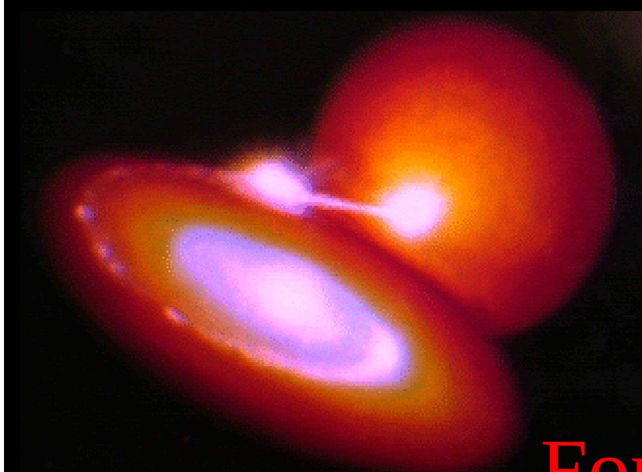
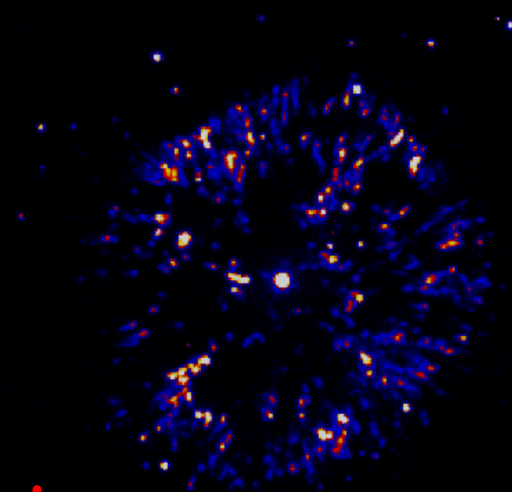
Nuclear Astrophysics at TRIUMF with the TUDA facility



Alison Laird
For the TUDA collaboration



Outline

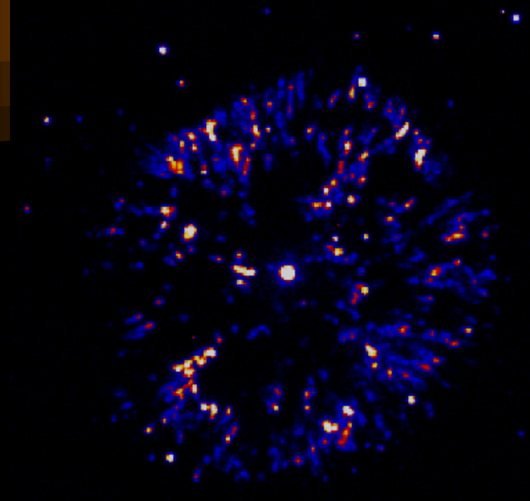
- Experimental nuclear astrophysics
- Overview of the TUDA facility
- Indirect measurements
- Direct measurements
- Future programme

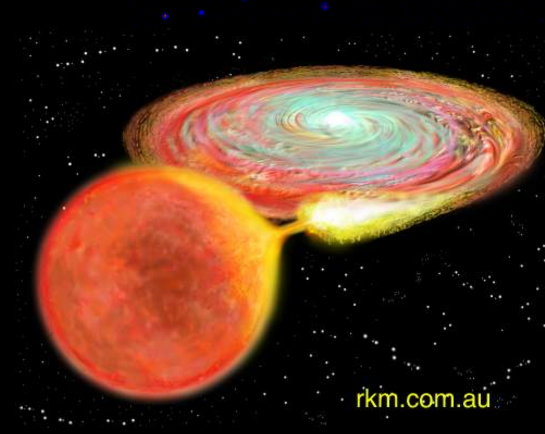
Exploding Stars:
Novae, Supernovae, X-ray bursters

- Cataclysmic stellar events in binary systems
- Accretion of hydrogen-rich material, onto compact object, initiating thermonuclear runaway
- High temperatures – up to few 10^9 K
- Nuclear reactions (p,γ), (p,α), (α,p), (α,γ) supersede β-decays

➢ Radioactive nuclei play critical role

➢ Radioactive beams vital to study these scenarios

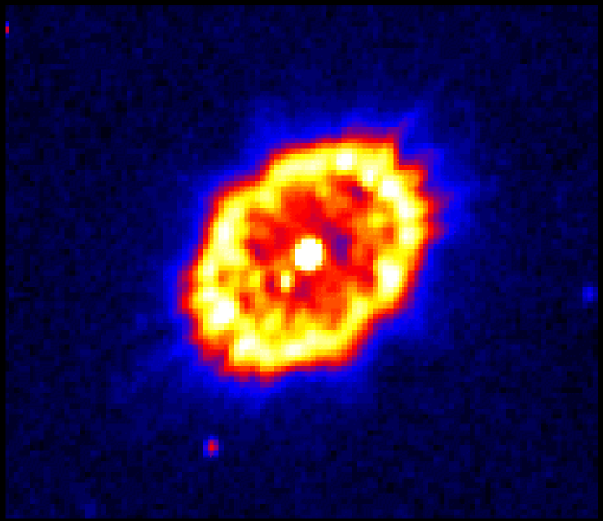




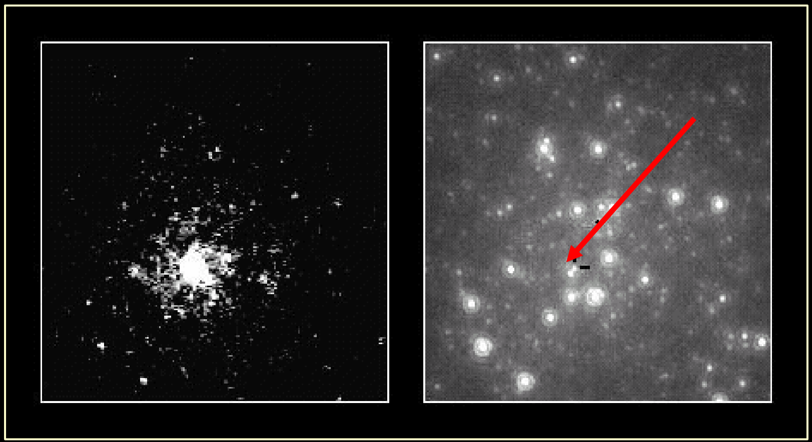
Novae and X-ray Bursters

- White dwarf
- Temperature: up to 3 x 10^8K
- Time: 100-1000s to eject layer

- Neutron star
- Temperature: up to 2 x 10^9K
- Time: 1-10s to eject layer



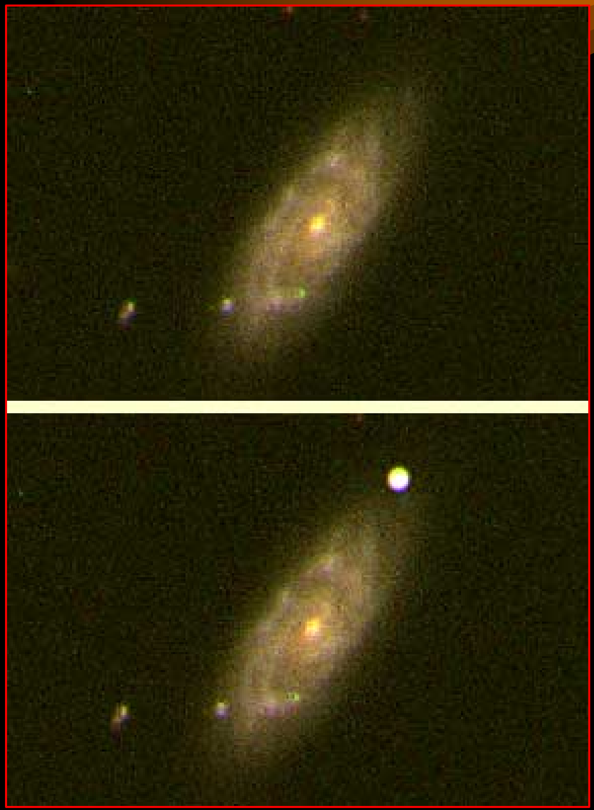
Nova Herculis 1934: AAT



X-ray burster in NGC 6624: HST

Supernovae Type 1a

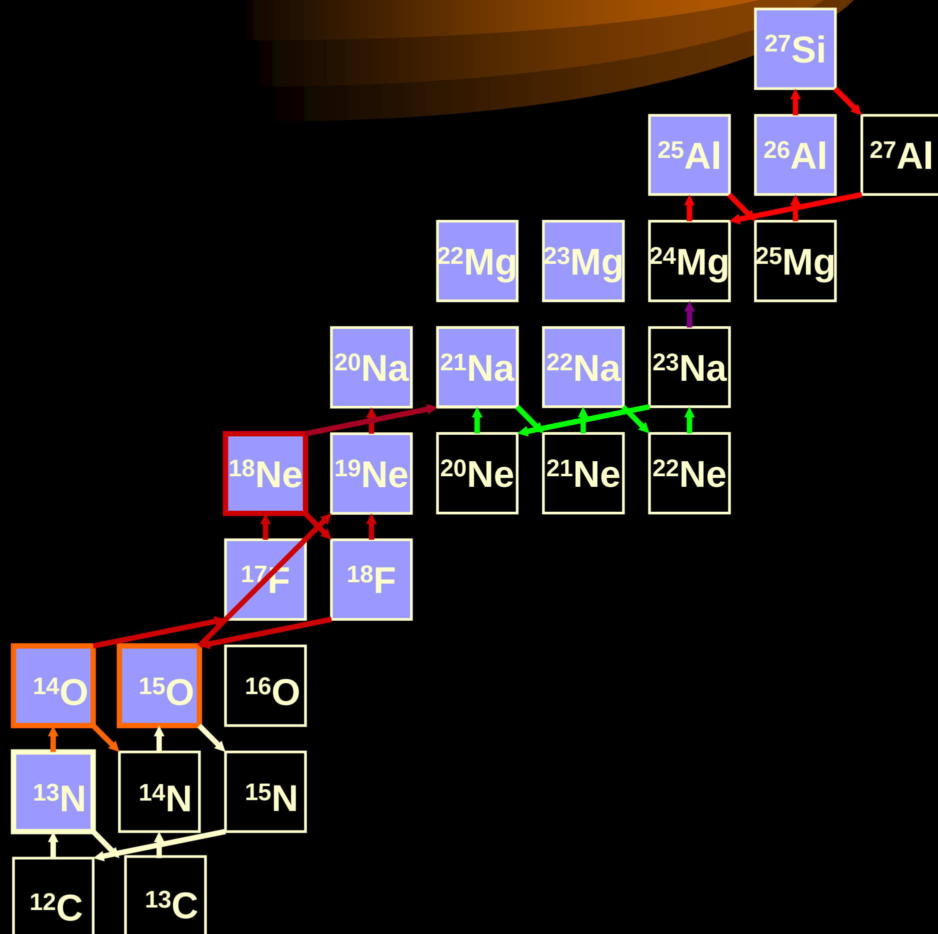
- White dwarf
- Accreted material builds up until Chandrasekhar mass limit reached
- Electron degeneracy pressure no longer supports star
- Carbon ignited explosively in the core
- Resulting explosion destroys star
- Used as standard candles



SN1999BE: CGCG 089-013
One week after outburst

Explosive hydrogen burning

- CNO cycle dominates above 2 x 10^7K
- Above 10^8K, ^{13}N(p,γ)^{14}O supersedes β-decay of ^{13}N
- Above 4 x 10^8K, ^{14}O(α,p)^{17}F supersedes β-decay of ^{14}O
- Build up of material in ^{15}O and ^{18}Ne
- Breakout reactions ^{15}O(α,γ)^{19}Ne and ^{18}Ne(α,p)^{21}Na control subsequent energy generation



Experimental Nuclear Astrophysics What can we measure in the lab?

Want to measure nuclear reaction rates

Can do this directly by measuring

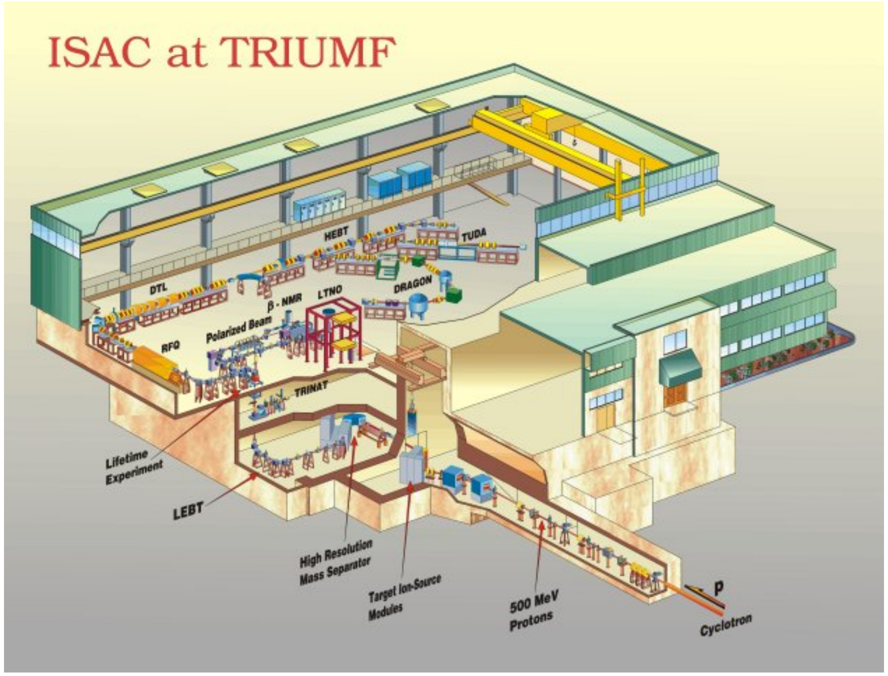
- Cross sections
- Resonance strengths

or if yields too low, indirectly by measuring

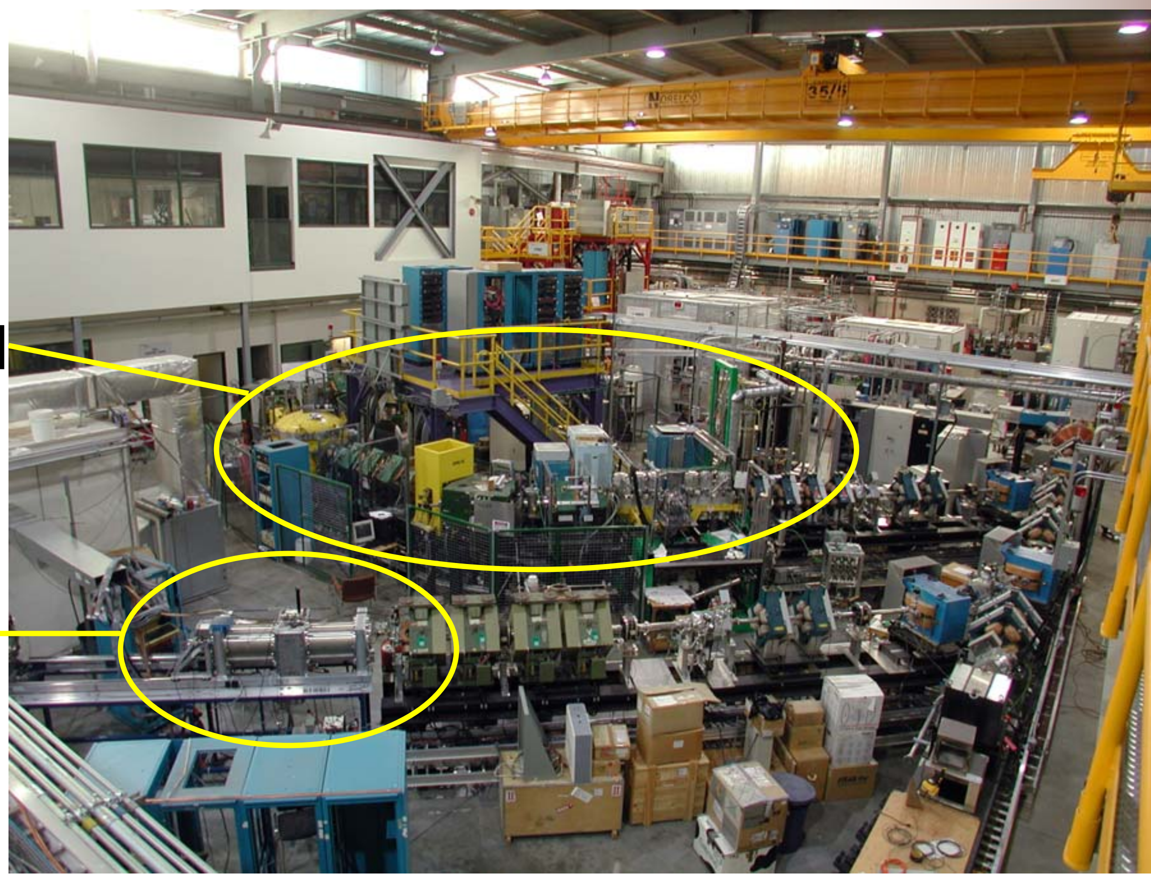
- Energies
- Spins and parities
- Widths
- Partial widths, branching ratios

Radioactive Ion Beams ISAC @ TRIUMF

- Isotope separation on line technique - ISOL
- Worlds largest cyclotron – 500 MeV protons
- After target, second acceleration stage – RFQ and DTL
- Beam energies between 0.15 and 1.5 MeV/u
- Isotopes up to mass 30
- Ion sources:
  - Surface
  - Laser
  - Febiad (this summer)

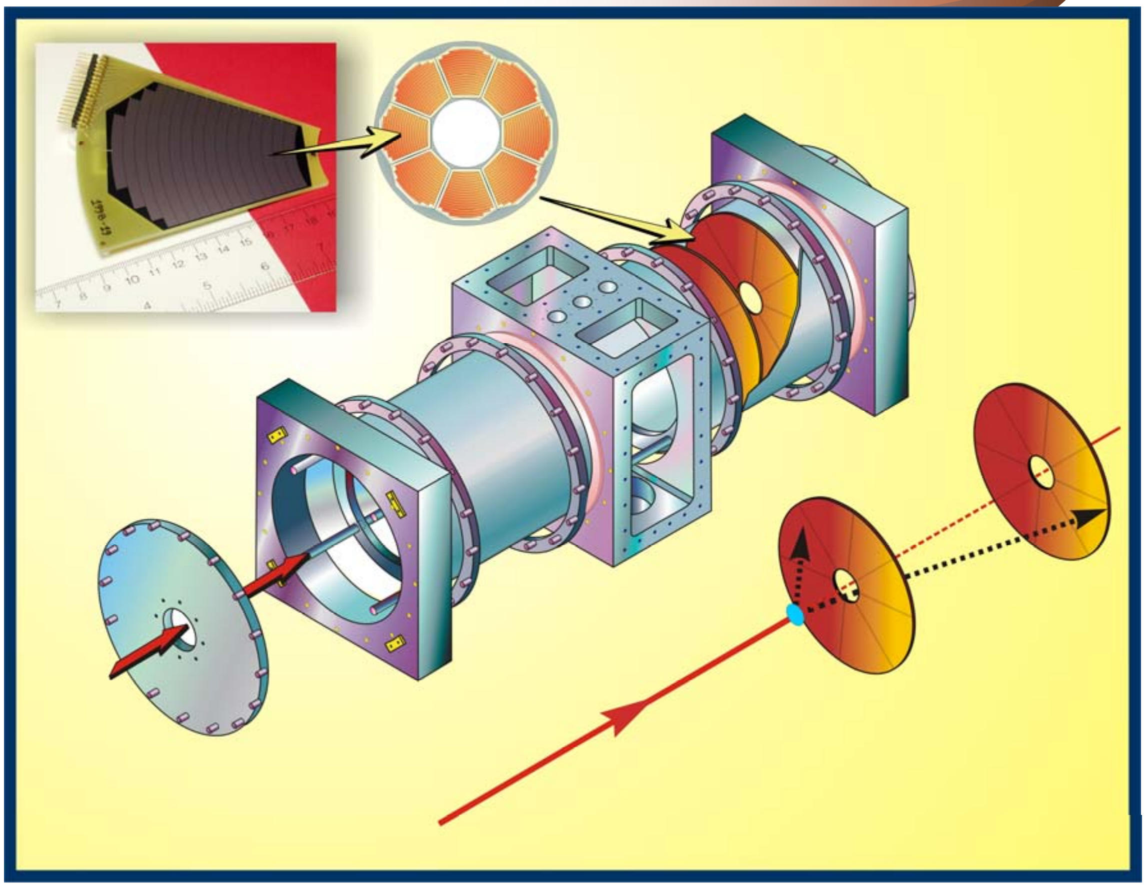


Nuclear Astrophysics at ISAC: the TUDA and DRAGON facilities

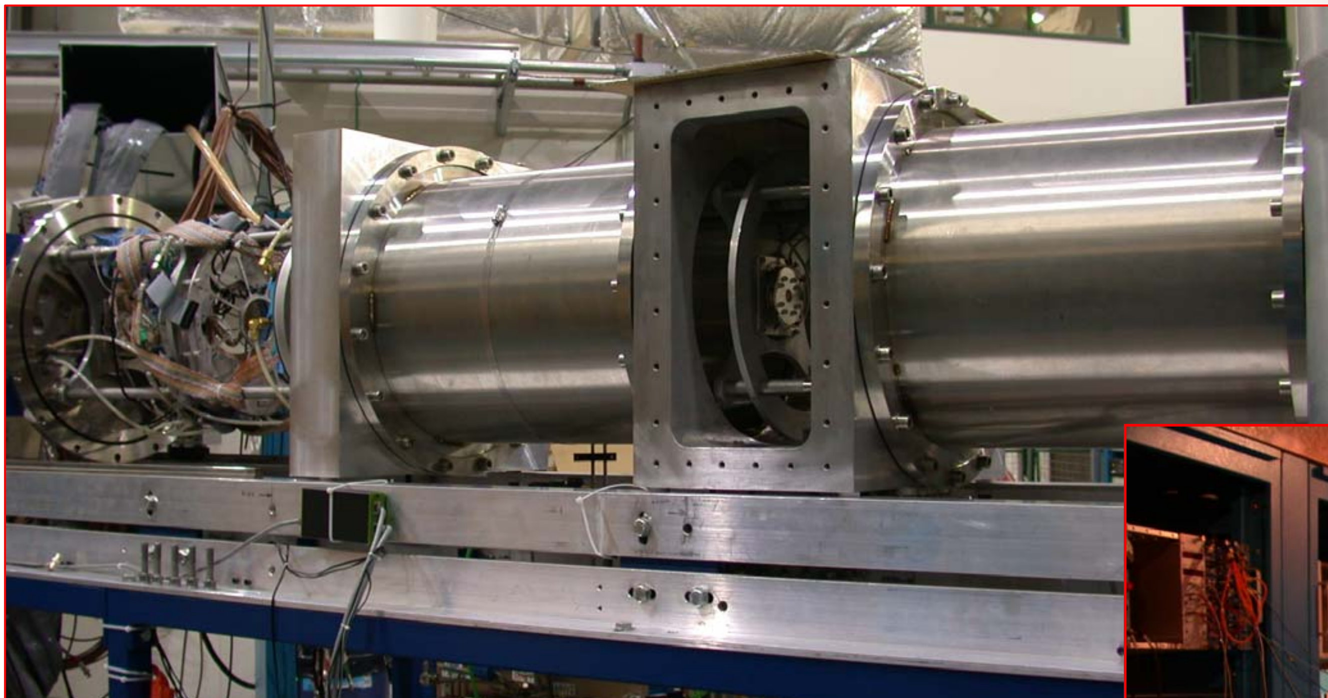


TUDA:
*the **T**RIUMF **U**K **D**etector **A**rray*

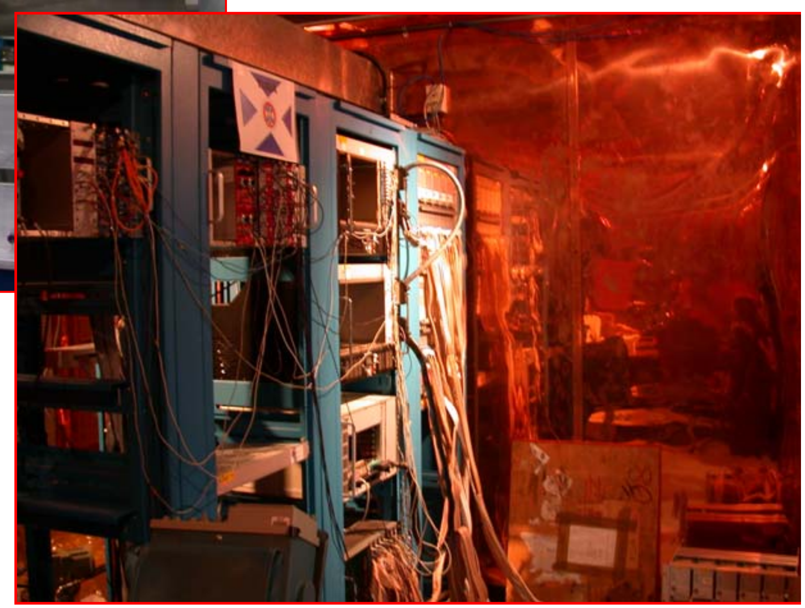
- Studying charged particle reactions,
  e.g (p,p’), (α,p), (d,p)
- Large area, high multiplicity silicon strip arrays – LEDA and CD
- Solid/gas targets
- Up to 512 channels of RAL/Edinburgh instrumentation
- Isolated chamber and electronics to reduce noise
- VME DAQ



TUDA:
*the **T**RIUMF **U**K **D**etector **A**rray*

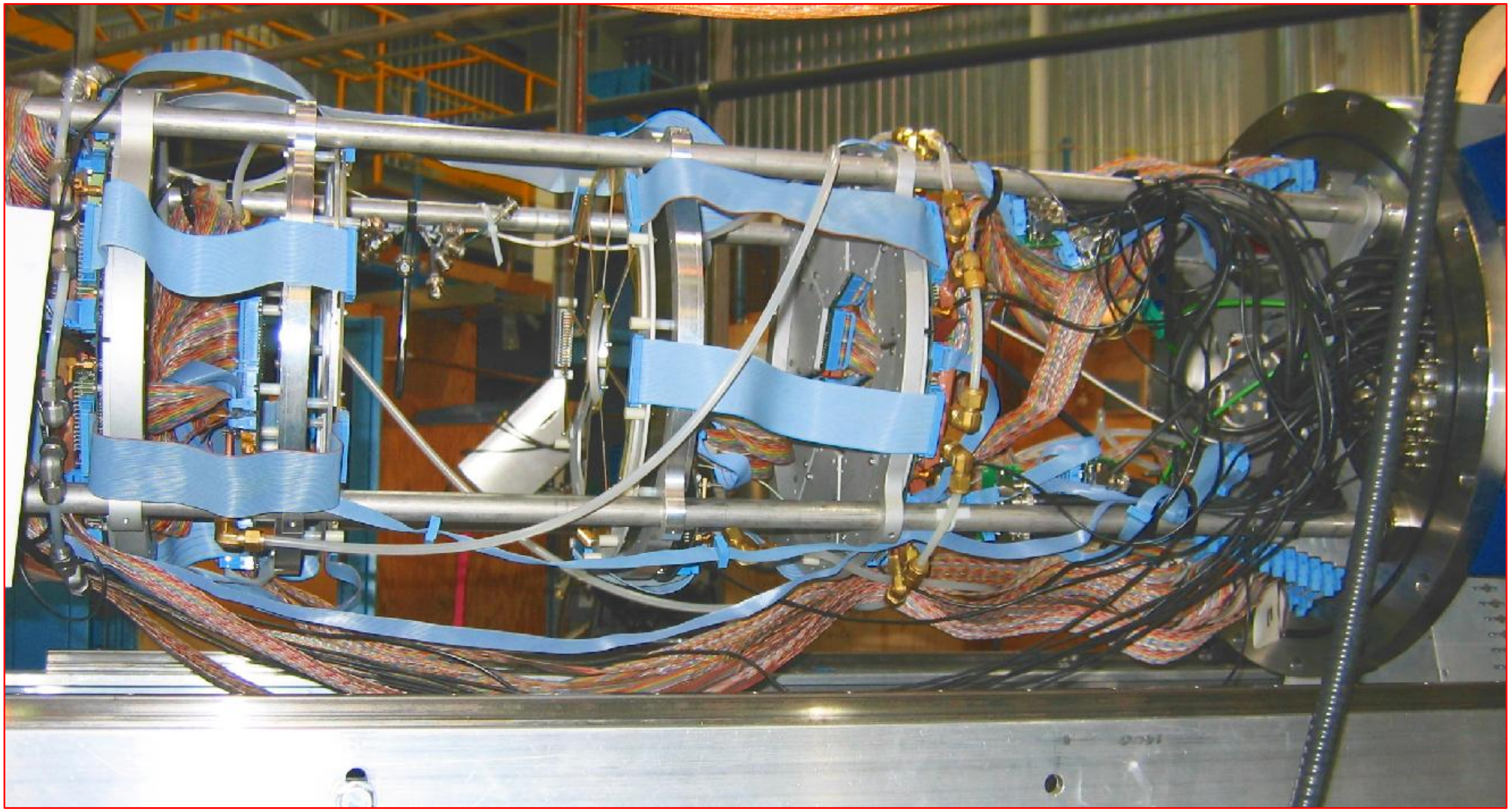


TUDA chamber



TUDA's 'Copper Shack'

TUDA Layout

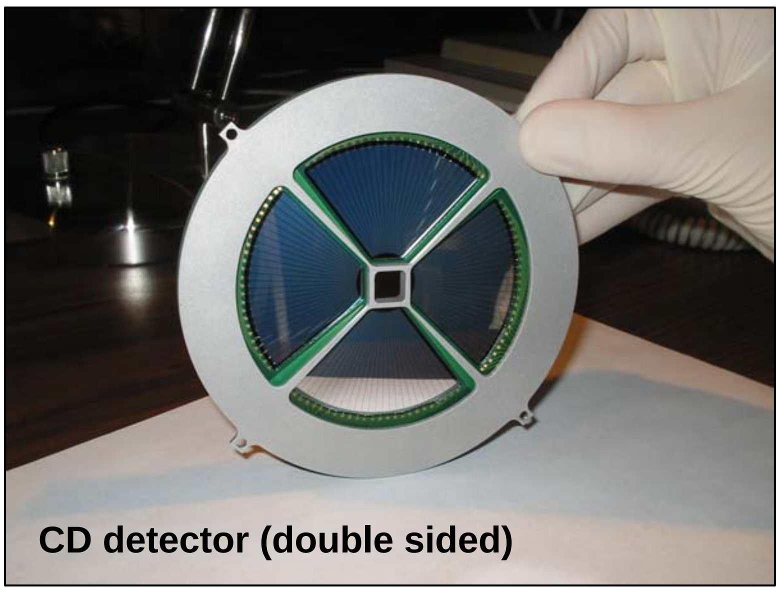


- 4-vane beam monitor
- Anti-scatter collimator
- Preamplifier assembly
- Upstream detector/s
- Downstream detector/s
- Preamplifier assembly
- 4-vane beam monitor
- Beam dump FC

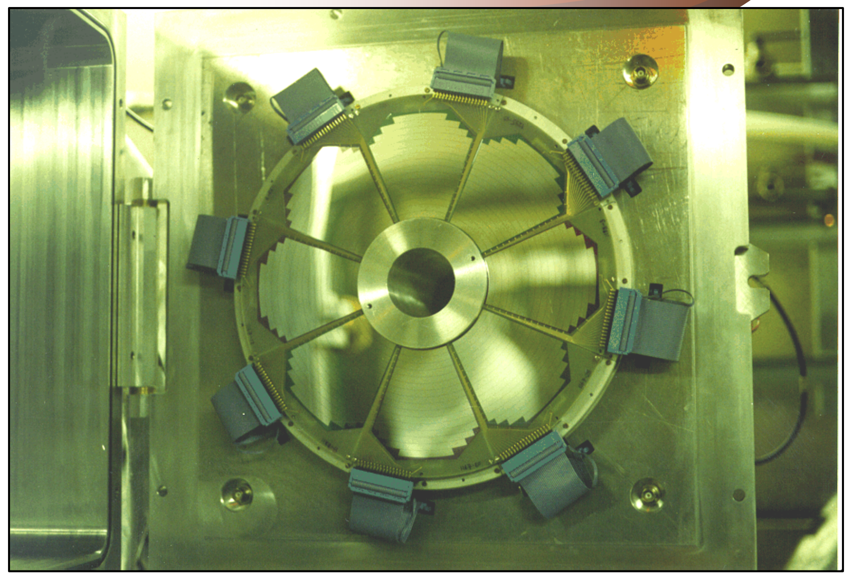
Detectors : LEDA

Louvain ***E****dinburgh* ***D****etector* ***A****rray*

- Large area, highly segmented silicon strip array



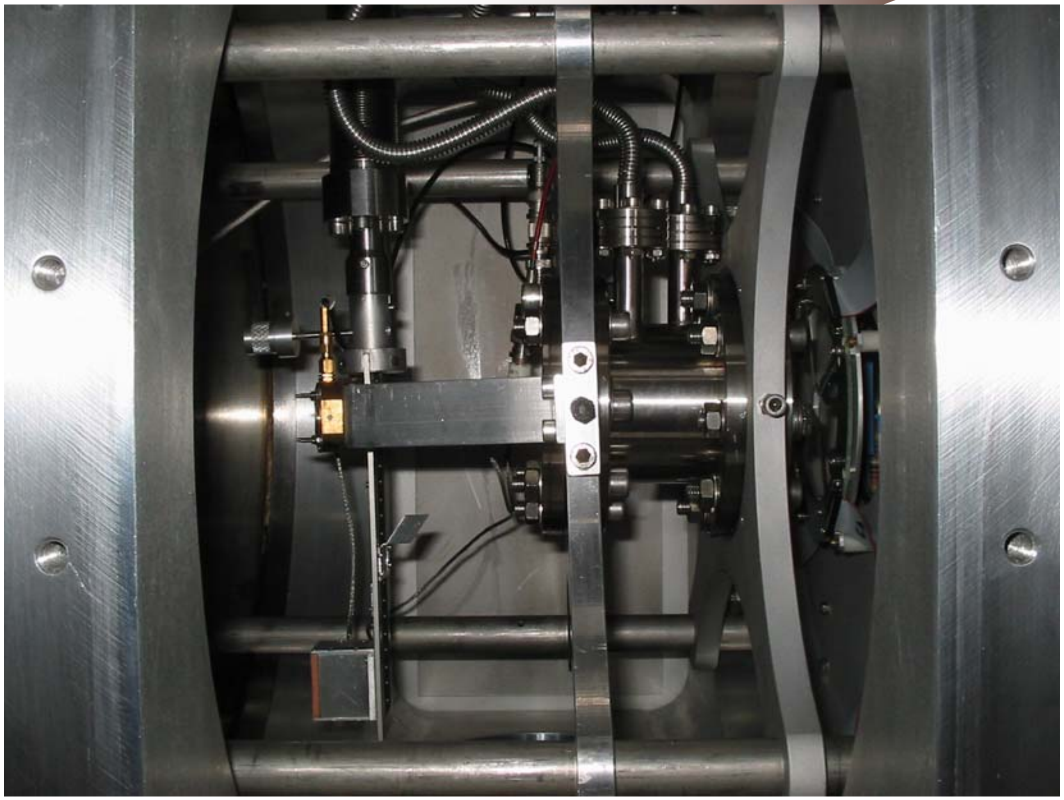
CD detector (double sided)



Can be used in various configurations to cover the required angular range

TUDA Targets

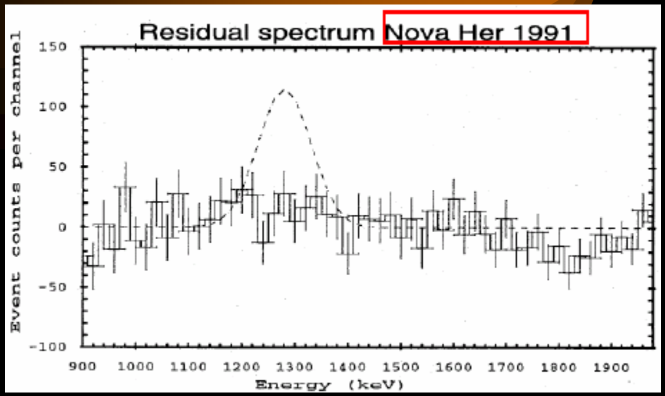
- Solid targets
  - CH_2
  - CD_2
  - Gold foils
  - Carbon foils
- Gas target
  - Helium filled cell
  - Cryogenic ^{3}He cell (on loan from E. Rehm/ANL)

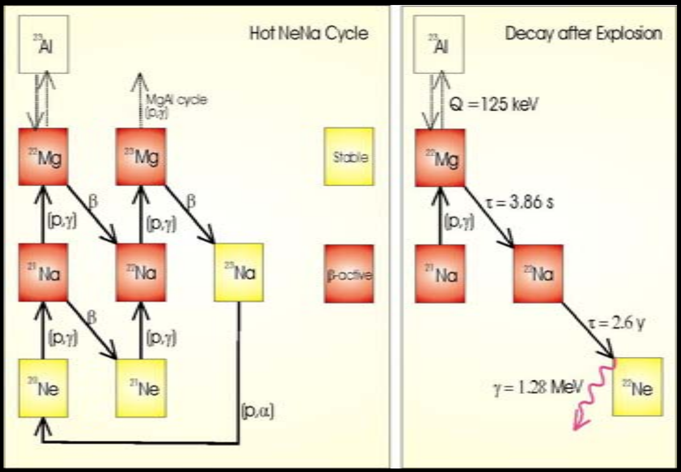


Indirect measurements

Novae observables – ^{22}Na

- Decay of ^{22}Na results in characteristic gamma line
- Observation of such gammas would put constraints on nova models (no observation to date!)
- Largest uncertainty in abundance due to ^{21}Na(p,γ)^{22}Mg rate



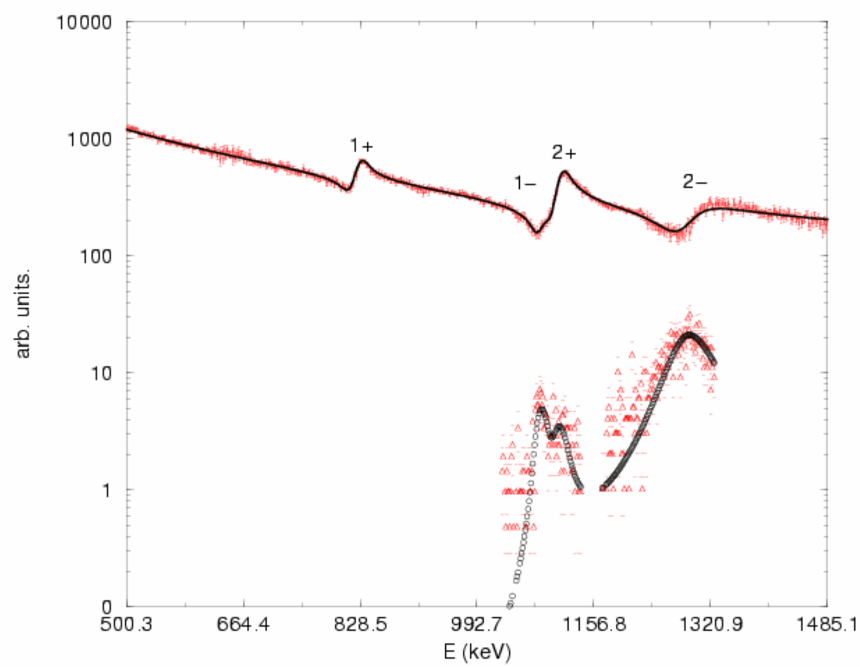


One of the aims of INTEGRAL is the detection of 1.275MeV γ-ray

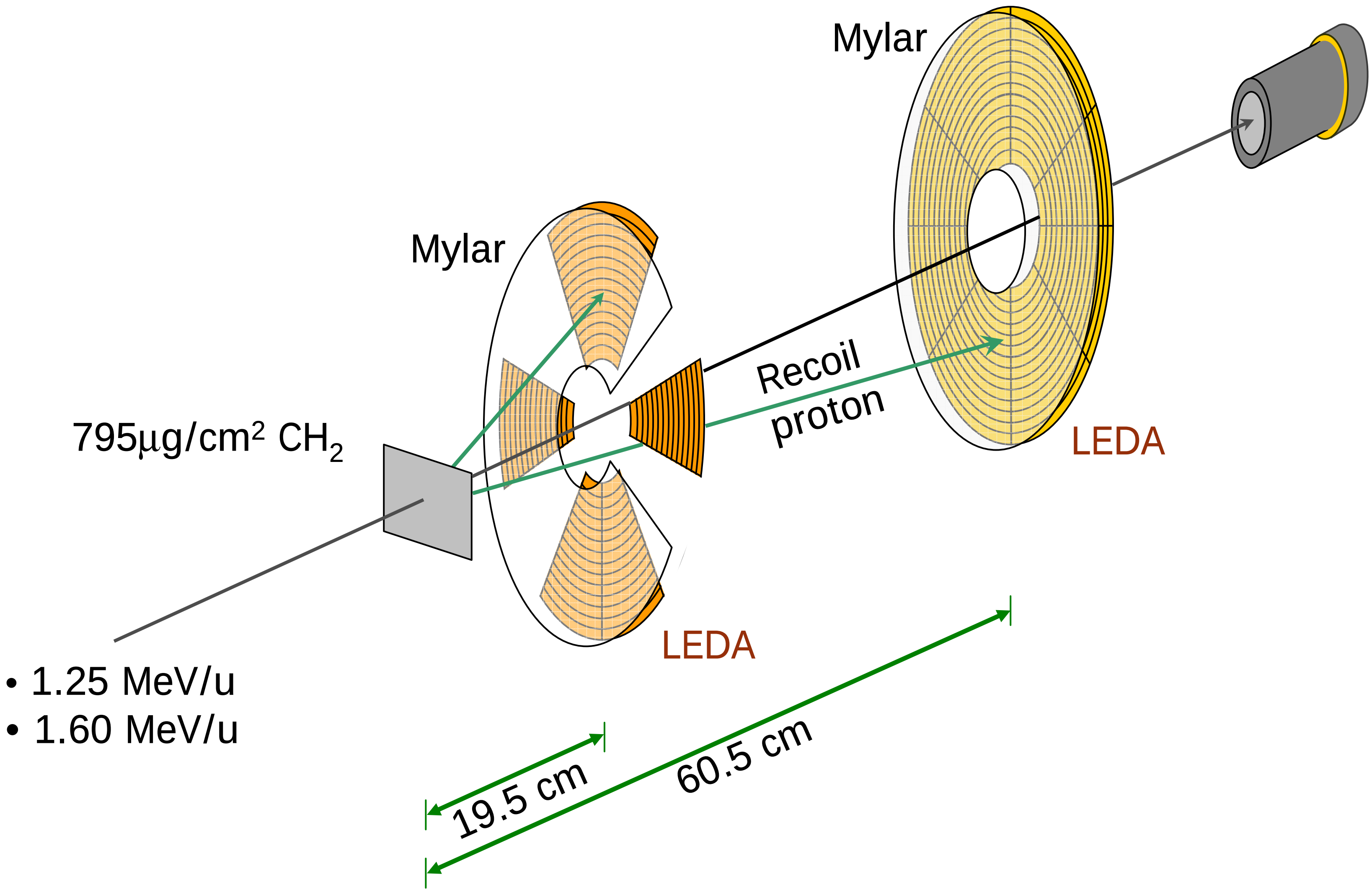
Indirect measurements with TUDA

^{21}Na(p,p)^{21}Na

- Studied states in ^{22}Mg via resonant elastic scattering
- ^{21}Na beam impinging on CH_2 target
- Proton energy spectrum exhibits resonant features
- R-matrix analysis of proton data provides information on energies and spins of states populated in ^{22}Mg



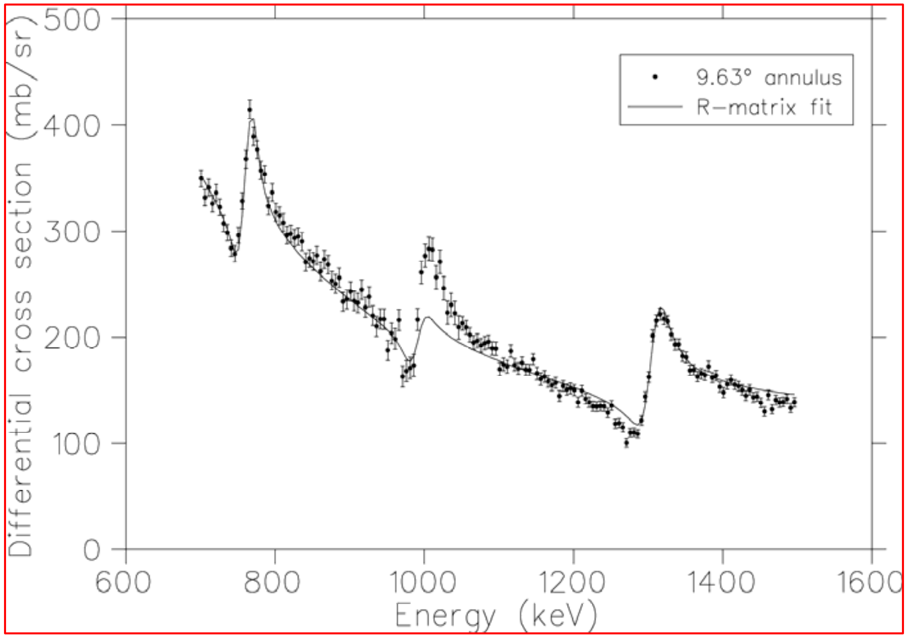
Courtesy of Chris Ruiz
(University of Edinburgh/TRIUMF)
C. Ruiz et al., PRC 71 (2005) 025802

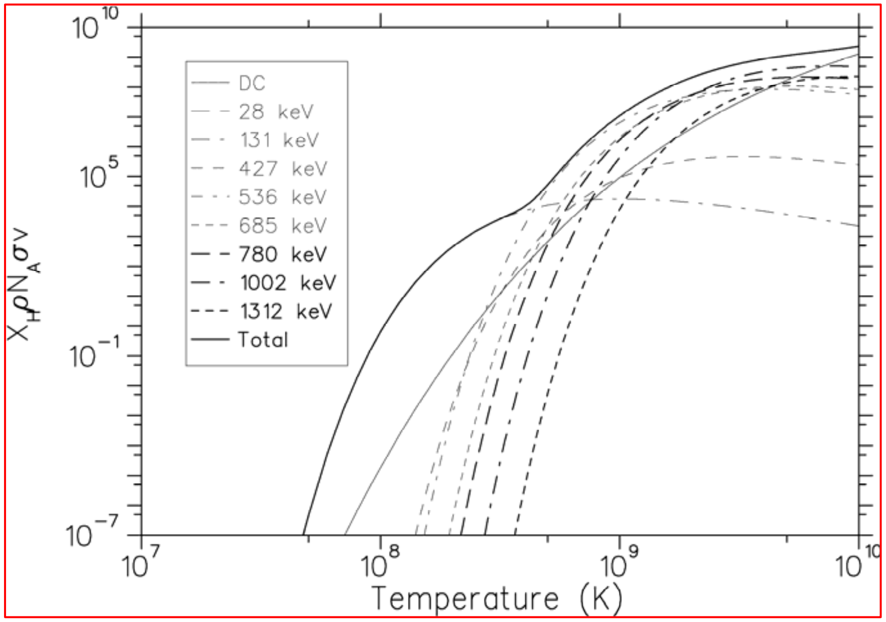


Mylar
Mylar
795μg/cm2 CH2
Recoil
proton
LEDA
LEDA
• 1.25 MeV/u
• 1.60 MeV/u
19.5 cm
60.5 cm

Indirect measurements with TUDA
^{20}Na(p,p)^{20}Na

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



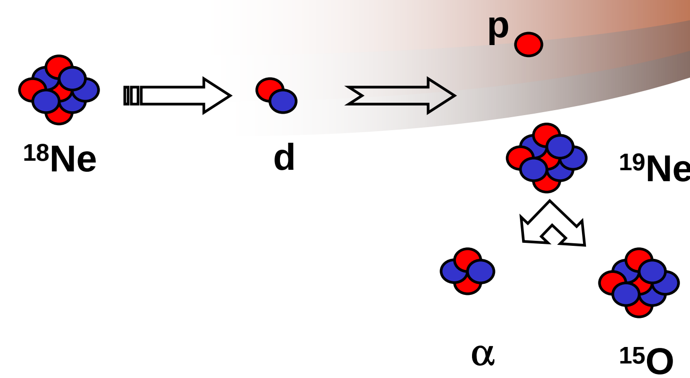


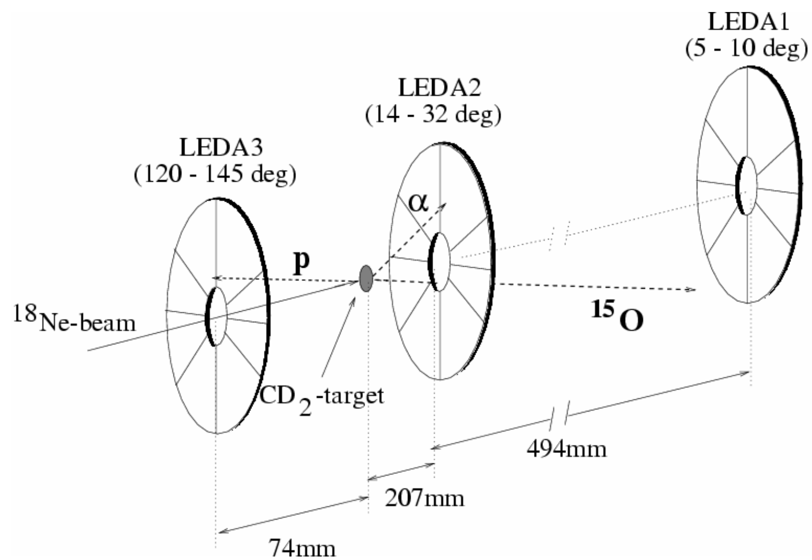
Figures courtesy of A. Murphy (U. of Edin.)

A. St. J. Murphy et al., accepted by PRC

Indirect $^{15}O(\alpha,\gamma)^{19}Ne$ with TUDA: $d(^{18}Ne,p)^{19}Ne^*(\alpha)^{15}O$

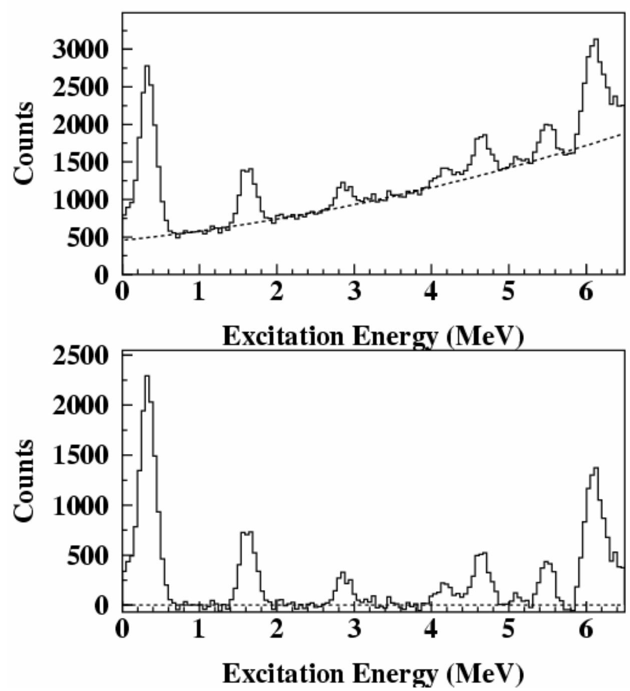
- HCNO breakout reaction
- Reaction rate dominated by resonances
- Populate excited states in ^{19}Ne by neutron transfer
- Proton tags excited state and coincident α and ^{15}O identify decay
- Measure α-branching ratios to determine reaction rate





Previous results and improvements

- First measurement undertaken at CRC in Belgium
- States in ^{19}Ne populated and α-decays seen from higher lying states
- No decay from astrophysically important state at 4.033MeV seen
- New measurement planned for ISAC II
- Higher beam intensity by factor of 1000 and longer running time
- Improved detector setup

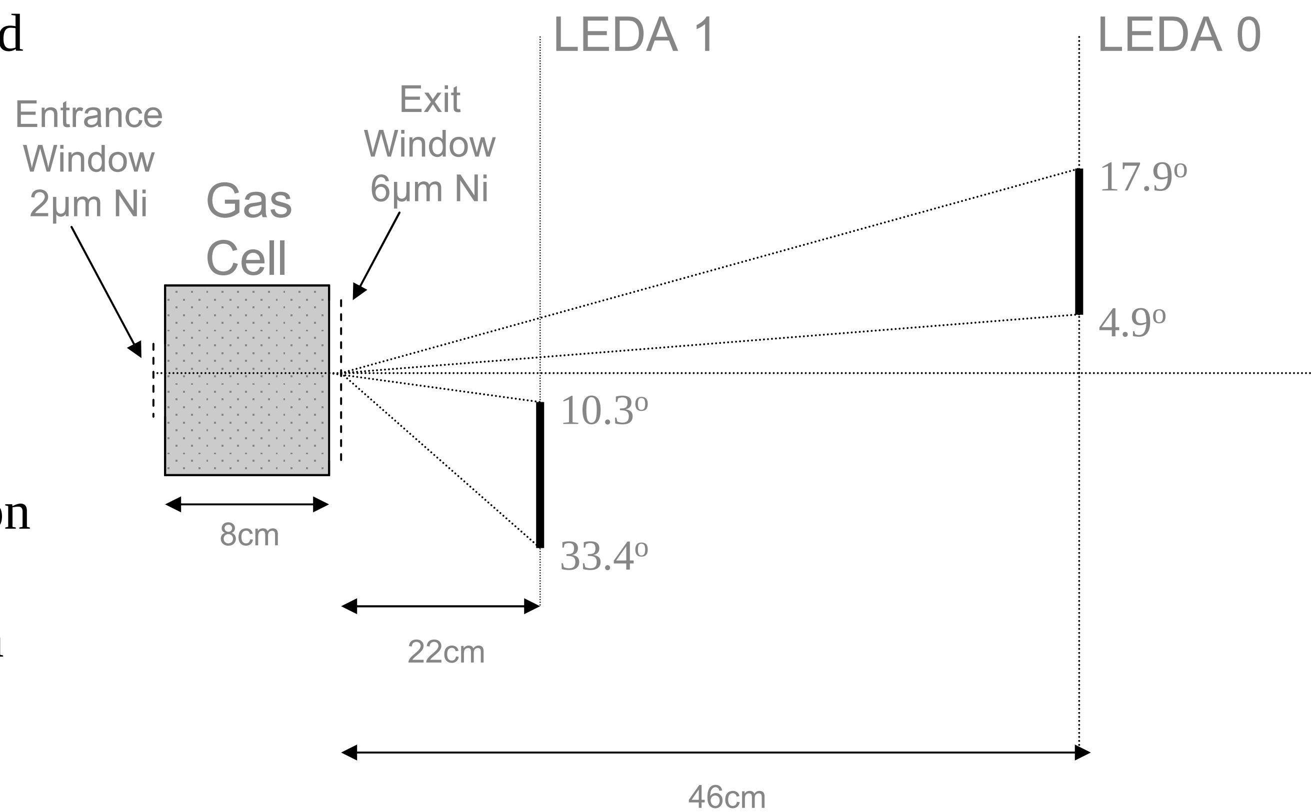


^{19}Ne excitation energy spectrum from first measurement
A.M. Laird *et al*., Phys. Rev C 66 (2002) 048801

Direct measurements

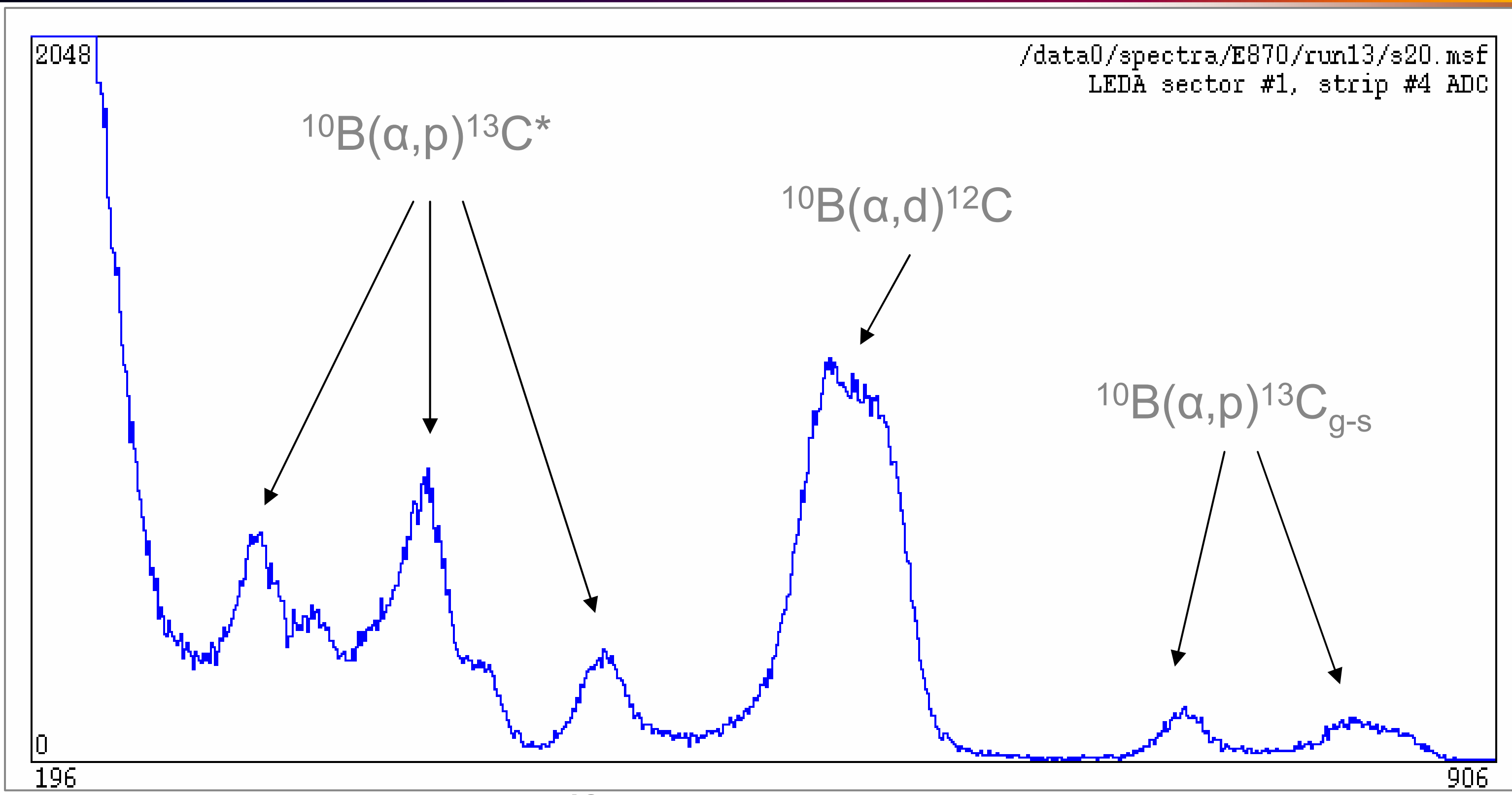
Direct measurement with TUDA
$^{18}Ne(\alpha,p)^{21}Na$

- 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



^{10}B test measurement

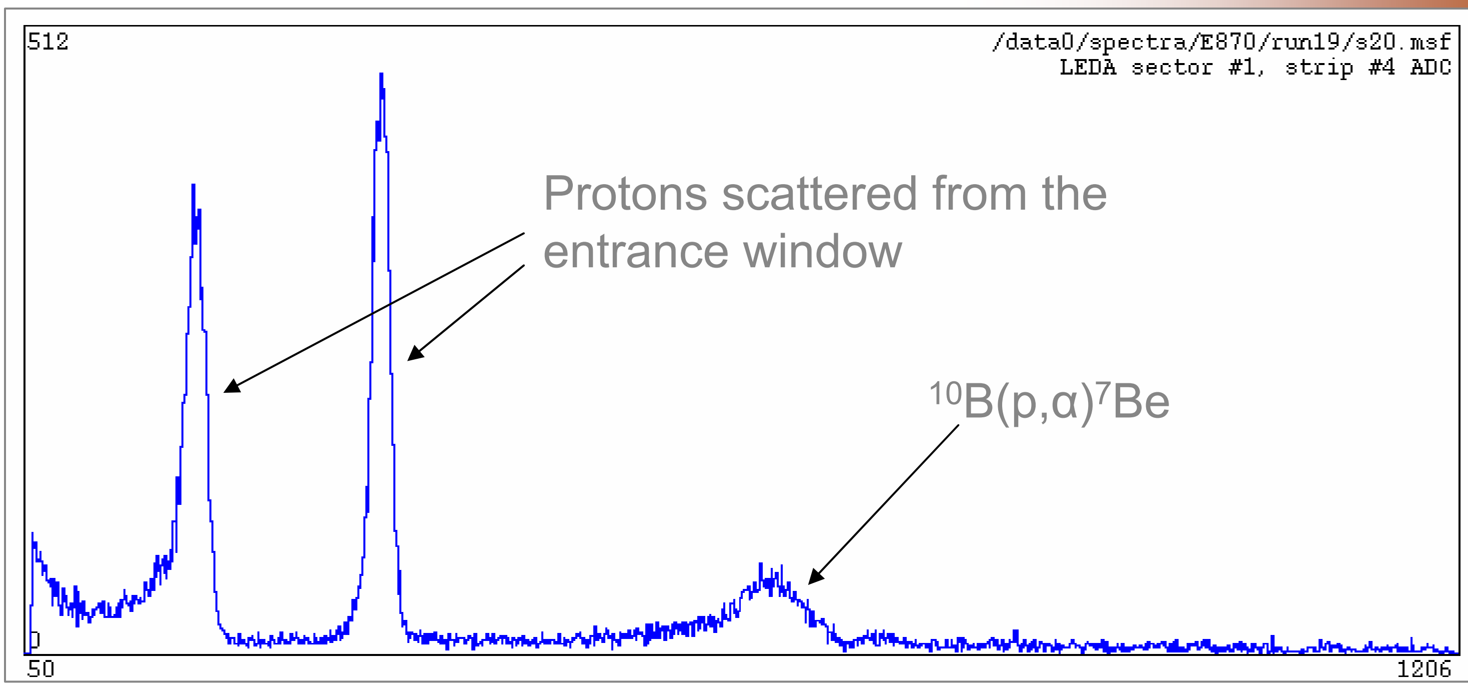
Preliminary results (Aug. 2005)



^{10}B 12.3MeV

Gas Cell at 300 mbar

Background results

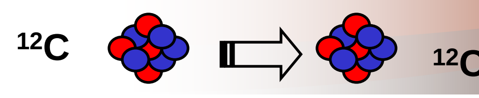


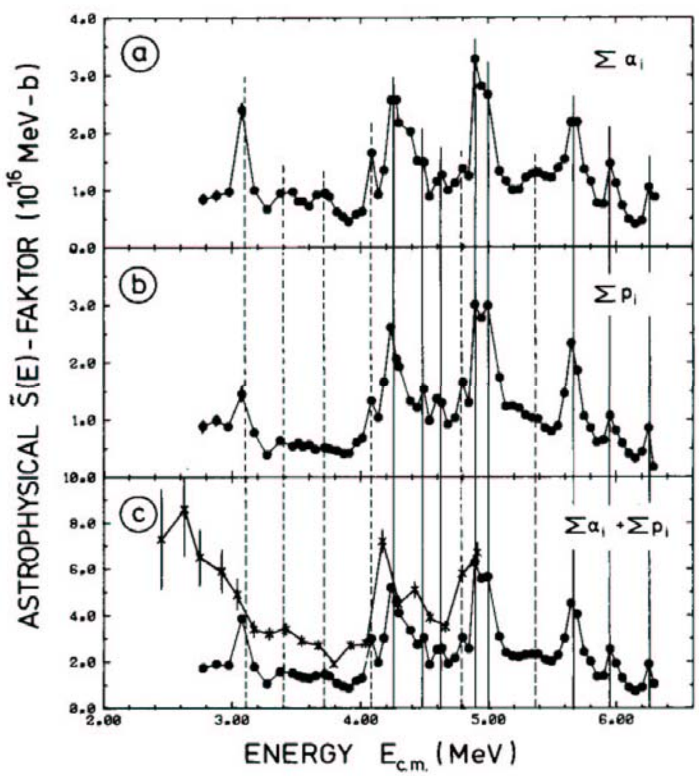
^{10}B 12.3MeV

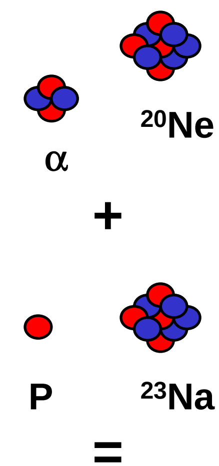
Gas Cell ‘empty’

$^{12}C+^{12}C$ fusion at astrophysical energies

- Extremely important for understanding both quiescent carbon burning in >7 $M_{\odot}$ stars and explosive carbon burning in type 1a supernovae
- At relevant energies, 1-3 MeV in the centre of mass, reaction is dominated by p and α exit channels
- Most recent measurements (1981) reach down to 2.45 MeV
- However, discrepancies exist in data even at higher energies
- Resonant features make extrapolations to lower energies difficult to do with confidence

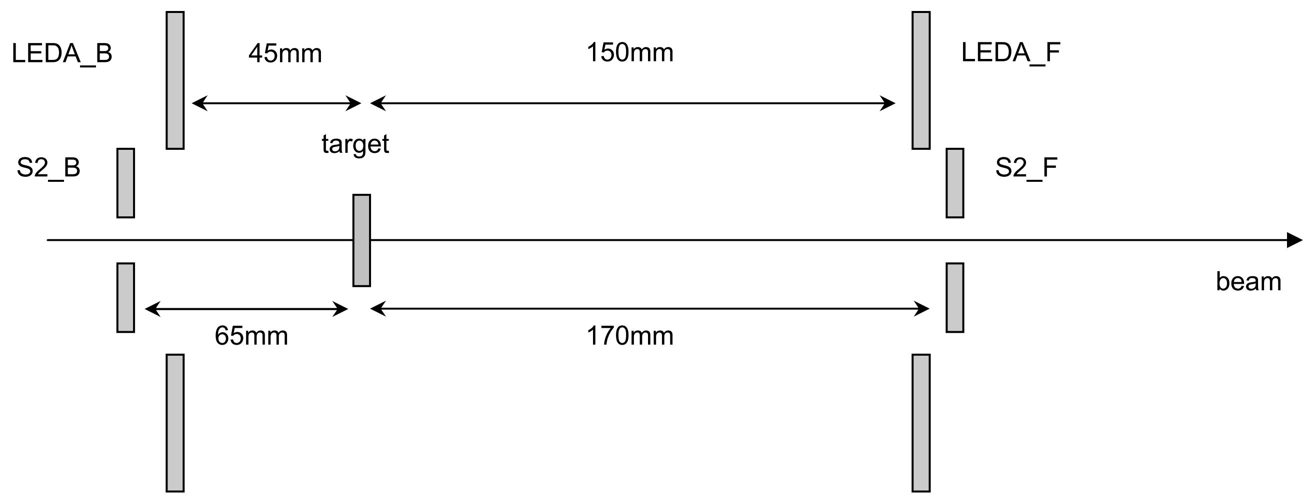






Becker et al.,
Z. Phys. A 303(1981) 305

Experimental set up for $^{12}C+^{12}C$



Aim is to measure:

➢ angular distributions and
➢ excitation functions for alpha and proton channels

in the region between E_{cm} = 3.0 – 4.0 MeV (ΔE_{cm} = 100 keV)

➢ particle discrimination via TOF and DE/E
➢ energy and angle measurement with strip detector arrays
➢ absolute cross-section ⇔ normalisation to Mott scattering data

First measurement July 2005 – analysis ongoing

Experimental Challenges

- Cross section drops off rapidly with energy
  - low statistics
  - require excellent beam energy determination
    - large solid angle coverage
    - energy determination with DRAGON

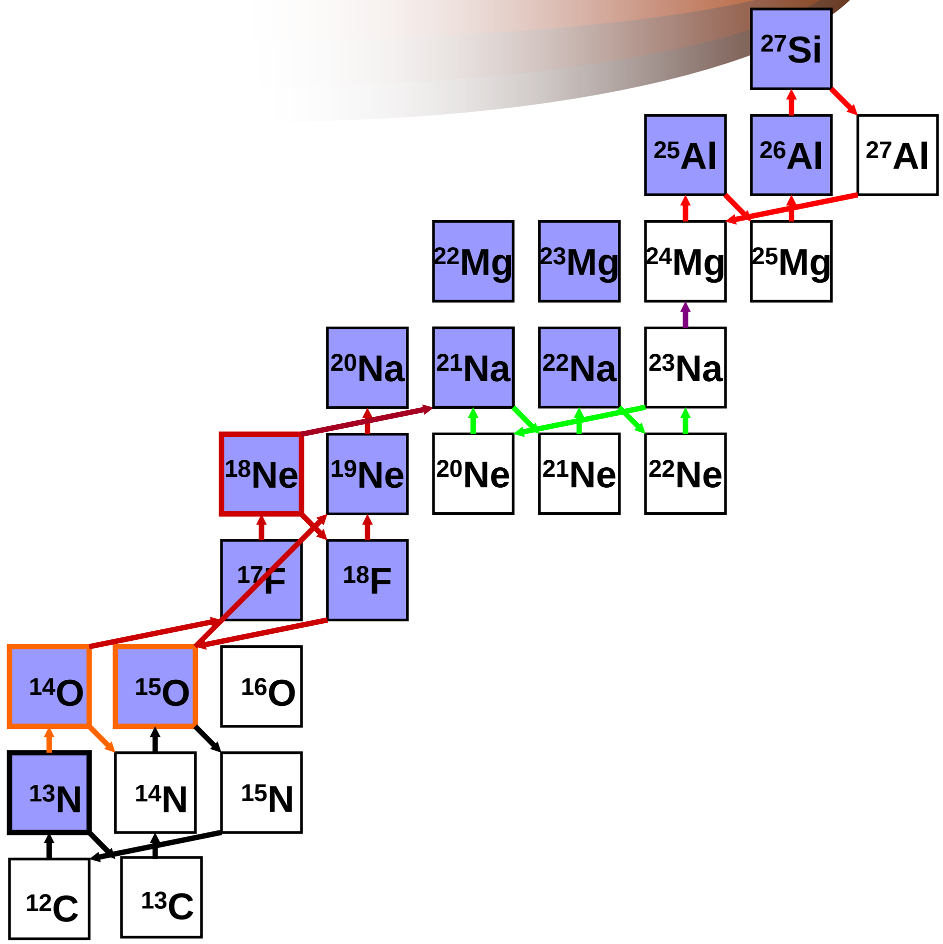
- Proton contamination on target (from water and hydrocarbons)
  - background from elastically scattered protons
  - additional background from D(^{12}C,^{13}C)p reaction
    - target heating
    - (particle ID)

- Carbon build-up during runs (from hydrocarbons)
  - affects target thickness and effective interaction energy
    - target thickness measurements
    - tests to determine significance

First measurement July 2005 – analysis ongoing

Approved measurements at TUDA

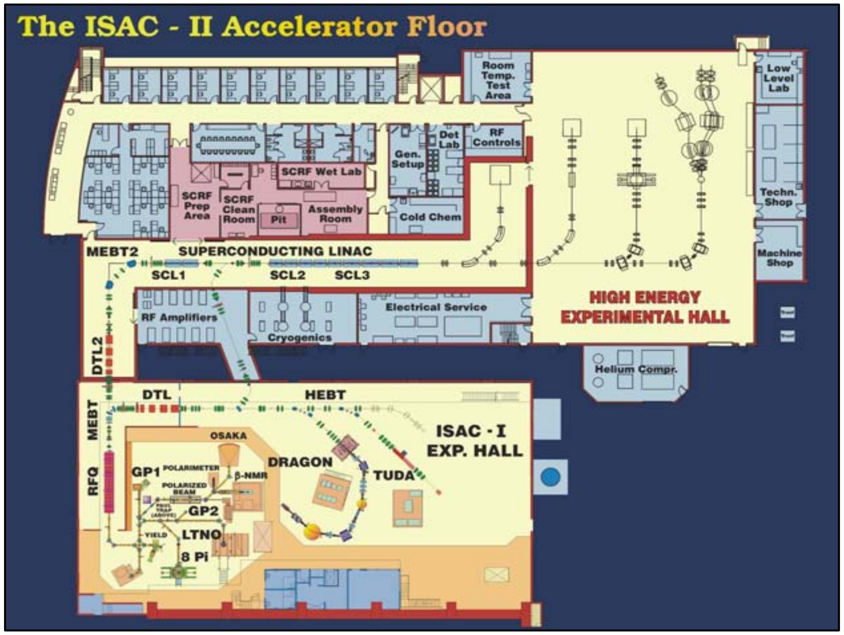
- $^{18}Ne(\alpha,p)^{21}Na$
- $^{18}Ne(d,p)^{19}Ne$
- $^{17,18}Ne(^{3}He,p)^{19,20}Na$
- $^{14}O(\alpha,p)^{17}F$
- $^{15}O(^{6}Li,d)^{19}Ne$
- $^{18}F(p,\alpha)^{15}O$
- $^{12}C+^{12}C$



The future…..ISAC II

- *Expansion to higher energies and wider range of beams*
  - *Up to 6.5 MeV/u*
  - *Masses up to 150*
- *New experimental facilities*
  - *EMMA (ElectroMagnetic Mass Analyser)*
  - *TIGRESS (gamma spectrometer)*
  - *TUDA*
  - *combinations of above*

ISAC II



- Extension to ISAC
- Initial stage (2006) - energies up to 4.3 MeV/u and masses up to 60
- Second stage, energies up to 6.5 MeV/u

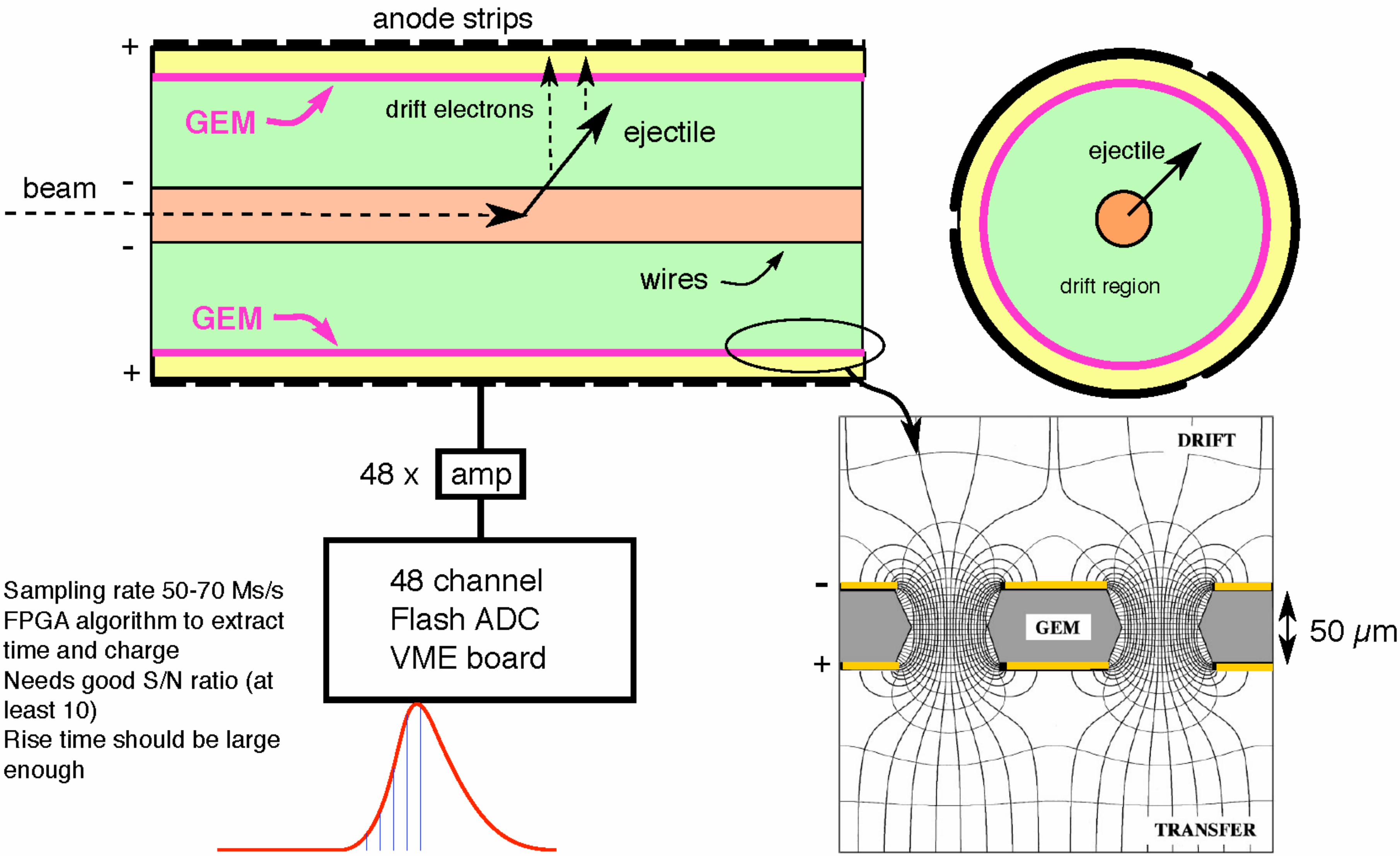
Experimental Nuclear Astrophysics at low energies

- Studying directly key nuclear reactions for nucleosynthesis and energy generation in explosive sites – novae, supernovae and X-ray bursters

- Experimental conditions
  - Beam energies: about 0.1 – 2 MeV/u (up to few 10^9 K)
  - Charged particle energies of few MeV down to ~ 100 keV
  - Radioactive beams – high background, low intensity
  - Cross sections can be low - < mbarn

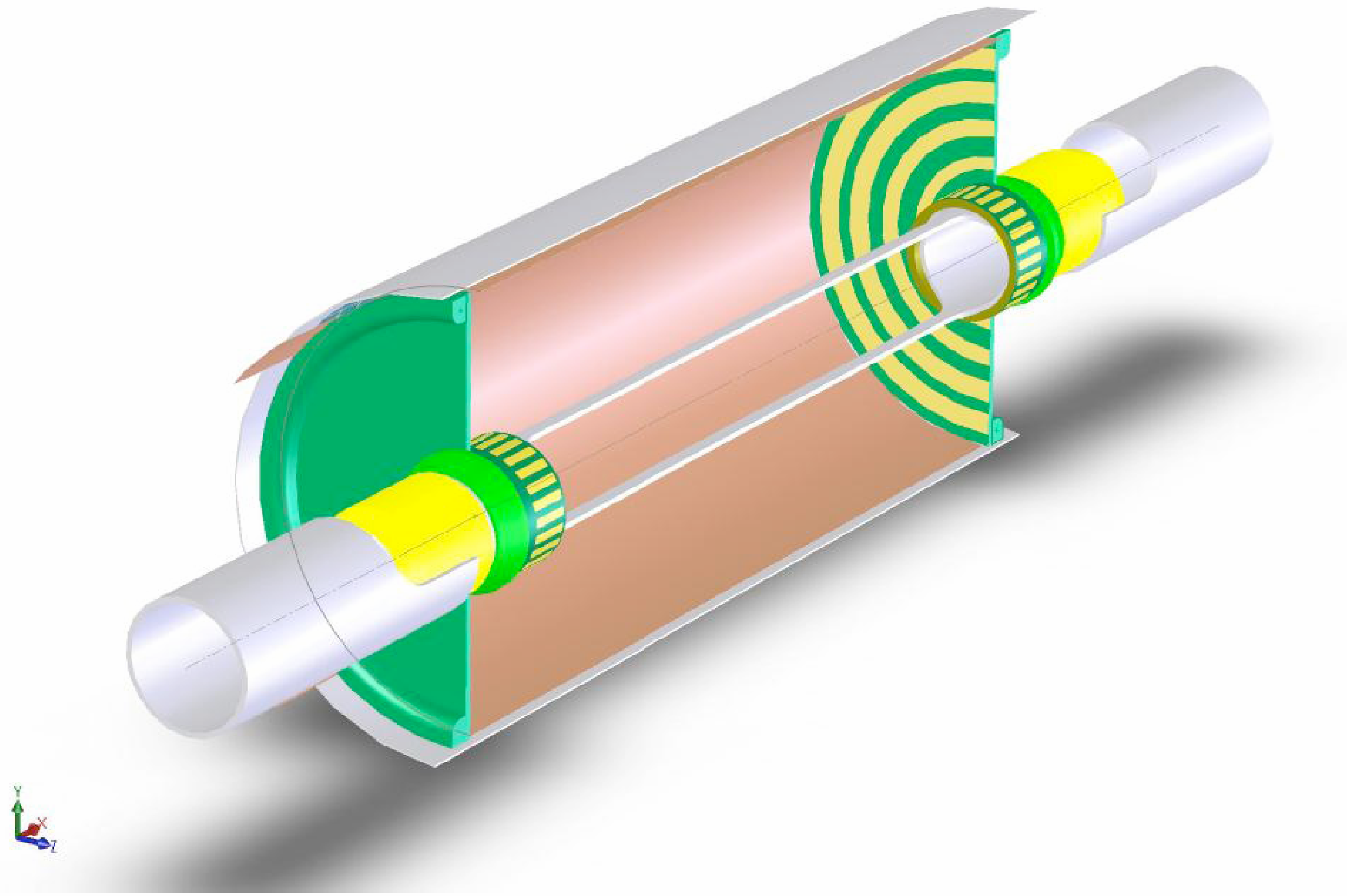
- Need high efficiency, large solid angle detector arrays with low detection threshold

TACTIC



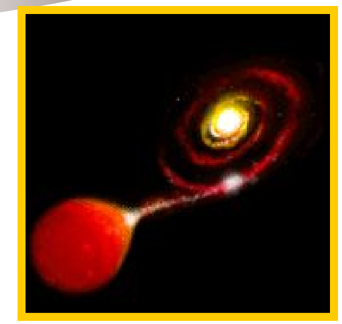
Sampling rate 50-70 Ms/s
FPGA algorithm to extract time and charge
Needs good S/N ratio (at least 10)
Rise time should be large enough

Schematic design of TACTIC detector



Future research programme
(what are we trying to achieve and how)

- Understand explosive binary systems and their influence on the surrounding universe
  - – energy generation
  - – nucleosynthesis



➢ Need to understand the nuclear processes that influence energy generation and nucleosynthesis (not necessarily the same reactions)

  ➢ Comprehensive study of key nuclear reactions (directly, indirectly, any way we can!)
  ➢ Maintain links with theory and models to ensure key reactions are identified

Many thanks to…..

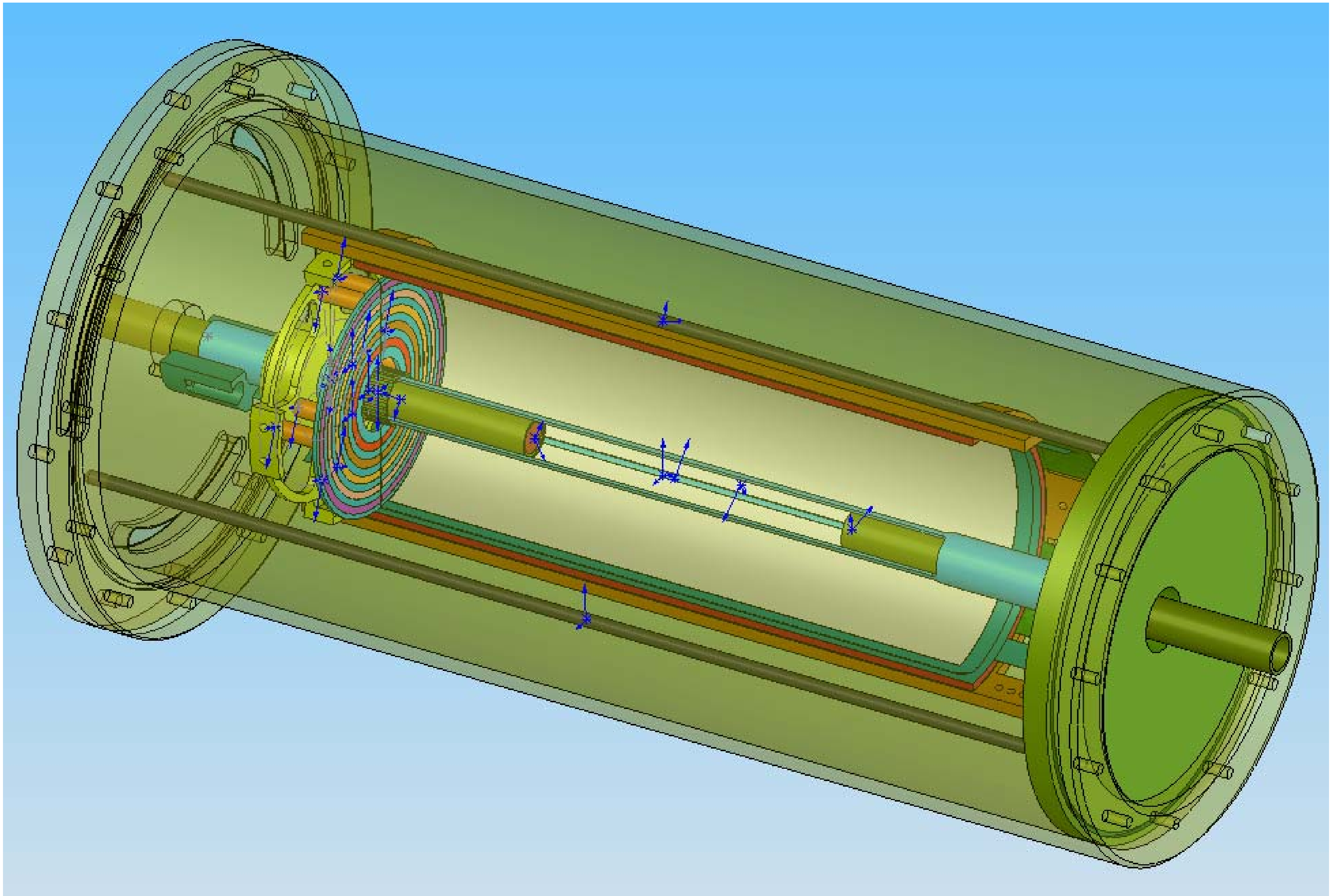
The TUDA collaboration

(University of Edinburgh, TRIUMF and University of York)

and the

PH-122 collaboration

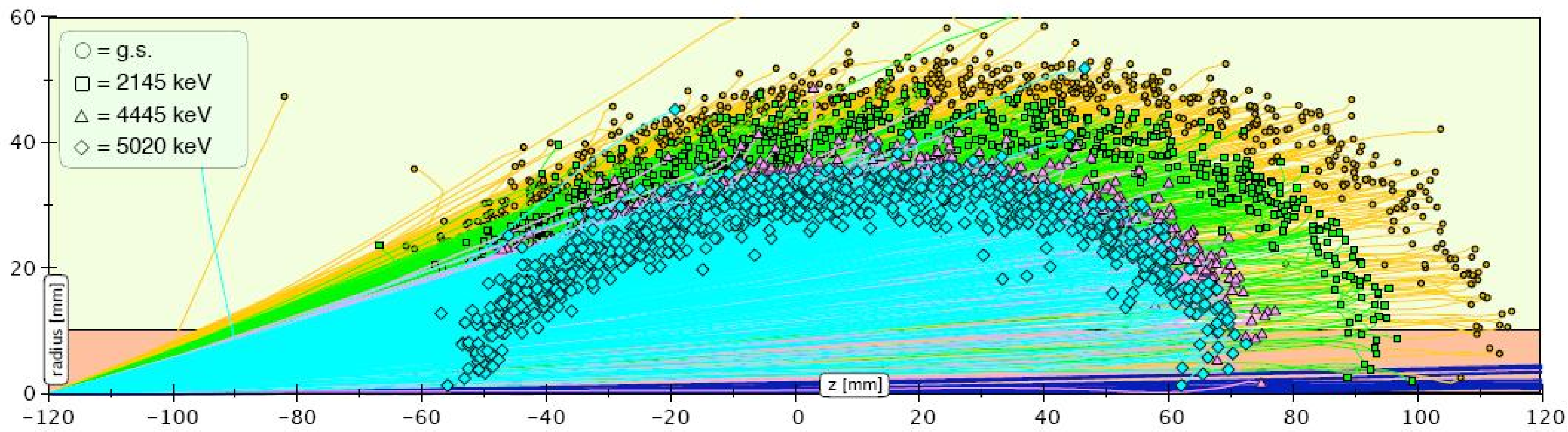
(Universities of Edinburgh, Louvain-la-Neuve and Catania)



GEANT 4 Simulations

- Currently developing GEANT 4 simulations of prototype cylindrical chamber
  – stopping powers of low energy charged particles not well reproduced

^{11}B end points, 9 MeV ^{8}Li beam, 250 mbar 90/10 He/CO_2



Vertical Distance from beam axis [mm]

Distance along beam axis from start of target region [mm]