Nucleosynthesis in Explosive Astrophysical Sites

Lecture 3

Brian Fulton
University of York

SLENA 2012
26-29 November 2012
Saha Institute. Kolkata, India

In the first lecture we discussed the astrophysical objects where explosive nucleosynthesis occurs Novae, X-ray Bursters and Supernovae).

We saw how the nucleosynthesis in these site is dominated by reactions between exotic (short lived) nuclei.

This creates difficulties in measuring the reaction cross sections, unless we can get beams of radioactive nuclei.

In the second lecture we looked at how these beams could be produced and at some of the facilities that have been built to provide the beams we need for our experiments

In this lecture we will look at some of the experimental challenges and at the detection equipment that has been developed for the measurements

Let's take a reaction this is important for observing gamma rays from novae

$p + {}^{18}F > \alpha + {}^{15}O$

Using a radioactive beam of ^{18}F, so low intensity - let's take 10^6/s

Target of plastic has hydrogen (protons) and has 10^{18} /cm^2

Cross section is small as low energy - let's say 1mb

Detector for the α particles is 5x5 cm and is a distance 25cm from the target

How many a particles are emitted per second?

How long would it take to measure this cross section to an accuracy of 10%?

Answer: Rate = 10^{-3}/s (86 counts per day)

Detector only covers 1/314 of 4p
So if emission isotropic rate in detector is 0.28 per day

So for 10% uncertainty (100 counts) we need 1 year

We see from our calculation that experiments with radioactive beams have low yields, so we need our detection systems to be as efficient as possible

So need large arrays of detectors covering as much of 4π around the target as possible

Could be looking to detect:

- Projectile-like or target-like nuclei
- Recoiling compound nucleus
- Gamma rays from de-excitation of these

We will look at:

Particle detector array	TUDA
Gamma array	TIGRESS
Combined particle/gamma	SHARC
Recoil detector	DRAGON
Tracking detectors	TACTIC

A couple of overarching aspects

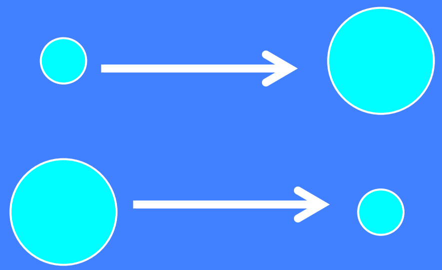
In an astrophysical site, the most abundant nuclei are usually H and He, so usually interested in reactions between H or He with a target nucleus.

And in the case of explosive nucleosynthesis, the target nucleus is radioactive so we have to do the experiment the other way round using it as the projectile

This is often called "inverse kinematics"

"Usual" experiment

Radioactive beam experiment



The main effect is that the reaction products are thrown forward and focused at small angles

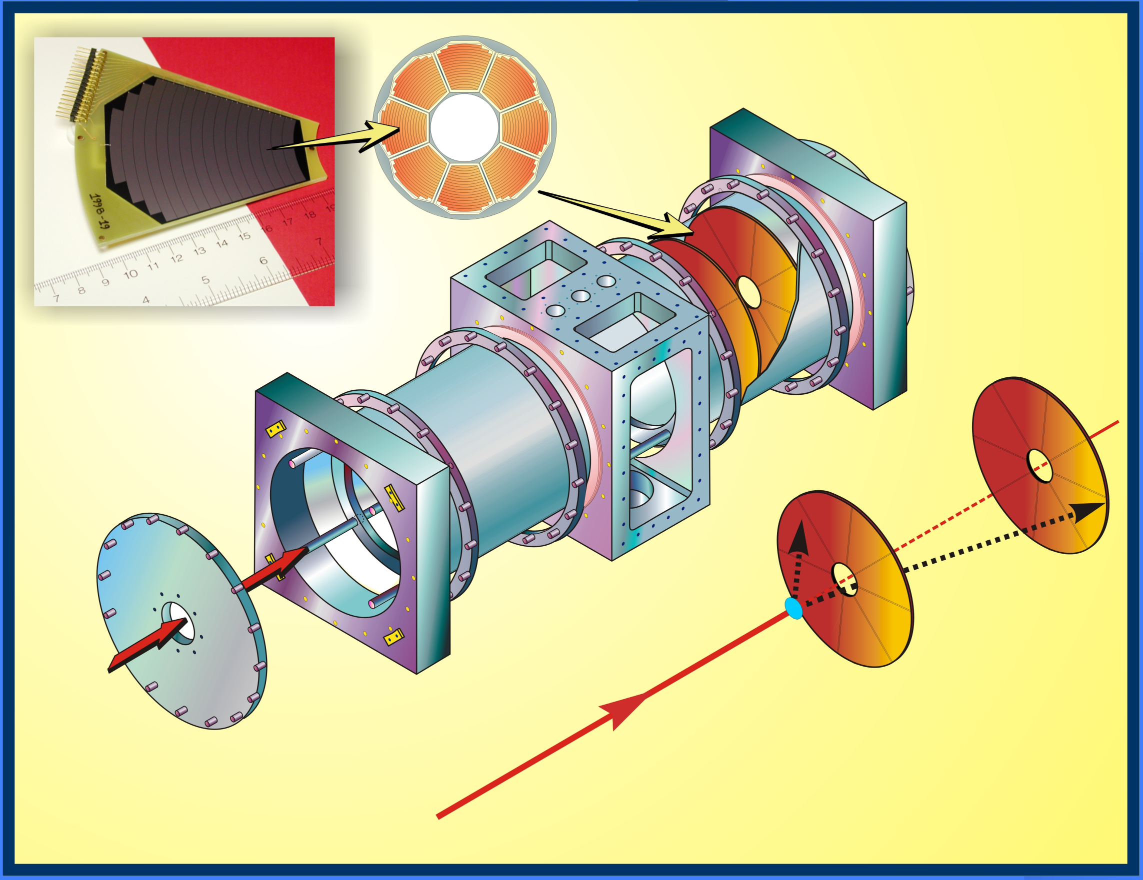
GOOD	Helps with detection efficiency
BAD	Need very good angular resolution to see details

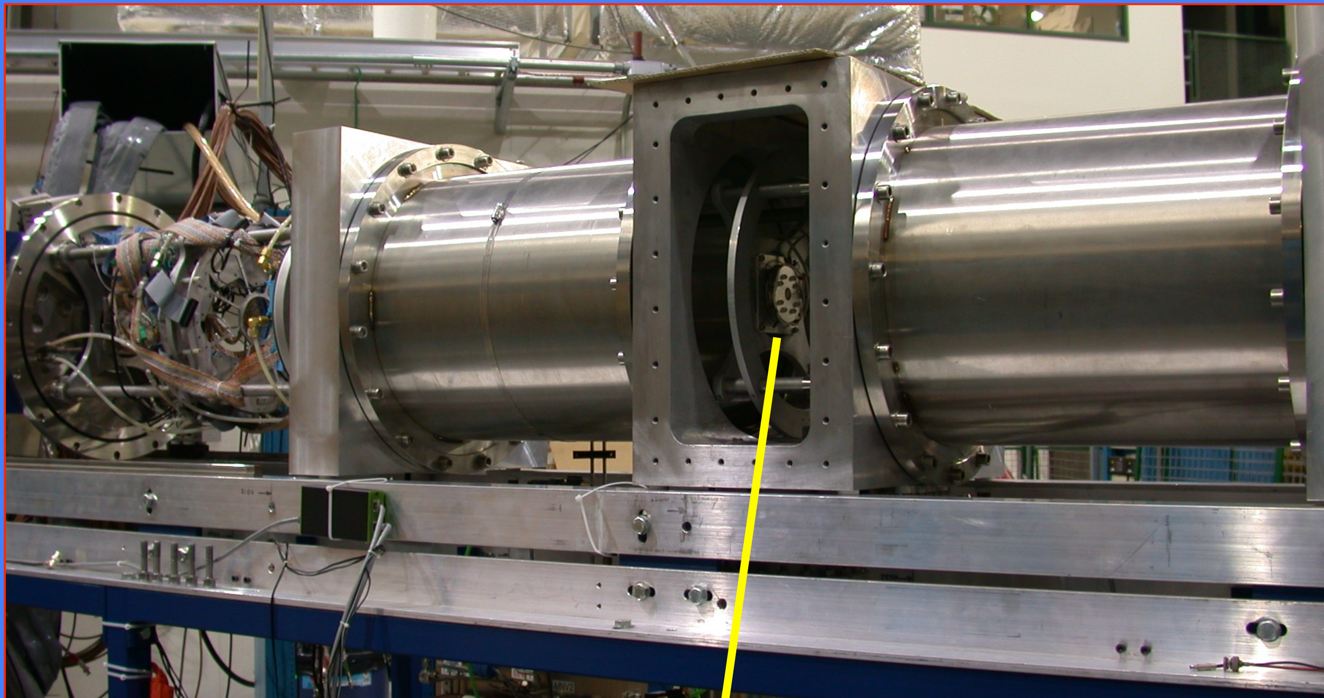
Target usually	H	Plastic foil (C_xH_y) or occasionally gas target
	He	Gas target (windowless) or implanted

Particle detector array TUDA

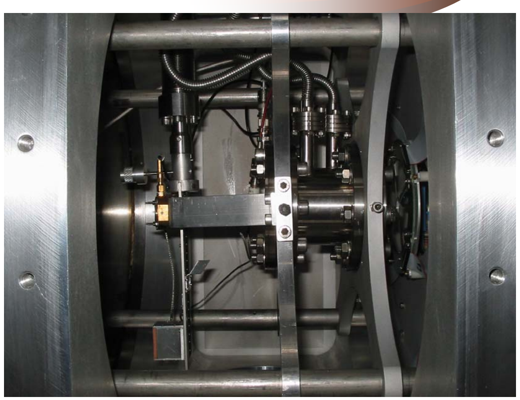
Studying charged particle reactions e.g (p,p’), (α,p), (d,p)

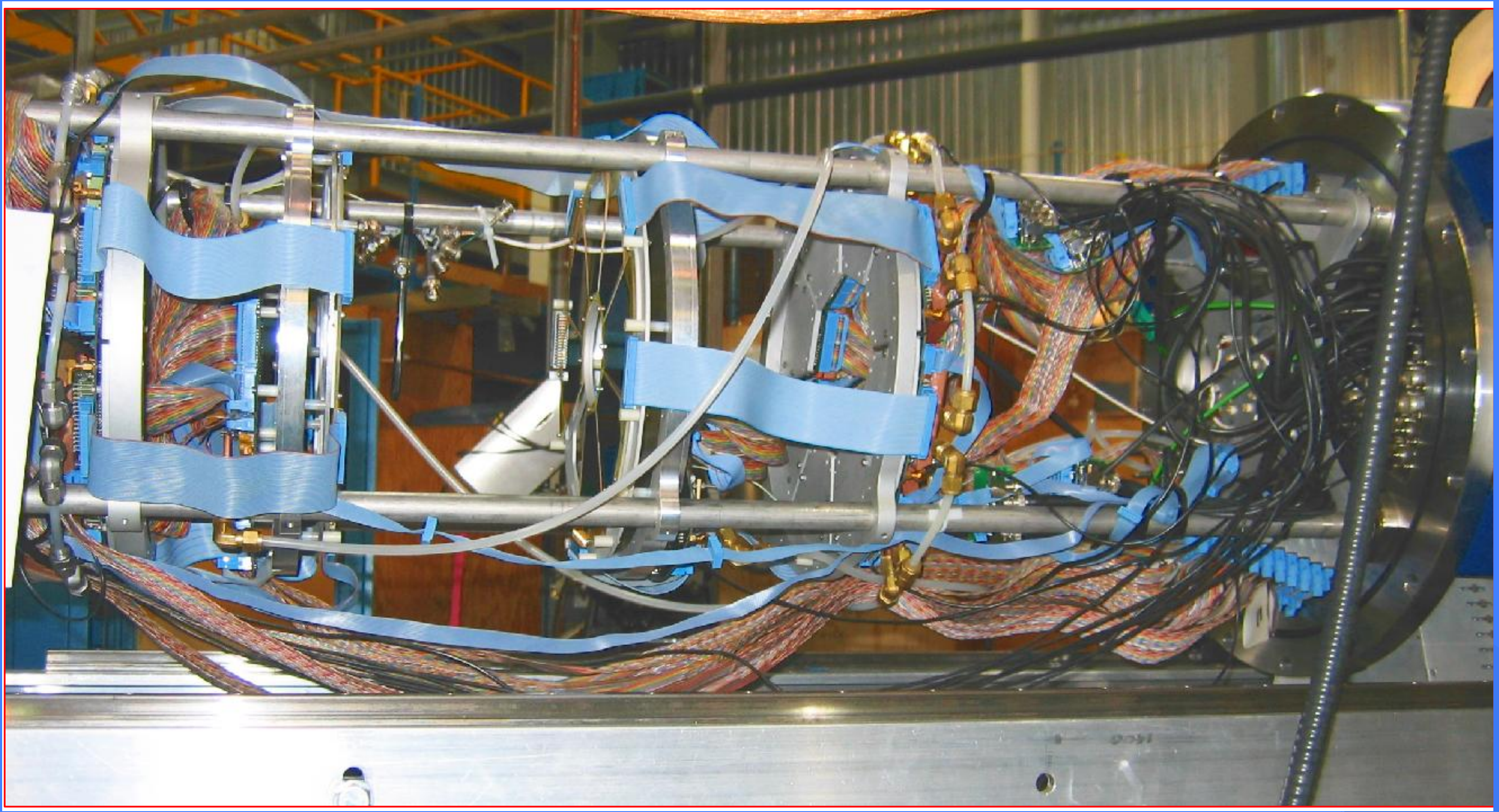
Large area, high multiplicity silicon strip arrays
Isolated chamber and electronics to reduce noise
Solid/gas targets
Up to 512 channels





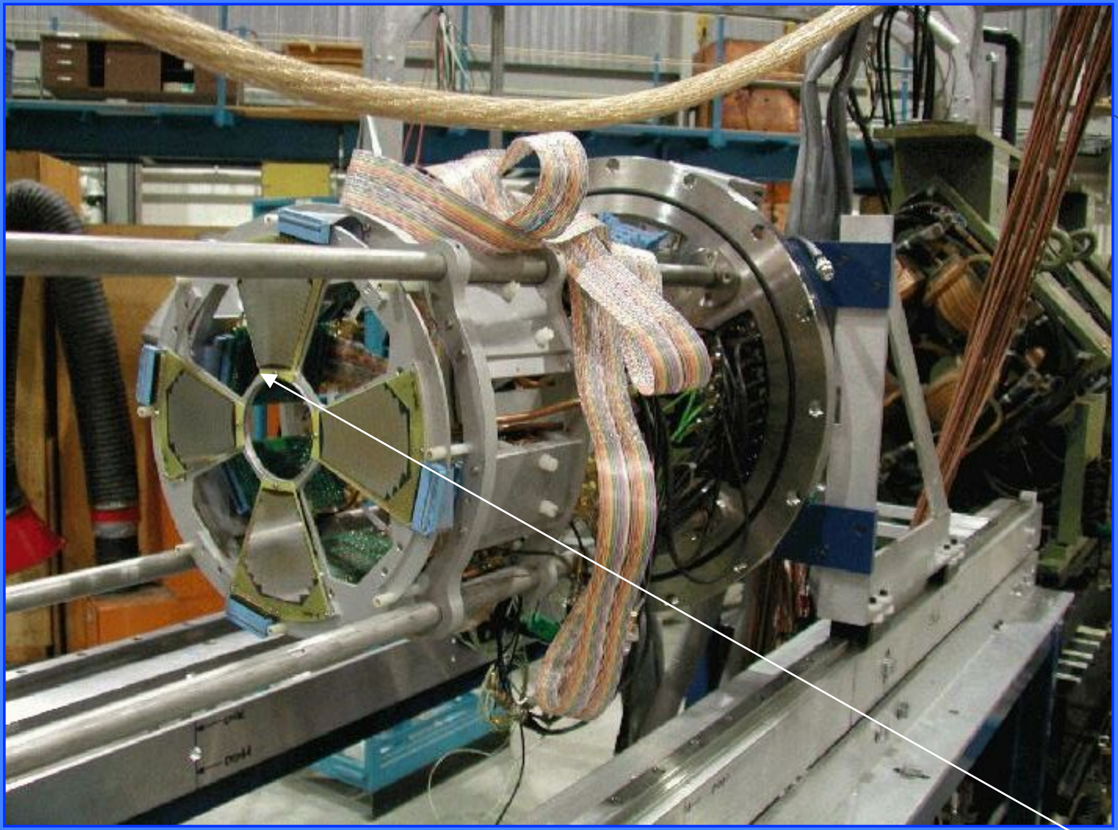
- Solid targets
  - CH_2
  - CD_2
  - Gold foils
  - Carbon foils
- Gas target
  - Helium filled cell
  - Cryogenic ^3He cell (on loan from E. Rehm/ANL)

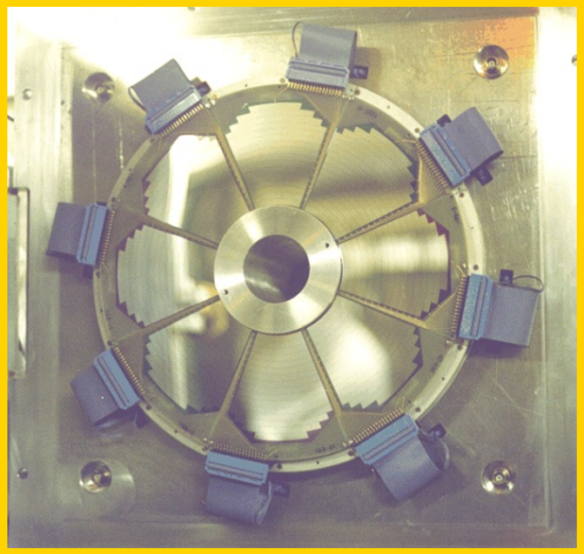




512 channels of electronics and data acquisition housed inside copper lined counting room to reduce electronic noise

Detectors cooled to reduce leakage (noise)

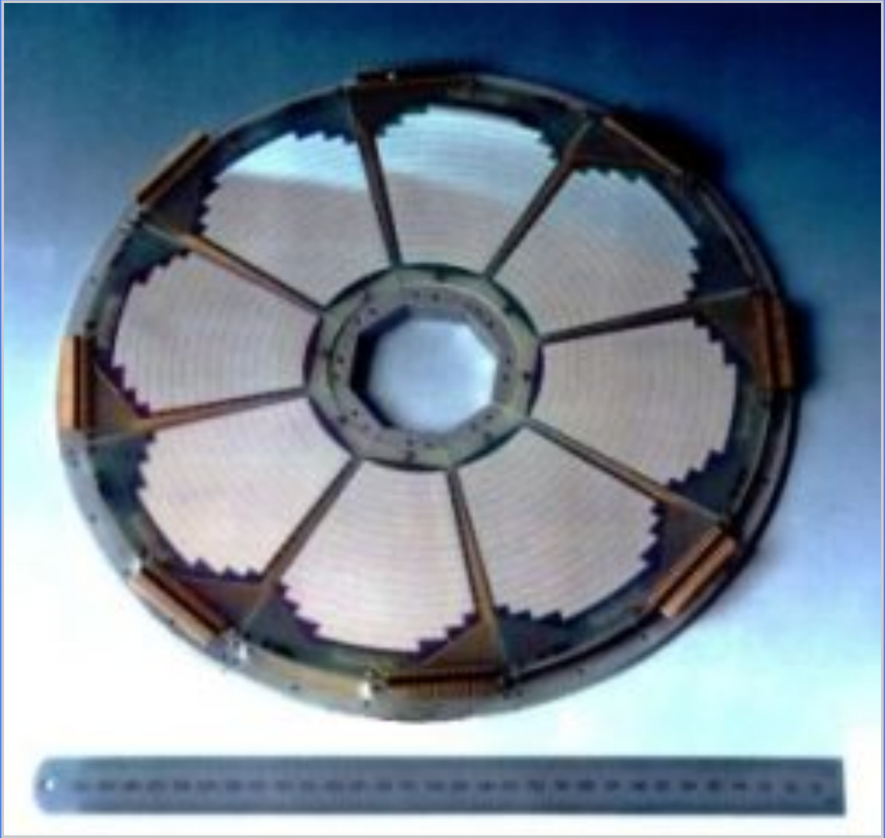




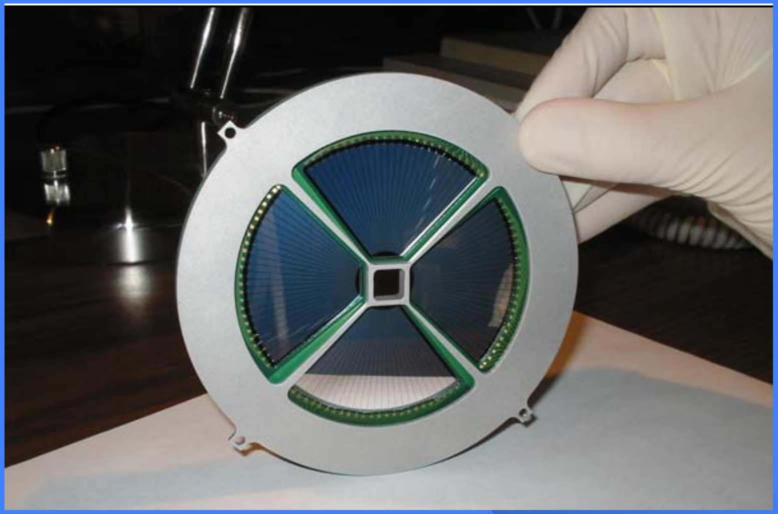
Detectors record the particle energy and time of arrival

This gives ToF (Time of Flight from the target to the detector) which enables the particles to be identified

Double sided silicon strip detectors (pixelated detectors)



"LEDA" Design
Front 16 aximuthal strips
Rear 16 radial strips



"CD" Design
Front 24 aximuthal strips
Rear 16 radial strips

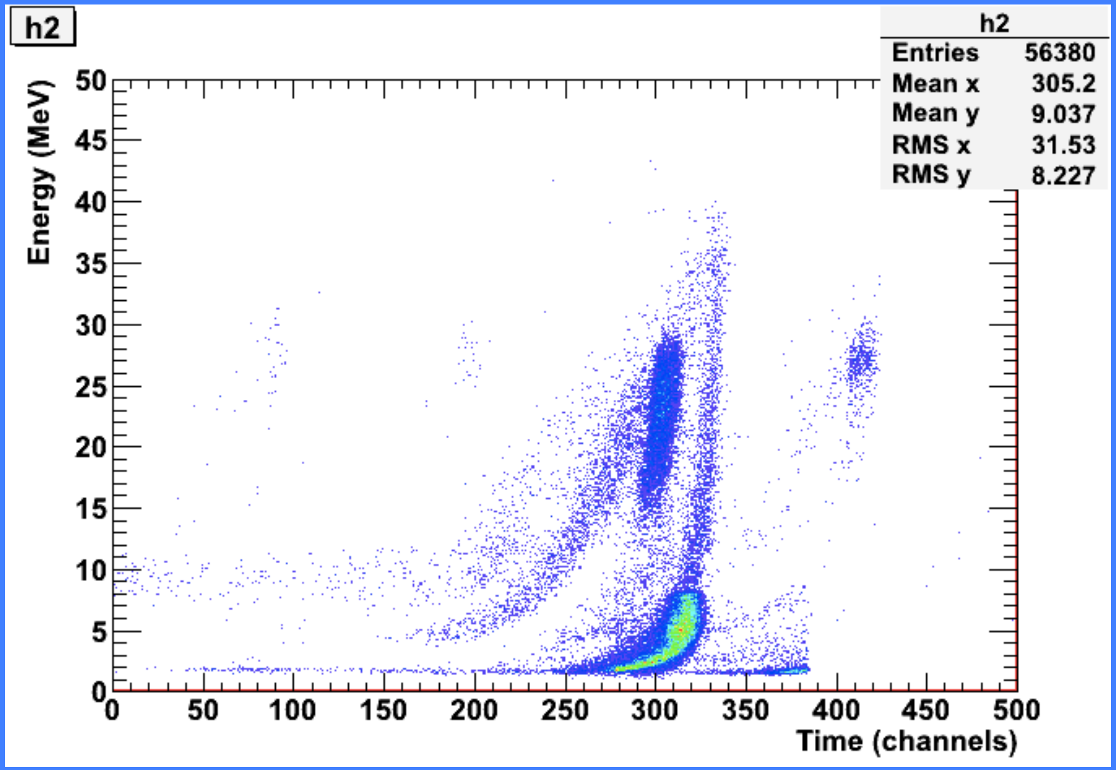
Depending on distance from target can give ~1^{o} resolution in-plane and out-of-plane

Energy $E = \frac{1}{2}mv^2$

For a given strip the distance (d) from the target to the detector is fixed

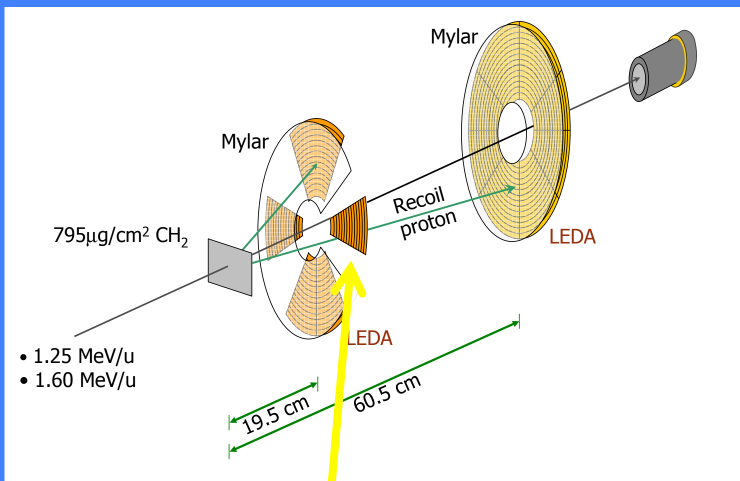
So time take $t = d/v$

Which means $E = \frac{1}{2}md^2/t^2$ or E proportional to m/t^2



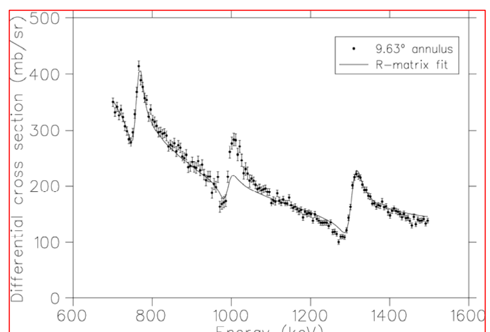
Plot of E versus T shows different parabola for each type of particle

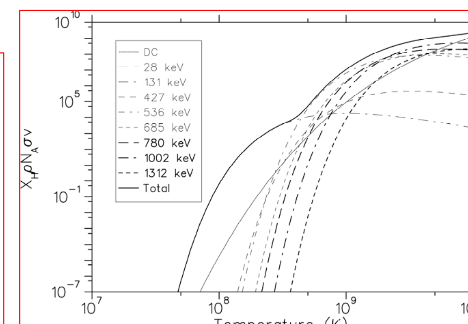
Information to help determine the ^{22}Na production in novae by measuring p(^{21}Na,p') to detect resonances in ^{22}Mg



Detectors covered with mylar film to absorb scattered ^{21}Na to protect detectors – a sector left uncovered to record elastic scattering for normalisation

- Studied states in ^{21}Mg via resonant elastic scattering
- ^{20}Na beam impinging on CH_2 target



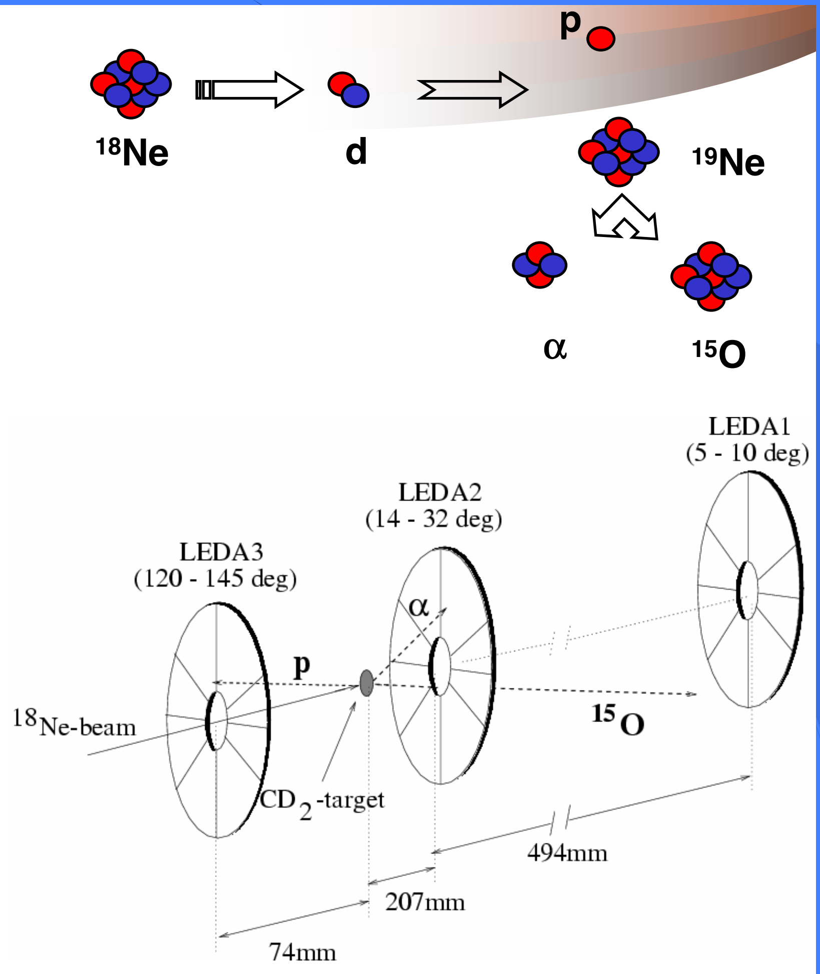


Figures courtesy of A. Murphy (U. of Edin.)
A. St. J. Murphy et al., accepted by PRC

Information to help calculate the $^{15}O(a,\gamma)^{19}Ne$ reaction rate

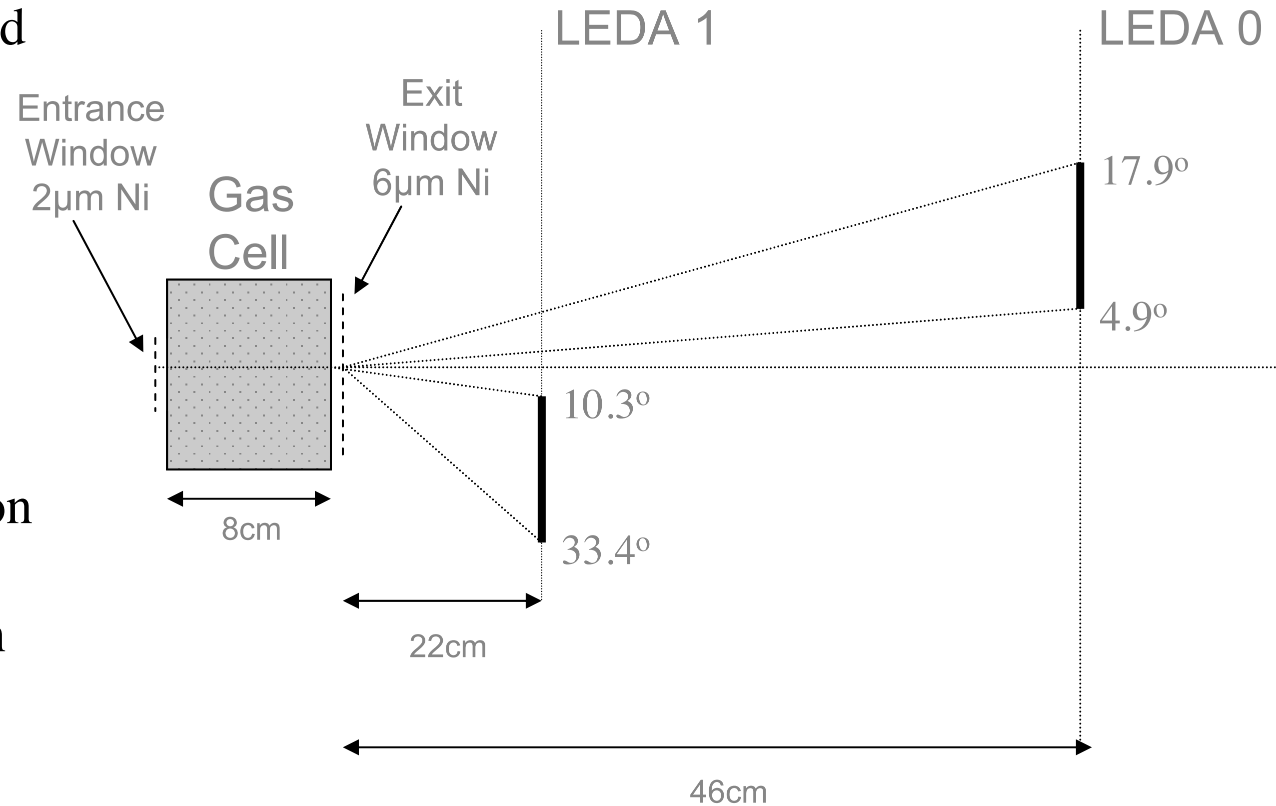
from a measurement of $d(^{18}Ne,p)\,^{19}Ne^* > \alpha + ^{15}O$ reaction

- HCNO breakout reaction
- Reaction rate dominated by resonances
- Populate excited states in ^{19}Ne by neutron transfer
- Proton tags excited state and coincident α and ^{15}O identify decay
- Measure α-branching ratios to determine reaction rate

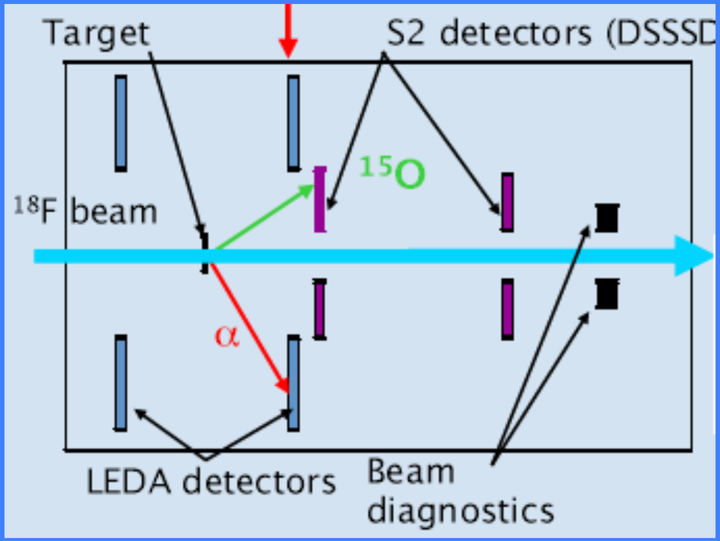


Direct measurement of $^{18}Ne(\alpha,p)$ reaction rate

- Breakout from HCNO cycle
- Reaction rate dominated by resonances in compound system
- Reaction protons detected in LEDA
  - Use time of flight to identify protons
  - Yield and cross section for each resonance
  - Reaction rate for each resonance



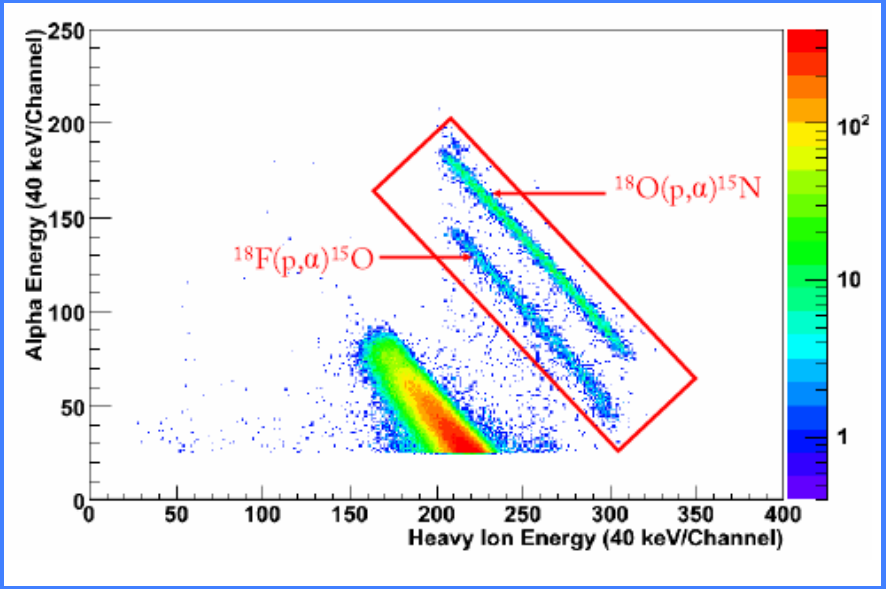
Coincident detection also helps reject events from beam contaminants



Detector arrangement for measurement of the reaction $p + {}^{18}F > a + {}^{15}O$

In this case there was a contaminant of ^{18}O mixed in the beam

So the measurement is impossible as we don't know which alpha particles result from reactions by the ^{18}F beam particles



From conservation of energy

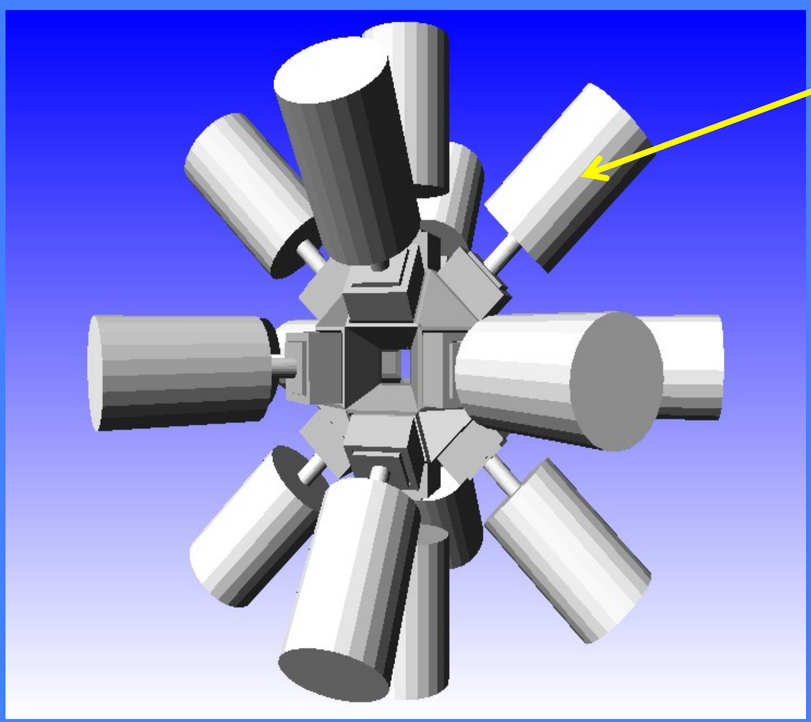
$E_a + E_O = Ebeam + Q_1$
$E_a + E_N = Ebeam + Q_2$

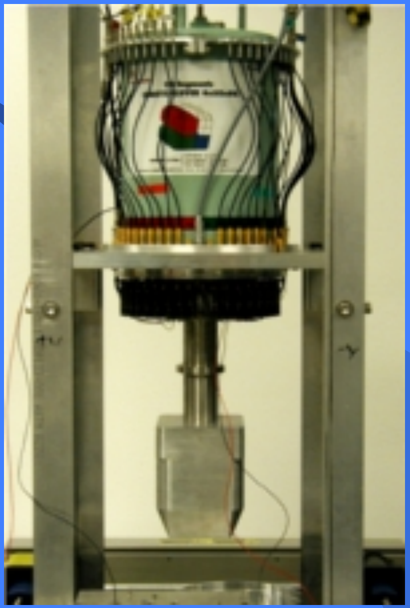
But Q-values different, so if plot energies of two particles against each other, the events from the different reactions can be distinguished

Gamma array TIGRESS

CONCEPT

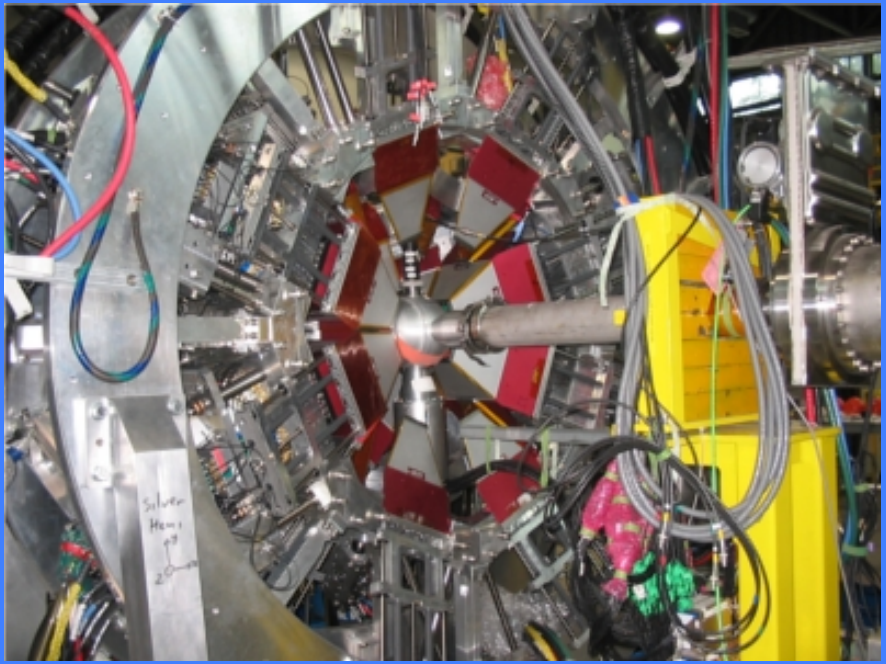
Surround target with 4π coverage with high resolution, high efficiency Ge gamma detectors

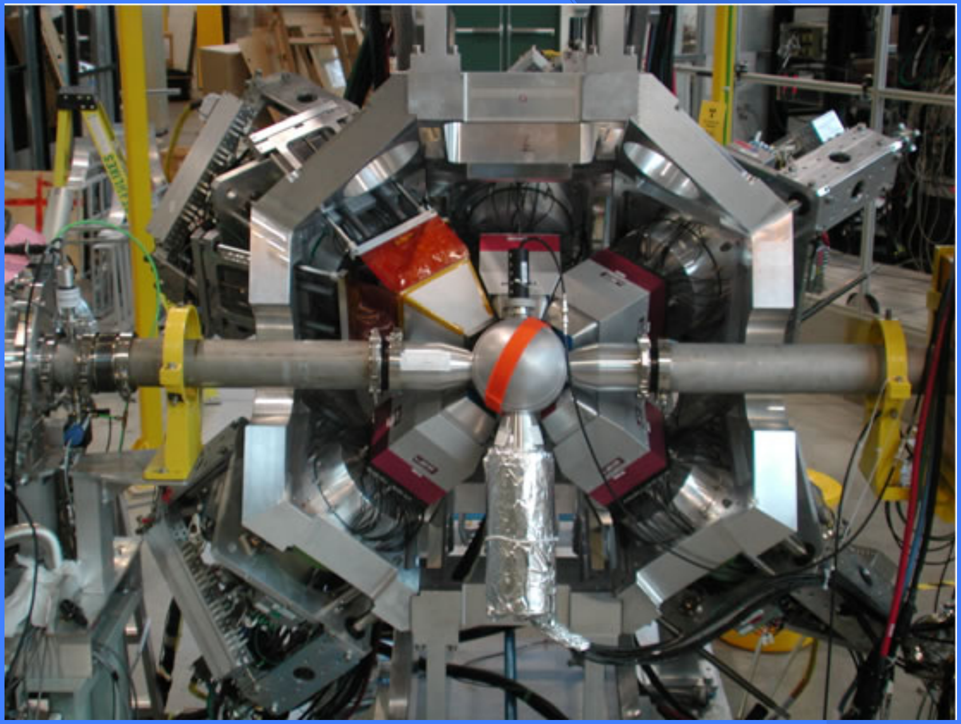


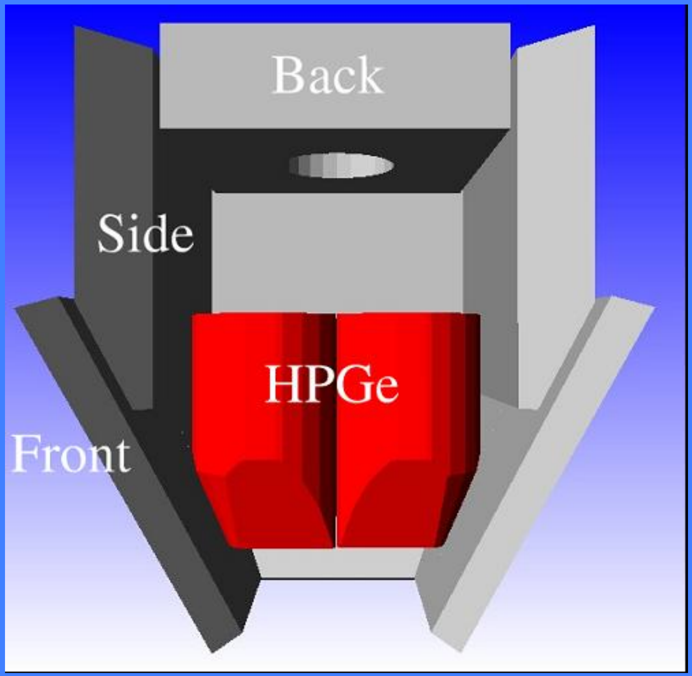


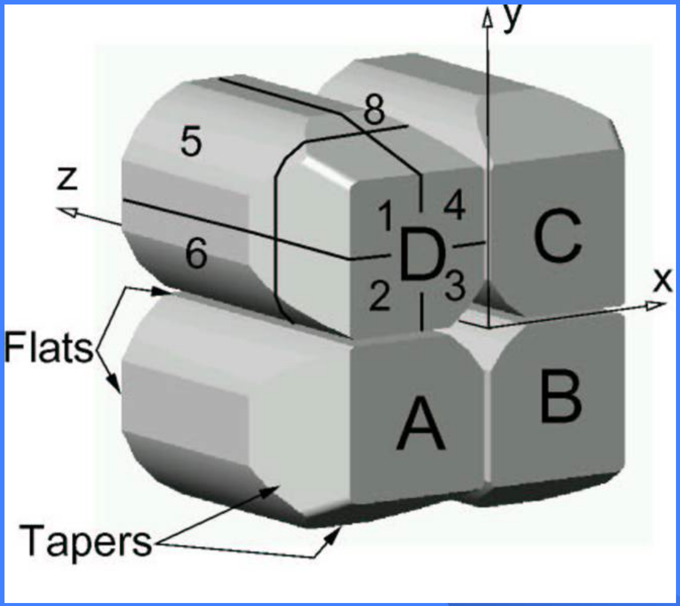
12 HPGe detectors of “Clover” design

Similar in concept to INGA





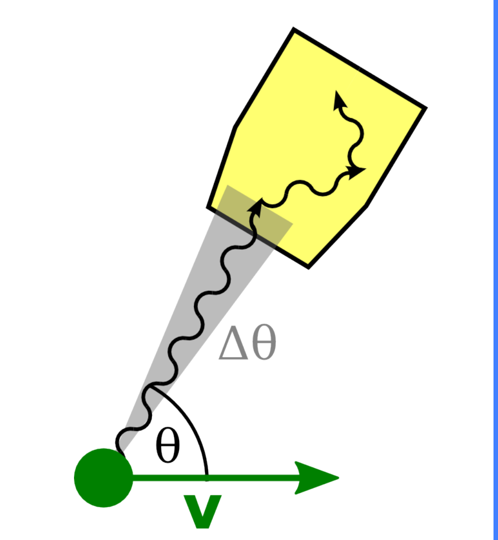




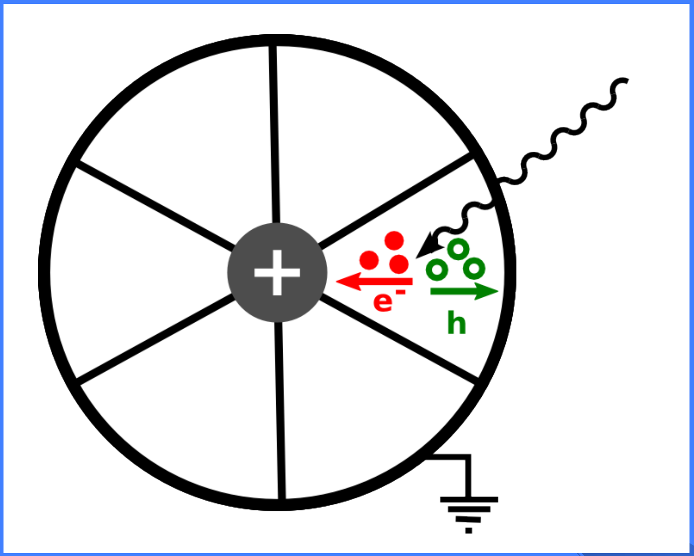
Each detector has four independent crystals

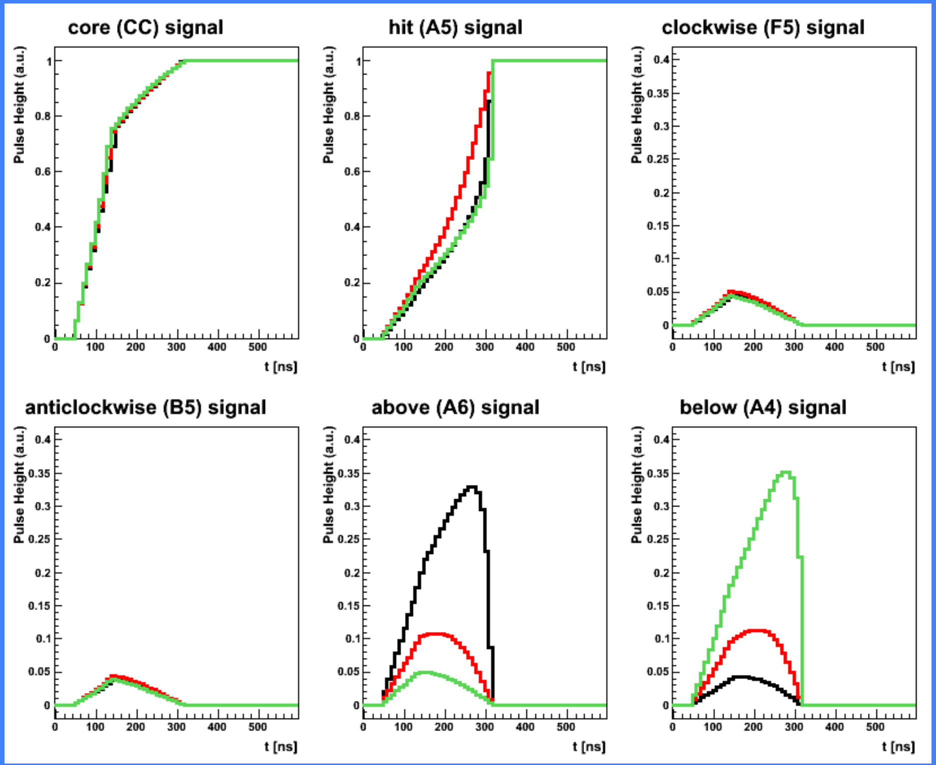
Each crystal is in turn segmented into 8 sectors (“cores”)

Surrounded by scintillator veto counters fro anti-Compton rejection



$$\Delta E_{\gamma}^{\mathrm{lab}} = E_{\gamma}^{\mathrm{rest}} \cdot \frac{\beta \sin\theta}{\sqrt{1-\beta^2}} \cdot \Delta\theta.$$



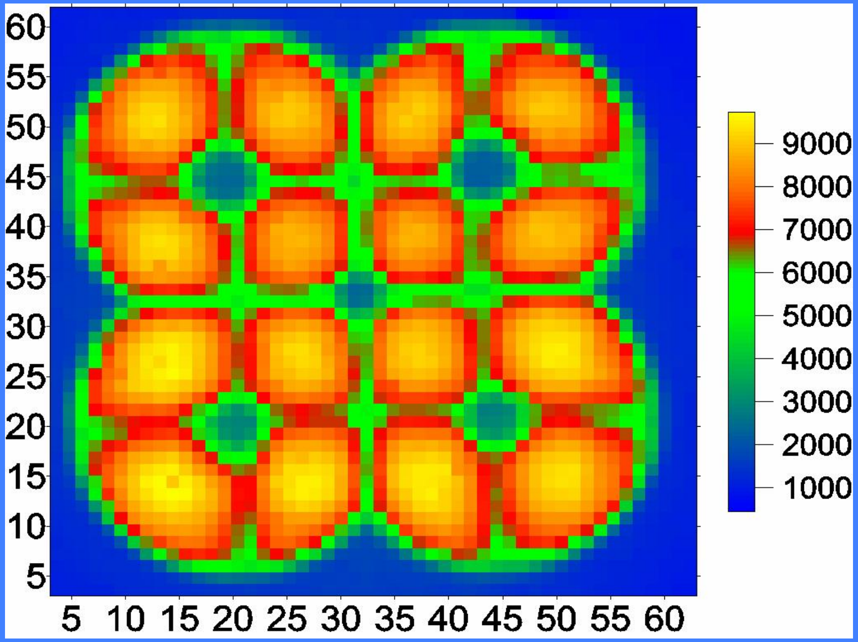


Induced signals on each electrode develops differently and so contains information on where in the crystal the gamma interacted

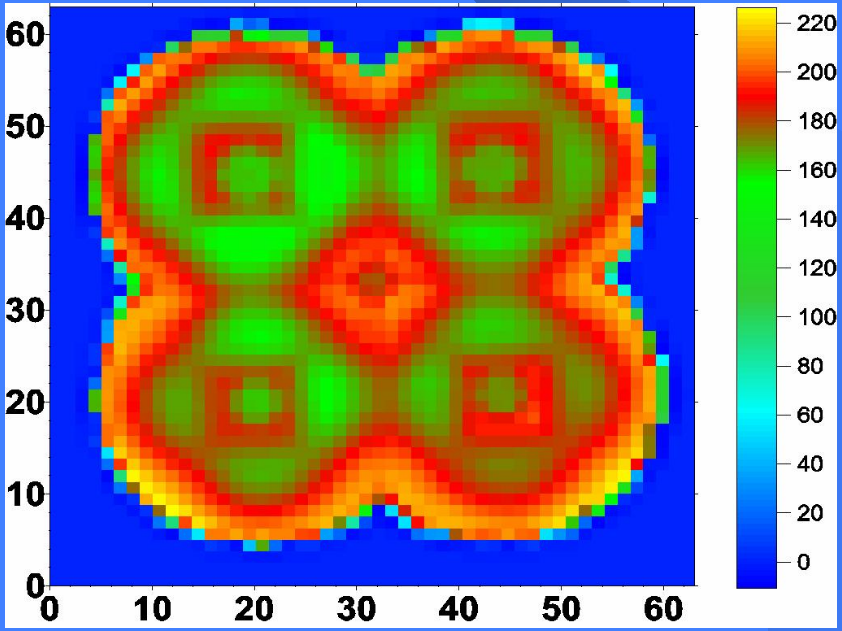
From Stefanie Klupp Diplom Thesis (TUM)

Careful calibration of each detector is required to enable the processing to achieve position accuracy of order 1mm

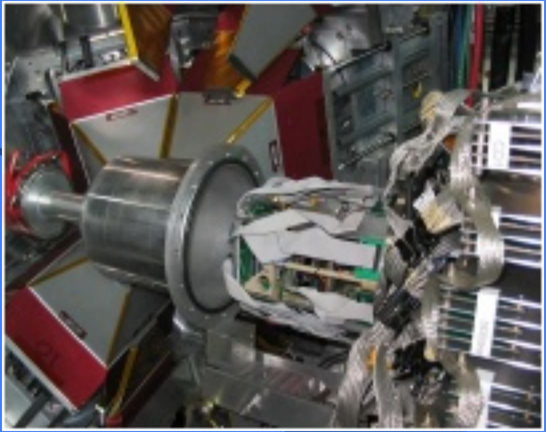
Mapping of energy response



Mapping of rise time



Combined particle/gamma SHARC

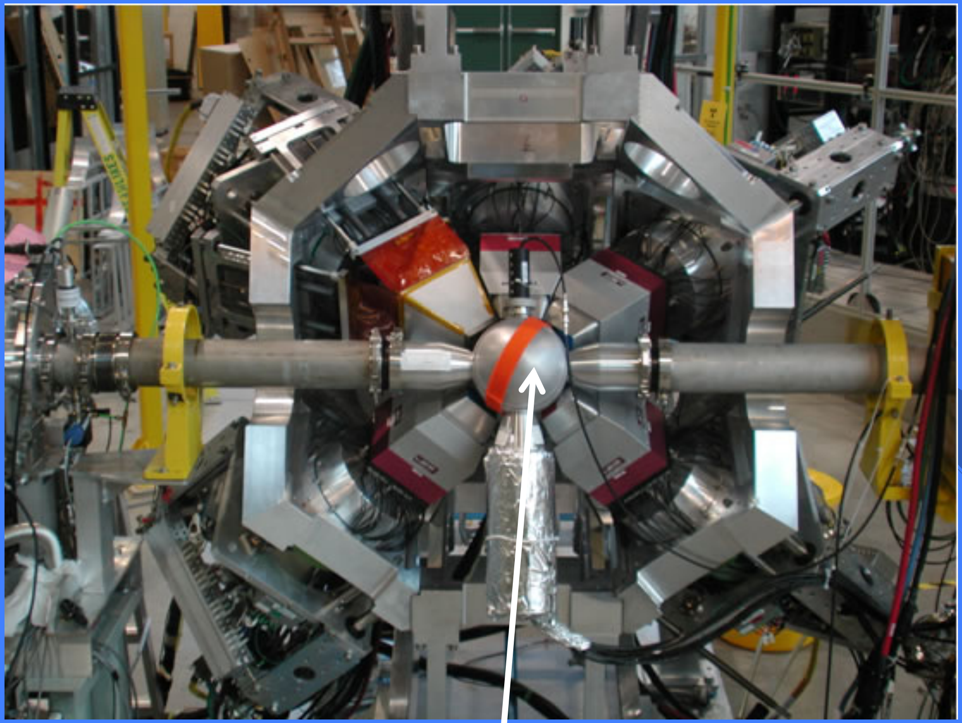


Concept

Build a highly pixellated, 4π coverage charged particle detector to fit inside the TIGRESS gamma ray array

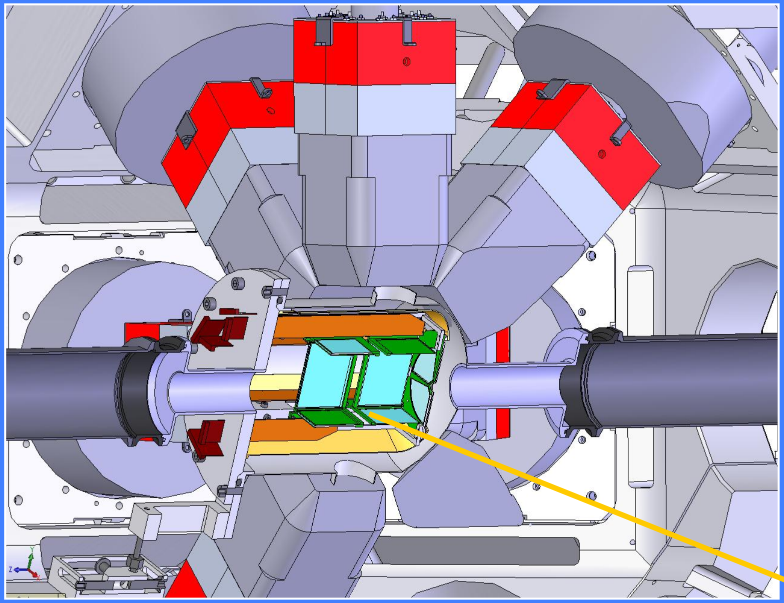
Charged particle – gamma ray coincidences

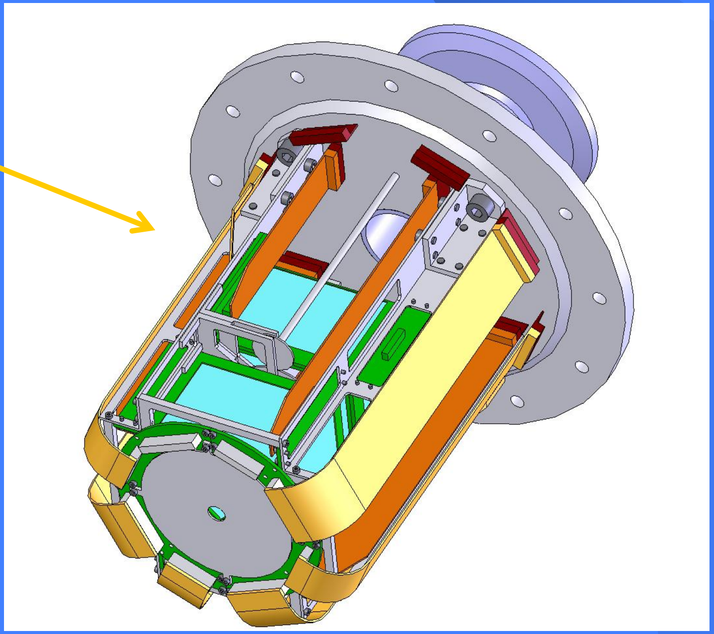
Use for Coulex and transfer reactions for structure studies and nuclear reaction measurements (focus on nuclear astrophysics)



11cm radius volume to fit detectors into and to bring ~1000 signals out of

SHARC – silicon detector array inside TIGRESS gamma array

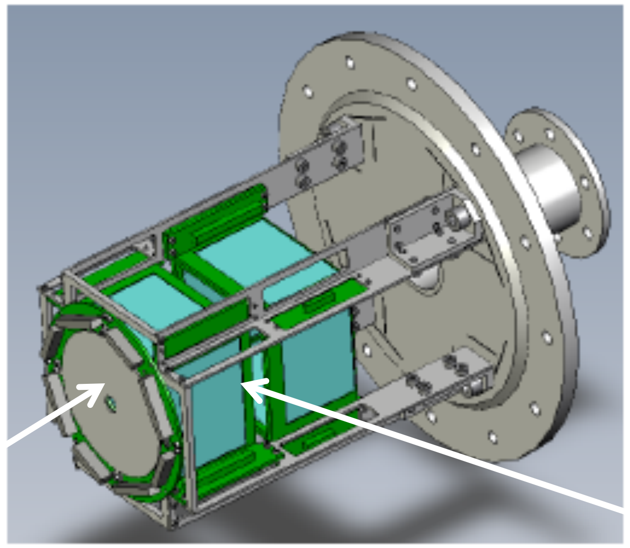




Annular "CD" detectors at forward and backward angles and "box" of detectors for mid angles gives almost 4π coverage

High segmentation gives ~ degree resolution

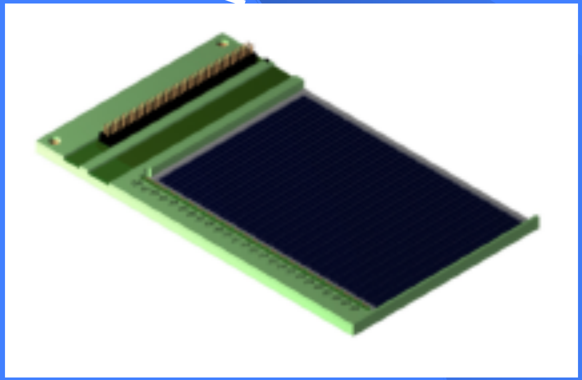
SHARC (Silicon Highly Segmented Array for Reactions and Coulex)



Annular “CD” detectors at forward and backward angles and “box” of detectors for mid angles gives almost 4π coverage

High segmentation gives ~ degree resolution

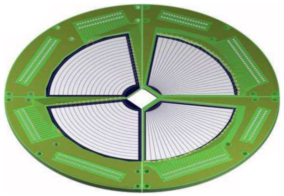
Annular detectors forward and backward
4 sectors
16 annular strips
24 radial strips
140μm



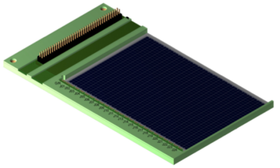
4 DSSD upstream and downstream
72mm with 24 strips
48mm with 48 strips
140μm

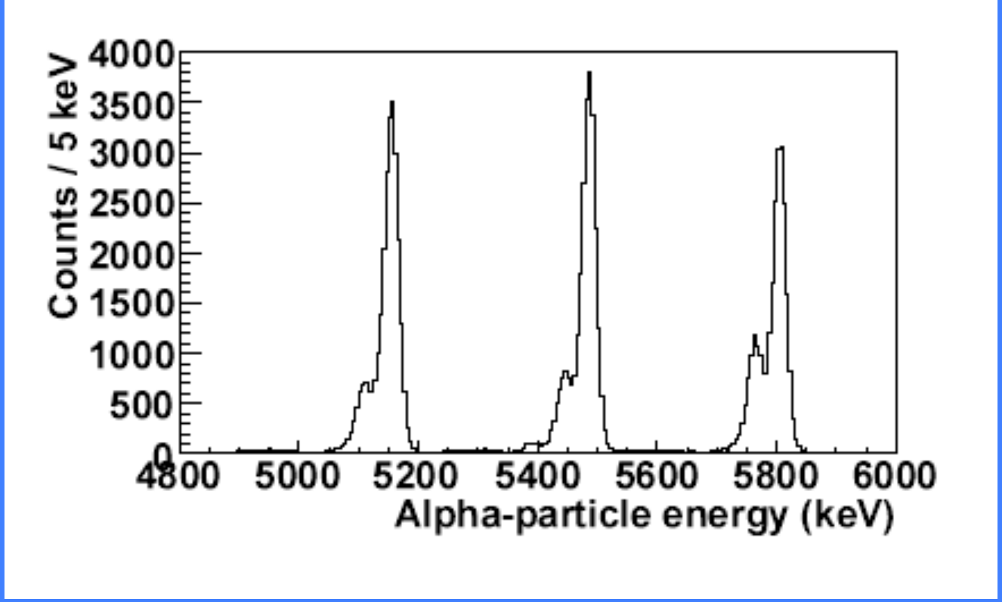
SHARC Detector performance

- Angular coverage: $\approx 2\pi$.
- Angular resolution: $\delta\theta = 1.6$ deg.
- Energy range: 25MeV.
- Energy resolution: $\approx 30\,$keV.
- Particle identification: δE-E.
- CD detectors (Micron QQQ2):
  - Thickness: 80 μm (ΔE) + 1000 μm (E-pad).
  - 4 quadrants each covering: 9.0 mm to 41 mm radius (16 annular and 24 radial strips).
  - 80% coverage for θ = 8.5–31.5 and 148.5–171.5 degree.



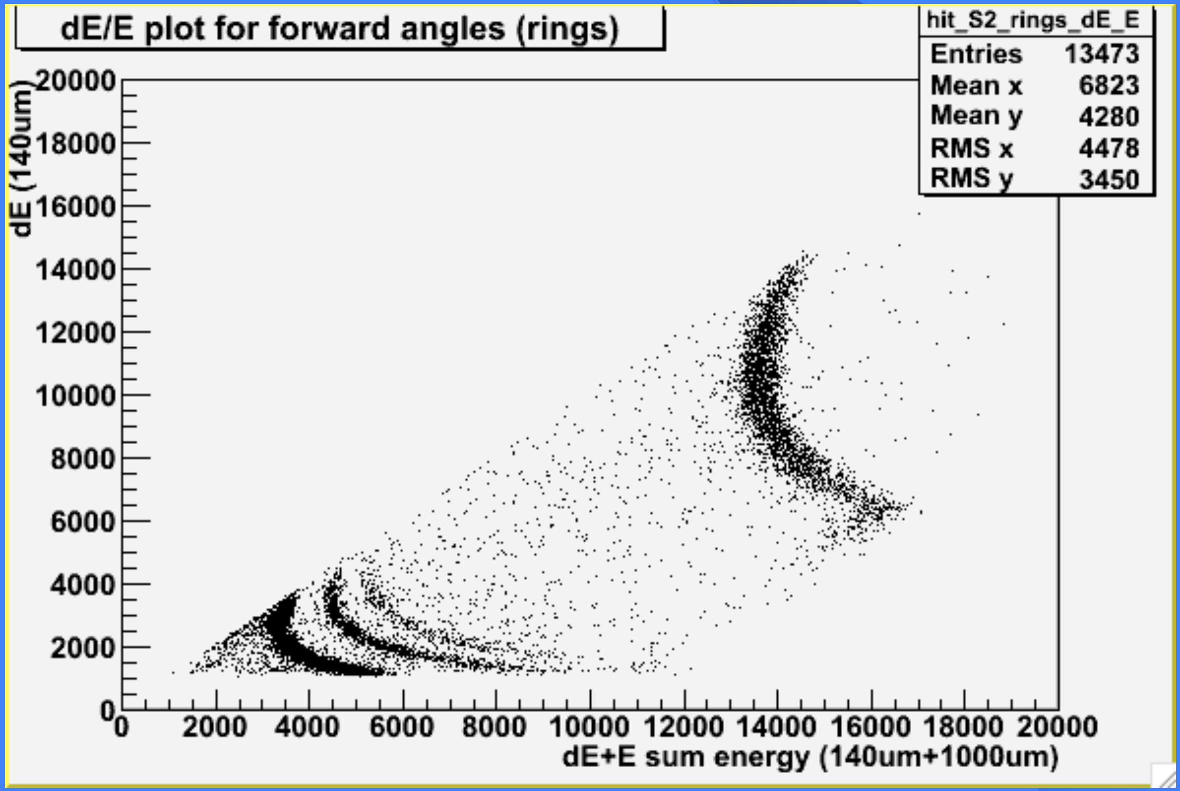
- Box DSSSDs: 72 mm $\times$ 48 mm (24 $\times$ 48 strips).
  - Downstream box: 4 DSSSDs, thickness 140 μm, backed by 1000μm pad detectors, 75% coverage for $\theta = 136$–99 deg.
  - Downstream box: 2 DSSSDs, thickness 140 μm, backed by 1000μm pad detectors, 37% coverage for $\theta = 44$–81 deg.

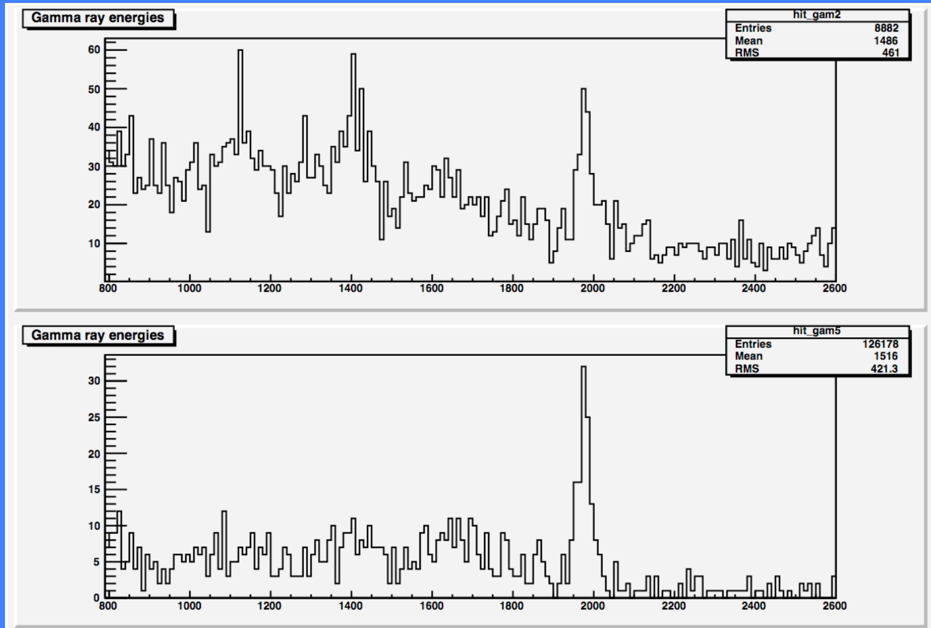




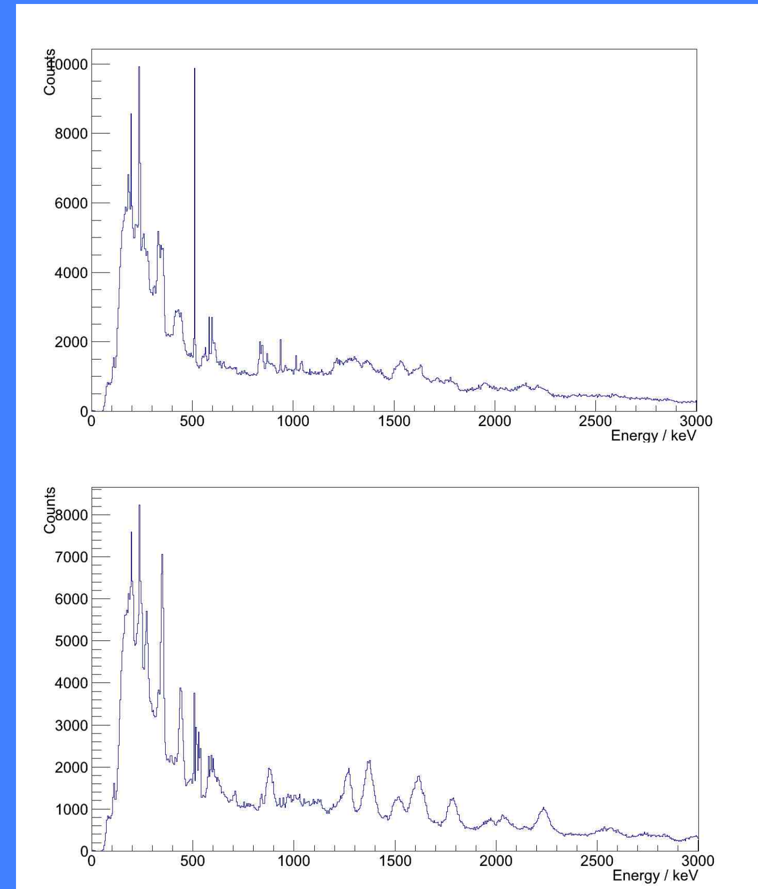
Triple alpha calibration source (best resolution seen ~28keV)

Downstream CD
$^{18}O+CD_2$





Particle coincidence



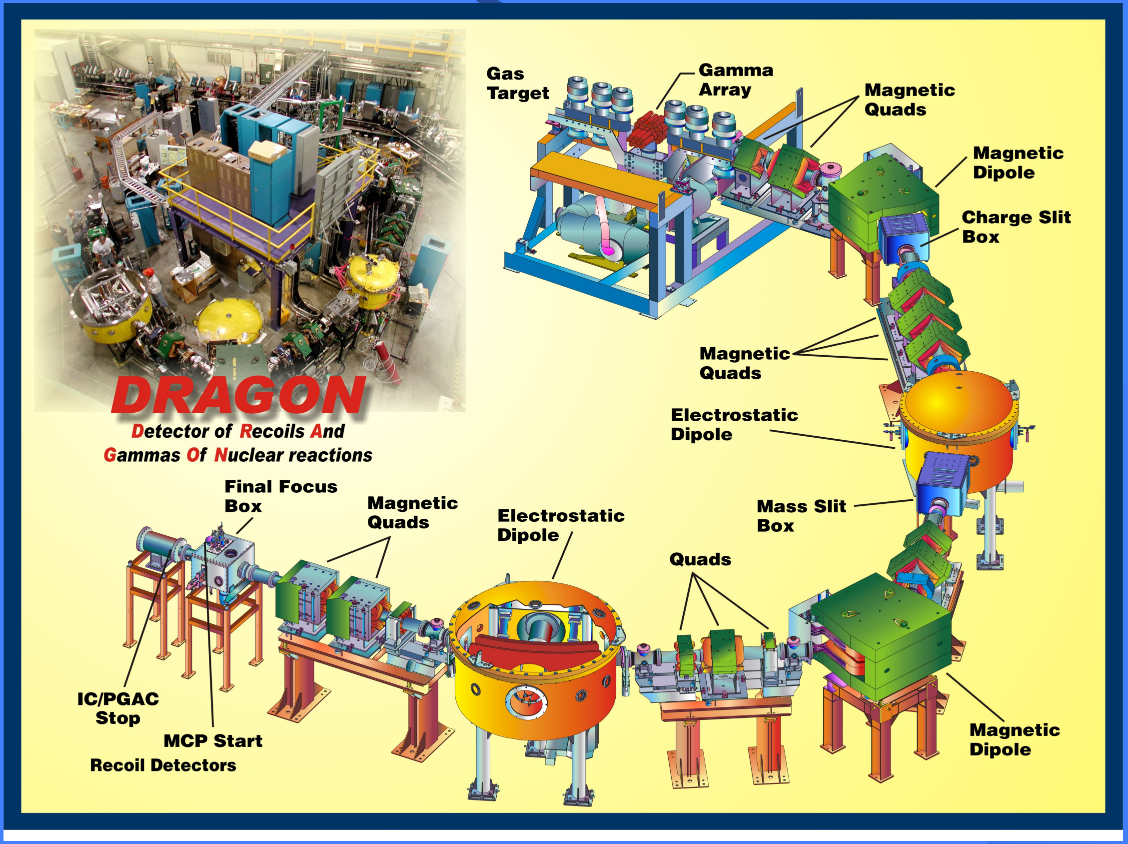
Doppler correction
(only using core information so far)

First experiment on ^{20}Na(^{6}Li, α)^{22}Mg* > ^{21}Na+p in analysis (states in ^{22}Mg for ^{18}Ne(α,p)

Experiments approved to tackle spectroscopy for ^{14}O(α,p) and ^{15}O(α,γ) reactions

Recoil detector DRAGON

For radiative capture reactions - (p,γ), (α,γ)
Recoil mass separator
Windowless gas target
Gamma array
End detectors – silicon/gas
Acceptance 20mrad
Rejection 10^{10}-10^{14}



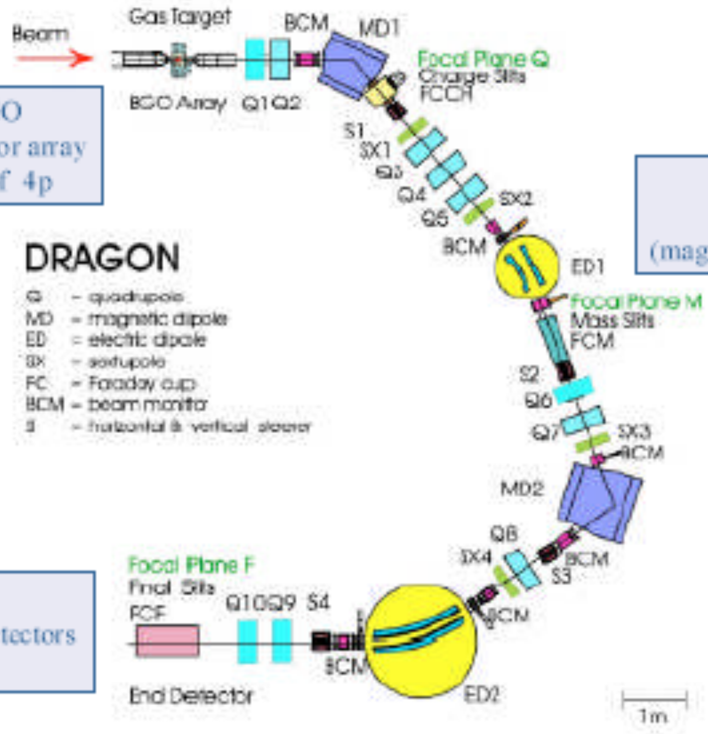
Detector of Recoils And Gammas Of Nuclear reactions

differentially pumped
window-less
gas target (~ 12cm)

30 BGO
g-ray detector array
~90% of 4p

(start)

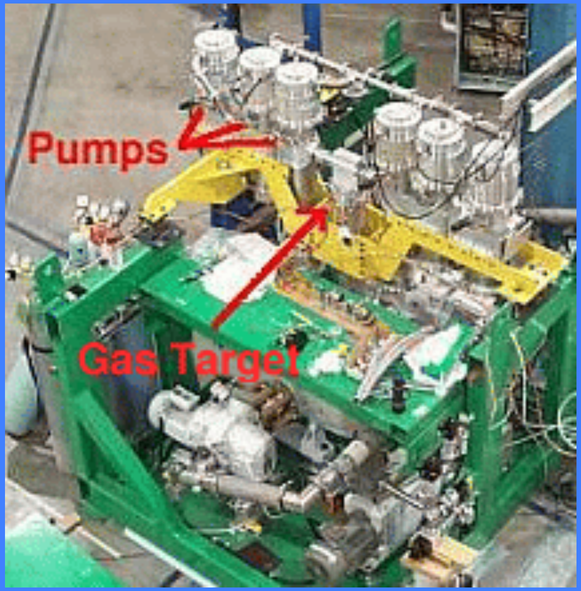
two-stage
recoil separator
(magnetic and electric dipoles)



(stop)

DSSSD
double sided silicon strip detectors
for recoil detection

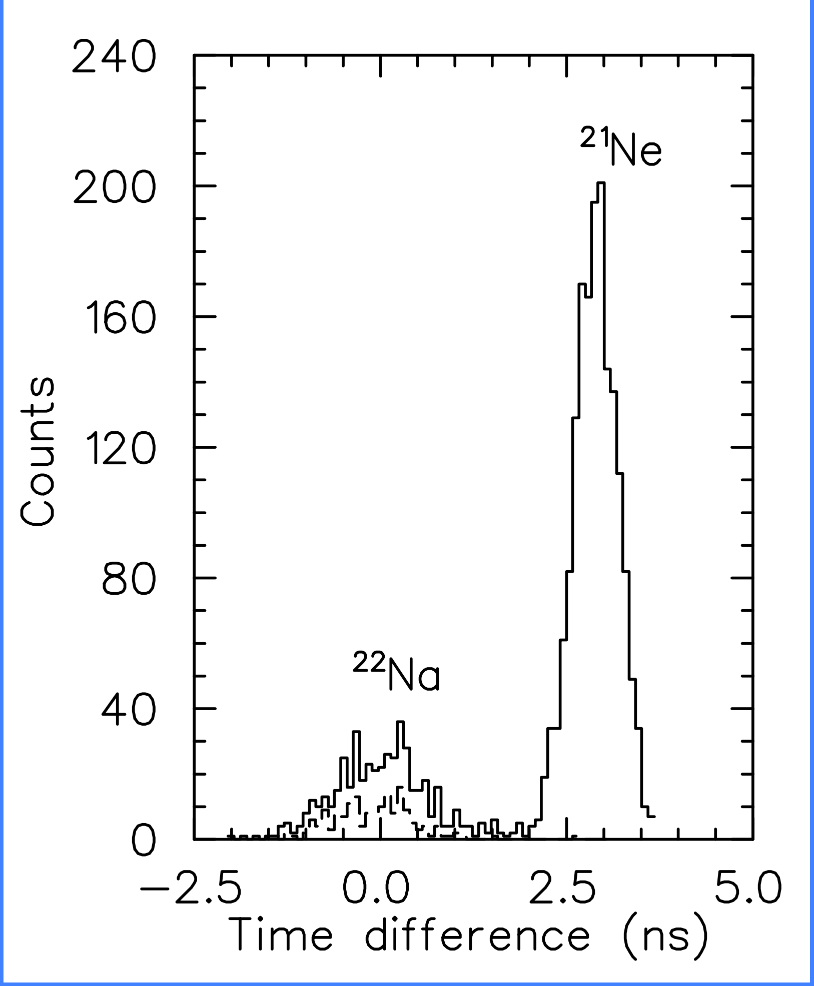
see: J.M. D'Auria et al., Nucl Phys A 701 (2002) 625 and D. Hutcheon et al., NIM A 498 (2003) 190 for details

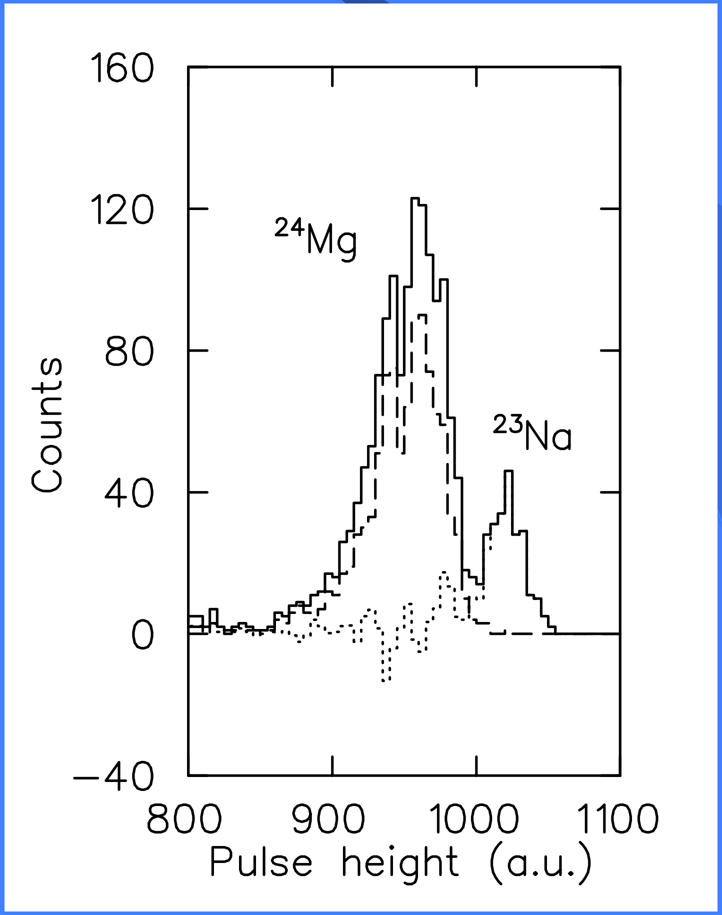


Array of 30 BGO detectors giving a ~50 % efficiency for 5 MeV photons

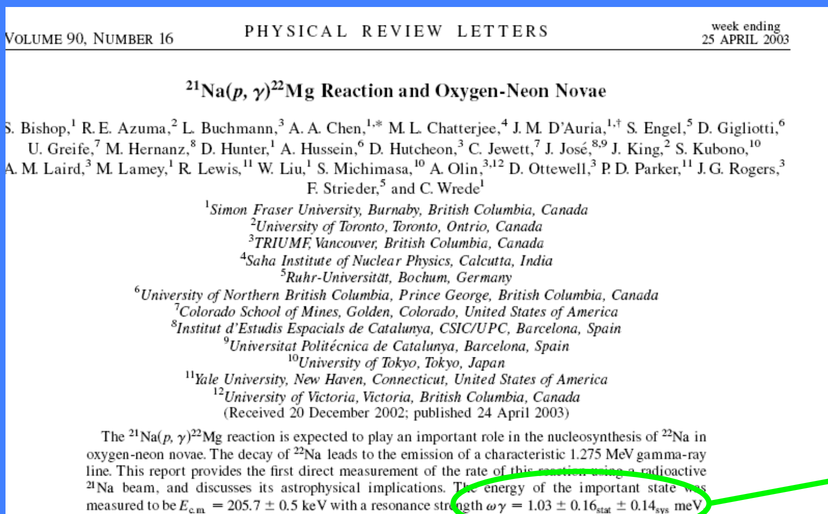
Always get some beam particles scattering inside the separator and making it through to the focal plane

Can use ToF or Energy measurement to distinguish events at the end detector





First results from DRAGON

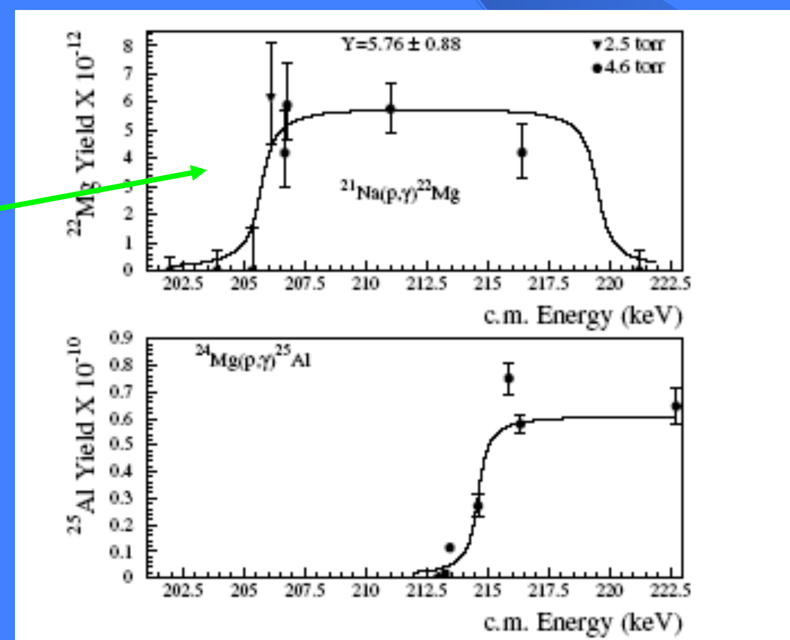

VOLUME 90, NUMBER 16 PHYSICAL REVIEW LETTERS week ending 25 APRIL 2003

$^{21}Na(p,\gamma)^{22}Mg$ Reaction and Oxygen-Neon Novae

S. Bishop,[1] R. E. Azuma,[2] L. Buchmann,[3] A. A. Chen,[1,*] M. L. Chatterjee,[4] J. M. D'Auria,[1,†] S. Engel,[5] D. Gigliotti,[6] U. Greife,[7] M. Hernanz,[8] D. Hunter,[1] A. Hussein,[6] D. Hutcheon,[3] C. Jewett,[7] J. José,[8,9] J. King,[2] S. Kubono,[10] A. M. Laird,[3] M. Lamey,[1] R. Lewis,[11] W. Liu,[1] S. Michimasa,[10] A. Olin,[3,12] D. Ottewell,[3] P. D. Parker,[11] J. G. Rogers,[3] F. Strieder,[5] and C. Wrede[1]

[1]Simon Fraser University, Burnaby, British Columbia, Canada
[2]University of Toronto, Toronto, Ontrio, Canada
[3]TRIUMF, Vancouver, British Columbia, Canada
[4]Saha Institute of Nuclear Physics, Calcutta, India
[5]Ruhr-Universität, Bochum, Germany
[6]University of Northern British Columbia, Prince George, British Columbia, Canada
[7]Colorado School of Mines, Golden, Colorado, United States of America
[8]Institut d'Estudis Espacials de Catalunya, CSIC/UPC, Barcelona, Spain
[9]Universitat Politécnica de Catalunya, Barcelona, Spain
[10]University of Tokyo, Tokyo, Japan
[11]Yale University, New Haven, Connecticut, United States of America
[12]University of Victoria, Victoria, British Columbia, Canada
(Received 20 December 2002; published 24 April 2003)

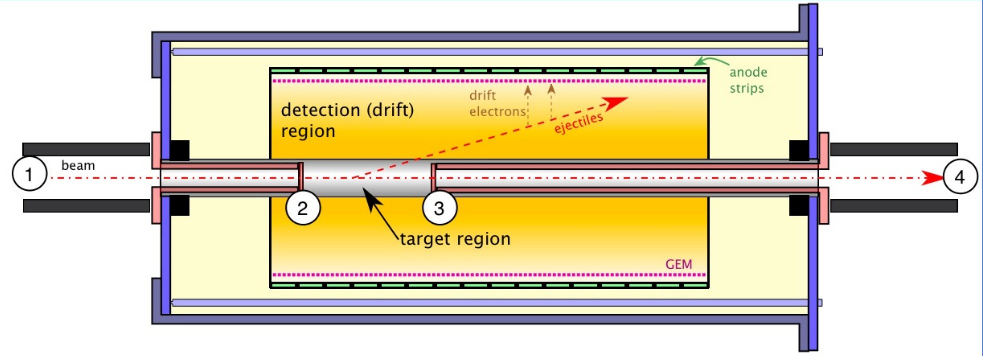
The $^{21}Na(p,\gamma)^{22}Mg$ reaction is expected to play an important role in the nucleosynthesis of ^{22}Na in oxygen-neon novae. The decay of ^{22}Na leads to the emission of a characteristic 1.275 MeV gamma-ray line. This report provides the first direct measurement of the rate of this reaction using a radioactive ^{21}Na beam, and discusses its astrophysical implications. The energy of the important state was measured to be $E_{c.m.} = 205.7 \pm 0.5$ keV with a resonance strength $\omega\gamma = 1.03 \pm 0.16_{stat} \pm 0.14_{sys}$ meV.



The first radioactive beam measurement at ISAC – $^{21}Na(p,\gamma)$

Tracking Detectors TACTIC

A major problem with astrophysics measurements is that because of the low energy the emerging particles have small energies and are hard to detect



Solution

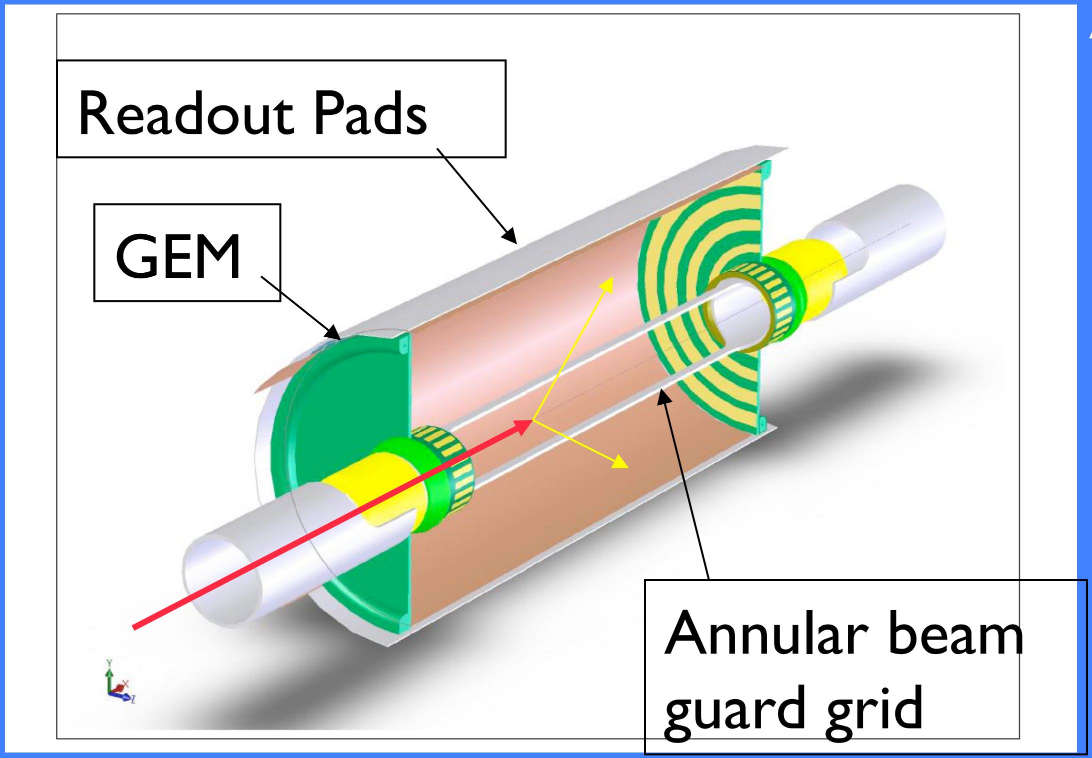
For those experiments that use a gas target (many), why not make the target also act as the detector

Build an active target with recoil tracking capability to enable direct measurement of low energy reaction rates for nuclear astrophysics studies - like a TPC (Time Projection Chamber) in Particle Physics

Key aims are detection at low energies with high efficiency using gas targets

“Design” experiment is $^{8}Li(a,n)$, but ongoing programme planned

TACTIC – a novel approach for low energy astrophysics measurements



Active target – ionisation from recoils tracked to give trajectory (Time Projection Chamber)

Grids to shield beam region – high count rate

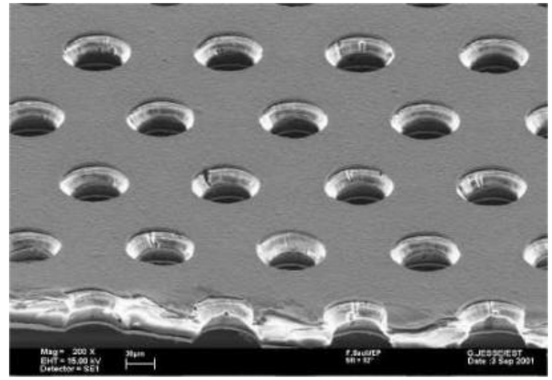
GEMs give additional gain

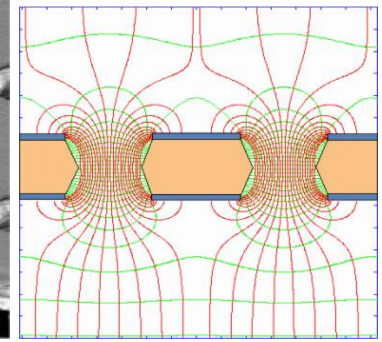
Annular geometry for 4π

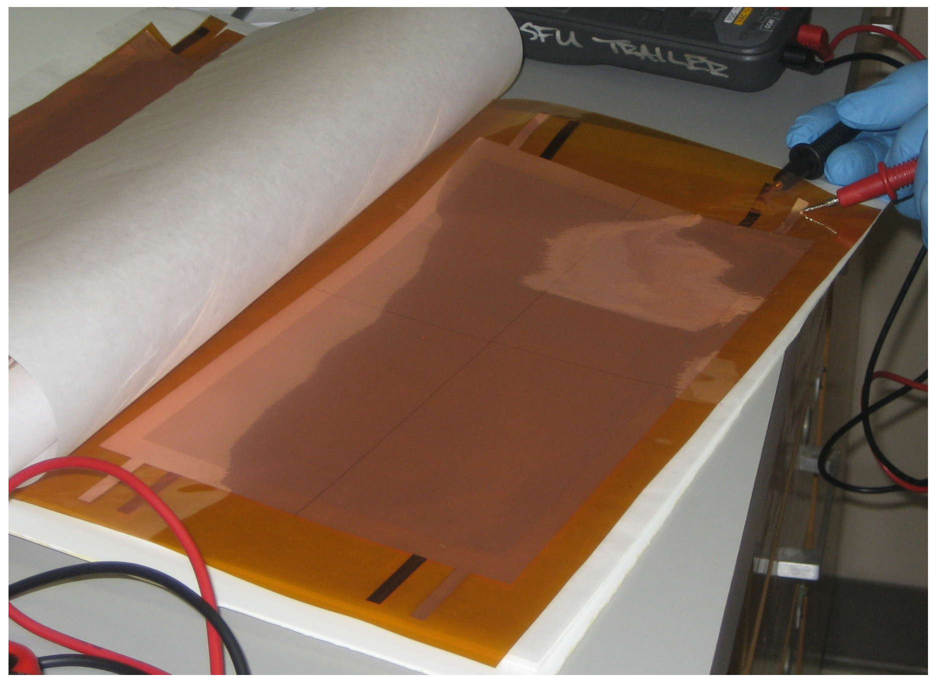
Low energy threshold

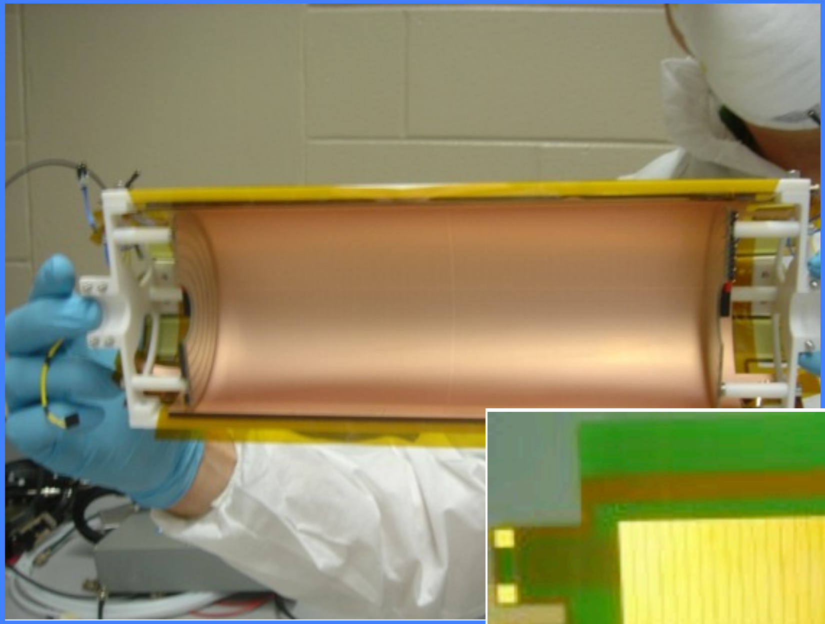
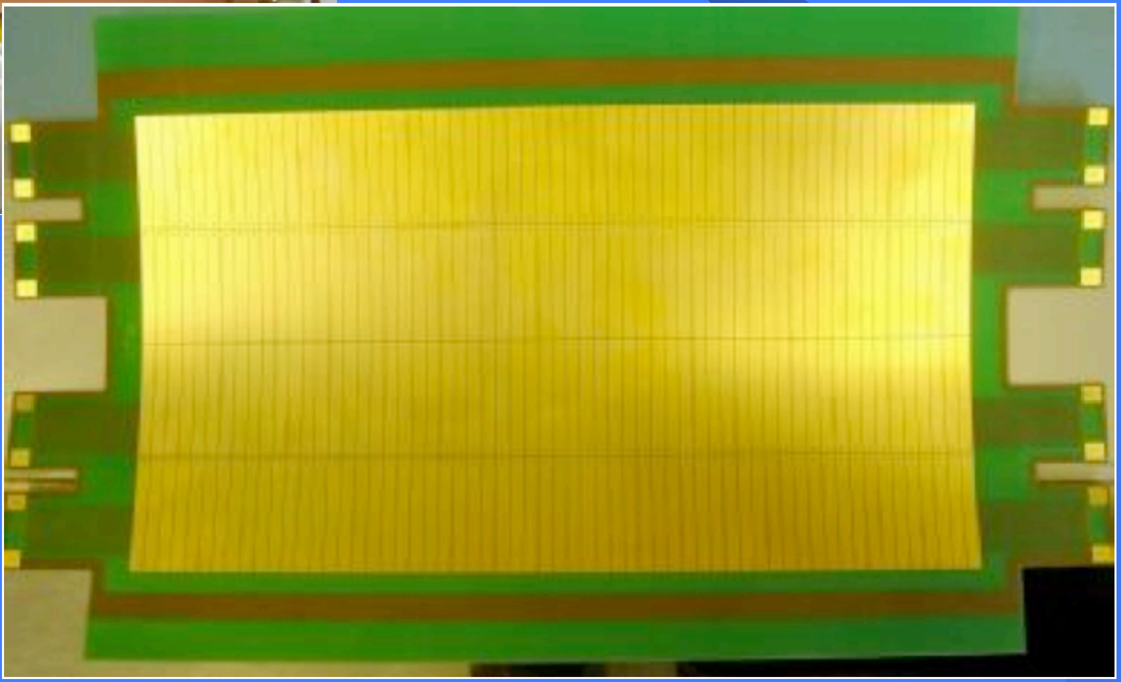
GEM

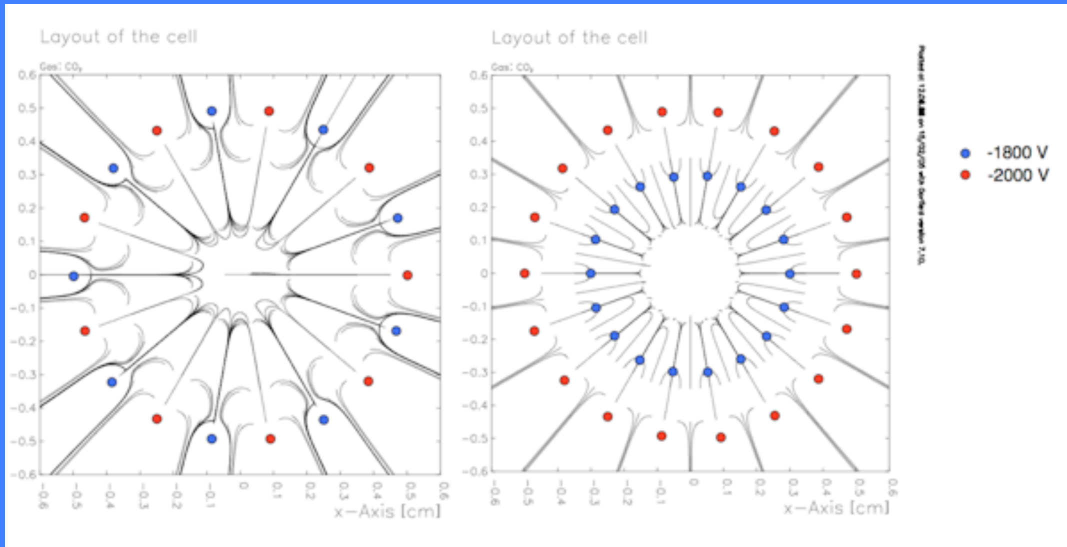
- Thickness 50 μm
- Holes:
  50 μm diameter
  150 μm pitch
- HV ≈ 350 V

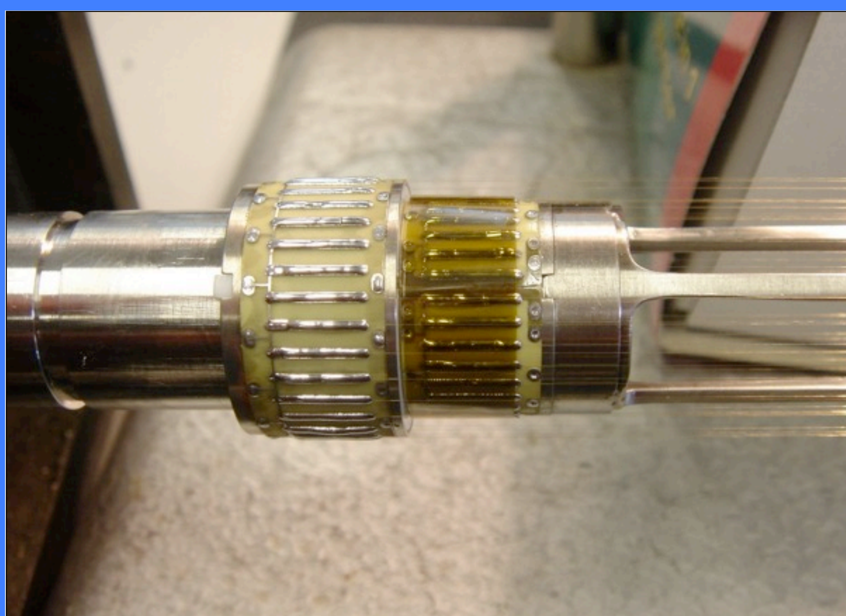




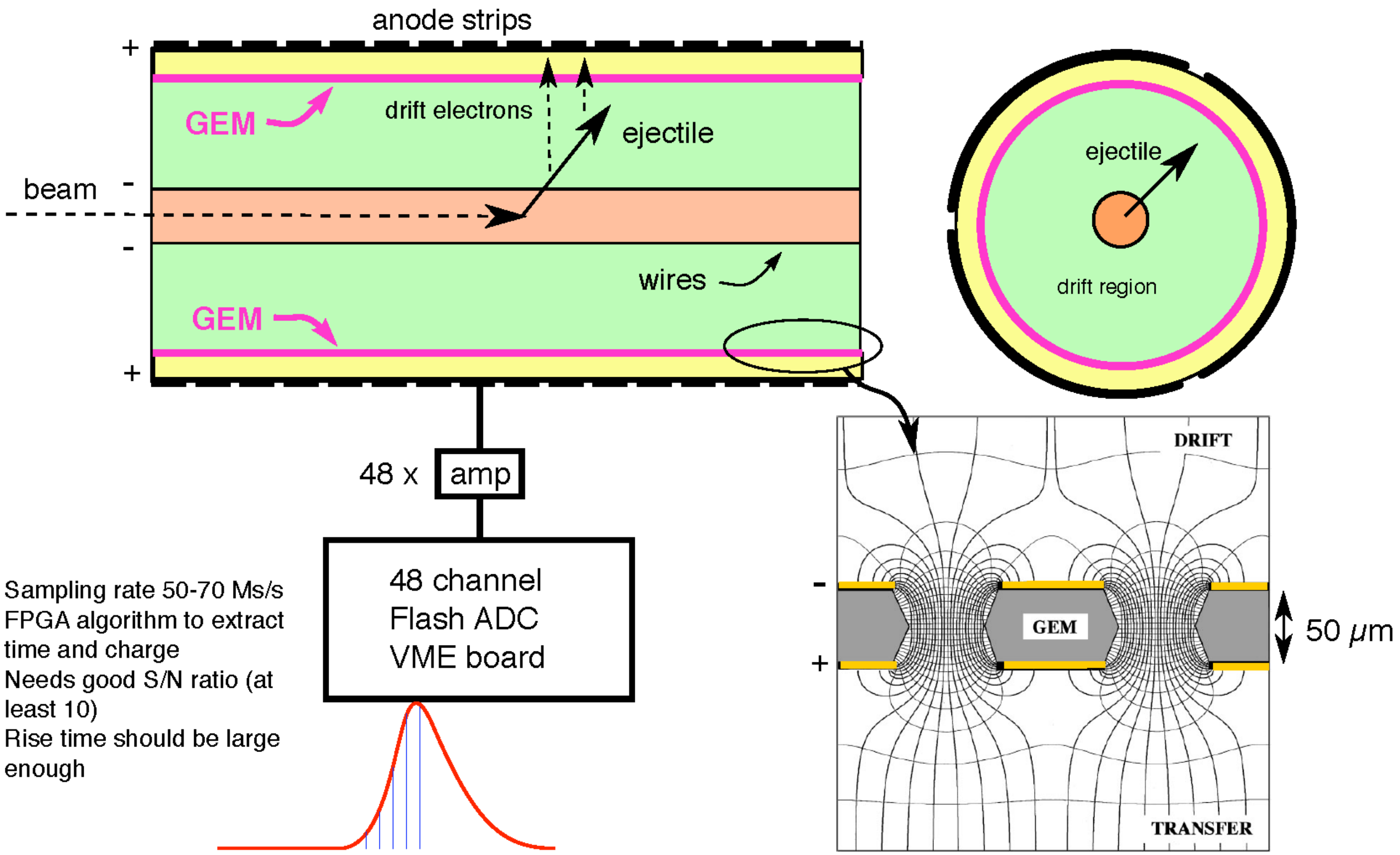



Layout of the cell
Gas: CO_2
x−Axis [cm]
Layout of the cell
Gas: CO_2
x−Axis [cm]
-1800 V
-2000 V

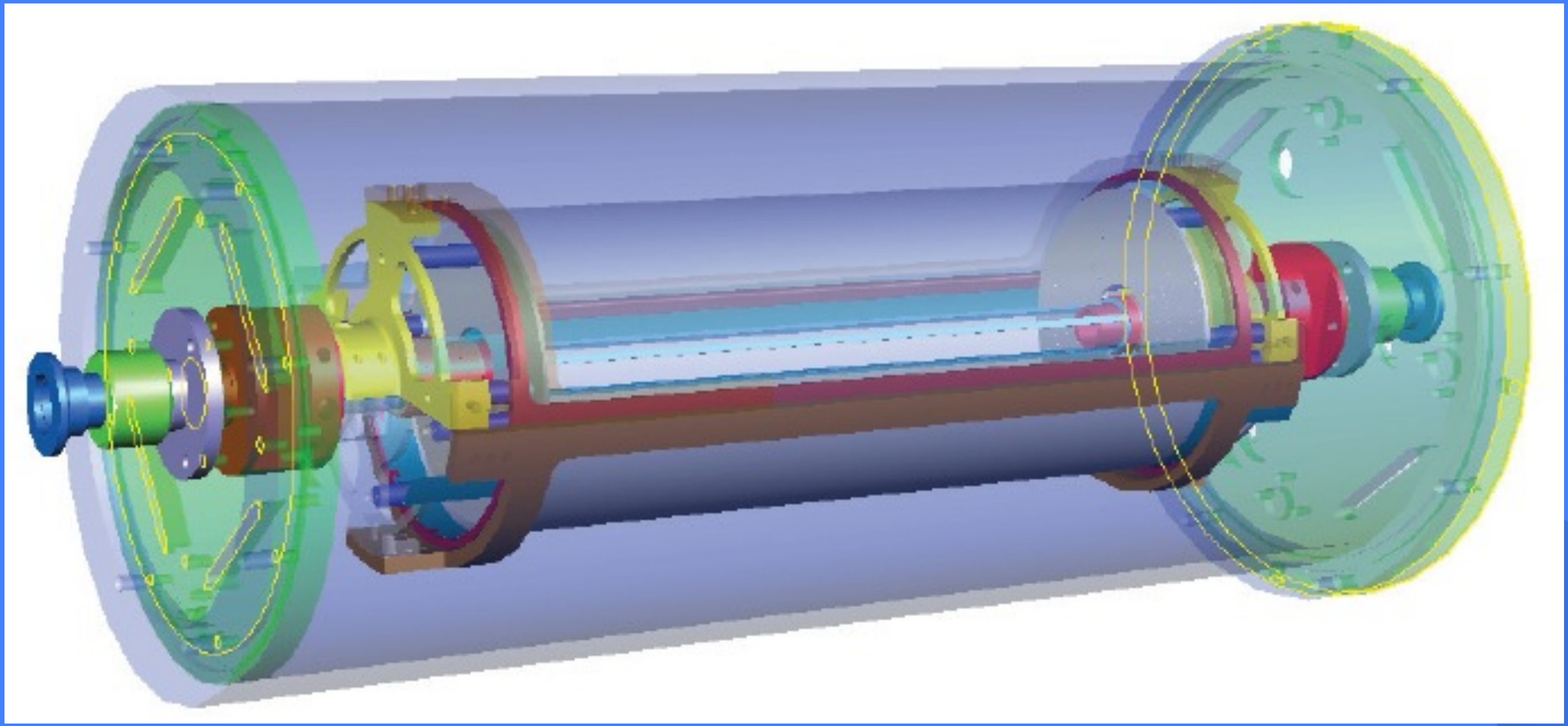


New Set-up using a Gas Electon Multiplier and Flash ADCs



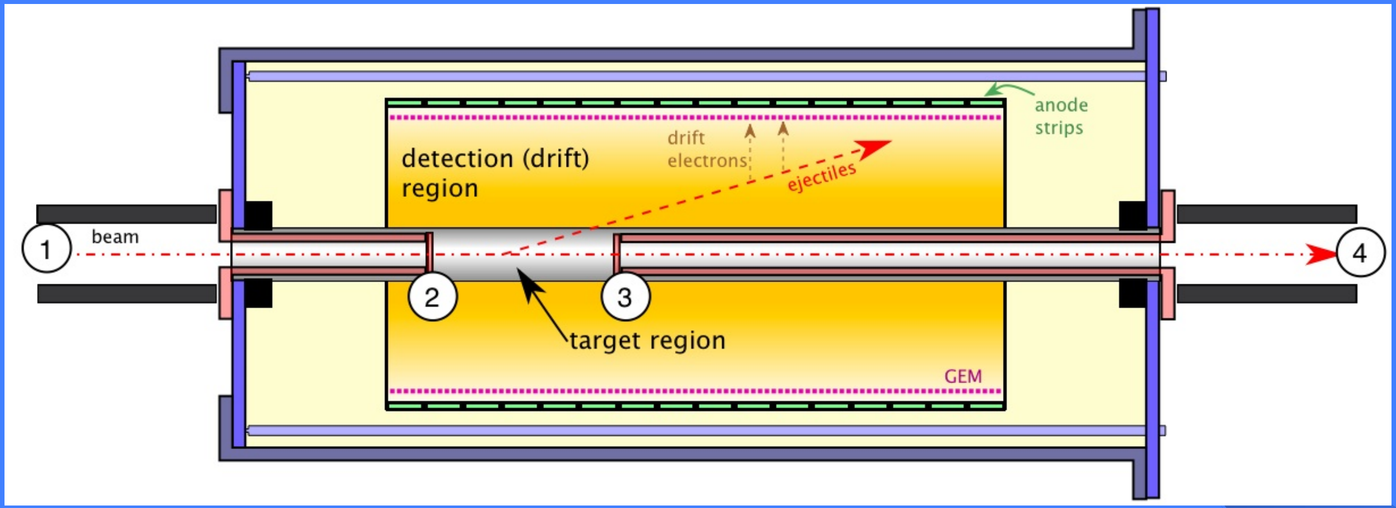
Sampling rate 50-70 Ms/s
FPGA algorithm to extract time and charge
Needs good S/N ratio (at least 10)
Rise time should be large enough

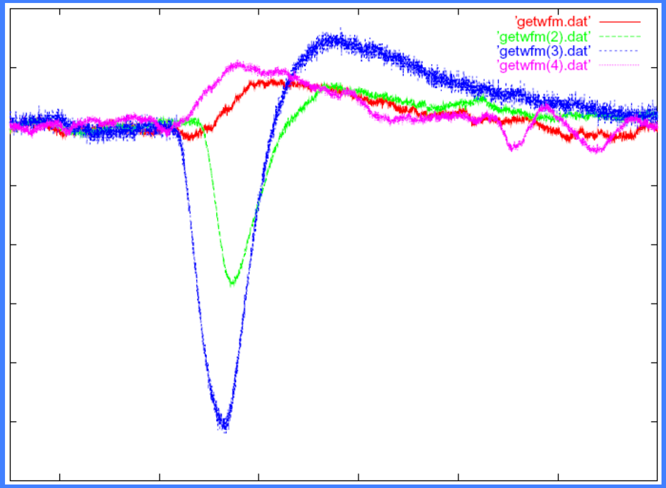
Technical details

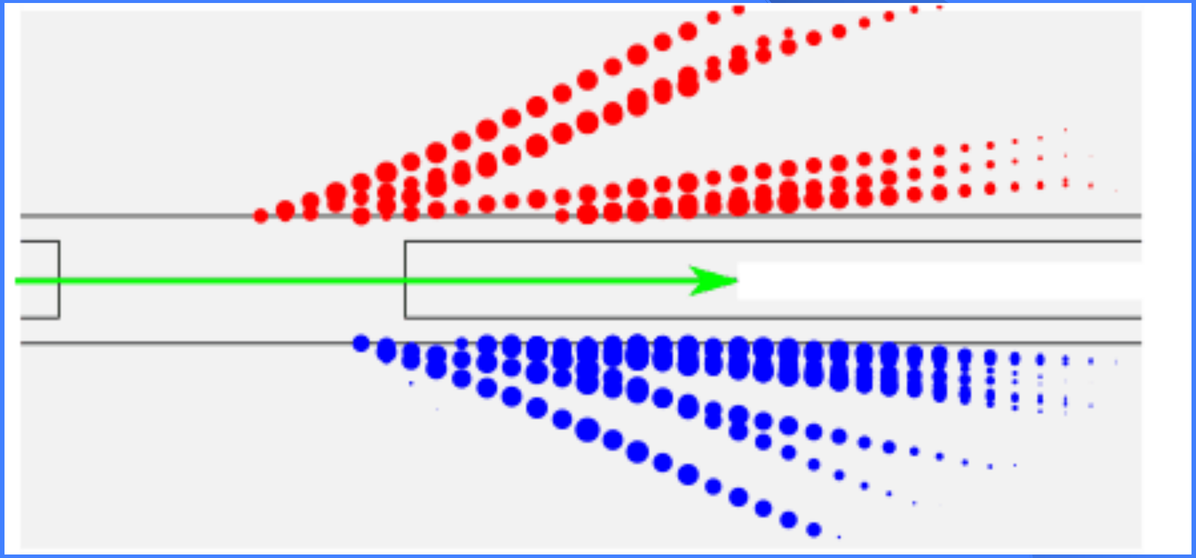


- 8 sectors with 60 pads per sector (pitch of 4 mm)
- Length 240 mm with cathode at 12 mm and anode at 50 mm
- Gas 90% Helium with 10% CO_2
- Operating pressure typically 100 mbar – 700 mbar (have run as low as 60 mbar
- Drift voltage 500-1000 V (anode held at ground)
- Drift times up to 6 μs

First Tracks out of TACTIC







First commissioning run completed – track reconstruction algorithms being developed

First experiment $^{8}Li(\alpha,n)$ – key route to heavy ion build-up in SN explosion