Research Opportunities with HELIOS

Ben Kay, Argonne National Laboratory

Workshop on Nuclear Astrophysics Opportunities at ATLAS 2019

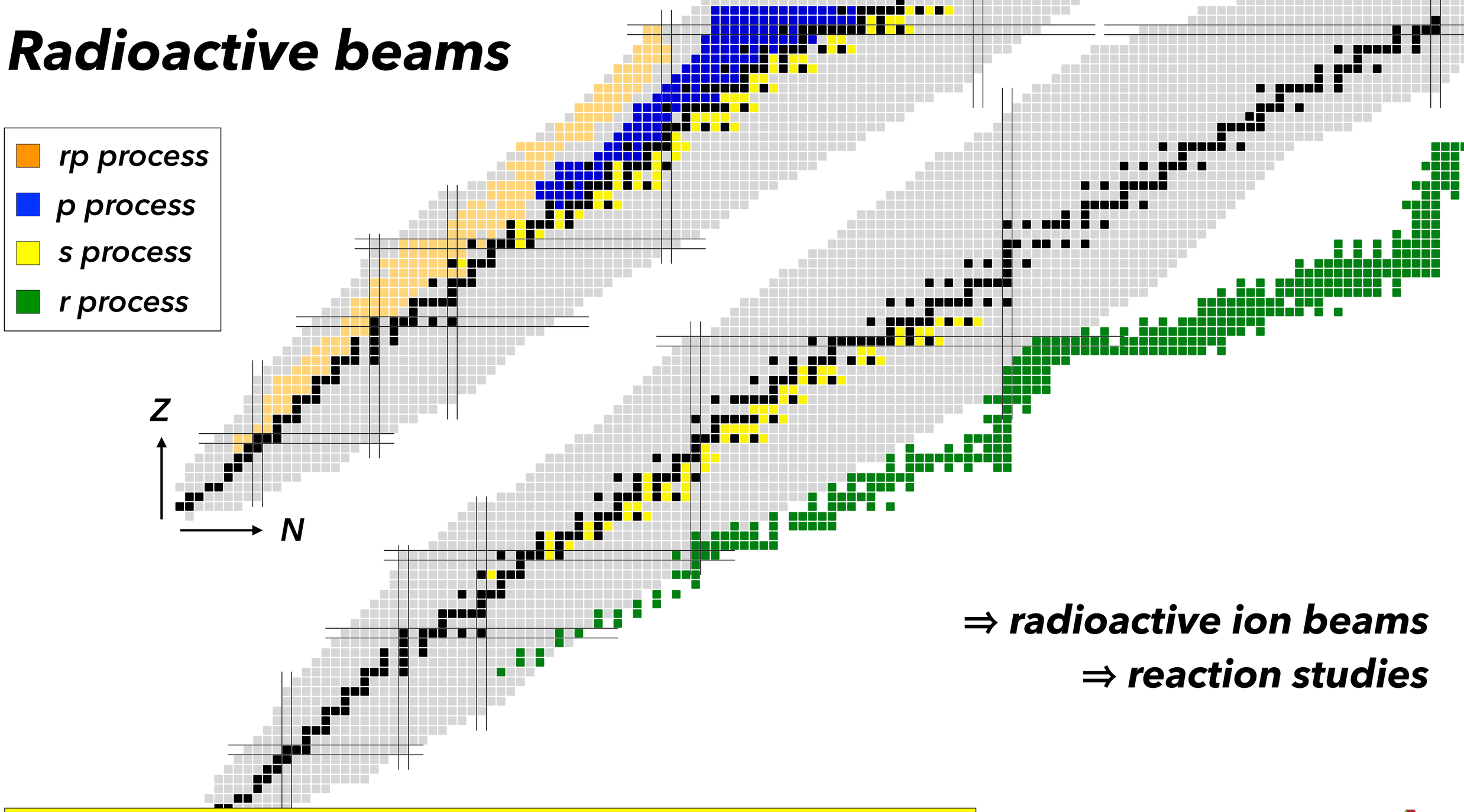
Overview

The HELIOS spectrometer as a tool for nuclear astrophysics

- *Nucleosynthesis => Direct reactions with RI beams*
- *Why the solenoidal spectrometer solution?*
- *HELIOS at ATLAS, so far*
- *Challenges and opportunities*

www.anl.gov/phy/helical-orbit-spectrometer

Radioactive beams



⇒ *radioactive ion beams*

⇒ *reaction studies*

Nuclei involved in the rp-, p-, and s-process M. S. Smith and K. E. Rehm, Annu. Rev. Nucl. Part. Sci. ***51****, 91 (****2001****)*

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Reaction studies

~10 MeV/u (3-20 MeV/u), >10^4 pps (stable and radioactive)

Reactions used as a tool in nuclear astrophysics:

- *Populate states / determine E, j^π*
- *Cross sections → rates*
- *Cross section → overlaps*
- *Exploit mirror systems*

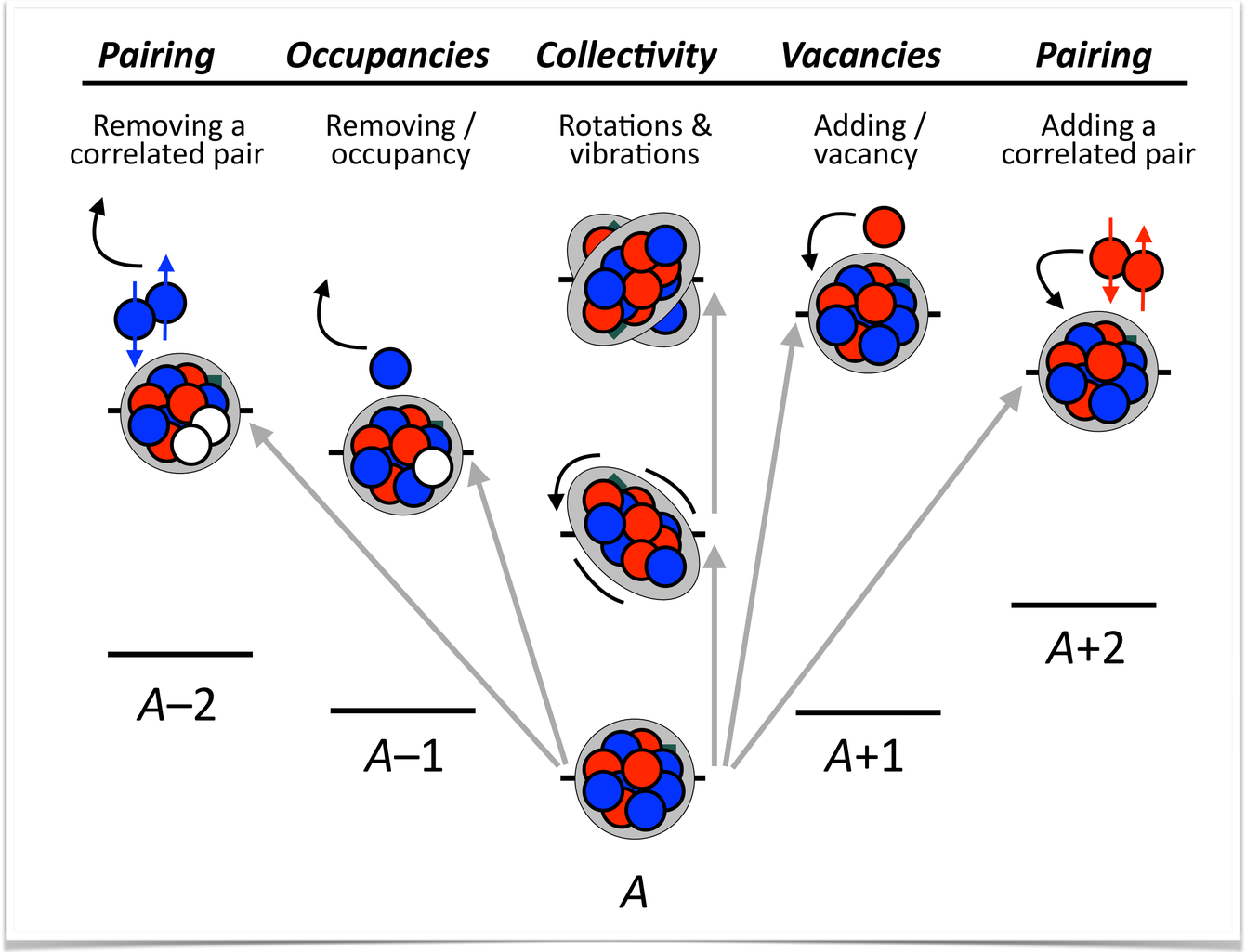
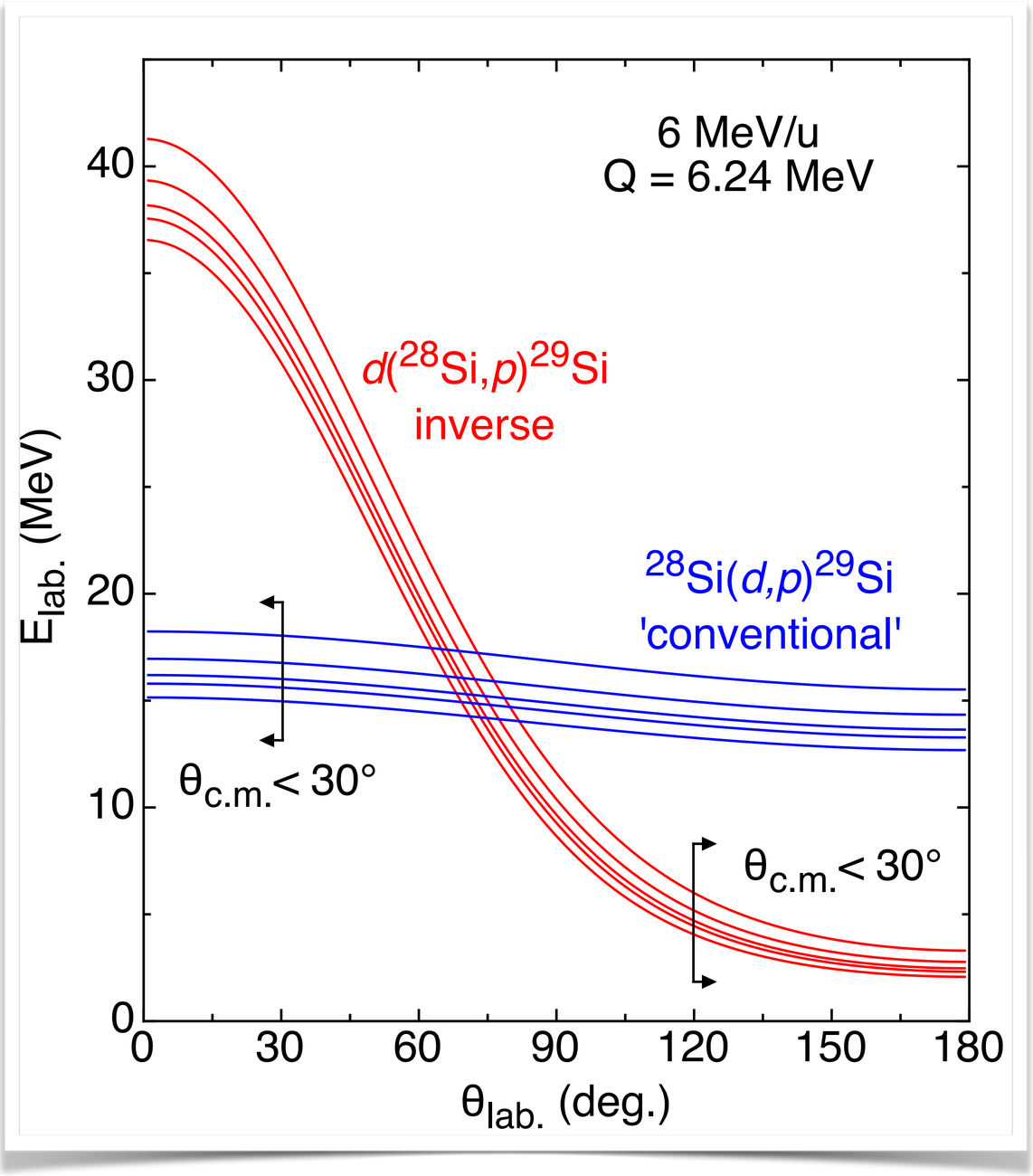


Figure inspired by B. B. Back

Kinematics: normal vs. inverse



In contrast to normal kinematics

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

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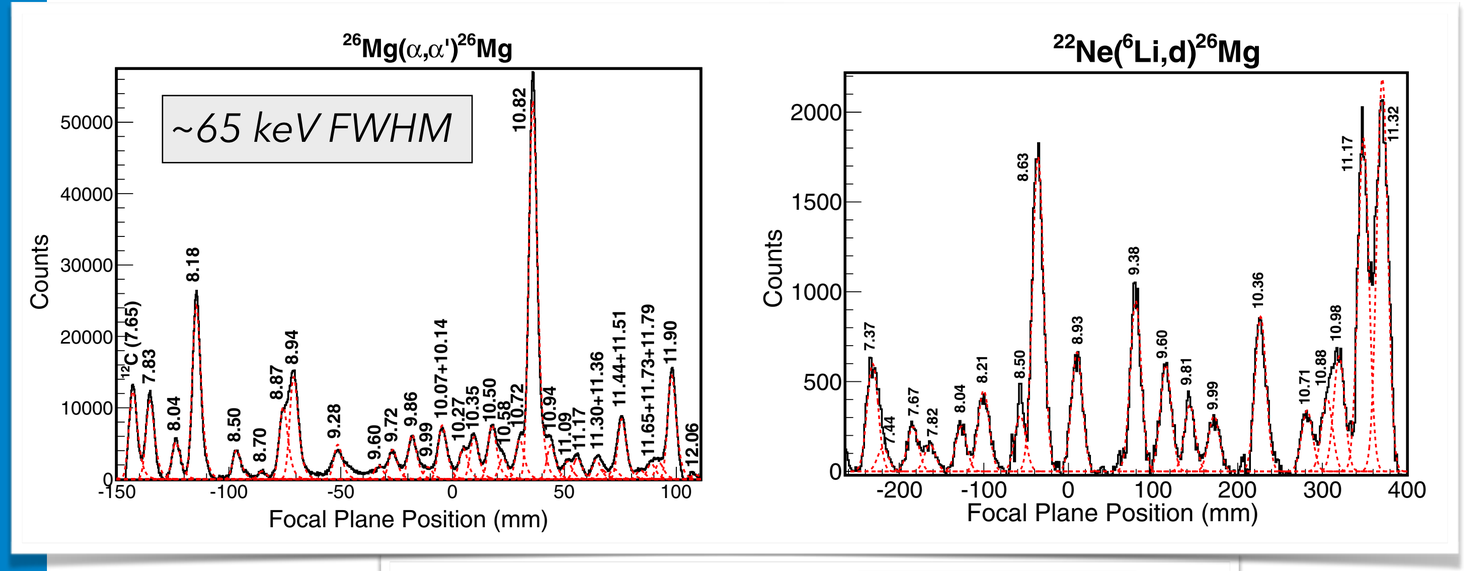
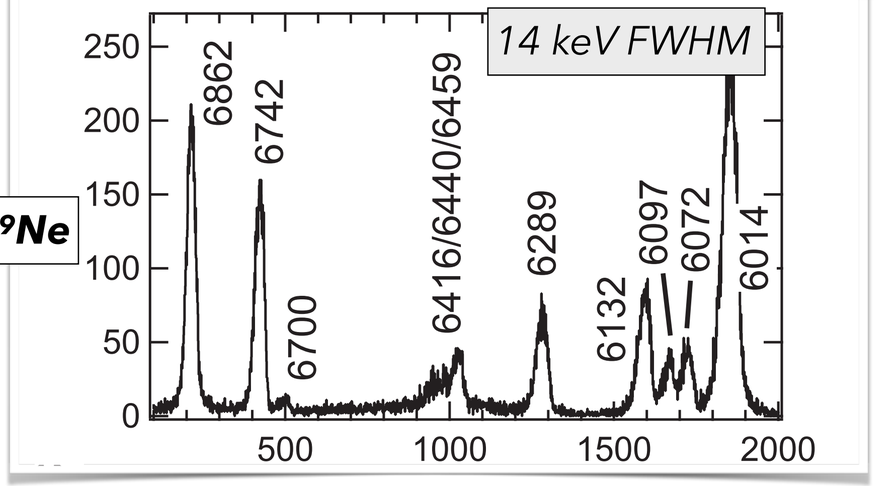
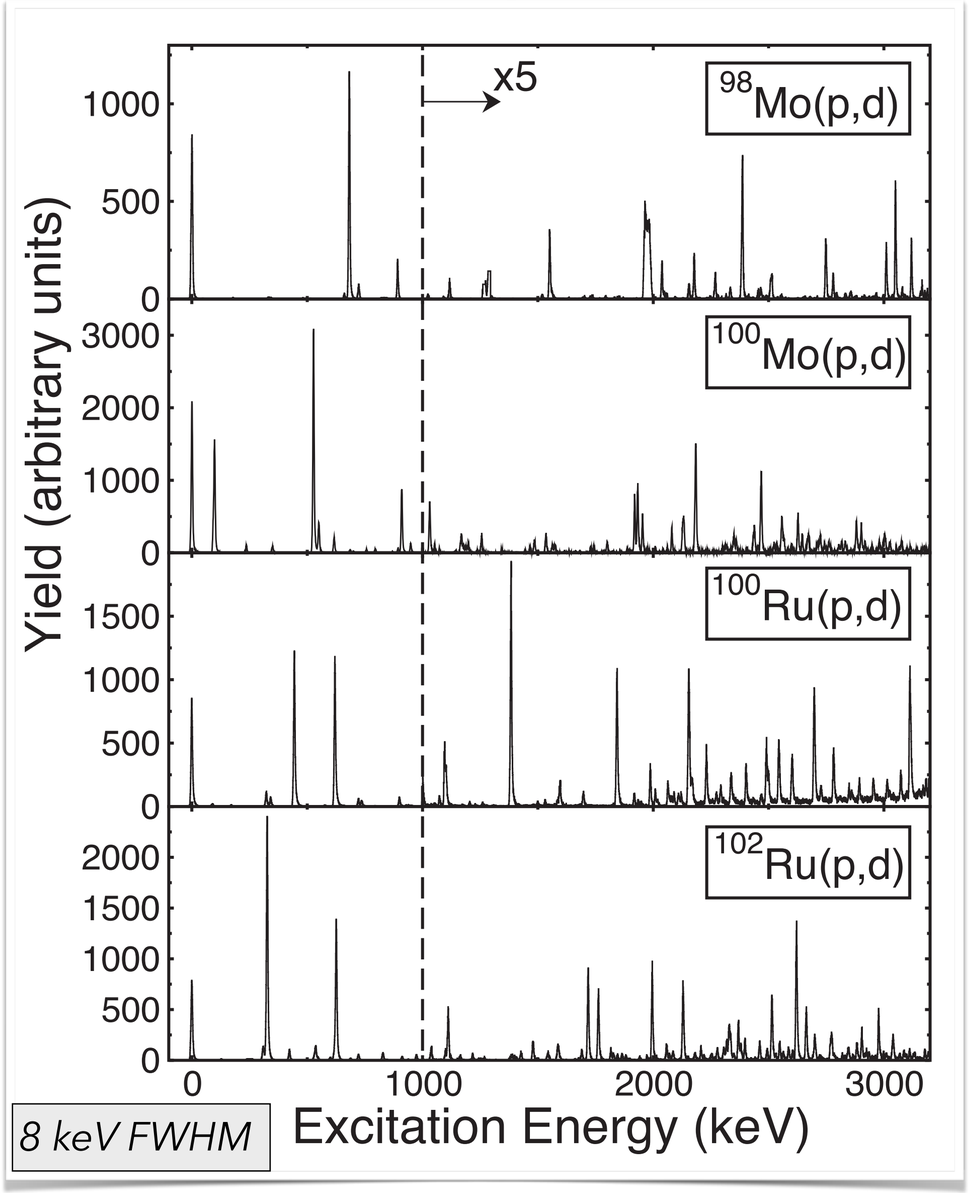
Kinematics: normal vs. inverse (resolution)







e.g. A. M. Laird et al., Phys. Rev. Lett. **110**, 032502 (**2013**)

e.g. R. Talwar et al., Phys. Rev. C **93**, 055803 (**2016**)

e.g. S. J. Freeman et al., Phys. Rev. C **96**, 054325 (**2017**)

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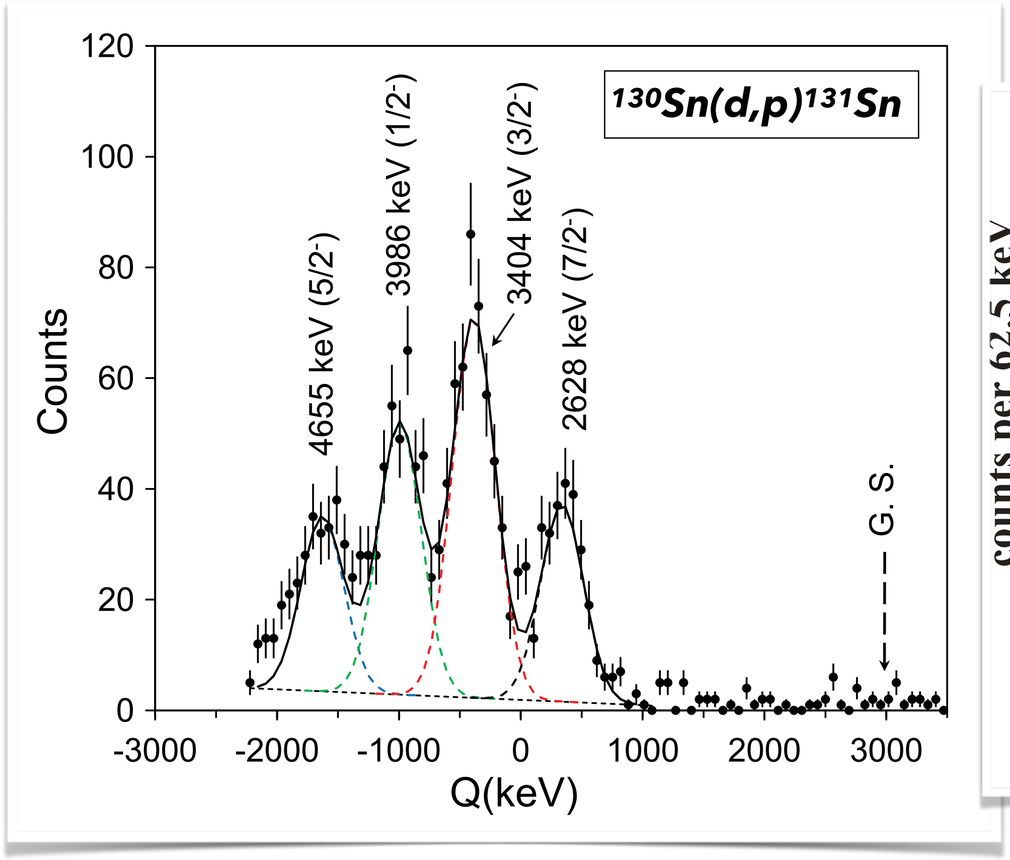
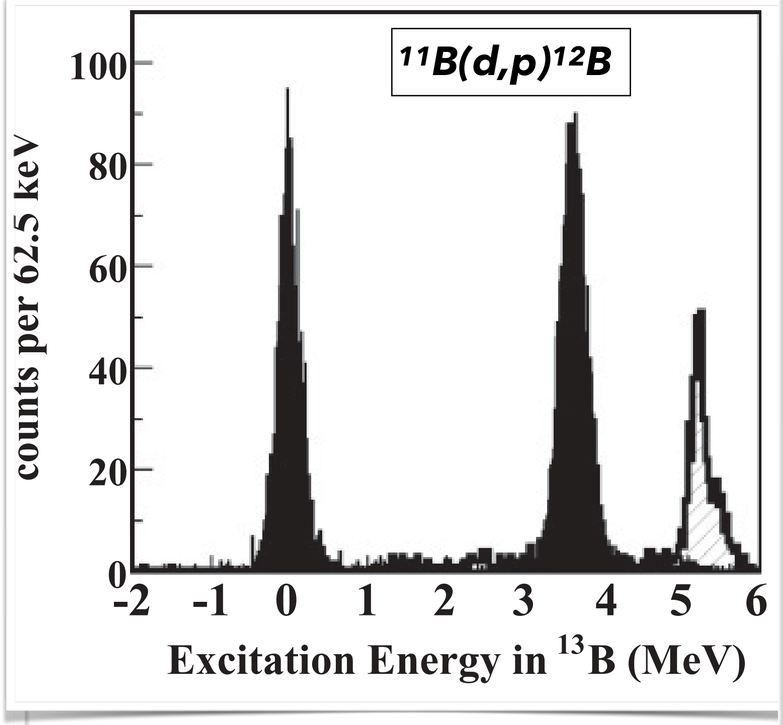
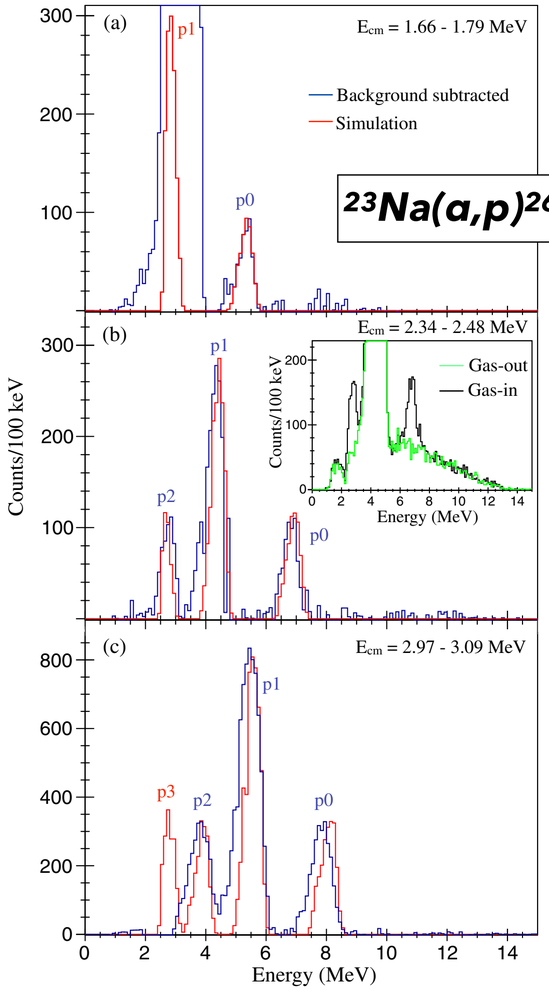
Kinematics: normal vs. inverse







Necessities: *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), TUDA (TRIUMF), etc.*

R. L. Kozub et al., PRL ***109****, 172501 (****2012****), H. Y. Lee et al., PRC* ***81****, 015802 (****2010****), J. R. Tomlinson[Kay] et al., PRL* ***115****, 052702 (****2015****)*

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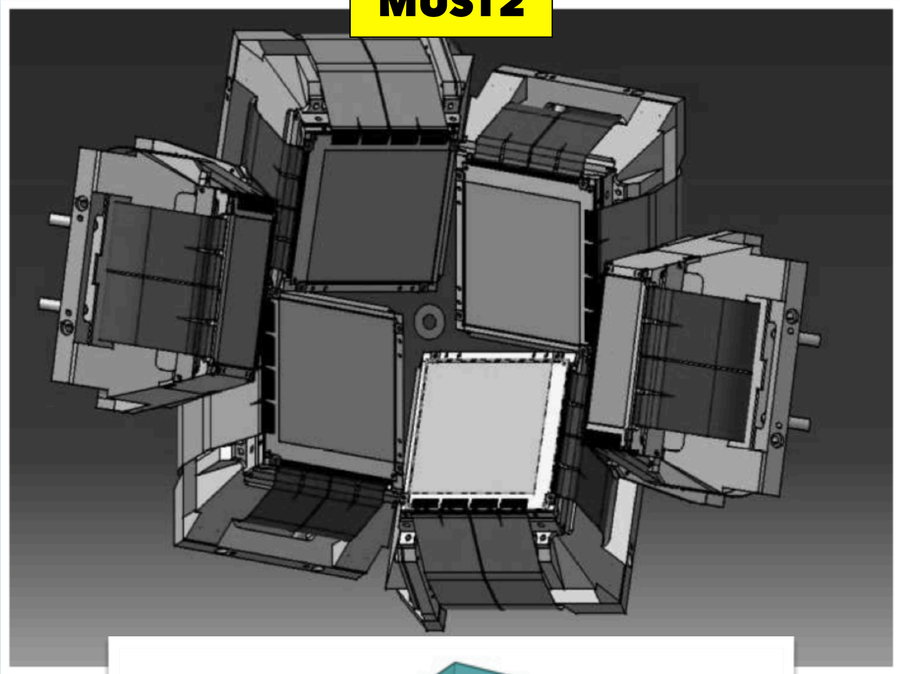
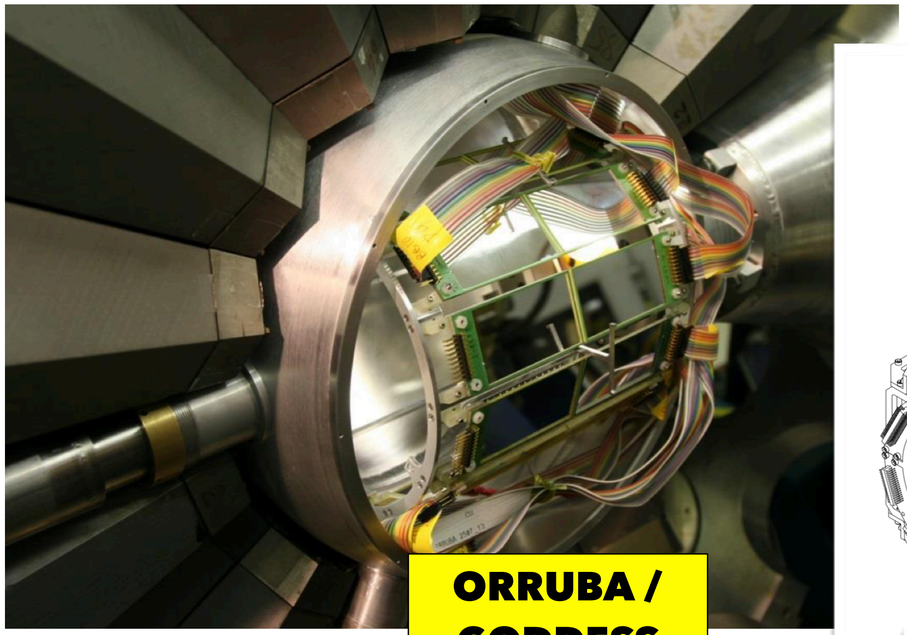
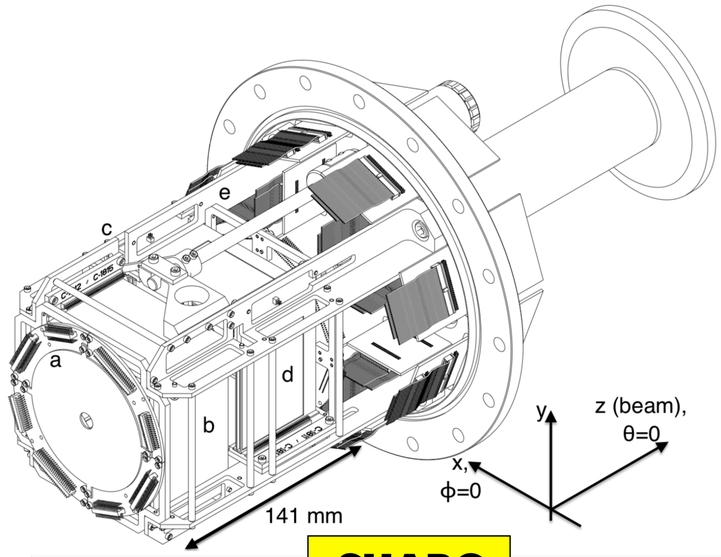
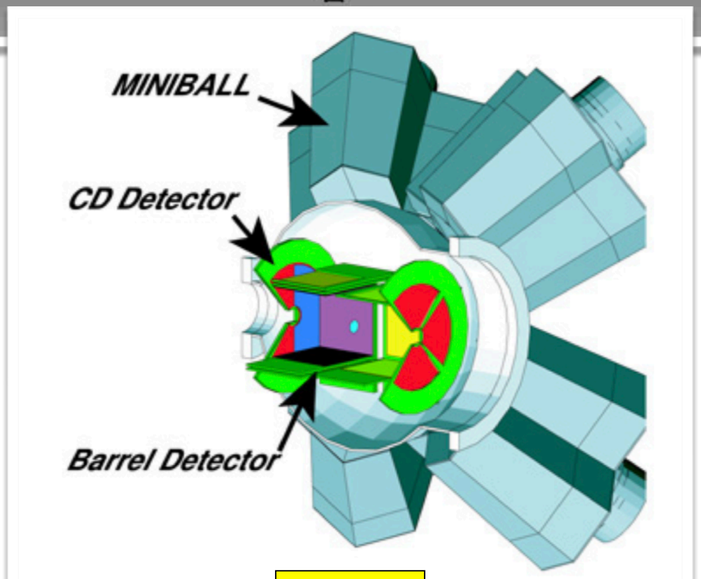
MUST2





ORRUBA / GODDESS

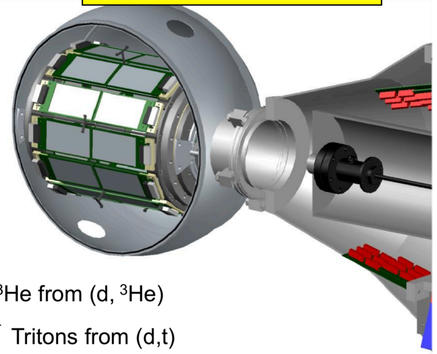




TREX

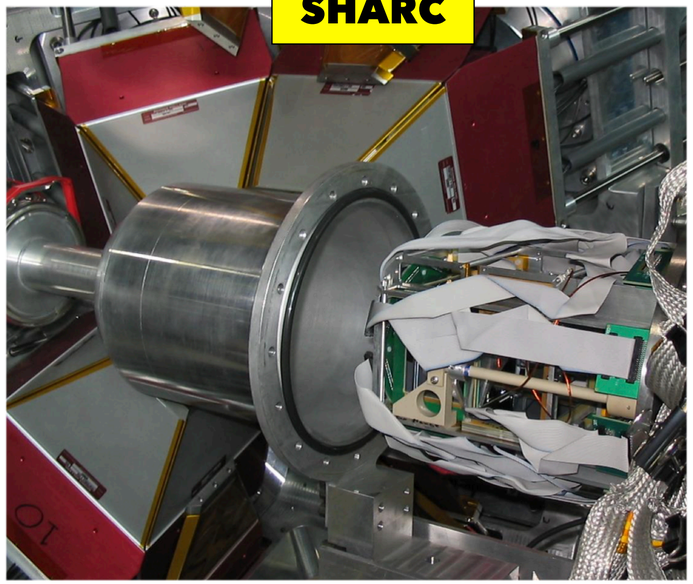
Polar angle coverage

15 to 165 degree coverage (>75%)



Forward endcap | Barrel | Backward endcap

SHARC



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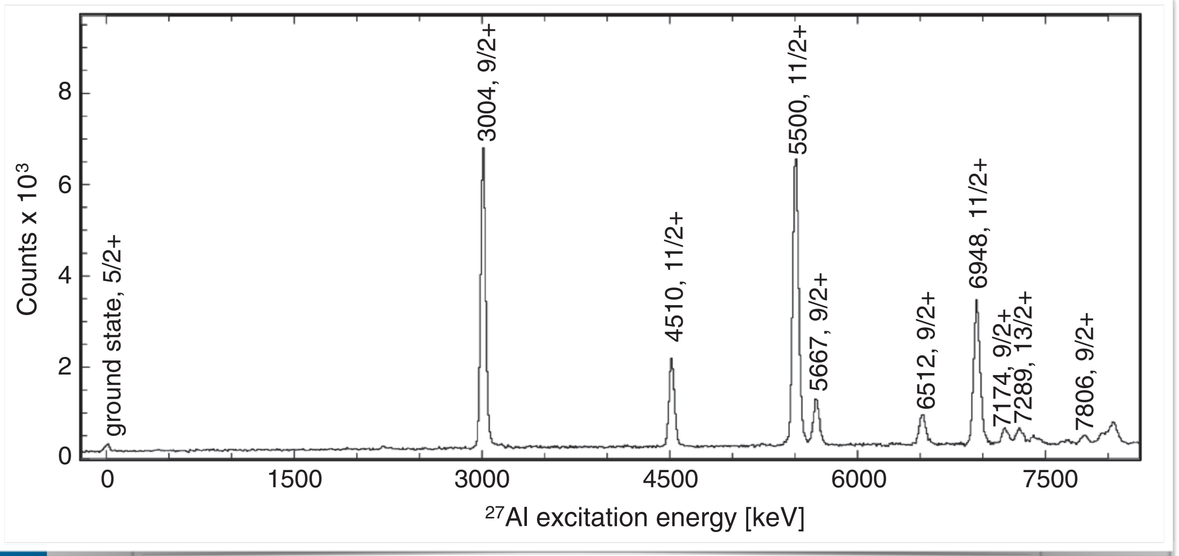
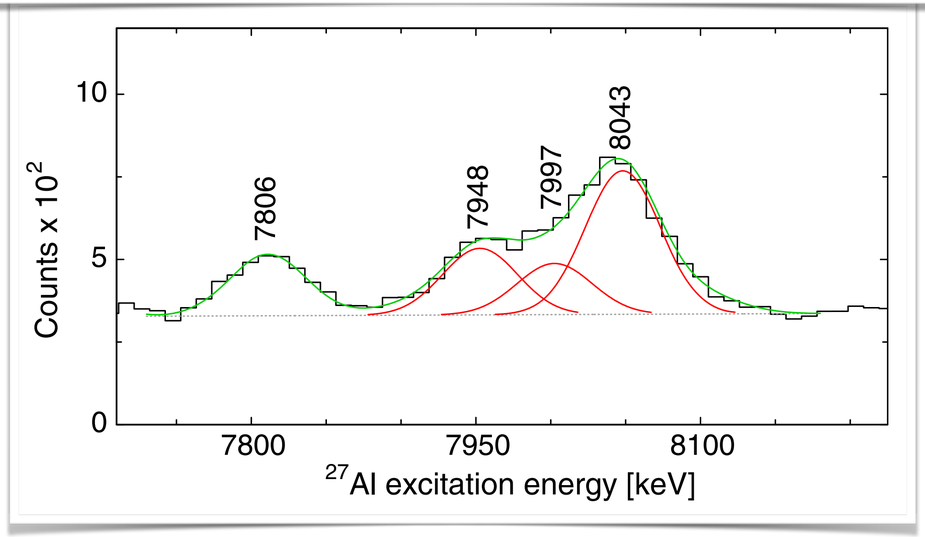
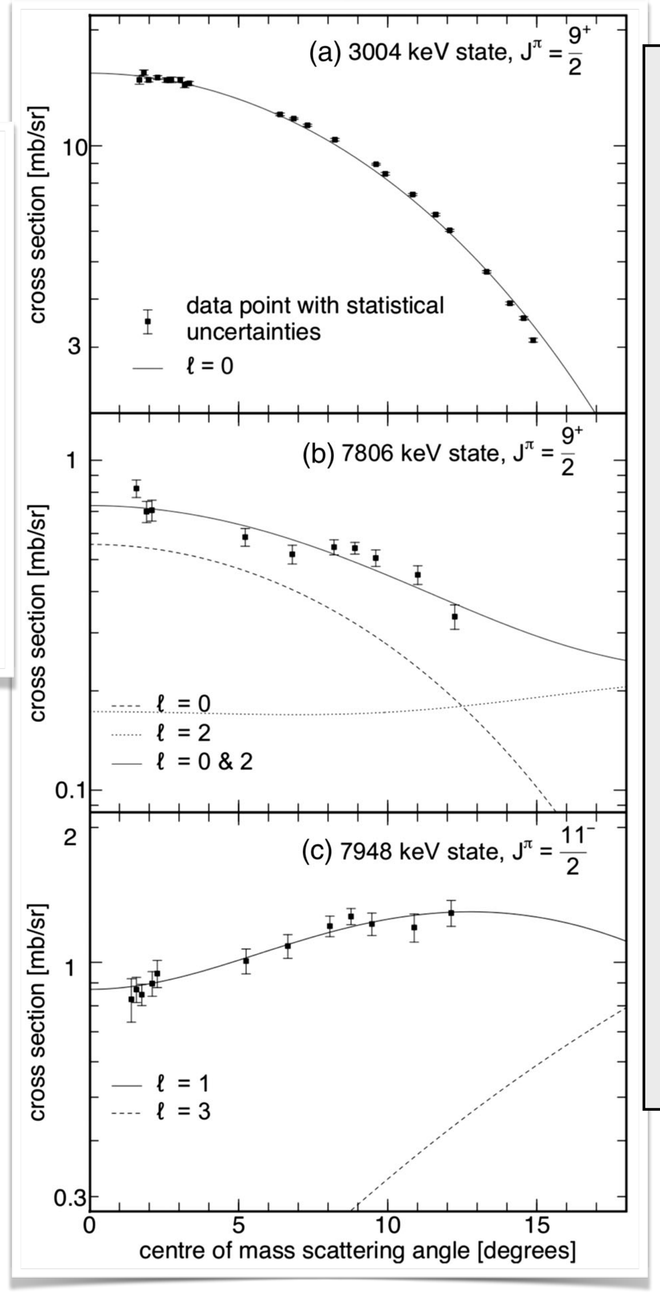
If conditions are favorable …

Q-value resolution of 40 keV FWHM

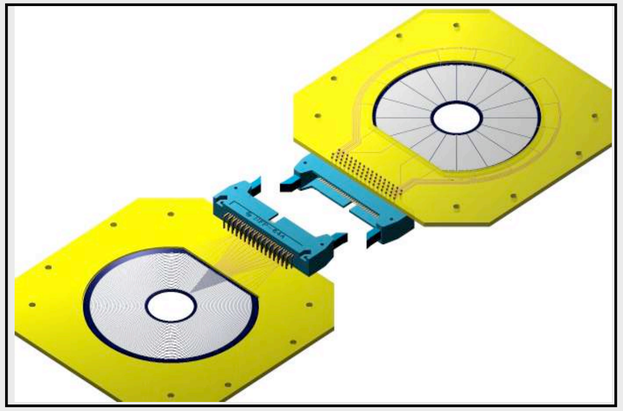




V. Margerin et al., Phys. Rev. Lett. ***115****, 062701 (****2015****)*



- *Beam: 6 MeV/u, 1pnA (****6.25×10⁹ pps****)*
- *Target: 50 μg/cm²*
- *Highly idealized setup, afforded by* ***very intense ²⁶Al beam*** *at TRIUMF*
- *Place detectors far way*
- *Annular Si detectors*



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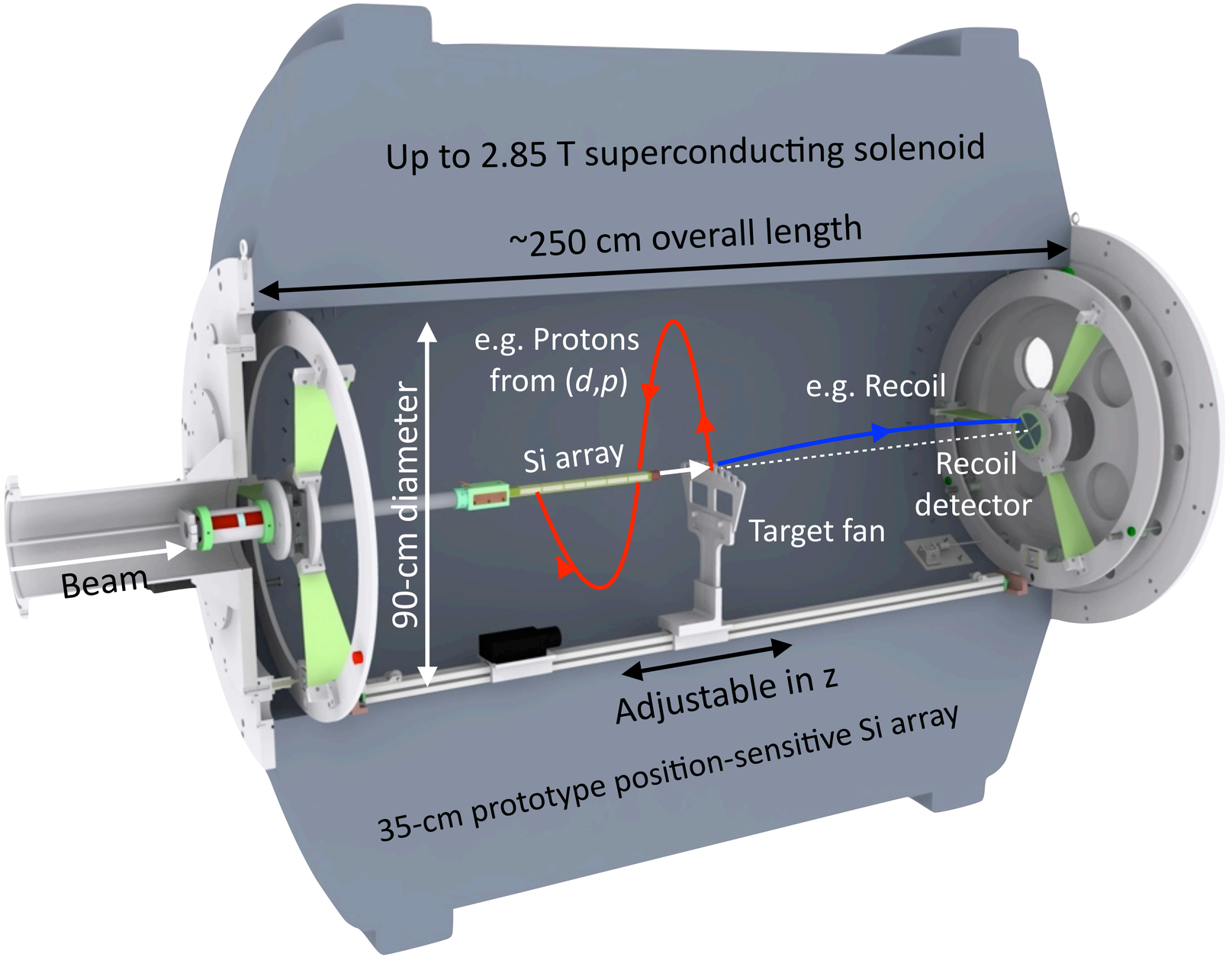
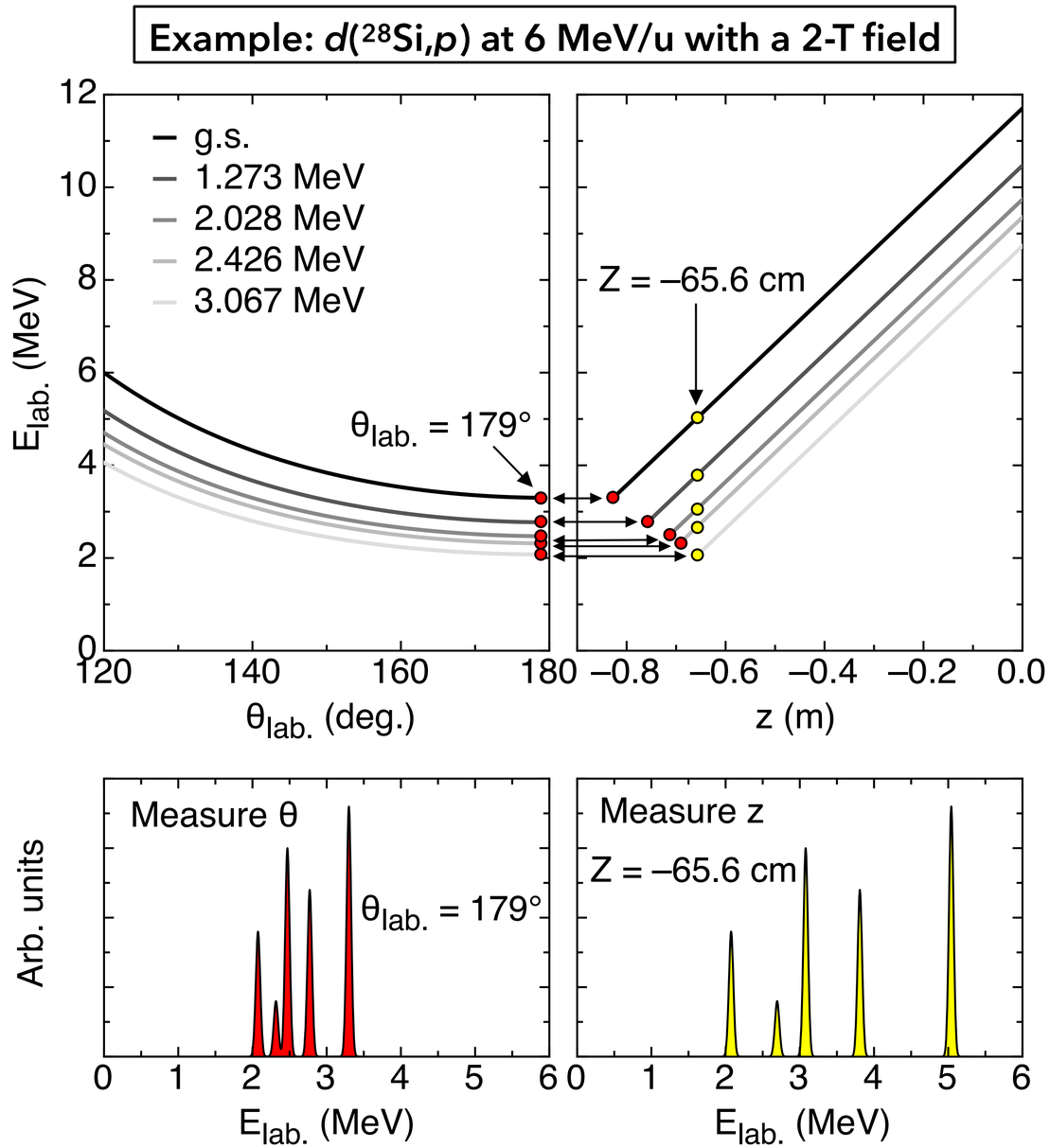


*Comment by **John P. Schiffer**, Proceedings of the Workshop on Experimental Equipment for an Advanced ISOL Facility, 1998*

Transport through a 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 *~2-3 improvement in resolution*
- … and an MRI magnet seems ideal

$$E_{\mathrm{cm}} = E_{\mathrm{lab}} + \frac{m}{2}V_{\mathrm{cm}}^2 - \frac{mV_{\mathrm{cm}}\,z}{T_{\mathrm{cyc}}}$$

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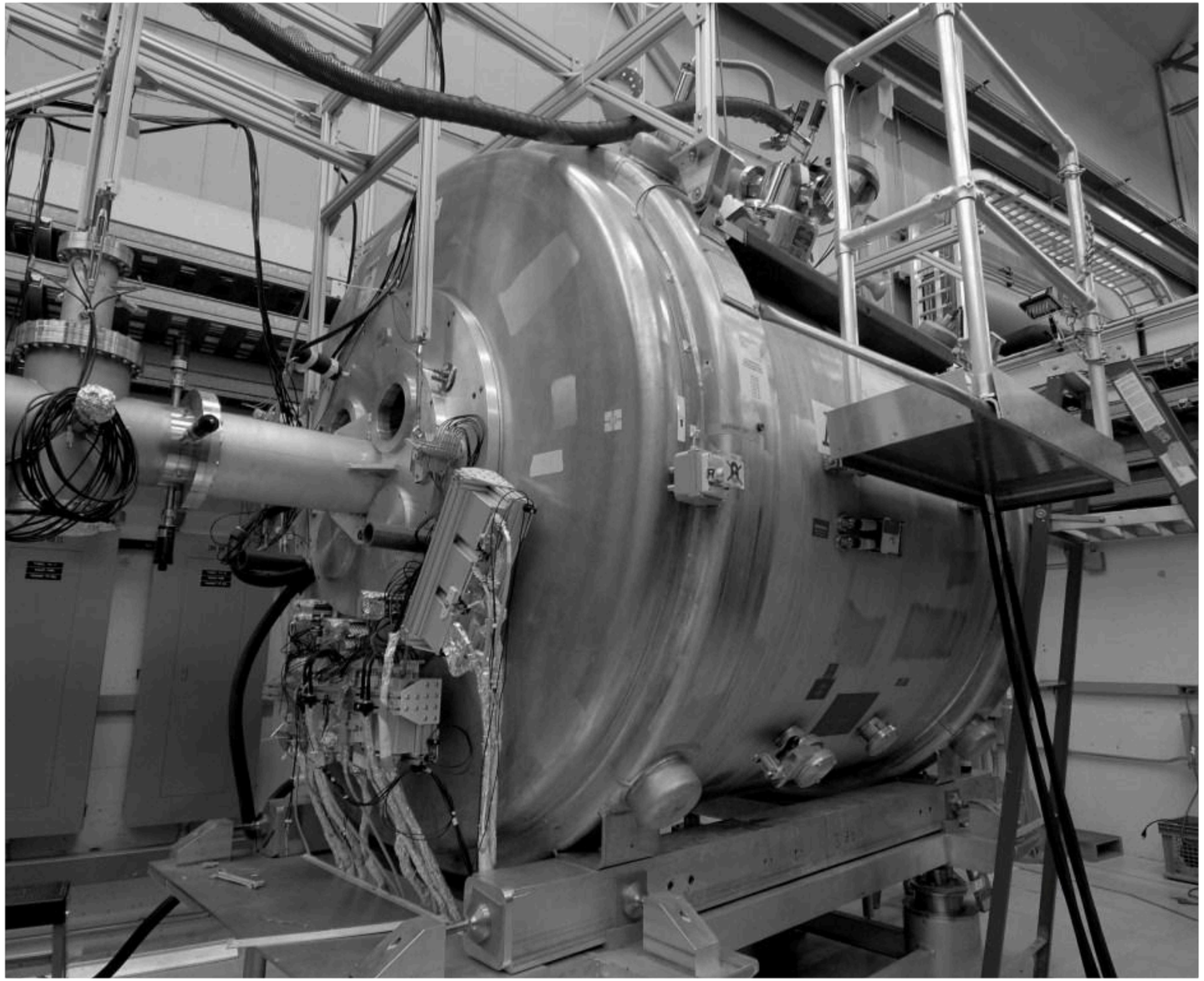
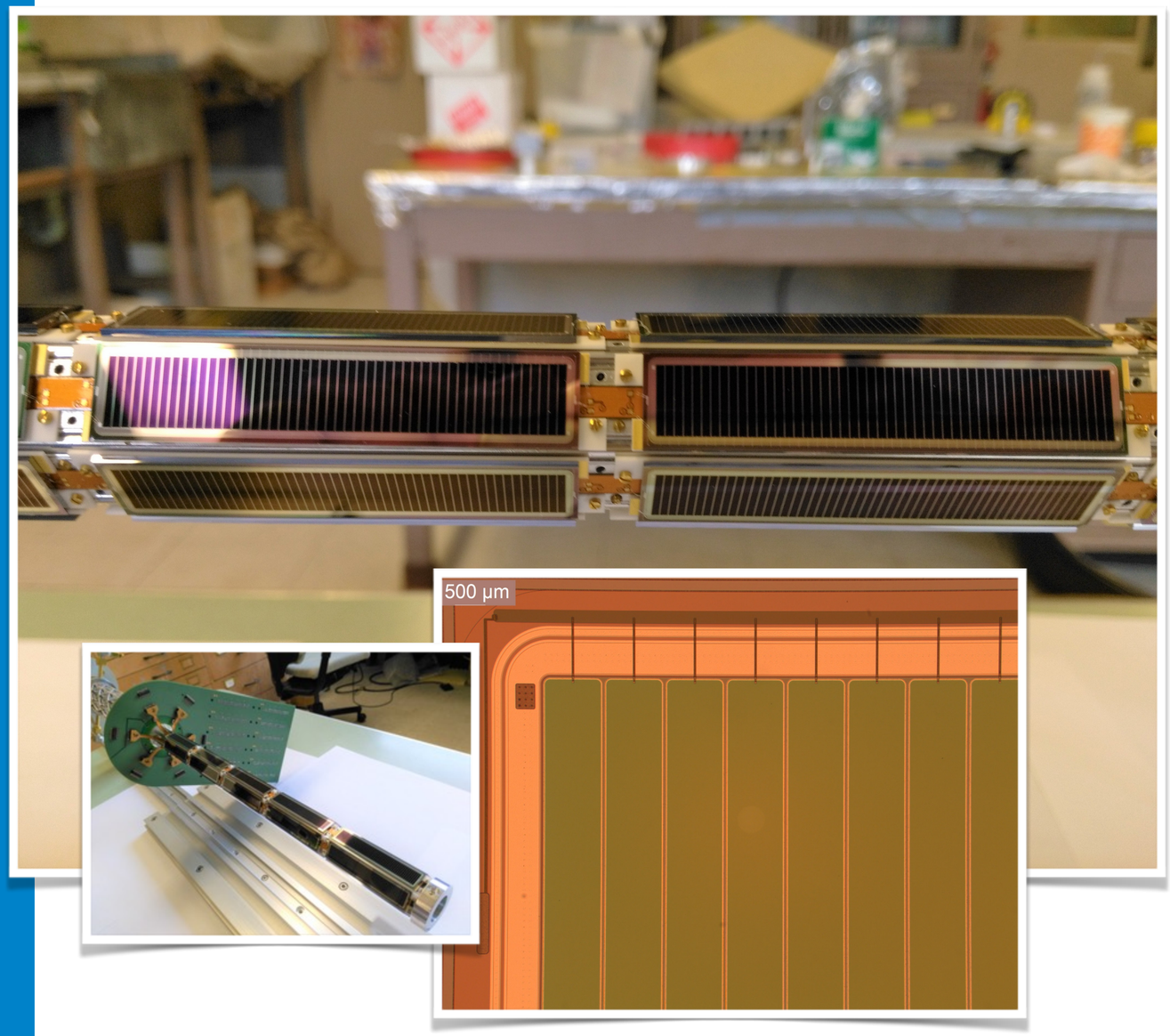
HELIOS



Left photo: unknown, right photo: A. H. Wuosmaa

New array and digital data acquisition



- *New DAQ implemented in FY17, used at CERN in FY18, running now [current run ^{29}Al(d,p)]*
- *New sort routines for 'quasi' live feedback (appreciated by users)*
- *New "complete system awareness" monitors*

Daniel McNeel, Calem Hoffman, Ryan Tang, et al.

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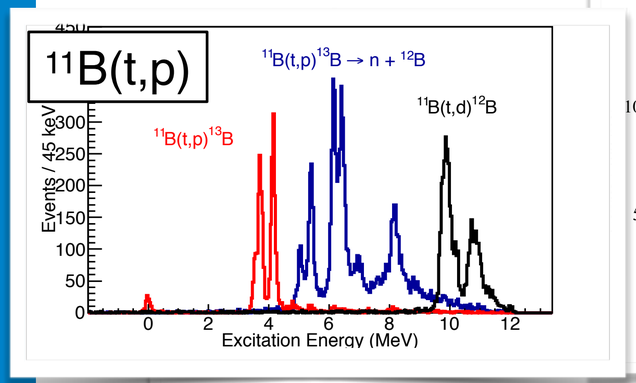
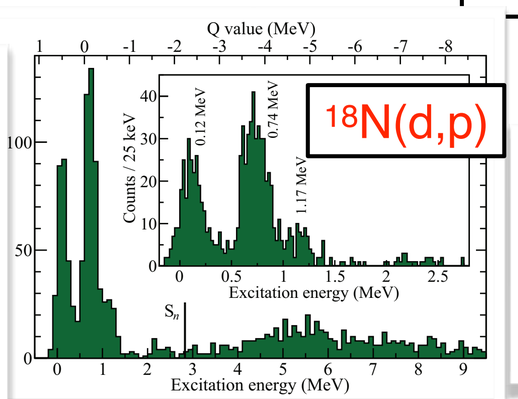
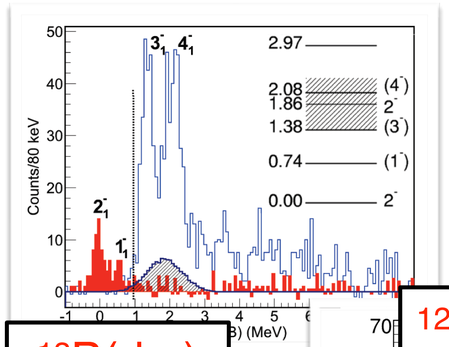
Snapshot

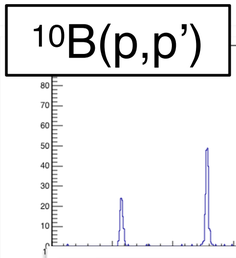
A highly versatile instrument

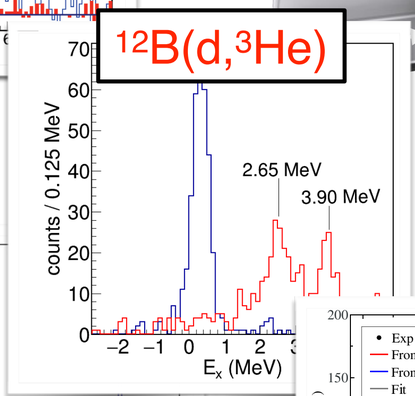
Apollo, gas target, ion chamber, backwards, forwards, tritium target, … all routine

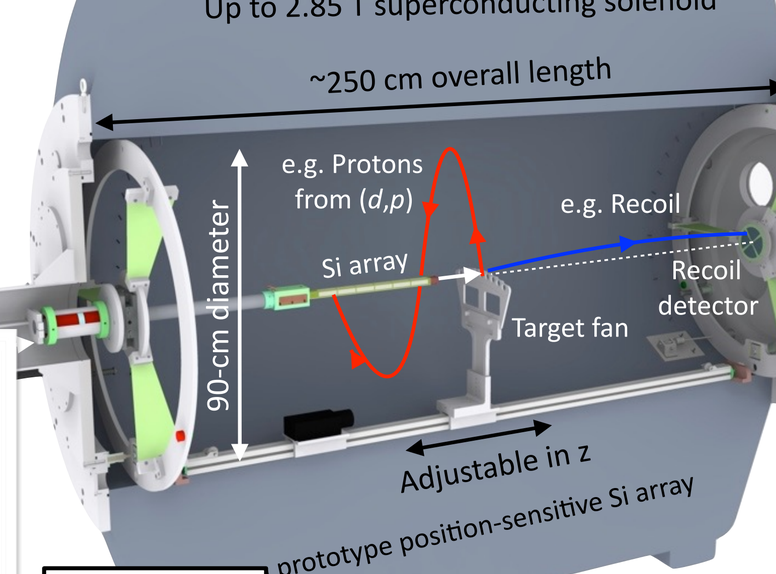


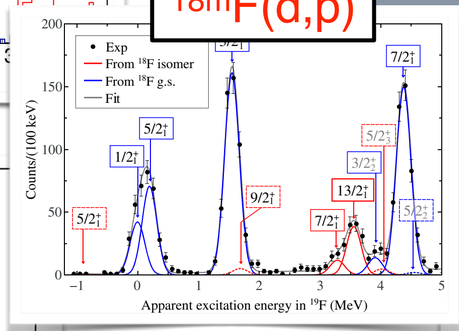


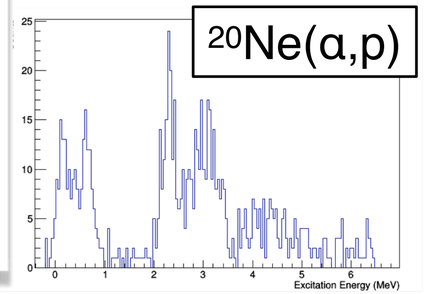


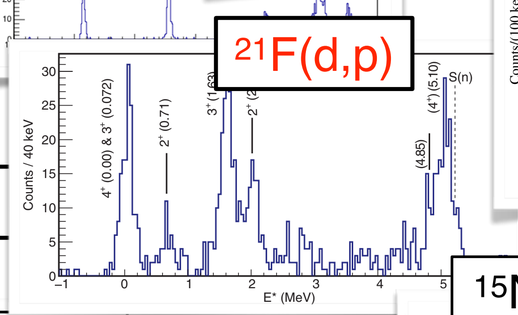


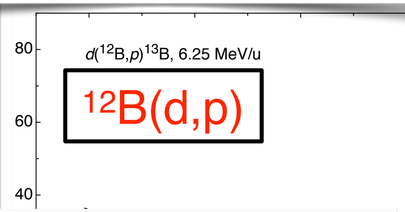


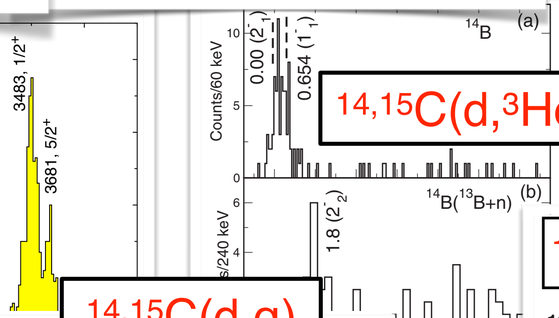


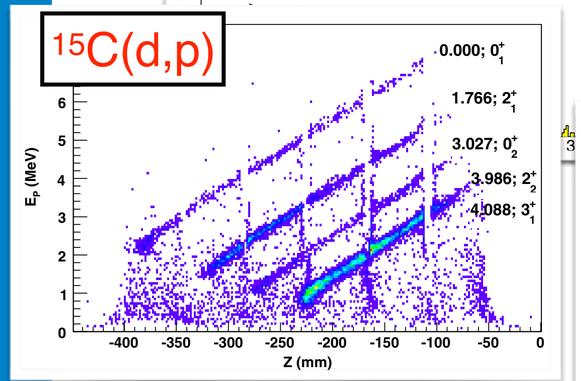


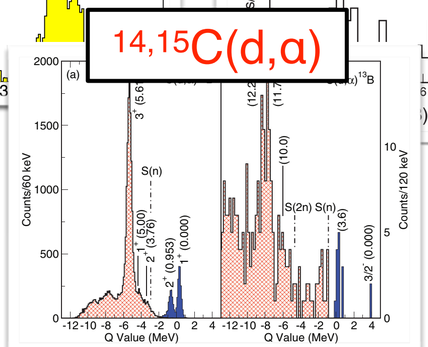


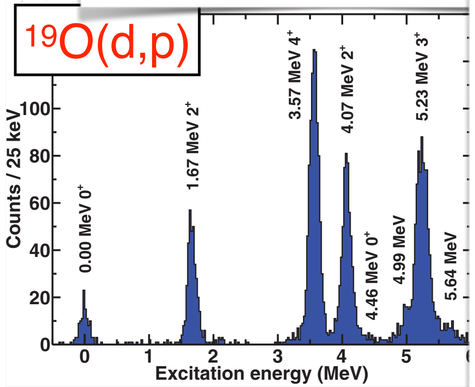


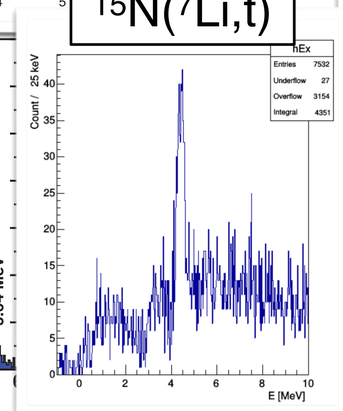


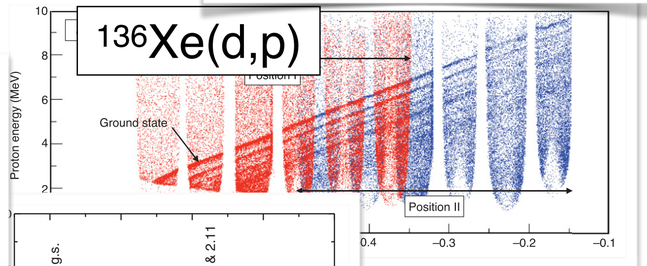


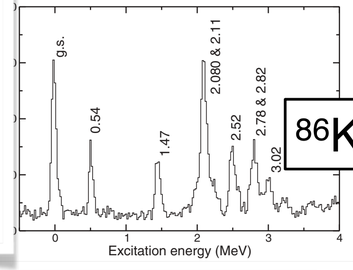












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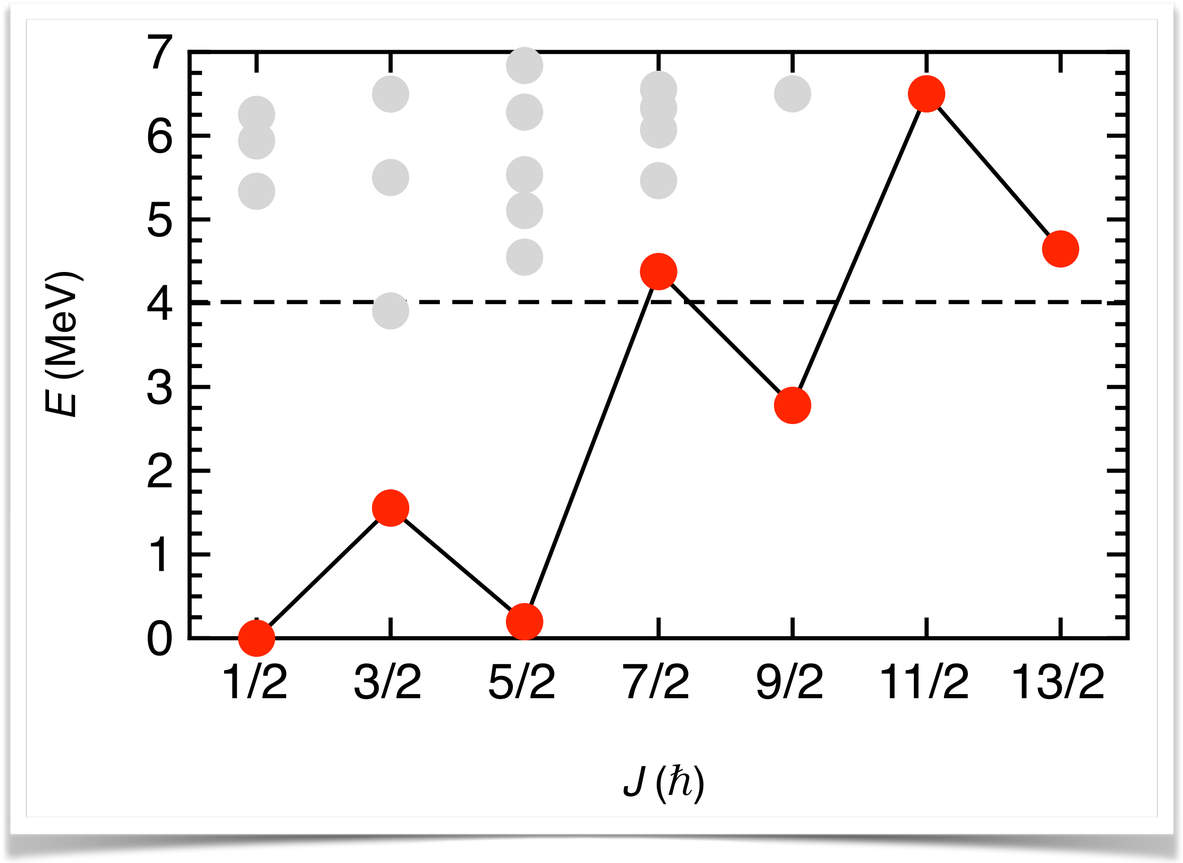
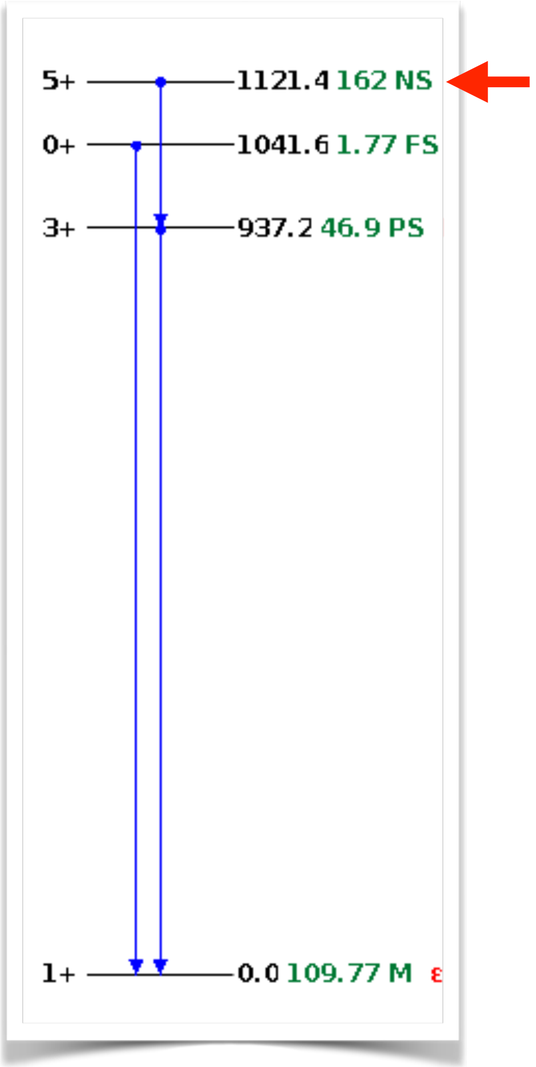
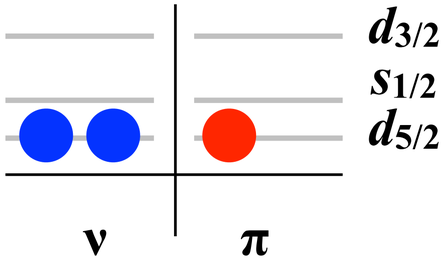
^{18}F, isomers, rotation, "high" spin

^{18g}F$^{(1+)}$(*d*,*p*)^{19}F l = 0, 2

^{18m}F$^{(5+)}$(*d*,*p*)^{19}F l = 0, 2



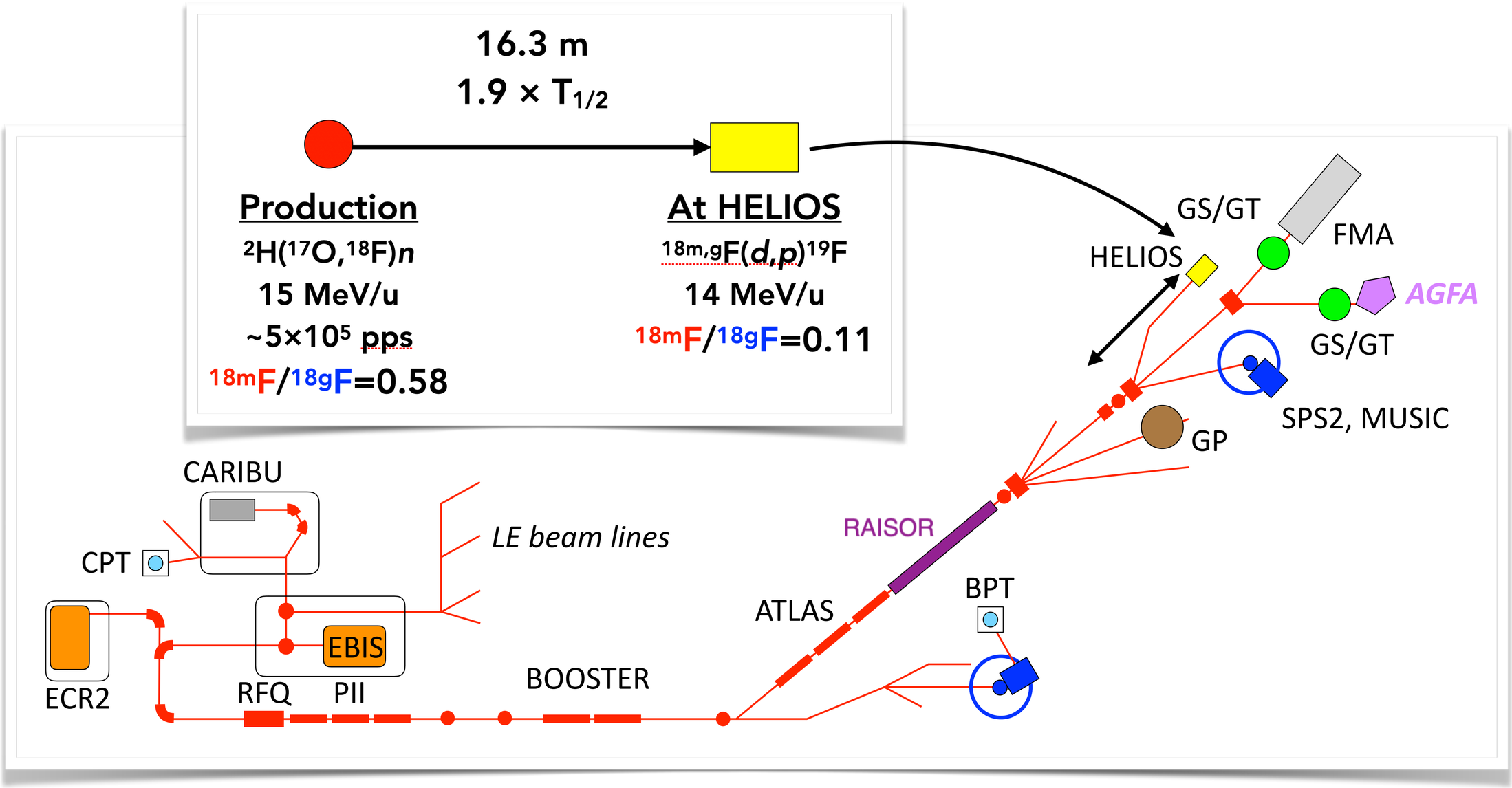




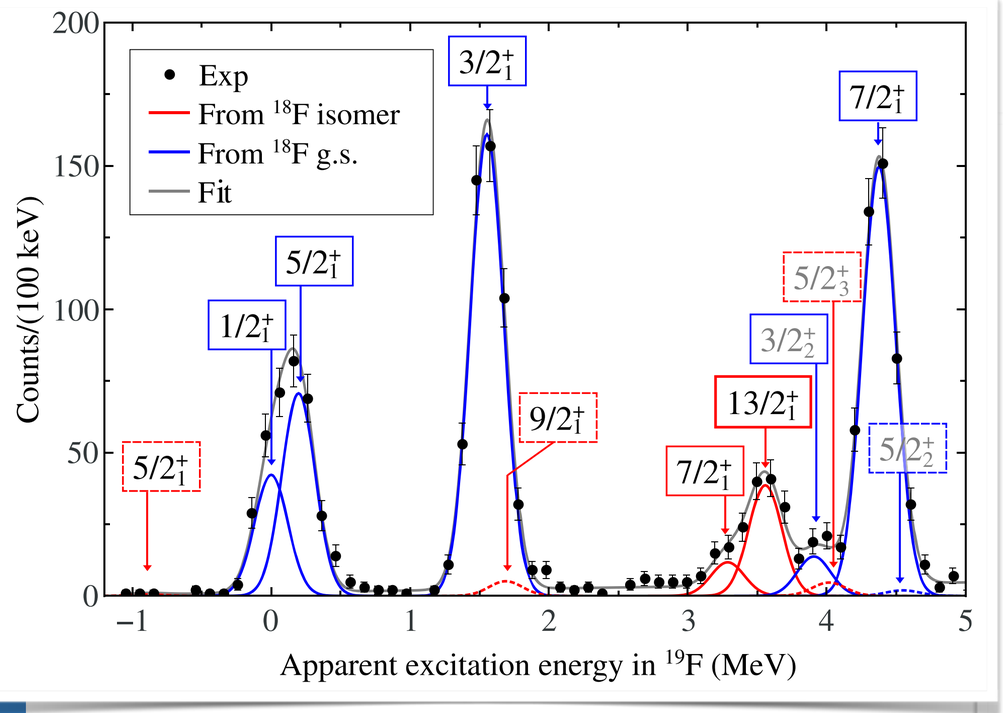
^{18g}F, 1^{+}

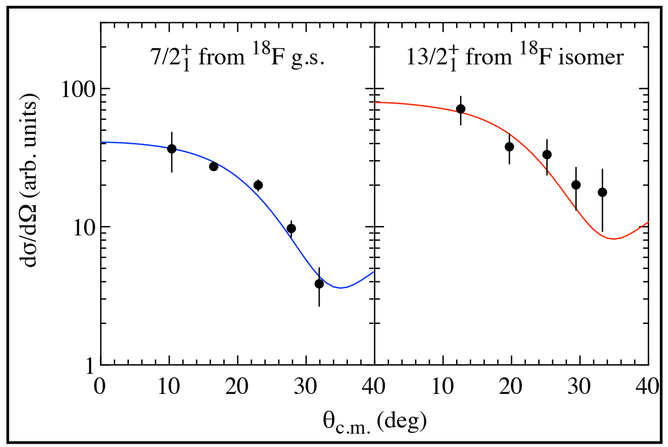
^{18m}F, 5^{+}, 1121 keV

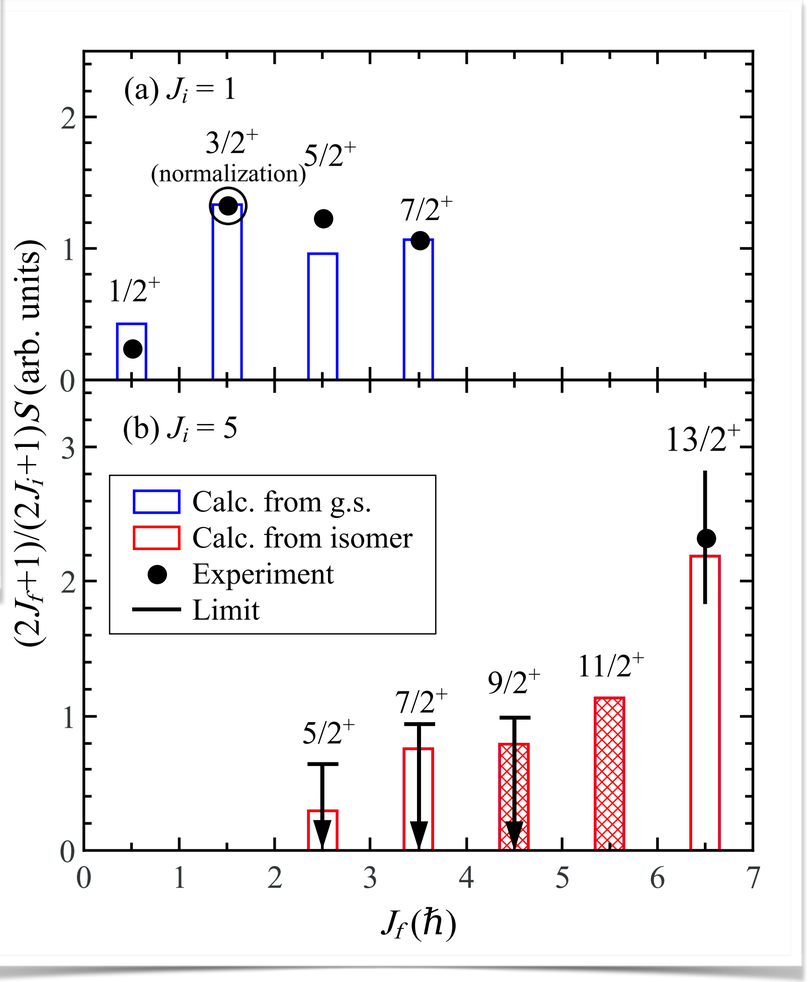
Making an isomeric beam of ^{18}F



Single-particle picture of ^{19}F







Excellent agreement with shell-model calculations (perhaps not surprisingly).

***Powerful technique**, many future possibilities … with AIRIS*

D. Santiago-Gonzalez et al. Phys. Rev. Lett. ***120****, 122503 (****2018****)*

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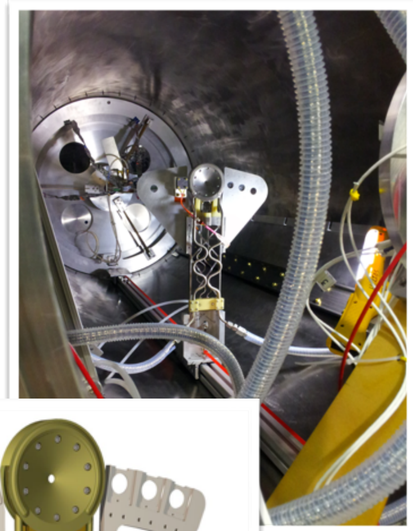
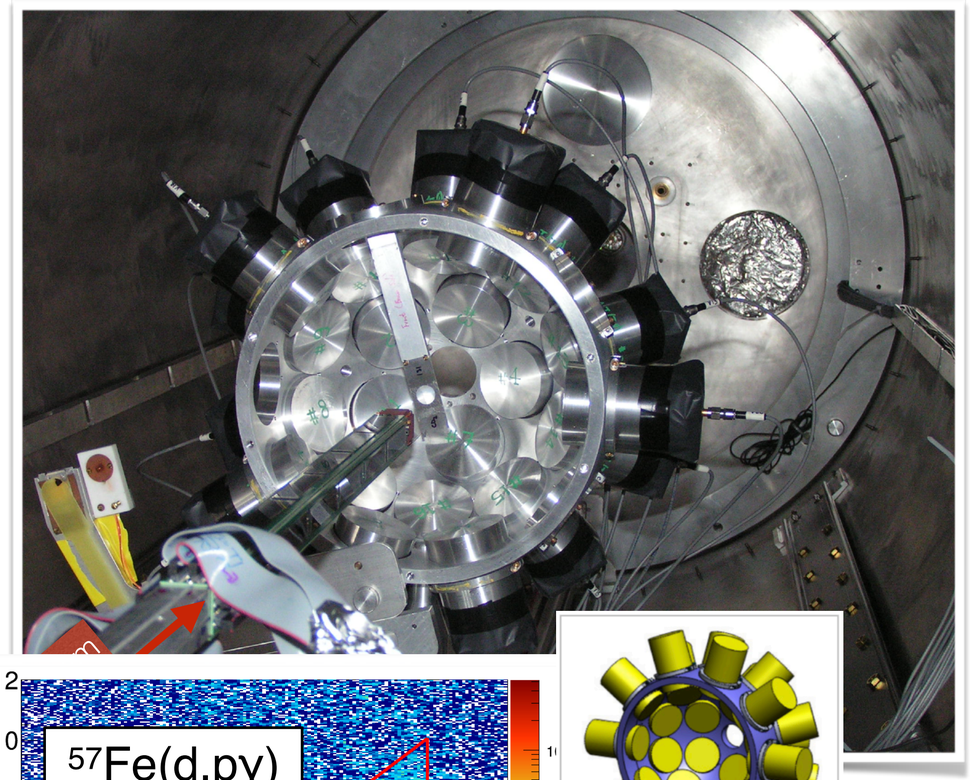
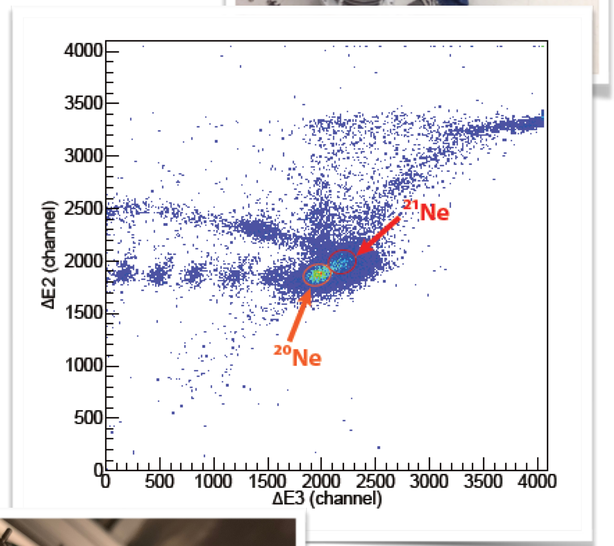
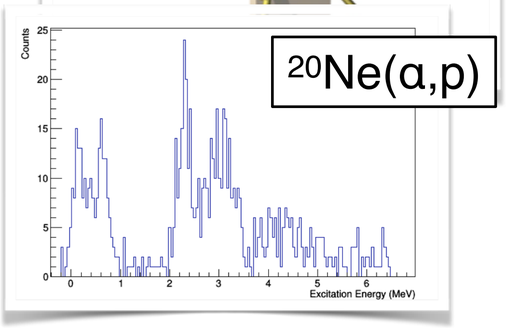
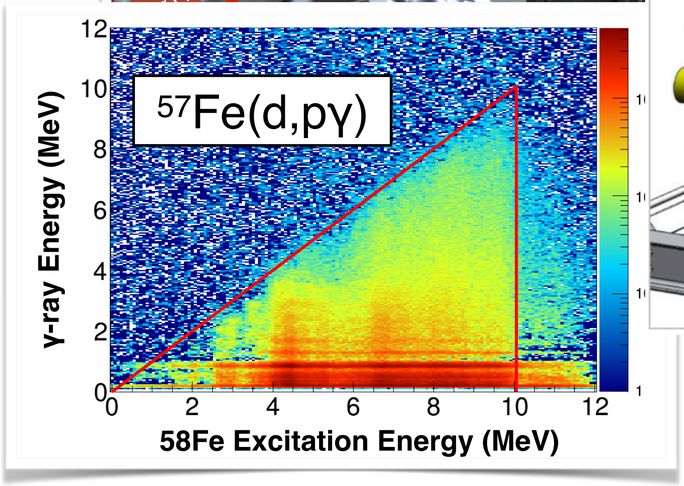
Related equipment

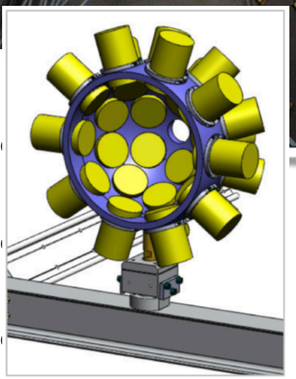


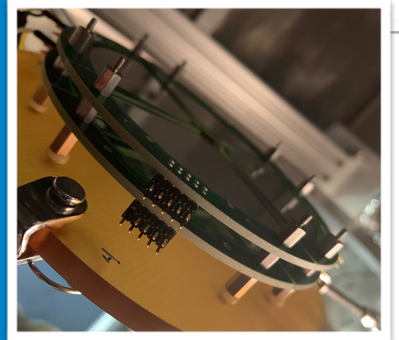






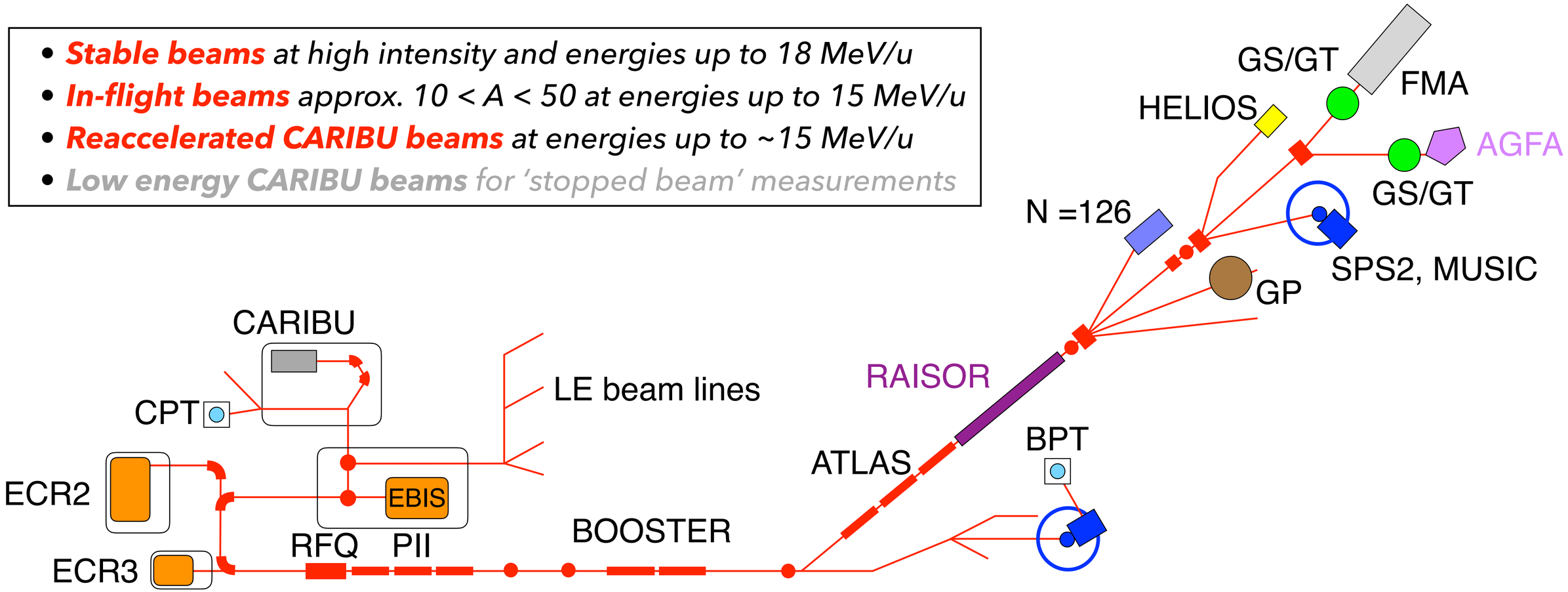






ATLAS

- ***Stable beams*** *at high intensity and energies up to 18 MeV/u*
- ***In-flight beams*** *approx. 10 < A < 50 at energies up to 15 MeV/u*
- ***Reaccelerated CARIBU beams*** *at energies up to ~15 MeV/u*
- ***Low energy CARIBU beams*** *for 'stopped beam' measurements*



https://www.anl.gov/atlas

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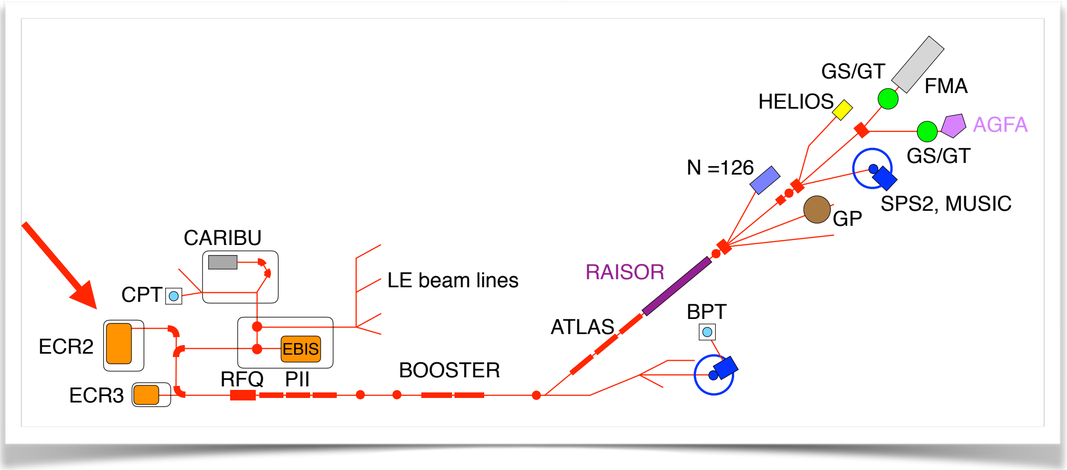
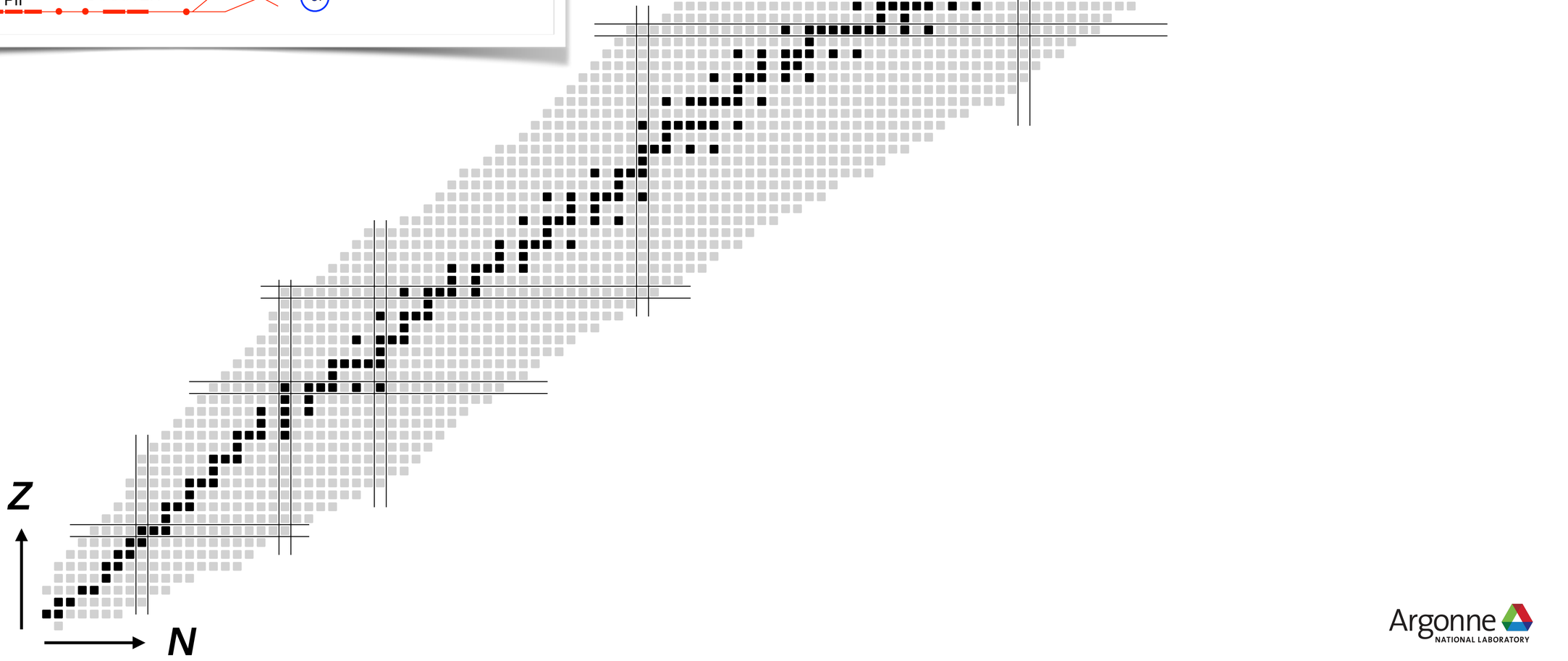
The landscape





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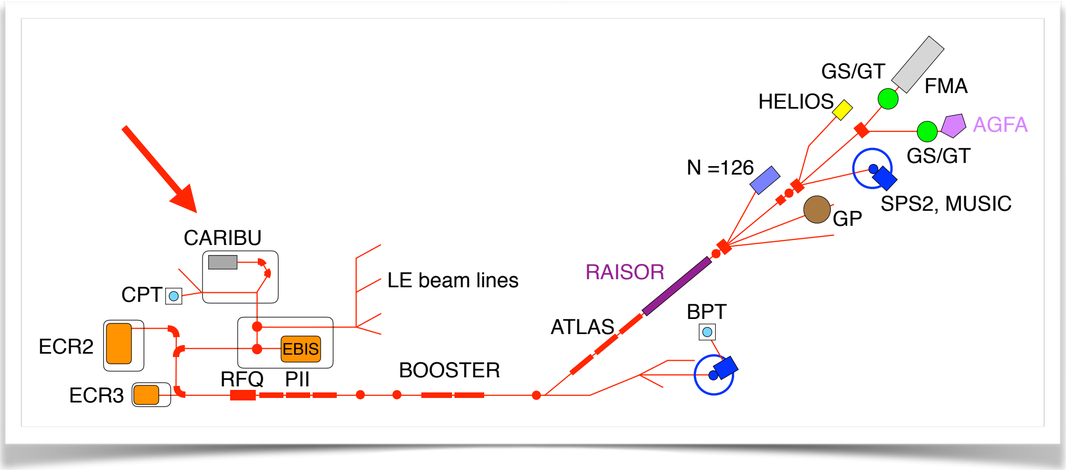
CARIBU, Cf-252



In the context of s- and r-processes

https://wwwndc.jaea.go.jp/cgi-bin/FPYfig

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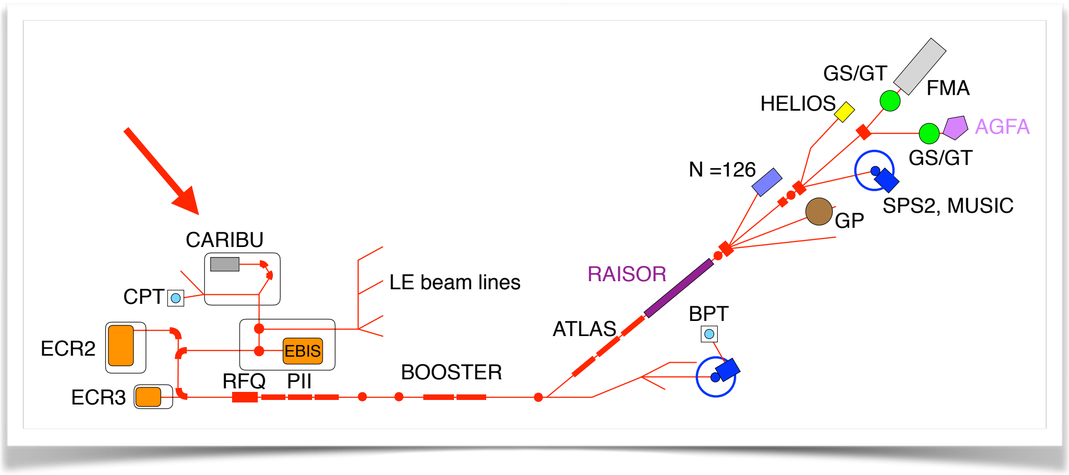
*nu*CARIBU, Am-241



In the context of s- and r-processes

s-process

r-process

*nu*CARIBU [10^{-4}]

*nu*CARIBU [10^{-3}]

Z

N

https://wwwndc.jaea.go.jp/cgi-bin/FPYfig

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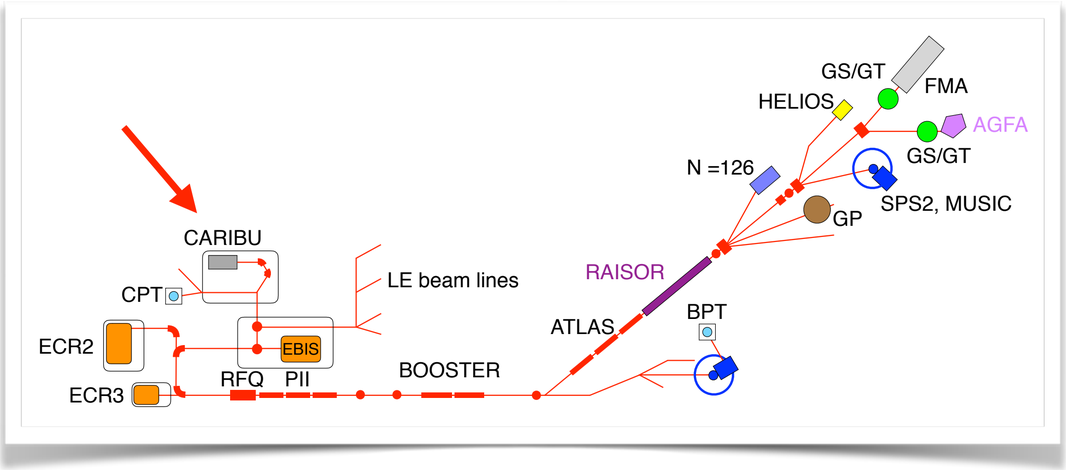
*nu*CARIBU, Am-242



In the context of s- and r-processes

s-process

r-process

*nu*CARIBU [10^{-4}]

*nu*CARIBU [10^{-3}]

Z

N

https://wwwndc.jaea.go.jp/cgi-bin/FPYfig

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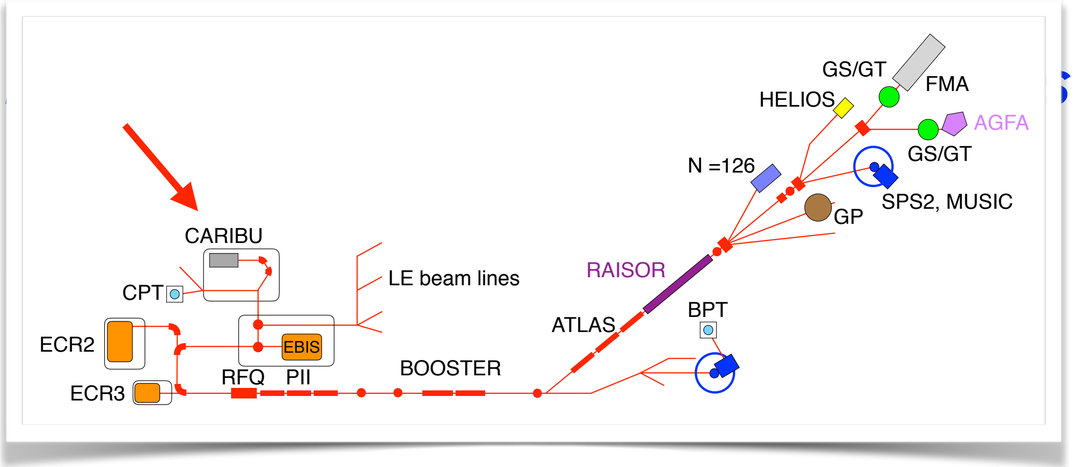
*nu*CARIBU, Pu-239



In the context of s- and r-processes

https://wwwndc.jaea.go.jp/cgi-bin/FPYfig

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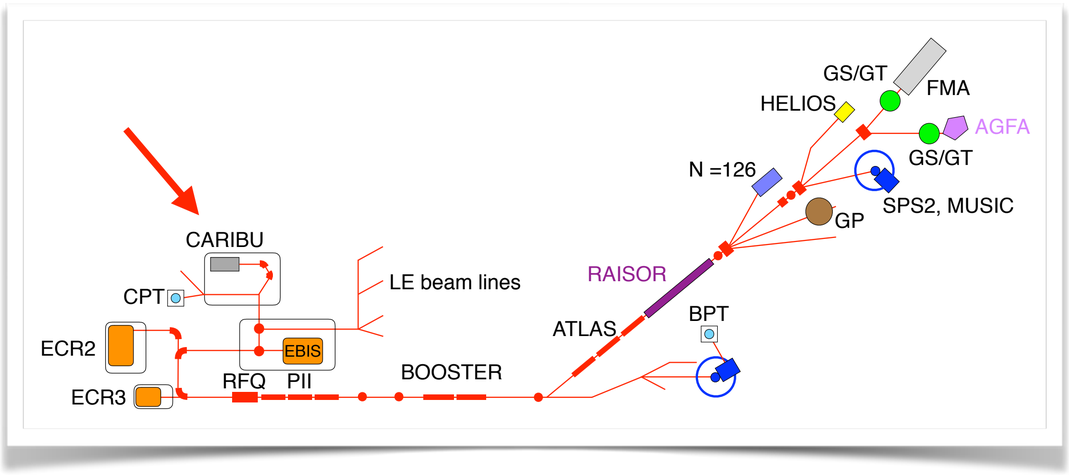
*nu*CARIBU, U-235



In the context of s- and r-processes

s-process

r-process

*nu*CARIBU [10^{-4}]

*nu*CARIBU [10^{-3}]

Z

N

https://wwwndc.jaea.go.jp/cgi-bin/FPYfig

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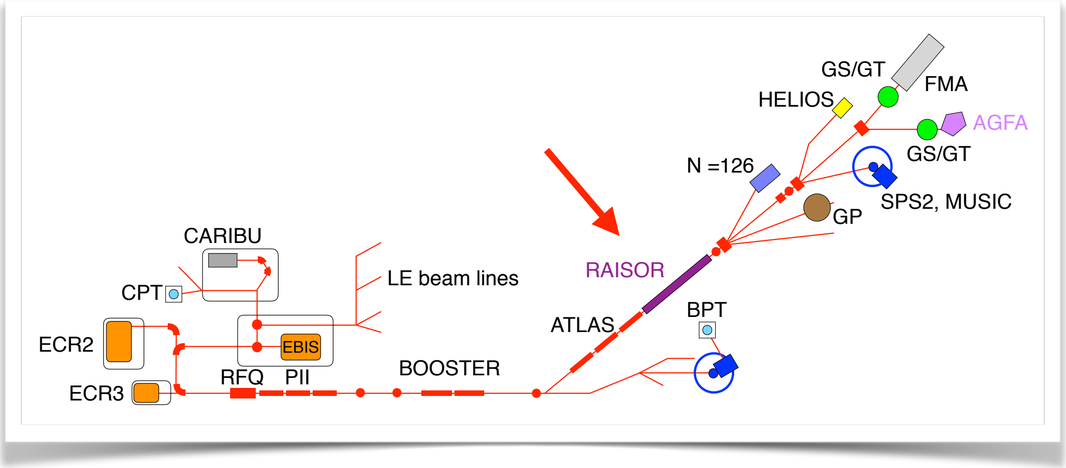
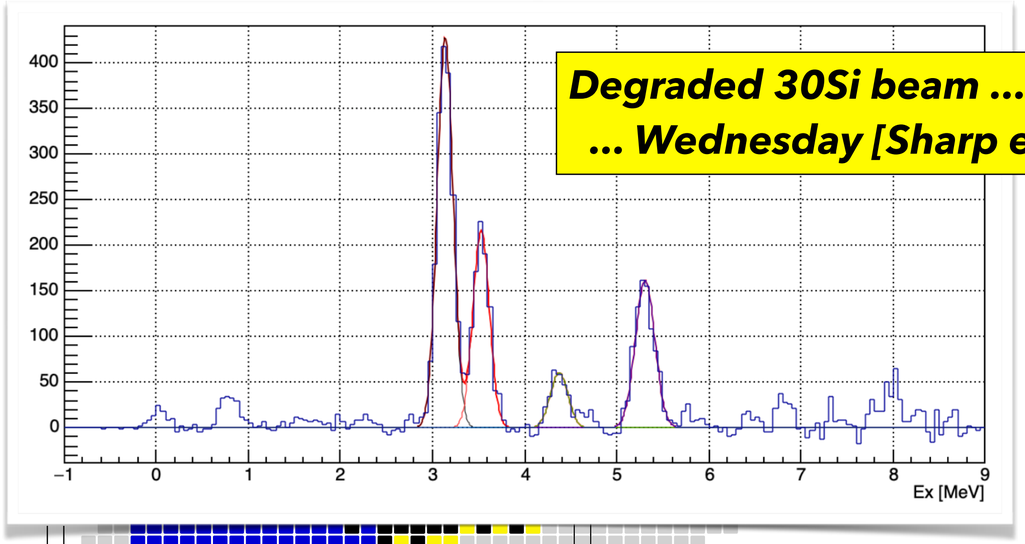
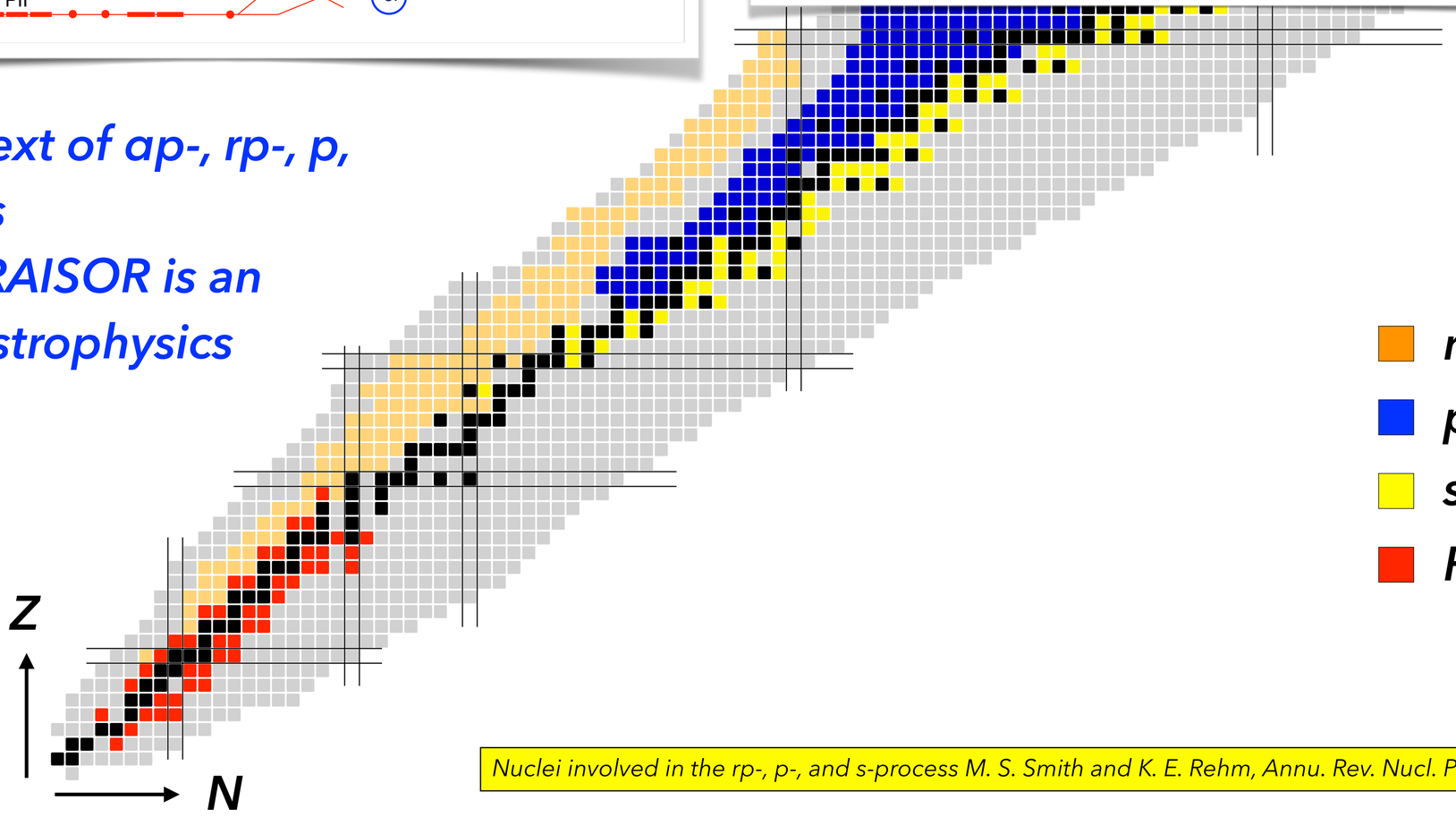
RAISOR-2019





In the context of ap-, rp-, p, s-processes

HELIOS + RAISOR is an excellent astrophysics synergy



- *rp-process*
- *p-process*
- *s-process*
- *RAISOR 2019, >10^4*

Nuclei involved in the rp-, p-, and s-process M. S. Smith and K. E. Rehm, Annu. Rev. Nucl. Part. Sci. ***51****, 91 (****2001****)*

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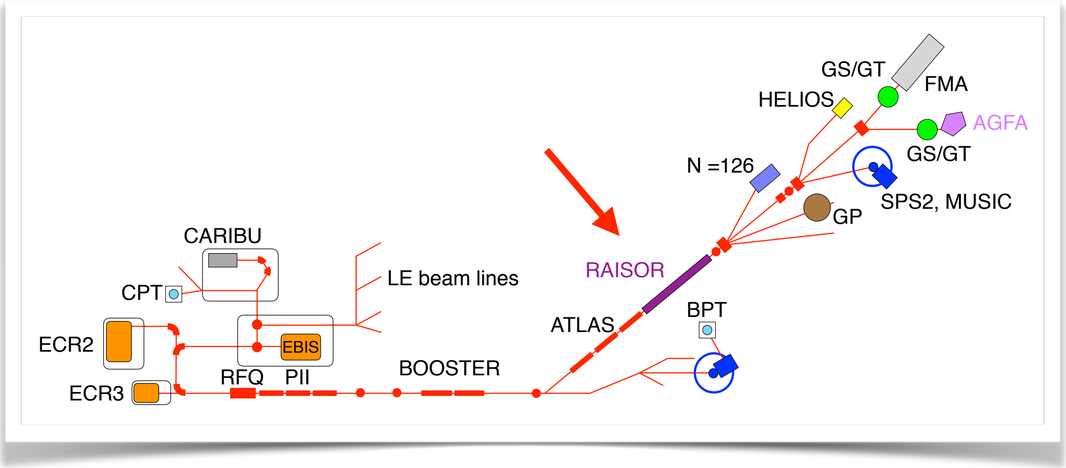
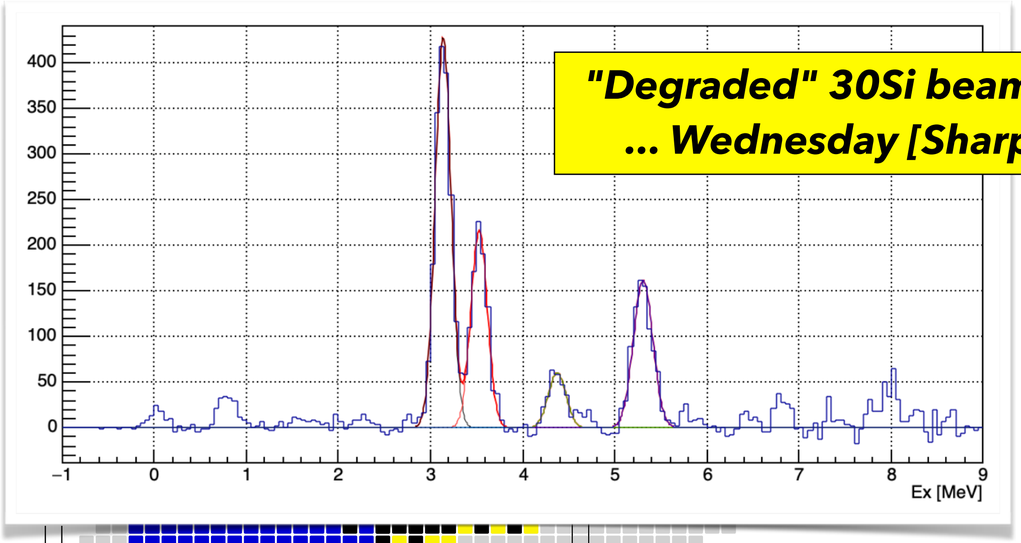
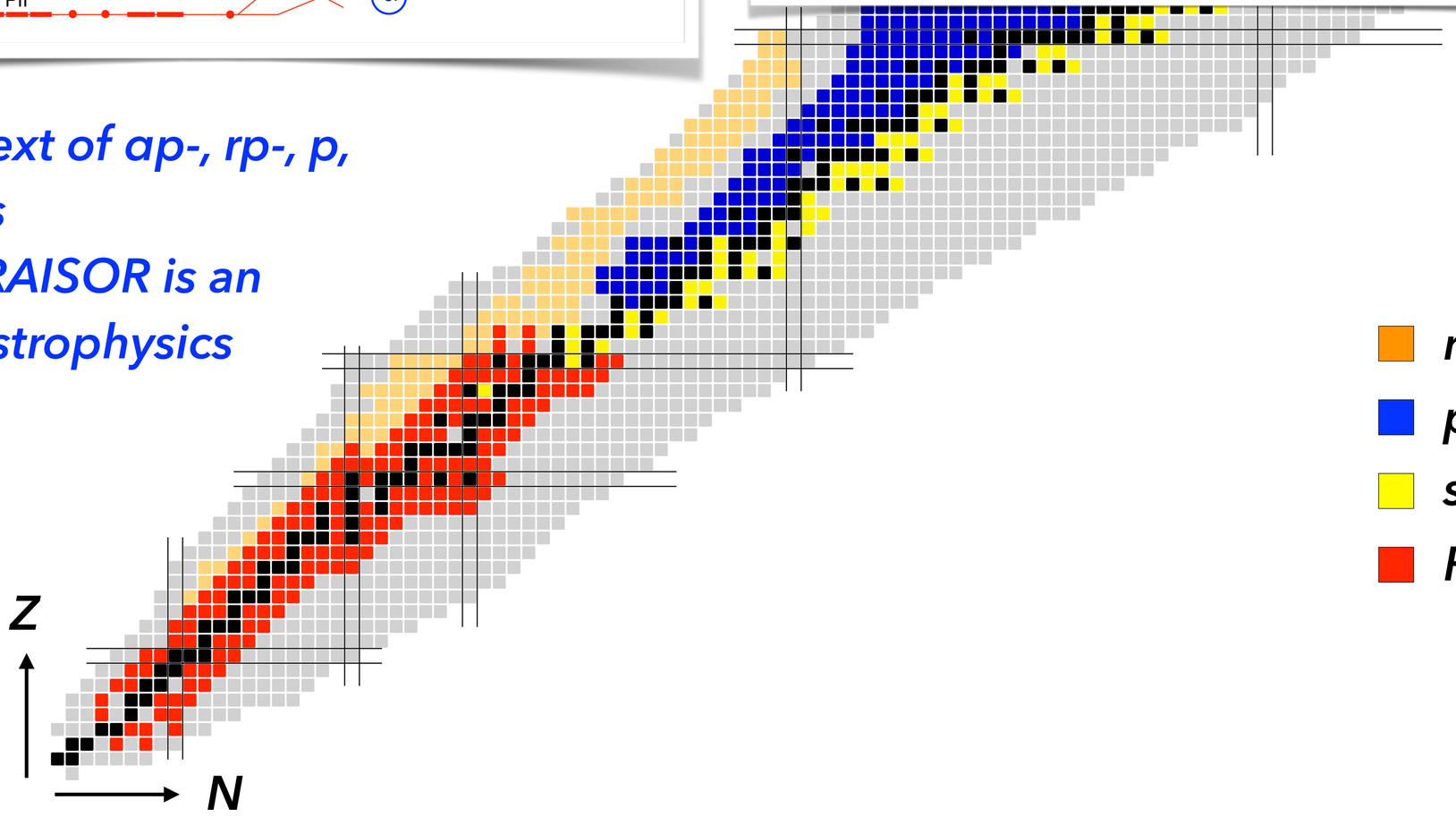
RAISOR-optimum





In the context of ap-, rp-, p, s-processes

HELIOS + RAISOR is an excellent astrophysics synergy



- *rp-process*
- *p-process*
- *s-process*
- *RAISOR, >10^4*

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Challenges / opportunities

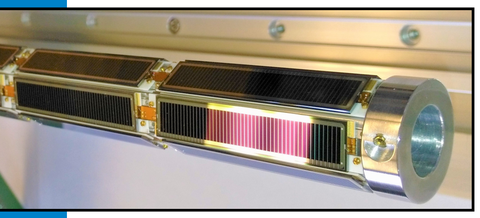
Reactions: *often proton adding, He-induced, Li-induced reactions … speaks to gas targets, low cross sections, etc.*

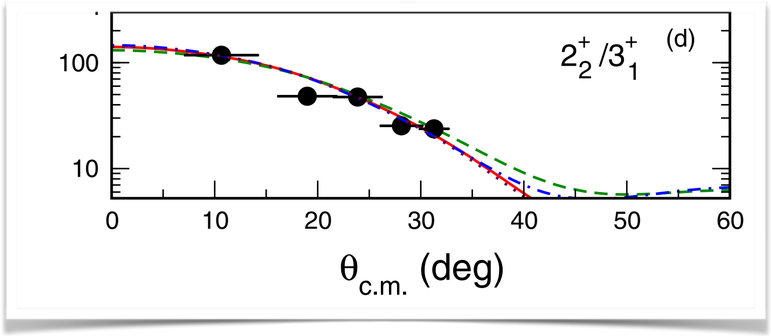
Isomer beams:

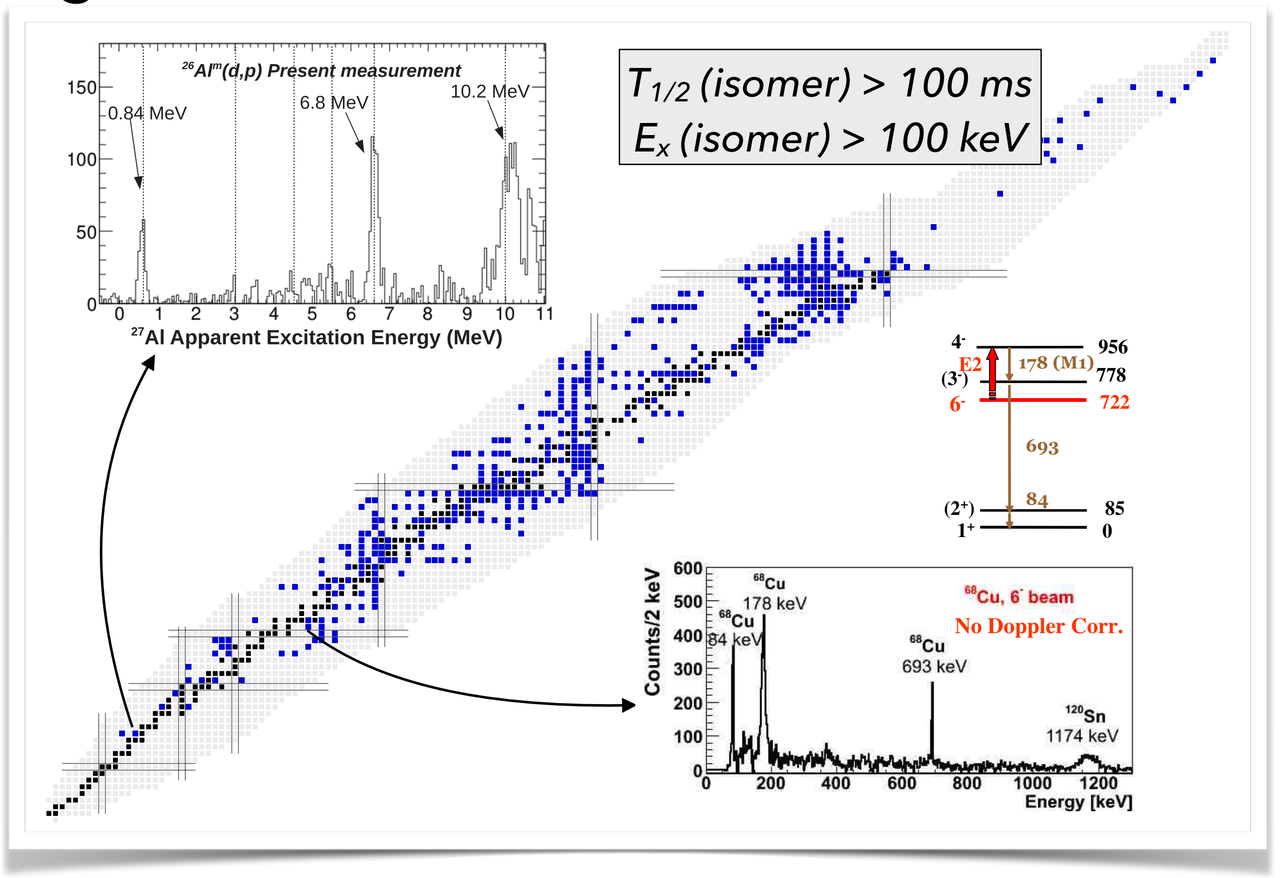
^{26}Al, ^{18}F, … more to come? … ^{34}Cl

Recoil detection: *heavy beams, higher rates*

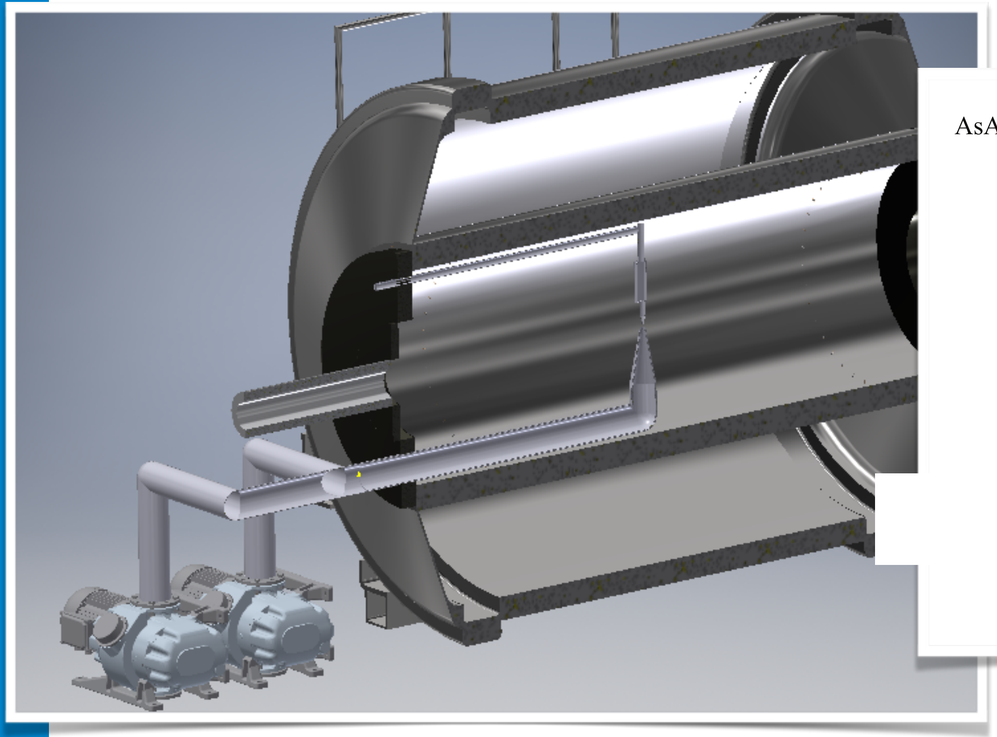
Forward angle detection:

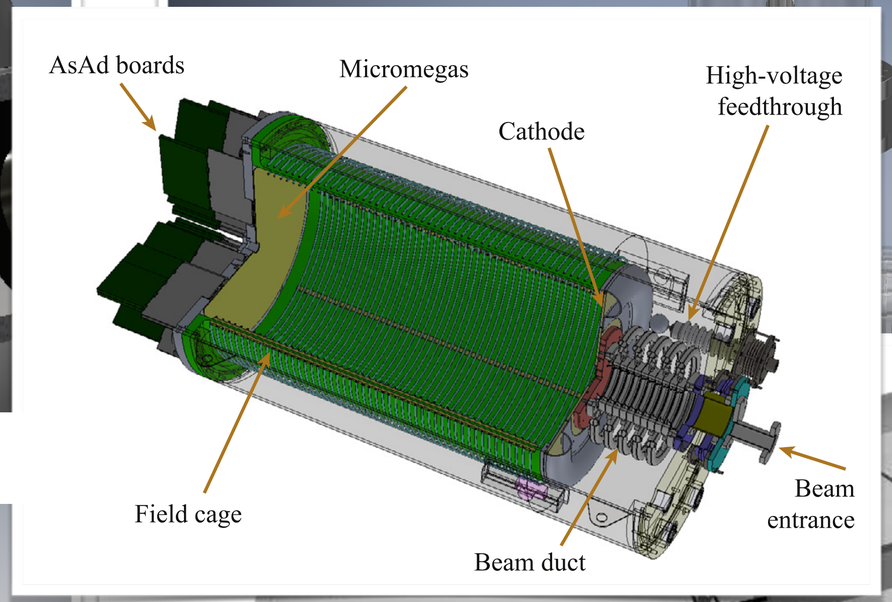


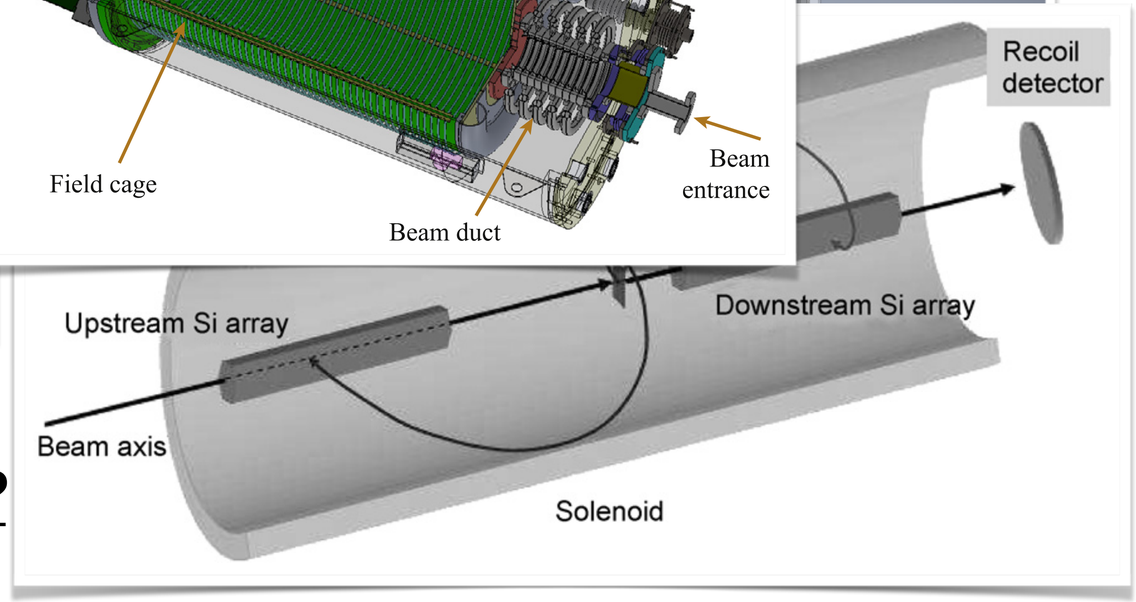


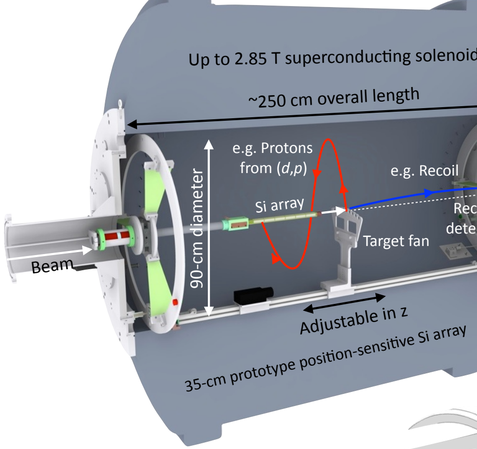


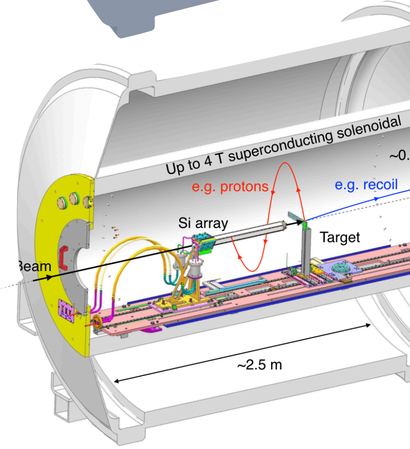
Challenges / opportunities

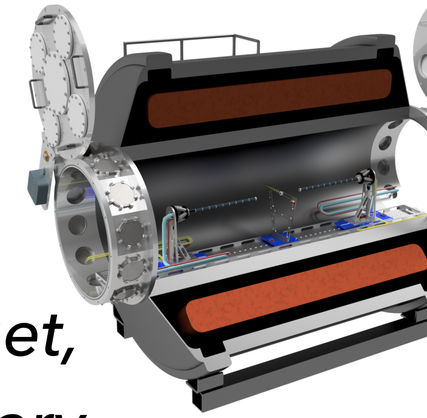












Gas-jet target, …, neutron detection? pAT-TPC/AT-TPC?

Upgrades planned*: HELIOS was a first, built on a shoe string budget, hope to install new more flexible supports system for targets, auxiliary detectors … aided by lessons learned/new solenoidal spectrometers*

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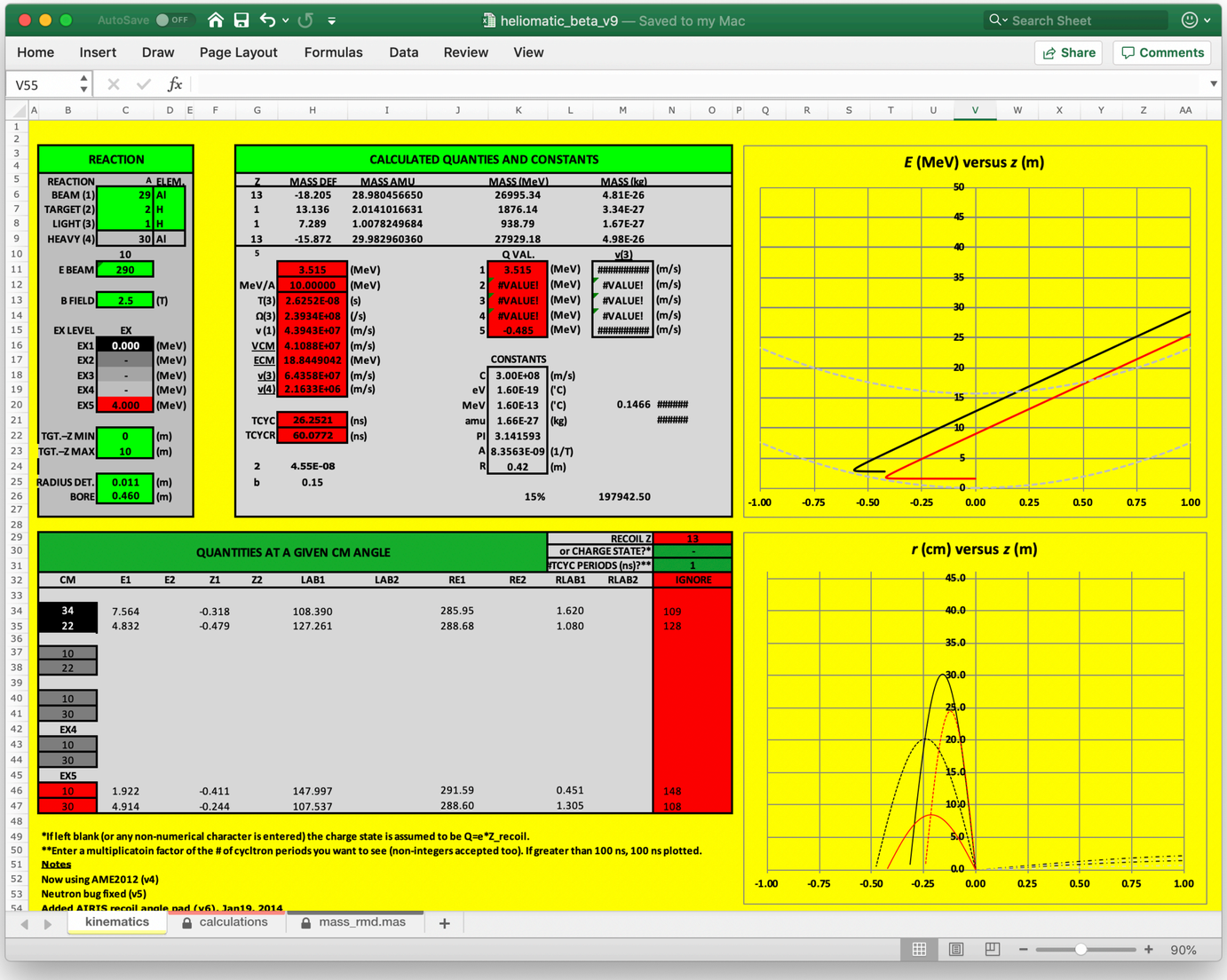
Closing comments

- *HELIOS is an outstanding instrument for studying direct reactions in inverse kinematics*
- *… has a high degree of flexibility*
- *ATLAS provides (and will provide ever more) beams that overlap exquisitely with astrophysical interests*
- *ATLAS + HELIOS have significant potential to address some key questions in nuclear astrophysics, both via specific/key measurements and by systematic studies*
- *We welcome users, and would prosper significantly from high-level engagement in HELIOS and a strong astrophysics program*

www.anl.gov/phy/helical-orbit-spectrometer

Heliomatic ... beta ... v9



Check the feasibility of a given experiment in seconds ... even astrophysics-y ones

Disclosure: Ryan Tang [ttang@anl.gov] has a slightly better version

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