Astrophysics Research with the AMS technique

Workshop on Nuclear Astrophysics Opportunities at ATLAS

Philippe Collon, University of Notre Dame

What is Accelerator Mass spectrometry

Accelerator Mass Spectrometry or “finding the needle in the haystack”

AMS orders of magnitude

Isotopic ratios from 10^{-12} to 10^{-17}

"Current" volume of lake Michigan: 4.9×10^{18} l

Ratio of a bottle of vodka in lake Michigan: 2.1×10^{-19}
→ Vera bad idea anyway

Ratio of Olympic pool in lake Michigan: 5.1×10^{-13}

4.2×10^{-17} corresponds to about 200l of liquid

Principle of AMS

The determination of the concentration of a given radionuclide in a sample can be done in 2 ways:

a) measure the radiation emitted during the decay

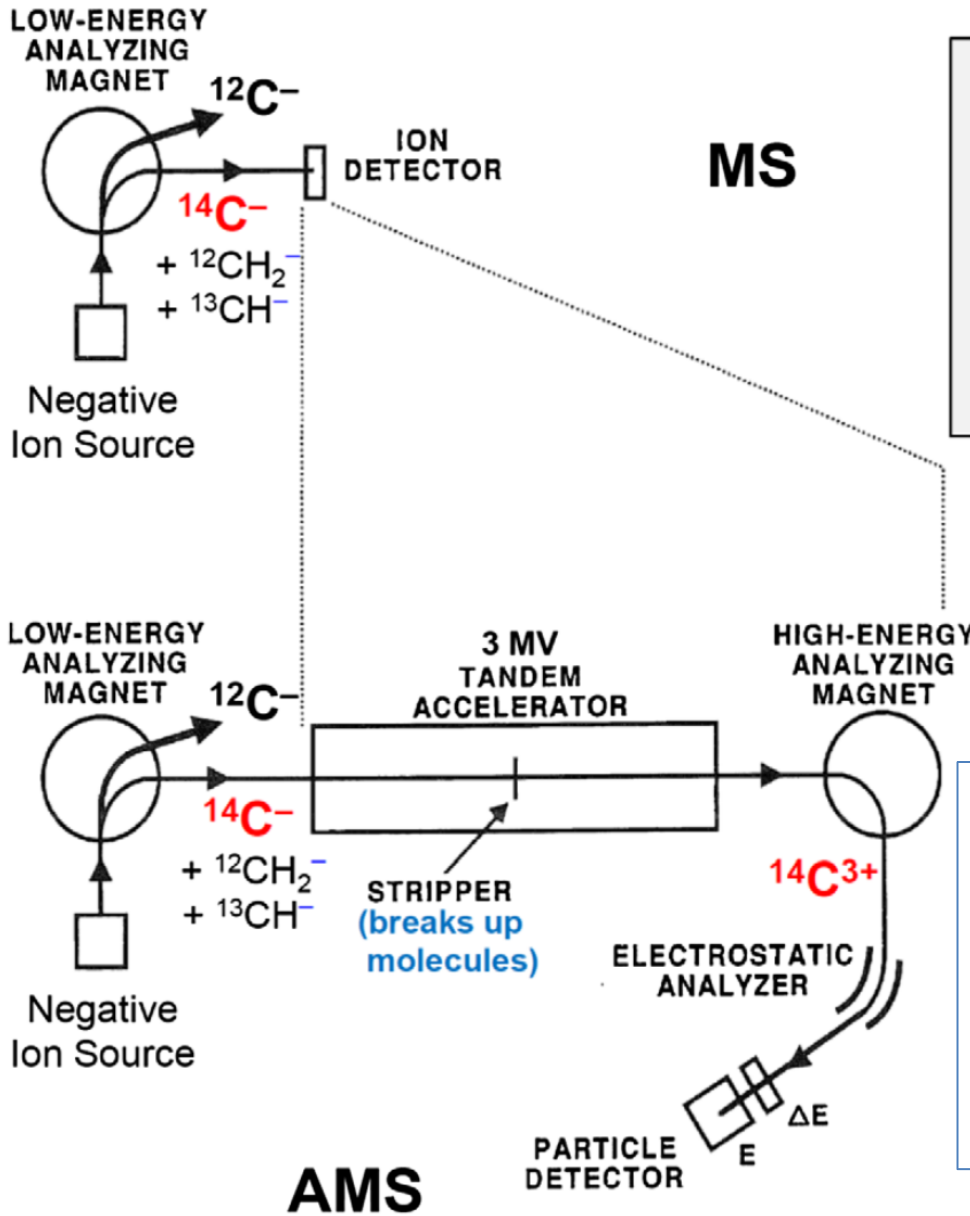
In many cases where concentrations and/or small or long $t_{1/2}$ this becomes impractical

1mg carbon = 6×10^7 at ^{14}C $\equiv$ ~1 decay/hour

b) count the number of atoms themselves

In a Mass Spectrometer a sample material is converted to an ion beam that is then magnetically (and electrostatically) analysed

→ MS separates ions by their mass only



Composition of a negative carbon beam

$^{12}C^-$	98.9 %
$^{13}C^-$	1.1 %
$^{14}C^-$	0.000 000 000 1 %
$^{12}CH_2^-$	~0.1%
$^{13}CH^-$	~0.001%
$^{14}N^-$	0 !

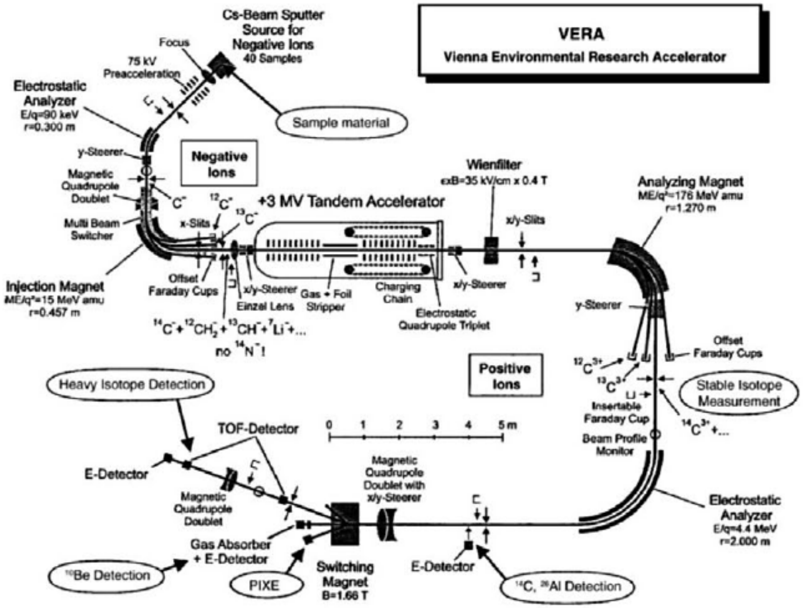
An AMS measurement is generally relative:

-Stable isotope (F-cup)

- single atom counting

→ Stability of System

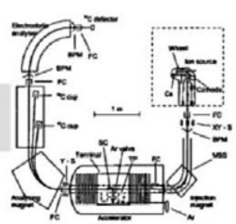
AMS facilities over the years



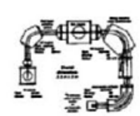
Standard AMS, TV = 3 MV
16 mx 12 m = 192 m²
VIENNA

3 MV, 200 m²

500 kV, 30 m²



Compact AMS, TV = 0.5 MV
6 m x 5 m = 30 m²
POZNAN

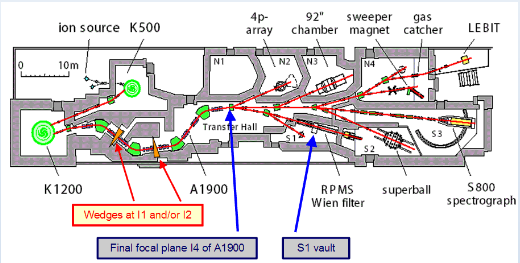


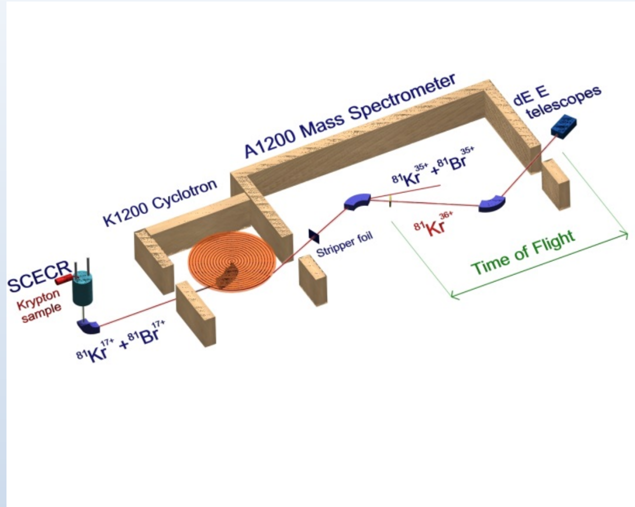
Mini AMS, TV = 0.2 MV
3.0 m x 2.3 m = 6.9 m²
ZURICH

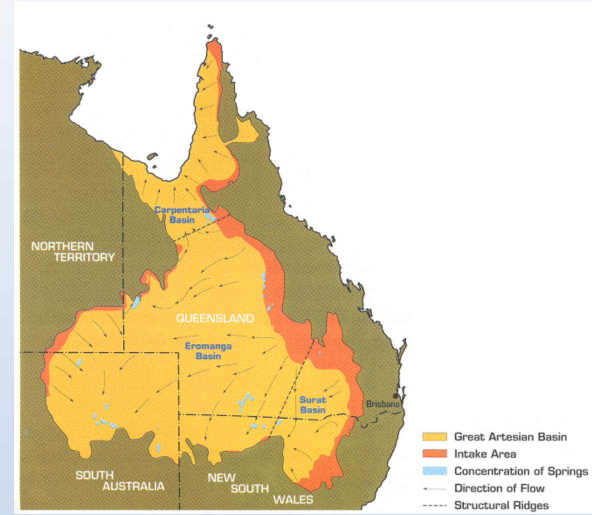
200 kV, 7 m²

W. Kutschera 2016

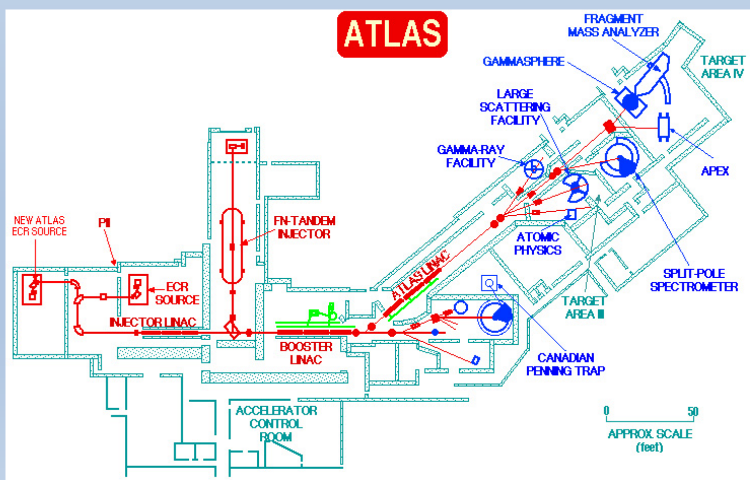
However AMS measurements have been (and still are being) pursued at large facilities

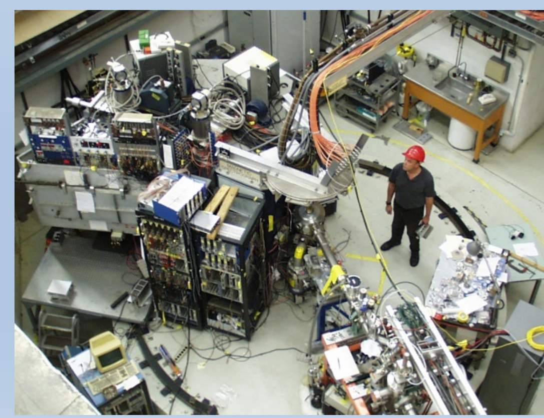


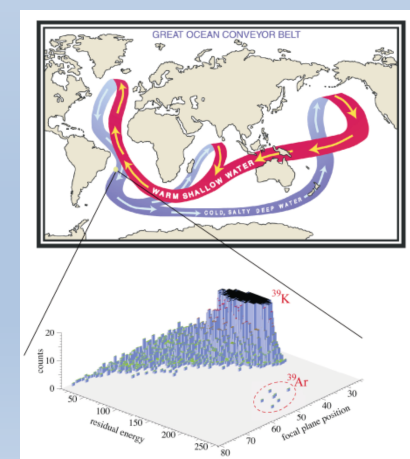




NSCL and ATLAS are 2 typical examples







Main challenge for an AMS measurement

To this day most AMS measurements rely on the measurement of a relative concentration:

Relative to a standard, as an absolute concentration measurement (even on a small machine) is extremely difficult

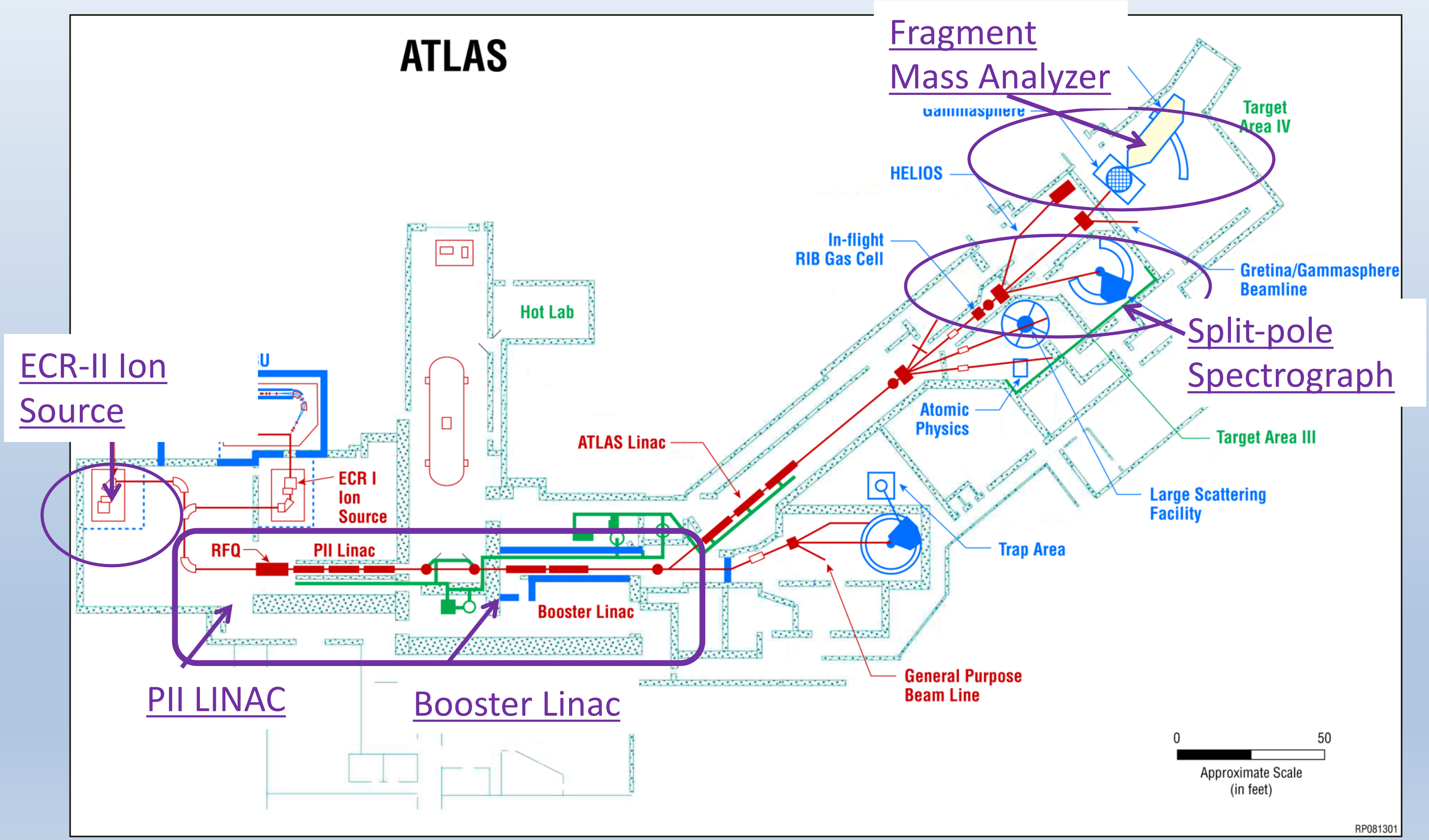
This requires stability and reproducibility of beam tunes (i.e. beam optics) over long periods of time.

The measurements require a regular switch between individual selected isotopes tunes

The larger the accelerator system… yes you guessed it

Requires ensuring high-energy reliability of ATLAS (E > 8-9 MeV/u to provide reliable, rapid switching between different M/q species

ATLAS AMS Typical Configuration



ATLAS as an AMS facility

Control system programmable to allow rapid configuration changes

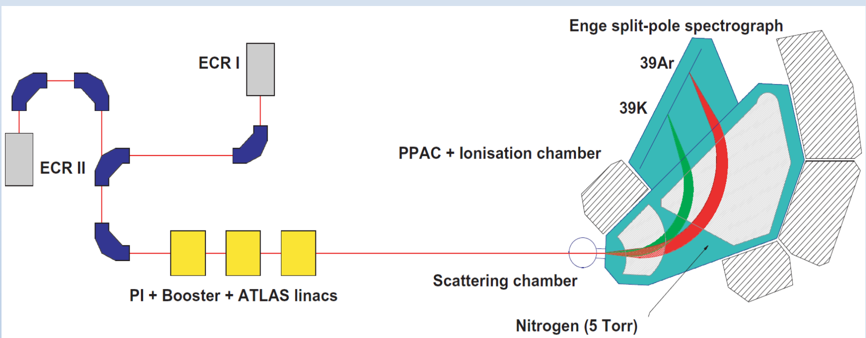
- All dipoles set by gauss
- Magnetic quadrupoles set using a specific pattern to reduce hysteresis effects
- Multiple (M/q) configuration stored
  - Rapid switching between configuration automatically by master clock
  - Normalization by beam current at source or base material measurement at detector
    - Precise attenuation with non-resonant beam sweeper.

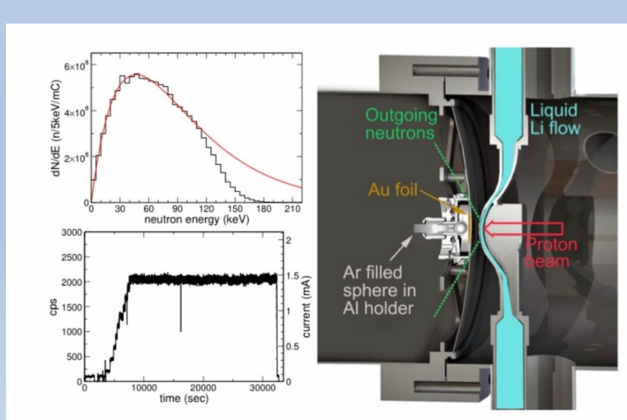
These upgrades have resulted in a highly improved large scale AMS facility with a number of different detection "stations"

ATLAS is probably the only large-scale AMS facility where mid-heavy nuclides (A~100-150) can be uniquely identified

The gas-filled magnet technique at the Enge Split-pole spectrograph

From Ocean circulation to stellar synthesis of neutron-light nuclides





Studying the $^{36,38}Ar(n,\gamma)^{37,39}Ar$ reaction at quasi-Maxwellian neutron energies

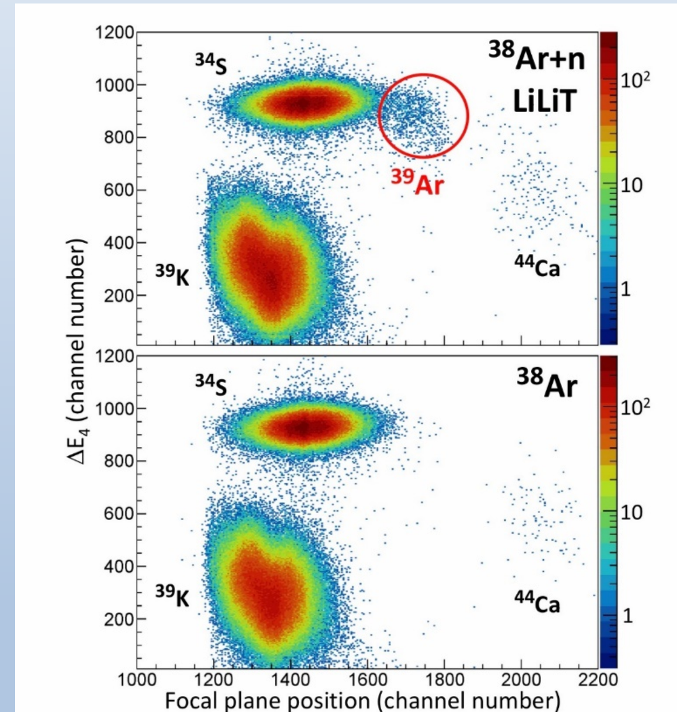
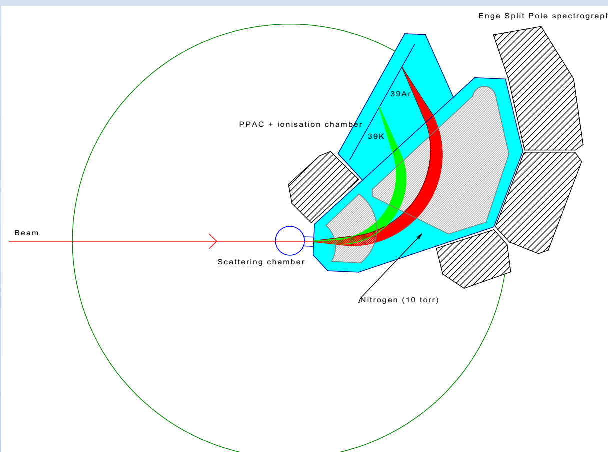


FIG. 3. Identification spectrum of ^{39}Ar ions in the detector measured for the LiLiT irradiated ^{38}Ar gas (top) and for non-irradiated ^{38}Ar gas (bottom). The horizontal axis represents dispersion along the focal plane and the vertical axis a differential energy loss signal measured in the fourth anode of the focal-plane ionization chamber [36].

Extracted reaction rates and comparison to theoretical values



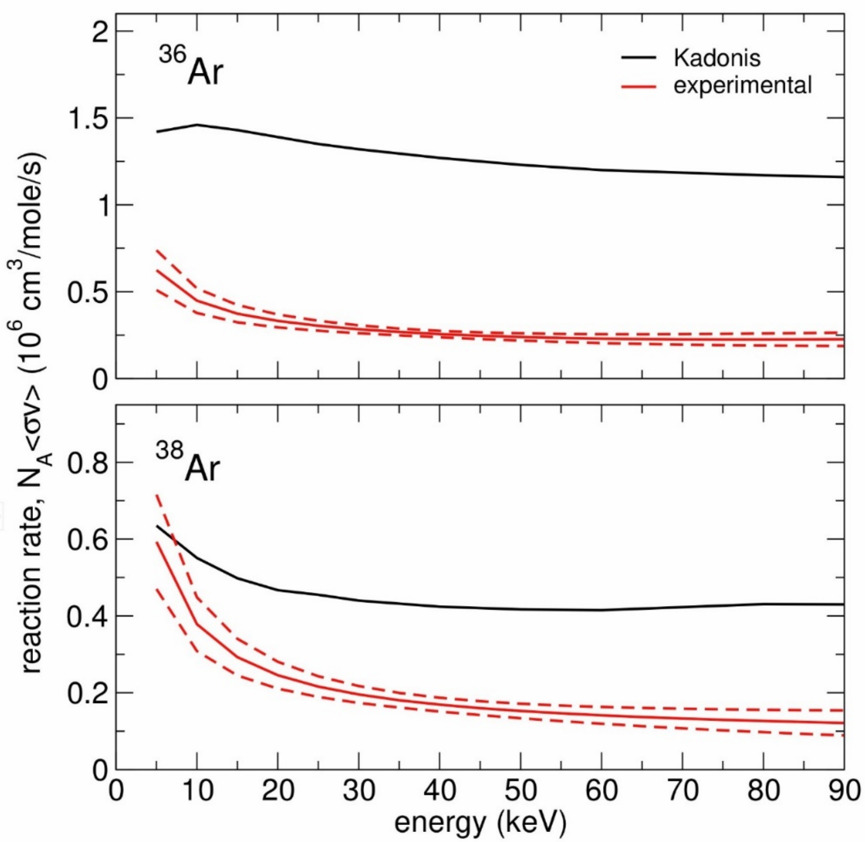


FIG. 4. (Color online) Comparison of the ^{36}Ar (top) and ^{38}Ar (bottom) (n, γ) reaction rates ($N_A \langle \sigma v \rangle$) extracted from this work (red) to the Kadonis [49] recommended values (black). The dashed curves encompass the estimated 1σ uncertainty.

Half-life of ^{146}Sm

^{146}Sm is a chosmochronometer that serves to determine the chronology of solar system formation and planetary differentiation. Previously determined as $T_{1/2}$= 103±5My

- re-determination of ^{146}Sm half-life:

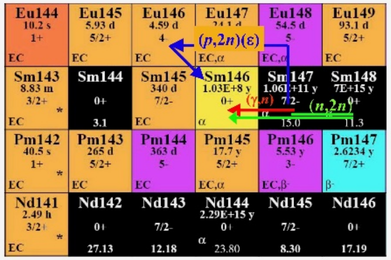
$$A_{146} = \frac{\ln 2}{T_{146}} \times N_{146} \qquad A_{147} = \frac{\ln 2}{T_{147}} \times N_{147}$$

$$T_{146} = \frac{A_{147}}{A_{146}} \times \frac{N_{146}}{N_{147}} \times T_{147}$$

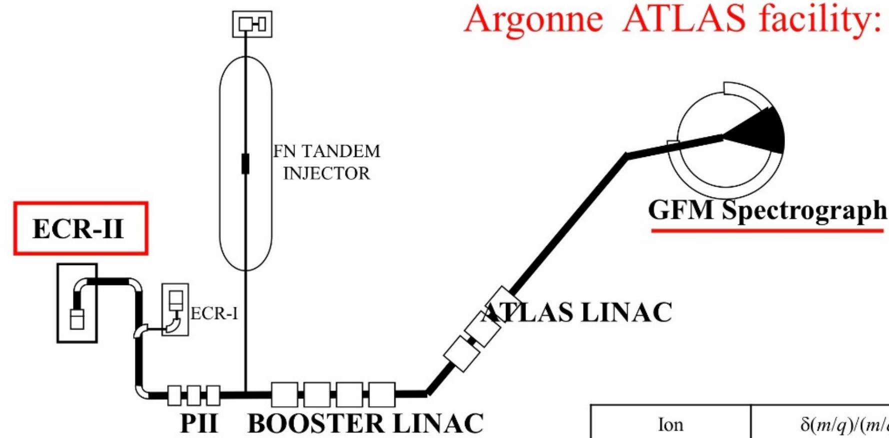
T_{147}= (1.17 ± 0.02) × 10^{11} yr

N. Kinoshita et al. J. Nucl. Radiochem. Sci. 4, 5 (2003)

Activation of ^{147}Sm to ^{146}Sm



Argonne ATLAS facility:



Accelerated Ions: iso-(m/q)

$^{146}Sm^{22+}$,$^{146}Nd^{22+}$

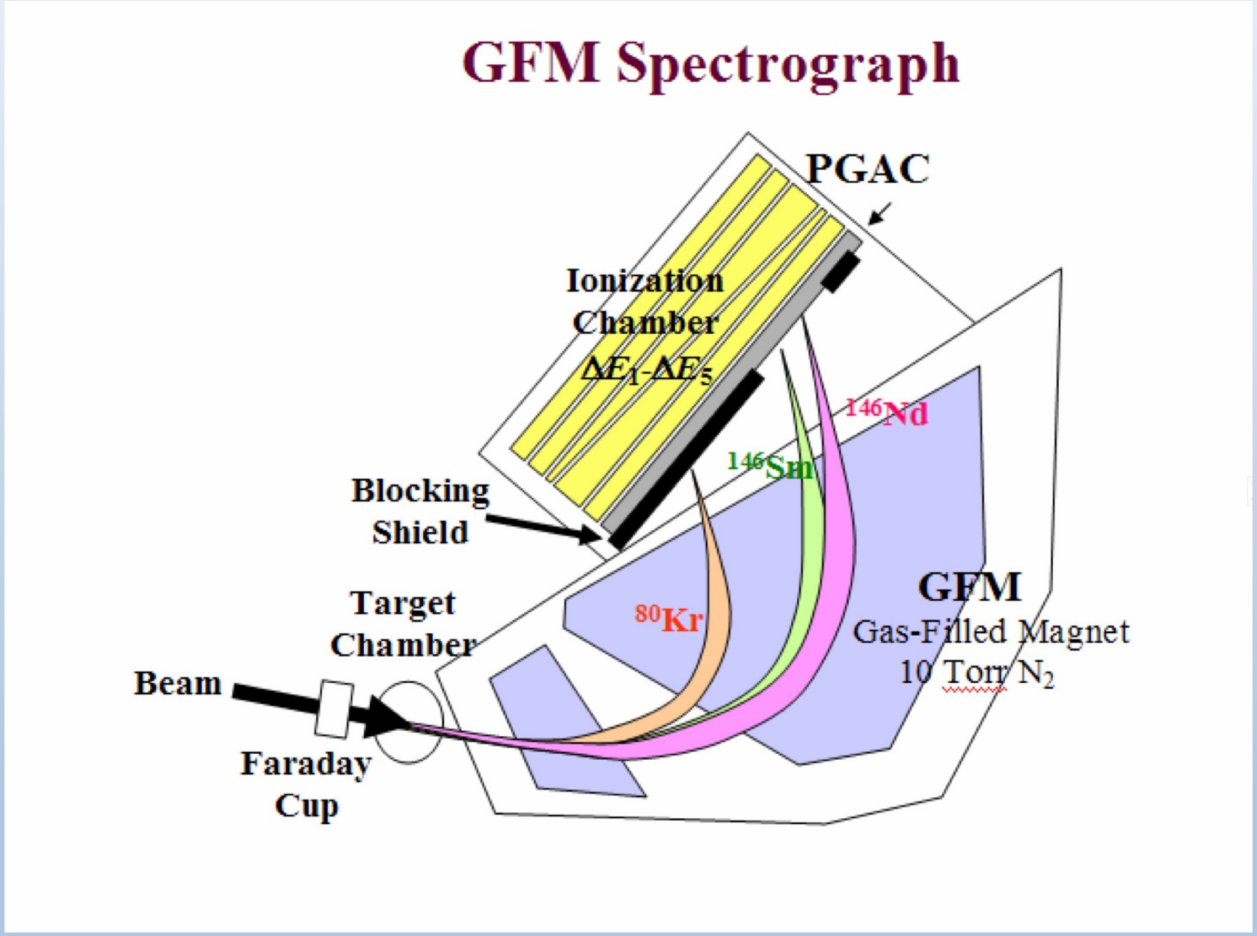
m/q=146/22

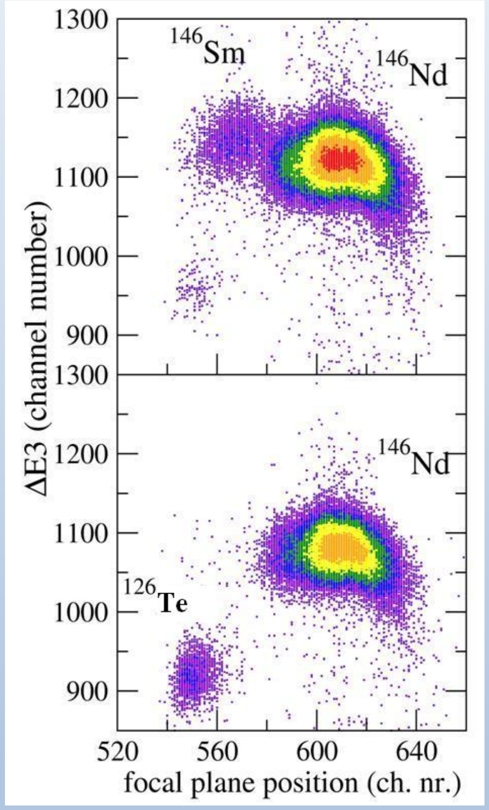
Pilot beam (by m/q scaling) :

$^{80}Kr^{12+}$,$^{147}Sm^{22+}$, $^{152}Sm^{23+}$

Ion	$\delta(m/q)/(m/q)$ %
146Sm22+	0.000
146Nd22+	0.000
152Sm23+	– 0.417
80Kr12+	+ 0.457
133Xe20+	+ 0.205
139La21+	– 0.261
166Er25+	– 0.055

Separation of ^{146}Sm from ^{146}Nd

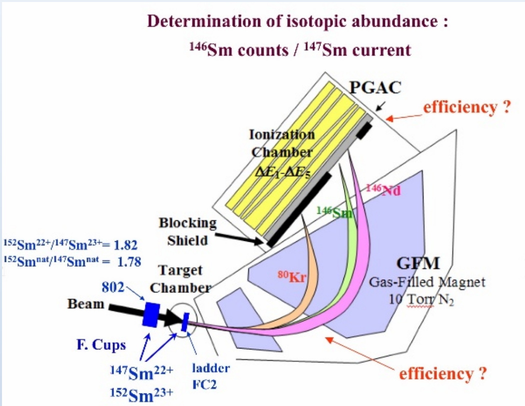




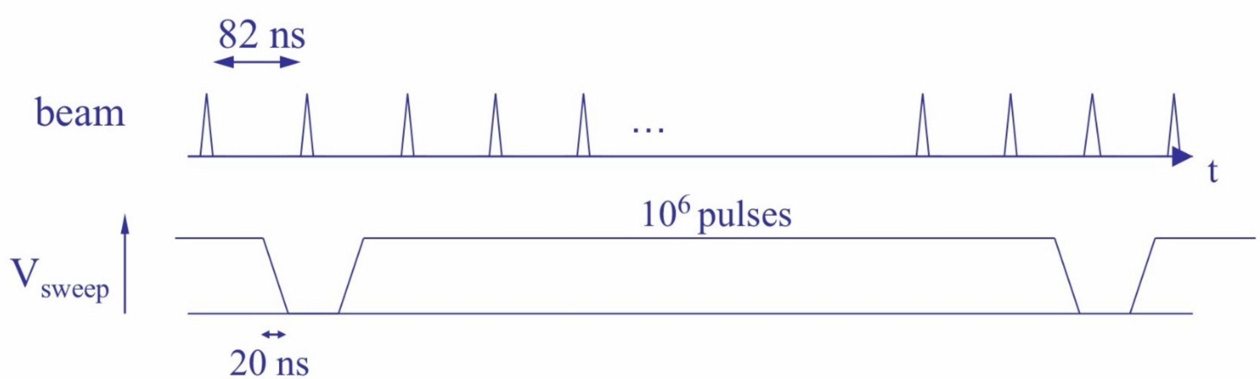
Traditional beam attenuators

Useful they are, but…. repeatable they are not

Quantitative beam attenuation



measuring ^{146}Sm AND stable ^{147,152}Sm isotopes in focal-plane detector of GFM by quantitatively attenuating stable isotopes (e.g. factor 10^6), using beam sweeper:



$T_{1/2}$=68 ± 7My

i_{ave}($^{147}Sm^{22+}$)= 4 epA, ~0.1 ion per bunch, ~5 ^{147}Sm ions/minute

for ^{146}Sm/^{147}Sm= 10^{-7}, ^{146}Sm = ~0.5 count per minute (DC)

MANTRA: Measurement of Actinide Neutron TRAnsmutations

Improved integral neutron capture cross section data for Actinides essential for GenIV reactor and advanced fuel cycle development

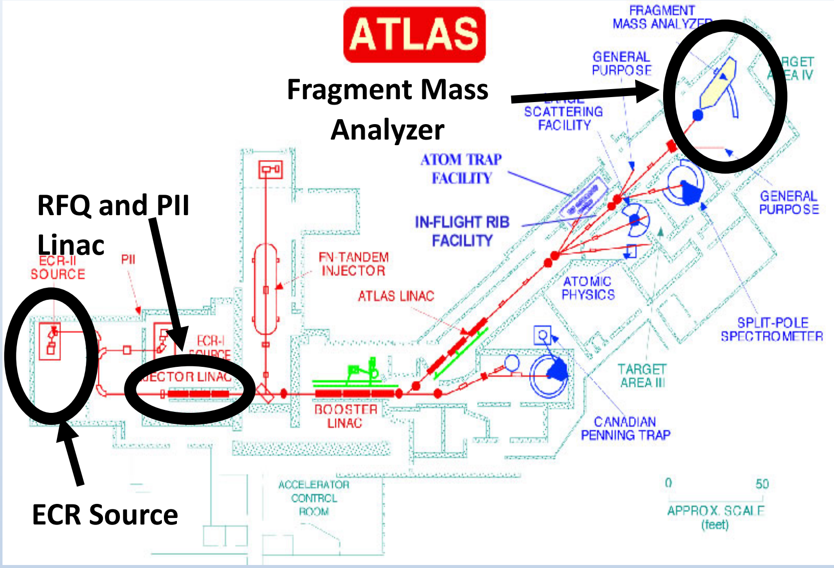
MANTRA: 1) pure actinides irradiated at ATR (INL)

235U, 238U, 237Np,242Pu, 244Pu, 243Am, 248Cm

2) Measure isotopic ratios with AMS

3) Infer integral cross sections

$$\bar{\sigma}_{A_{capture}} \approx \frac{\dfrac{N_{A+1}(t_f)}{N_A(t_f)} - \dfrac{N_{A+1}(t_i)}{N_A(t_i)}}{\tau}$$



Development work at ATLAS to improve AMS facilities to improve precision and handle large number of samples:

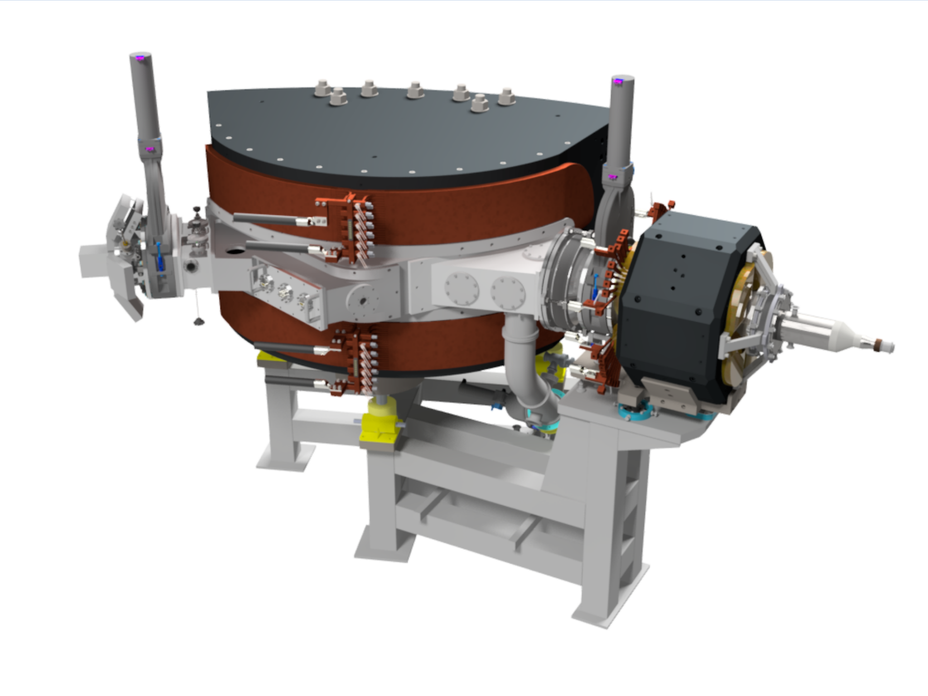
1) Laser Ablation at ECR

2) Multi-Sample Changer

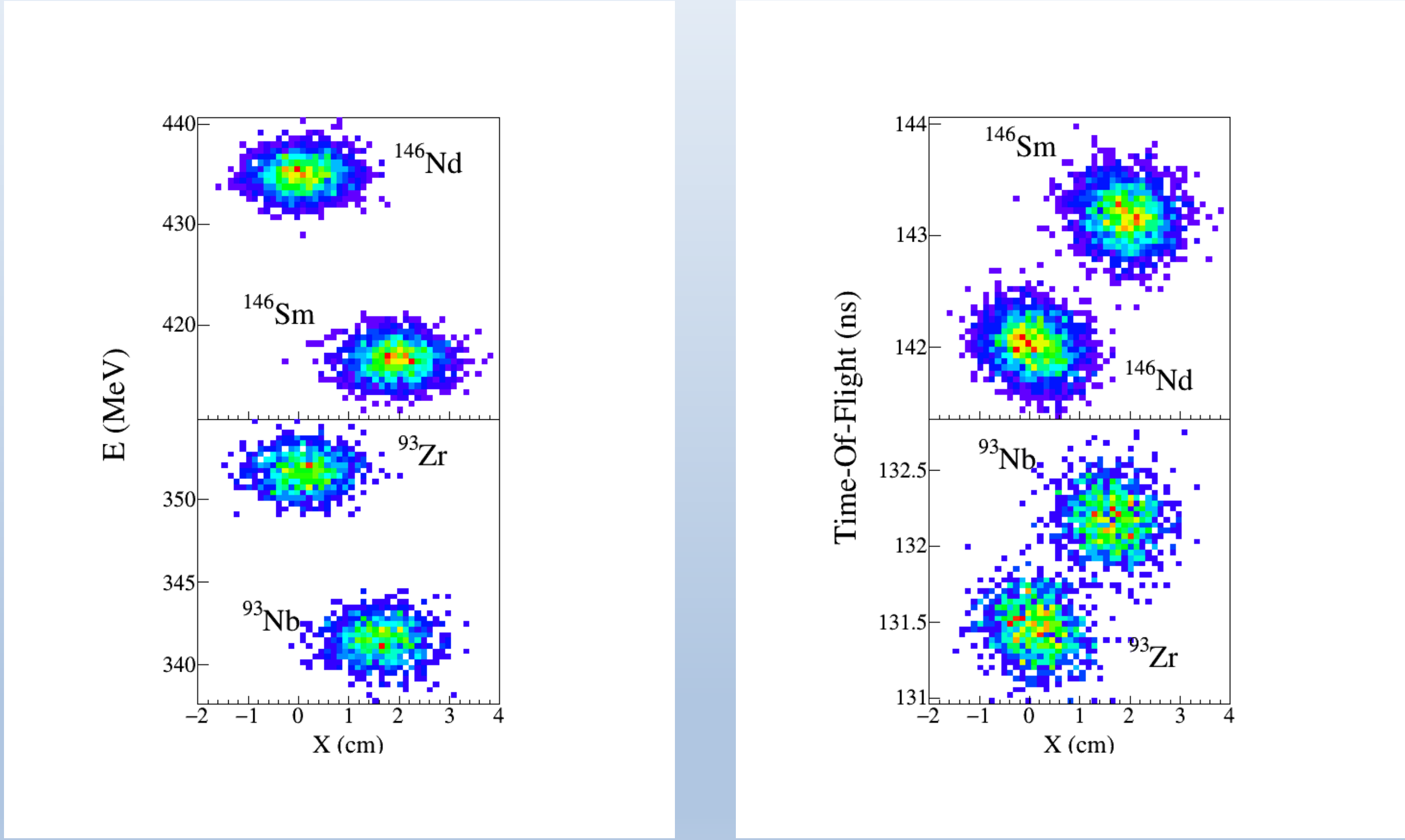
3) Automated accelerator control (“Clock Program”)

Developing AMS at AGFA

The proposed program focuses on the extension of AMS to the heavy region of nuclides, in the mass range A ~ 100-200 unexplored so far with important implications in nuclear physics and astrophysics. The high energy of the ATLAS accelerator and the proposed use of a new device, the Argonne Gas-Filled Analyzer (AGFA) offer unique prospects owing to the high magnetic rigidity specifications of AGFA.



Simulated isobaric separation



Simulated two-dimensional spectra showing expected discrimination between isobaric pairs ^{93}Zr-Nb and ^{146}Sm-Nd at the focal plane of the AGFA spectrometer.

ATLAS as an AMS facility

Control system programmable to allow rapid configuration changes

- All dipoles set by gauss
- Magnetic quadrupoles set using a specific pattern to reduce hysteresis effects
- Multiple (M/q) configuration stored
  - Rapid switching between configuration automatically by master clock
  - Normalization by beam current at source or base material measurement at detector
    - Precise attenuation with non-resonant beam sweeper.

These upgrades have resulted in a highly improved large scale AMS facility with a number of different detection "stations"

ATLAS is probably the only AMS facility where mid-heavy nuclides (A~100-150) can be uniquely identified

Does however require a very close collaboration and level of communication with Both the Ion Source group and the operators to guarantee successful stability and reproduceability

Thanks