Science & Technology Facilities Council

# Neutron Sources – Past, Present and Future

***F P Ricci XIII SoNS School***

***Erice 2015***

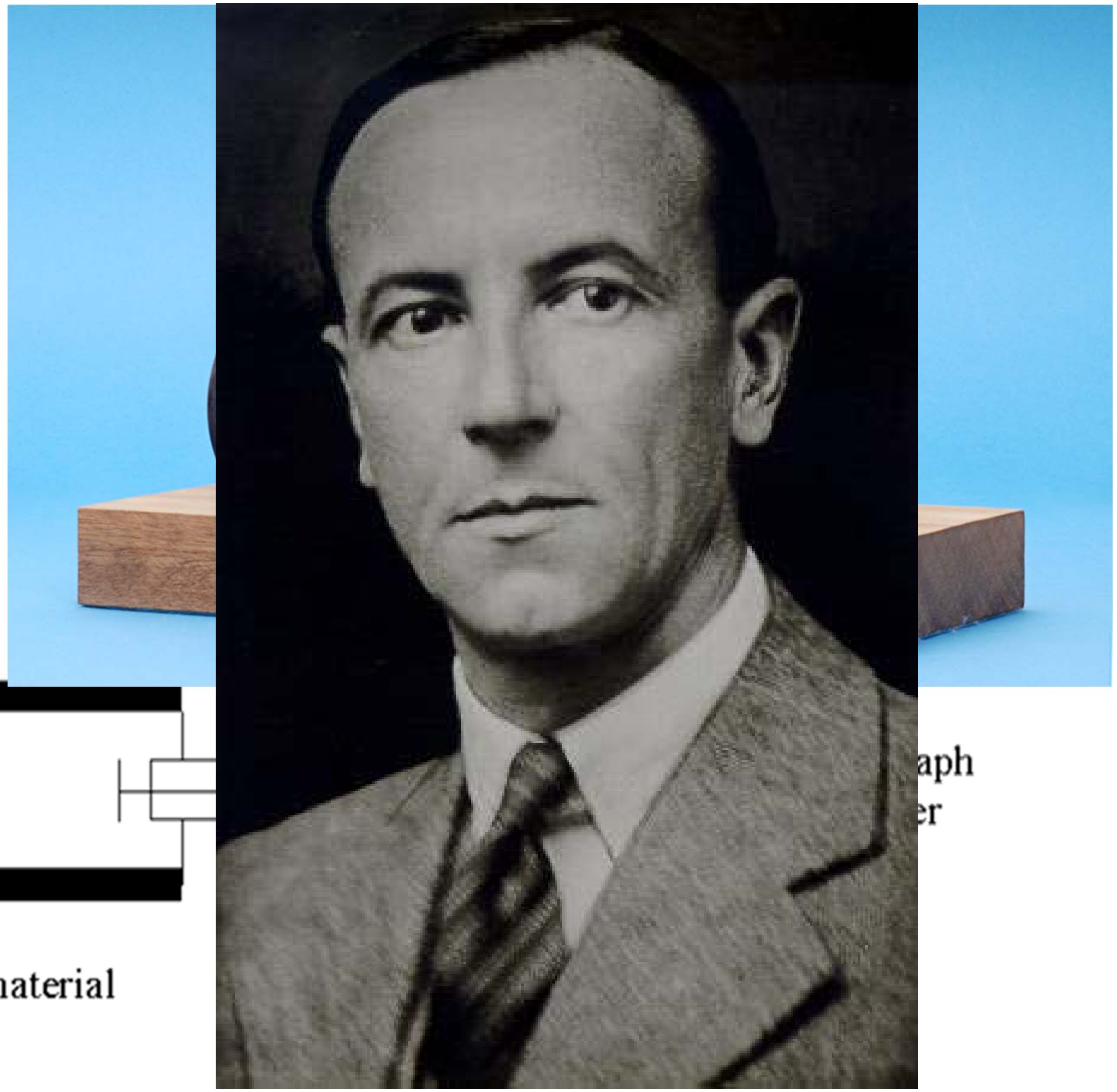
*30th July 2015*

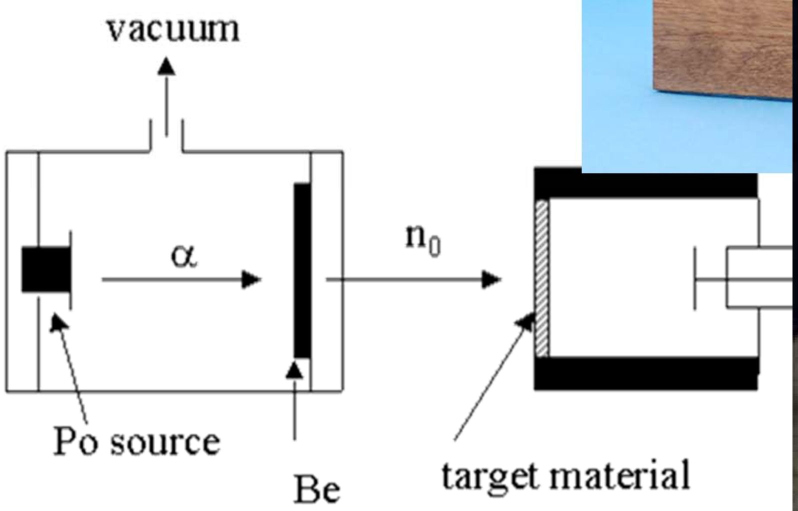
***Andrew Taylor***

# Outline

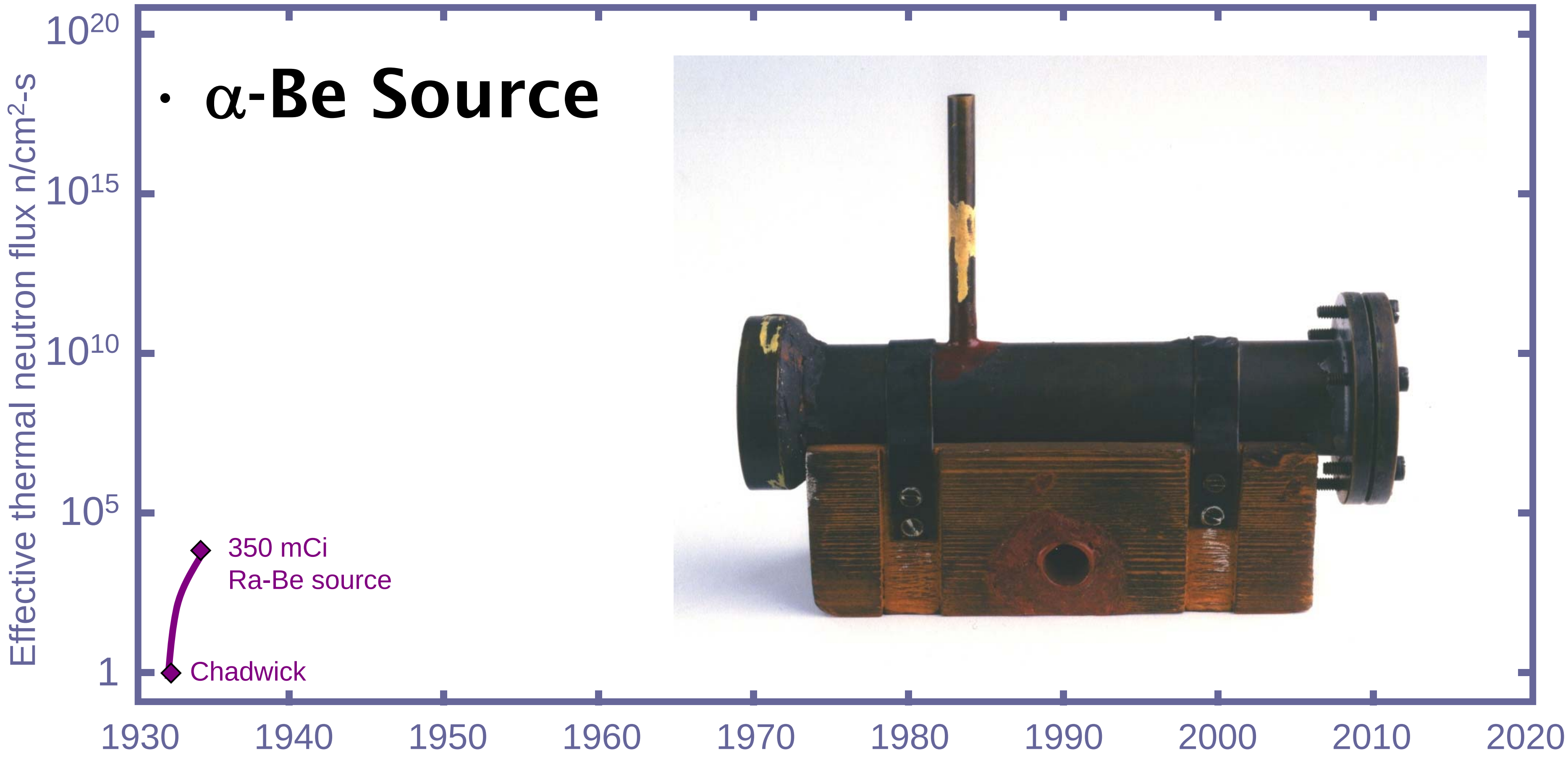
- **Neutron Sources – past, present and future**
- **Effectiveness of Neutron Facilities**
- **What we are doing in the UK**
- **What the future might hold**

# The First Neutron Source



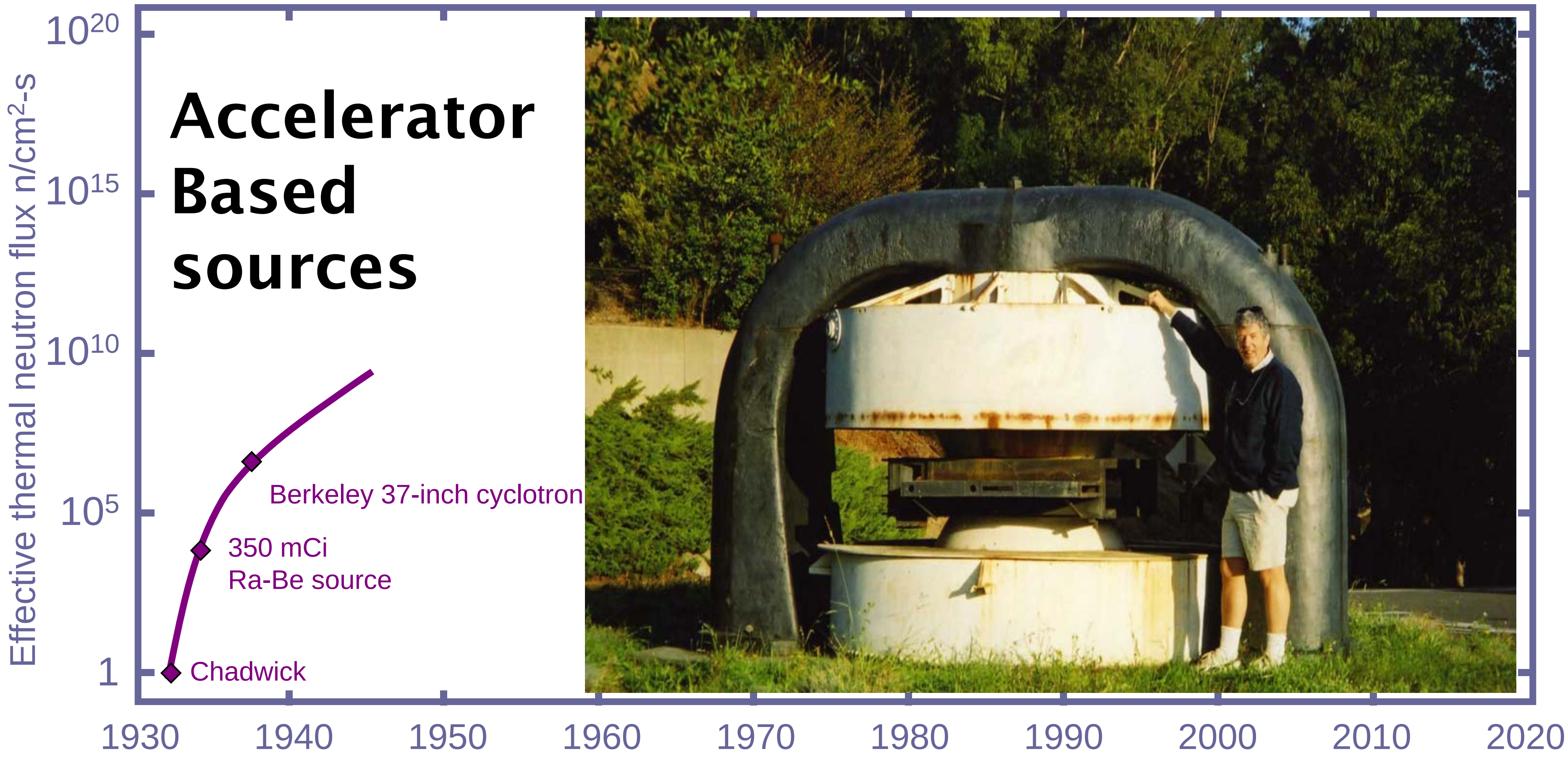


# Neutron Sources



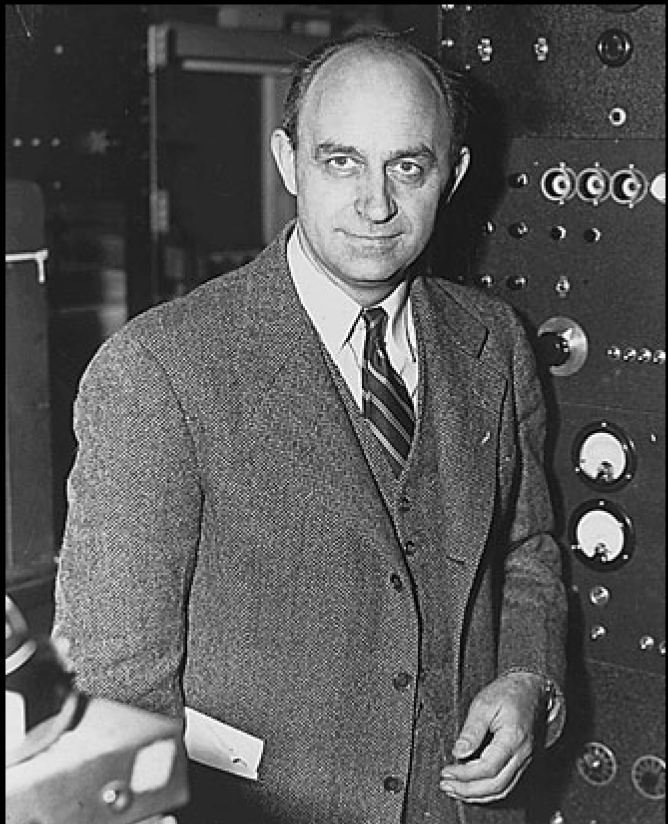

(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

# Neutron Sources



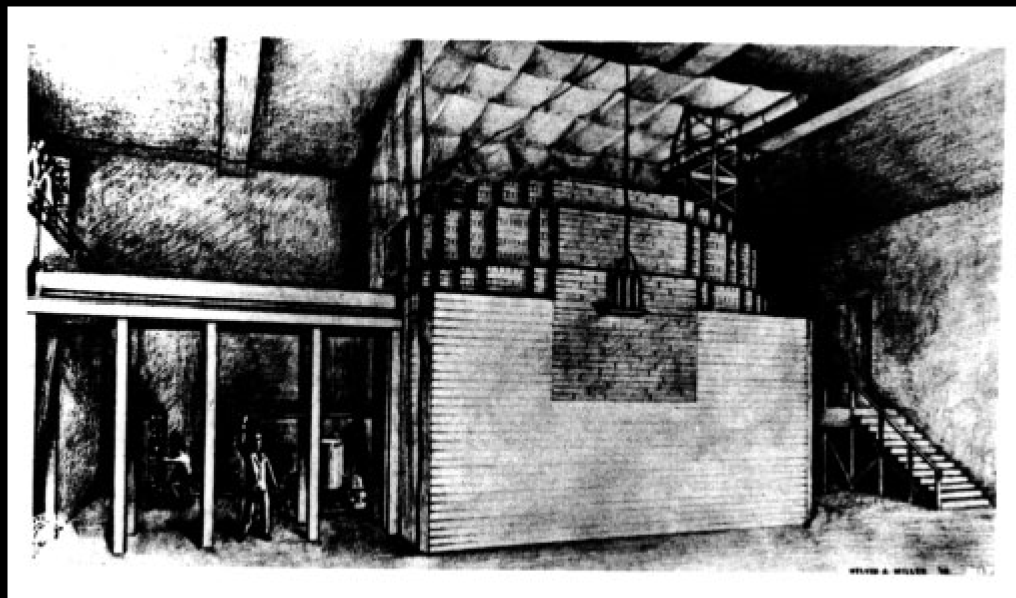

(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

# Enrico Fermi 1901-1954



2nd December 1942 first ‘atomic pile’

‘Chicago Pile -- CP1’



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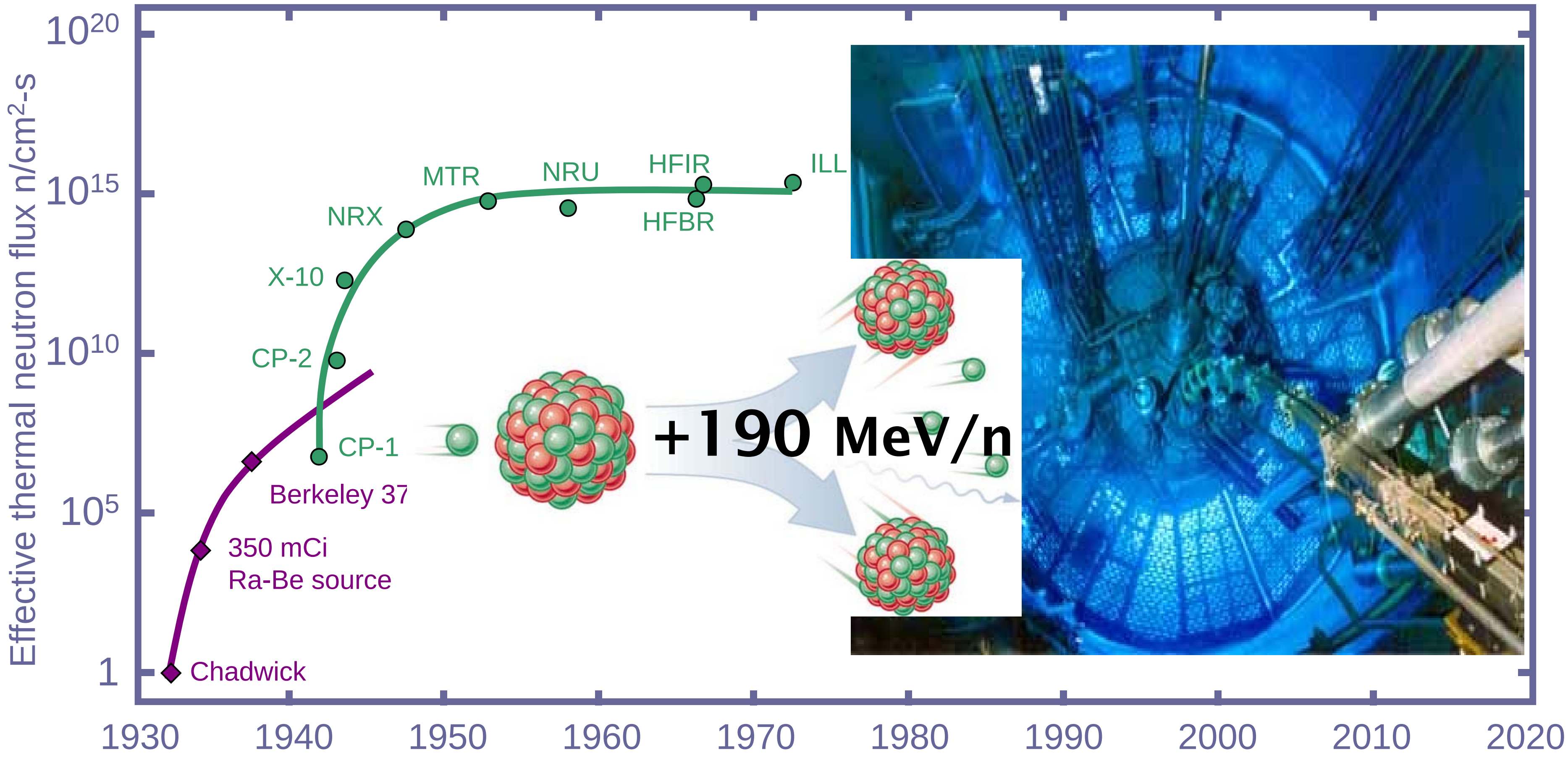
# Neutron Sources

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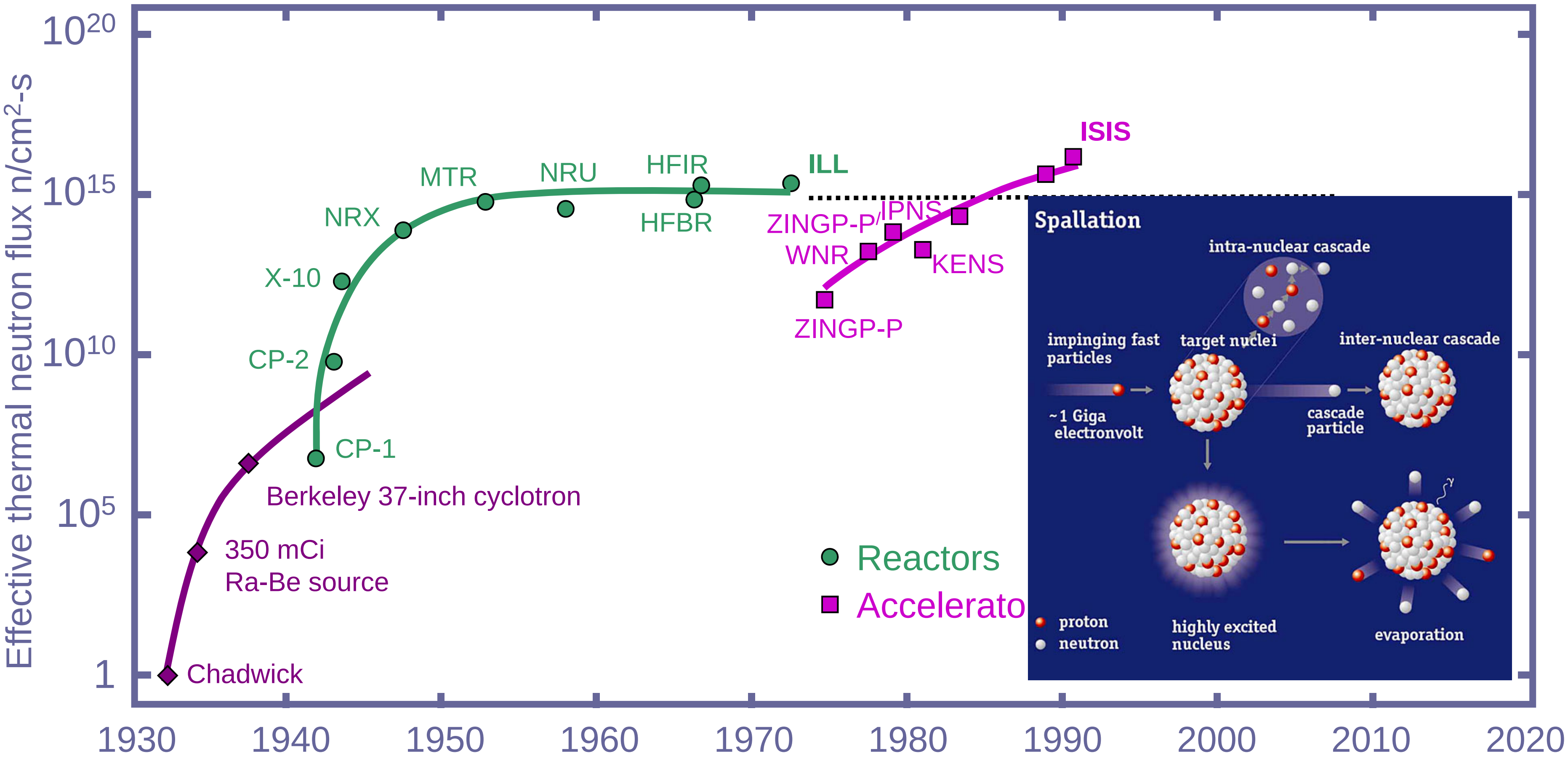
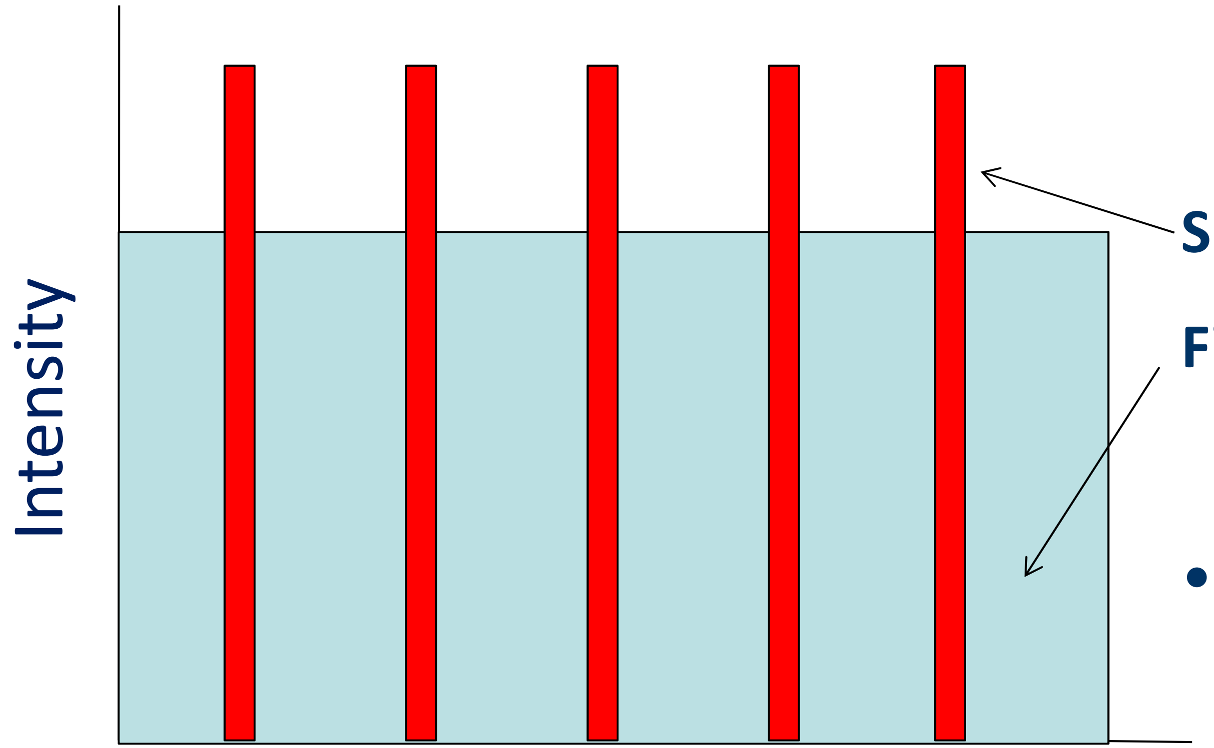
# Neutron Sources




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

# Pulsed versus Steady State



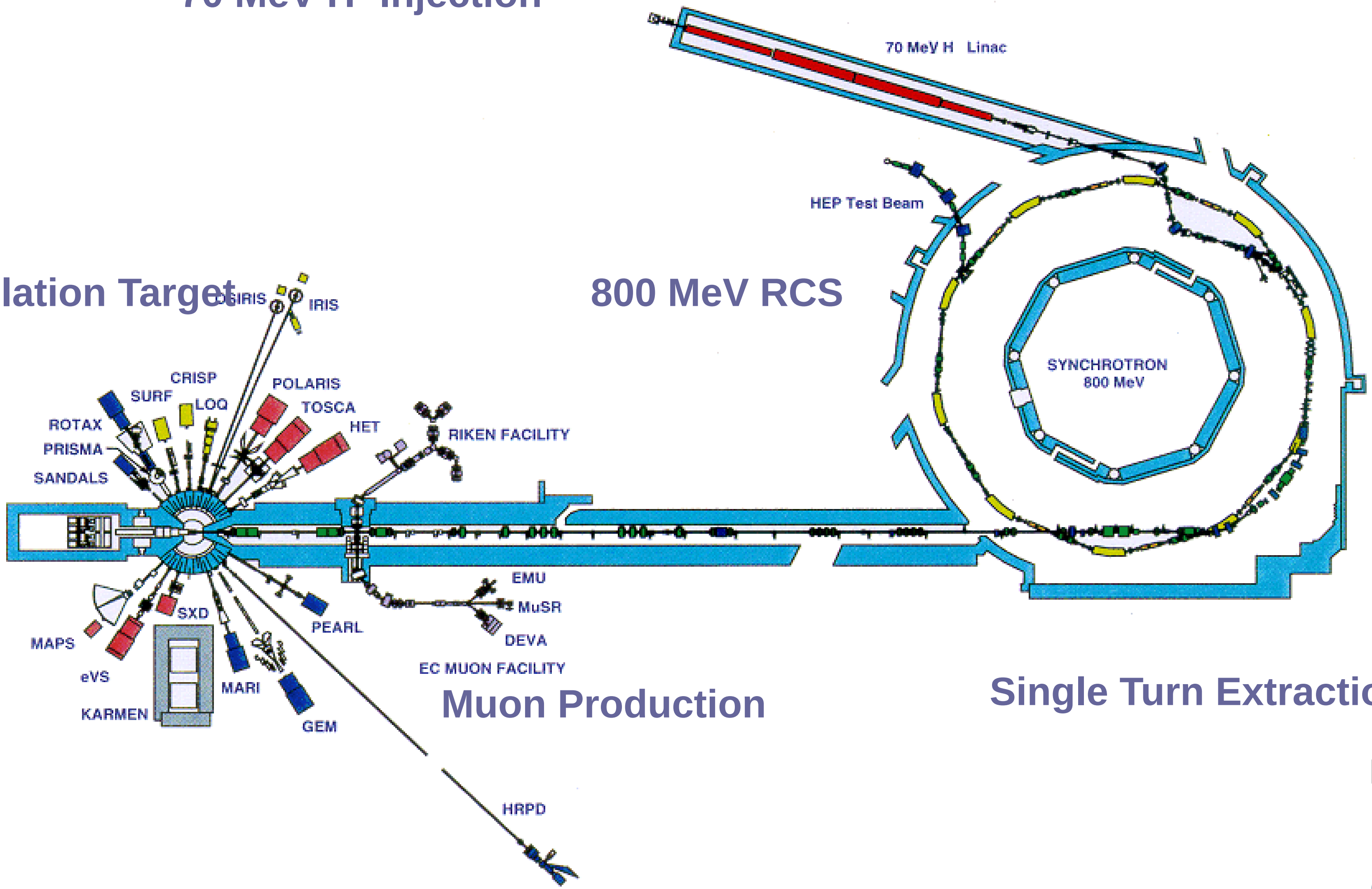

- T-o-F techniques

# ISIS Pulsed Spallation Source.

70 MeV H- Injection

Spallation Target

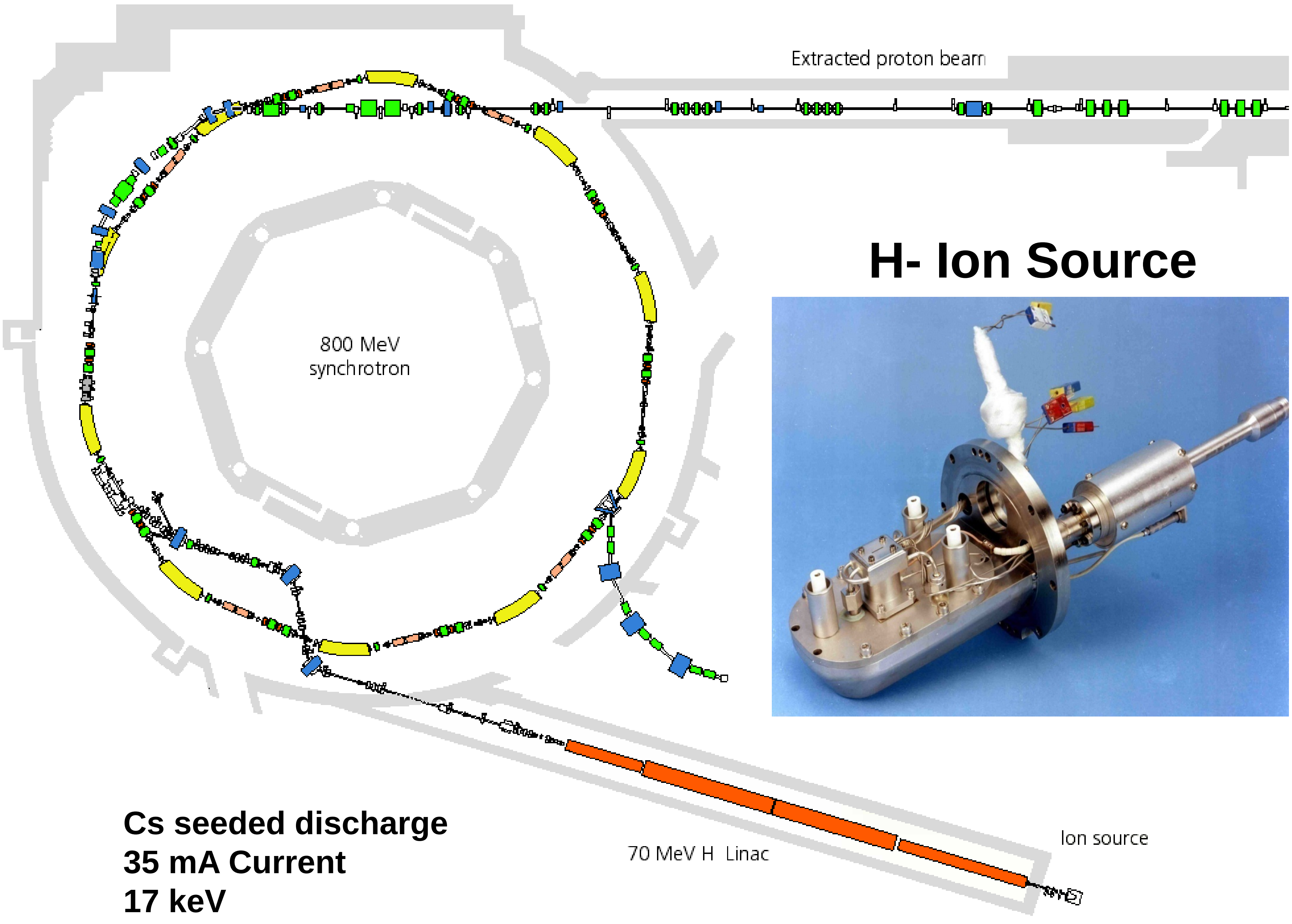
800 MeV RCS



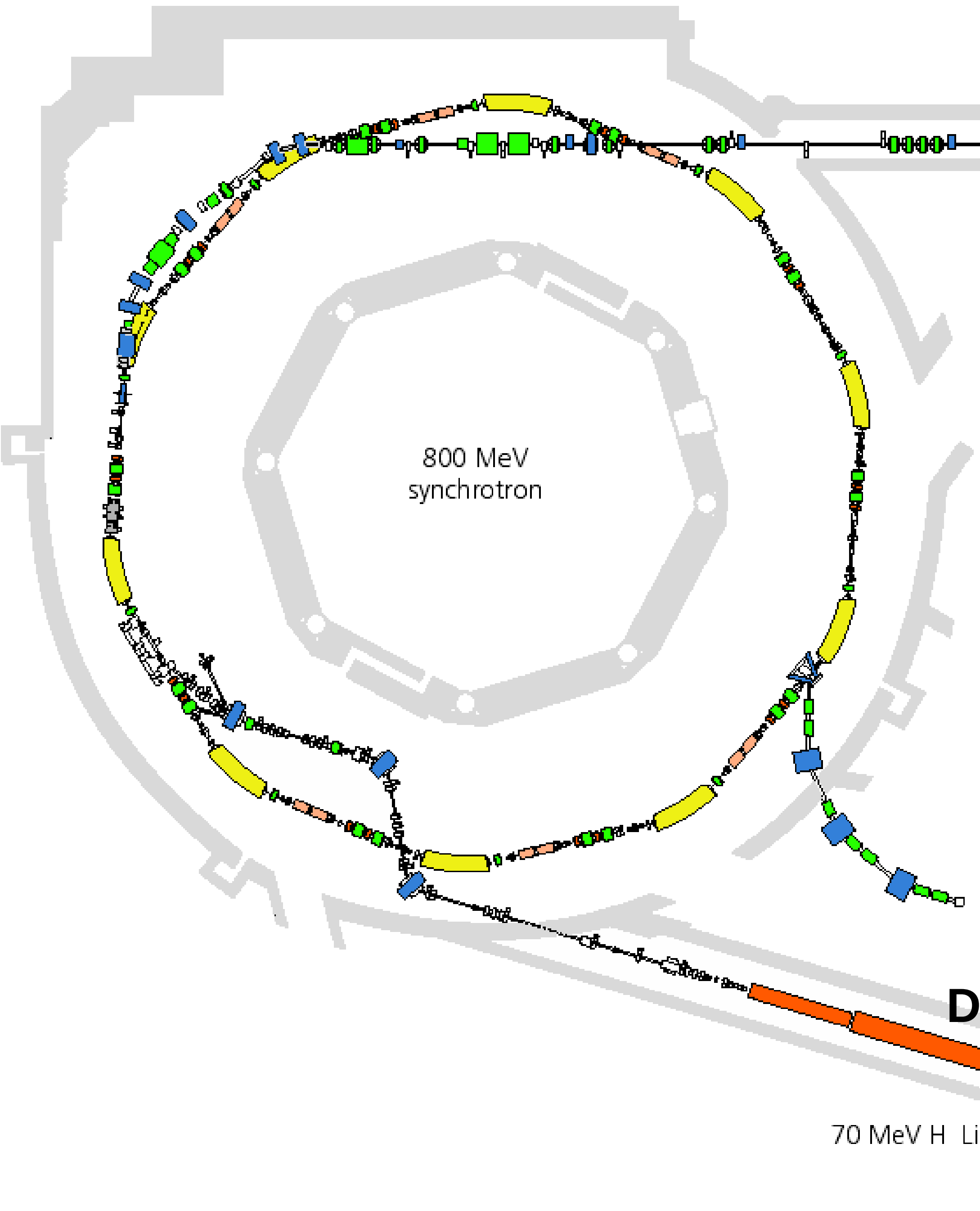

Muon Production

Single Turn Extraction

# H- Ion Source




**Cs seeded discharge**
**35 mA Current**
**17 keV**




# 665 keV C-W

**Donated to the Cockcroft Institute**

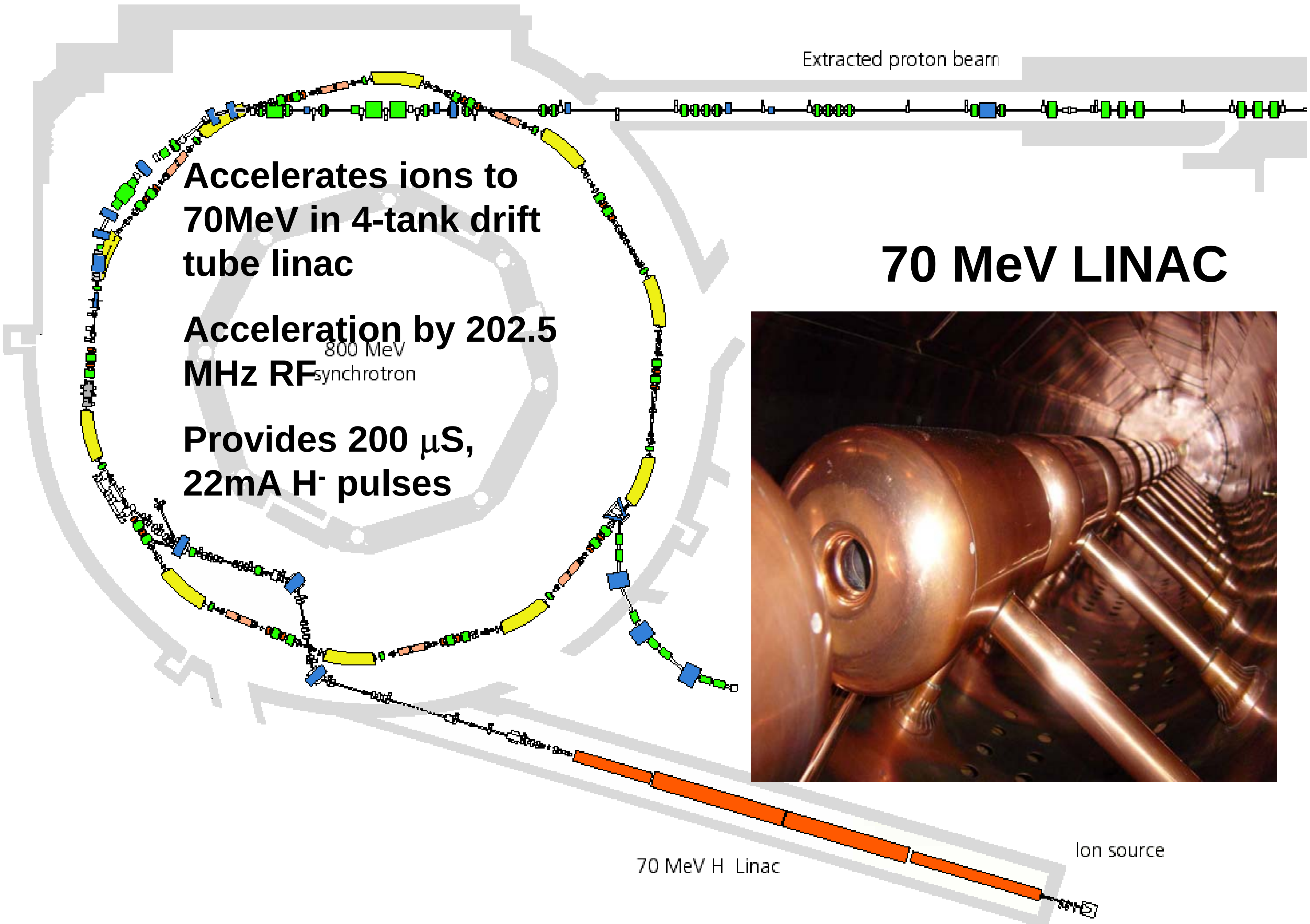
# 665 keV RFQ

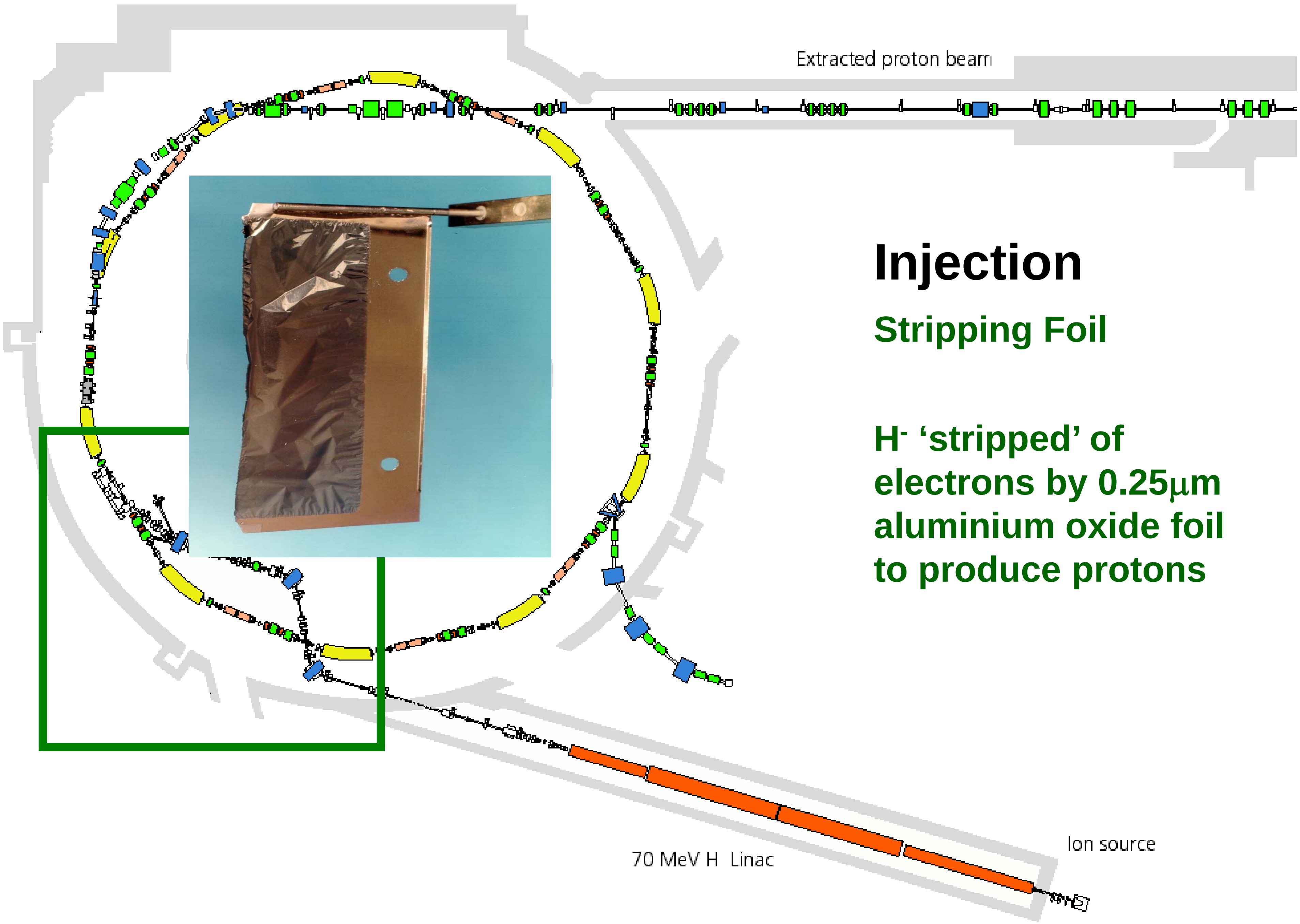
# 70 MeV LINAC

Accelerates ions to 70MeV in 4-tank drift tube linac

Acceleration by 202.5 MHz RF

Provides 200 $\mu$S, 22mA $H^-$ pulses

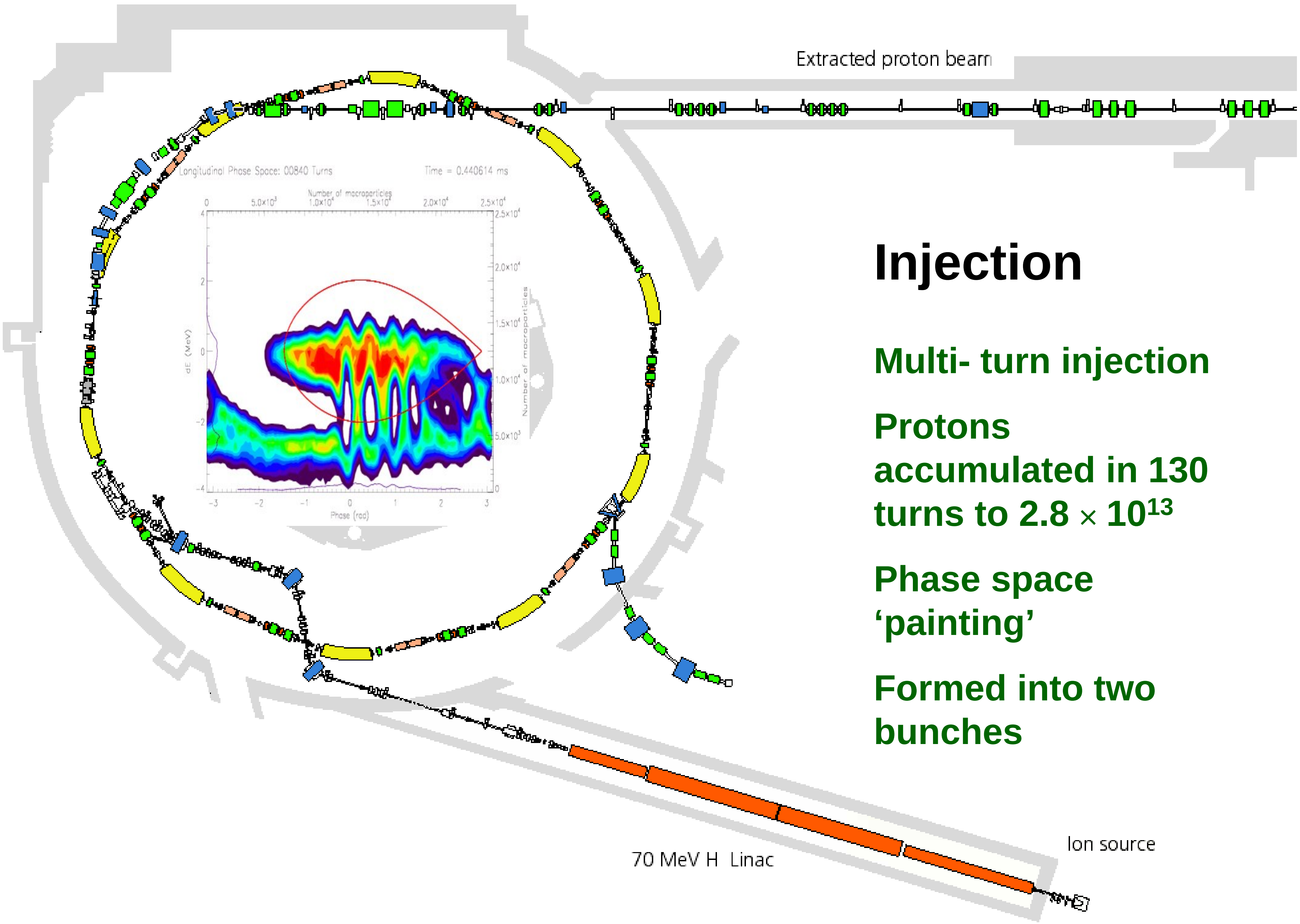





# Injection

## Stripping Foil

**$H^-$ ‘stripped’ of electrons by 0.25μm aluminium oxide foil to produce protons**



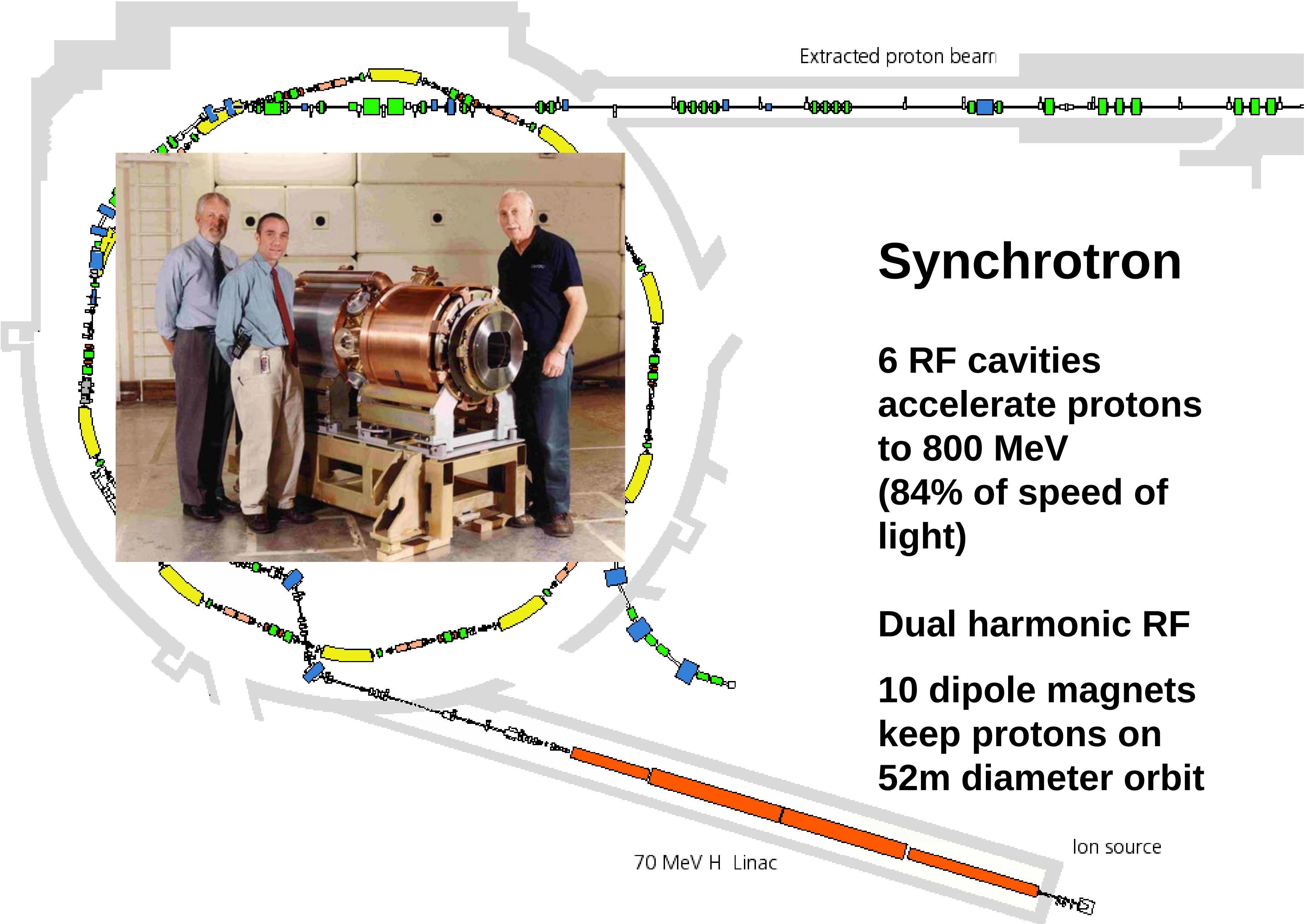

# Injection

## Multi- turn injection

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

## Phase space 'painting'

## Formed into two bunches

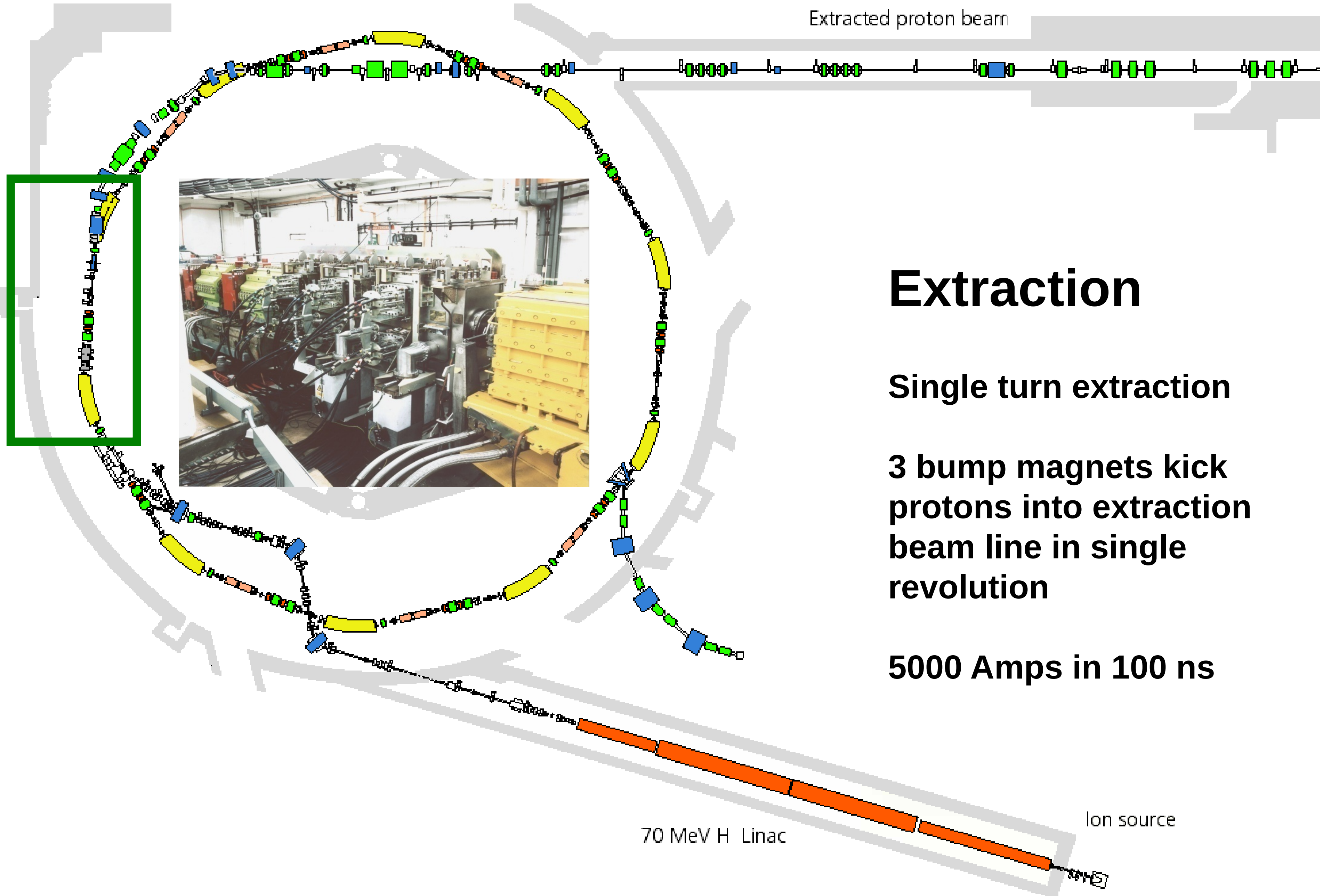



# Synchrotron

**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**

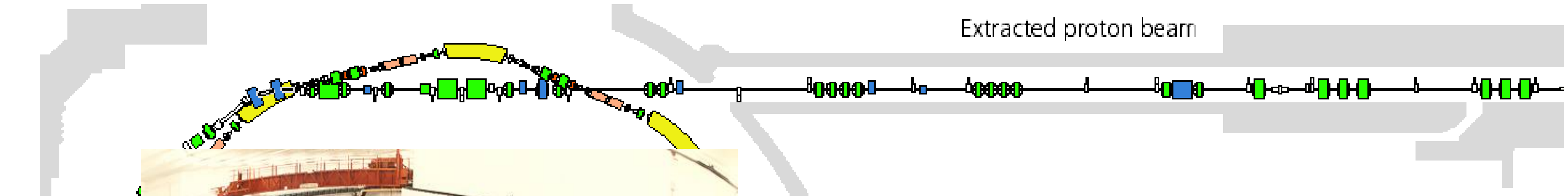


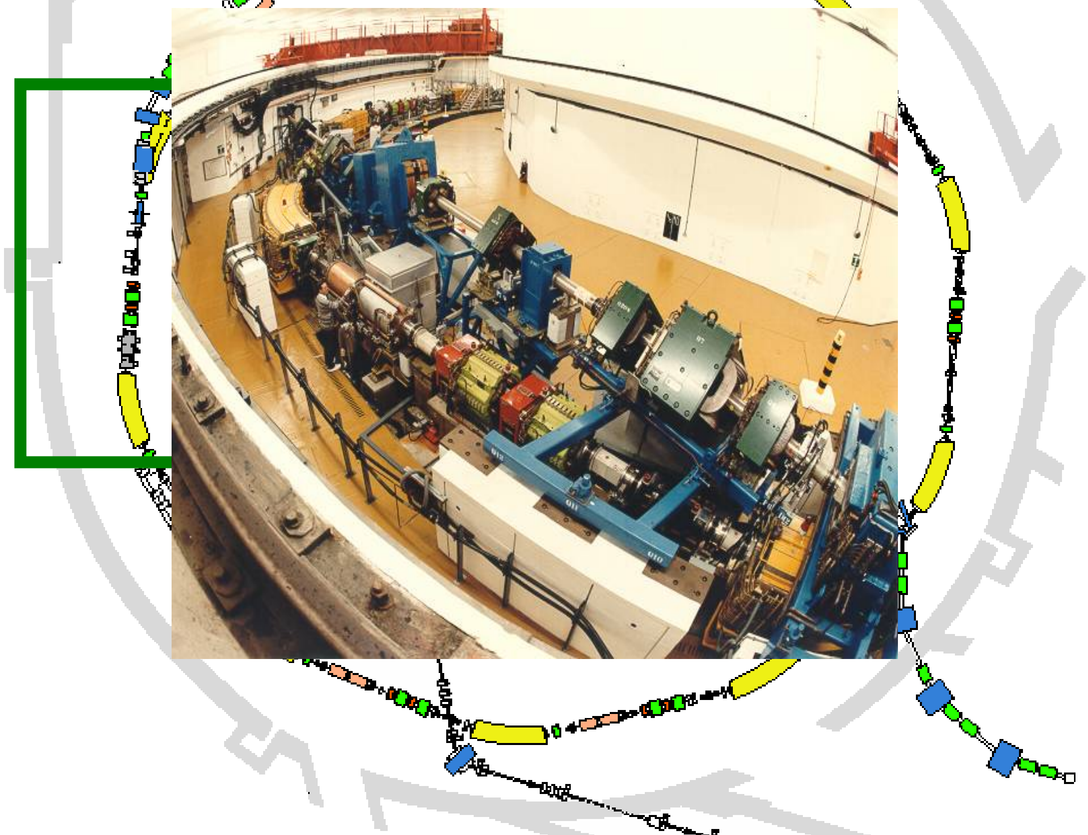
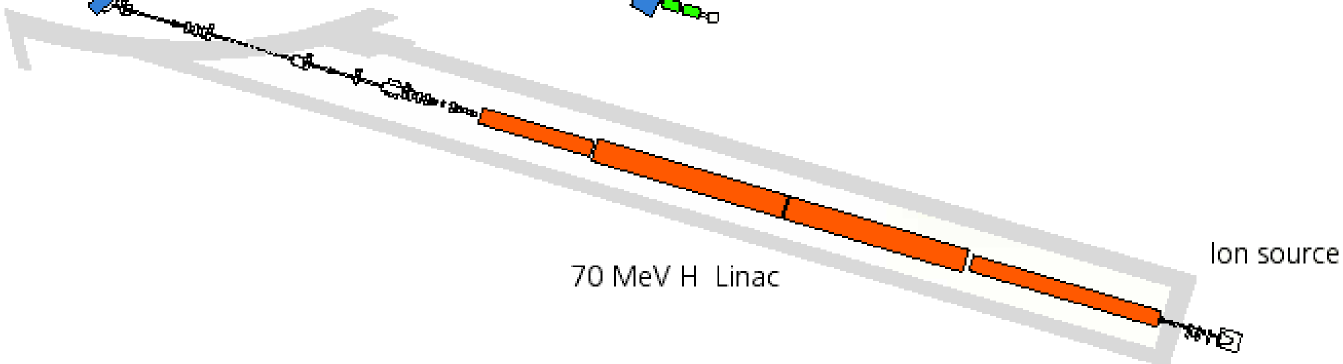

# Extraction

**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 µC (2.5×10$^{13}$) protons**

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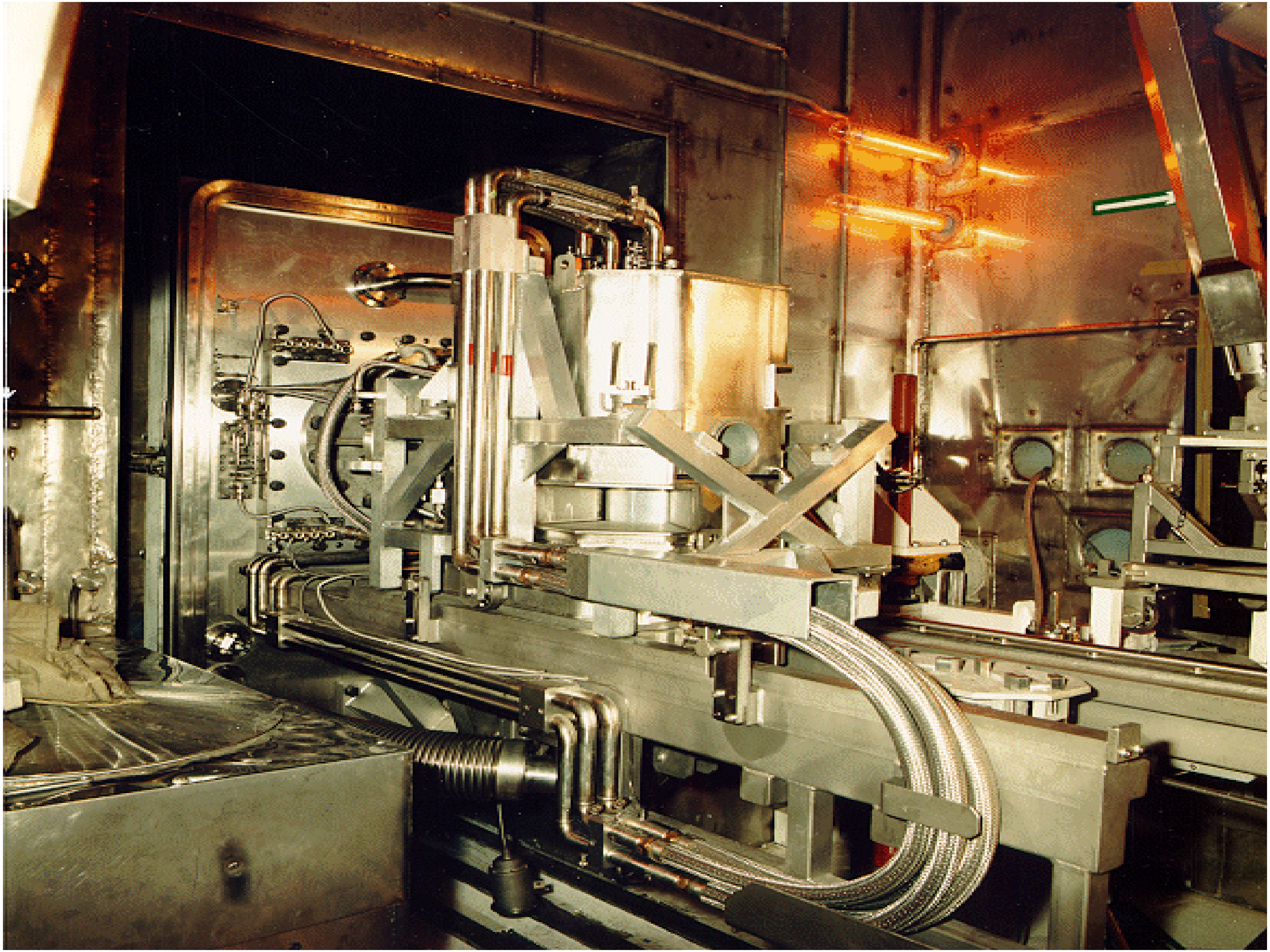
Wt 17 TON
M108
RADIATION
HAZARD



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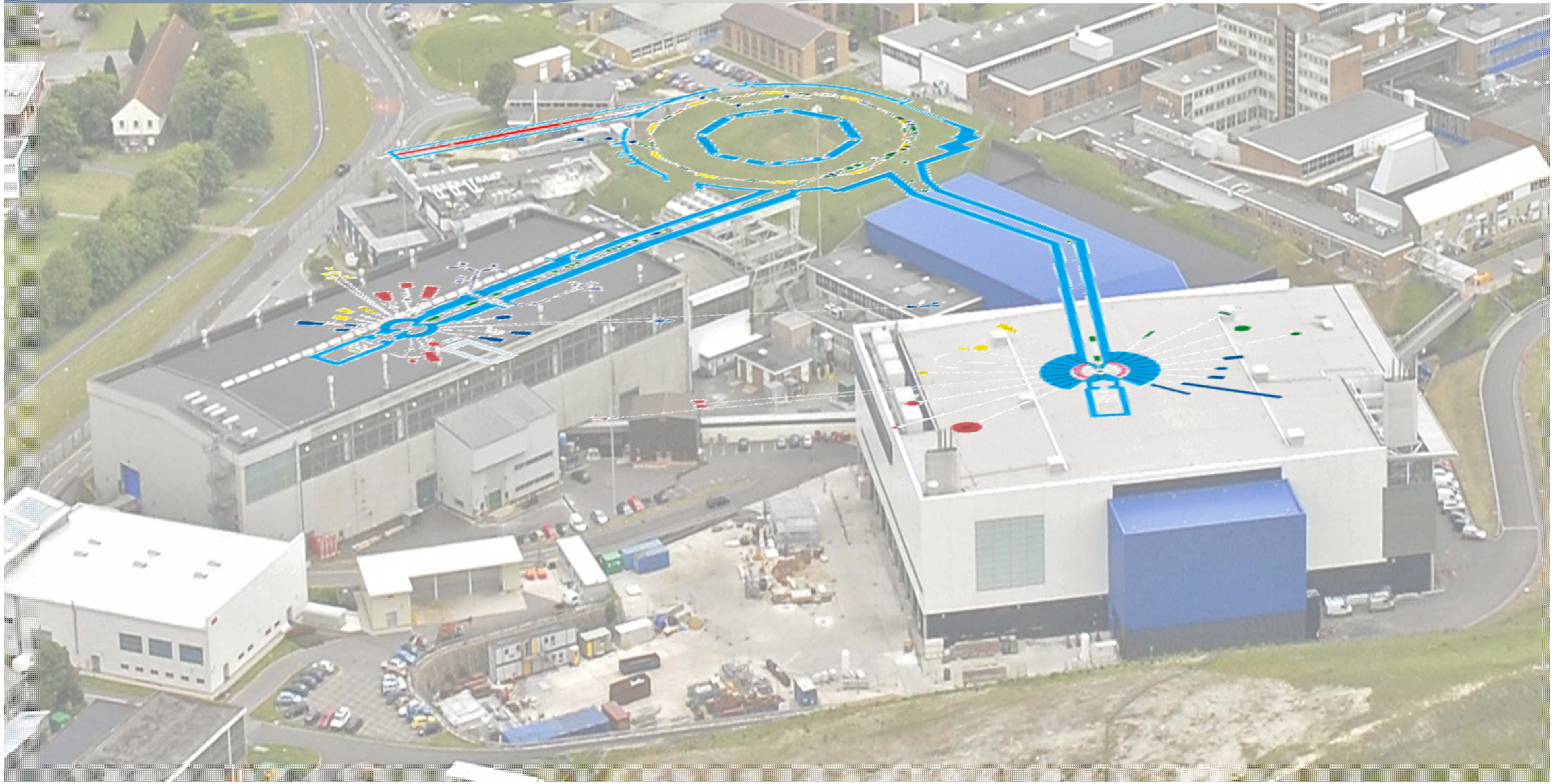
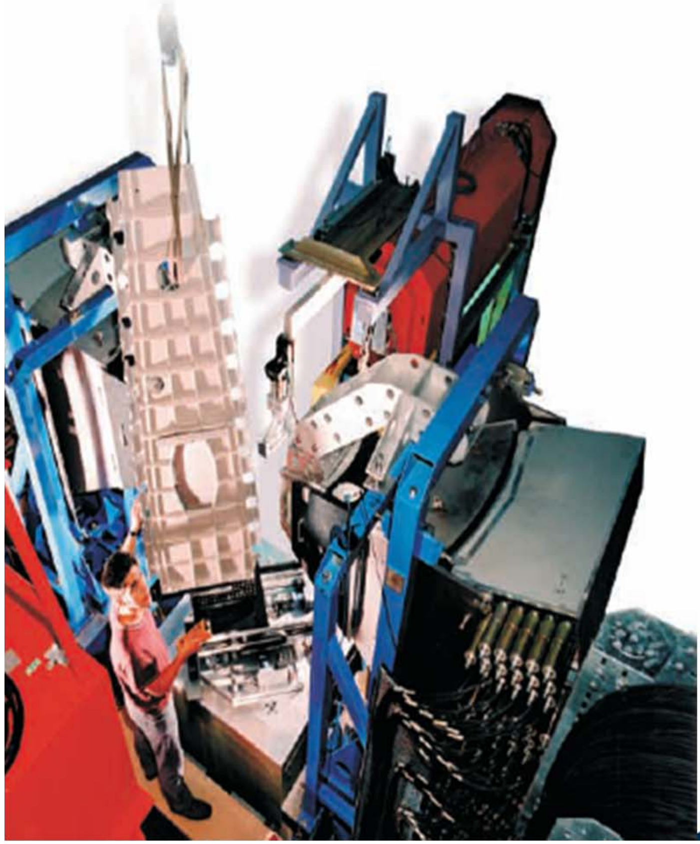
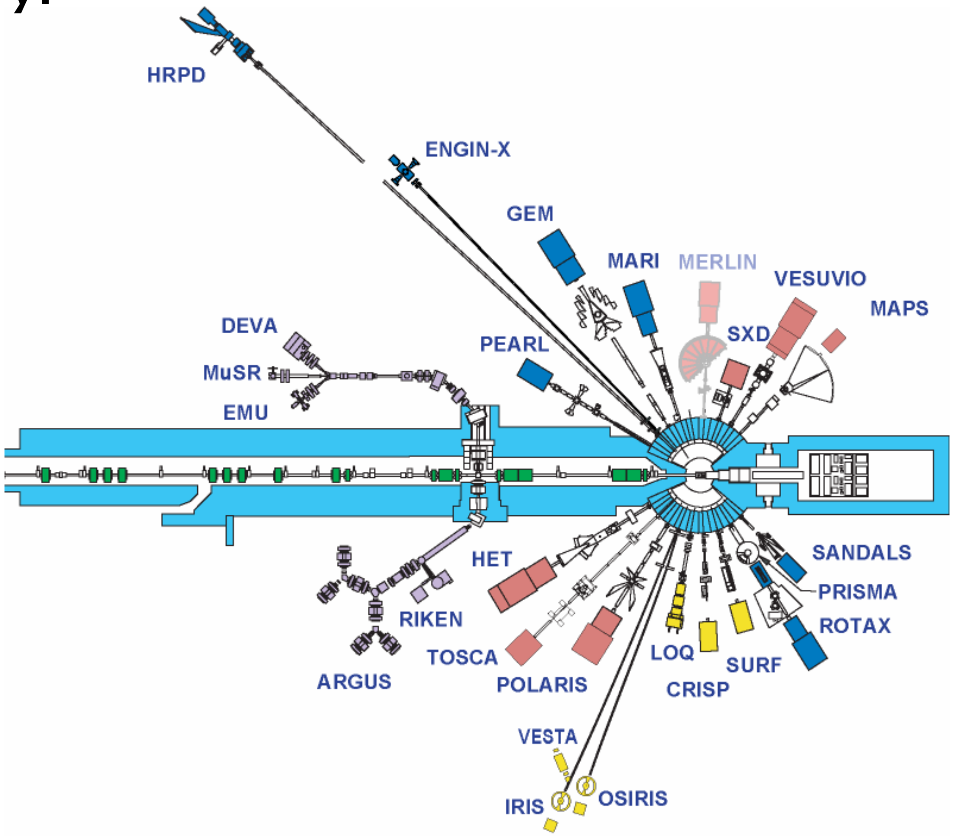


# A World Centre for Research in the Physical and Life Sciences with Neutrons and Muons

- 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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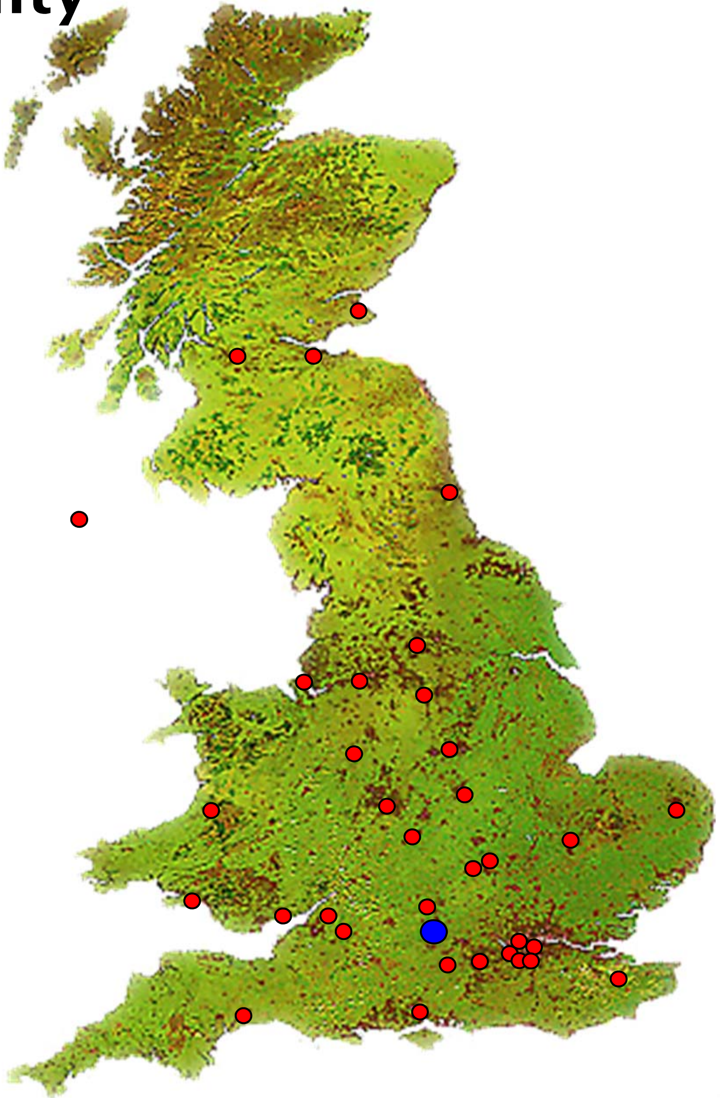
# ISIS UK Community

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



Leeds
Leicester
Liverpool
London
Manchester
Nottingham
OU
Oxford
Reading
Sheffield
Southampton
St. Andrews
Surrey
Swansea
Warwick

EPSRC
Pioneering research and skills

NATURAL ENVIRONMENT RESEARCH COUNCIL

MRC Medical Research Council

BBSRC bioscience for the future

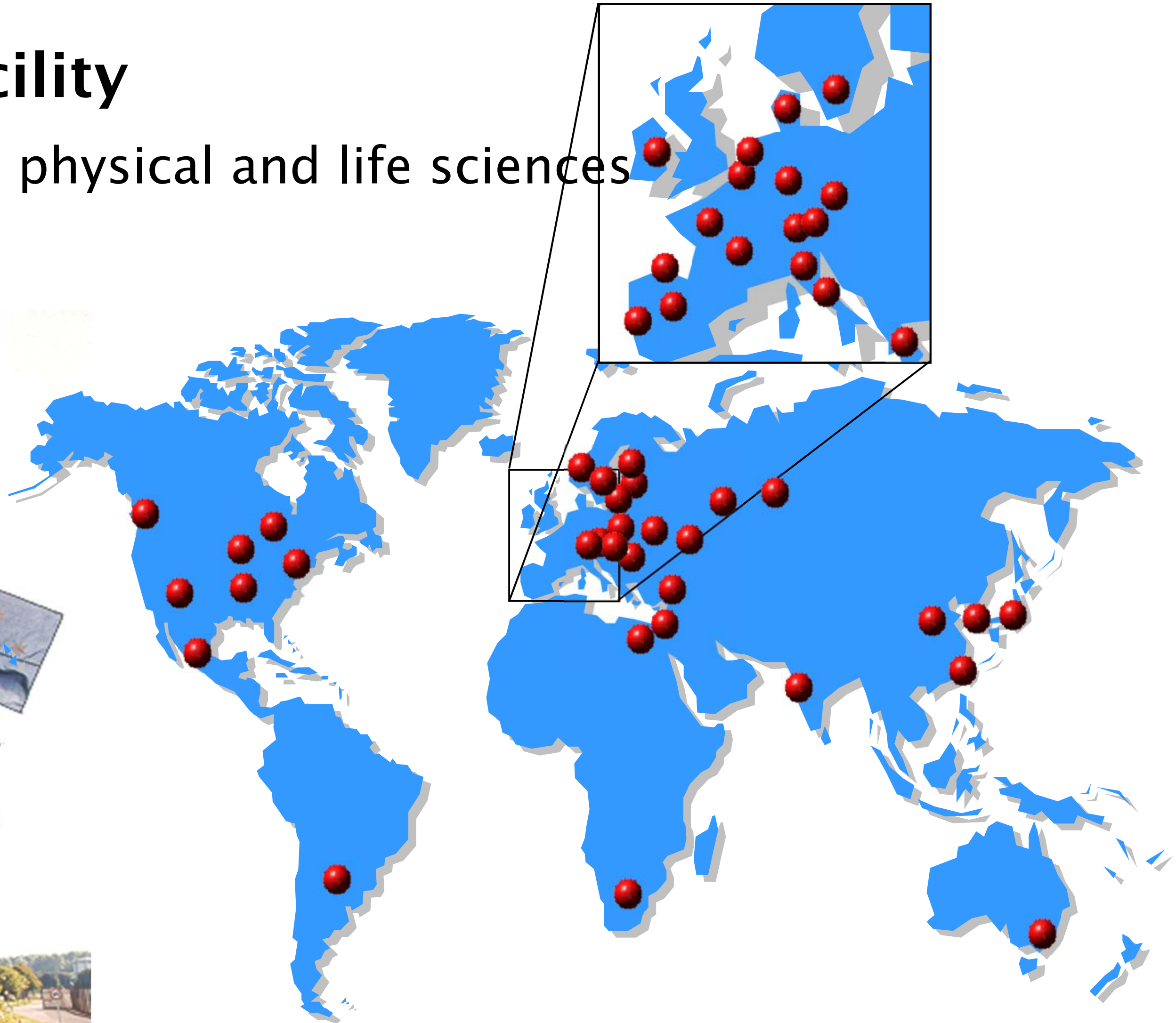
RESEARCH COUNCILS UK

wellcome trust

Science & Technology Facilities Council

# A world leading facility

for research in the physical and life sciences

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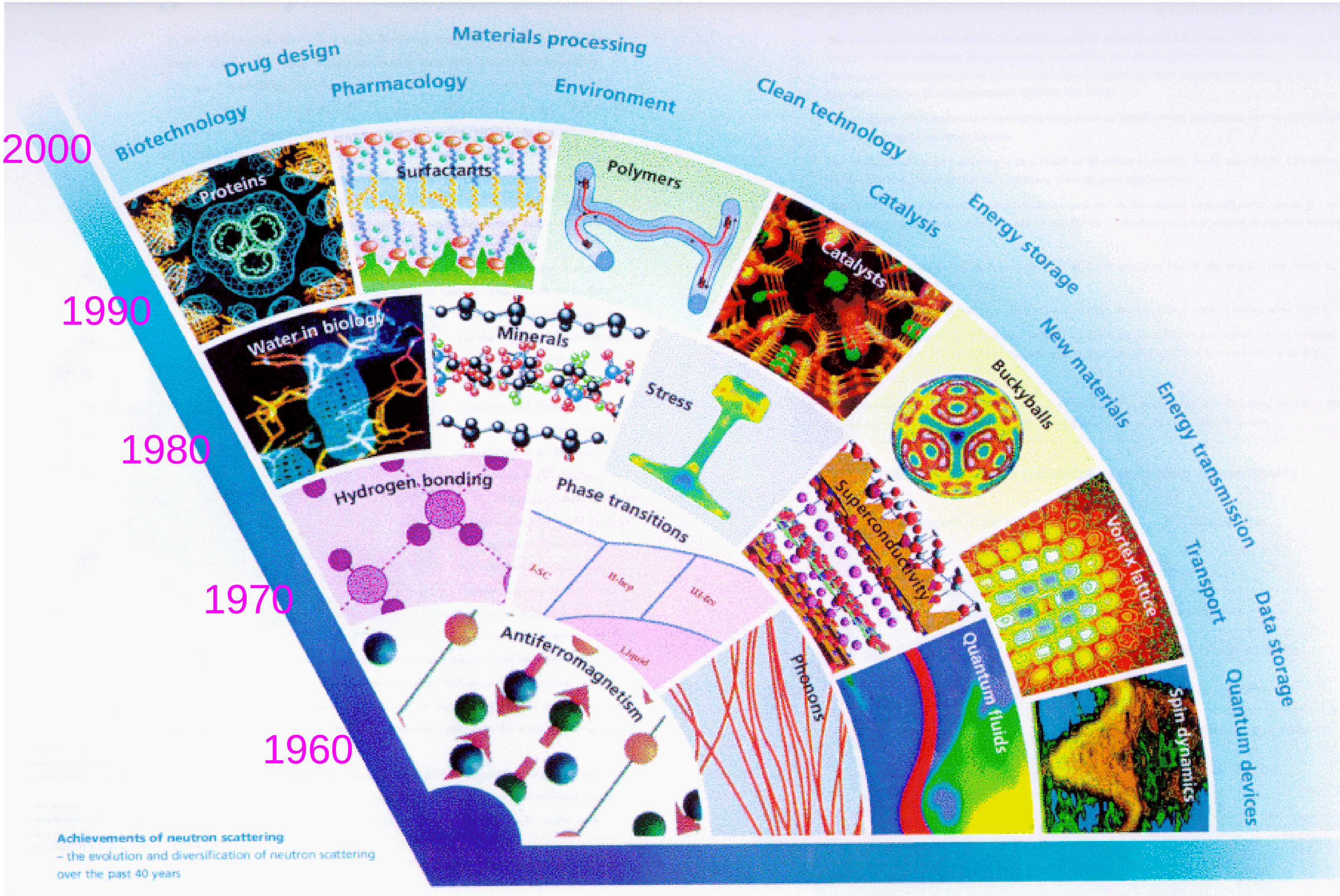
# No One Experiment




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

# US Spallation Neutron Source

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# JPARC – Tokai


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CSNS

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ISIS

*remains*
a world
**leading**
pulsed
neutron
and muon
research
centre

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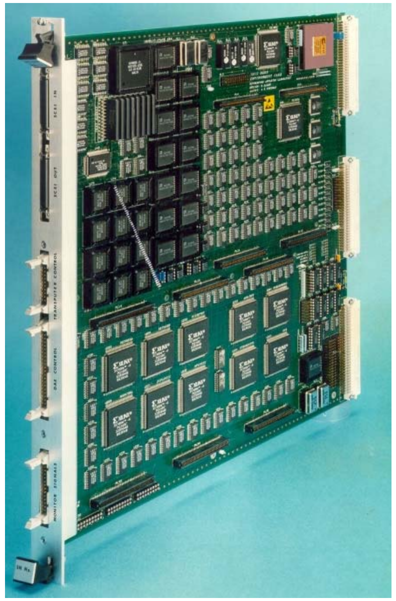
# Advanced Technology

# STFC Technology Transfer

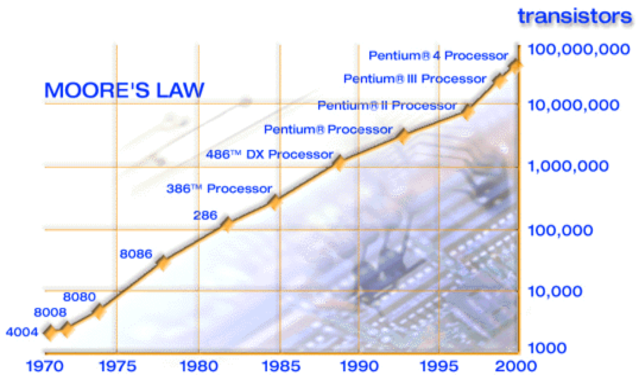

efficient large solid angle detectors...

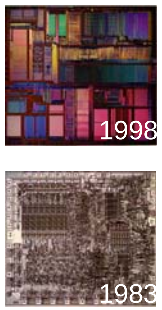
…fast electronics

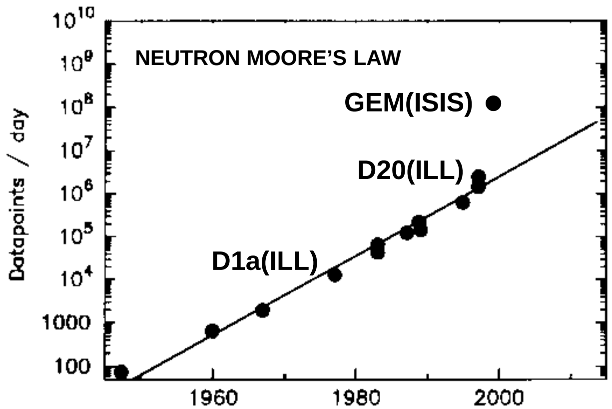


detectors and advanced data acquisition - unique synergy within STFC

4 orders of magnitude in 30 years

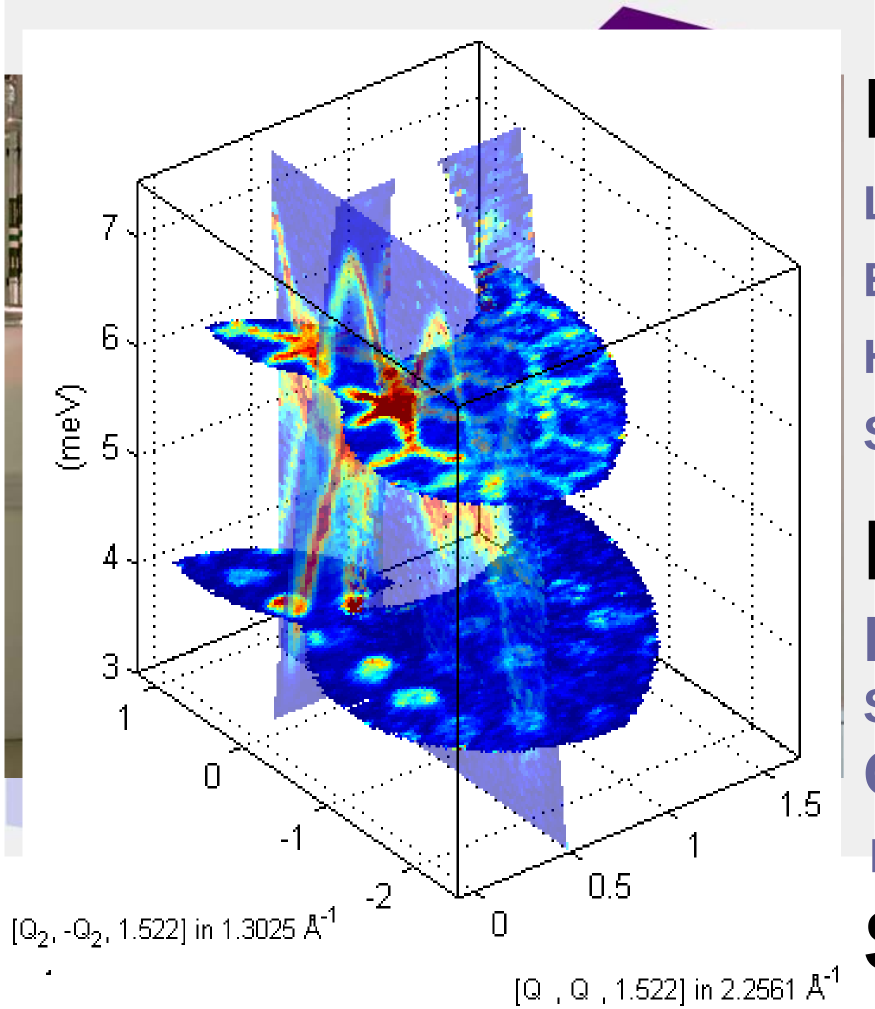



Neutron powder diffraction data rates (1950-2010) (4 orders of magnitude gain with ILL/ISIS alone)

# Instrument Development




## Detectors

| | |
|---|---|
| LAD → GEM | x 30 |
| ENGIN → ENGIN-X | x 20 |
| HET → MAPS | x 25→ LET x3 |
| SXD → SXD11 | x 11→ SXD' x5 |

## R&D

**Detectors,**

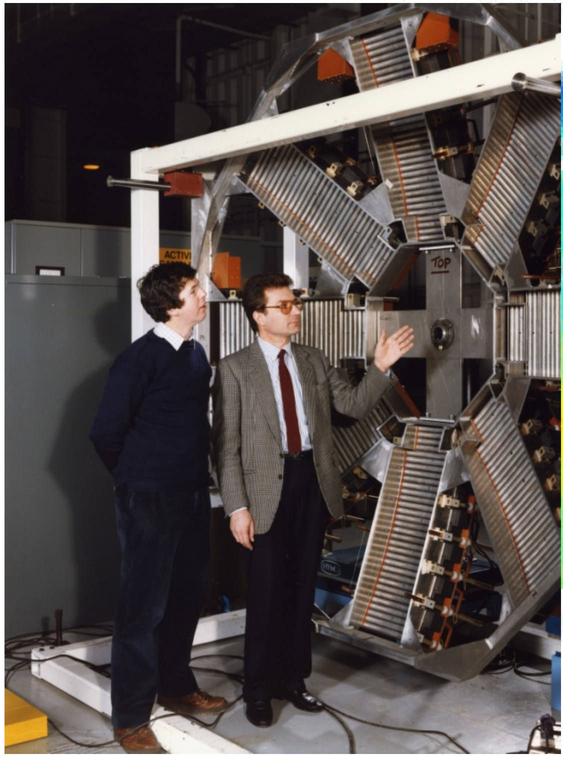
Smaller pixels, Higher Rates, Lower Costs

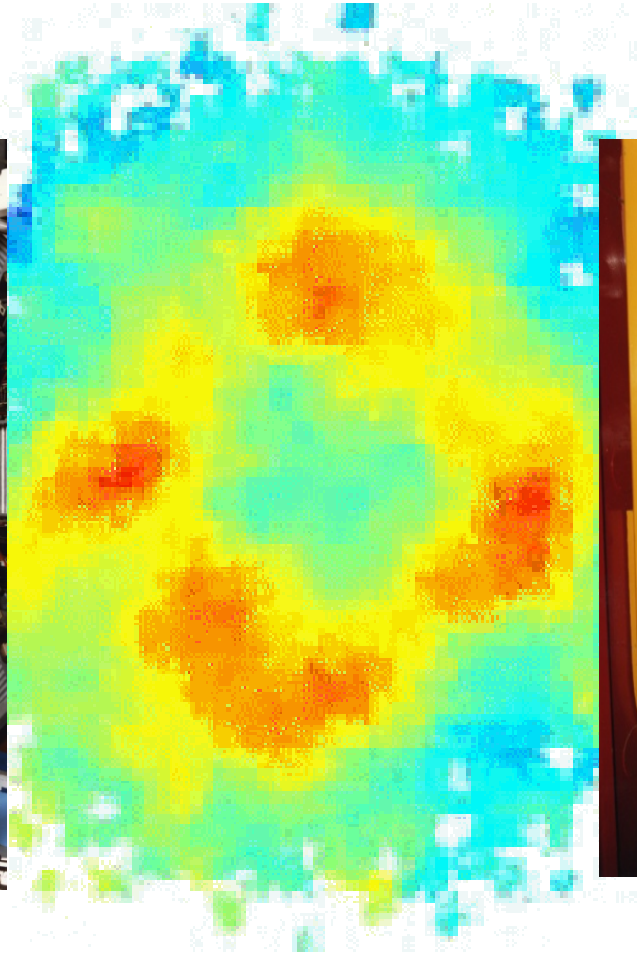
**Optics, Pol Filters, Choppers**

HRPD → HRPD' x 10

## Sample Environment

## Software





# HET : December 1984 - December 2008

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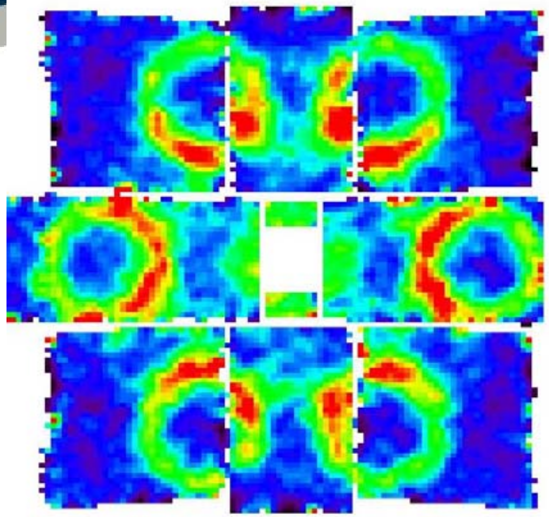
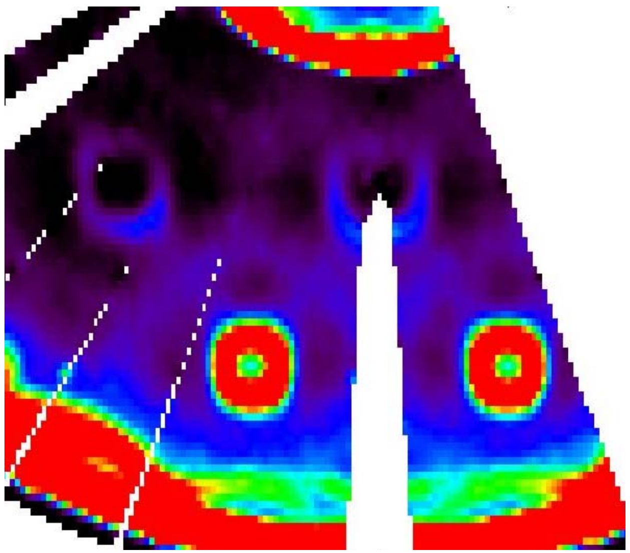
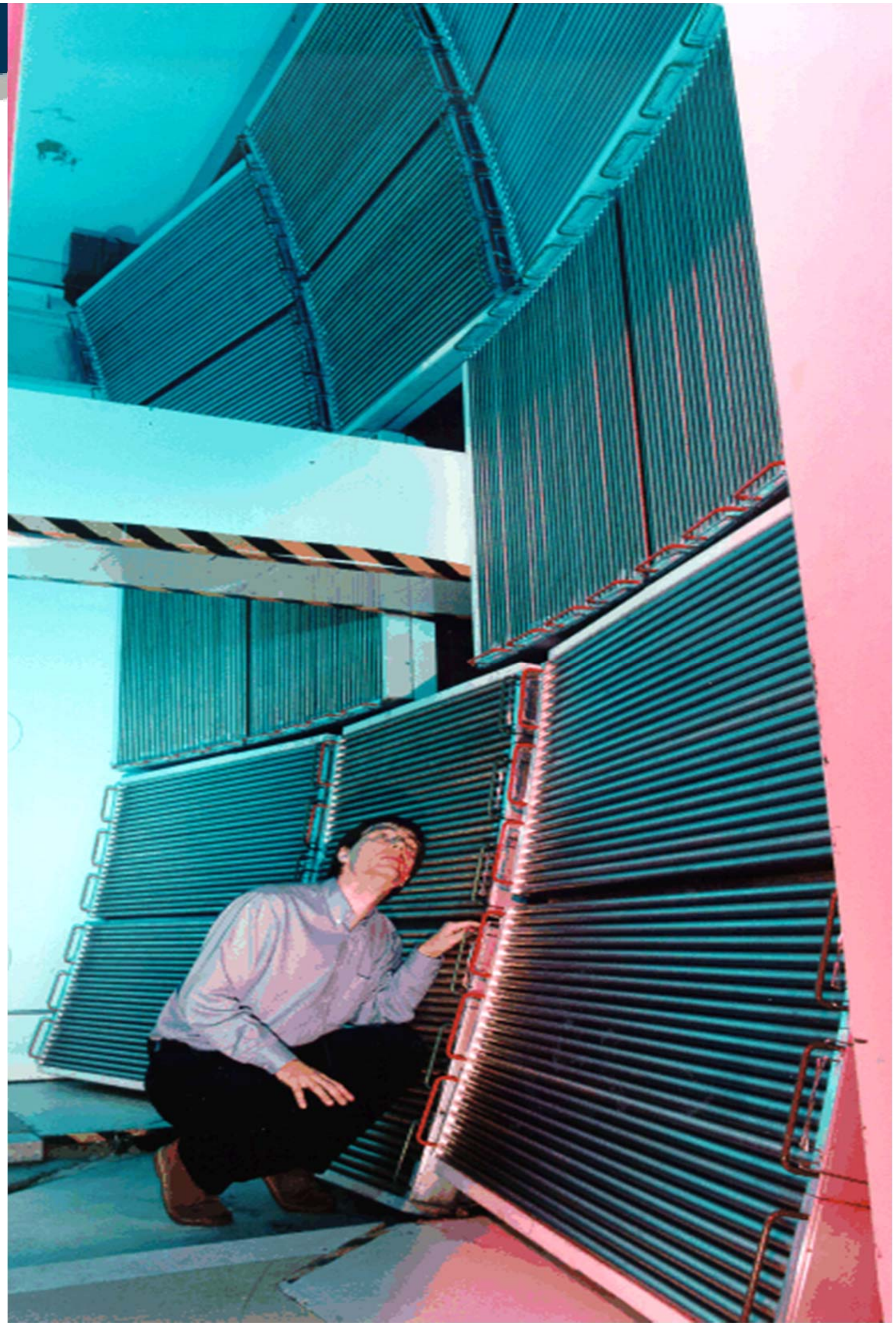
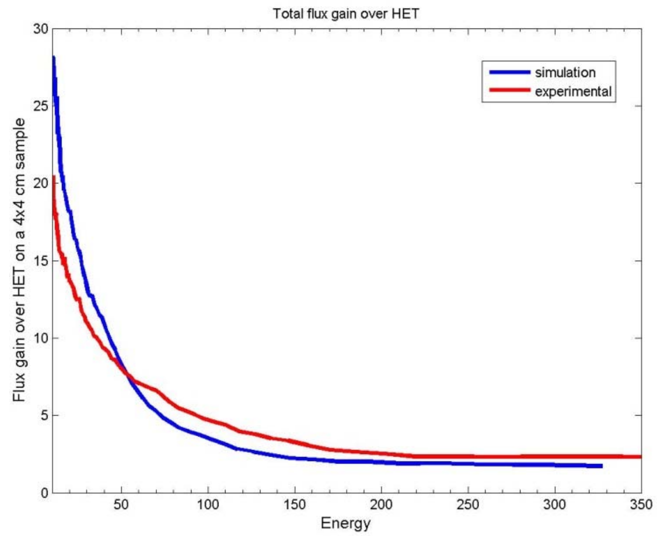


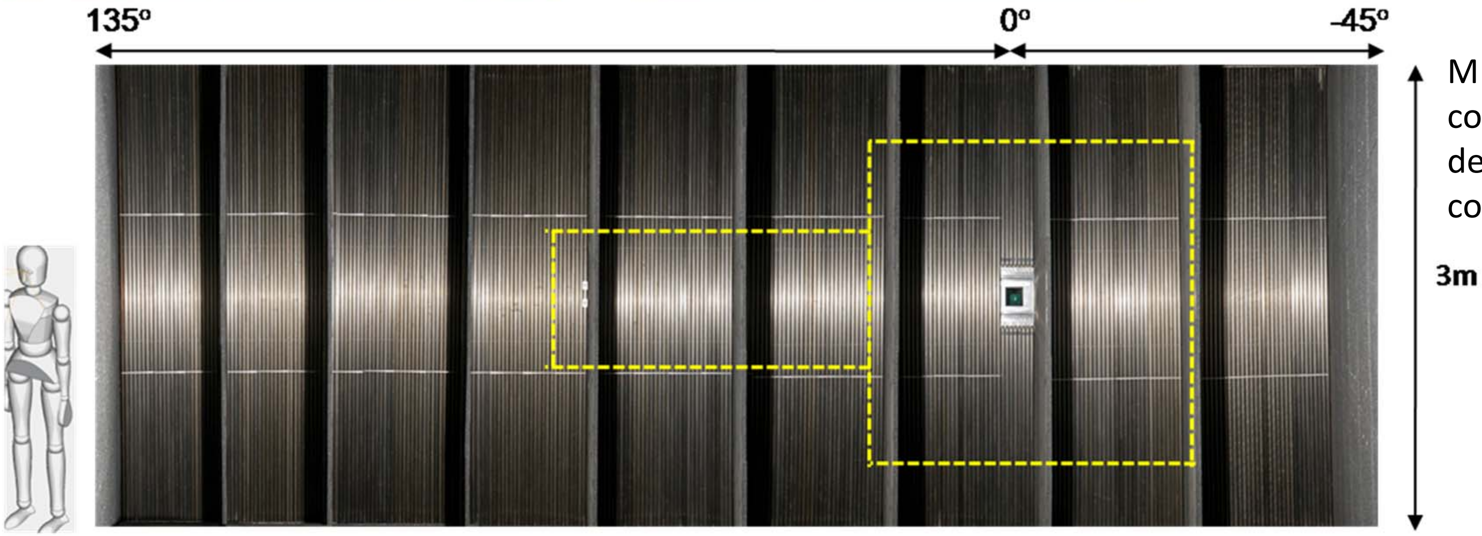





Pelloby


Flux gain over HET due to guides and new moderator

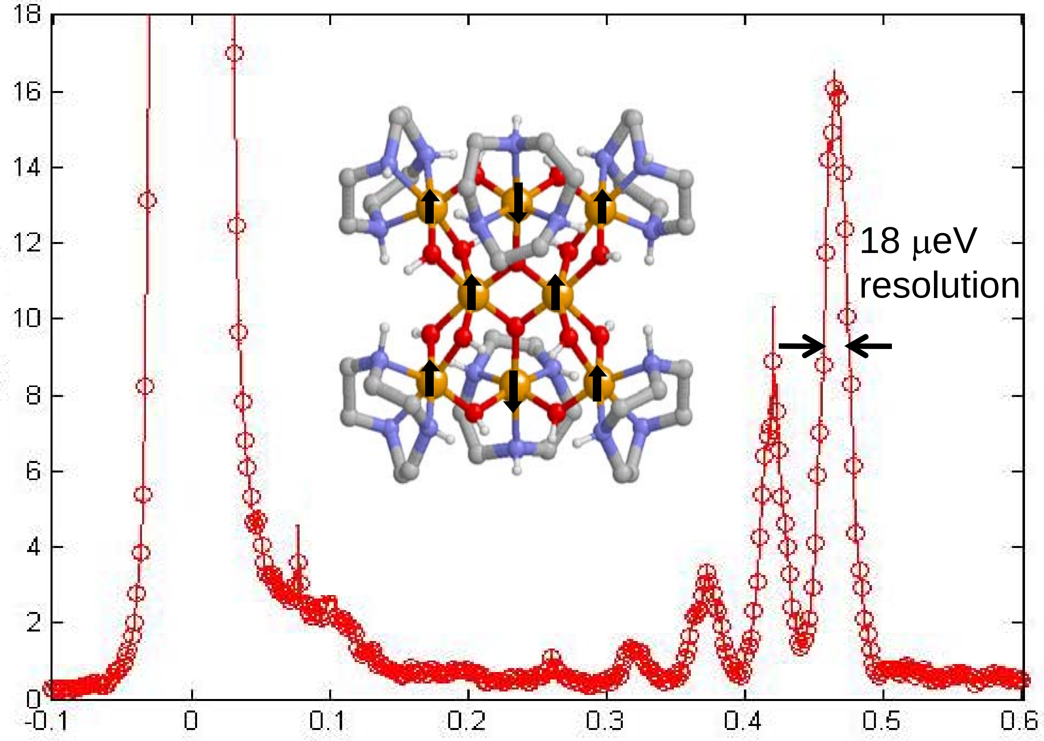



MERLIN detector bank covering Pi Steradians. MAPS detectors drawn on for comparison.

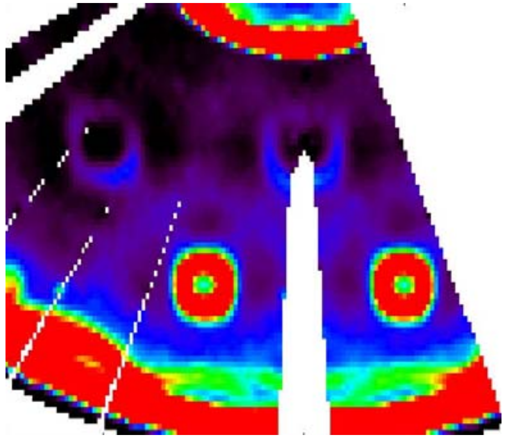
# Novel Instrumentation

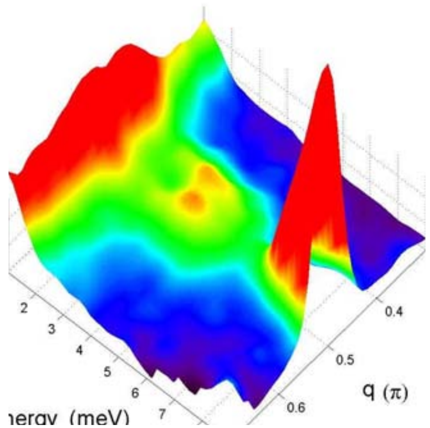
A new spectrometer capable of measuring excitations from 20 μeV to 80 meV

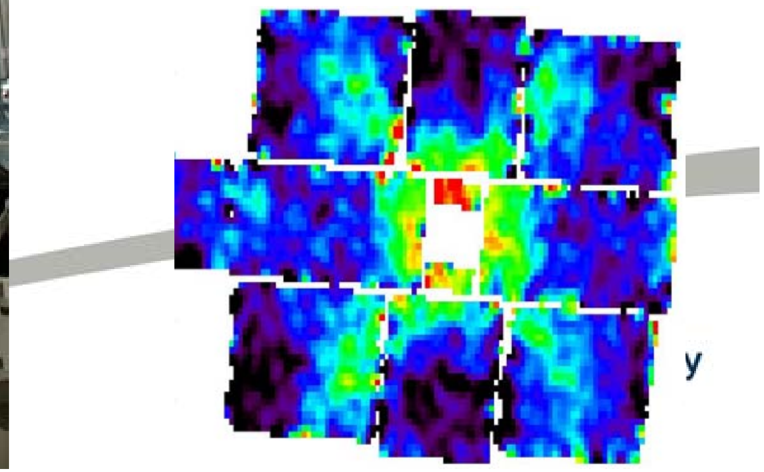
Excitations of Fe8 molecular cluster



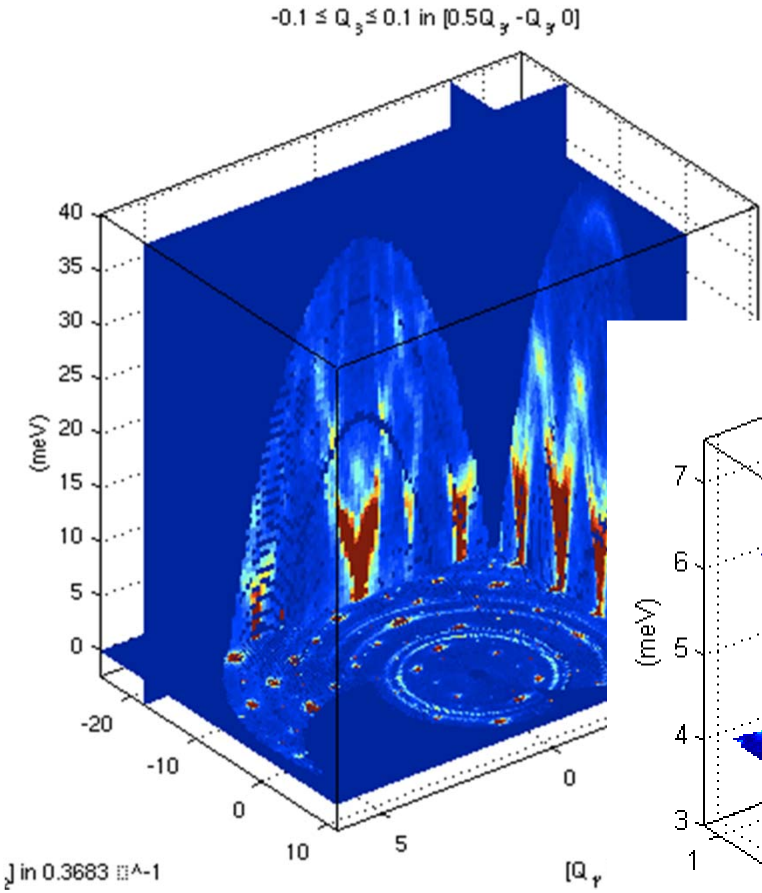
# Magnetism and Molecular motion



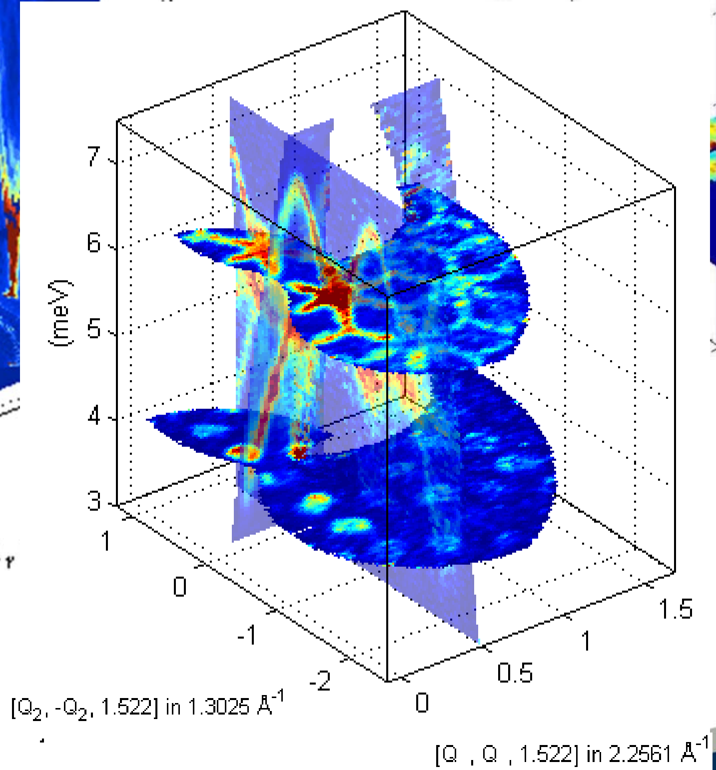


# Horace : Examples of measurements on MERLIN spectrometer

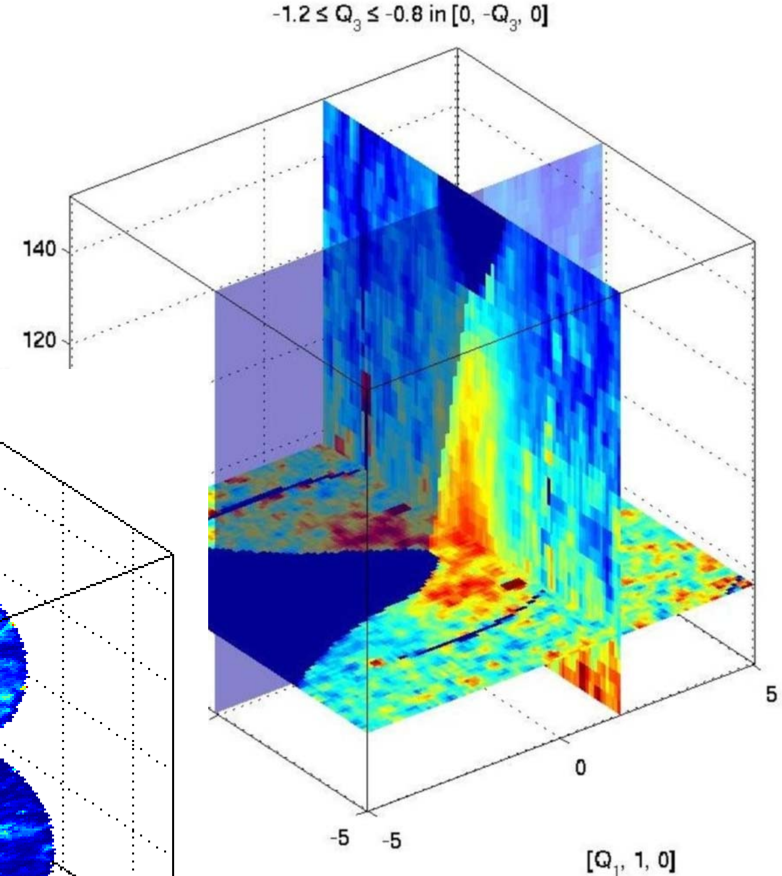



Calcite
*(Dove, Cope)*




$Sr_3Cr_2O_8$
*(Lake)*

S=1/2




MnSi
*(Perring, Ewings)*

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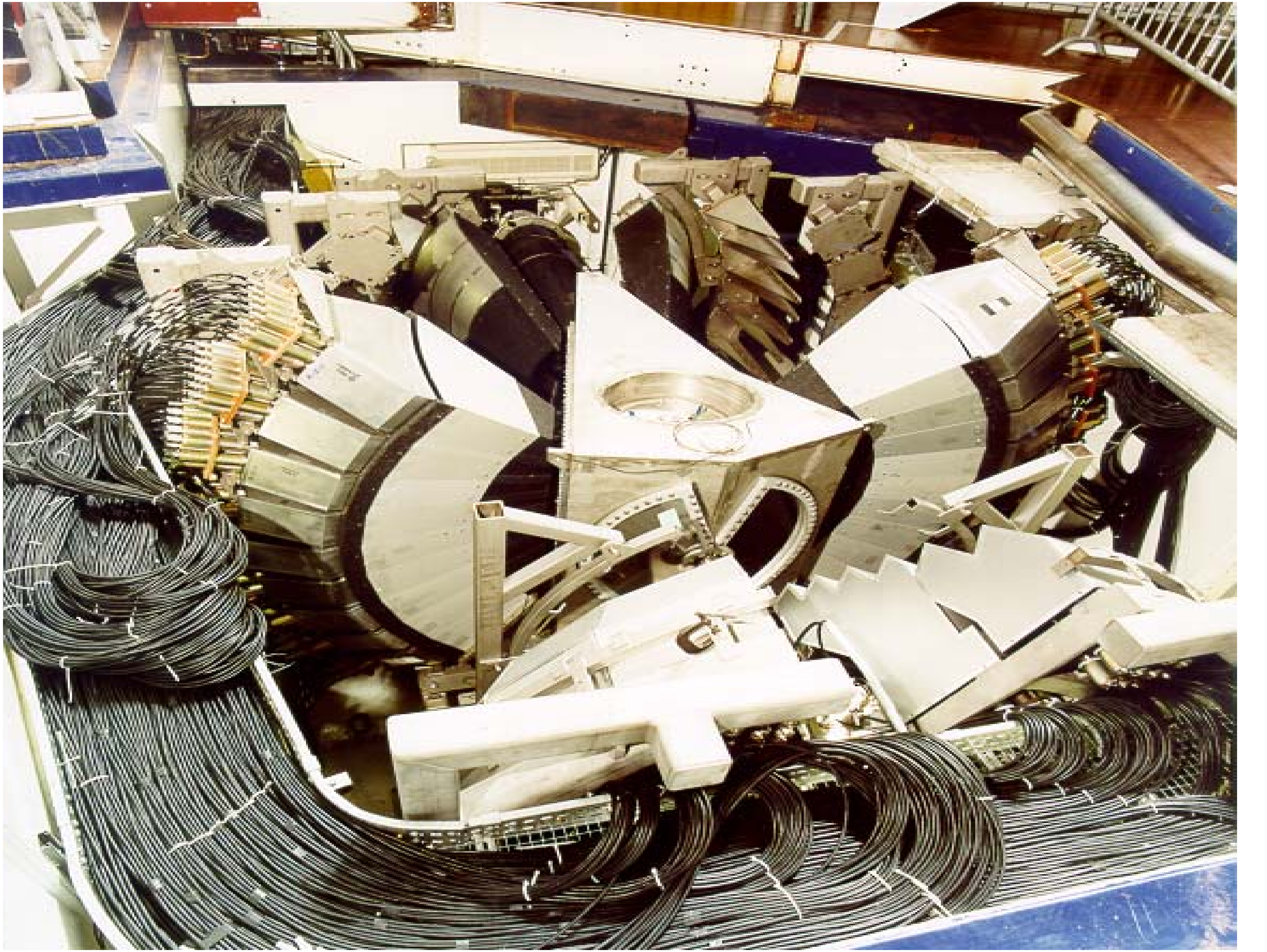
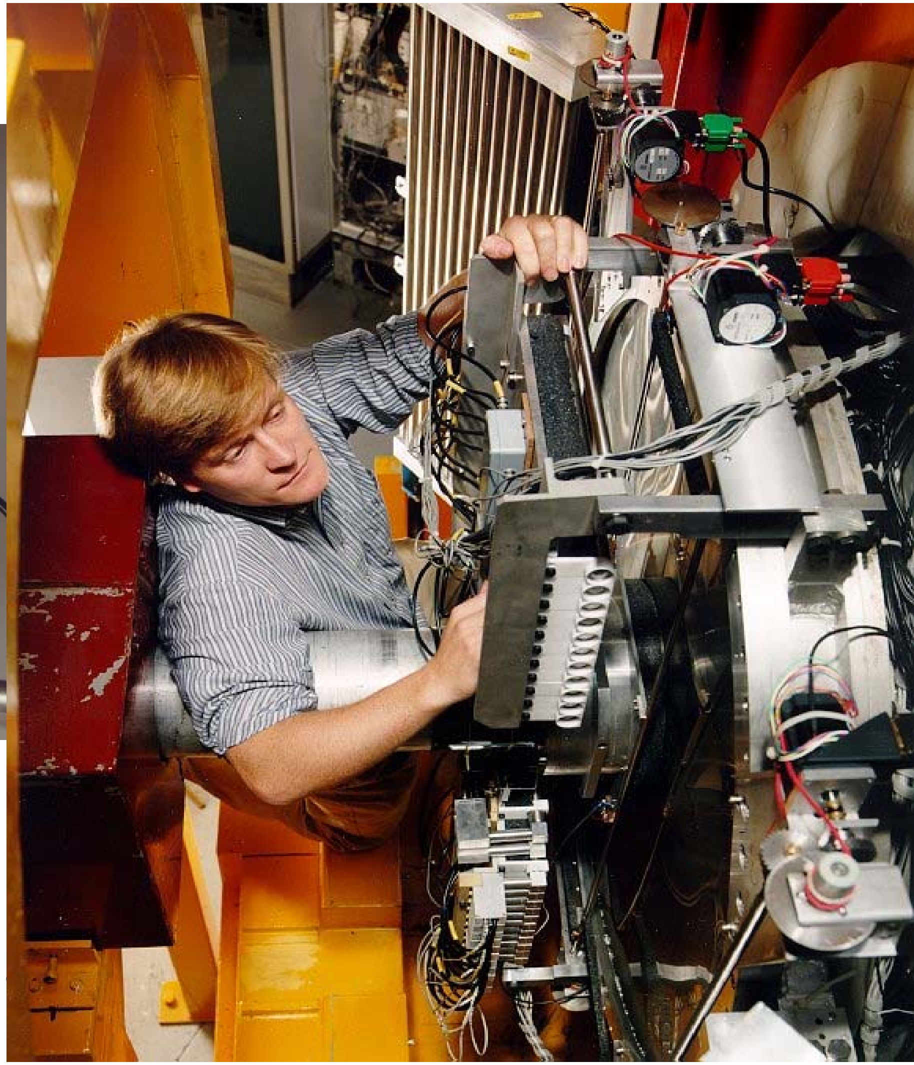
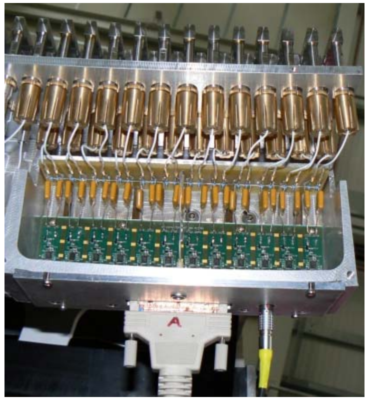


# Resistive Detectors : HET to WISH





Original HET

He3 proportion

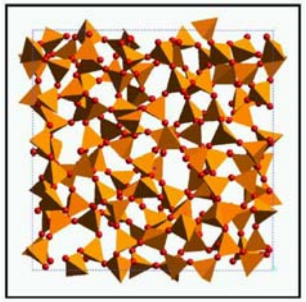
counter

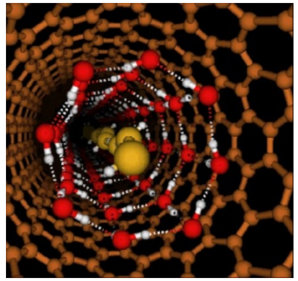
WISH

2010

TS2 ISIS second target station project

# Structures

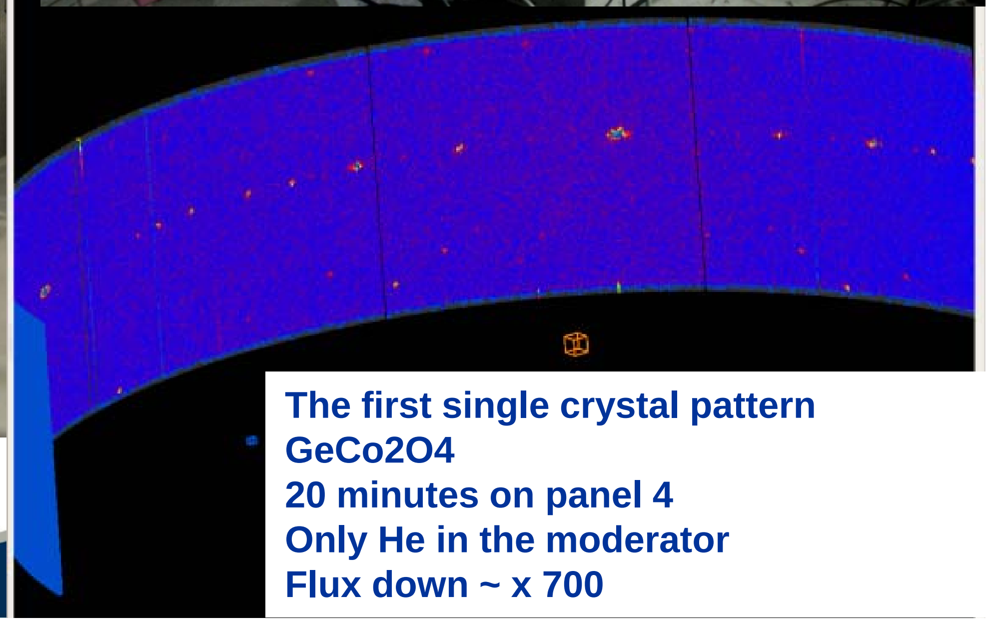




# WISH detectors

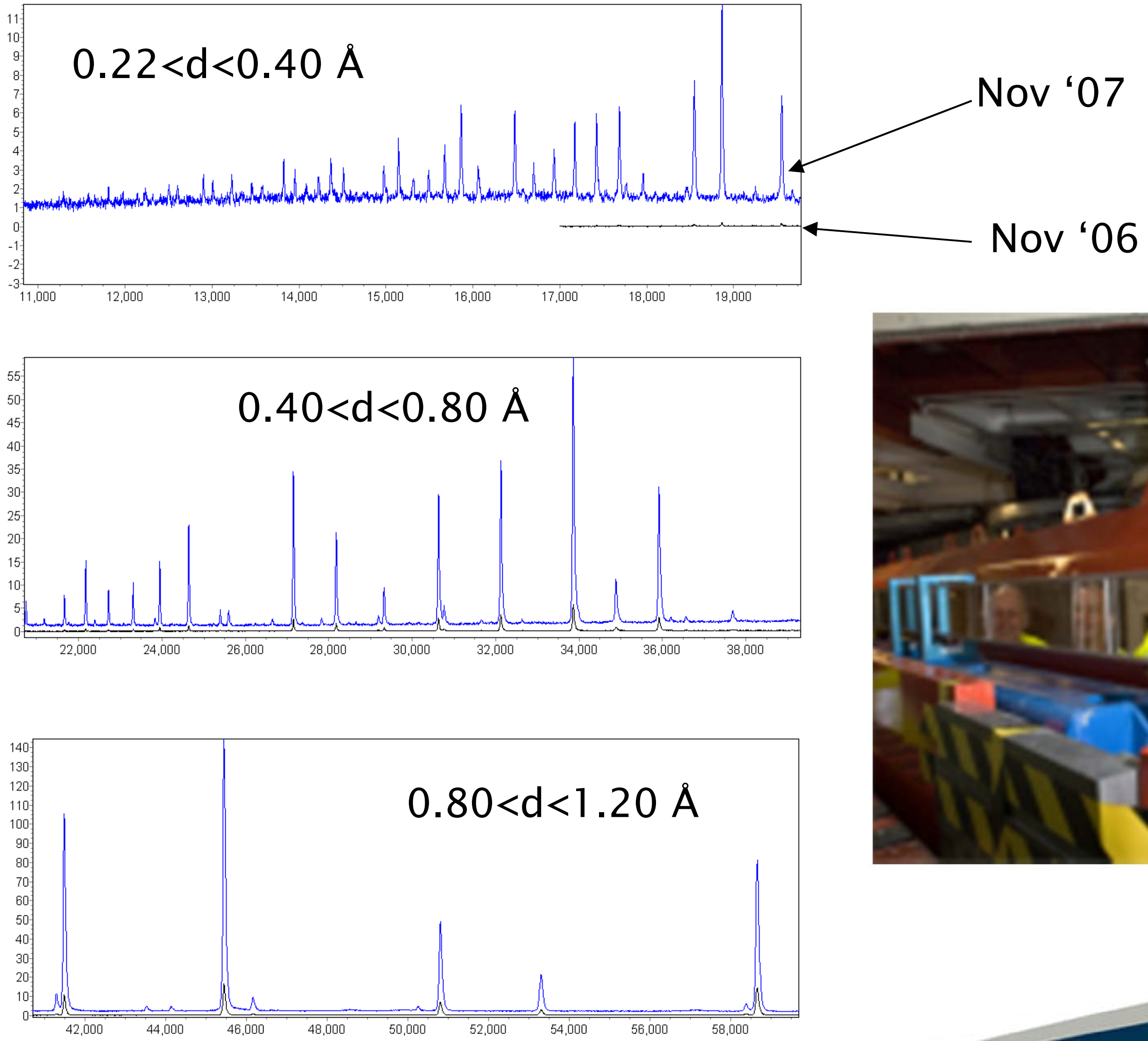
**152 gas detectors per panel**
**1 m long, 8 mm dia**
**15 bar 3He + stopping gas**
**5 panels installed and working well**

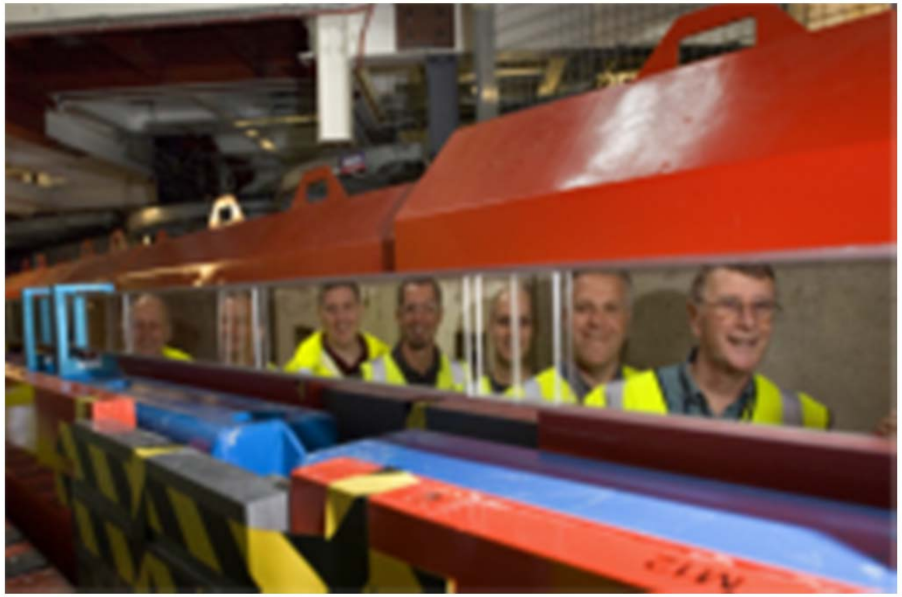
**The first complete panel in December 08**



**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



λ (Å)

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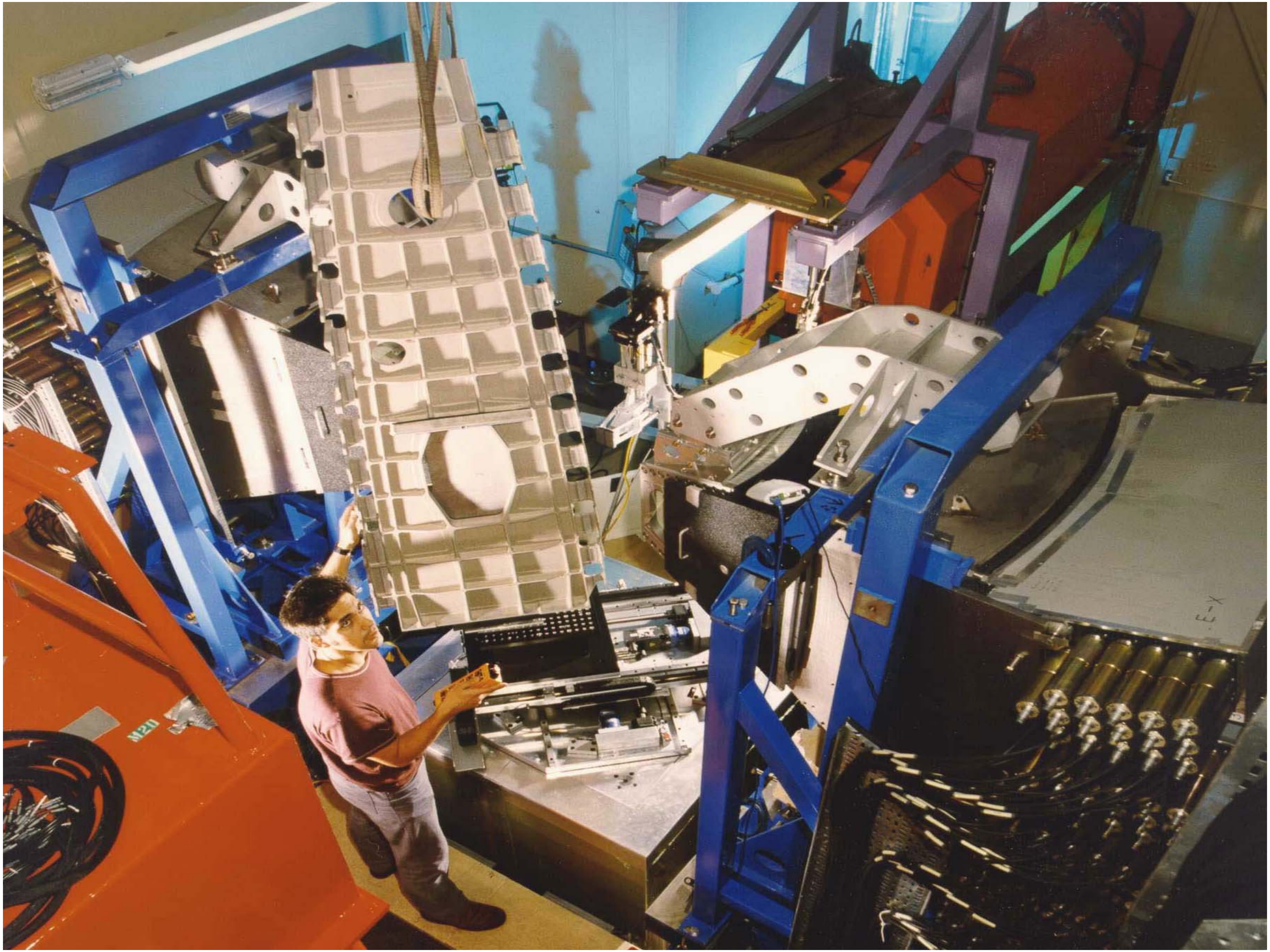


# Inward Investment

Japan: Nobel laureate
Prof Ryoji Noyori
President of RIKEN

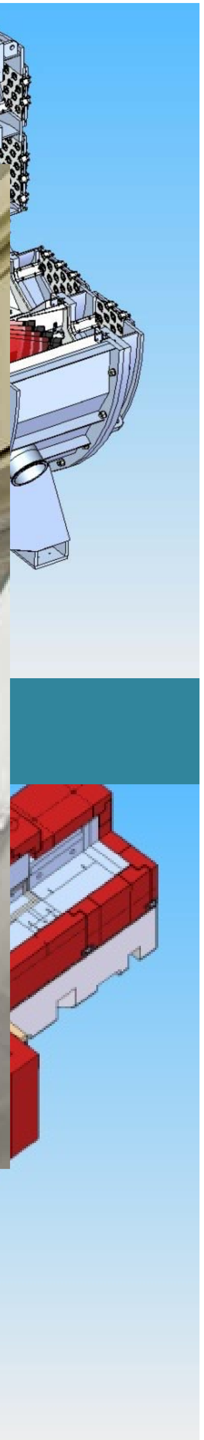



Italy: Visit from president of CNR; Spain -

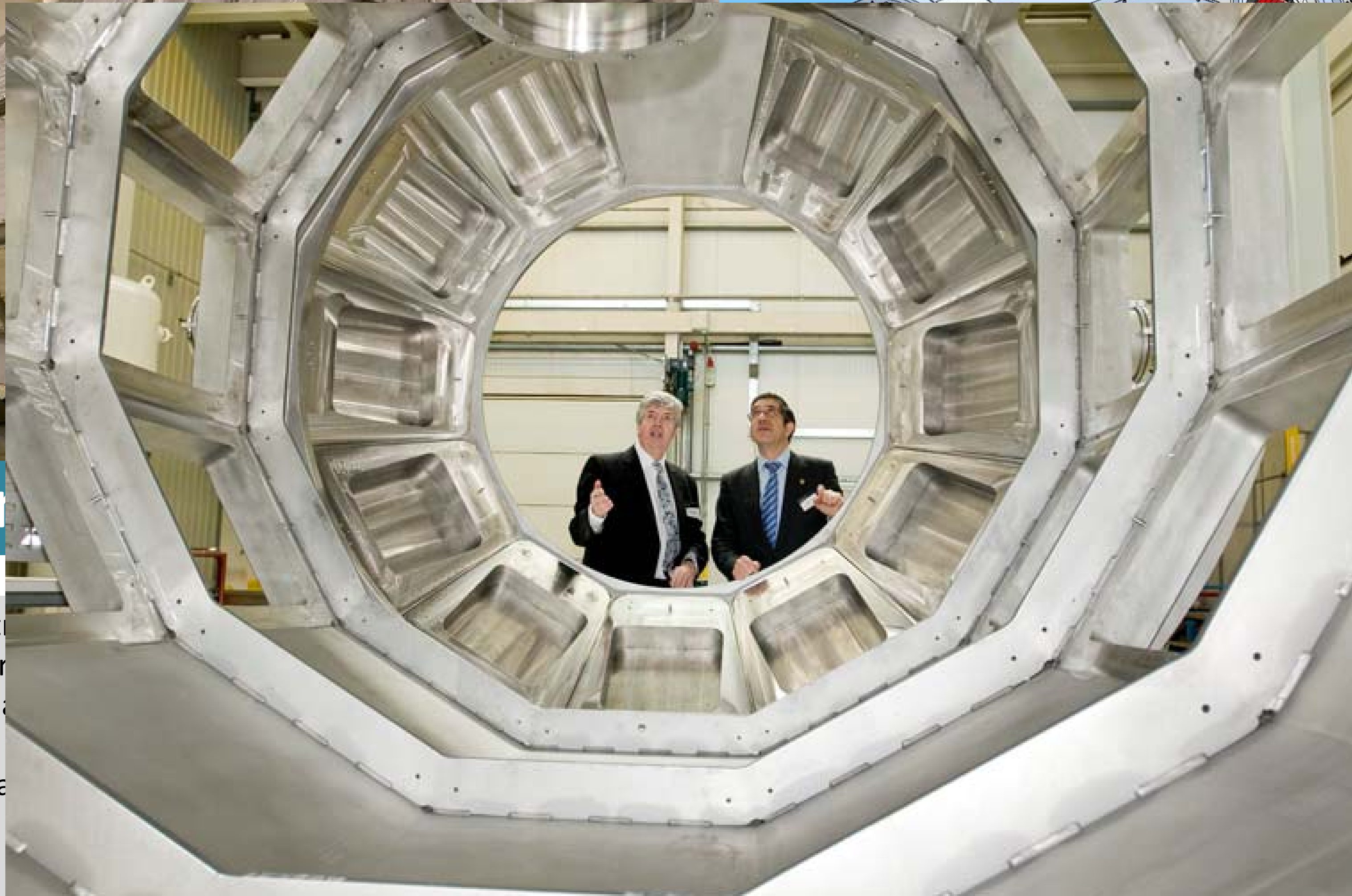



Netherlands: Visit from chair of NWO and rector of Delft University

Sweden, Spain and Japan: New funding recently approved



# Polar

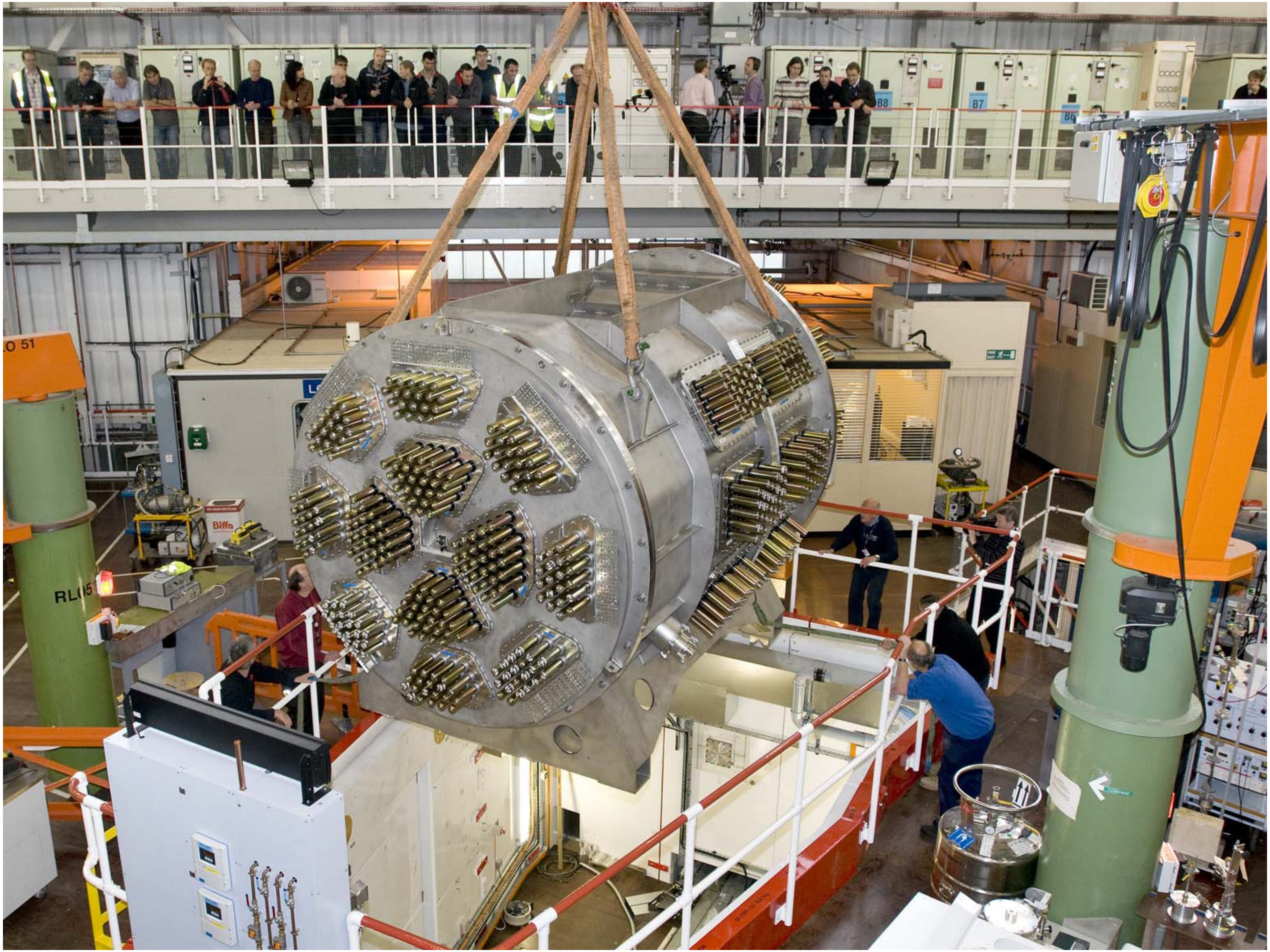


A new instr
has an extr
detector ba

A novel ma
expertise.

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

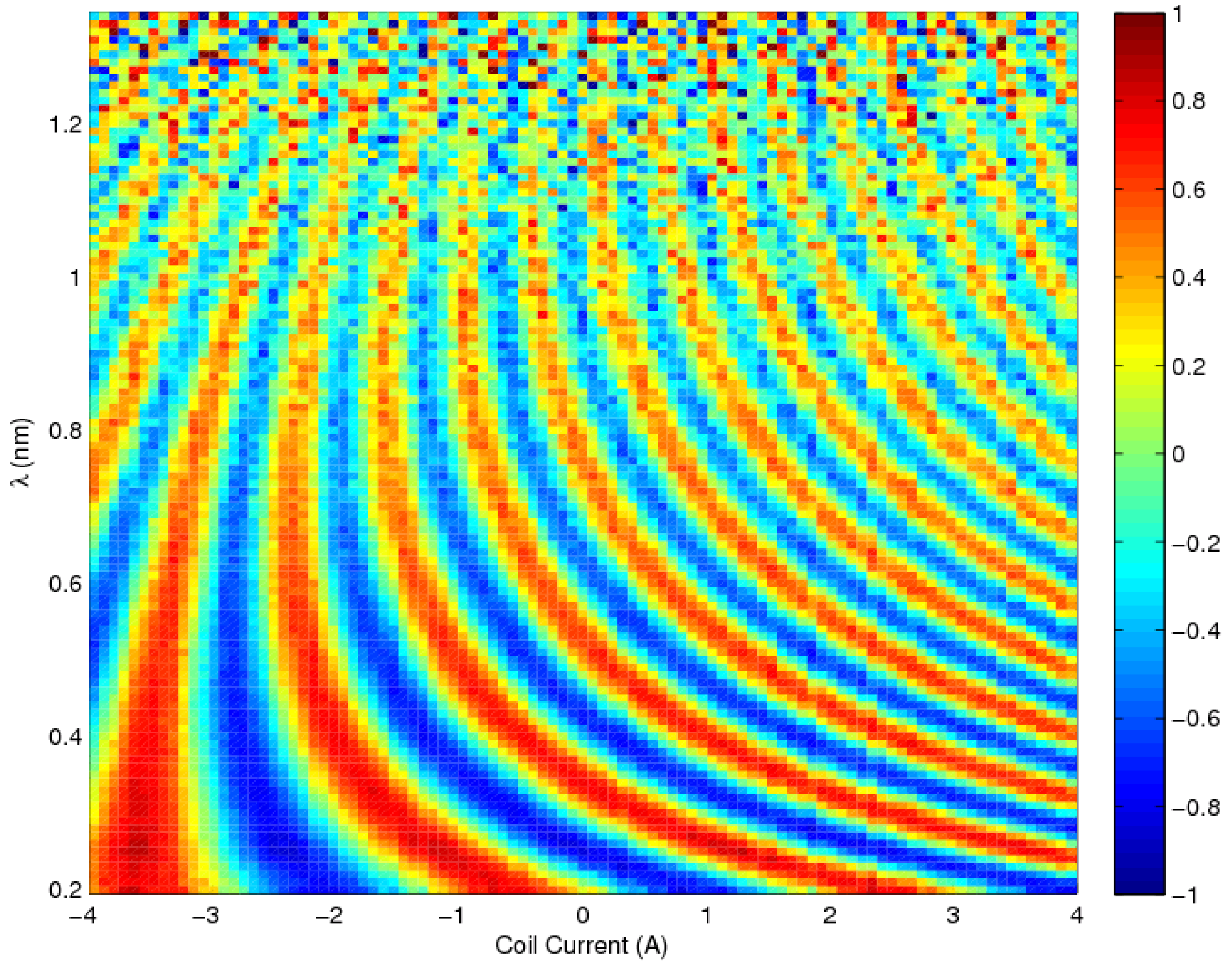
Polaris contains 2954 detecting elements and 460 km of optical fibre.


LO 51
B8
B7
Biffo


OffSpec
magnet D

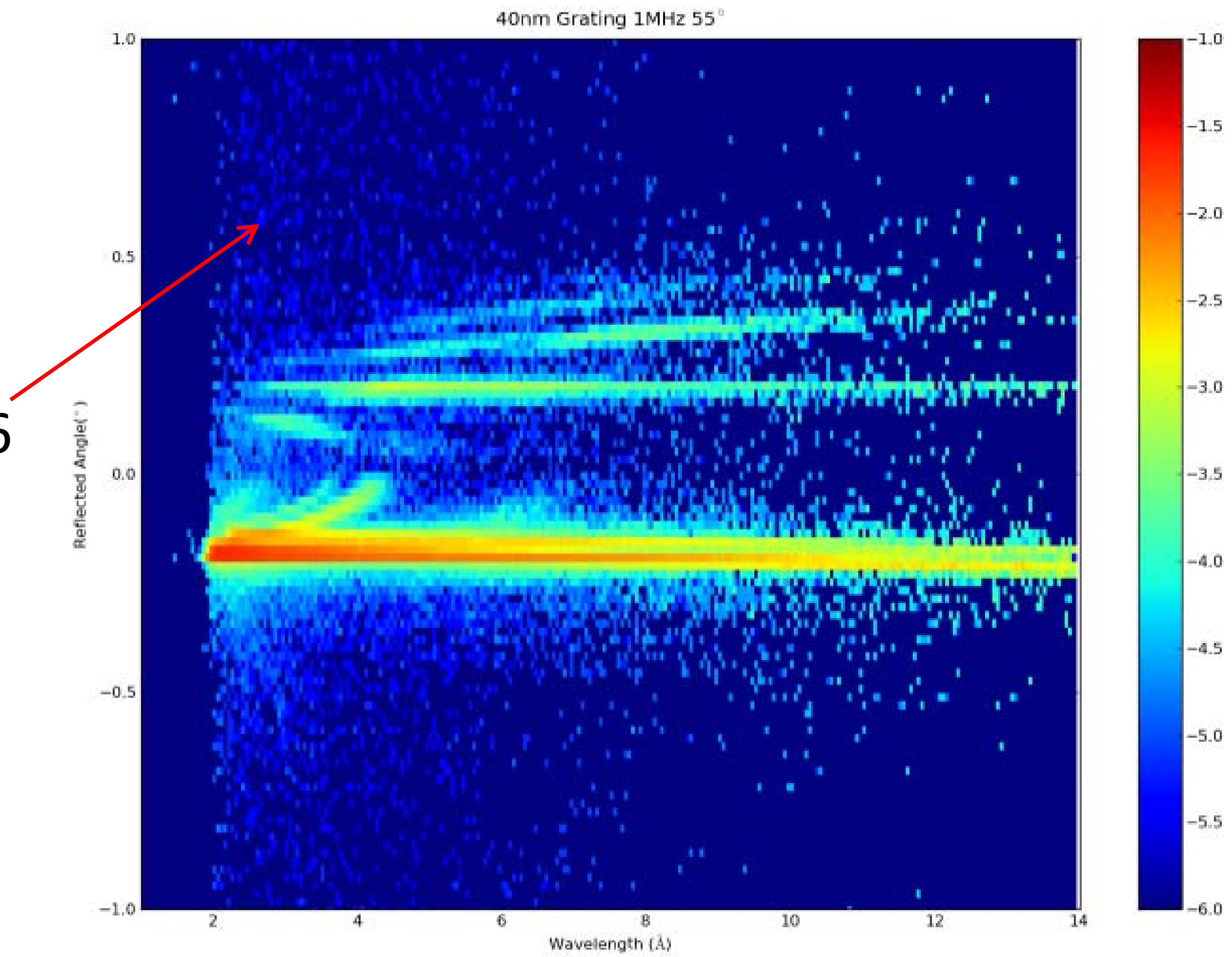
- **Spin-Echo at ISIS**

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



# Very Low Backgrounds

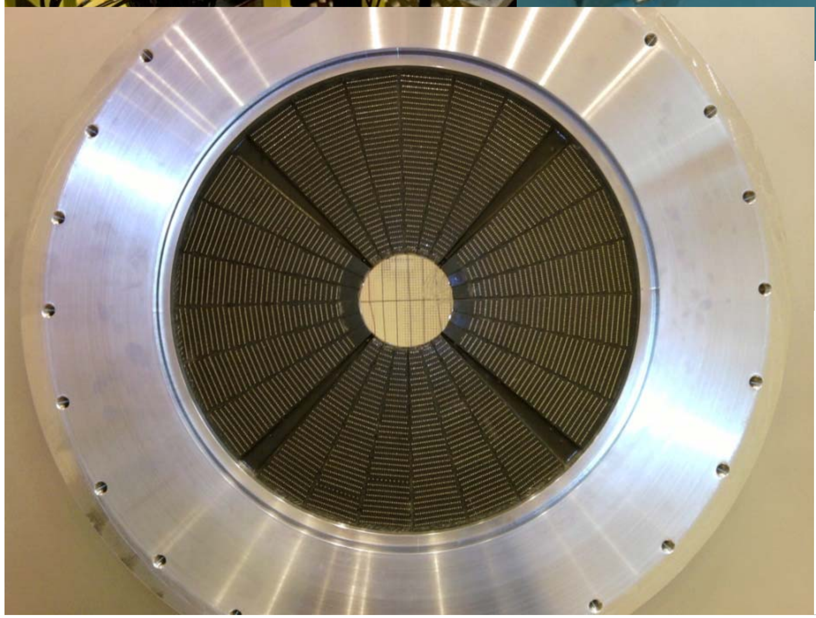
- 3 Hours Data
  - Less than 16 counts per hour/pixel



# NIMROD

# NIMROD scintillation detector

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



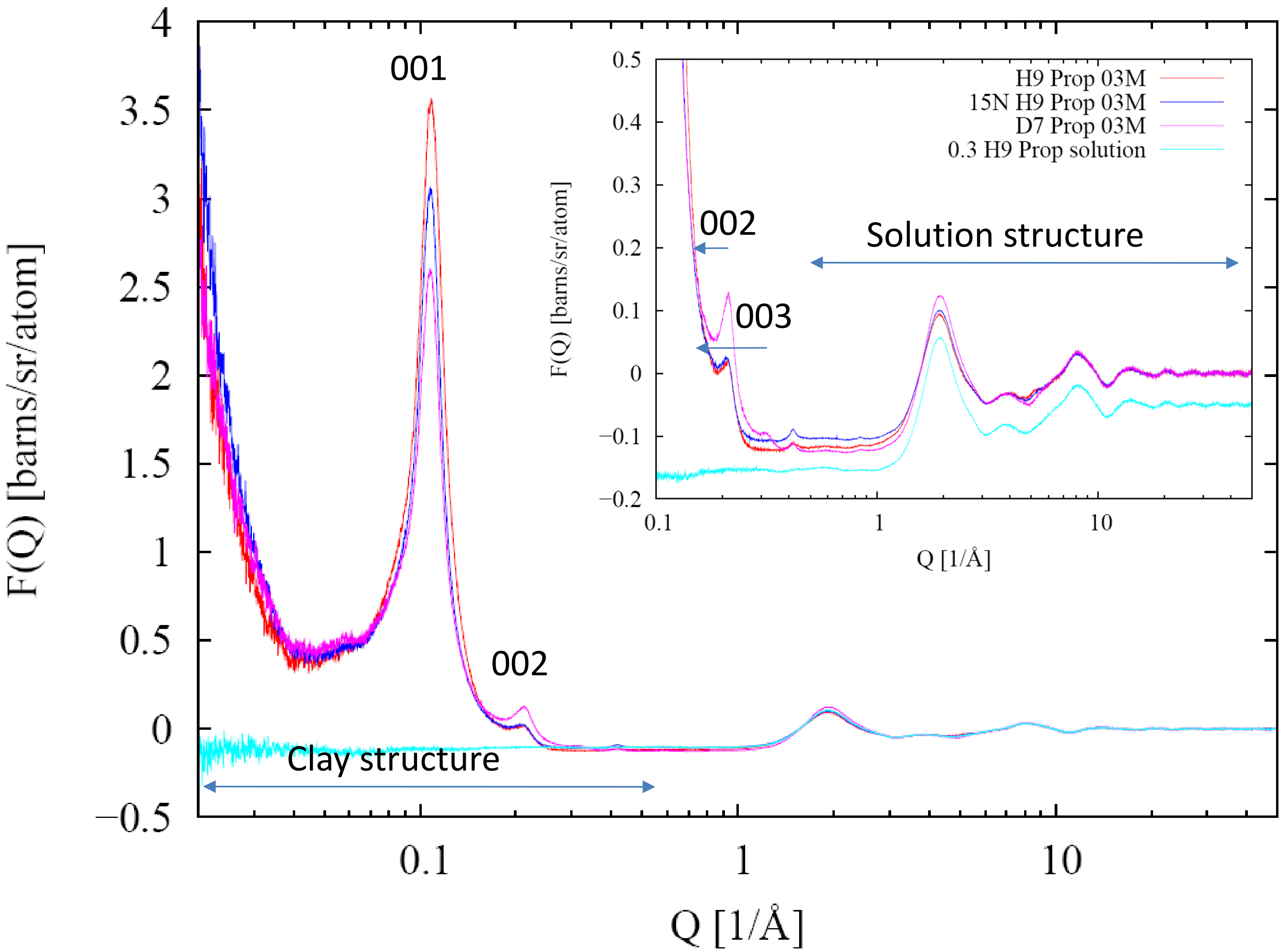
**Low Angle Bank:**

**Comprises of 8 detector modules**

**756 elements 2Cn fibre coded to 120 PMTs**

**Successfully upgraded and now operational**

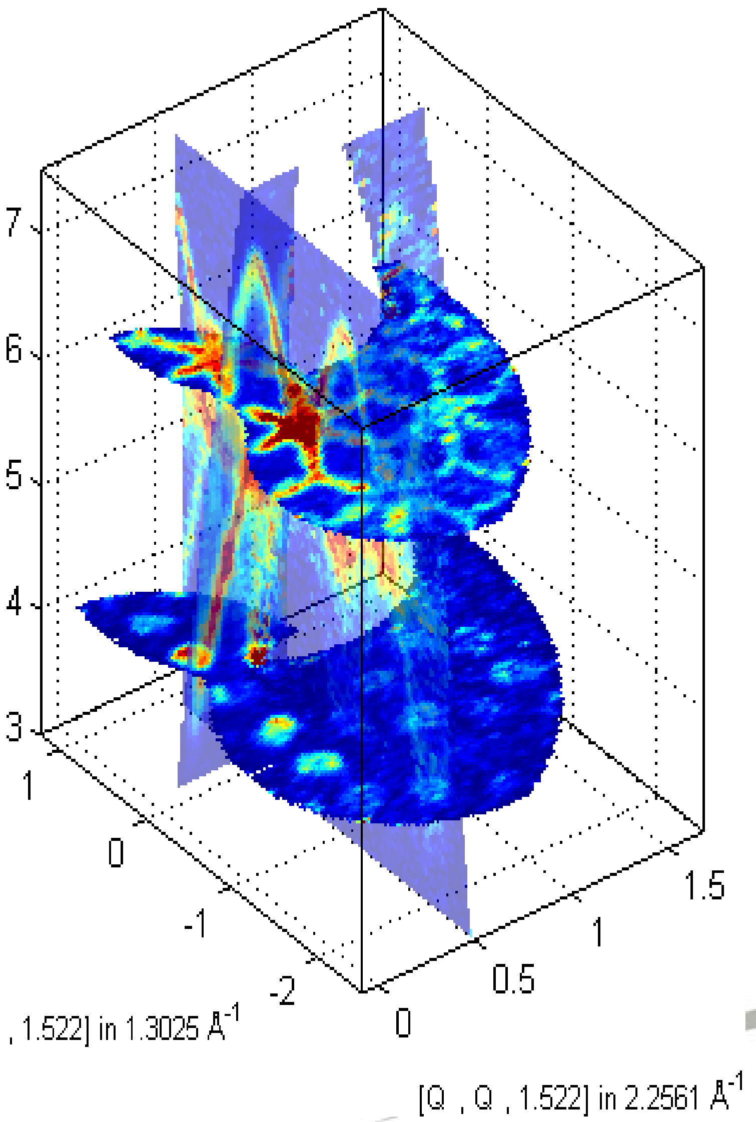
NIMROD's view of vermiculite clays and the aqueous solutions that cause them to expand



# International Partnerships


Science & Technology Facilities Council
ISIS

# Transfer of Technology




**Big Science ➔ Small Science**

- Accelerators
- Detectors
- Cryogenics
- Software
- Visualisation

Science & Technology Facilities Council

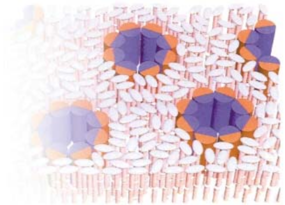
# ISIS Second Target Station

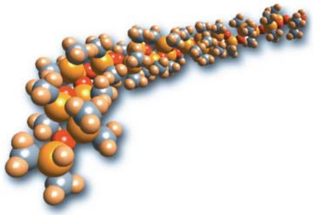
Science & Technology Facilities Council

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

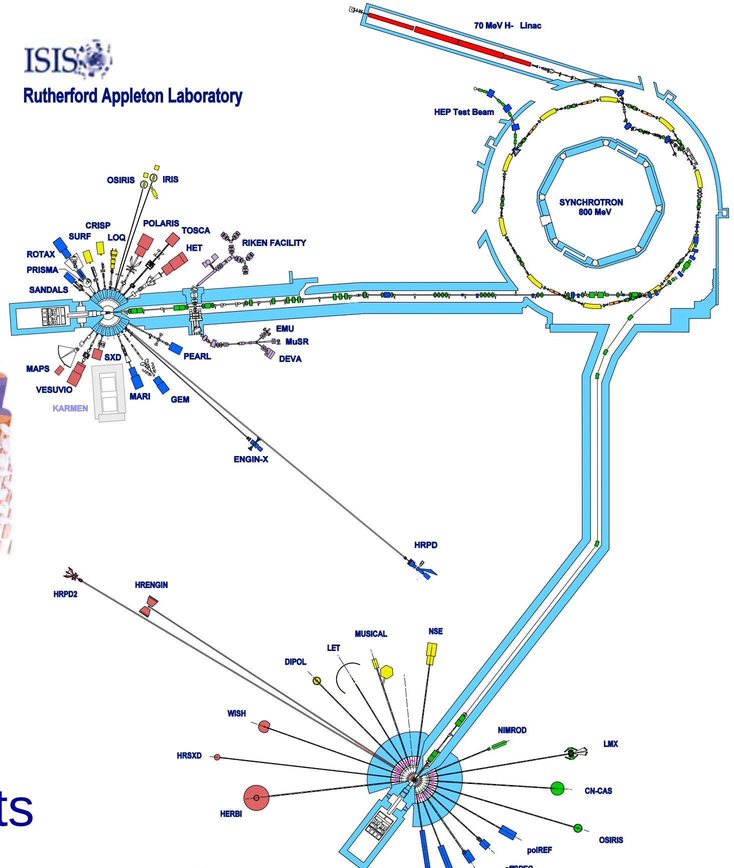
- Soft Matter
- Advanced Materials
- Bio-molecular Science

***Nanoscience***





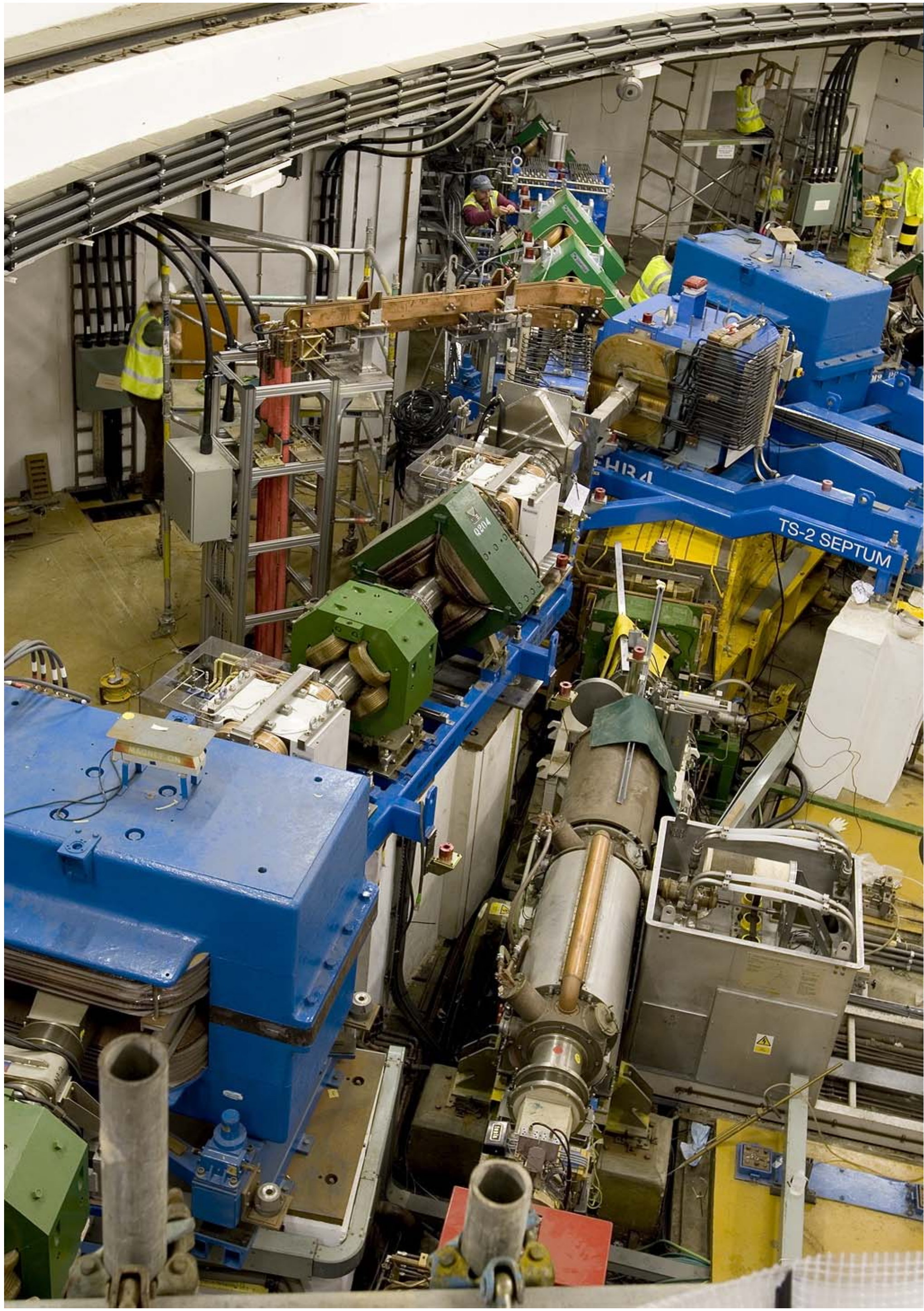
- complex multi-phase or multi-component materials
- difficult or complex environments
- kinetic processes
- parametric studies
- smaller samples

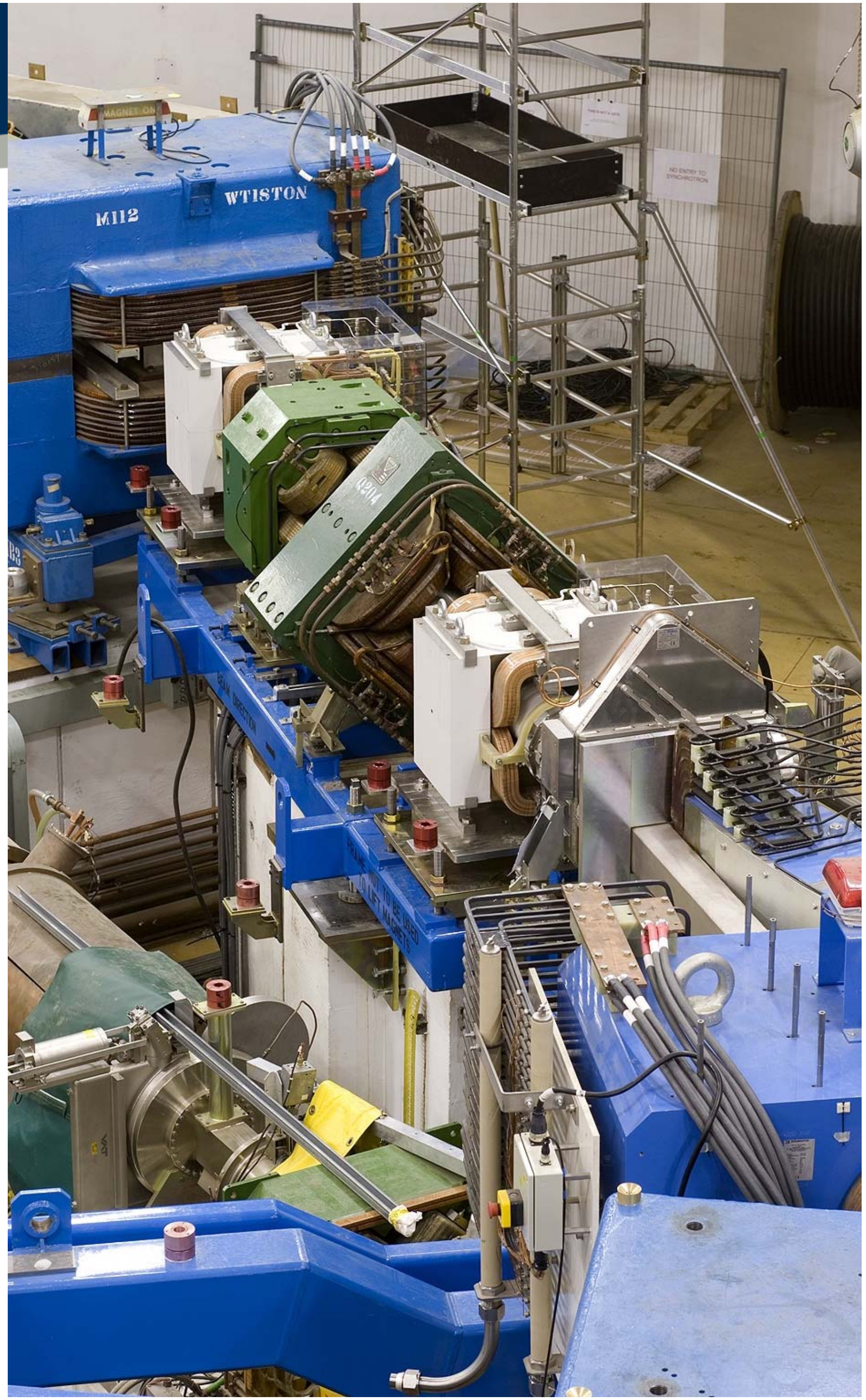


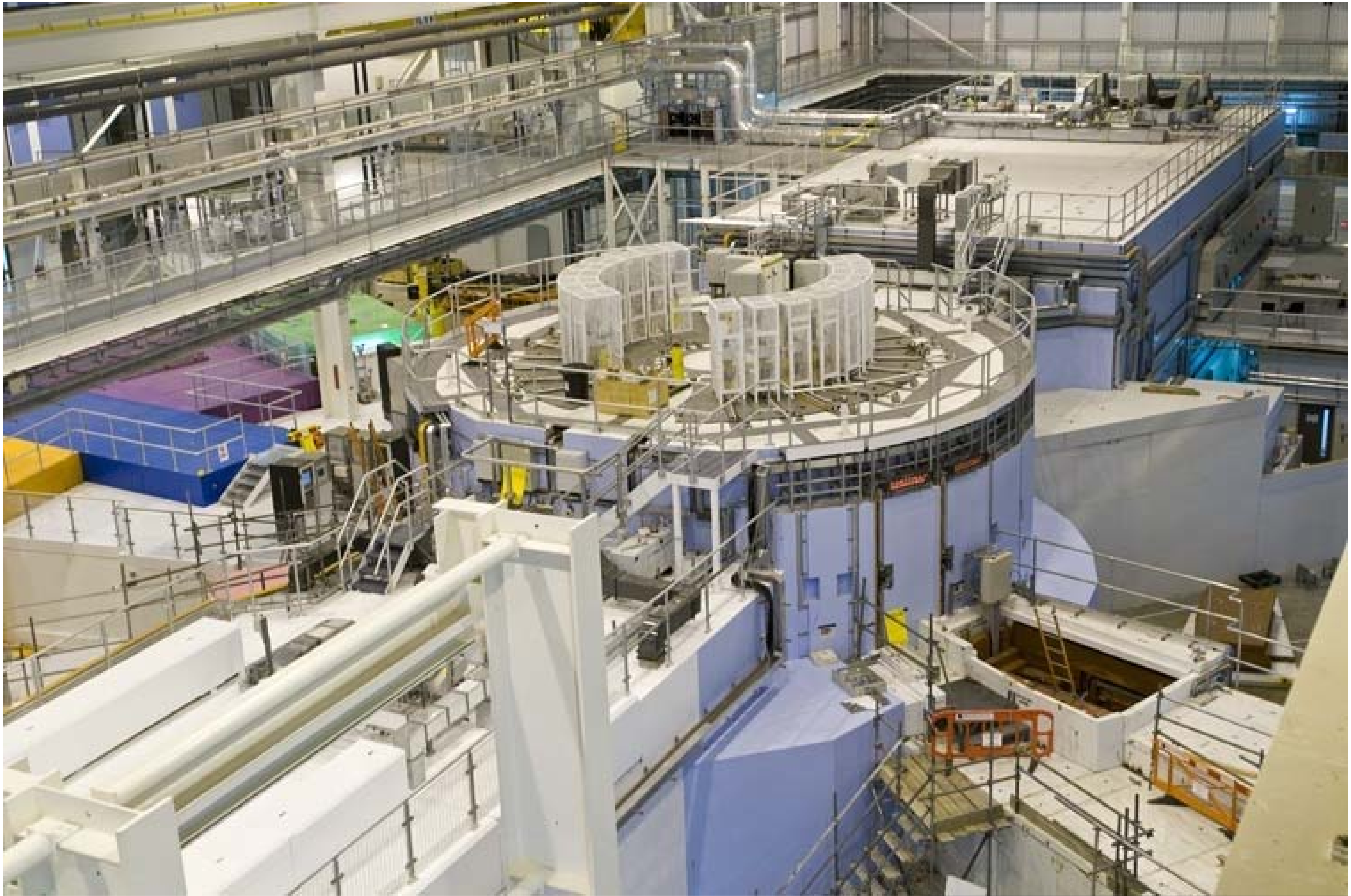

TS2 ISIS

Science & Technology Facilities Council

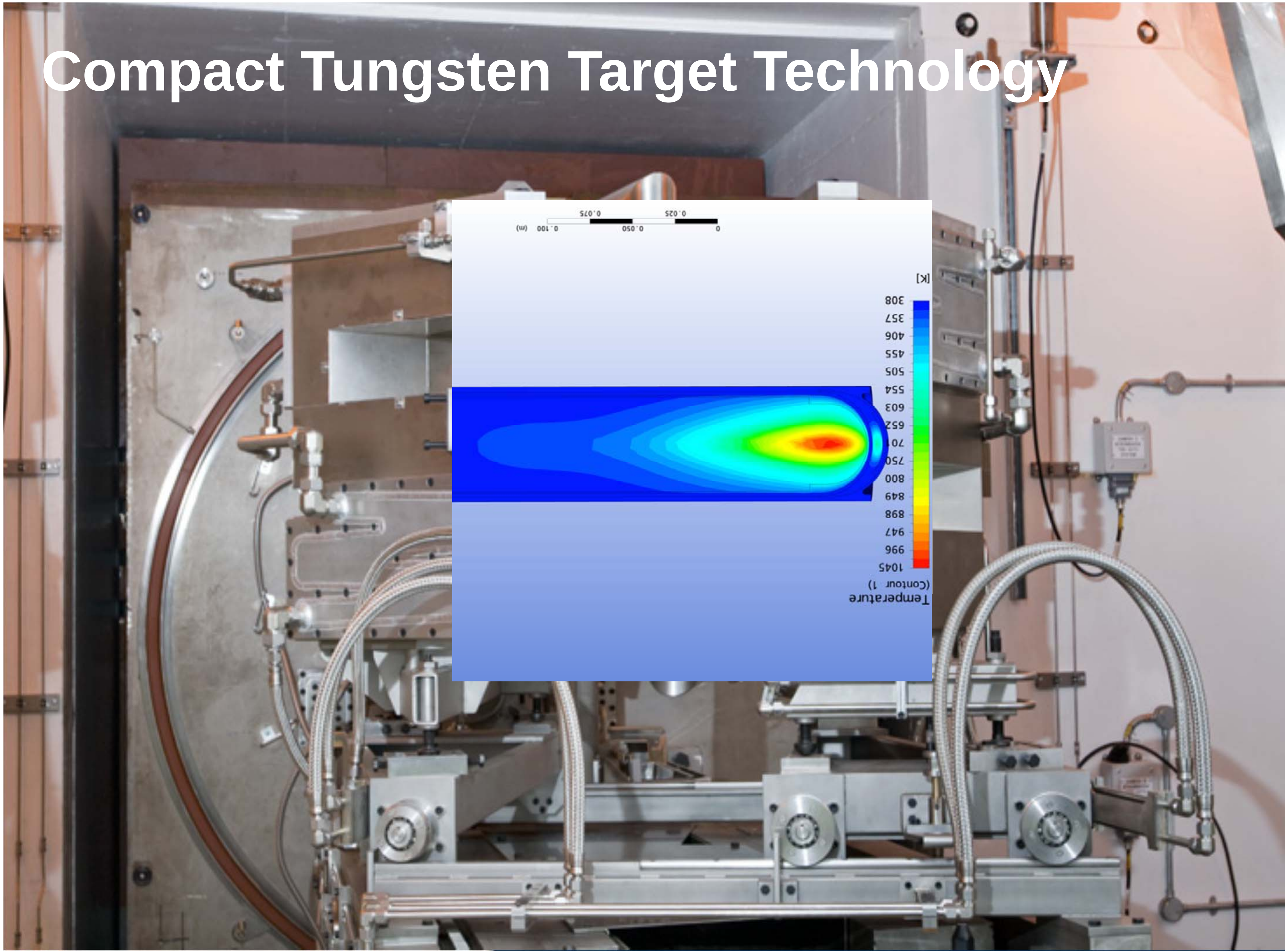
# 2008

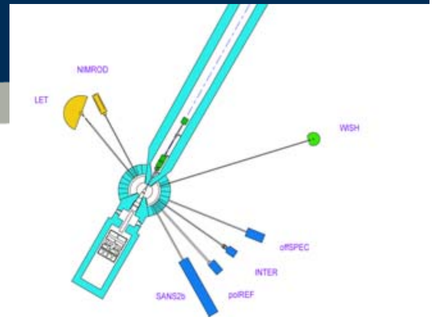

TS-2 SEPTUM


M112
WTISTON

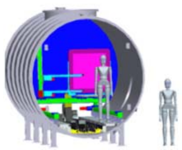
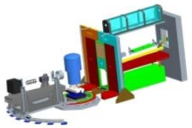
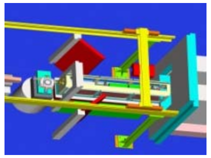
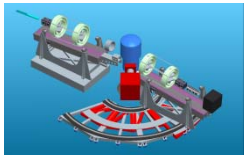
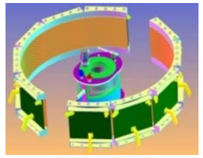
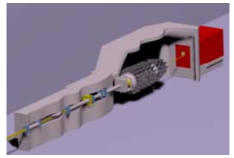
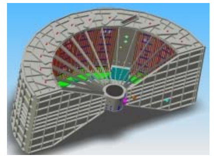


# Compact Tungsten Target Technology






# TS2 Phase 1 instruments are outstanding!

| SANS2D | POLREF | INTER | OFFSPEC | WISH | NIMROD | LET |
|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |
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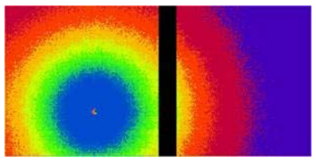
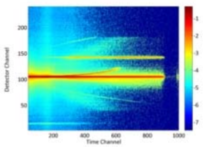
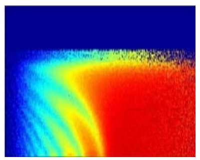
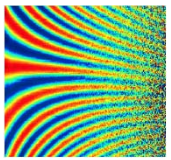
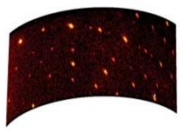
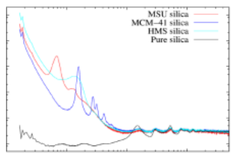
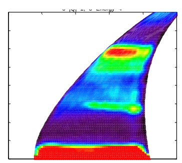
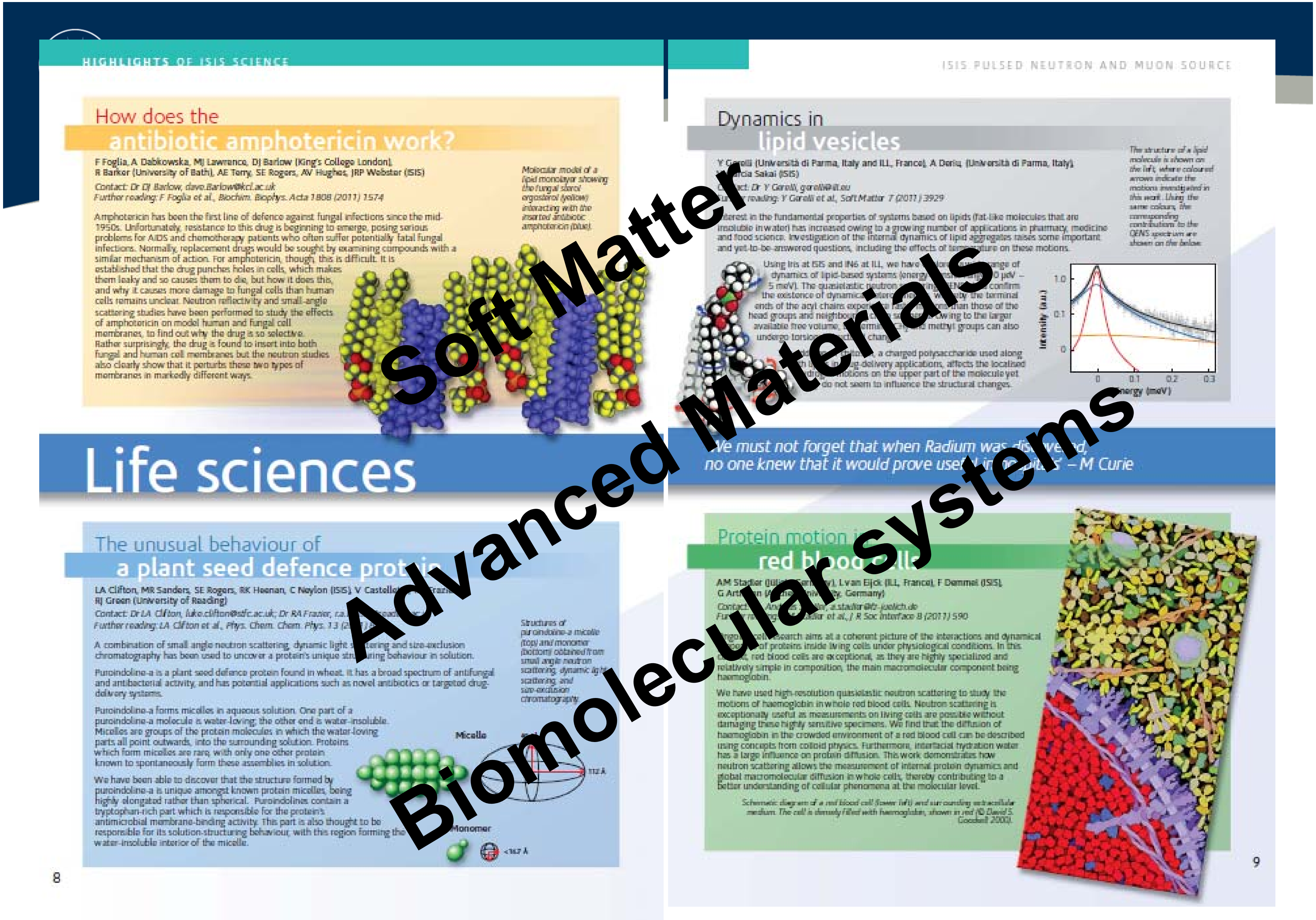
|  |  |  |  |  |   |  |

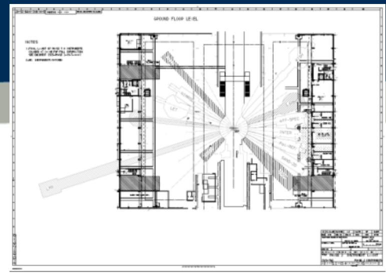
TS2 Phase I: 2004-9

Soft Matter

Advanced Materials

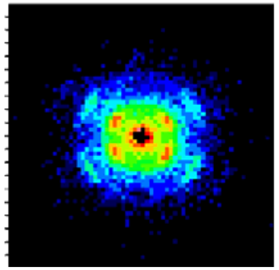
Biomolecular systems

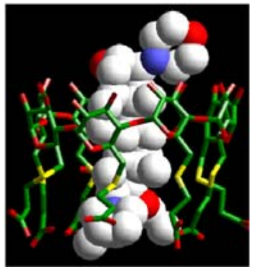


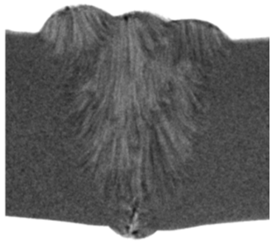


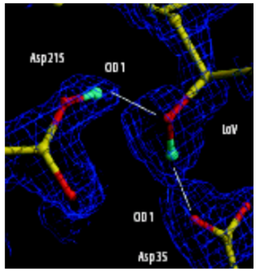
# TS2 Phase 2 instruments

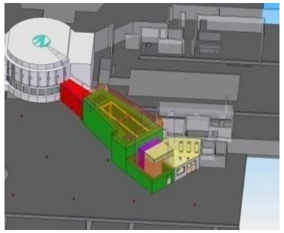
CHIPIR ZOOM LARMOR IMAT LMX

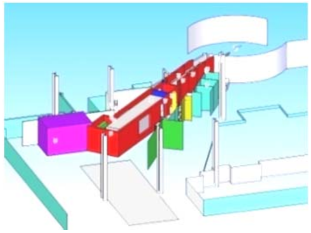


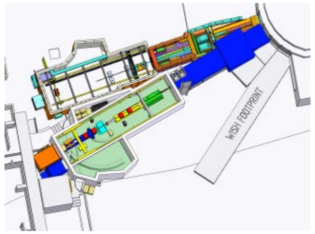


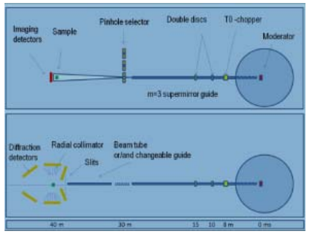


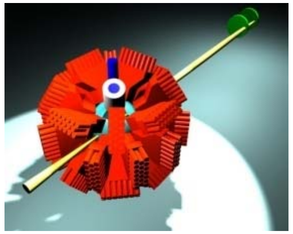




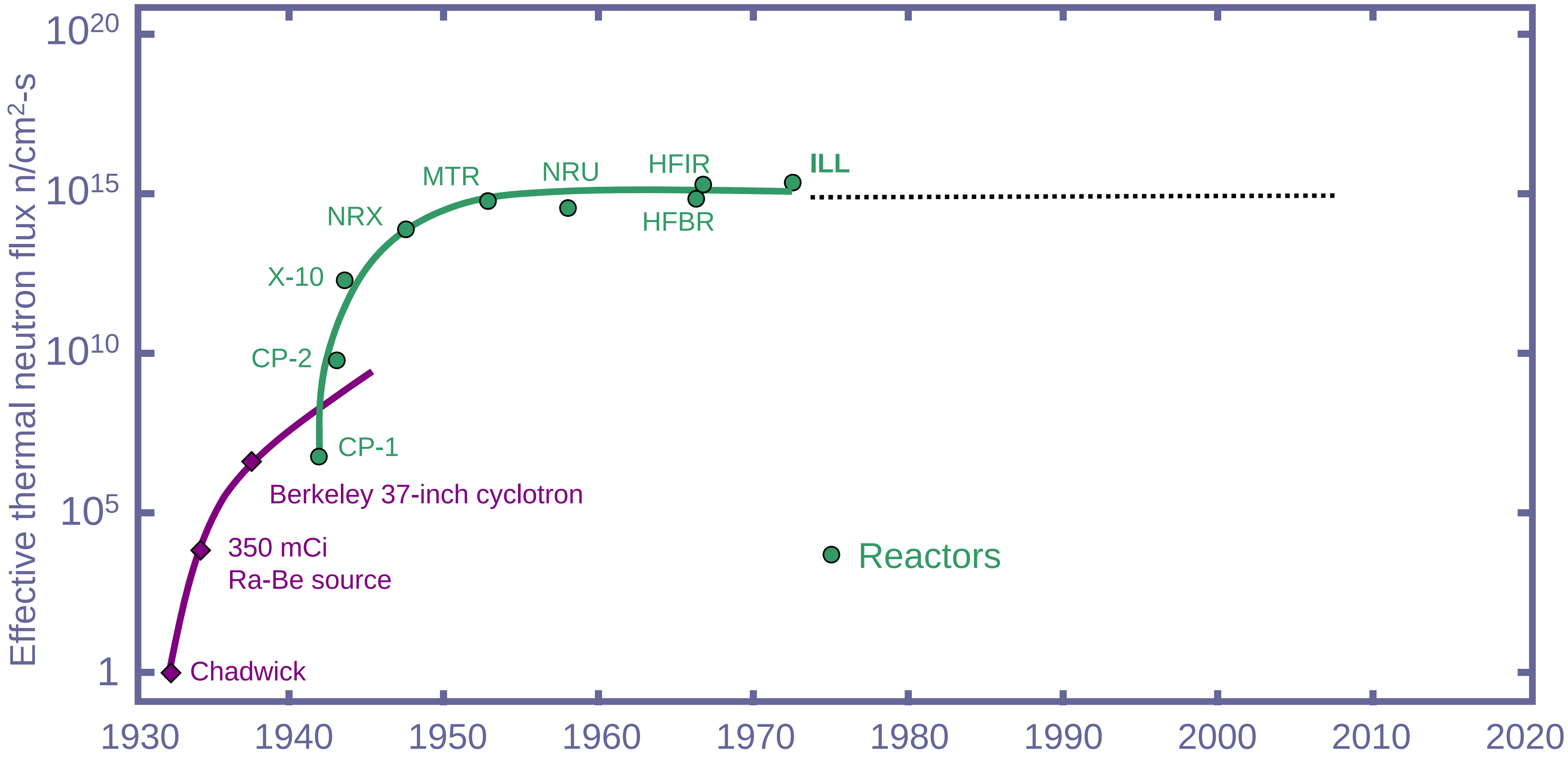






TS2 Phase II: 2011-16

# Reactor Sources




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

# ILL: instrument suite

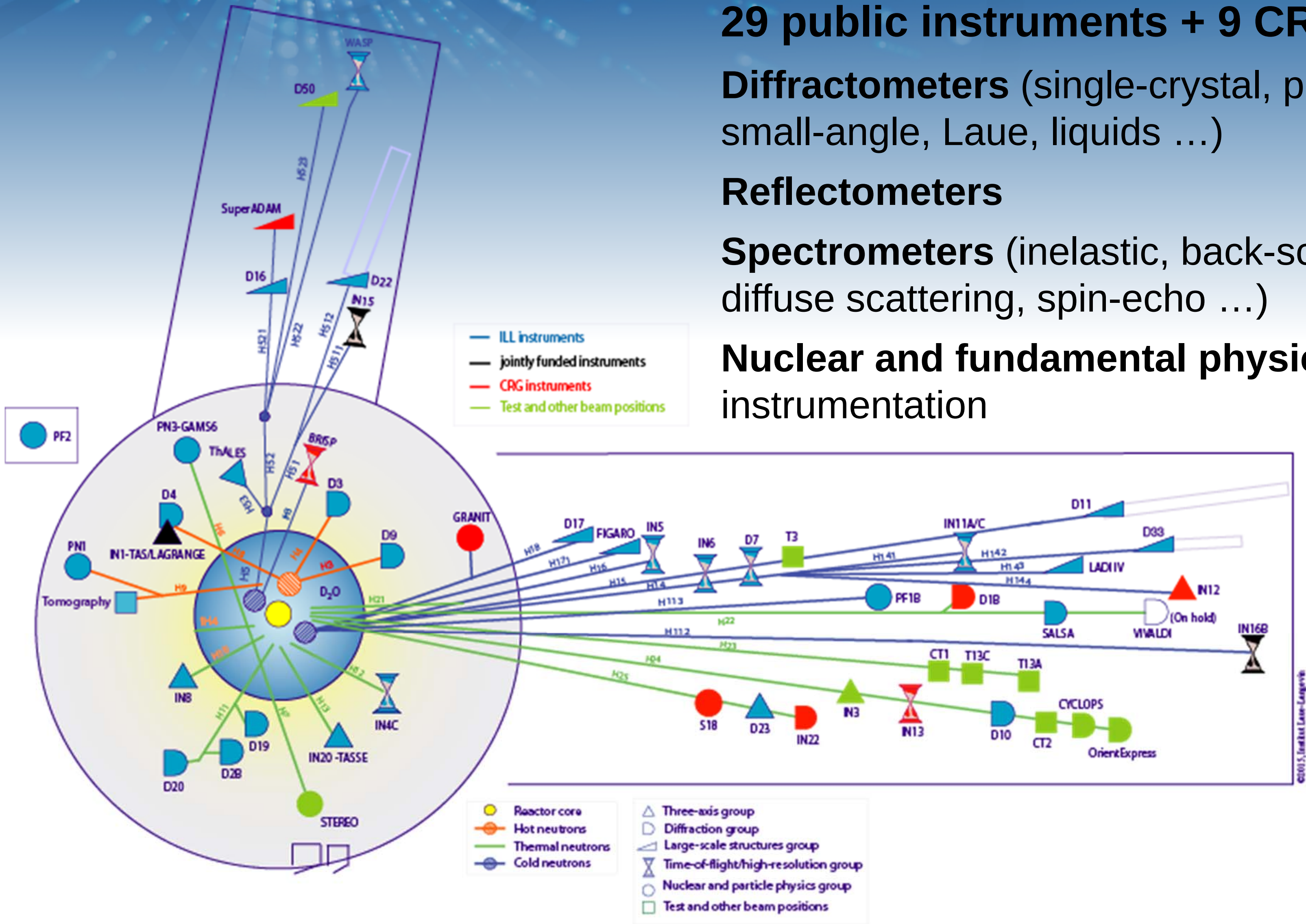
**29 public instruments + 9 CRGs**

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

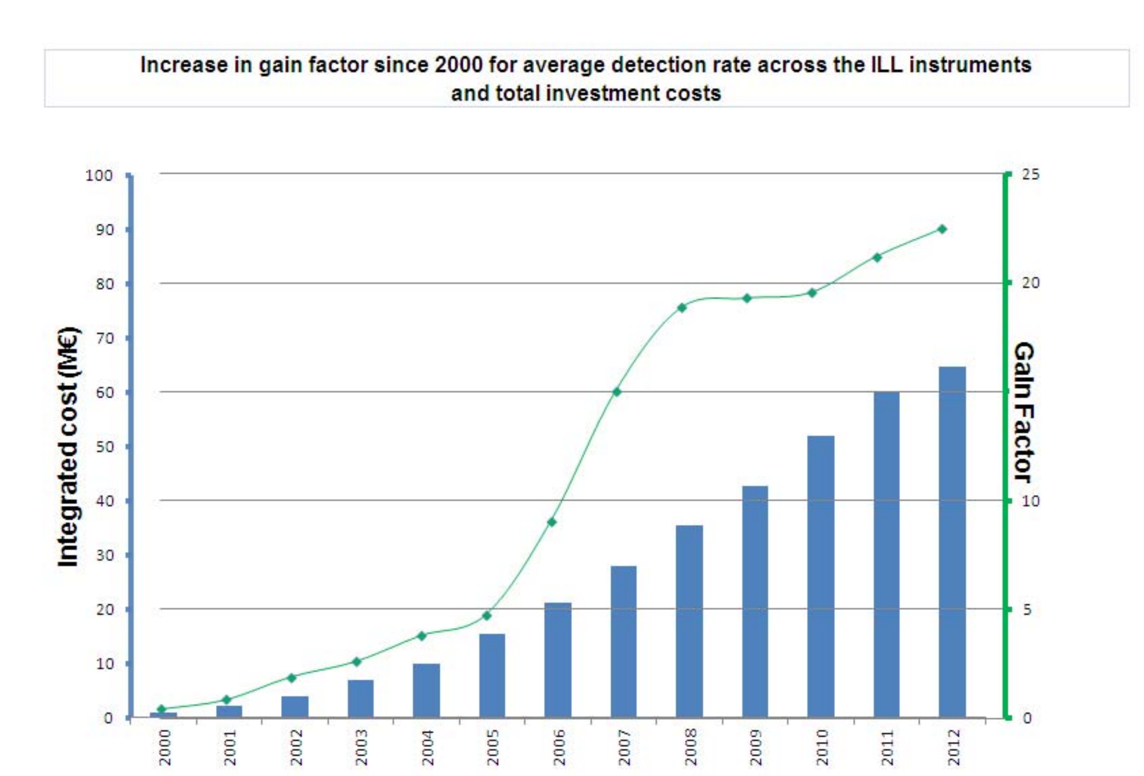
**Reflectometers**

**Spectrometers** (inelastic, back-scattering, diffuse scattering, spin-echo …)

**Nuclear and fundamental physics** instrumentation

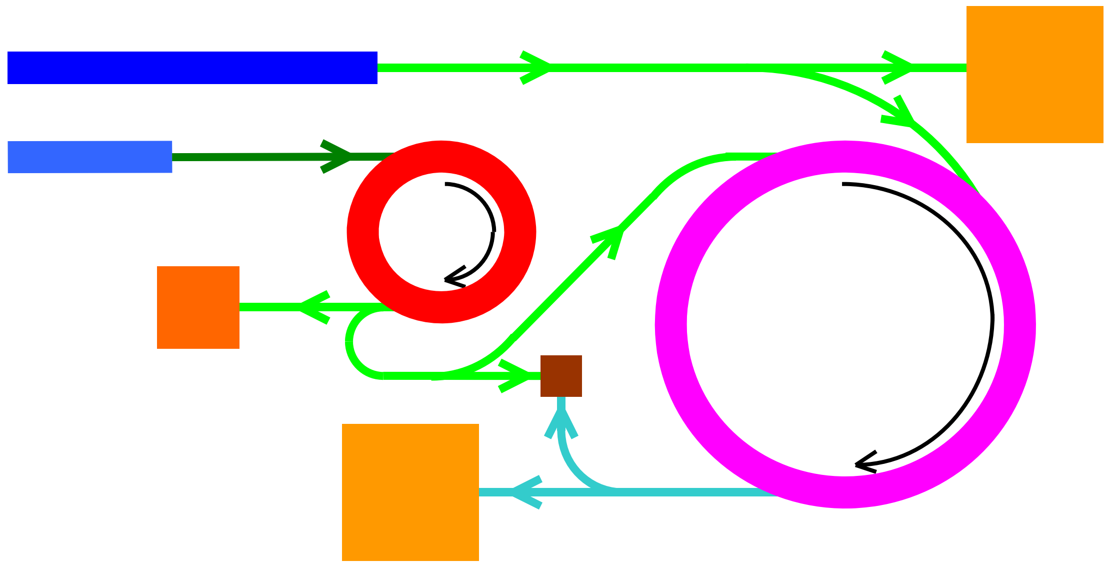


# The Millennium Programme




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

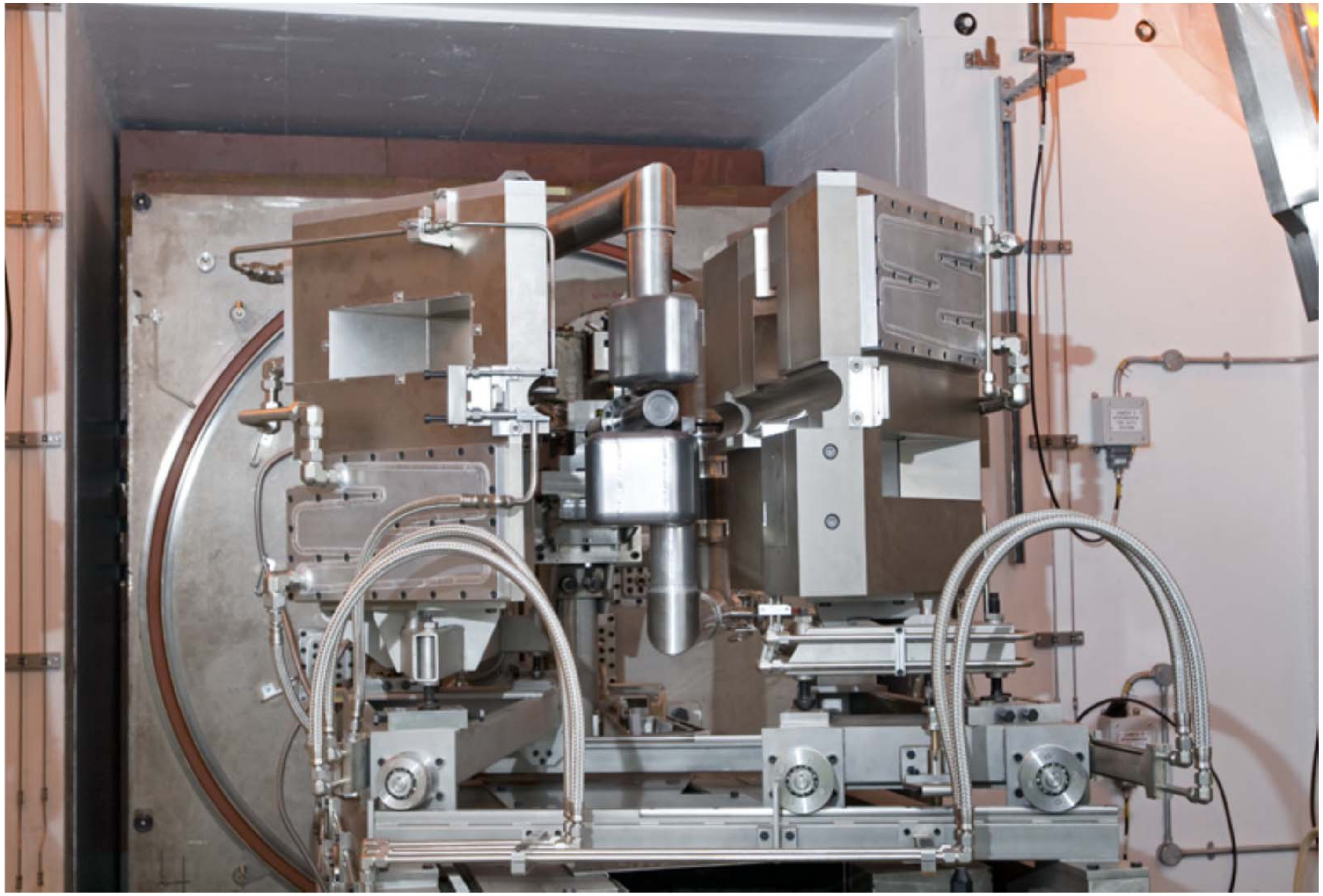
# Possible Future Options



# MW ISIS Options

Science & Technology Facilities Council
ISIS

# ISIS MW Upgrade ?

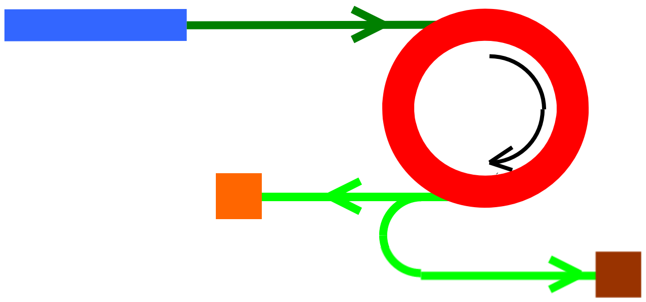


**TS1 Target Moderator Upgrade**
**x 2-3**

# ISIS upgrade schemes

At present

0.2 MW, 40 + 10 pps



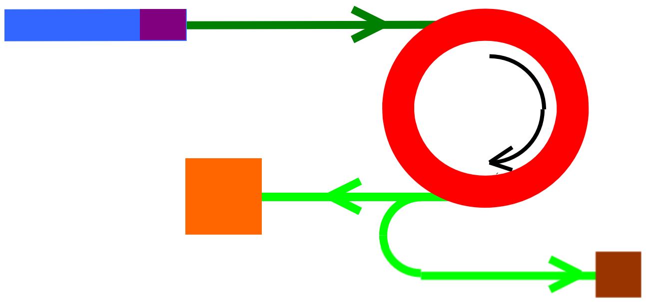
Science & Technology Facilities Council ISIS

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 × 1, TS-1 neutrons × 2-3



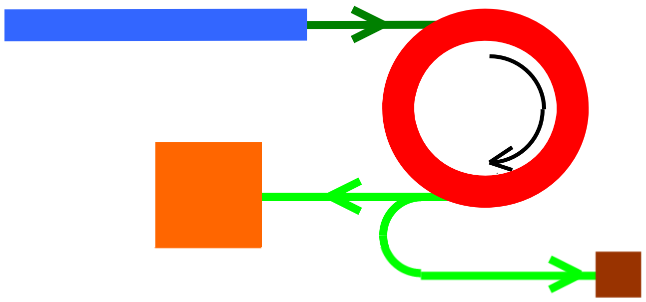
~£15M total

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

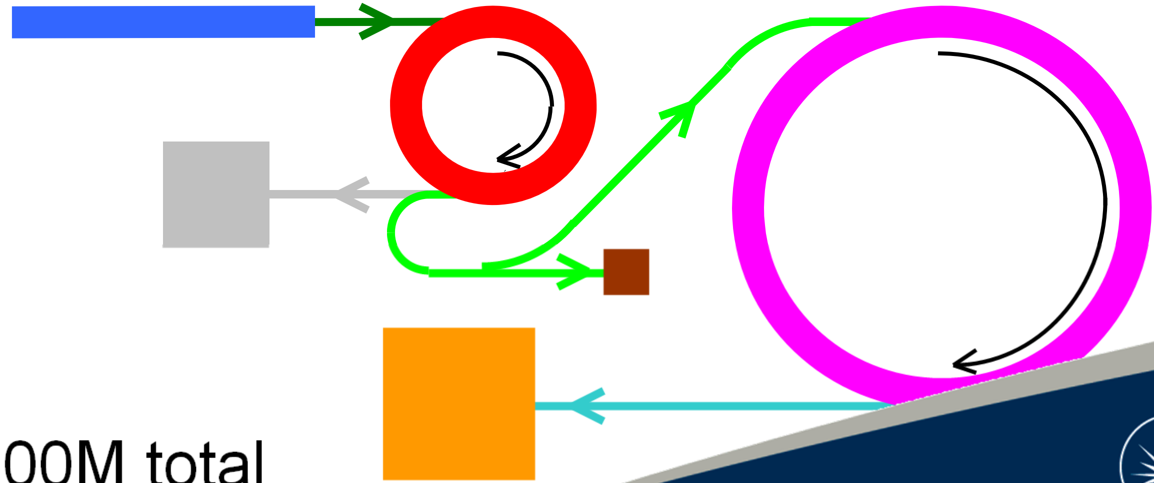
2. Add ~3 GeV synchrotron

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



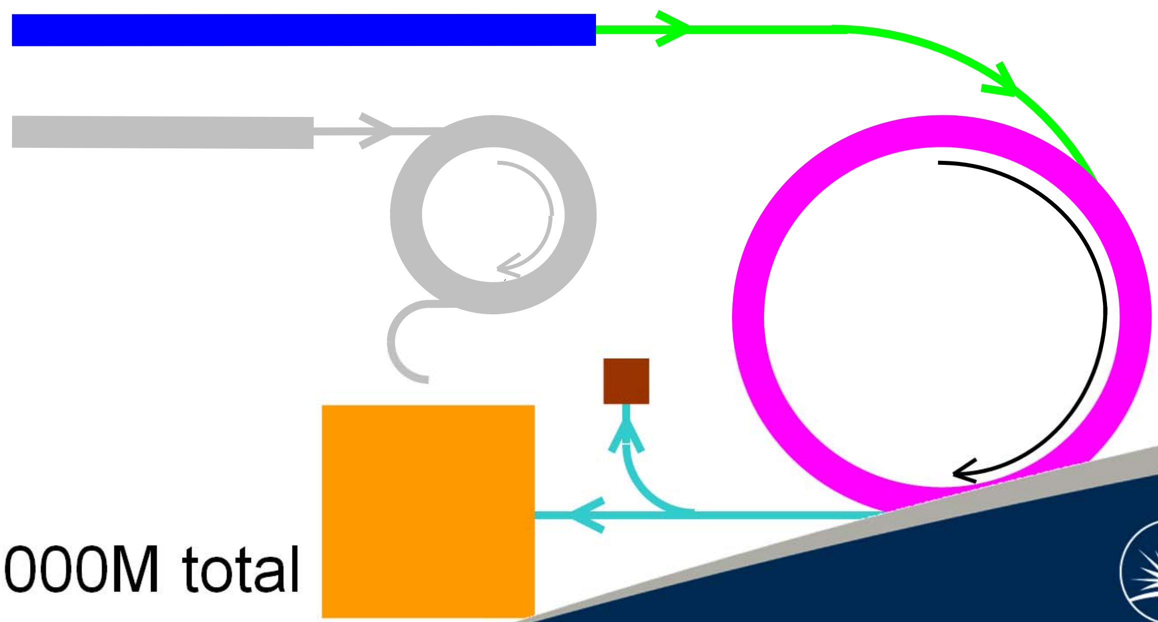
~£700M total

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?

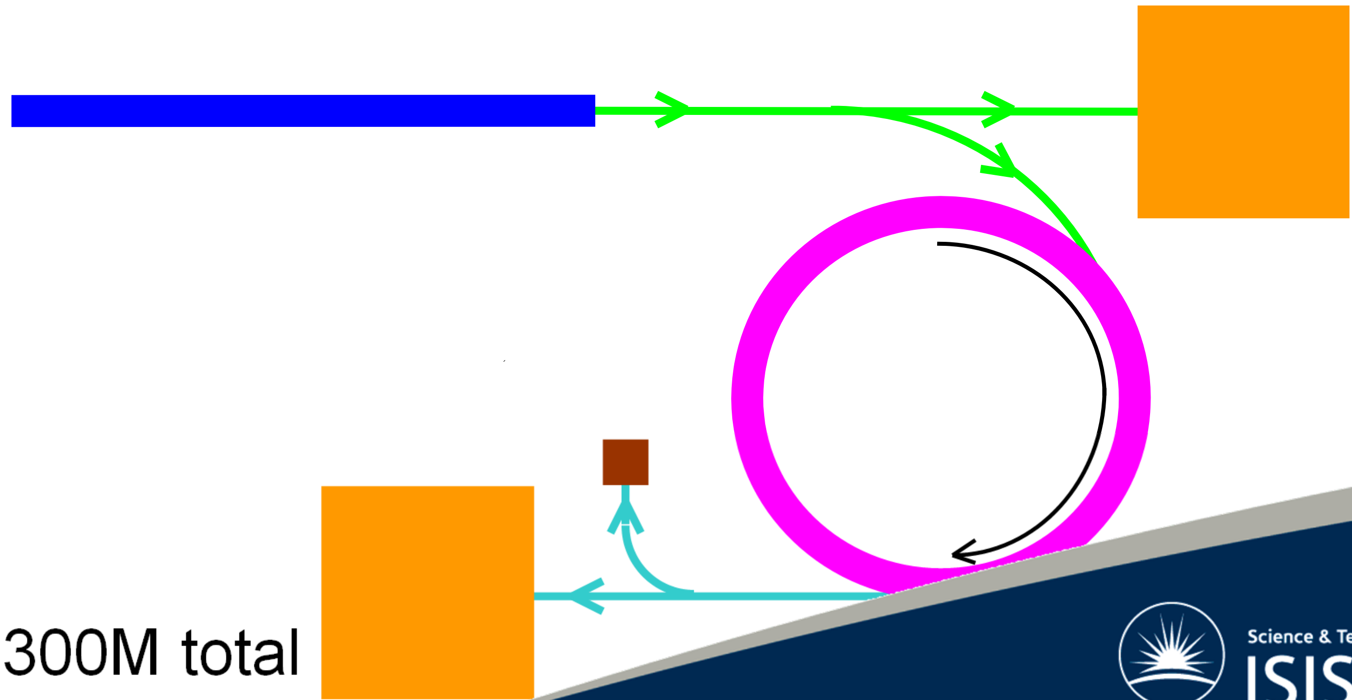


~£1000M total

4. ~3 GeV synchrotron + long pulse option

~2002 ESS

~2½ + ~2½ MW



~£1300M total

# "ESFRI – ESS"

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

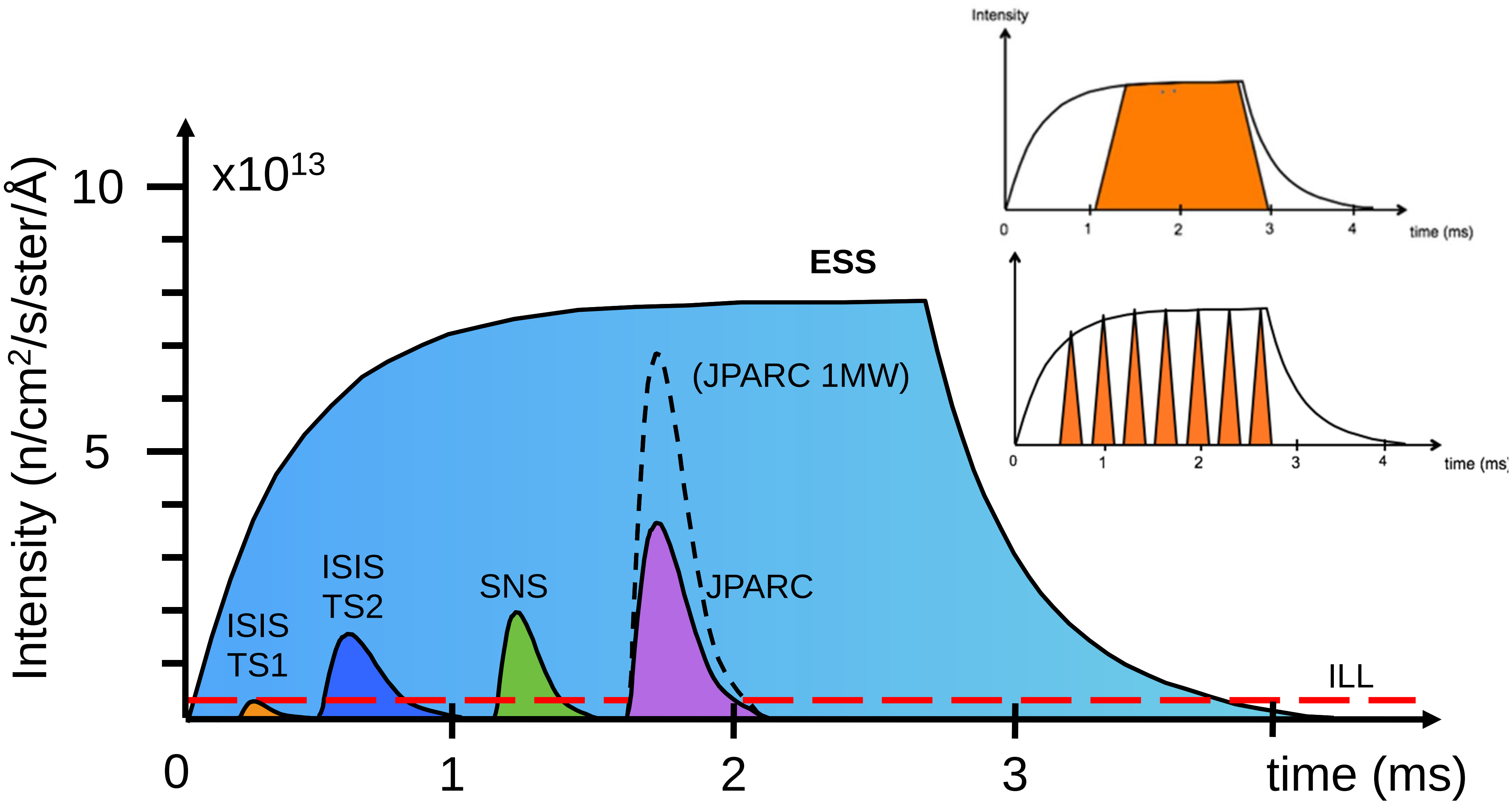
**Drivers –**

- **Science**
- **Addresses ILL Vulnerability**
- **Regional Investment**
- **European Pride -- "loose our lead"**

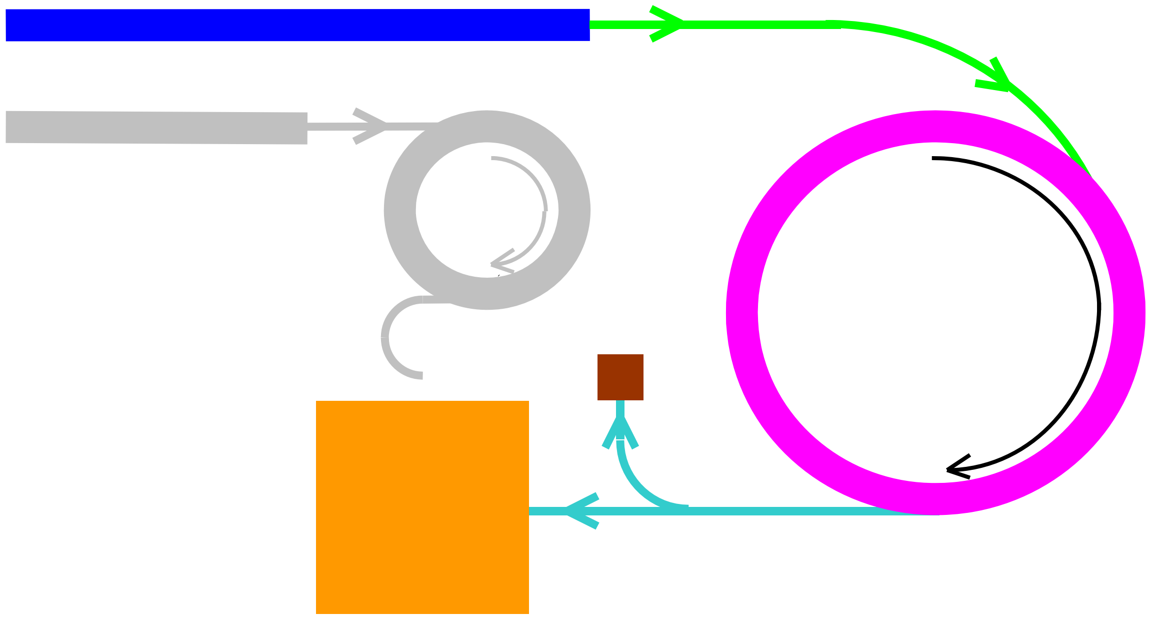
**ILL Lifetime ~ 2030**

EUROPEAN SPALLATION SOURCE

# ESS long pulse potential

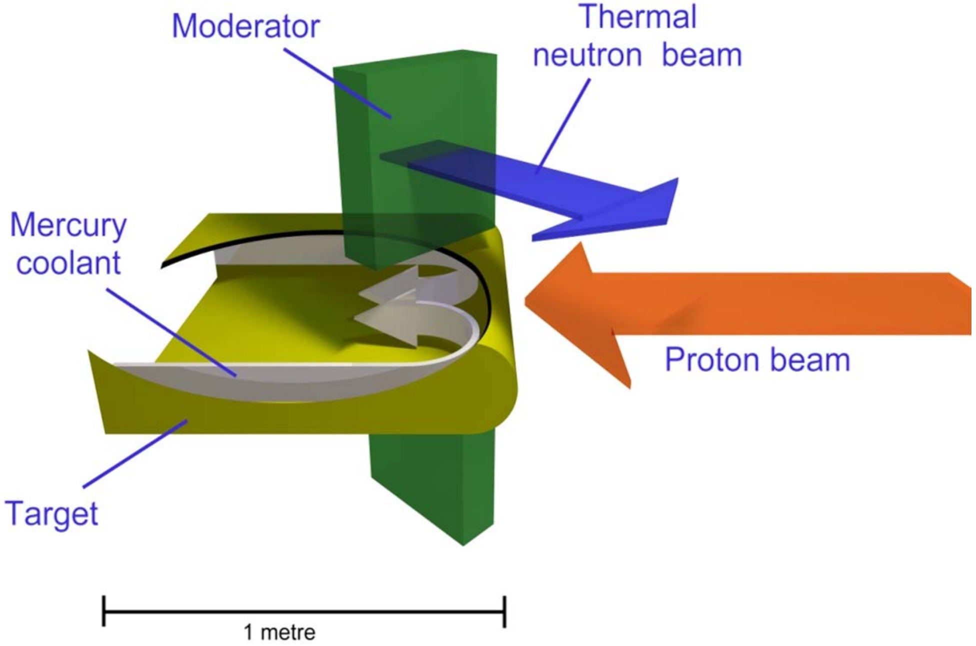


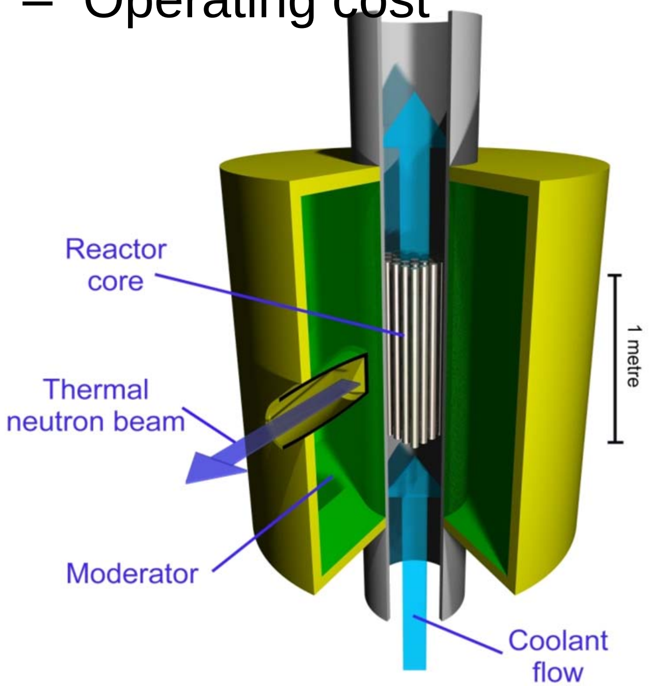
# ISIS MW Upgrade
x 20



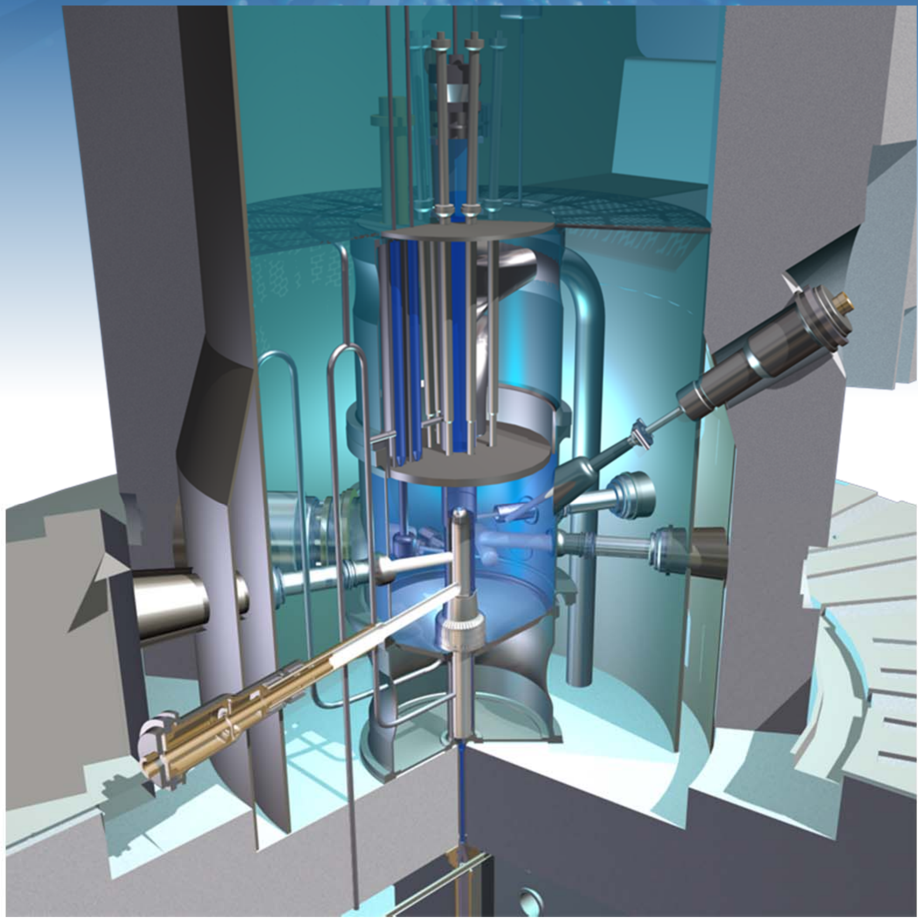
# Limitations of current neutron sources

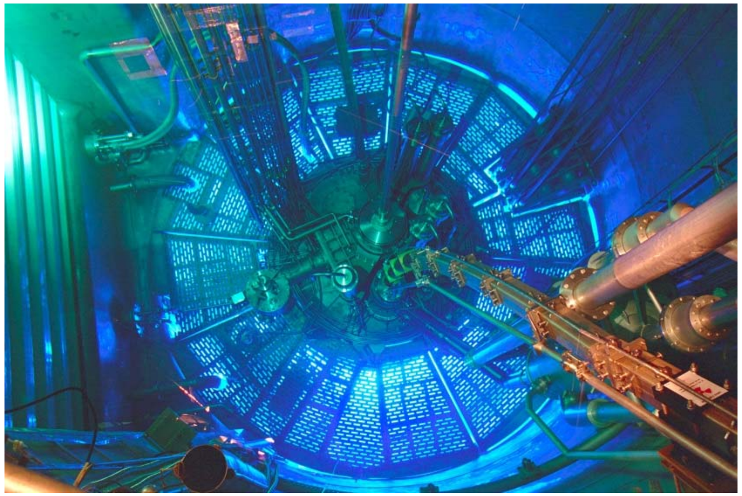
- Current source are limited either:
  - Heat removal from target
  - Shock waves
  - Radiation damage
  - Operating cost



# The ILL High Flux Reactor





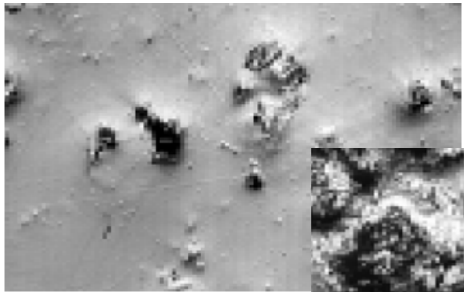
58 MW reactor operating ~190-200 days/year; 4 Cycles of ~50 days /year;

# Radiation Damage in MW+ Targets

$10^4$ cycles

**JAERI Data**

**Pitting ~ (Power)$^4$**

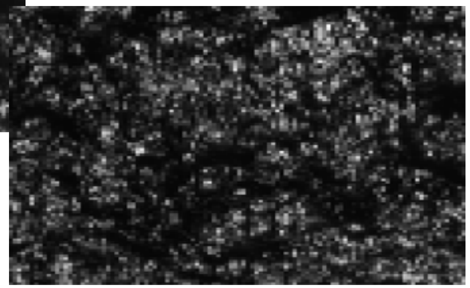


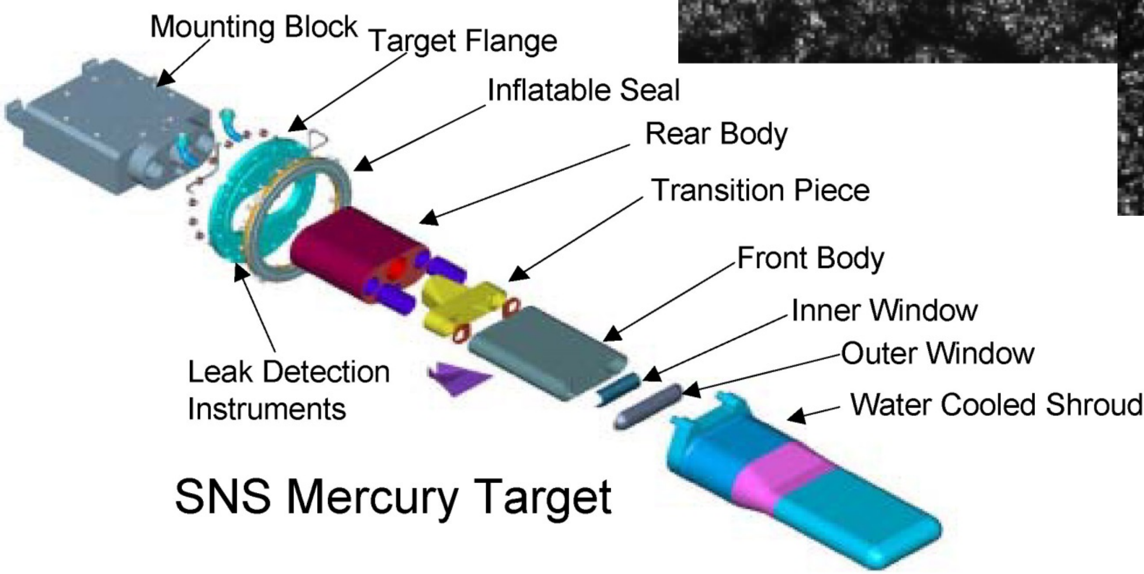
$10^5$ cycles

25 μm

$10^6$ cycles

2 x $10^7$ cycles

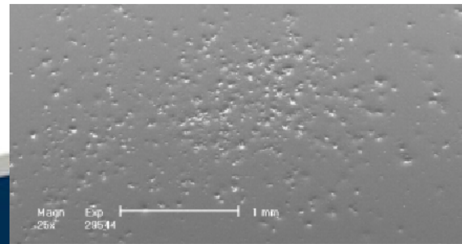


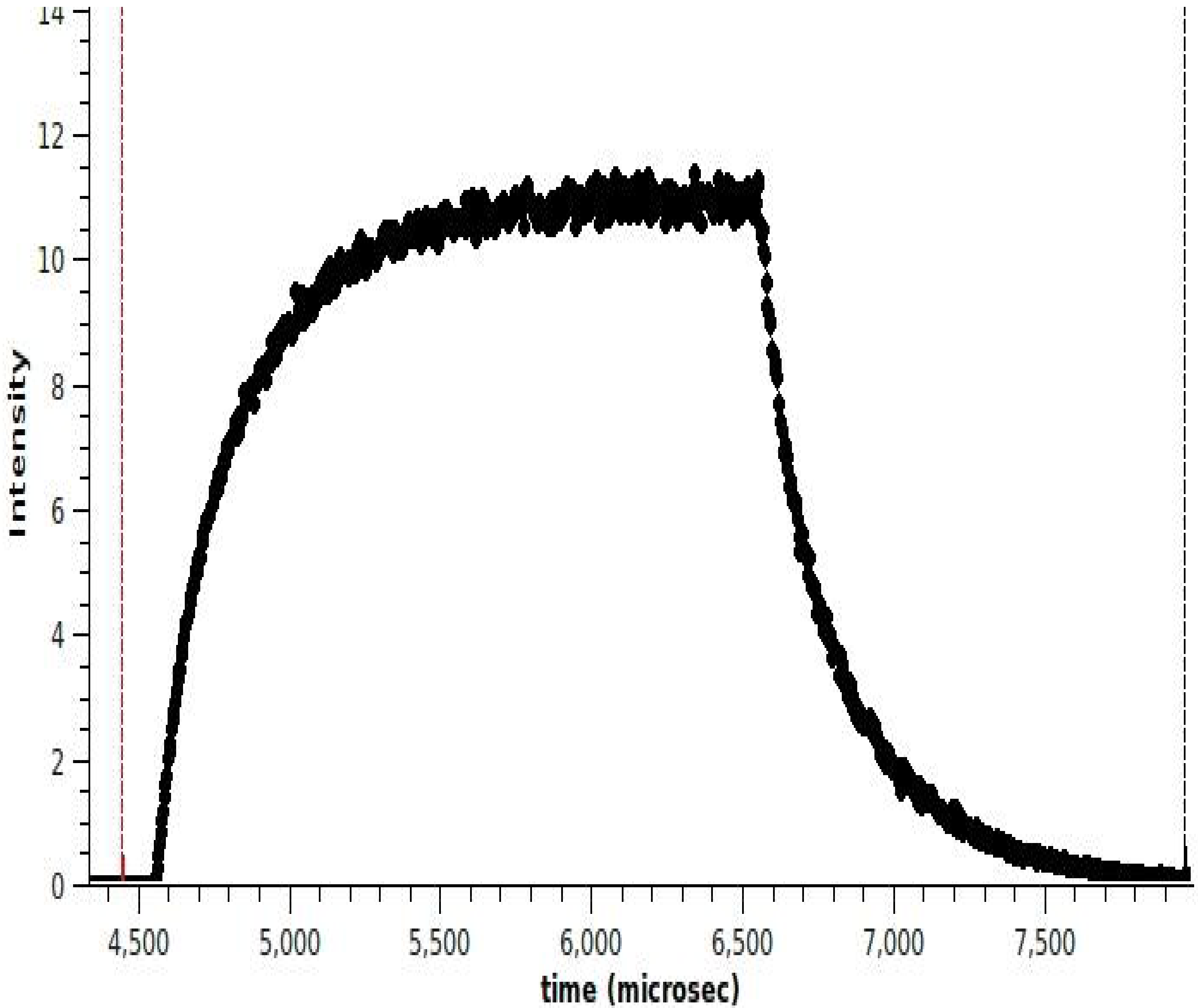



SNS Mercury Target

Pitting in steel at WNR

SNS Data (100 proton pulses)

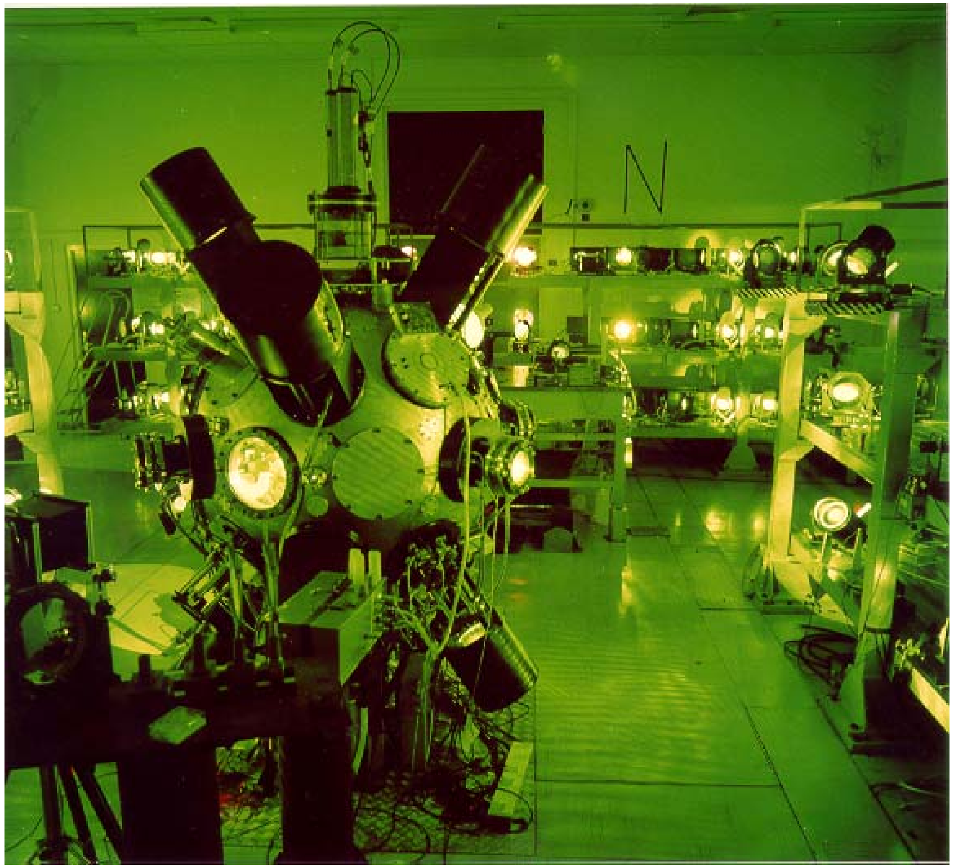




Intensity
time (microsec)
0
2
4
6
8
10
12
14
4,500
5,000
5,500
6,000
6,500
7,000
7,500

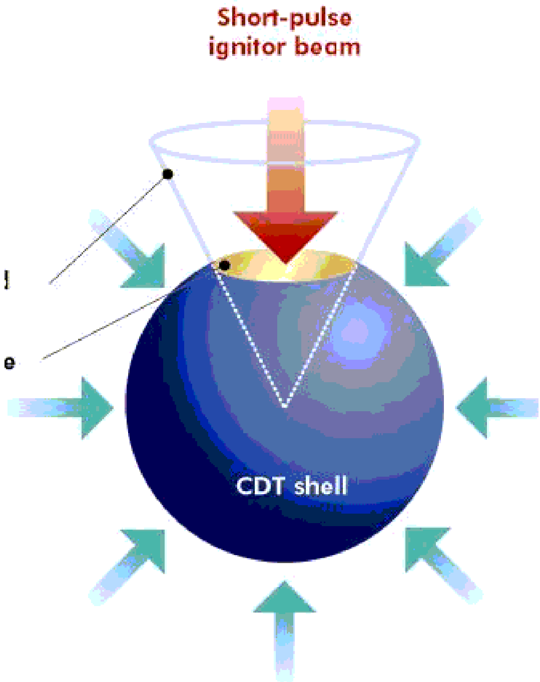

Laser- Driven Neutron Source

# 'Blue Skies' Neutron Source



## Fast Ignition

**x 1000 enhancement**

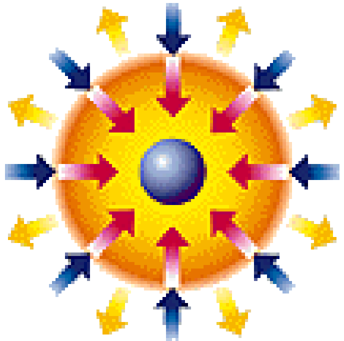



**$10^{19}$ 14 MeV n/pulse**

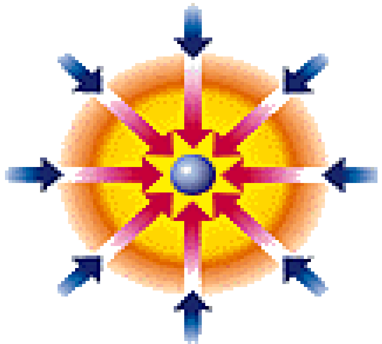
**100- 1000 x ISIS**

# Inertially confined fusion

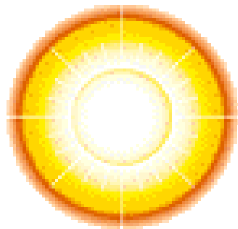
Lasers or X-rays symmetrically irradiate pellet



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



Material is compressed to ~1000 $gcm^{-3}$



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

# Laser Fusion is a reality … NIF

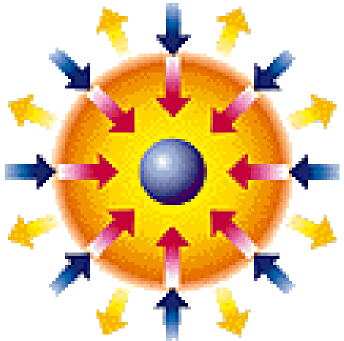
Science & Technology Facilities Council

# …on an enormous scale

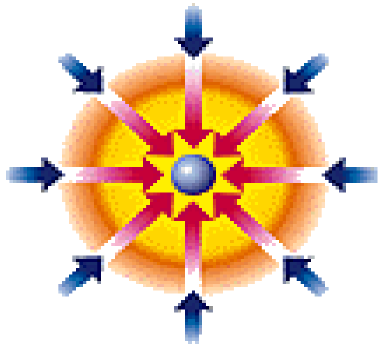
Science & Technology
Facilities Council

# Fast Ignition Fusion

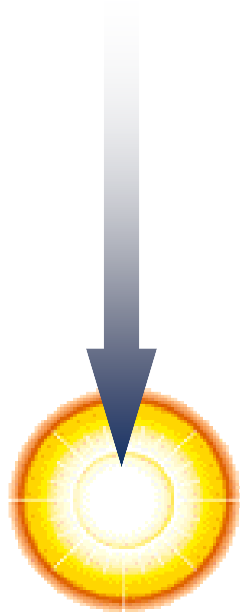
Lasers or X-rays symmetrically irradiate pellet



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



Material is compressed to ~300 $gcm^{-3}$



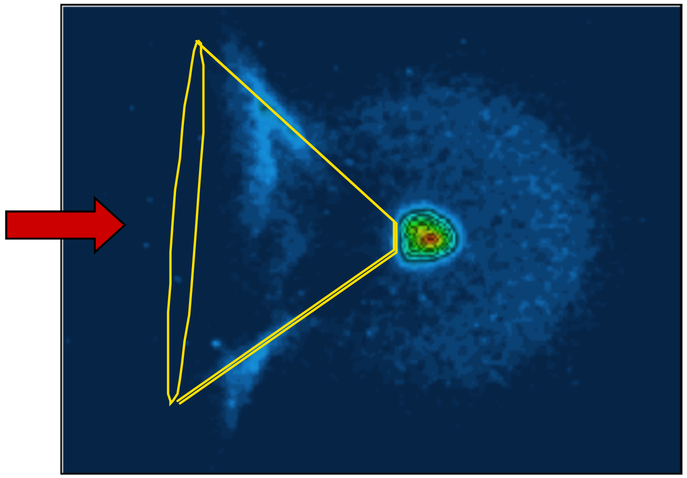
Picosecond pulse heats the plasma and ignites the compressed fuel

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

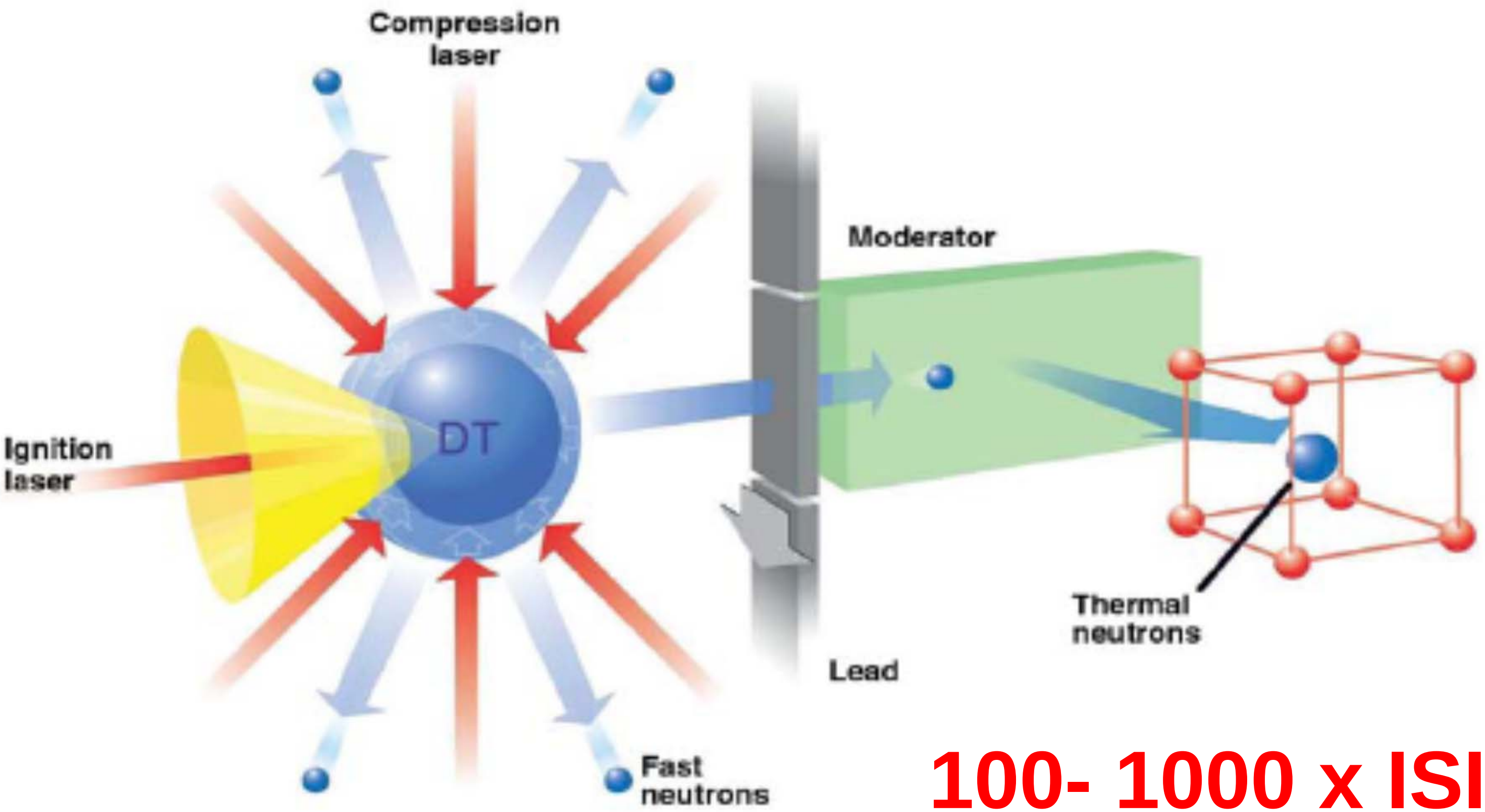
# Advanced fast ignition

Advanced Fast Ignition further changes the landscape

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



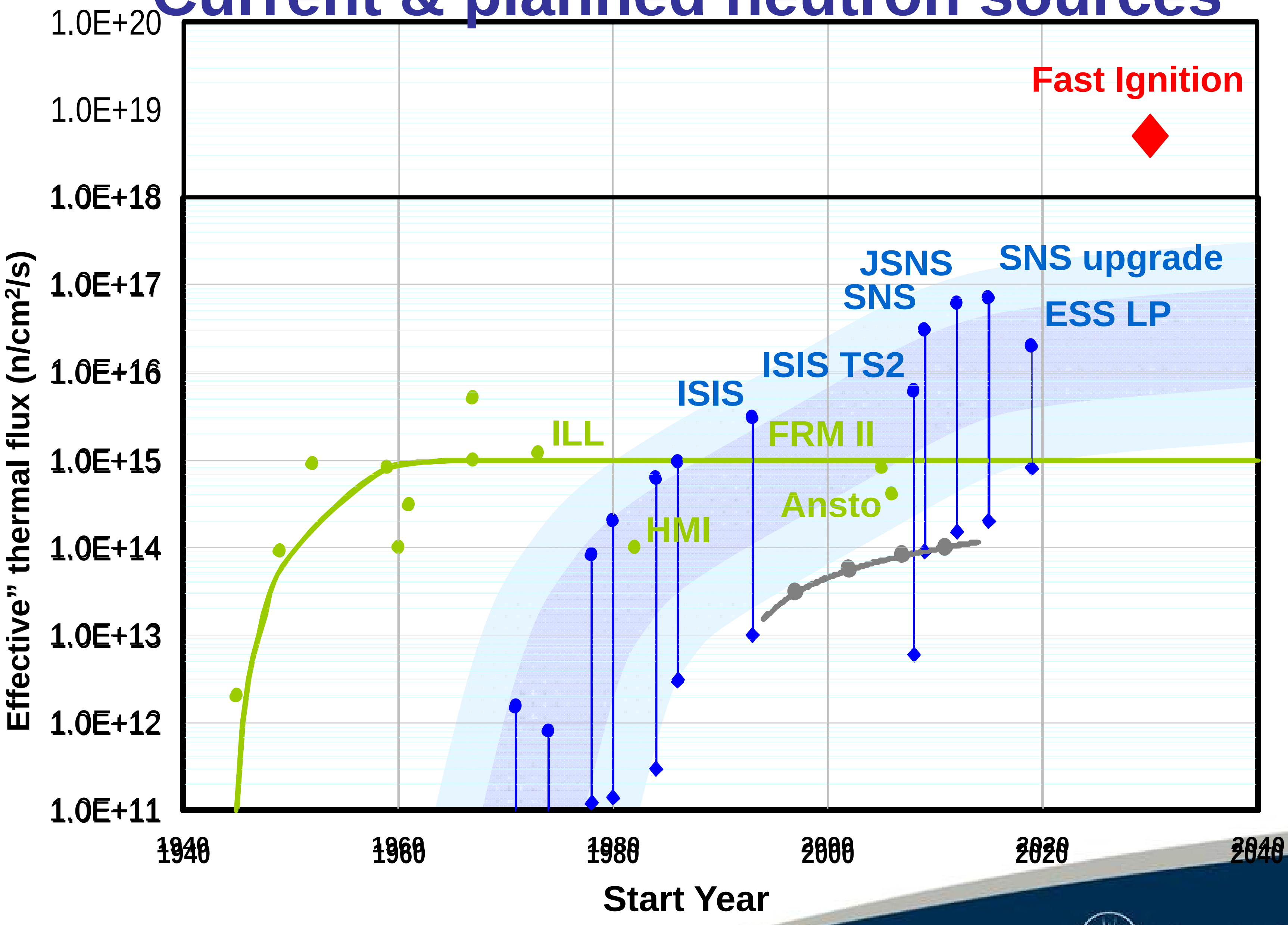
# Fast Ignition Source




**100- 1000 x ISIS**

**Taylor et al SCIENCE, Feb 2007**

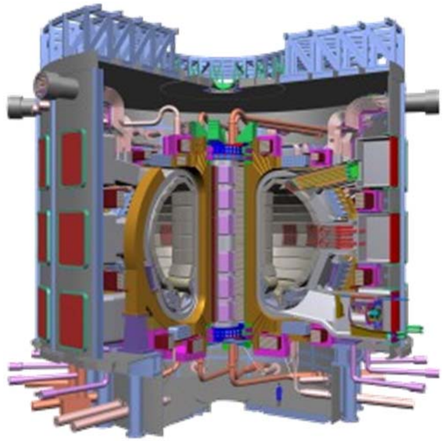
# Current & planned neutron sources




Science & Technology Facilities Council

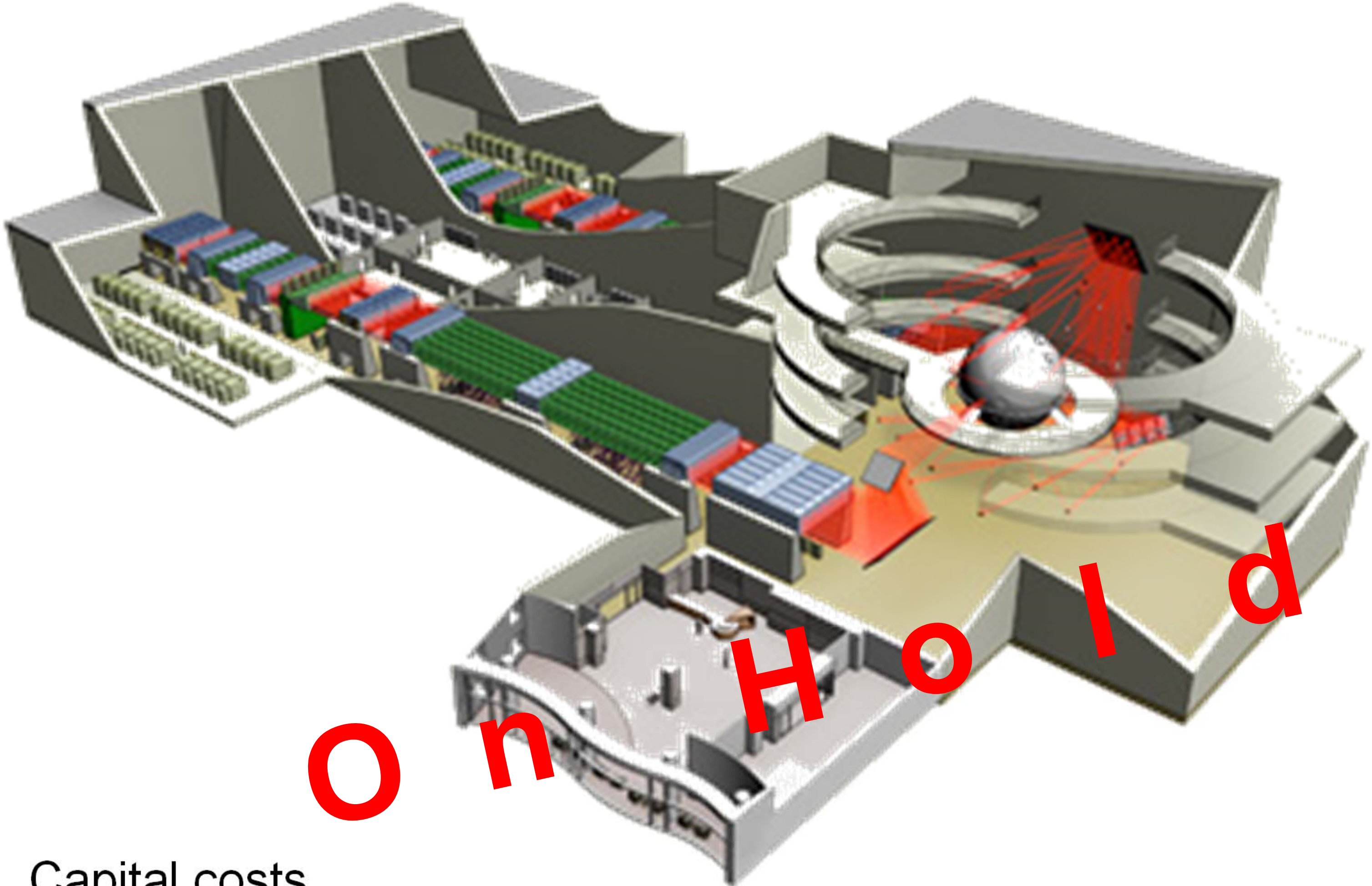
# Serious Engineering Challenges

- 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

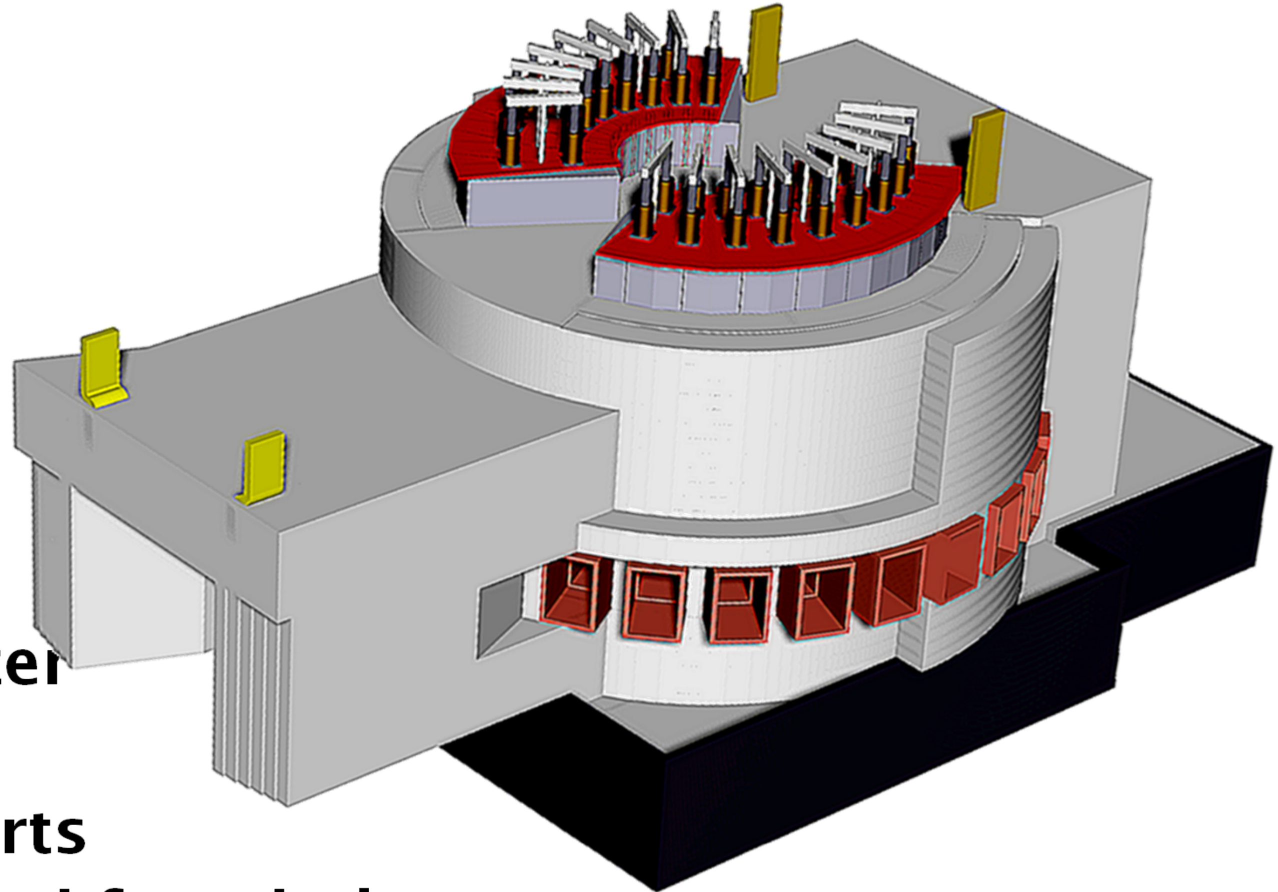



- Capital costs
  - Scales with laser. Fast ignition requires lasers only 10% of the size of normal inertial confinement lasers
  - (£, $, €, … ) 1 – 2 billion

# Compact Neutron Sources

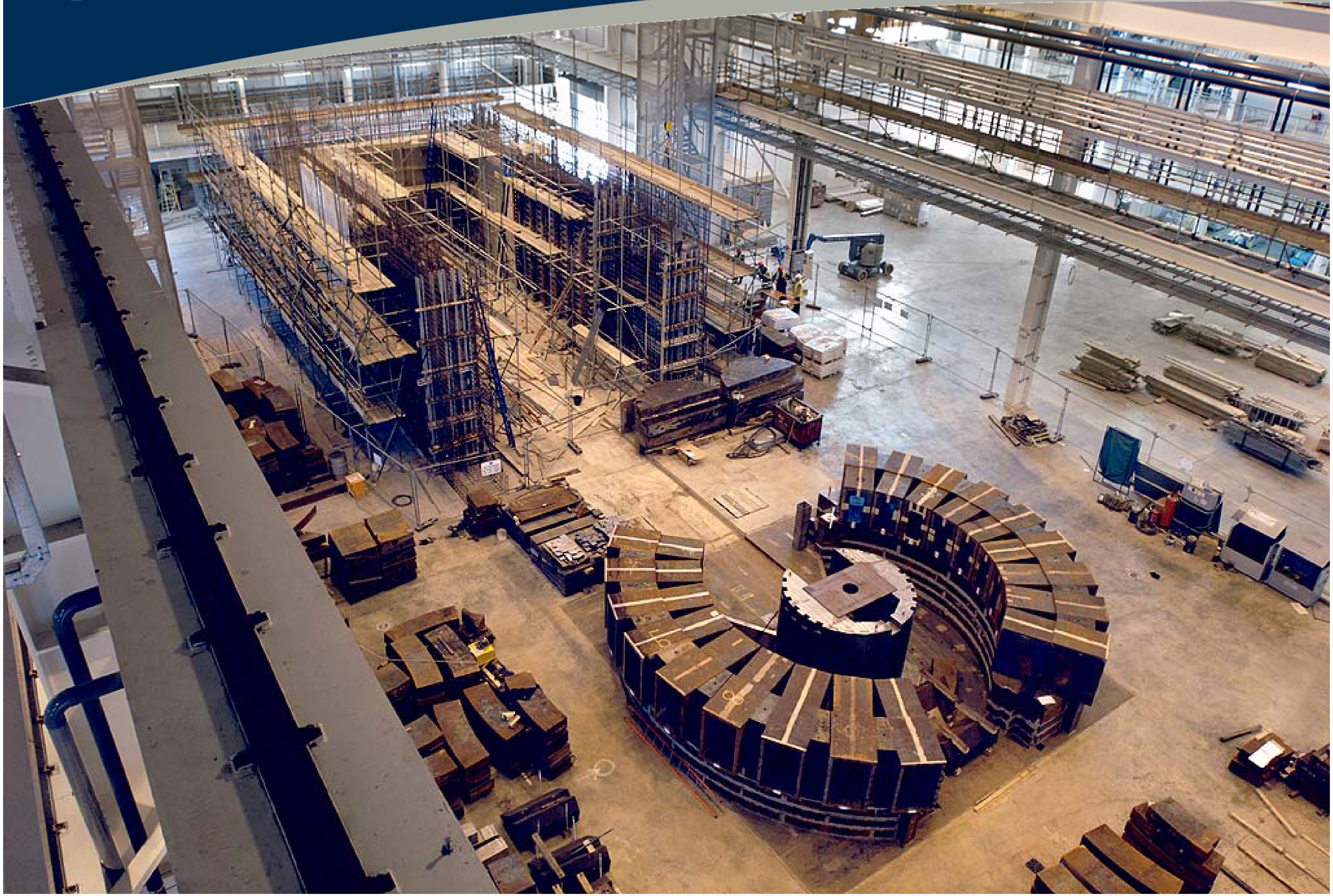
- Spallation Sources
- Shielding a major issue
- (P,n) reactions

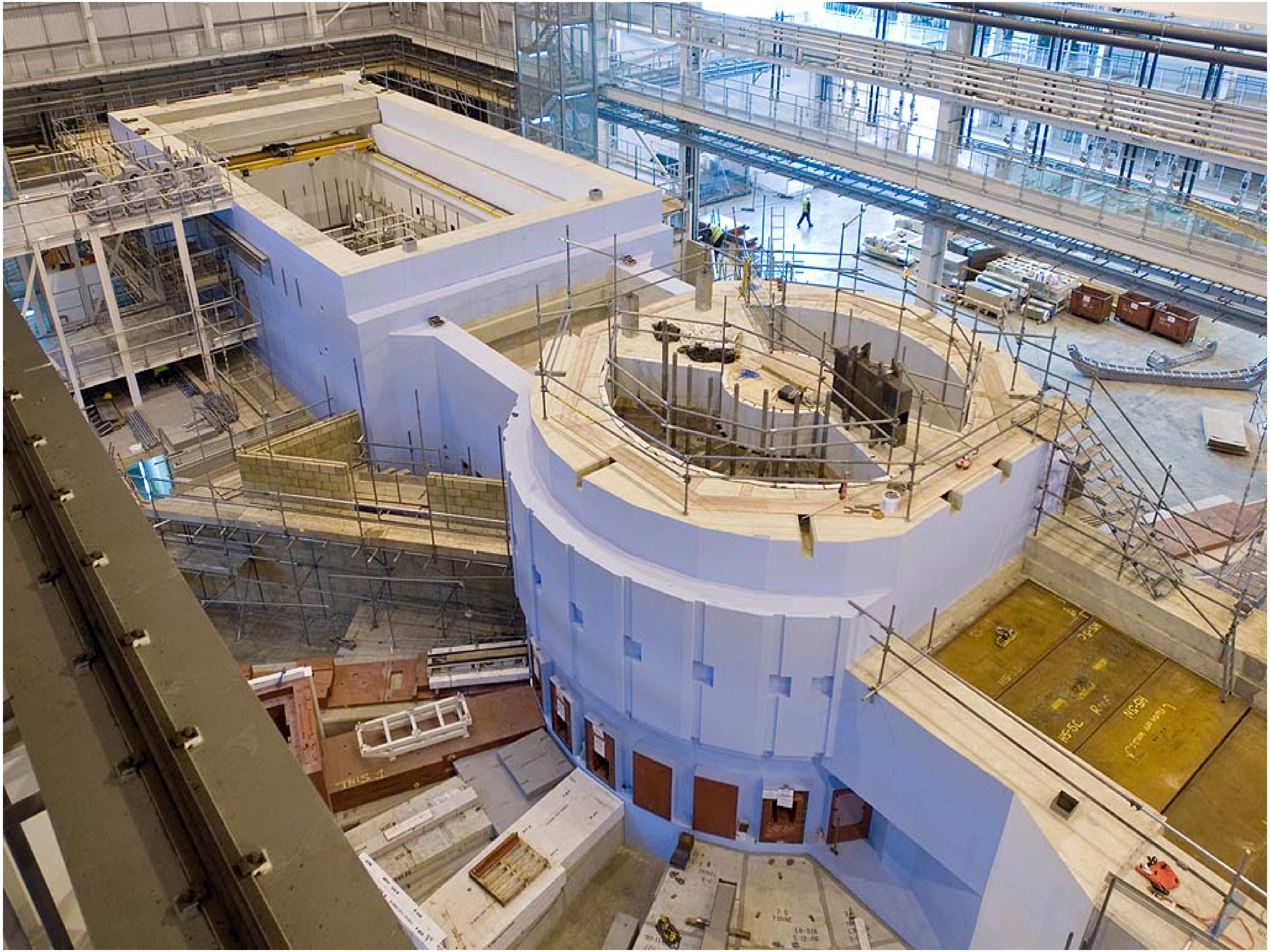
# Target station monolith



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

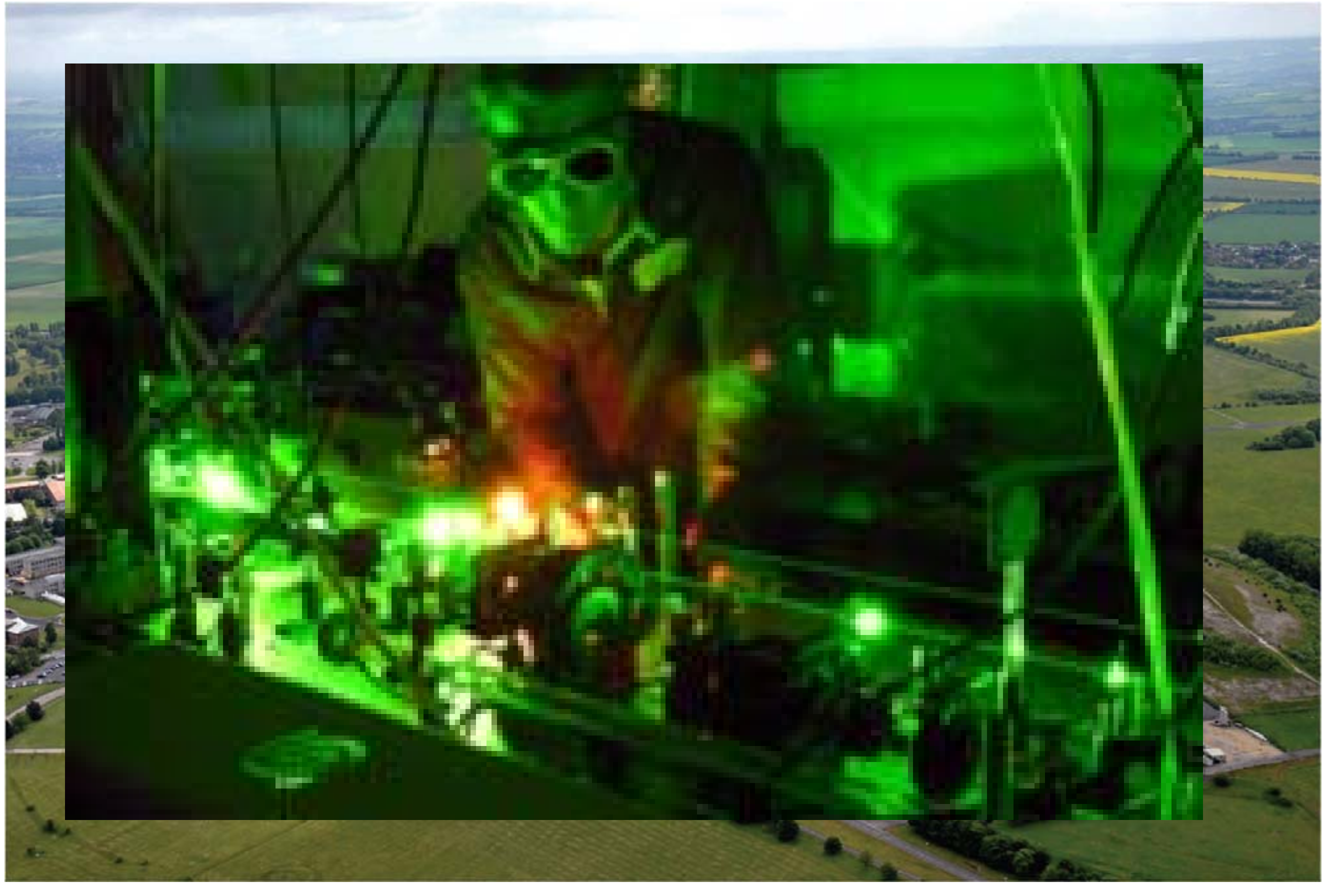
# September 2006





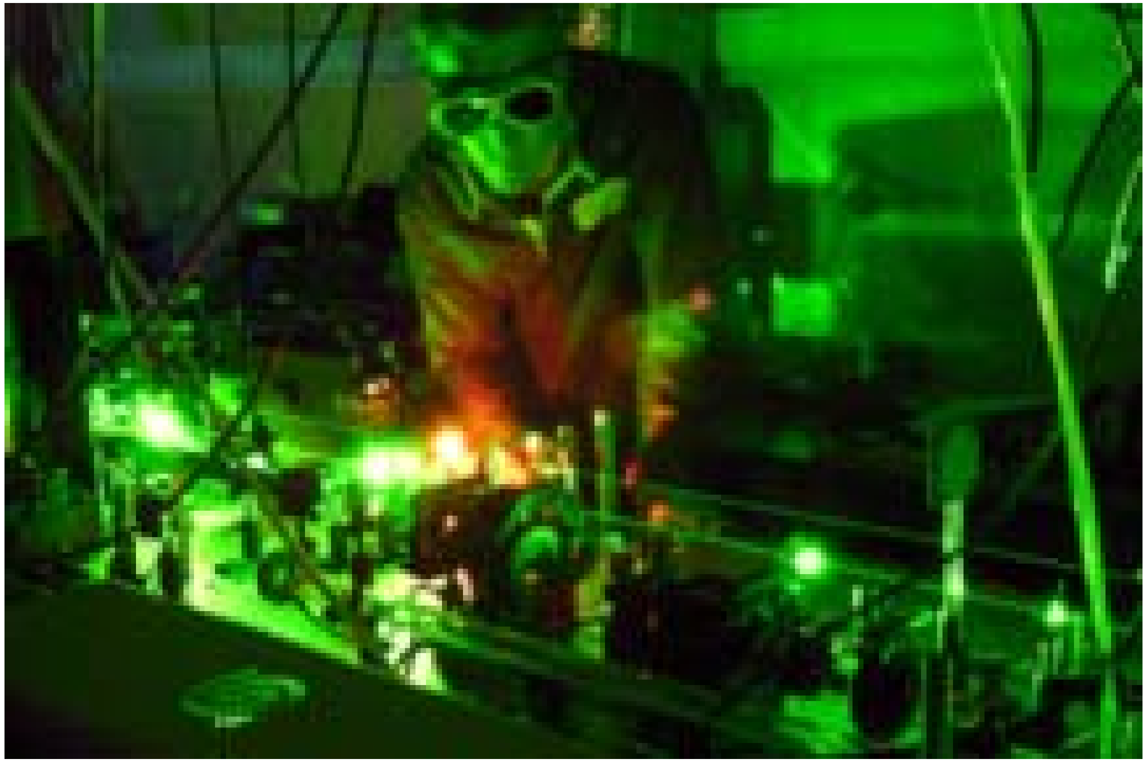
# International Year of Light

International
Year of Light
2015



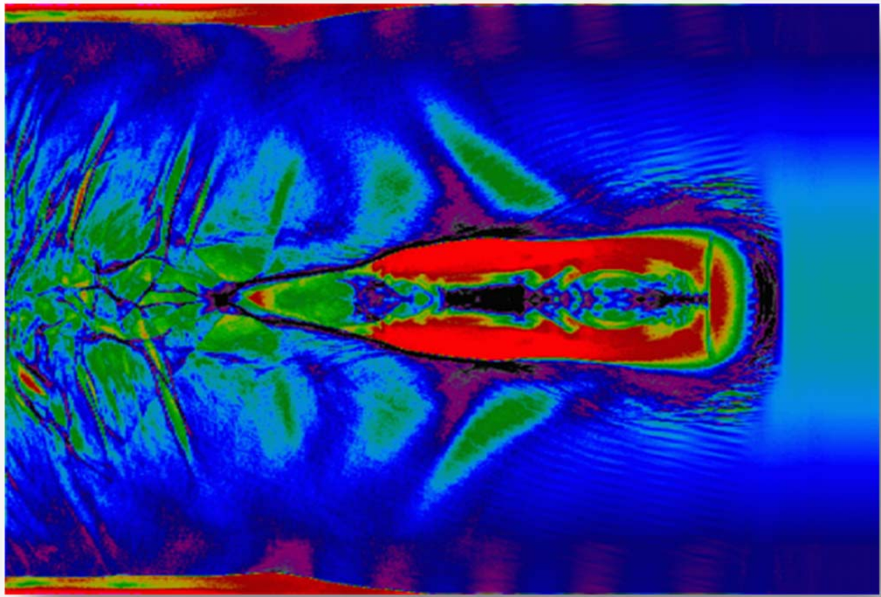
# Diode-Pumped Lasers

International
Year of Light
2015



# Diode-Pumped Lasers

International
Year of Light
2015

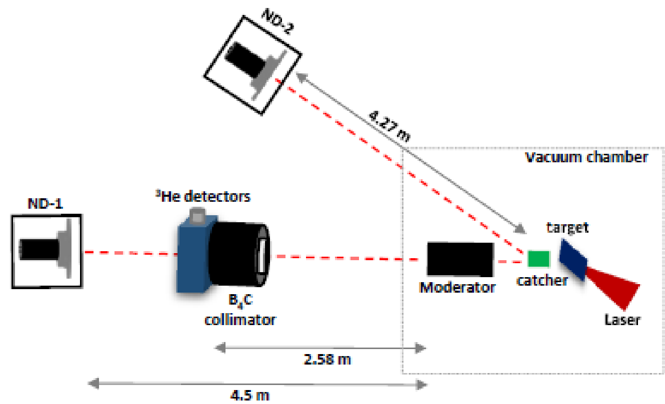


**Wakefield accelerators**

**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)


# 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**