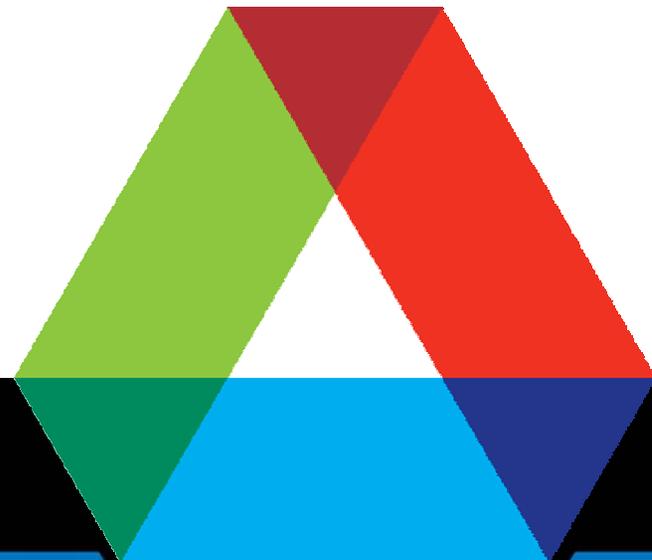


# *Concepts for a Major Advance in Reaccelerated Rare Isotope Capabilities*

*Donald Geesaman  
Argonne National Laboratory*

*ATLAS User Meeting*

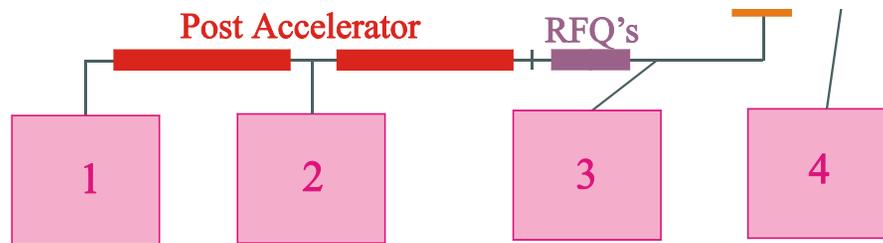
*April 8, 2006*



## RIA history

- 1996 NSAC Long Range Plan recommendation for in-flight facility (NSCL CCF) and a reaccelerated beam facility when RHIC construction substantially complete.
- ~1998 NSCL CCF and RIKEN RIBF in-flight facilities started.
- 1999 NSAC ISOL Task Force:
  - *RIA concept- The scientific potential of the RIA facility will be maximized by integrating multiple techniques for producing and separating then accelerating and utilizing these isotopes.*
  - *The RIA design should accommodate fast in-flight separated beams.*
- 2002 NSAC Long Range Plan:
  - The community wants RIA.
- 2001 GSI FAIR conceived. Government go-ahead in 2003.
- Extensive RIA R&D have resolved the technical issues.
- Argonne, with the entire community, wants RIA to be built.

# Each of the four beam energy ranges is required for important physics



Experimental Areas:

1: < 12 MeV/u 2: < 1.5 MeV/u 3: Nonaccelerated 4: In-flight fragments

## < 12-15 MeV/u

Framework of single-particle states and closed shells

Interplay of deformation and single particle effects

Physics at the proton drip line

Heavy elements

Fission barriers

Indirect measurements of astrophysical processes

## APPLICATIONS

## < 1.5 MeV/u

Direct measurements of reactions in hot stars. rp-process and breakout of hot CNO cycle

## Non-accelerated

Fundamental symmetries. PV, EDM, Beta-decay studies of physics beyond the standard model

Masses - r-process, rp-process, symmetries

Nuclear moments by hyperfine interactions

Beta decay studies of rare nuclei

## APPLICATIONS

## In-Flight

Limits of stability at drip lines

Decay studies at the limits of stability

Matrix elements connecting to ground state. E&M and breakup

Halos and skins

Indirect measurements of astrophysical processes

Nuclear equation of state

### From Dennis Kovar's talk to the NRC RISAC, 12 March 06

#### **Implement a plan to remain among the leaders in nuclear structure/astrophysics**

- Operate the facilities and support the research community to extract the science
- Invest at domestic and foreign facilities to allow U.S. researchers to do forefront science  
(ATLAS and HRIBF accelerator/detector upgrades)  
(Experimental equipment at facilities with forefront exotic beam capabilities)
- Support R&D to start construction of a U.S. exotic beam facility at end of this 5-year period.

### From Ray Orbach's presentation to NSAC, 2 March 06

“PED money in 2011 for a reaccelerated beam facility.”

“This should be a moment of cheering.”

“An exotic beam facility is in our plan.”



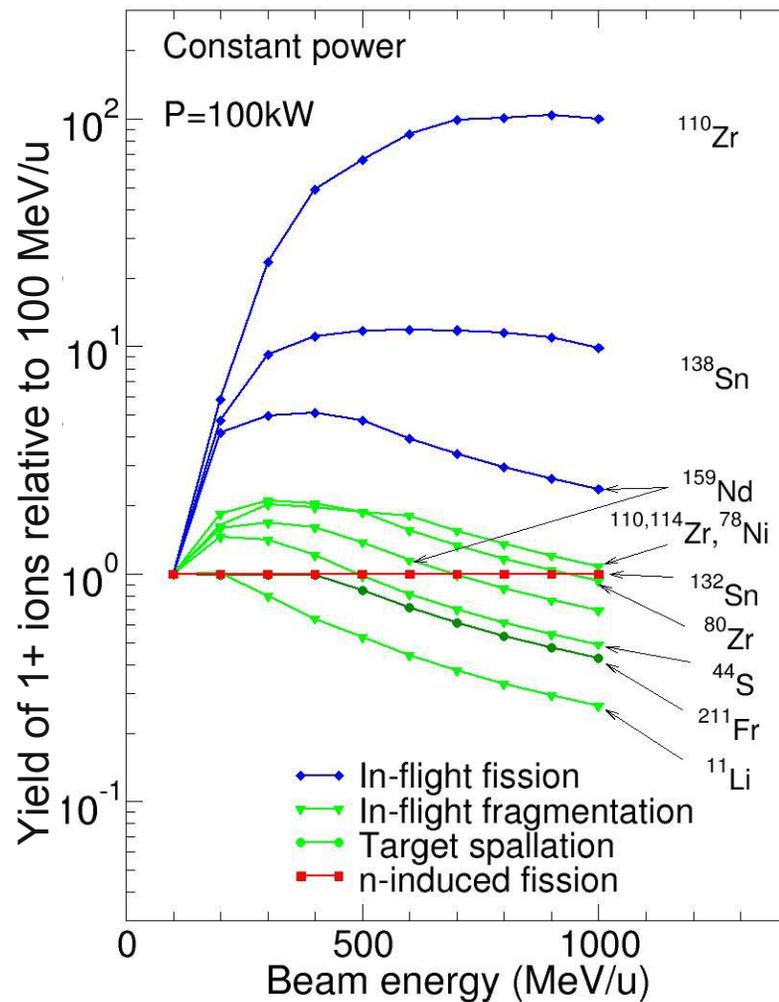
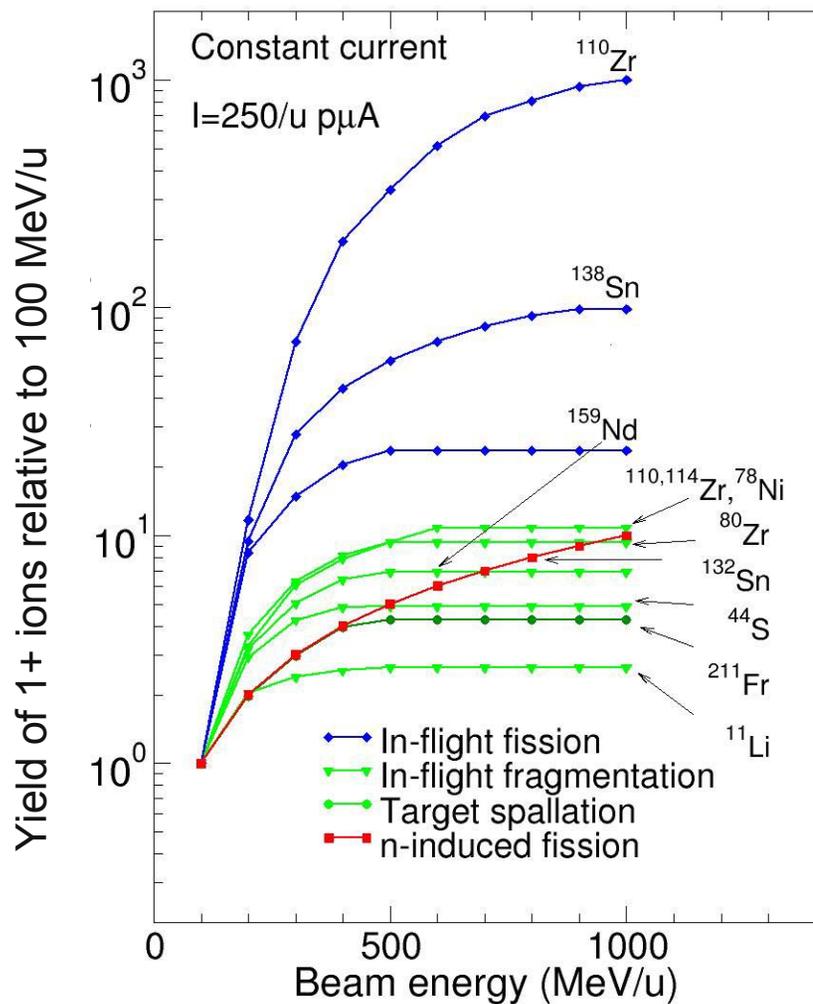
## *The community needs to define what this new facility should be?*

- I am presenting some of our ideas
- We were asked to provide this information for RISAC
- This needs to be an important step in preparing for the 2007 NSAC Long Range Plan
- Is this what the community wants?
- We need a new name for this facility
  - I will simply use Advanced Exotic Beam Laboratory, **AEBL**, for the rest of this presentation

## *If you need to reduce the scale of RIA*

- For reaccelerated beams, the issue is production rate, impacted by:
  - cross section vs energy,
  - separator acceptance vs energy,
  - charge state purity vs energy,
  - for many isotopes, beam power is more important than energy.
- No other facility proposes **reaccelerated** beams produced by fragmentation and in-flight fission of heavy ions followed by **gas stopping**.
- There are only limited plans at other facilities for any reaccelerated beams above 9 MeV/u (until EURISOL).
- For in-flight experiments, changing the primary beam energy leads to some physics issues – beam purity gets worse for heavy nuclei that are not fully stripped ( $Z > 50$ ); optimum energy too low for some types of experiments.
- RIKEN (2008, 350 MeV/u) and GSI (2011, 2000 MeV/u ) will have fast in-flight beams. Complementarity is a very important consideration for DOE.

# Energy dependence of rare isotope production



## *Smaller scale concept - AEBL*

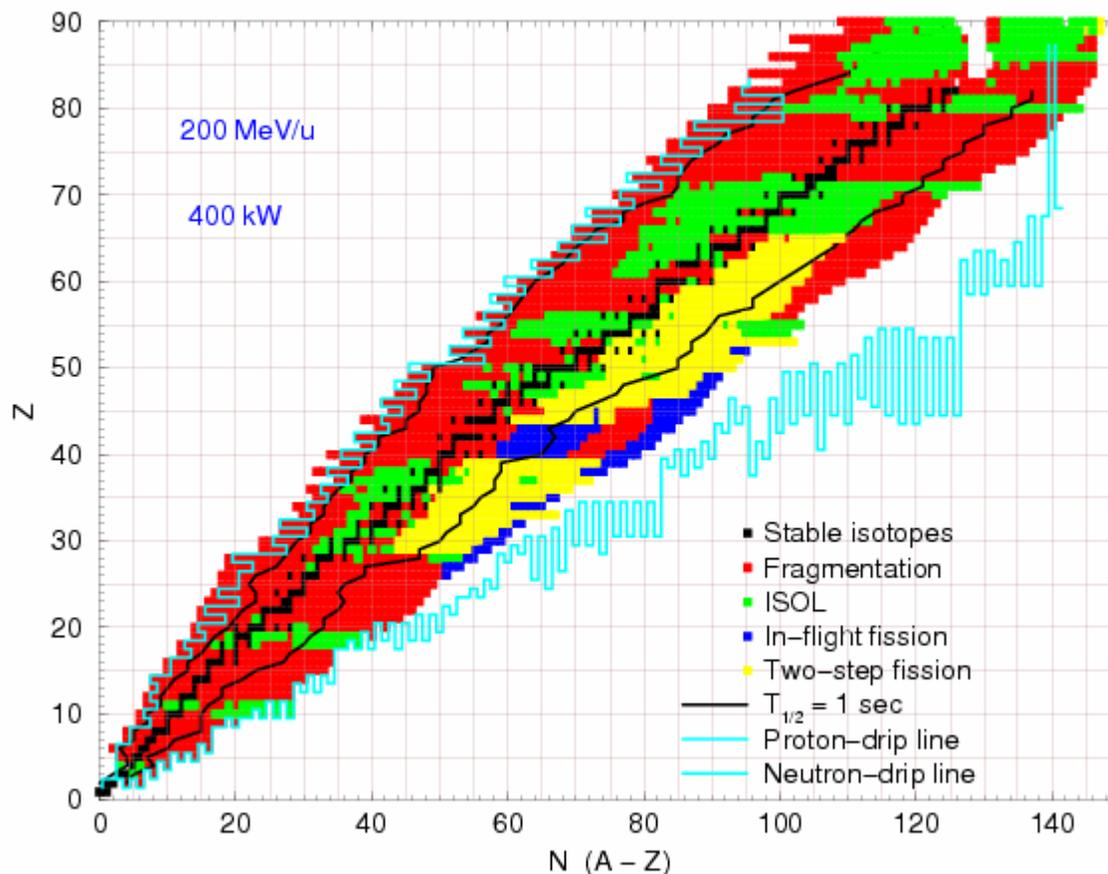
- Superconducting linac that accelerates several charge states simultaneously: 550 MeV protons to 200 MeV/u uranium- 400 kW.
  - **Same beam power as RIA**
  - **Focus on reaccelerated beams**
  - 1 in-flight target and separator for gas cell
  - 2 ISOL targets
  - TPC \$525M-570M (\$FY06)
    - *30% contingency*
    - *includes \$30M for new experimental equipment*
    - *existing ATLAS, and experimental equipment: CPT, FMA, Gammasphere; under construction: reaction solenoid, Gretina.*
- Relative to full RIA
  - small in-flight area for identification and collection of implanted ions, i.e. half-lives for r-process.
  - for most isotopes, reaccelerated beam intensities comparable to RIA.
  - in worst cases intensities 10-20% of RIA.

# Cost reductions

- 200 MeV/u
  - 216 superconducting cavities vs 300.
  - scales cryo plant, tunnels, beam transport systems.
- Remove higher resolution in-flight separator, large in-flight experimental area and most of in-flight experimental equipment.
- number of ISOL target stations reduced to 2.
- Smaller stopped beam, astrophysics and reaccelerated beam experimental areas.
- Smaller support space for labs and offices.
- Limited multi-user capability (for ISOL beams only).
  - important for simultaneous ISOL source development and isotope harvesting.

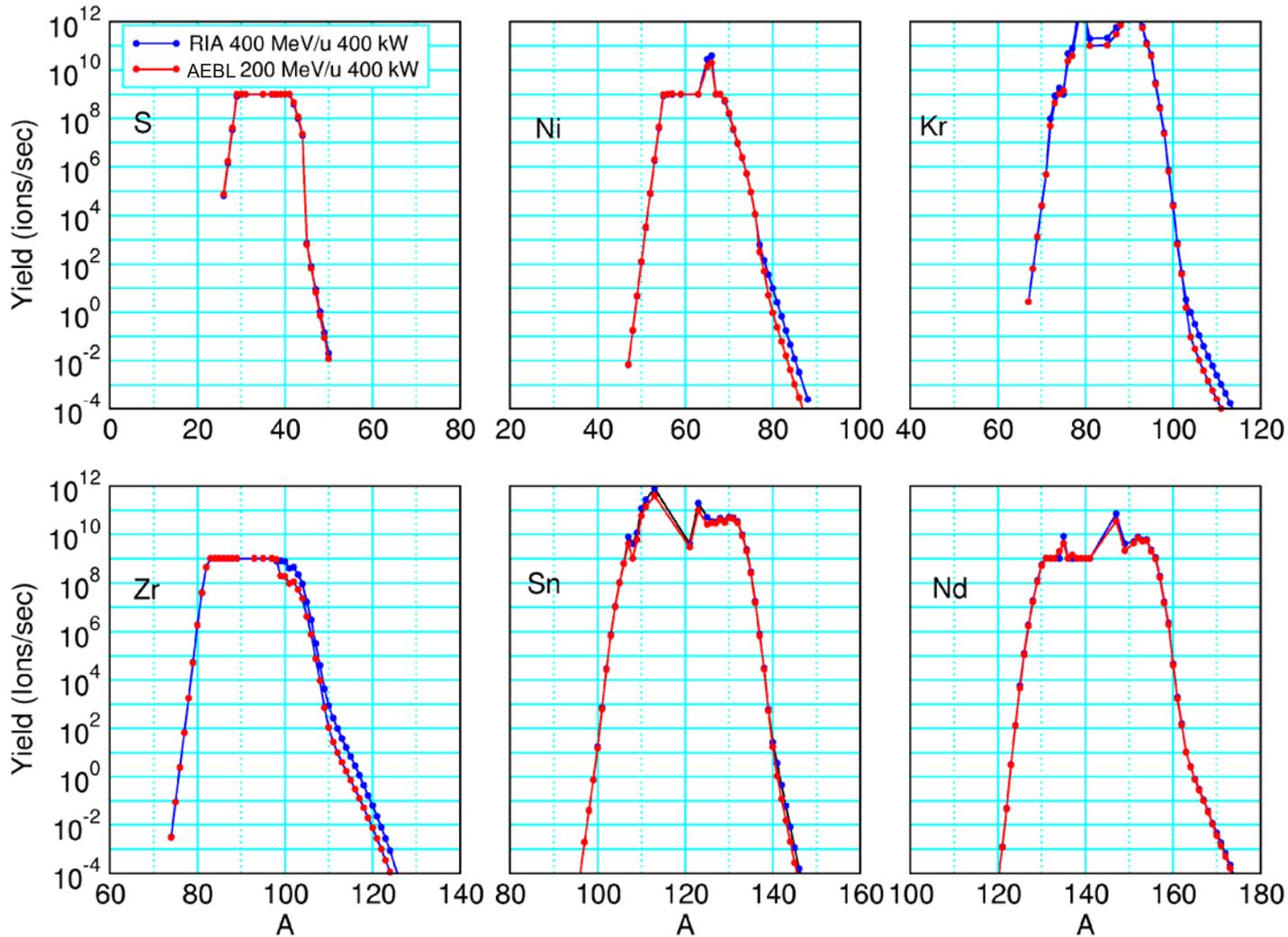
# Optimum production technique for $1^+$ ions for stopped and reaccelerated beams at 200 MeV/u

Reaction Mechanism for Highest Yield of Each Separated Isotope

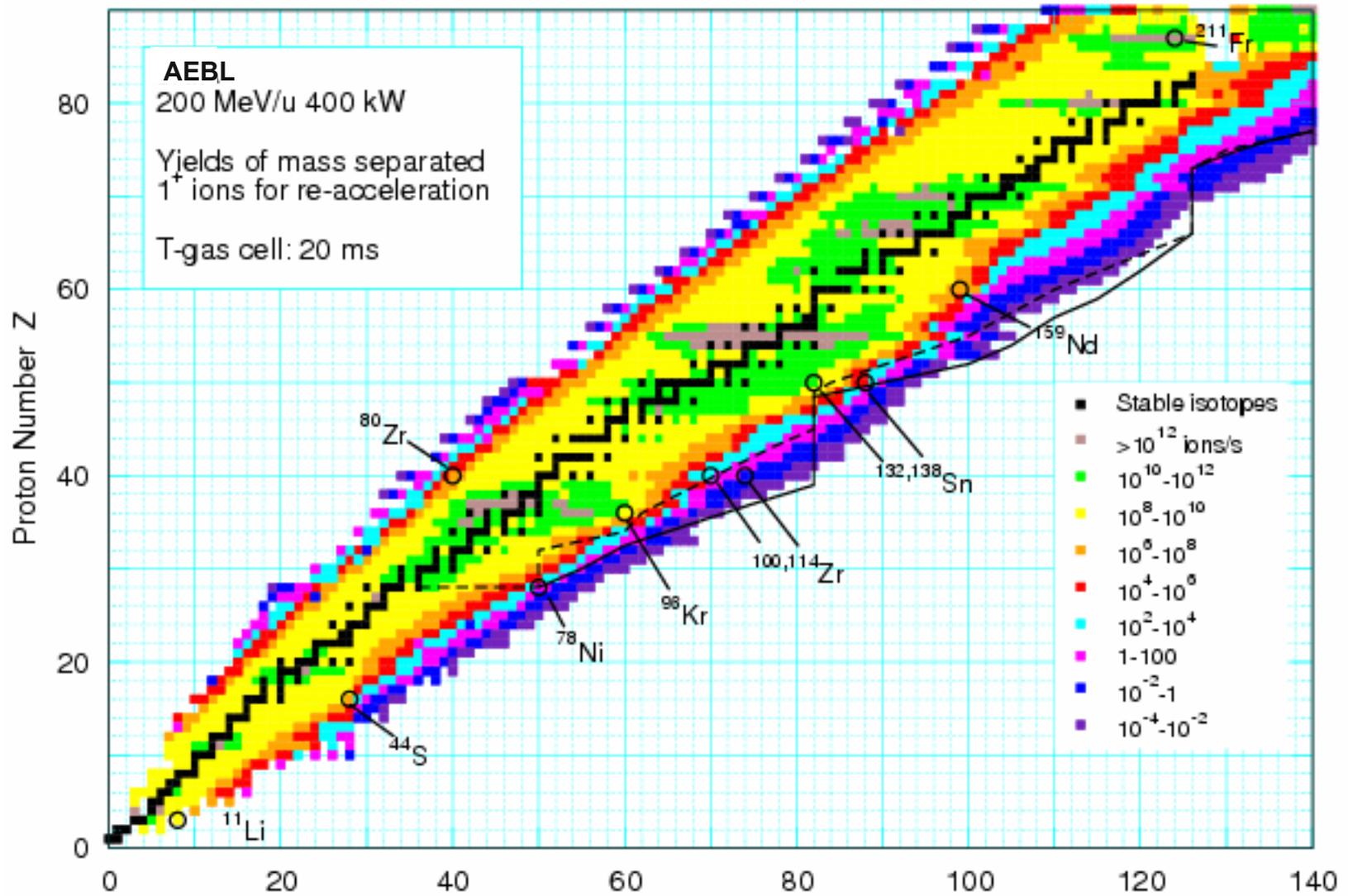


ANL March 2006

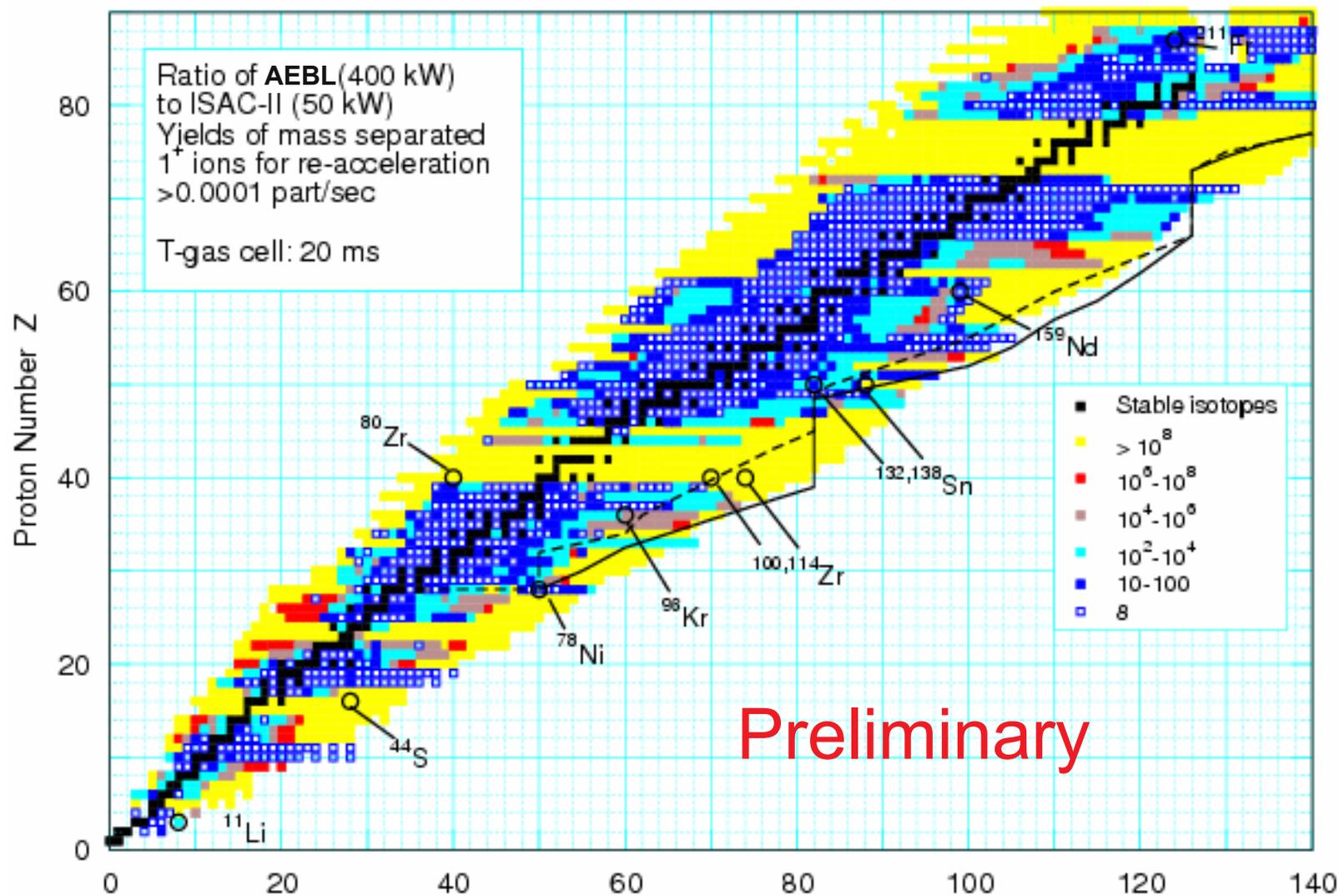
# RIA vs 200 MeV/u 400kW comparison for $1^+$ ions for traps and reacceleration



# 200 MeV/u 400 kW 1<sup>+</sup> yields for reacceleration

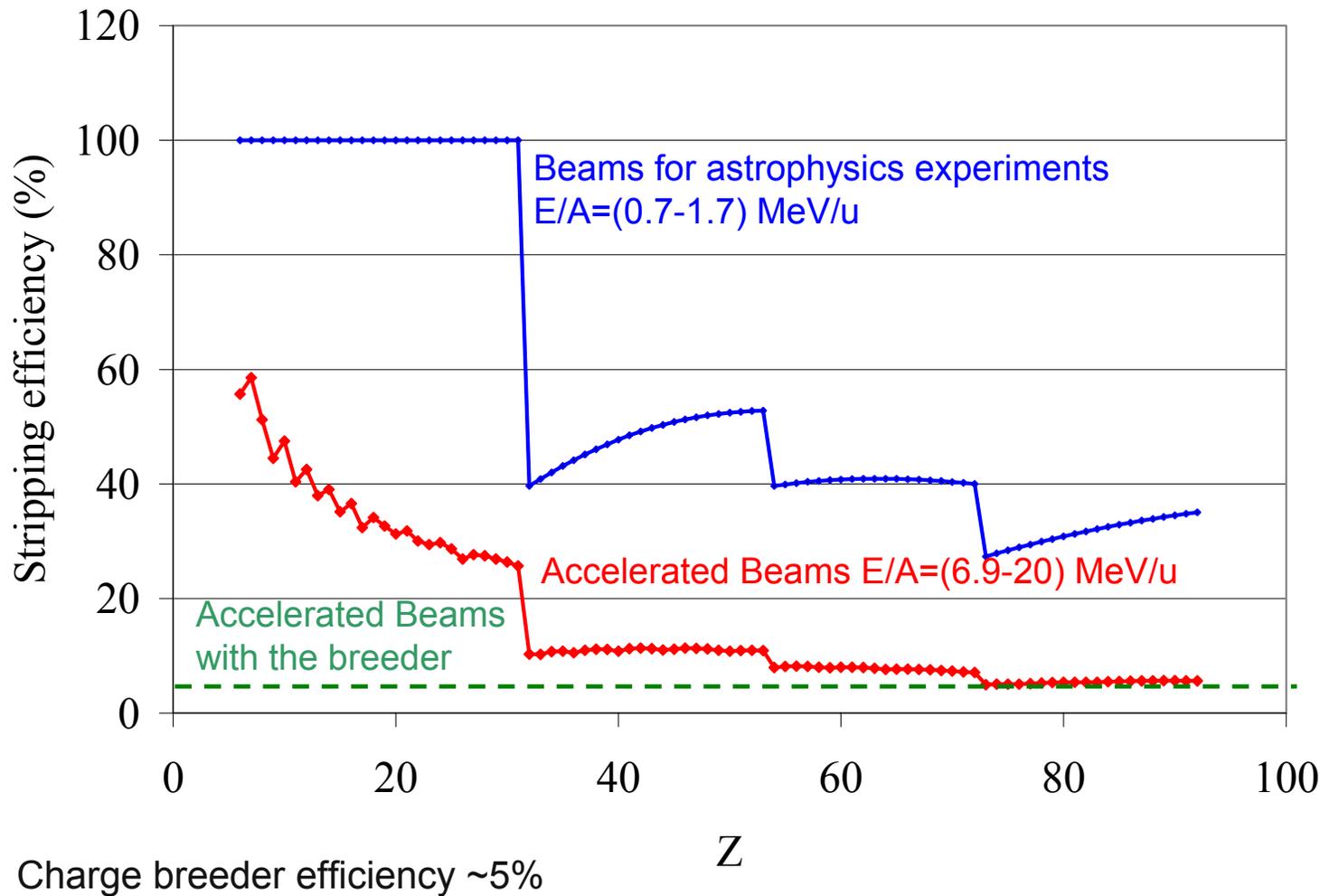


# Comparison with ISAC

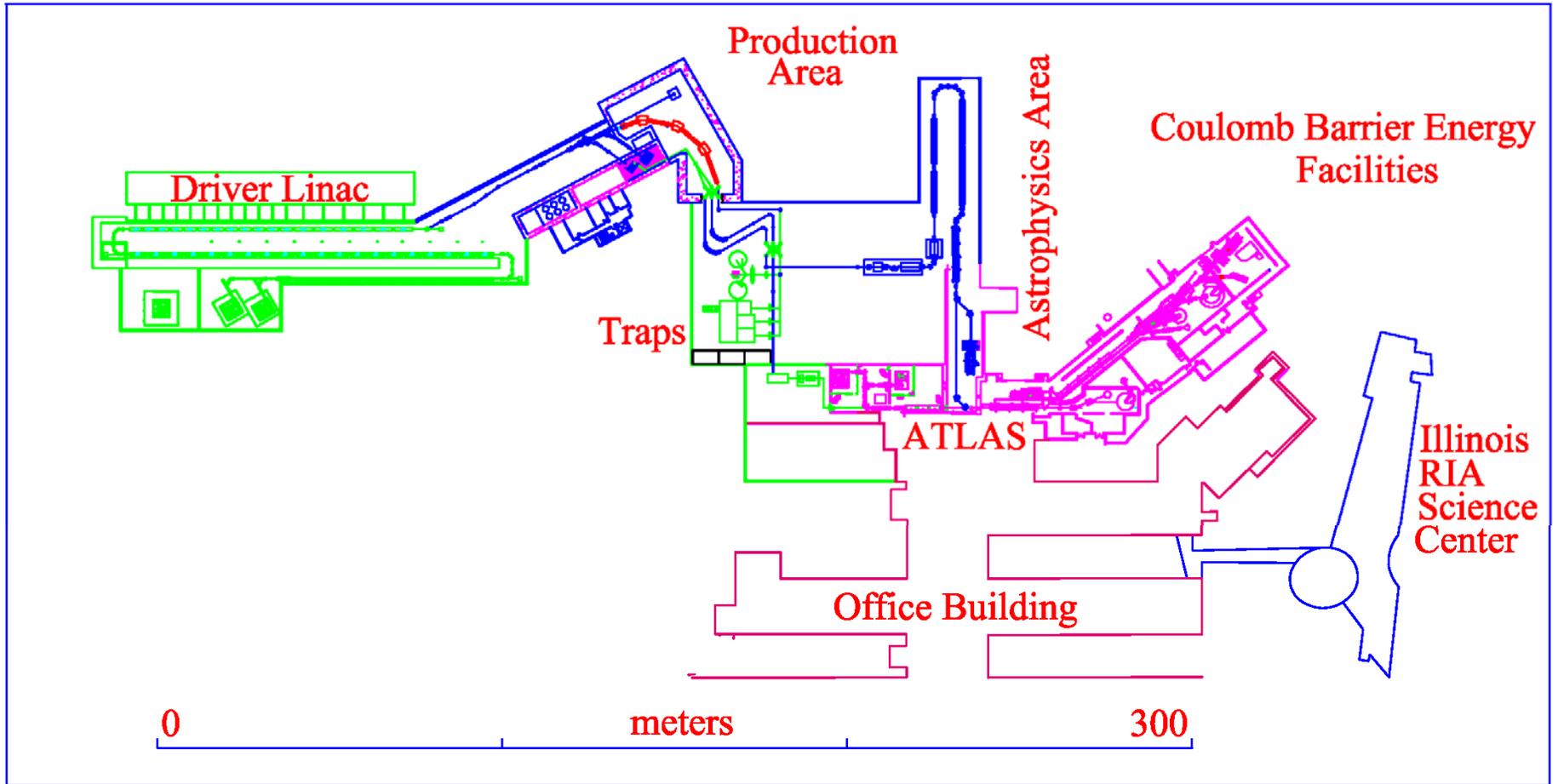


Preliminary

# Reduction in reaccelerated beams if you give up RIA style reacceleration-injector and using charge breeding instead.



# Layout



# Driver linac beams

Z	A	-----ECR-----		First Stripper			In - Second Stripper - Out				OUTPUT BEAM		
		I source pμA	Qinj	Energy MeV/A	Qstrip	Frac	Energy MeV/A	Qfinal	Frac	Energy MeV/A	I out pμA	Energy MeV/A	Power kW
1	1	904	1	85.4	-	-	298.3	-	-	-	723.0	553	400
2	3	402	2	63.4	-	-	220.6	-	-	-	321.3	415	400
1	2	750	1	51.2	-	-	175.1	-	-	-	600.2	333	400
8	18	117	6	37.4	8	0.80	150.1	-	-	-	75.2	296	400
18	40	54	8	24.6	18	0.80	139.5	-	-	-	34.7	288	400
36	86	28	14	20.4	34.9	0.90	122.4	36	0.90	117.5	18.1	257	400
54	136	20	18	16.7	50.2	0.90	105.7	54	0.90	101.5	12.7	232	400
92	238	7 *	28-29	14.9	77.5	0.82	88.0	88	0.90	84.5	8.4	200	400

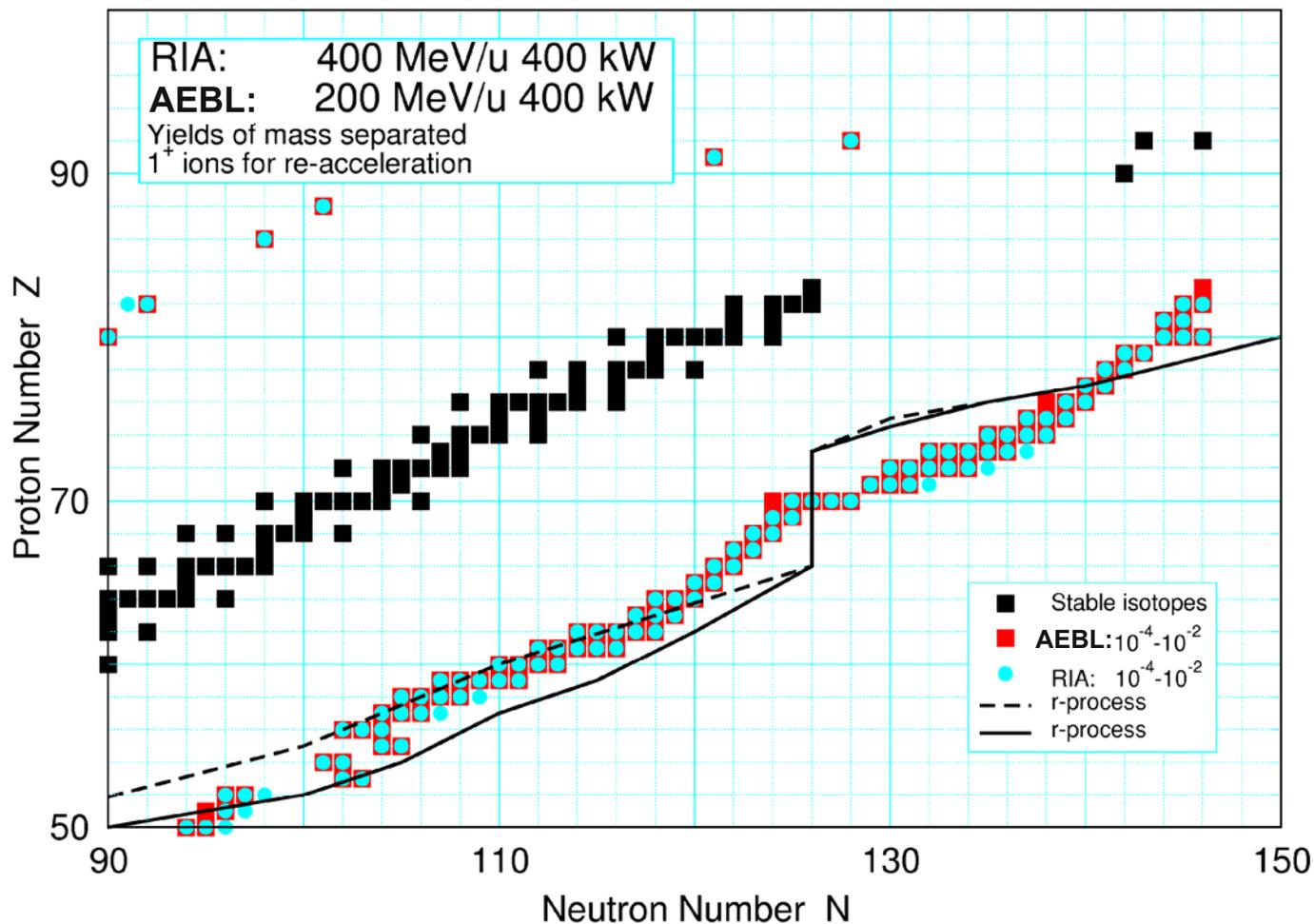
\* single charge state

## *What science is emphasized with AEBL?*

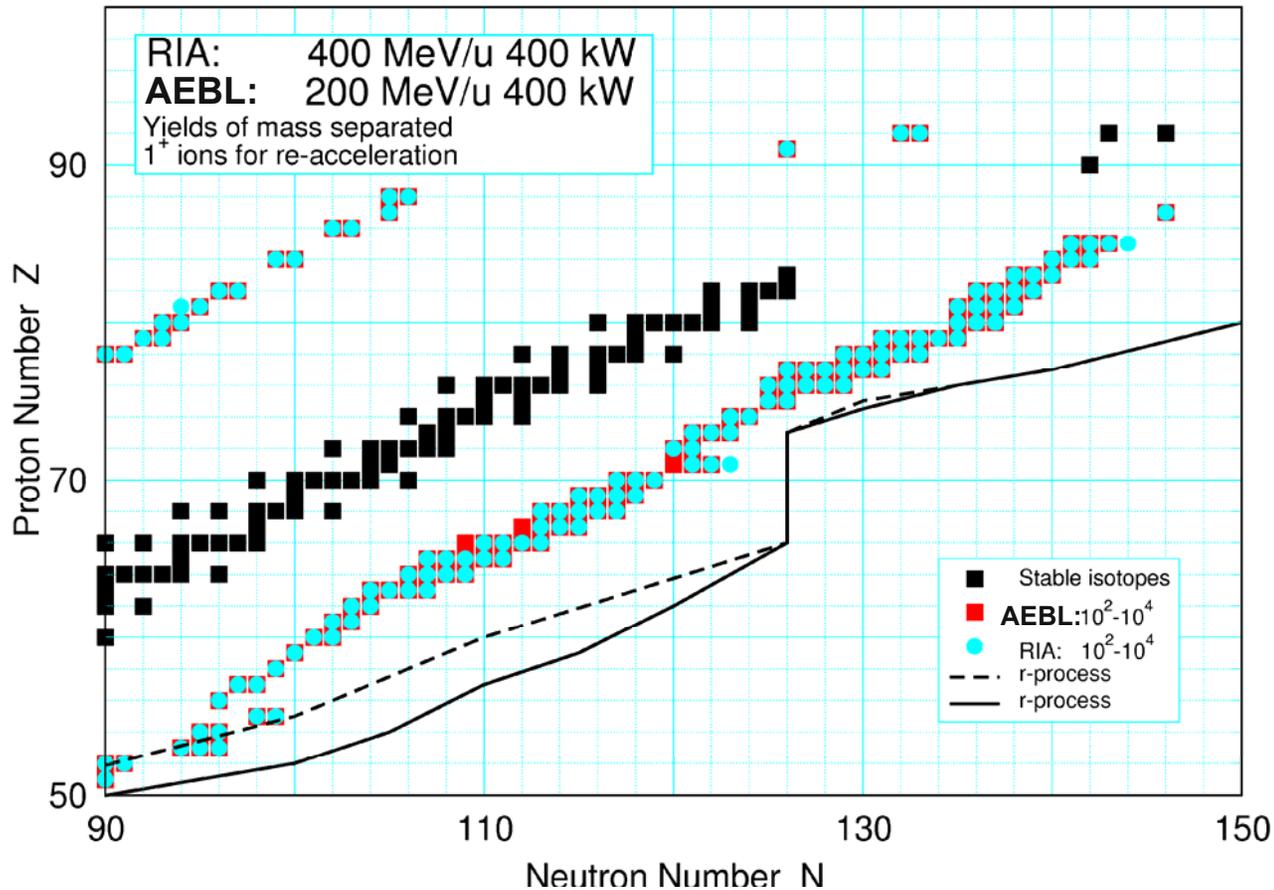
- Stopped beams (the lower energy is actually an advantage)
  - precision mass measurements to 0.001 ions/sec,
  - fundamental interactions,
  - applications.
- Direct measurements at energies of stellar explosions.
- Comprehensive nuclear structure information
  - evolution of single particle levels,
  - nature of pairing,
  - shape transitions,
  - fission barriers of n-rich nuclei.
- Production of super-heavy elements.
- Precisely implanted beams for applications.



## Last nuclei for which Penning trap quality mass measurements are feasible with RIA and AEBL



# Last nuclei for which fission barrier measurements and other reaction studies of nuclear structure are feasible with reaccelerated beams at RIA and AEBL



(d,p) reactions to establish fission barriers

## Changes in shell structure?

### QUESTION:

Are there major new shell gaps developing in the neutron-rich region, that could have major implications for structure and nucleosynthesis?

### METHOD:

Proton-adding reactions on Sn isotopes studied with a new solenoid spectrometer

### EXAMPLE:

$^{138}\text{Sn}(\alpha, t)^{137}\text{Sb}$

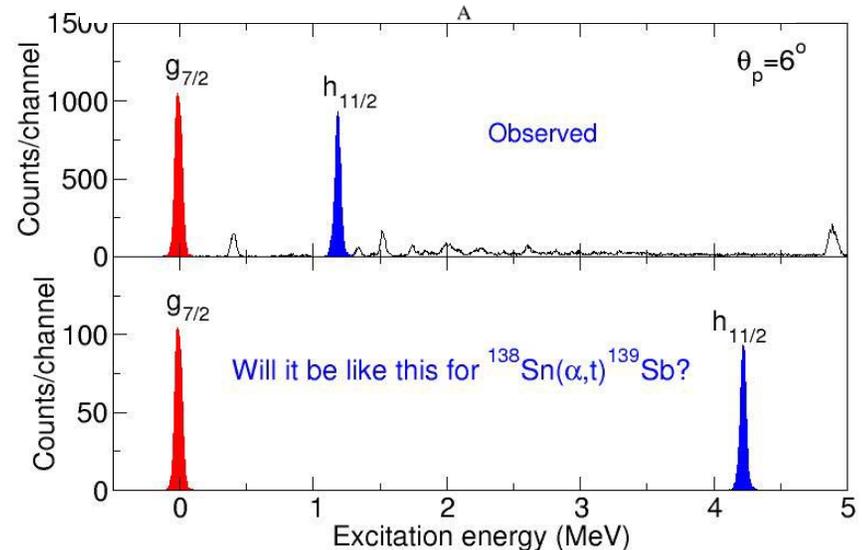
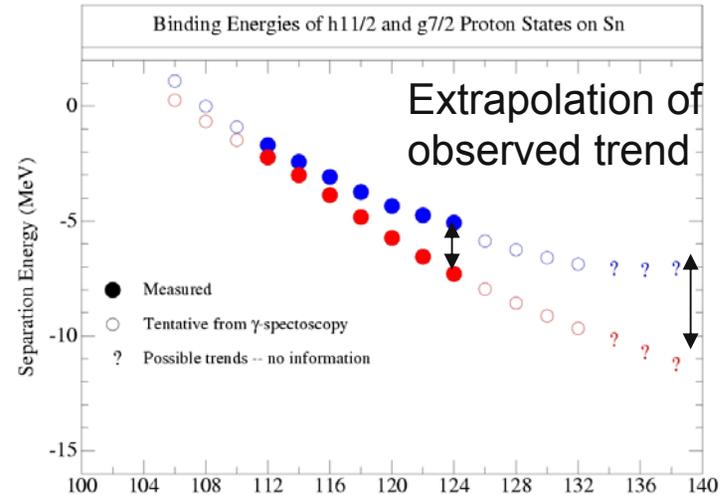
$^4\text{He}$  target  $\sim 50\mu\text{g}/\text{cm}^2$

$10^4$  particles/s

12 MeV/u beam

5 mb/sr over at least 1 sr:

$\sim 300$  cts/wk for each state



## Breakdown of BCS pairing?

### QUESTION:

Does BCS pairing that concentrates the  $L=0$  strength in the ground state break down in neutron-rich nuclei?

### METHOD:

Neutron-pair transfer on Sn isotopes studied with a new solenoid spectrometer

### EXAMPLE:

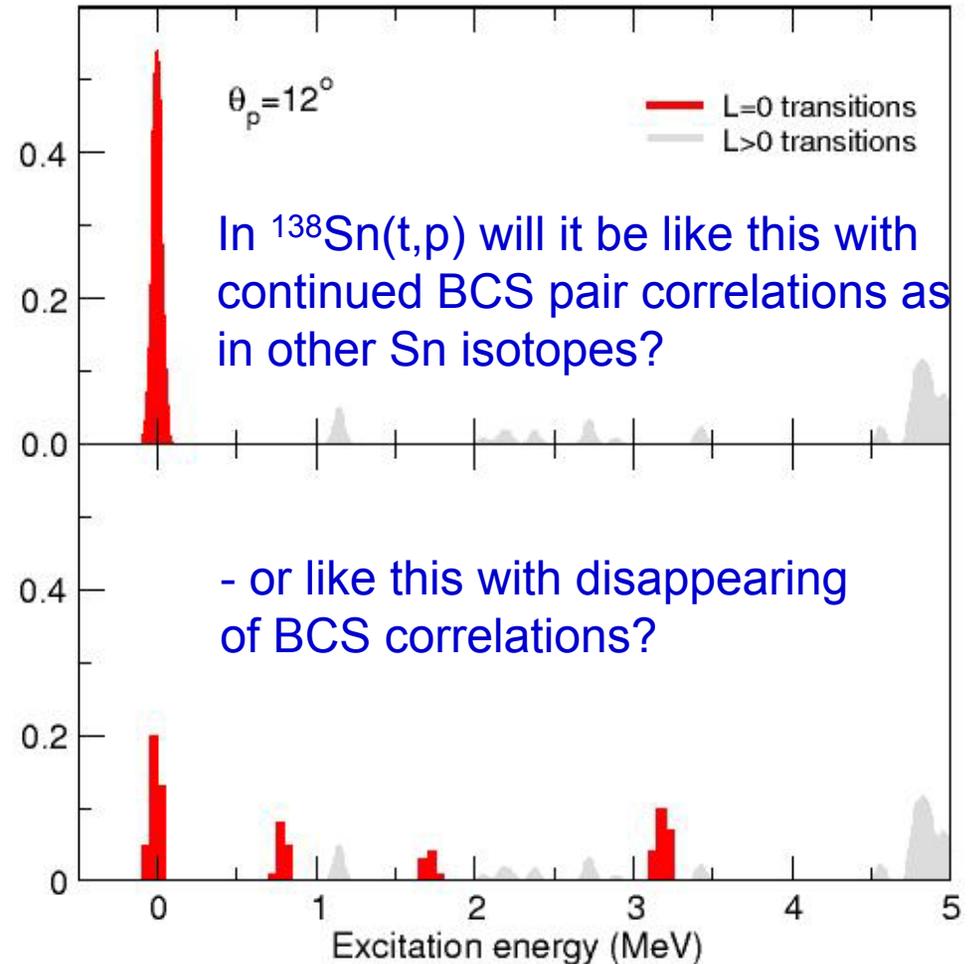
$^{138}\text{Sn}(t,p)^{140}\text{Sn}$

Tritium target  $\sim 50\mu\text{g}/\text{cm}^2$

$10^4$  particles/s

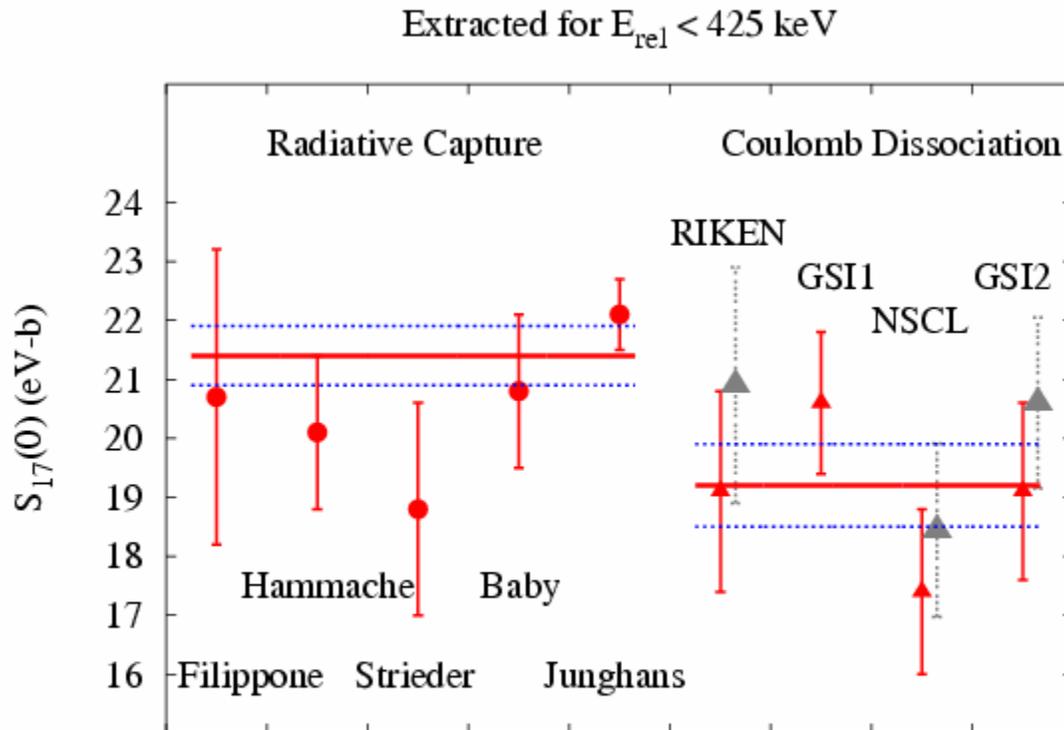
0.5 mb/sr over at least 1 sr:

$\sim 30$  cts/wk for each state





# Direct vs indirect measurements for astrophysics: ${}^7\text{Be}(p,\gamma)$



## Other examples

- ${}^{44}\text{Ti}$  production and destruction

- ${}^{15}\text{O}(\alpha,\gamma)$

- rp-process

- ....

## *What species have been extracted from the gas catcher so far?*

Gas catcher should be a **“universal” approach** ... how diverse are the species that have been extracted so far: **43 elements**

- Neutron-deficient isotopes

- Cs, Xe, Te, Sb, Sn, In, Rh, Ru, Tc, Mo, Se, As, Ge, Ga, As, Zn, Co, Fe, V, Ti, Cl, Al, Mg, Na, O

- Neutron-rich isotopes

- Nd, Ce, Pr, La, Ba, Rh, Ru, Tc, Mo, Sr

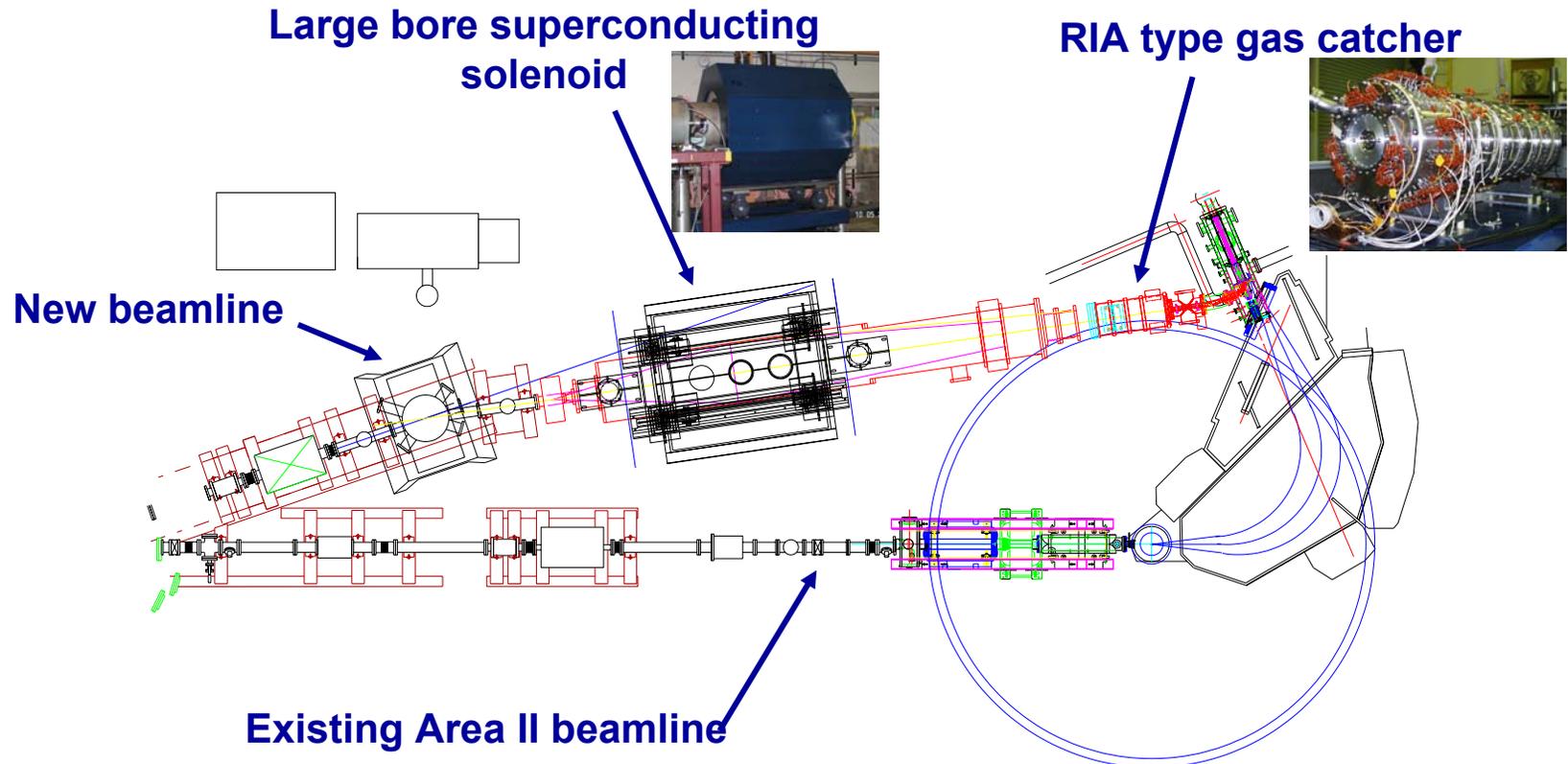
- Stable isotopes

- Xe, Kr, Ti, Ca, Ar, S, Na, Ne

All attempted species, from the “easy” (alkali atoms and noble gases) up to the very refractory cases (Mo, Tc, Co, etc ...) , have been extracted.

All with **high efficiency** ... in excess of the 20% efficiency used for the RIA yield calculations.

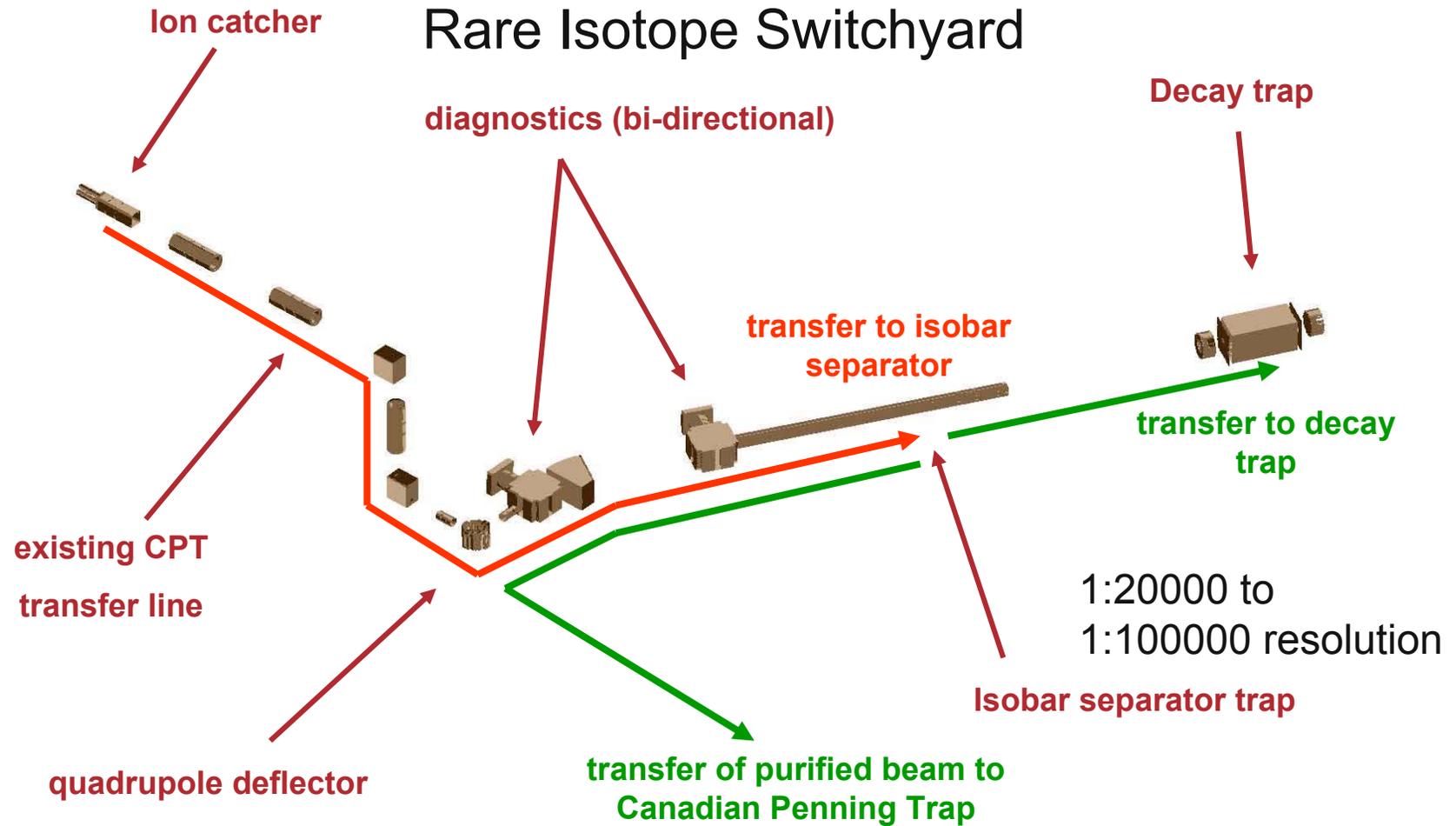
# A high-intensity gas catcher test, with conditions similar to RIA, will be run this year at ATLAS



Gas catcher test with incoming intensity, energy, position and energy distribution similar to those expected behind the RIA fragment separator to demonstrate operation at  $10^9$  ions per second ... and see how much further this approach can be pushed.

**Our CARIBU project (2006-2009) is based on this technology.**

*We have lots of experience cleaning up rare ion beams*

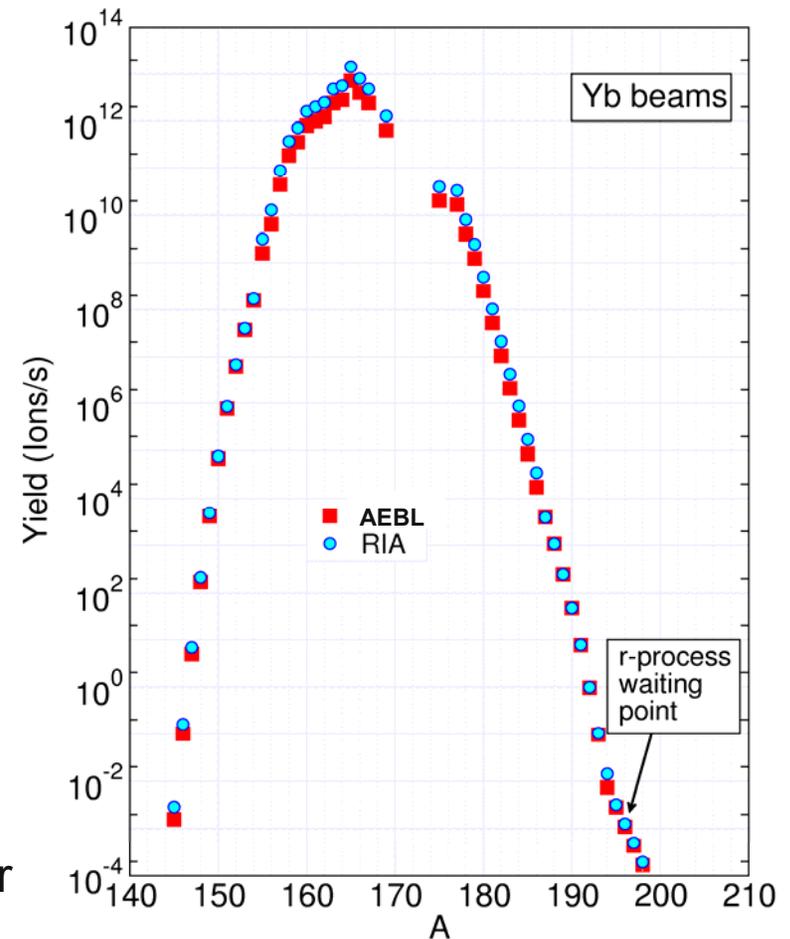


AMS experiments run beams at  $10^{-5}/s$  level.

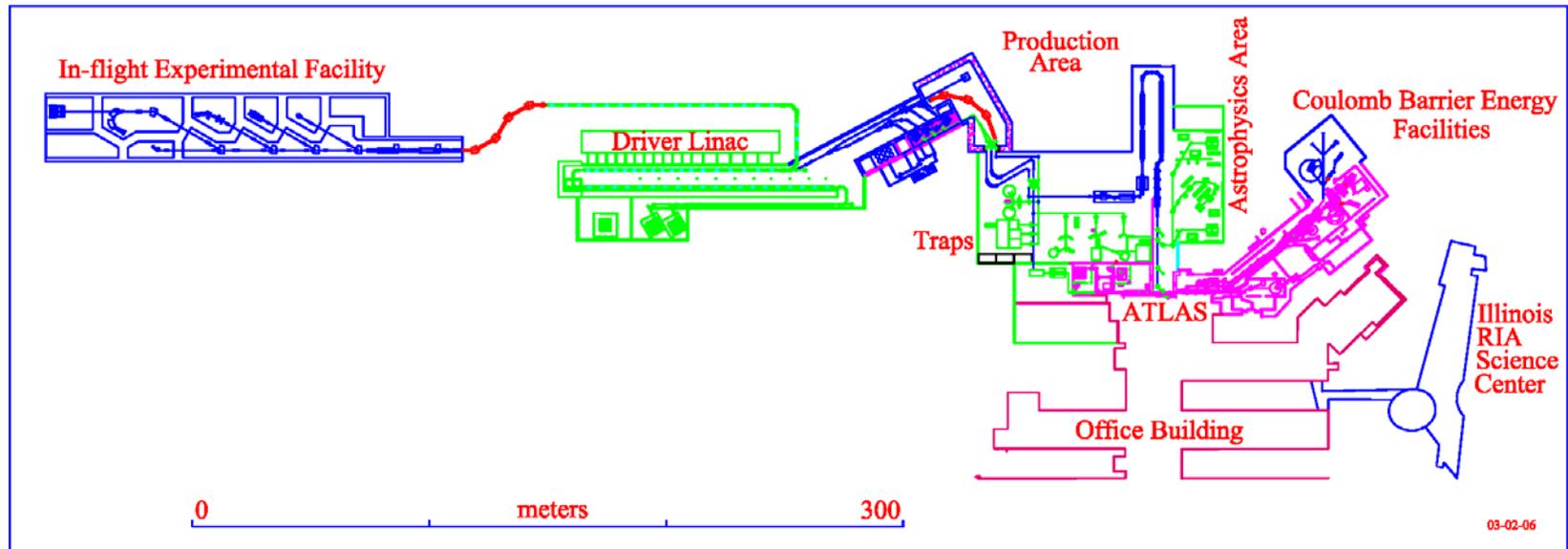
# What do we lose with AEBL compared to a full RIA?

- 1-2 neutrons in reach in half-life measurements for r-process nuclei, but will get to longest waiting points
- Neutron drip line except for light nuclei
- ~5 neutrons in reach for single particle breakup and Coulomb excitation to lowest 2+ states (~1-3 relative to RIKEN and GSI)
- Charge exchange reactions to measure electron-capture rates (at  $10^7$  ions/s)
- Equation of state of hot nuclei matter
- **Limited simultaneous user capability**

In all cases the yields are an extrapolation and subject to an order of magnitude uncertainty.



## There is an upgrade path



Ample expandability to incorporate higher energy, full in-flight capability as well as other possible expansions.

## Summary

- RIA is the facility that addresses all the physics issues. It is what the community wants, and what Argonne is committed to.
- A 400 kW 200 MeV/u reaccelerated rare isotope facility focusing on stopped and reaccelerated beams offers unique physics reach in isotopes and reaccelerated beam energy.
- It complements the world-wide efforts in rare isotope physics, in particular the fast beam projects at GSI and RIKEN and ISOL production at ISAC.
- It is far better than any ISOL facility for the many isotopes that do not diffuse easily from a thick target.
- It can be built for about half the cost of RIA.
- It offers natural upgrade paths as we explore the physics of this new regime of unknown nuclei.

## Action

- Is this the facility the community wants to focus its efforts on?
- We have to organize our efforts for the long range plan
- We have to make the case for this facility, not RIA.
- RISAC is going to ask the community how a lower cost facility addresses the science goals.
- We have to work with all our low energy colleagues to present unified front for the Long Range Plan.

