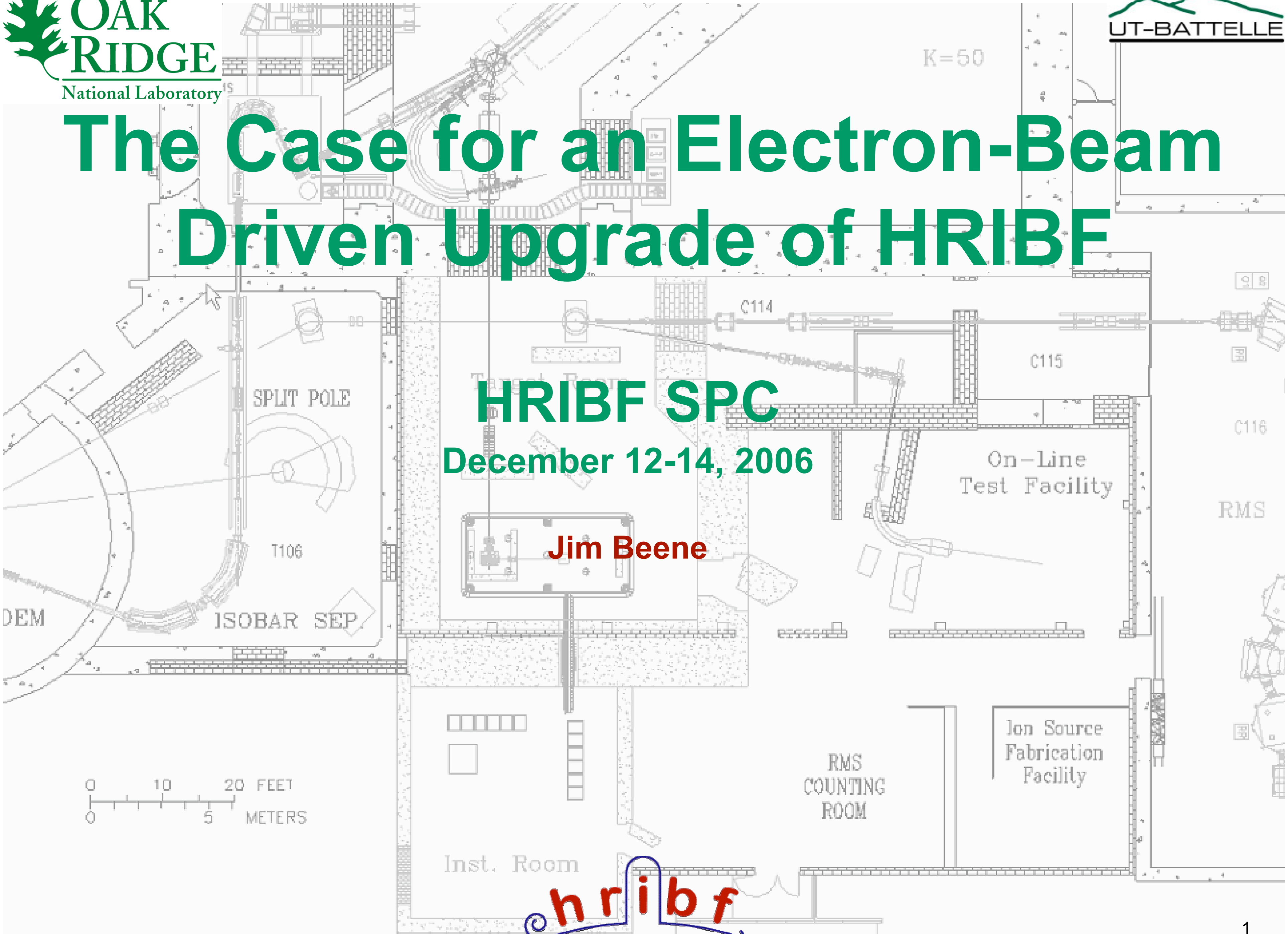
The Case for an Electron-Beam Driven Upgrade of HRIBF

HRIBF SPC

December 12-14, 2006

Jim Beene



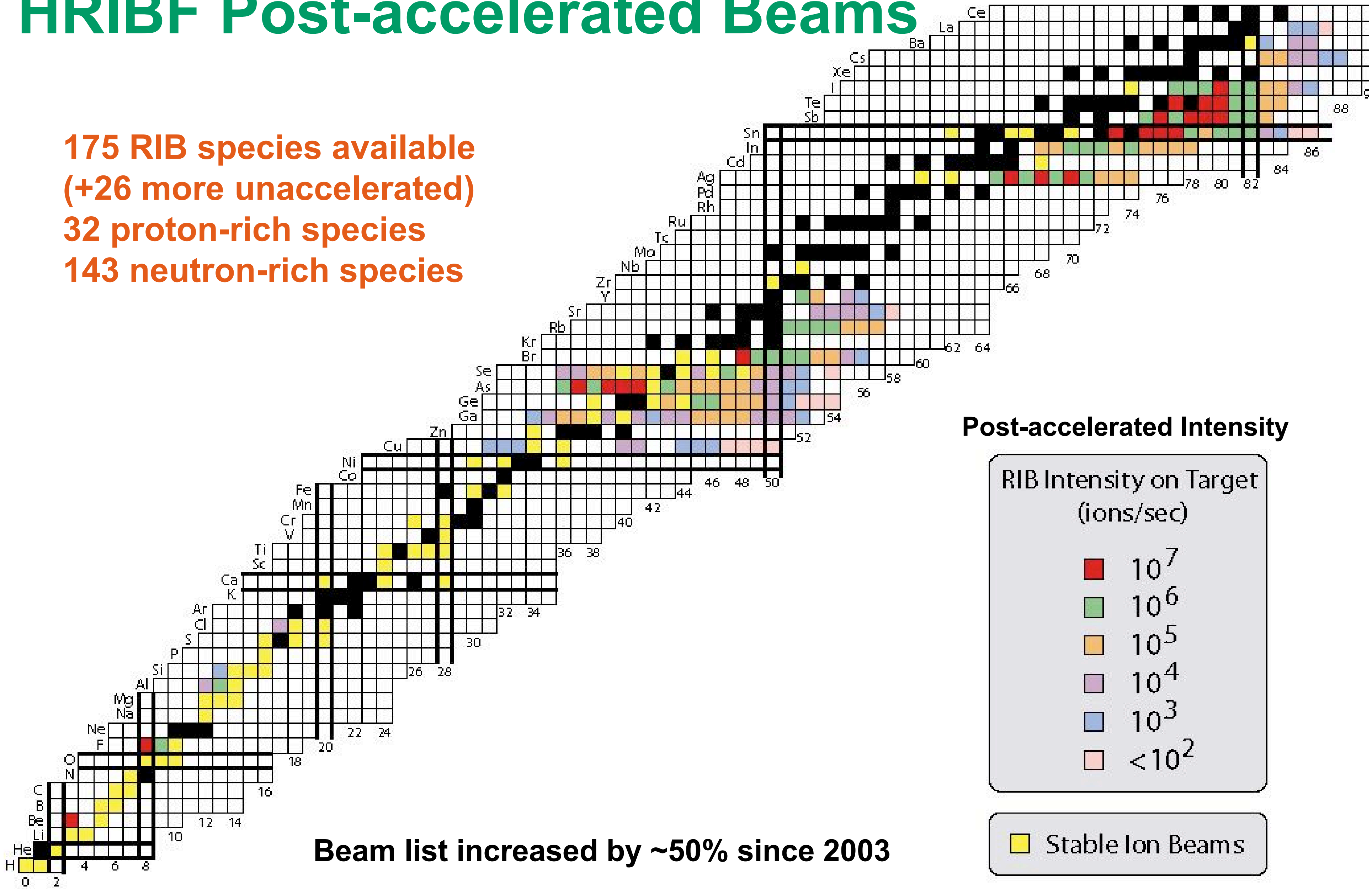
Holifield Radioactive Ion Beam Facility
Oak Ridge National Laboratory

Outline

- **Baseline performance of a photofission facility**
- **Target and power issues**
- **Science with a photofission facility**

HRIBF Post-accelerated Beams

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

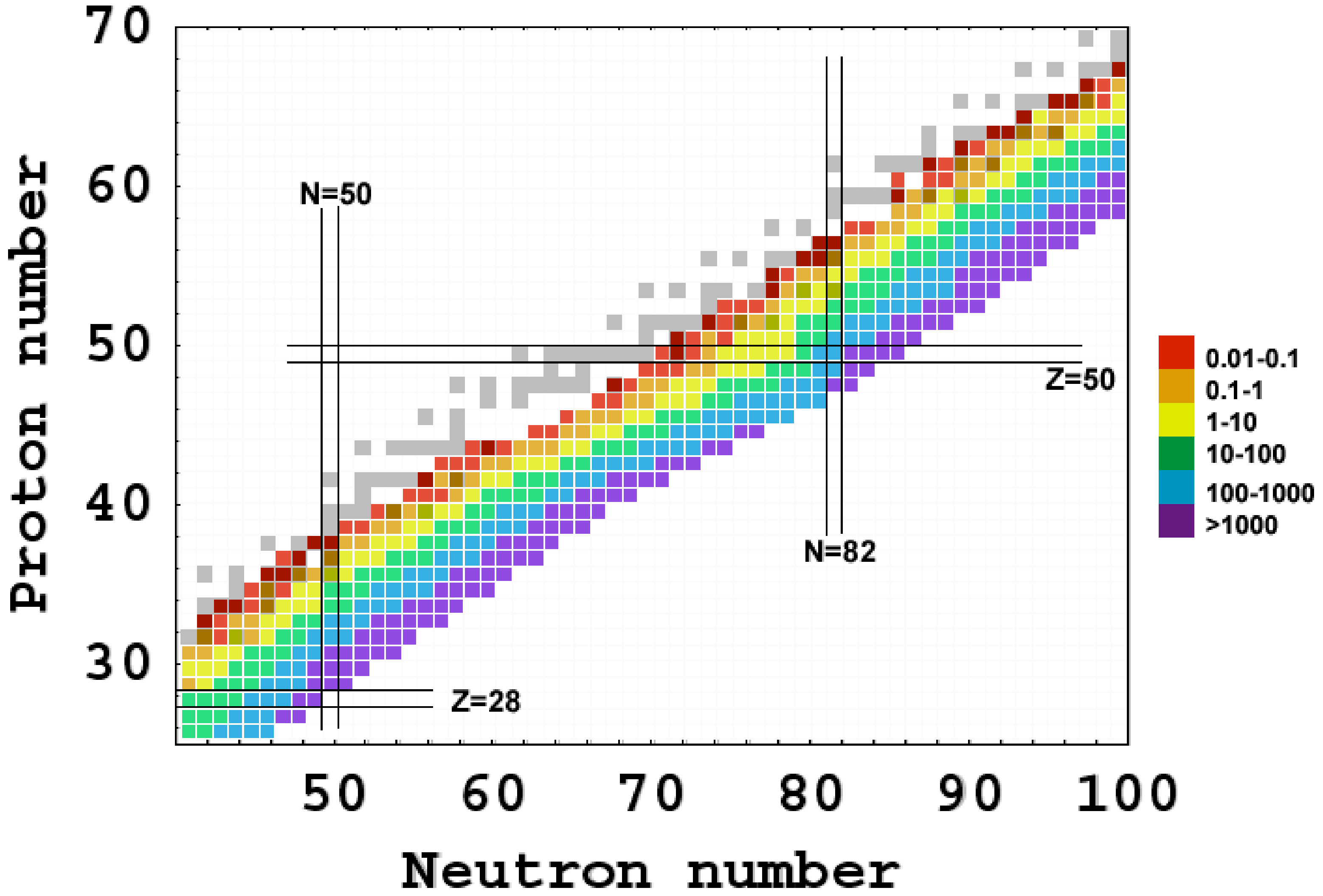


Beam list increased by ~50% since 2003

HRIBF as a two driver facility

- We are developing a proposal for a turn-key electron accelerator (e-machine), capable of providing CW ~ 100kW beams with energies at or above 25 MeV.
- This accelerator would be dedicated to producing neutron-rich species by photofission of actinide targets.
- Such an accelerator is by far the most cost effective means to achieve in-target fission rates in the mid 10^{13} /s scale.
- Target development to support operation at >10^{13}f/s (~50kW)is well in hand. Thus we are confident we can reach fission rates about 25 times larger than current HRIBF capability.
- The increase in fission rate is not, however a good comparative metric.
  - Photofission is a “colder” process than proton induced fission.
  - It results in lower actinide excitation, and less neutron evaporation from both the excited actinide system and the fragments.
  - Consequently production of very neutron-rich species can be enhanced by a substantial factor compared to 50 MeV proton induced fission, at the same fission rate.
- An improved ORIC (with axial injection) would offer substantially increased capability for the proton-rich program

RIB production by photofission



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

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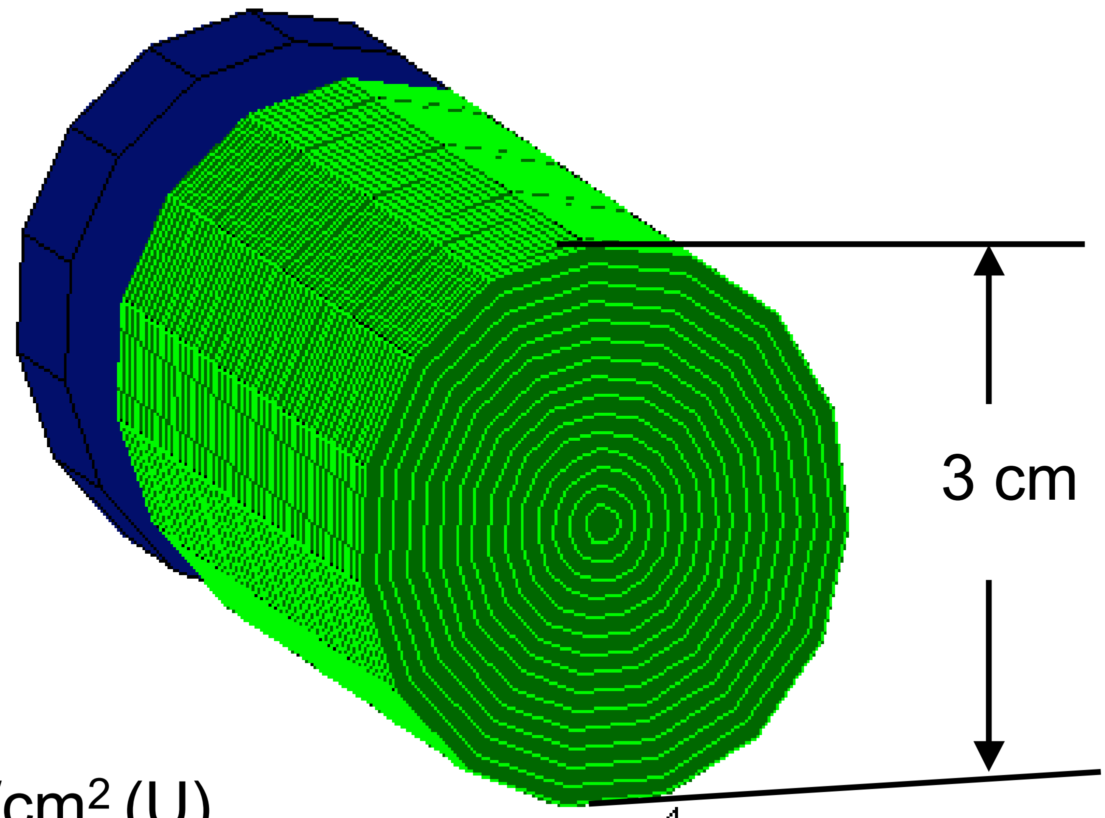
Conservative target design for performance determination

ρ=3 g/cm^3
d=3 cm (0.3 R_M)
t=30g/cm^2 5X_0 (10cm)
M=212 g

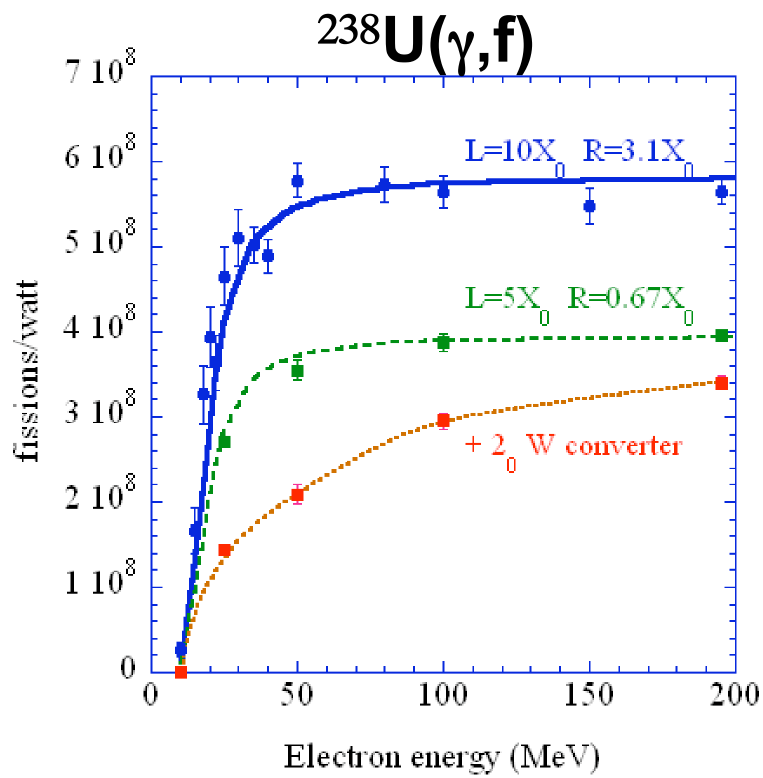
ρ=6 g/cm^3
d=3 cm (0.6 R_M)
t=30g/cm^2 5X_0 (5cm)
M=212 g

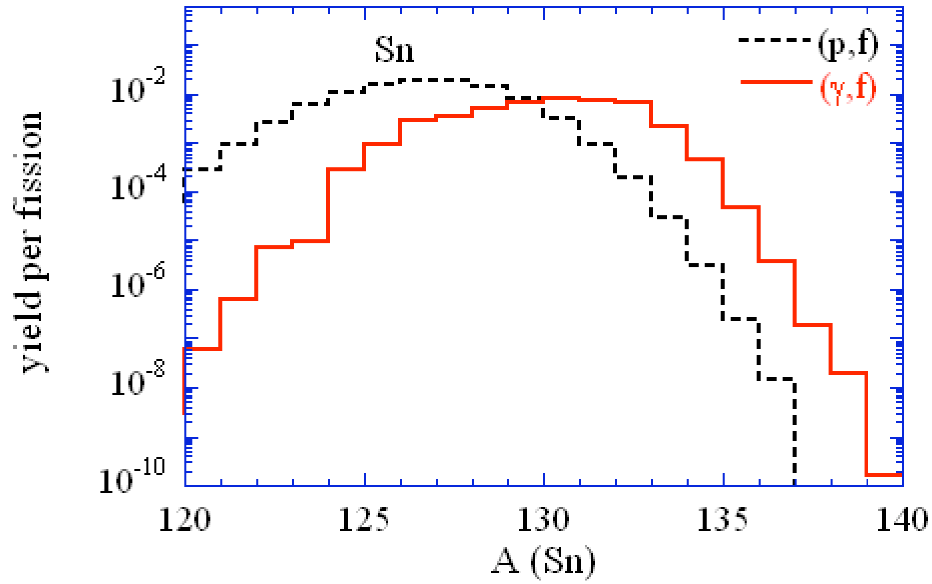


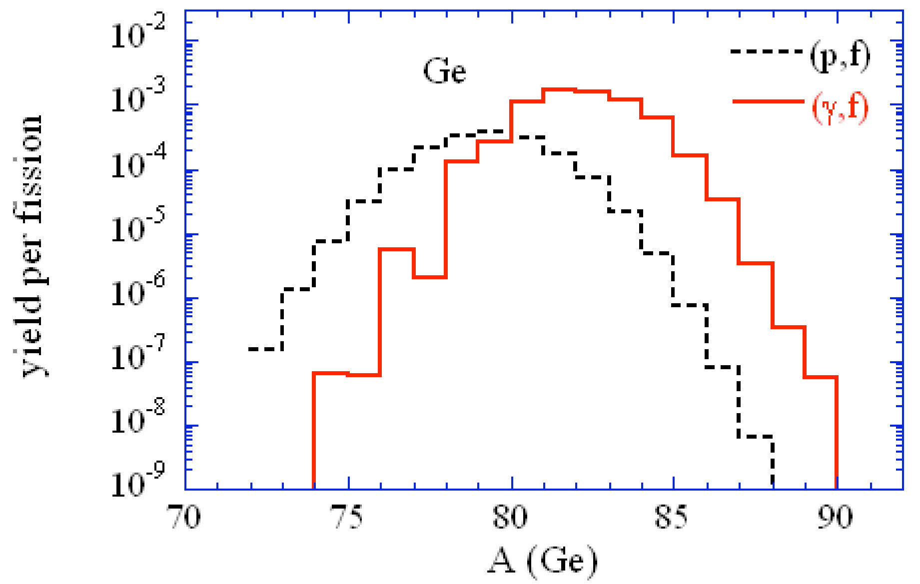
X_o=6 g/cm^2 (U)

Photofission yields

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

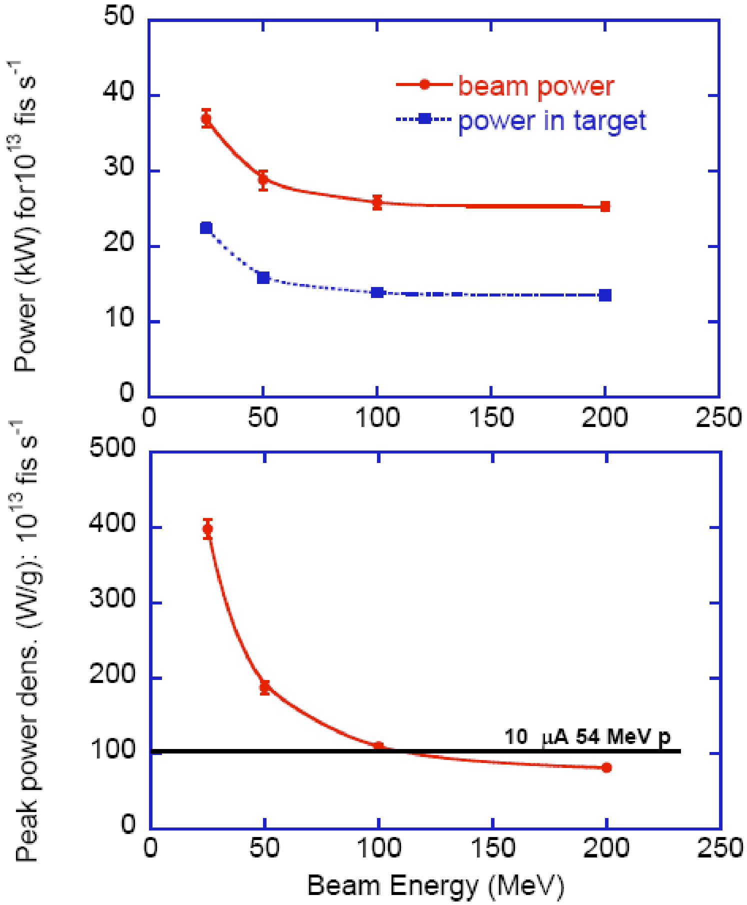






Photofission target issues/ limitations

Direct bombardment



- e-beam directly incident on targets
- If 10^{13} goal is to be met, beam energies less than ~80 MeV may give problems using current target technology without further testing and or development.

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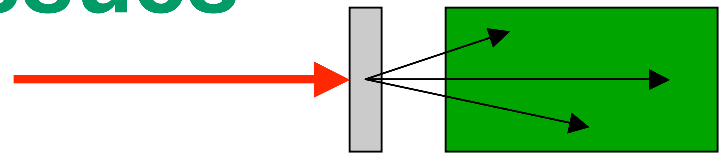
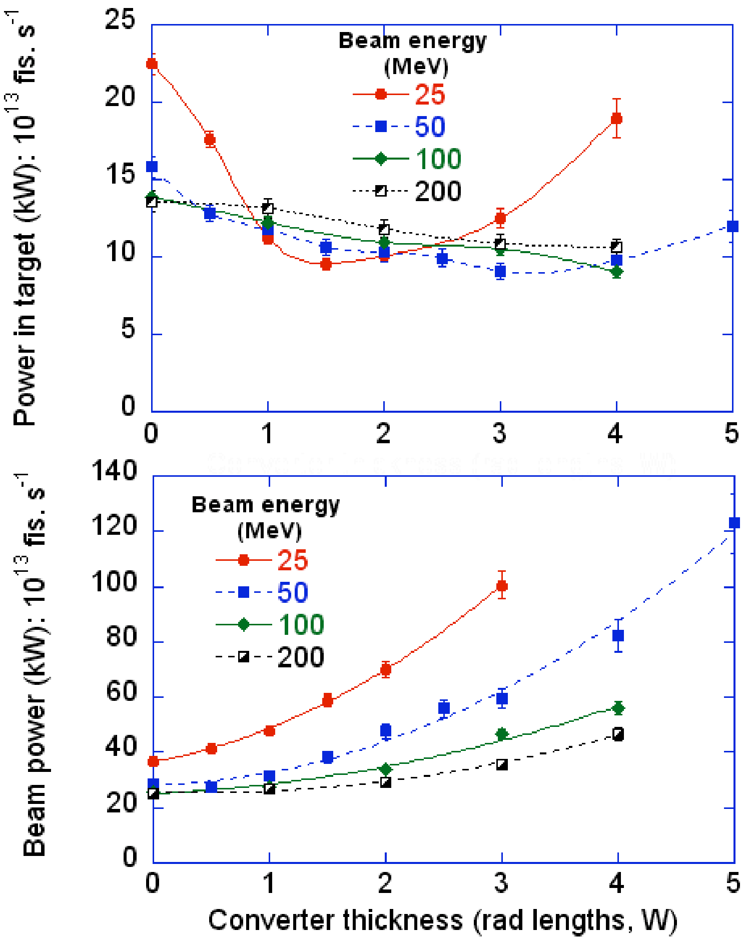
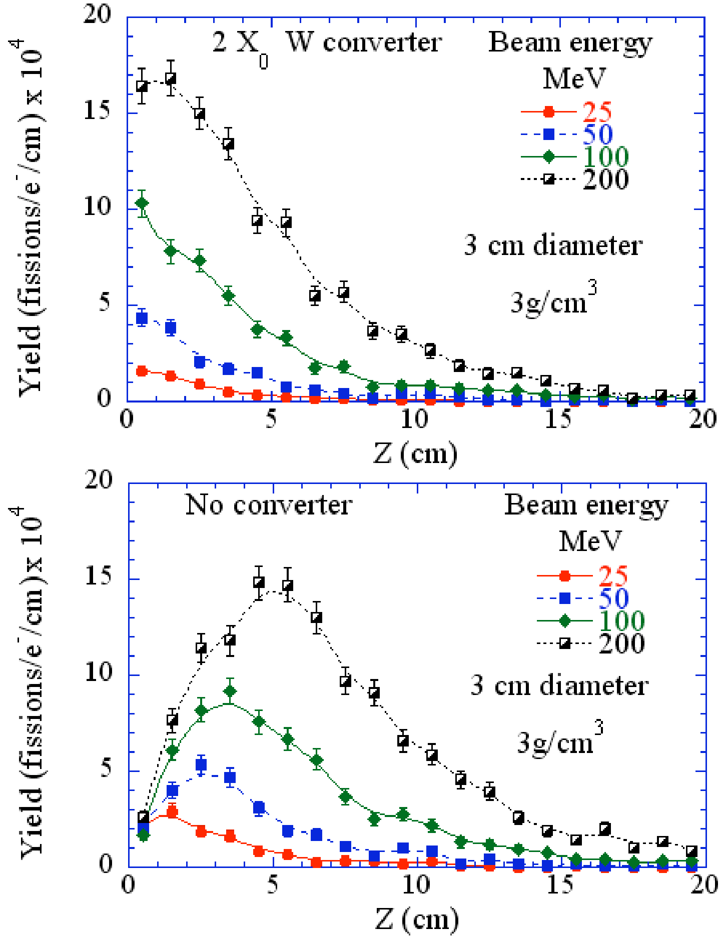
Photofission target issues

Converter + target





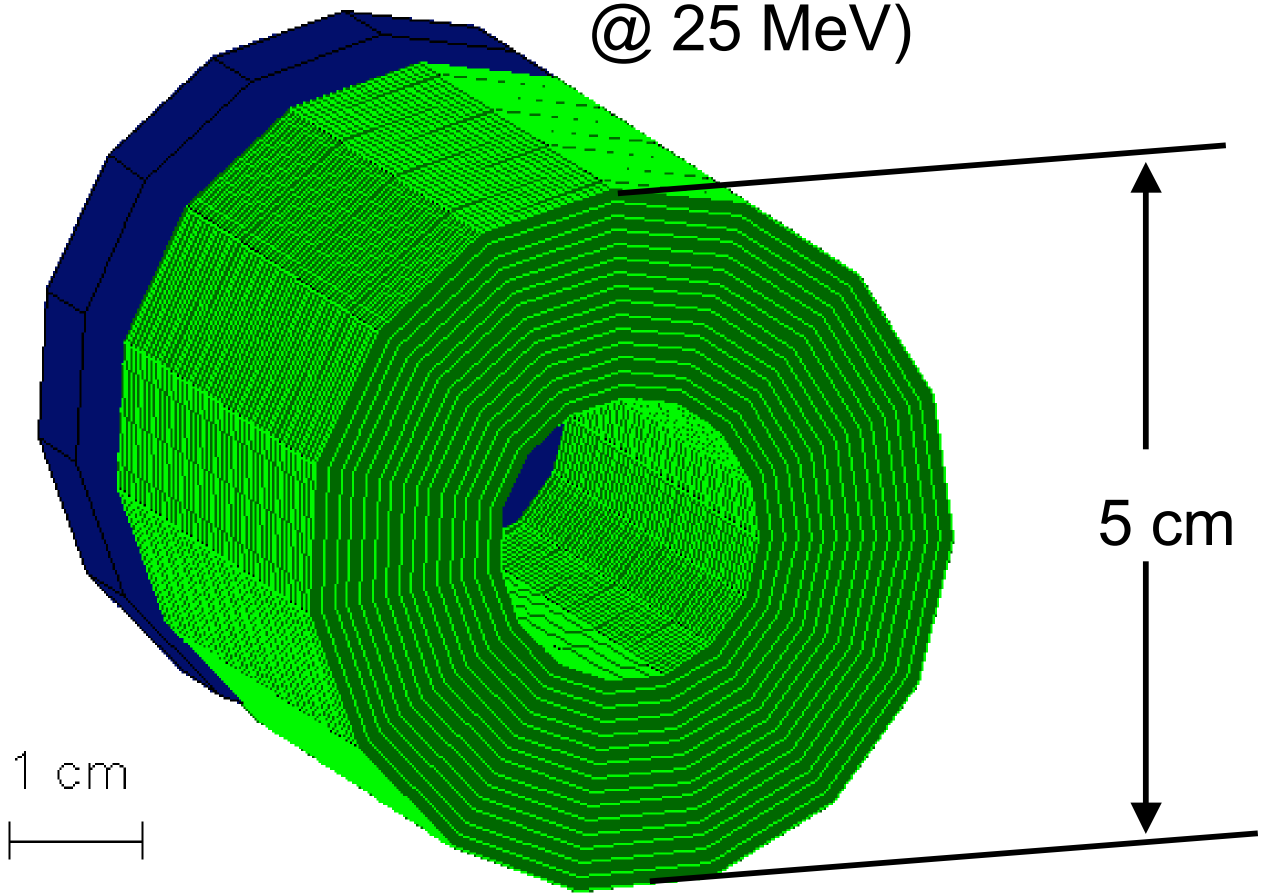


An example of a somewhat more aggressive design

Similar power required to reach 10^{13} f/s (52kW @ 25 MeV)

r=6 g/cm3
d=6 cm (0.6 R_M)
t=30g/cm2 ($5X_0$)
M=494 g

2.3 x UC_x front surface area compared to 3 cm dia. Cylinder



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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

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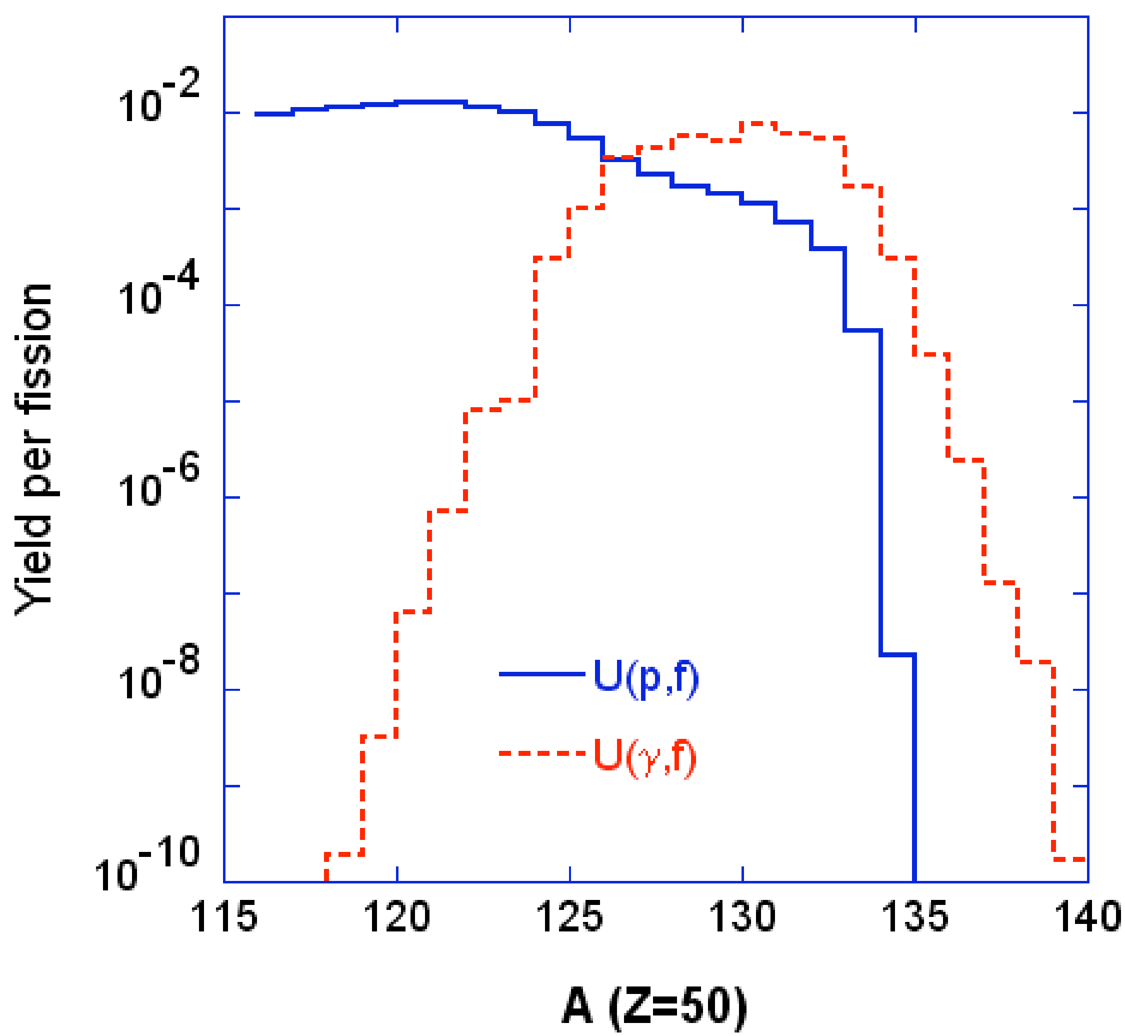
U(γ,f) vs U(p,f) 1 GeV



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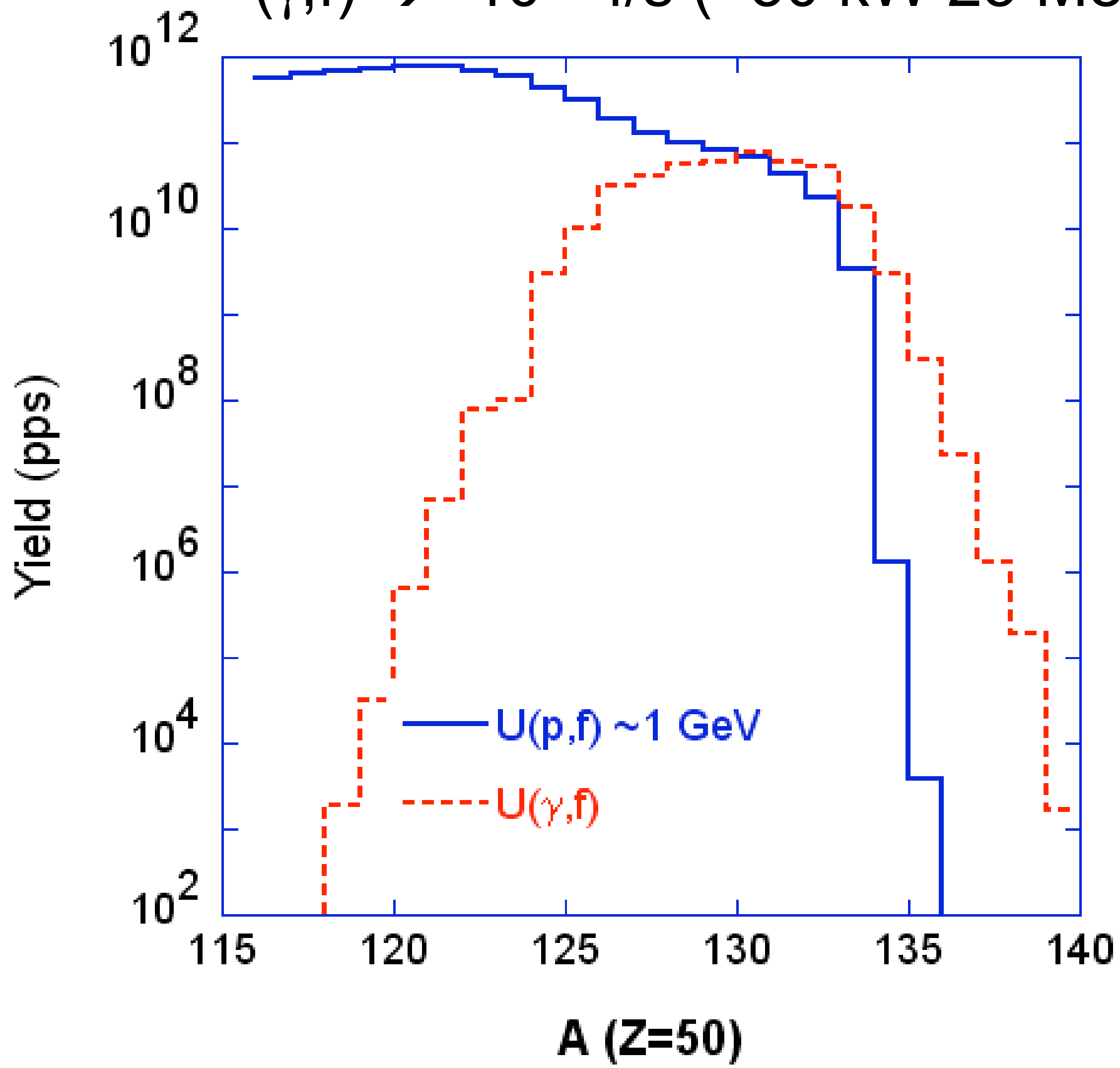
U(γ,f) vs U(p,f) 1 GeV

(p,f) → 100 μA on 30 g/cm^2 → 5x10^{13} f/s

(γ,f) → 10^{13} f/s (~50 kW 25 MeV)



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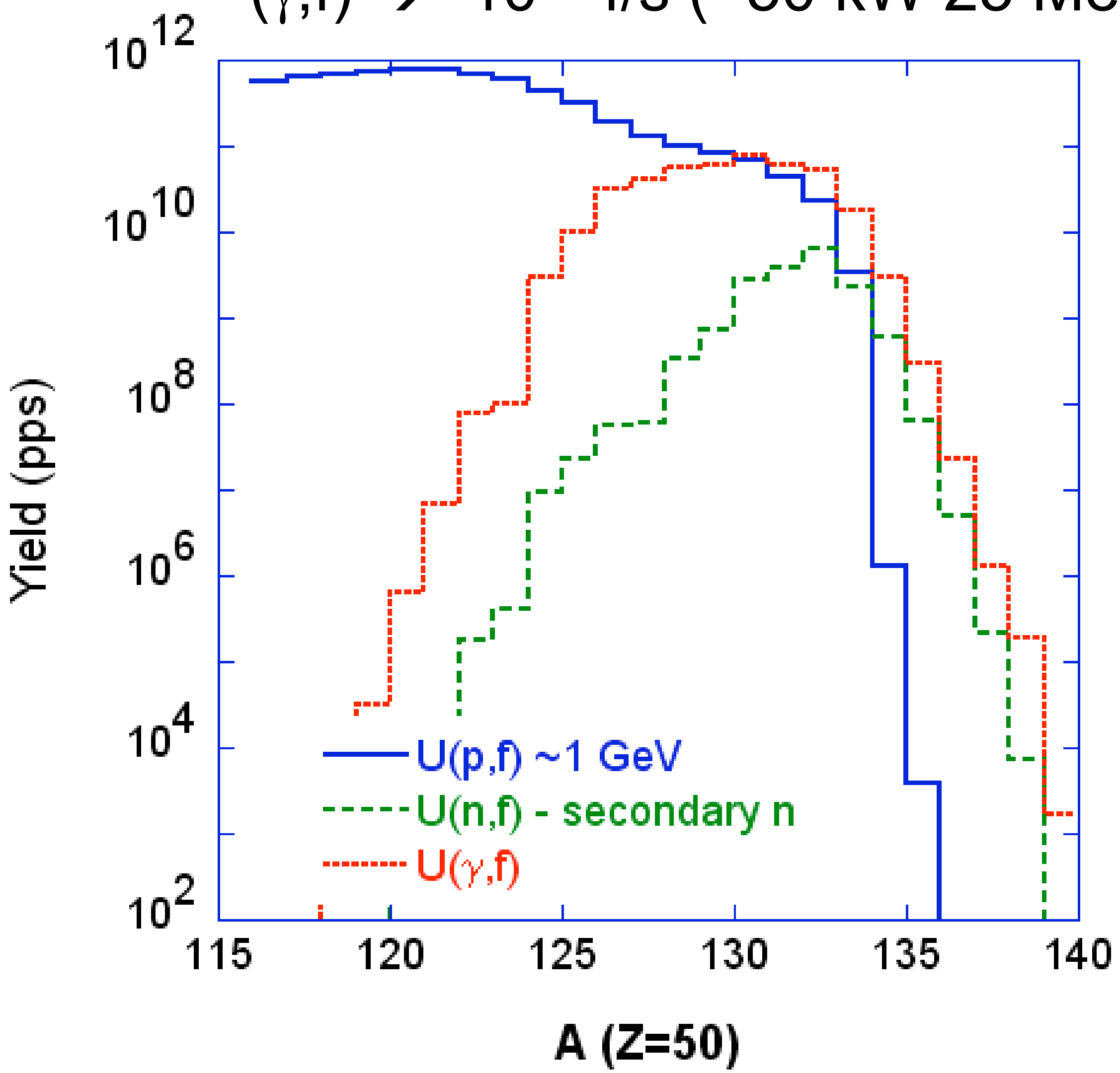

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Photo-fission yield

In target

HRIBF UC target production rates
(produced via photofission of U-238 at 10^{13} fissions/second)

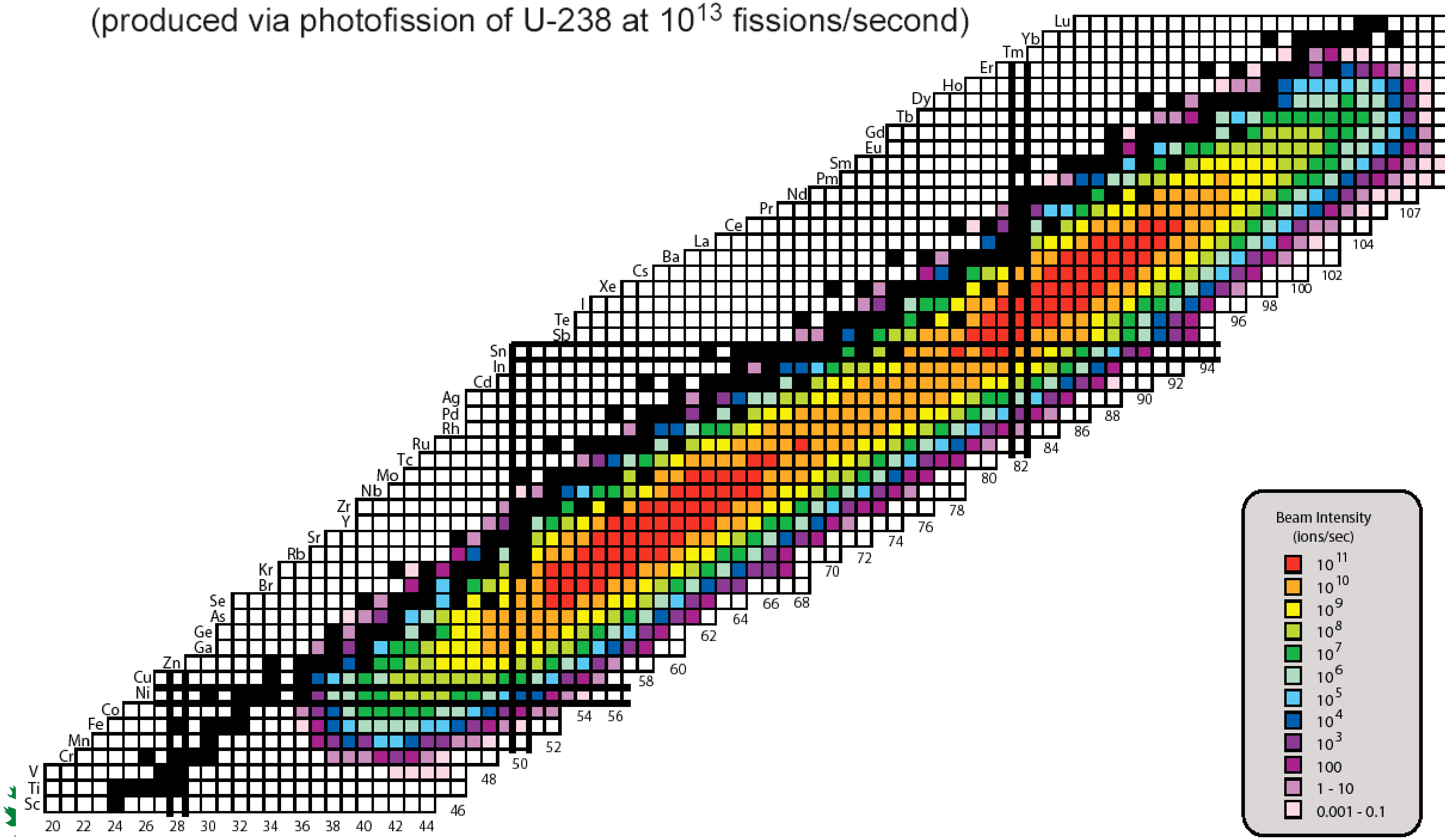


Photo-fission yield

From ion source

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

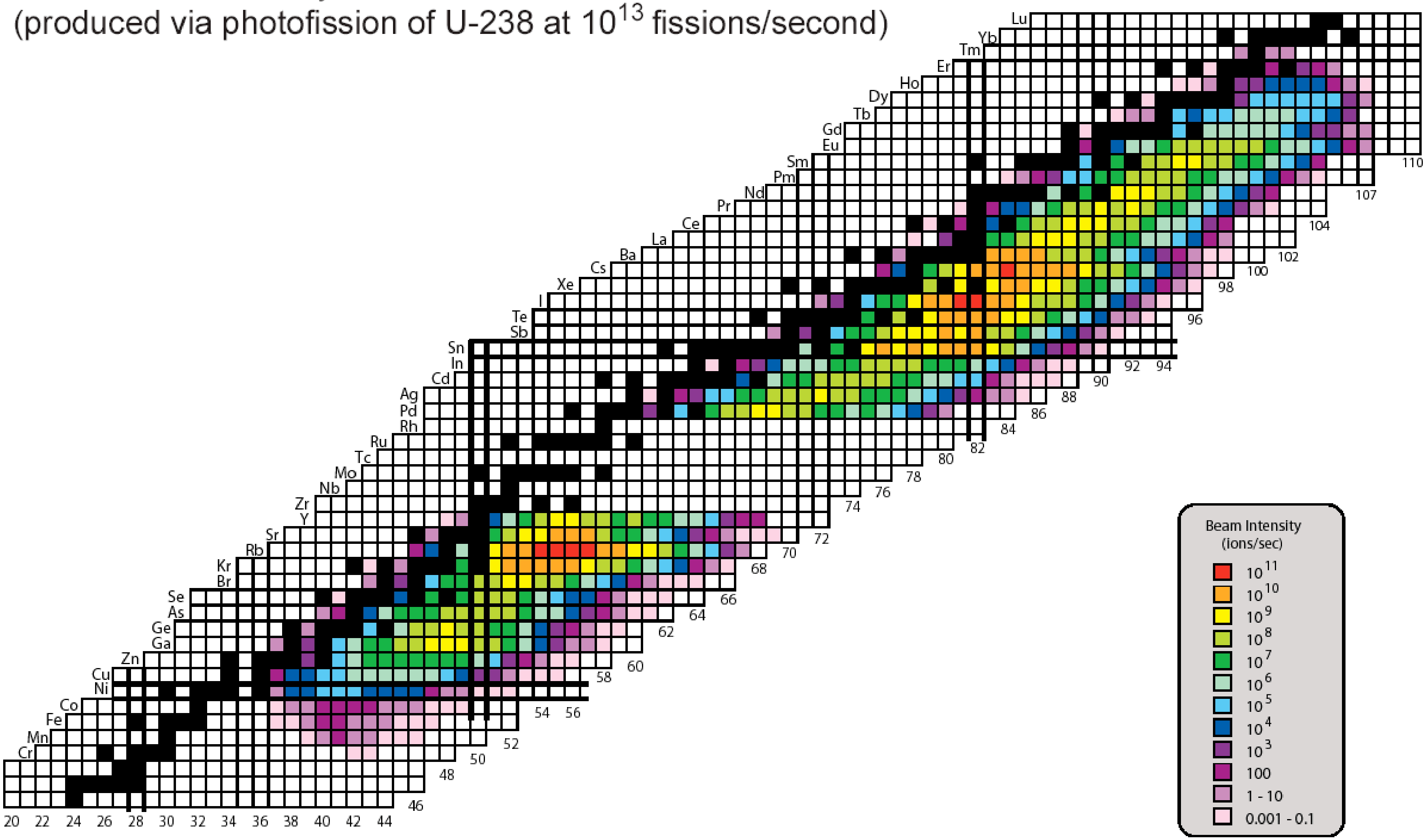
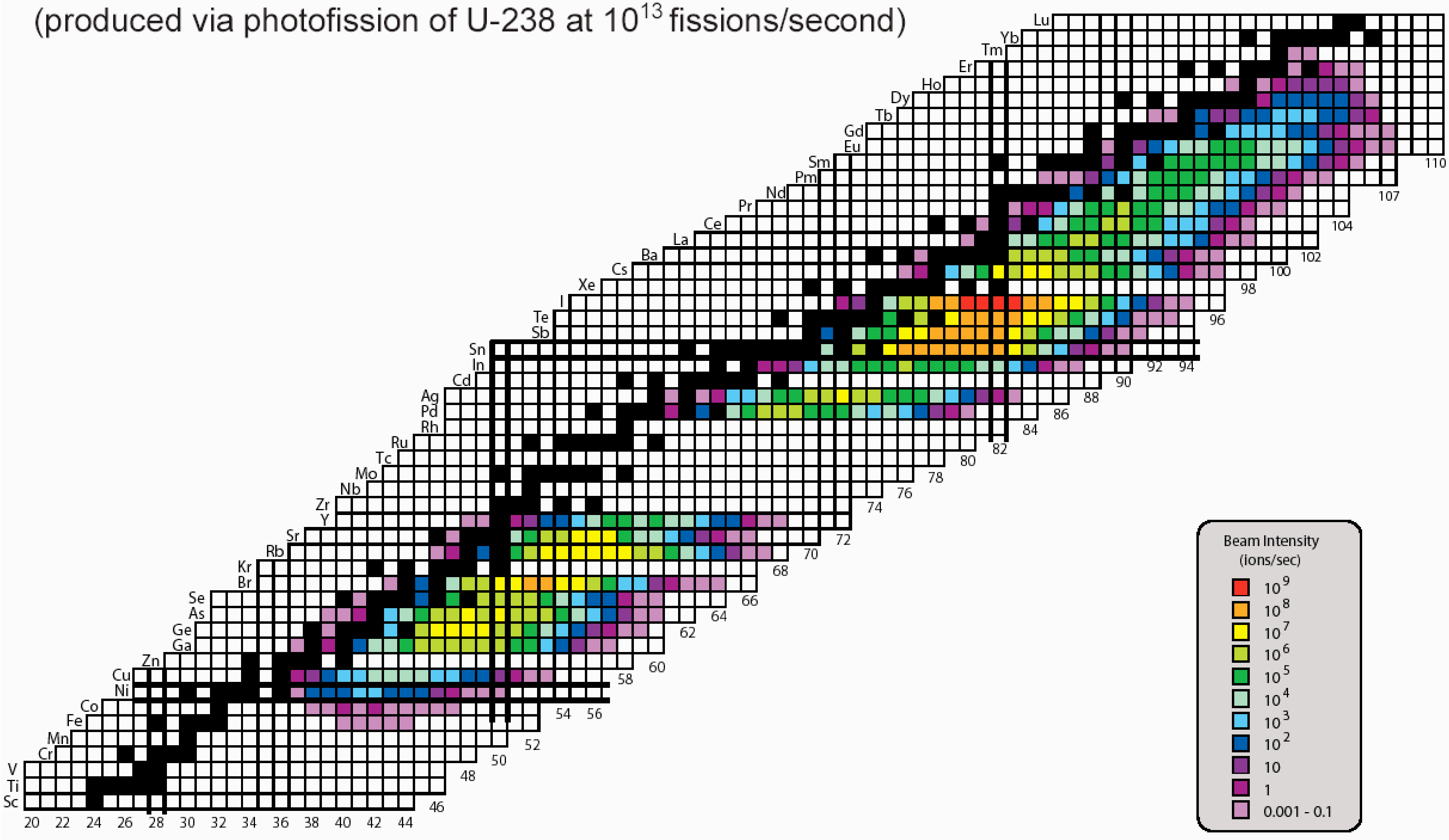


Photo-fission yield

Post-accelerated

HRIBF accelerated beam-on-target intensities
(produced via photofission of U-238 at 10^{13} fissions/second)



Broad program to study reactions with and structures of neutron-rich nuclei

- *Structure studies:* Isospin-dependent changes in
  - single-particle properties
  - collectivity
  - symmetries
  - pairing
- *Reaction studies:*
  - interplay between structure and reaction (SHE synthesis)
  - one- and multi-nucleon transfer
- *Domain:* Uncharted- or barely-explored regions
  - at or near doubly magic ^{78}Ni & ^{132}Sn
  - around magic numbers Z=28, 50 and N=50, 82
  - new transitional nuclei (N=50-60, 82-90)
  - unexplored deformed nuclei (N~90)
- *Tools:* Newly developed techniques and detectors

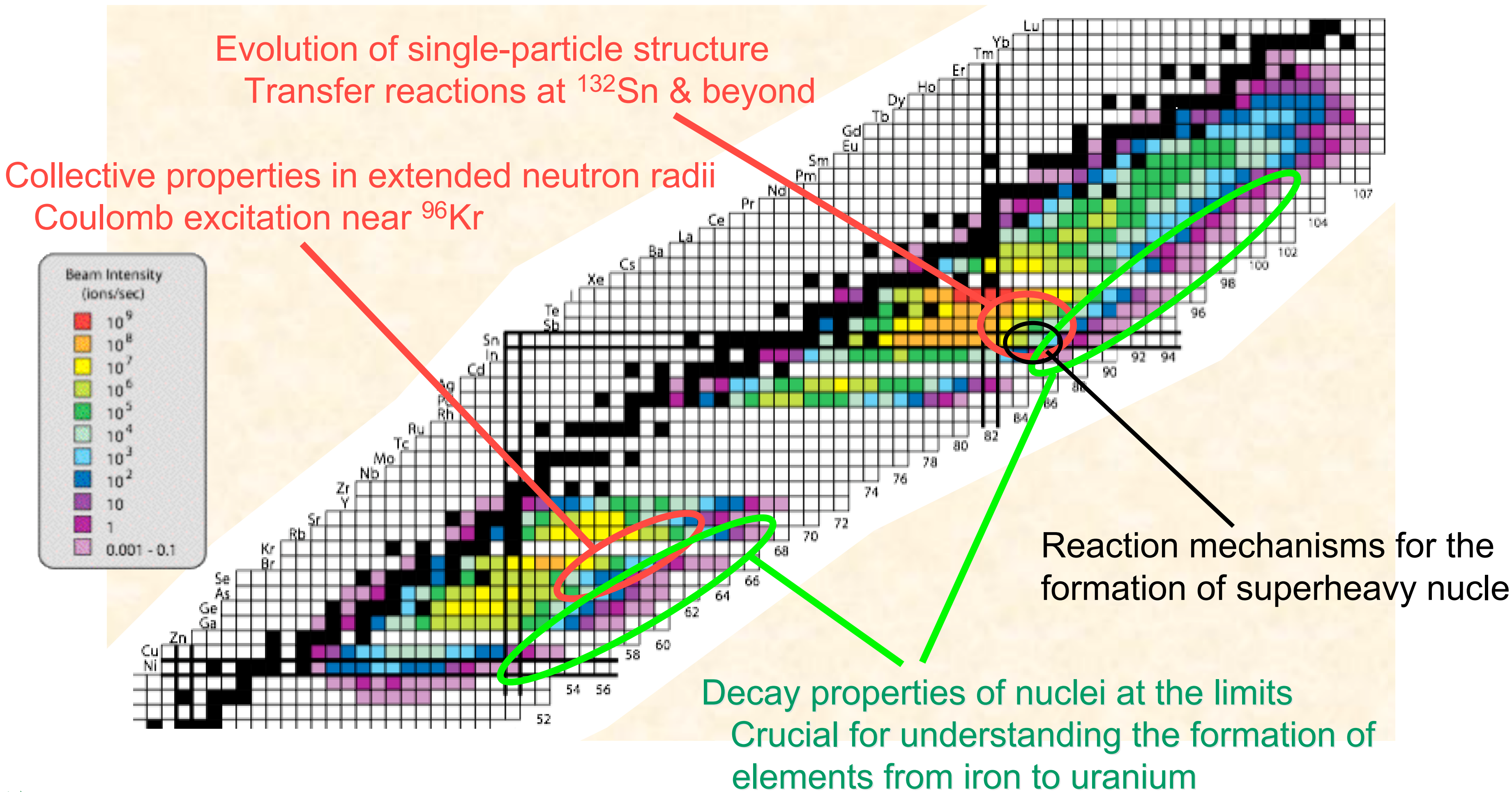
Measurements to probe shell structure far from stability

- **Gross properties:**
  - **Masses (binding energies)**
  - **Half lives**
  - **Radii**
  - **Level densities**
  - **$\sigma(n,\gamma)$ -- related to r-process abundances, [use (*d,p*)]**
- **Single-particle properties:**
  - **Energy, spin, parity, spectroscopic factors, g-factors**
  - **Parallel momenta in knock out reactions (fast beams)**
- **Collective properties:**
  - **Low-lying energy spectra (*e.g.,* 2^+ states, 4^+)**
  - **B(E2) & electromagnetic moments**
  - **Higher spin states (band structures)**

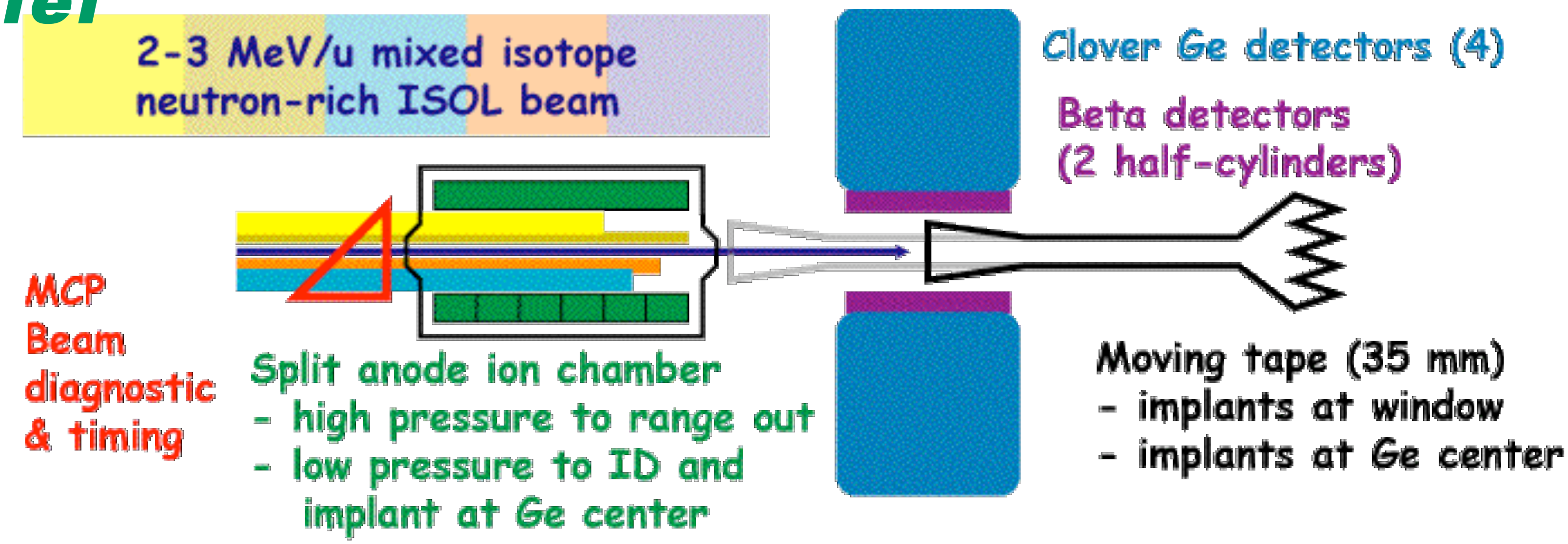
We will have an unparalleled opportunity to use transfer, decay and in-beam spectroscopic tools to employ these probes in uncharted regions of n-rich nuclei.

Science highlights with eMachine

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

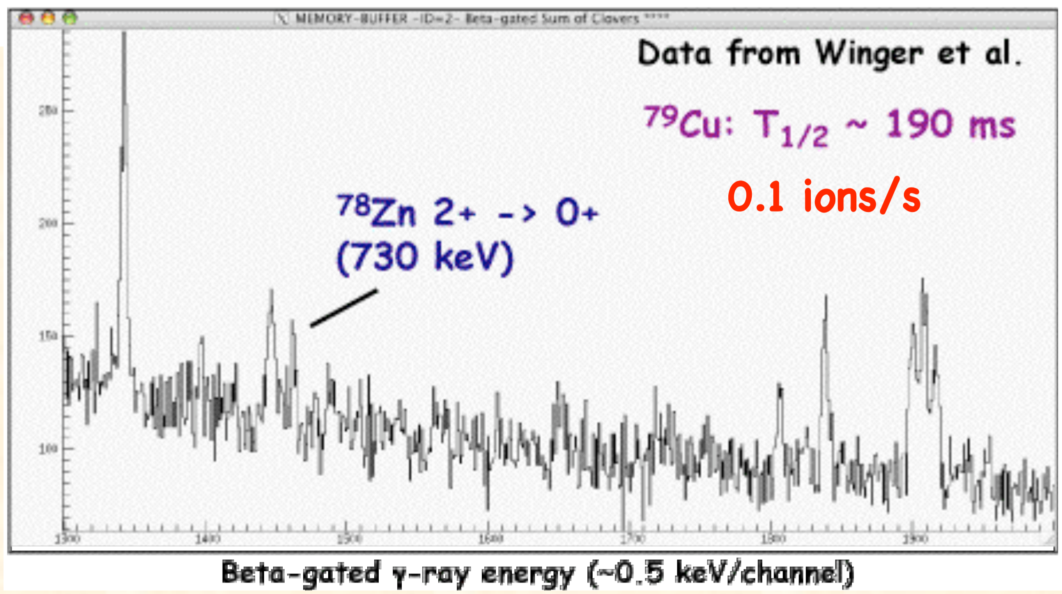


Decay studies pushing the frontier of n-rich nuclei



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

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, $\nu s_{1/2}$ in N=51 ^{83}Ge
^{84}Ga	0.085	2^+ in N=52 ^{84}Ge, $\nu s_{1/2}$ in ^{83}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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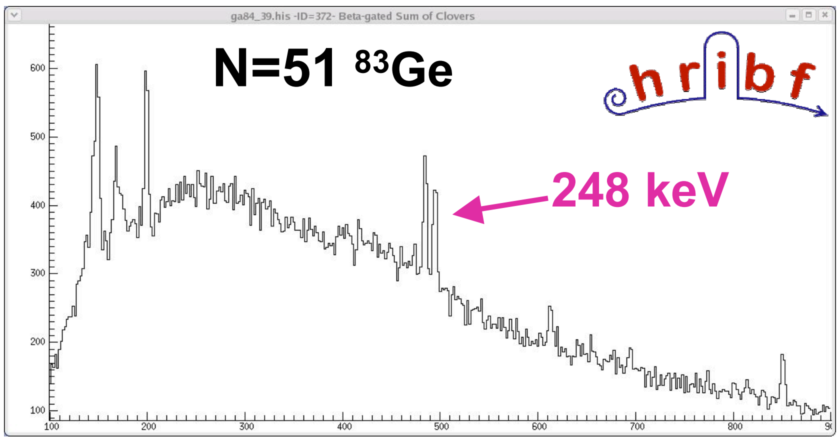
The evolution of single-particle levels and shapes in very neutron-rich nuclei beyond the N=50 shell closure

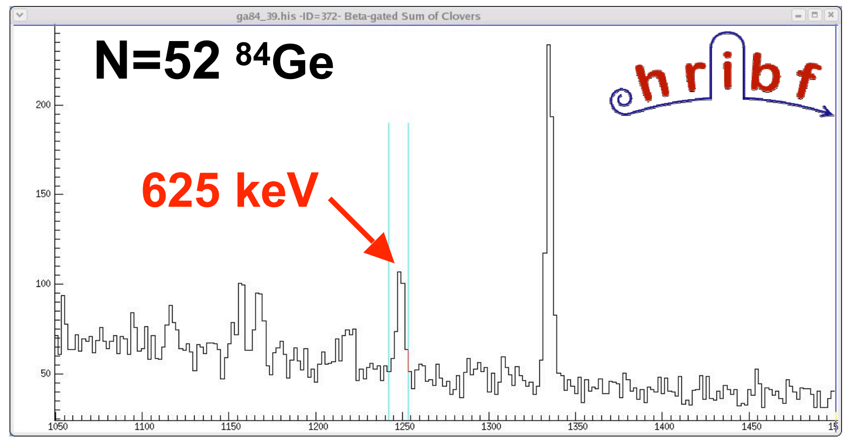
Nov'06 : experiment with 2 pps of 3 MeV/u ^{84}Ga

$^{84}Ga \xrightarrow{\beta} {}^{84}Ge^{*} \xrightarrow{n} {}^{83}Ge^{*}\ (\nu s_{1/2}) \xrightarrow{\gamma} {}^{83}Ge(\nu d_{5/2})$

$^{84}Ga \xrightarrow{\beta} {}^{84}Ge^{*}\ (2+) \xrightarrow{\gamma} {}^{84}Ge\ (0+)$



β-gated γ-spectrum (0.5 keV/ch)

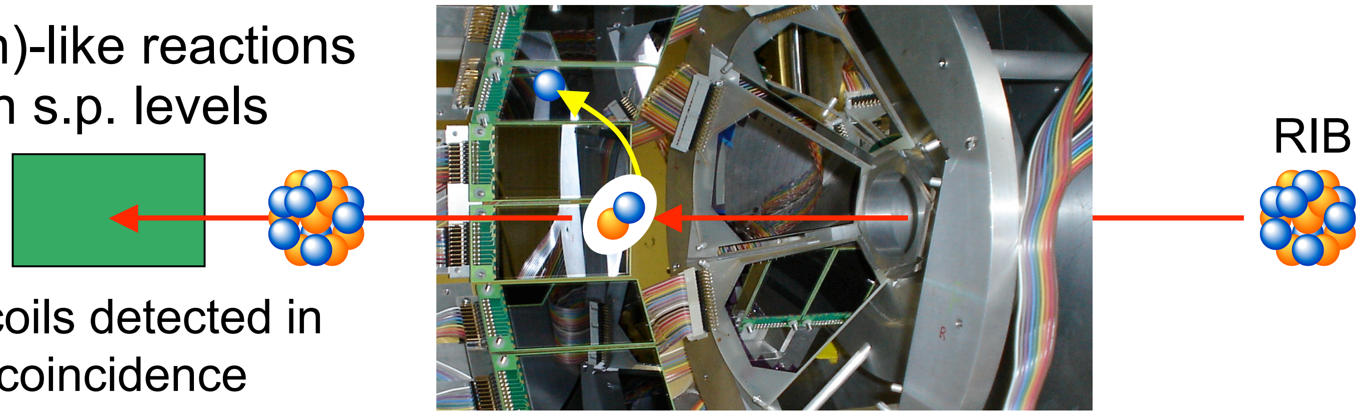


β-gated γ-spectrum (0.5 keV/ch)

Transfer reactions: shell structure of n-rich nuclei

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

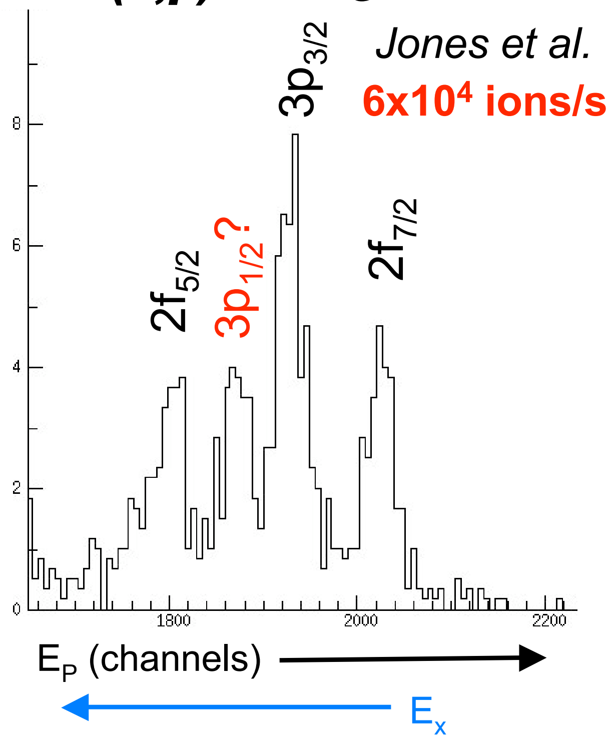
Example: (d,n)-like reactions
→ neutron s.p. levels



Recoils detected in coincidence

protons detected in Si-array

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



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

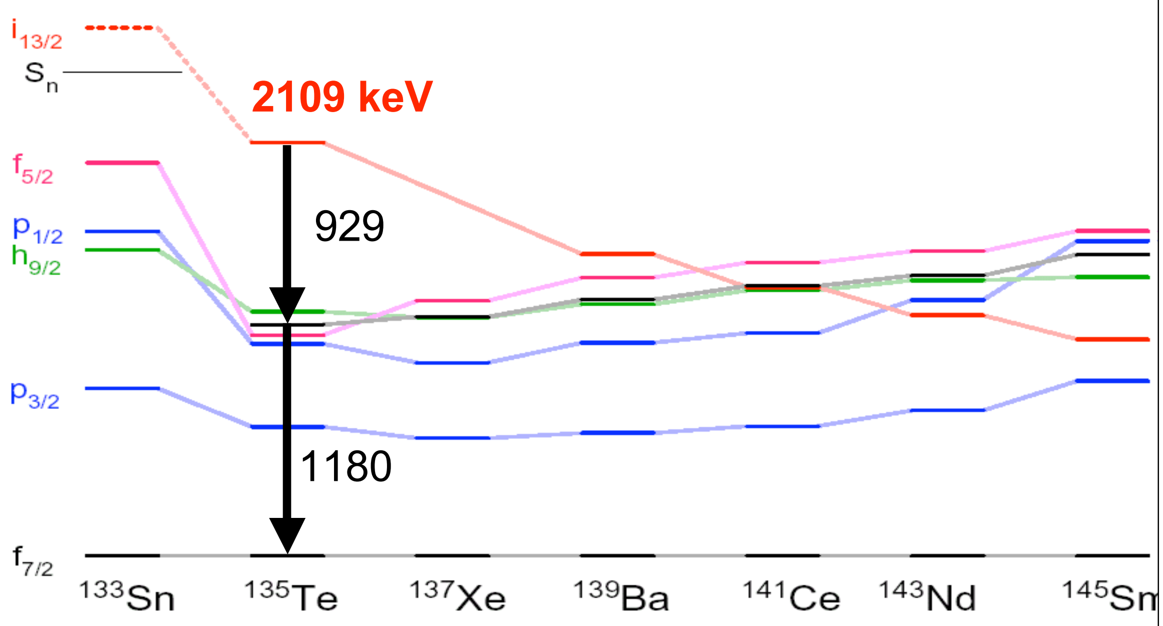
Reactions of interest

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

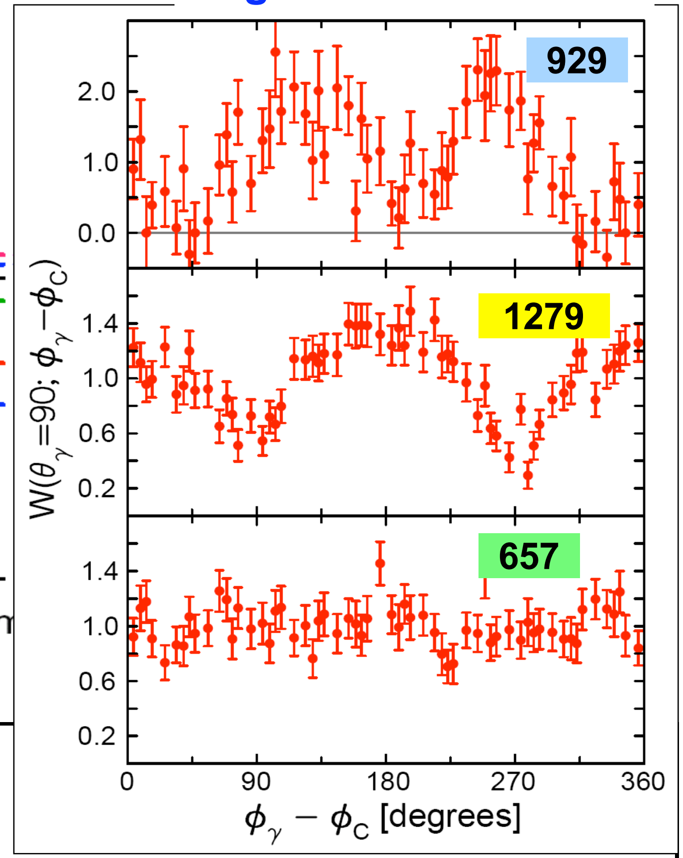
with the eMachine

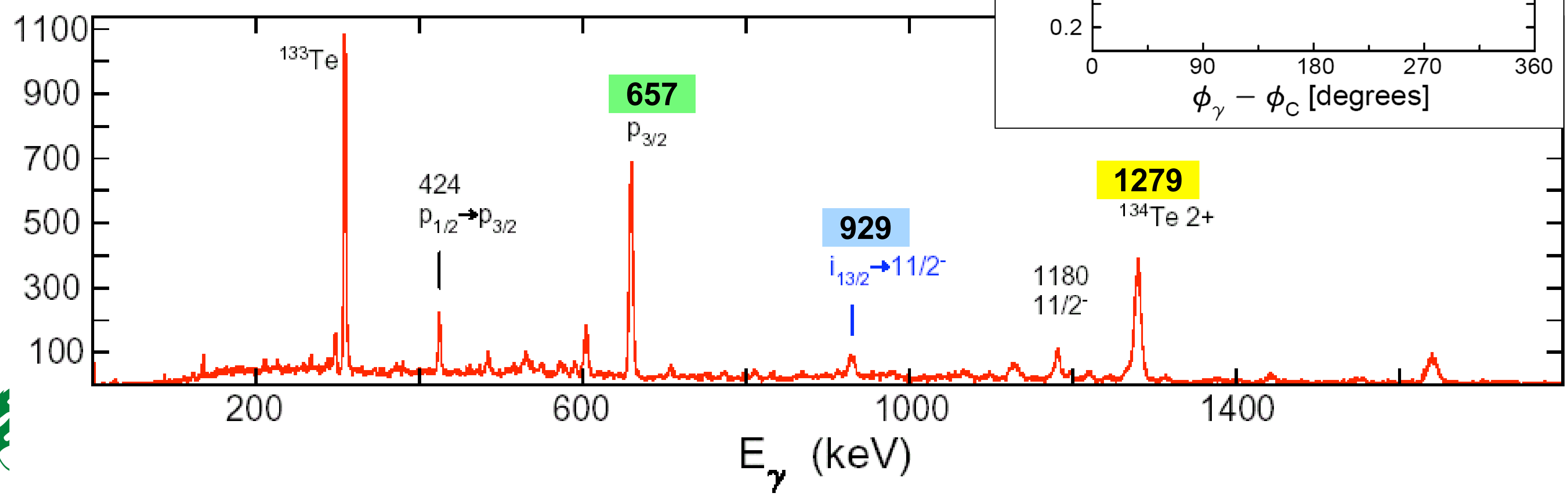
Ion	Intensity (ions/s)	$t_{1/2}$ (s)
^{84}Ge	3x10^5	0.9
^{88}Se	3x10^4	1.5
^{96}Sr ^{98}Sr	7x10^4 1x10^4	1.1 0.65
^{134}Sn	3x10^6	1.0
^{138}Te ^{140}Te	5x10^6 2x10^4	1.4 ?

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

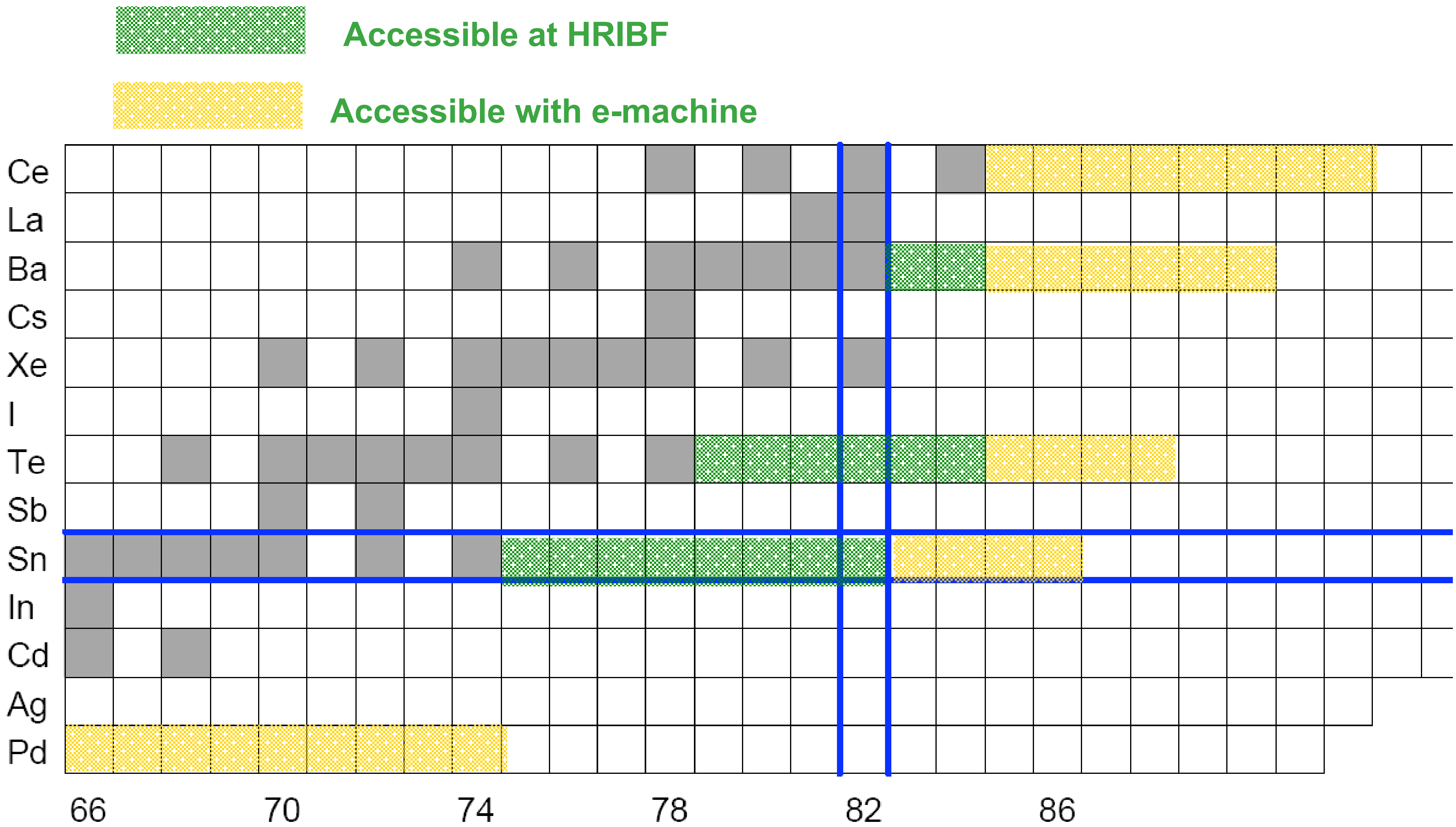


Particle-gamma angular correlations





Neutron transfer reactions



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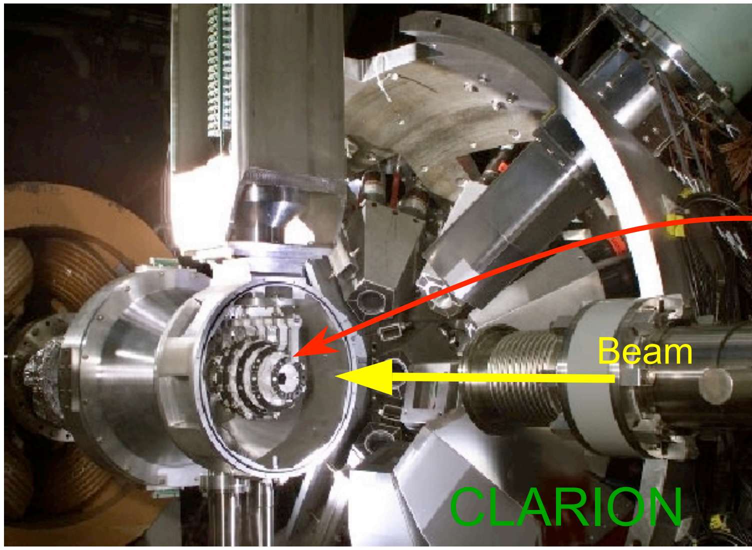
Coulomb excitation in n-rich systems

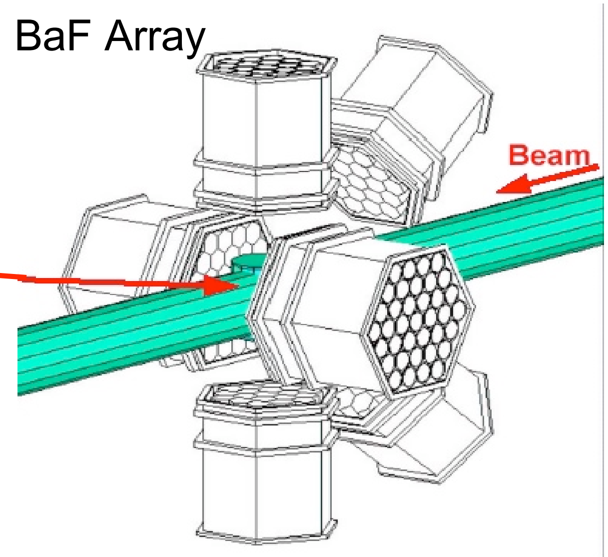
Probes the evolution of collective motion in loosely-bound, neutron-rich nuclei

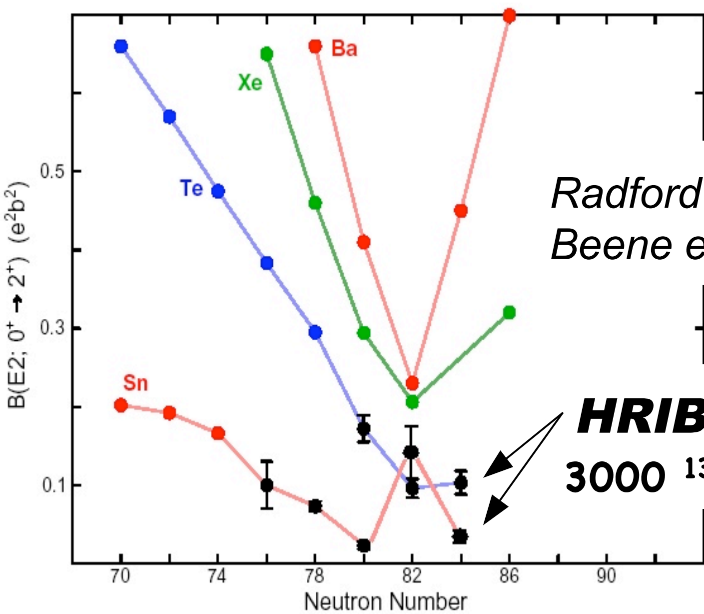


n-rich beams

C, Ti, Zr
target

Charged-particle
⊗
Gamma array





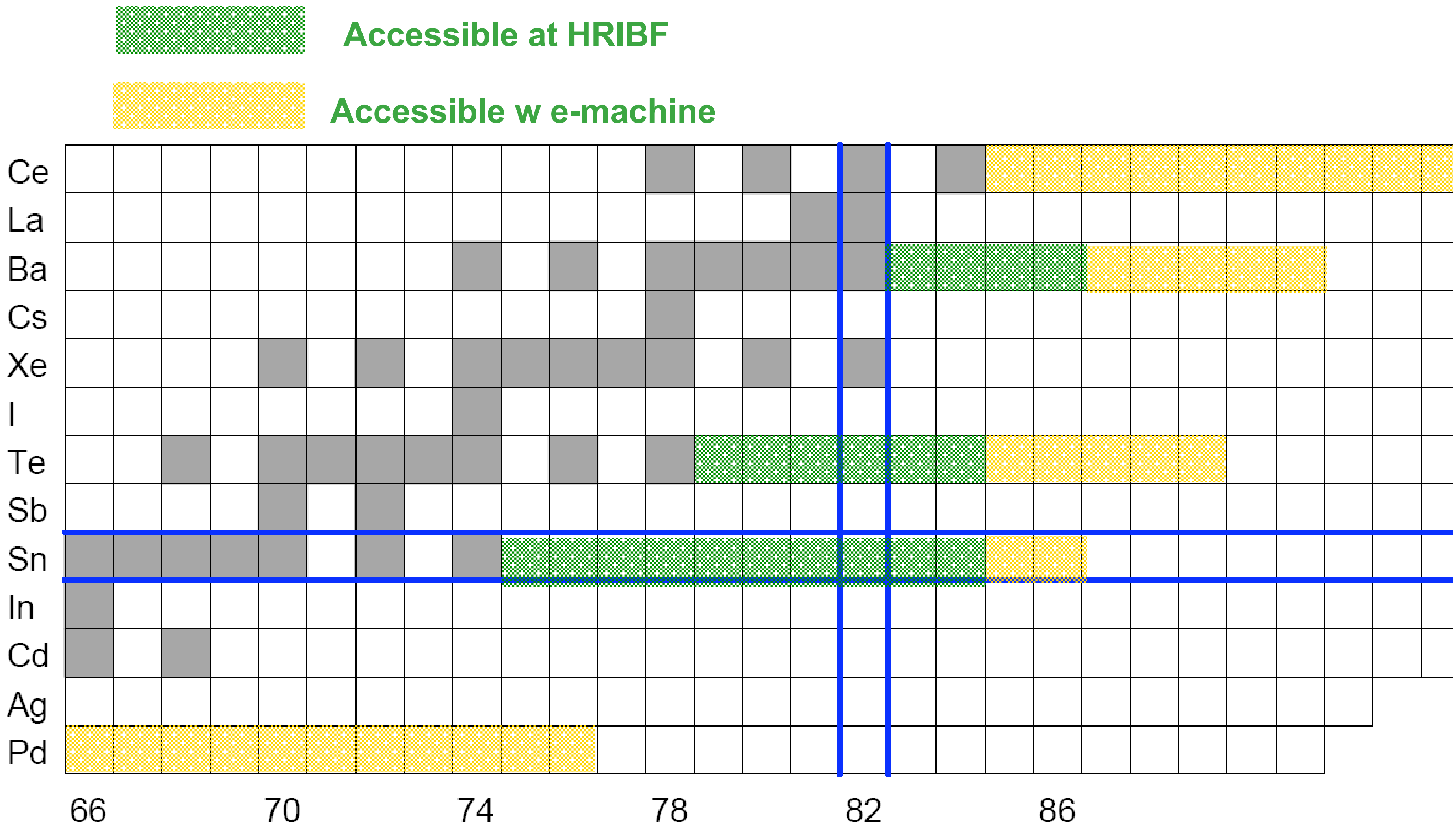
Radford et al.
Beene et al.

HRIBF
3000 ^{134}Sn/s

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	3x10^5	0.9
^{88}Se	3x10^4	1.5
^{98}Sr	1x10^4	0.65
^{136}Sn	700	0.25
^{138}Te ^{140}Te	5x10^6 2x10^4	1.4 ?

Coulex (1-step)



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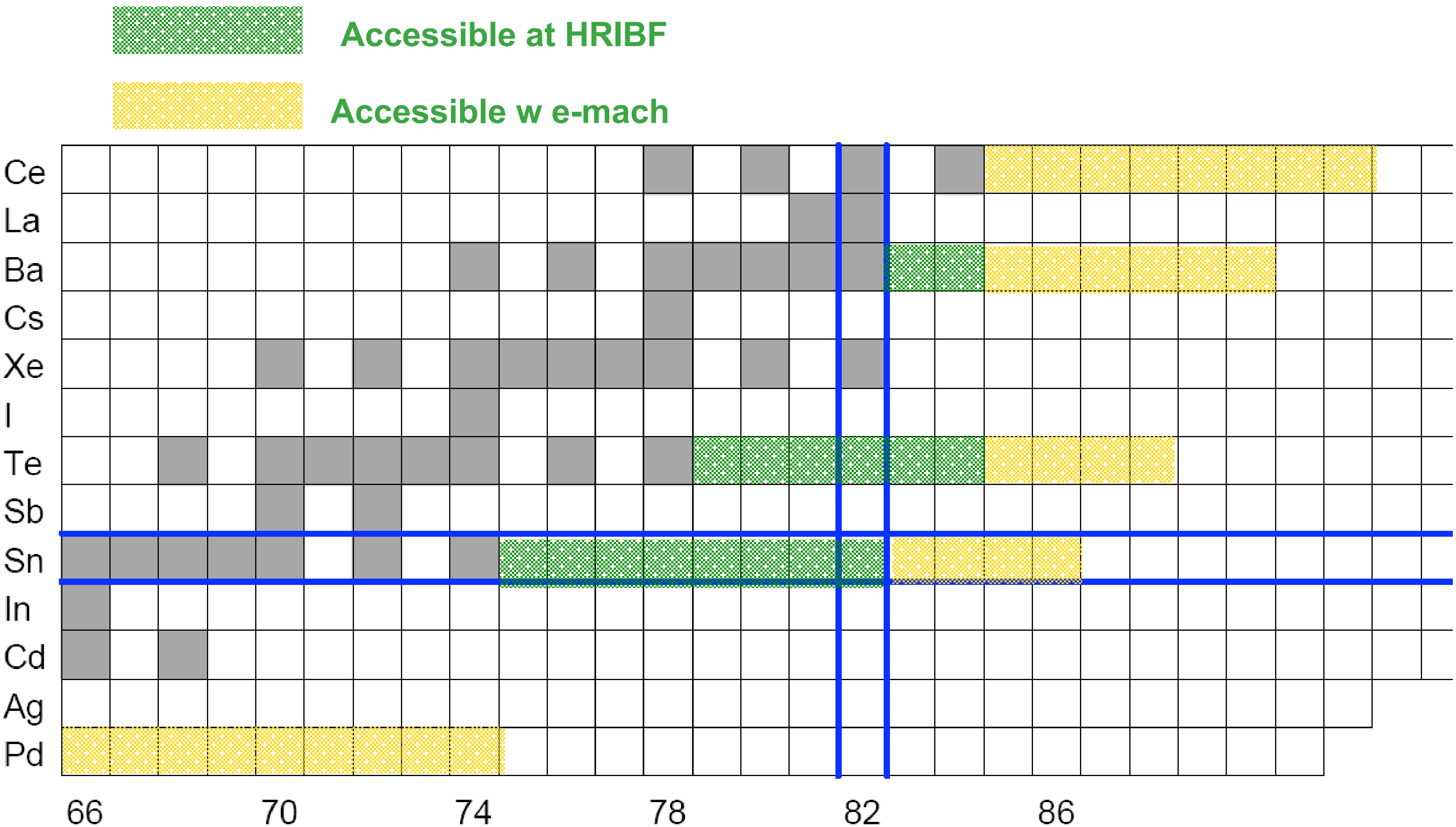
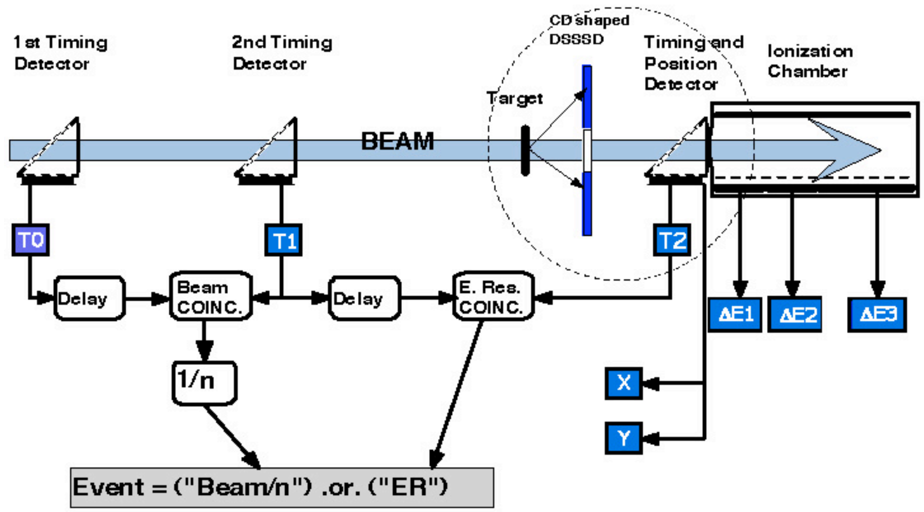
Multi-step Coulex

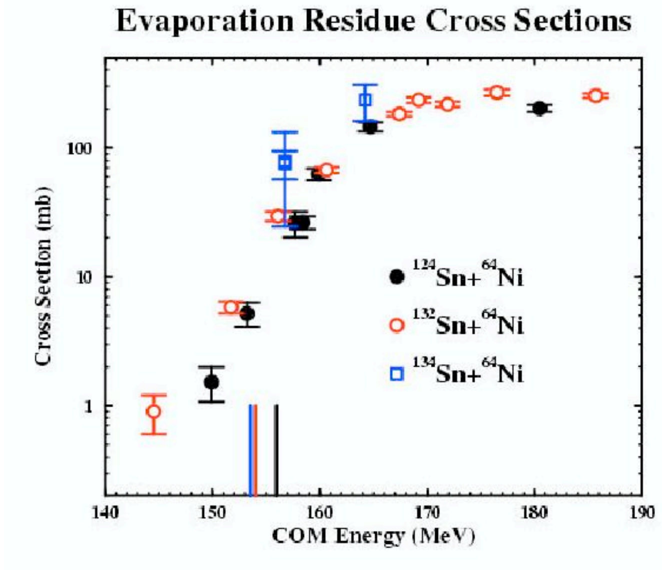


Heavy ion fusion reactions

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



HRIBF Results



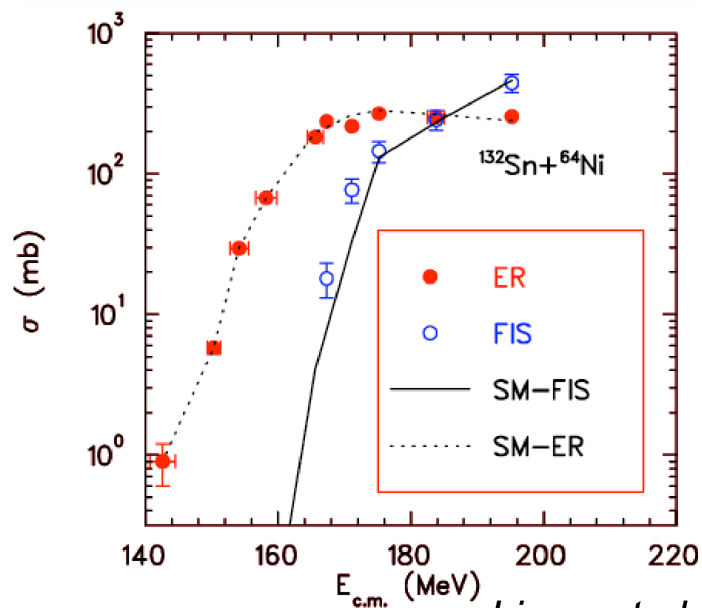
with eMachine

Ion	Intensity (ions/s)	$t_{1/2}$ (s)
^{92}Br	2x10^5	0.34
^{134}Sn ^{136}Sn	3x10^6 600	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

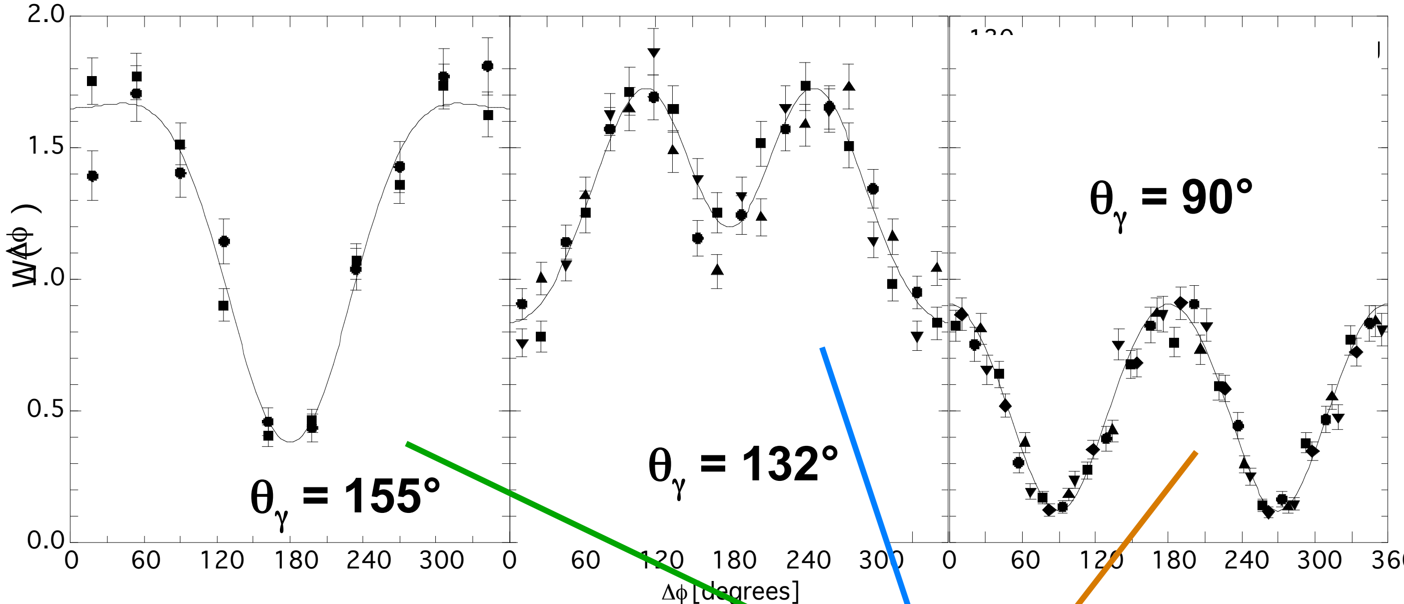


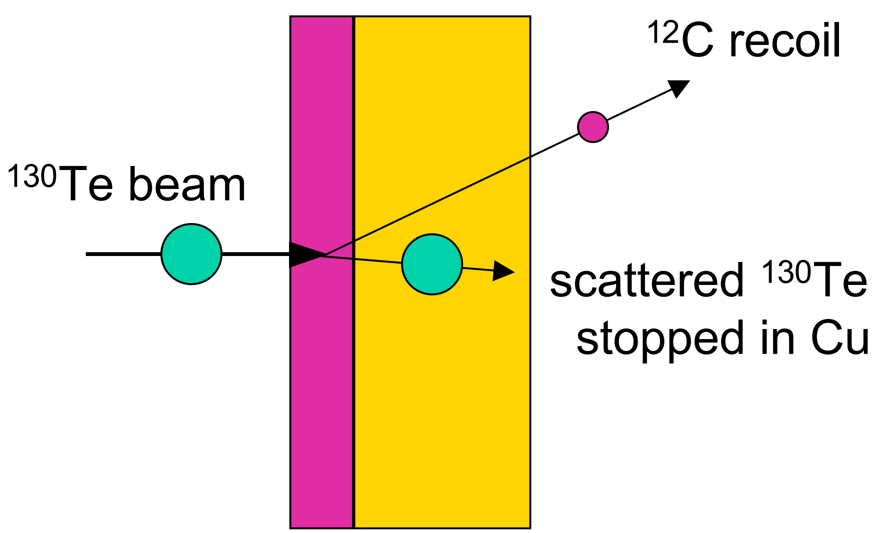
Liang et al.

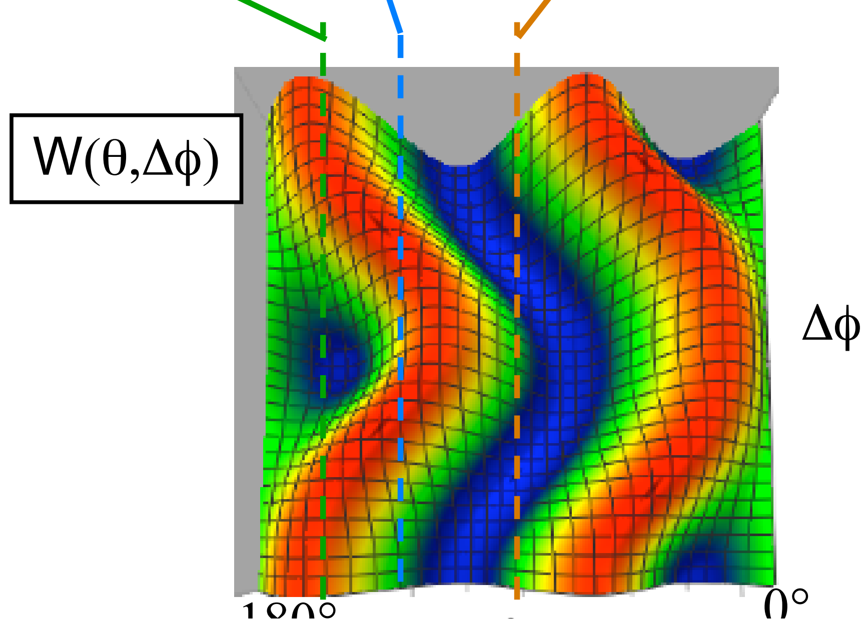
Unattenuated angular correlations: Theory & experiment

^{130}Te SIB

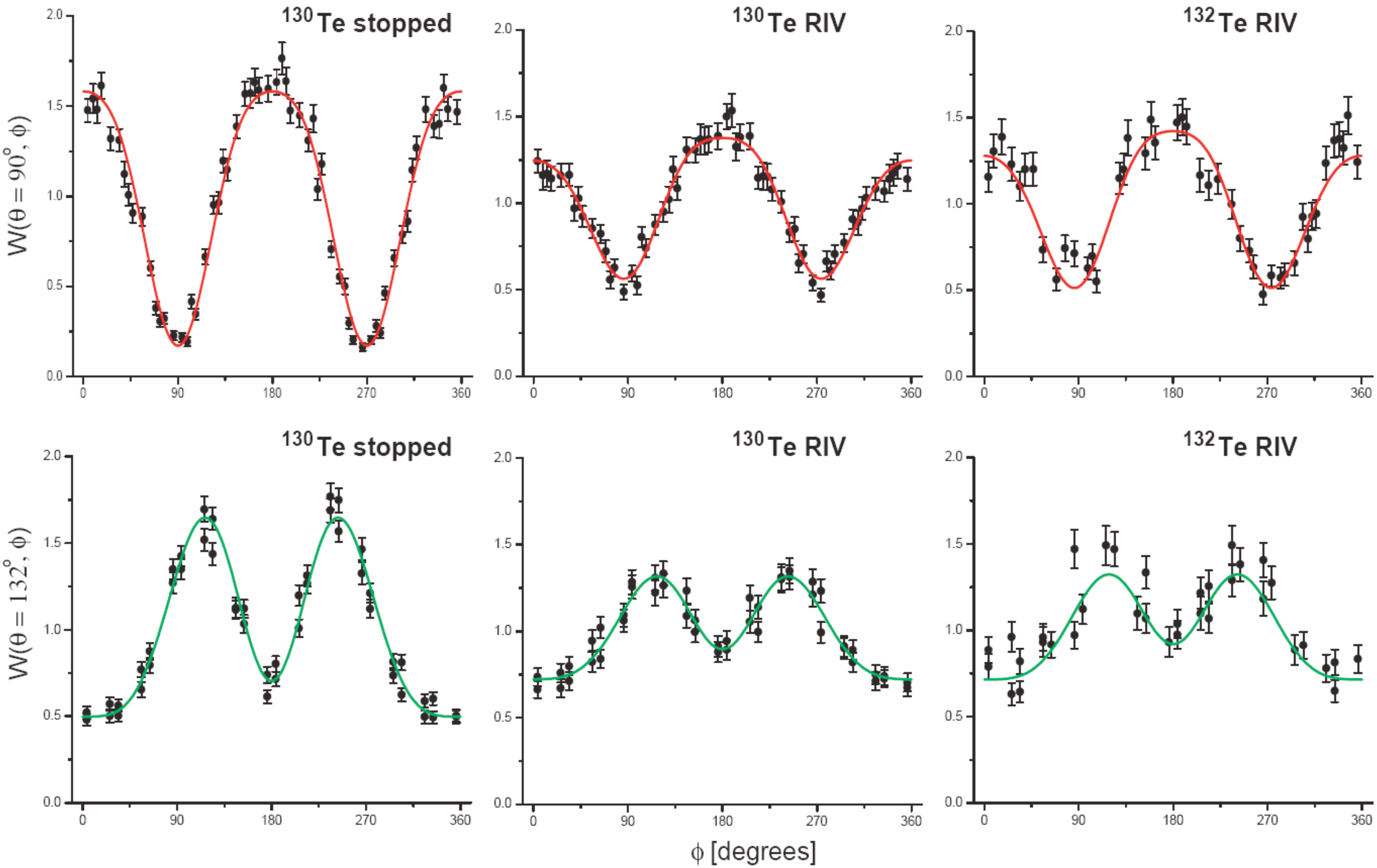
Hyball Ring 2



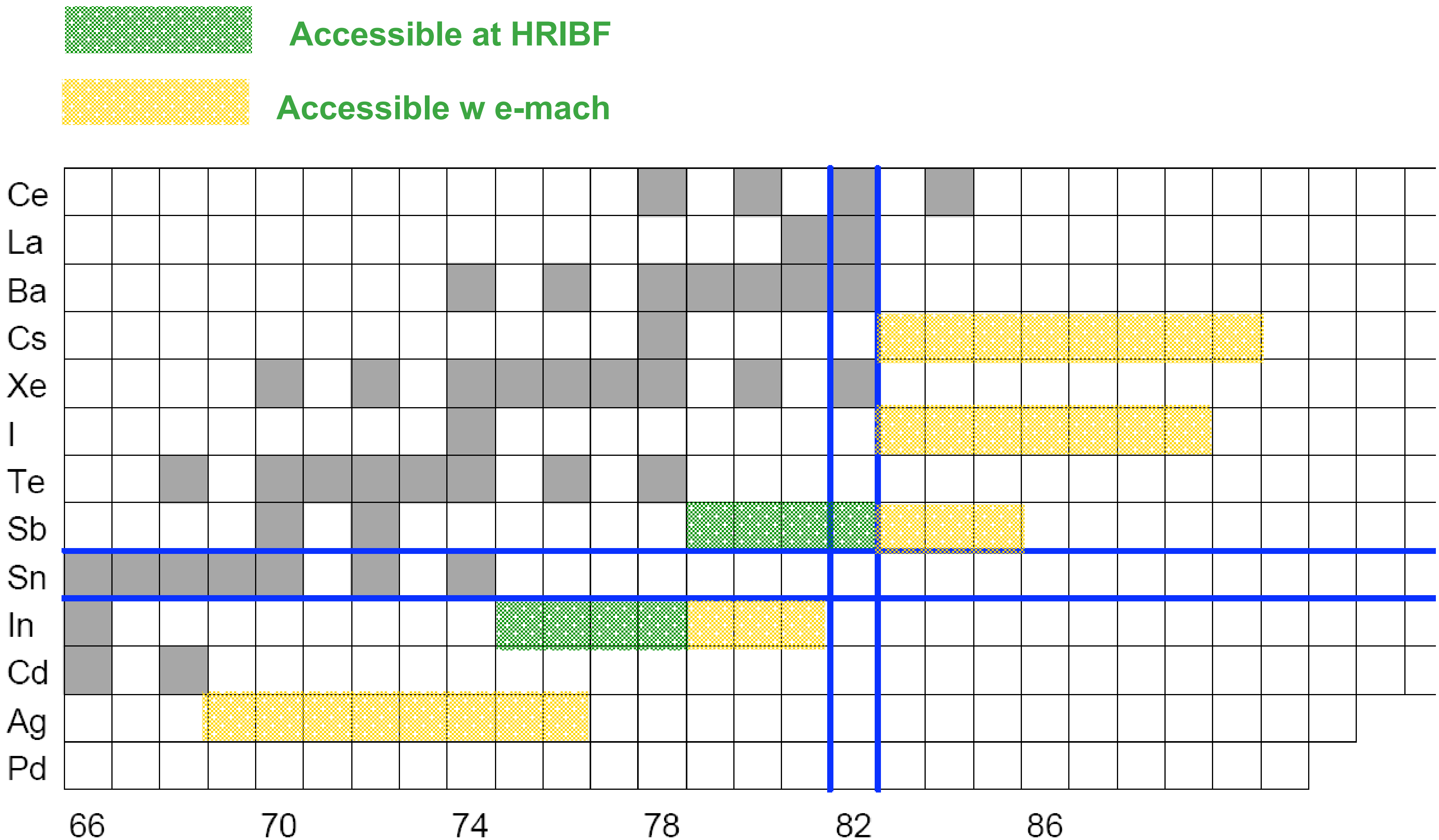




Magnetic moment: RIV attenuated angular correlations



g-factor measurements



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RISAC Science Drivers

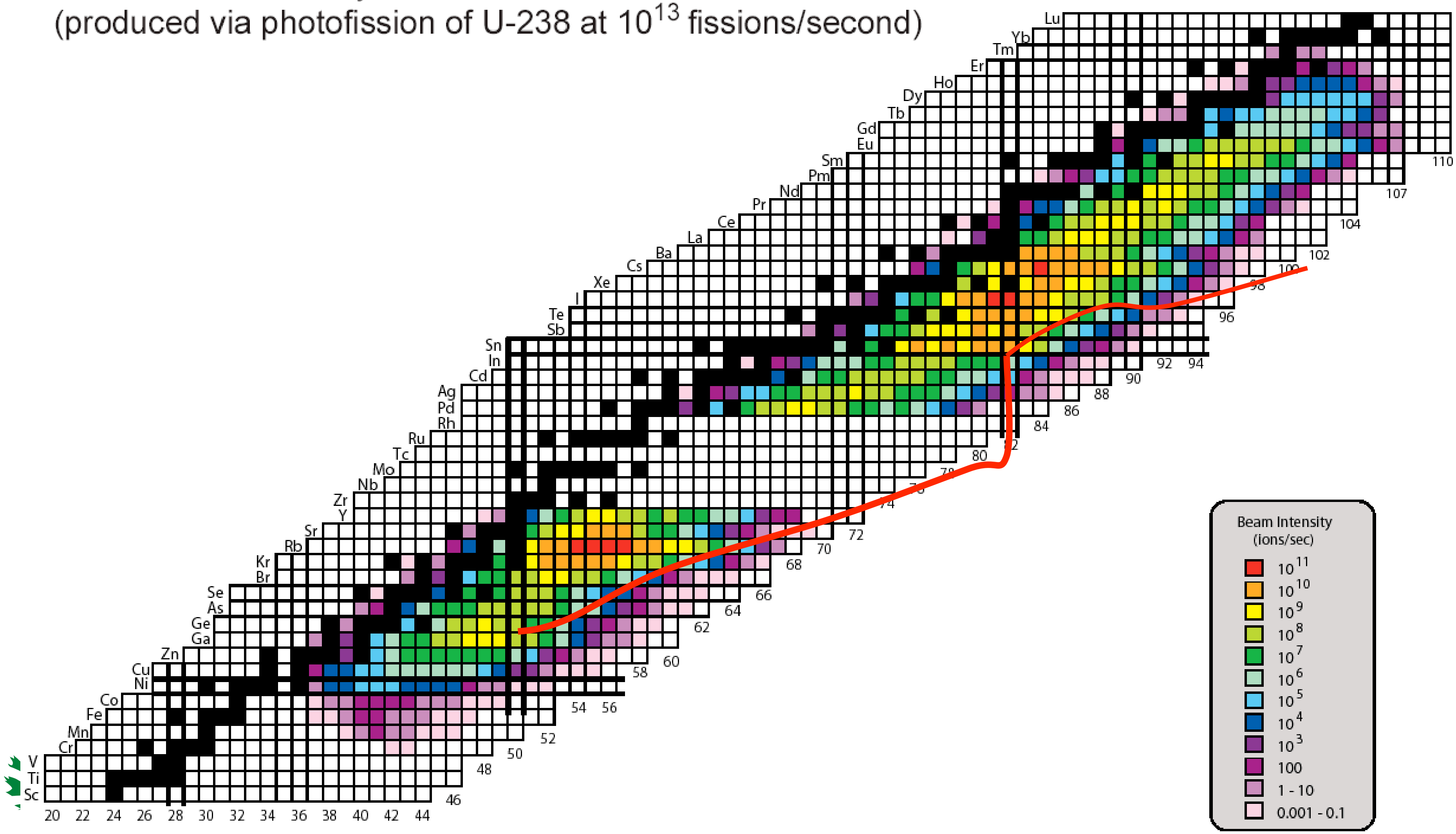
& the electron driver

- **Nuclear Structure**
  - Probing the disappearance of shells
    - Spectroscopy & reactions in ^{132}Sn, ^{78}Ni regions
  - Evolution of collective motion
    - We can probe ^{112}Zr and ^{96}Kr regions (not ^{156}Ba)
  - Neutron Skins
    - Structure/reaction studies of the most n-rich
  - SHE
    - Reactions with ^{132}Sn (~10^9) and vicinity
    - For Z=112, N=184, reaction mech. Studies with $^{92,94}Sr$ (10^6, 10^7)
- **Nuclear Astrophysics**
  - Decay spectroscopy (βn, τ)
- **Stockpile Stewardship**
  - Surrogate reaction s (n transfer, etc.)

Photo-fission yield

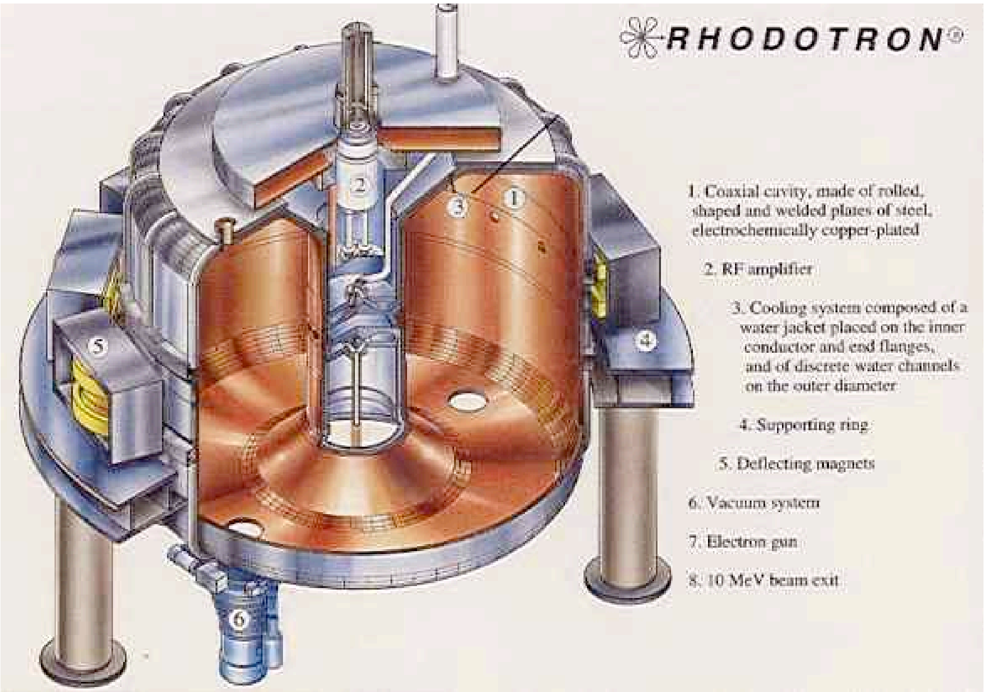
From ion source

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



A Photo-fission Facility
-Driver

- **Requirements**
  - **~25 MeV or higher, CW, turnkey**
  - **100 kW or more at 25 MeV**
  - **80 kW or more at 50 MeV**
- **Turnkey options**
  - **25 MeV rhodotron**
  - **50 MeV SC linac**
- **Costs are similar**



OAK RIDGE National Laboratory

Conclusion

- An electron-beam based facility can produce intense beams in a cost-effective way
- Such a facility would be competitive world-wide for neutron-rich beams until FRIB is available
- Cost containment is important
- There is a relatively short window during which such a facility is relevant.