17, 2010

U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

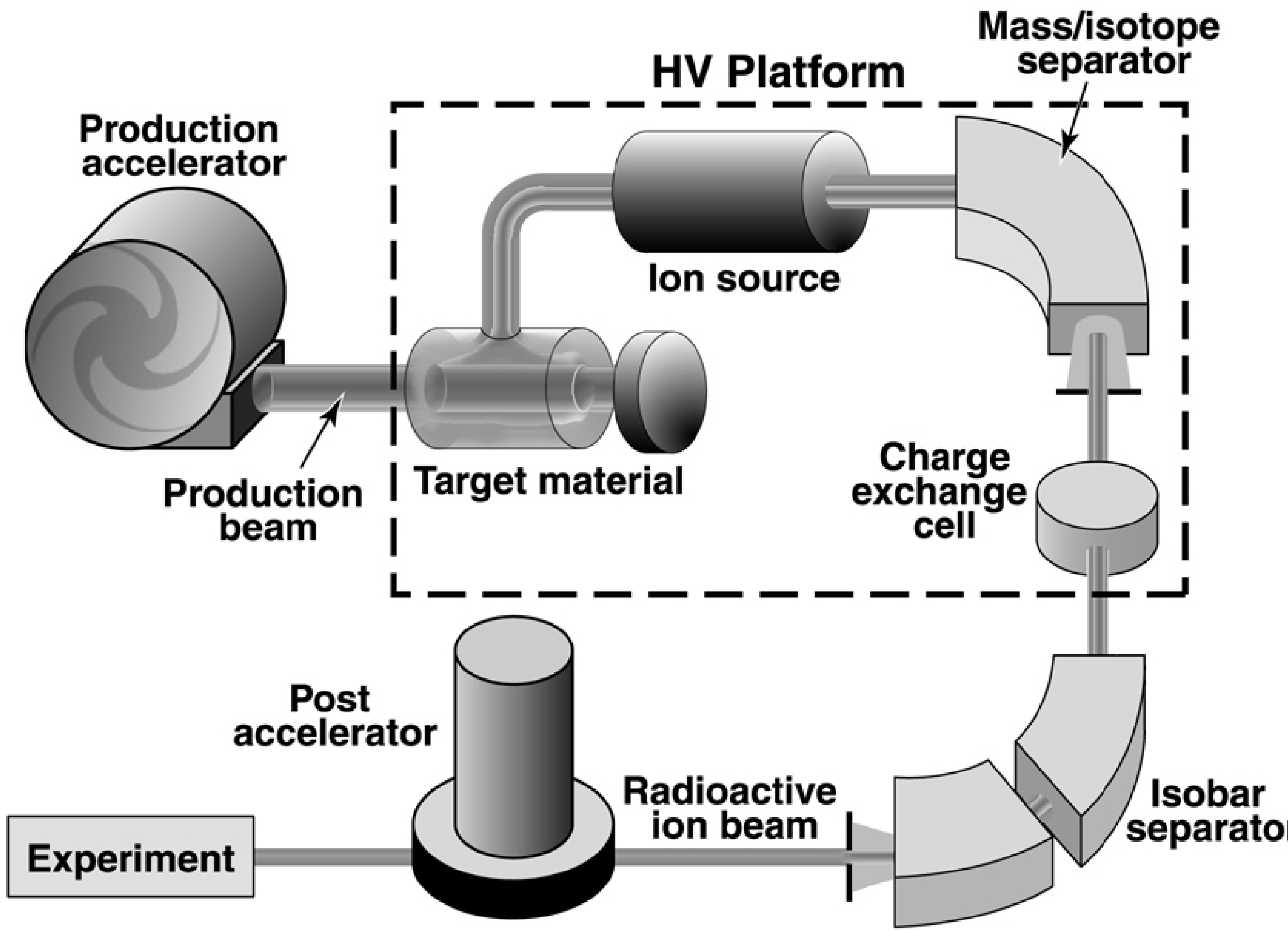
Holifield Radioactive Ion Beam Facility (HRIBF)

- Produces high-quality post-accelerated beams of unstable nuclei
  - Radioactive ion beams (RIBs) using ISOL technology
- A national user facility for RIB science
  - Developed out of existing accelerator complex [relatively low cost]
  - Users group has 570 members
  - Operates 5 day 24 hour schedule
    - 1500 – 1900 hours of RIB per year
    - 4500 – 5000 total operation hours per year
- Only facility of its type in the US
- Has capabilities that are unique worldwide
- Helping to develop the ISOL technique for RIB production
  - Pioneering techniques, developing technology
  - Helping to develop, maintain a user base for a next-generation facility

HRIBF Core Science Programs

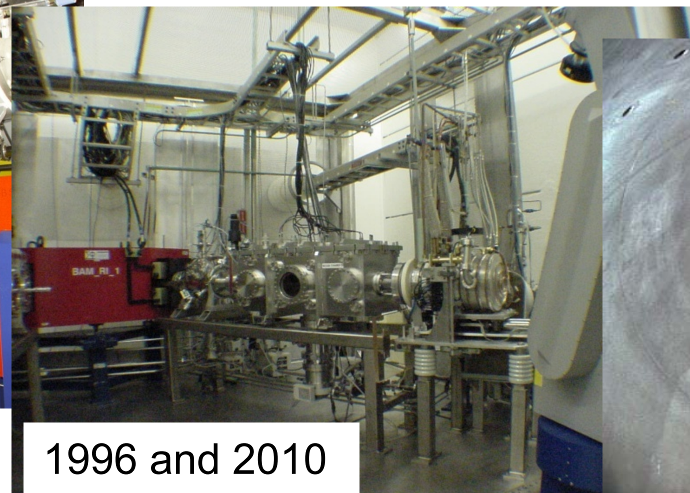
- Astrophysics
  - Reactions relevant to explosive nucleo-synthesis
- Nuclear structure and reactions
  - Reactions in very neutron-rich systems
  - Decay spectroscopy
- ISOL science and technology
  - RIB ion sources
  - RIB production targets
  - Techniques to enhance RIB quality (intensity and purity)

Schematic of RIB Production at the HRIBF



Accelerators at the Holifield Radioactive Ion Beam Facility

ORIC (k=100)



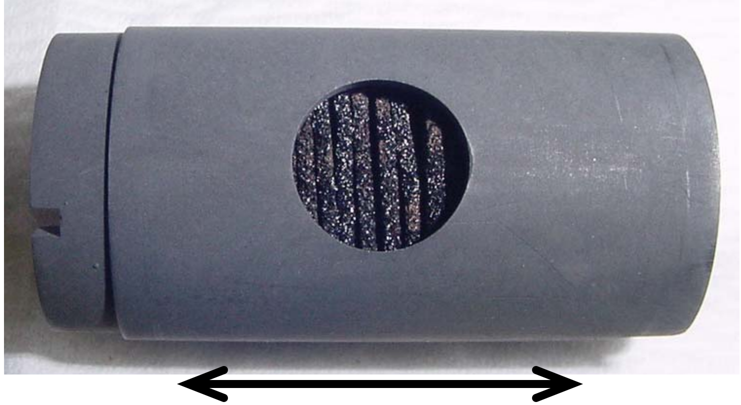
RIB Injectors

Tandem (25 MV)

- HRIBF has 3 Primary Systems – must operate concurrently to deliver RIBs
- Can also operate independently – stable beams from Tandem to experiments
- The cyclotron is a variable-energy, multi-particle accelerator
- Tandem provides high quality beam with easy energy variability

Effects of using 50 MeV ^{1}H beams for RIB production

- Low beam energy ➔ short range in targets
  - typically, a few g/cm^2 for protons
  - for p-rich, use compound nucleus reactions
    - large σ (100's mb) at specific resonant energies
    - limited to products close to the target nucleus
  - for n-rich (fission), yield proportional to target thickness
  - high local power density in target

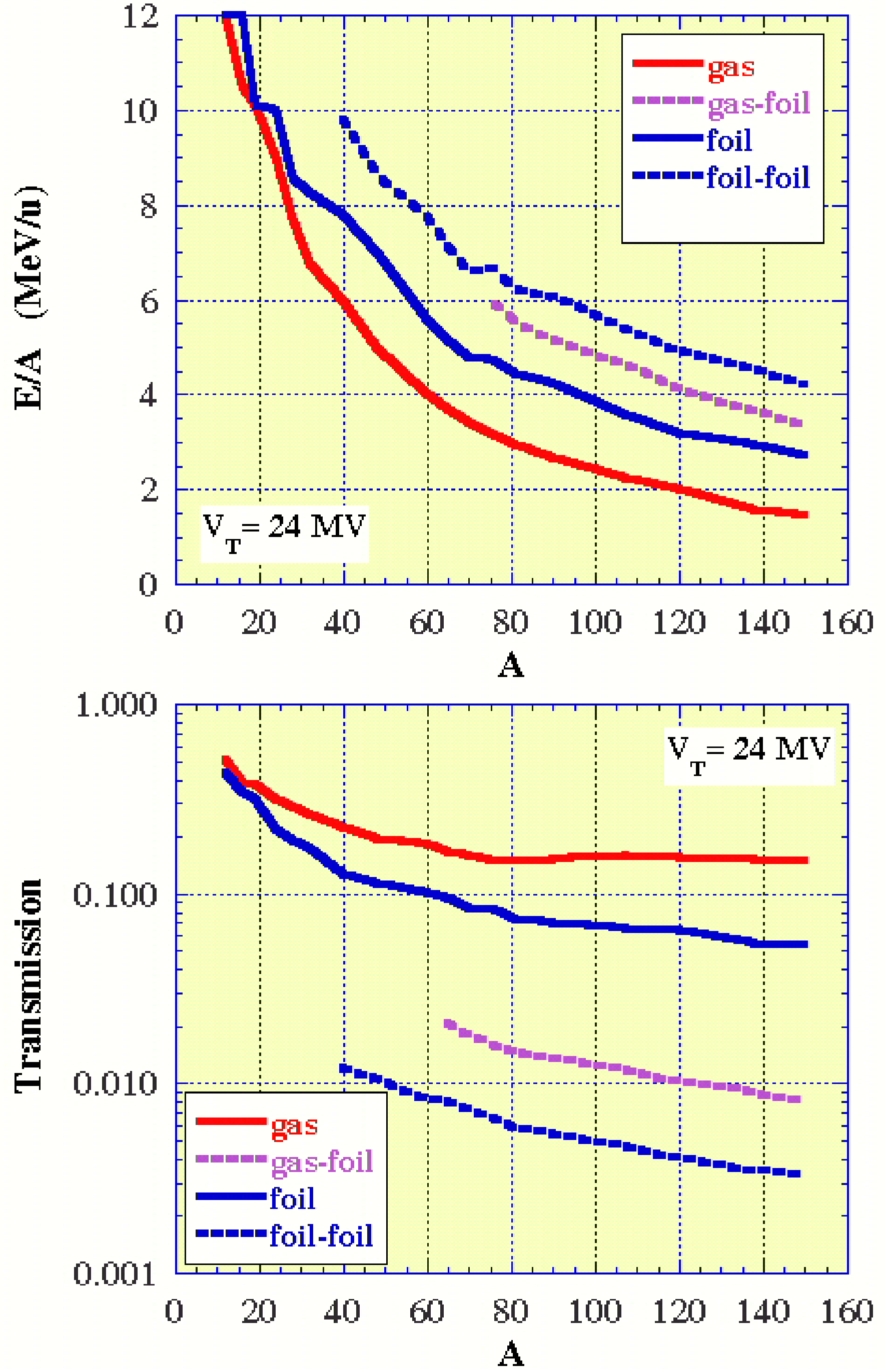


24 mm

Characteristics of Tandem Post-accelerator

- Simple, reliable, economical
- Wide range of operating voltage
  - 1MV - 26 MV
  - beam energy easily changed
- 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/ΔE >10^4)
  - low emittance (0.3-1.0 π mm mrad)

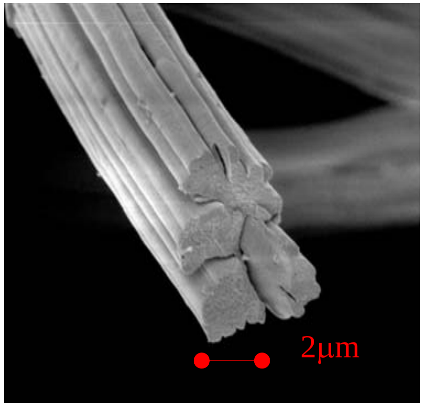
- Must double strip for A>80
  - to reach E/A~5 MeV/amu (up to A~140)
- Negative-ion accelerator

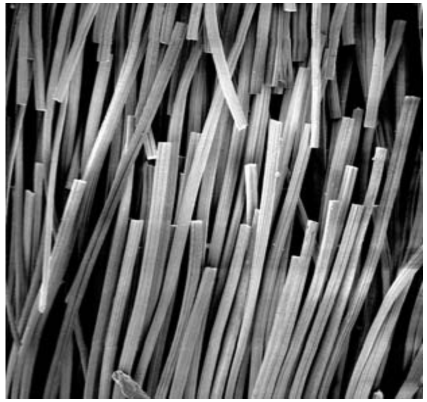


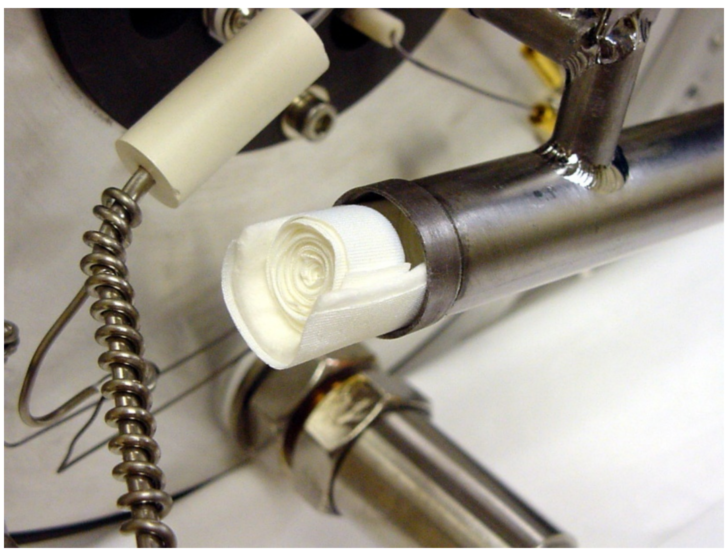
RIB Production Targets

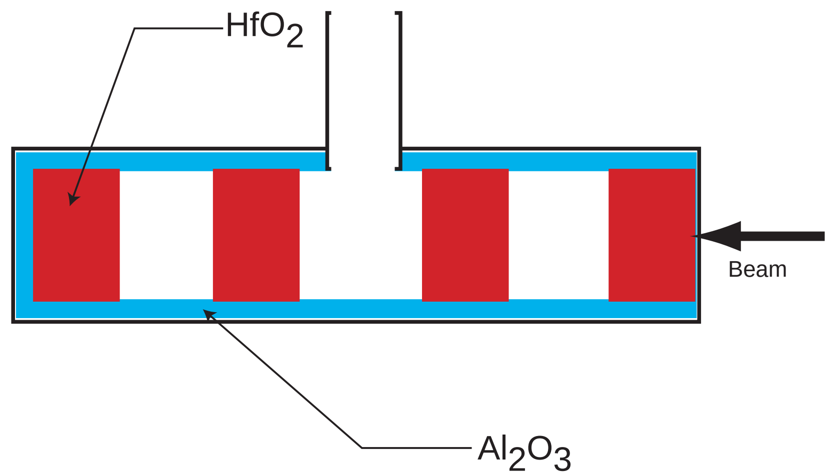
- HfO_2 fibers (production of ^{17}F and ^{18}F)
- Uranium carbide (production of n-rich beams via proton-induced fission)
- Molten metals
  - germanium for production of As, Ga, and Se isotopes
  - nickel for production of Cu isotopes
- Ni pellets (^{56}Ni via (p,p2n) reaction – ^{56}Co contamination)
- Cerium sulfide (production of ^{33}Cl and ^{34}Cl)
  - thin layers deposited on W-coated carbon matrix
- Silicon carbide (production of ^{25}Al and ^{26}Al)
  - fibers (15 μm), powder (1 μm), thin layers on carbon matrix, solid discs
  - also developing metal silicides (e.g. Nb_5Si_3 disks)
- Aluminum oxide (production of ^{26}Si and ^{27}Si)
  - thin fibers (6μm) with sulfur added for transport
- ^{7}Be, ^{10}Be, ^{26g}Al, ^{82}Sr sputter targets
  - mixed with copper, silver, or niobium powders

HfO_2 Target Assembly







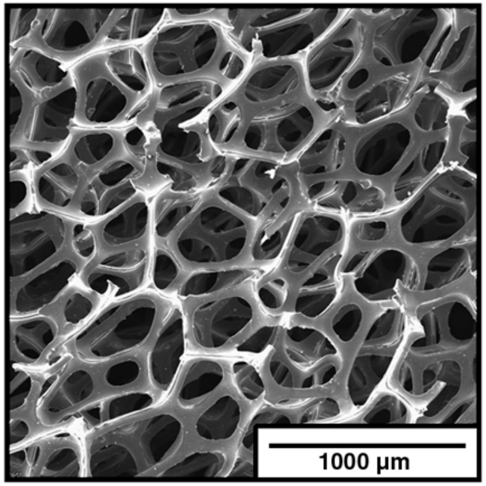


$^{16}O(d,n)^{17}F$ & $^{16}O(\alpha,pn)^{18}F$

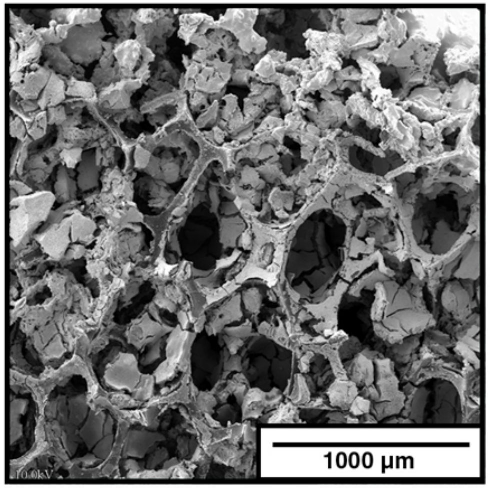
UC/RVC Fabrication Process

- Saturate RVC matrix with uranyl nitrate solution
  - Reticulated vitreous carbon (RVC) material supplied by ERG Materials and AeroSpace Corporation, Oakland, CA, USA
  - Fiber diameter is 60 μm, density is 0.06 g/cm^3, UC_2 coating is about 10 μm
- Heat to 300 C for a few hours (convert to uranium oxide)
- Repeat until the desired mass of uranium is achieved (about 1.2 g/cm^3)
- Heat to 2000 C (convert to uranium carbide and sinter)
- Density varies from 0.6 - 1.4 g/cm^3

Uncoated RVCF



UC_2 Coated RVCF
Thickness: ~10 µm



Pressed-powder UC targets at HRIBF

- UC targets are fabricated by ORNL personnel in the Materials Science & Technology Division
  - uranyl nitrate solution is mixed with graphite powder and heated to 1925 C to form UC_2
  - UC_2 is ground down to ~ 3-micron diameter powder
  - This UC_2 powder is mixed with a customized graphite powder
    - 64% natural graphite (Graftech)
    - 16% synthetic graphite (SGL Carbon KRB2000)
    - 20% resin (Durite SC-1008)
  - The mixture is pressed at low pressure and heated to 350 C for a few hours
  - The disk is then sintered at about 1800 C for about 4 hours in a vacuum furnace
  - Density is about 2.2 g/cm^3
  - Compared to the UC/RVC targets
    - The cost is low
    - Excellent reproducibility

Recent yields from the UC_x pressed-powder targets

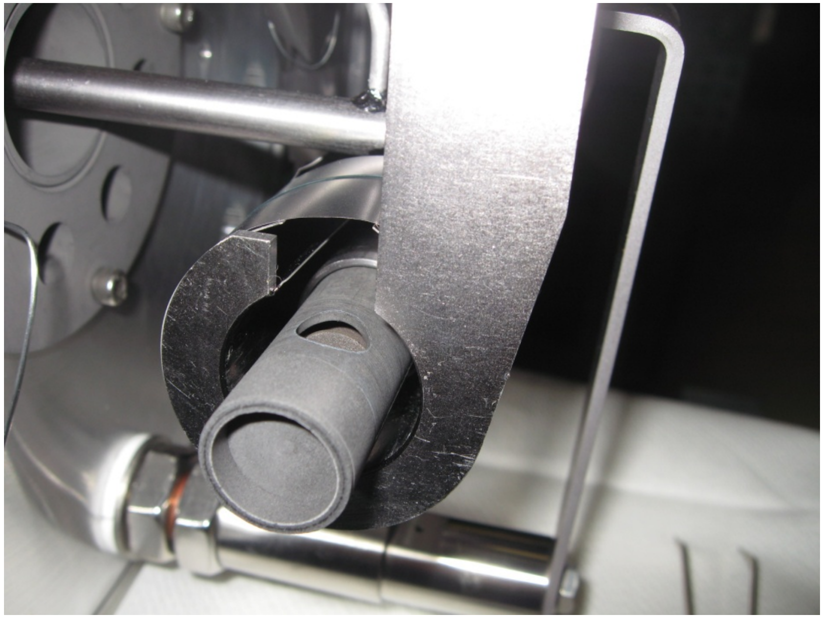
Isotope	$T_{1/2}$ (secs)	Expected rate (pps) from UC/RVC target	Delivered RIB (pps) from UC/C target	Ratio of yields
^{76}Cu	0.65	150	200 – 300	2
^{77}Cu	0.46	20	15 – 30	1.5
^{78}Cu	0.35	1.5	1 – 3	2
^{83}Ga	0.30	20	60	3
^{84}Ga	0.08	1.9	0.5 – 2.7	1.4
^{78}Ge	88	2×10^6	1×10^6	0.5
^{80}Ge	29.5	2×10^5	1×10^5	0.5
^{84}Se	186	8000	25000	3.1
^{130}Sn	223	5×10^5	2×10^5	0.4
^{132}Sn	39.7	1.2×10^5	5×10^4	0.4
^{134}Sn	1.04	700	300 – 700	1
^{132}Te	2.8×10^5	4×10^7	6×10^7	1.5
^{134}Te	2520	3×10^5	3.3×10^5	1.1

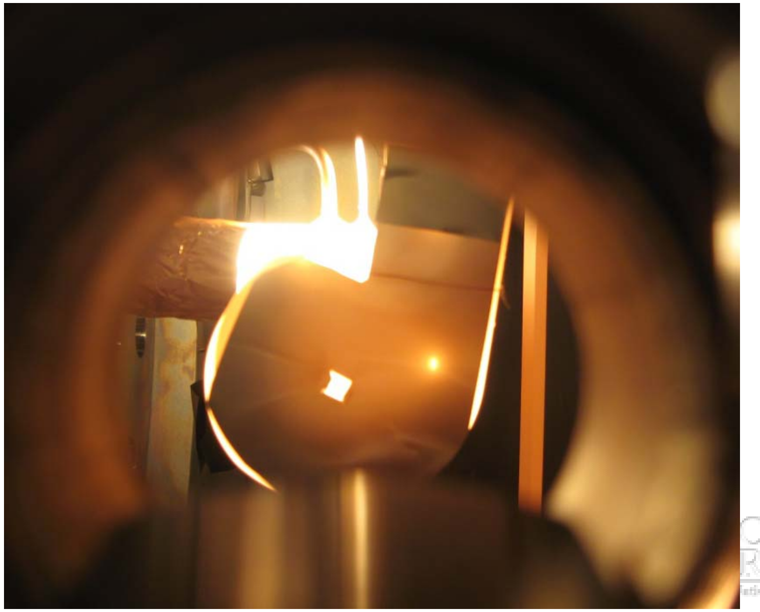
2010 test with UC_2 targets from SPES

- Seven UC_2 samples prepared by University of Padova group
- Densities in the range of 4.2 g/cm^3
- Used the SPES design where the disks are separated to allow for enhanced radiation to the walls of the container
- Heated to 2000° C for about two weeks without any out-gassing or obvious change in structure (samples observed after the on-line test)

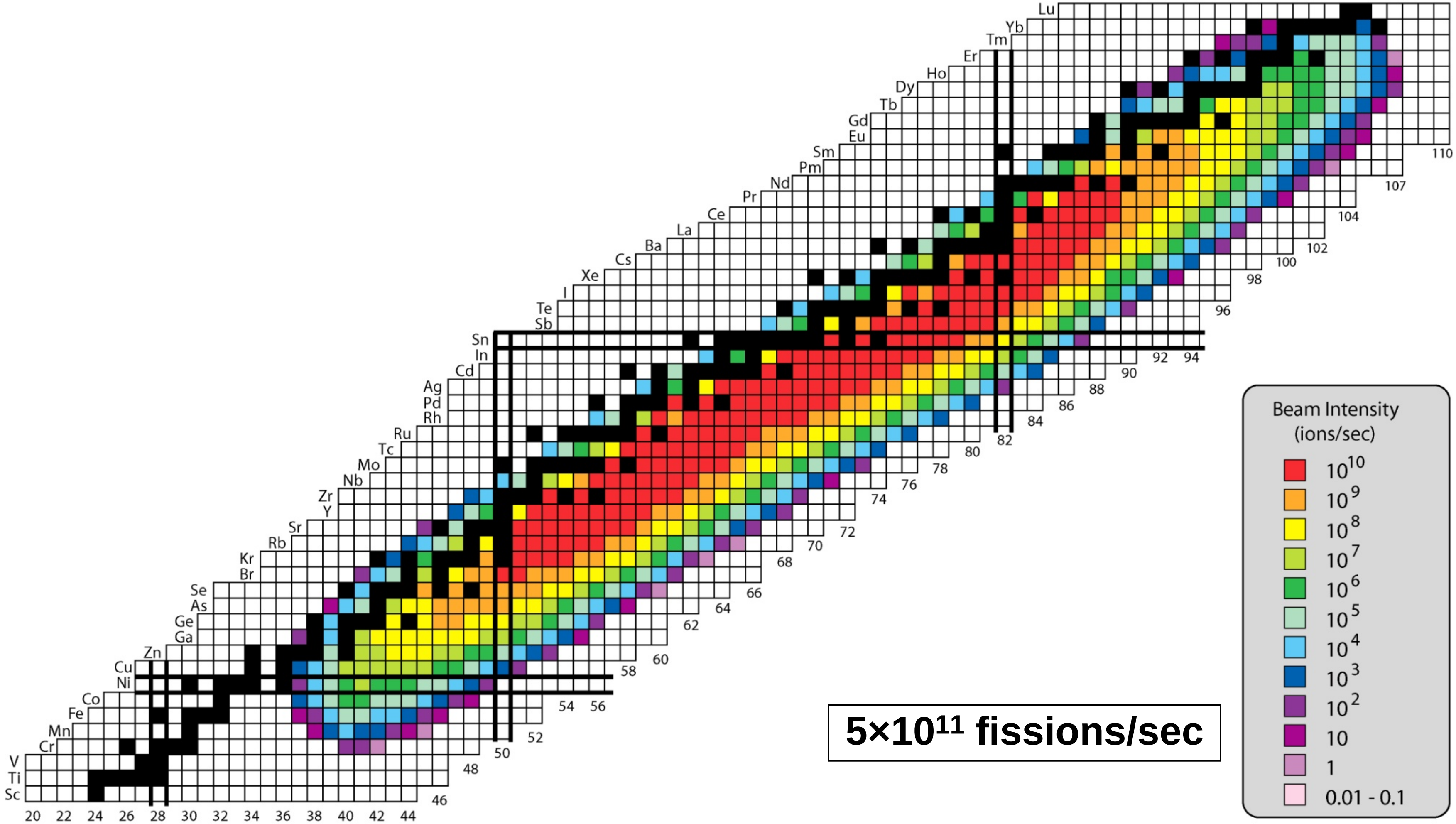
Recent test with UC_2 targets from SPES

- Yield measurements were made at the HRIBF using low intensity proton beams from the Tandem (40 MeV, 50 nA)
- Measured beam intensities of 20 elements (several isotopes each) at 3 target temperatures (1600°, 1800°, and 2000° C)
- On-line analysis indicates these targets performed as well as lower density targets presently in use at HRIBF (fiber and pressed-powder)
- Complete analysis of the yield data is continuing





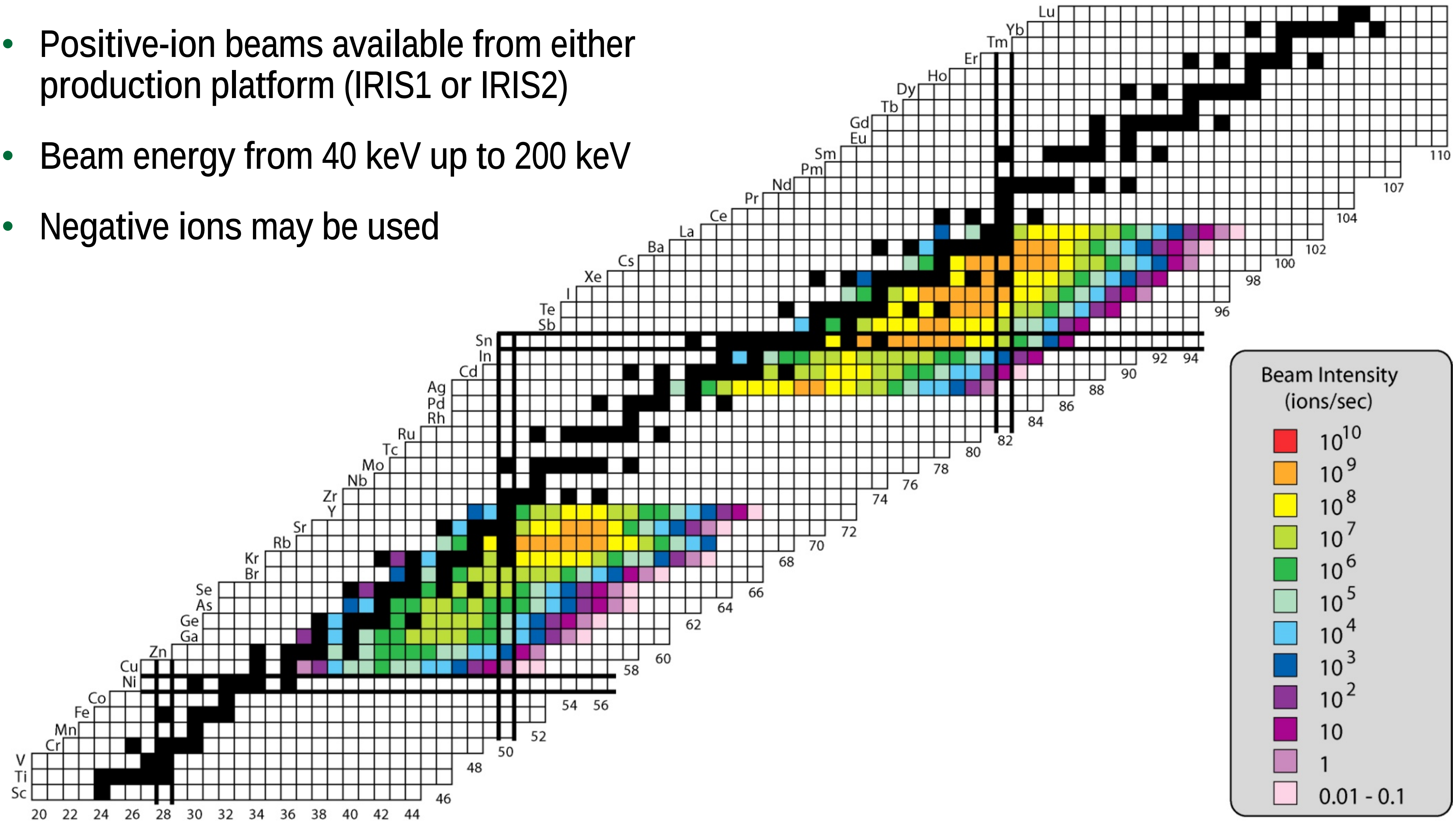
Production Rate of Fission Fragments in the HRIBF UC target using 12 μA of 50 MeV protons



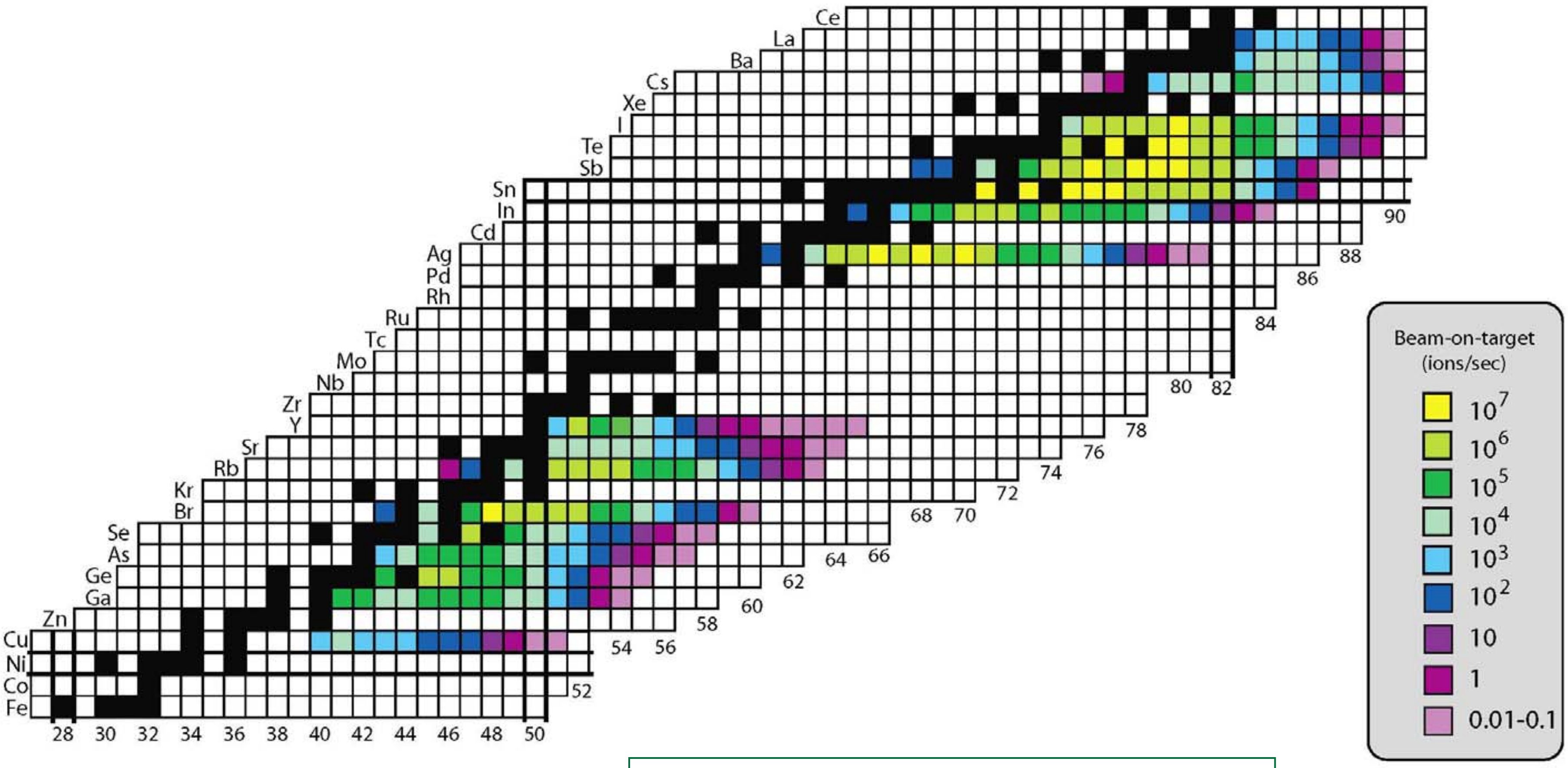
5×10^{11} fissions/sec

Low-energy Neutron-rich Radioactive Ion Beams (directly from the HRIBF ion source)

- Positive-ion beams available from either production platform (IRIS1 or IRIS2)
- Beam energy from 40 keV up to 200 keV
- Negative ions may be used



Accelerated Neutron-rich Radioactive Ion Beams (over 160 beams with intensities ≥10^3 ions/sec)

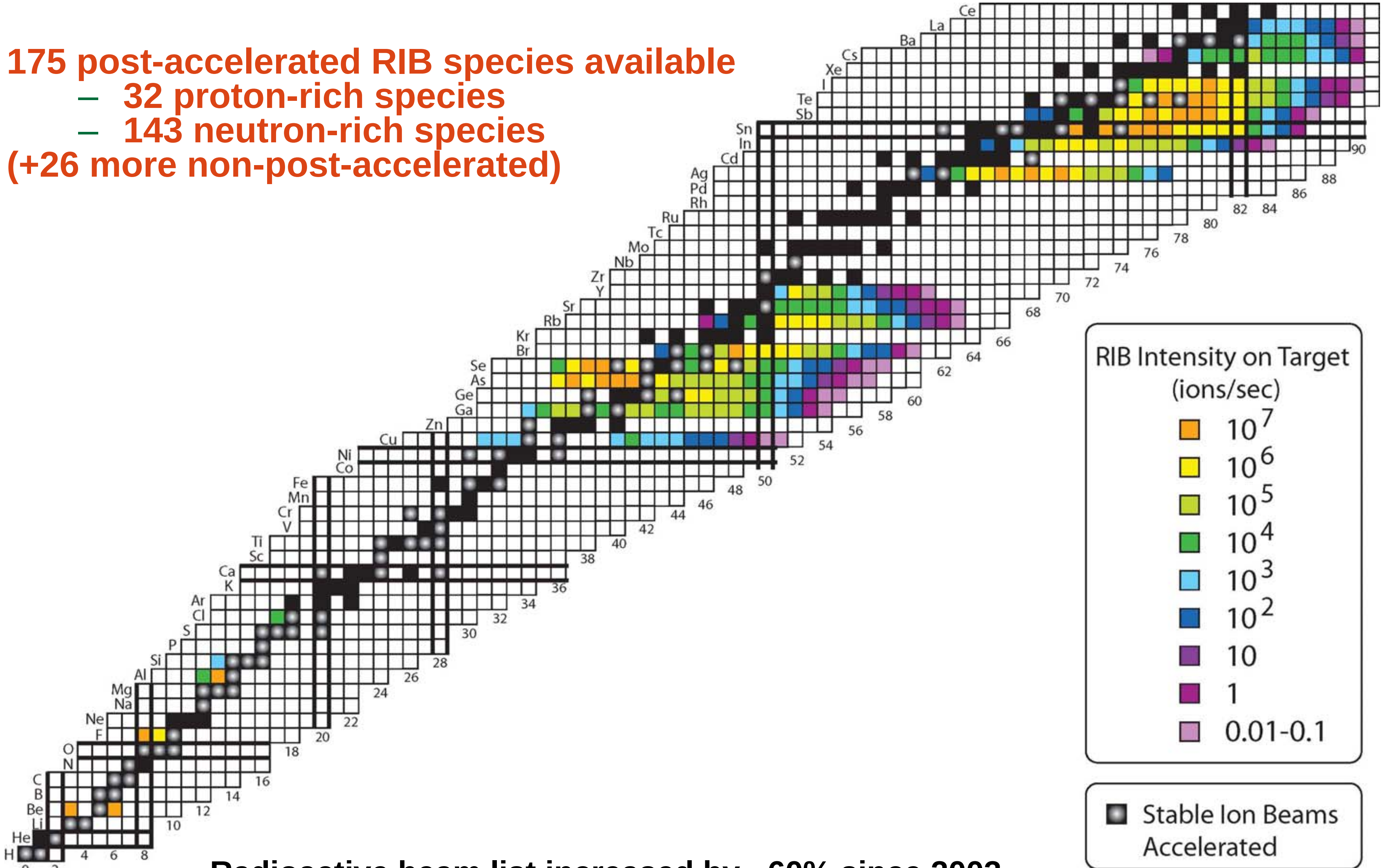


Energy ≥ 3 MeV/amu

HRIBF Beams

175 post-accelerated RIB species available
- **32 proton-rich species**
- **143 neutron-rich species**

(+26 more non-post-accelerated)



Radioactive beam list increased by ~60% since 2003

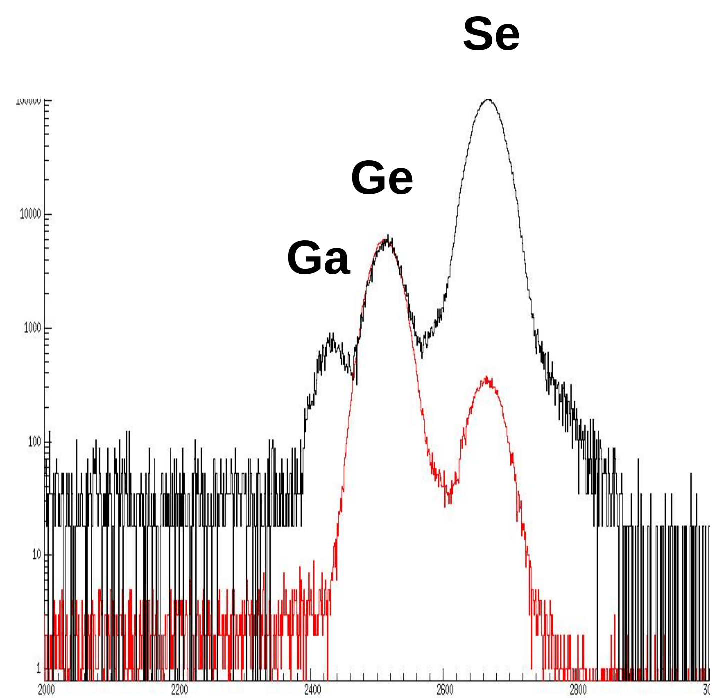
Radioactive Beams

- Three factors affect the quality of the radioactive beam experiment
  - RIB intensity
  - purity of the beam
  - selectivity of the detectors
- The RIB intensity can be increased by
  - increased production (target)
  - faster diffusion and release (target)
  - higher ionization efficiency (ion source)
  - better transmission (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

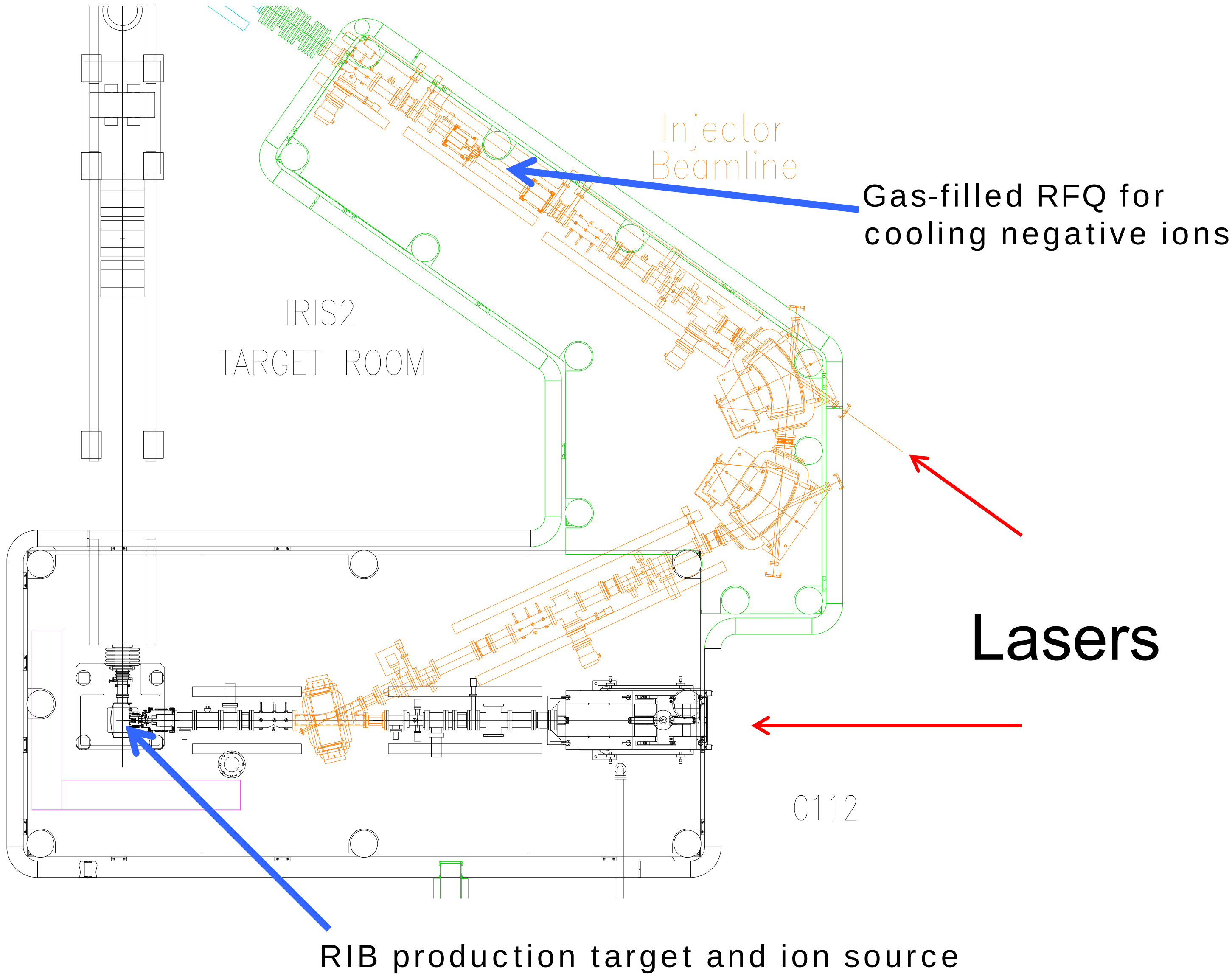
Pure Sn and Ge Beams

- Most of the neutron-rich Sn beams are contaminated
  - the A=132 beam is 85% Te, 14% Sb, 1% Sn
- Solution: extract from EBP ion source as SnS^+ (add sulfur as 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 available
  - for A=80, the Se beam was reduced by a factor of 300
  - ^{80}Ge beam purity went from 6% up to 95%

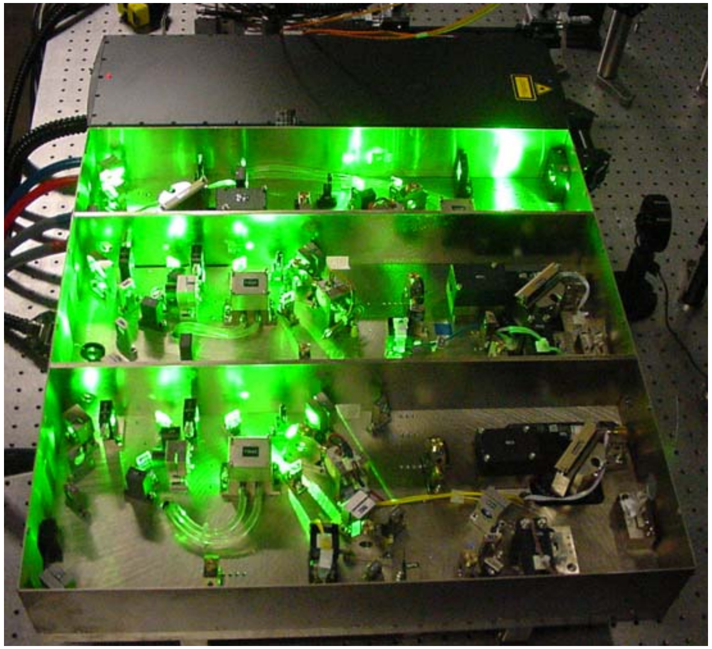


Use of lasers on the IRIS2 Platform



Laser Ion Source Measurements

- Ion beams of 13 elements have been produced using the RILIS at HRIBF which includes a system of three Nd:YAG pumped Ti:Sapphire lasers. These lasers have the optics for doubling, tripling, and quadrupling the frequency.
- 9 of these elements were ionized for the first time with Ti:Sapphire lasers



Element	Sn	Ni	Ge	Cu	Co	Ga	Mn	Fe	Al	Ho	Tb	Dy	Sr
Efficiency Measured (%)	22	2.7	3.3	2.4	>20					40			

Y. Liu, et al., *Nucl. Instr. and Meth. B* 243 (2006) 442-452

T. Kessler, et al., *J. Phys. B* 40 (2007) 4413-4432

Y. Liu, et al., *Rev. Sci. Instrum.* 80, 083304 (2009)

Isobar Suppression by Photodetachment

There are a number of negative RIBs for which photodetachment can be used to selectively suppress the isobar contaminants.

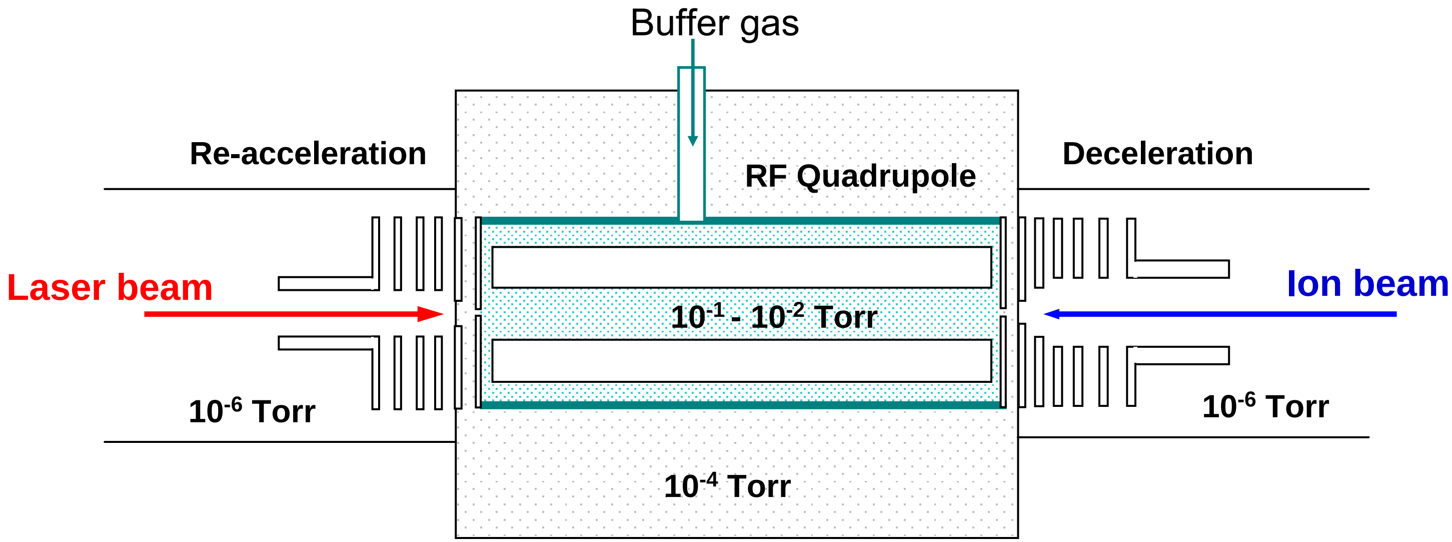
A novel technique has been developed:

- **A gas-filled RFQ ion cooler is used to slow down the negative RIB so that the interaction time with the laser beam is about 1ms.**
- **The laser energy must be greater than the electron affinity (EA) of the contaminant and, ideally, less than the EA of the RIB of interest.**

RIBs of particular interest: (^{56}Ni, ^{56}Co), (^{17,18}F, ^{17,18}O), (^{33,34}Cl, ^{33,34}S)

Y. Liu, J.R. Beene, C.C. Havener, and J.F. Liang, Appl. Phys. Lett. 87 (2005) 113504

Beam purification by photodetachment in RFQ Ion Cooler



Negative Ion	EA (eV)	Transmission (%)
O	1.461	24 ± 2
F	3.399	36 ± 2
Ni	1.156	52 ± 3
S	0.661	49 ± 3
Cl	3.617	54 ± 2
Cu	1.228	52 ± 2

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

99.9 % neutralization of Co
22 % neutralization of Ni

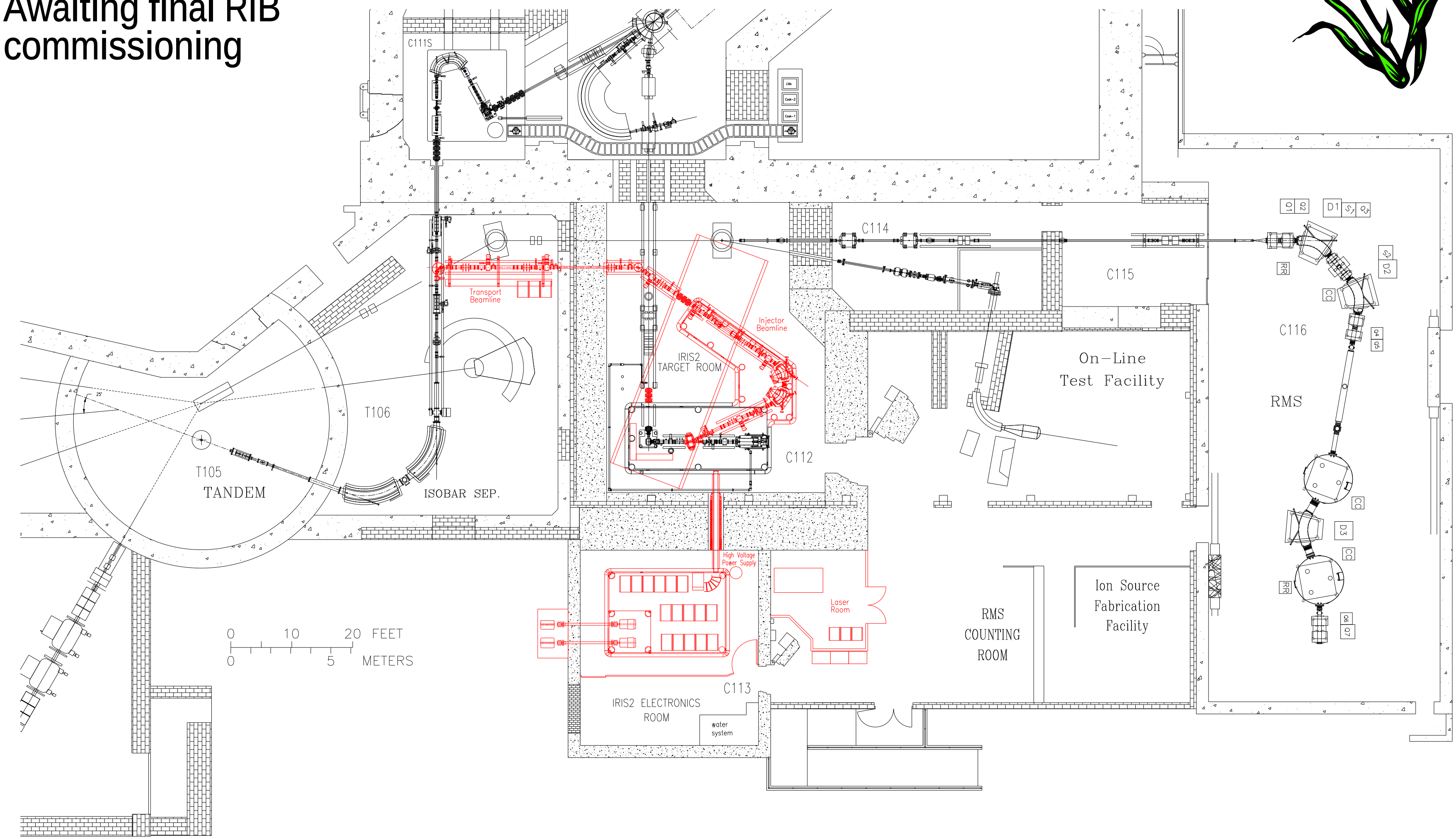
1% $^{56}Co^{-}$
99% $^{56}Ni^{-}$

Collaborations for ISOL development

- Mainz, TRIUMF (laser ion source, Ti:Sapphire lasers)
- Legnaro - SPES (UC target tests, target characterization)
  - Plan to test a UC target with carbon nanotubes in Spring 2011
- ISOLDE (high density UC target tests – October, 2010)
- ORNL Isotopes program (cross-section and branching ratio measurements)
- LLNL (novel actinide materials for RIB production)
- MSU (EBIT charge breeder)

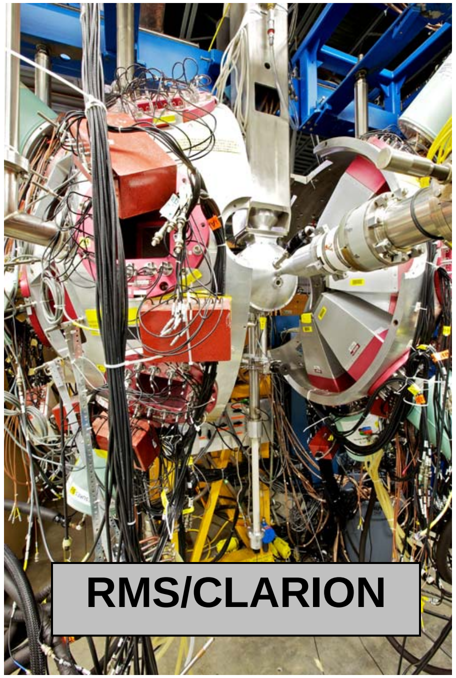
Injector for Radioactive Ion Species 2 (IRIS2)

- IRIS2 construction is complete
- $5 M budget
- Awaiting final RIB commissioning



Experimental System Upgrades

- New/Improved experimental tools
  - LeRIBSS
    - Addition to decay spectroscopy capability
    - Beam direct from IRIS target-ion source, positive ions, uses isobar separator
    - Decay spectroscopy program is attracting numerous students
  - ORRUBA silicon array
    - Benefits from NNSA Stockpile Stewardship program (Rutgers/ORAU)
    - Close collaboration with HRIBF astrophysics group
    - Large group of students
- Additional tools under development
  - MTAS: total absorption spectrometer
  - VANDLE and 3Hen neutron arrays
  - ORISS – multi-pass time of flight isomer separator and spectrometer
- GRETINA (plan to host this detector starting in late 2012)
  - Opportunity to host national facility for gamma spectroscopy
  - Opportunity to collaborate with leading outside experts in this area


RMS/CLARION


LeRIBSS

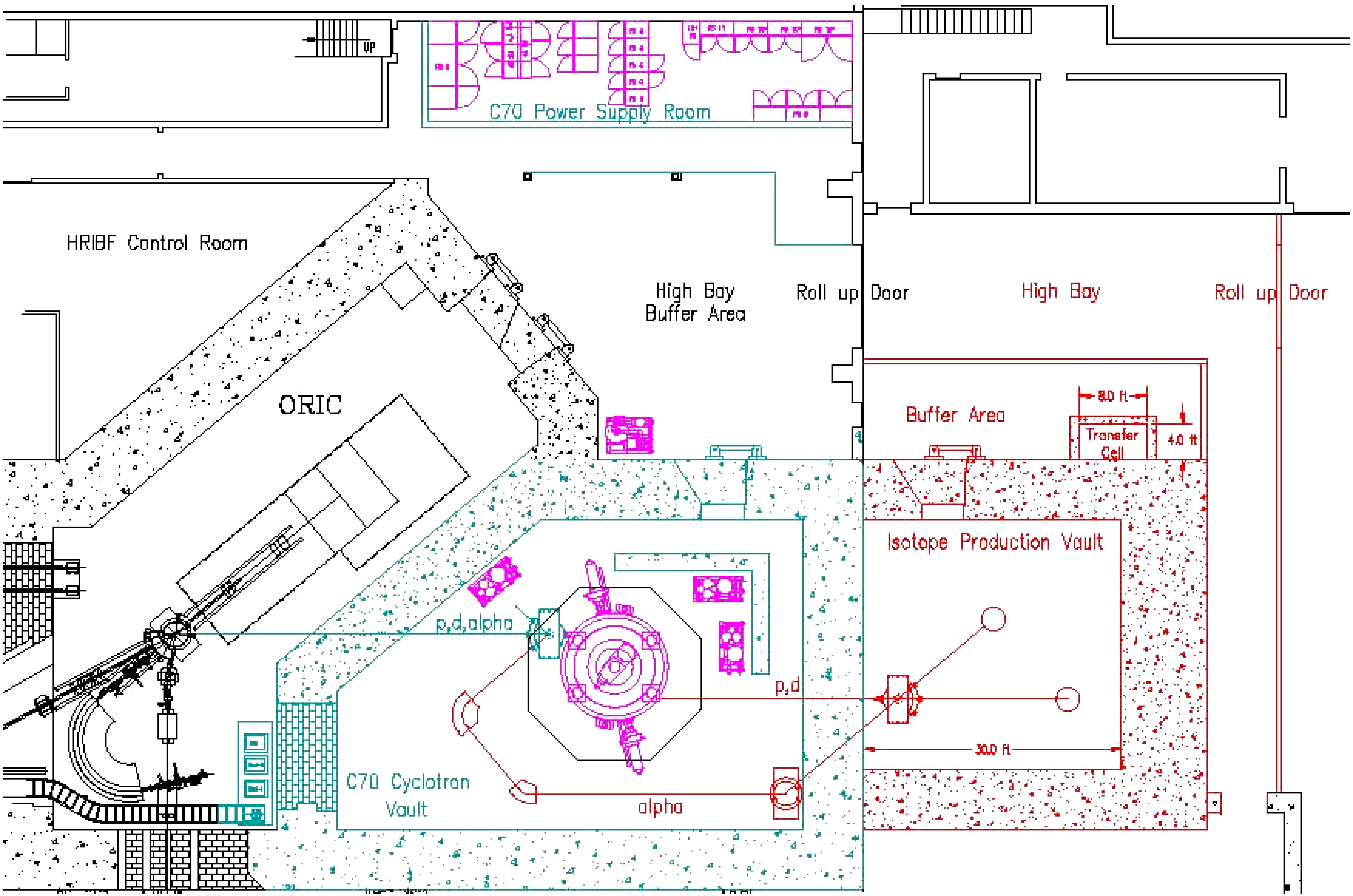
Driver Accelerator Upgrade Proposal

- Replace ORIC with a commercial cyclotron
  - One possible solution is the 70 MeV machine manufactured by IBA
  - Better performance than any ORIC upgrade scenario
    - Large increase in RIB production rates (combined with target development)
    - Much improved reliability (effect on both p- and n-rich beams)
    - Lower operating cost (15% of ORIC)
  - Offers medical isotope R&D option (dual extraction)
  - No new construction, except for the isotope program

Machine Specifications (courtesy of IBA)

- Multiple beam capability, variable energy
- 750 μA proton, variable up to 70 MeV, dual port, H^{-} with foil extraction
- >50 μA deuteron, variable up to 35 MeV, dual port, D^{-} with foil extraction
- ~50 μA alpha, fixed at 70 MeV, single port, $^{4}He^{++}$ with deflector extraction

C70 Vault and Isotopes Production Vault



Pioneering nuclear astrophysics studies

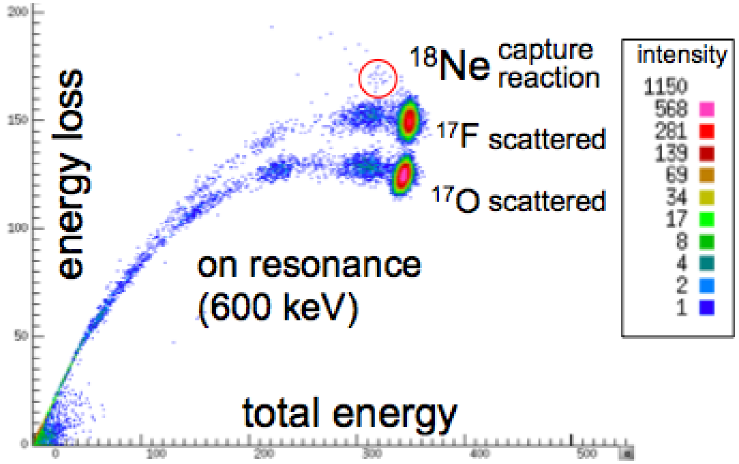
First direct measurement of $^{17}F(p,\gamma)$ and ^{18}F synthesis

PRL **102,** 152502 (2009) PHYSICAL REVIEW LETTERS week ending 17 APRIL 2009

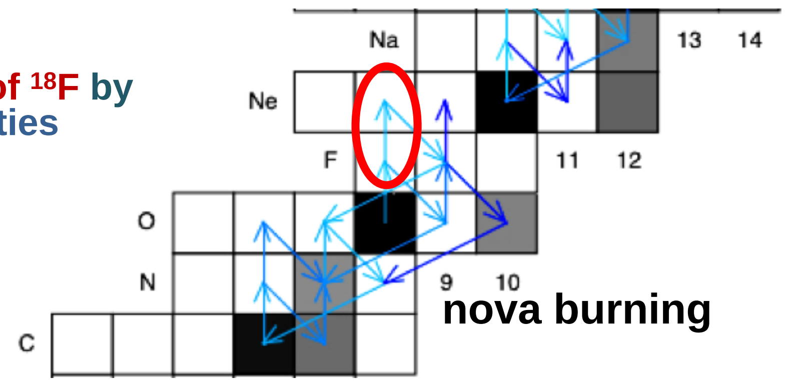
First Direct Measurement of the $^{17}F(p,\gamma)^{18}Ne$ Cross Section

K. A. Chipps,[1,*] D. W. Bardayan,[2] J. C. Blackmon,[3] K. Y. Chae,[4] U. Greife,[1] R. Hatarik,[5] R. L. Kozub,[6] C. Matei,[7] B. H. Moazen,[4] C. D. Nesaraja,[2,4] S. D. Pain,[2,4] W. A. Peters,[5] S. T. Pittman,[4] J. F. Shriner, Jr.,[6] and M. S. Smith[2]

Ph.D. Thesis of Kelly Chipps, Colorado School of Mines



- in novae, new reaction rate increases synthesis of ^{18}F by factor of 1.6 in some models, reduces uncertainties from factor of 15 to factor of ~ 2.5
- in X ray bursts, new reaction rate changes synthesis of ^{17}O by factor of 10, and reduces uncertainties from factor of 100 to factor of ~ 5.

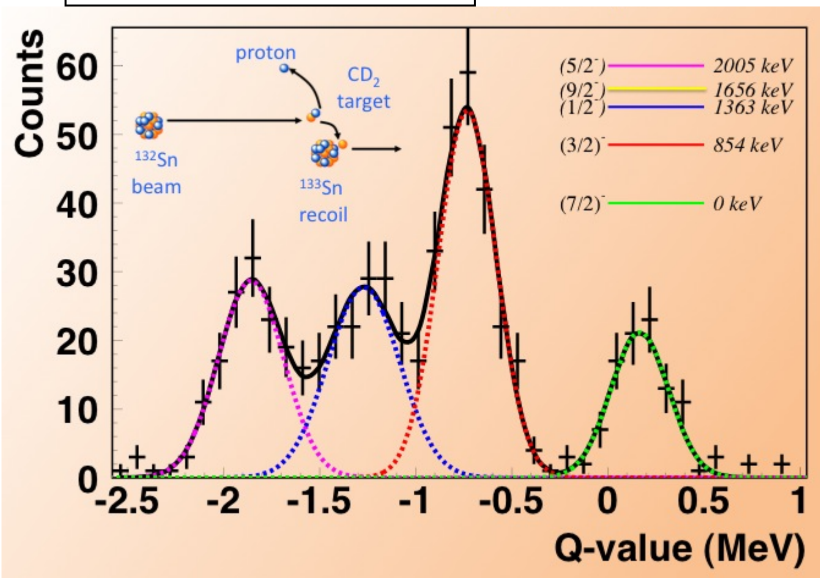


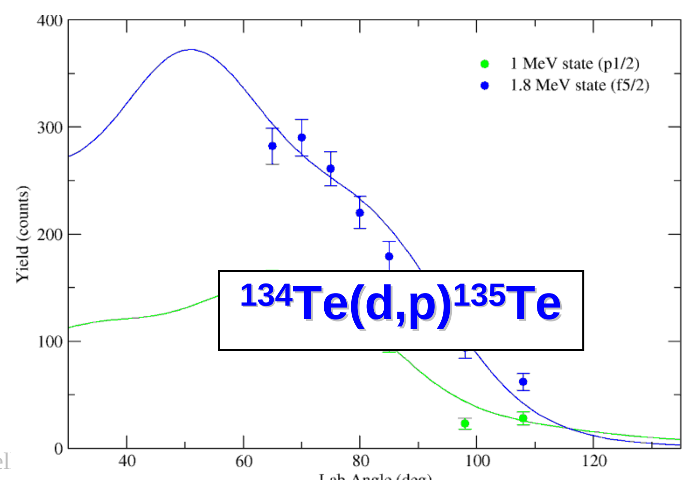
- J.F. Liang et al., Phys. Lett. B 681, 22 (2009): Coulomb dissociation of ^{17}F
- G. Hagen et al., Phys. Rev. Lett. 104, 182501 (2010): Ab Initio coupled-cluster computation of the ^{17}F proton halo state

Pioneering nuclear astrophysics studies

Rapid neutron capture process (d,p) studies

^{132}Sn(d,p)^{133}Sn





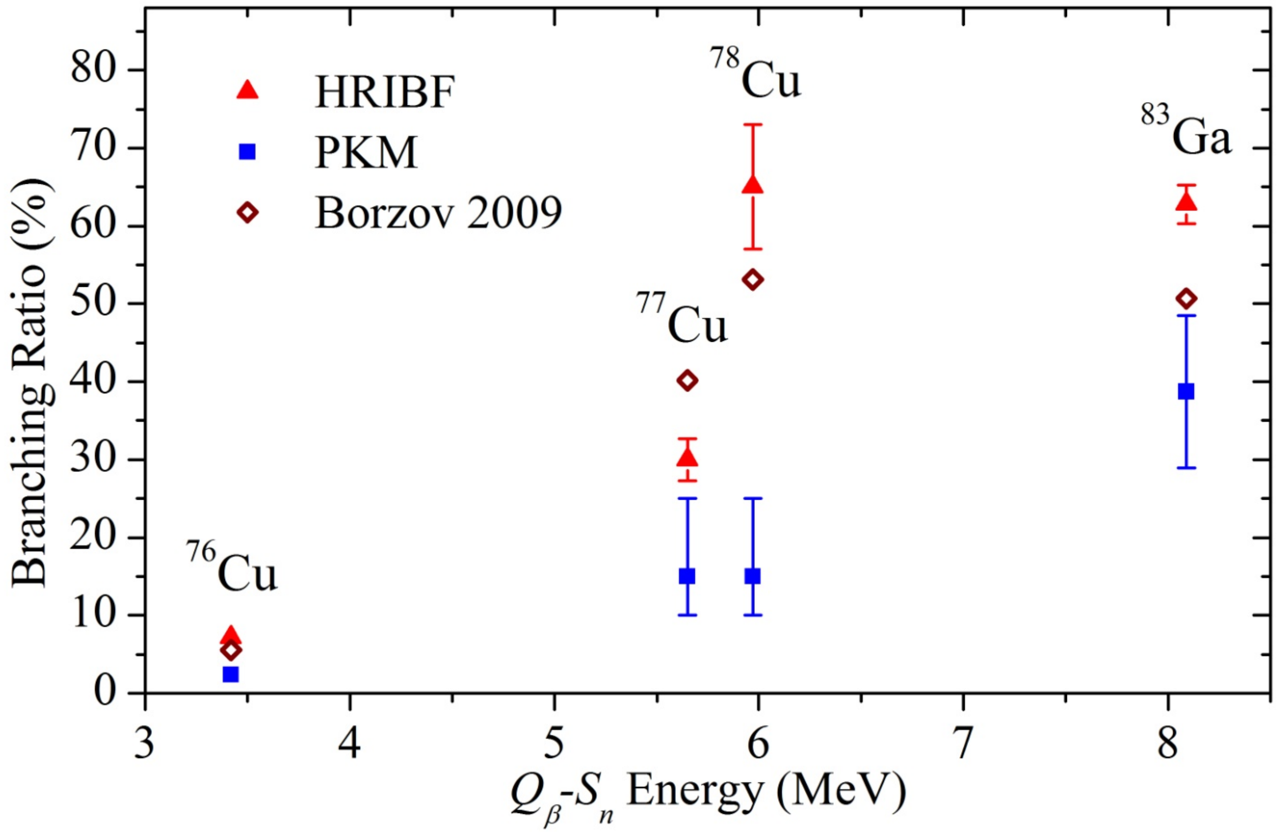
- ^{132}Sn(d,p)^{133}Sn [Kate Jones et al. Nature 465(2010)454]
  - Observed new state at 1408 keV
  - Normalized angular distributions for g.s. and 854 keV states
  - Indicates l=3 transfer for g.s. (as expected)
  - compatible with l=1 state for 854 keV state

- ^{130}Sn(d,p)^{131}Sn [Ray Kozub et al.]
  - Previously unobserved states
  - Relative locations very similar to those in ^{133}Sn
  - Significant astrophysical impact

- ^{134}Te(d,p)^{135}Te [Steve Pain et al.]
  - Single particle strengths more fragmented
  - Have preliminary candidate for $f_{5/2}$ strength (1.8 MeV)

β-decay Studies in the heavy Cu isotopes

RIB	Half-live (sec)	Intensity (pps)
^{75}Cu	1.22	2000
^{76}Cu	0.65	150
^{77}Cu	0.46	20
^{78}Cu	0.35	1.5
^{79}Cu	0.19	0.13



- J.A. Winger et al., Phys. Rev. Lett. 102, 142502 (2009): **β-delayed neutron branching ratios for nuclei near doubly magic ^{78}Ni**
- J.A. Winger et al., Phys. Rev. C 81, 044303 (2010): **possible new spherical subshell closure at N=58 created by the nearly degenerated $\nu 3s_{1/2}$ and $\nu 2d_{5/2}$ orbitals**
- S. V. Ilyushkin et al., Phys. Rev. C 80, 054304 (2009): **$\pi 1f_{5/2}$ g.s. in ^{77}Cu**
- S. V. Ilyushkin et al., submitted to Phys. Rev. C: **β decay studies of ^{75}Cu and the structure of ^{75}Zn**