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John Thomason

A journey through ISIS



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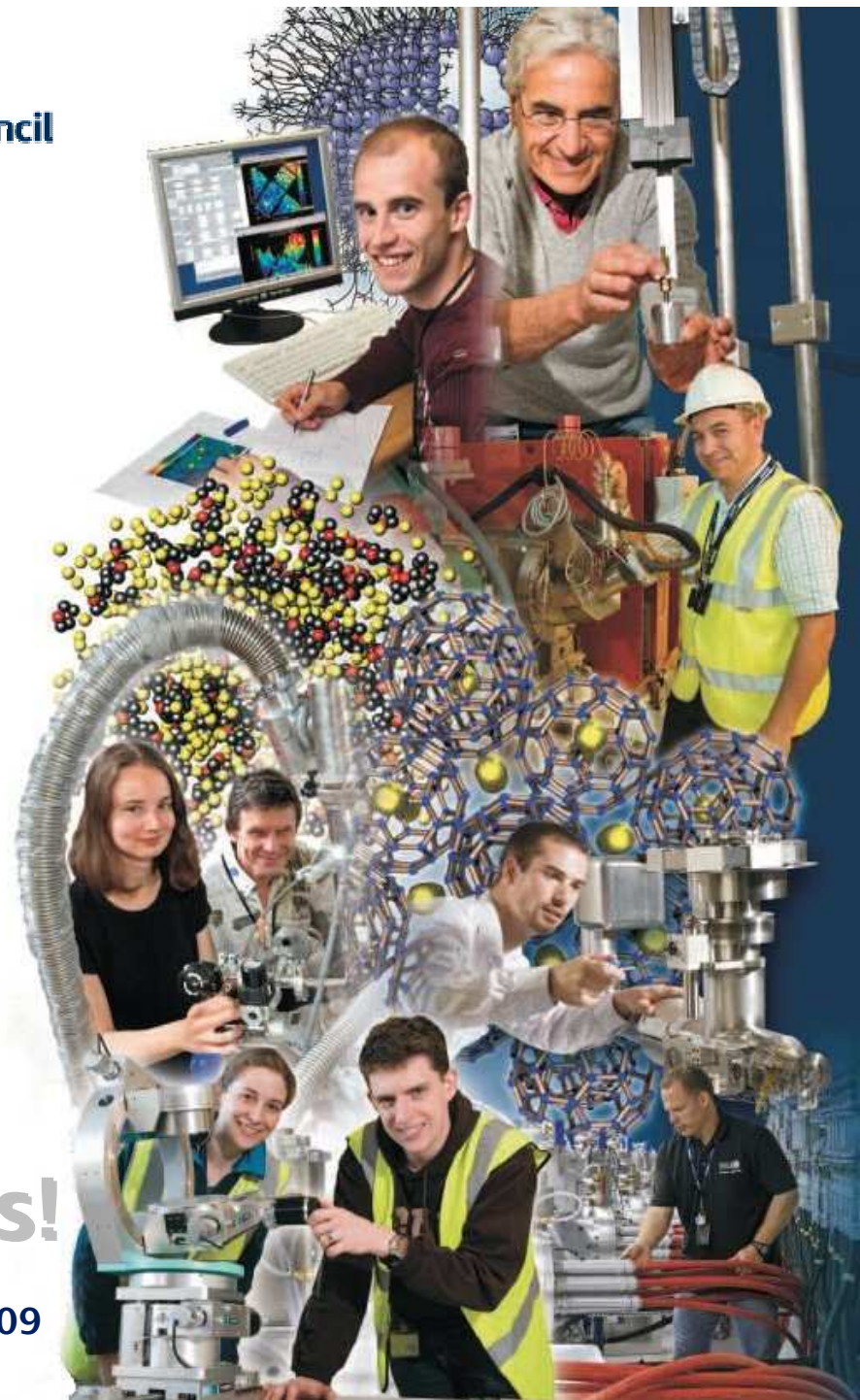
# ISIS

is the  
world's  
leading  
pulsed  
neutron  
and muon  
research  
centre



## 25 years!

16 December 2009





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## Facility Impact

**Source**

**X**

**Instrumentation**

**X**

**Innovation**

**X**

**Scientific Leadership**

**X**

**SE Facilities**

**X**

**Quality of Support**

**X**

**Investment**

**X**

**Cost Effectiveness**

**X**

**User Community**





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# No One Experiment




# Why Neutrons?

# The Nobel Prize in Physics 1994




Clifford G. Shull, MIT, Cambridge, Massachusetts, USA, winner on half of the 1994 Nobel Prize in Physics for development of the neutron diffraction techniques.



**S**hull made use of atoms scattering  $\lambda$  of neutrons which change direction without losing energy when they collide with atoms.

Because of the tiny masses of neutrons, a diffraction pattern can be recorded which indicates where in the sample the atoms are situated. Even the placing of light elements such as hydrogen in molecule, in solids, in liquids, in organic substances can be determined. The pattern also shows how atoms are displaced in magnetic materials, superconductors are affected by magnetic fields. Shull also made use of this phenomenon in his neutron diffraction technique.



Research reactor

Neutrons show where atoms are

Neutrons bounce against atomic nuclei. They also react to the magnetism of the atoms.

Neutrons show what atoms do

Static measurements with neutron crystals and magnetic materials

Atoms in a crystal lattice

Dynamic measurements with neutron crystals and magnetic materials

Changes in the way atoms move in the materials are that measured in a neutron

**Neutrons use neutrons, not X-rays**

It is not as obvious as X-ray diffraction, but neutrons can be used to study the structure of materials. Neutrons are scattered by the nuclei of atoms, not by the electrons as in X-ray diffraction. This means that neutrons can be used to study the structure of materials with a different kind of contrast.

**Neutrons reveal inner structure**

It is the fact that neutrons are scattered by the nuclei of atoms, not by the electrons, that makes them so useful for studying the structure of materials. Neutrons can be used to study the structure of materials with a different kind of contrast.

**Neutrons show what atoms overreact**

It is the fact that neutrons are scattered by the nuclei of atoms, not by the electrons, that makes them so useful for studying the structure of materials. Neutrons can be used to study the structure of materials with a different kind of contrast.

Neutrons behave as particles and as waves

The Royal Swedish Academy of Sciences has awarded the 1994 Nobel Prize in Physics for pioneering contributions to the development of neutron scattering techniques for studies of condensed matter.

# Neutrons reveal structure and dynamics

Neutrons show where atoms are

Neutrons show what atoms do


Neutrons show what atoms overreact

Neutrons reveal inner structure

Neutrons show what atoms overreact

Neutrons reveal inner structure

Olav Roald Neilsen, University of Oslo, Norway, winner on half of the 1994 Nobel Prize in Physics for his development of neutron scattering.



**B**rockhouse made use of neutron scattering (a form of neutron scattering) to study the structure of materials. Neutrons can be used to study the structure of materials with a different kind of contrast.

Neutrons show what atoms do

Neutrons show what atoms overreact

Neutrons reveal inner structure

Neutrons show what atoms overreact

Neutrons reveal inner structure

KUNGLIGA TEKNISKA HOGSKOLEN I STOCKHOLM

THE ROYAL INSTITUTE OF TECHNOLOGY

STOCKHOLM, SWEDEN

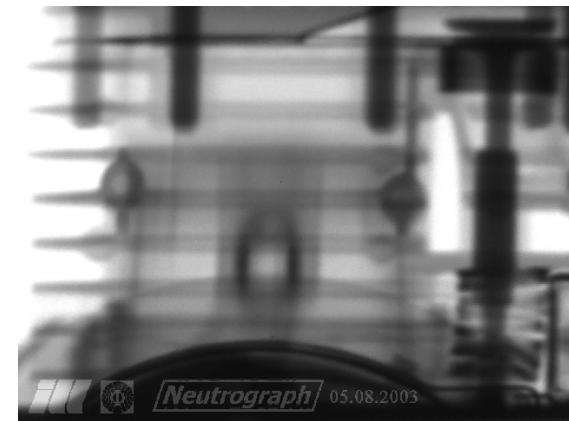
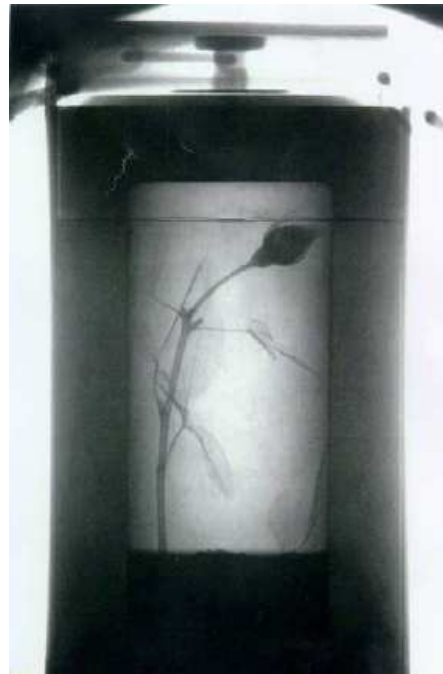
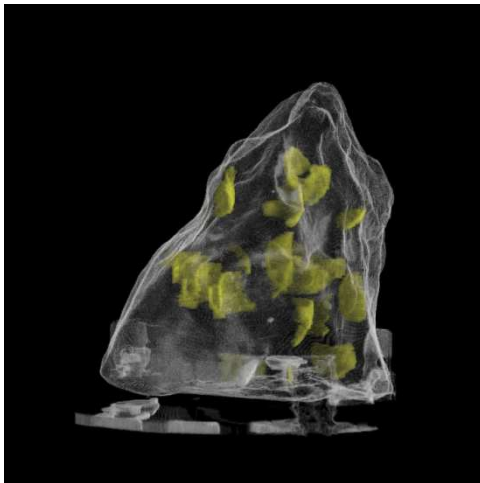
‘Neutrons tell you where atoms *are* and what atoms *do*’



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# Neutrons see the world in a *unique* way

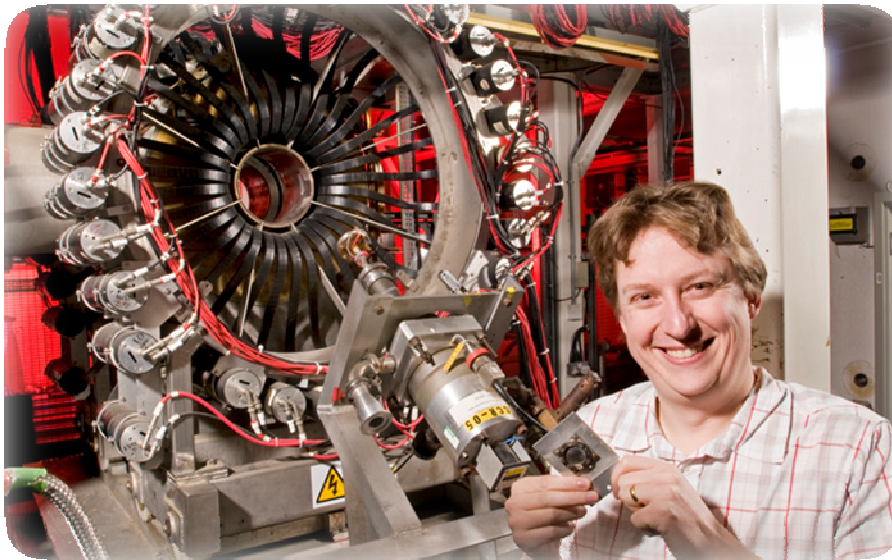




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# What About Muons?



●●●●●●●●○○○○○○○  
LIGHT HEAVY

<http://www.isis.stfc.ac.uk/groups/muons/>









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# Impact of ISIS Science



Global challenges	ISIS
Energy	✓✓✓✓ 
Living with environmental change	✓✓✓ 
Global threats to security	✓ 
Ageing: Life-long health and wellbeing	✓✓ 
Digital economy	✓✓✓ 
Nanoscience: through engineering to application	✓✓✓ 





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## Three kinds of “traditional” elementary particle:

- Electrons (in atom,  $\approx$  eV)
- Protons (in (hydrogen) atom,  $\approx$  eV)
- Neutrons (in nucleus,  $\approx$  MeV)

Many more resources required for producing neutrons than electrons or protons



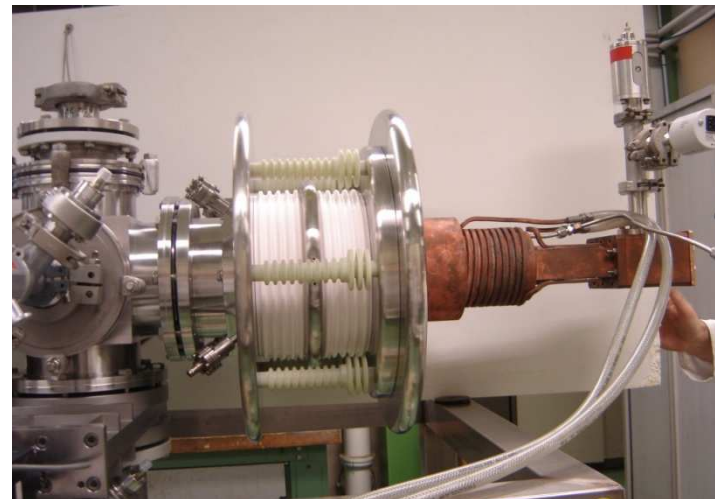
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LIGHT HEAVY

Electron source



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LIGHT HEAVY

Proton source



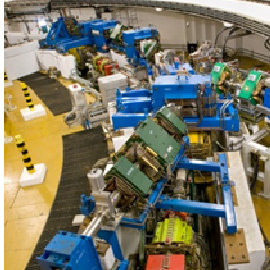
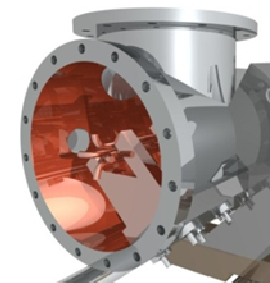
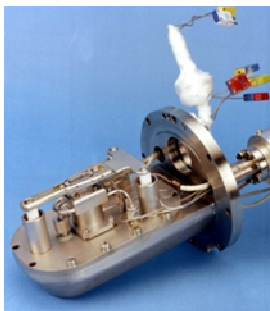


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# Neutron Source

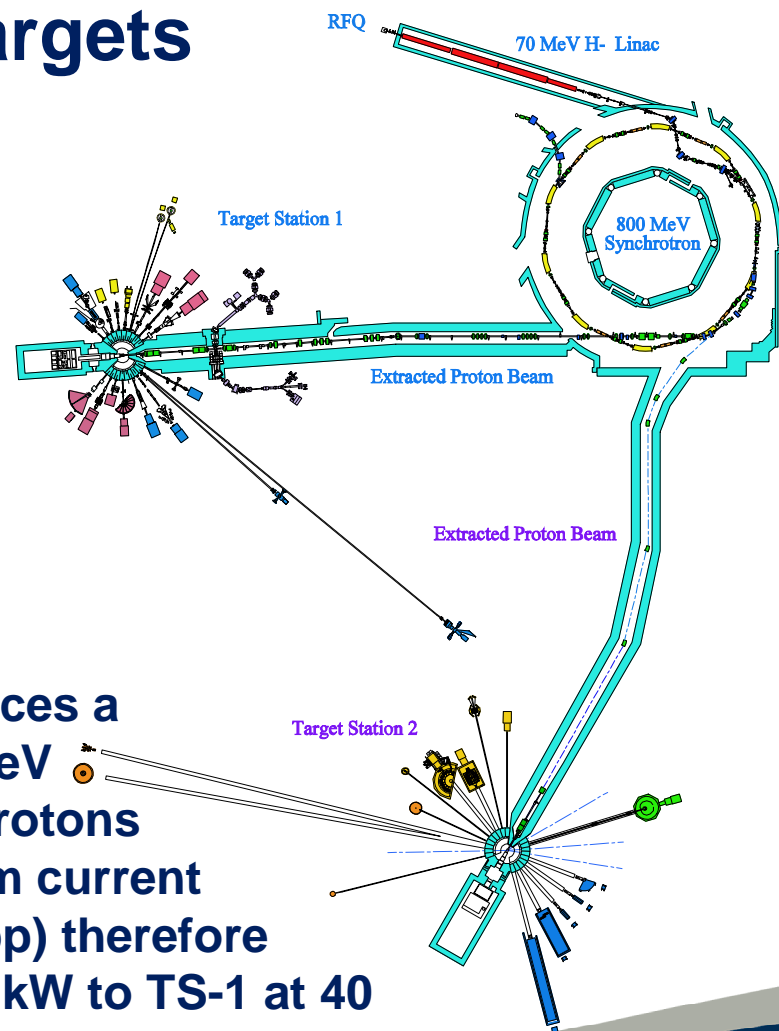




# ISIS Accelerators and Targets

- H<sup>-</sup> ion source (17 kV)
- 665 kV H<sup>-</sup> RFQ
- 70 MeV H<sup>-</sup> linac
- 800 MeV proton synchrotron
- Extracted proton beam lines
- Targets
- Moderators

The accelerator produces a pulsed beam of 800 MeV (84% speed of light) protons at 50 Hz, average beam current is 230  $\mu\text{A}$  ( $2.9 \times 10^{13}$  ppp) therefore 184 kW on target (148 kW to TS-1 at 40 pps, 36 kW to TS-2 at 10 pps).



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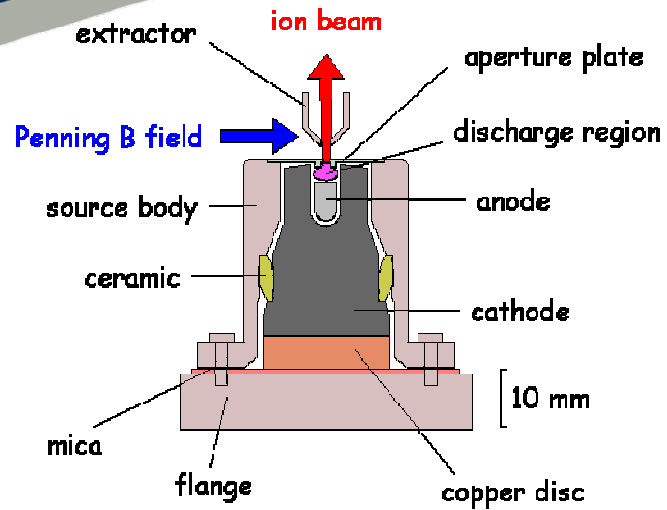
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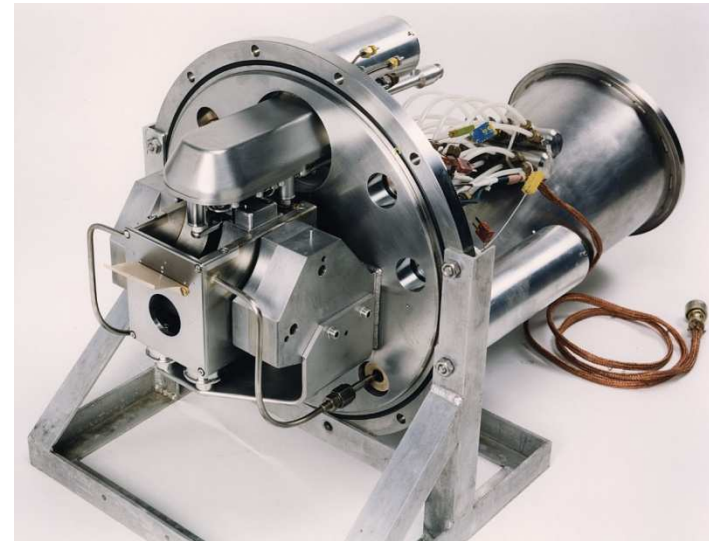
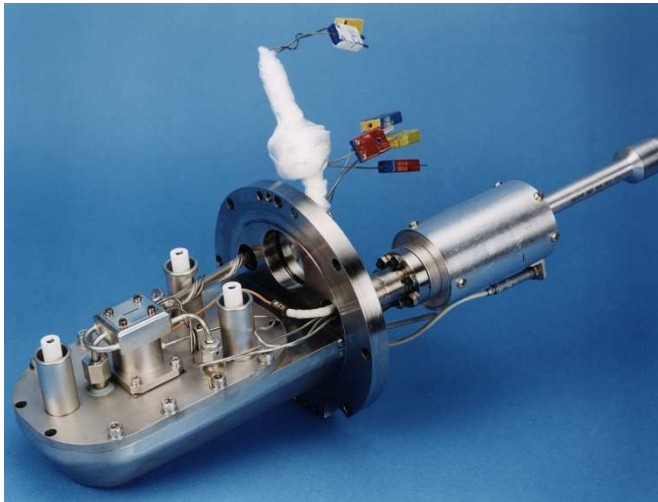
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## H<sup>-</sup> ion source



- Hydrogen gas
- Arc,  $\approx 50$  A arc current
- Plasma
- Caesium to lower work function
- 50 mA of H<sup>-</sup> ions in a 200  $\mu$ s pulse at 50 Hz

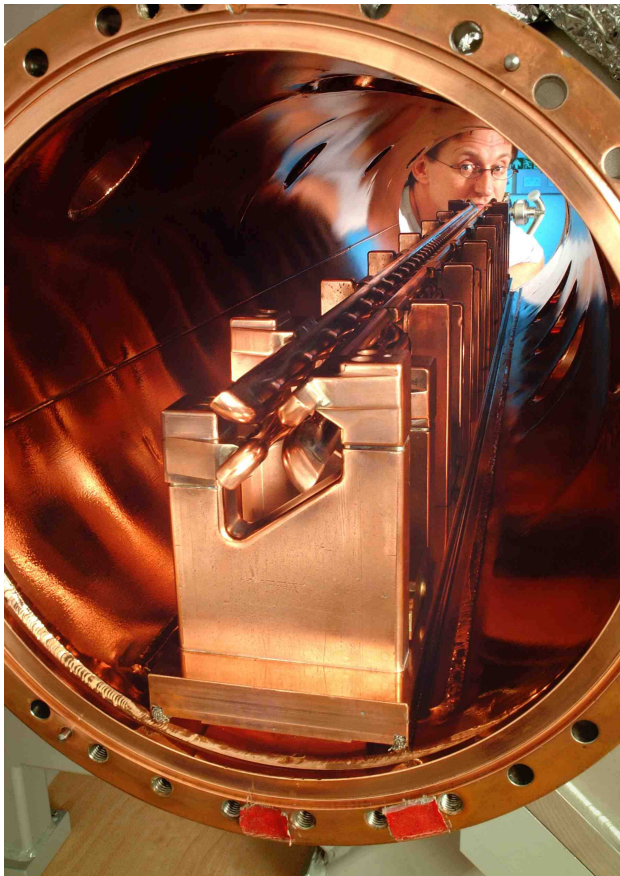




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# RFQ Accelerator



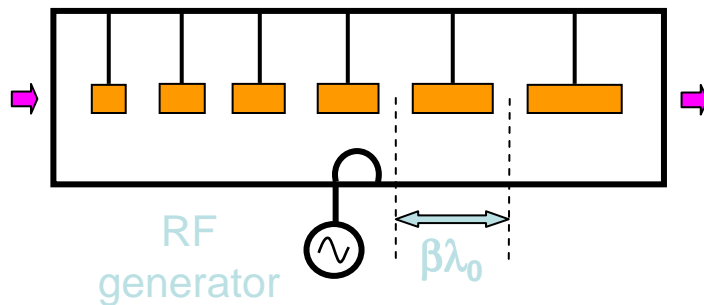
- 35 kV DC accelerates  $H^-$  from ion source to 35 keV
- RFQ accelerates  $H^-$  from 35 keV to 665 keV
- Creates  $\approx 1$  ns long bunches of  $H^-$  at 202.5 MHz
- Compact, low external voltage structure



# Linear Accelerator



- 4-section (-tank) drift tube linac
- Acceleration to 70 MeV by 202.5 MHz RF
- Each tank  $\approx 10$  m long,  $\approx 1$  m diameter.
- Hide particles inside drift tubes while sign of oscillating accelerating field wrong



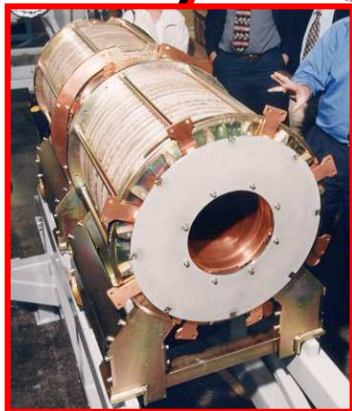
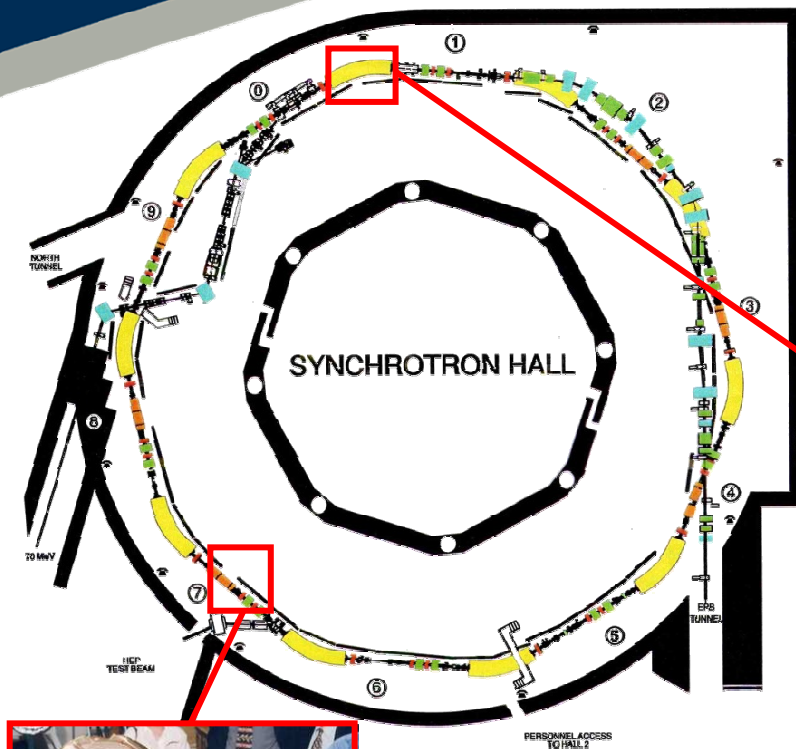


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# Synchrotron

- Circular machine 70 – 800 MeV
- Magnets to bend particles round in circle
- RF electric fields to accelerate particles
- H<sup>-</sup> ions stripped to protons when injected
- Fifty 10 ms acceleration cycles per second



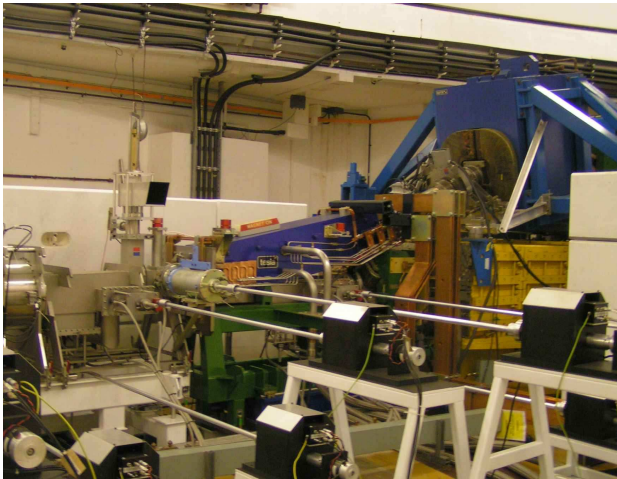
*Synchrotron* because strength of magnetic field and frequency, amplitude and phase of RF all have to be *synchronised*.



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# Extracted Proton Beamlines



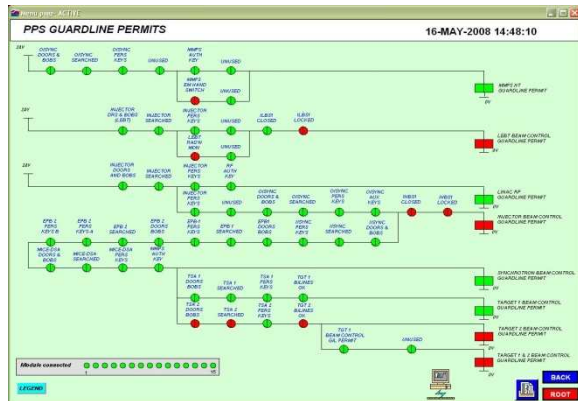
- Kickers powered by PFNs 0-5,000 A in  $< 200$  ns
- Extract septum runs at  $\approx 9,000$  A DC
- 800 MeV beam runs to via EPB with DC magnets
- 1 in 5 pulse pairs to sent to TS-2 by new kicker and septum magnets



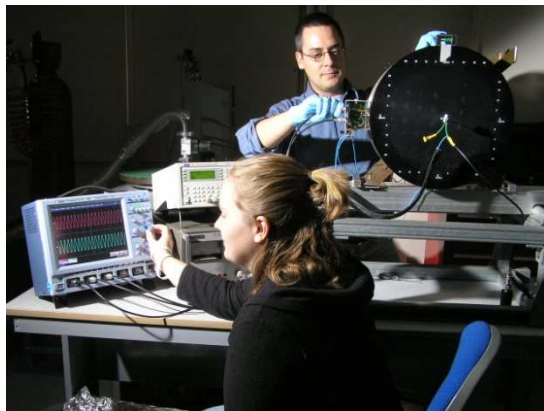
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# And Not Forgetting...



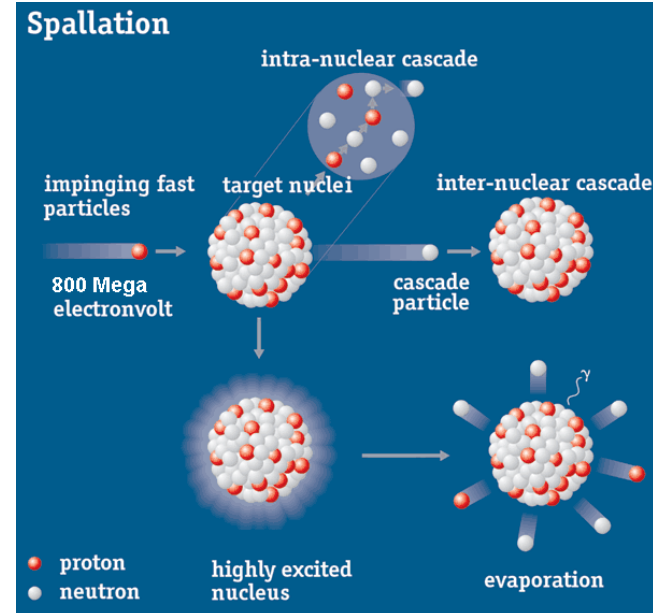
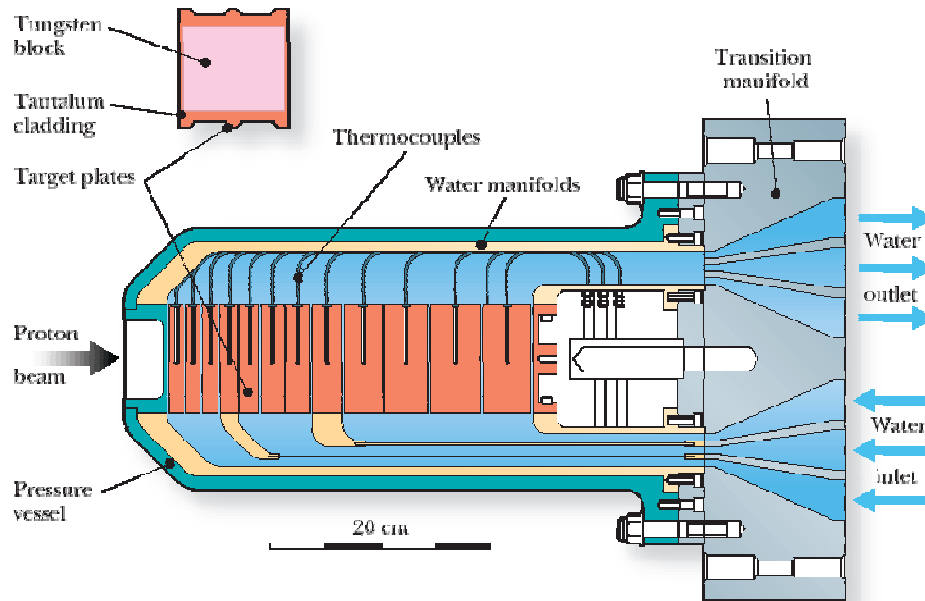
- Vacuum technology
- Beam diagnostics
- Controls
- Interlocks





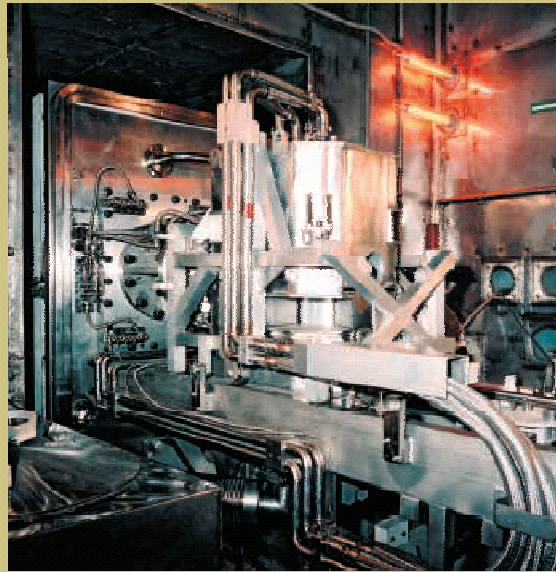
# TS-1 Target

- $\approx 2.3 \times 10^{13}$  (4  $\mu\text{C}$ ) ppp on to TS-1 tantalum coated tungsten target (40 pps)
- $\approx 15\text{--}20$  neutrons/proton,  $\approx 4 \times 10^{14}$  neutrons/pulse
- Primary neutrons from spallation: evaporation spectrum ( $E \approx 1$  MeV) + high energy tail

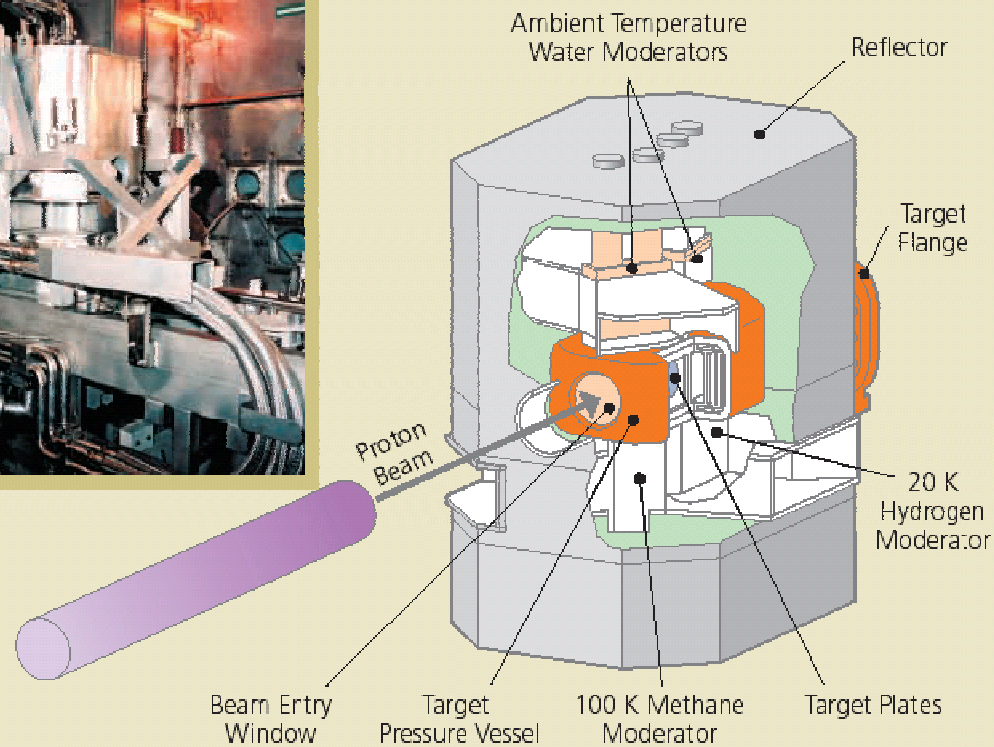




# Target Assembly



**Fig. 31:**  
*The target, reflector  
and moderator  
assembly (TRAM)  
(85RC2936).*



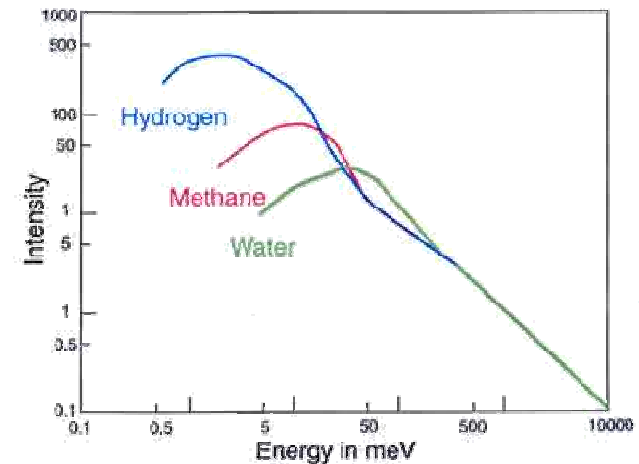
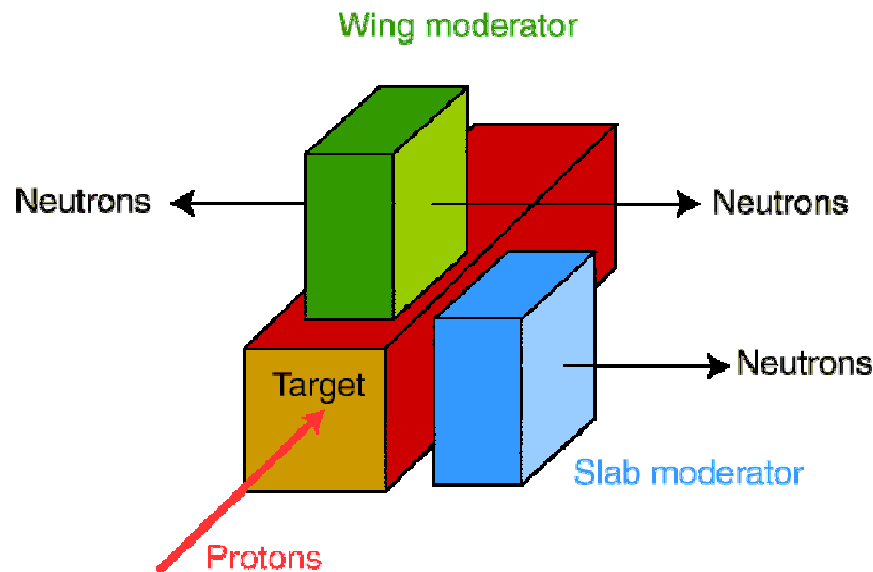


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# Moderators

- But want meV, not MeV
- Moderation - elastic nuclear scattering - low A
- Liquid hydrogen (20K), Methane (100K), Water (23°C)

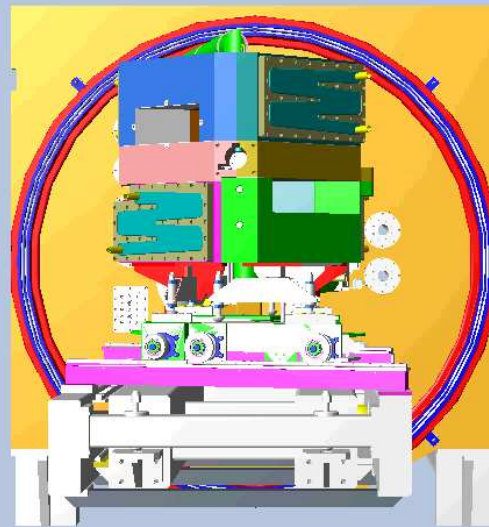




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## TS-2 Target

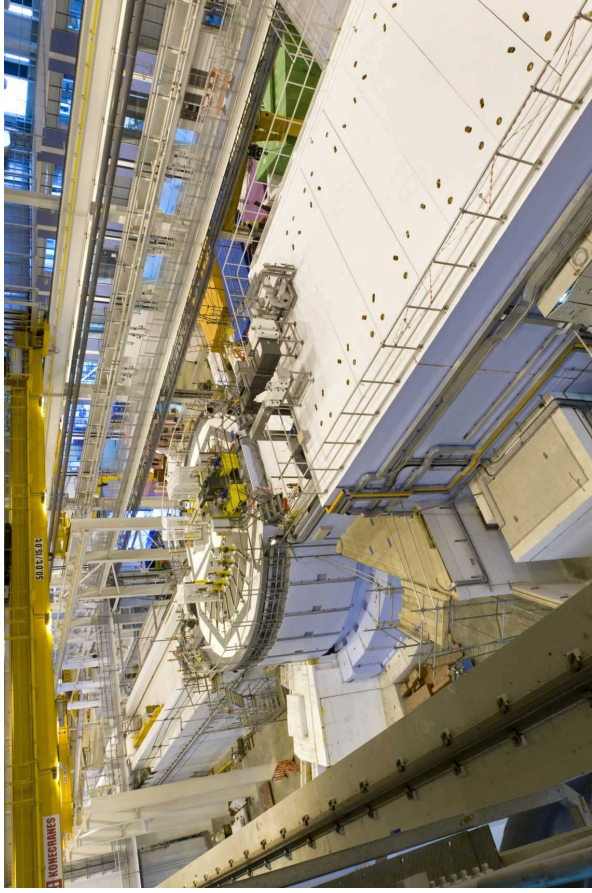
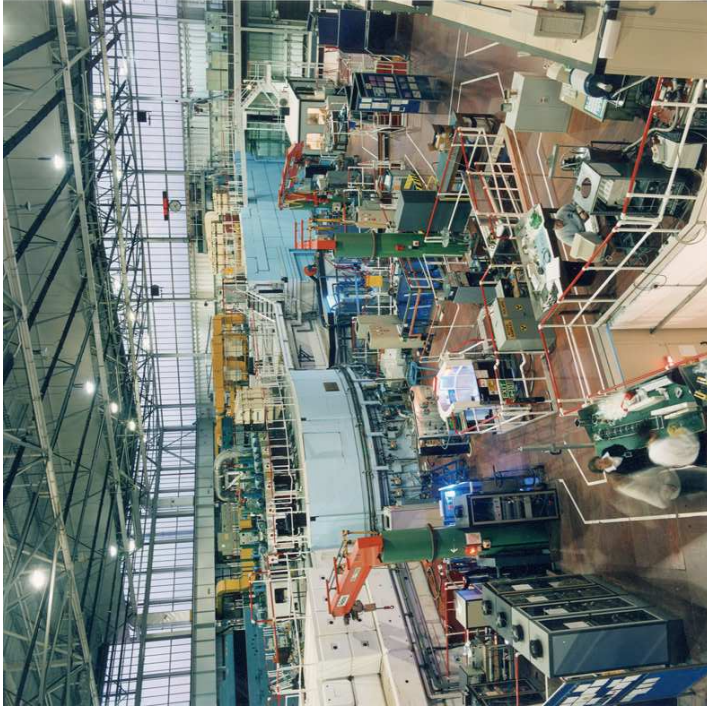


- Solid tungsten cylinder, tantalum coated, heavy water surface cooled, 68 × 307 mm



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# Neutron Interactions

**X-ray scattering lengths vary with atomic number  $A$ .**

**Neutron scattering lengths vary more randomly**

- Can see heavy atoms in the presences of light ones e.g. hydrogen
- Can distinguish between different ions with the same charge e.g.  $\text{Ti}^{4+}$ ,  $\text{Ca}^{2+}$  and  $\text{K}^{+}$  or  $\text{K}^{+}$  and  $\text{Cl}^{-}$

neutrons X-rays

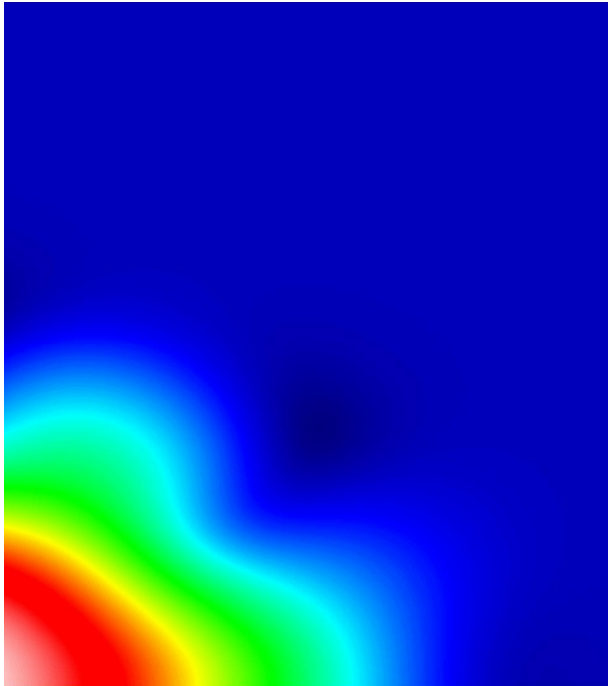
H		
Li		
C		
O		
S		
Mn		
Zr		
Cs		



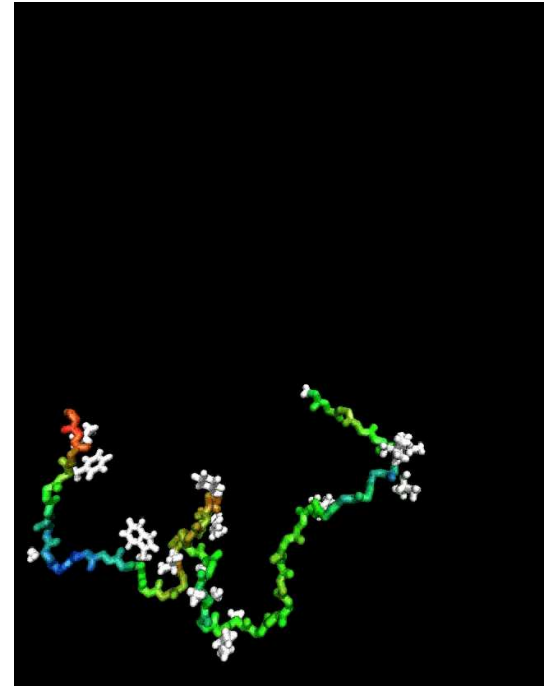
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# Neutron Interactions



From hydrogen wave function ...



... to protein folding

## Length and time scales

$10^{-11} - 10^{-6} \text{ m}$

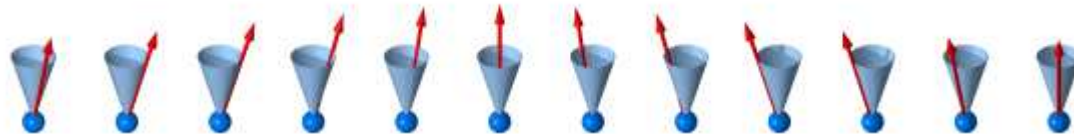
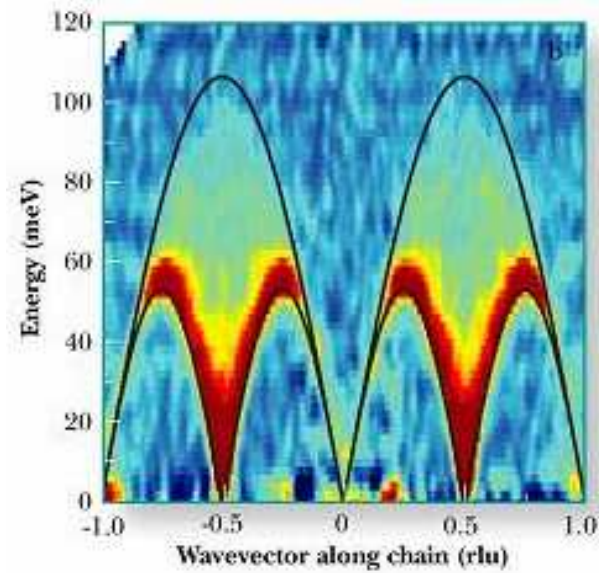
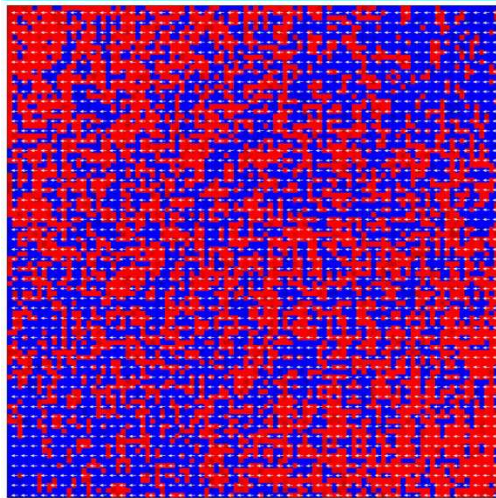
$10^{-14} - 10^{-6} \text{ s}$



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# Neutron Interactions



## Magnetism

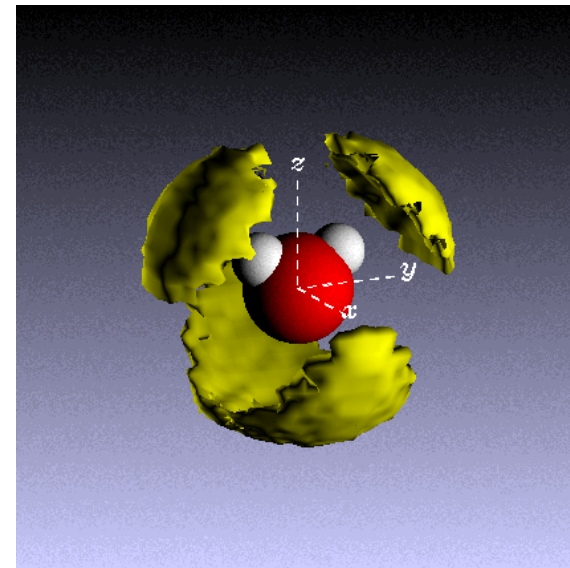
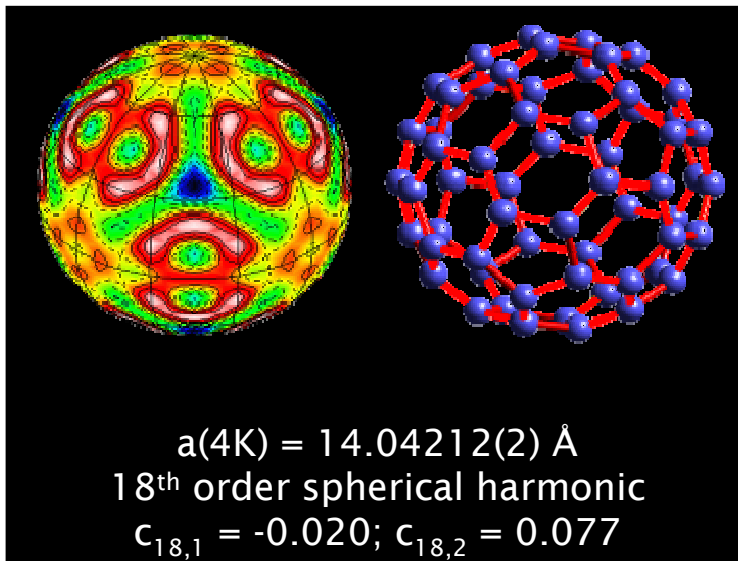
The neutron has a magnetic moment but no charge



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# Neutron Interactions



## Precision

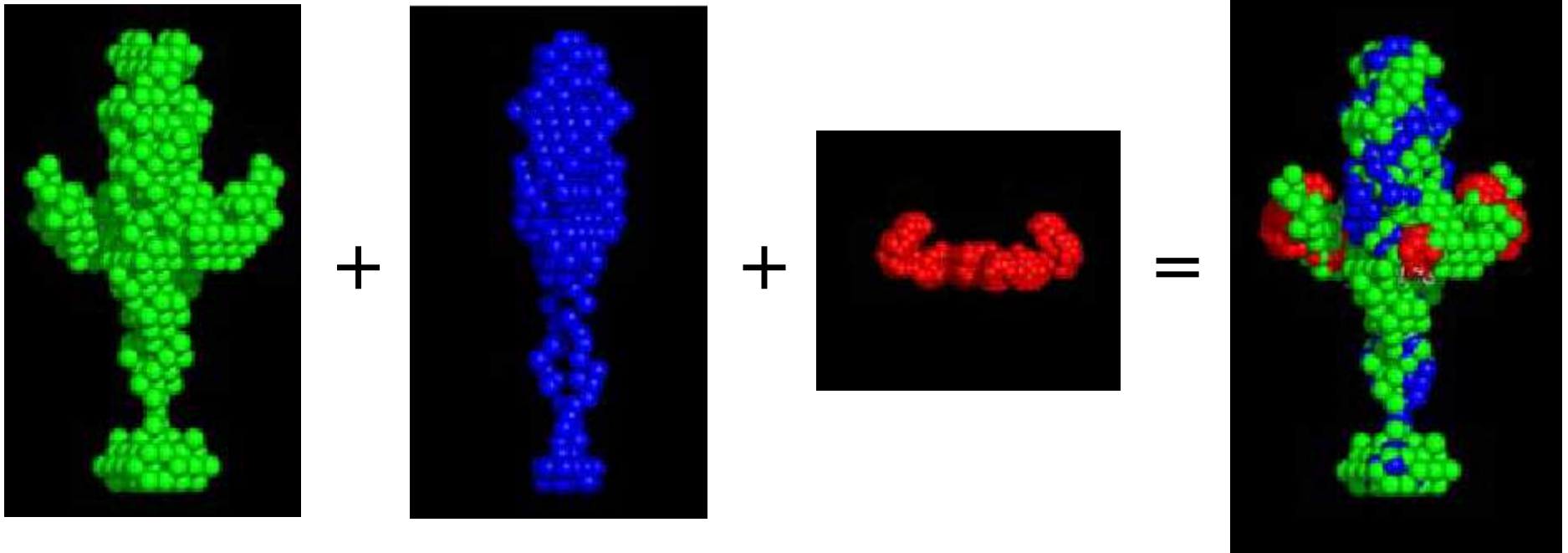
Weak interaction, simple interaction



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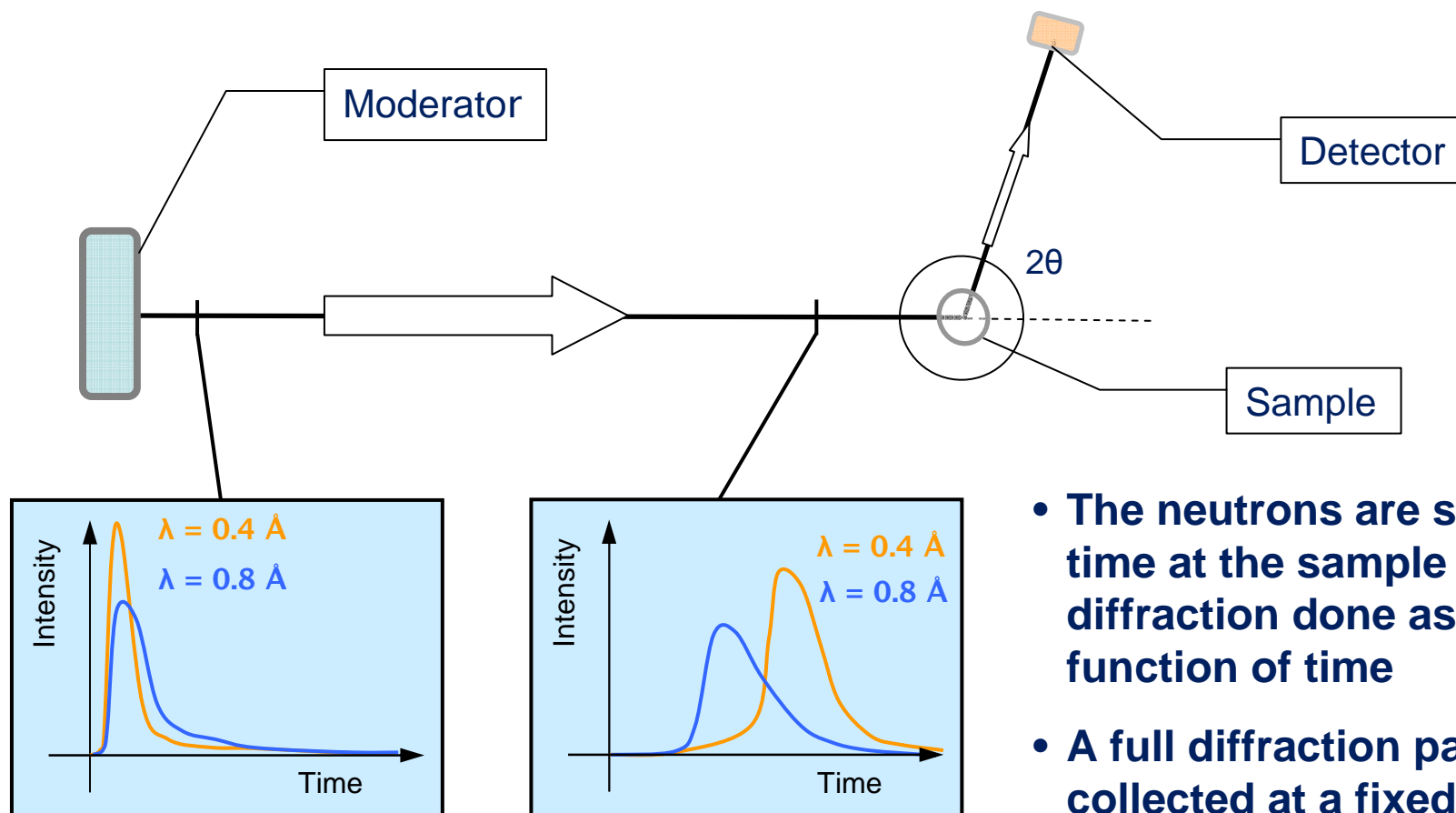
# Neutron Interactions



**Sensitivity and selectivity**

Isotopic substitution/contrast variation

# Diffraction on a Pulsed Source



The initial pulse from the moderator contains all neutron wavelengths

As they travel down the instrument the faster shorter wavelength neutrons arrive first



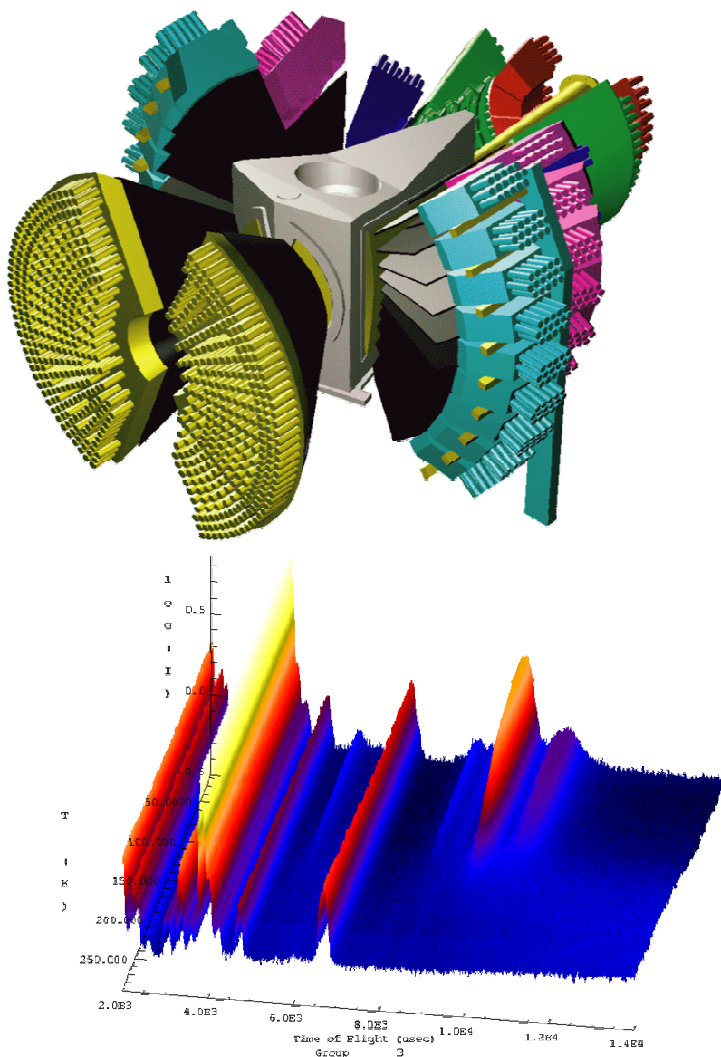
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# Diffraction

**GEM - A high intensity/high resolution powder diffractometer**

- Huge detector area (3.5 Sr)
- Rapid data collection for parametric studies

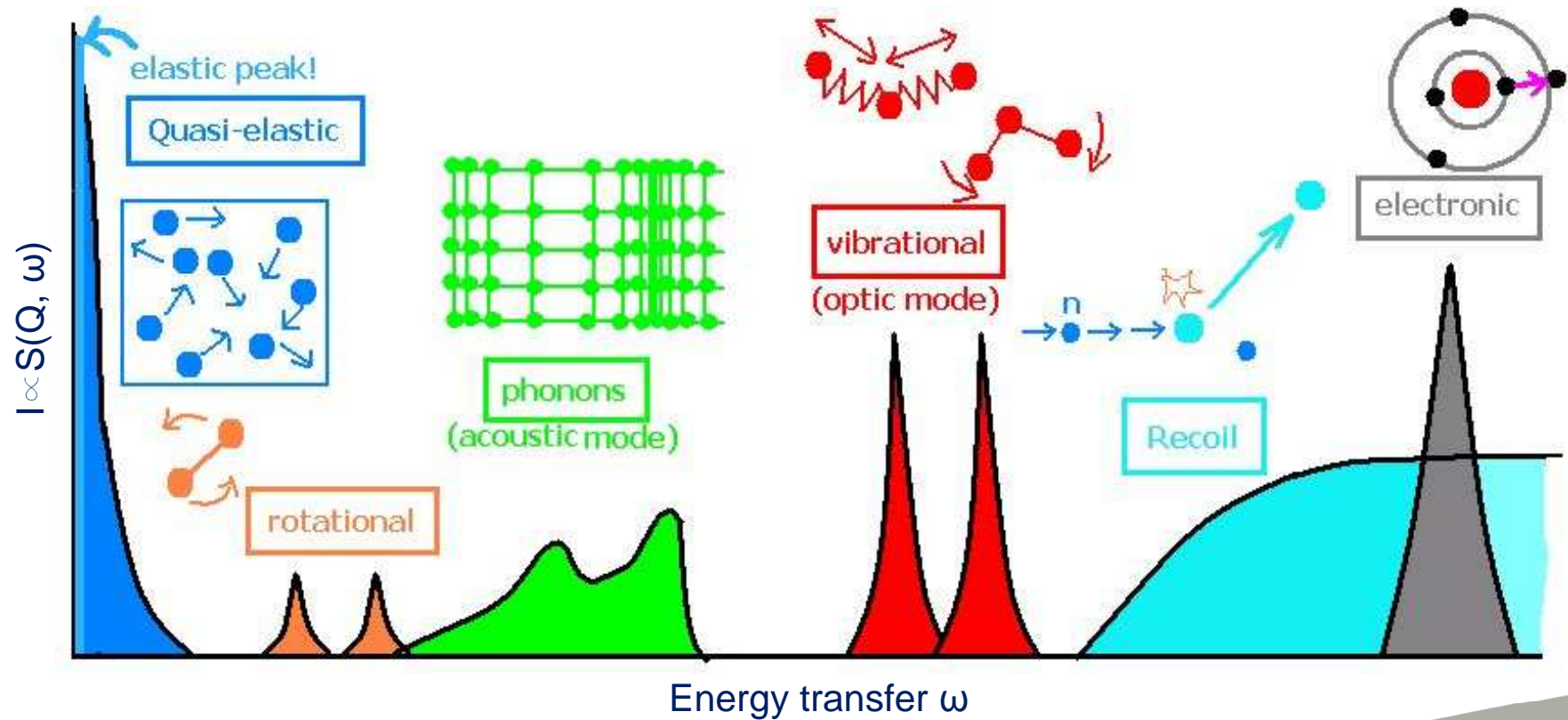


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# Inelastic Neutron Scattering

- Neutrons can transfer energy to and from a material

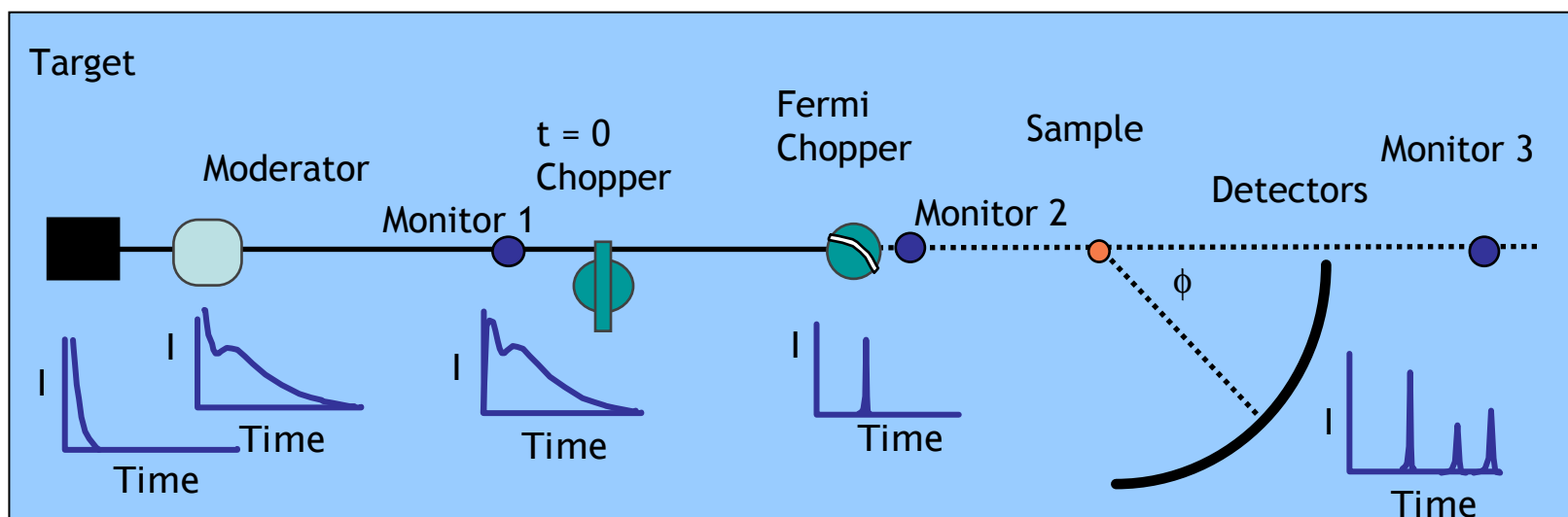


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# Time of Flight Spectroscopy

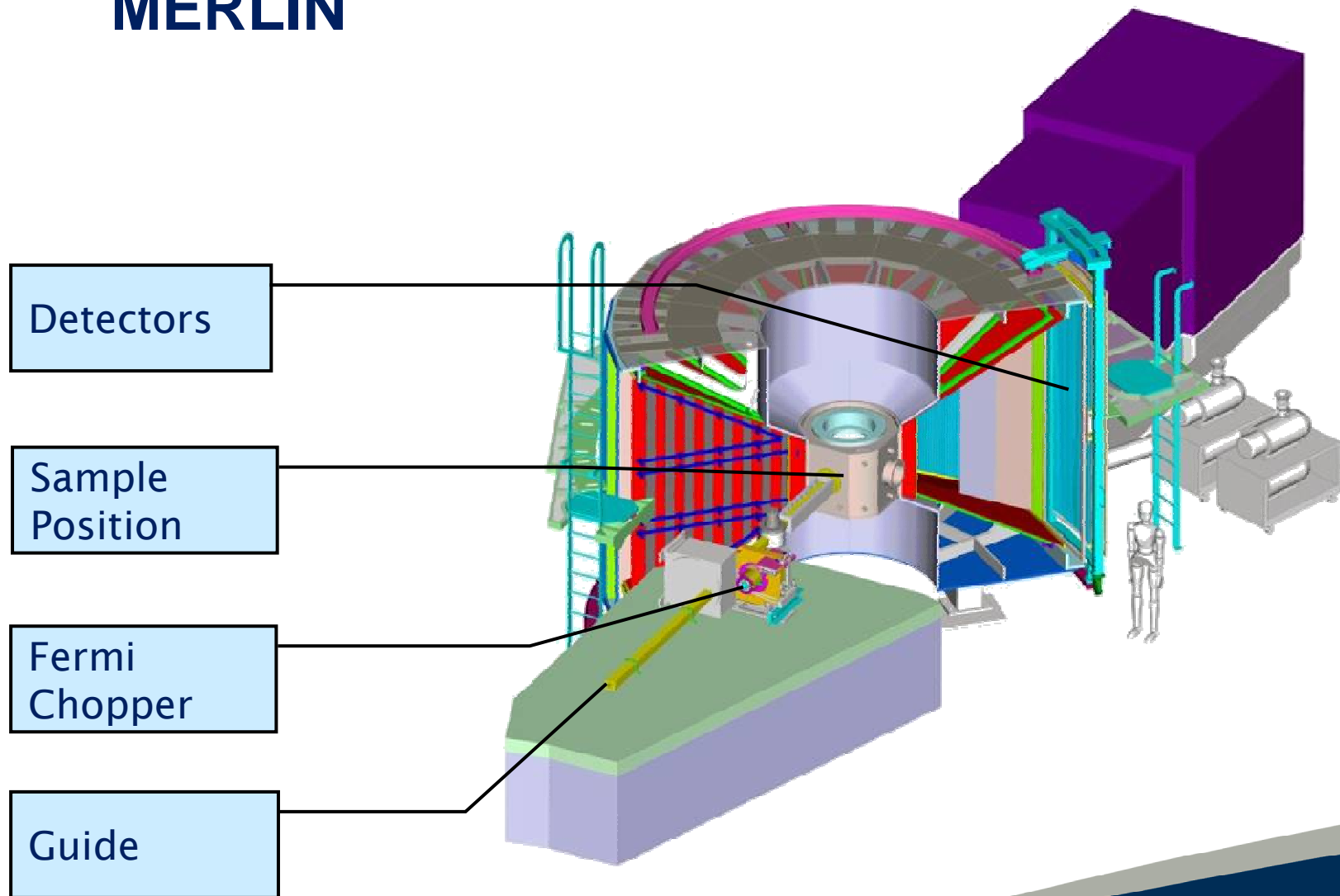
- Fermi Chopper spectrometer



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# MERLIN

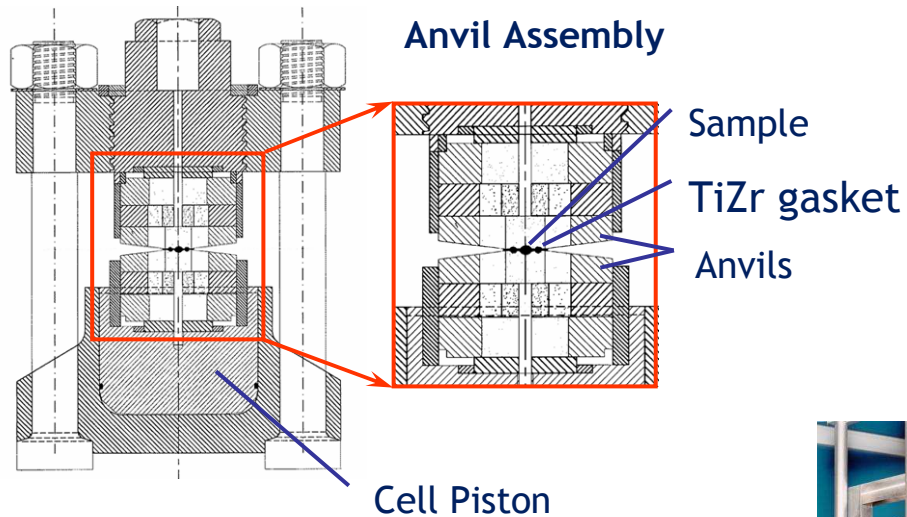


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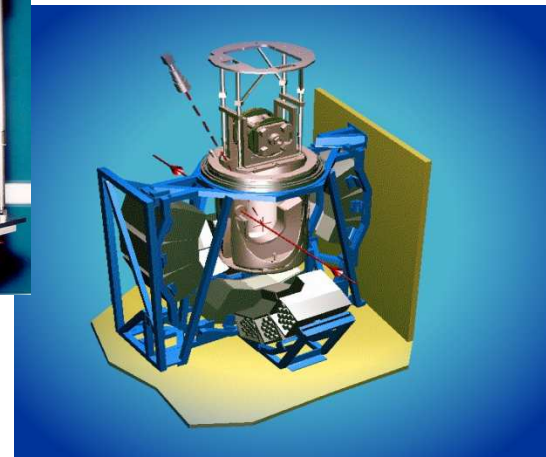
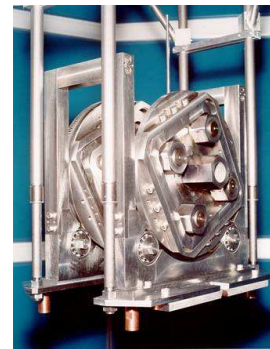
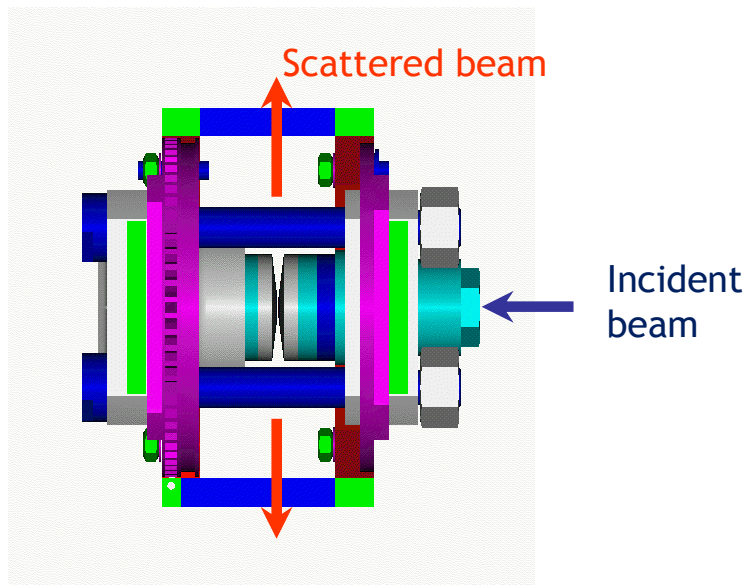
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# High Pressure Studies

## The Paris-Edinburgh Pressure Cell



- Routinely get to pressures of 25GPa (250 kbar)
- Makes use of the penetrating power of neutrons
- Makes use of the fixed detector geometry of time-flight diffraction



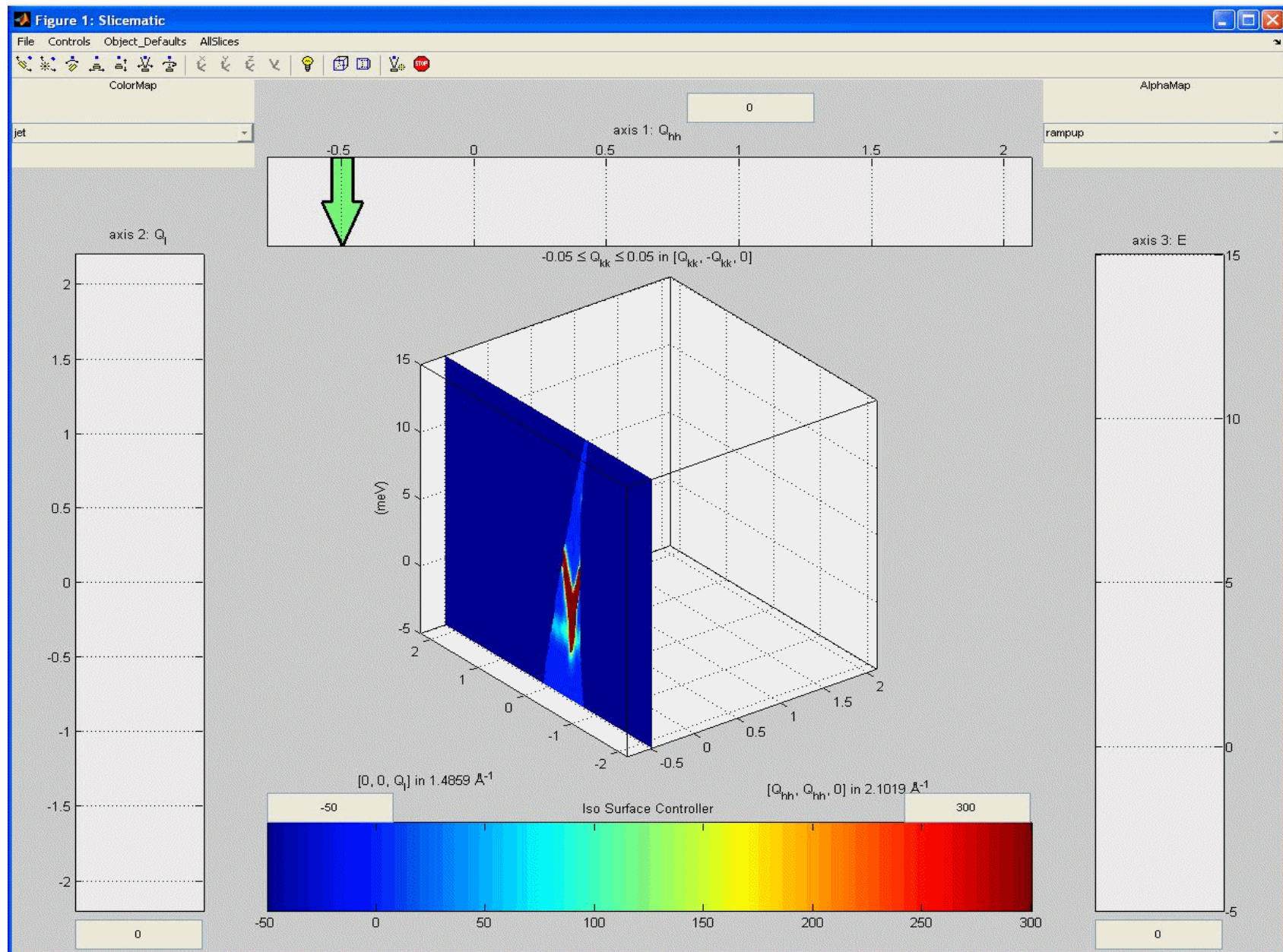
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- **Visualisation software**

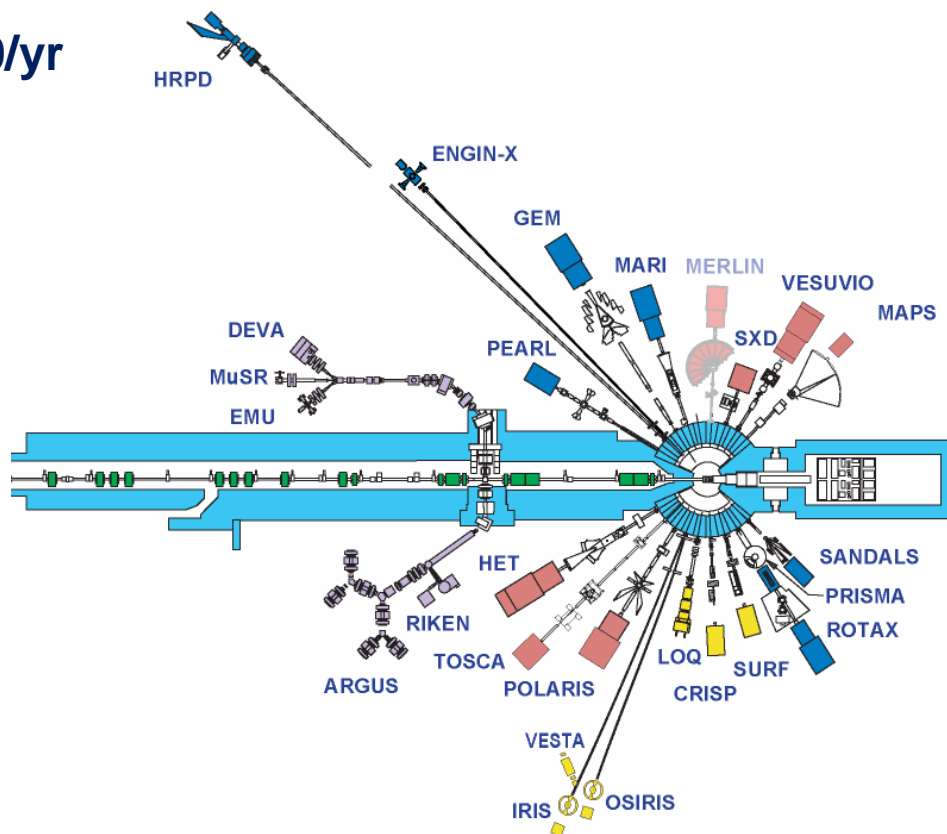
**Combine ~200 datasets  $\Rightarrow$  full map of  $S(Q, \omega)$**   
**40GB  $10^9$  pixels**

## Bespoke visualisation software (“HORACE”)



# A World Centre for Research in the Physical and Life Sciences with Neutrons and Muons

- Broad Academic Base ~1500/yr
- Resonating with the strengths of UK SEB
- 90% of UK Users 5/5\* Depts
- 700 Experiments/ yr
- 500 Publications/ yr



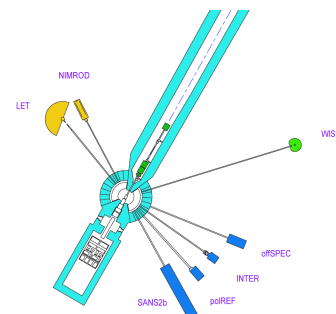
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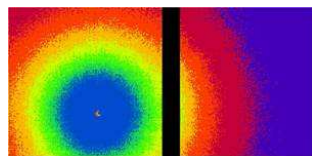
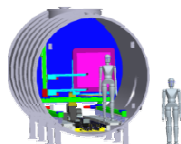
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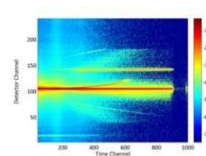
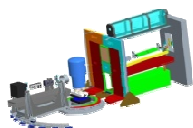


## TS2 Phase 1 instruments are outstanding!

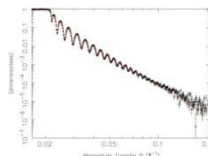
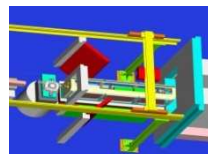
SANS2D



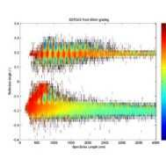
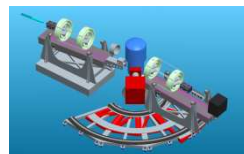
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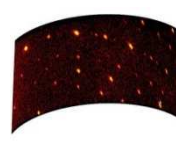
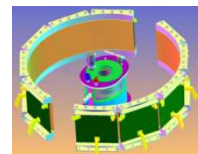
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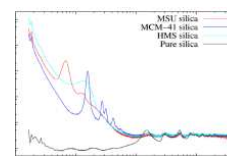
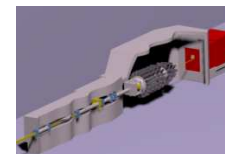
OFFSPEC



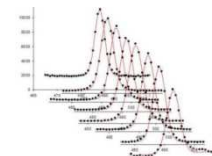
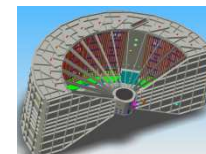
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NIMROD



LET

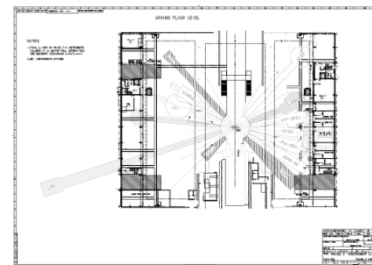


TS2 Phase I: 2004-9



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ISIS

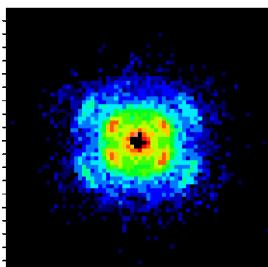


## TS2 Phase 2 instruments are being designed

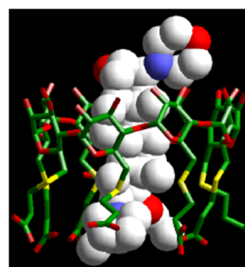
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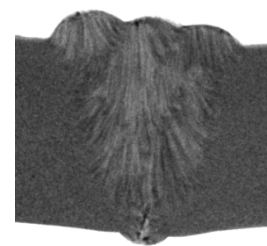
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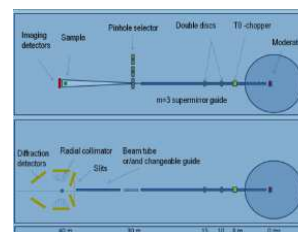
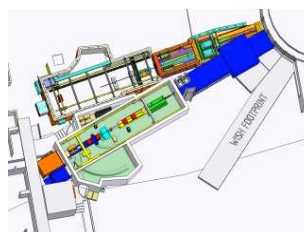
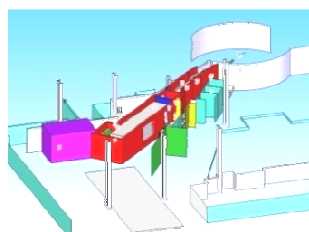
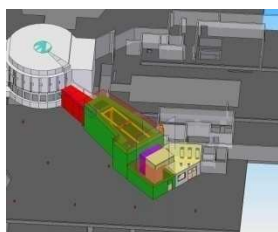
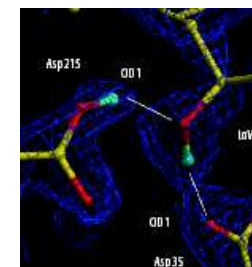
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IMAT



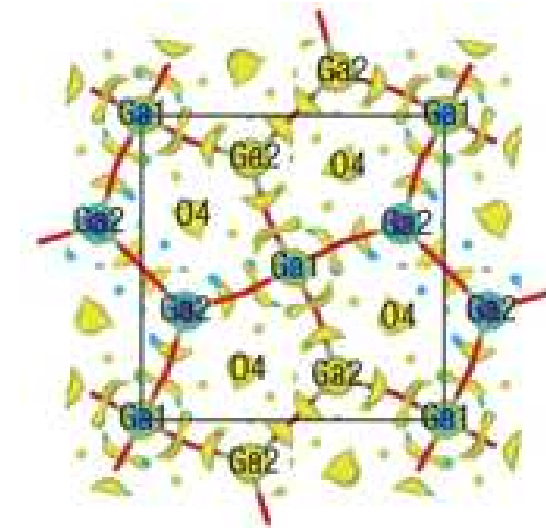
LMX



TS2 Phase II: 2009-13

# ISIS helps mobile phone component manufacturers

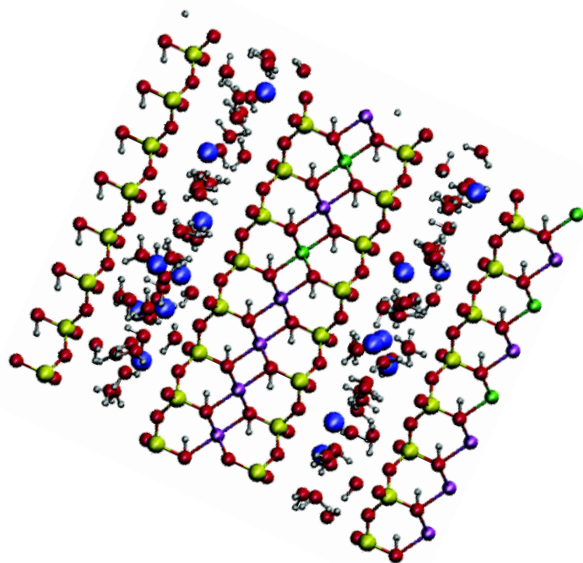
- Mobile phones and base stations contain ceramic antennas called dielectric resonators
- ISIS recreated the firing stage of ceramic components at more than 1000 °C
- Testing at ISIS has aided manufacture of ceramic resonators to the correct specification.



“ISIS, in collaboration with Liverpool University, generated the intrinsic data necessary for the understanding of the structure of these complex materials”  
– David Iddles, Powerwave UK,  
Ceramics Development manager

# ISIS helps unclog the cholesterol of crude oil

- **Asphaltenes** are a complex mixture of molecules that can sometimes **block oil pipes**
- Research to more easily **predict** and **prepare** for the formation of asphaltene deposits
- Result in **fewer blockages** and **big savings** for the oil industry.



“ISIS allowed us to understand more clearly how asphaltenes aggregate, an important observation from a flow assurance point of view and should allow more efficient extraction of hydrocarbons in the future.”  
–Edo Boek, Schlumberger Cambridge Research, Senior Research Scientist

**Schlumberger**

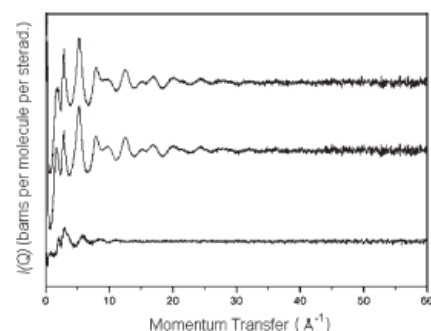
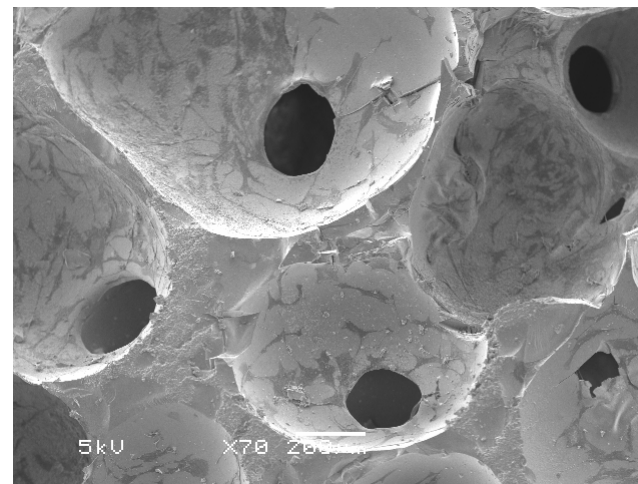


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**ISIS**

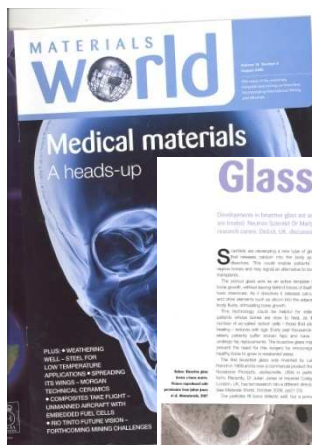
# Bioactive glass for bone growth

- Thousands of **elderly patients** undergo hip or knee **transplants** every year
- New bioactive glass releases **calcium** as it dissolves
- **Stimulates bone growth** and could spell an end to transplants
- Clinical trials expected within 5 years.
- Imperial, Kent, Warwick, NHS



“ISIS has enabled us to move forward with the programme. The key outcome of our experiments has been a full understanding, at the level of atomic arrangements, of why it is that calcium is able so easily to leave the glass at the rate required to generate the desired response.”

–Bob Newport, University of Kent

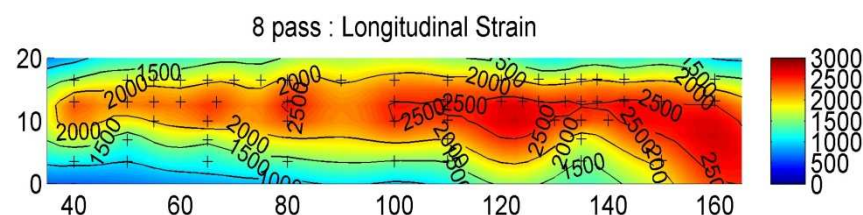
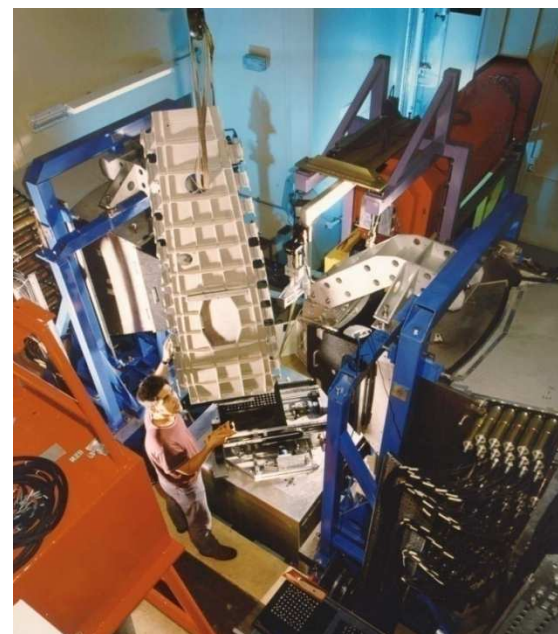


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# Wing quality soars at ISIS

- Aircraft manufacturer Airbus has used ISIS since 2006
- Research into aluminium alloy weld integrity for aircraft programmes
- **Residual stresses** from welding cause weaknesses and the possibility of cracks
- ISIS neutrons look deep inside engineering components to measure stress fields



“Residual stress measurement at ISIS has been invaluable in researching and developing existing and novel material manufacturing and processing techniques.”  
– Richard Burguete, Airbus  
Experimental Mechanics Specialist



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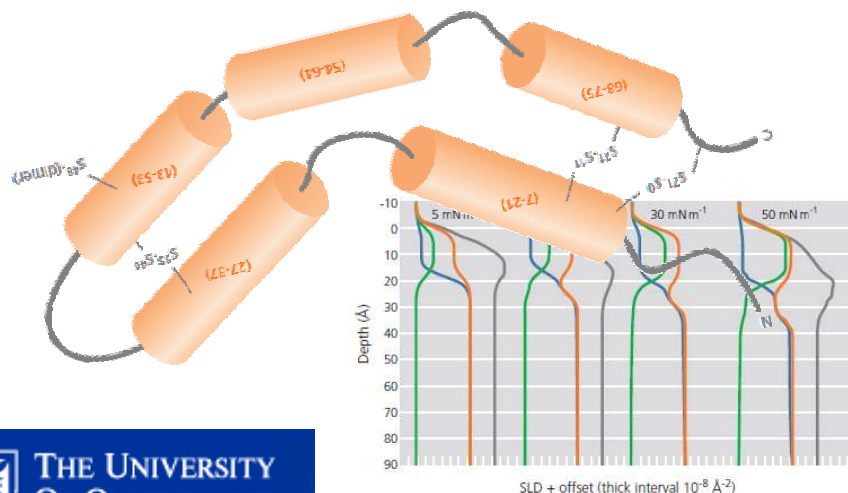
# Understanding infant lung structure

- Natural lung surfactant allows oxygen into the bloodstream
- Absence in premature babies causes breathing difficulties
- ISIS mimicked change in lung capacity to discover how proteins and phospholipids act together
- Helping to develop synthetic lung surfactants which can be more precisely targeted at clinical needs to help save babies' lives



"ISIS is the premier place in the world to work with neutrons and liquid surfaces. In collaboration with the University of Queensland we were able to discover how proteins and phospholipids act together to enable lung function."

- Dr Stephen Holt, ISIS neutron scientist



# Spintronics for IT, automotive and health sectors

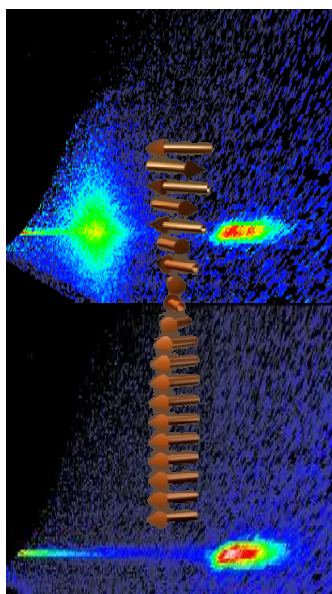
- Spintronics underpins applications as diverse as biosensors for blood screening, computer memory and safety systems for cars
- Potential for smaller, faster devices with more capacity and lower power consumption
- Most promising materials for future devices only work at low temperatures and high magnetic field
- ISIS supporting global efforts through Spin@RT consortium of UK universities and industry



Seagate 

**TOSHIBA**  
Leading Innovation >>>

**HITACHI**  
Inspire the Next



“Many of the most promising materials to deploy in future devices only work under extreme conditions. ISIS gives a unique nanoscale understanding of the materials in the quest to make them work at room temperature.”  
– Sean Langridge, ISIS Senior Fellow,  
Visiting Professor University of Leeds

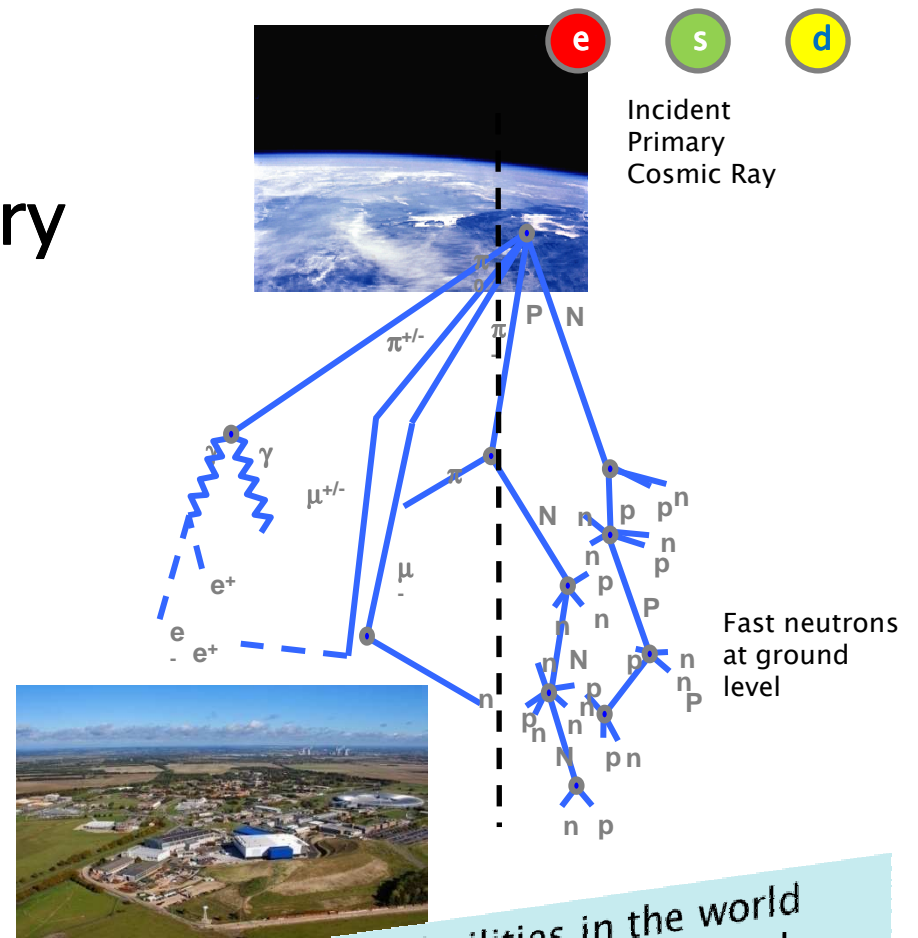


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**ISIS**

# Fast neutron testing for the semiconductor industry

- **Atmospheric neutrons** collide with microchips and **upset microelectronic devices** every few seconds
- **300 x greater effect** at **high altitude**
- **ISIS enables manufacturers to mitigate against the problem** of cosmic radiation
- **Increased confidence** in the quality and safety of aerospace electronic systems



"ISIS is one of few facilities in the world capable of producing enough very high energy neutrons to perform accelerated testing."  
 –Andrew Chugg, MBDA, SEEDER consortium

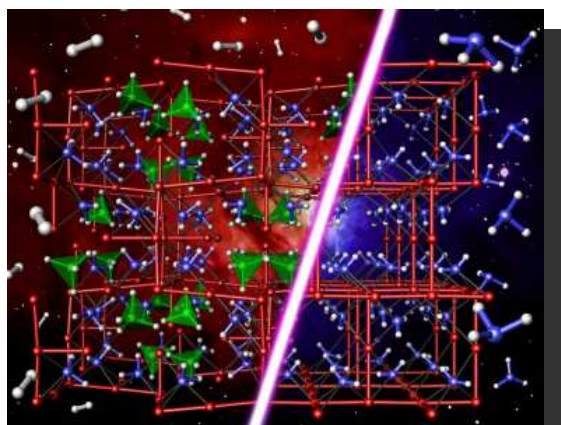


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# ISIS contributes to zero-emission vehicles

- **Hydrogen-powered cars** are **feasible** using today's technology
- Harmful **emissions** reduced to **zero**
- Method of **safe, low-cost hydrogen storage** on-board **holding up deployment**
- **Hydrogen-rich solids** safely releasing hydrogen developed using ISIS neutrons
- **New materials** hold upwards of **10 percent** of their own **weight** in **hydrogen**



"We've discovered new sets of materials that can store hydrogen more efficiently than hydrogen itself. Neutrons are without doubt the best way to see hydrogen entering and leaving in real time."  
—Professor Bill David, ISIS Senior Scientist



UK-SHEC

EPSRC

Technology Strategy Board  
Driving Innovation



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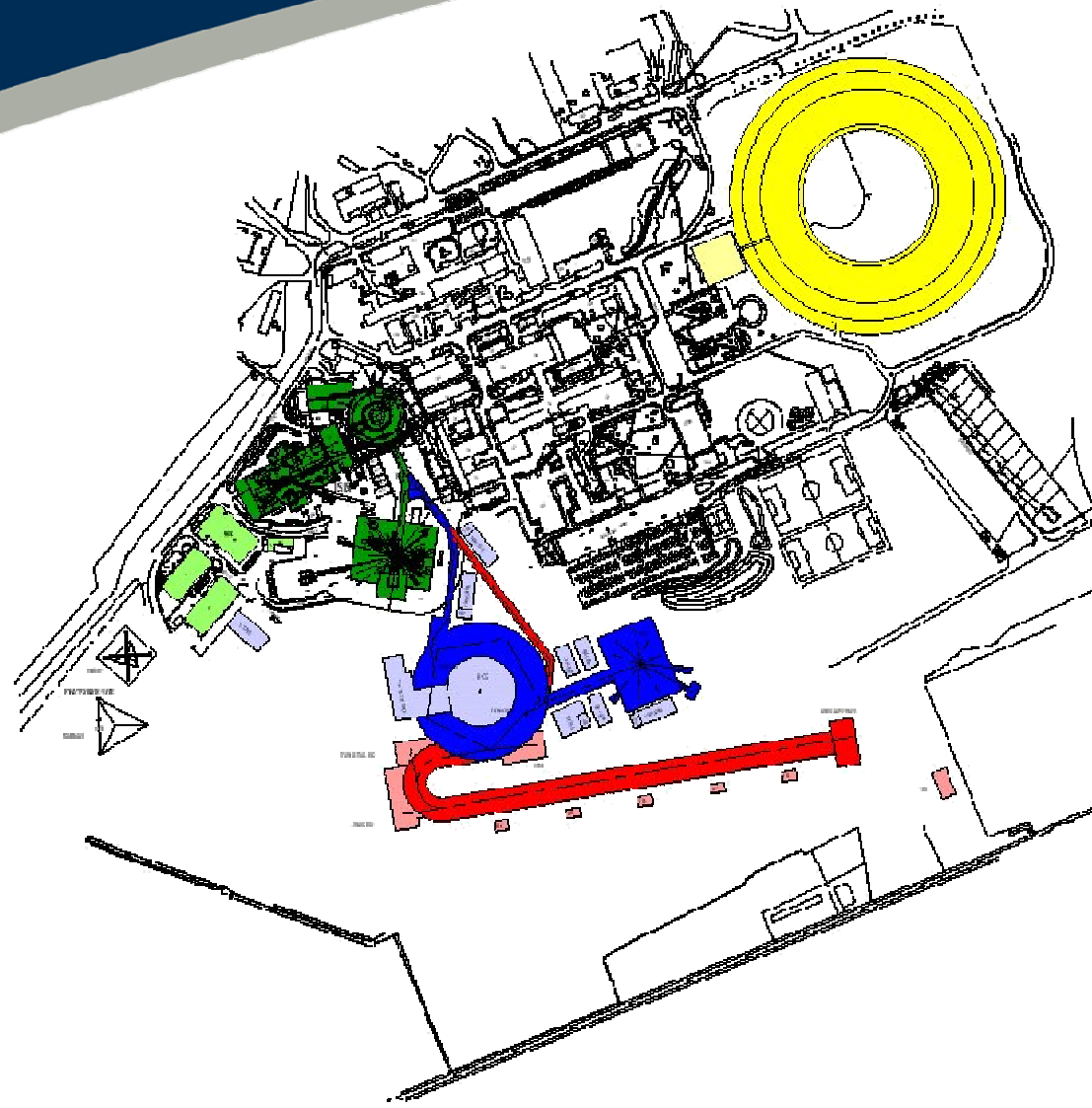
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# ISIS MW Upgrades

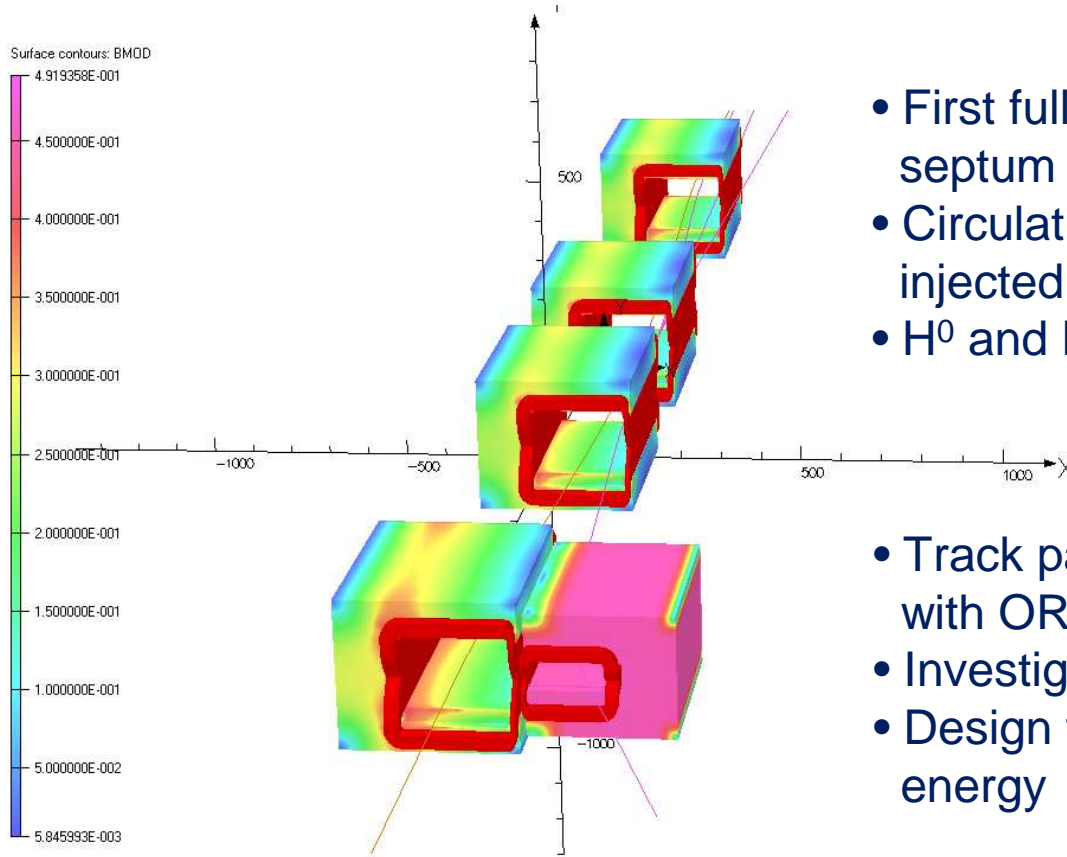



- Replace present ISIS linac with a new ~ 180 MeV linac (0.5MW)

- Based on a ~ 3 GeV RCS fed by bucket-to-bucket transfer from ISIS 800 MeV synchrotron (1MW)

- RCS design also accommodates multi-turn charge exchange injection to facilitate a further upgrade path where the RCS is fed directly from an 800 MeV linac (2 – 5 MW)

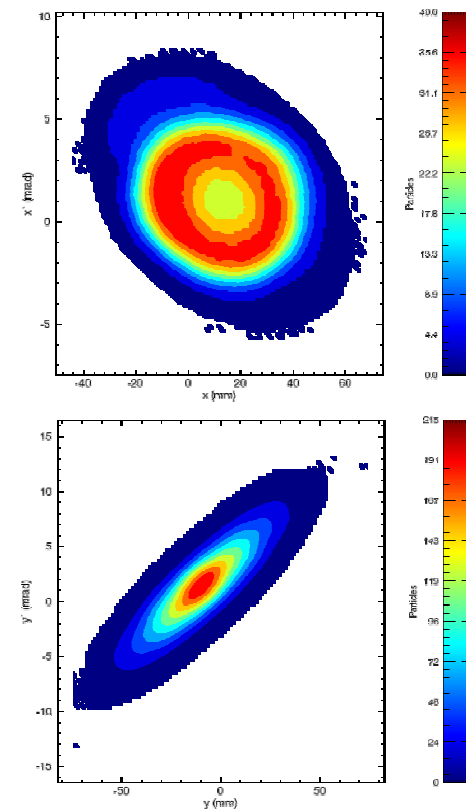
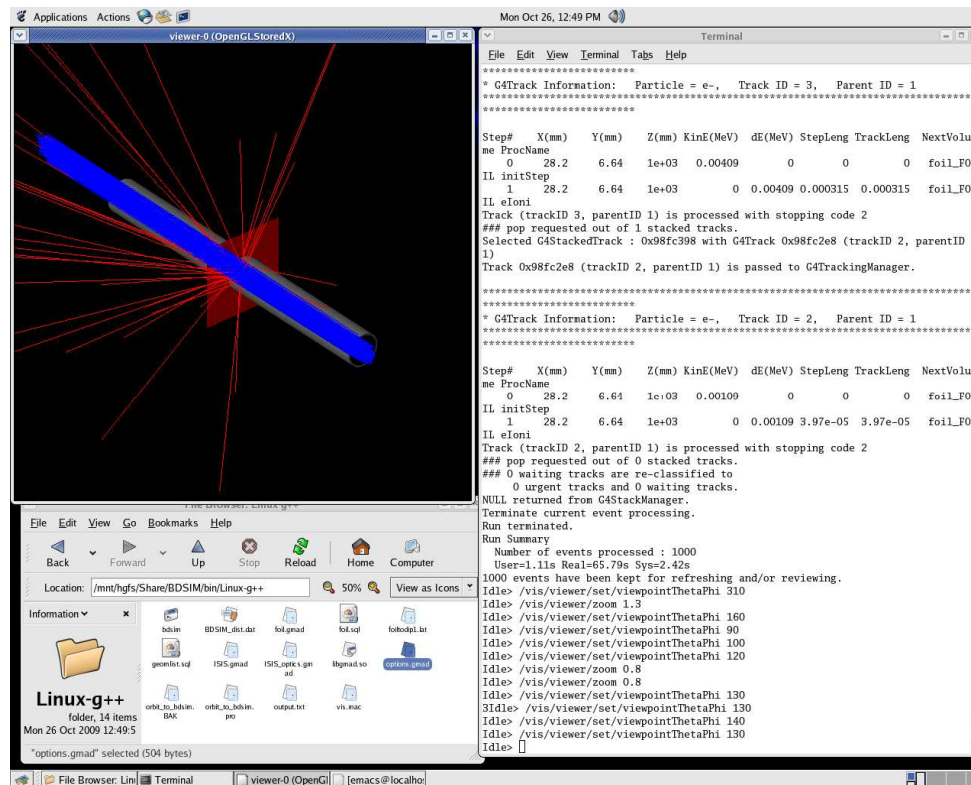
# FE Model of Injection Straight



- First full model of injection septum and dipole at 70 MeV
  - Circulating beam and injected beam tracked through
  - $H^0$  and  $H^-$  tracked
- 
- Track particles and compare with ORBIT model
  - Investigate transient effects
  - Design for higher ( $\sim 180$  MeV) energy

Vector Fields  
software for electromagnetic design

# 200 MeV Foil Interaction Modelling

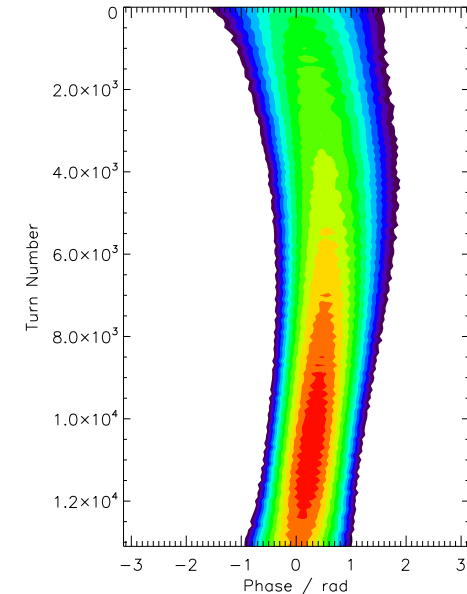
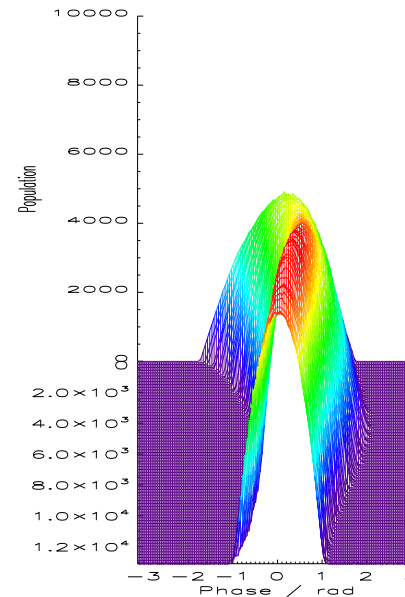
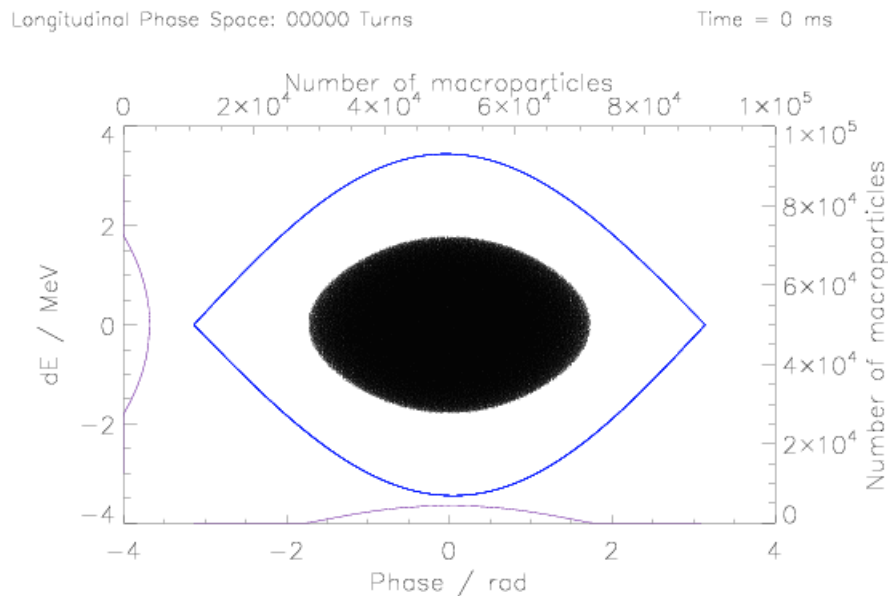


- Results for scattering and energy loss look reasonable
- Next investigate  $H^-$  stripping



# Longitudinal Beam Dynamics

- Beam Energy = 180 – 800 MeV
- Protons/bunch =  $4 \times 10^{13}$
- Beam power = 0.5 MW



- Simulations with space charge promising: indicate low losses

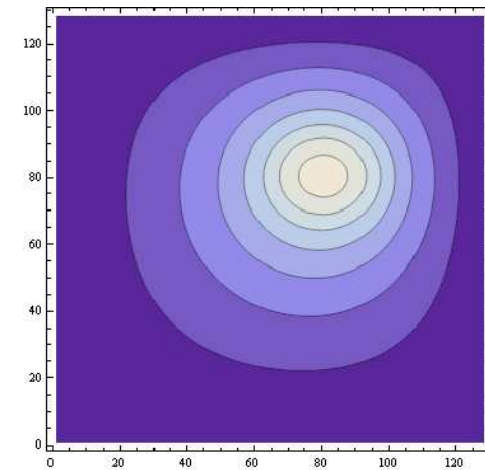
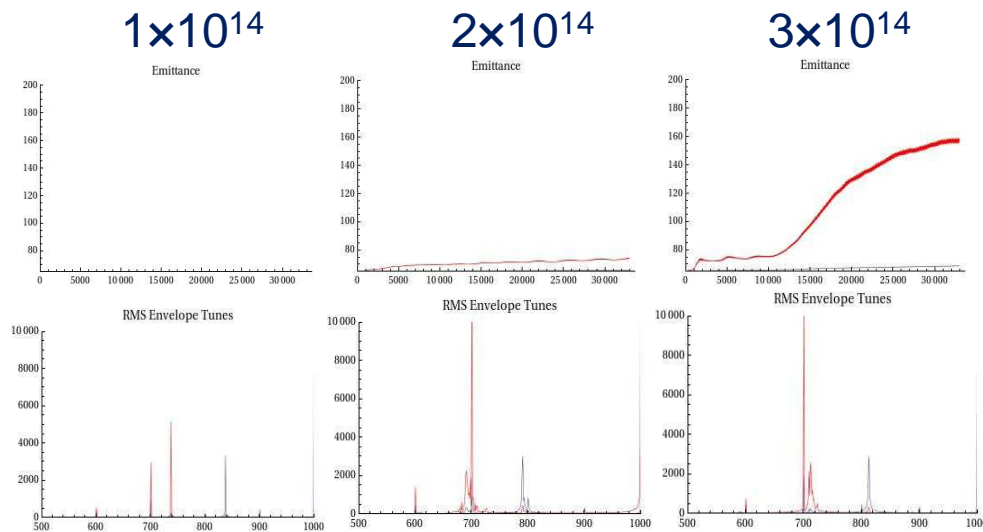
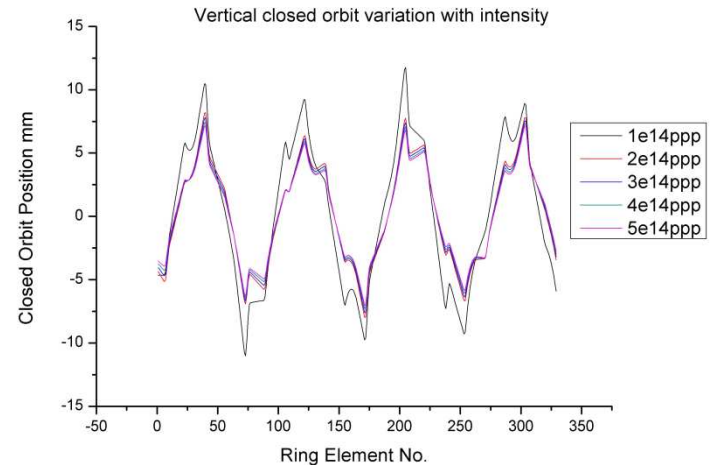


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# Transverse Beam Dynamics

- Simulation of space charge limit
- Behaviour of closed orbits at high intensity



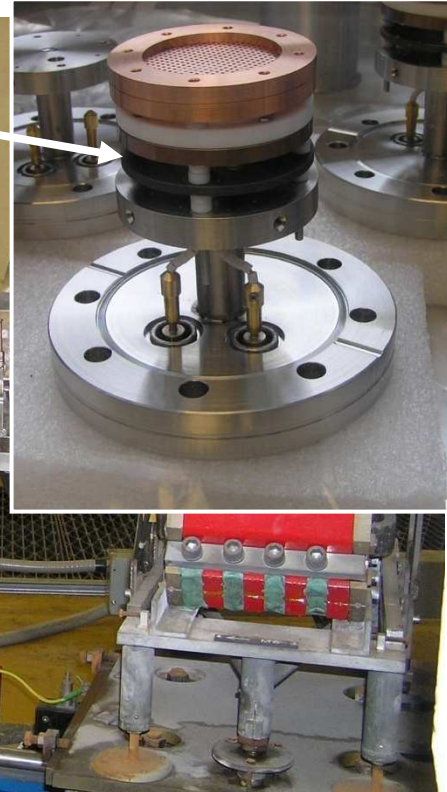
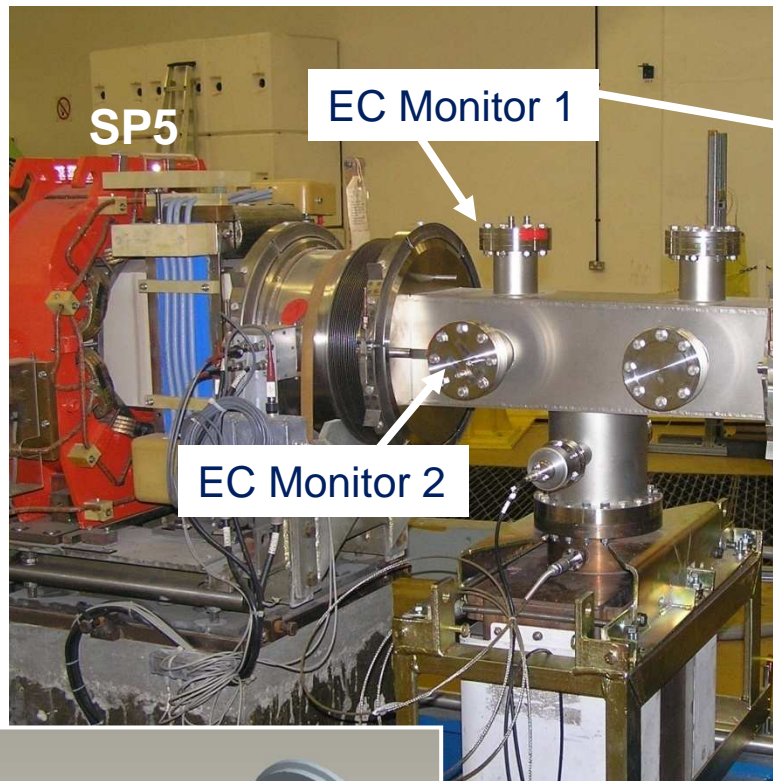
Injection at 180 MeV,  $a_1=0.01$ ,  $b_1=0.01$



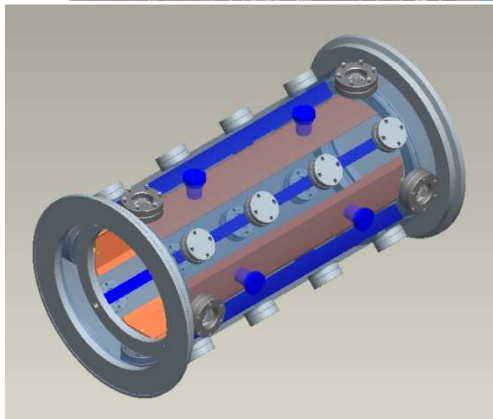
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# New Diagnostics for ISIS Upgrades



- Electron cloud (EC) induced beam instabilities could pose a problem for future high intensity and high energy ISIS upgrades
- Work underway to provide suitable diagnostics using Retarding Field Analyser (RFA) EC monitor



- Strip line monitor under design to measure beam instabilities in accelerator ring (whatever the cause) seen as high frequency beam envelope oscillations (will work hand in hand with RFA monitors)



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<http://www.isis.stfc.ac.uk/>



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