Solenoidal Spectrometers and Techniques: HELIOS and SOLARIS

Ben Kay, Argonne National Laboratory
ISS meeting, Manchester 2017

Overview

Why develop a solenoidal spectrometer?

- ➡ *Why inverse kinematics, concept*

HELIOS

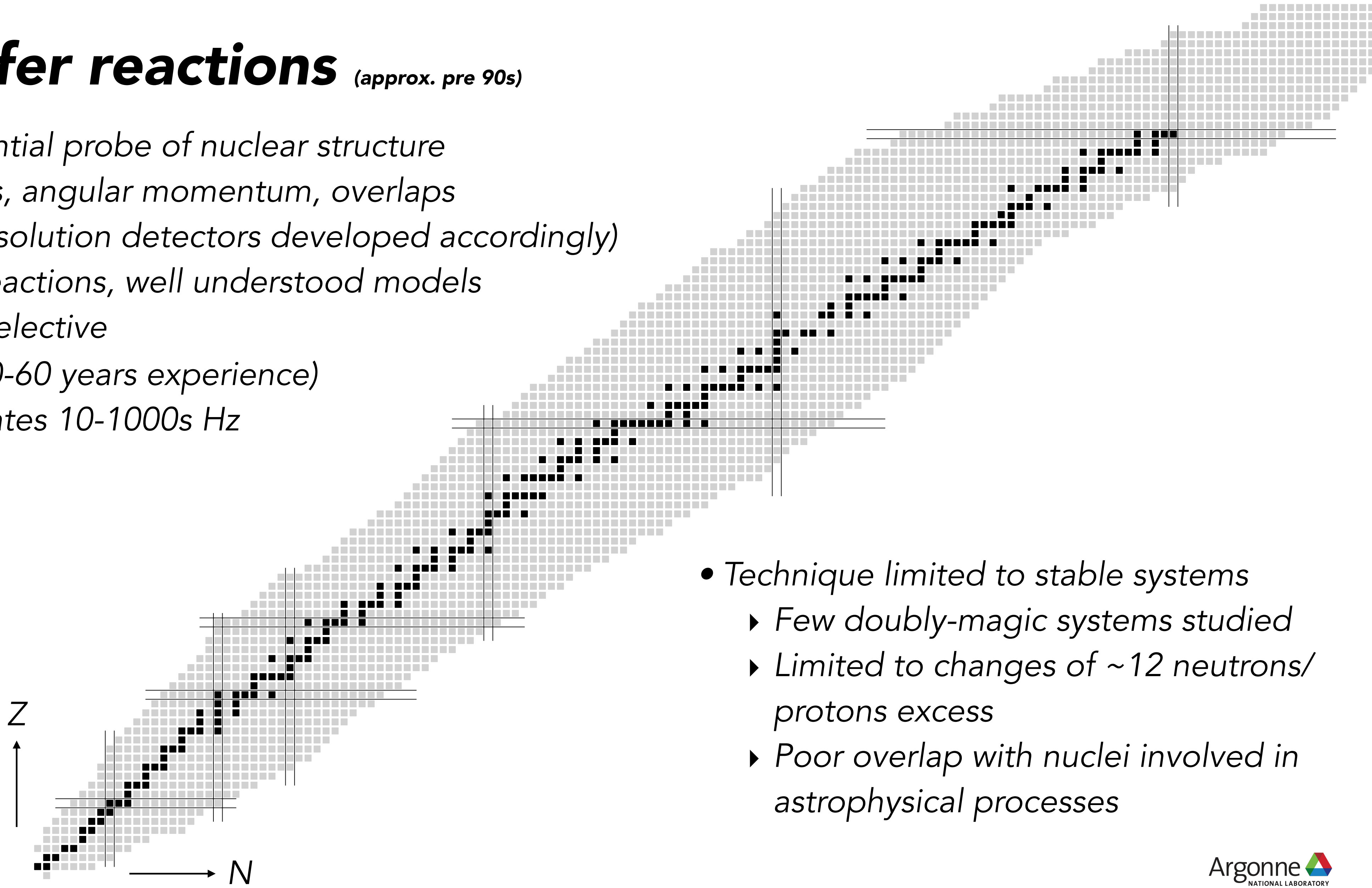
- ➡ *The first generation, how it works in reality*
- ➡ *Things we have learnt*

Next steps in the US

- ➡ *SOLARIS @ FRIB, 3rd generation*
- ➡ *ISS @ ISOLDE*

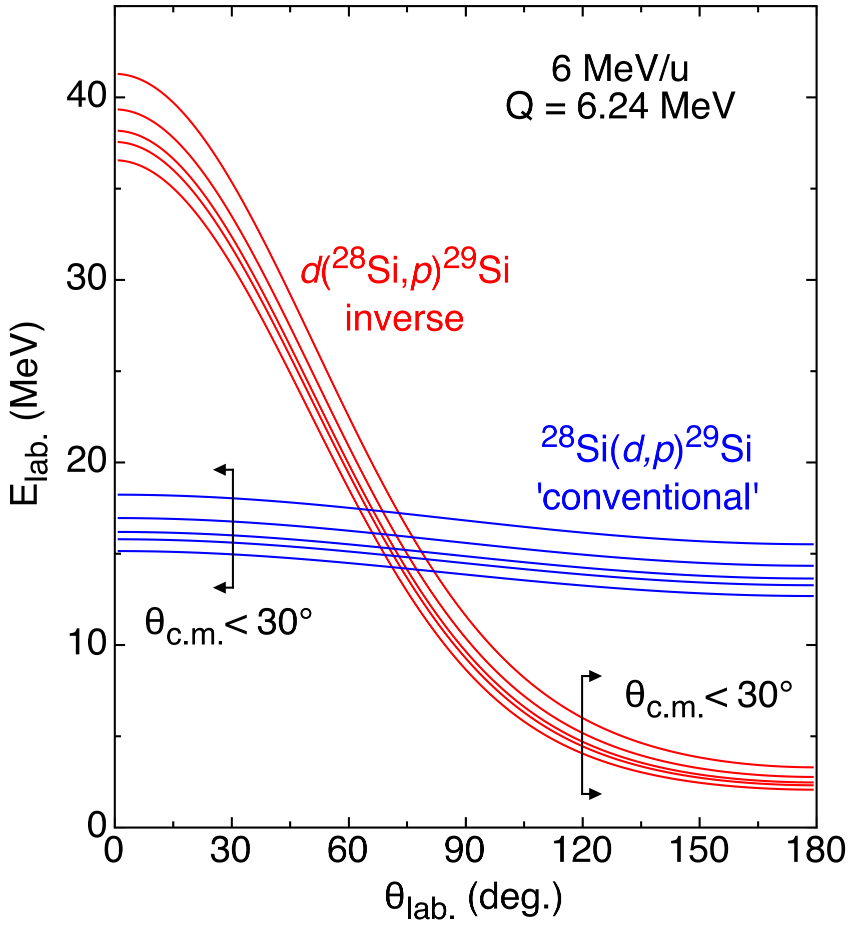
Transfer reactions *(approx. pre 90s)*

- *An essential probe of nuclear structure*
- *Energies, angular momentum, overlaps*
- *(High-resolution detectors developed accordingly)*
- *Direct reactions, well understood models*
- *Highly selective*
- *(Over 50-60 years experience)*
- *Count rates 10-1000s Hz*



- *Technique limited to stable systems*
  - *Few doubly-magic systems studied*
  - *Limited to changes of ~12 neutrons/ protons excess*
  - *Poor overlap with nuclei involved in astrophysical processes*

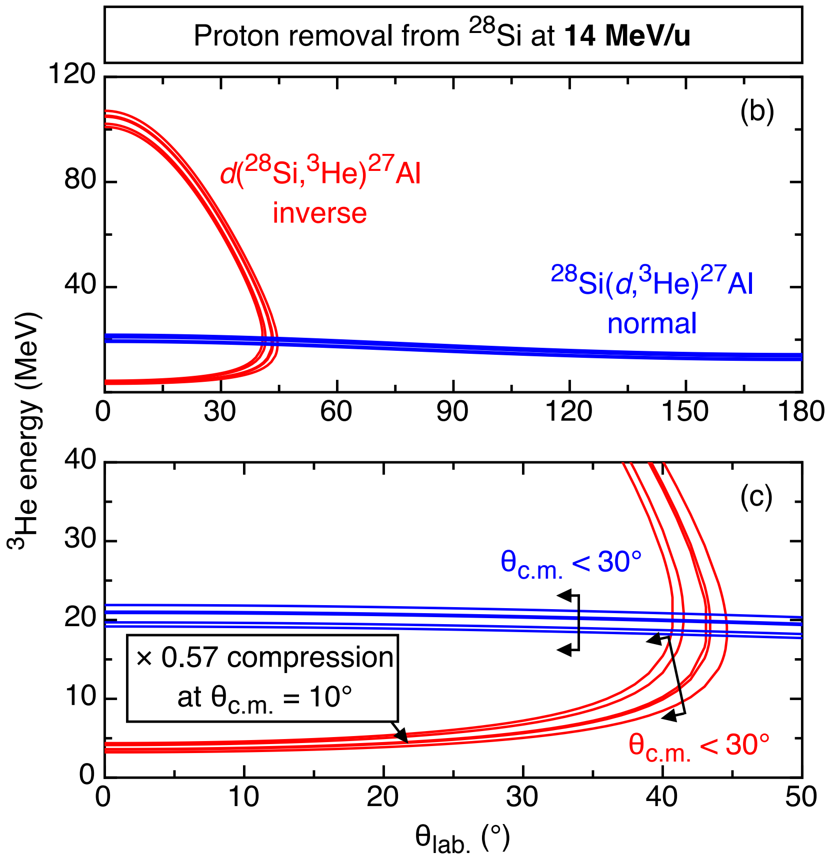
Kinematics: normal vs. inverse



Inverse-kinematics challenges:

- Particle identification, ΔE-E techniques more challenging at low energies
- Strong energy dependence with respect to laboratory angle
- Kinematic compression at forward c.m. angles (in fact nearly all angles)
- Typically leading to poor resolution (100s of keV)
- … and beams a few to 10^6 orders of magnitude weaker

Kinematics: normal vs. inverse



$$\tan\theta^{\mathrm{lab}}_{\mathrm{max.}} = 1/\sqrt{(V/\bar{v})^2 - 1}$$

V is c.m. velocity of the system, *v* is the velocity of the outgoing ion in the c.m. frame

- For negative Q-value reactions e.g. (d, ^{3}He) there is a *double-valued kinematic solution* …
- … ions cannot scatter beyond $\theta_{max.}$ in the laboratory, in this case $\theta_{lab.} = 44.6°$
- Particularly challenging for fixed lab-angle measurements, especially near $\theta_{max.}$

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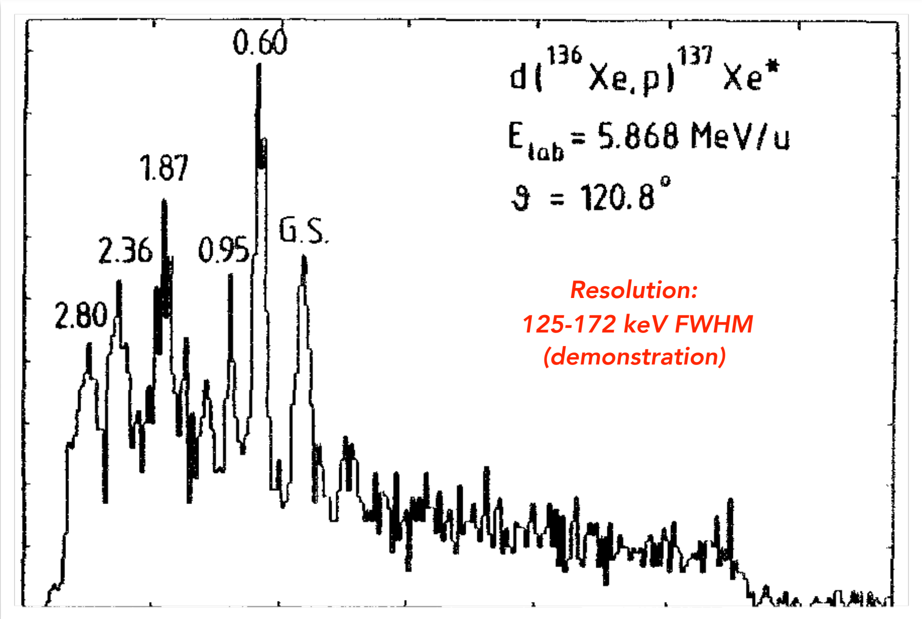
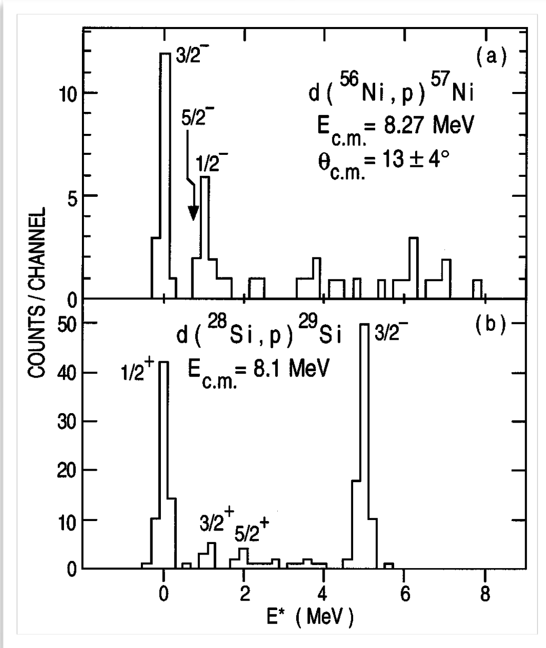
Early inverse-kinematics studies

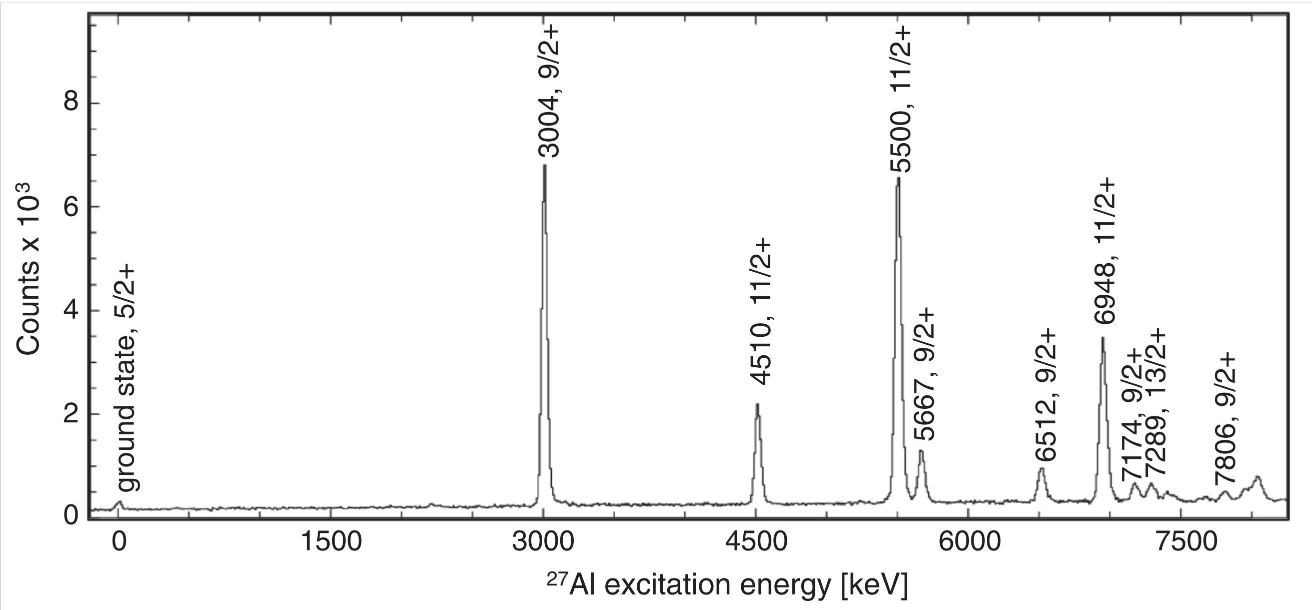


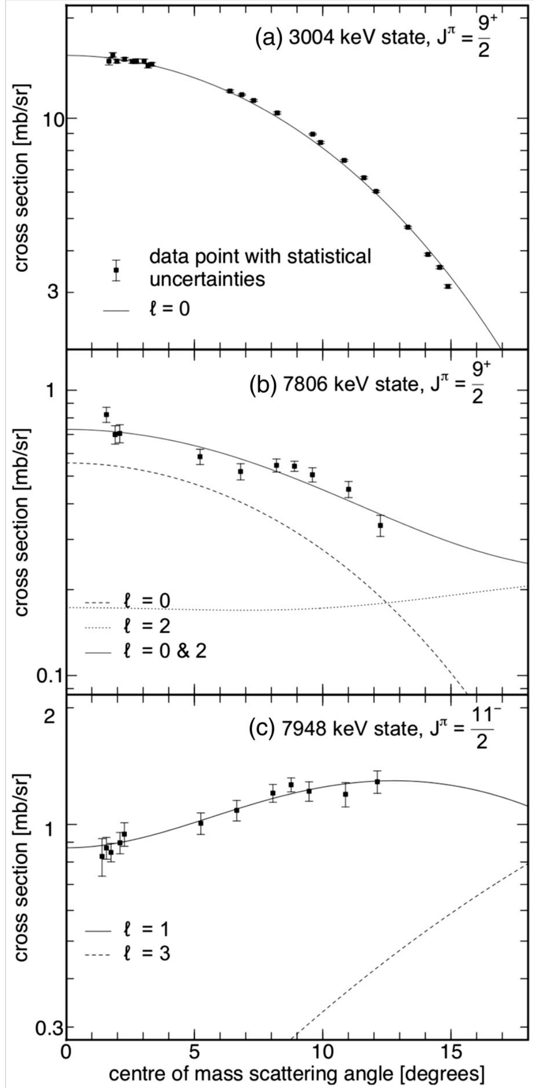


<u>**Necessities:**</u> complex Si arrays, ***high intrinsic resolution***, ***high angular granularity***, low thresholds, large acceptance, often coincident gamma-ray detection, e.g., MUST-2 (GANIL), T-REX (ISOLDE), SHARC (TRIUMF), ORRUBA (ORNL), TIARA (GANIL), etc.

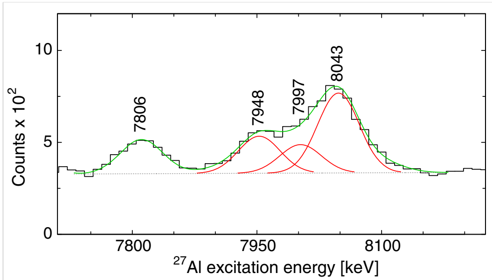
Kraus et al., Z. Phys. A ***340****, 339 (1991), K. E. Rehm et al., Phys. Rev. Lett.* ***80****, 676 (1998)*

Recent 'state-of-the-art' *(highly idealized conditions)*





Q-value resolution of 40 keV FWHM



V. Margerin et al., Phys. Rev. Lett. ***115****, 062701 (2015)*

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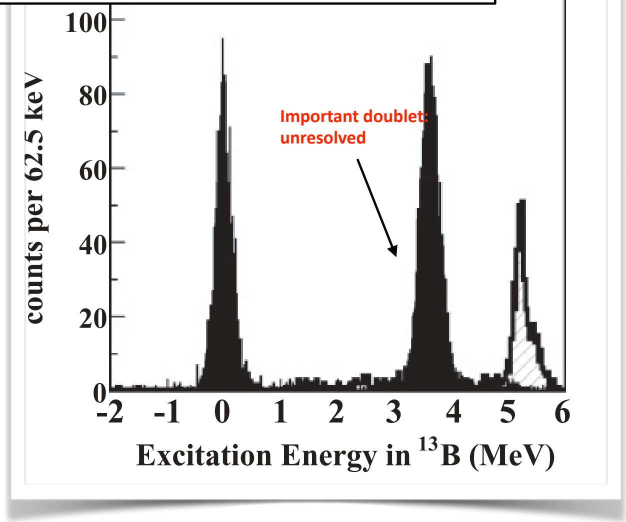
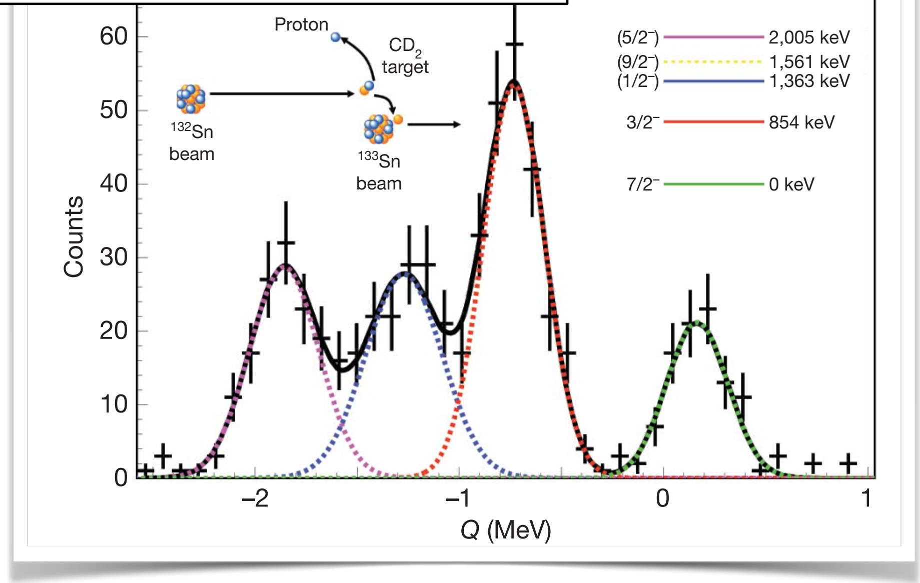
On the whole, results are often limited

Using the traditional approach of placing a segmented Si detector at a fixed laboratory angle can result in poor excitation-energy resolution, ***typically of the order of ~300 keV*** (better can be achieved for light nuclei).

e.g. $d(^{12}B,p)^{13}B$, ~250 keV FWHM



e.g. $d(^{132}Sn,p)^{133}Sn$, ~300 keV FWHM



<u>Would like an approach that consistently:</u>

- *Gives better than 100-keV FWHM resolution*
- *7-10 day runs with RI beams (10^4 pps, 100 μg/cm^2 targets)*

*H. Y. Lee et al., Phys. Rev. C **81**, 015802 (2010), K. L. Jones et al., Nature **465**, 454 (2010).*

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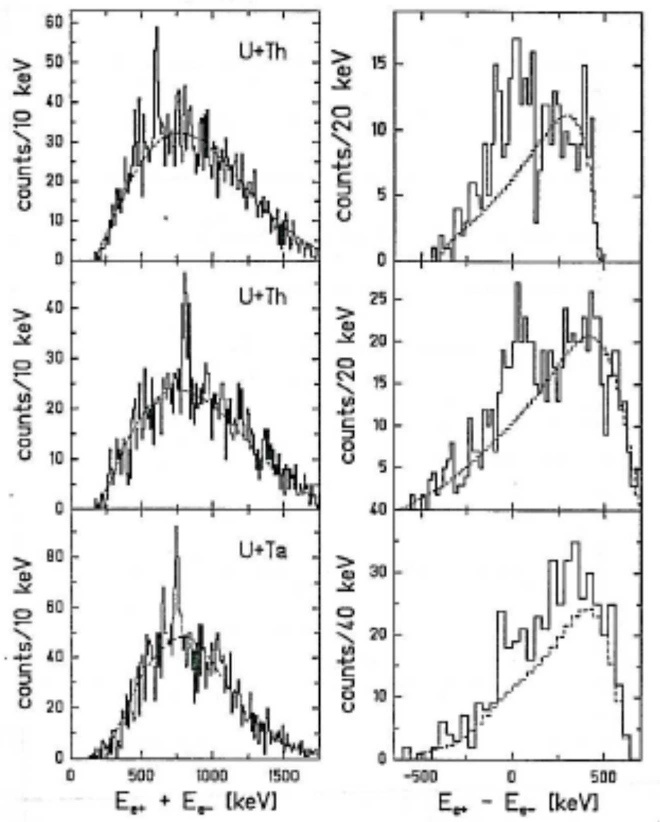
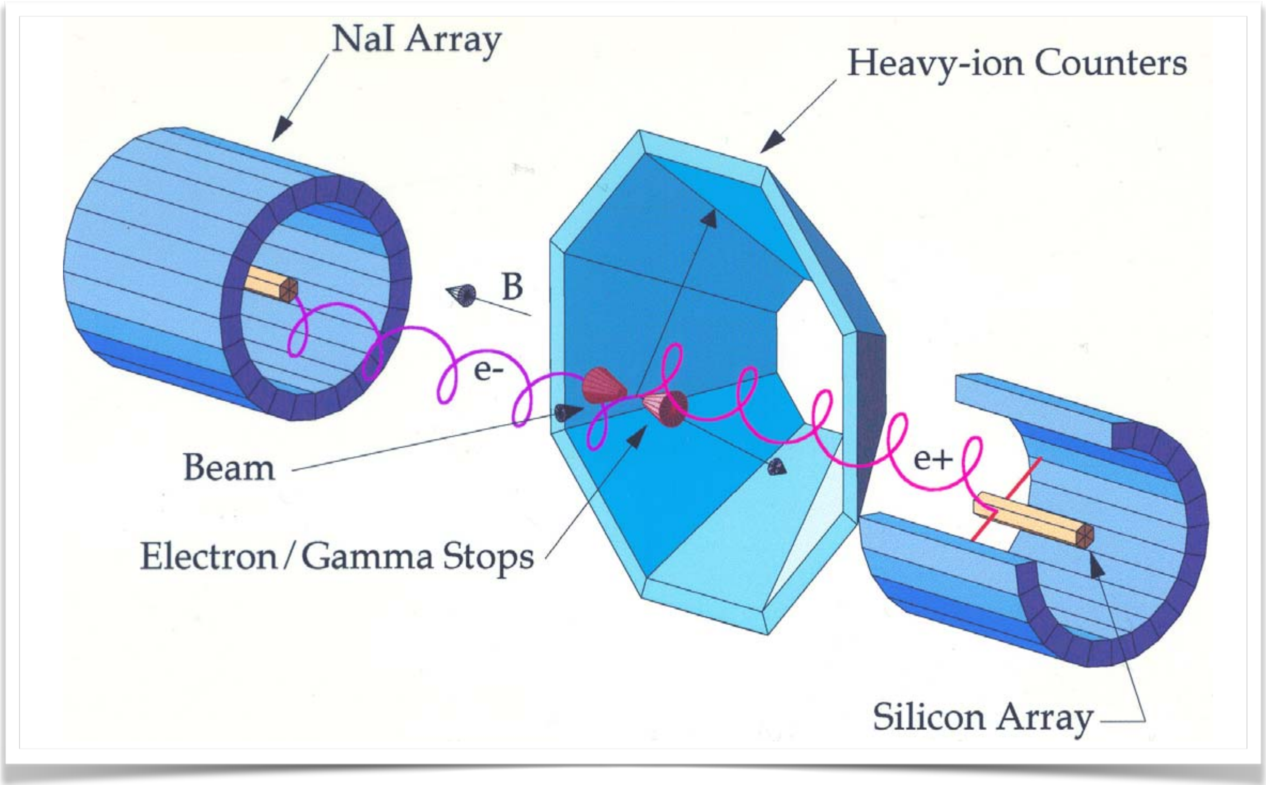
Solenoids …





APEX experiment, Argonne

Solenoids …

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Connection made …

Interestingly DGS was mentioned … now a reality

processing of pulse shapes. Digital processing provides the additional benefit of allowing higher count rate. Currently, intensive R&D work is being carried out and prototype electronics have already been constructed. However, further developments in miniaturization and cost reduction

As was GRETA / GRETINA … now a reality

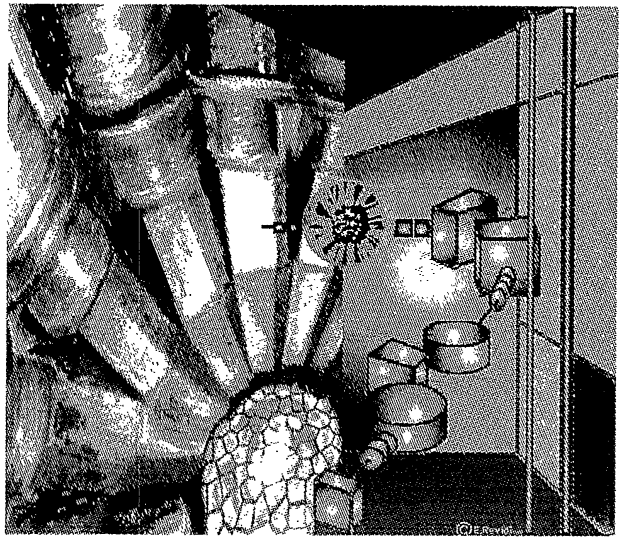
pursued. One concept, called GRETA (Gamma-Ray Energy Tracking Array) builds on the Gammasphere concept of segmentation of large HpGe crystals. About 60 of the present Gam-

HELIOS … now a reality

a) Solenoidal Geometry

A magnetic solenoid with its axis oriented along the beam direction could serve as a very large-acceptance magnetic spectrograph for low-energy light particles from inverse reactions such as $d(^{132}\mathrm{Sn},p)^{133}\mathrm{Sn}$. In this case the protons of interest are emitted in the backwards hemisphere with energies of 1-10 MeV. The particle energy measurements are done via silicon detector barrels surrounding the beam axis. This type of magnetic spectrograph deserves further study.

Experimental Equipment for an Advanced ISOL Facility



March 1999

… by John P. Schiffer, Argonne

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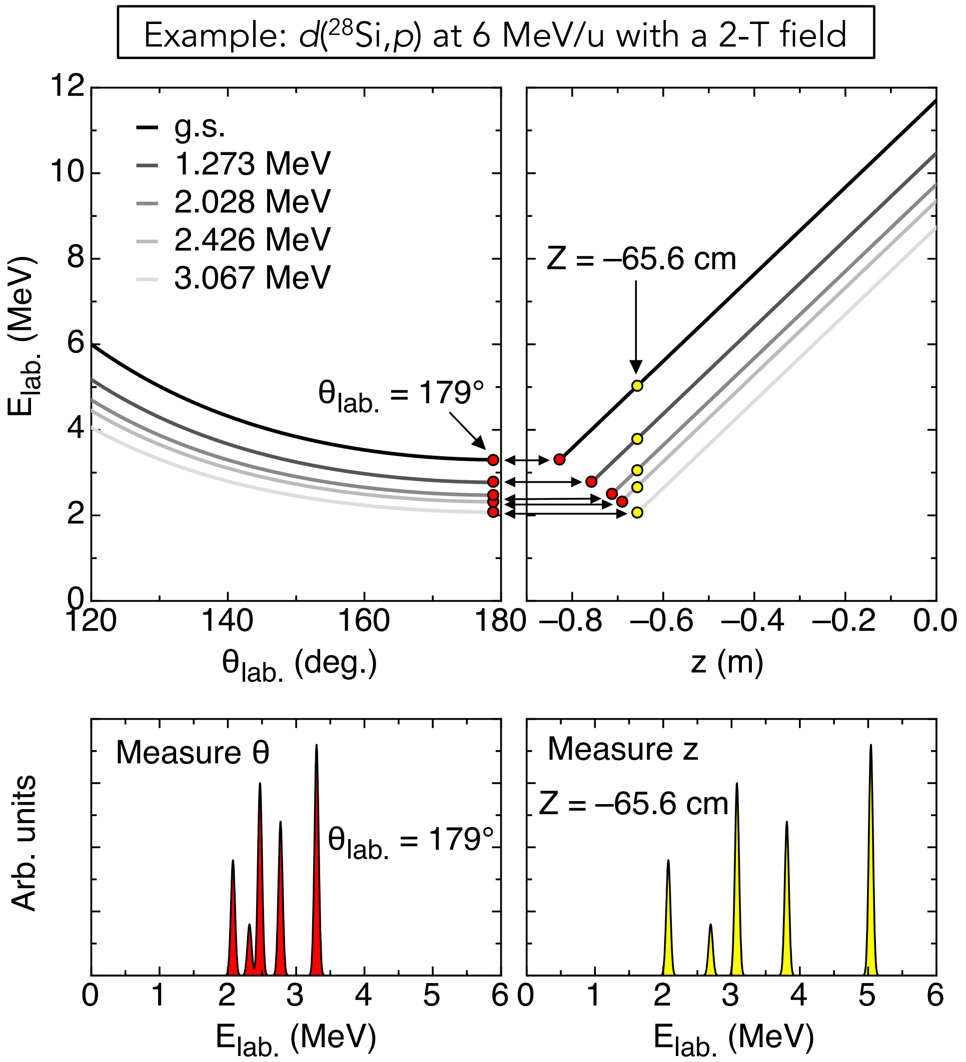
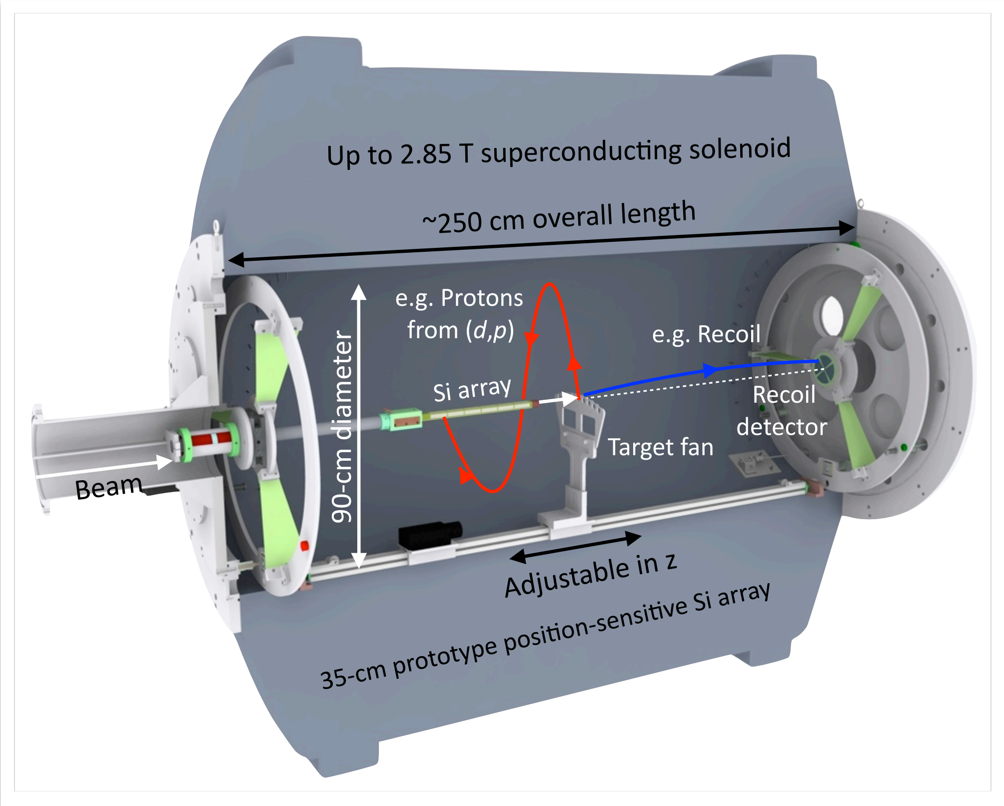
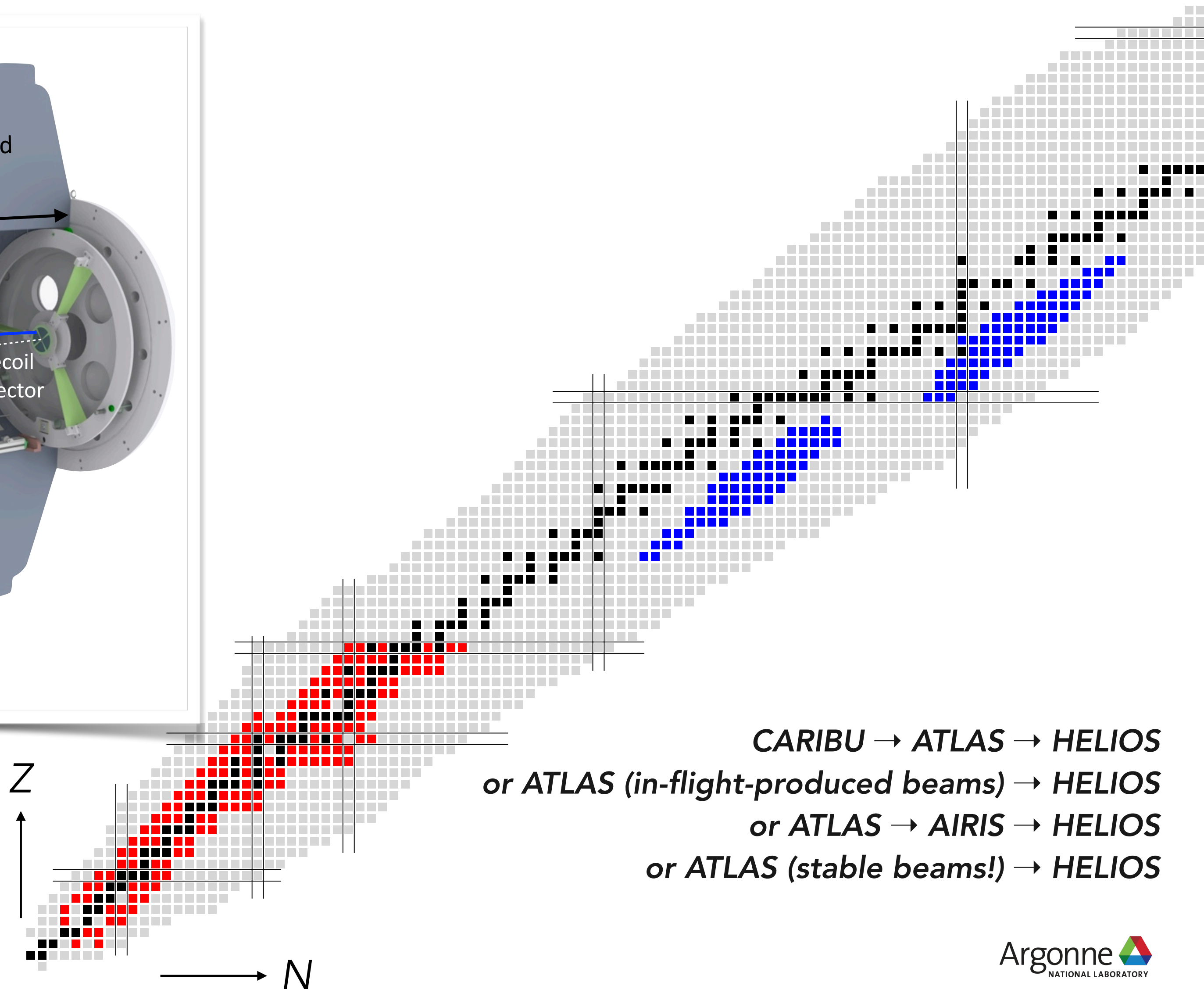
Transport through solenoid



- A simple **linear** relationship between energy and z, where the energy separation is (nearly) **identical** to the excitation energy in the residual nucleus.
- Removes **kinematic compression**.
- Factor of ~2.4 improvement in resolution (for this example)
- … and an MRI magnet seems ideal (in fact too good)

A helical orbit spectrometer





CARIBU → ATLAS → HELIOS
or ATLAS (in-flight-produced beams) → HELIOS
or ATLAS → AIRIS → HELIOS
or ATLAS (stable beams!) → HELIOS

Argonne and WMU and Manchester and others

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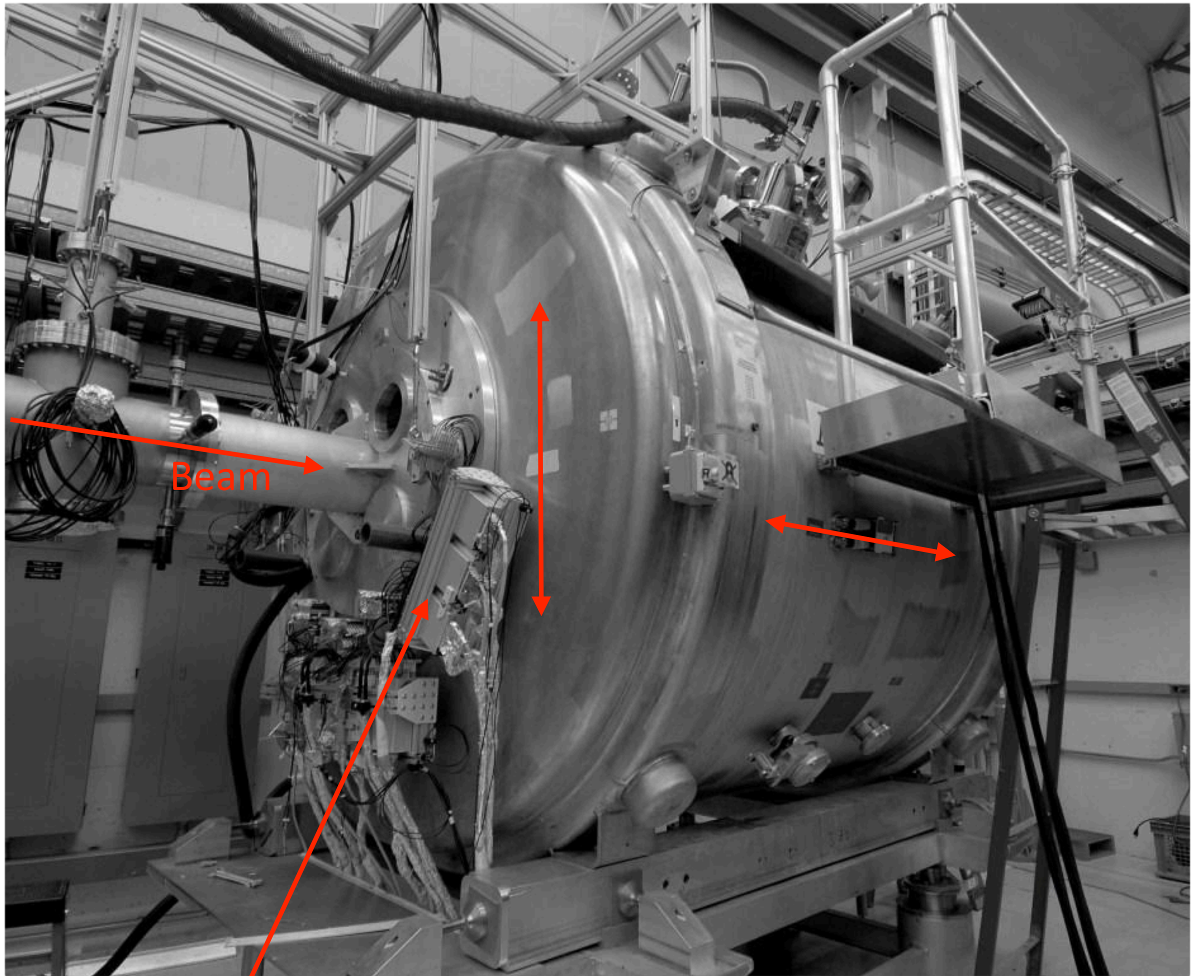
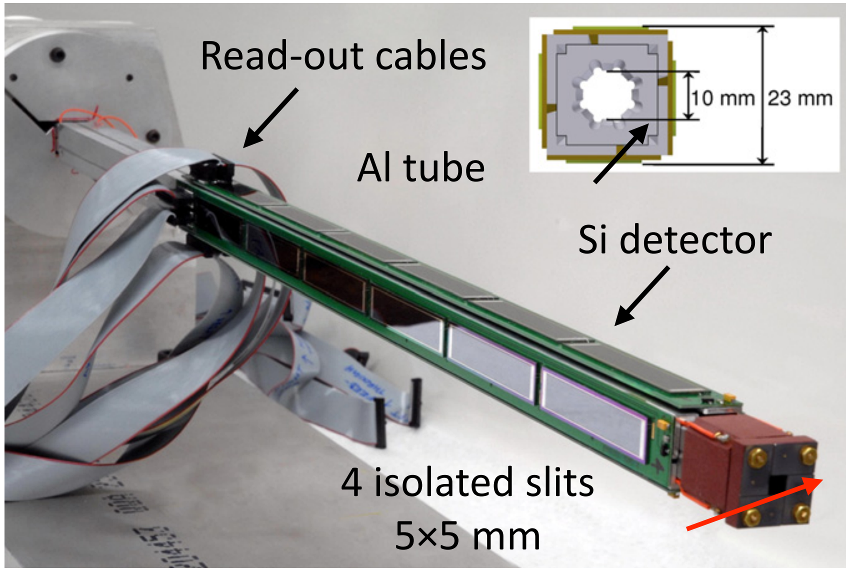
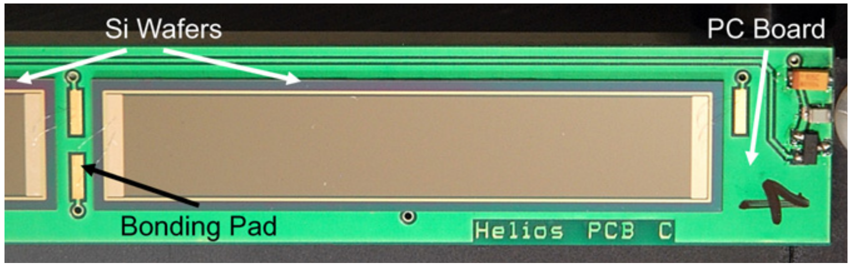
Photo from upstream



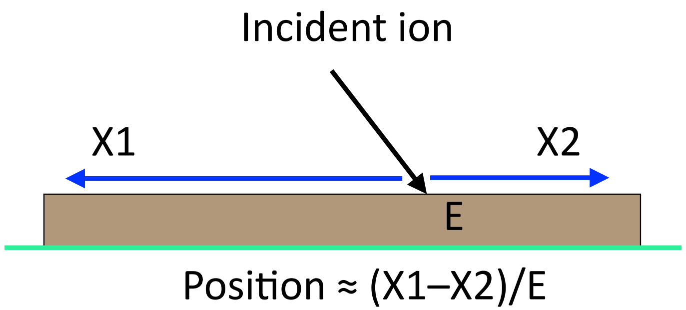
Preamps

Prototype Si array



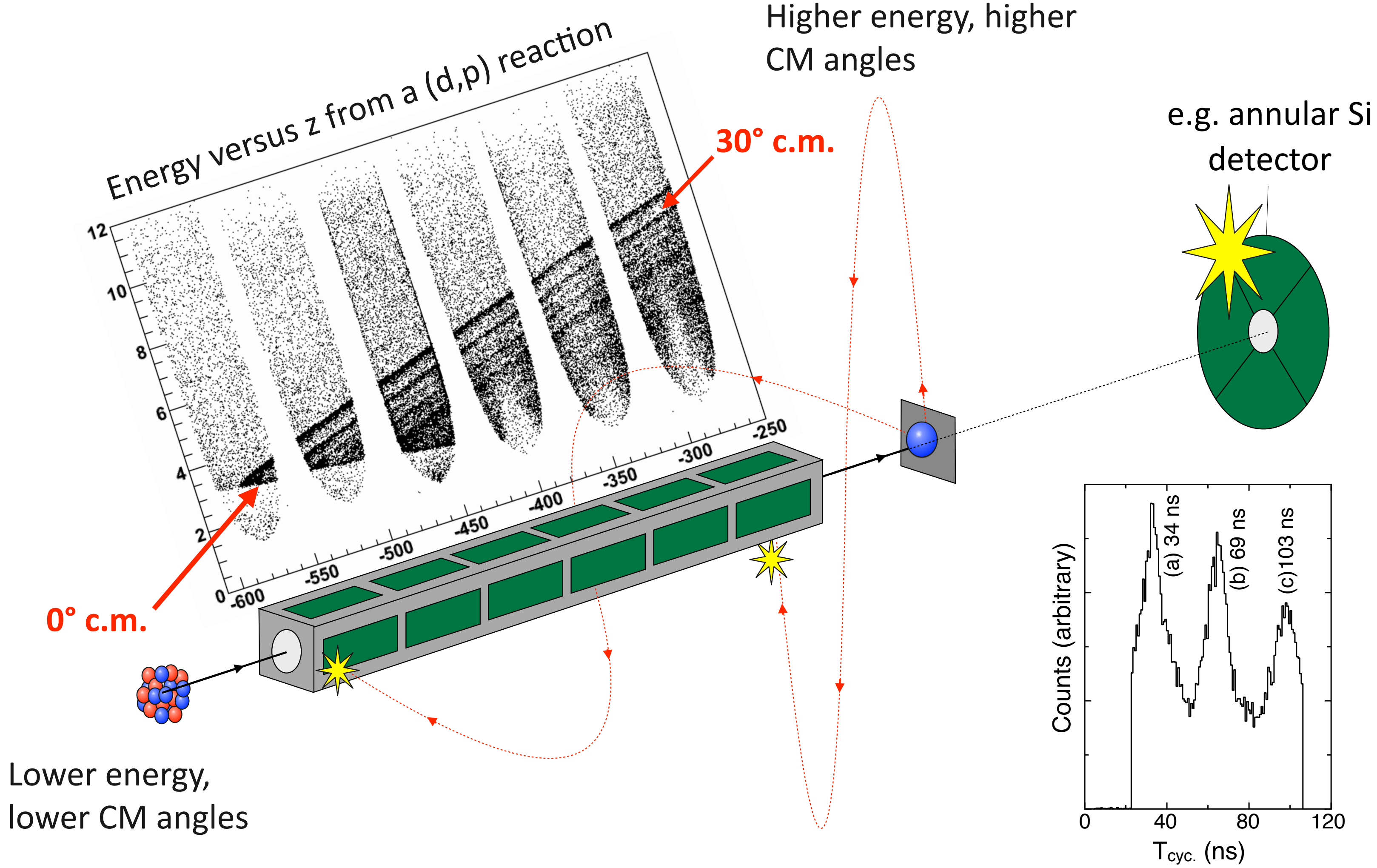


- 4 sides, 6 elements long
- Detector size, 9×50 mm
- 700-μm thick (e.g. ~10 MeV protons)
- Φ coverage, ***0.48 of 2π***
- $\Omega_{element}$ = 21 msr
- Ω_{array} = ***493 msr***



*J. C. Lighthall et al., Nucl. Instrum. Methods Phys. A **662**, 97 (2010)*

Motion of ions *(bad cartoon)*



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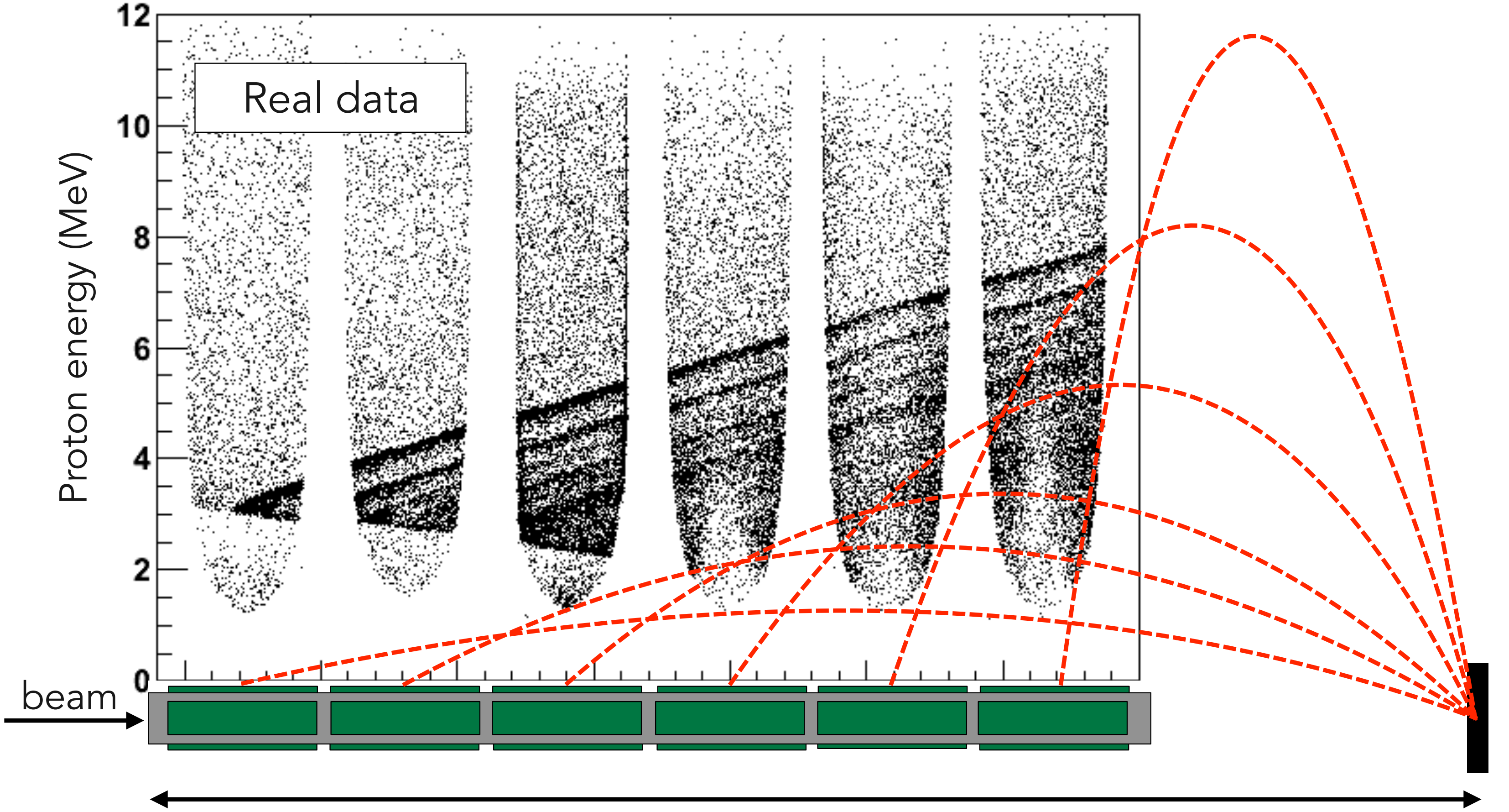
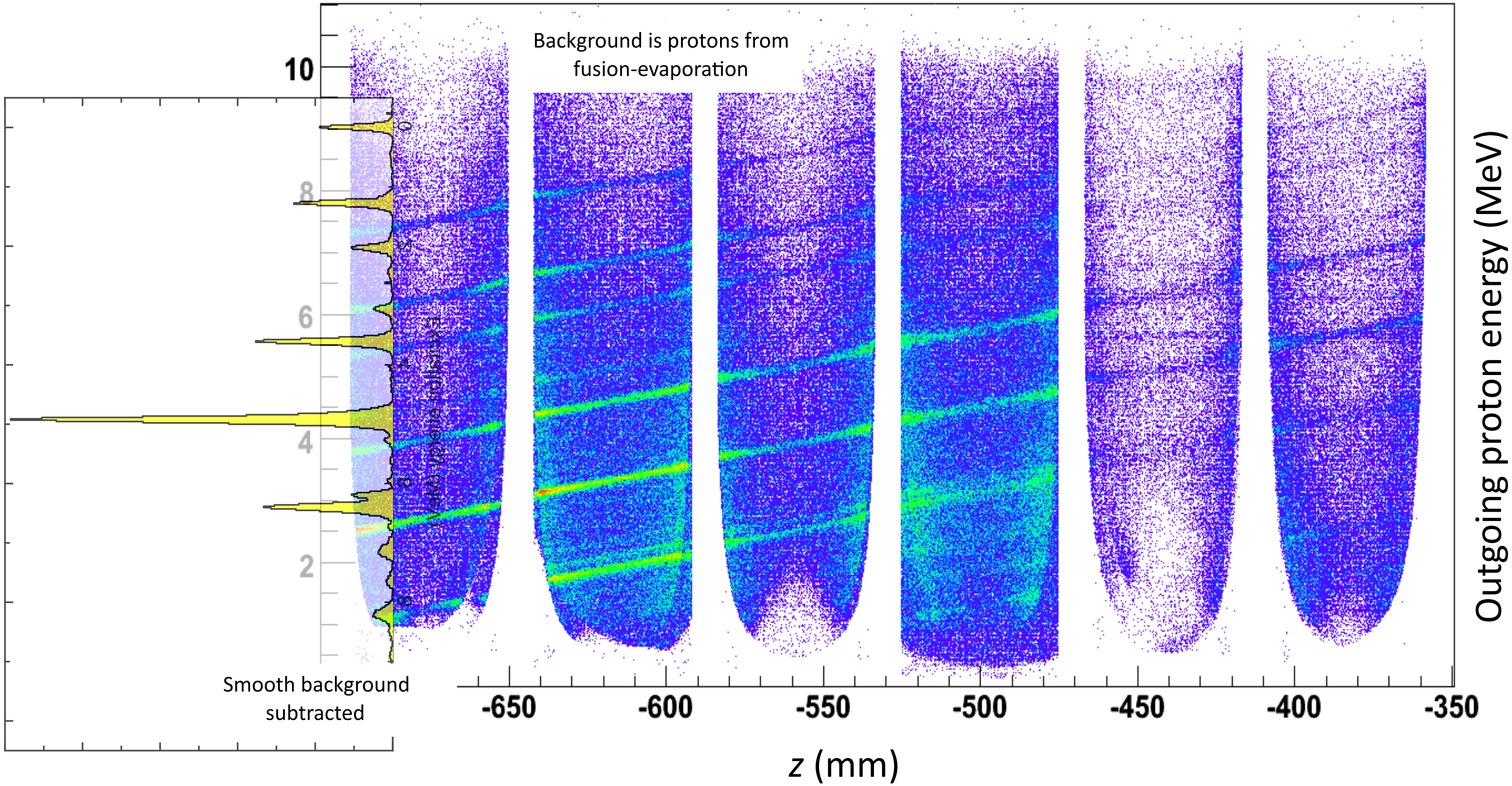
Energy, distance, time



z axis (also the beam axis, ***most of the time!***)

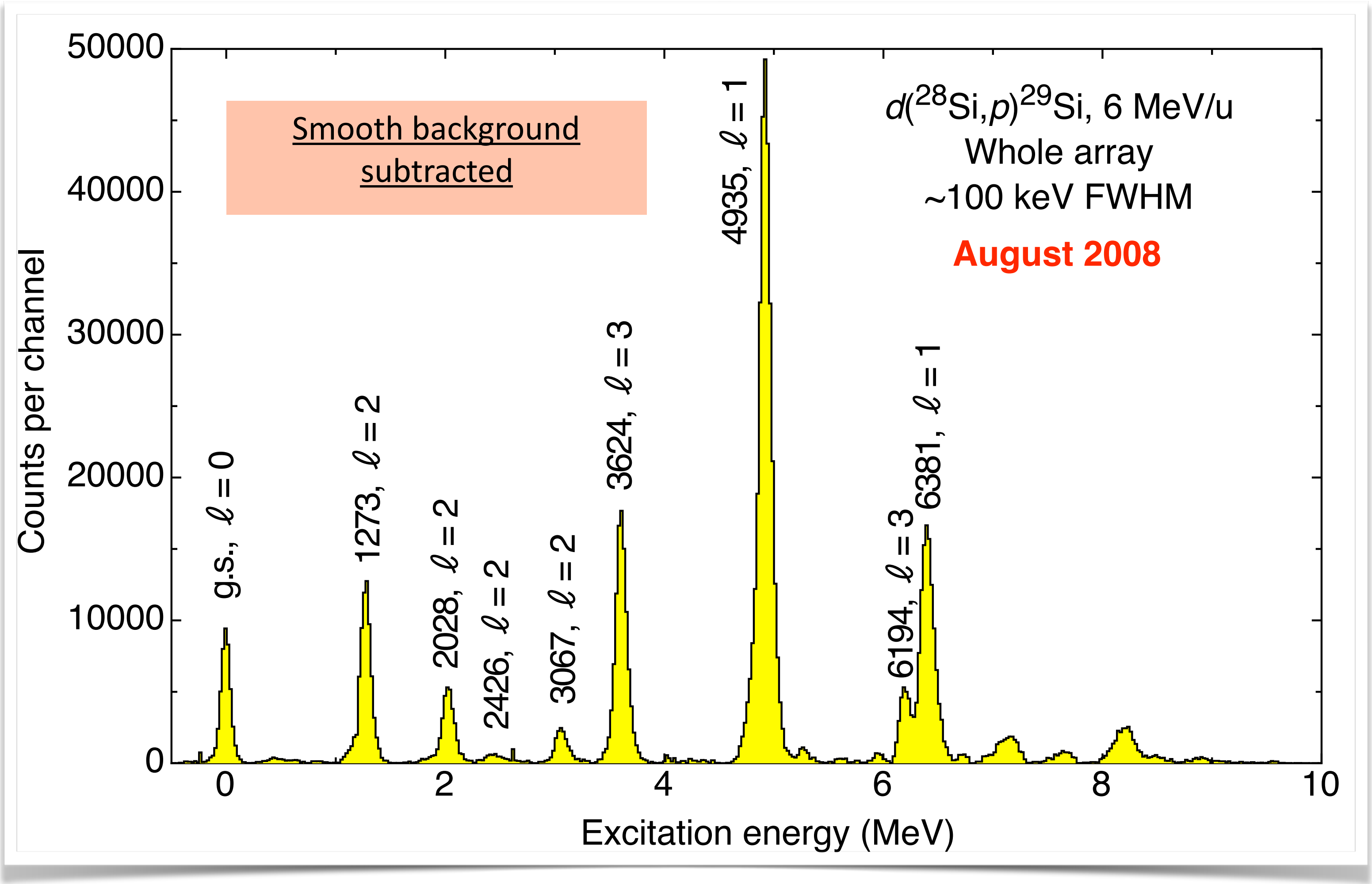
Note: array ~35-cm long, 4 sides, 6 detectors on each

Analysis



We measure E vs. *z*, which ***is*** the excitation-energy spectrum of the residual nucleus

Final analysis



*J. C. Lighthall et al., Nucl. Instrum. Methods Phys. A **662**, 97 (2010)*

Some milestones

Major component of the first 10 years of HELIOS has been instrument / technique R&D …
this has been a nontrivial exercise

- ***Tuning techniques (a major challenge)***
- ***Beam monitoring, absolute cross sections***
- Types of reactions (single-nucleon, pair, cluster, inelastic scattering, etc)
- Full multi-final body reconstruction (decays from unbound states, branching ratios)
- *Recoil detection* (fast ionization) [a talk in itself — still not ideal]
- *Gamma-ray detection* with Apollo (LaBr and CsI)
- *Gas targets* (for astrophysics)
- Electron spectroscopy

- Light masses ($A < 30$), ***mastered***
- Around $A \sim 130$-140 looks plausible soon
- AIRIS will be a game changer (Calem’s talk)

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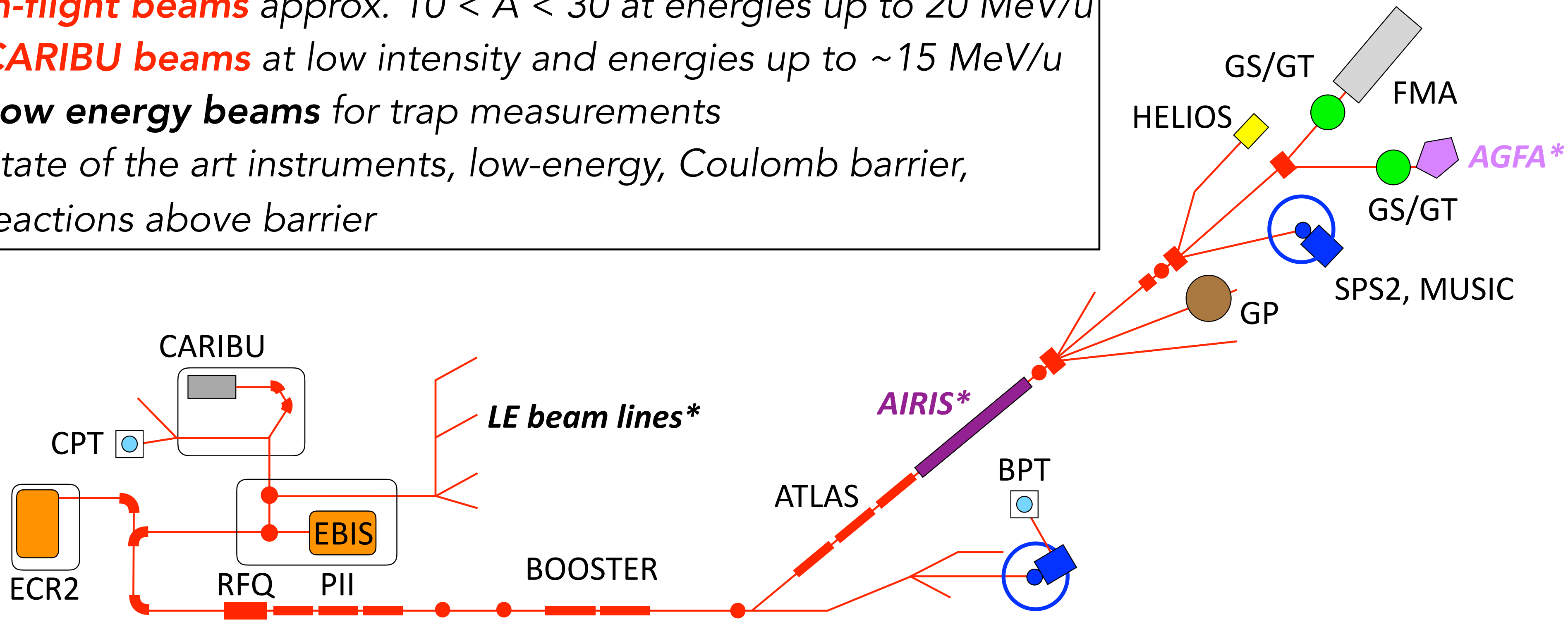
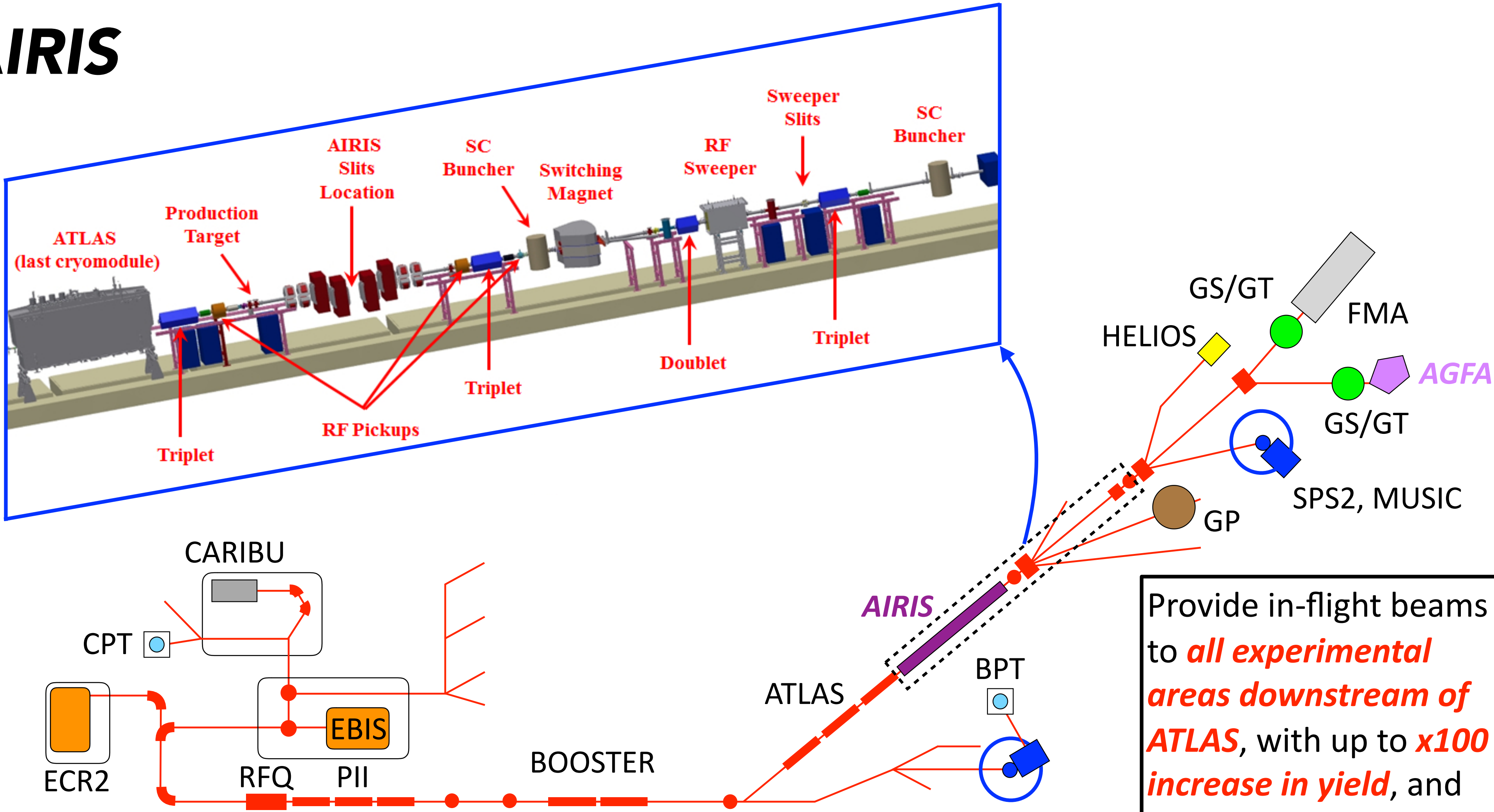
ATLAS (today and near future)

- ***Stable beams*** *at high intensity and energies up to 20 MeV/u*
- ***In-flight beams*** *approx. 10 < A < 30 at energies up to 20 MeV/u*
- ***CARIBU beams*** *at low intensity and energies up to ~15 MeV/u*
- ***Low energy beams*** *for trap measurements*
- *State of the art instruments, low-energy, Coulomb barrier, reactions above barrier*



*upcoming instruments / capabilities

AIRIS



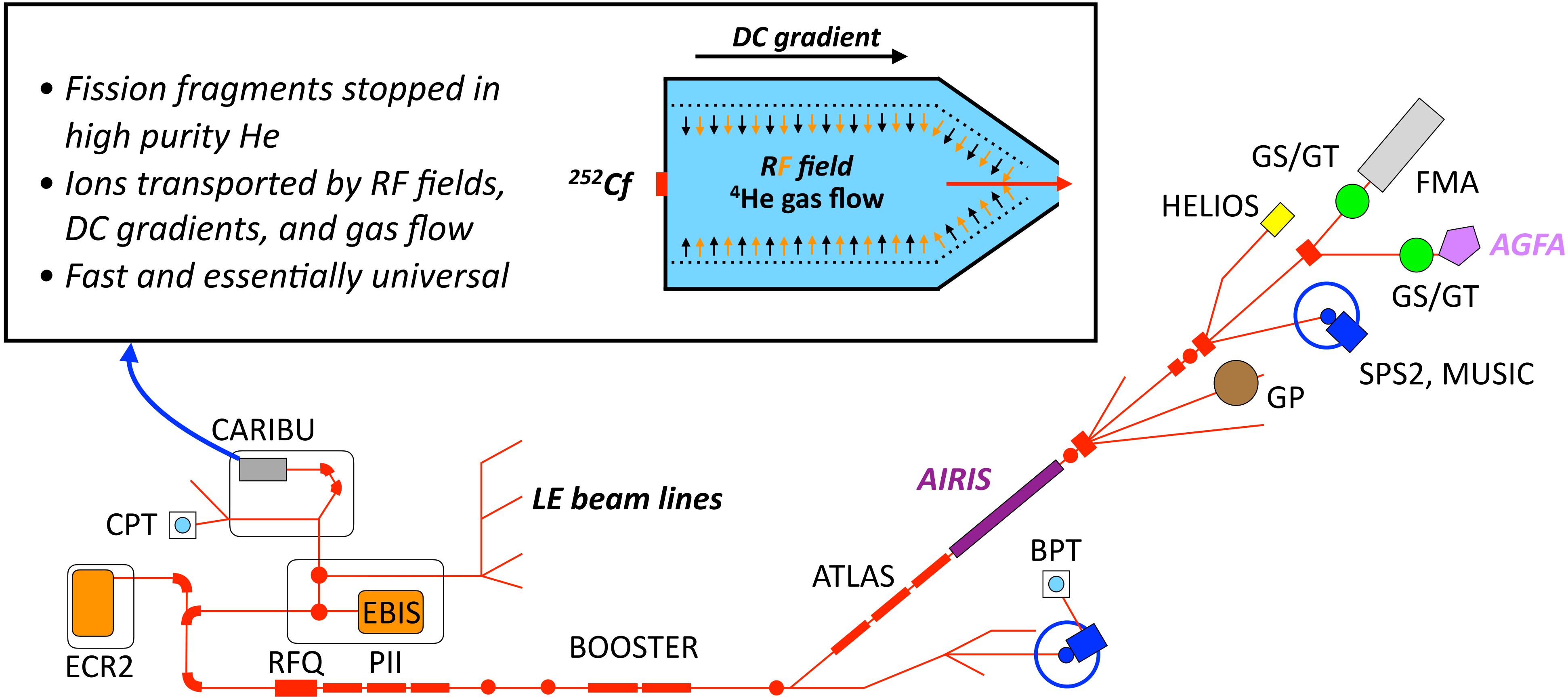
Provide in-flight beams to ***all experimental areas downstream of ATLAS***, with up to ***x100 increase in yield***, and access to ***higher mass beams***

Primary beam from ATLAS, a few to 20 MeV/u, <few pμA

See e.g. website *http://www.phy.anl.gov/airis/index.html*

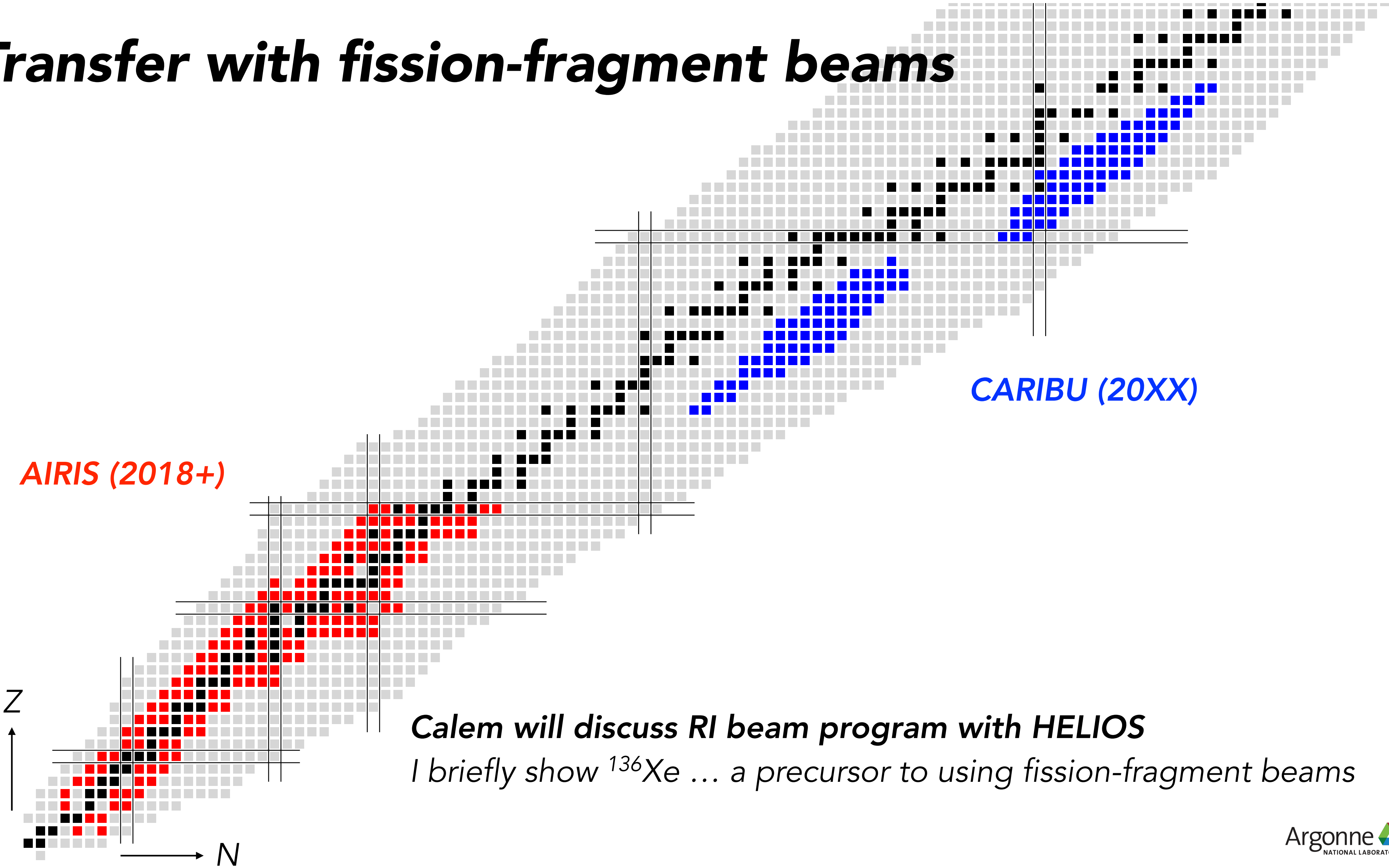
CARIBU

- *Fission fragments stopped in high purity He*
- *Ions transported by RF fields, DC gradients, and gas flow*
- *Fast and essentially universal*



EBIS source has been installed, commissioned, and beam accelerated
N.B. 2015 campaign used the ECR1 ion source for CARIBU beams
CARIBU: G. Savard et al., Hyperfine Interactions 199, 301 (2011)

Transfer with fission-fragment beams



Calem will discuss RI beam program with HELIOS

I briefly show ^{136}Xe … a precursor to using fission-fragment beams

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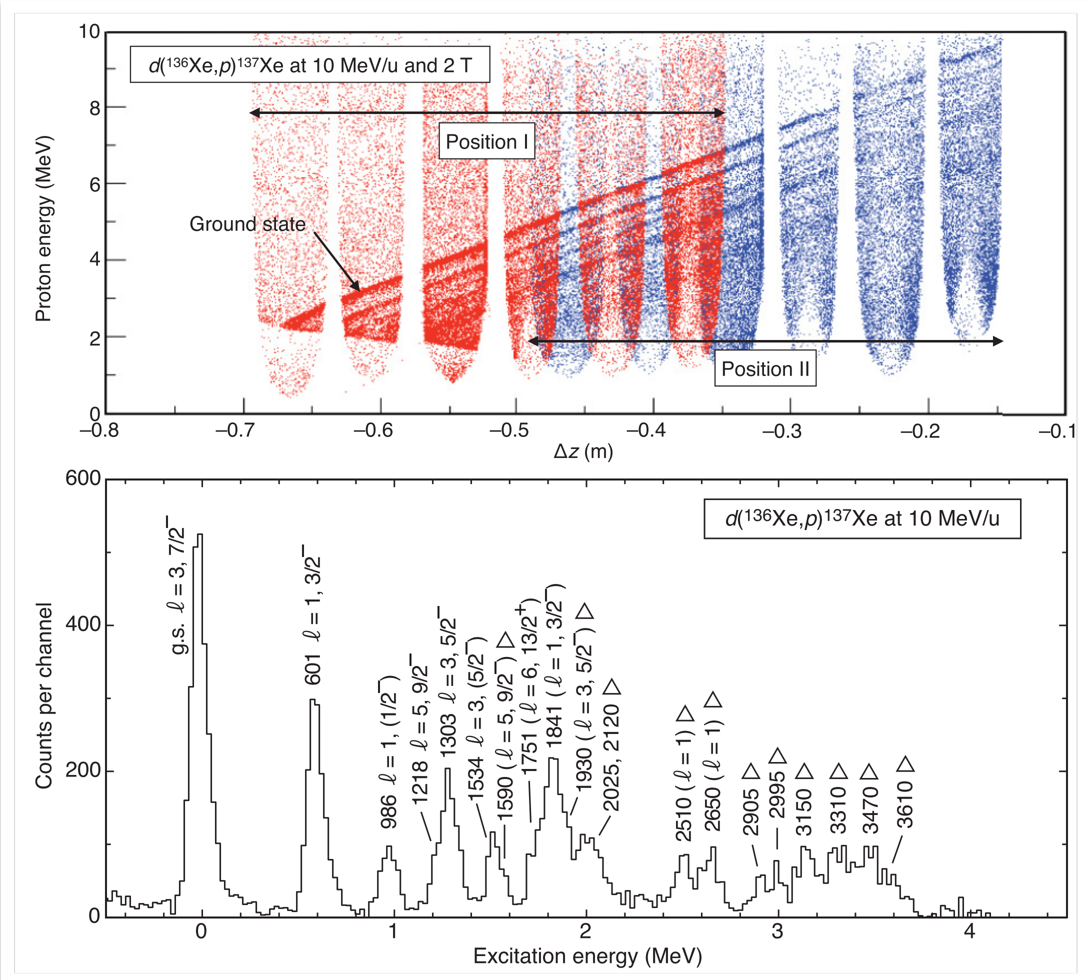
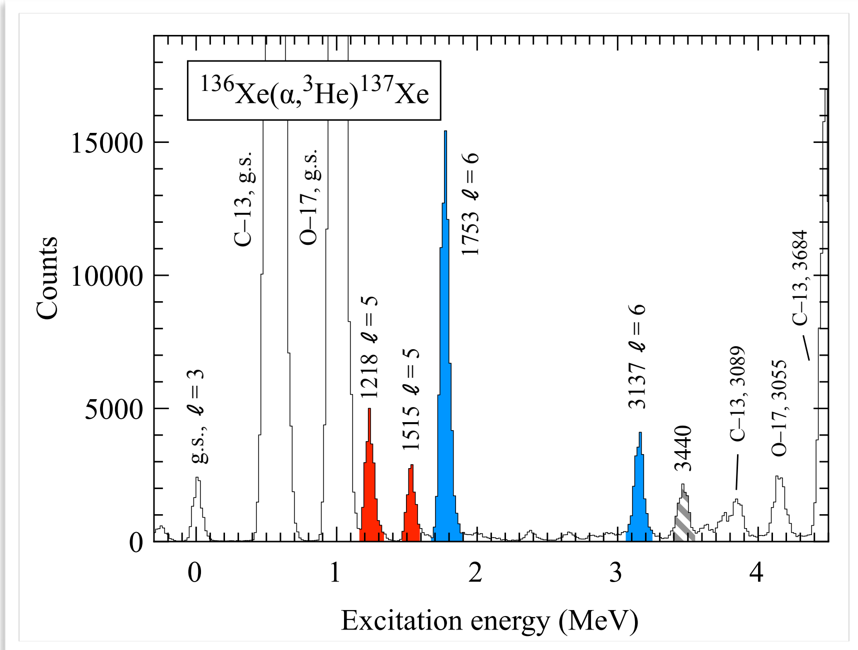
A 10 MeV/u study of ^{137}Xe via (d,p)



*Cautionary tale though — high-j states are tough (though results [C^{2}S] comparable). It is likely the **improved resolution** of ISS will help.*



*Kay et al., Phys. Rev. C **84**, 024325 (2011) and Talwar et al., to appear in Phys. Rev. C 2017*

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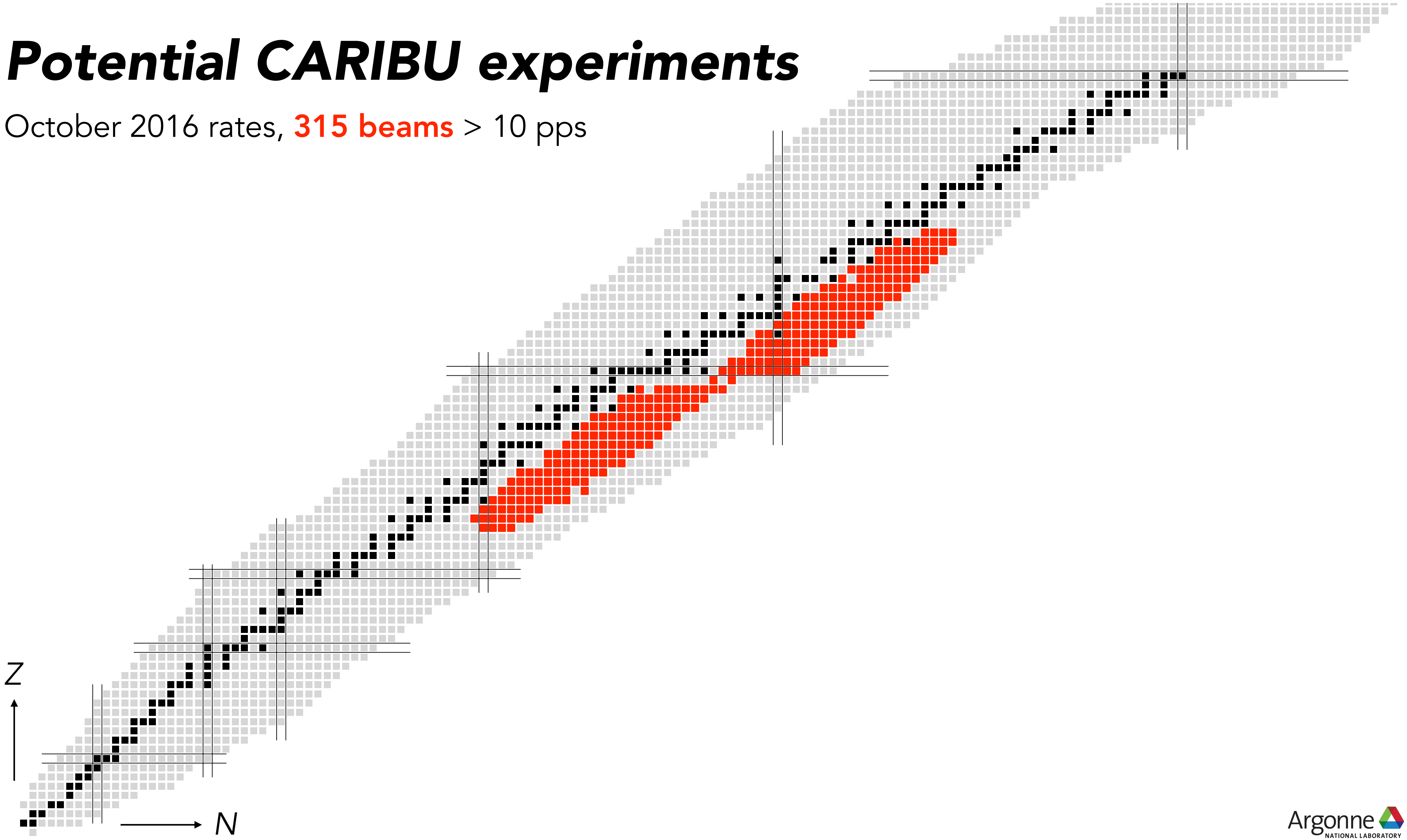
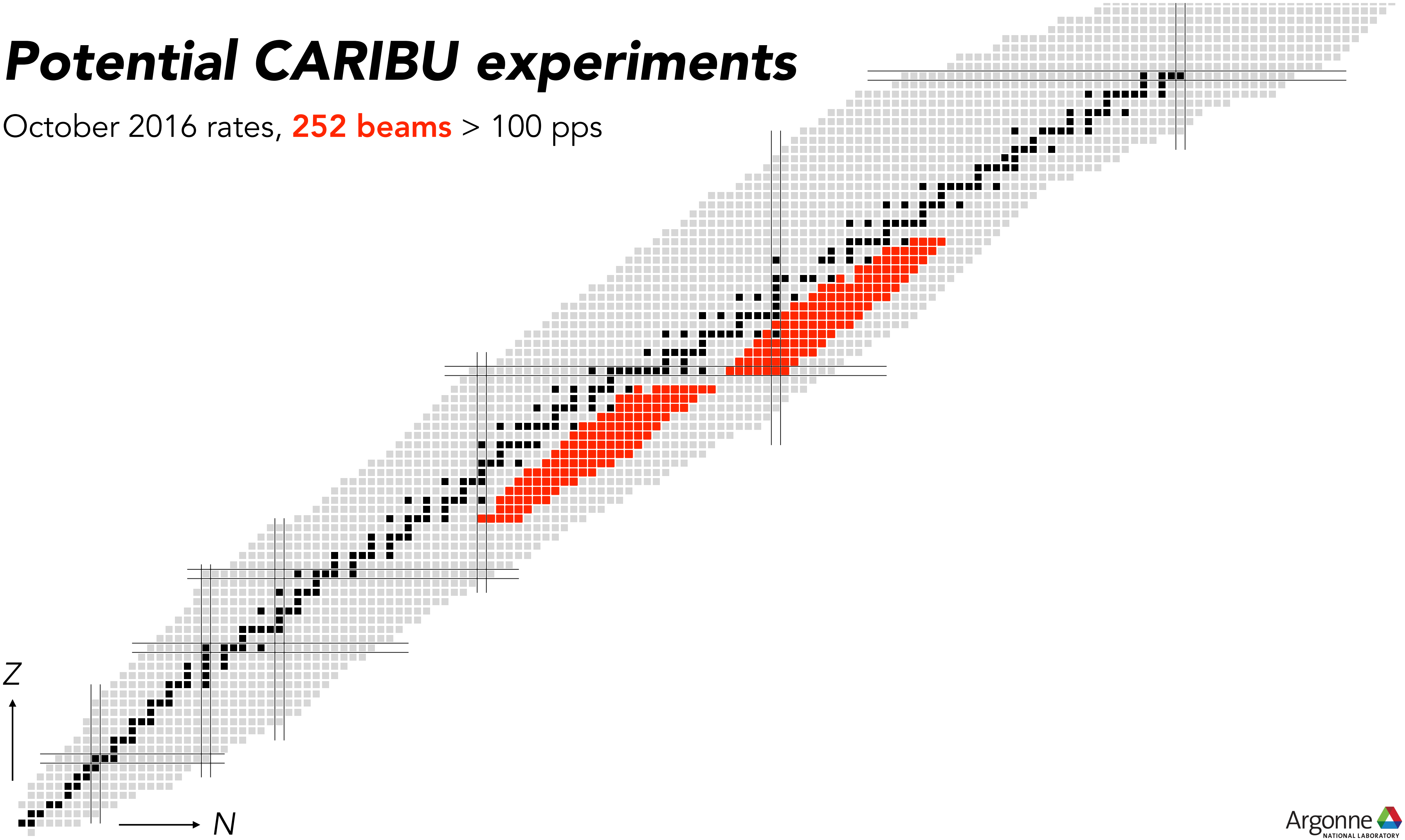
Potential CARIBU experiments

October 2016 rates, **315 beams** > 10 pps



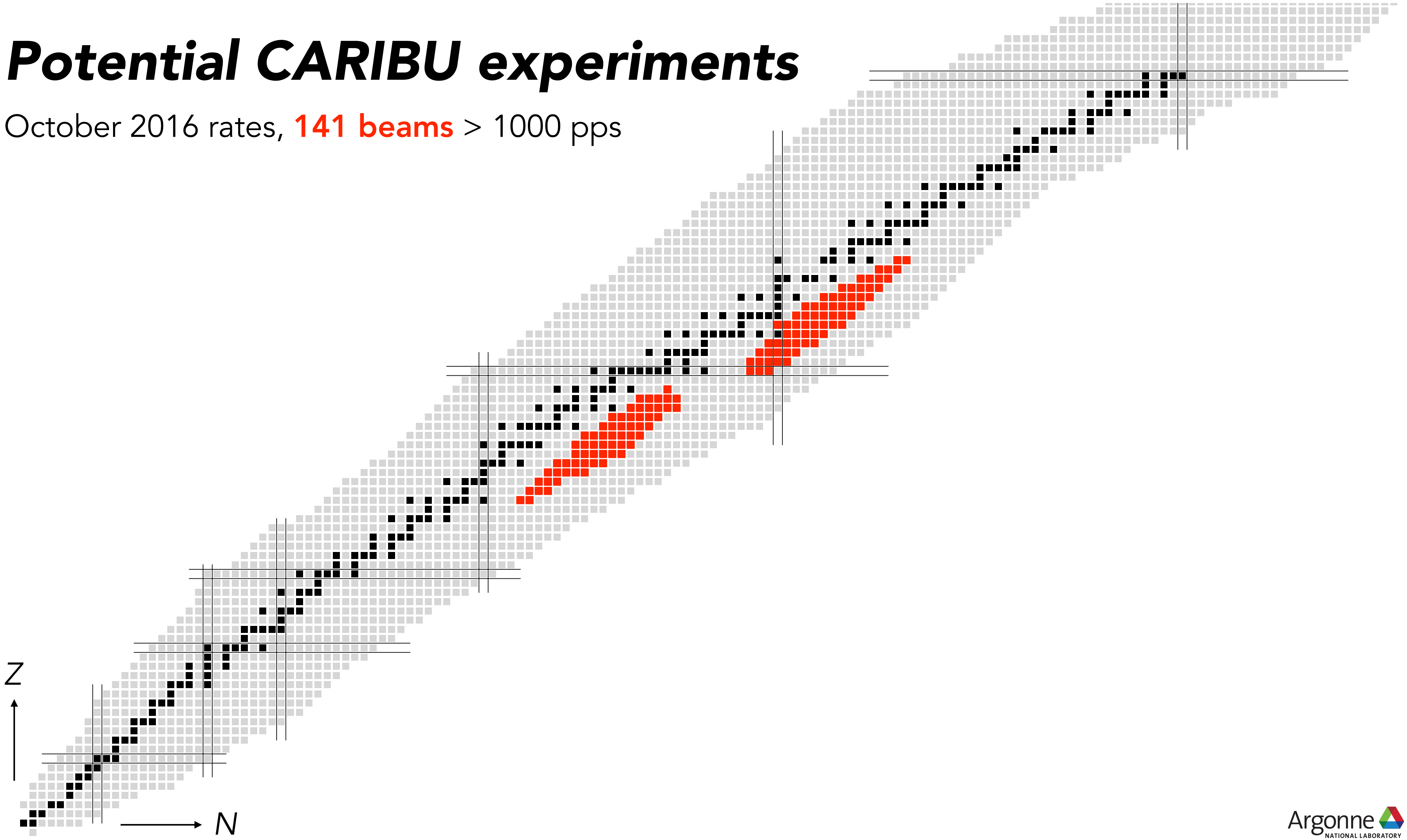
Potential CARIBU experiments

October 2016 rates, **252 beams** > 100 pps



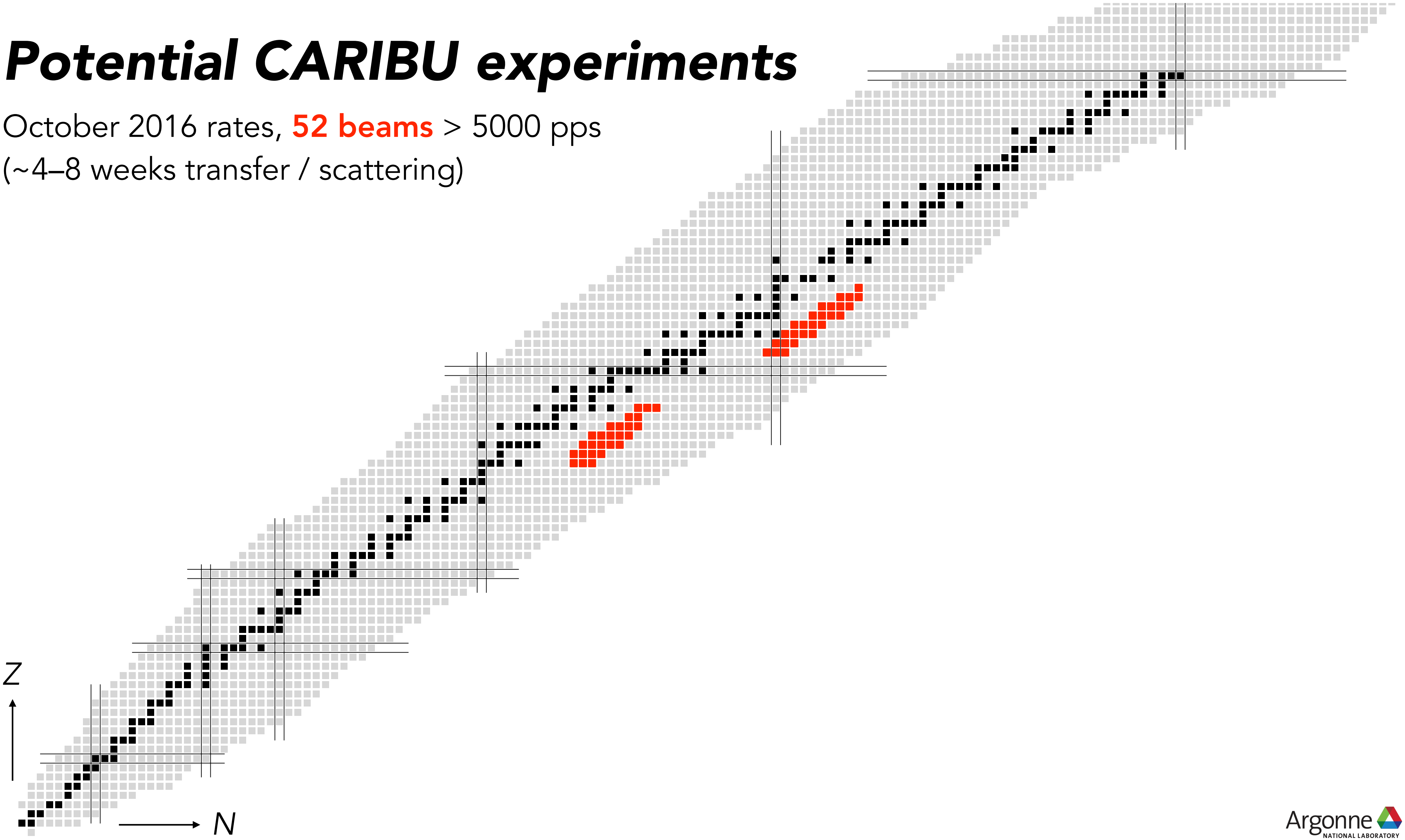
Potential CARIBU experiments

October 2016 rates, **141 beams** > 1000 pps



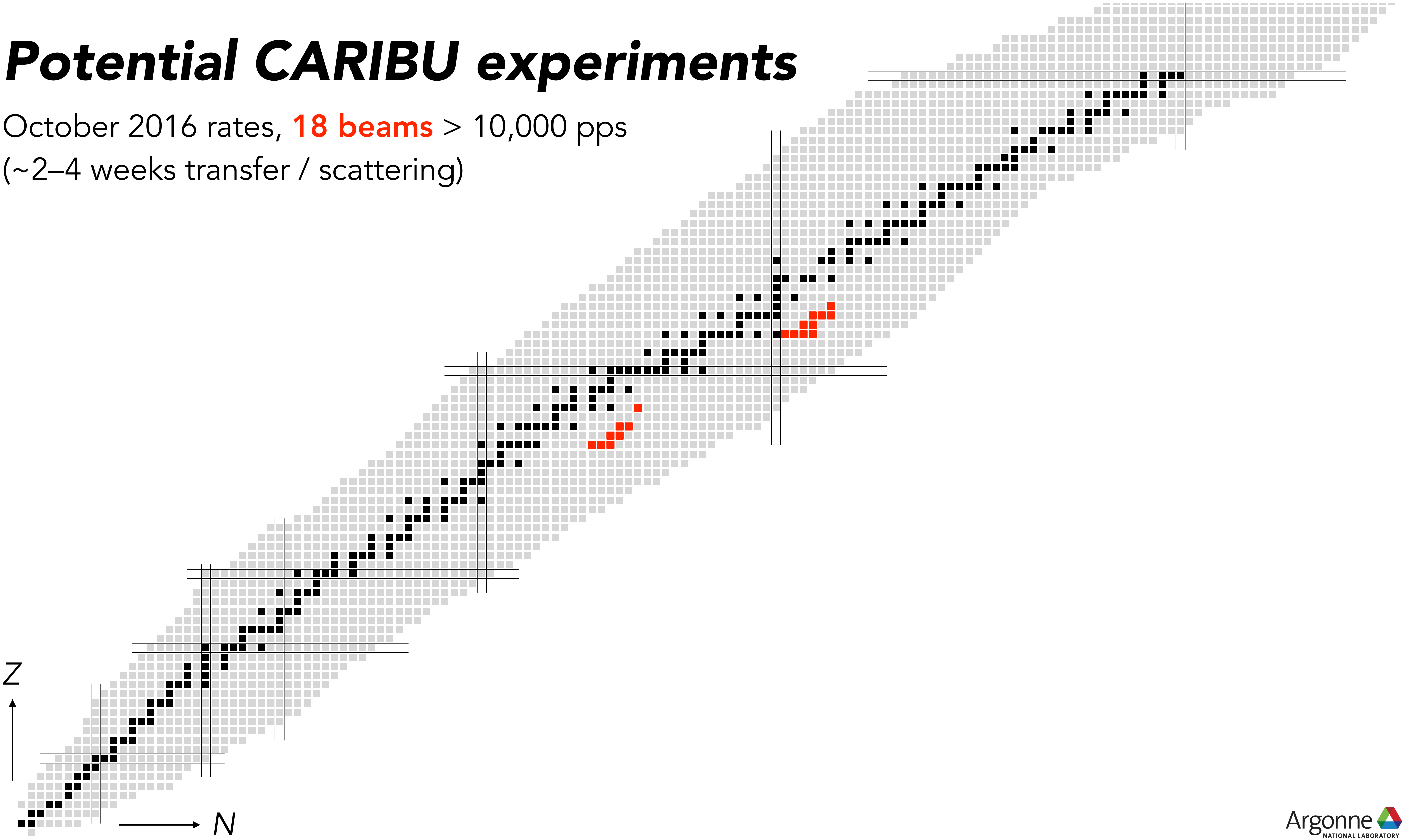
Potential CARIBU experiments

October 2016 rates, **52 beams** > 5000 pps
(~4–8 weeks transfer / scattering)



Potential CARIBU experiments

October 2016 rates, **18 beams** > 10,000 pps
(~2–4 weeks transfer / scattering)



Potential CARIBU experiments

October 2016 rates, **18 beams** > 10,000 pps
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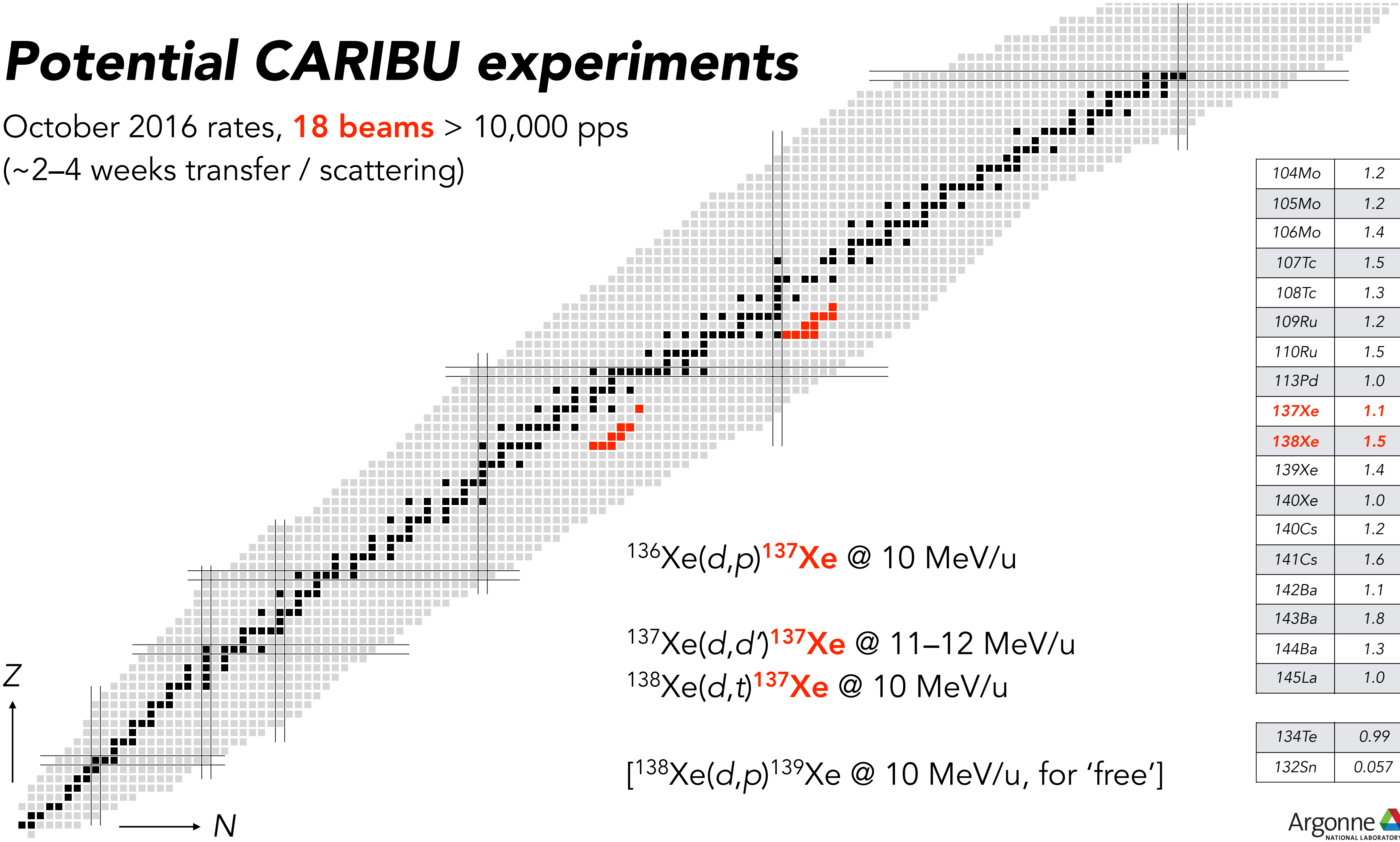

^{136}Xe(*d*,*p*)^{137}**Xe** @ 10 MeV/u

^{137}Xe(*d*,*d'*)^{137}**Xe** @ 11–12 MeV/u
^{138}Xe(*d*,*t*)^{137}**Xe** @ 10 MeV/u

[^{138}Xe(*d*,*p*)^{139}Xe @ 10 MeV/u, for 'free']

104Mo	1.2
105Mo	1.2
106Mo	1.4
107Tc	1.5
108Tc	1.3
109Ru	1.2
110Ru	1.5
113Pd	1.0
137Xe	**1.1**
138Xe	**1.5**
139Xe	1.4
140Xe	1.0
140Cs	1.2
141Cs	1.6
142Ba	1.1
143Ba	1.8
144Ba	1.3
145La	1.0

134Te	0.99
132Sn	0.057

What could be done next?

In context of this work, ***^{134}Te(d,p) is obvious*** … and approved

^{143}Nd is a nucleus where "complete" spectroscopy has been done:
^{142}Nd(*d,p*)^{143}Nd — singles-particle states
^{143}Nd(*d,d'*)^{143}Nd — particles coupled to the surface vibrations
^{144}Nd(*d,t*)^{143}Nd — holes coupled to pairing vibration

Maybe we could do the same with ^{137}Xe? And potentially lower Z systems in time with either CARIBU or ISOLDE

Gd-146	Gd-148	Gd-148
Eu-145	Eu-146	Eu-147
Sm-144	Sm-145	Sm-146
Pm-143	Pm-144	Pm-145
Nd-142	Nd-142	Nd-142
Pr-141	Pr-142	Pr-143
Ce-140	Ce-141	Ce-142
La-139	La-140	La-141
Ba-138	Ba-139	Ba-140
Cs-137	Cs-138	Cs-139
Xe-136	Xe-137	Xe-138
I-135	I-136	I-137
Te-134	Te-135	Te-136
Sb-133	Sb-134	Sb-135
Sn-132	Sn-133	Sn-134
***N*=82**		***N*=84**

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FRIB and SOLARIS

- FRIB will be the US flagship nuclear physics lab. It is progressing at an outstanding rate
- Has a major reaccelerated beam component, ReAX, where X is around 3 currently
- ‘Fast beams’ and a reaccelerated beam program
- Instrumentation is king, natural to develop a solenoid spec (HELIOS and a “super HELIOS” discussed in 2009, and every year since)
- The ‘model’ will be similar to the European ISS one. A 4-T solenoid being home to a Si array spectrometer and an active target system

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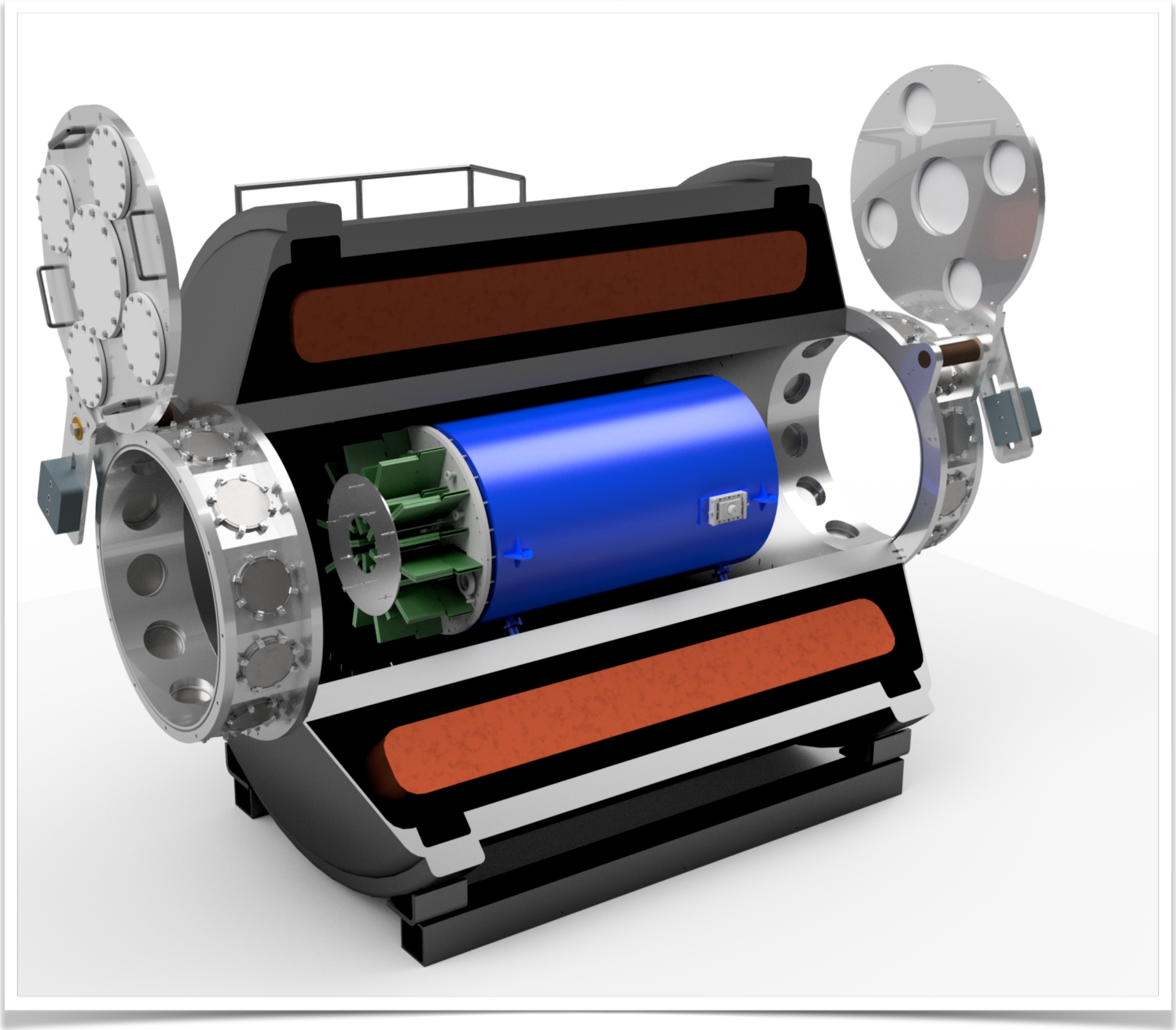
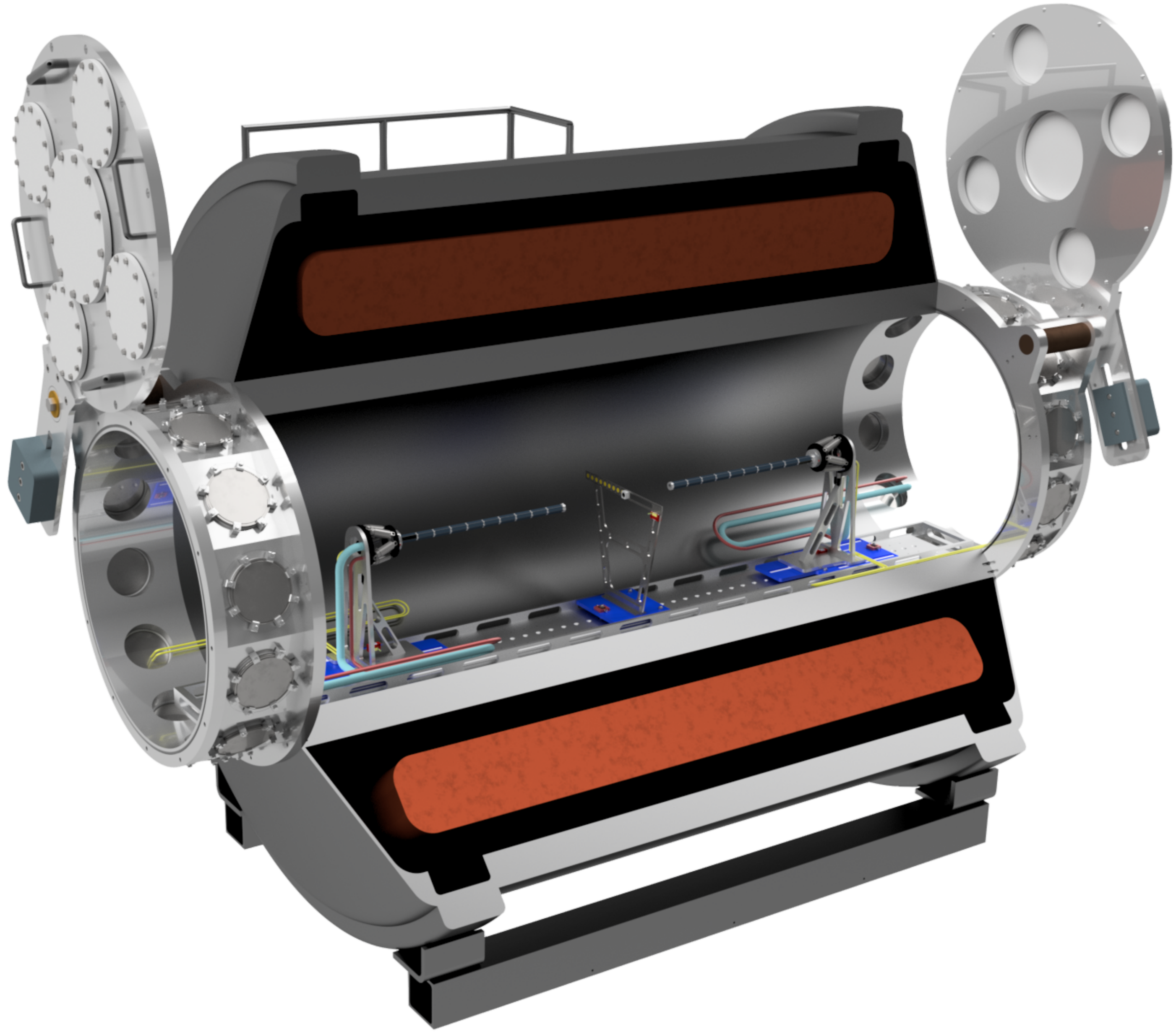
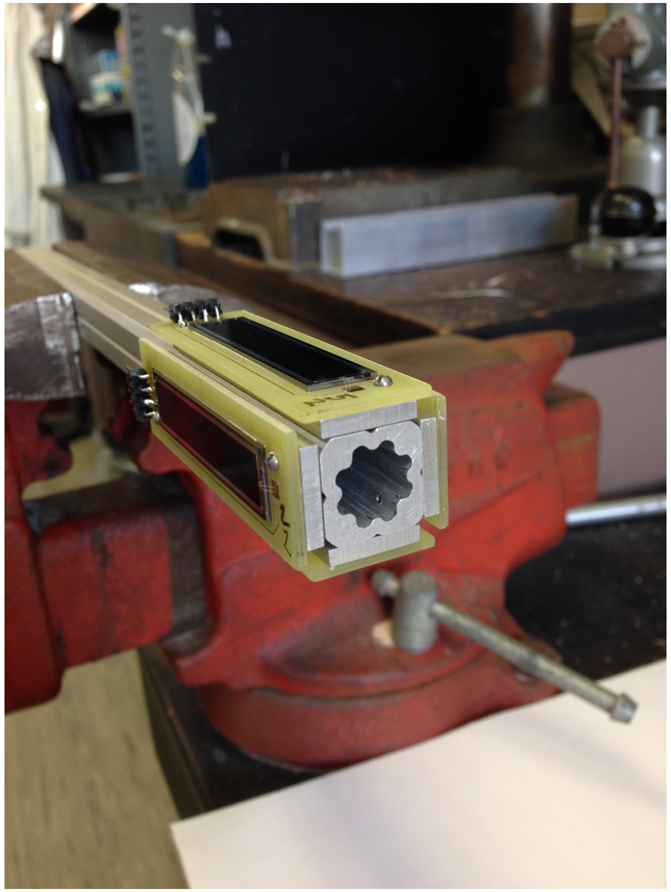


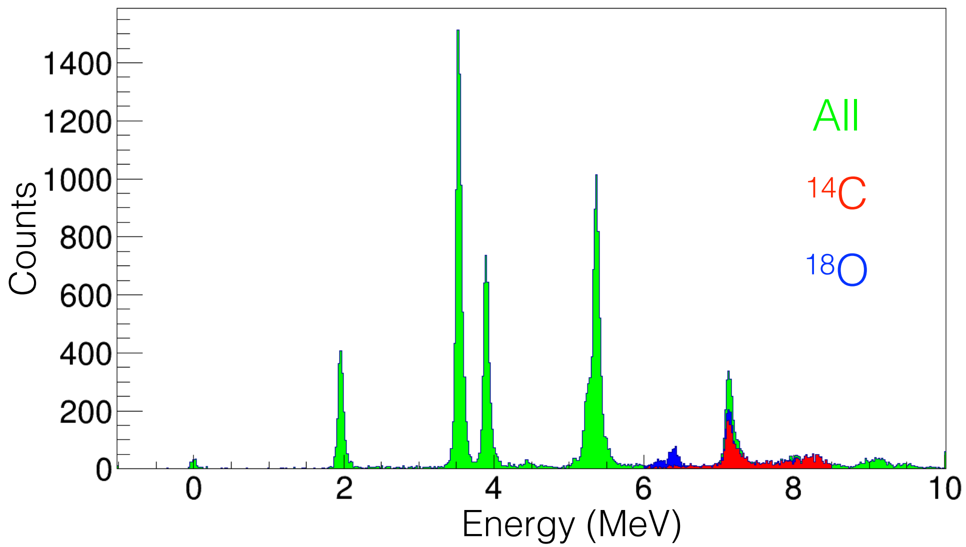
Brad DiGiovine, Argonne (chief engineer/designer on SOLARIS project) — concept



Upcoming HELIOS run



^{6}He(d,d'), (d,p) run and the “stub” array … our first ‘dual array’ measurement. Likely a nice way to commission the ISS ‘stub’ array



Jie Chen, FRIB-China fellow, Argonne (End of August 2017)

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Summary

Solenoid spectrometers offer a very attractive approach to studying transfer and inelastic scattering reactions

- ➡ *simple set ups, good resolution, outstanding efficiency, highly versatile*

The success of the ANL device evident from published results

- ➡ *It is now being emulated elsewhere*

The technique is still relatively new. Lots of scope for improvements. Higher B-field devices and exciting facilities coming …