Oak Ridge National Laboratory

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HRIBF
Facility / Science Overview
and Development Plans

JUSTIPEN & LACM Workshop
March 9, 2007

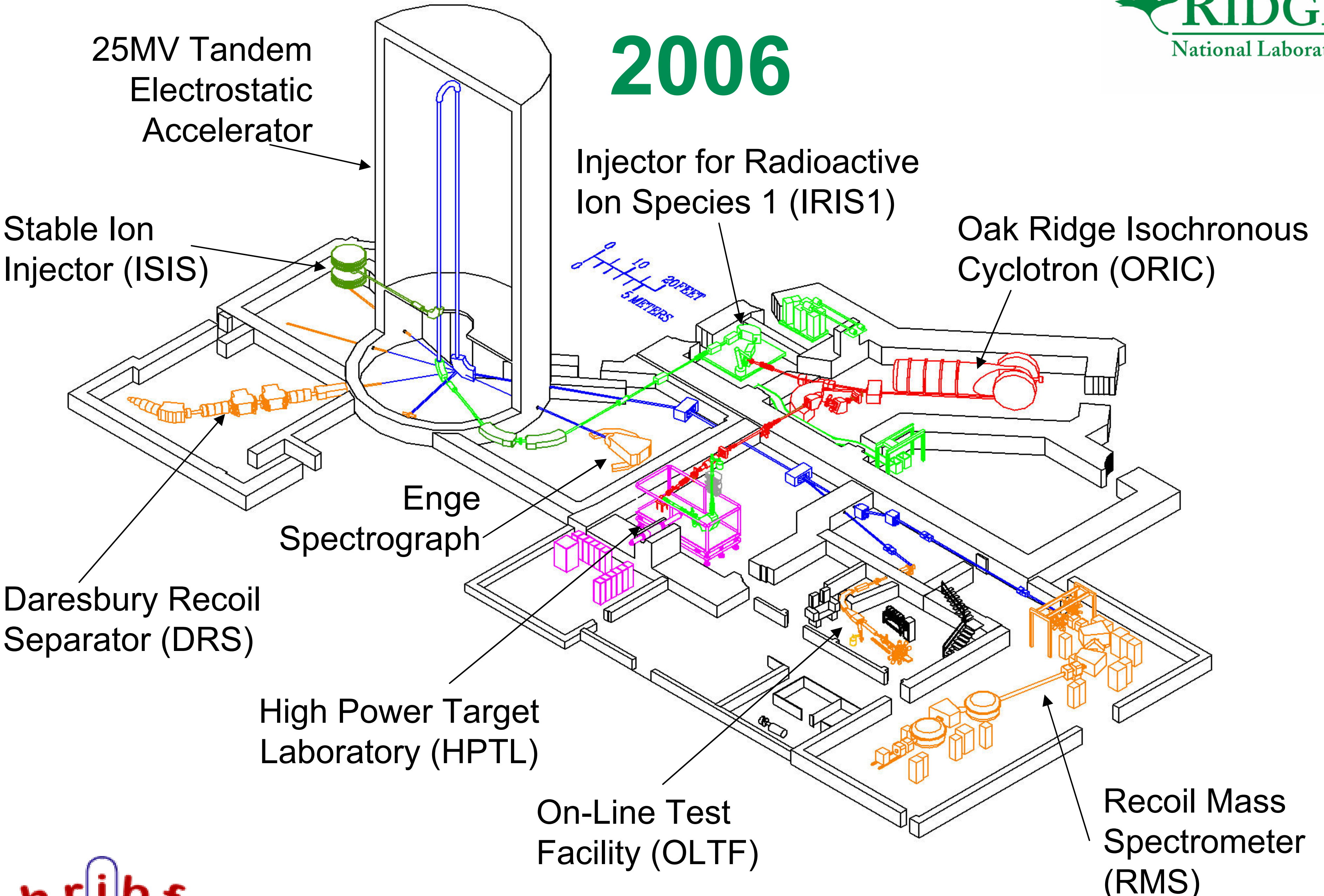
Jim Beene

hribf
Holifield Radioactive Ion Beam Facility
Oak Ridge National Laboratory

Outline

- **Introduction to HRIBF**
  - **Facility operation and operating modes**
  - **Facility development in progress**
  - **Recent Science highlights**
- **Future development / upgrade plans**
  - **Science with the upgraded facility**

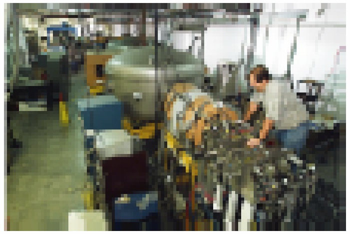
HRIBF 2006



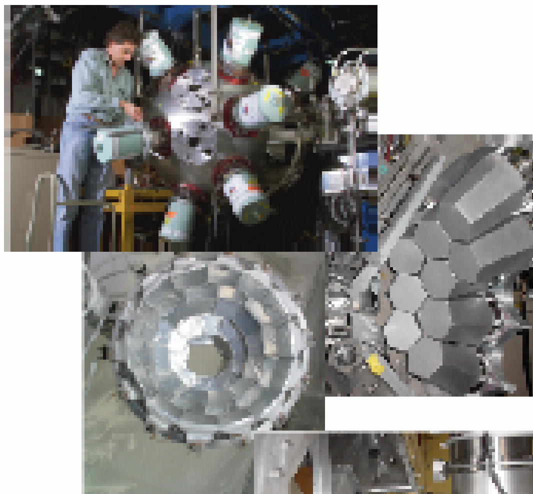
25MV Tandem Electrostatic Accelerator
Stable Ion Injector (ISIS)
Injector for Radioactive Ion Species 1 (IRIS1)
Oak Ridge Isochronous Cyclotron (ORIC)
0 10 20 FEET
0 5 METERS
Enge Spectrograph
Daresbury Recoil Separator (DRS)
High Power Target Laboratory (HPTL)
On-Line Test Facility (OLTF)
Recoil Mass Spectrometer (RMS)

HRIBF Equipment

Nuclear Structure



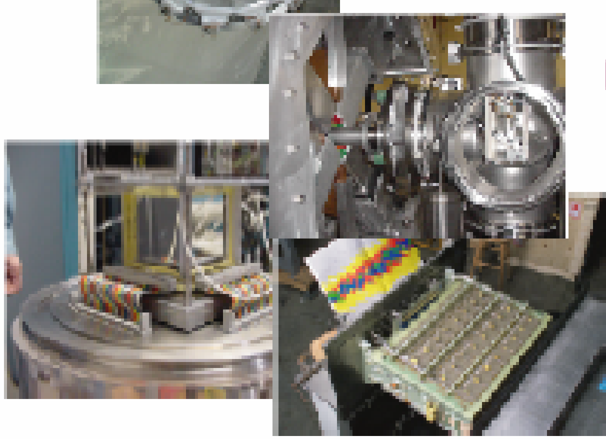
Recoil Mass Spectrometer (Gross/Rykaczewski)
- Mass/charge separator at 0° optimized for fusion-evaporation reactions, accepts many detectors



Clarion (Radford/Yu)
- Versatile, segmented 11 clover Ge detector array
- Upgrade proposal to almost double efficiency (4.2%)

Neutron array (Yu/Radford)
- 19 element neutron detector array for p-rich fusion evaporation reactions

HyBall (Galindo-Uribarri/Radford)
- 4π version optimized for fusion-evaporation
- 2π version optimized for RIB Coulex/transfer



Focal plane (Rykaczewski/Grzwacz/Gross)
- Position sensitive MCP(s) optimized for efficiency at high count rates followed by :
- Ion chamber for recoil Z identification
- Si strip detectors for proton, α, β radioactivity
- MTC and Clarion elements for μs isomers and β radioactivity
- DSP DAQ optimized for fast decays and count rate

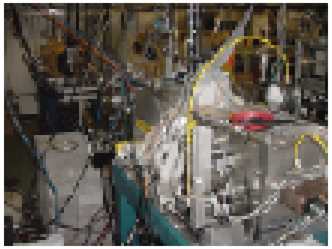
HRIBF Equipment

Nuclear Astrophysics

Daresbury Recoil Separator (Blackmon/Smith)
Velocity filter separator at 0^o optimized for low-energy capture reactions

Windowless Gas Cell (Blackmon/Smith)
Windowless gas volume with uniform density over 10 cm used for capture reactions

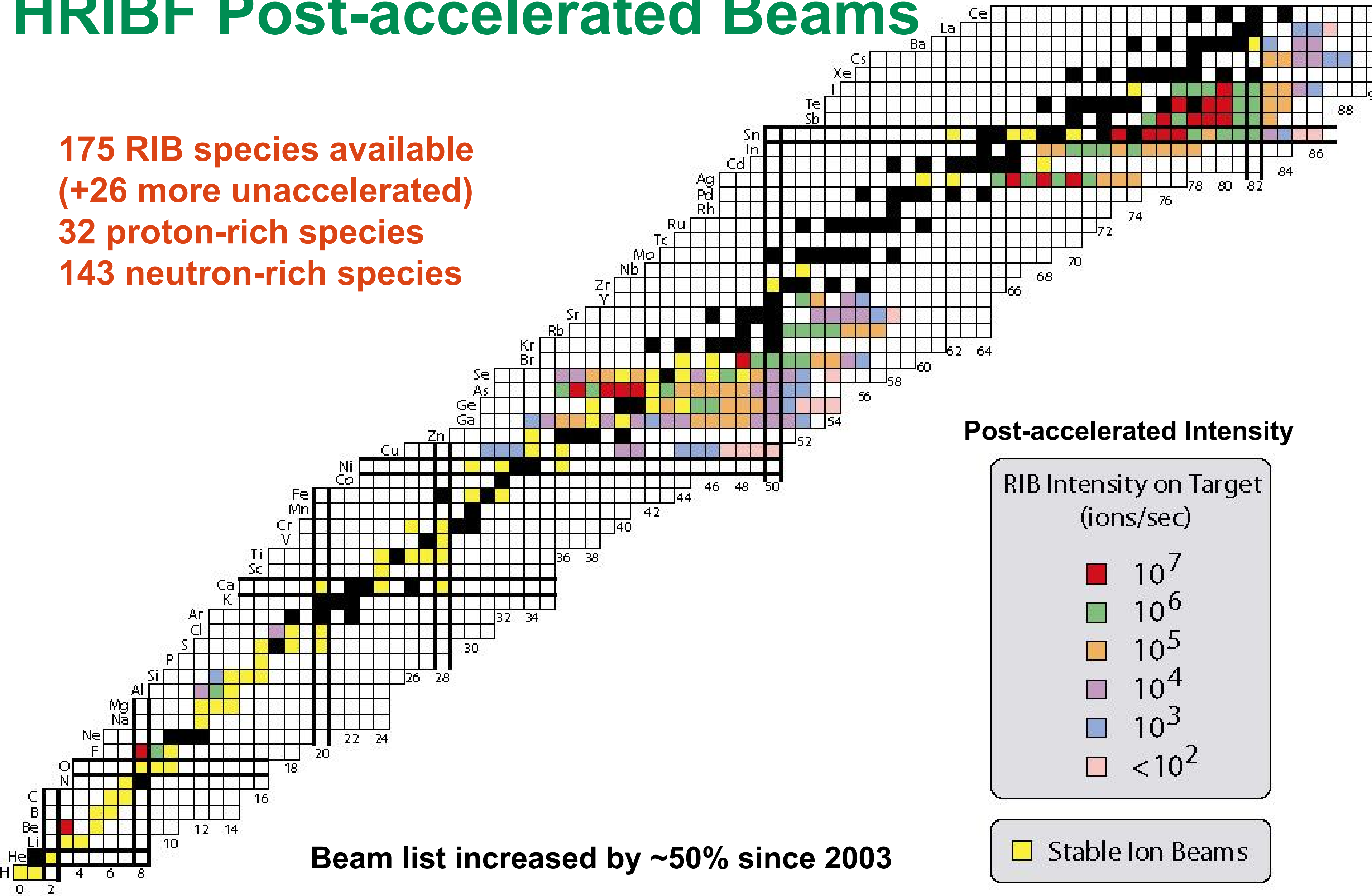
SIDAR (Bardayan/Smith)
Flexible silicon strip array used for (d,p) recations in inverse kinematics. Many additional Si strip detectors for specific experiments.



Ionization Chamber (Blackmon/Bardayan)
Flexible chamber for DRS focal plane or SIDAR compatible operation for low-intensity ($<10^5$ i/s) RIBs at 0^o

HRIBF Post-accelerated Beams

175 RIB species available
(+26 more unaccelerated)
32 proton-rich species
143 neutron-rich species

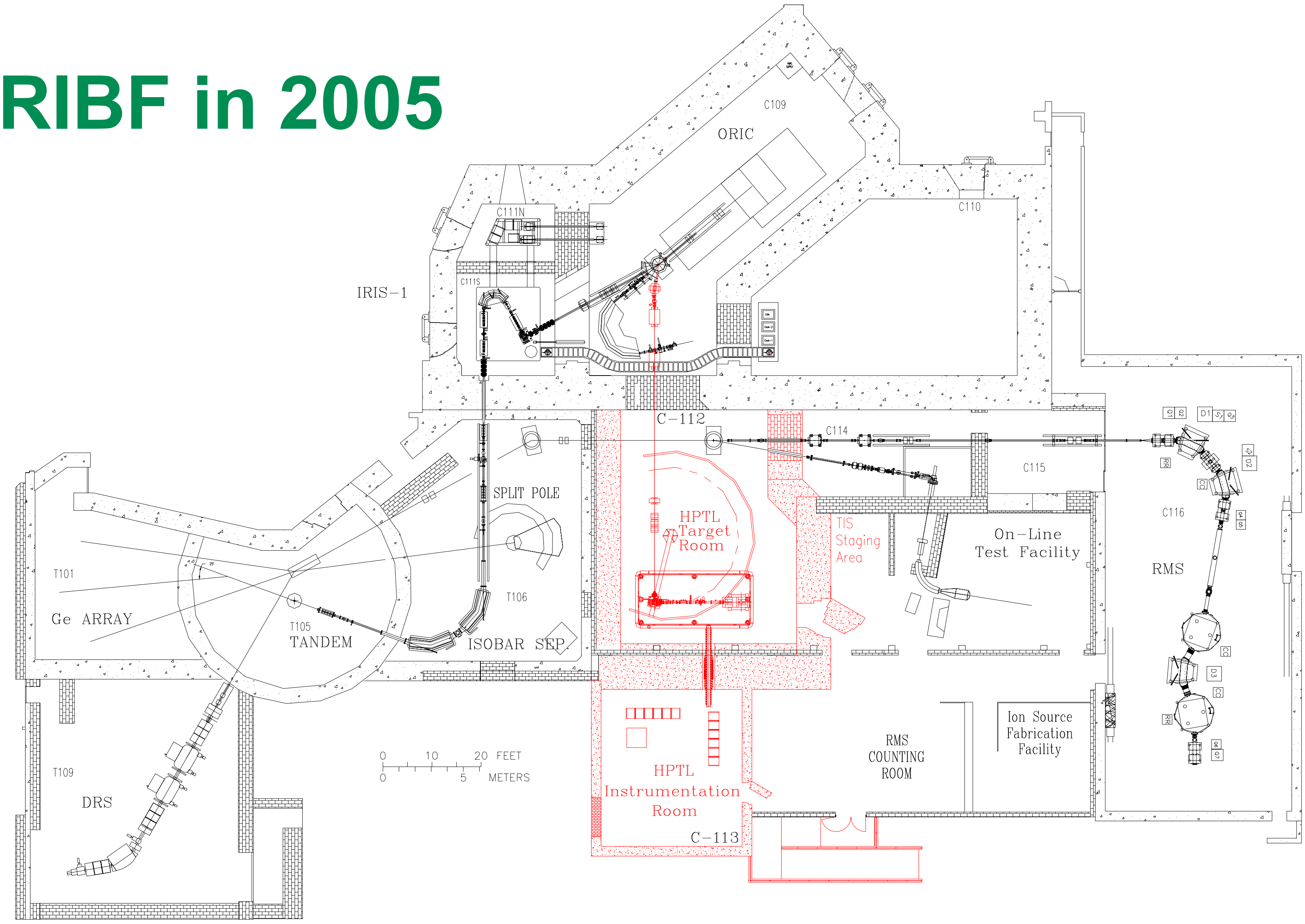


Beam list increased by ~50% since 2003

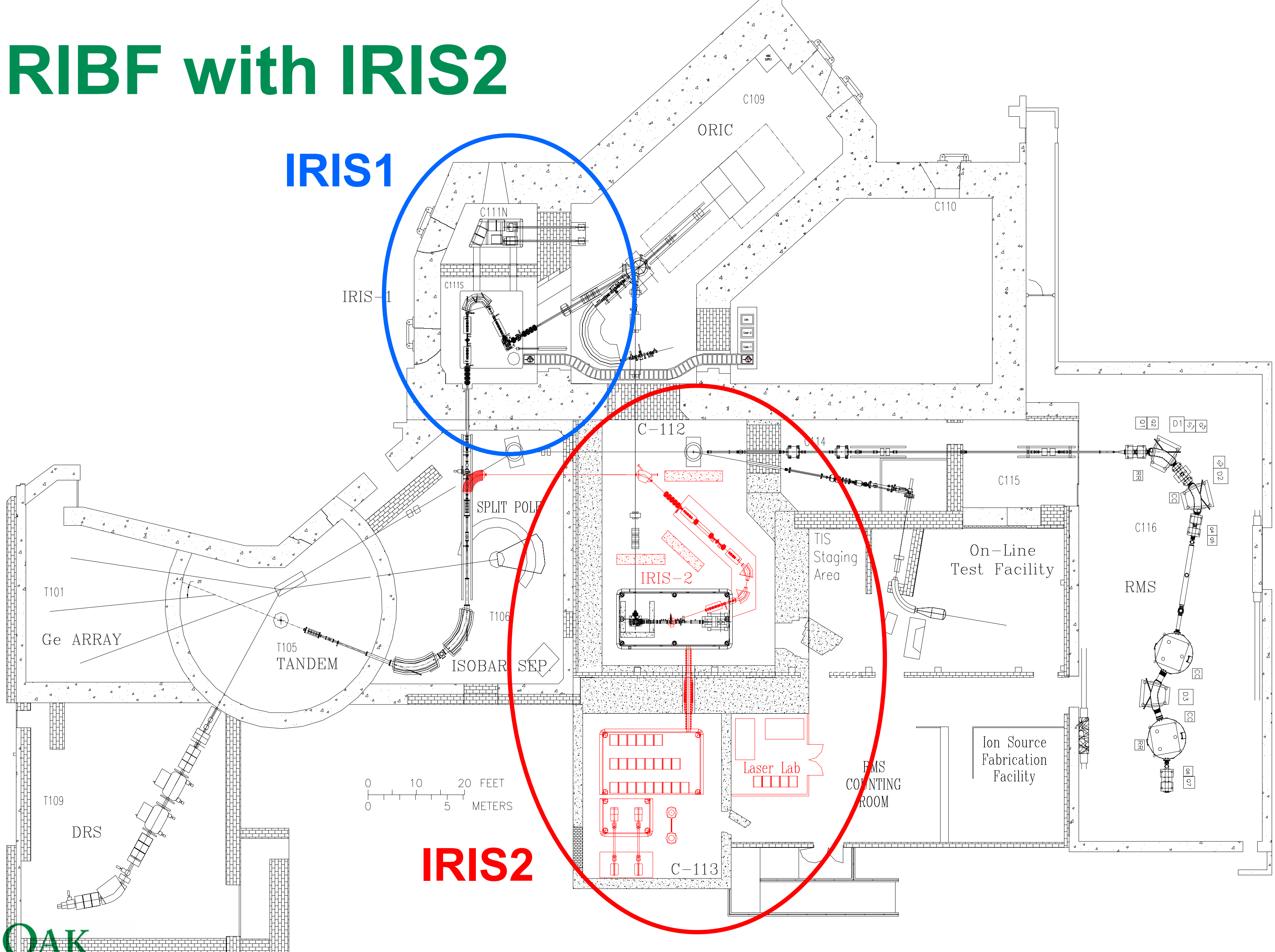
Facility Development Plan

- Experimental systems
  - Hi-res. γ-detector (CLARION) upgrades
  - Gas target upgrades
  - Unaccelerated beam facility (LeRIBSS)
  - Polarized target
  - New Si arrays
  - Neutron detection for βn
  - Total absorption spectrometers (TAS, GROMIT)
  - High performance fusion/fission system
  - Computing and data acquisition
  - New beamlines
- RIB production systems
  - Beam production system upgrade
    - HPTL, IRIS2
  - Driver accelerator upgrade
  - Post-accelerator upgrade
- FY03-FY05
  - HPTL – Completed
- FY06-FY08
  - IRIS2 – Funded, in Progress
- FY07-FY10
  - ORIC axial injection external development
- FY09-FY11
  - Electron driver
- FY12
  - ORIC axial injection installation

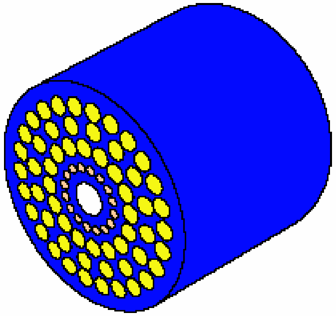
HRIBF in 2005



HRIBF with IRIS2



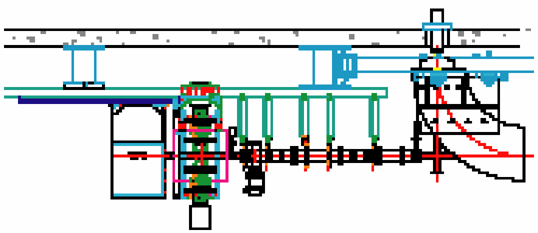
HRIBF Equipment Under Development



HRIBF β-n counter (ORNL,LSU)
High-efficiency n counter for decay spectroscopy of neutron-rich species.

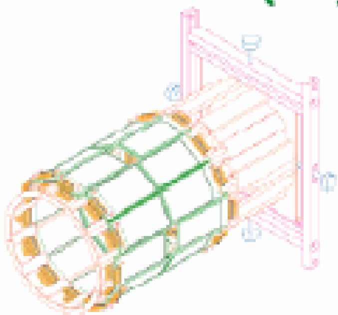
Gas-jet Target (ORNL, CSM)
High-density gas target for (pγ) and (α,γ)

LeRIBSS (LSU,ORNL,UNIRIB)



Low energy beamline for decay spectroscopy; accepts RMS focal plane equipment; will be fed by IRIS-1 and IRIS-2 via the isobar separator

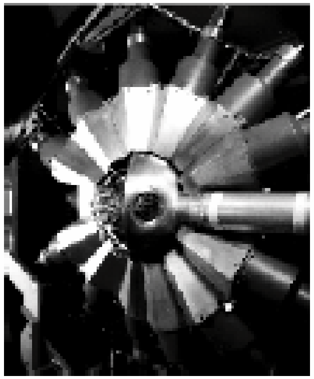
ORRUBA (Rutgers, ORAU, ORNL)



Si array centered about 90° for (p,d) reactions in inverse kinematics 12 telescopes each of 1000/140 & 1000/65 μ

New multi-purpose, high energy beamline for more flexibility

Spin Spectrometer (recommission)



4π NaI array for transfer & COULEX RIB experiments

Clarion Upgrade (ORNL)

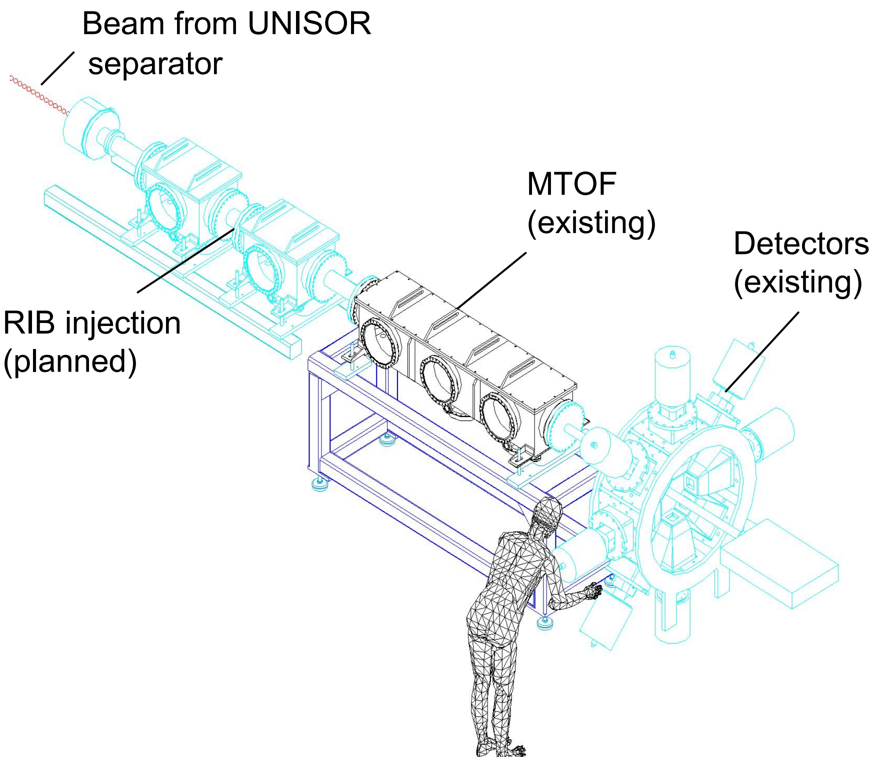
12 additional single-crystal Ge to improve efficiency from 2.2% to 4.2% @ 1.33 MeV for γγ coincidence experiments

Tracking Ion Chamber for Fusion Cross Section Measurements (ORNL,OSU,Mexico, etc.)

Efficient detection of evaporation residues & fission events at the same time with 50k i/s primary beam

HRIBF Equipment Under Development II

MTOF (UNIRIB)



Small footprint

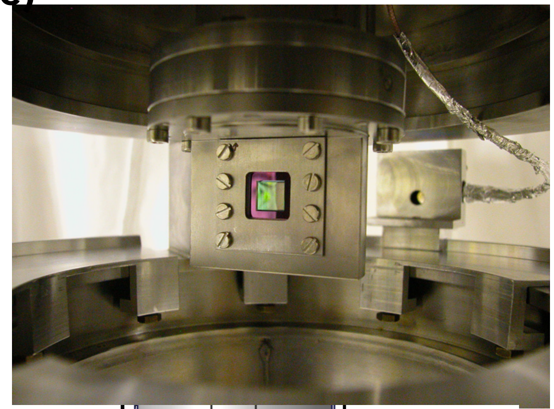
Demonstrated mass resolving power (FWHM) as spectrometer 29,000

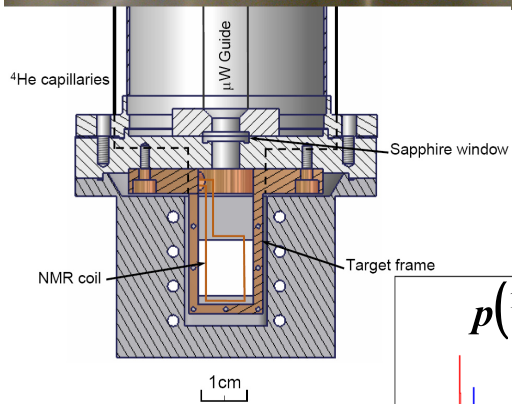
Estimated mass resolving power as separator 15,000

Estimated transmission including injection 20-50%

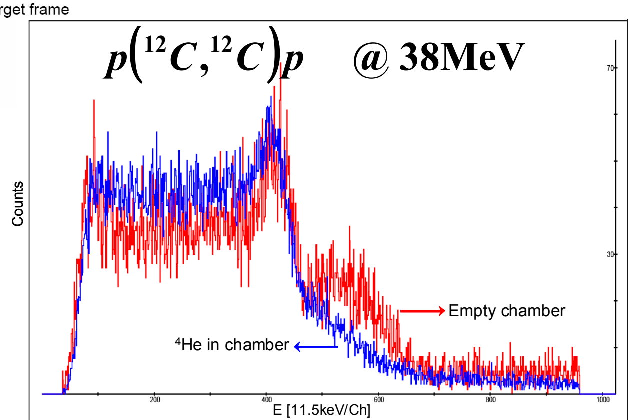
Polarized Hydrogen Target

- P_p ~84%, P_d~40%
- Thickness ~20-200μm Polystyrene
- T=90mK, B=2.5T
- P relaxation times: ~240h at 90mK and B=0.8T (off-line)





A cooling target cell with 500 nm thick Si_3N_4 windows proved to be leak tight at 300mK. Superfluid ^{4}He film inside the chamber has little influence on the proton recoil spectrum



Recent Scientific Accomplishments (structure and reactions)

- Pioneering experiments to explore the structure of exotic nuclei around doubly magic ^{132}Sn and magic ^{82}Ge
  - E. Padilla-Rodal et al. Phys. Rev. Lett. 94, 122501 (2005)
  - C.-H. Yu et al., Eur. Phys. J. A 25, s01, 395 (2005)
  - D.C. Radford et al., Nucl. Phys. A752, 264c (2005)
  - R.L. Varner et al., Eur. Phys. J. A 25, s01, 391 (2005)
- Observation of fusion enhancement at sub-barrier energies in ^{134}Sn+^{64}Ni
  - D. Shapira et al., Eur. Phys. J. A 25, s01, 241 (2005)
- First RIB g-factor measurement using Recoil-in-Vacuum Technique
  - N. Stone et al. Phys. Rev. Lett. 94, 192501 (2005)
- Discovery of superallowed alpha decays above ^{100}Sn (^{109}Xe→^{105}Te→^{101}Sn)
  - S.N. Liddick et al. Phys. Rev. Lett. 97, 08250, (2006)
- Probing wave functions of short-lived proton emitters: fine structure in proton decays in ^{141}Ho
  - M. Karny et al. Phys. Rev. Lett., in preparation
- Probing shell structure and decay properties in neutron-rich species around ^{78}Ni: Decay studies of post-accelerated ^{83,84,85}Ga and ^{76,77,78,79}Cu
  - J. Winger et al.,

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Recent Scientific Accomplishments (astrophysics)

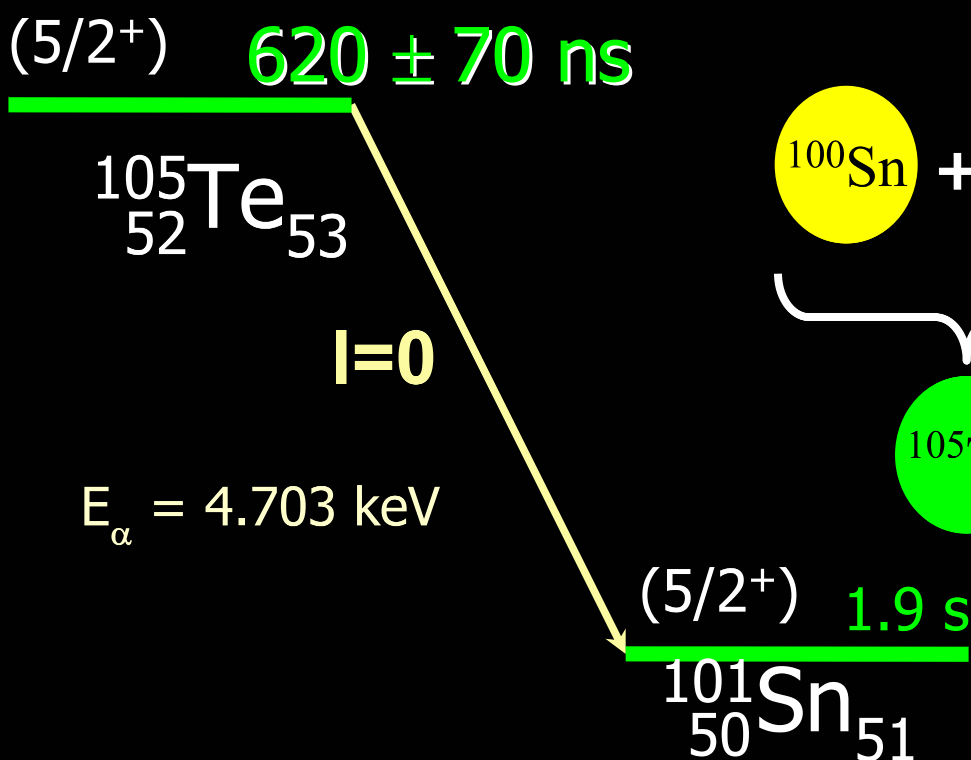
- **Transfer studies relevant to r-process:**
  - **$^{2}H(^{84}Se,p)^{85}Se$ and $^{2}H(^{82}Ge,p)^{83}Ge$**
    - **J. Thomas et al., Phys, Rev. C71, 021302 (2005); Nucl. Phys. A 758, 663c (2005); Eur. Phys. J. 25, s01, 371 (2005)**
  - **$^{2}H(^{132}Sn, p)^{133}Sn$, $^{2}H(^{130}Sn, p)^{131}Sn$ and $^{2}H(^{134}Te, p)^{135}Te$ – Jones et al.**
- **Solar physics: first statistically significant measurement of $^{7}Be(p,\gamma)^{8}B$ reaction with a radioactive ^{7}Be beam**
- **First Constraint on Very Low Temperature $^{18}F(p, \alpha)^{15}O$ reaction rate in Novae**
  - **K. Chae et al., Phys, Rev. C (2006)**
- **Proton-transfer Study of unbound ^{19}Ne states via $^{2}H(^{18}F, \alpha+^{15}O)n$ for novae**
  - **C.R. Brune et al., in preparation**

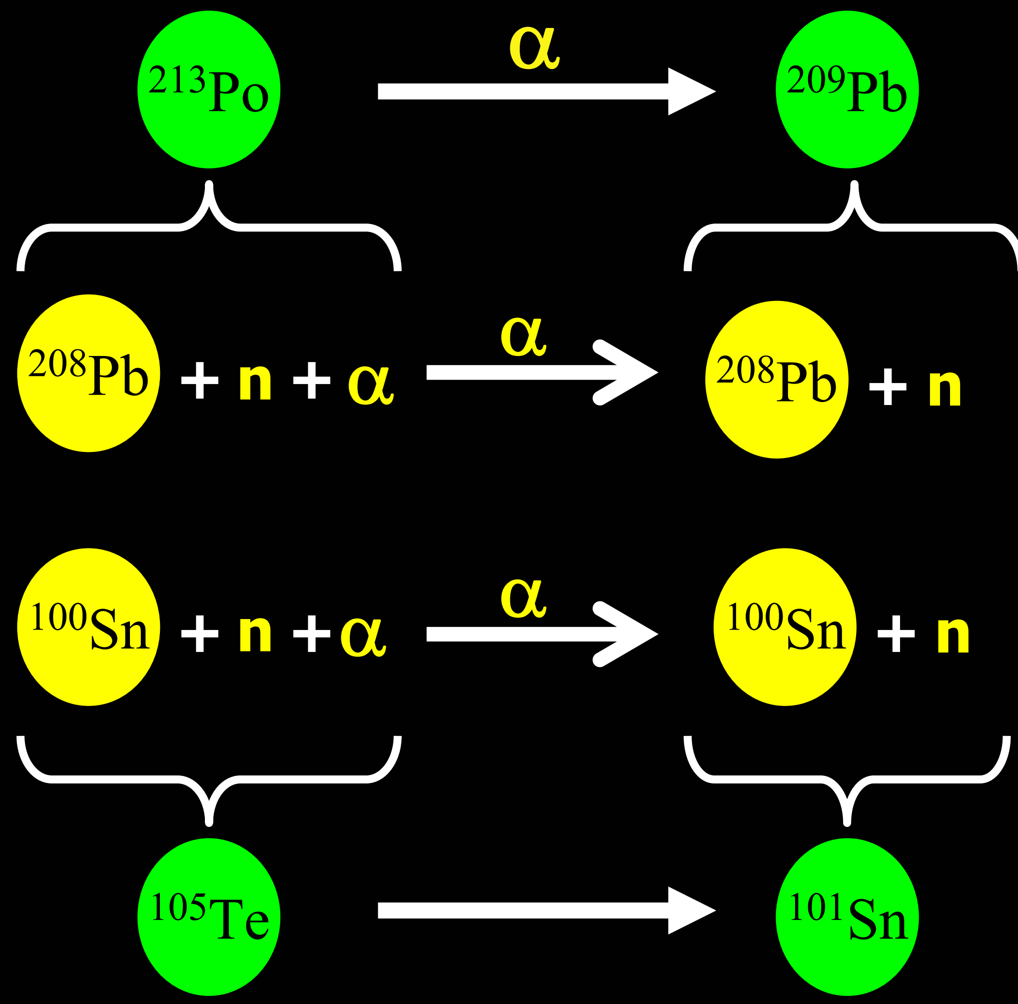
Applications

- **Pushing the Limits of Accelerator Mass Spectrometry**
  - **The ^{36}Cl-to-Cl ratio was measured as low as a few times 10-16 in seawater samples proving that ^{36}Cl can be measured at the levels required for a tracer in oceanography**
  - **A. Galindo-Uribarri et al. (NIM, in press)**

Superallowed α-decay $^{105}Te \rightarrow {}^{101}Sn$

S. Liddick et al., PRL 97,2006,082501

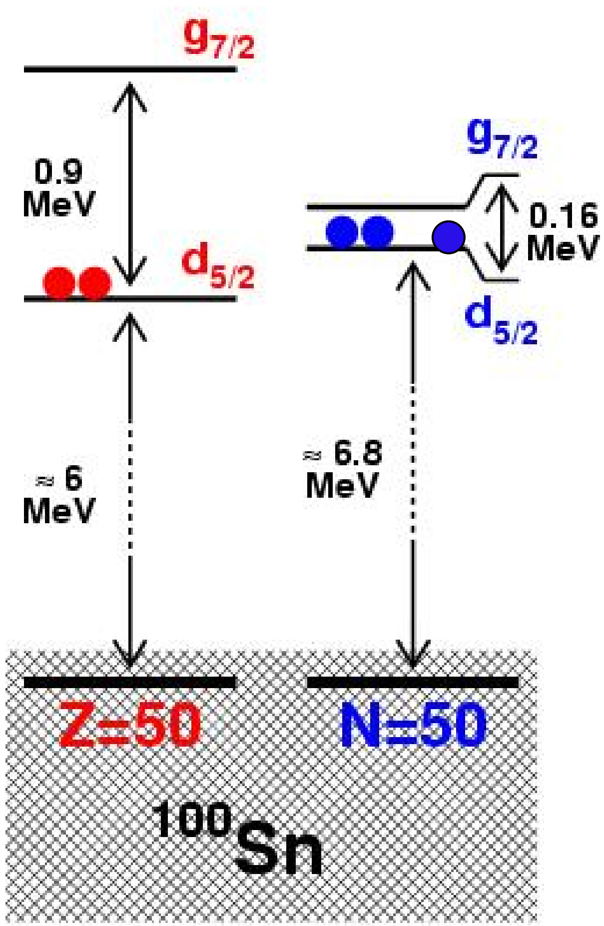




$\delta^2(^{105}Te)/\delta^2(^{213}Po)$ ~ 3

$^{105}Te = {}^{100}Sn + n + \alpha$

α made out of π and ν on the **same** orbitals

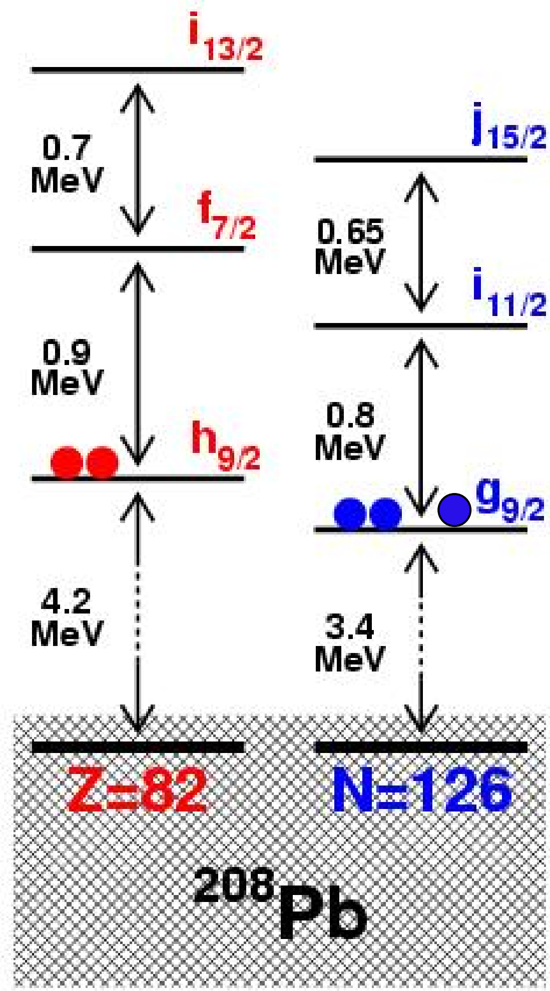


superallowed α-decay of ^{105}Te

Macfarlane and Siivola, PRL 14,114,1965

$^{213}Po = {}^{208}Pb + n + \alpha$

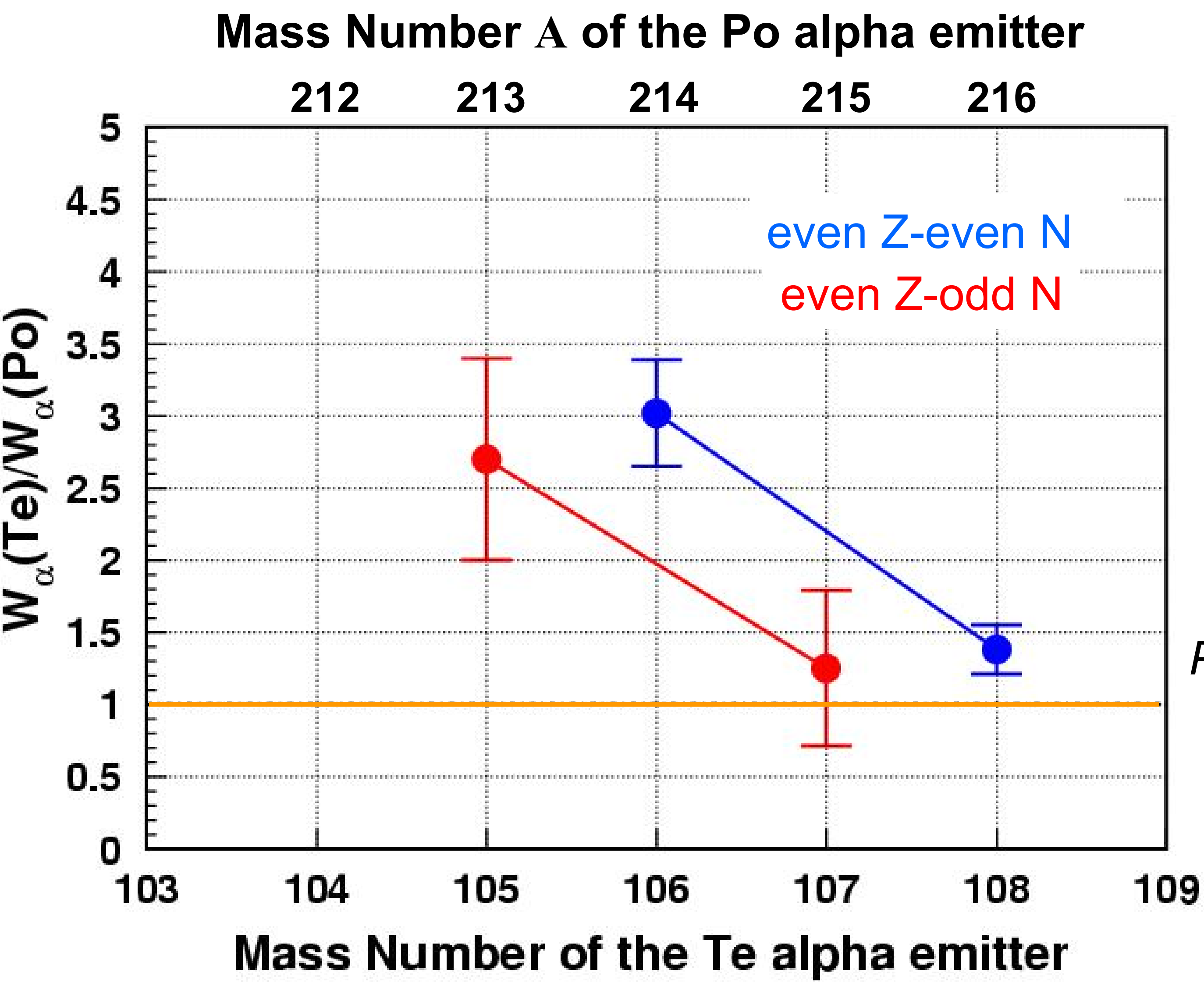
α made out of π and ν on **different** orbitals



corresponding α-decay of ^{213}Po

Comparison of the reduced decay width W_α

$$^{A}_{84}Po \longrightarrow {}^{(A-4)}_{82}Pb \quad \text{and} \quad ^{A}_{52}Te \longrightarrow {}^{(A-4)}_{50}Sn$$



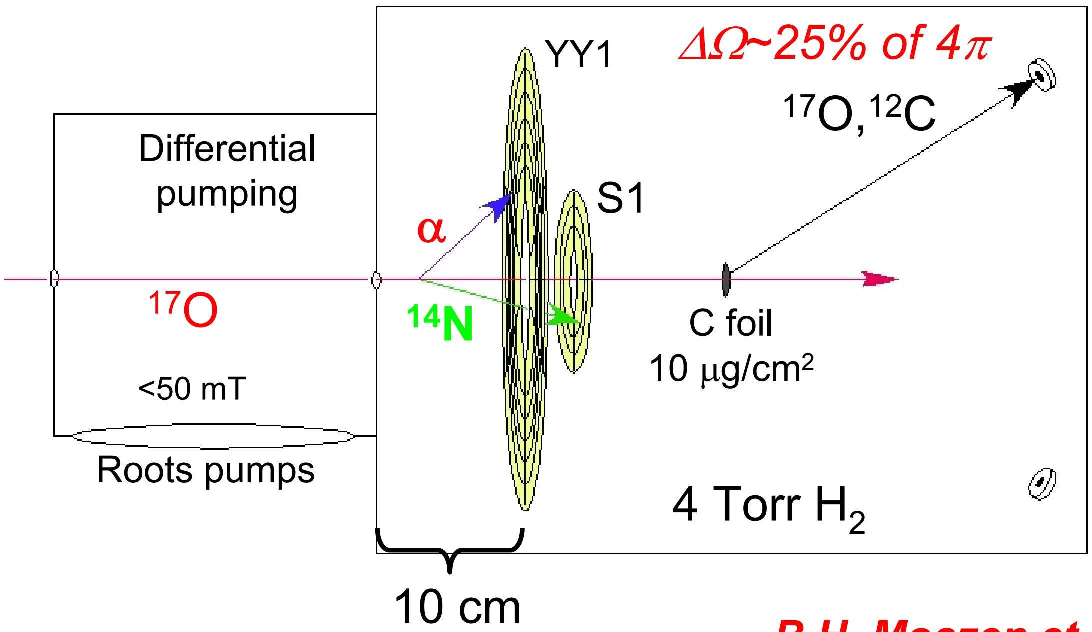
See also :

P.Mohr, EPJ A31, 2007, 23

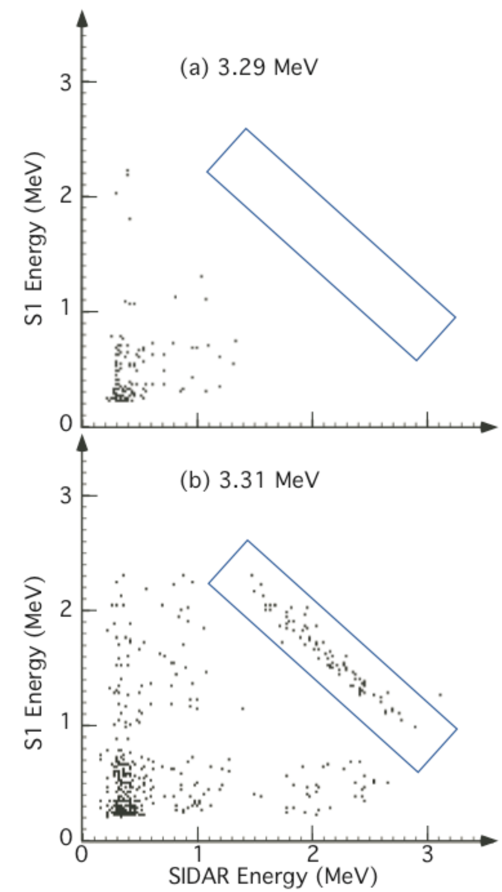
S.Xu,Z.Ren, PR C74, 2006, 037302

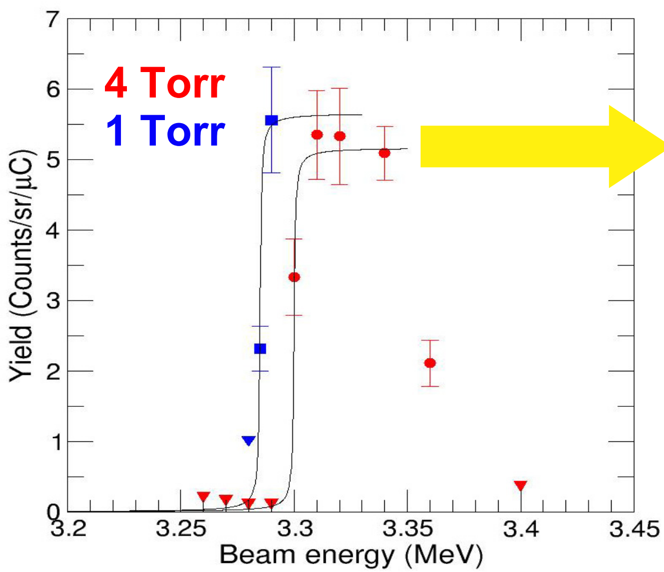
Novel approach to (p,α) with gas target

Demonstration: $^{17}O(p,\alpha)^{14}N$ @ E_{cm}=183 keV ($V_{terminal}$=1.6 MV !)



Yield ~ 3x that with CH_2 targets





B.H. Moazen et al. Submitted to PRC

$$\omega\gamma_{p\alpha}=1.70\pm0.15 \text{ meV}$$

$$E_r=183.5^{+0.1}_{-0.4}$$

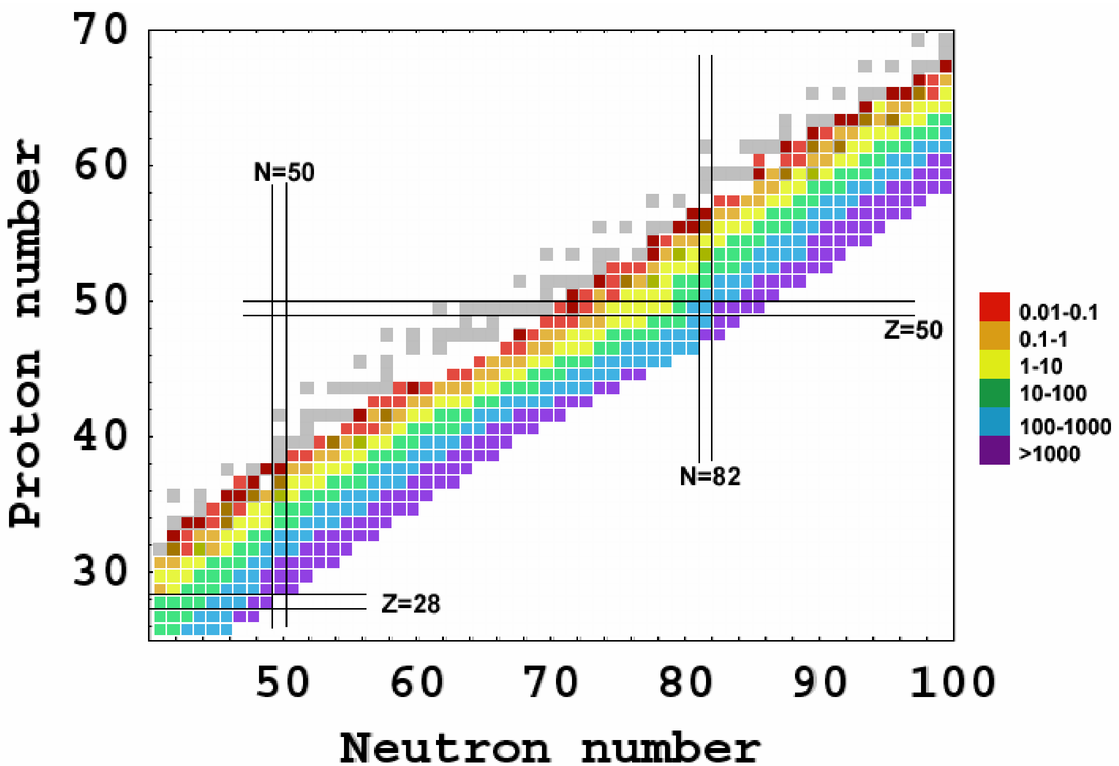
Agrees with recently reported first observation of this resonance Chafa *et al*., PRL**95** (2005)

$^{17}O(p,\alpha)^{14}N$ reaction rate increased by 20x
Less ^{18}F production in novae

RIB-165: Apply this technique to measure $^{18}F(p,\alpha)^{15}N$

RIB production by photofission

- Can enhance HRIBF n-rich yields by a large factor very cost-effectively
- Implement a ~100kW turn key electron accelerator with energy 25 to 50 MeV
  - Photofission Driver
- A minimum fission yield of 10^{13} f/s can be achieved with present target technology – larger with advanced target
- Factors well over 10^3 for enhancement of very neutron rich species
- Needs to be generating RIBS by 2012 .



$$\frac{10^{13}\ \text{ph-f/s}}{10\ \mu\text{A}\ 40\ \text{MeV p}}$$

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Photo-fission yield

In target

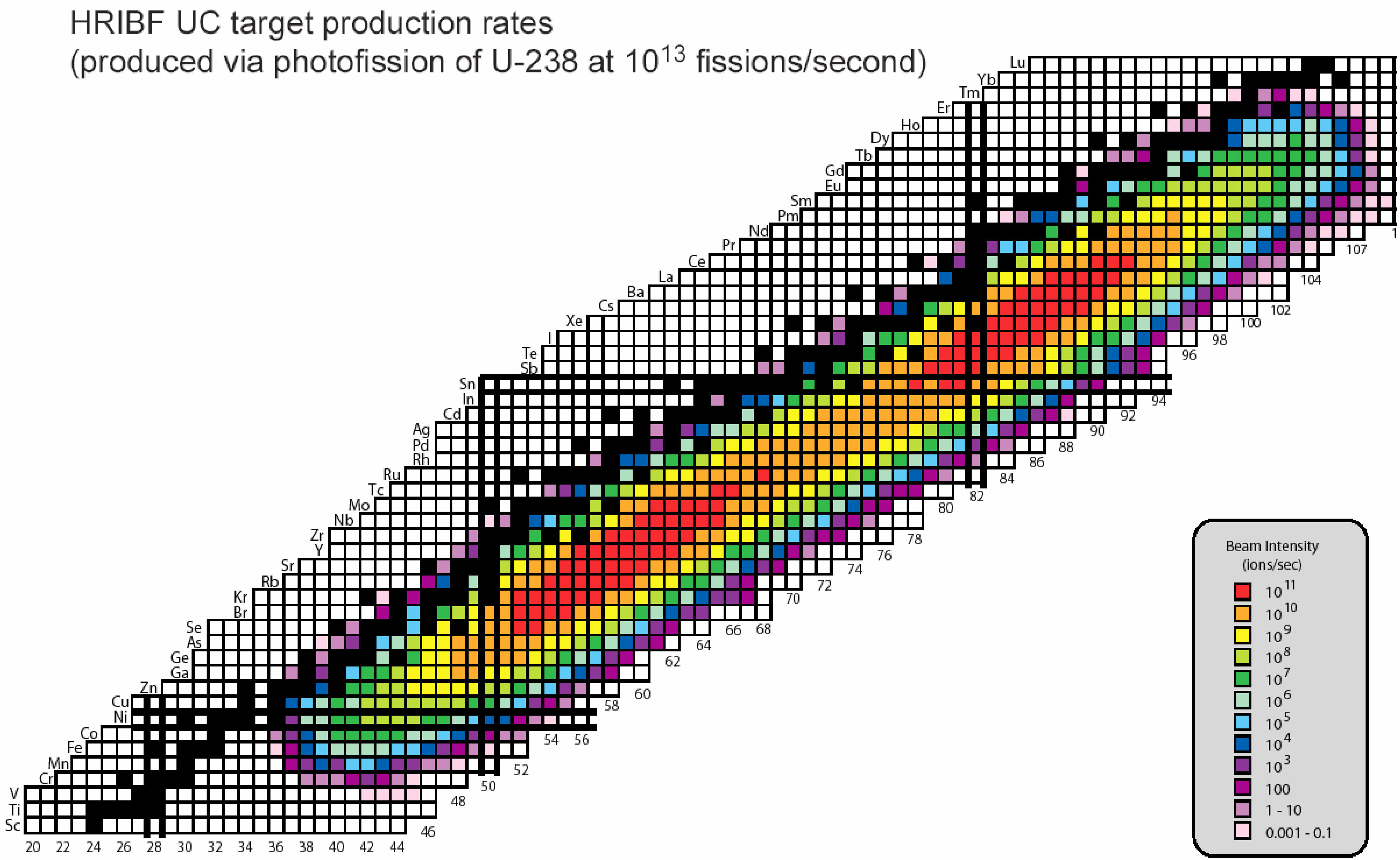


Photo-fission yield

From ion source

HRIBF beams directly from the ion source - unaccelerated beams
(produced via photofission of U-238 at 10^{13} fissions/second)

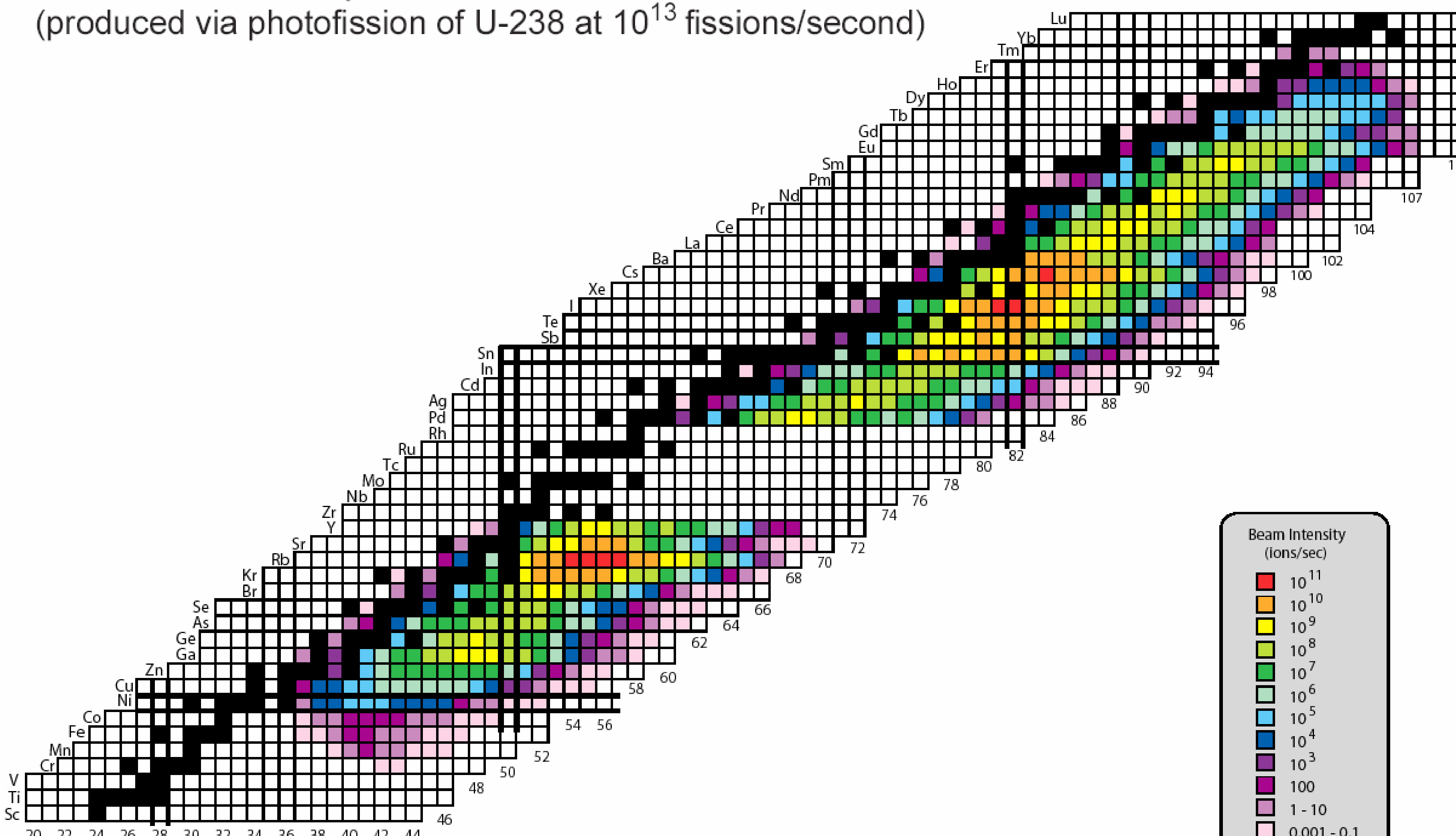
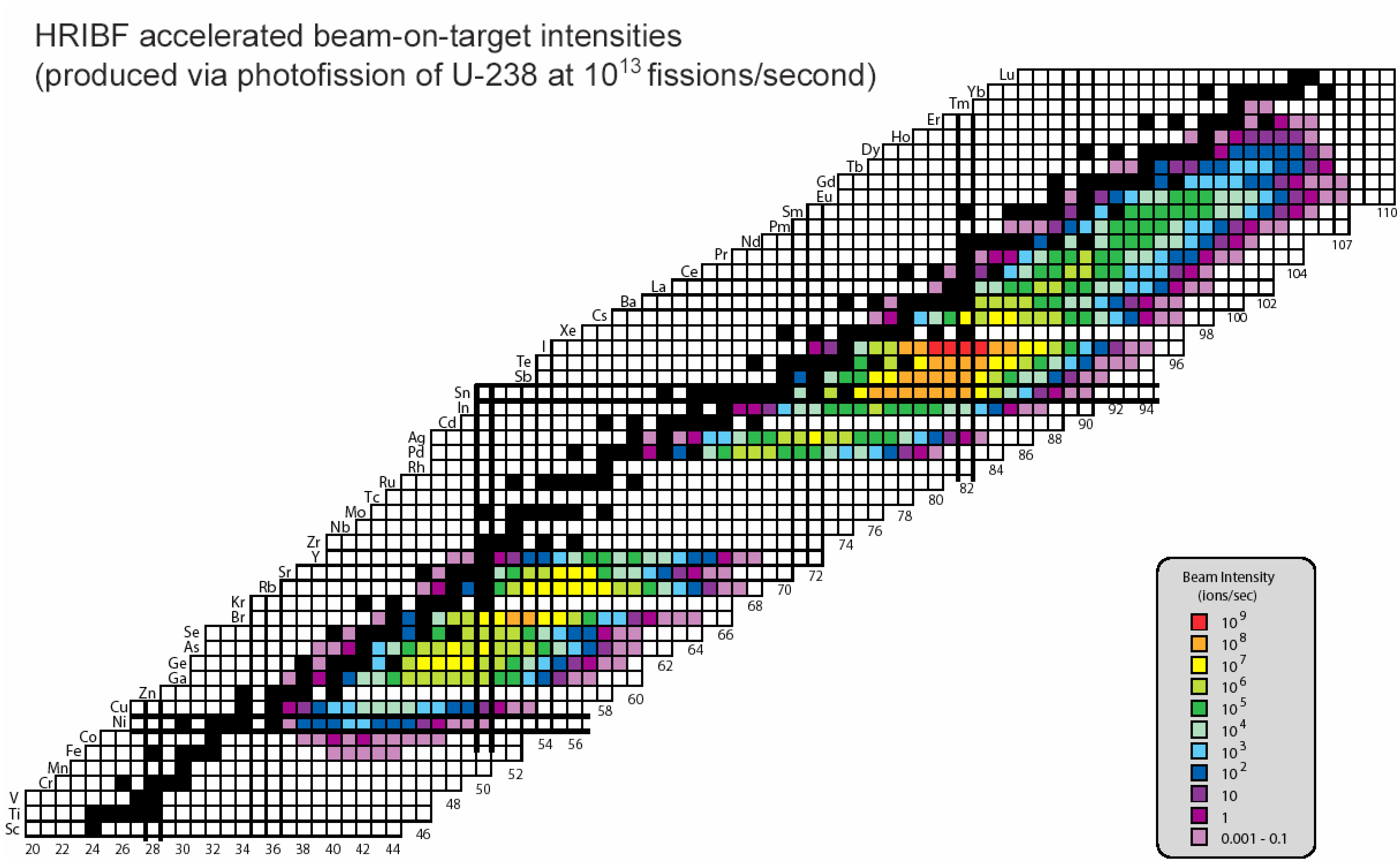


Photo-fission yield

Post-accelerated



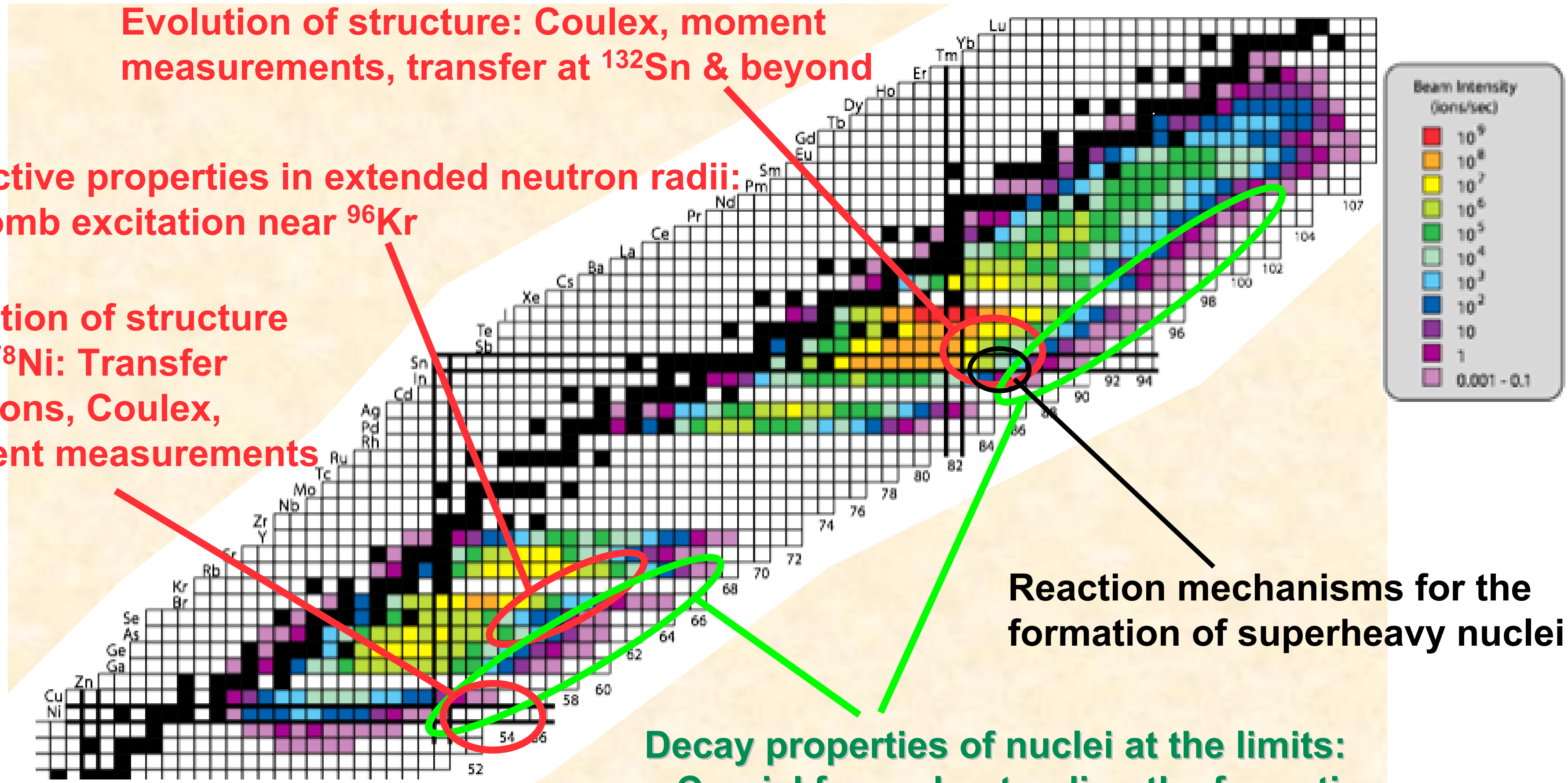
Science highlights with Photofission Driver

→ Will test the evolution of nuclear structure to the extremes of isospin
→ Will improve our understanding of the origins of the heavy elements

Evolution of structure: Coulex, moment measurements, transfer at ^{132}Sn & beyond

Collective properties in extended neutron radii: Coulomb excitation near ^{96}Kr

Evolution of structure near ^{78}Ni: Transfer reactions, Coulex, moment measurements



Reaction mechanisms for the formation of superheavy nuclei

Decay properties of nuclei at the limits:
Crucial for understanding the formation of elements from iron to uranium

The evolution of single-particle levels and shapes in very neutron-rich nuclei beyond the N=50 shell closure

β-decay experiments with postaccelerated (3 MeV/u) *pure* neutron-rich RIBs, Oct-Nov 2006

beam	$T_{1/2}$ (s)	main results
^{76}Cu	0.65	βn-branching ratio $I_{\beta n}$
^{77}Cu	0.46	$I_{\beta n}$, ν- levels in N=47 ^{77}Zn
^{78}Cu	0.35	$I_{\beta n}$, I^{π} of $^{78}Cu_{49}$ revised
^{79}Cu	0.19	βnγ decay observed first time
^{83}Ga	0.30	βnγ,βγ, ν$s_{1/2}$ in N=51 ^{83}Ge
^{84}Ga	0.08	2^+ in N=52 ^{84}Ge
^{85}Ga	~0.07	rate of 0.1pps…

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Jeff Winger *et al.*, RIB-108 and 122

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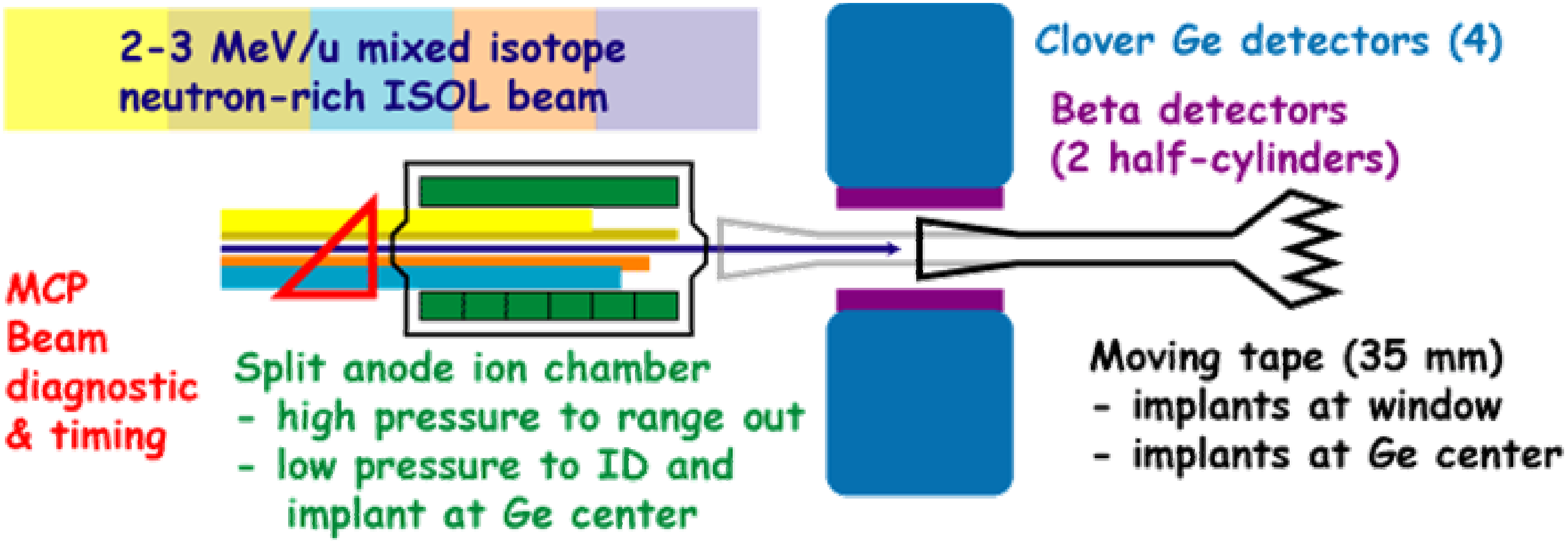
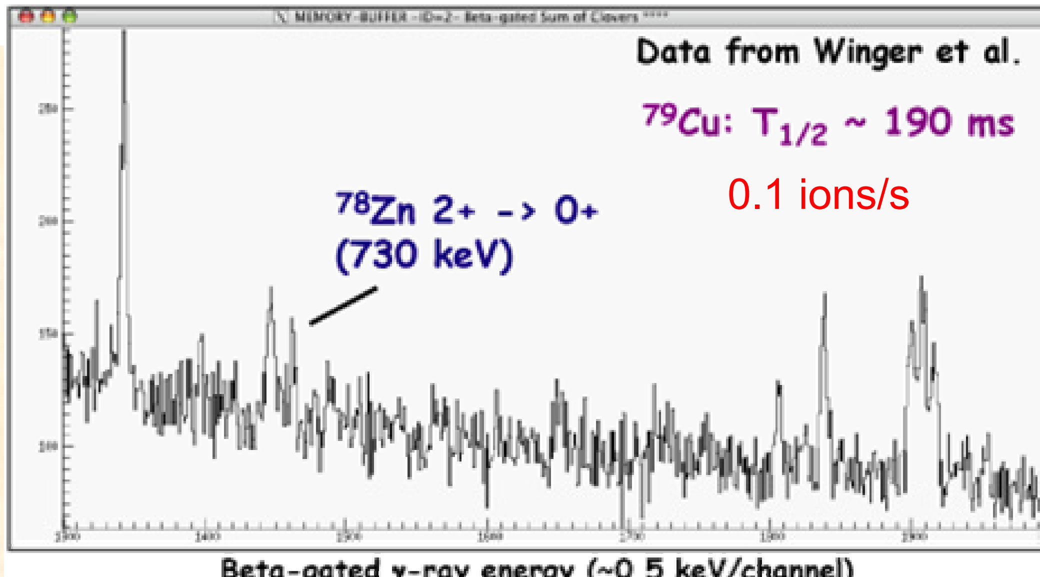
Decay studies pushing the frontier of n-rich nuclei



Examples with eMachine

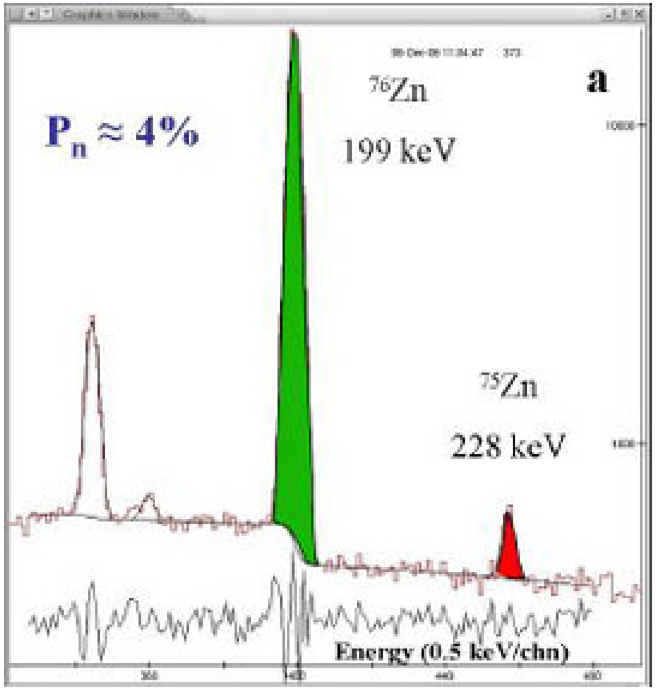
Ion	200 keV (ions/s)	Tandem (ions/s)	$t_{1/2}$ (s)
^{78}Ni	0.3	0.001	0.11
^{80}Cu ^{81}Cu	1000 7	4 0.3	? ?
^{82}Zn	5000	0	?
^{94}Br ^{96}Br	1x10^4 56	100 4	0.07 ?
^{137}Sn ^{138}Sn	1800 89	45 2	0.19 ?
^{137}Sb ^{140}Sb	9x10^5 980	2x10^4 17	? ?
^{149}Cs	2x10^4	4	?

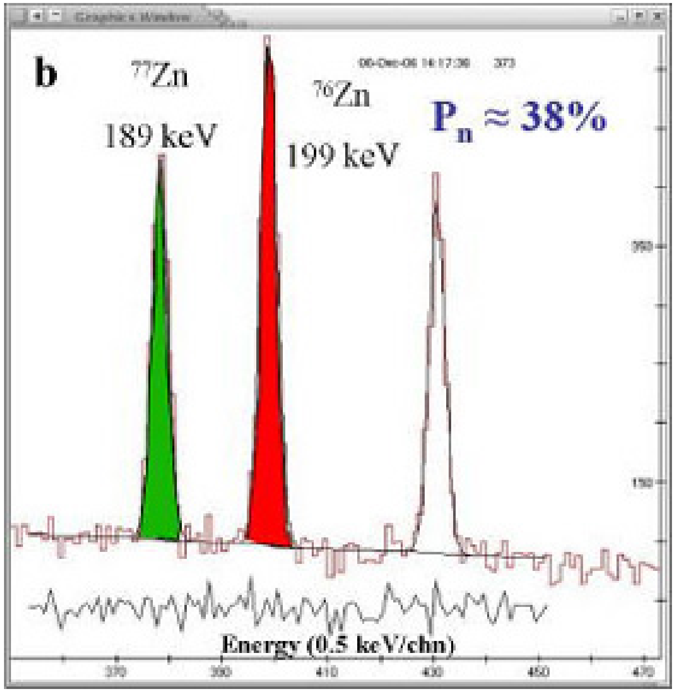


$t_{1/2}$ & βn rates for many r process nuclei are accessible
Energy levels test evolving nuclear structure

Decay Studies of $^{76-79}$Cu and ^{83,84}Ga

The evolution of single-particle levels and shapes in very neutron-rich nuclei beyond the N=50 shell closure

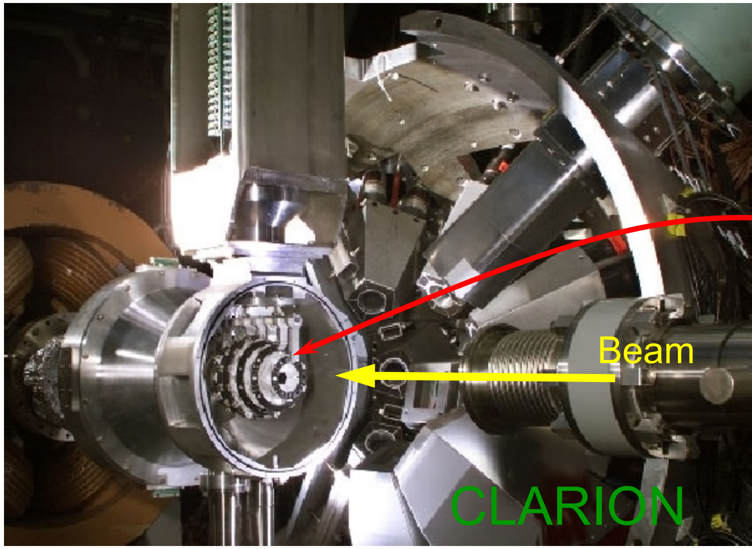




- **Peaks analyzed to deduce βn branch of ^{76}Cu**
- **Peaks used to deduce βn branch from ^{77}Cu**

Coulomb excitation in n-rich systems

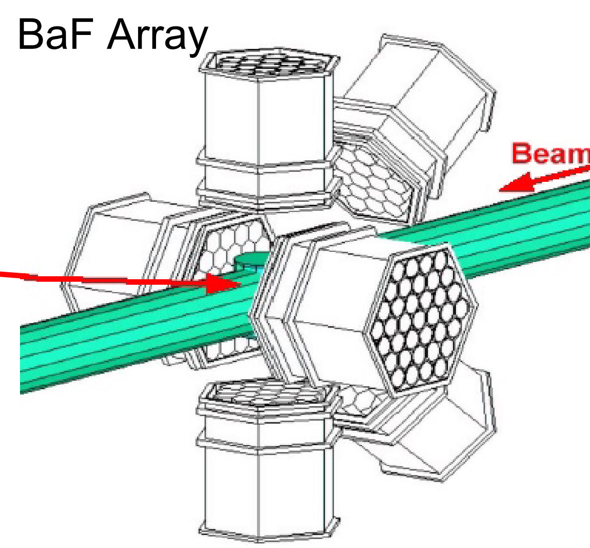
Probes the evolution of collective motion in loosely-bound, neutron-rich nuclei

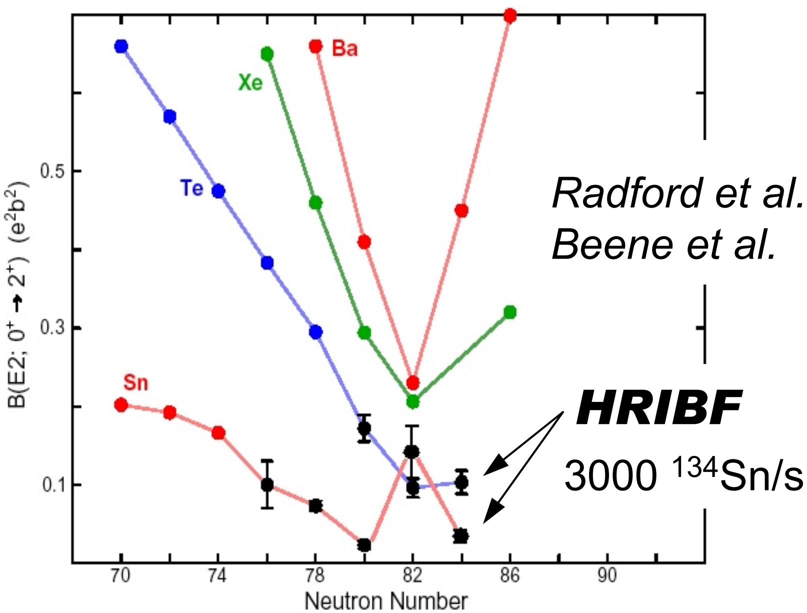


n-rich beams

C, Ti, Zr
target

Charged-particle
⊗
Gamma array

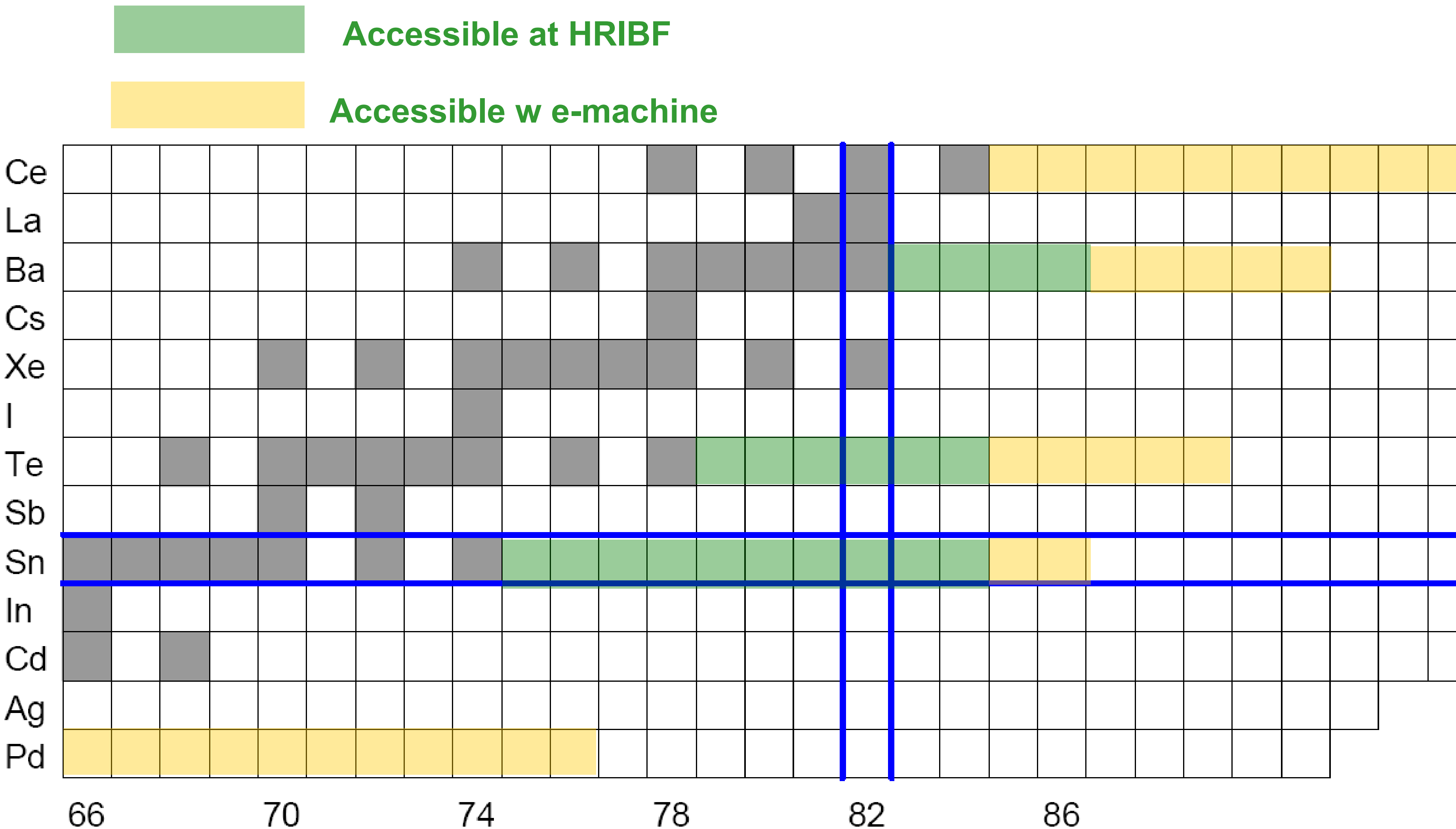




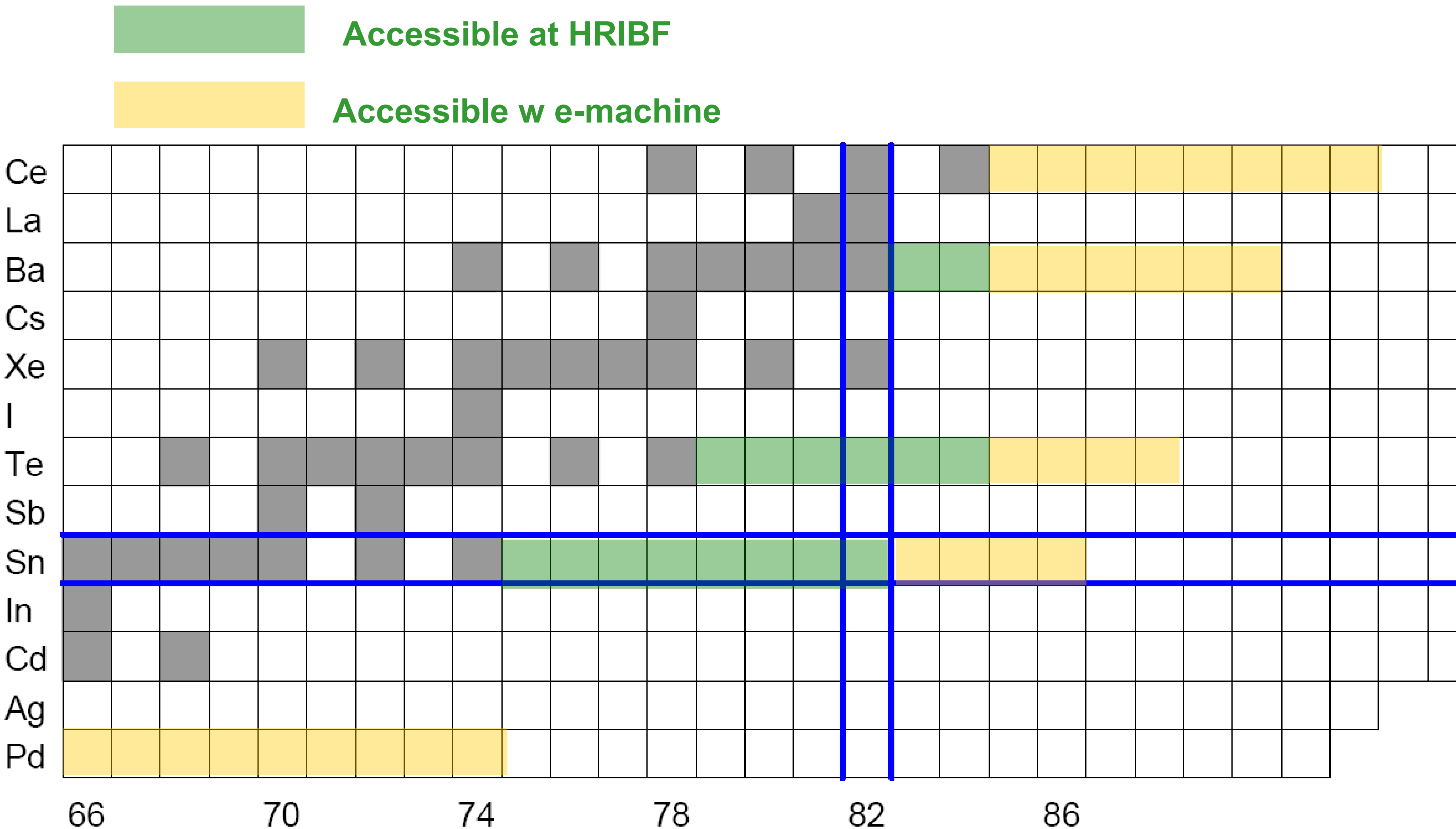
With eMachine: neutron-rich nuclei from N=50 to N=82 (and beyond) are accessible

Ion	Intensity (ions/s)	$t_{1/2}$ (s)
^{84}Ge	3×10^5	0.9
^{88}Se	3×10^4	1.5
^{98}Sr	1×10^4	0.65
^{136}Sn	700	0.25
^{138}Te ^{140}Te	5×10^6 2×10^4	1.4 ?

Coulex (1-step)



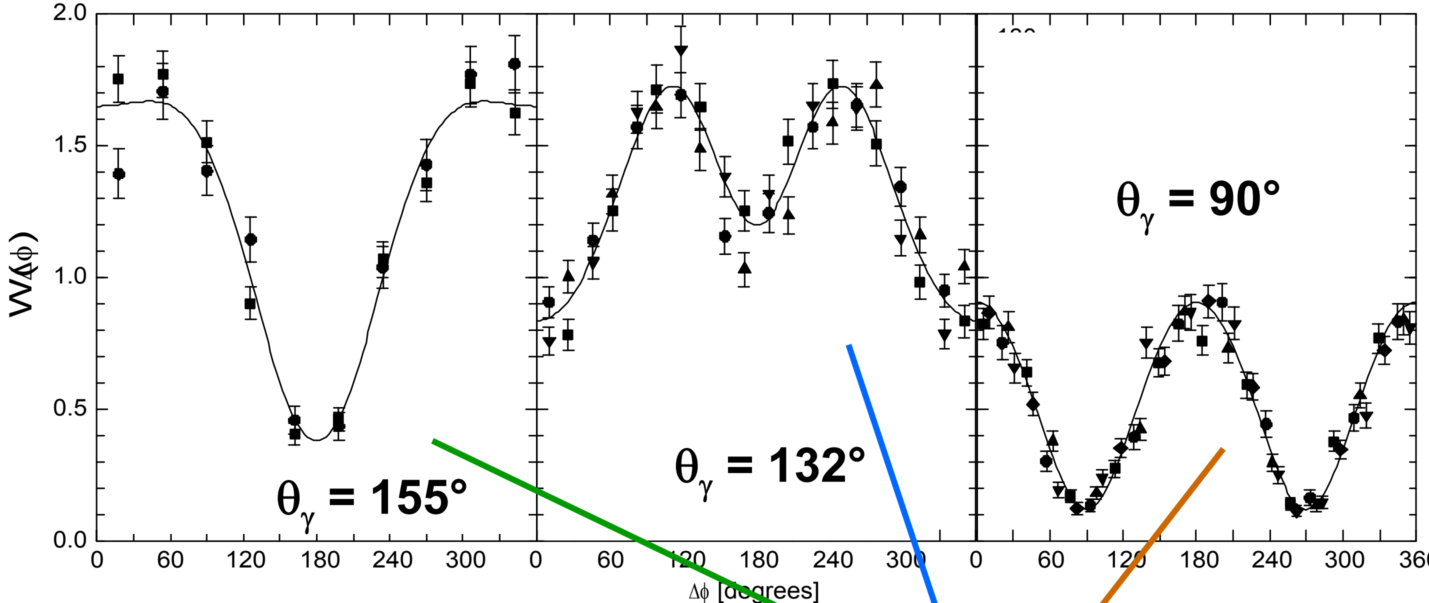
Multi-step Coulex

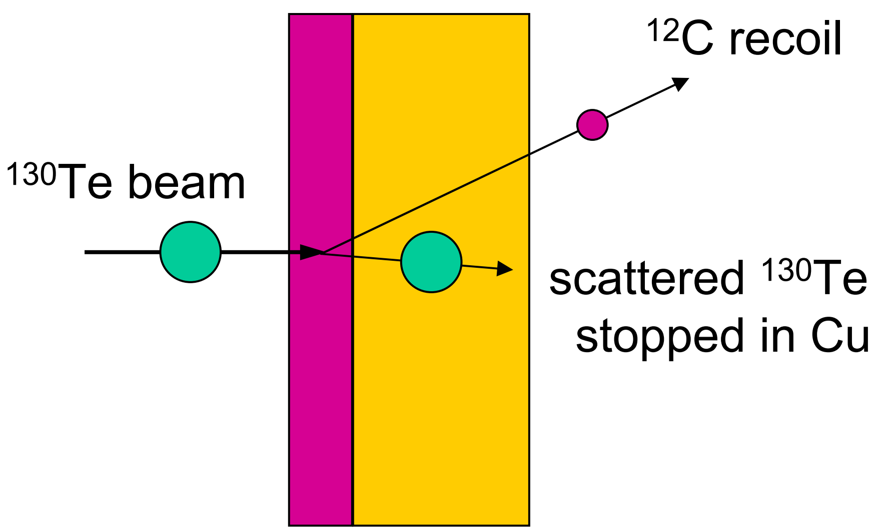


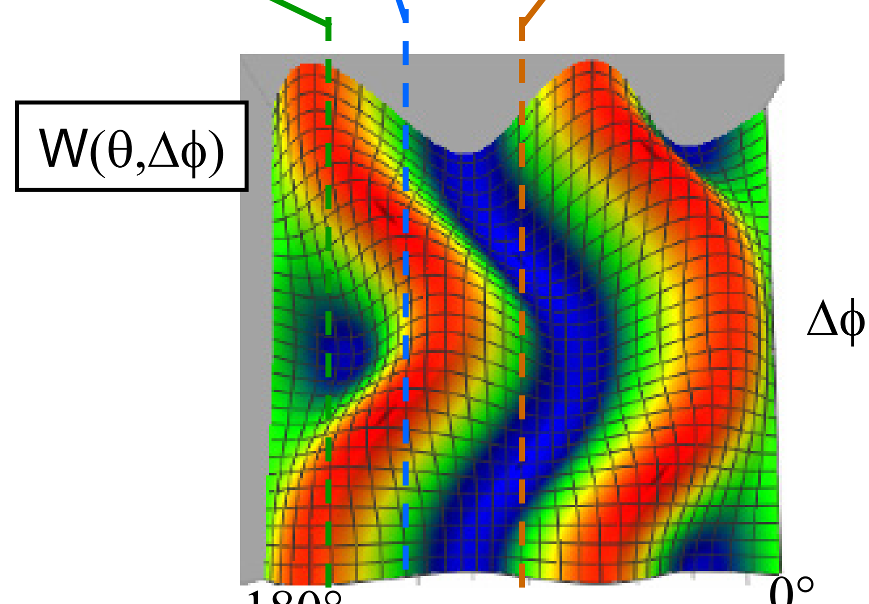
Unattenuated angular correlations: Theory & experiment

^{130}Te SIB

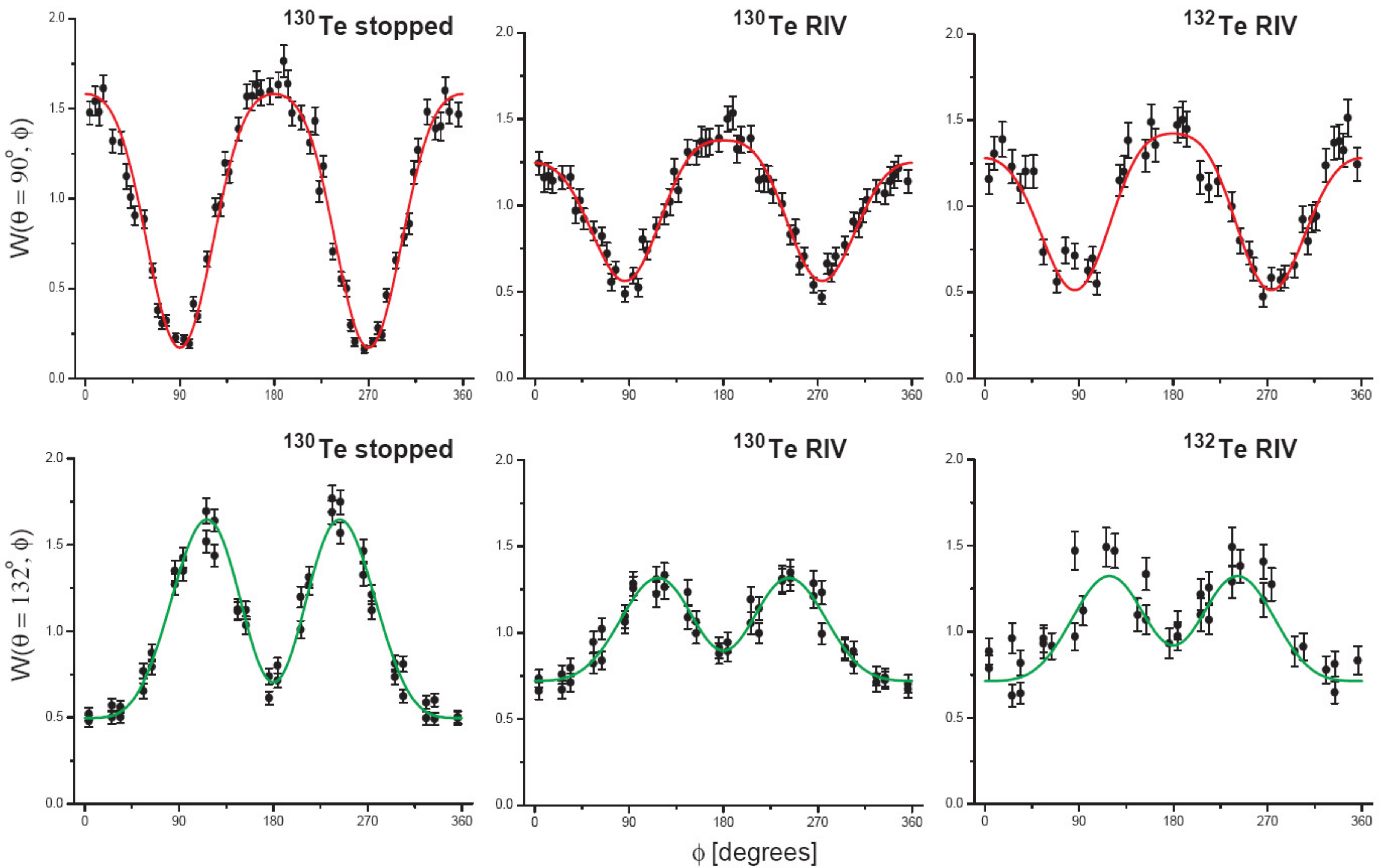
Hyball Ring 2







Magnetic moment: RIV attenuated angular correlations



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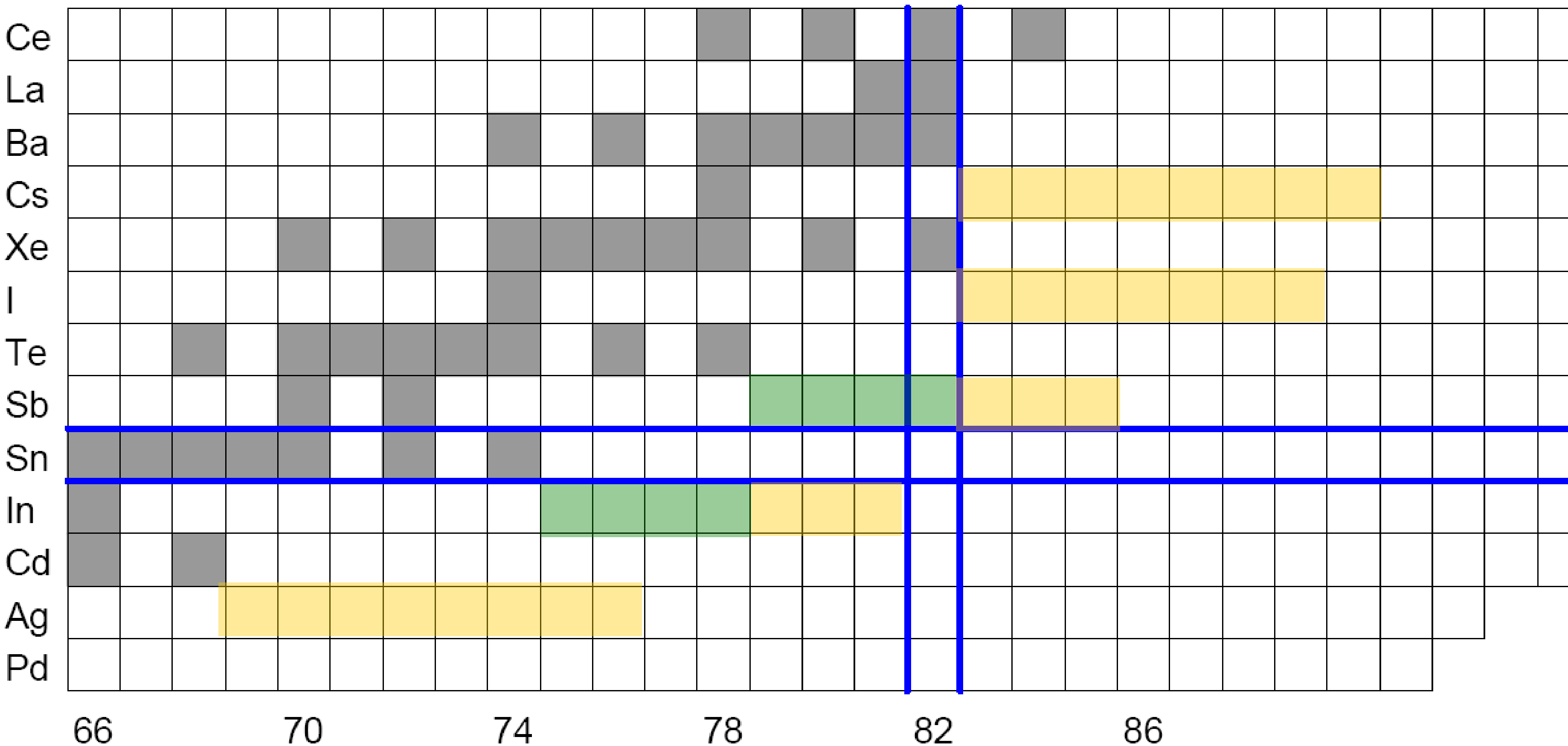
g-factor measurements

Accessible at HRIBF

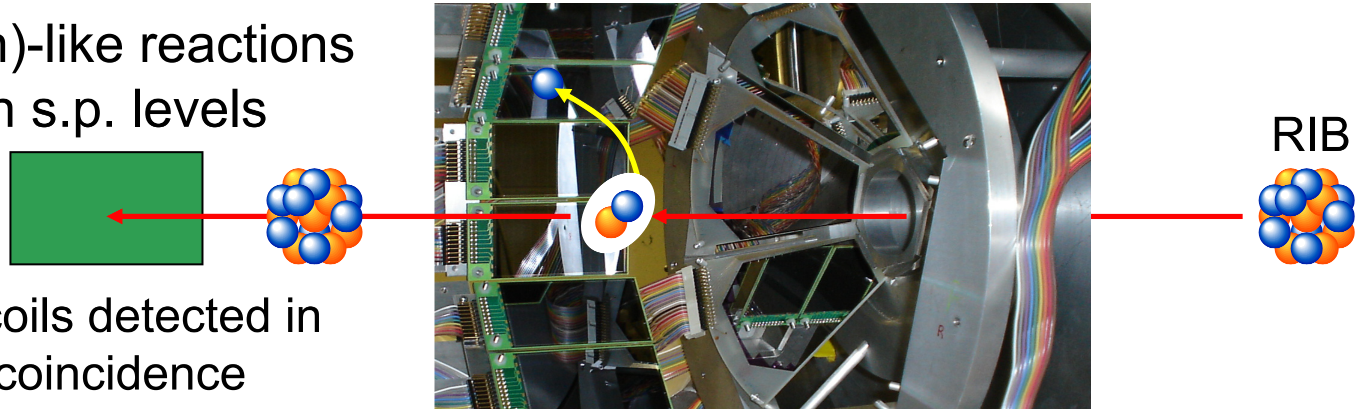
Accessible w e-mach



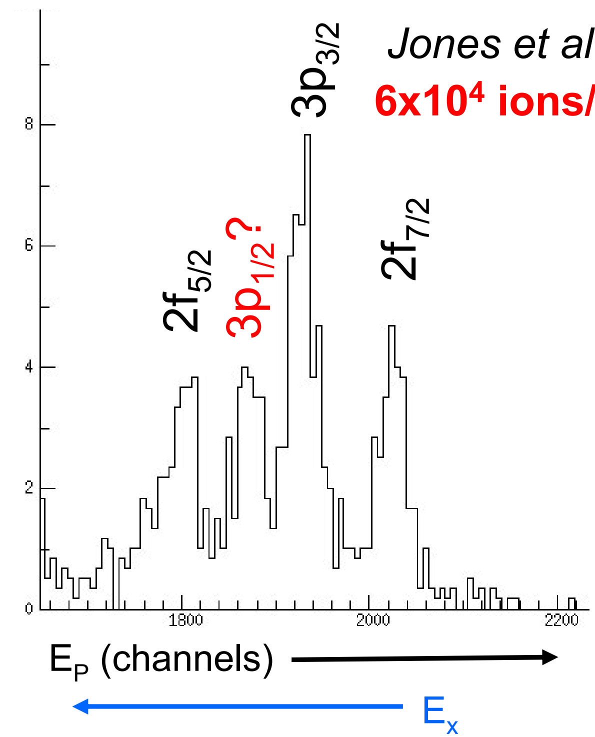
Transfer reactions: shell structure of n-rich nuclei

Single-particle states around closed shells provide a fundamental shell model test

Example: (d,n)-like reactions
→ neutron s.p. levels



$^{132}Sn(d,p)^{133}Sn$ @ HRIBF



Single-particle transfer near ^{78}Ni and ^{132}Sn

Reactions of interest

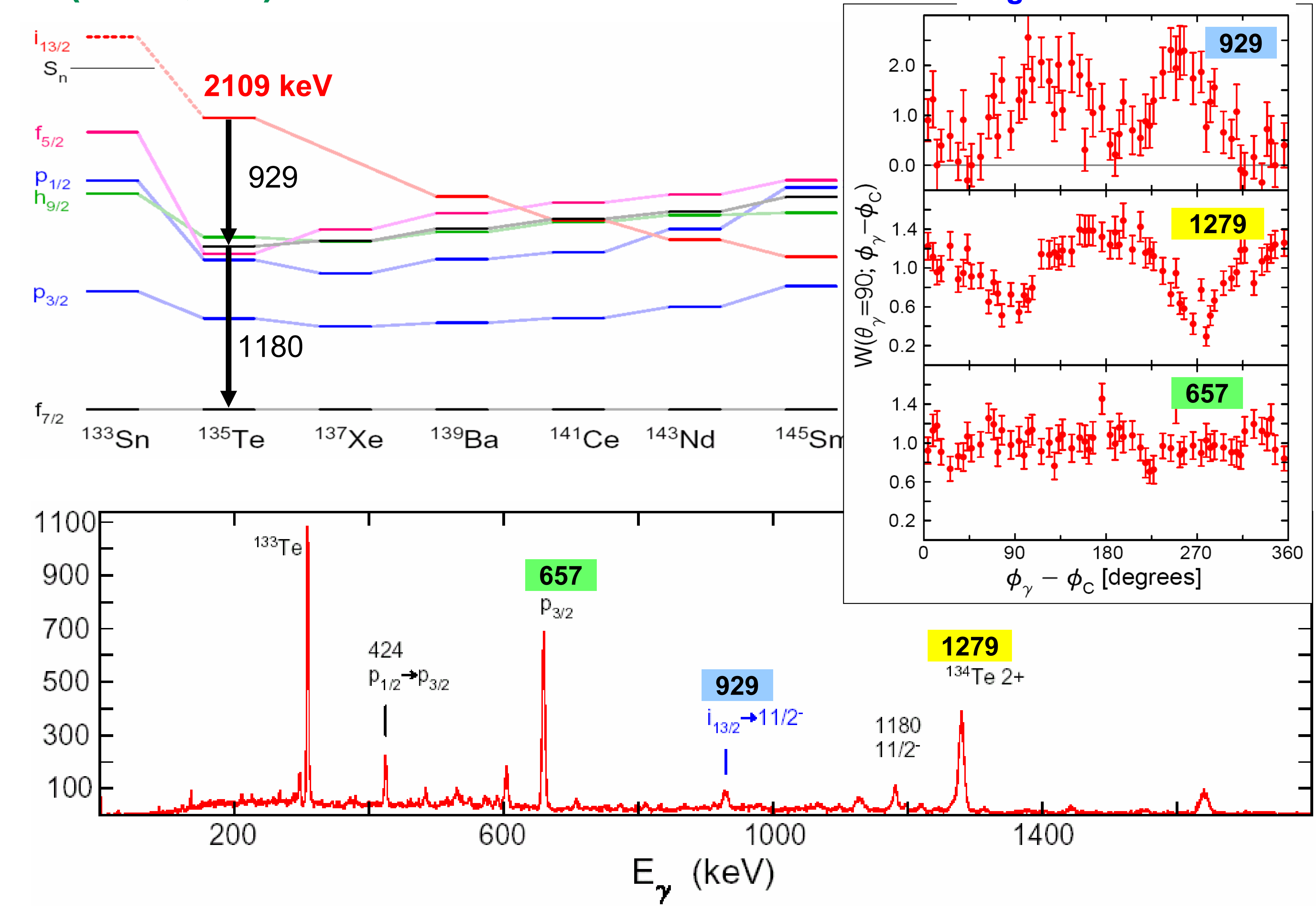
(d,p)
(^{9}Be,^{8}Be)
(^{3}He,d)
(^{3}He,α)
(^{7}Li,^{8}Be)

with the eMachine

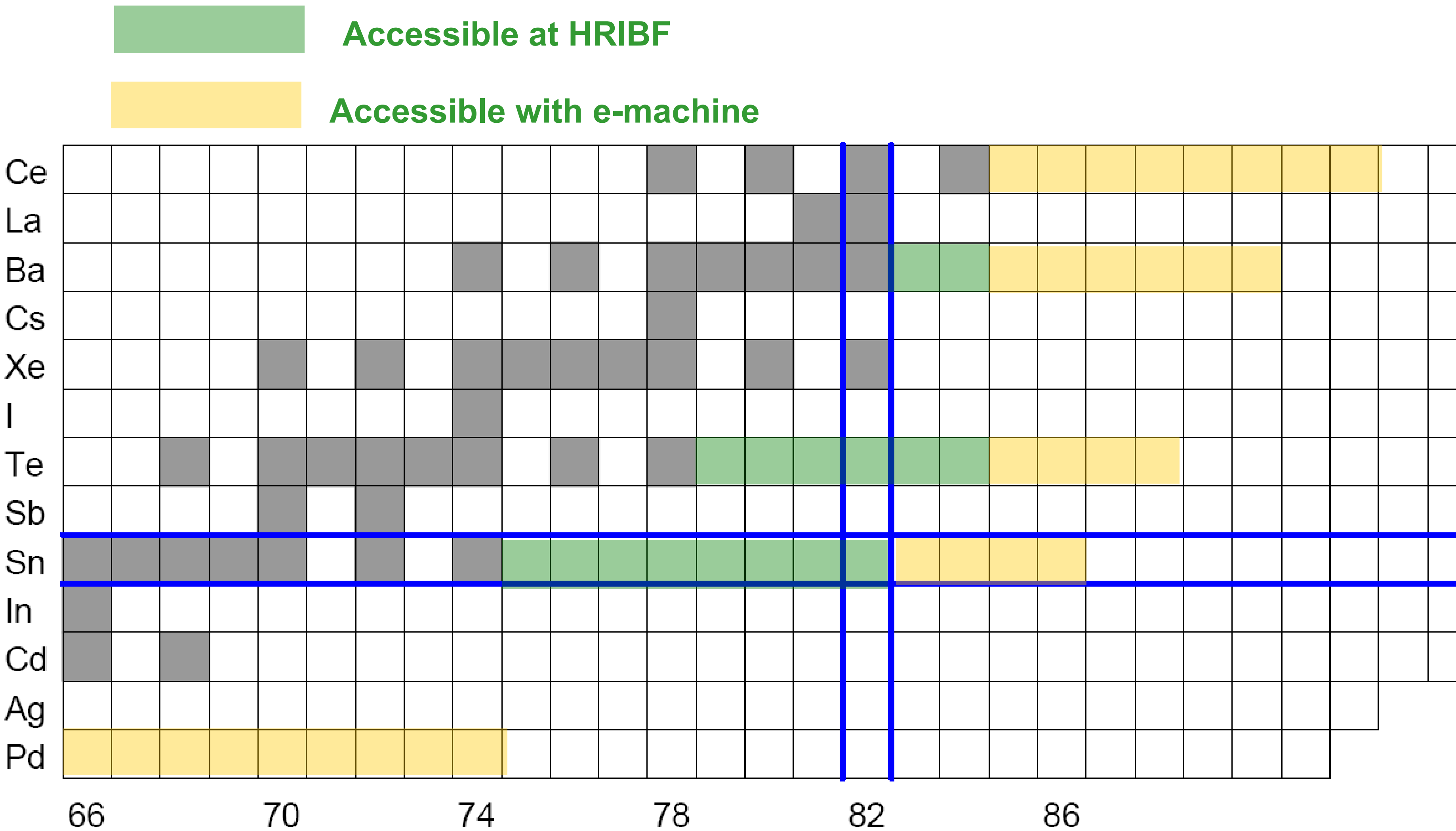
Ion	Intensity (ions/s)	$t_{1/2}$ (s)
^{84}Ge	3×10^{5}	0.9
^{88}Se	3×10^{4}	1.5
^{96}Sr ^{98}Sr	7×10^{4} 1×10^{4}	1.1 0.65
^{134}Sn	3×10^{6}	1.0
^{138}Te ^{140}Te	5×10^{6} 2×10^{4}	1.4 ?

$^{13}C(^{134}Te,^{12}C)^{135}Te$ neutron transfer

Particle-gamma angular correlations

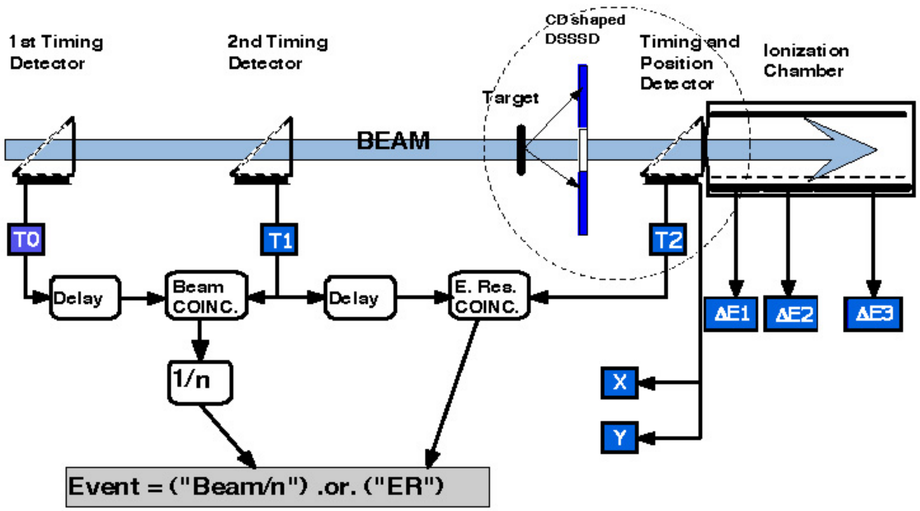


Transfer reaction studies

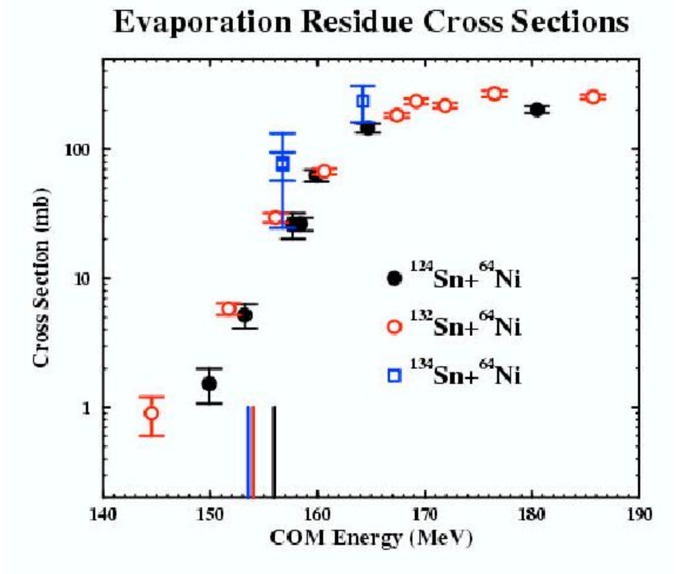


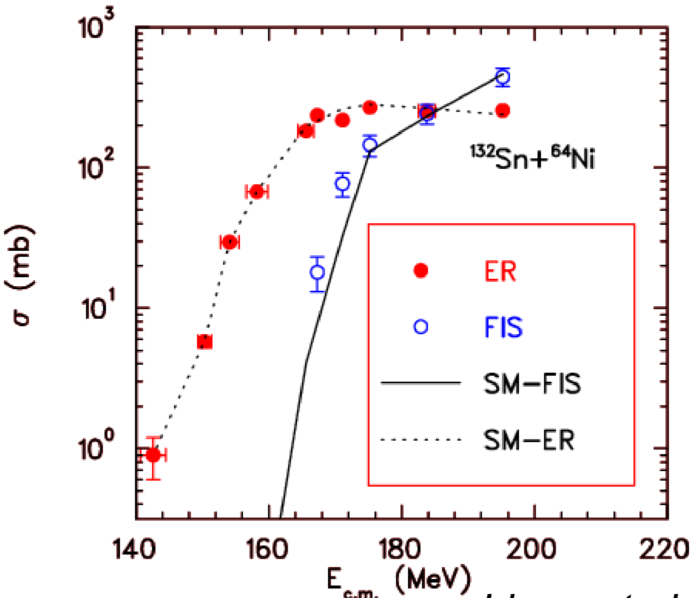
Heavy ion fusion reactions

Probes the influence of neutron excess on fusion at and below the Coulomb barrier
→ important for superheavy element synthesis



HRIBF Results





Liang et al.

with eMachine

Ion	Intensity (ions/s)	$t_{1/2}$ (s)
^{92}Br	2×10^5	0.34
^{134}Sn ^{136}Sn	3×10^6 600	1.0 0.25

More n-rich projectiles

Further below barrier
^{134}Sn below 10 mb

Transfer reaction studies on the same system will help to understand reaction mechanism

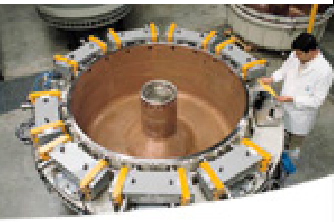
Summary

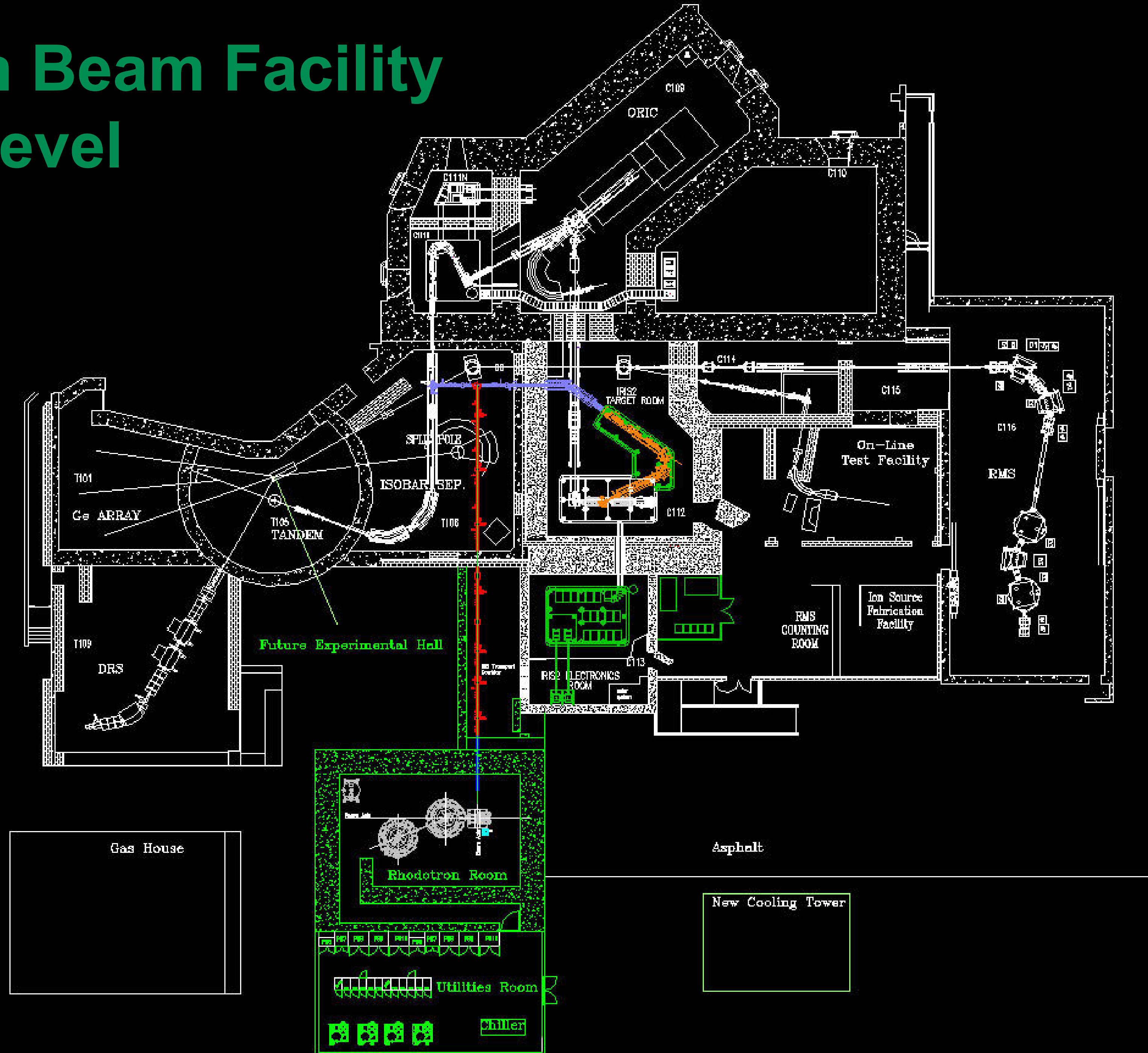
- **A vigorous, healthy and creative research program has been developed at HRIBF, in spite of facility limitations**
- **Upgrades now funded and underway will substantially improve facility operational efficiency and reliability**
  - **Research equipment**
  - **RIB production capabilities**
- **Addition of a modest-scale electron accelerator would greatly enhance our neutron-rich beam capability and enhance our science capability**

Conclusions

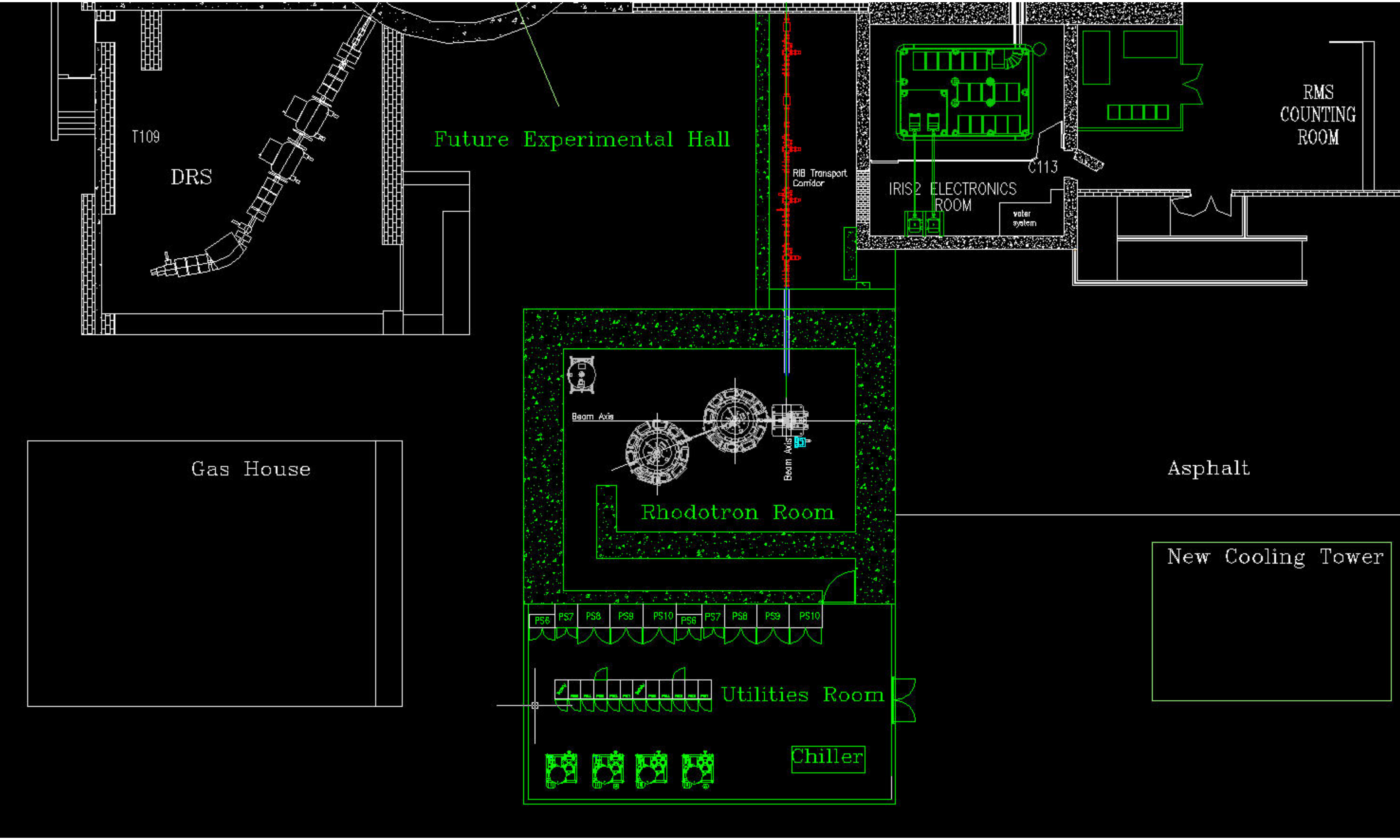
- 10^{13} f/s can be achieved with 50 kW facility
  - Requires only modest sized targets
    - 3 cm x 5 c m (212 g)
  - <10 kW deposited in target
  - 25 MeV e beam can be used with converter
    - Rhodotron technology can be considered
- 3-5 x 10^{13} can be achieved with larger targets and higher beam powers
  - 500g to 1kg & 100-150 kW
  - What is release time

Electron Beam Facility Upper Level

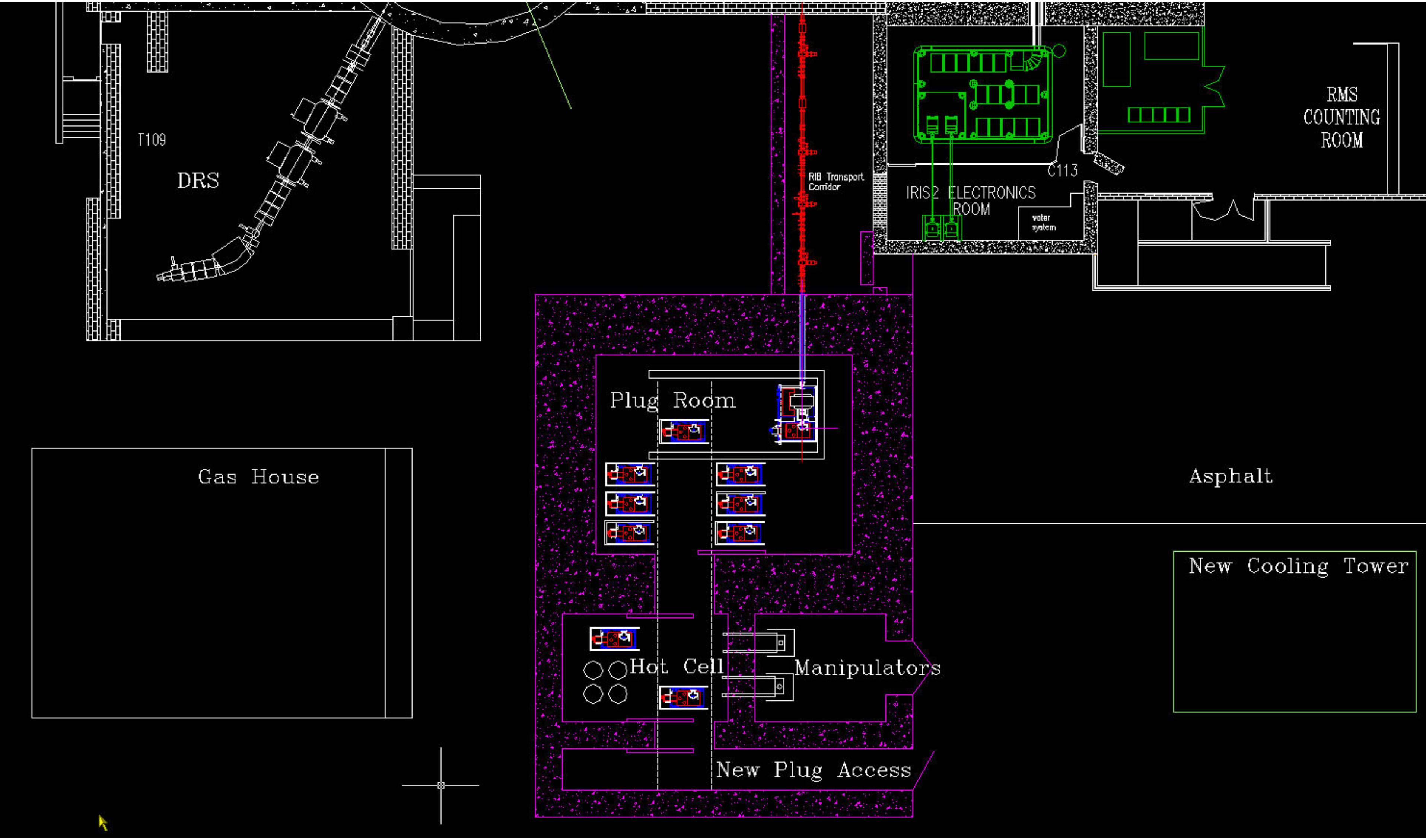




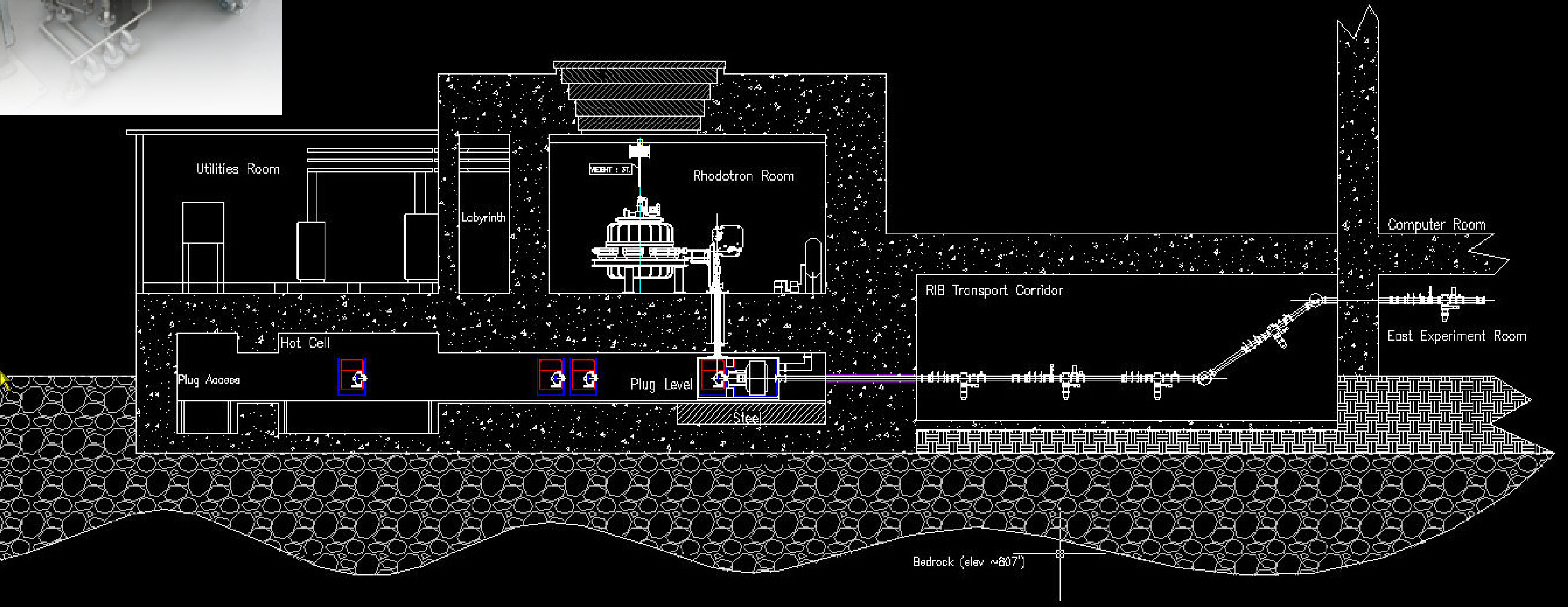
Rhodotron Facility Upper Level



Rhodotron Facility Lower Level



Electron Beam Facility Elevation



Photofission yields

- 10^{13} f/s "easily" achieved
- About 20x current HRIBF
- But real gain >> 20x