



Science & Technology
Facilities Council

Neutron Sources – Past, Present and Future

F P Ricci XIII SoNS School

Erice 2015

30th July 2015

Andrew Taylor

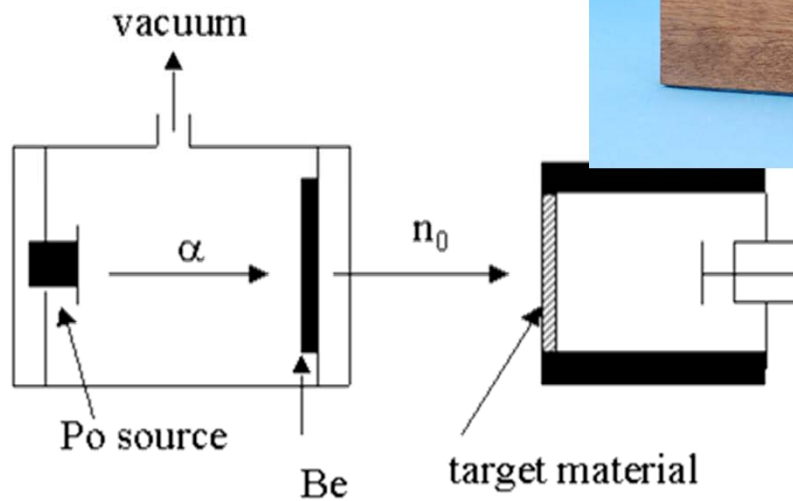


Outline

- **Neutron Sources – past, present and future**
- **Effectiveness of Neutron Facilities**
- **What we are doing in the UK**
- **What the future might hold**



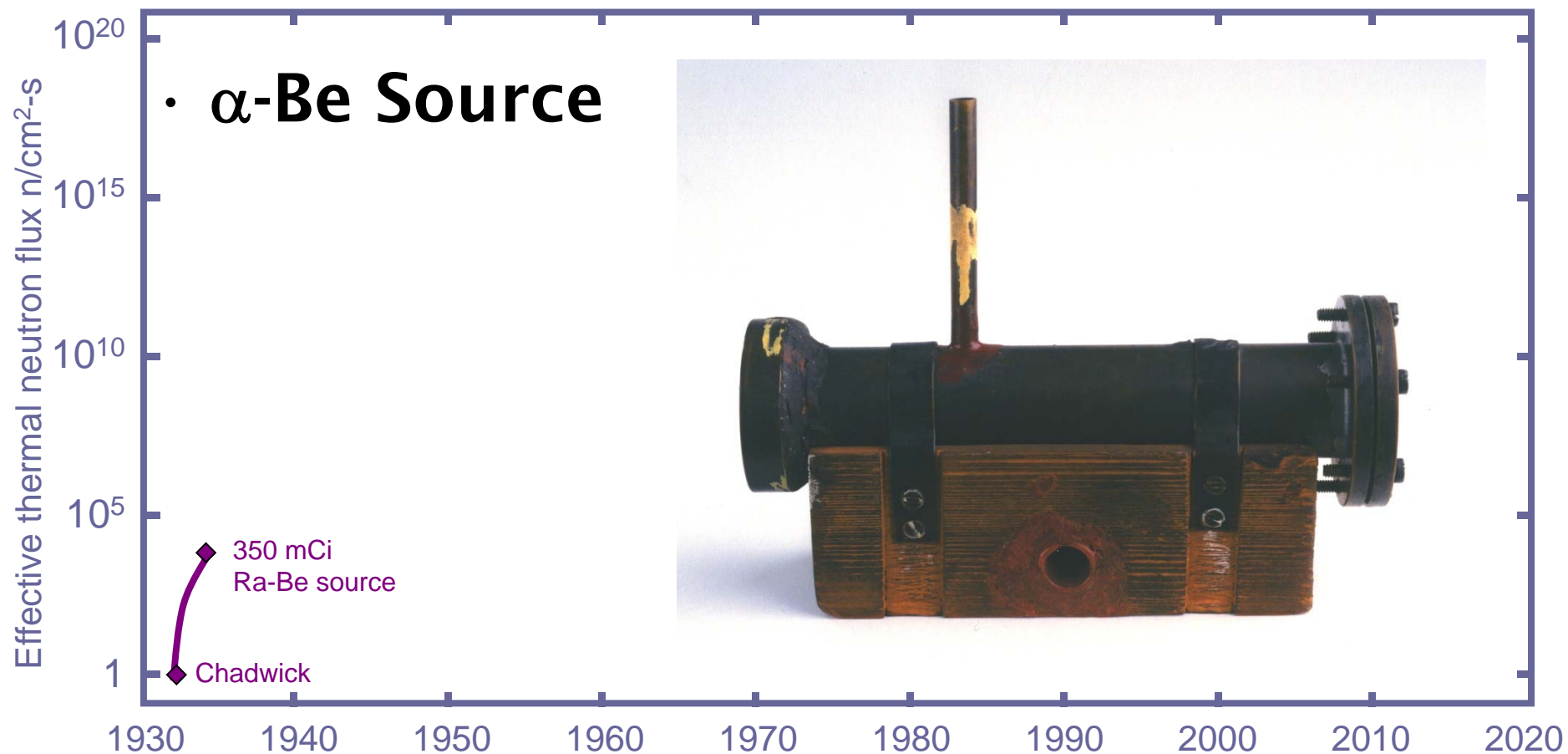
The First Neutron Source



aph
er



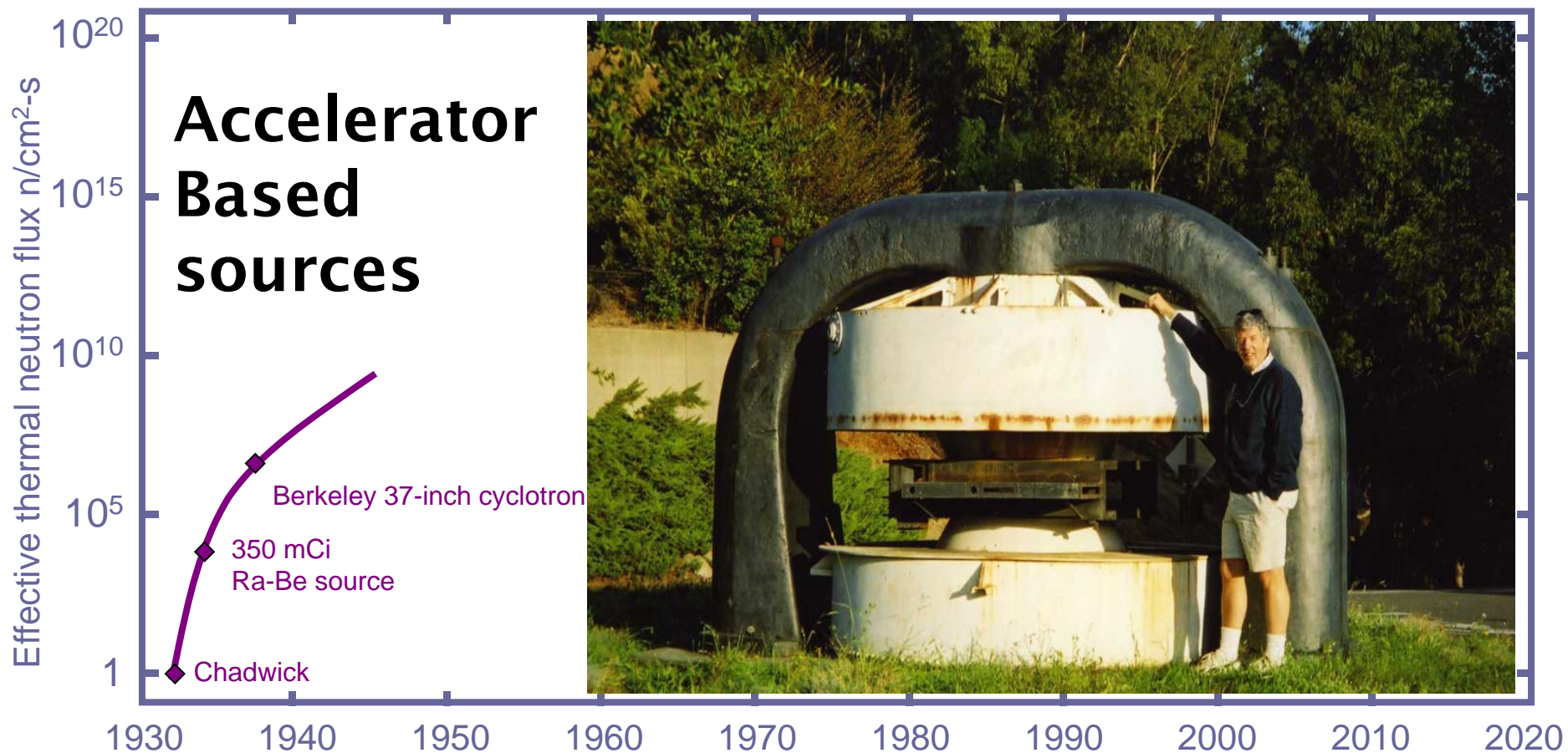
Neutron Sources



(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

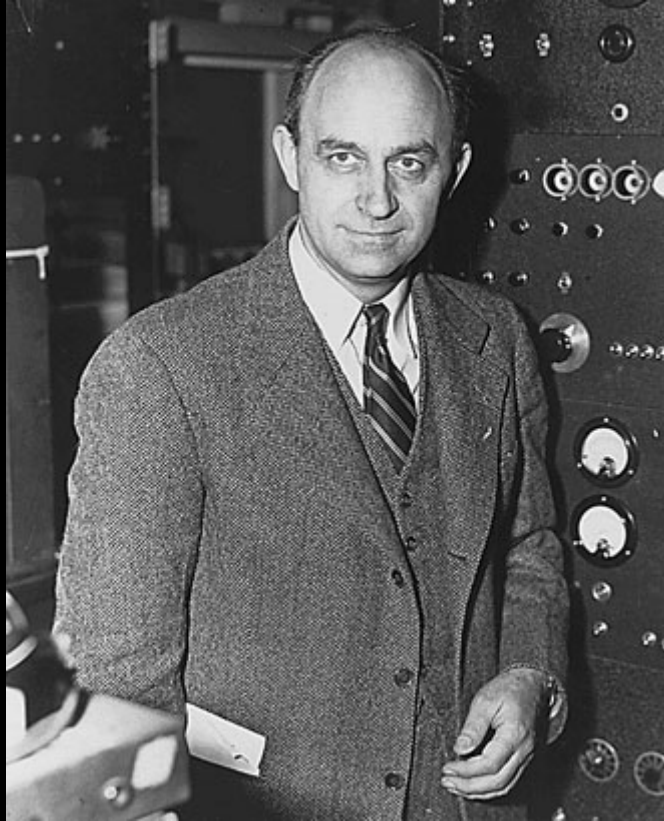


Neutron Sources



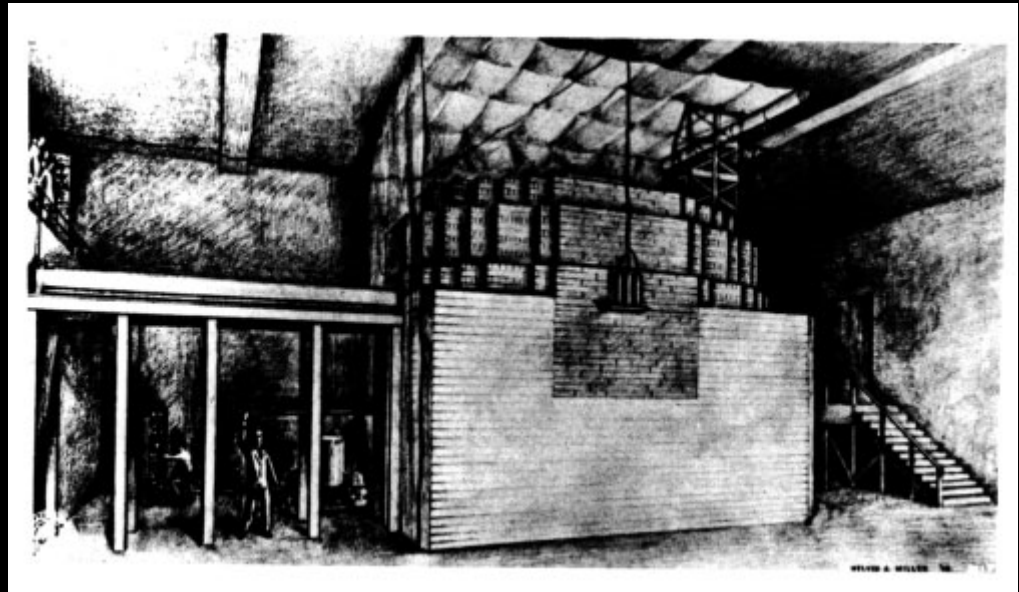
(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

Enrico Fermi 1901-1954



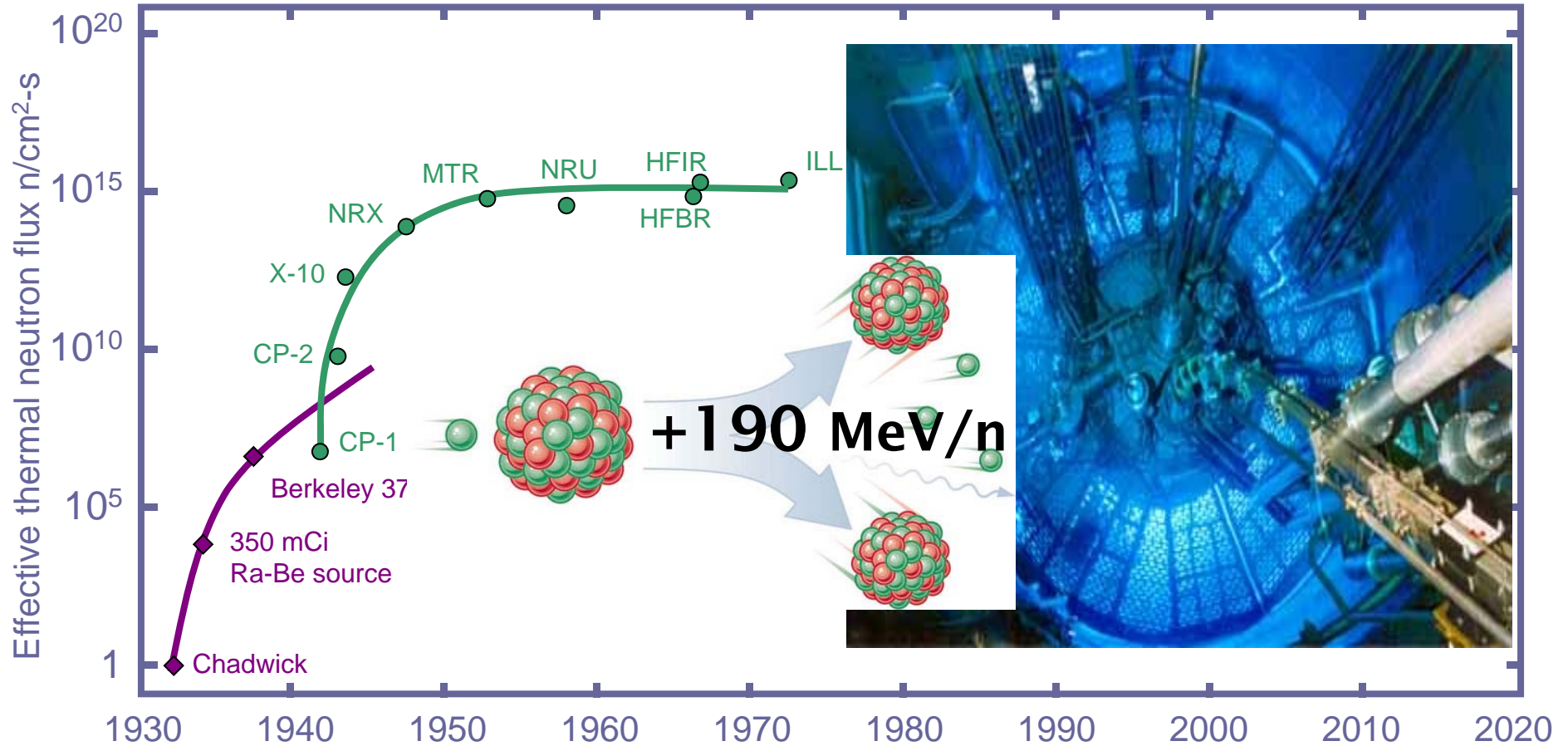
2nd December 1942 first 'atomic pile'

'Chicago Pile -- CP1'





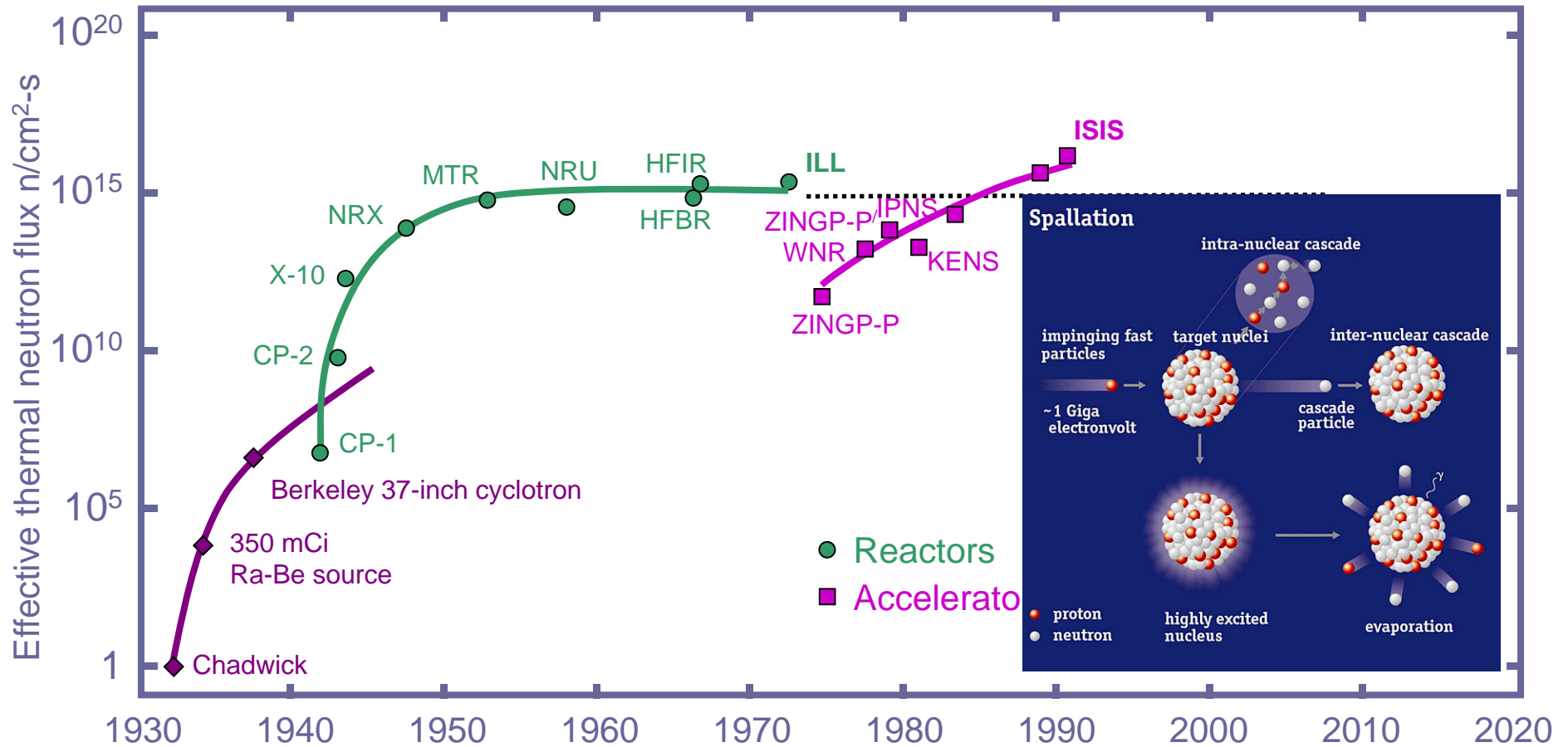
Neutron Sources



(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)



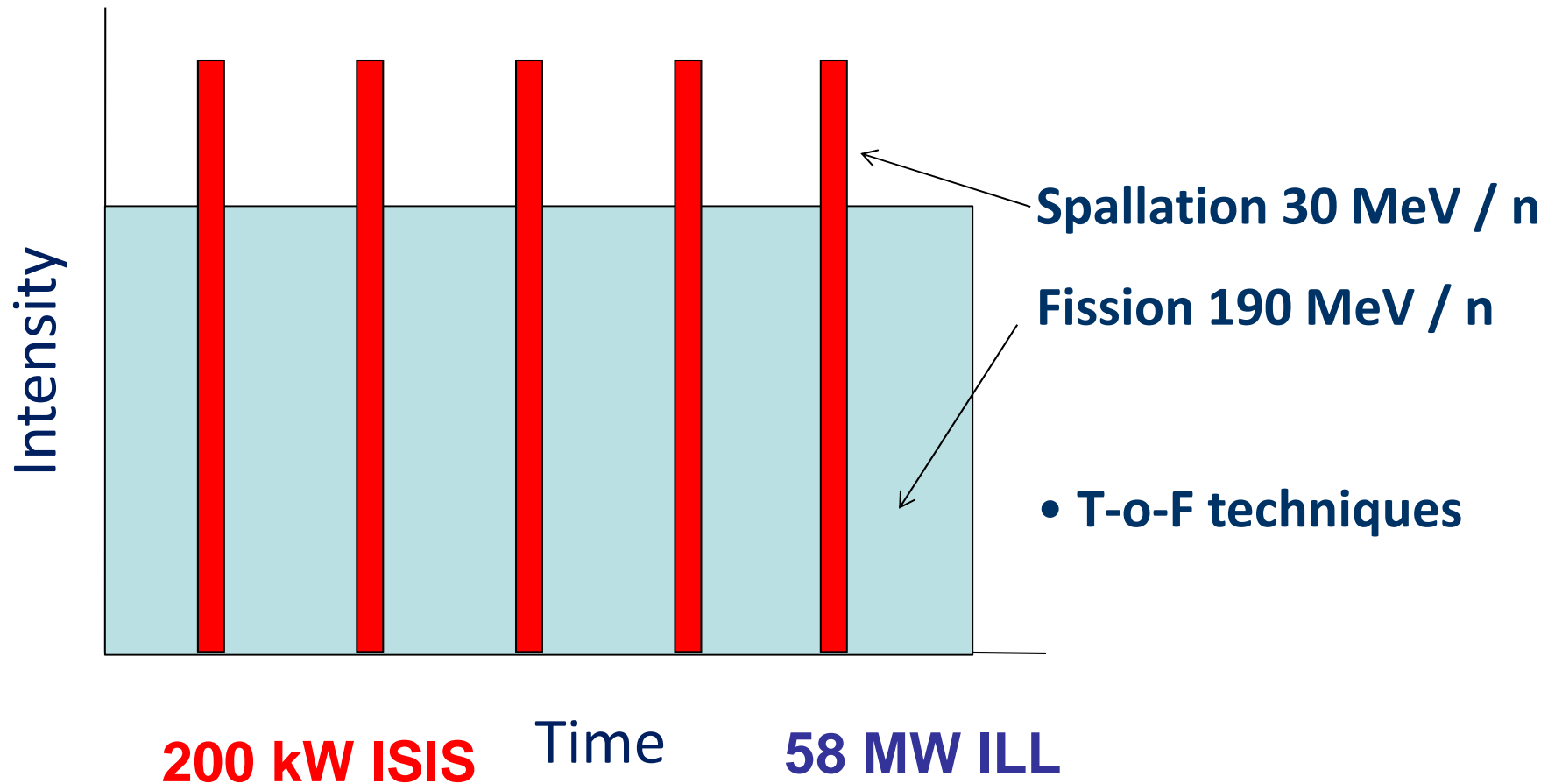
Neutron Sources



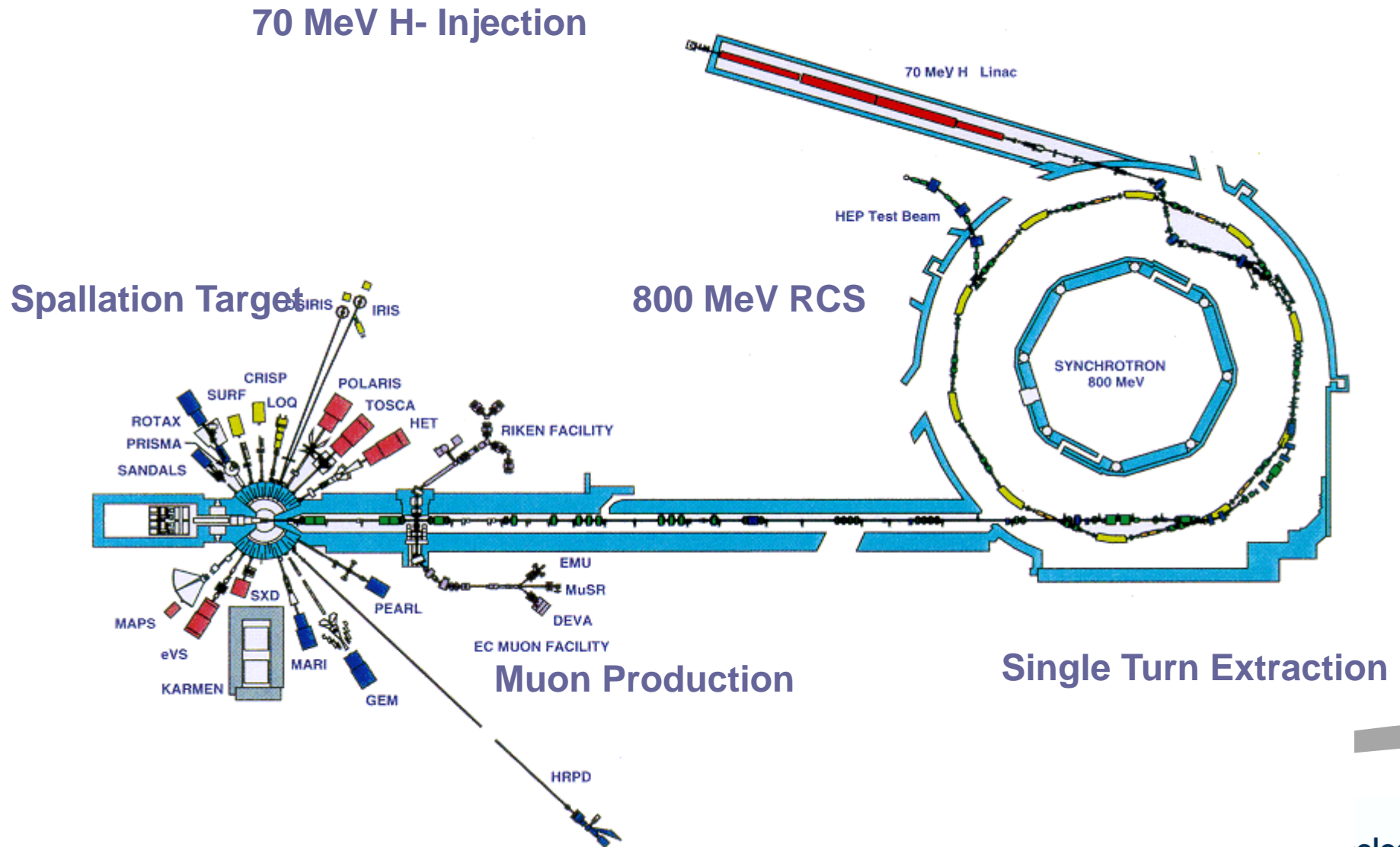
(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

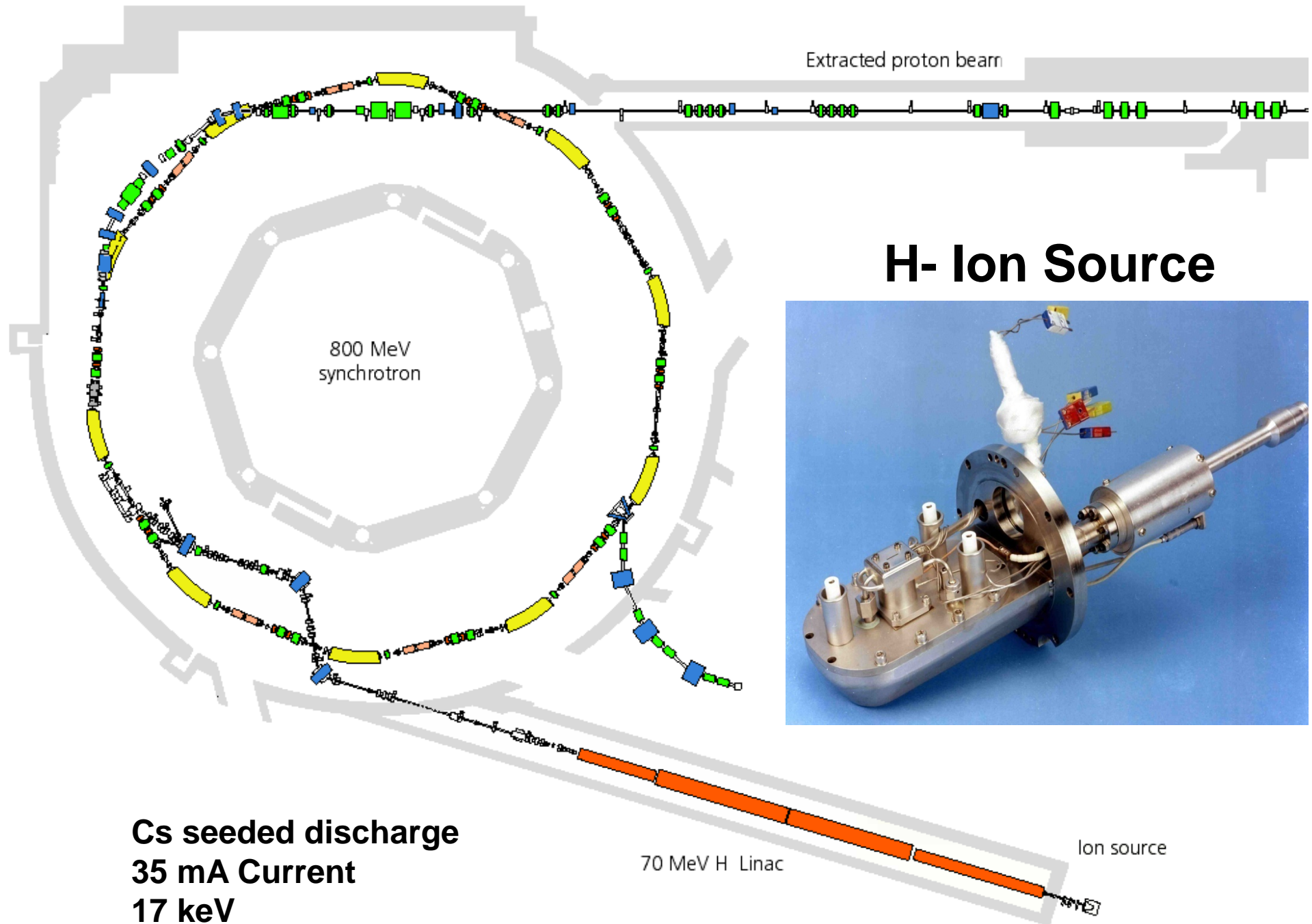


Pulsed versus Steady State

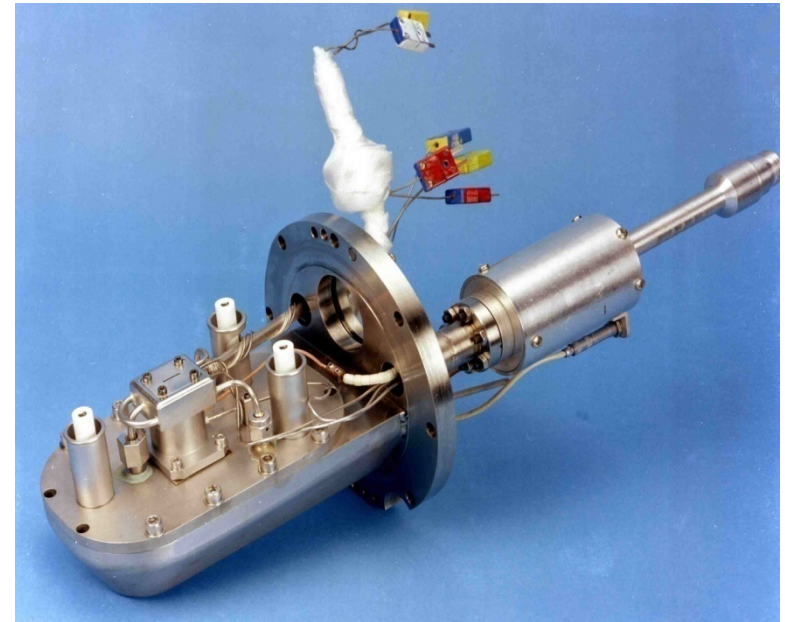


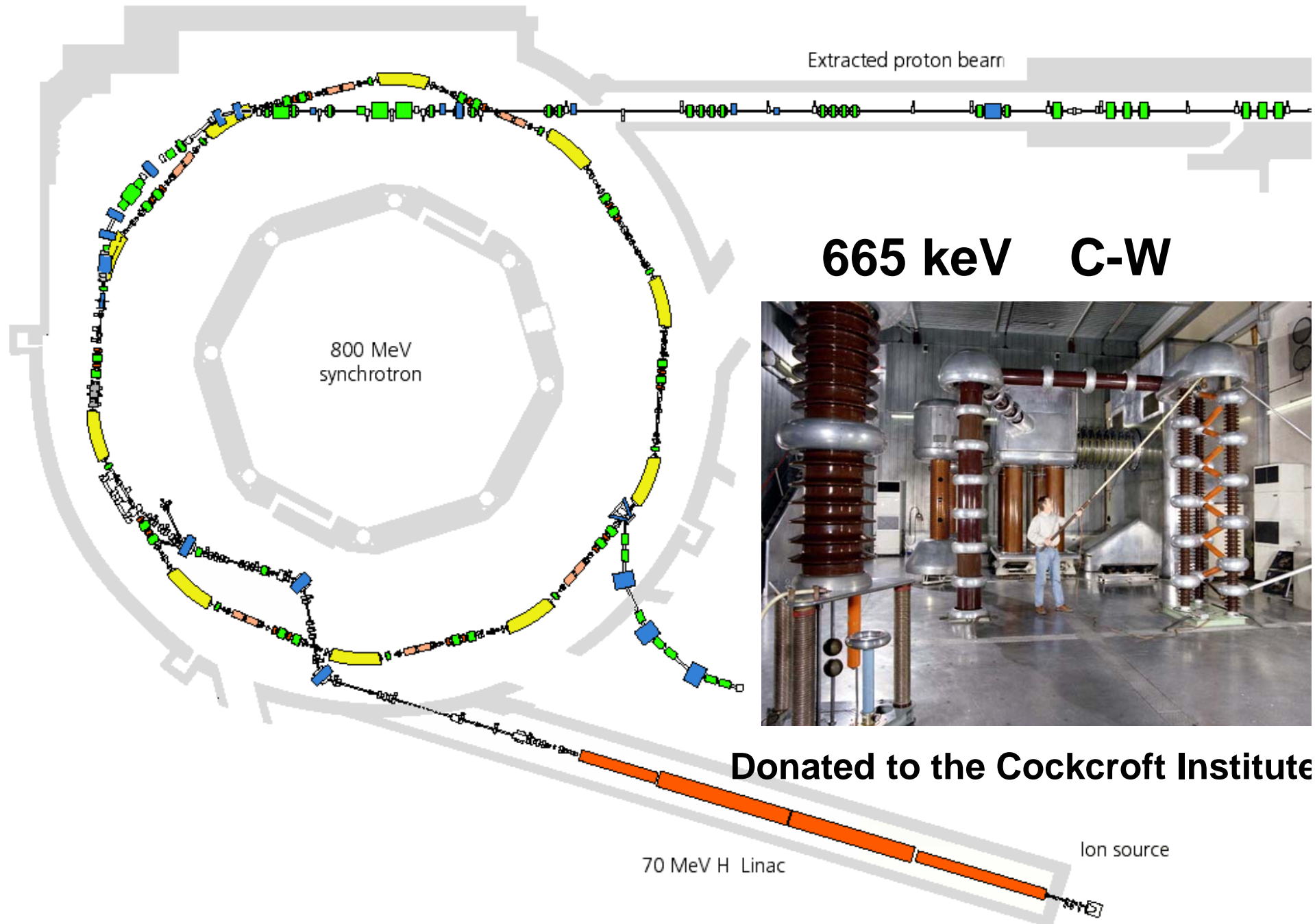
ISIS Pulsed Spallation Source.





H- Ion Source



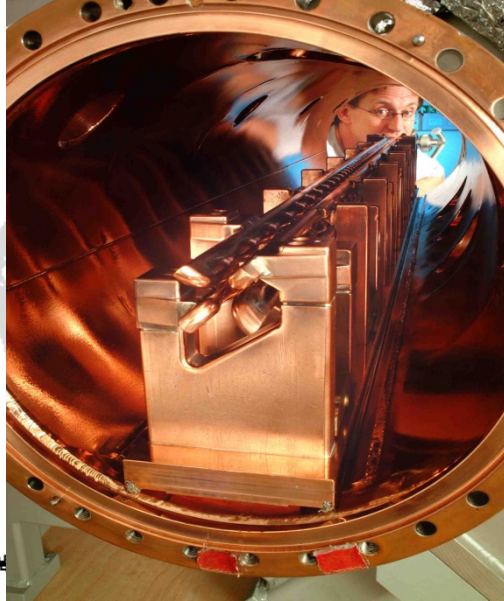


665 keV C-W

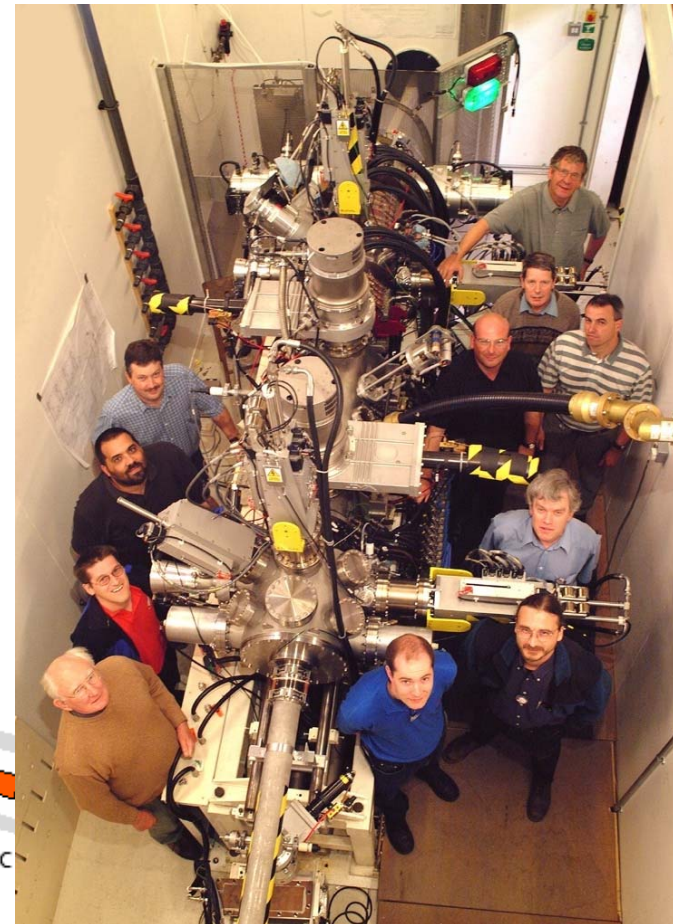


Donated to the Cockcroft Institute

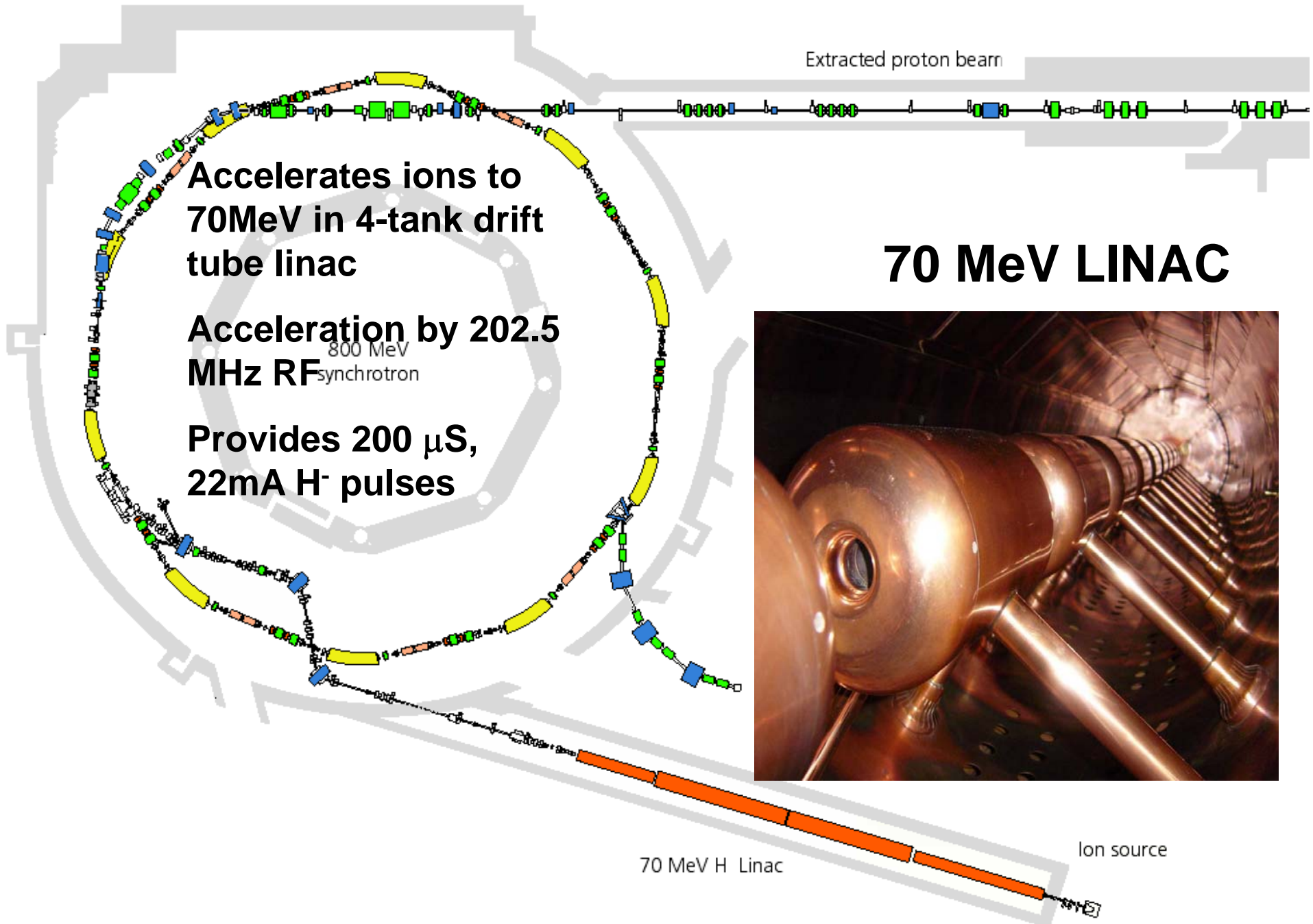
Extracted proton beam



665 keV RFQ

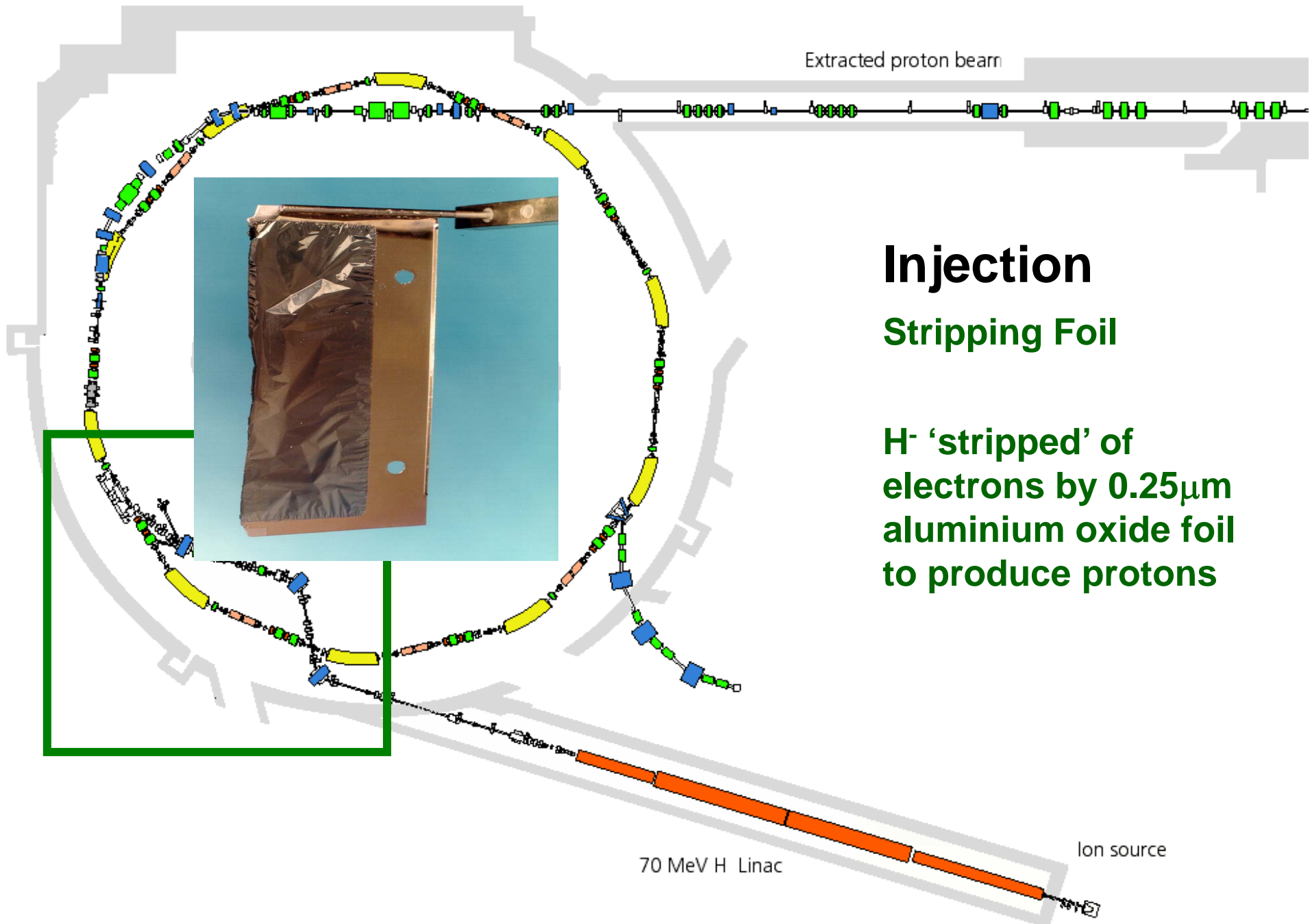


70 MeV H Linac



70 MeV LINAC





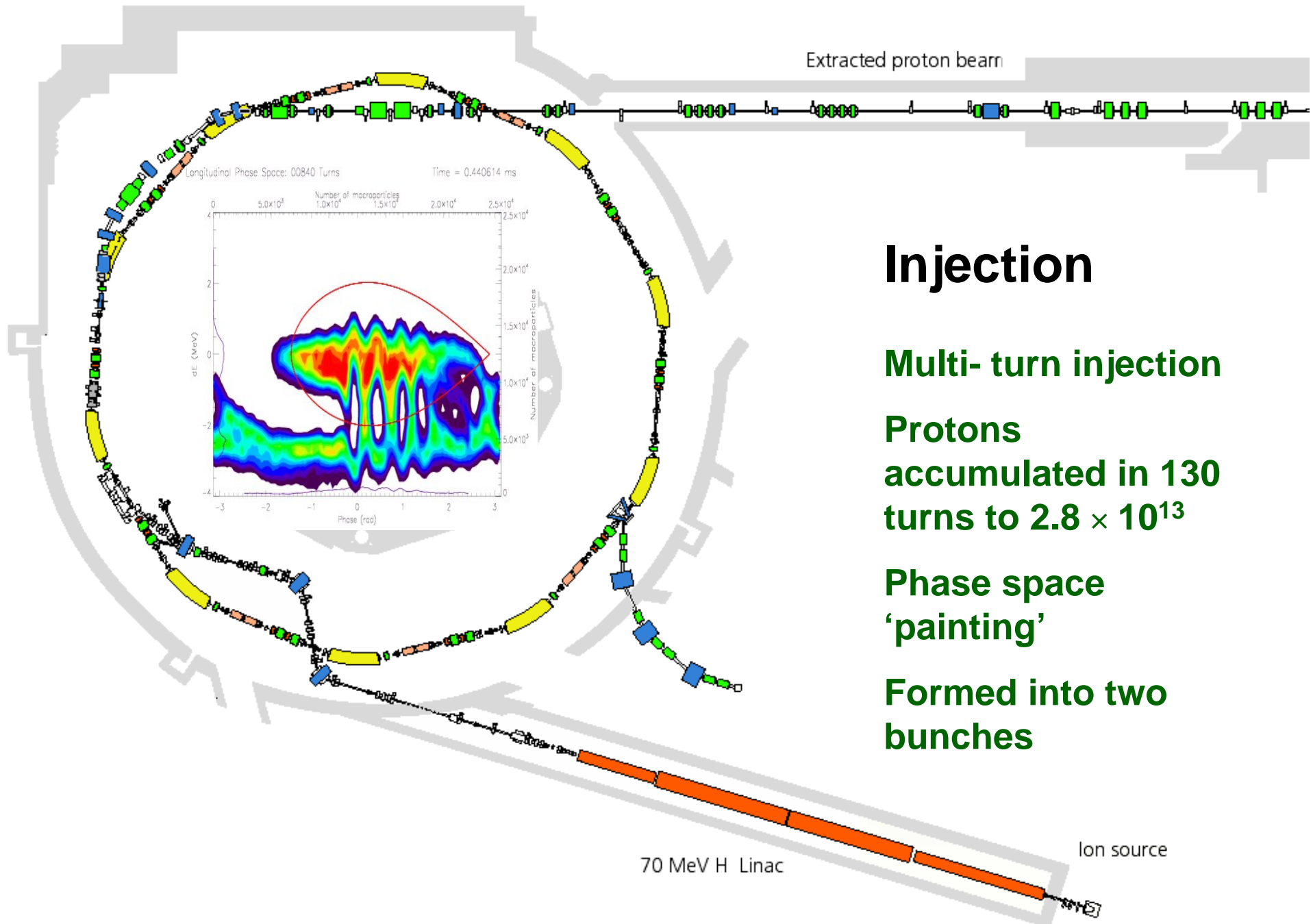
Extracted proton beam

Injection Stripping Foil

H⁻ 'stripped' of electrons by 0.25μm aluminium oxide foil to produce protons

70 MeV H Linac

Ion source



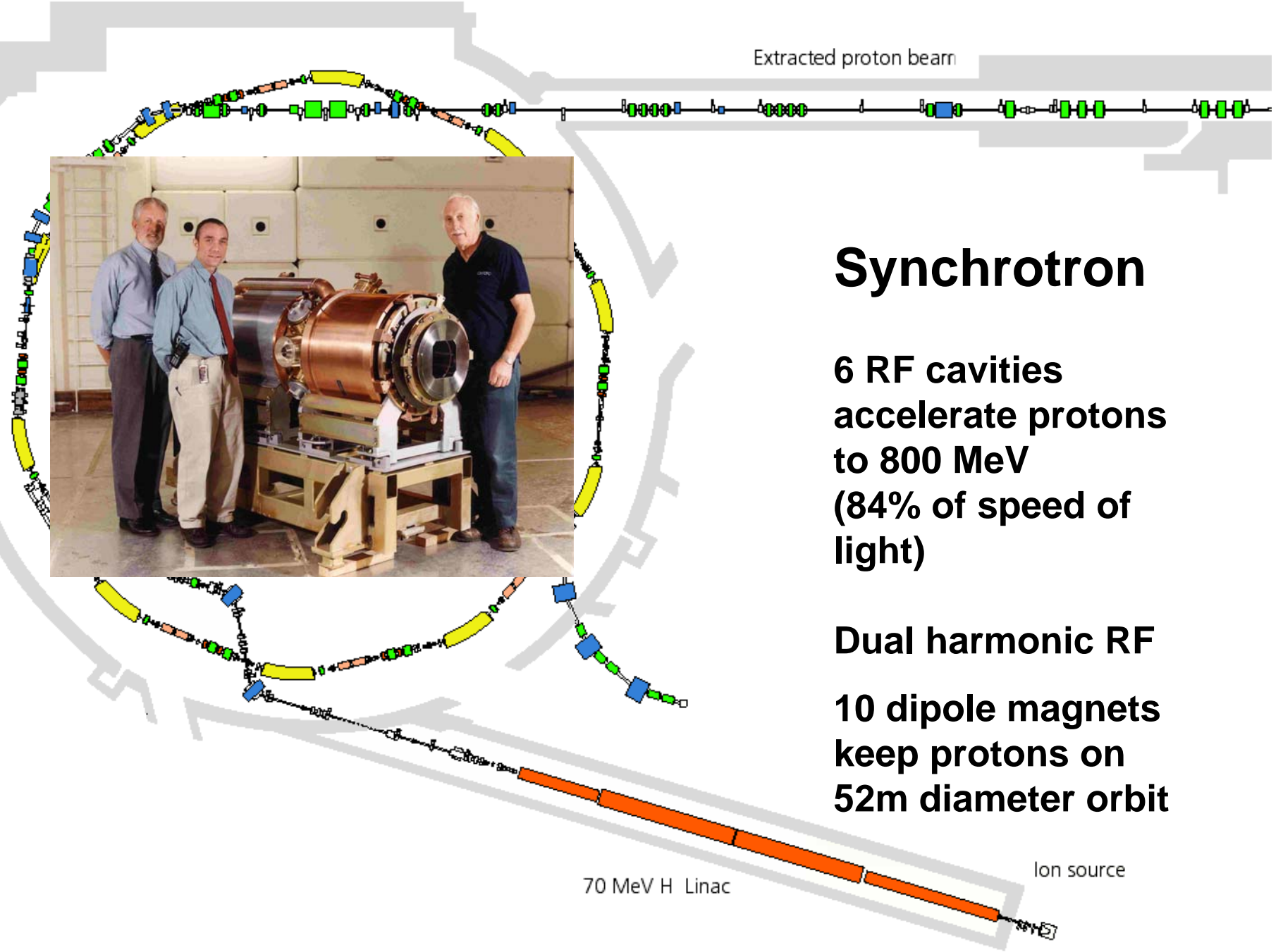
Injection

Multi- turn injection

Protons accumulated in 130 turns to 2.8×10^{13}

Phase space 'painting'

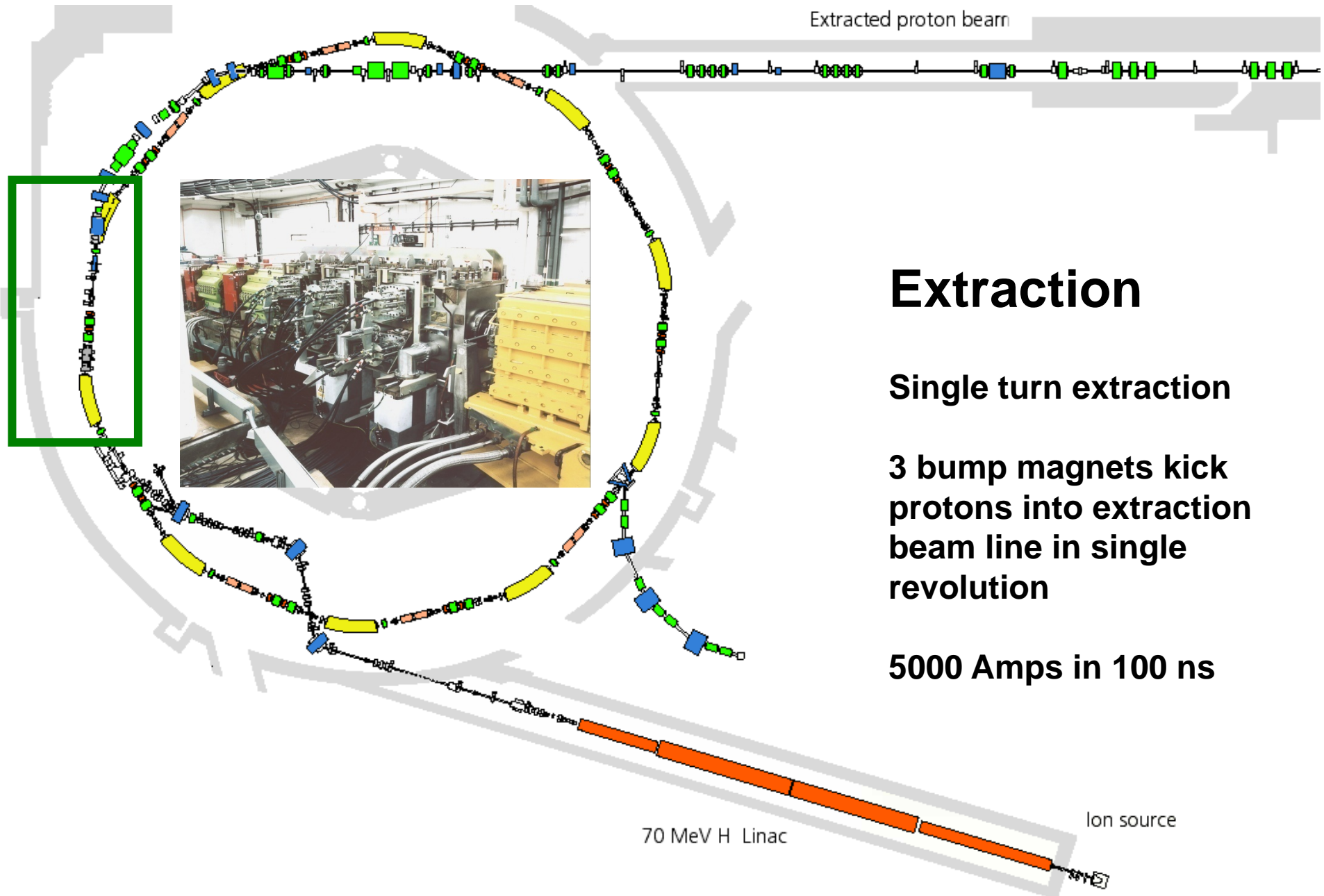
Formed into two bunches



Synchrotron

**6 RF cavities
accelerate protons
to 800 MeV
(84% of speed of
light)**

**Dual harmonic RF
10 dipole magnets
keep protons on
52m diameter orbit**



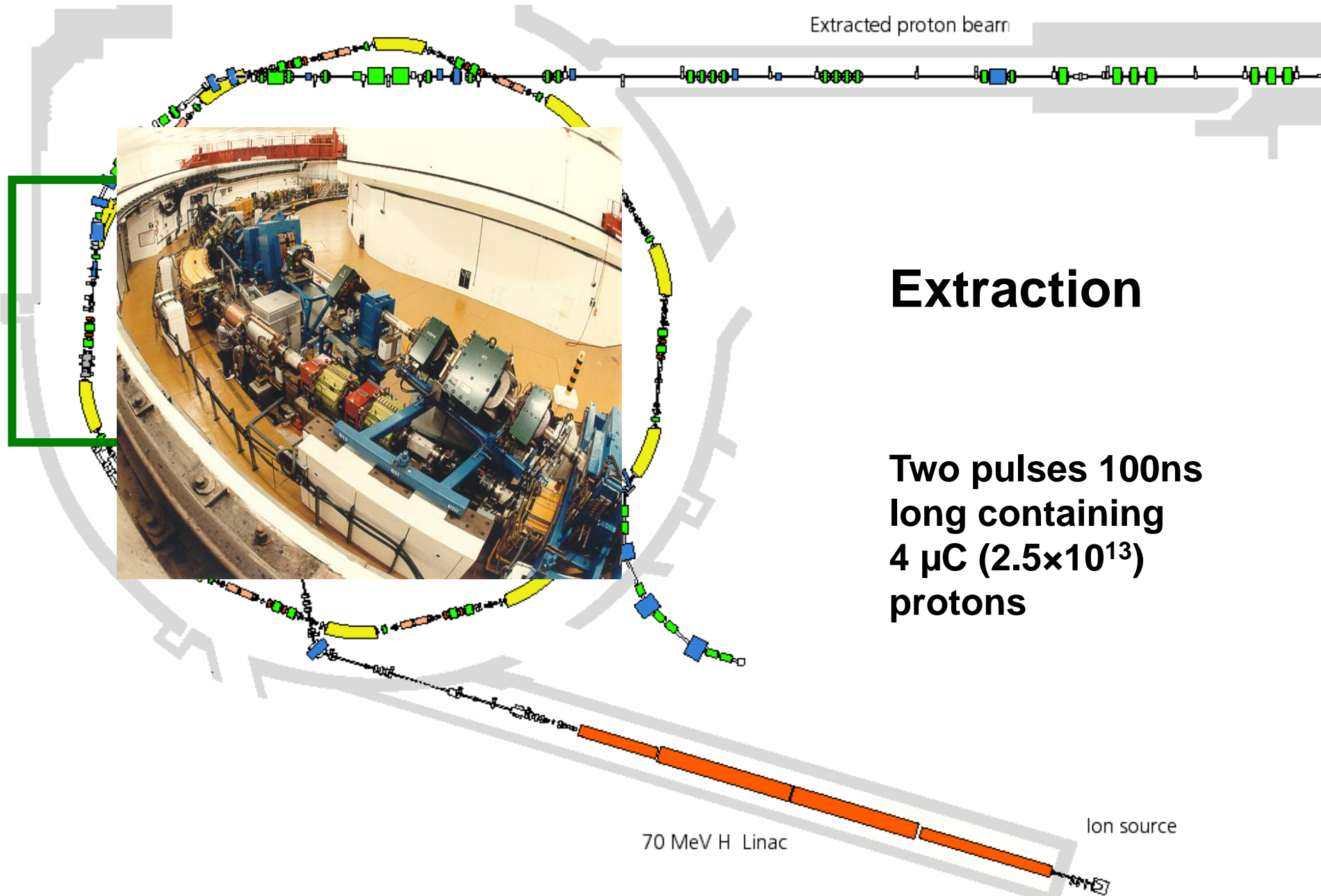
Extraction

Single turn extraction

3 bump magnets kick protons into extraction beam line in single revolution

5000 Amps in 100 ns



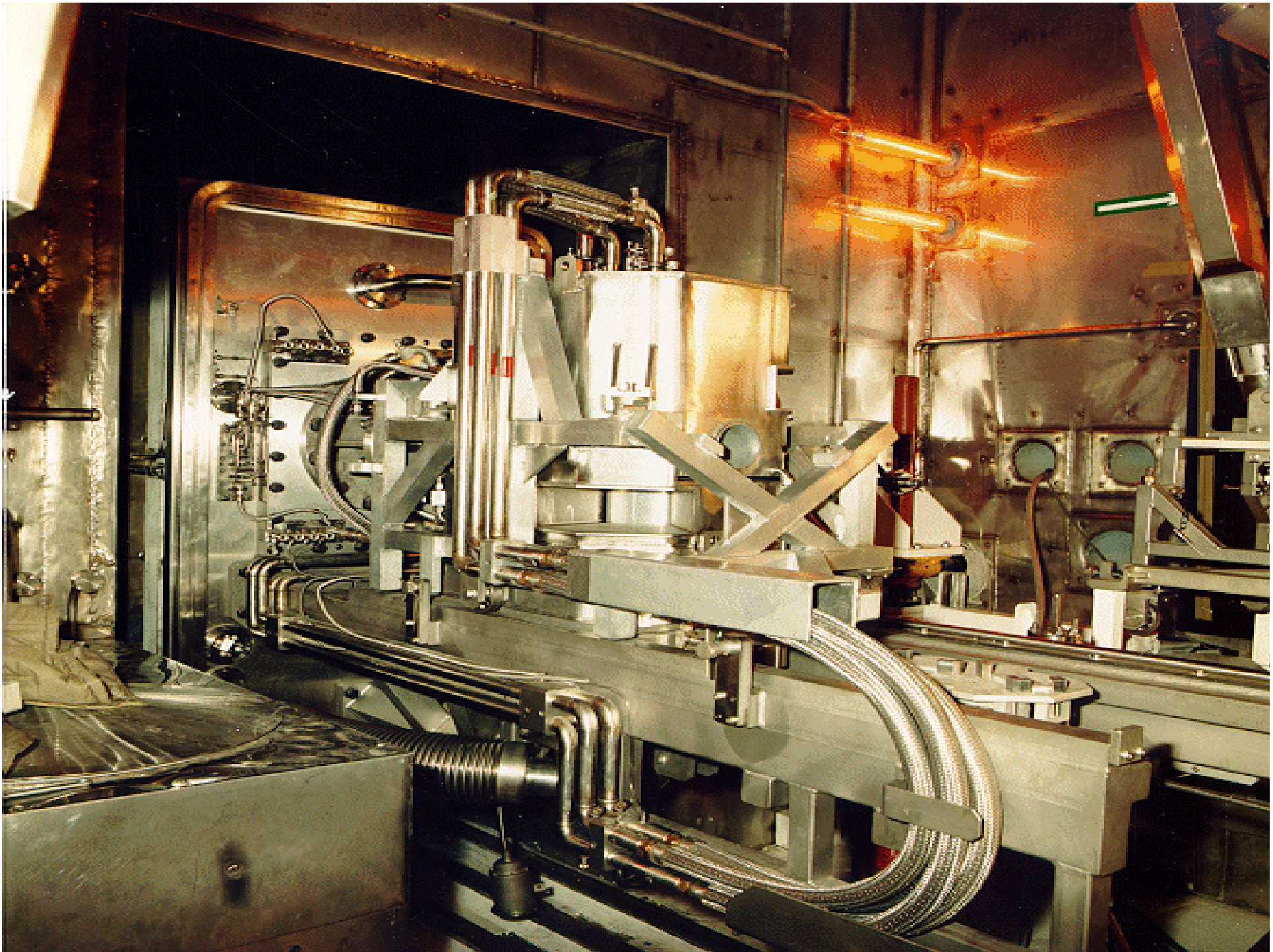


Extraction

Two pulses 100ns
long containing
 $4 \mu\text{C}$ (2.5×10^{13})
protons

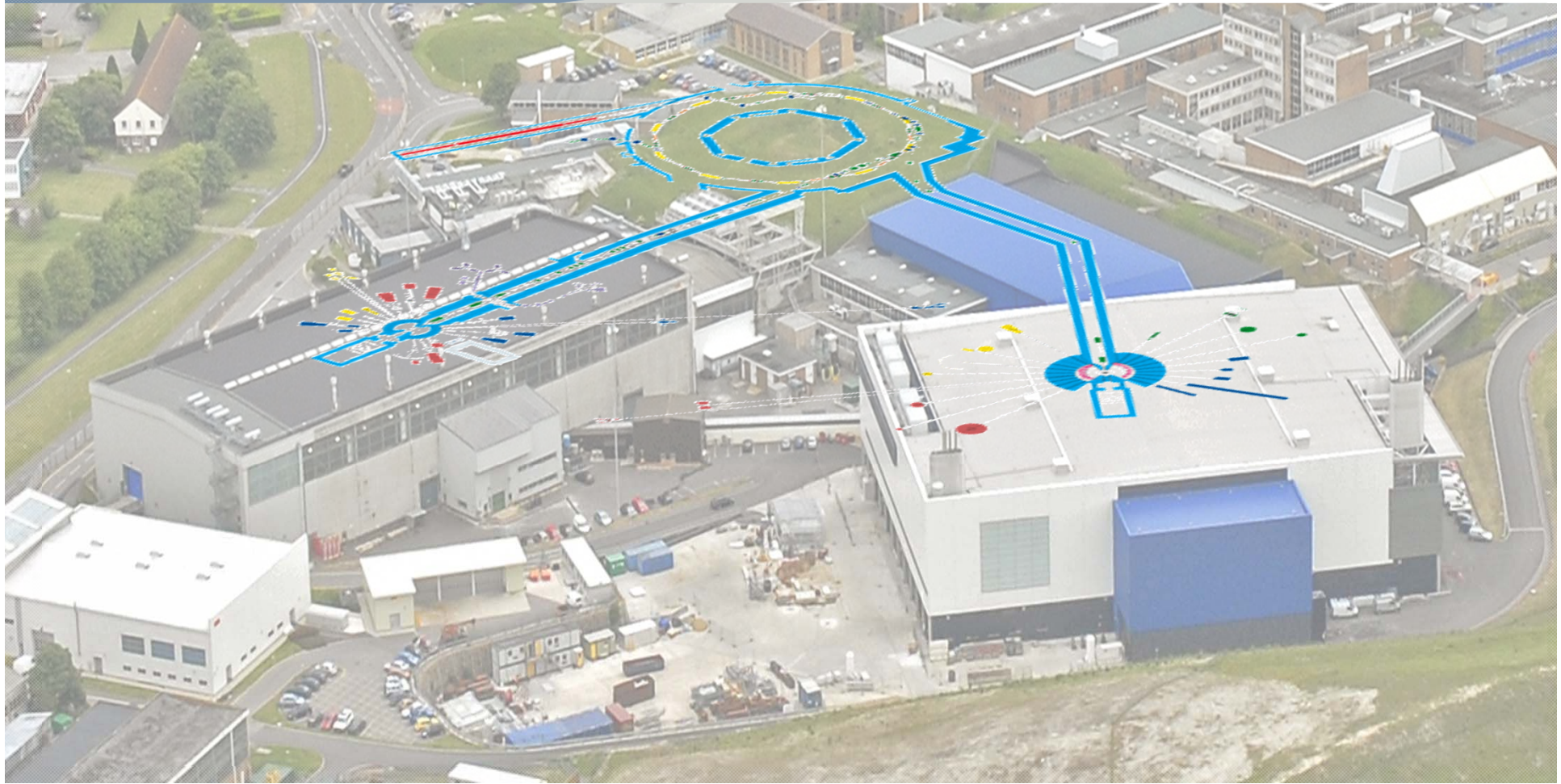






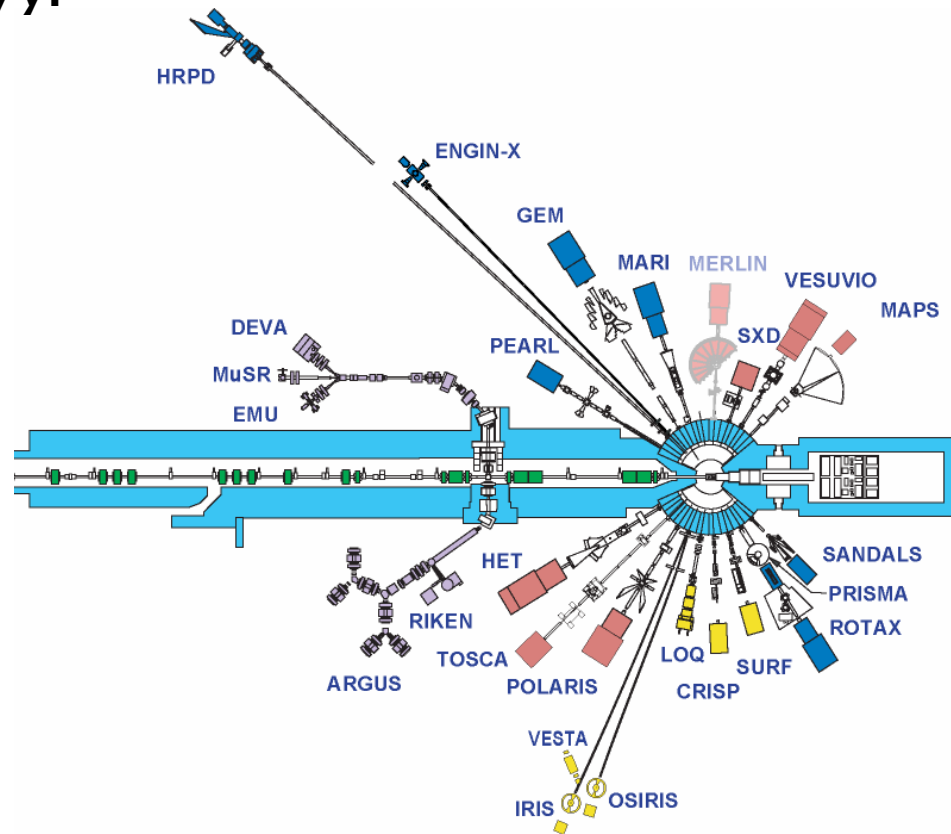


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A World Centre for Research in the Physical and Life Sciences with Neutrons and Muons

- Broad Academic Base ~2000/yr
- Resonating with the strengths of UK SEB
- 90% of UK Users 5/5* Depts
- 700 Experiments/ yr
- 500 Publications/ yr

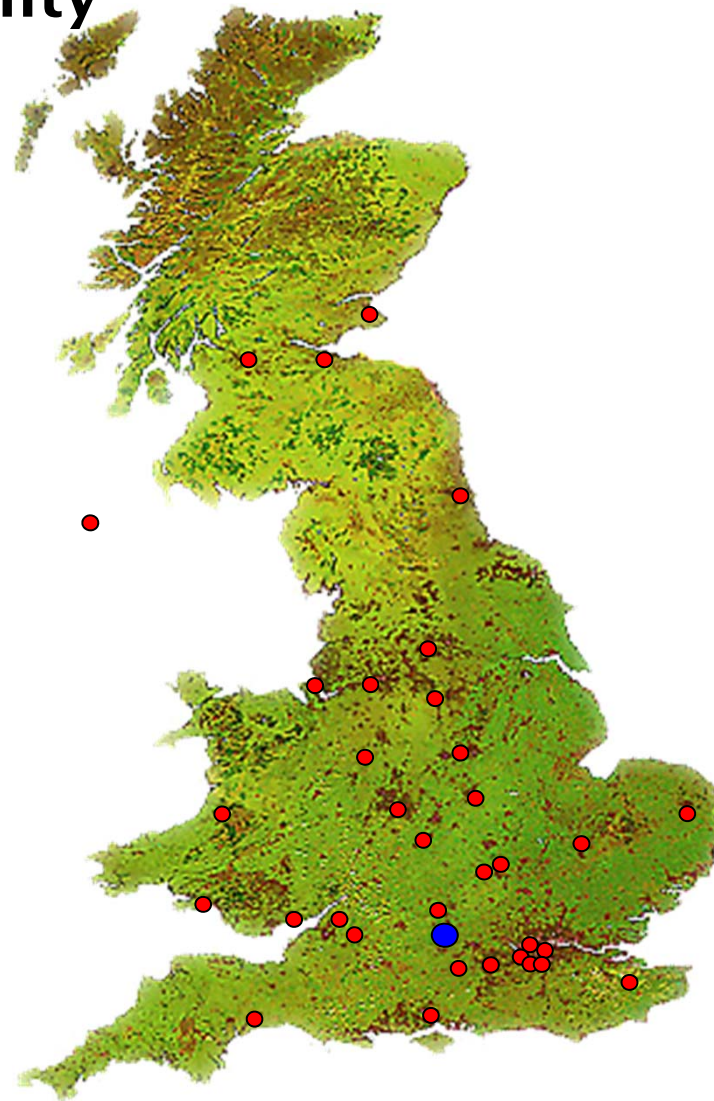


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ISIS

ISIS UK Community

Aberystwyth
Bath
Belfast
Birmingham
Bristol
Cambridge
Cardiff
Cranfield
Durham
East Anglia
Edinburgh
Exeter
Glasgow
Keele
Kent

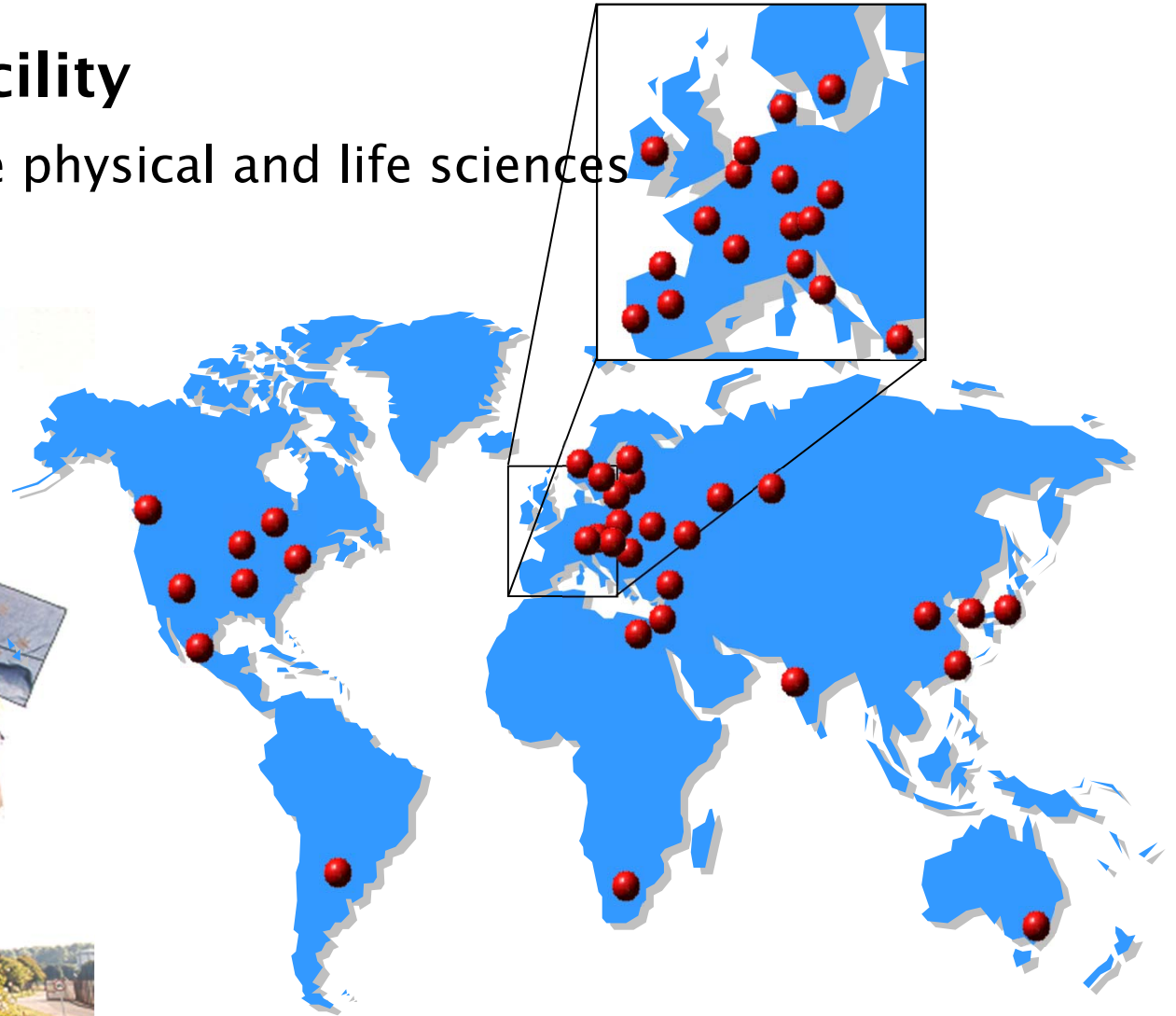
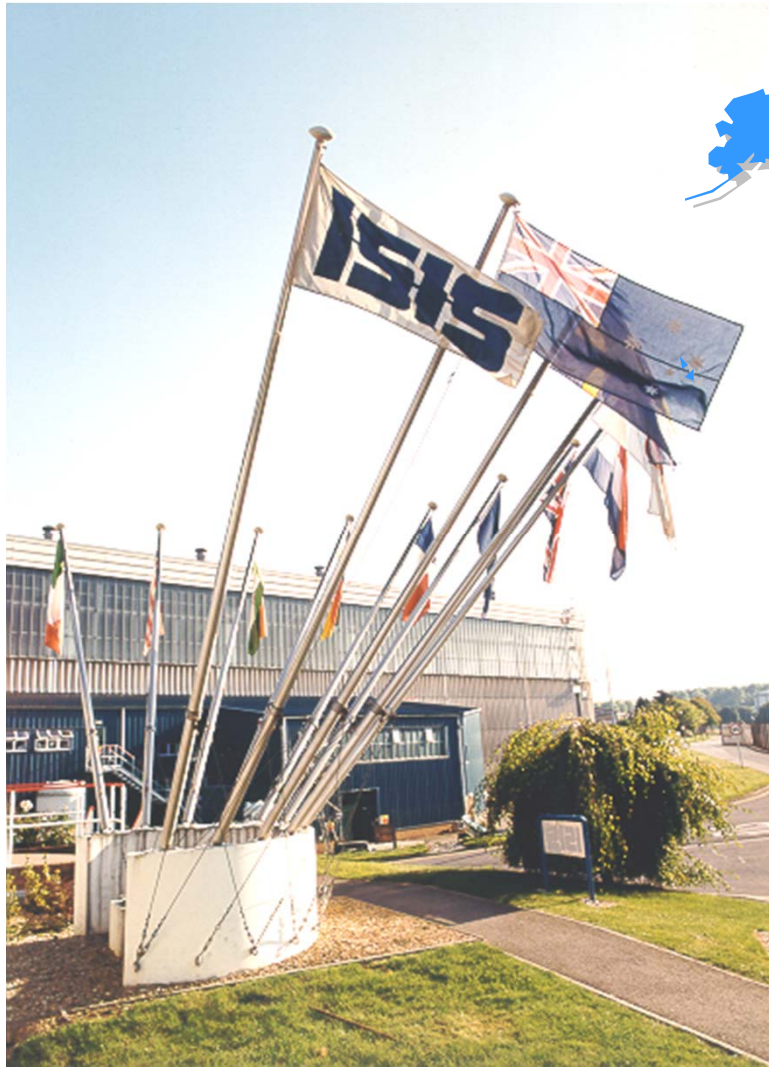


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OU
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Reading
Sheffield
Southampton
St. Andrews
Surrey
Swansea
Warwick



A world leading facility

for research in the physical and life sciences



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No One Experiment



Achievements of neutron scattering
– the evolution and diversification of neutron scattering
over the past 40 years



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US Spallation Neutron Source





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JPARC – Tokai







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ISIS 

remains
a world
leading
pulsed
neutron
and muon
research
centre

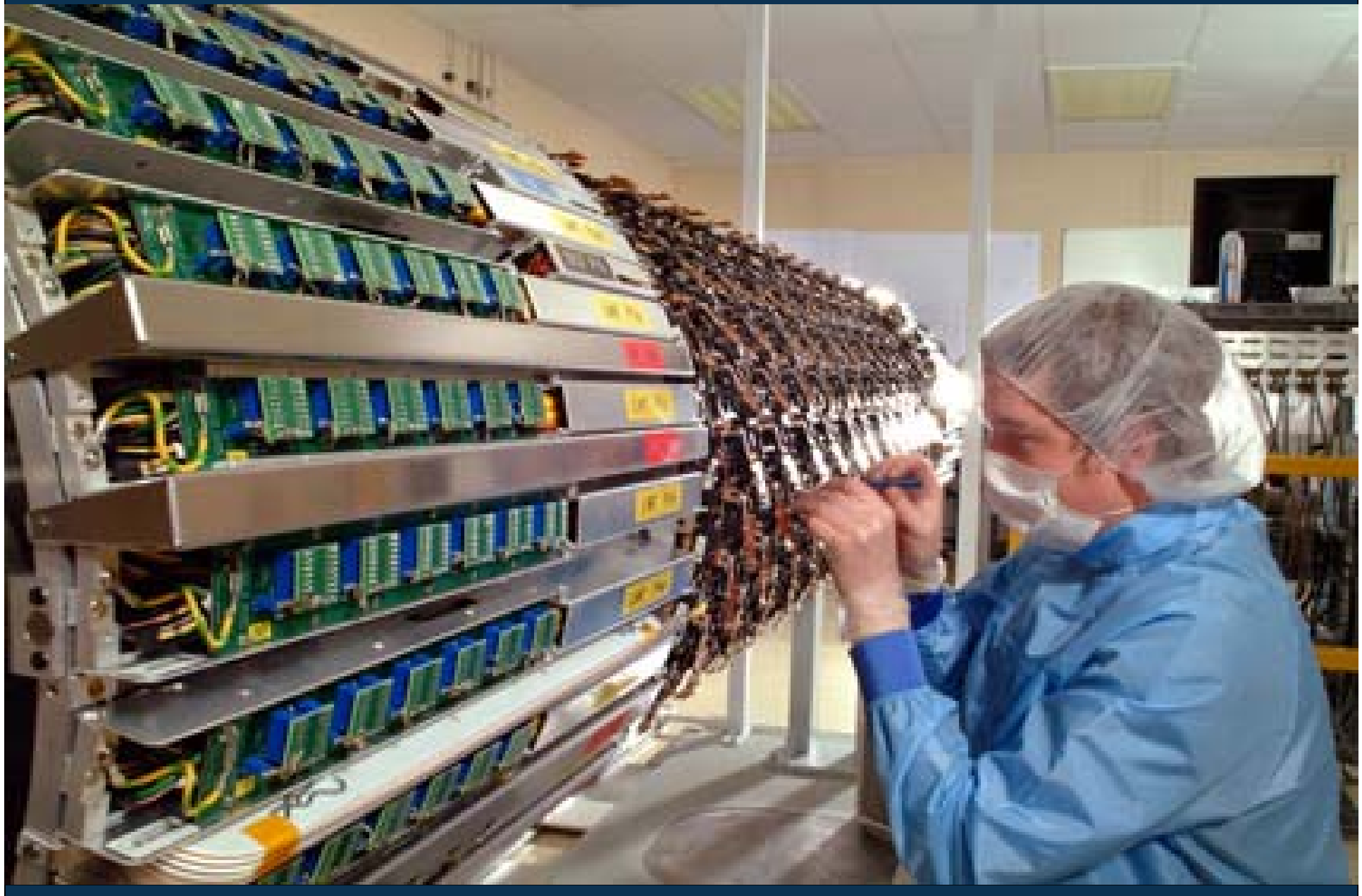


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Advanced Technology





STFC Technology Transfer



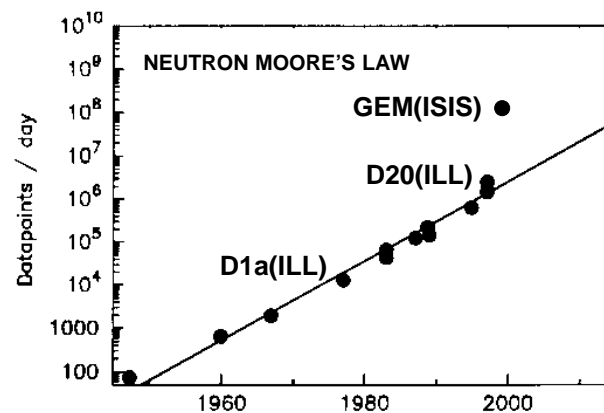
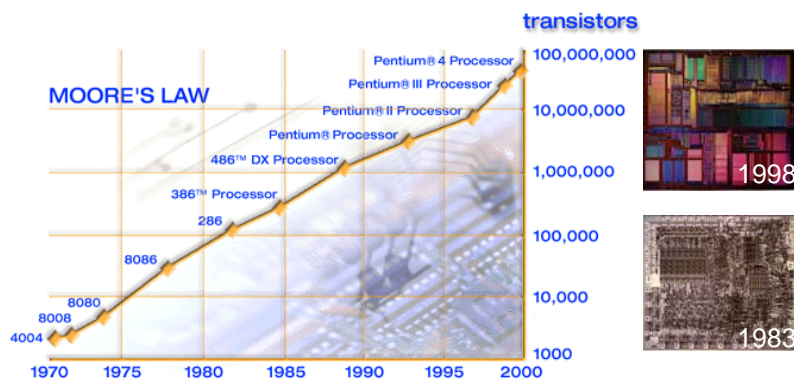
efficient large solid angle detectors...



...fast electronics

detectors and advanced data acquisition - unique synergy within STFC

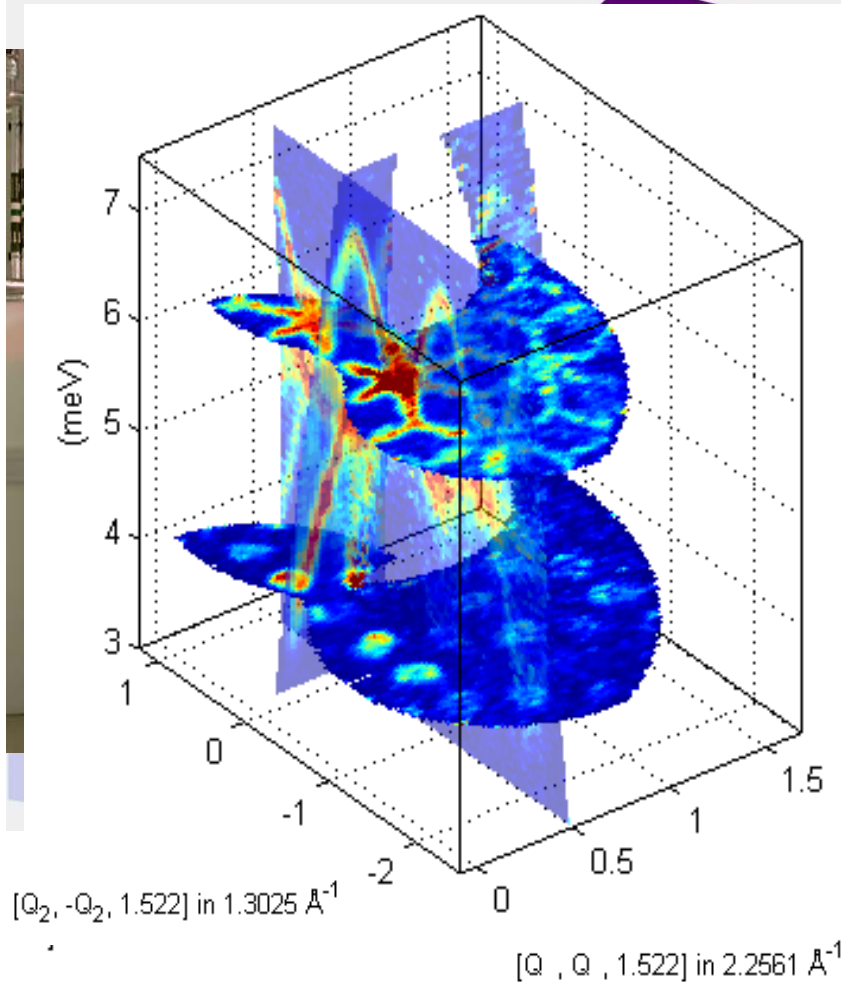
4 orders of magnitude in 30 years



Neutron powder diffraction data rates (1950-2010) (4 orders of magnitude gain with ILL/ISIS alone)



Instrument Development



Detectors

- LAD → GEM **x 30**
- ENGIN → ENGIN-X **x 20**
- HET → MAPS **x 25** → LET **x 3**
- SXD → SXD11 **x 11** → SXD' **x 5**

R&D

- Detectors,
Smaller pixels, Higher Rates, Lower Costs
- Optics, Pol Filters, Choppers
- HRPD → HRPD' **x 10**

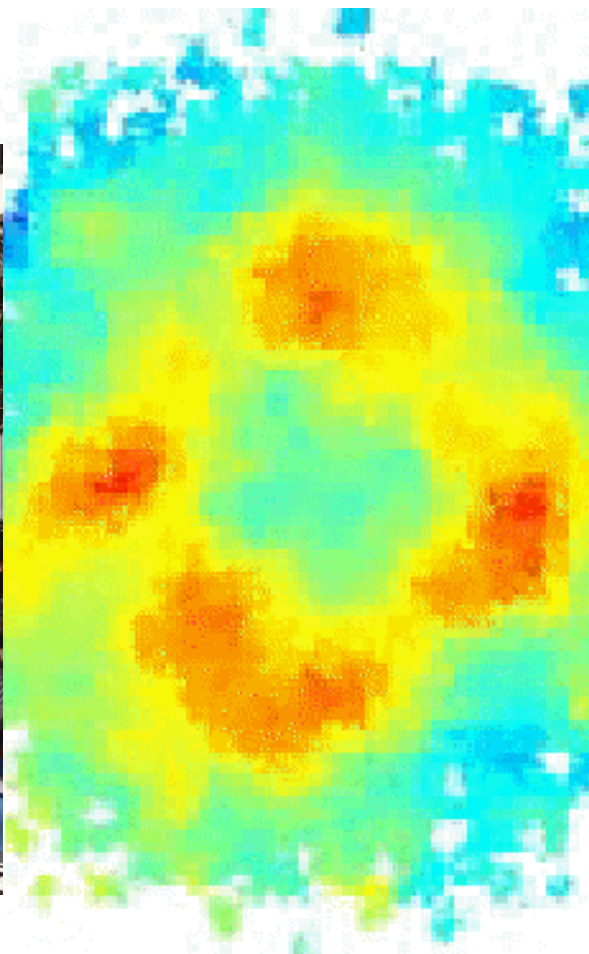
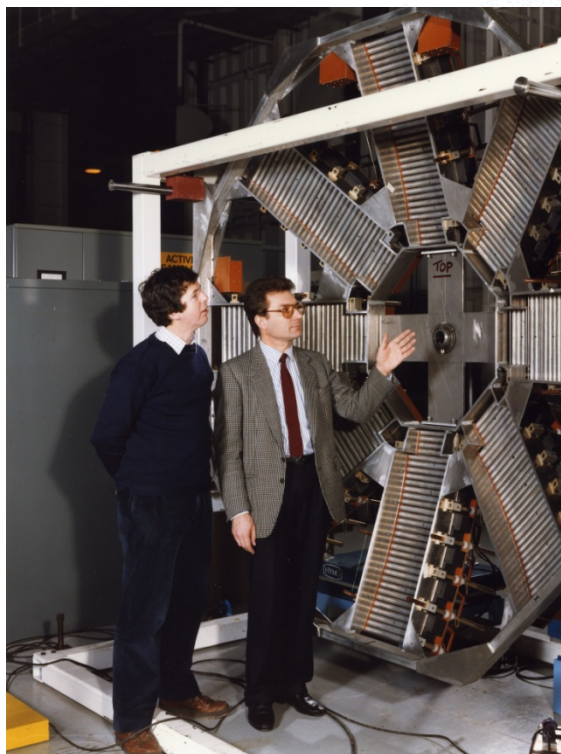
Sample Environment

Software



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ISIS

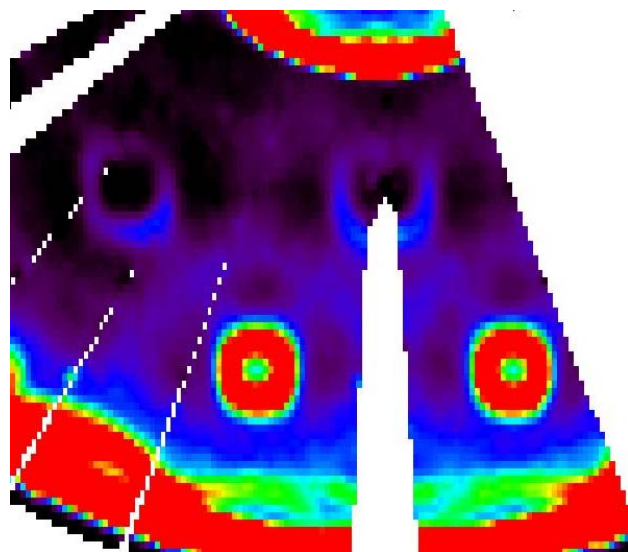
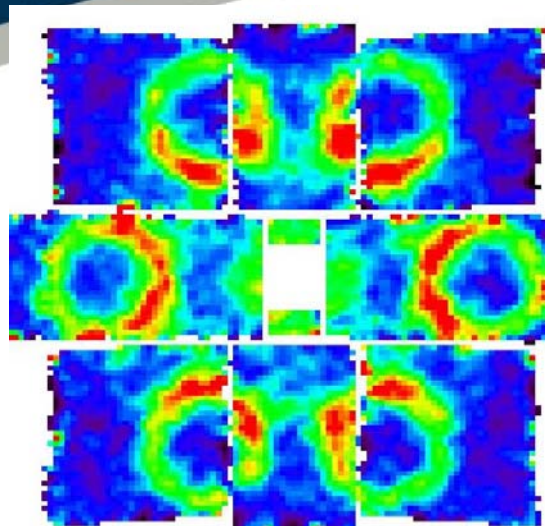


HET : December 1984 - December 2008

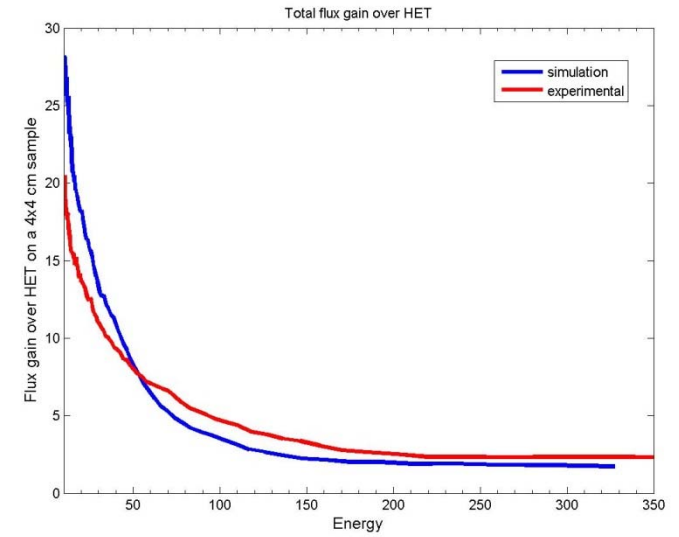


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ISIS





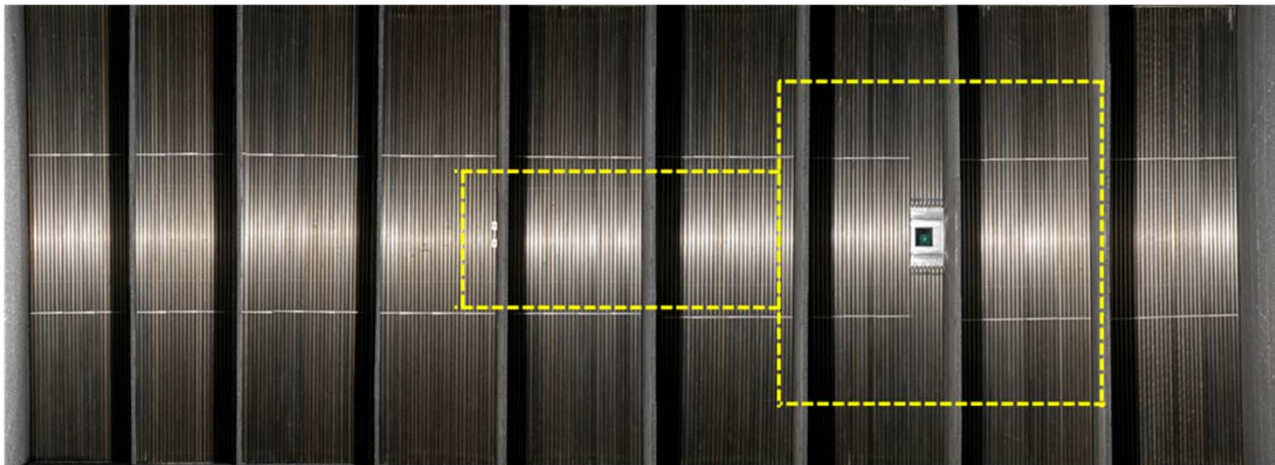


Flux gain over HET due to guides and new moderator

135°

0°

-45°



MERLIN detector bank covering π Steradians. MAPS detectors drawn on for comparison.

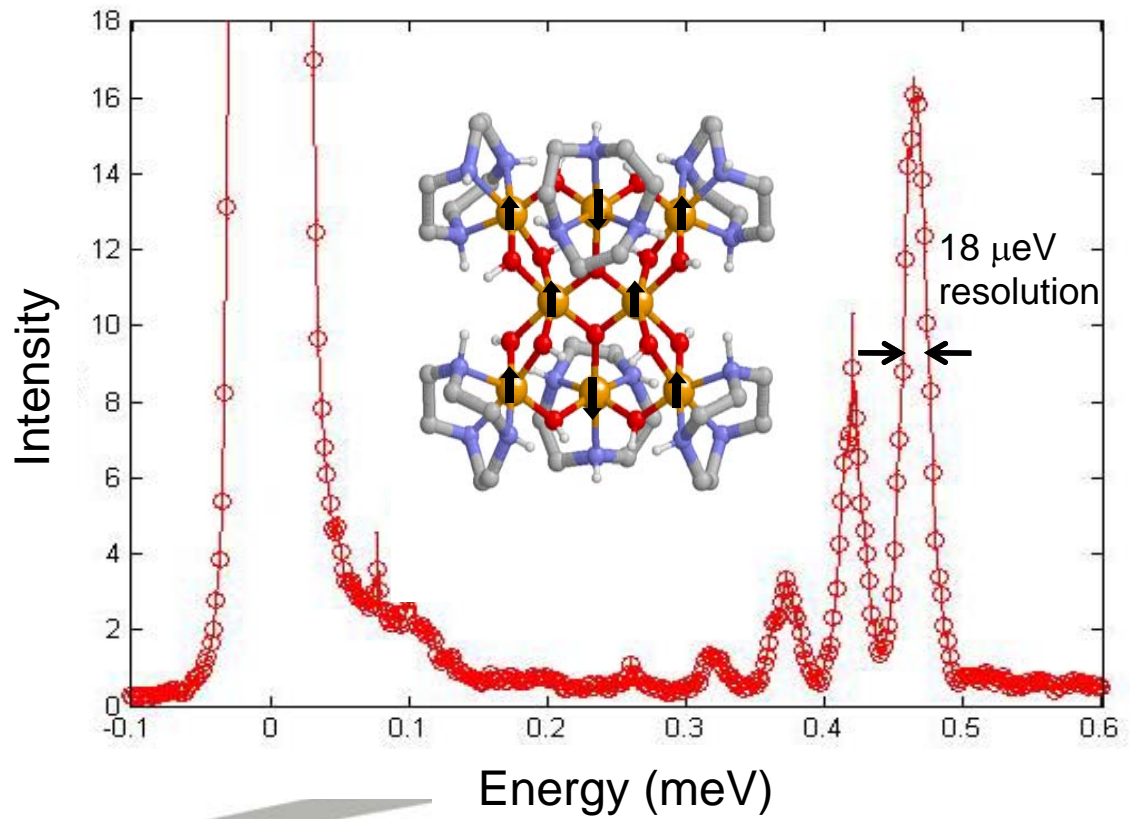
3m

Novel Instrumentation

A new spectrometer capable of measuring excitations from 20 μeV to 80 meV

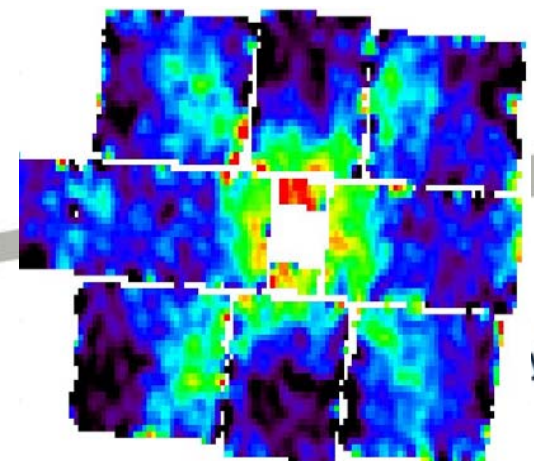
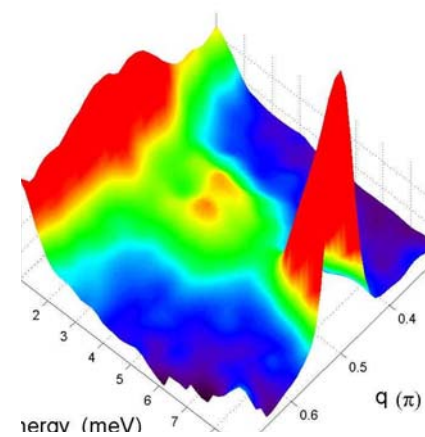
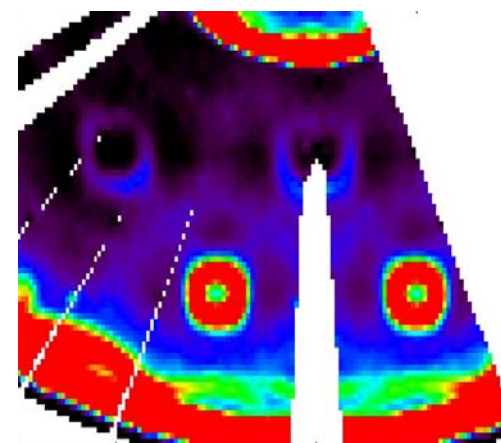


Excitations of Fe₈ molecular cluster

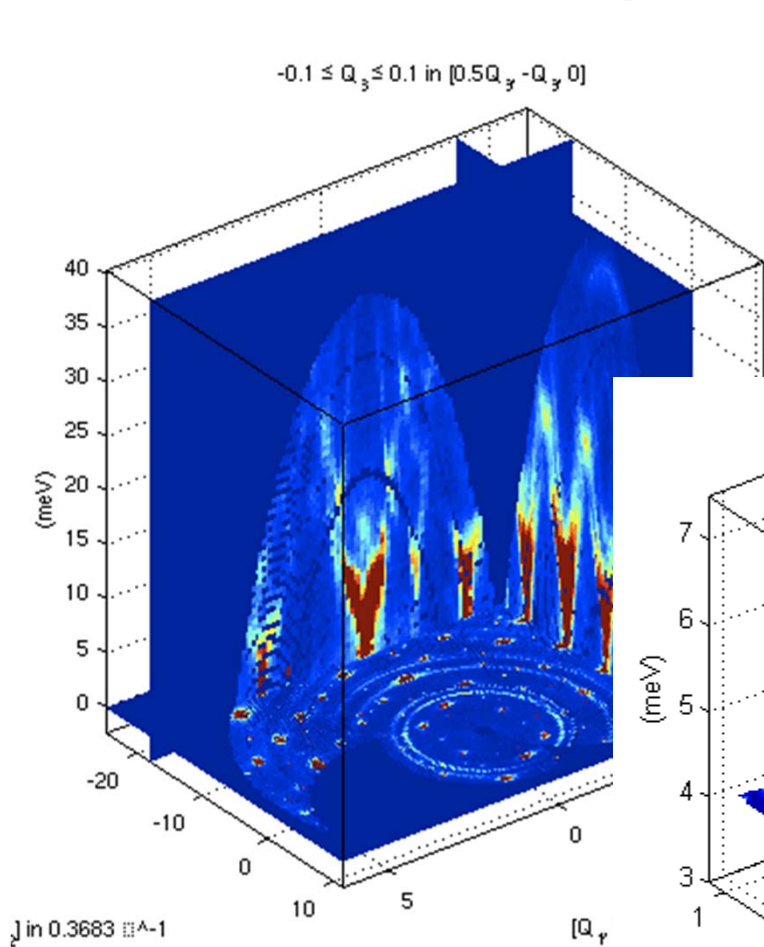


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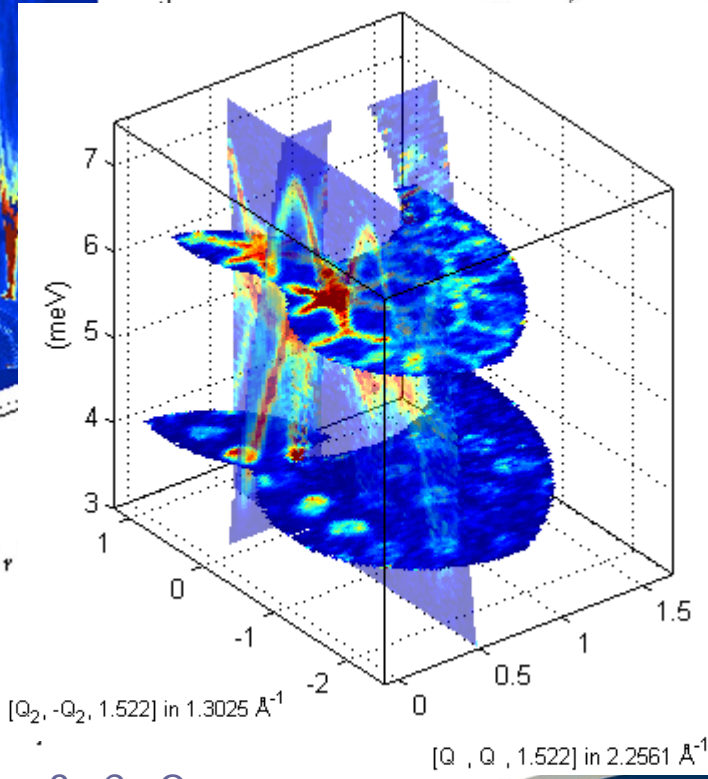
Magnetism and Molecular motion



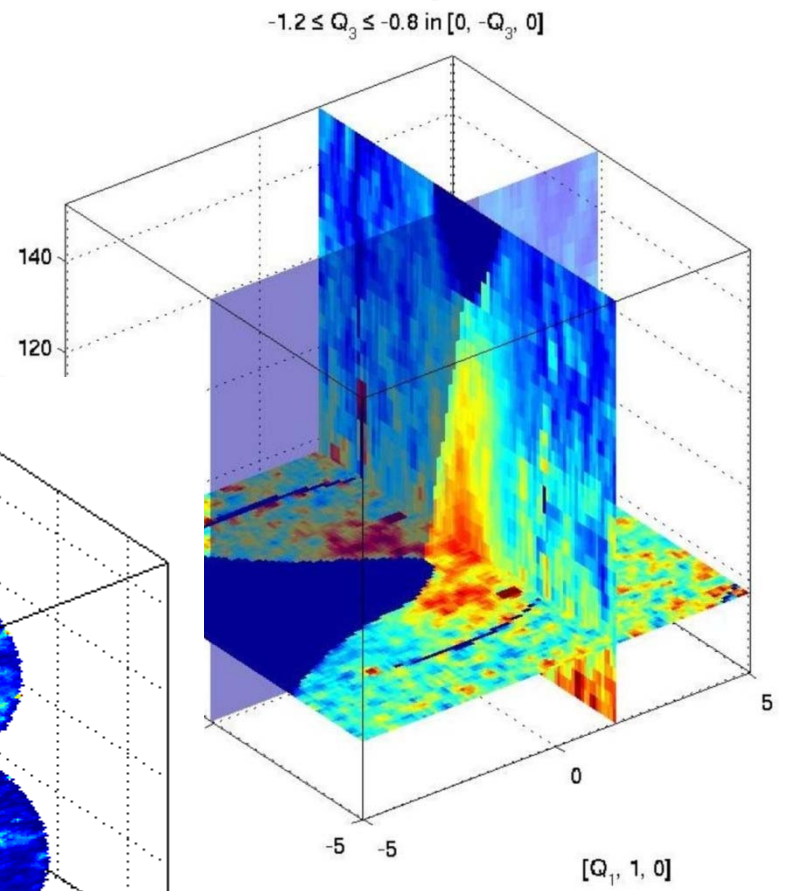
Horace : Examples of measurements on MERLIN spectrometer



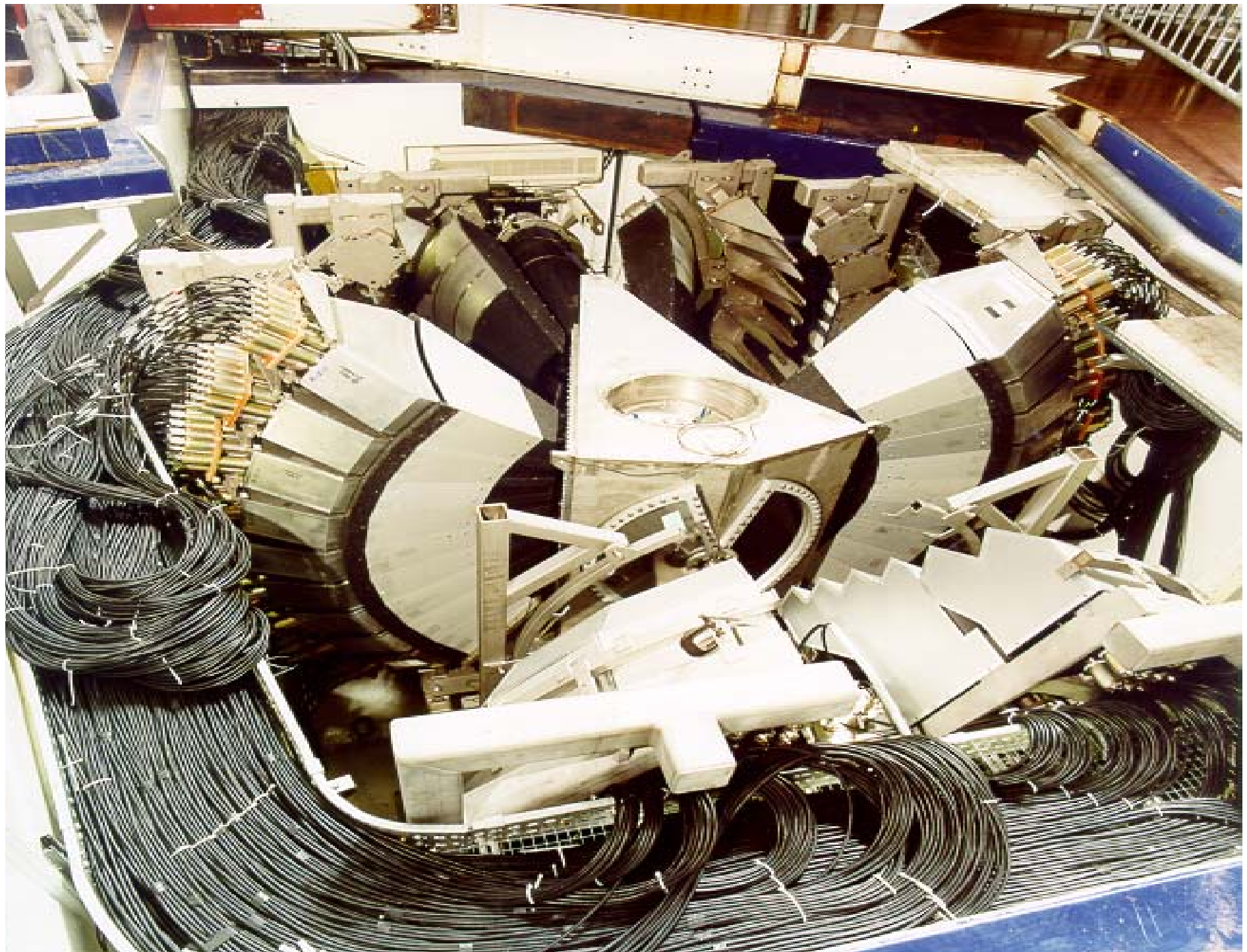
Calcite
(Dove, Cope)



$\text{Sr}_3\text{Cr}_2\text{O}_8$
(Lake) $S=1/2$



MnSi
(Perring, Ewings)

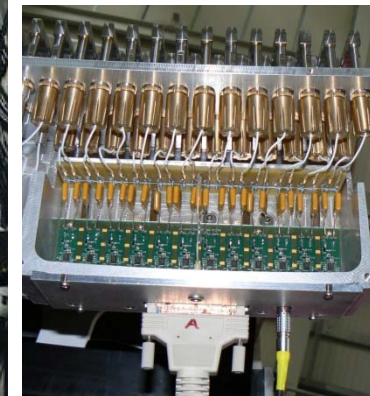
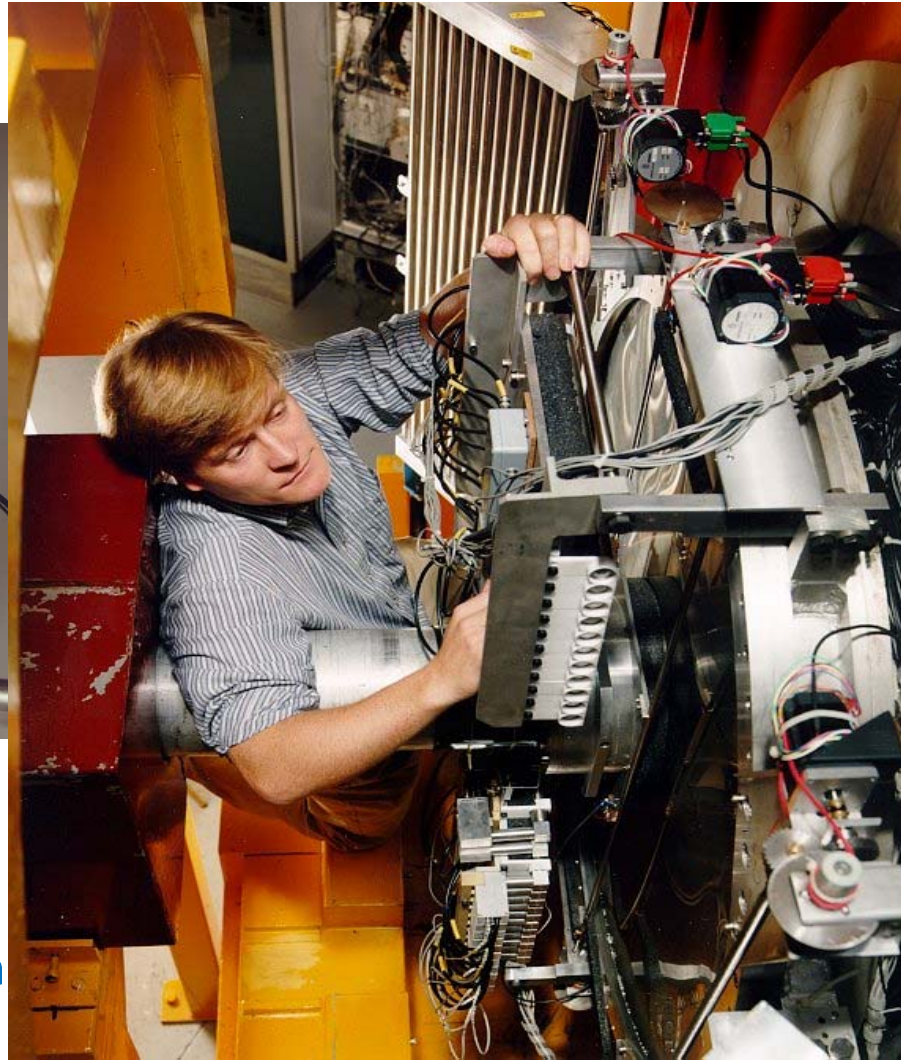




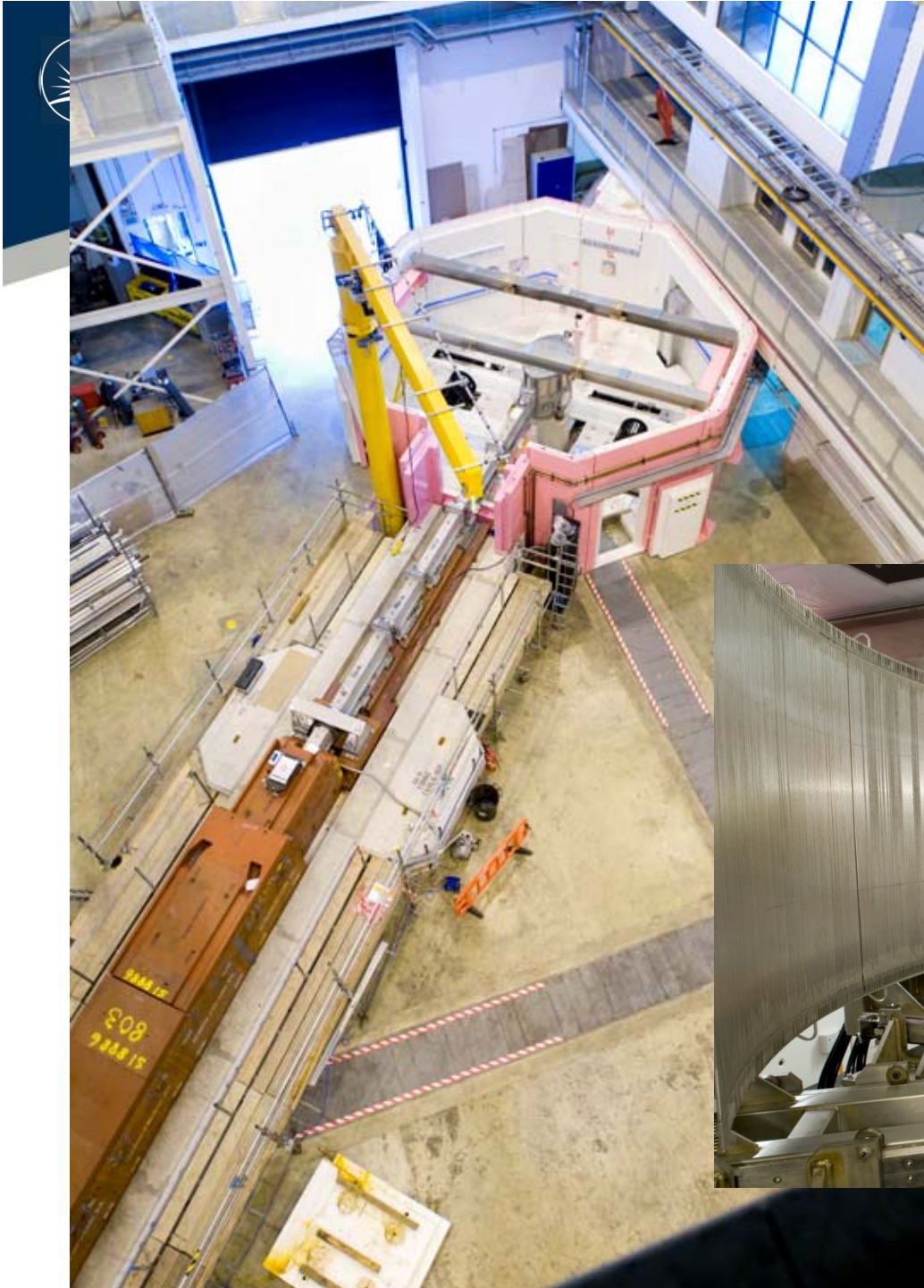
Resistive Detectors : HET to WISH



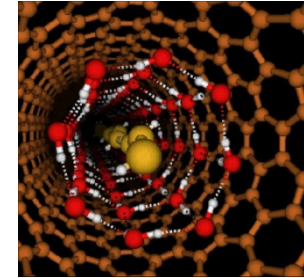
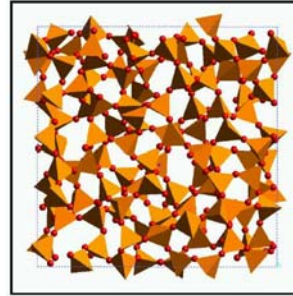
Original HET
He3 proportion
counter



WISH
2010



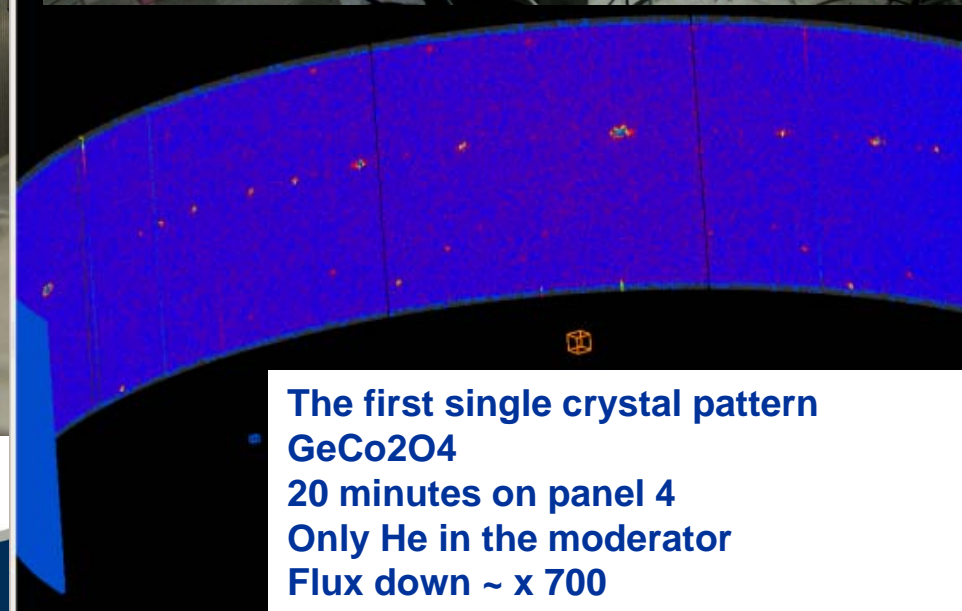
Structures



WISH detectors

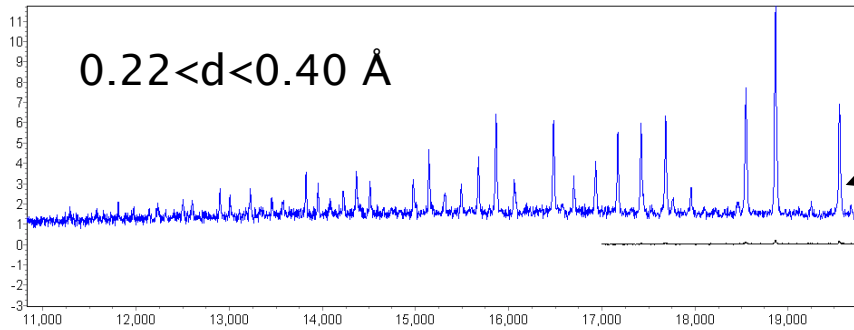
152 gas detectors per panel
1 m long, 8 mm dia
15 bar ^3He + stopping gas
5 panels installed and
working well

The first complete panel in December 08



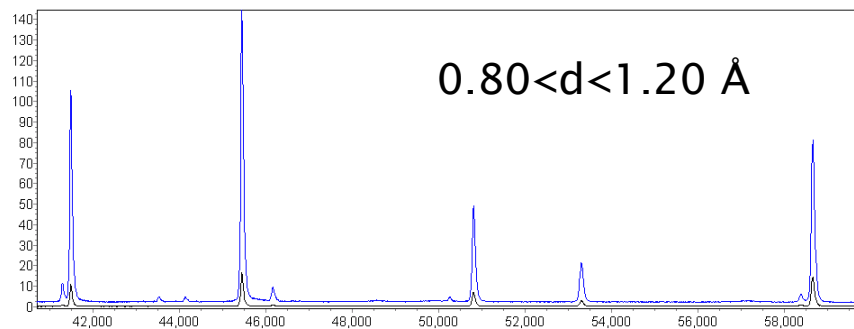
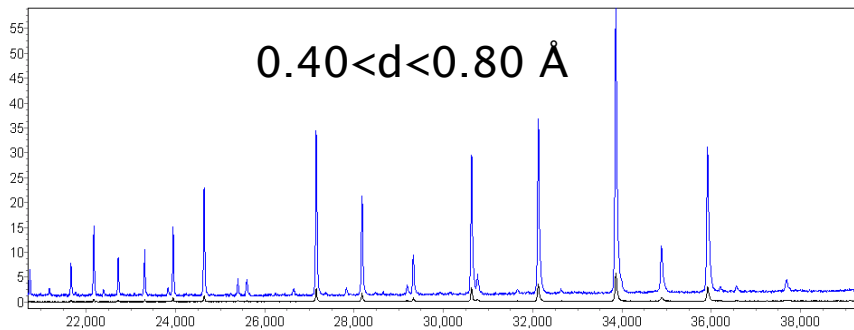
The first single crystal pattern
GeCo₂O₄
20 minutes on panel 4
Only He in the moderator
Flux down ~ x 700

HRPD Supermirror Guide – First results MgO



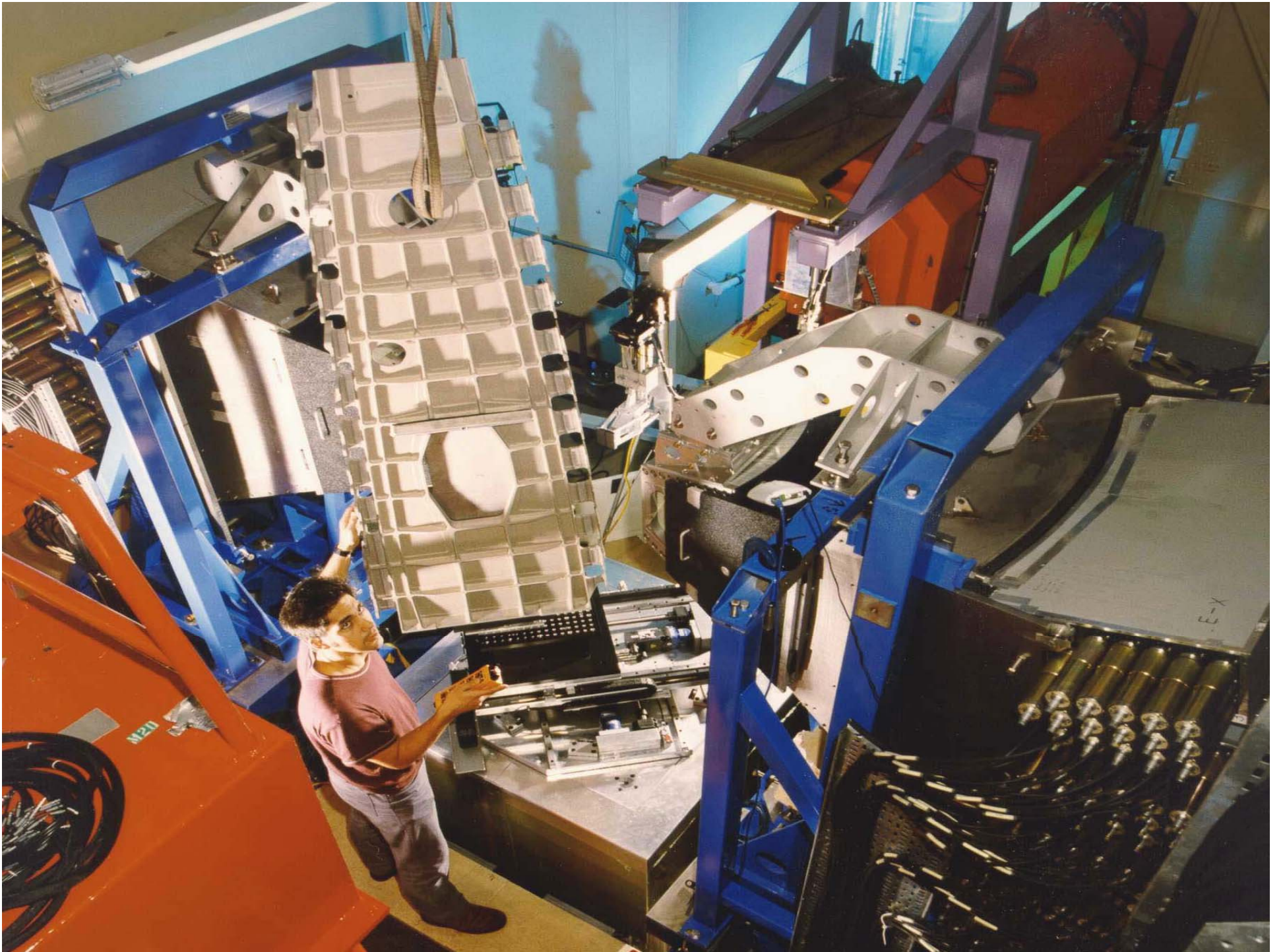
Nov '07

Nov '06



λ (Å)





Inward Investment

**Japan: Nobel laureate
Prof Ryoji Noyori
President of RIKEN**

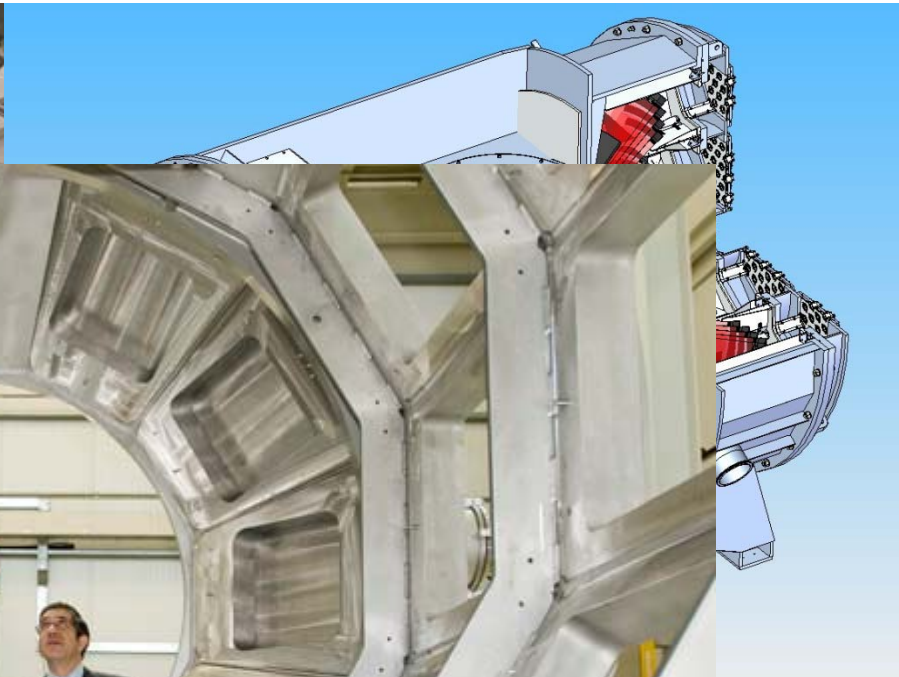
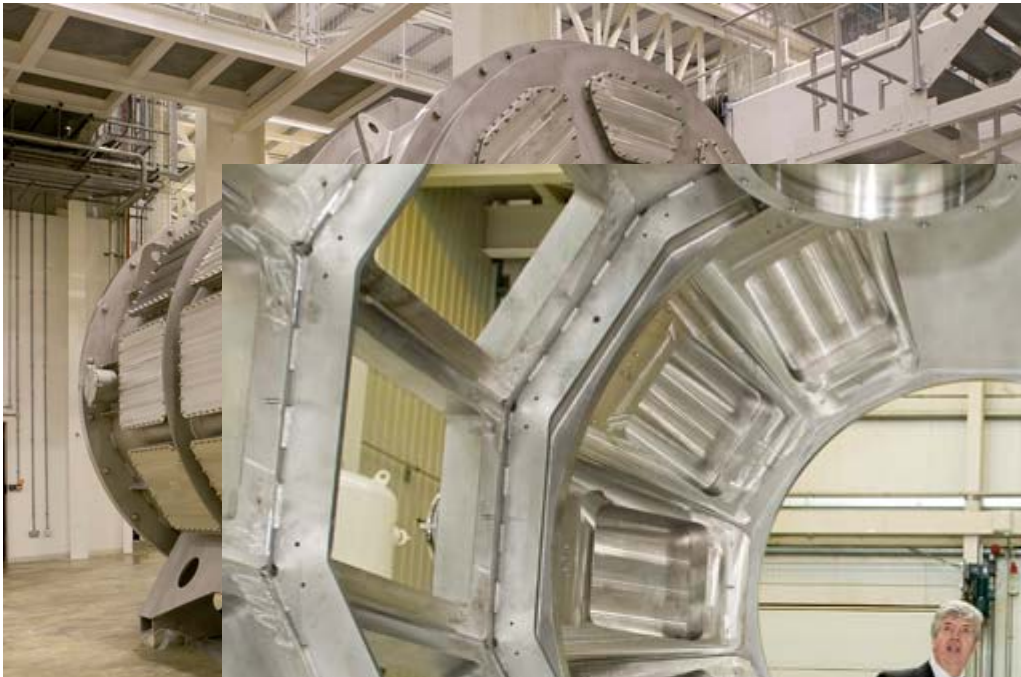


Italy: Visit from president of CNR; Spain -



Netherlands: Visit from chair of NWO and rector of Delft University

Sweden, Spain and Japan: New funding recently approved



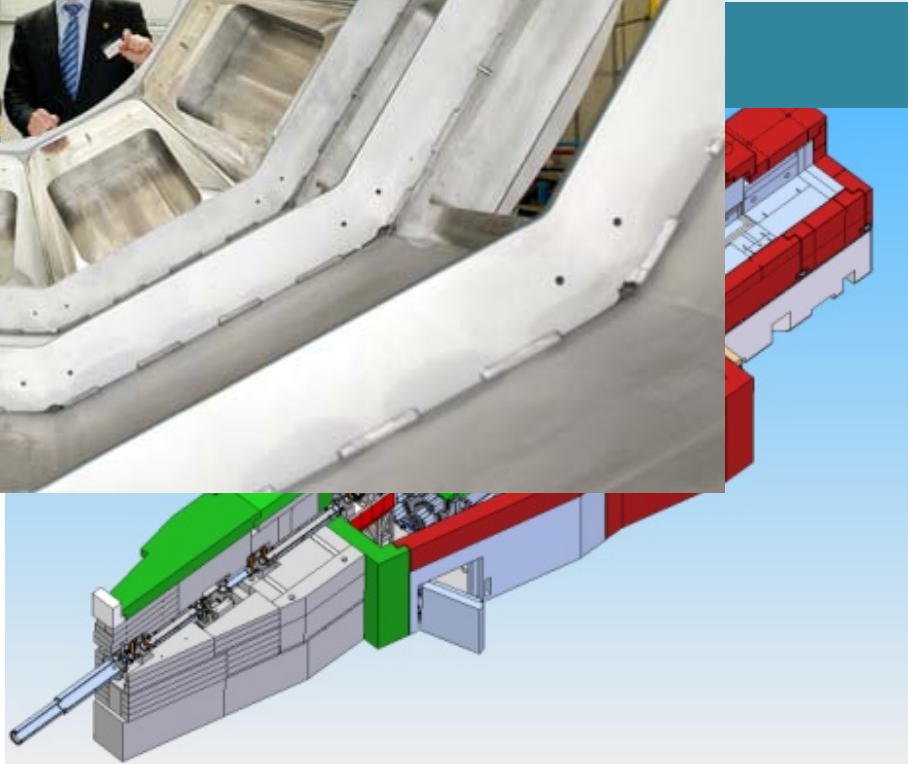
Polaris

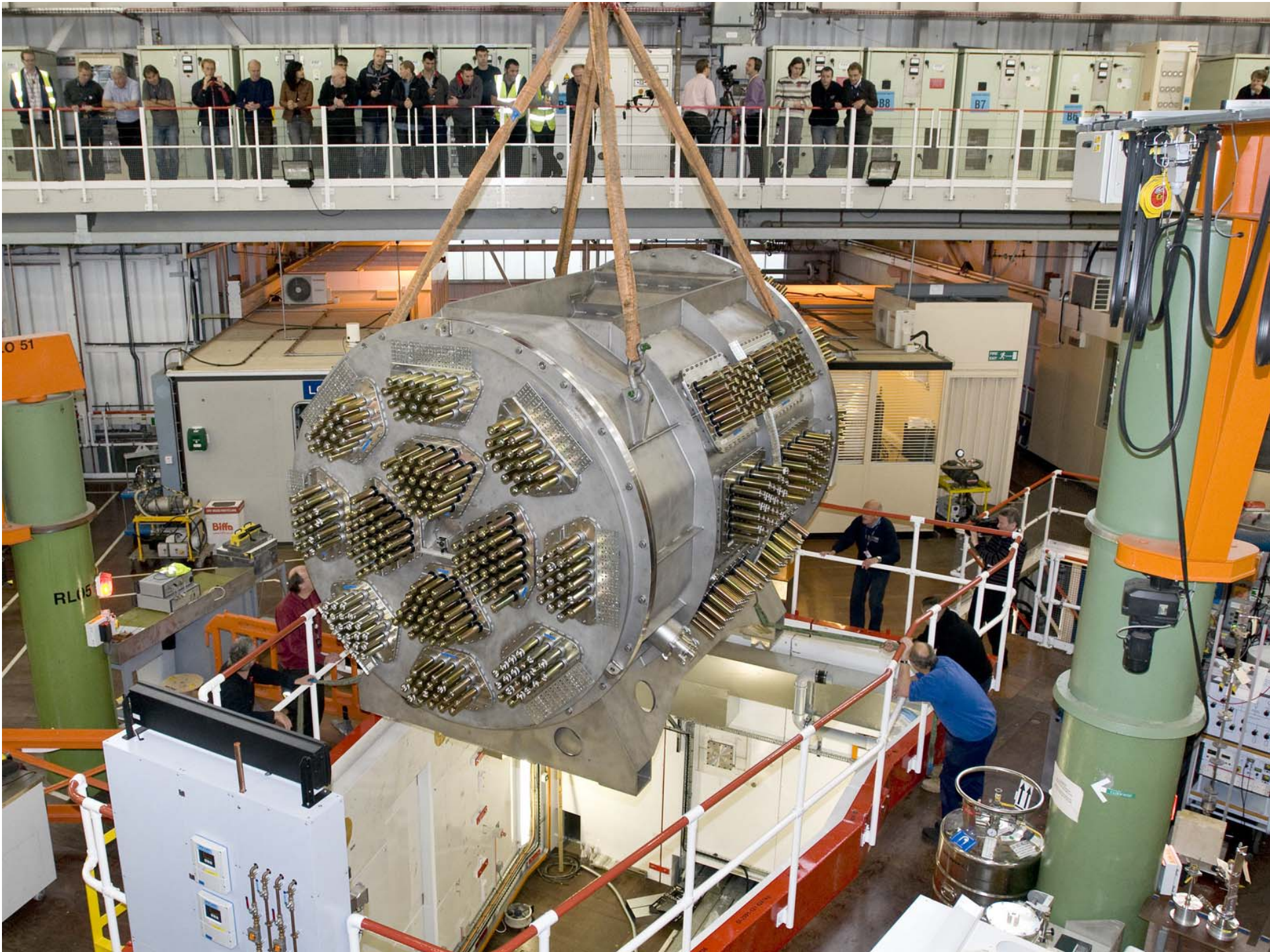
A new instrument
has an extremely
detector based

A novel manufacturing
expertise.

Detector manufacture has been a considerable injection
into UK detector manufacturing capability.

Polaris contains 2954 detecting elements and 460 km of
optical fibre.

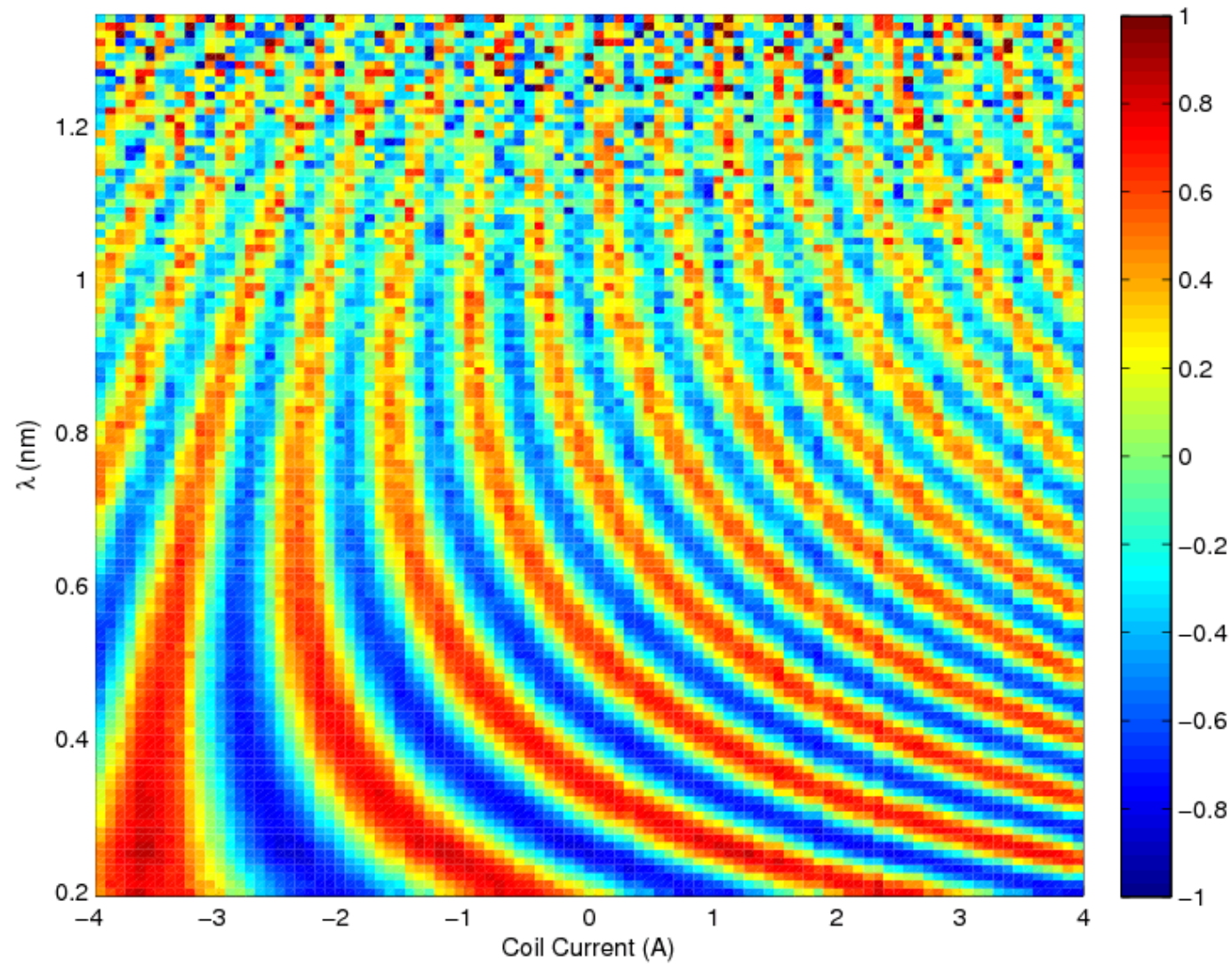






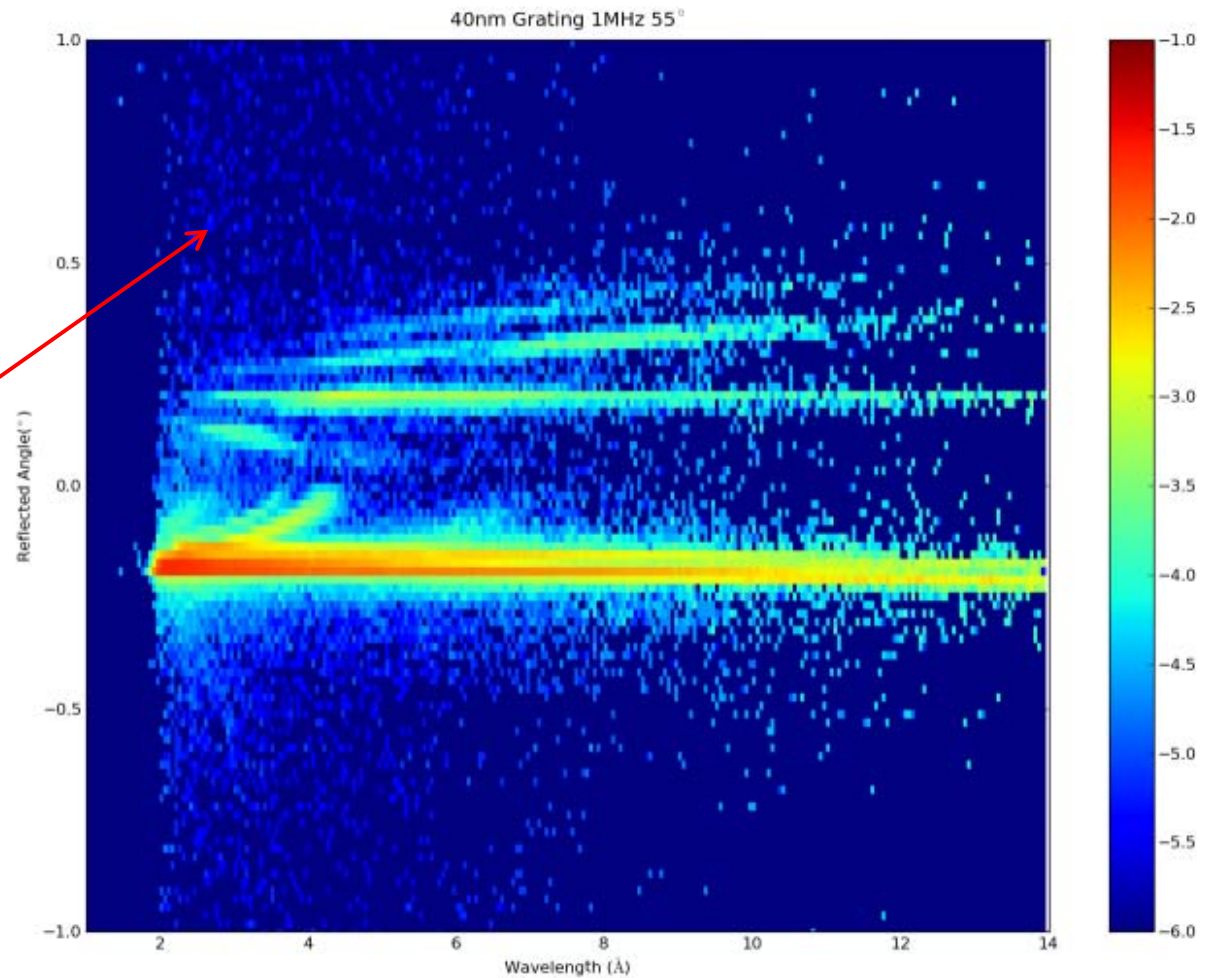
- **Spin-Echo at ISIS**

Neutron Spin-Echo was measured for the first time at ISIS



Very Low Backgrounds

- 3 Hours Data
 - Less than 16 counts per hour/pixel





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ISIS

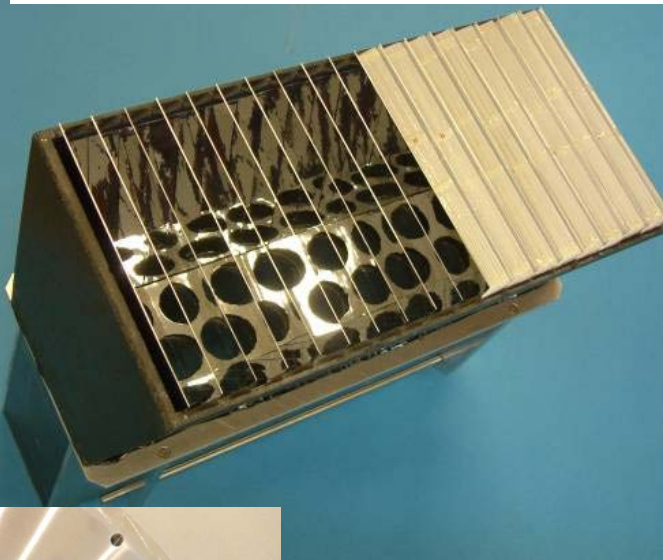
NIMROD



Disordered Systems

NIMROD scintillation detector

All 60 'day 1' modules plus prototype are installed and operational.



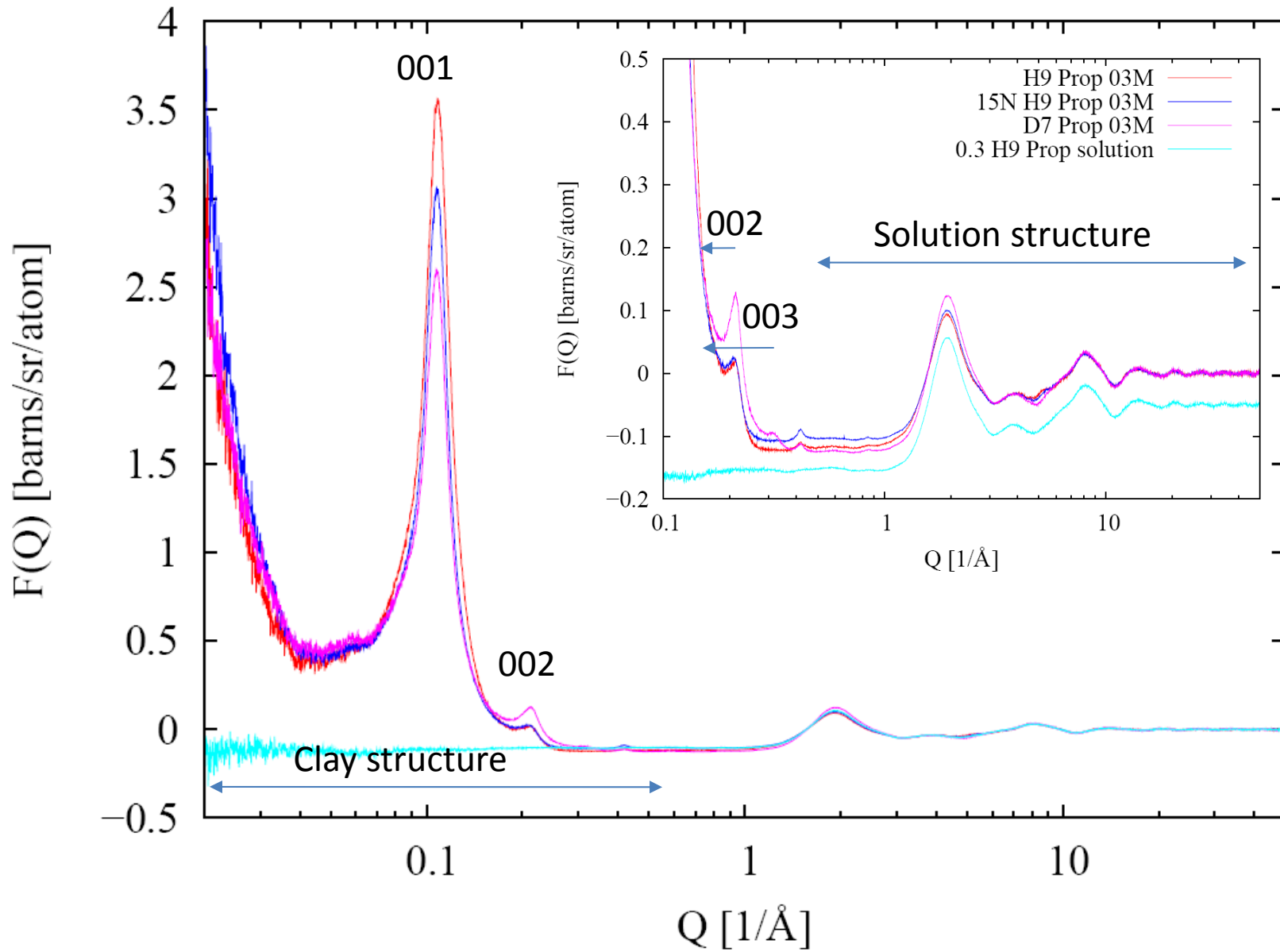
Low Angle Bank:

Comprises of 8 detector modules

756 elements 2Cn fibre coded to 120 PMTs

Successfully upgraded and now operational

NIMROD's view of vermiculite clays and the aqueous solutions that cause them to expand



International Partnerships

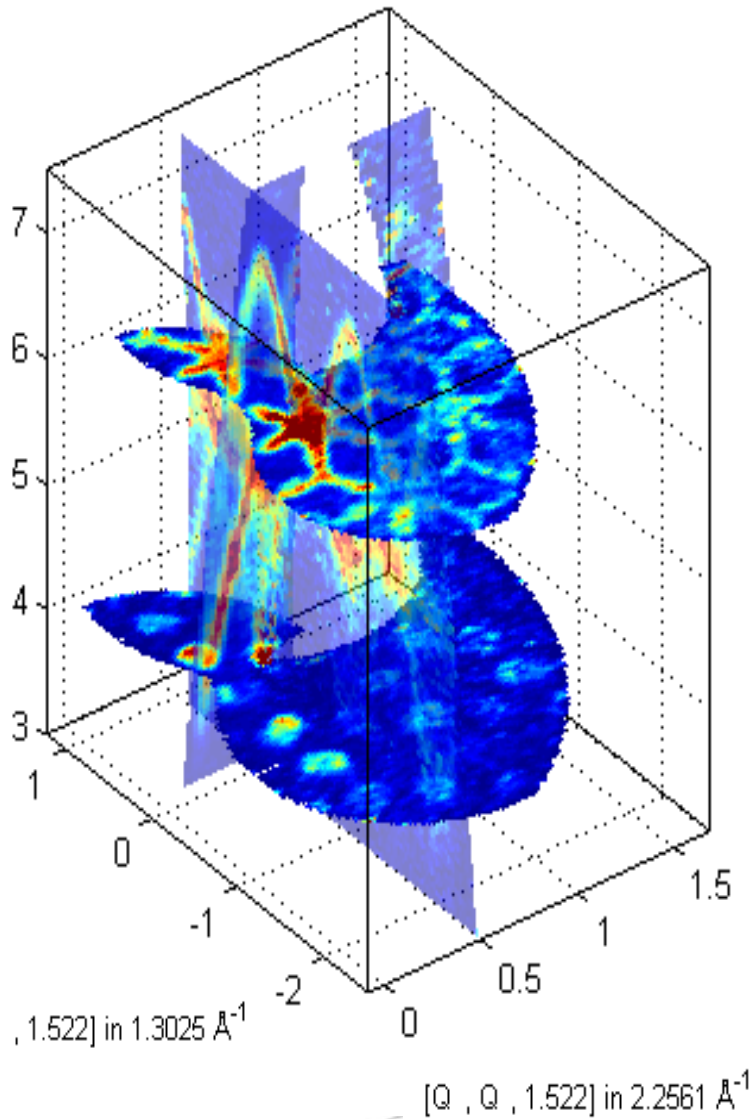


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ISIS

Transfer of Technology

Big Science → Small Science



- Accelerators

- Detectors

- Cryogenics

- Software

- Visualisation



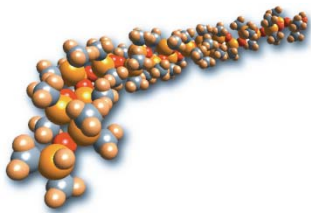
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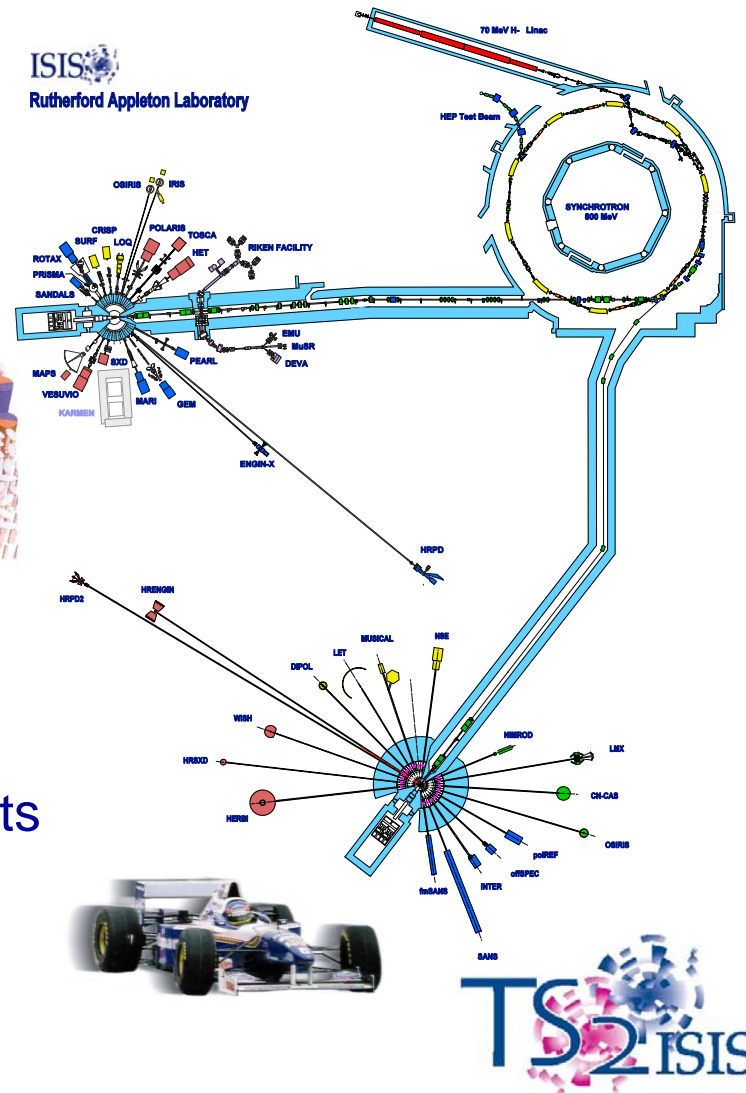
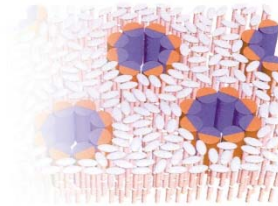
Designed to meet future scientific needs in the key areas of:

- Soft Matter
- Advanced Materials
- Bio-molecular Science

Nanoscience



- complex multi-phase or multi-component materials
- difficult or complex environments
- kinetic processes
- parametric studies
- smaller samples

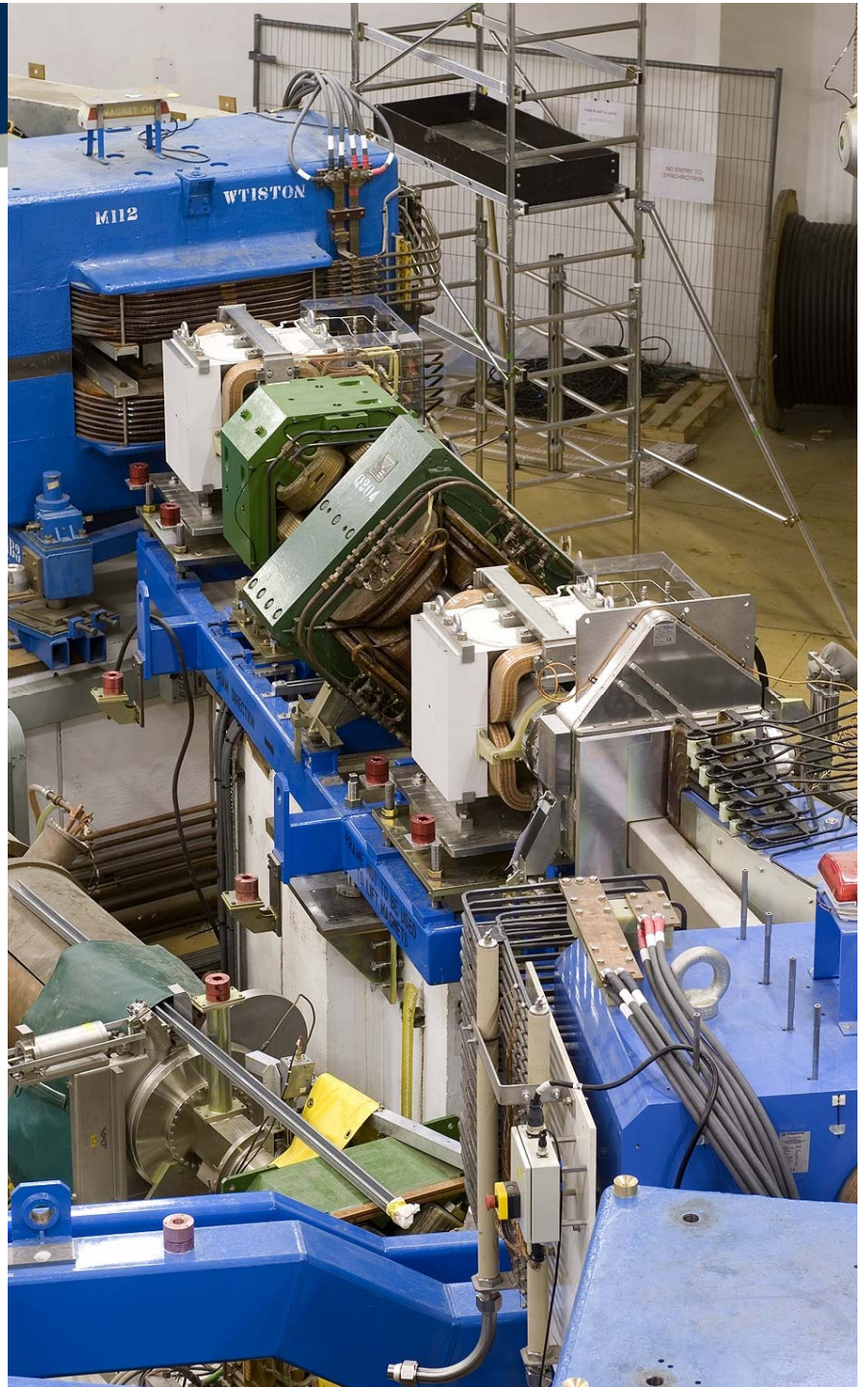
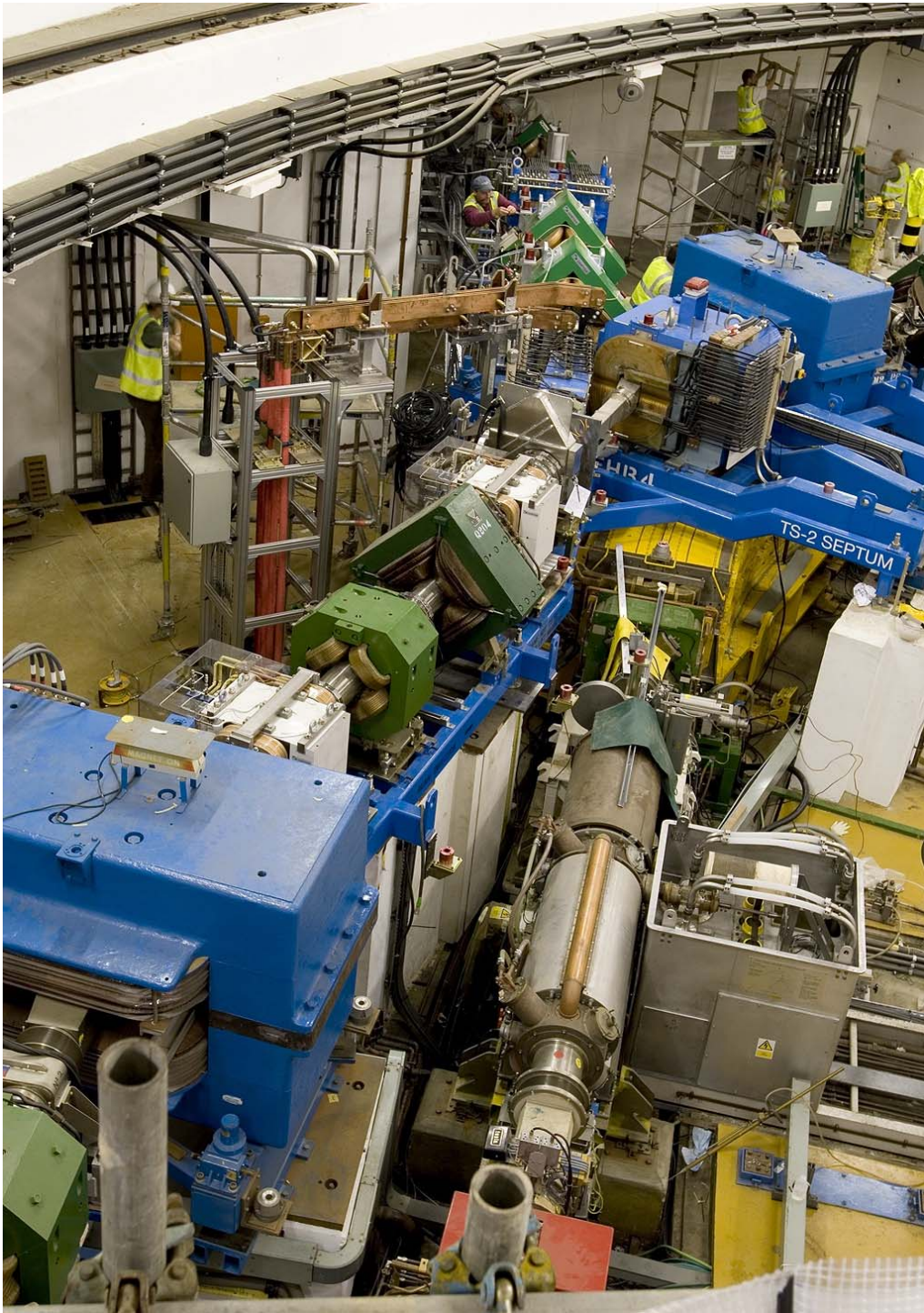


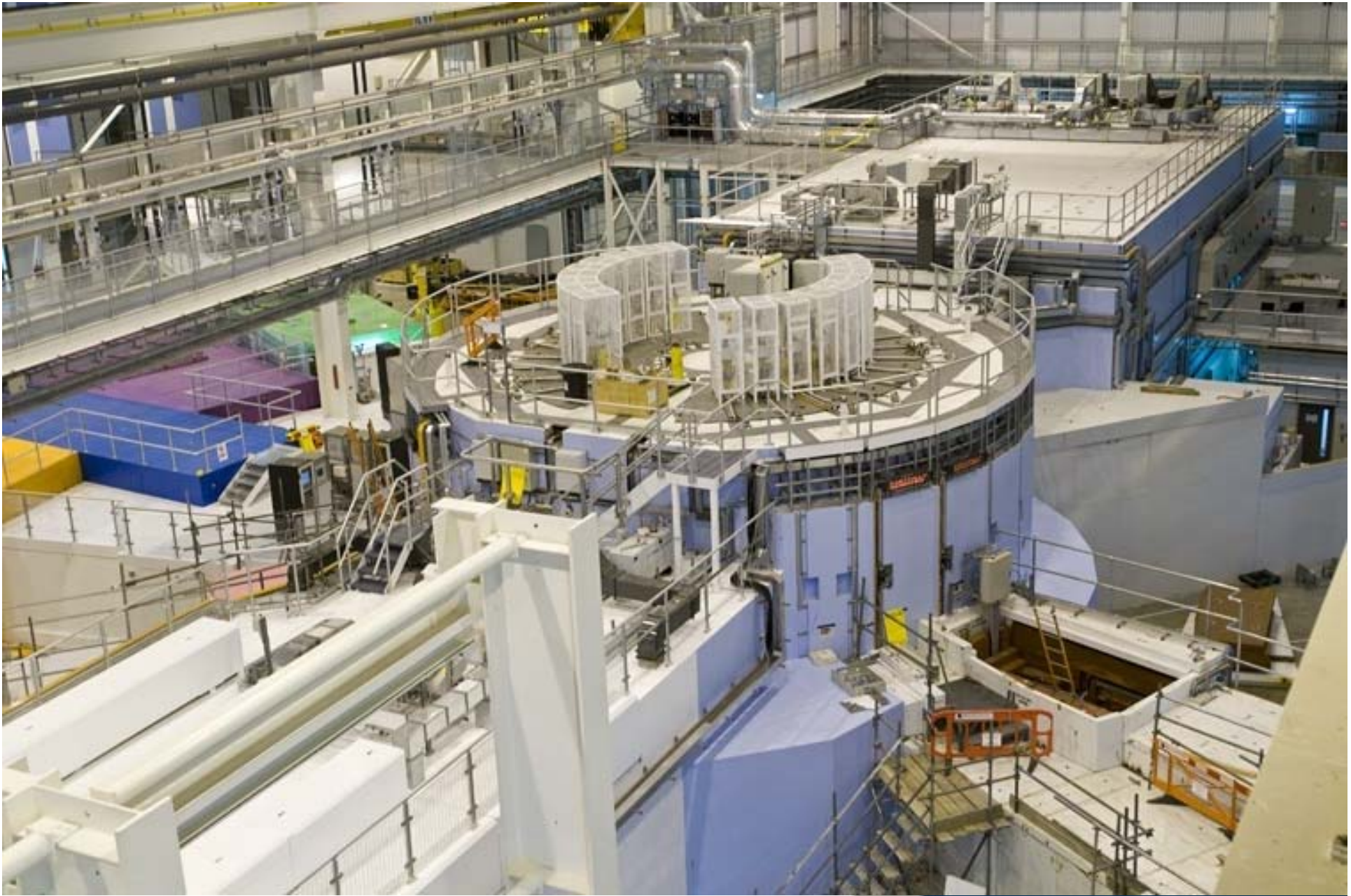


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2008



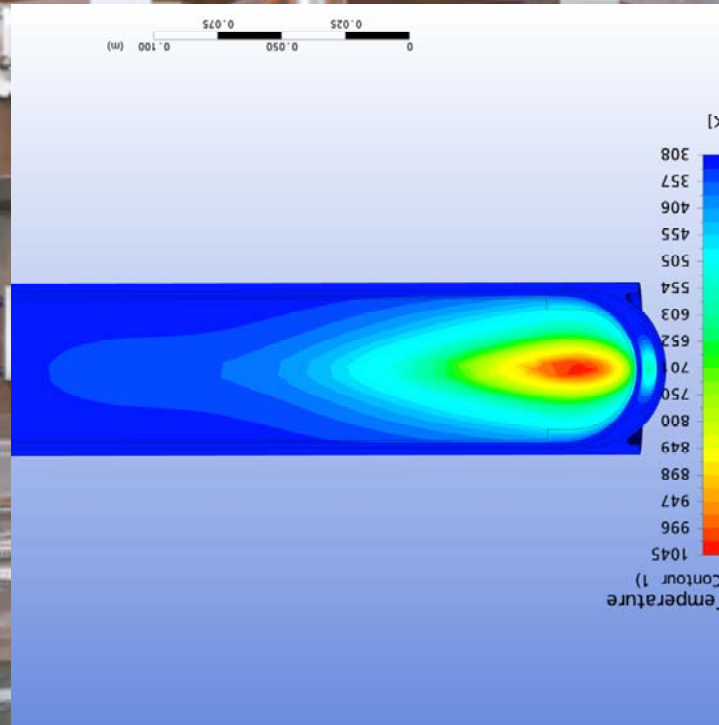


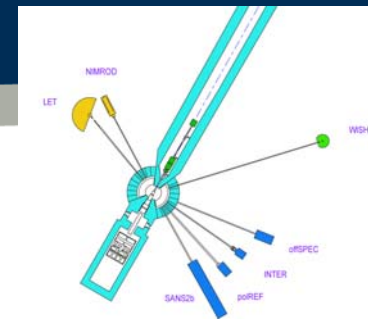


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ISIS

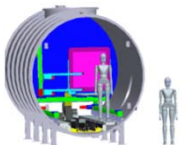
Compact Tungsten Target Technology



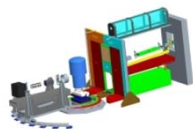


TS2 Phase 1 instruments are outstanding!

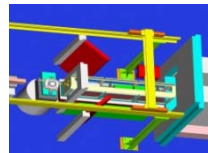
SANS2D



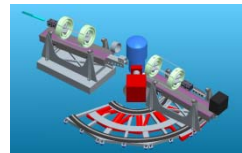
POLREF



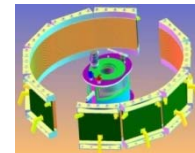
INTER



OFFSPEC



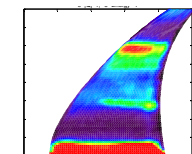
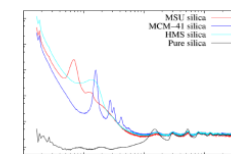
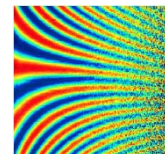
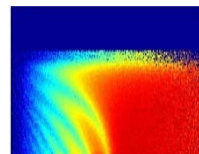
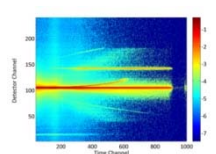
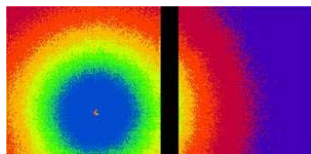
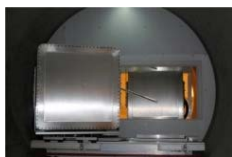
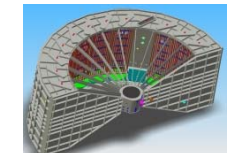
WISH



NIMROD



LET

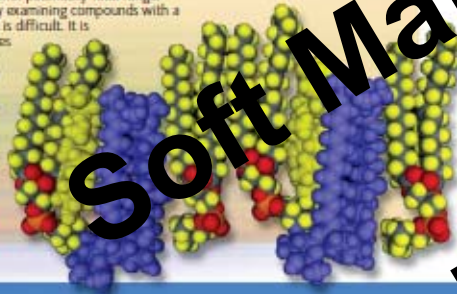


TS2 Phase I: 2004-9

How does the antibiotic amphotericin work?

F Foglia, A Dabkowska, M Lawrence, DJ Barlow (King's College London), R Barker (University of Bath), AE Terry, SE Rogers, AV Hughes, JRP Webster (ISIS)
 Contact: Dr DJ Barlow, dave.Barlow@kcl.ac.uk
 Further reading: F Foglia et al., *Biochim. Biophys. Acta* 1808 (2011) 1574

Amphotericin has been the first line of defence against fungal infections since the mid-1950s. Unfortunately, resistance to this drug is beginning to emerge, posing serious problems for AIDS and chemotherapy patients who often suffer potentially fatal fungal infections. Normally, replacement drugs would be sought by examining compounds with a similar mechanism of action. For amphotericin, though, this is difficult. It is established that the drug punches holes in cells, which makes them leaky and so causes them to die, but how it does this, and why it causes more damage to fungal cells than human cells remains unclear. Neutron reflectivity and small-angle scattering studies have been performed to study the effects of amphotericin on model human and fungal cell membranes, to find out why the drug is so selective. Rather surprisingly, the drug is found to insert into both fungal and human cell membranes but the neutron studies also clearly show that it perturbs these two types of membranes in markedly different ways.



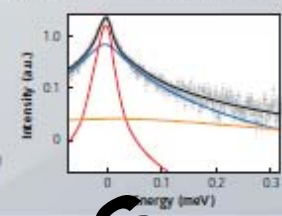
Molecular model of a lipid monolayer showing the fungal steroid ergosterol (yellow) interacting with the inserted antibiotic amphotericin (blue).

Dynamics in lipid vesicles

Y Gorelli (Università di Parma, Italy and ILL, France), A Deriu (Università di Parma, Italy), Garcia Sakai (ISIS)
 Contact: Dr Y Gorelli, gorelli@ill.eu
 Further reading: Y Gorelli et al., *Soft Matter* 7 (2011) 3929

Interest in the fundamental properties of systems based on lipids (fat-like molecules that are insoluble in water) has increased owing to a growing number of applications in pharmacy, medicine and food science. Investigation of the internal dynamics of lipid aggregates raises some important and yet-to-be-answered questions, including the effects of temperature on these motions.

Using I15 at ISIS and IN6 at ILL, we have investigated the dynamics of lipid-based systems (energy resolution 0.10 μeV – 5 meV). The quasielastic neutron scattering (QENS) data confirm the existence of dynamic heterogeneities whereby the terminal ends of the acyl chains experience faster motion than those of the head groups and neighbouring chains. This is due to the larger available free volume, and the terminal methyl groups can also undergo torsional motions.



The structure of a lipid molecule is shown on the left, where coloured arrows indicate the motions investigated in this work. Using the same colours, the corresponding contributions to the QENS spectrum are shown on the below.

We must not forget that when Radium was discovered, no one knew that it would prove useful in medicine – M Curie

Life sciences

The unusual behaviour of a plant seed defence protein

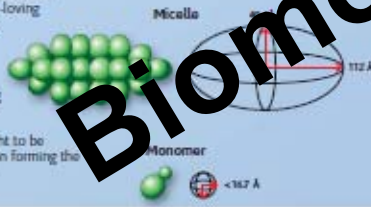
LA Clifton, MR Sanders, SE Rogers, BK Heenan, C Neylon (ISIS), V Castellano (University of Graz), RJ Green (University of Reading)
 Contact: Dr LA Clifton, luka.clifton@scf.ac.uk; Dr RA Frazier, r.a.frazier@scf.ac.uk
 Further reading: LA Clifton et al., *Phys. Chem. Chem. Phys.* 13 (2011) 1051

A combination of small angle neutron scattering, dynamic light scattering and size-exclusion chromatography has been used to uncover a protein's unique structural behaviour in solution.

Puroindoline-a is a plant seed defence protein found in wheat. It has a broad spectrum of antifungal and antibacterial activity, and has potential applications such as novel antibiotics or targeted drug-delivery systems.

Puroindoline-a forms micelles in aqueous solution. One part of a puroindoline-a molecule is water-loving, the other end is water-insoluble. Micelles are groups of protein molecules in which the water-loving parts all point outwards, into the surrounding solution. Proteins which form micelles are rare, with only one other protein known to spontaneously form these assemblies in solution.

We have been able to discover that the structure formed by puroindoline-a is unique amongst known protein micelles, being highly elongated rather than spherical. Puroindolines contain a tryptophan-rich part which is responsible for the protein's antimicrobial membrane-binding activity. This part is also thought to be responsible for its solution-structuring behaviour, with this region forming the water-insoluble interior of the micelle.



Structures of puroindoline-a micelle (top) and monomer (bottom) obtained from small angle neutron scattering, dynamic light scattering, and size-exclusion chromatography.

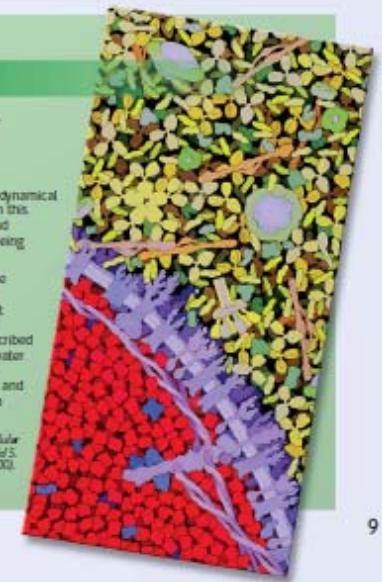
Protein motion in a red blood cell

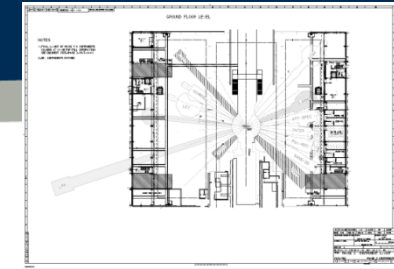
AM Stadler (Jülich, Germany), L van Eijck (ILL, France), F Demmel (ISIS), G Artzt (University of Jyväskylä, Germany)
 Contact: Alexander Stadler, a.stadler@joelich.de
 Further reading: Stadler et al., *J R Soc Interface* 8 (2011) 590

Biological research aims at a coherent picture of the interactions and dynamical motions of proteins inside living cells under physiological conditions. In this context, red blood cells are exceptional, as they are highly specialized and relatively simple in composition, the main macromolecular component being haemoglobin.

We have used high-resolution quasielastic neutron scattering to study the motions of haemoglobin in whole red blood cells. Neutron scattering is exceptionally useful as measurements on living cells are possible without damaging these highly sensitive specimens. We find that the diffusion of haemoglobin in the crowded environment of a red blood cell can be described using concepts from colloid physics. Furthermore, interfacial hydration water has a large influence on protein diffusion. This work demonstrates how neutron scattering allows the measurement of internal protein dynamics and global macromolecular diffusion in whole cells, thereby contributing to a better understanding of cellular phenomena at the molecular level.

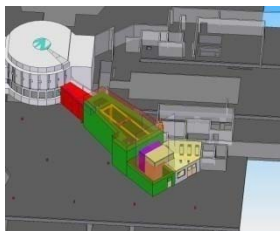
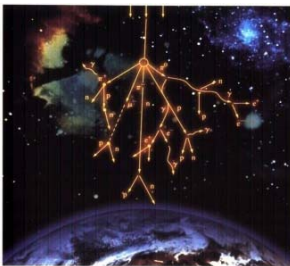
Schematic diagram of a red blood cell (lower left) and surrounding extracellular medium. The cell is densely filled with haemoglobin, shown in red (© David S. Goodsell 2000).



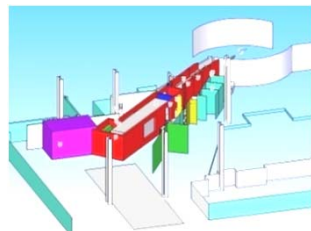
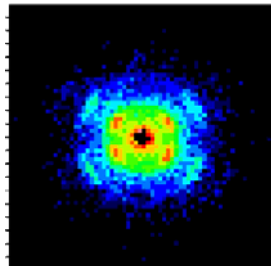


TS2 Phase 2 instruments

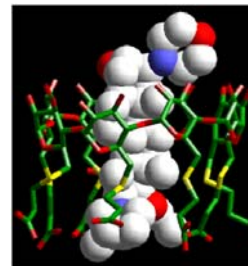
CHIPIR



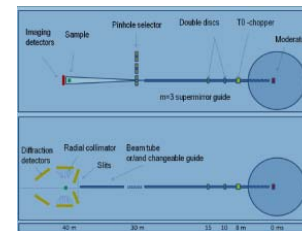
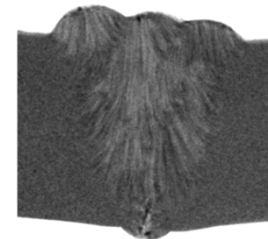
ZOOM



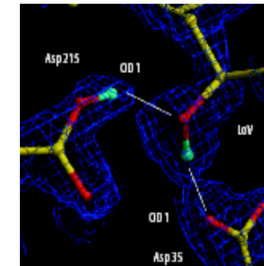
LARMOR



IMAT

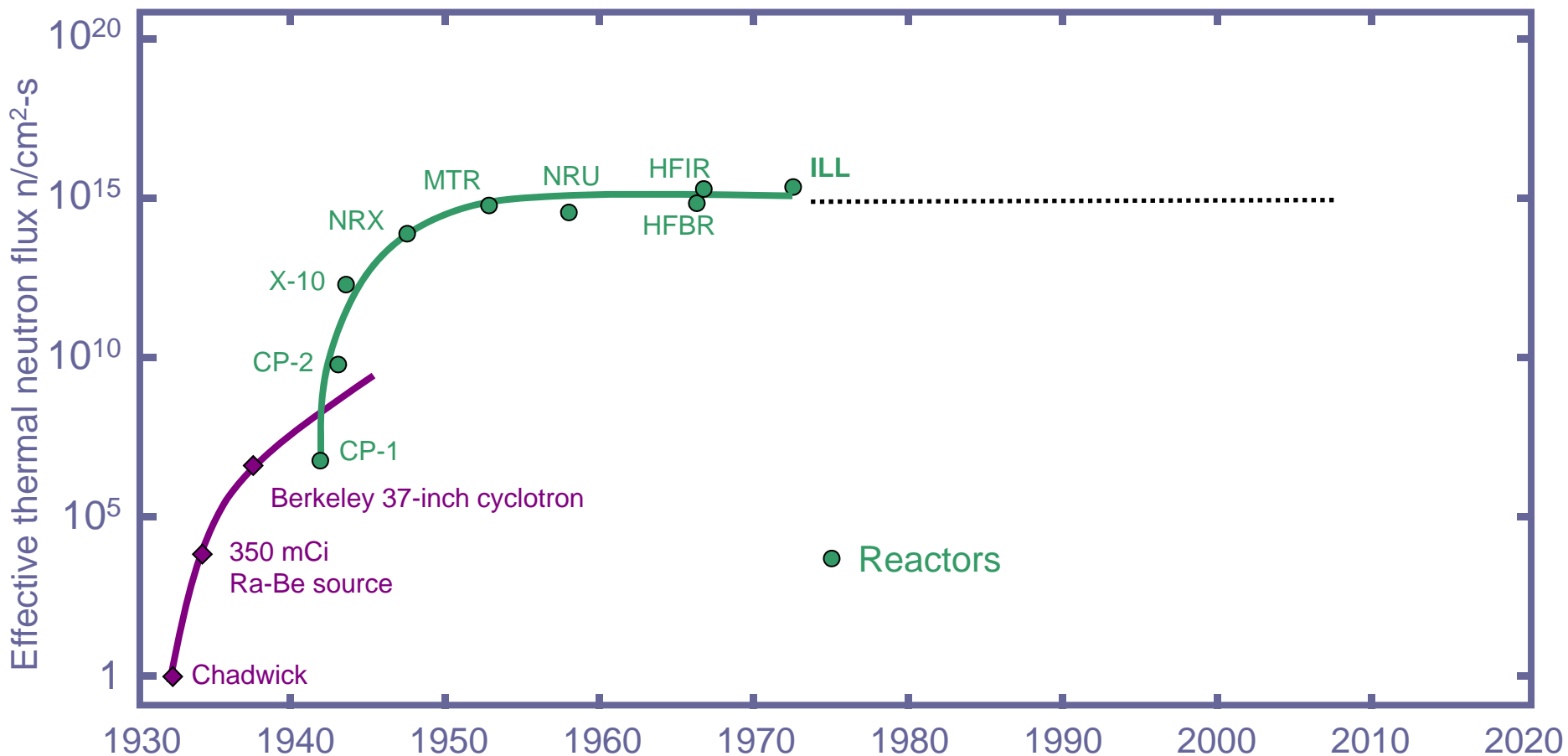


LMX





Reactor Sources



(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

ILL: instrument suite

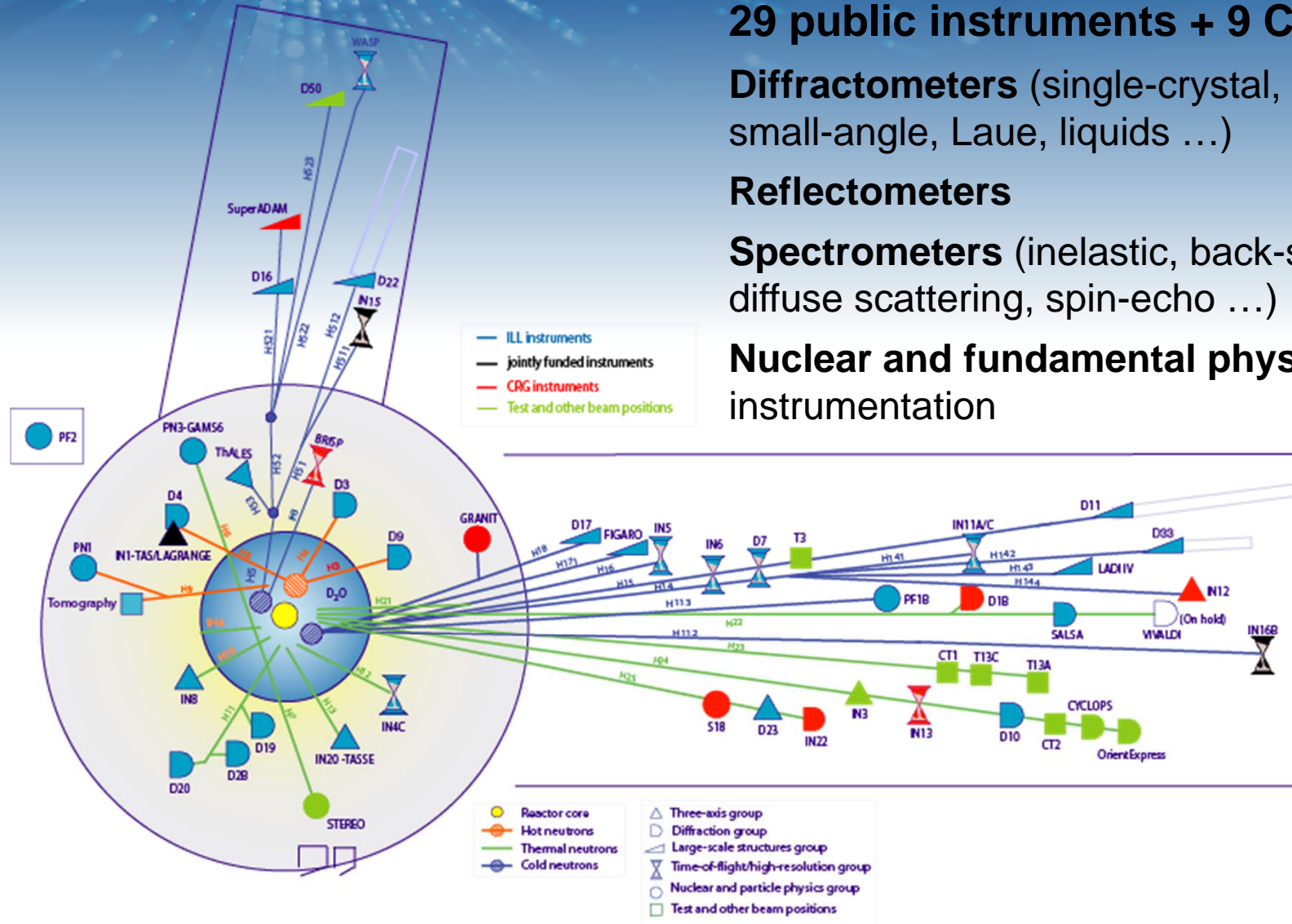
29 public instruments + 9 CRGs

Diffractometers (single-crystal, powder, small-angle, Laue, liquids ...)

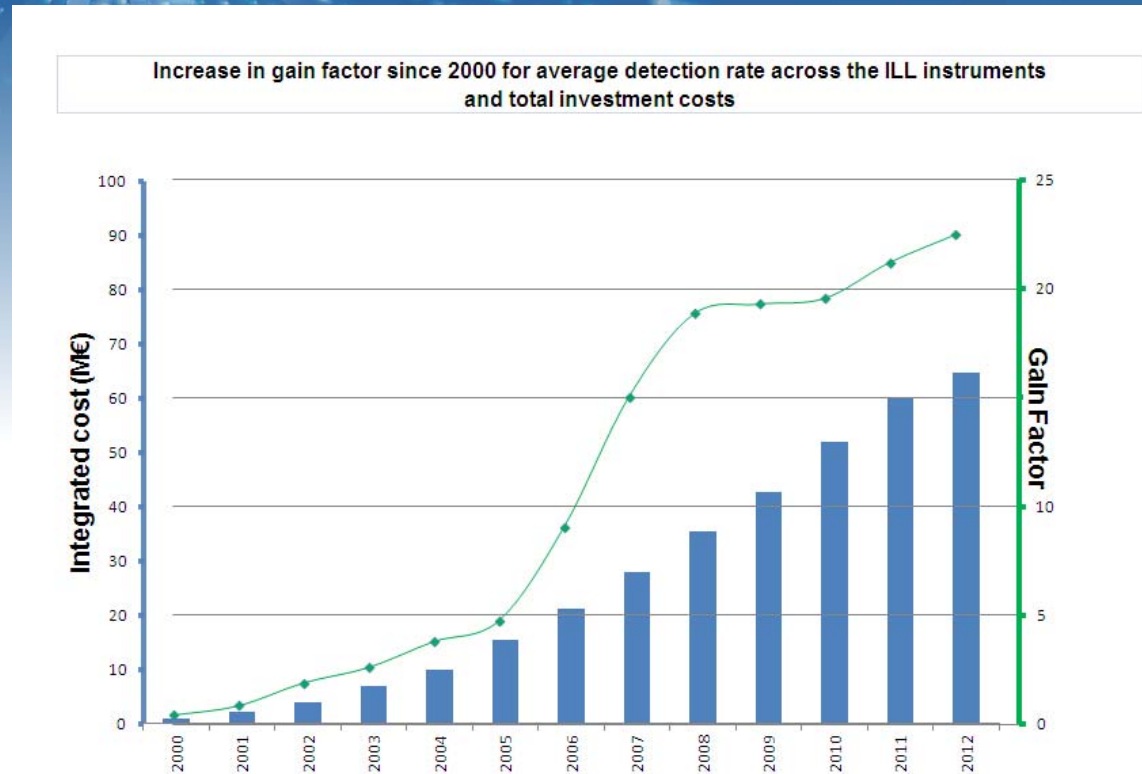
Reflectometers

Spectrometers (inelastic, back-scattering, diffuse scattering, spin-echo ...)

Nuclear and fundamental physics instrumentation



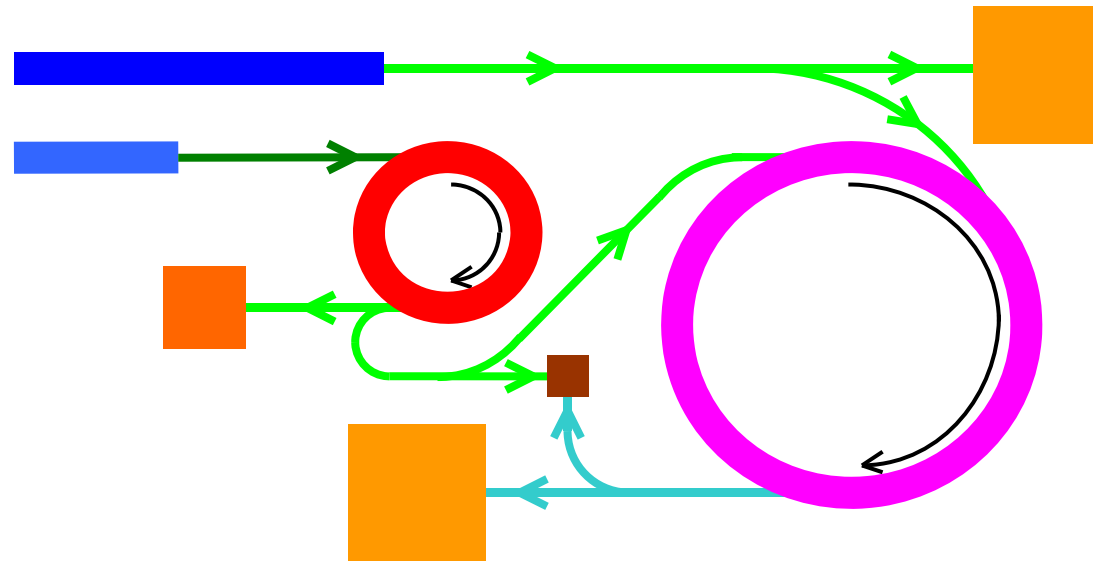
The Millennium Programme



- Upgrades to instruments, neutron optics ...
- Result - the average neutron detection rate on the instruments has been improved by more than 20



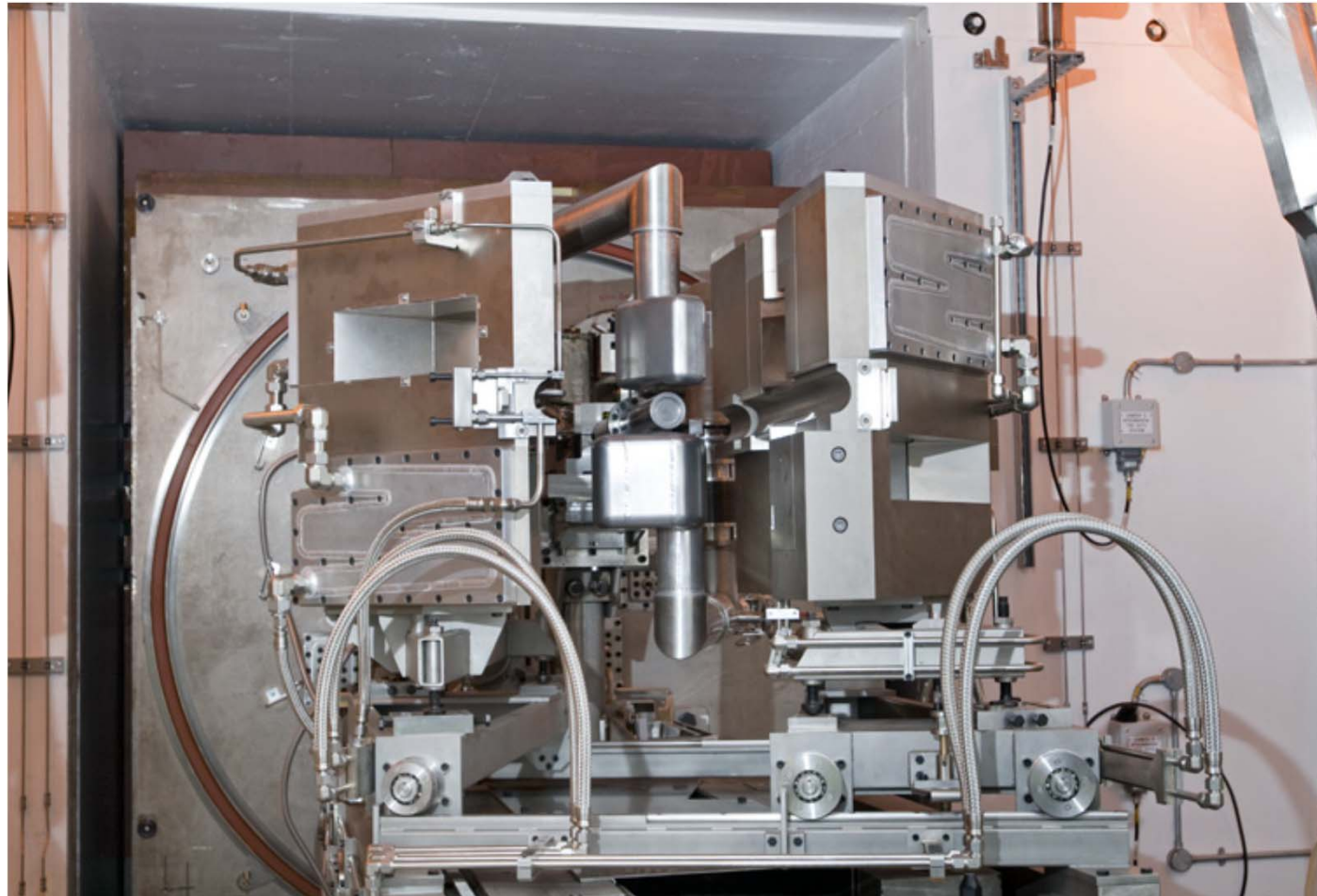
Possible Future Options



MW ISIS Options



ISIS MW Upgrade ?

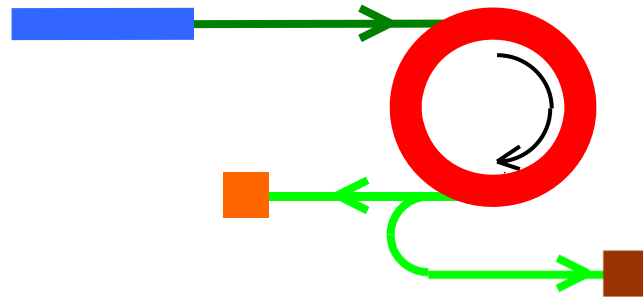


**TS1 Target Moderator Upgrade
x 2-3**

ISIS upgrade schemes

At present

0.2 MW, 40 + 10 pps



Science & Technology Facilities Council

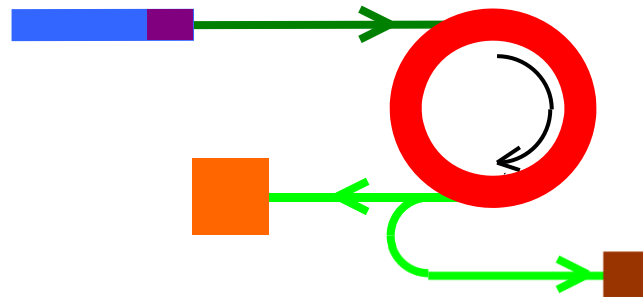
ISIS

0. Linac and TS-1 refurbishment

Replace Tank 4 (removes a major worry)

Re-engineer TS-1 targets to take advantages of techniques now exploited by TS-2

Cf. now: beam power $\times 1$, TS-1 neutrons $\times 2-3$



~£15M total



Science & Technology Facilities Council

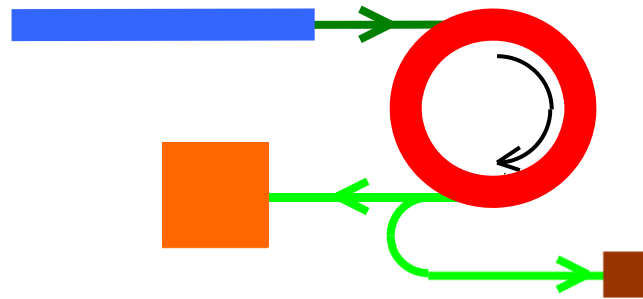
ISIS

1. New higher energy linac

Trap more charge in synchrotron by injecting at
~180 MeV *cf.* 70 MeV

~2 × beam power to TS-1

Cf. now: beam power × 2, TS-1 neutrons × 4



~£100M total



Science & Technology Facilities Council

ISIS

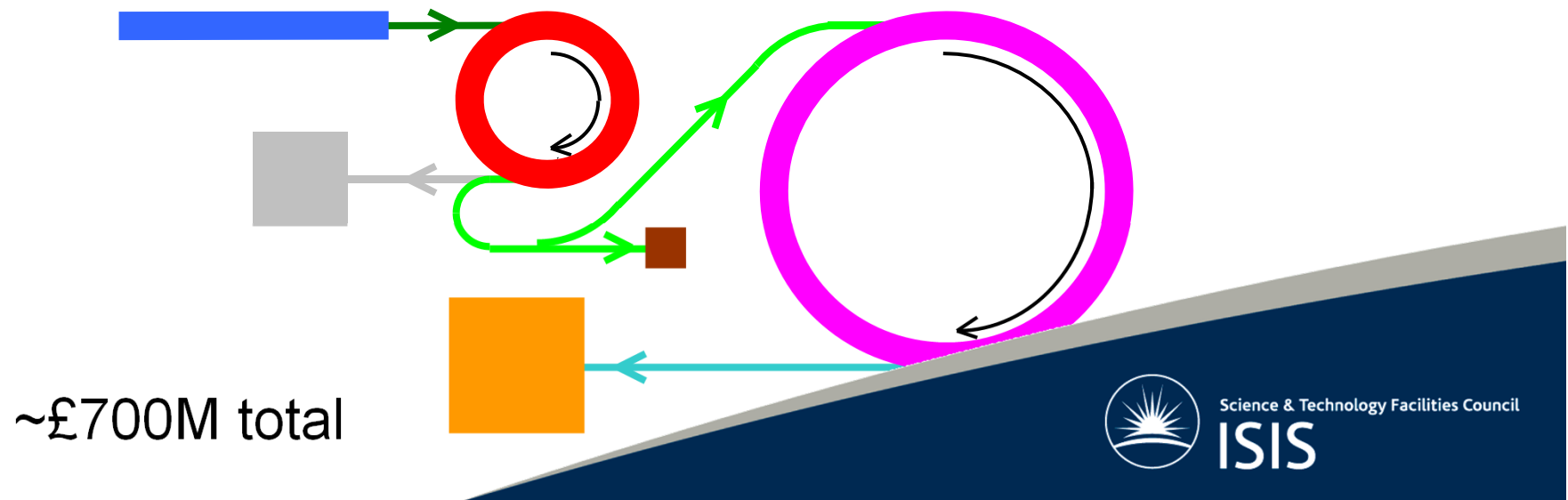
2. Add ~3 GeV synchrotron

Accelerator protons to ~3000 MeV, not 800 MeV

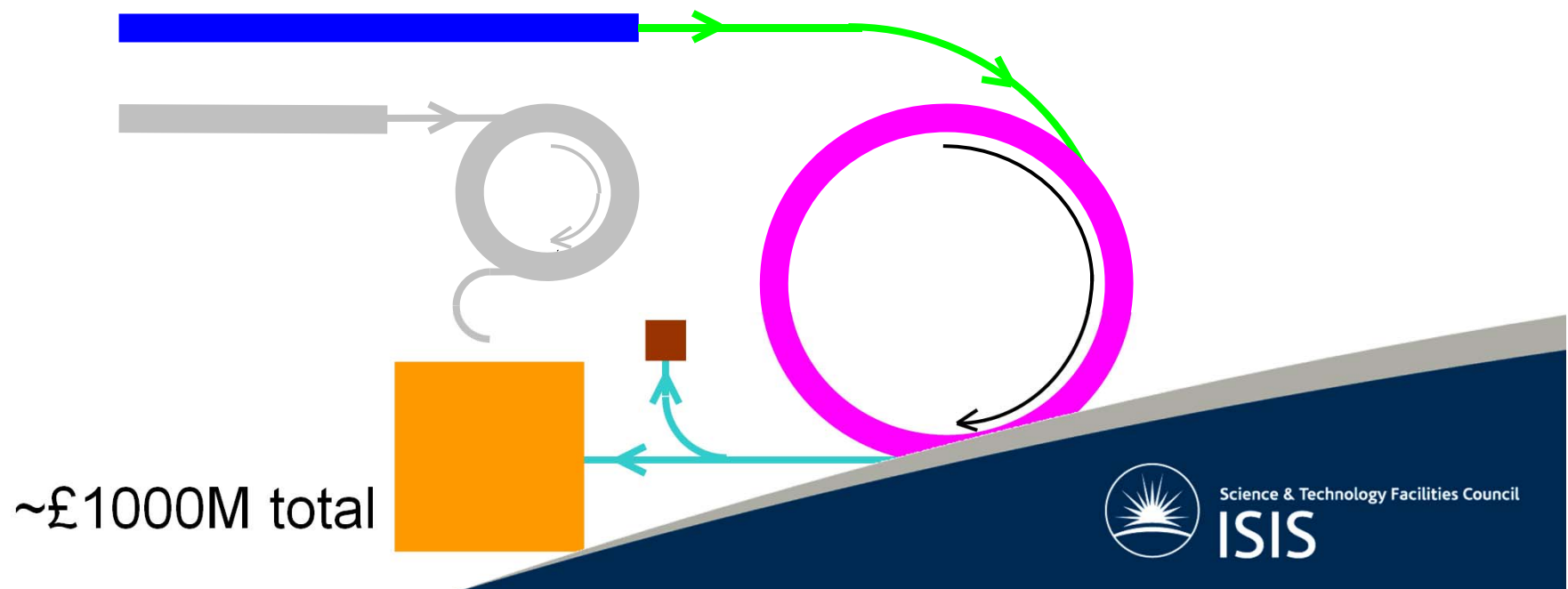
~1 MW beam power, bucket-to-bucket transfer

Need new TS-3 (presumably close TS-1)

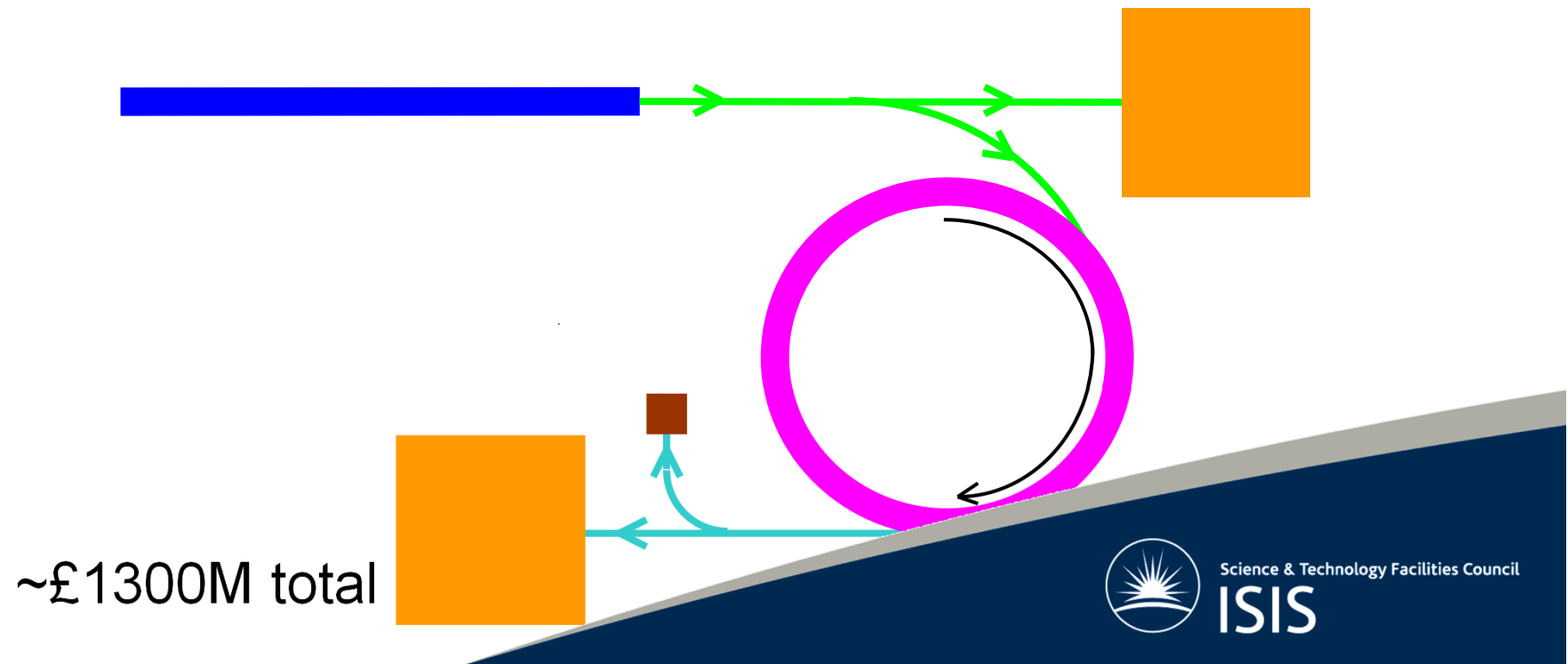
Issue of retaining TS-2



3. 800 MeV direct injection to ~3 GeV synchrotron
Now fill all buckets, and higher energy injection
~2½ MW beam power
Cf. now: performance × 20?



4. ~3 GeV synchrotron + long pulse option
~2002 ESS
~2½ + ~2½ MW





5 MW Long Pulsed Source
Reduced Target Risk
Construction Cost 2,000 M€
Operating Cost ~ ILL

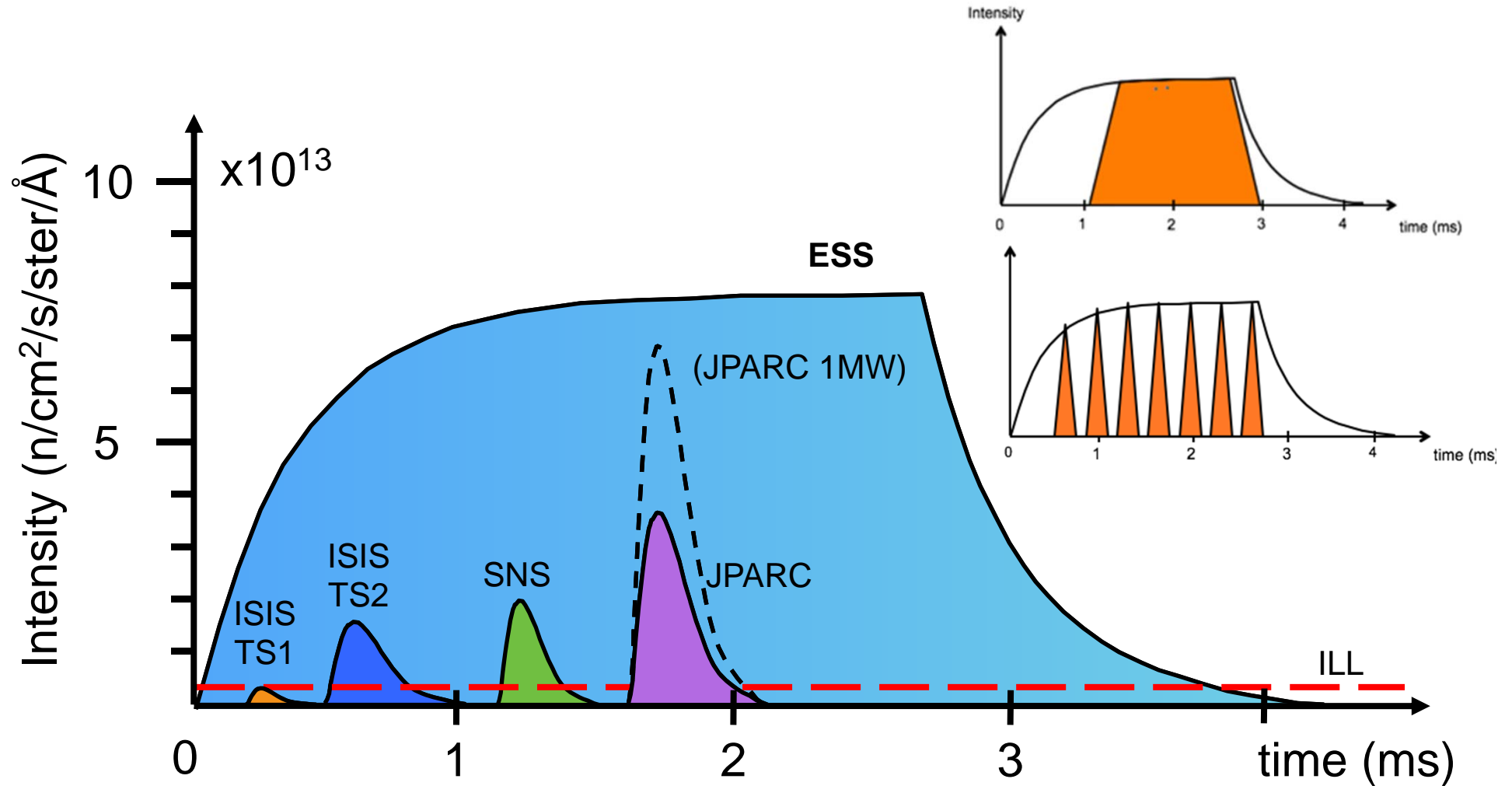
Drivers –

- + Science
- + Addresses ILL Vulnerability
- + Regional Investment
- + European Pride -- “loose our lead”

ILL Lifetime ~ 2030



ESS long pulse potential

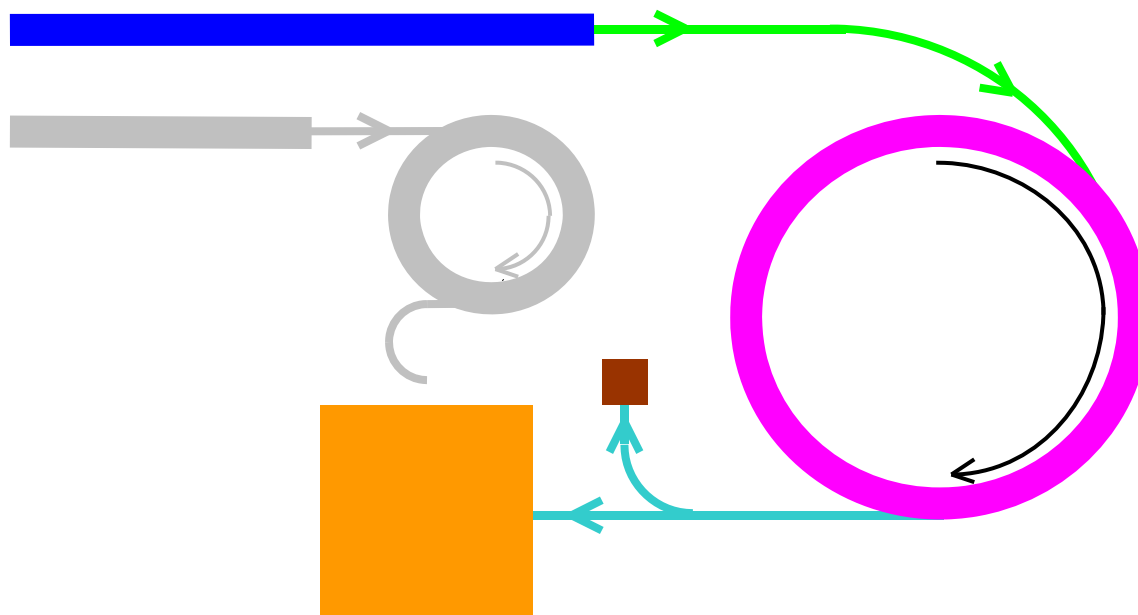




Science & Technology Facilities Council

ISIS

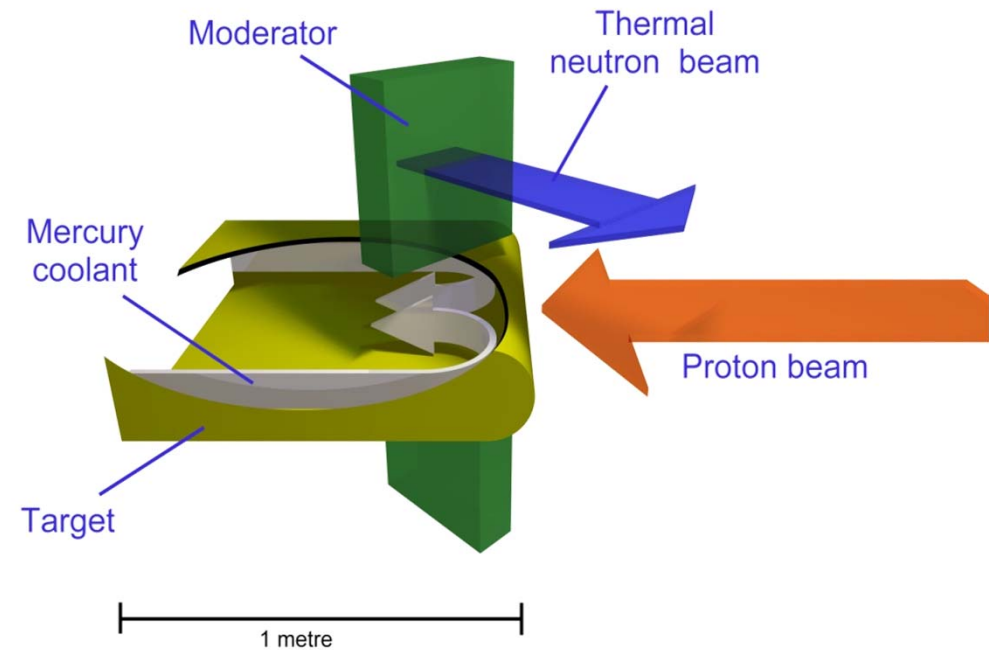
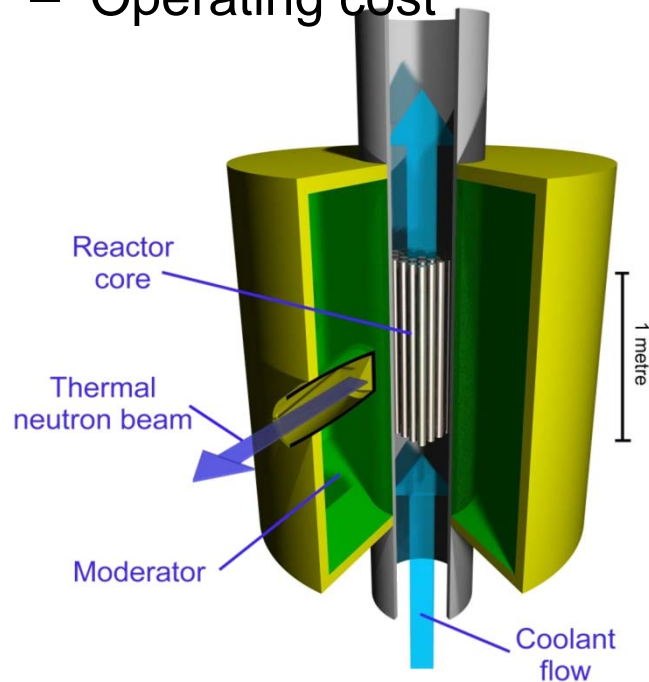
ISIS MW Upgrade x 20



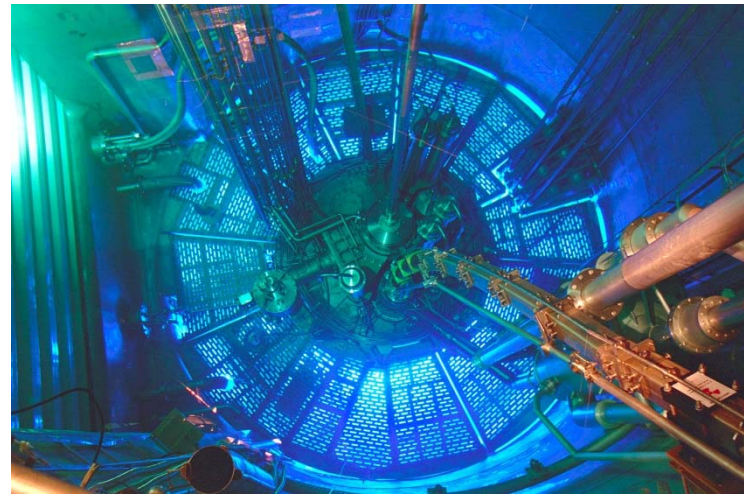
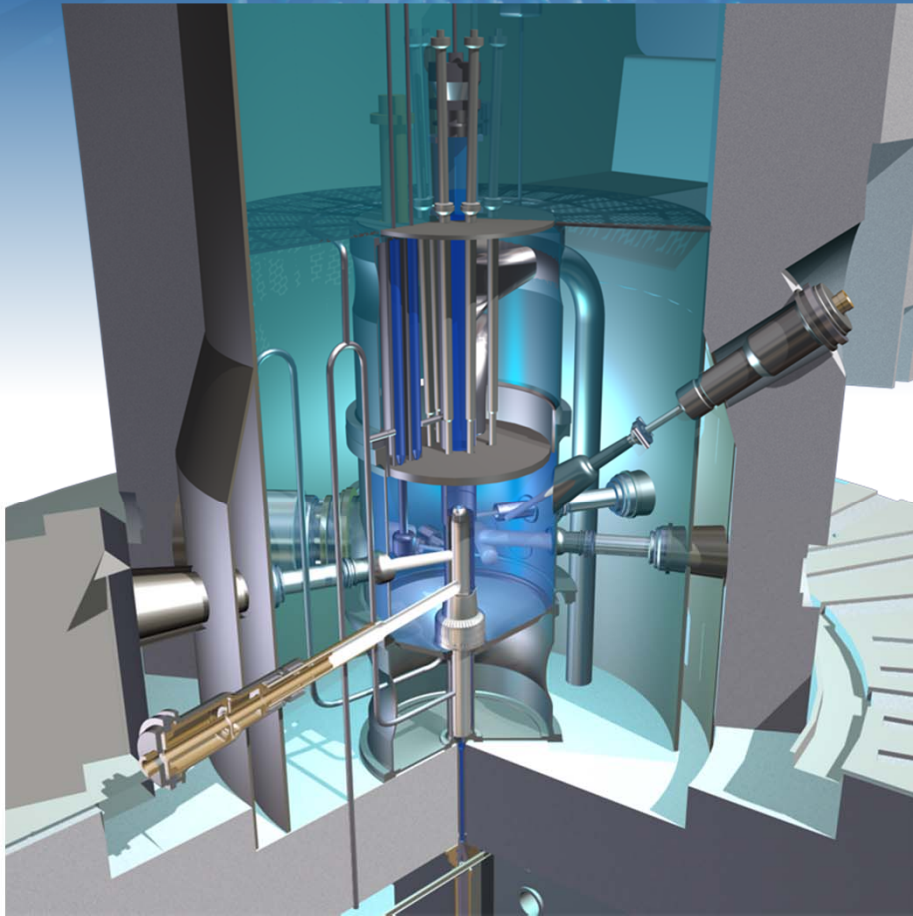


Limitations of current neutron sources

- Current source are limited either:
 - Heat removal from target
 - Shock waves
 - Radiation damage
 - Operating cost



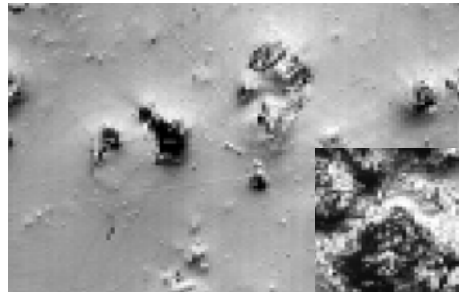
The ILL High Flux Reactor



58 MW reactor operating ~190-200 days/year; 4 Cycles of ~50 days /year;

Radiation Damage in MW+ Targets

10⁴ cycles



JAERI Data

10⁵ cycles



10⁶ cycles

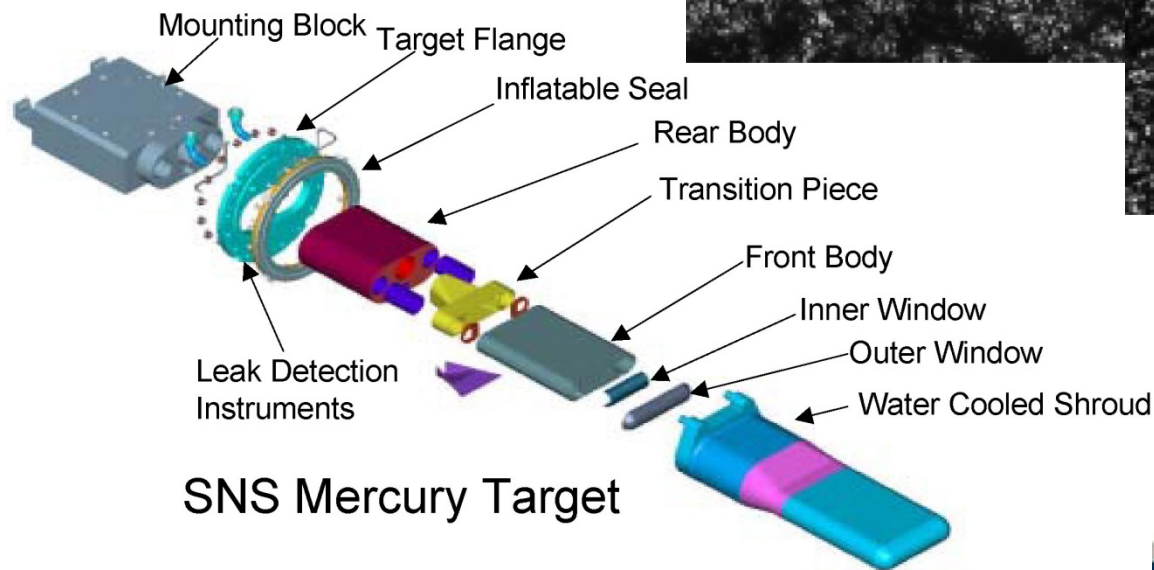


25 μm

2 x 10⁷ cycles

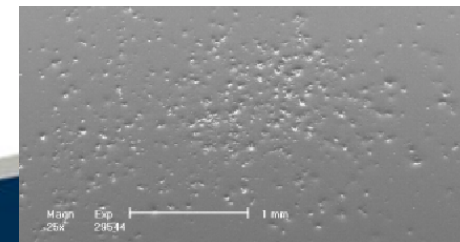


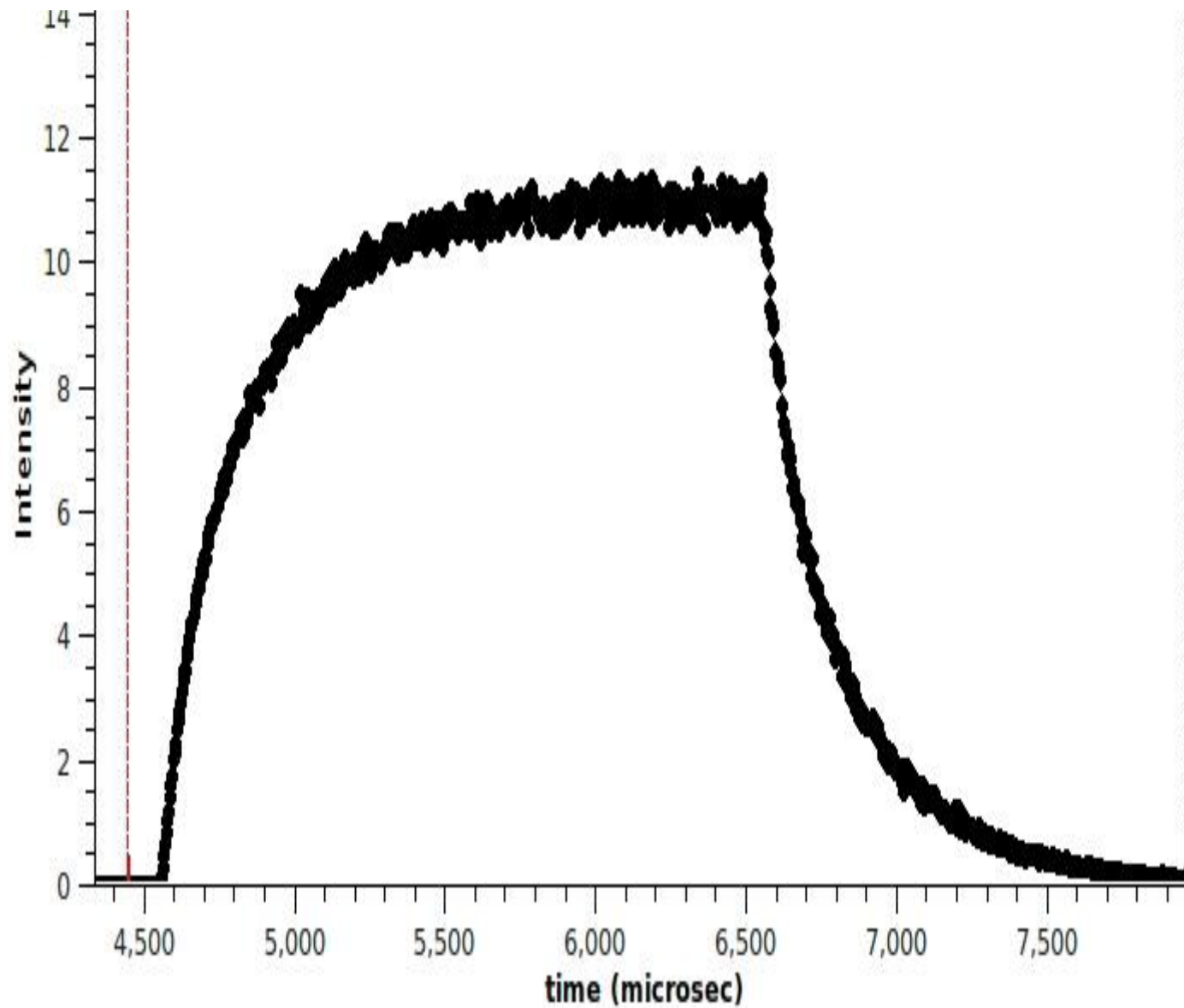
Pitting ~ (Power)⁴



SNS Mercury Target

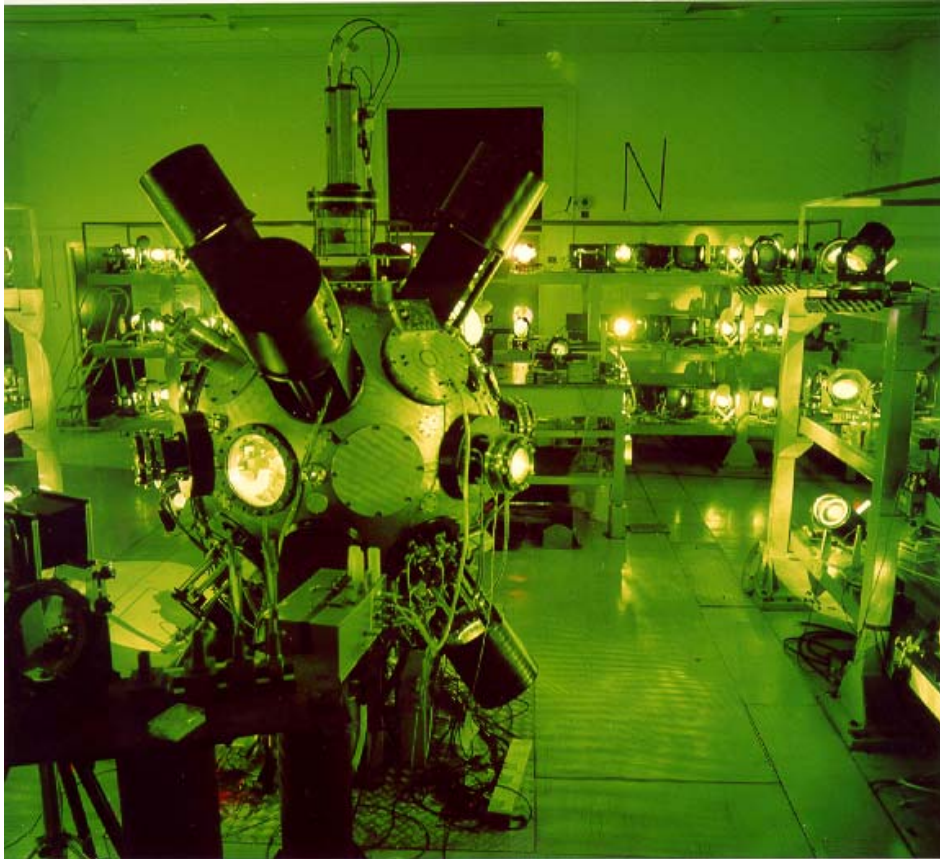
Pitting in steel at WNR
SNS Data (100 proton pulses)





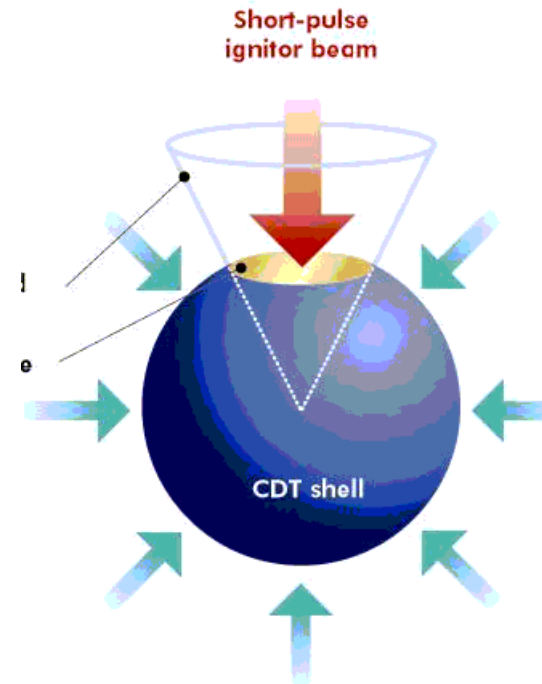


Laser- Driven Neutron Source



Fast Ignition

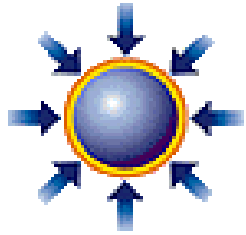
x 1000 enhancement



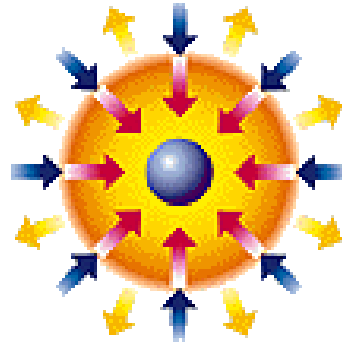
10^{19} 14 MeV n/pulse

100- 1000 x ISIS

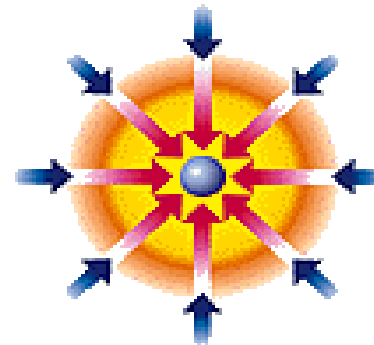
Inertially confined fusion



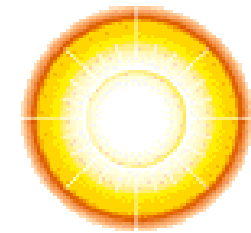
Lasers or X-rays symmetrically irradiate pellet



Hot plasma expands into vacuum causing shell to implode with high velocity



Material is compressed to $\sim 1000 \text{ gcm}^{-3}$



Hot spark formed at the centre of the fuel by convergence of accurately timed shock waves



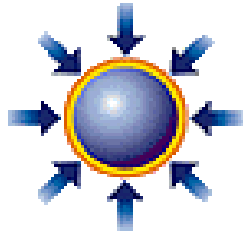
Laser Fusion is a reality ... NIF



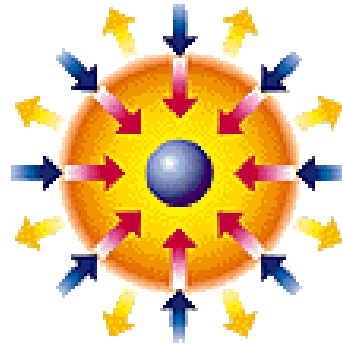
...on an enormous scale



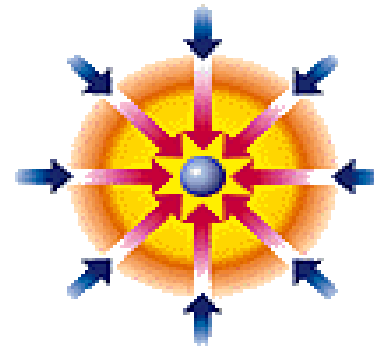
Fast Ignition Fusion



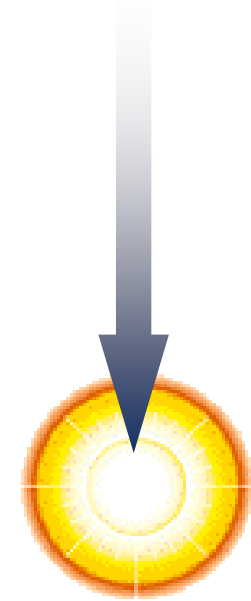
Lasers or X-rays symmetrically irradiate pellet



Hot plasma expands into vacuum causing shell to implode with high velocity



Material is compressed to $\sim 300 \text{ gcm}^{-3}$



Picosecond pulse heats the plasma and ignites the compressed fuel

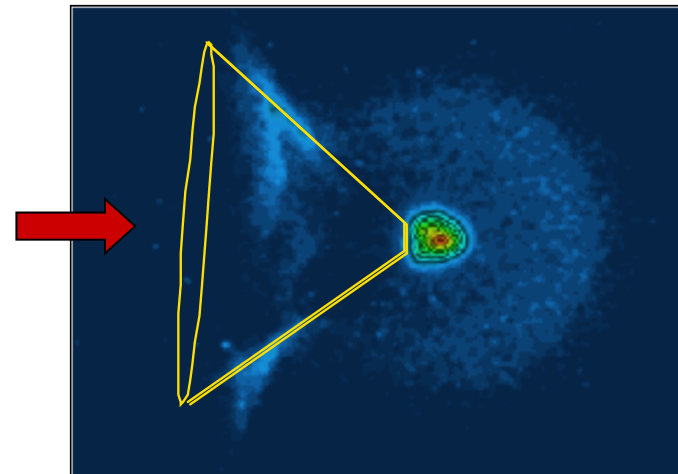
- **Lower temperatures – fewer Raleigh-Taylor instabilities**
- **Lower density and no shock wave heating required**



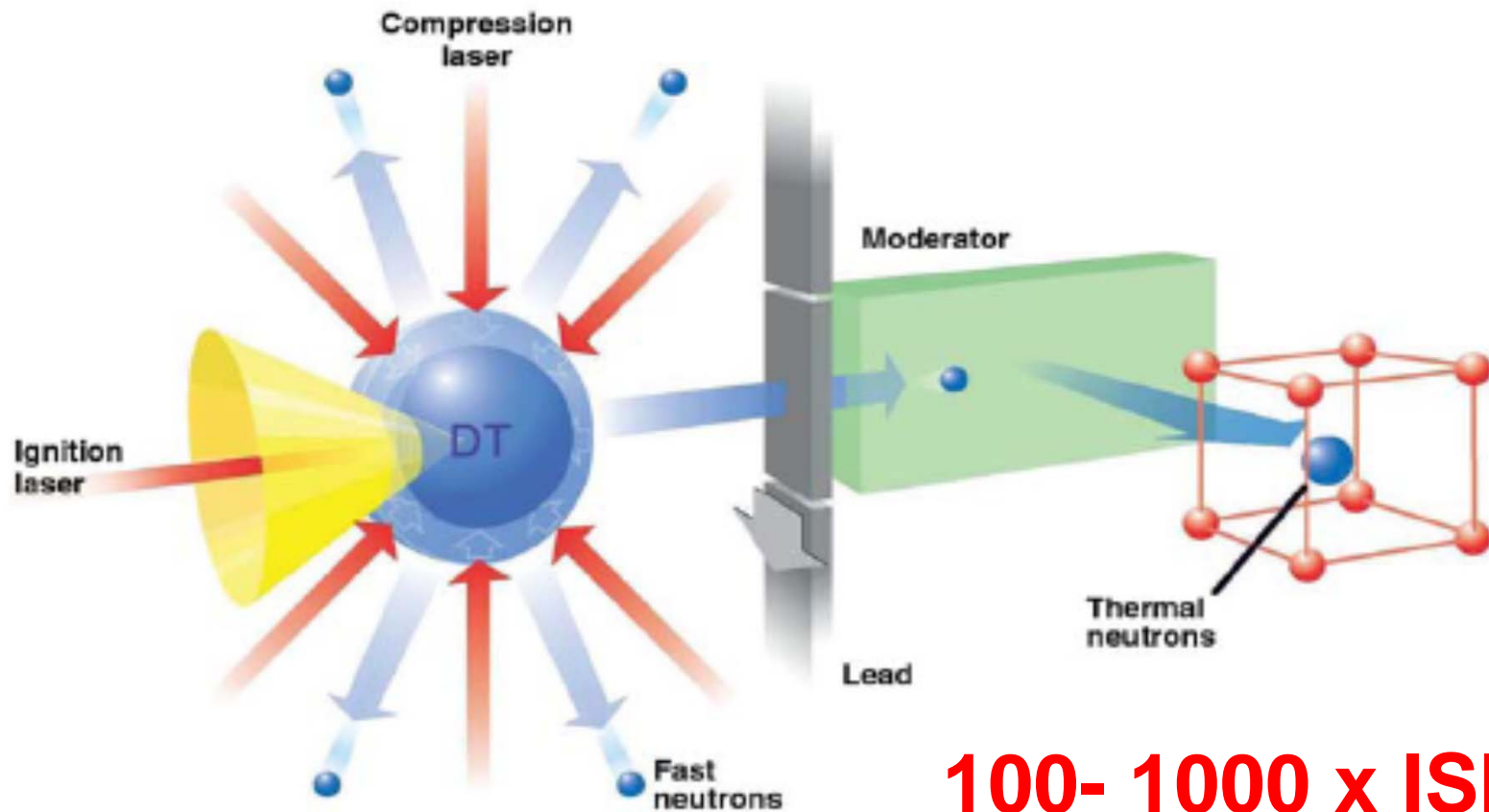
Advanced fast ignition

Advanced Fast Ignition further changes the landscape

- Demonstrated by UK / Japan team
- Neutron yields increased from 10^4 to 10^7



Fast Ignition Source



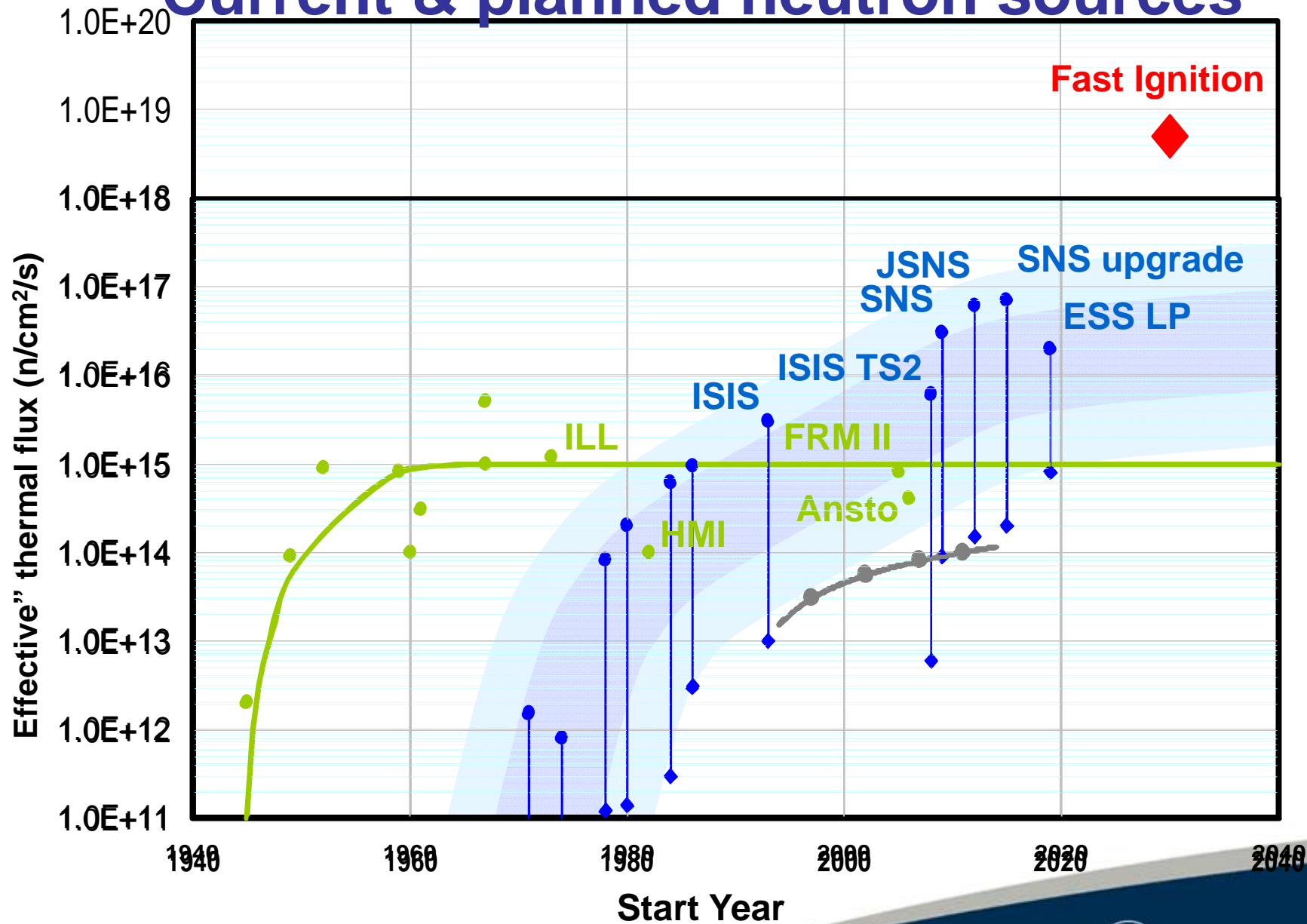
100- 1000 x ISIS

Taylor et al SCIENCE, Feb 2007



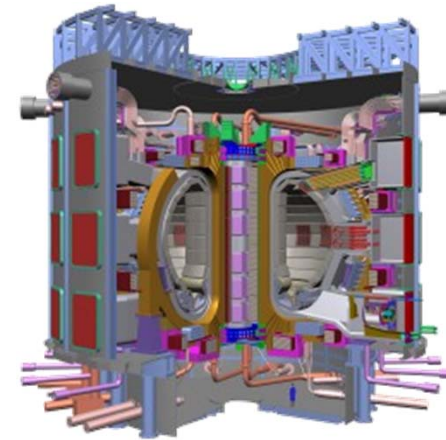
Science & Technology
Facilities Council

Current & planned neutron sources



Serious Engineering Challenges

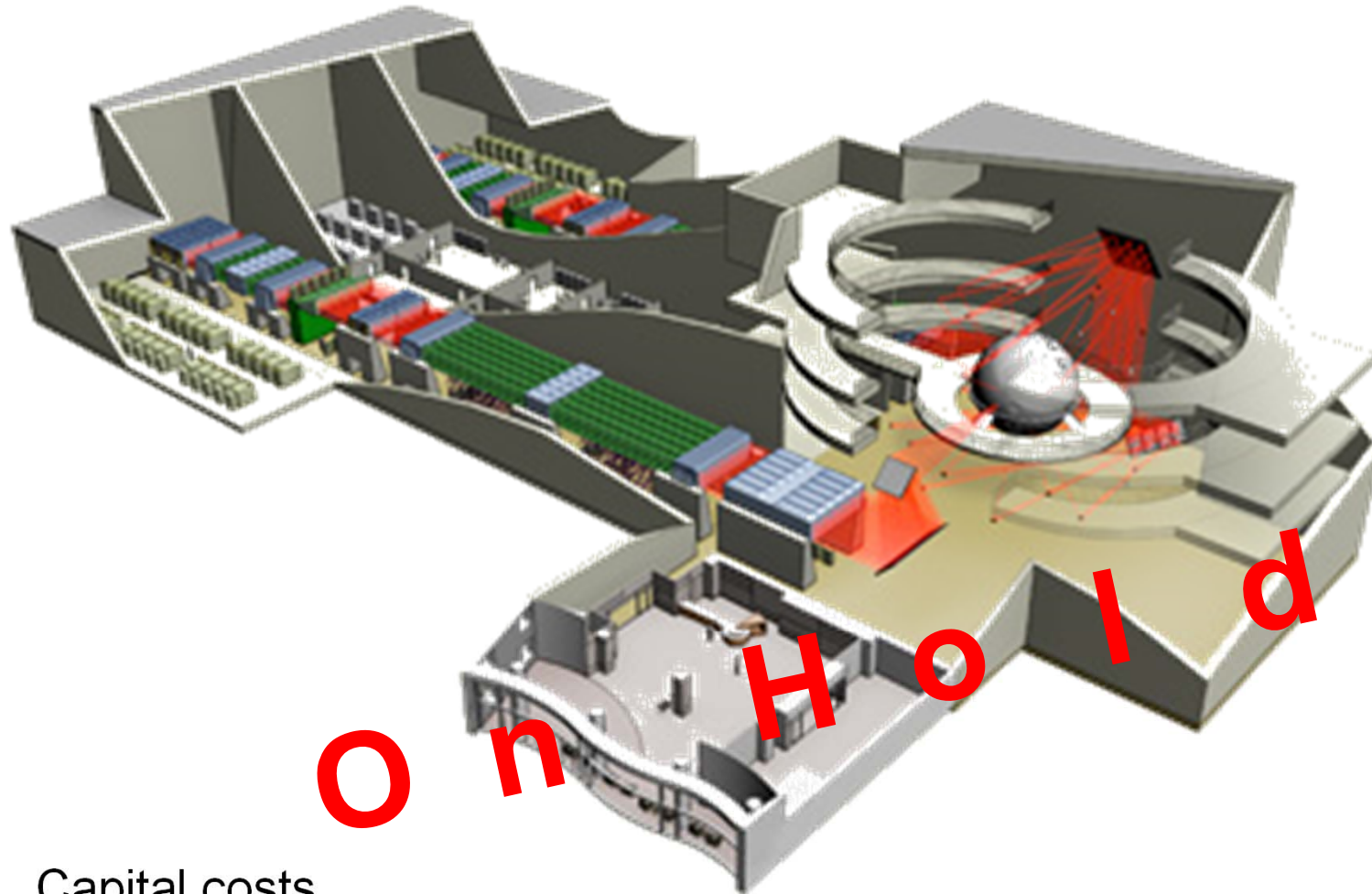
- Radiation damage limits the lifetime of the components
- Tritium breeding and pellet production
- Erosion of sacrificial layer
- Vacuum maintenance



**All problems that also
need to be solved for
ITER**



ESFRI Project -- HiPER



- Capital costs
 - Scales with laser. Fast ignition requires lasers only 10% of the size of normal inertial confinement lasers
 - (£, \$, €, ...) 1 – 2 billion



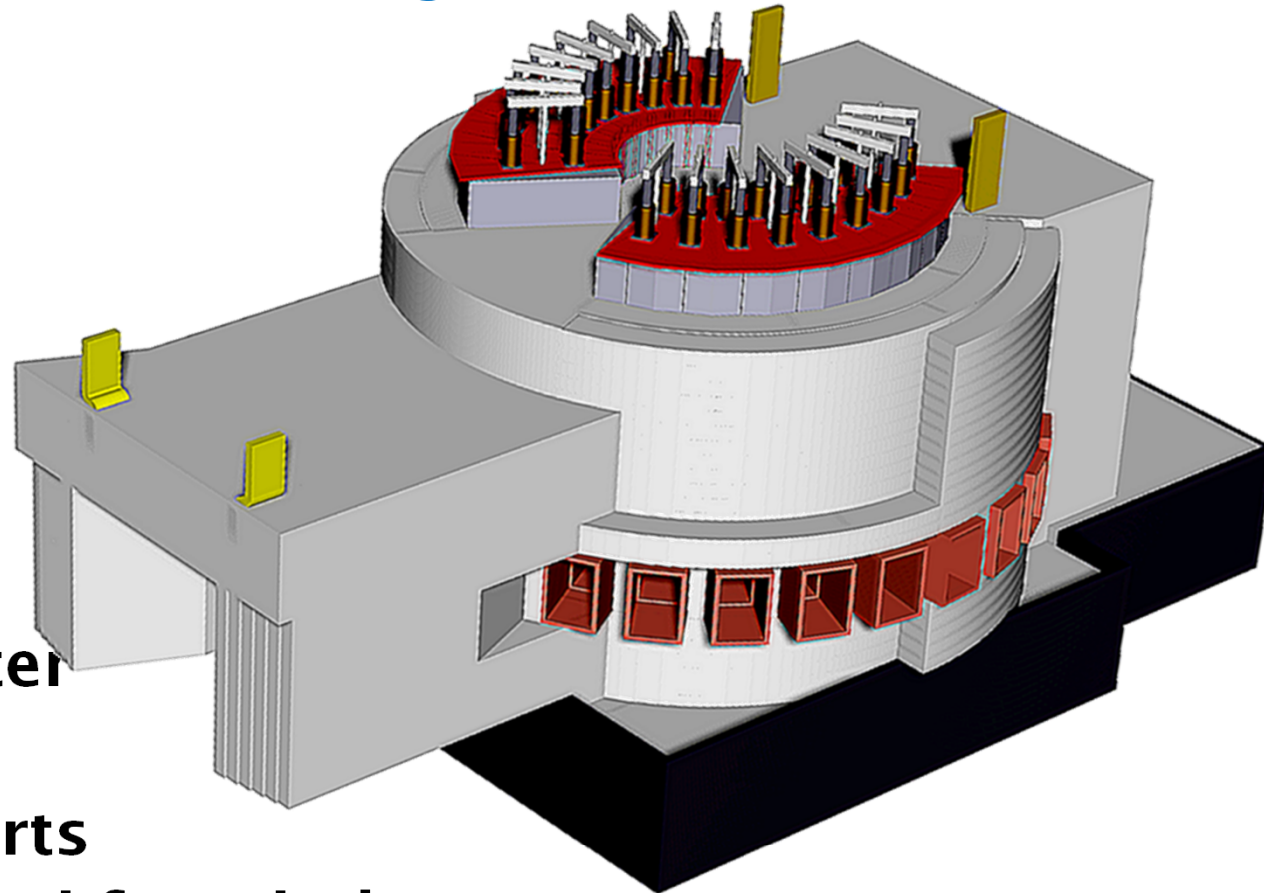


Compact Neutron Sources

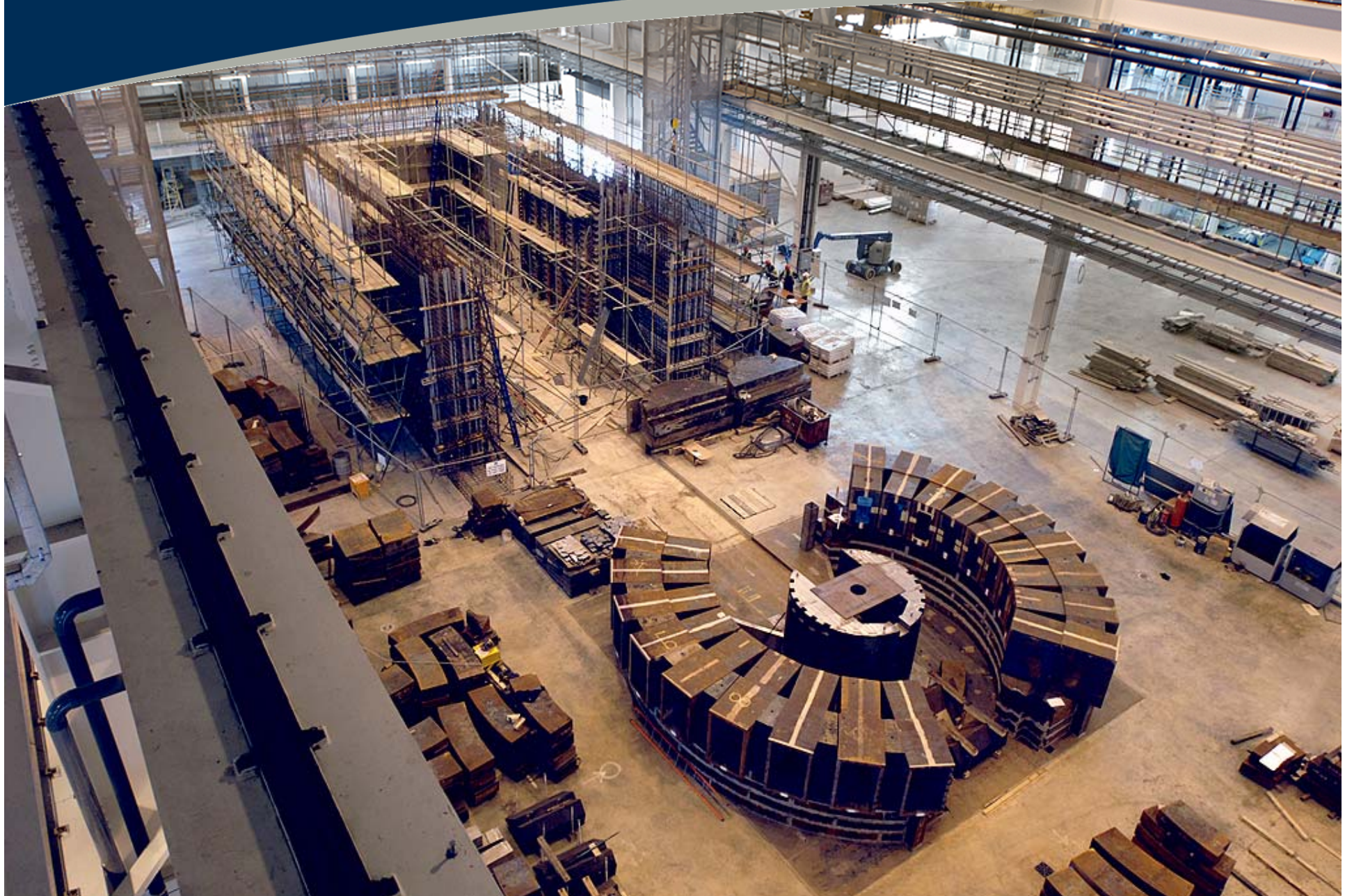
- Spallation Sources
- Shielding a major issue
- (P,n) reactions

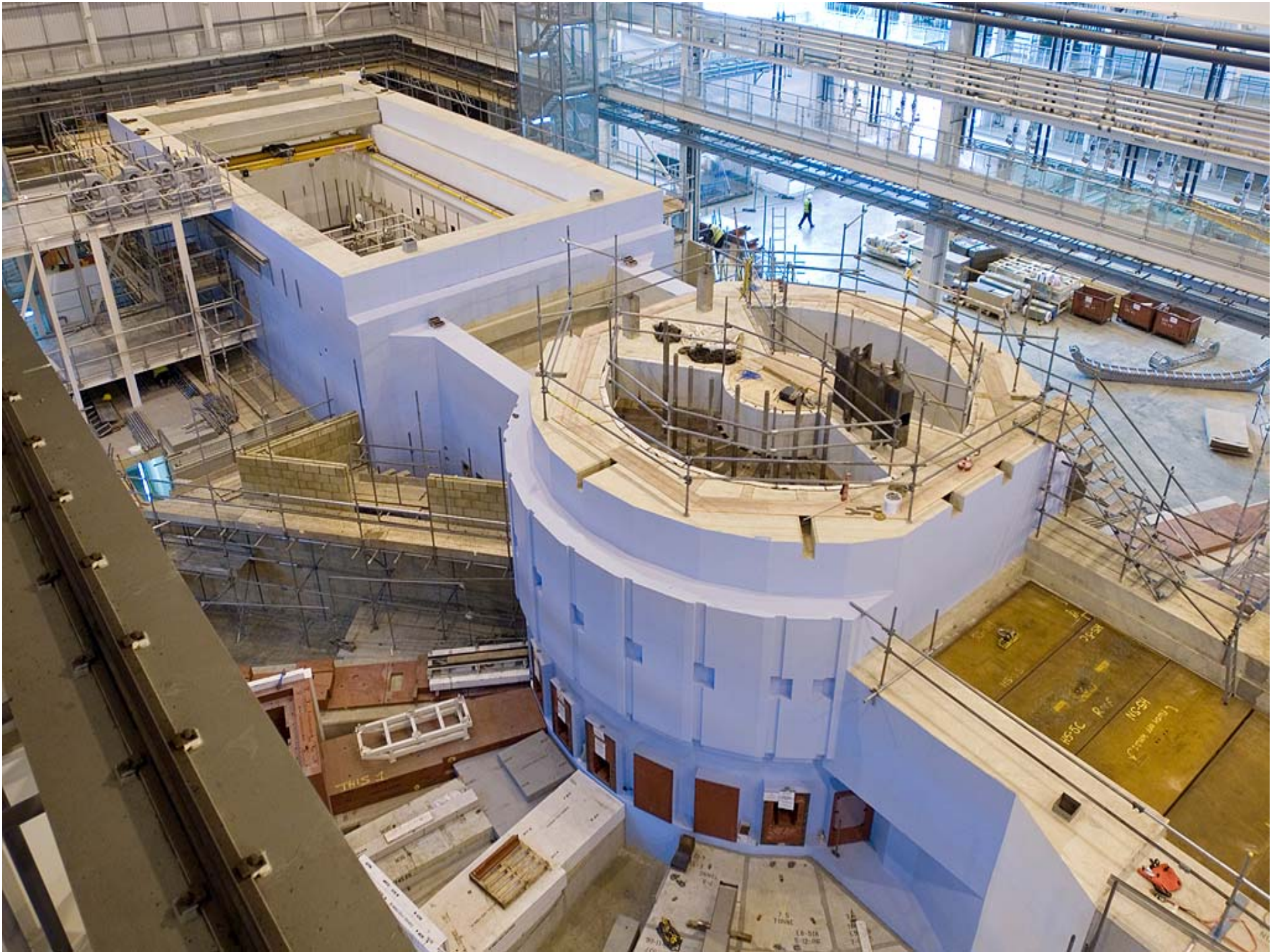


Target station monolith



- 12m diameter
- 7m high
- 18 beam ports
- 3m deep steel foundations
- Steel and concrete construction

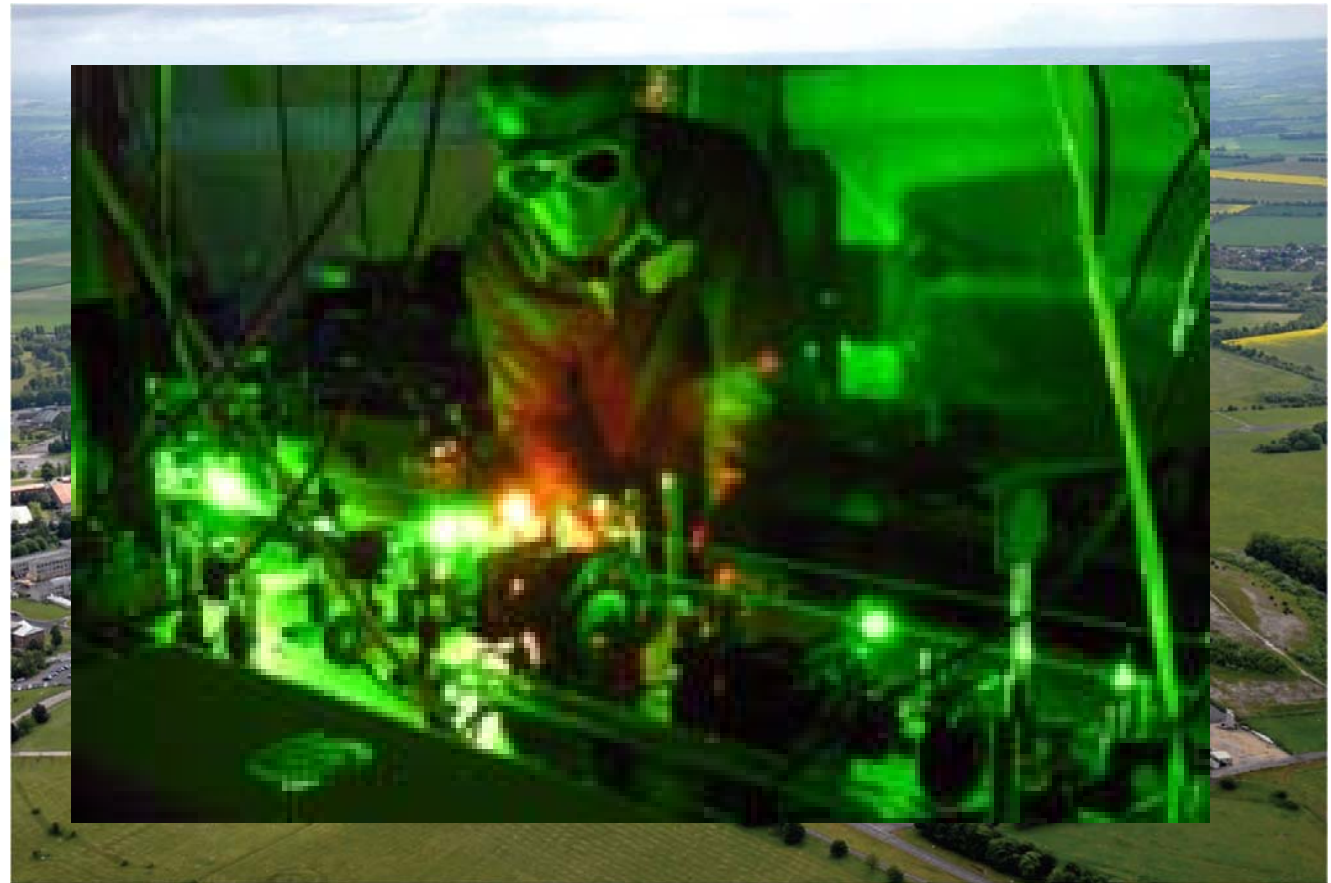




International Year of Light



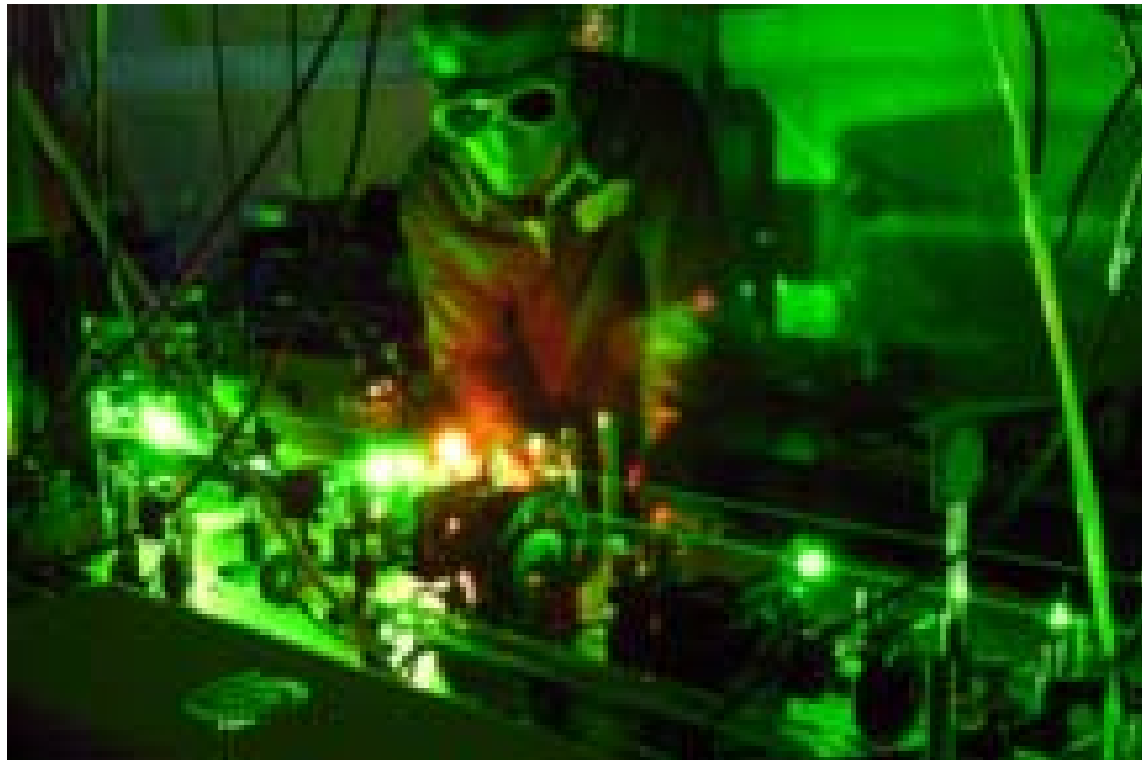
International
Year of Light
2015



Diode-Pumped Lasers



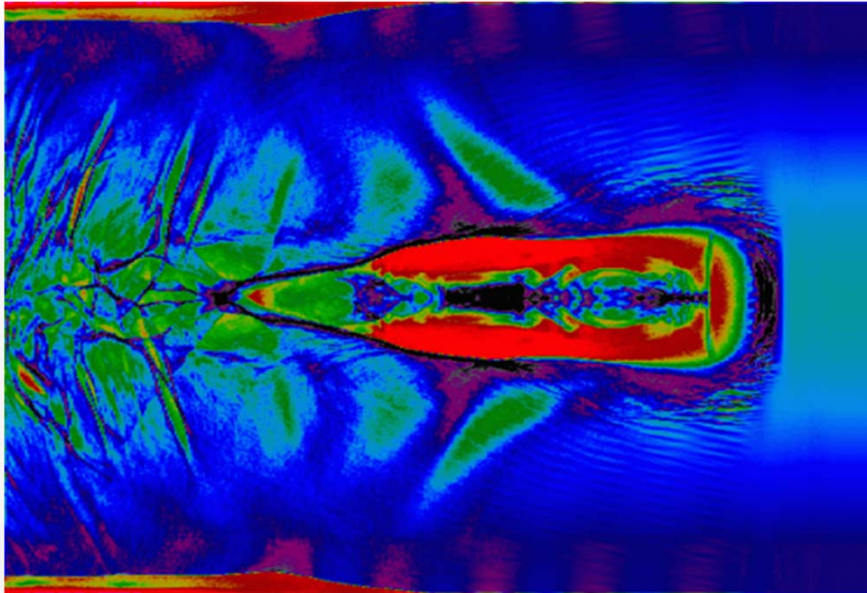
International
Year of Light
2015



Diode-Pumped Lasers



International
Year of Light
2015



Wakefield accelerators

Source of intense secondary radiation

Electrons

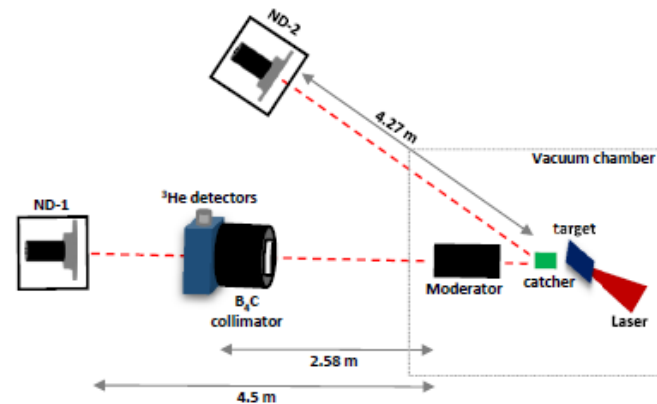
X-Rays

Protons.....

Compact Intense Neutron Sources



International
Year of Light
2015



**Laser-driven protons Au Target
Li(p,n)Be +compact moderator**

Kar et al (QEB)



Science & Technology Facilities Council

ISIS



Science & Technology Facilities Council

ISIS



EUROPEAN
SPALLATION
SOURCE



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