Australian Government

ansto

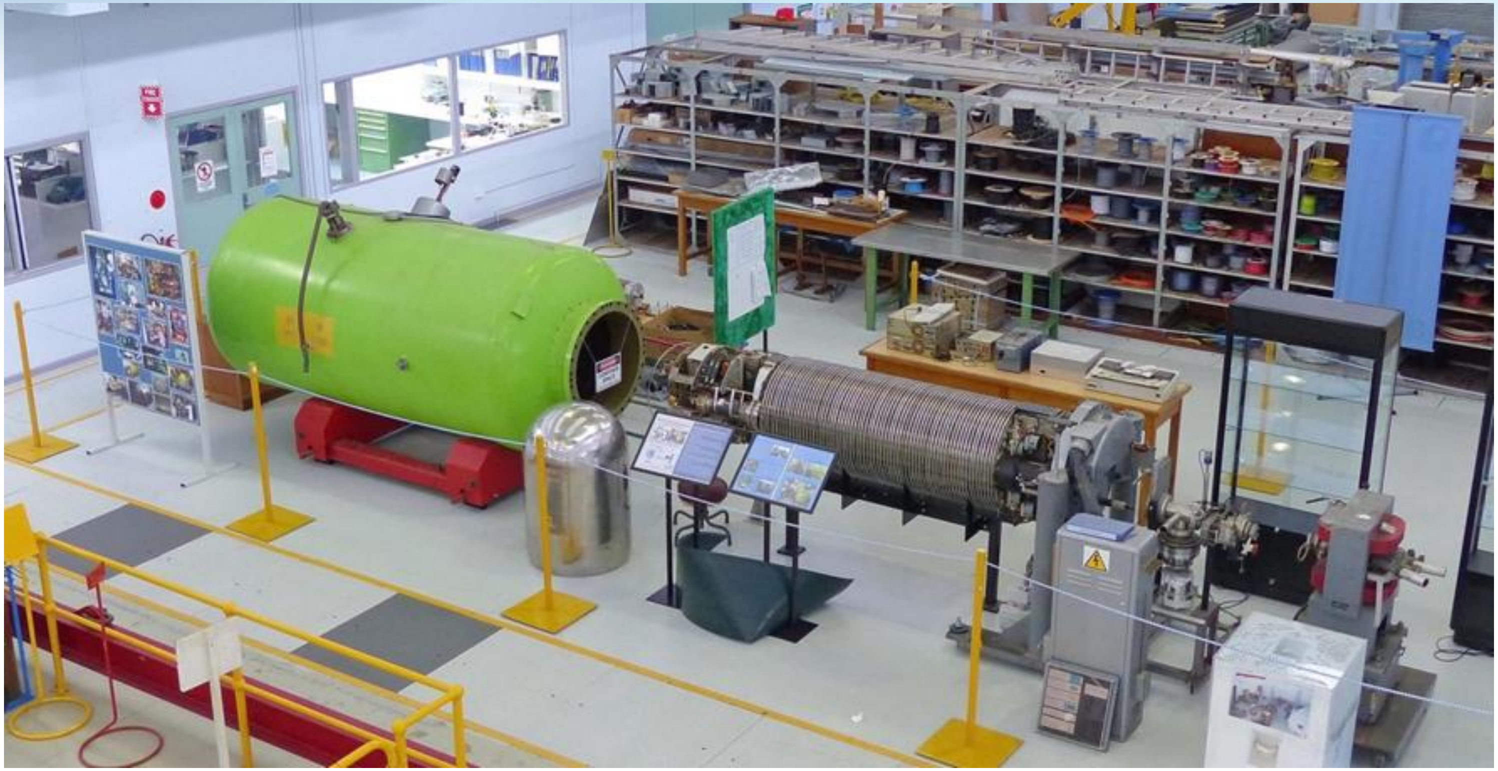
The Centre for Accelerator Science (CAS)

David Cohen, ANSTO, Australia

Centre for Accelerator Science (CAS)

- CAS facilities
- What is a positive ion tandem accelerator?
- Ion Beam Analysis (IBA)
- Accelerator Mass Spectrometry (AMS)
- Some typical applications of ion beams

Long History at ANSTO



ANSTO has a 50 year history of accelerator use.

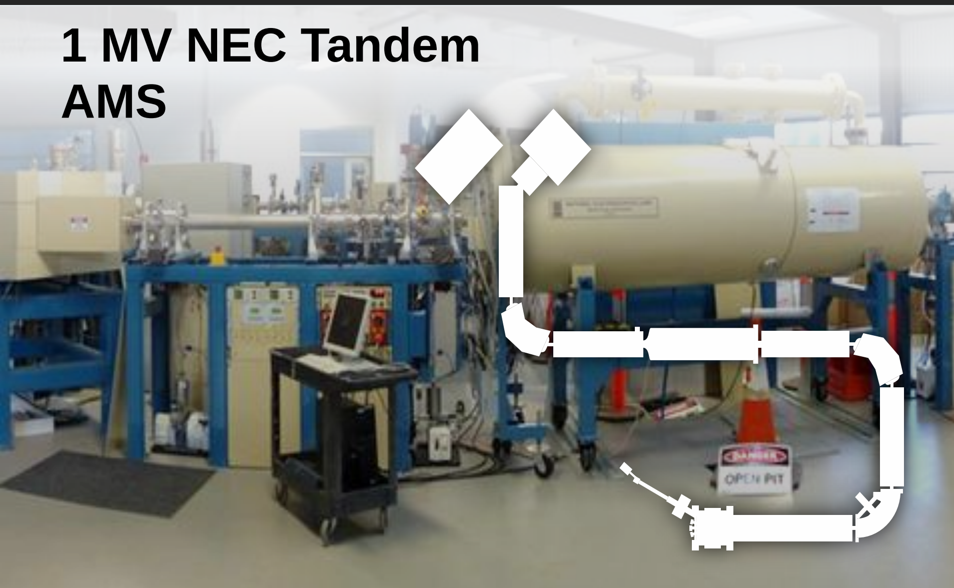
Seen as complementary to reactor based neutrons.

1st Microprobe done on this machine at ANSTO in 1964.

ANSTO was there when accelerator applications 'took off' in 1970's and 1980's.

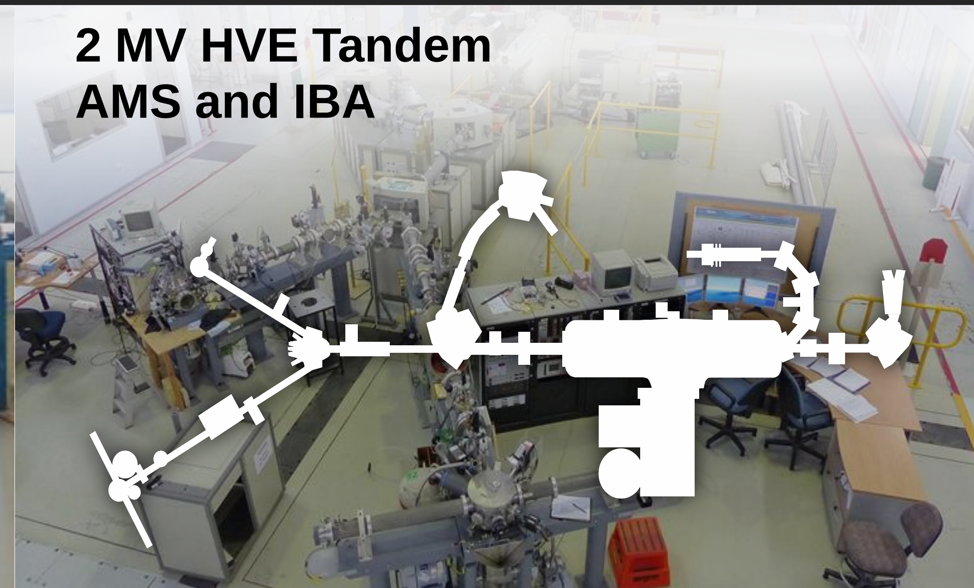
VEGA Accelerator

1 MV NEC Tandem
AMS



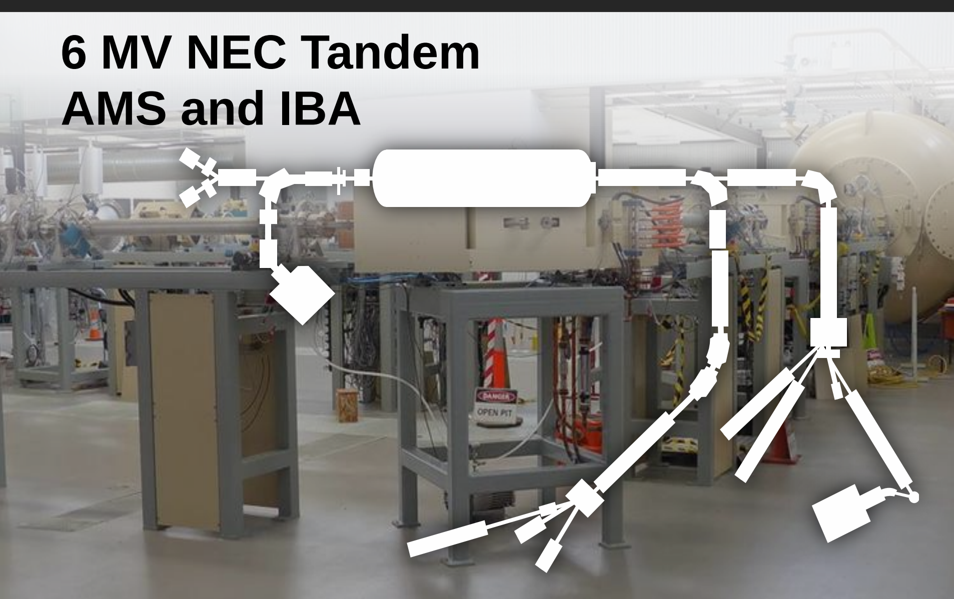
STAR Accelerator

2 MV HVE Tandem
AMS and IBA



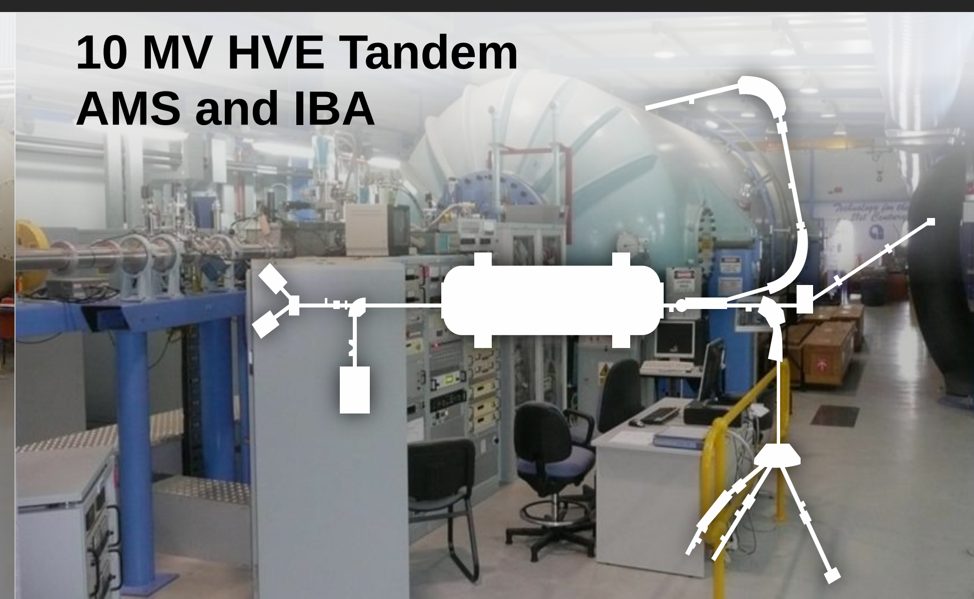
SIRIUS Accelerator

6 MV NEC Tandem
AMS and IBA



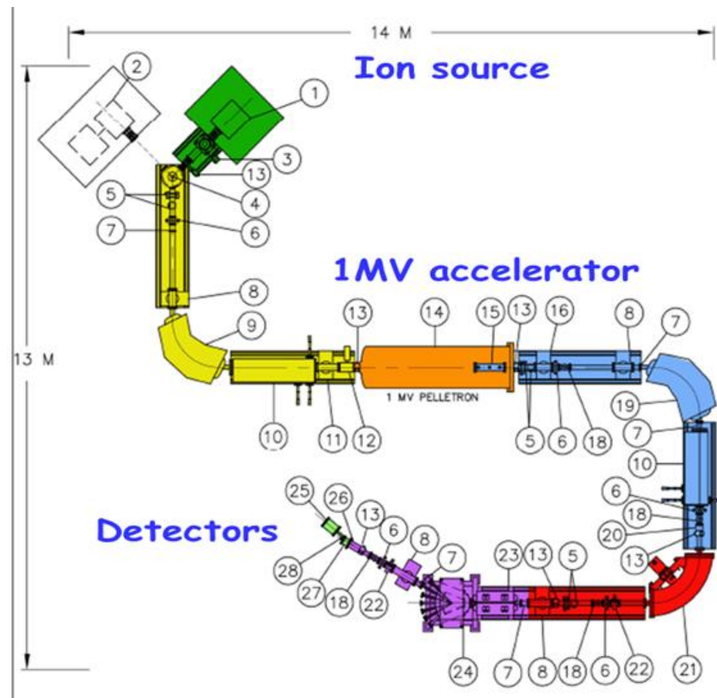
ANTARES Accelerator

10 MV HVE Tandem
AMS and IBA

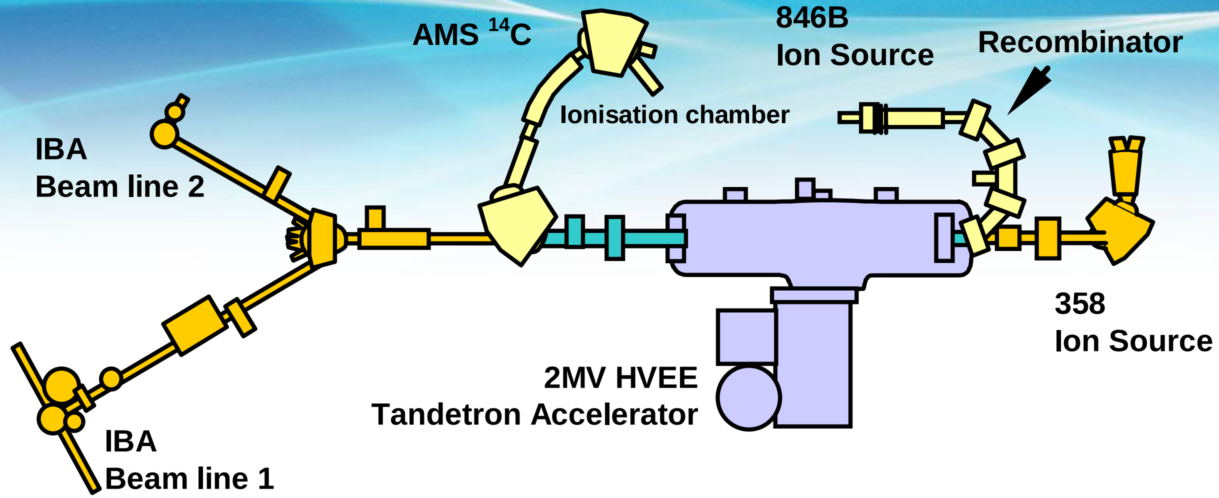


VEGA Accelerator (1MV)

- 1MV NEC Tandem
- 134 sample sputter ion source for heavy ions H to U, actinides.
- Single ‘torturous’ magnetic and electrostatic path for ions.
- Provides high precision isotope selectivity.



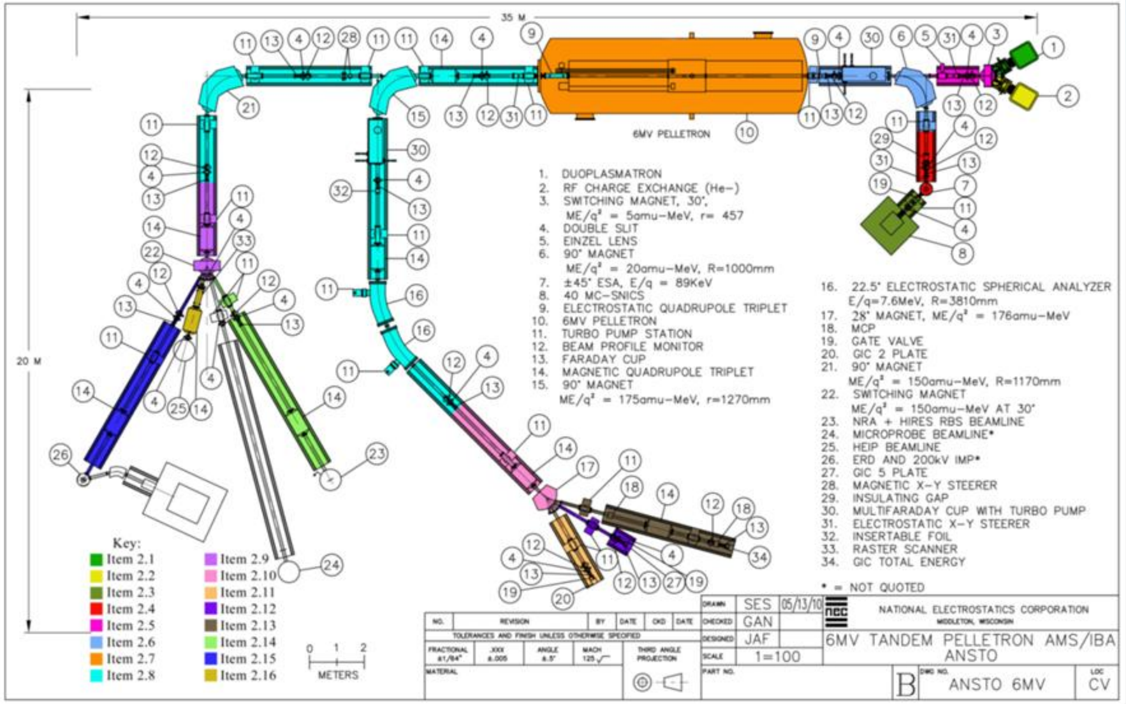
STAR Accelerator (2MV)



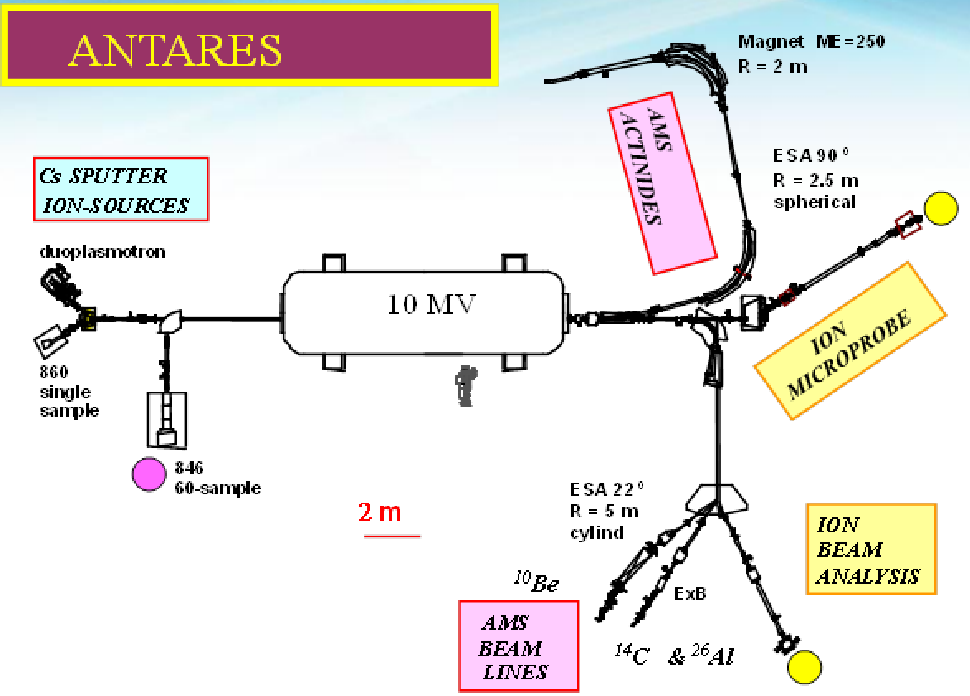
- 2MV HVE Tandem
- 2 Duoplasmatron ion sources for H, He
- 1 Sputter ion source for heavy ions C, ….
- 3 High energy beamlines; radiocarbon, materials characterisation, ion beam techniques.

SIRIUS Accelerator (6MV)

- 6 MV NEC Tandem.
- 3 ion sources for ions H-U.
- 4 IBA beamlines, heavy ion microprobe, heavy ion materials irradiation, surface analysis.
- 3 AMS beamlines, small sample, actinides, ^{10}Be, ^{26}Al, ^{14}C.



ANTARES Accelerator (10MV)



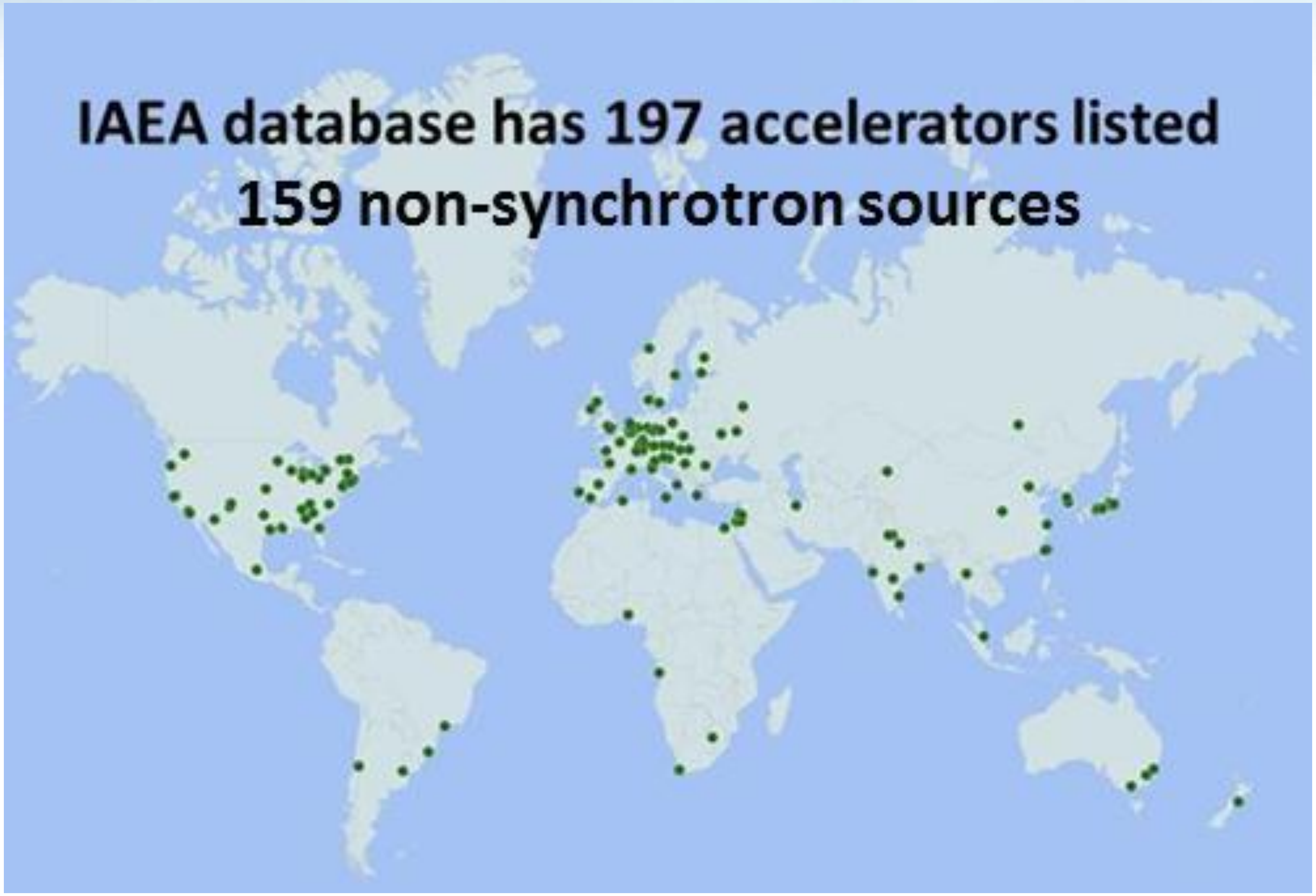
- 10 MV HVE Tandem.
- 3 ion sources for ions H-U.
- 2 IBA beamlines, heavy ion microprobe, heavy ion materials irradiation, surface analysis.
- 3 AMS beamlines, small samples, actinides, ^{10}Be, ^{26}Al, ^{14}C, ^{129}I, ^{36}Cl,..

The New Libby Building – AMS Sample Preparation

The new Libby building contains the following AMS laboratories for preparation of isotopes from ^{7}Be to ^{243}Pu:-

- **Actinides and Iodine lab.**
- **Quarantine and ice lab.**
- **Cosmogenic lab.**
- **Sample etching and cleaning lab.**
- **Sample crushing lab.**
- **Quartz separation lab (atomic absorption and heavy liquid separations).**
- **Cathode loading lab.**
- **Thermal ionisation mass spectrometer (TIMS) lab.**
- **Inductively coupled plasma mass. spect. (ICPMS) – lase ablation lab.**

Accelerators Globally



http://nucleus.iaea.org/sites/accelerators/Pages/default.aspx

The full range of accelerator facilities and capabilities at ANSTO puts us in the top five megavolt ion facilities globally.

What is a positive ion tandem accelerator?

It has three major components

High energy positive ions
100 keV to 120 MeV
p, He, C, …. U, Pu

Accelerator tank, stripper
volts +1MV to +10MV
q=+1 to +12 electrons

Low energy negative ions
volts -10kV to -100kV
q=-1, p, He, C, …. U, Pu

Ions ‘falling’ through megavolt (MV) potentials have mega-electron volt (MeV) energies.

A 1MeV proton travels at 4.6% the speed of light, i.e. 14m in a microsecond (10^{-6}s).

A 120 MeV uranium ion travels at 3.3% the speed of light.

Positive ion currents:

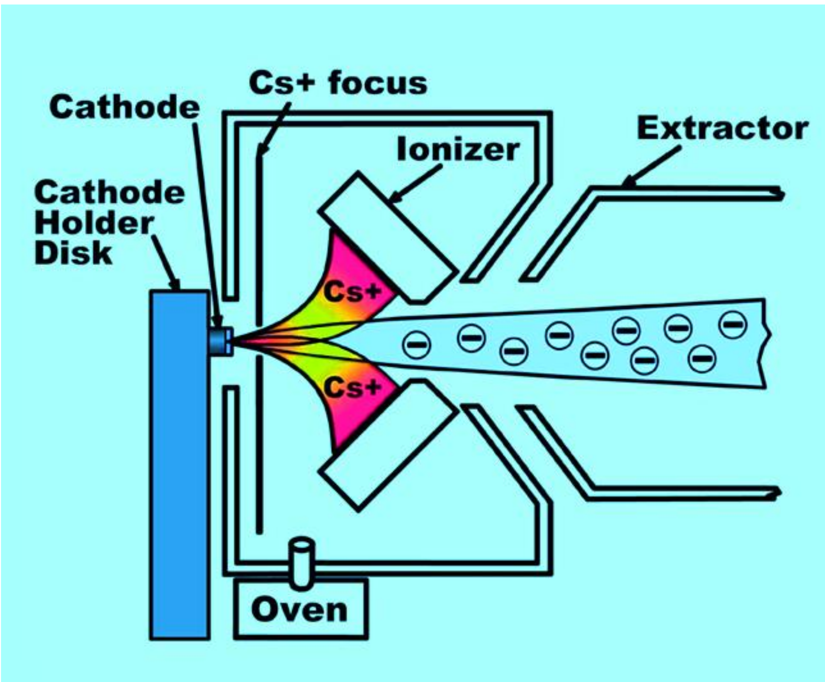
1 pA (10^{-12}A) = 6×10^{6} ions/ sec (q=+1)

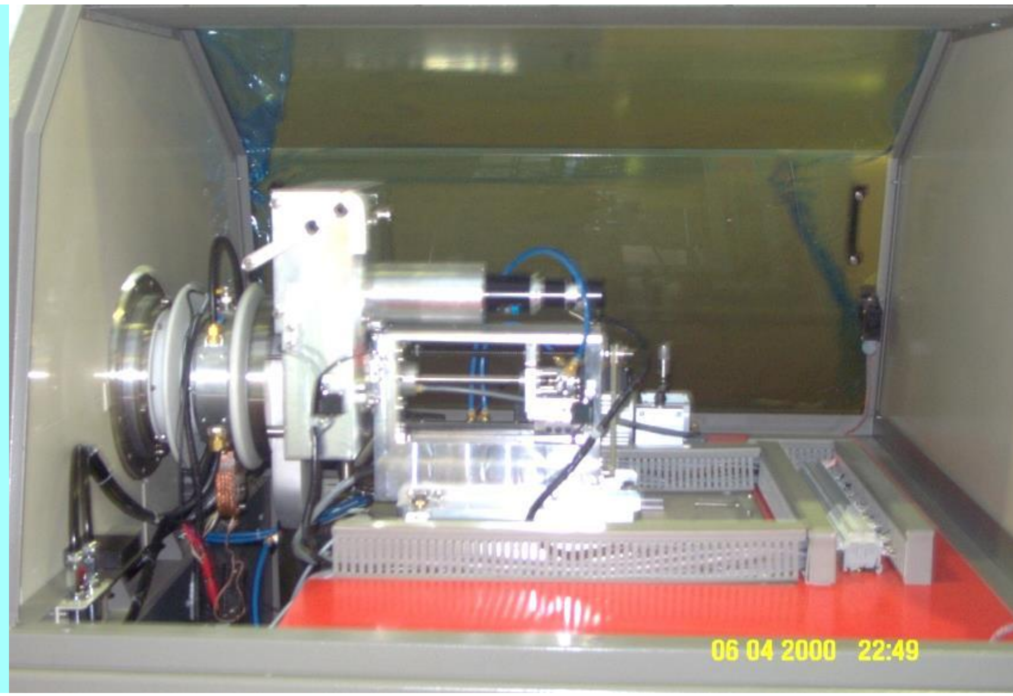
100 µA (10^{-6}A) = 6×10^{14} ions/ sec (q=+1)

Small currents produce many ions/ sec hence ultra-sensitive probes.

Ion Sources

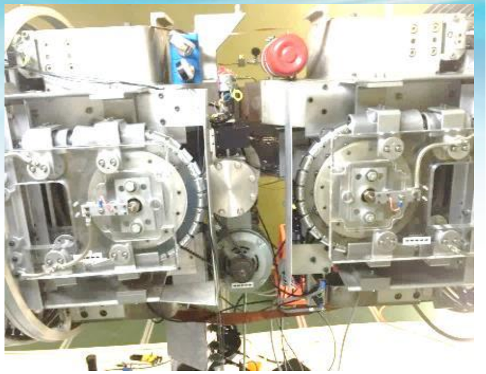
Solid Sample Ion Source: Cs sputter, Penning, ECR



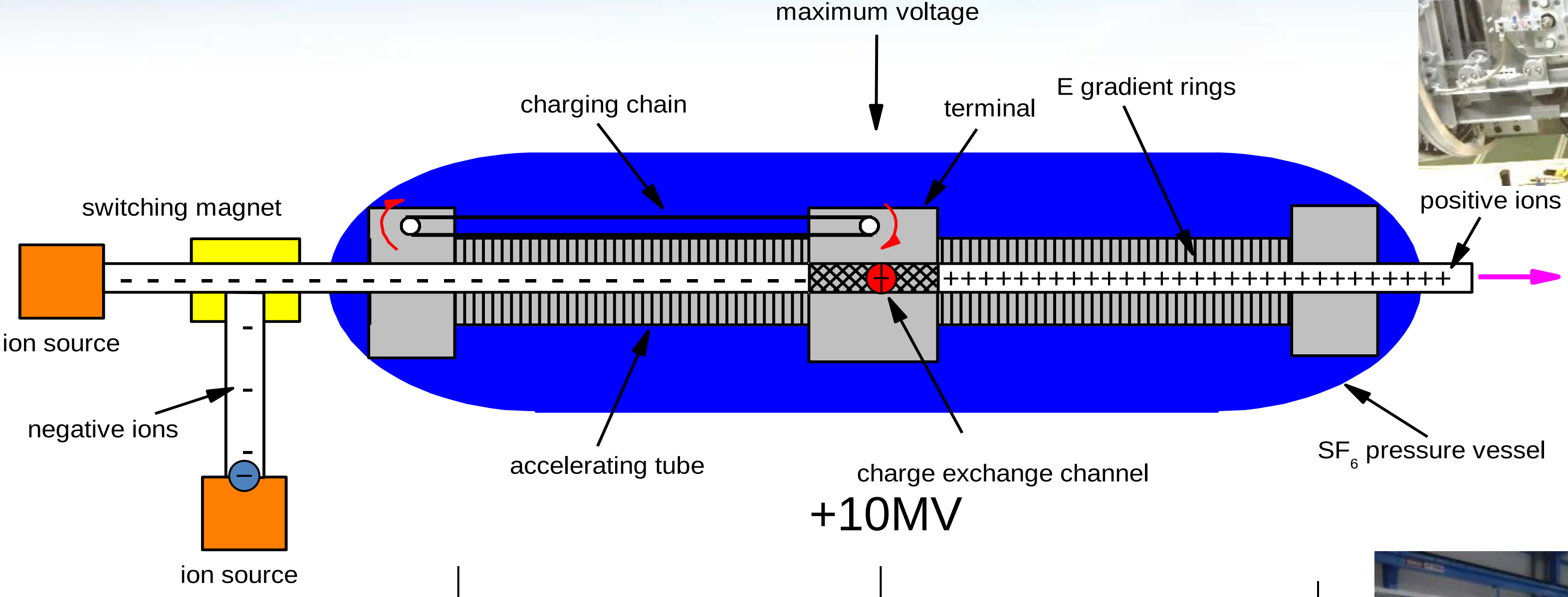


Characteristic Parameters: output current (nA to mA), brilliance, current stability

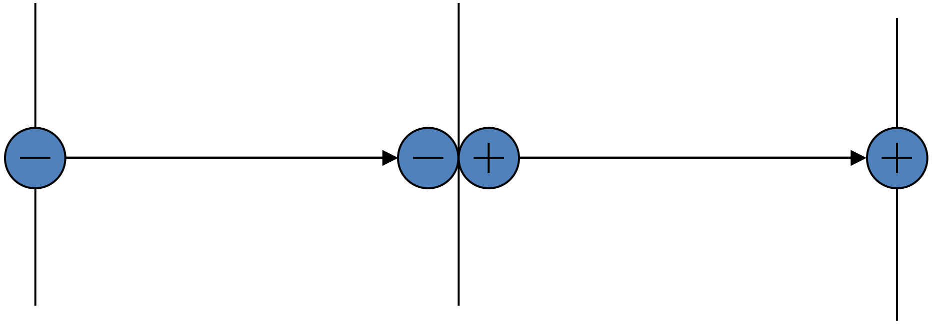
Electrostatic Linear Accelerators



Tandem Accelerators: Two acceleration stages



+10MV



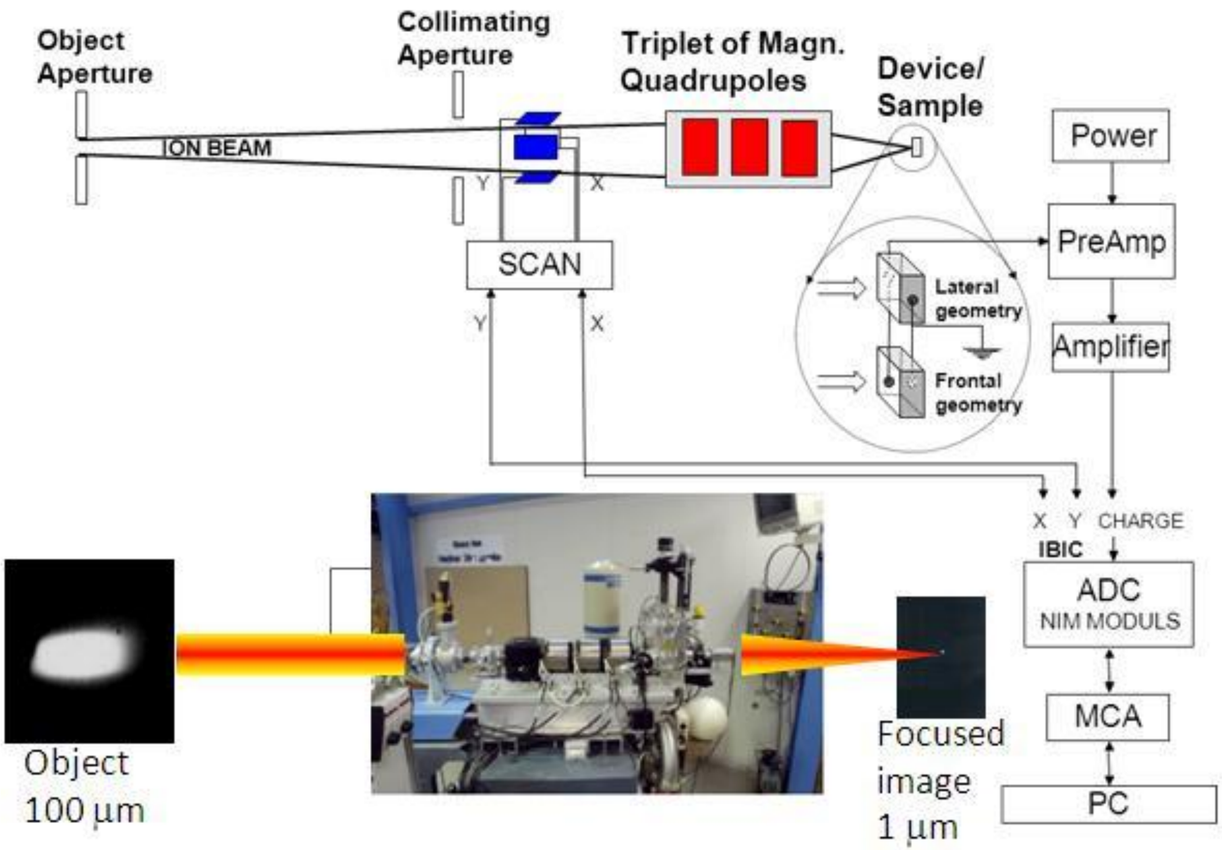
q=-1

E=10MeV
q:-1→ +1
q:-1→ +10

E=20MeV (q = +1)

E=110MeV (q = +10)

High Energy Beamlines
ANTARES Heavy Ion Microprobe



- Magnetic quadrupole triplet focusing system
- High excitation triplet (CDC)
- up to 120 MeV (ME/q^2) magnetic rigidity
- Medium image distance (150 mm)
- Demagnifications of D_x=-90 & D_y=-30

Applications: µPIXE (3 MeV H), HIXE (36 MeV C), RBS (1-3 MeV H, He), STIM (MeV He), IBIC (0.5 – 6 MeV H, He), ERDA (55 MeV I)

ANSTO Centre for Accelerator Science (CAS)

VEGA - the 1MV low energy multi-isotope accelerator

STAR - 2MV Tandetron Accelerator for IBA and ^{14}C AMS

SIRIUS - the 6MV medium energy tandem accelerator for IBA and AMS being tested in

ANTARES – the 10MV Tandem Accelerator

Machines available

1 MV VEGA small Tandem

- ^{14}C & actinide mass spectrometry

2 MV Star Accelerator

- Multi elemental surface analysis beamline
- High resolution depth profiling beamline
- ^{14}C AMS beamline

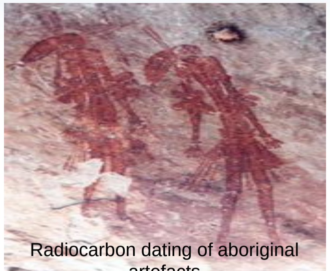
6 MV SIRIUS NEC Tandem

- Confocal heavy ion microprobe beamline
- Surface engineering beamline
- Nuclear reaction analysis beamline
- Heavy ion implantation beamline
- Time of flight AMS beamline
- ^{10}Be AMS beamline
- ^{36} Cl AMS beamline

10 MV ANTARES

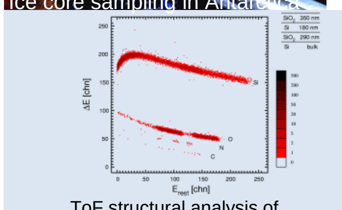
- Heavy ion microprobe beamline
- Elastic recoil detection beamline
- Actinide beamline
- ^{14}C AMS beamline
- ^{10}Be / ^{26}Al / ^{36} Cl AMS beamline
- Heavy ion gas filled magnet beamline

ANSTO Centre for Accelerator Science (CAS

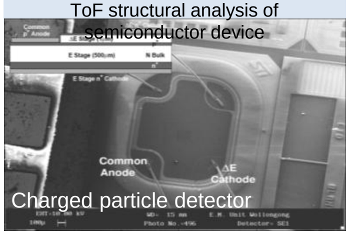


Radiocarbon dating of aboriginal artefacts

Ice core sampling in Antarctica



ToF structural analysis of semiconductor device



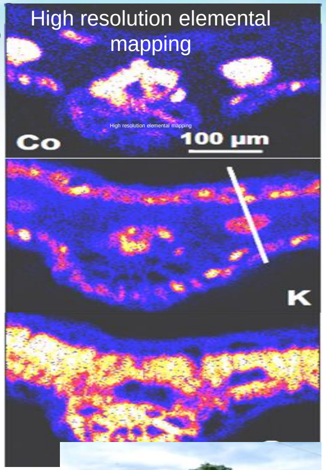
Charged particle detector

Accelerator Capabilities at ANSTO

- High sensitivity trace element analysis
- Trace element profiling & 2D mapping with micron resolution over square millimetre areas
- Ultra high sensitivity isotope counting of ^{14}C, ^{10}Be, ^{26}Al, ^{129}I, actinides (isotopes of U and P)
- Heavy ion irradiations for materials modification
- High energy, heavy ion implantation
- Nuclear reaction analysis
- Surface studies with monolayer resolution

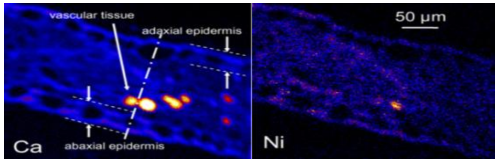
Key Accelerator Research Themes & Applications

- environmental monitoring, air pollution studies
- microspectroscopy, 2D elemental mapping
- microdosimetry, radiation damage studies
- thin films coatings
- ion beam modification of materials
- heavy metals in the environment
- heavy ion, surface, nuclear physics
- global climate change
- glacial geochronology
- geomorphology
- dendrochronology (tree rings)
- archaeology,
- atmospheric and oceanographic isotopic tracing
- nuclear safeguards

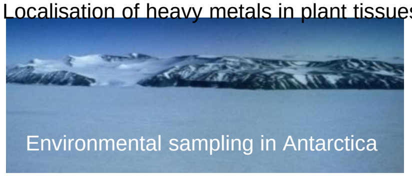


High resolution elemental mapping

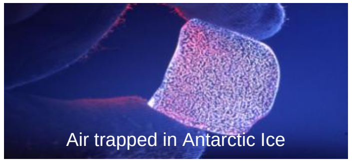
Aerosol Sampling



Localisation of heavy metals in plant tissues



Environmental sampling in Antarctica



Air trapped in Antarctic Ice

Why use accelerators?

Very sensitive

1 in 10^{23} atoms

Very small samples

1ng (10^{-9}g)

Very short processing time

Minutes to hours
not days to weeks

Accelerator Mass Spectrometry (AMS) Isotopic Dating

^{14}C

5,730yrs

100yrs – 60,000yrs

Climate and archaeology

^{36}Cl

301,000yrs

30,000yrs – 3,000,000yrs

Ground water management and geological exploration

^{10}Be

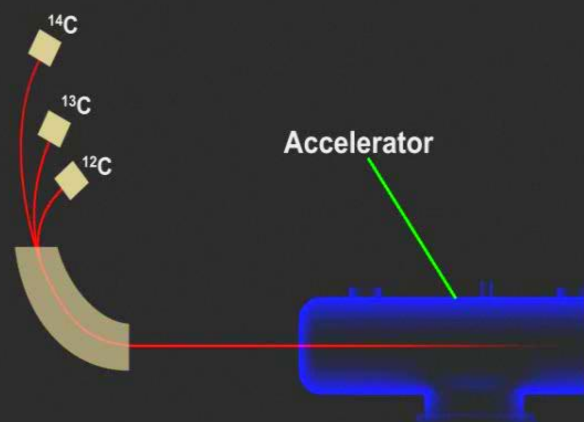
1,510,000yrs

500,000yrs – 15,000,000yrs

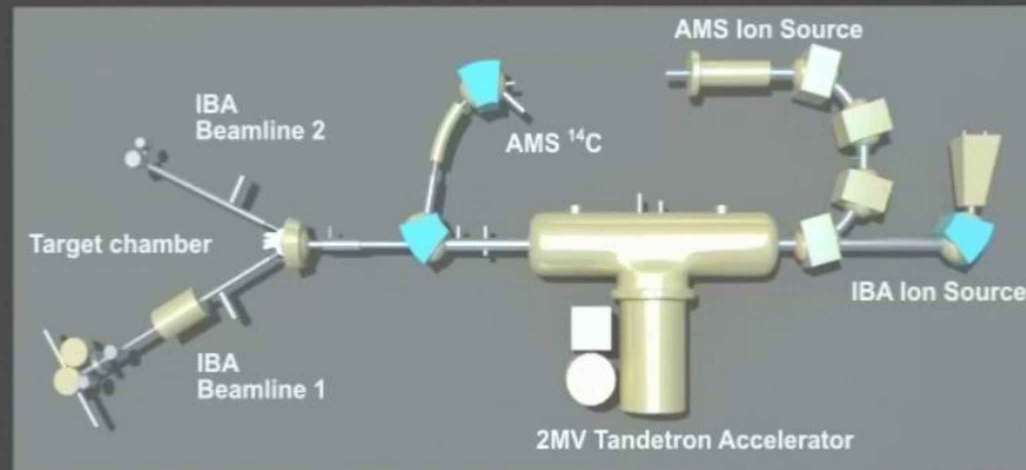
Soil erosion and geomorphology

Isotopic Separation on 2MV STAR

High energy analysis

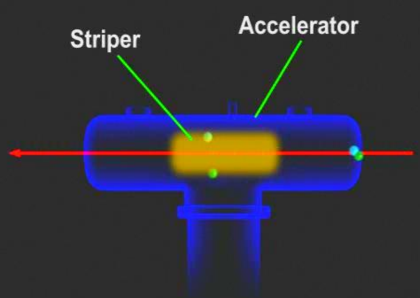


The remaining particles, consisting of carbon isotopes only, pass through an analysing magnet and the quantities of ^{12}C, ^{13}C and ^{14}C are measured.



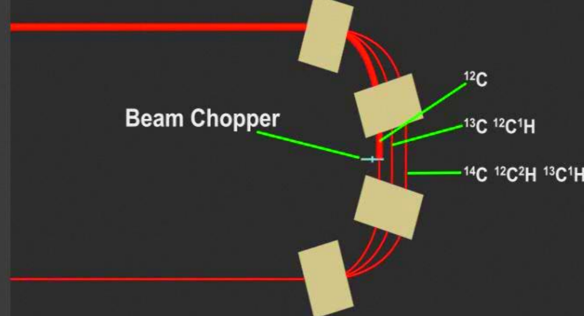
2 MV STAR Accelerator

Tank stripping



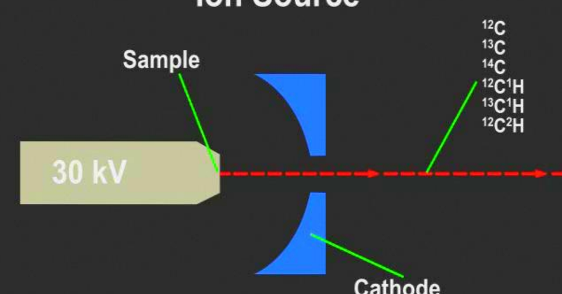
The beam then passes through an argon filled stripper located in the accelerator. This stripper tears away electrons from the particles and disassociates the CH molecules.

Low energy Injection



This ion beam travels through a recombinater where the abundant ^{12}C is reduced to comparable magnitudes to ^{13}C and ^{14}C

Ion Source



A sample of the material is placed in the AMS emittor where it is charged to 30kV, which causes the sample to emit ions including ^{12}C, ^{13}C and ^{14}C and molecules of $^{12}C_1H$, $^{13}C^{1}H$ and $^{12}C^{2}H$

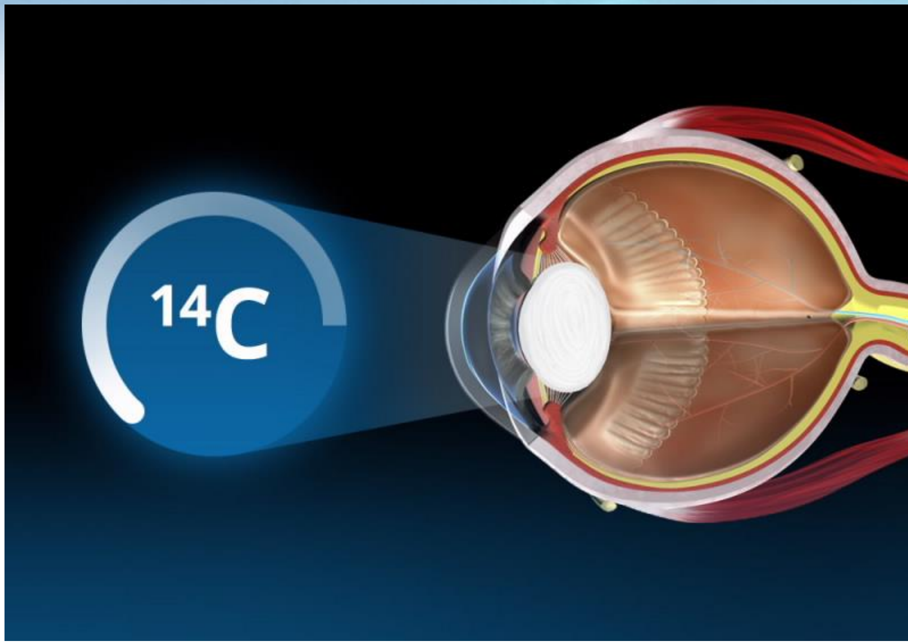
AMS Isotope Measurements

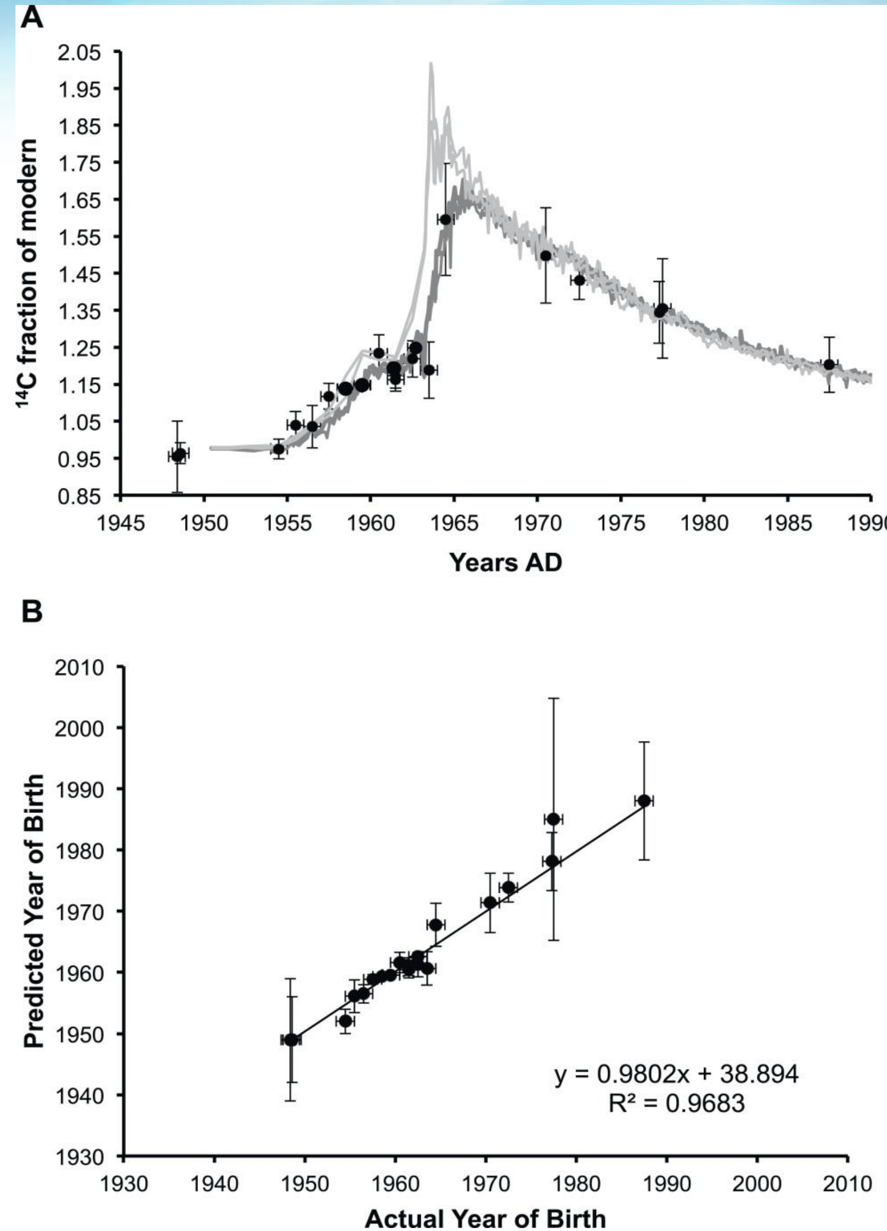
Ultra-high sensitivity required where isotopic ratios are extremely small:

- **eg ^{14}C : ^{12}C for radiocarbon dating**
- **ratios typically in range 10^{-12} to 10^{-15}**

	Halflife	*Isotopic ratio*	*Applications*
^{14}C	5700a	$^{14}C/^{12}C$	dating etc.
^{10}Be	1.51Ma	$^{10}Be/^{9}Be$	exposure age dating, erosion, solar variability, geomorphology
^{26}Al	717ka	$^{26}Al/^{27}Al$	exposure age dating, erosion
^{36}Cl	301ka	$^{36}Cl/Cl$	hydrology
^{129}I	15.7Ma	$^{129}I/^{127}I$	nuclear monitoring
^{236}U	23.4Ma	$^{236}U/^{238}U$	nuclear monitoring, U exploration
$^{239,240}Pu$	24110a, 6561a	^{240}Pu:^{239}Pu / ^{242}Pu	nuclear monitoring, sediment dating

Medical Applications – Radiocarbon





Anthropogenic Radiocarbon

- **Eye lens lipids:** certain lipids do not turn over but remain with you for life
- **ANSTO** in collaboration with University of Wollongong: Hughes et al. eLife 2015;4:e06003.
  DOI: 10.7554/eLife.06003

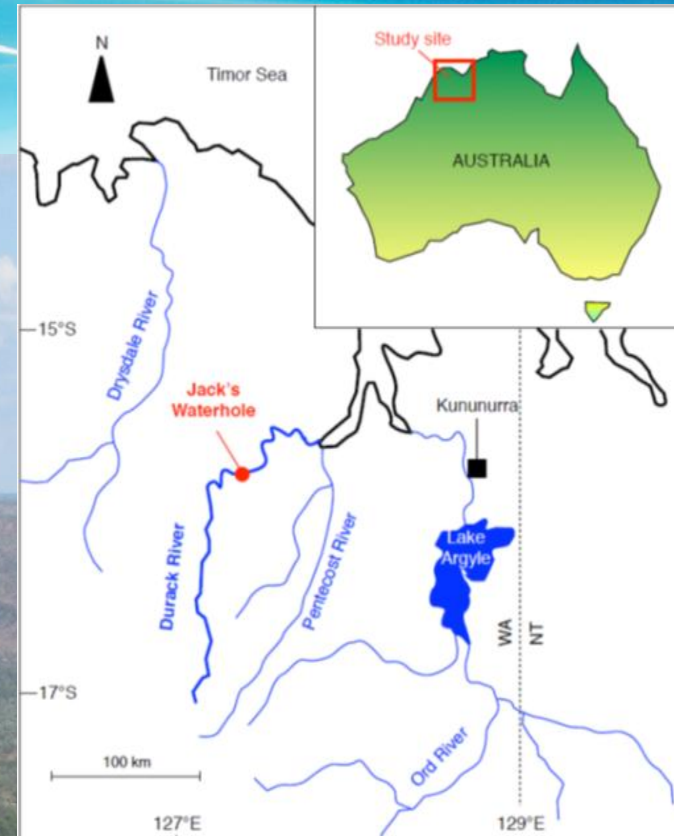
Other applications include kidney stones and human organs and body parts containing carbon.

Exposure age dating

Study site:
Semi-arid, monsoonal with summer tropical storms and cyclones. Sparse vegetation with minor eucalypt cover and grassland.

Cosmic ray interactions (neutrons) on N and O in the atmosphere produces ^{10}Be and ^{26}Al

Durack River Bed



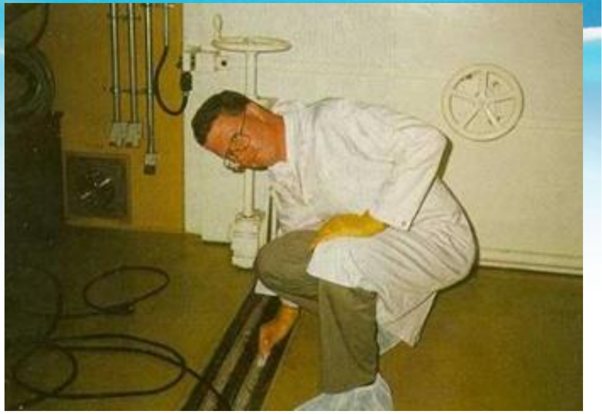
Within paleo-river channel, abundance of disconnected stacks of metre-sized slabs dislodged from adjacent and upstream bedrock sections.
Boulders excavated by hydraulic plucking of well-jointed sandstone bedrock.
Flood flipped boulders: in situ cosmogenic ^{10}Be ($T_{1/2}$ = 1.5Myr) evidence for extreme past flood events.

Actinides U, Pu by AMS

U and Pu isotopics and ^{129}I in variety of sample types

Applications include:

- Nuclear safeguards and nuclear forensics, as required for law enforcement, treaty monitoring and intelligence (for example International Atomic Energy Agency inspections)
- Dating sediments using the Pu 'bomb' pulse
- Environmental studies eg U, Pu migration / uptake at waste repositories and nuclear test sites



Swipe sampling: *D. Donohue,* Journal of Alloys and Compounds 271–273 (1998) 11–18.

By AMS, we can measure:

- ^{233,234,235,236,238}U isotopes down to 1ng total U
- ^{239,240,242}Pu isotopes down to 1fg
- ^{129}I to 1nBq in soils, etc

- weapons grade materials: U enrichment (235/238 ratio >20%) or low $^{240/239}$Pu ratio
- ^{236}U signature of irradiation
- ^{129}I signature of reprocessing

Accelerator Based Ion Beam Analysis

2MV STAR Accelerator

PIXE, PIGE, RBS, ERDA beamline

Beams of high energy ions (p, He, C….I) interact with sample surfaces. Spot sizes 1μm to 10mm.

Interactions with e^- ⇒ X-rays PIXE (Al-U)

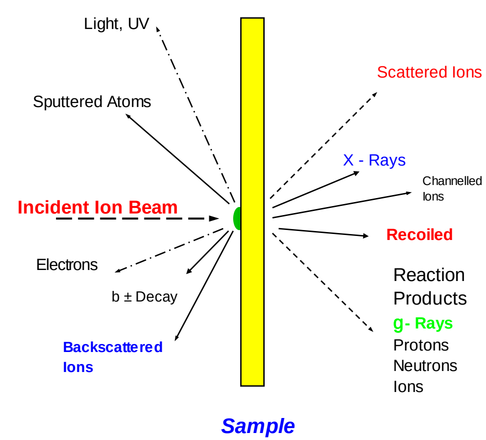
nucleus ⇒ γ-rays PIGE (Li, F, Na..)

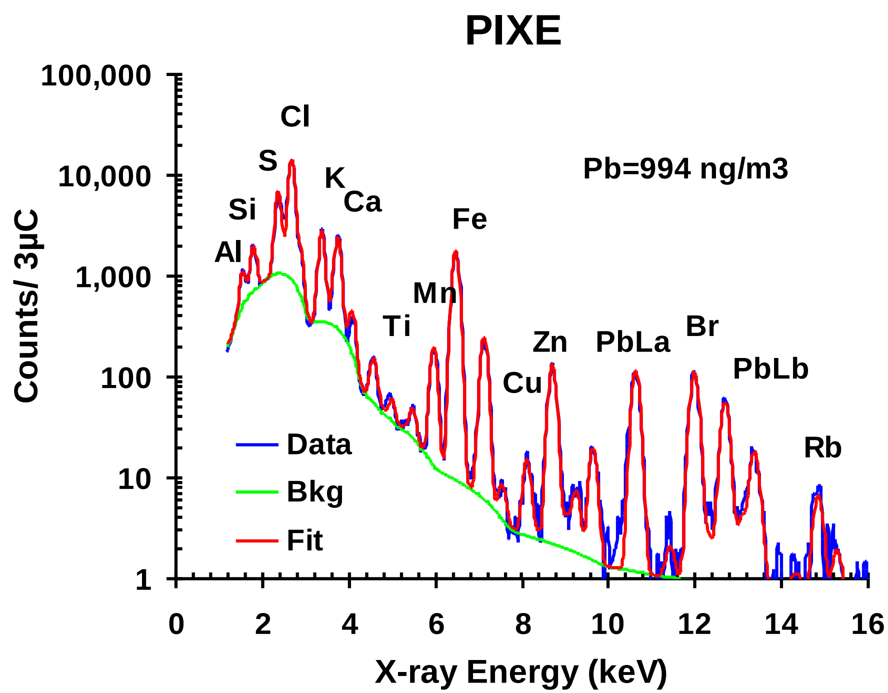
⇒ scattered and recoiled particles RBS, ERDA (H, C, N, O,..)

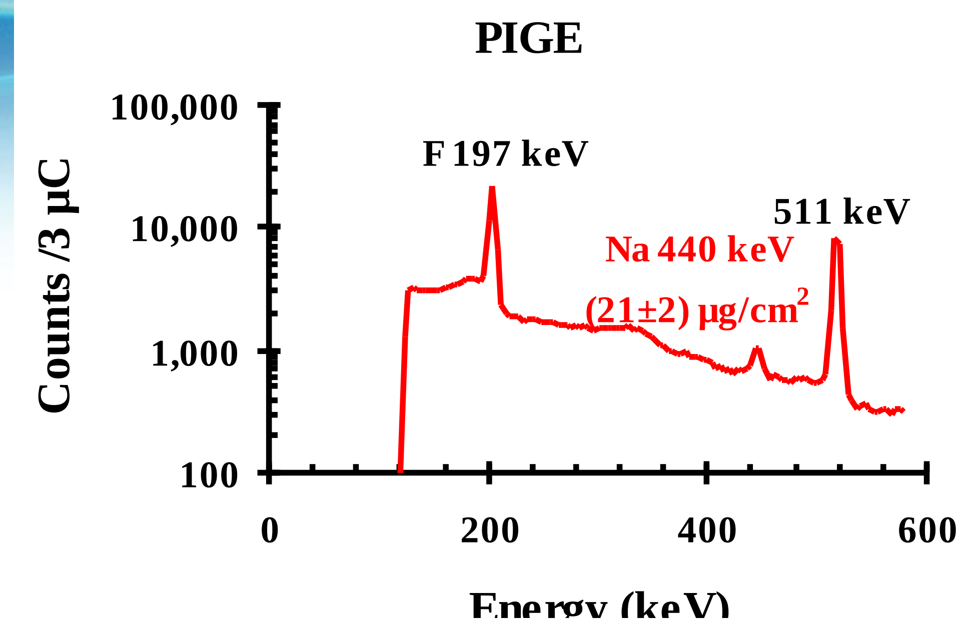
IBA techniques cover Periodic Table (H to U).

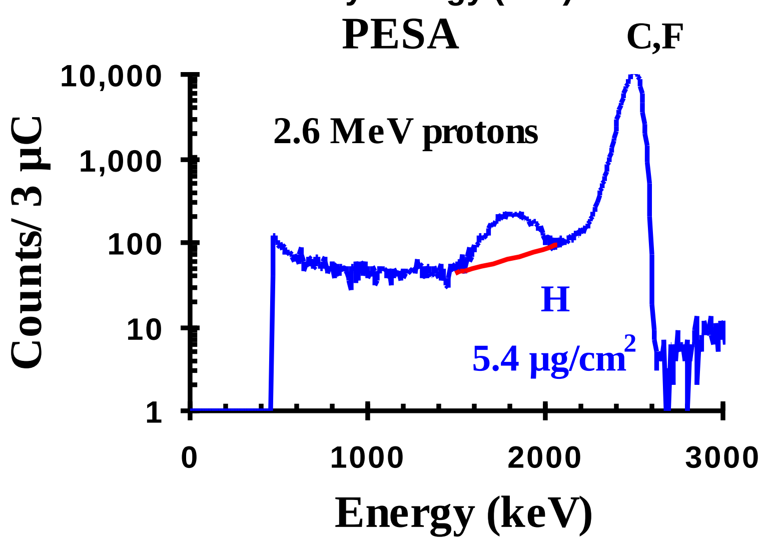
Very sensitive (μg/g) on small samples (pg).

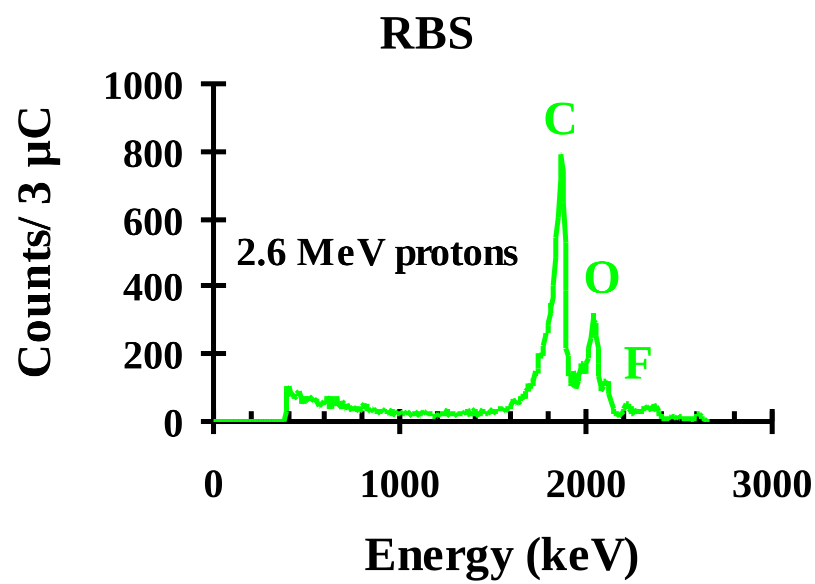
Fast (<5mins), essentially non destructive as counting individual atoms/ photons.



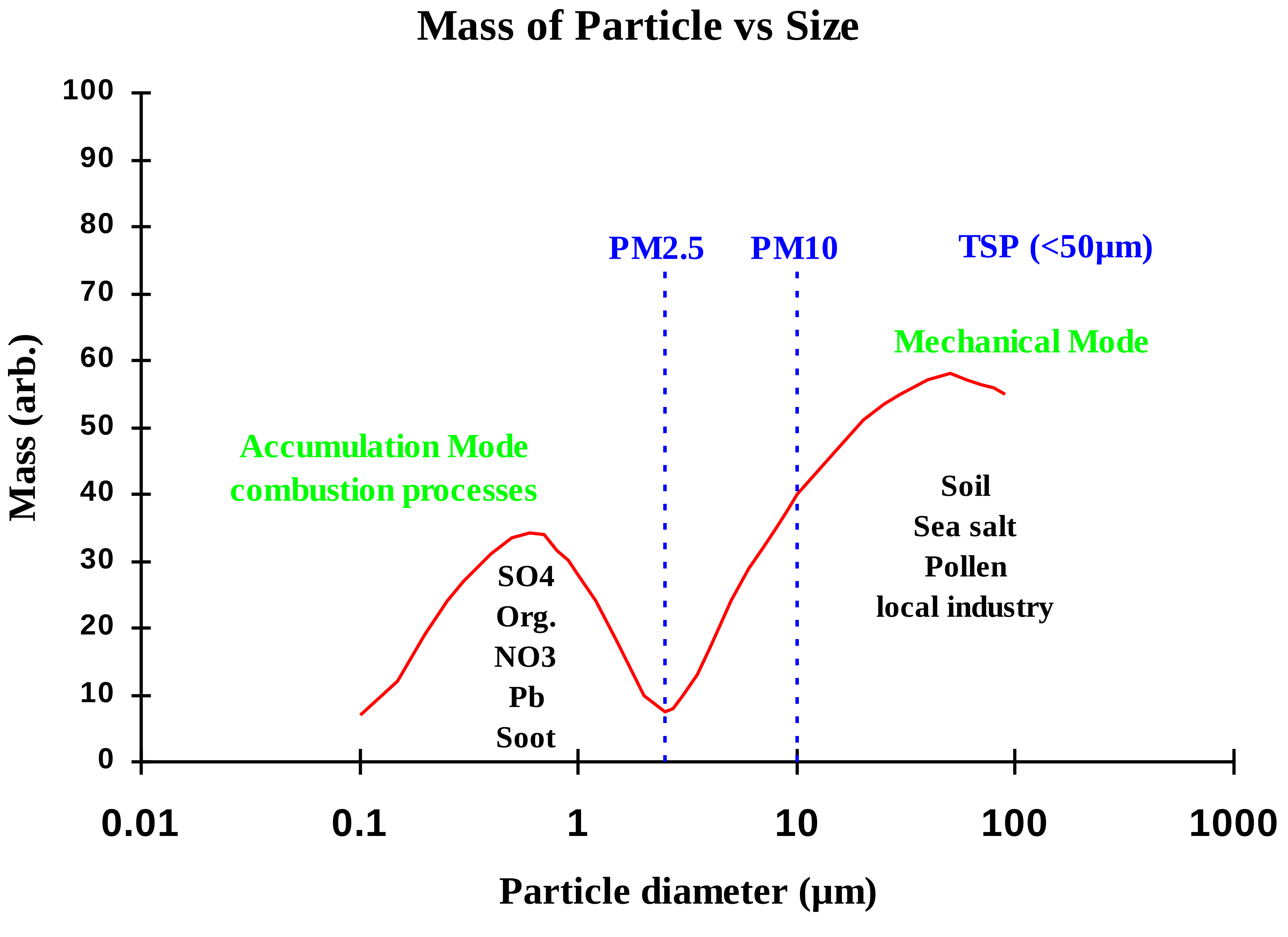








Four techniques cover most of the periodic table from H to U



Mass of Particle vs Size
Mass (arb.)
100
90
80
70
60
50
40
30
20
10
0
PM2.5
PM10
TSP (<50µm)
Mechanical Mode
Accumulation Mode
combustion processes
SO4
Org.
NO3
Pb
Soot
Soil
Sea salt
Pollen
local industry
0.01
0.1
1
10
100
1000
Particle diameter (µm)

Why Study Fine Particles?

Health implications

PM2.5 travel deep into the lungs, have direct access to the blood stream.

Absorb and scatter visible light

Fine particles are many times more efficient at scattering visible light than coarse particles. Public can see pollution!

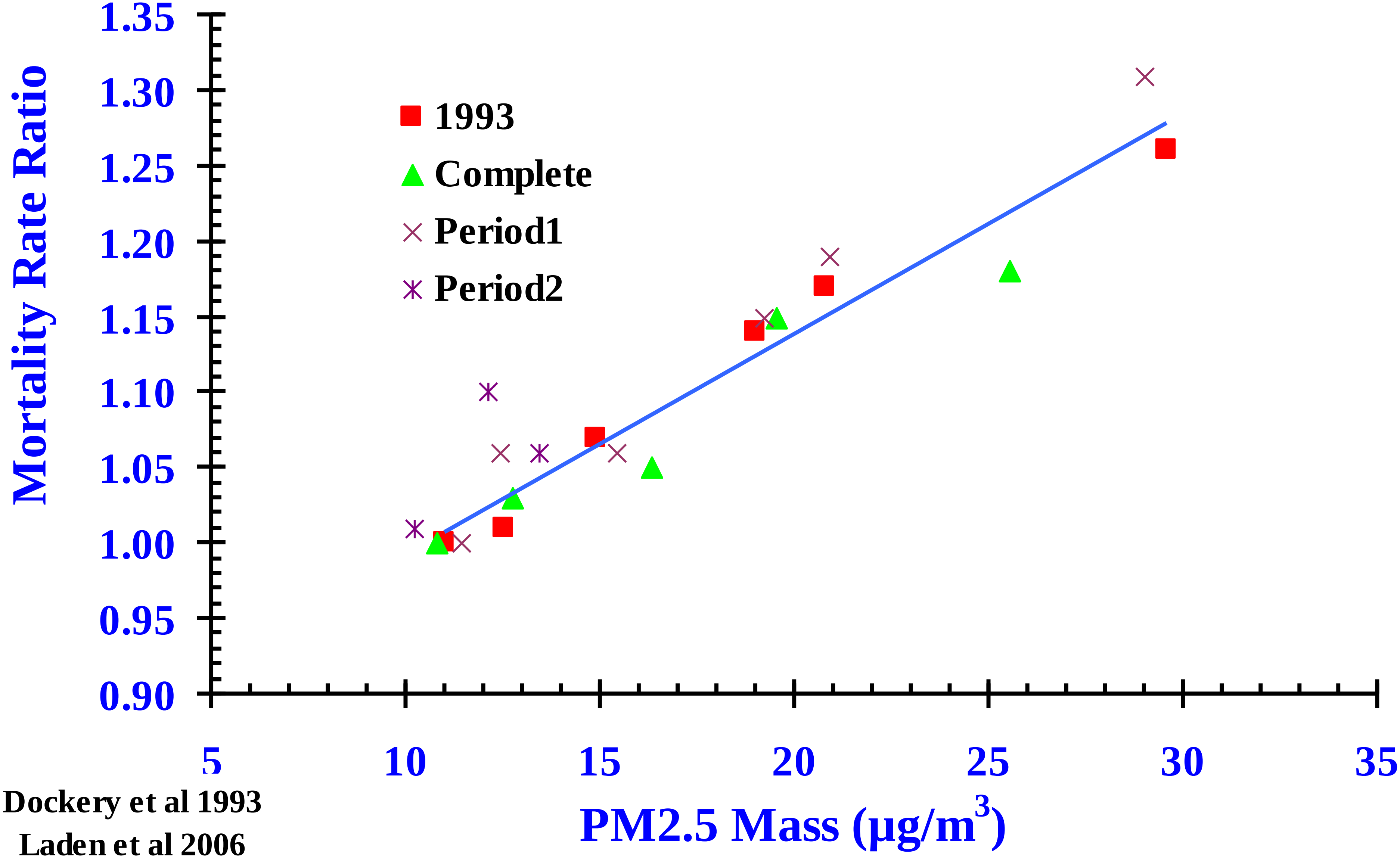
Travel large distances

Fine particles stay in the atmosphere for days and weeks travel around the globe. Transported across countries.

Affect climate

Fine particles may have a negative climate forcing effect comparable to the positive forcing of greenhouse gases. Better understanding needed for climate modelling.

Relative Mortality Rate Ratios
6 US Cities

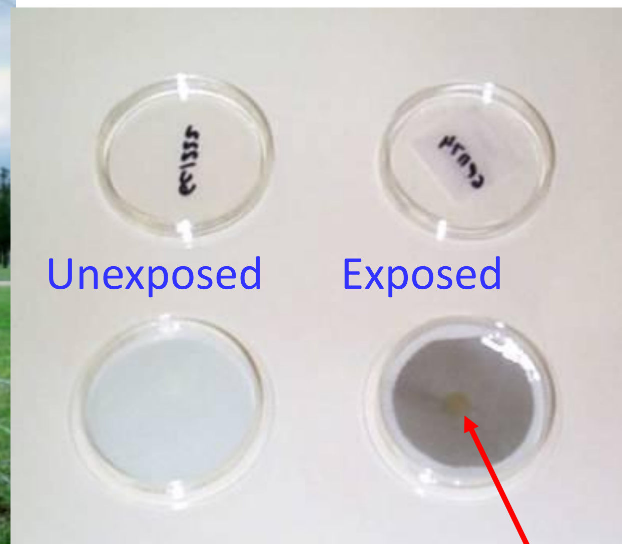


Dockery et al 1993
Laden et al 2006

Sydney, Australia on clear and polluted days

Aerosol Sampling Project (ASP) at ANSTO

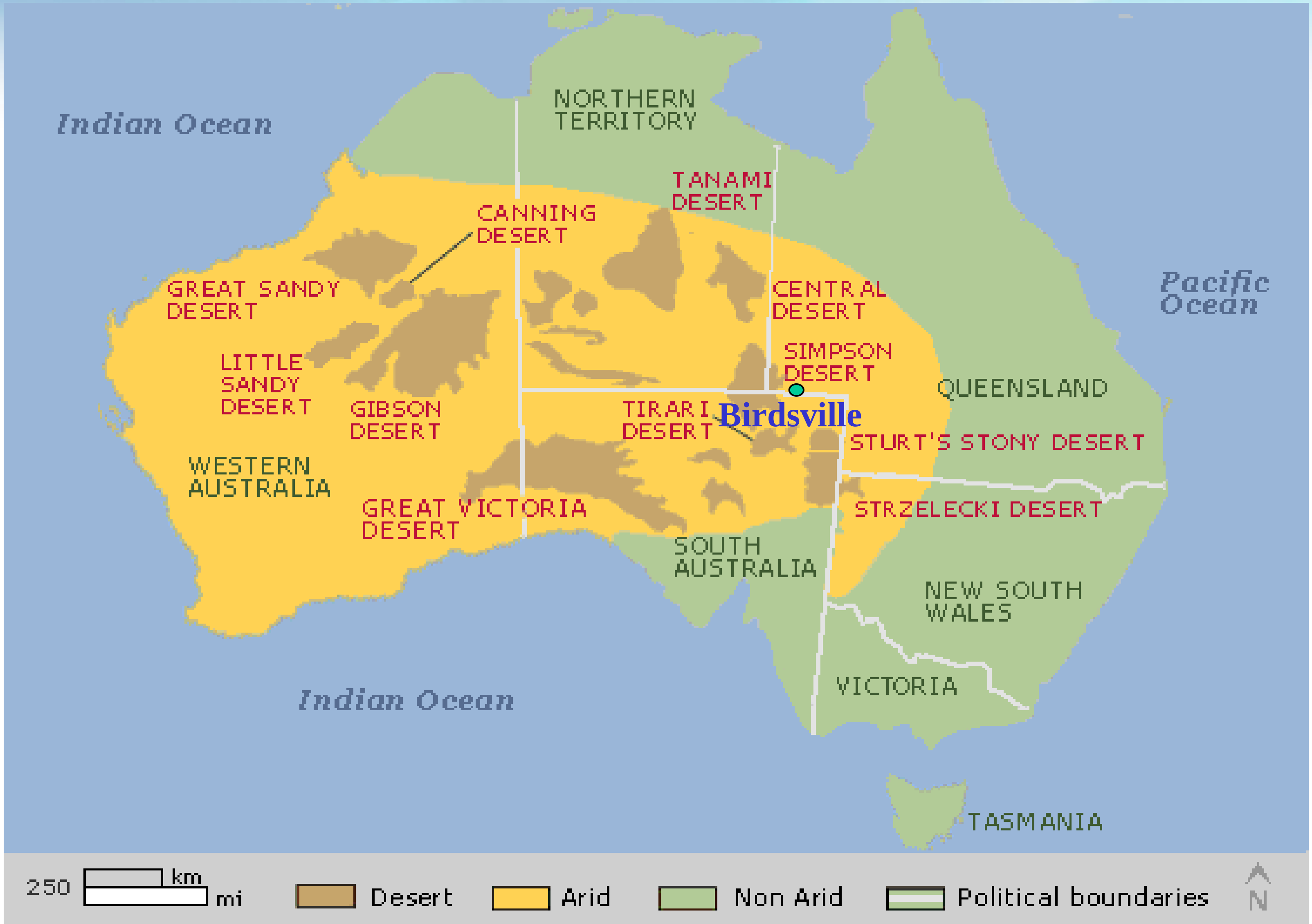
PM2.5 & PM10 samples



Typically use 10 nA beams of 2.6 MeV protons for IBA

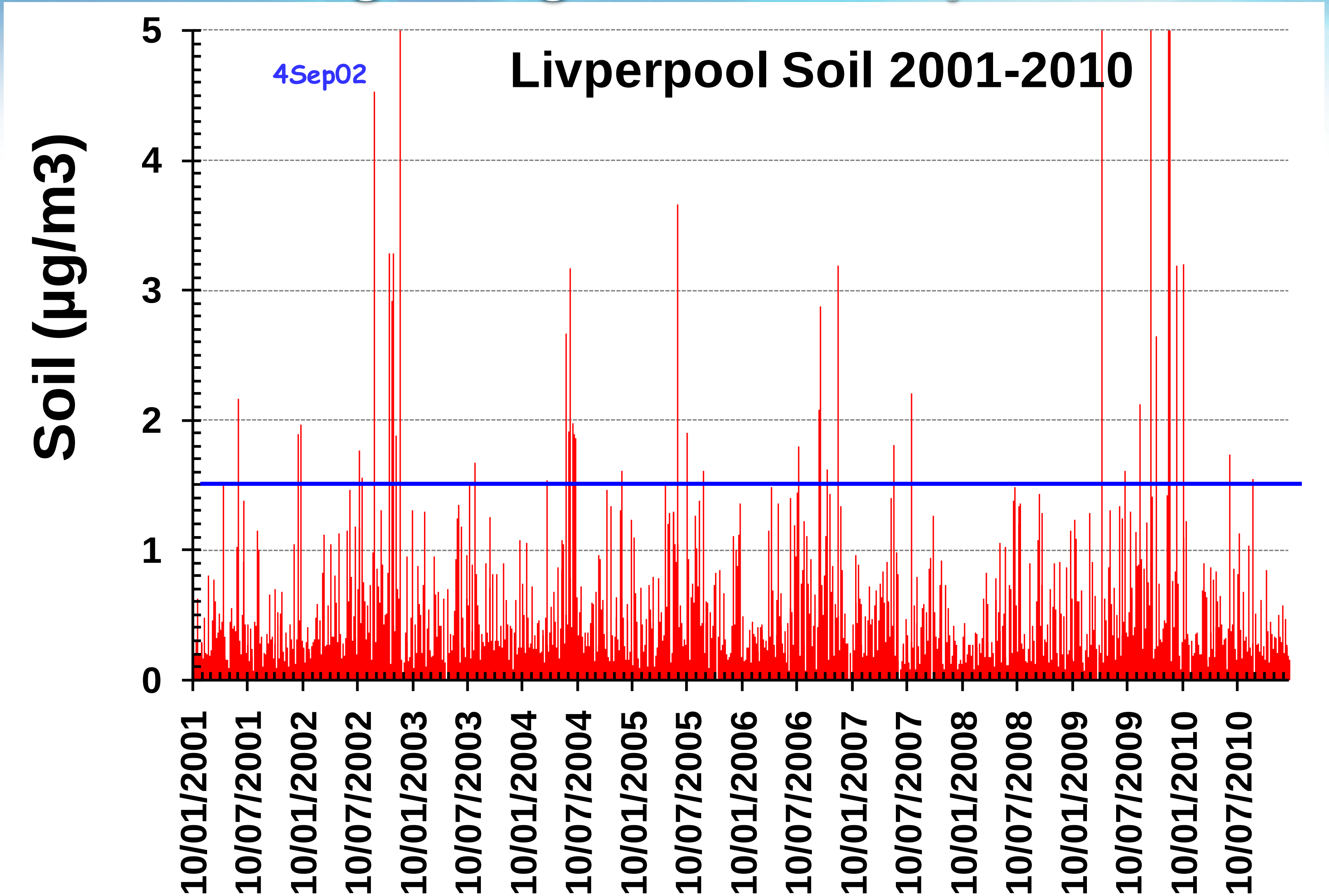
Collected over 55,000 filters in 25 years

Australian Deserts



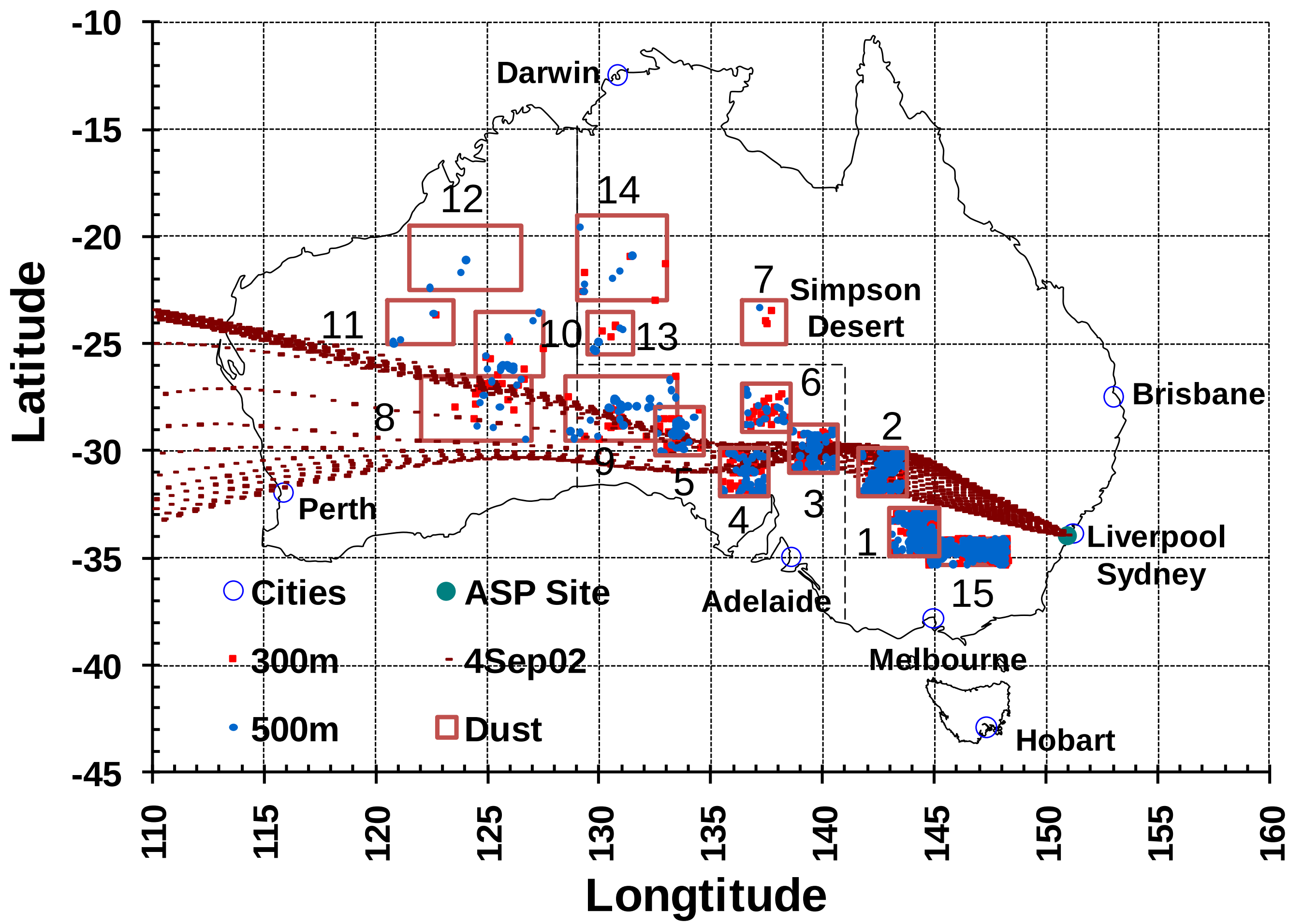
Deserts cover 17% of the land mass

Long Range Soil Transport



Look at extreme daily events with Soil>1.5 $\mu g/m^3$ between 2001-10

Transport of Desert Soil into Sydney Basin



Plot of 7 day back trajectories every hour with intersections for each desert region plotted for 300m and 500m starting heights for the Liverpool site.

The Riverina area (15) produced 33%-35% of extreme events!

This is a significant agricultural region – not a desert!!

Dust Storms in Australia 10 Mar 09

Hay, NSW

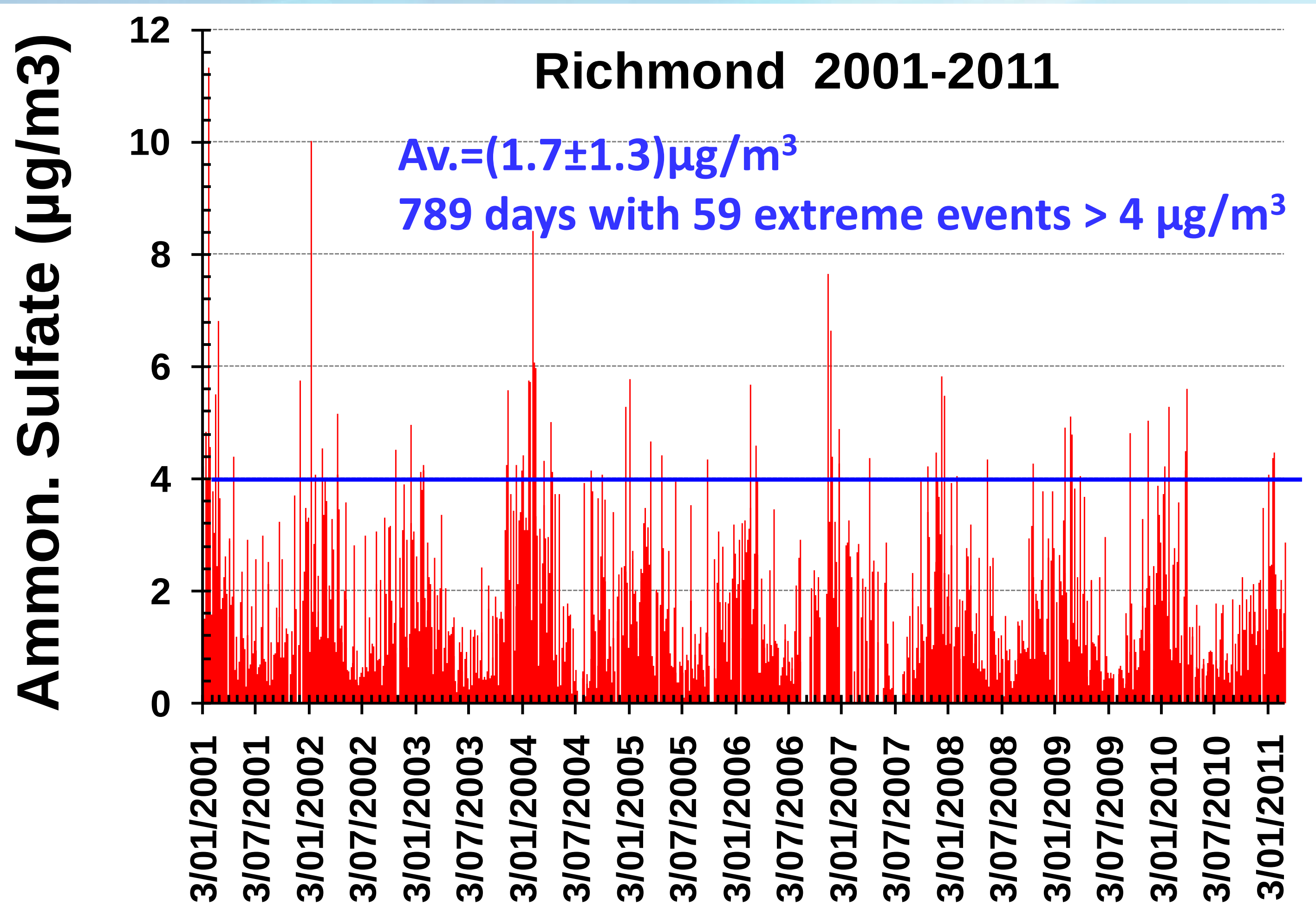
Deniliquin, NSW

Sources of Fine Secondary Sulfate

Typical secondary sulfate sources include:-

- Motor vehicles, diesels
- Sea spray [S/Na ratios ~8%]
- Industry, metals manufacturing
- Coal fired power stations,
  - 25MT/yr of coal (>0.5%S) in NSW
  - 250kT/yr of SO_2 in NSW → 500kT/yr of 2ndryS
  - 80MT/yr of CO_2 in NSW → ??

Ammonium Sulfate in Sydney Basin 2001-11



Use sulfate as an indicator of coal burning and industrial activities.

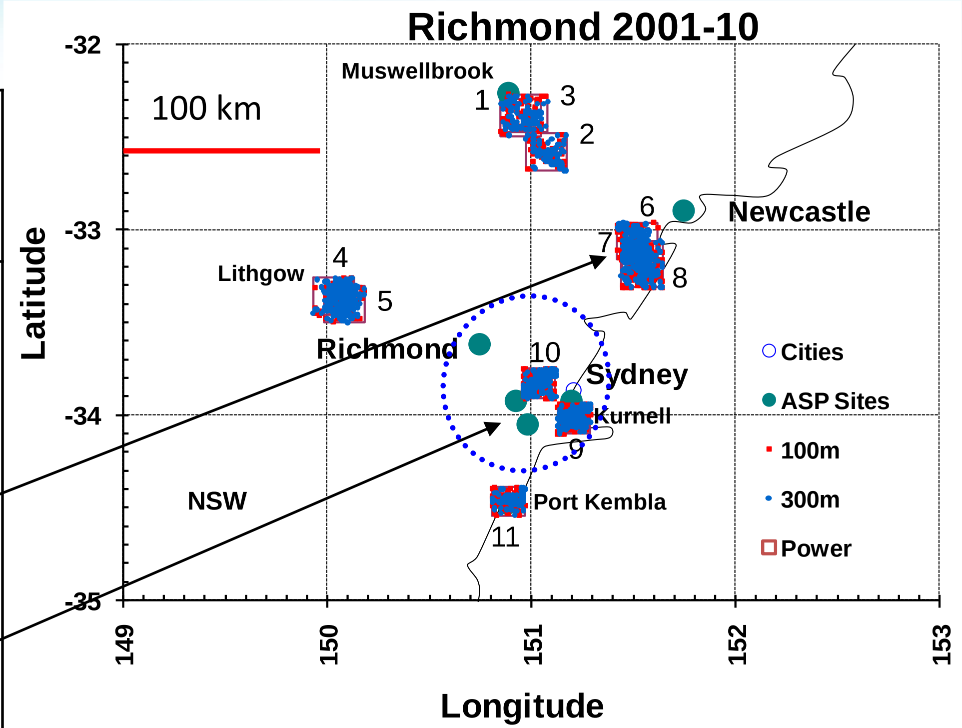
Look at all extreme daily events with SO_4>4µg/m³

Do Coal Fired Power Stations Impact the Sydney Basin?

Sampling site at Richmond

2001-11, 789 days, 59 extreme

Starting hts Source	100m SO_4	$\%SO_4$ Inter	300m SO_4	$\%SO_4$ Inter
1Bayswater Power	56	3.9	51	3.6
2Redbank Power	45	3.1	77	5.5
3Liddell Power	57	3.9	54	3.9
4MountPiper Power	63	4.4	131	9.4
5Wallerawang Power	61	4.2	142	10.1
6Eraring Power	186	12.9	147	10.5
7ValesPointB Power	177	12.2	154	11.0
8Munmorah Power	187	12.9	148	10.6
9Kurnell Refinery	213	14.7	170	12.1
10Rose Hill Refinery	260	18.0	238	17.0
11Port Kembla Steel	141	9.8	88	6.3
Total with SO_4>4 $\mu g/m^3$	1,446		1,400	
% of all intersections	9.9%		10.1%	



52% of extreme sulfate days at Richmond have back trajectories through either Lithgow or the mid-coast coal fired power stations!

Study of Sensitive Volume in μ-Dosimeters

- Study charge collection variations with
  - ➢ Location of ion strike on the device
  - ➢ Stopping power of the ion
  - ➢ Bias applied to micro-dosimeter
- IBIC using 3 MeV H^{+}, 9 MeV He^{2+}, 25 MeV C^{4+}

⇨ Improved dosimetry

⇨ Improved cancer treatment

Applications

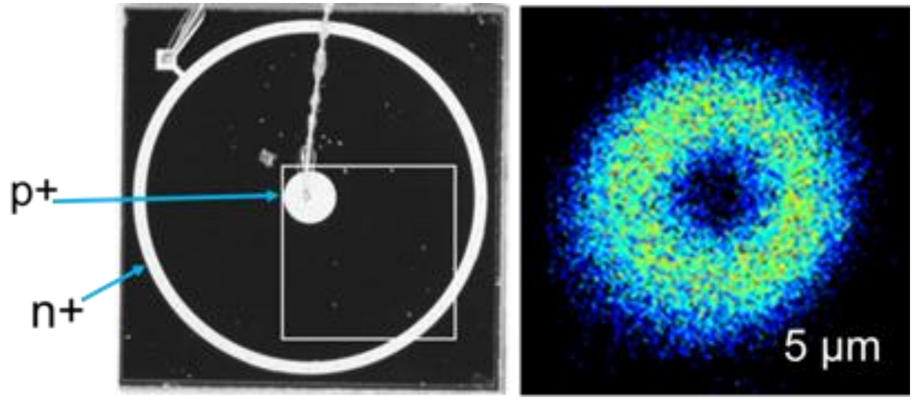
- Cancer treatment modalities which utilise high energy loss ions for radiation therapies (proton & heavy ions)

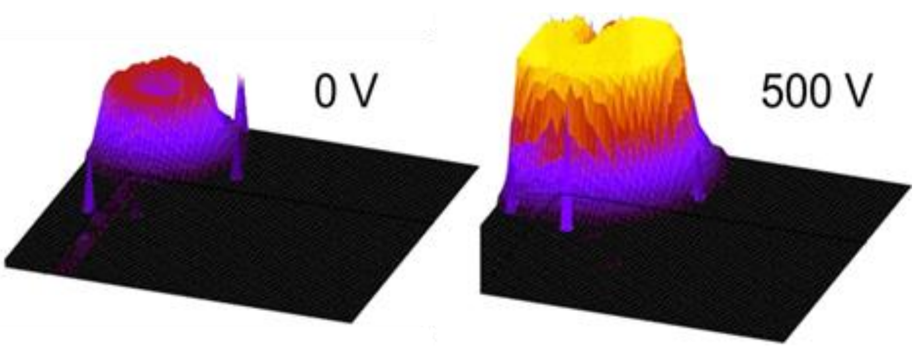
Accelerators calibrate novel micro-dosimeters for radiation studies

- A key requirement of radiation therapy is to limit the damage to healthy cells This requires new micro-devices to plan and monitor the therapy and the radiation fields on a micron scale.

- New silicon based micro-dosimeters need to be calibrated and functionality assessed.

- This is done using ion beam induced charge (IBIC) from accelerator based ion microprobes.





IBT Accelerator Science Technology Platform

Environmental tracing,
Hyper-accumulating plants
systems, salinity, erosion
environmental sensors

Isotopic ultra-tracing,
nuclear forensics,
bomb pulse, actinides,
bio uptake, diet, toxicology

Ion source
enhancement,
ECR ion source
development

Earth sciences,
Geomorphology,
landscape change,
Climate change

Microspectroscopy 2D, 3D
mapping, characterisation,
Bio-imaging

Materials modification,
Interface engineering,
Thin films coatings,
Multi-layers
Fission-fusion surfaces

Fine particle
air pollution

Platform

Facilities – 1-10 MeV accelerators
- Ion sources, 20-100keV implanters,
- Most ions in the periodic table.

Capabilities - Ion Beam Analysis (IBA)
- Accelerator Mass Spectrometry (AMS)
- Photon, particle, radiation detection
- Ion-atom interactions with matter
- High voltage, vacuum, electronic..

Archaeology
Archaeometry

Geology
Exploration Fluid
inclusions in
minerals

Fundamental physics,
K,L,M, X-ray cross sections,
Coster Kronig transitions,
Subshell fluorescence yields,
Heavy ion stopping
Nuclear reactions

Radiation dosimetry
Radiation damage
micro-dosimetry
micro-detectors
IBIC mechanisms

Nuclear security and
defence, safeguards

Hardware & software control,
High speed data acquisition,
High voltage systems,
Vacuum systems.

Users, universities, IAEA,
collaborators, commercial, training

External revenue, grants, contracts

Thank you

Questions?