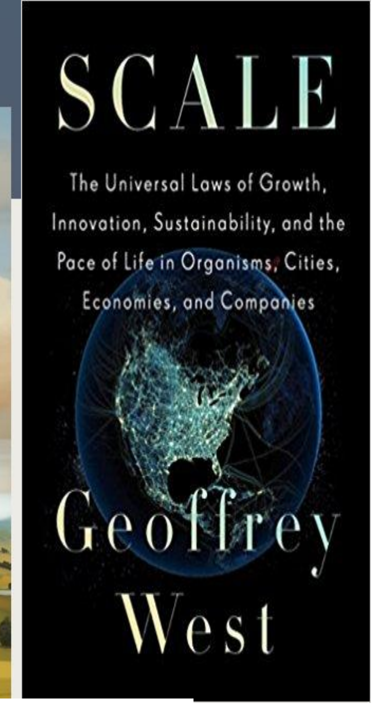
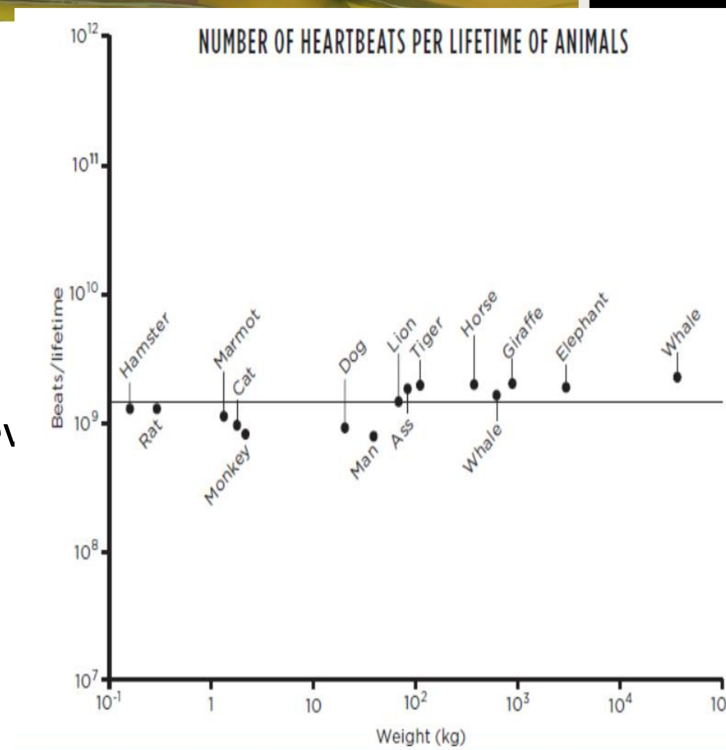


The West Scaling variable!

$$y = \frac{M}{\hbar^2 Q}(\hbar\omega - \hbar\omega_R)$$

Scaling can be applied from nuclear to nearly ev



Instruments for MeV Irradiation from eV to MeV

Roberto Senesi
Università degli Studi di Roma “Tor Vergata”, Dipartimento di Fisica and Centro NAST
CNR- IPCF Sezione di Messina
Associazione School of Neutron Scattering “Francesco Paolo Ricci “
Centro FERMI

Erice School “NEUTRON SCIENCE AND INSTRUMENTATION”: Neutrons for Chemistry and Materials Science Applications
July 4th -13th 2018

Roberto Senesi- Intro

[~]$ whoami

ComputerHope.com

My IP Address, Whoami (Who am I?) - Your Online Information, Browser Headers, DNS, Whois, SSL/TLS, ISP

Your IP address is: **160.80.2.38** and your connection is: **Secure (Encrypted)** More details below ↓

Università di Roma Tor Vergata

-Associate Prof. in Applied Physics, Univ. Roma Tor Vergata

SoNS

-President of SoNS, School of Neutron Scattering Francesco Paolo Ricci (complains here!)

Consiglio Nazionale delle Ricerche

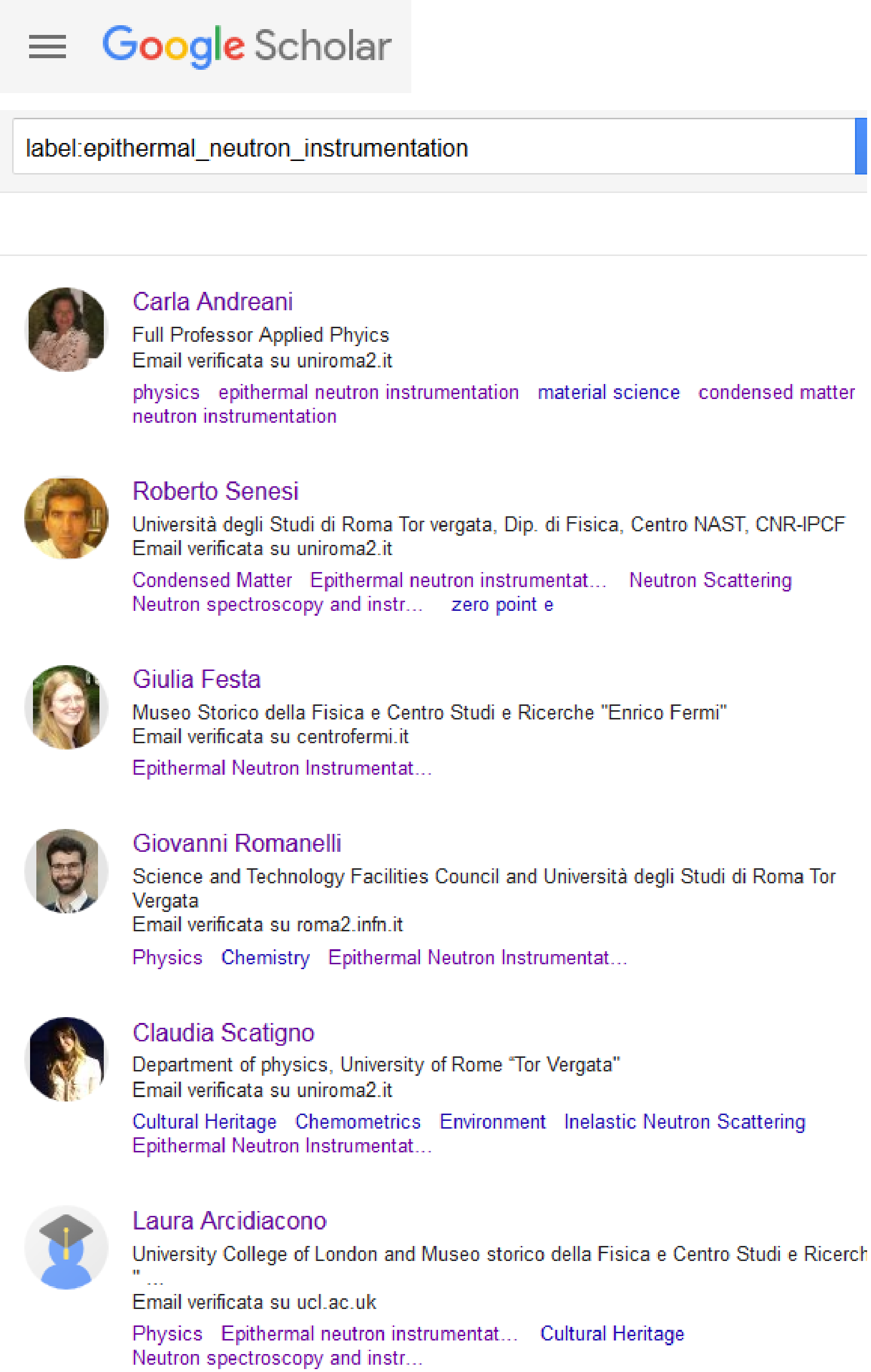
-Associate of Consiglio Nazionale delle Ricerche
 (neutron instrumentation development)

CENTRO FERMI

MUSEO STORICO DELLA FISICA E CENTRO STUDI E RICERCHE ENRICO FERMI

-Associate of Centro Fermi
 (techniques and applications developments)

Roberto Senesi- Intro



Focus on neutron instrumentation using epithermal (and above) neutrons

Applications to condensed matter, cultural heritage, electronics, structural materials, biophysics

Involvment into design, development, construction, implementation of:

-VESUVIO (ISIS)
-ChipIr (ISIS)
-IMAT (ISIS)
-Irradiation Module (ESS)
-VESPA (ESS)

Within the CNR-STFC and CNR-ESS agreements

SoNS **School of Neutron Scattering**

FRANCESCO PAOLO RICCI

2004-Palau: Small Angle (SANS) and Ultra Small Angle (USANS) Scattering
R. Triolo, F. Aliotta

2006-Pula: Structure and Dynamics of Magnetic Systems
P. G. Radaelli, D. Gatteschi

2008-Pula: Near and Intermediate Range Order in Liquids and Soft Matter
M. A. Ricci, M. Zoppi

2010- Frascati: Electron-volt neutron spectroscopy of materials
R. Senesi, C. Vasi

2012- Taormina: Neutron Investigation of Biosystems
C. Andreani, S. Magazù

2014- Erice: Introduction to the theory and techniques of neutron scattering and applications to Cultural Heritage
I. A. Anderson, G. Salvato, A. Scherillo

2015- Erice: ERICE School "NEUTRON SCIENCE AND INSTRUMENTATION": Instruments and devices for neutron scattering experiments
K. H. Andersen, R. Caciuffo

2016- Erice: ERICE School "NEUTRON SCIENCE AND INSTRUMENTATION": Designing and building a neutron instrument
K. H. Andersen, K. W. Herwig

2017- Erice: ERICE School "NEUTRON SCIENCE AND INSTRUMENTATION": Neutron Precession Techniques
P. Falus, K. Habicht

2018- Erice: ERICE School "NEUTRON SCIENCE AND INSTRUMENTATION": Neutrons for Chemistry and Materials Science Applications
P. Henry, T. Ramirez-Cuesta

2016 and 2018- Two courses on "Water and Water Systems"
R. Car, F. Mallamace, L. Petterson

- More than 300 students
- Lecture notes available on website
- multimedia

- From 2014: at the Ettore Majorana Foundation and Centre for Scientific Culture
C. Andreani
R. Caciuffo
R. McGreevy

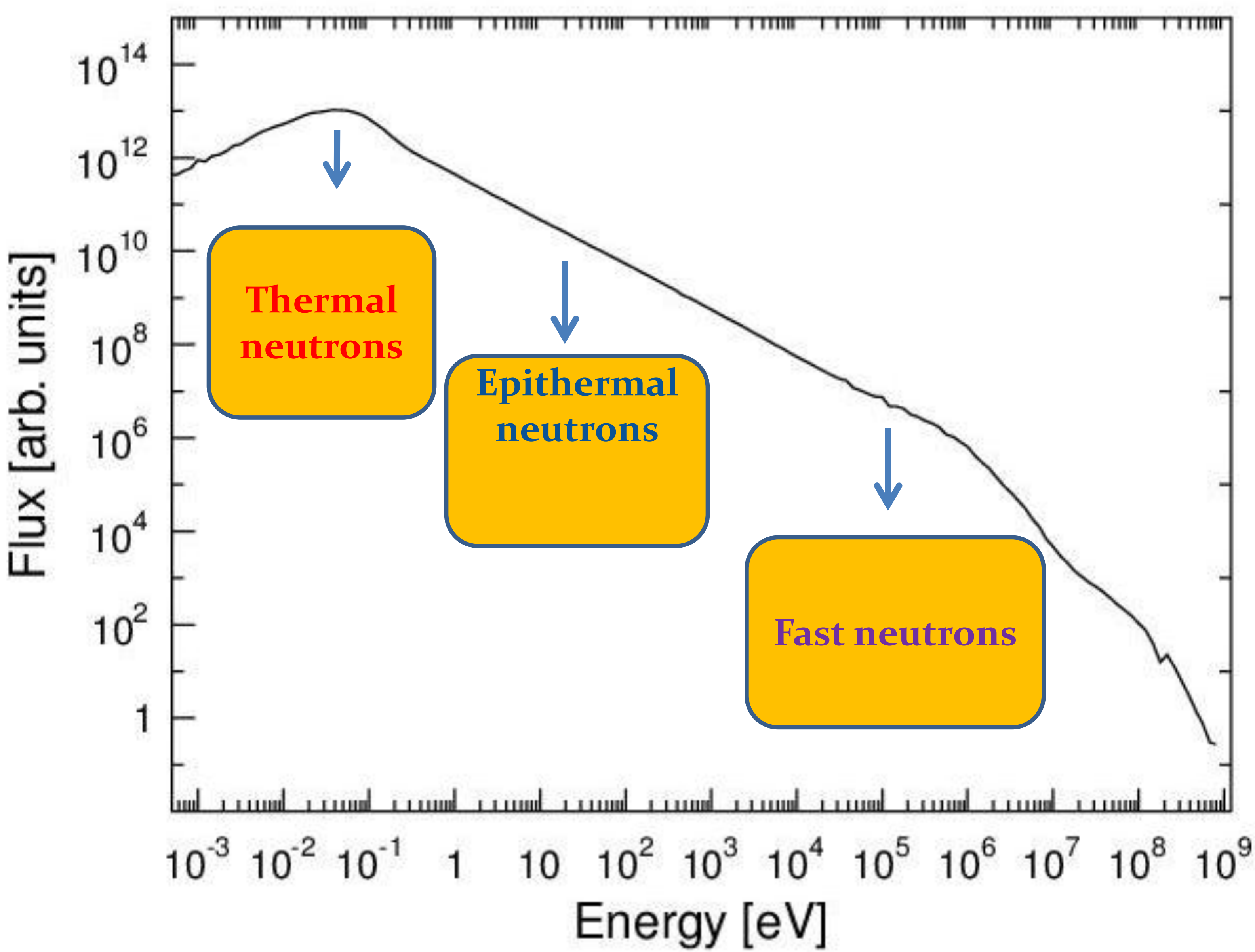
Outline

-MeV neutrons: facilities, in the atmosphere, in space, in extreme conditions

-Neutron instrumentation for radiation damage effects in electronics

-Neutron instrumentation to test neutron displacement damage in materials

Neutron spectrum from a water moderator at a Spallation source: 88% of neutrons have energies above 0.4 eV!

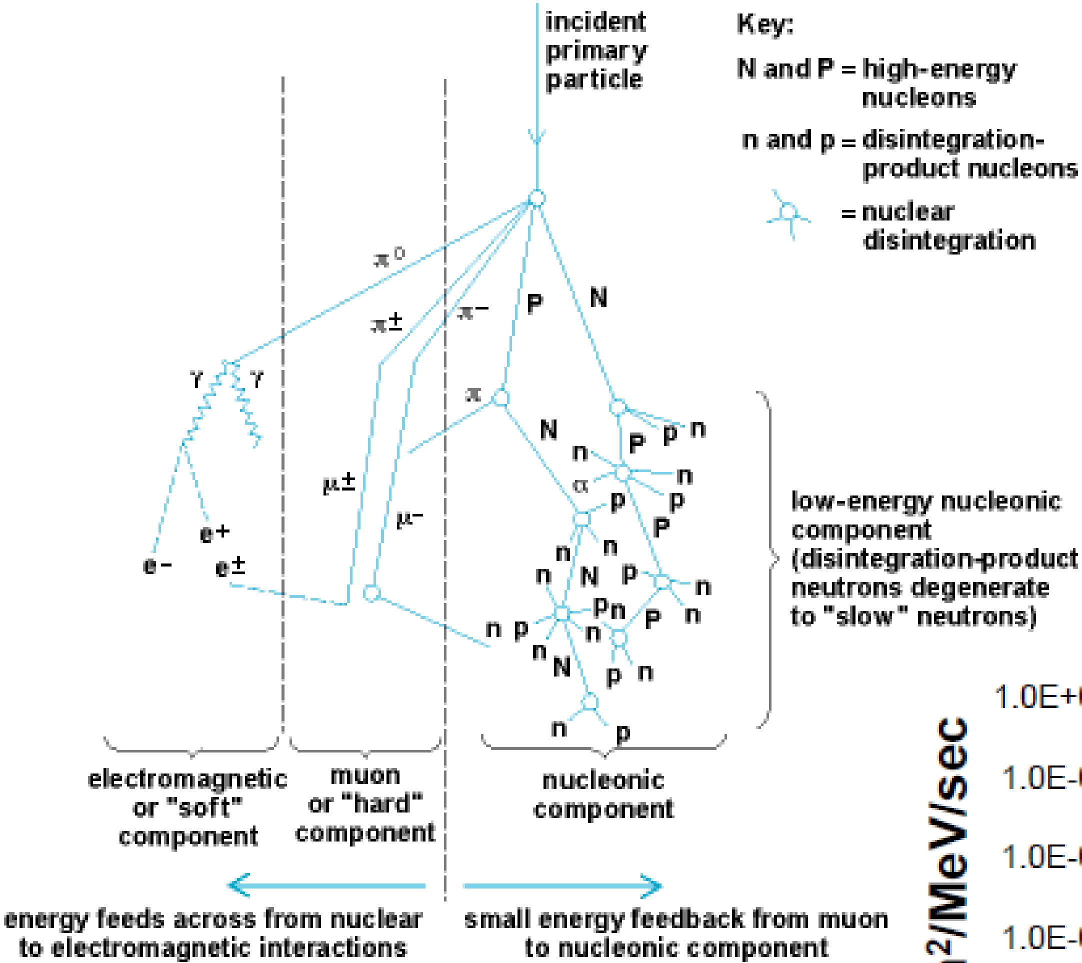


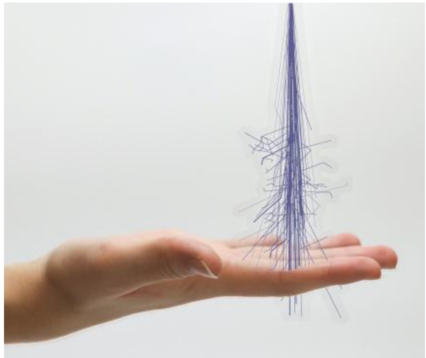
Neutron spectrum from a water moderator
Spallation source: 88% of neutrons have energies above 0.4 eV!

Energy [eV]	Wave length [Å]
0.4	0.45
1	0.29
10	0.09
20	0.06
50	0.04
100	0.03

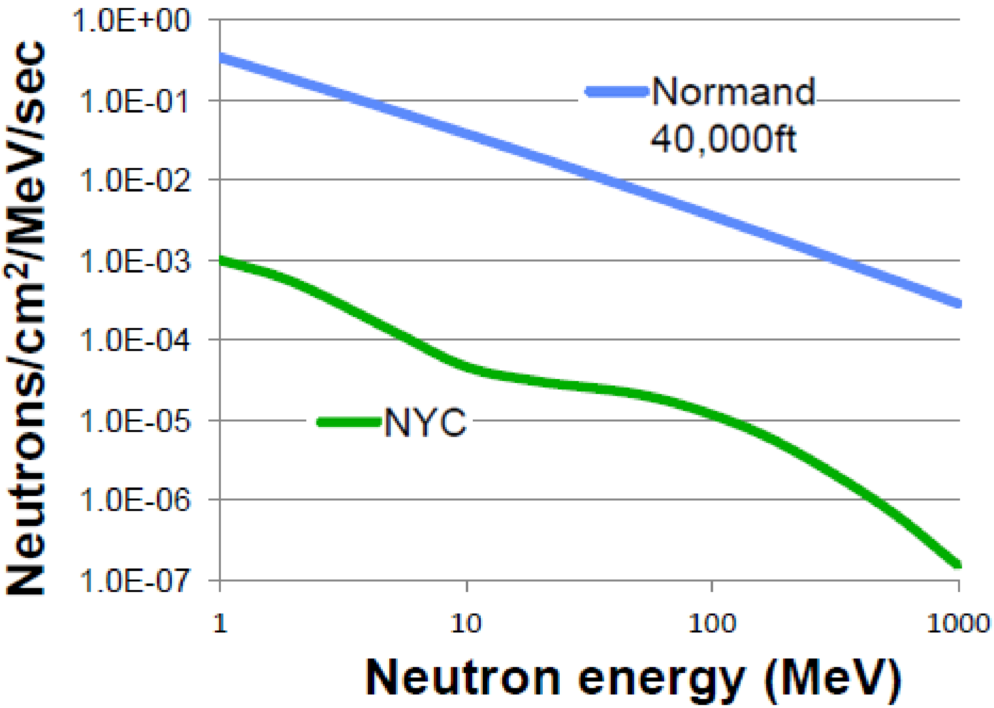
Which energy and length scales can be probed?

Neutrons in the atmosphere from primary cosmic rays

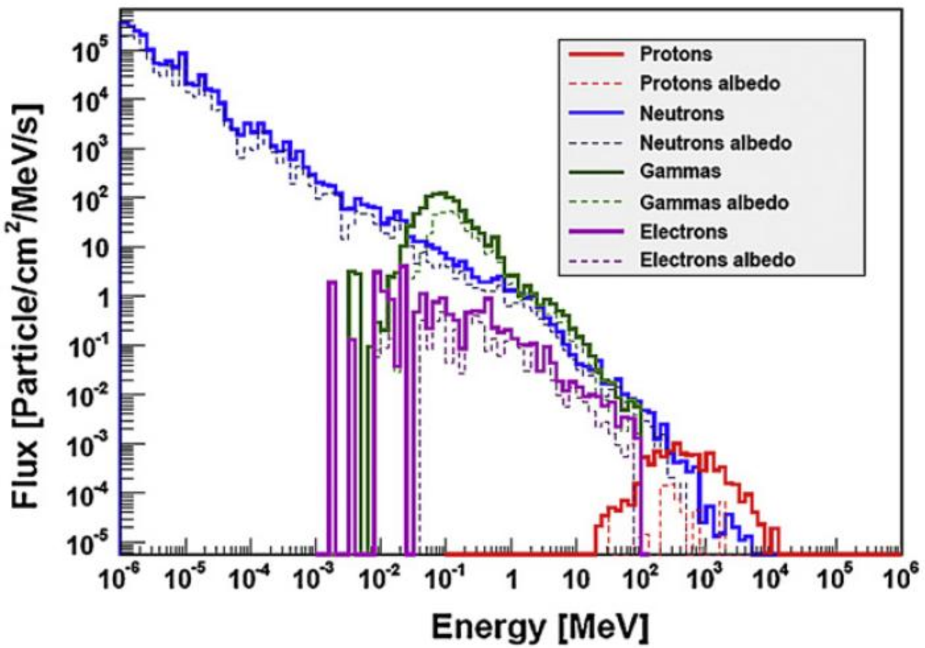




About 3 neutrons from the sky cross our hand in one second



Neutrons in space radiation environment (remember- no freely flying neutrons in space, they last only 14 minutes..)



Viking 1 landing site on Mars, S. McKenna-Lawlor et al. , 2011

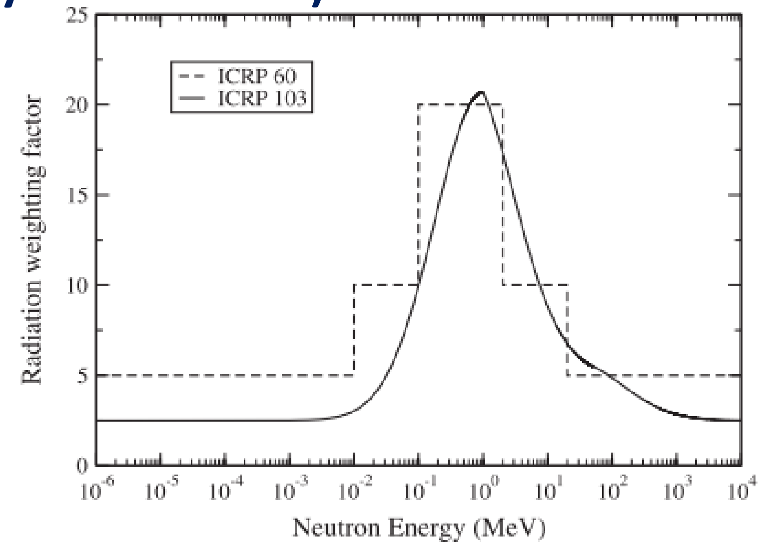
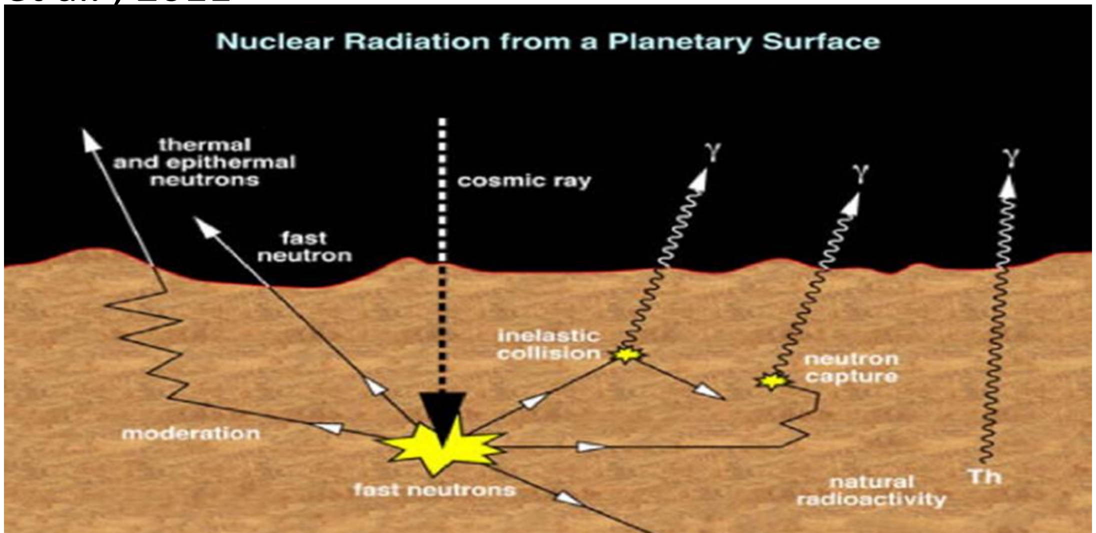
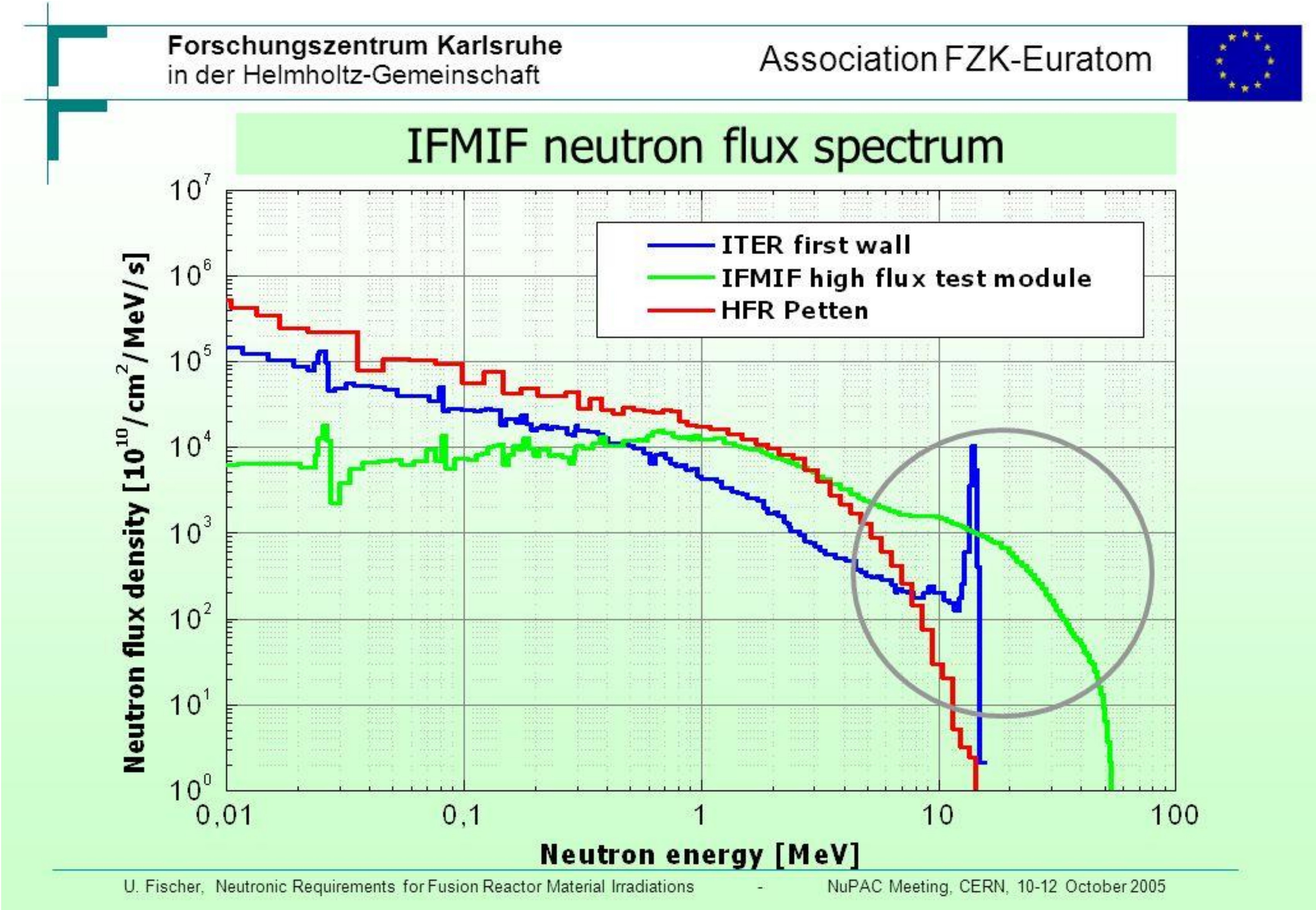


FIG. 2. Radiation weighting factor w_R for neutrons at different energies. The step function is from ICRP60 (1991), and the continuous function is the latest ICRP-103 (2007) recommendation.

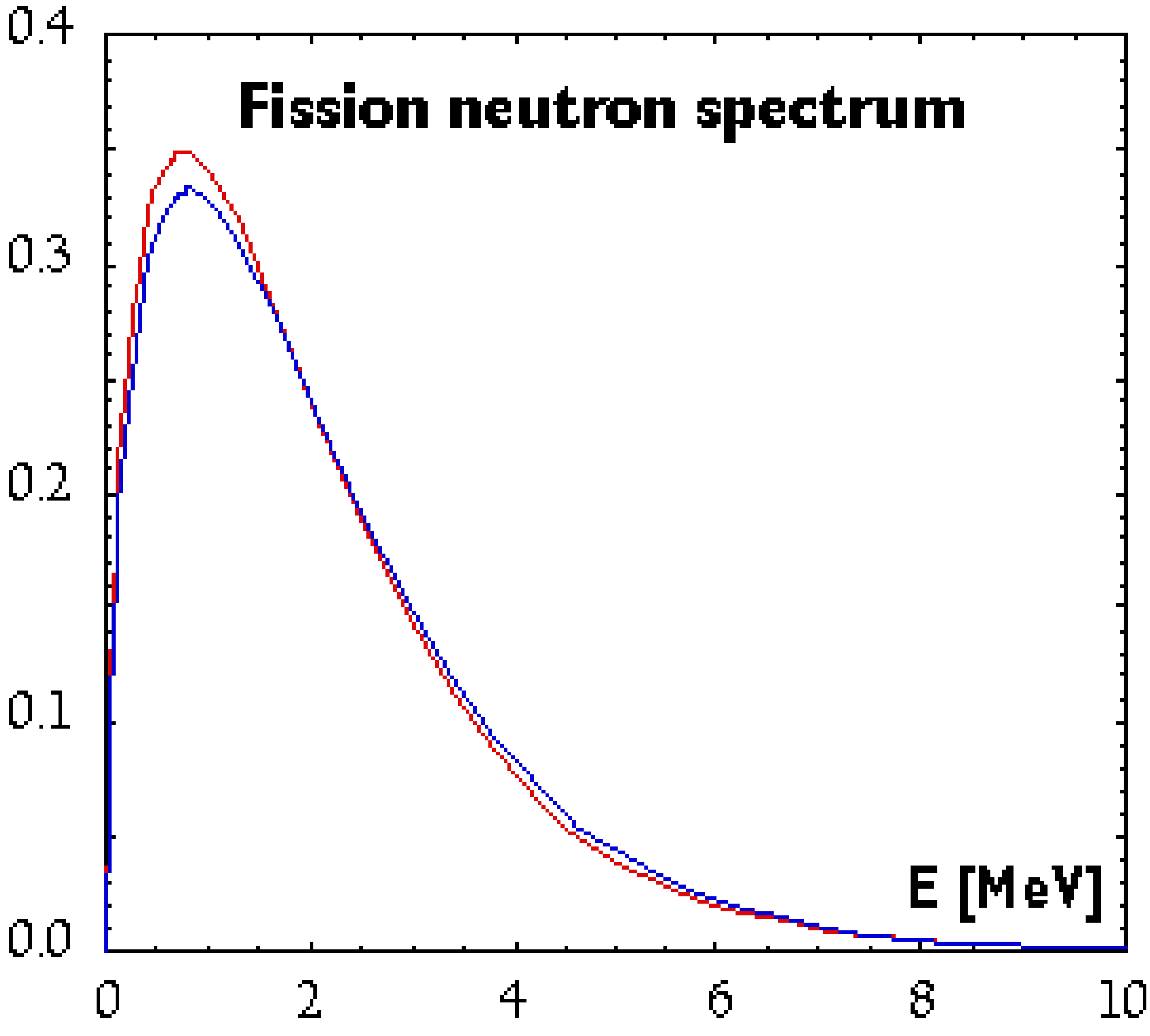
Durante et al, 2011



Neutrons in the fusion reactor environment



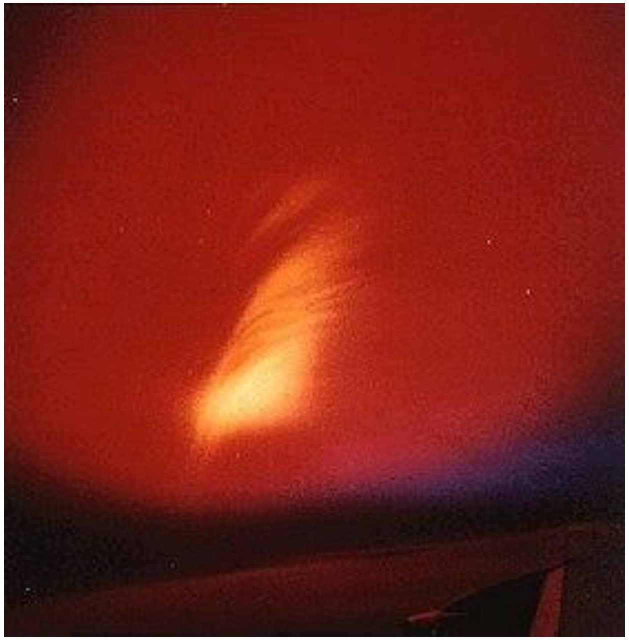
Neutrons in fission reactor environment



Radiation enevironment in extreme conditions- nuclear explosion

Date	July 9, 1962
Test type	Exoatmospheric
Yield	1.4 megatons (6.0 PJ)

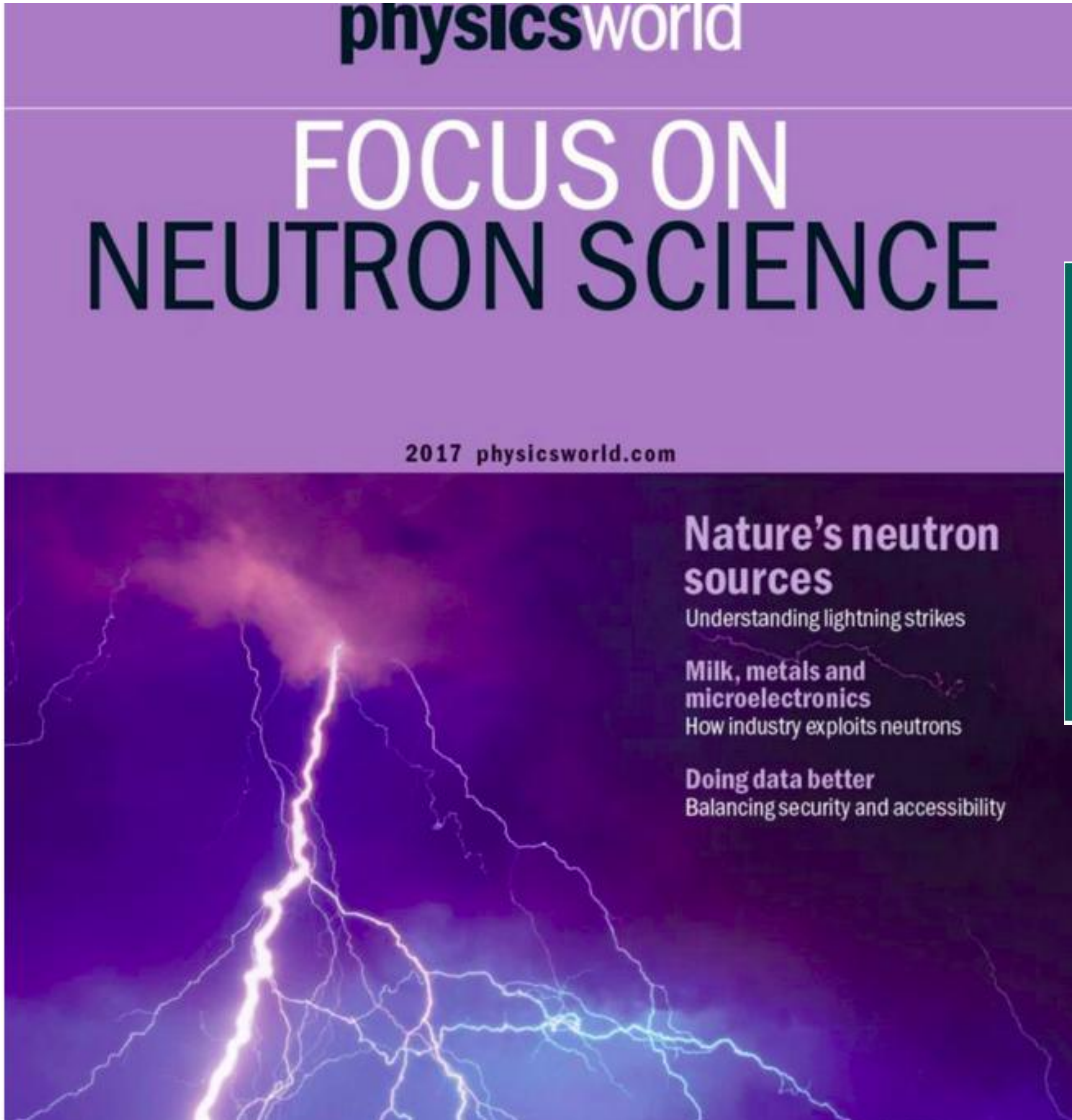
STARSHIP PRIME EXPLOSION

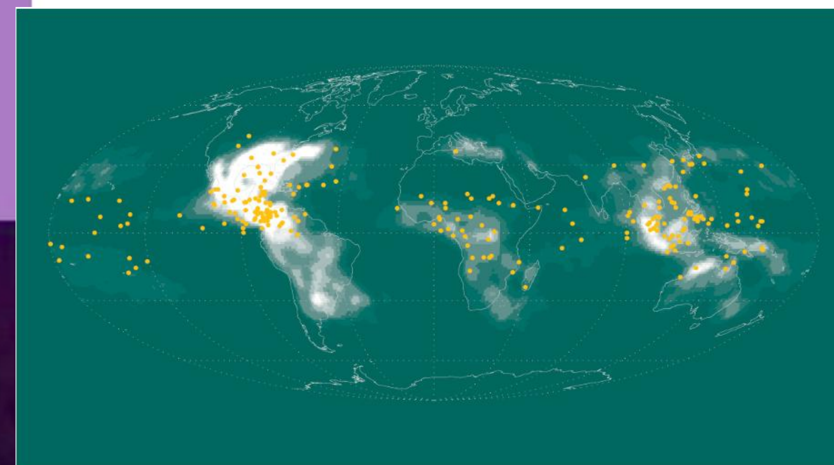


Radiation environment
3 minutes from explosion
From a surveillance airplane

Honolulu-1400 km away

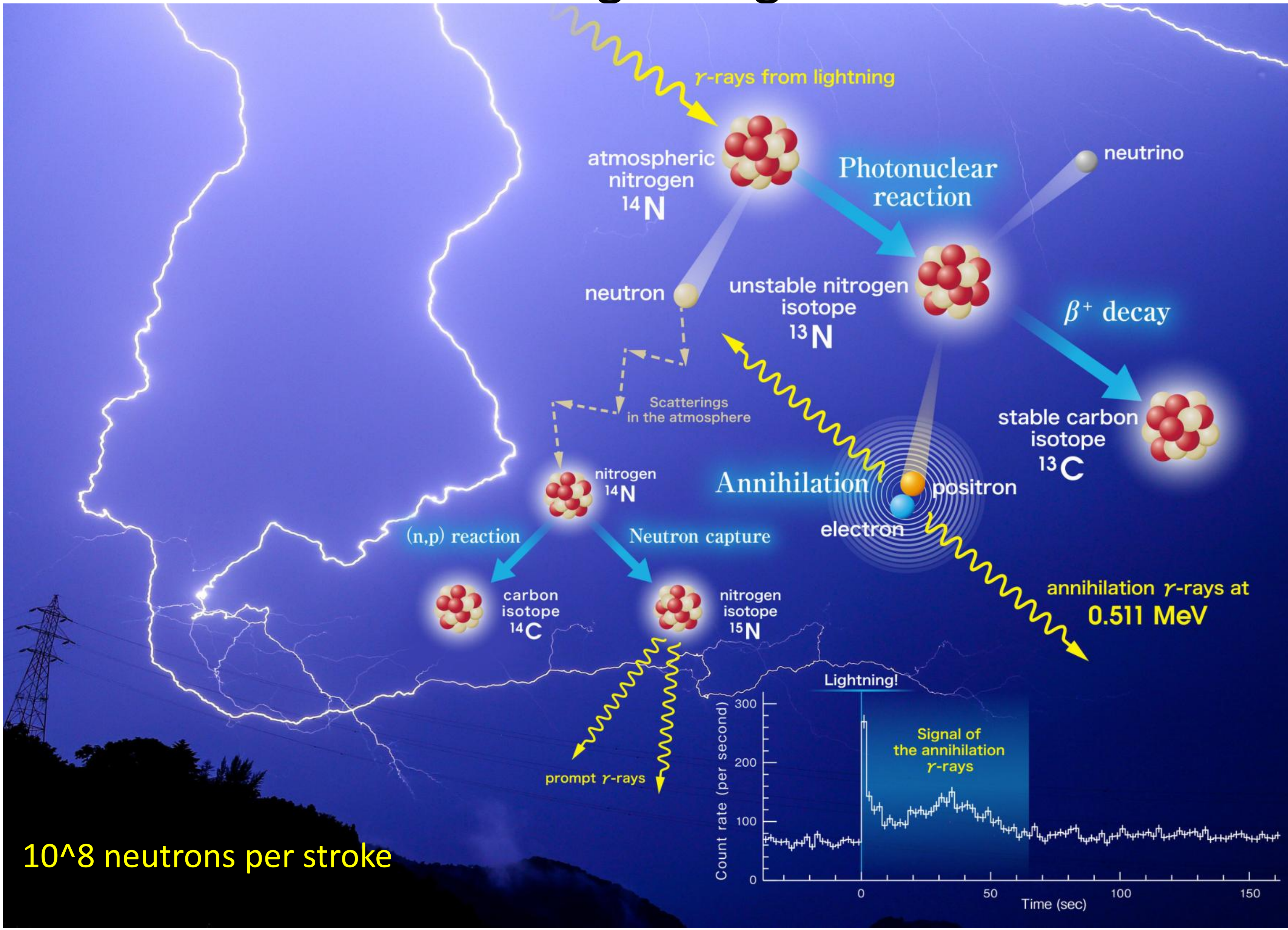
Neutron radiation enevironment in extreme conditions: lightning



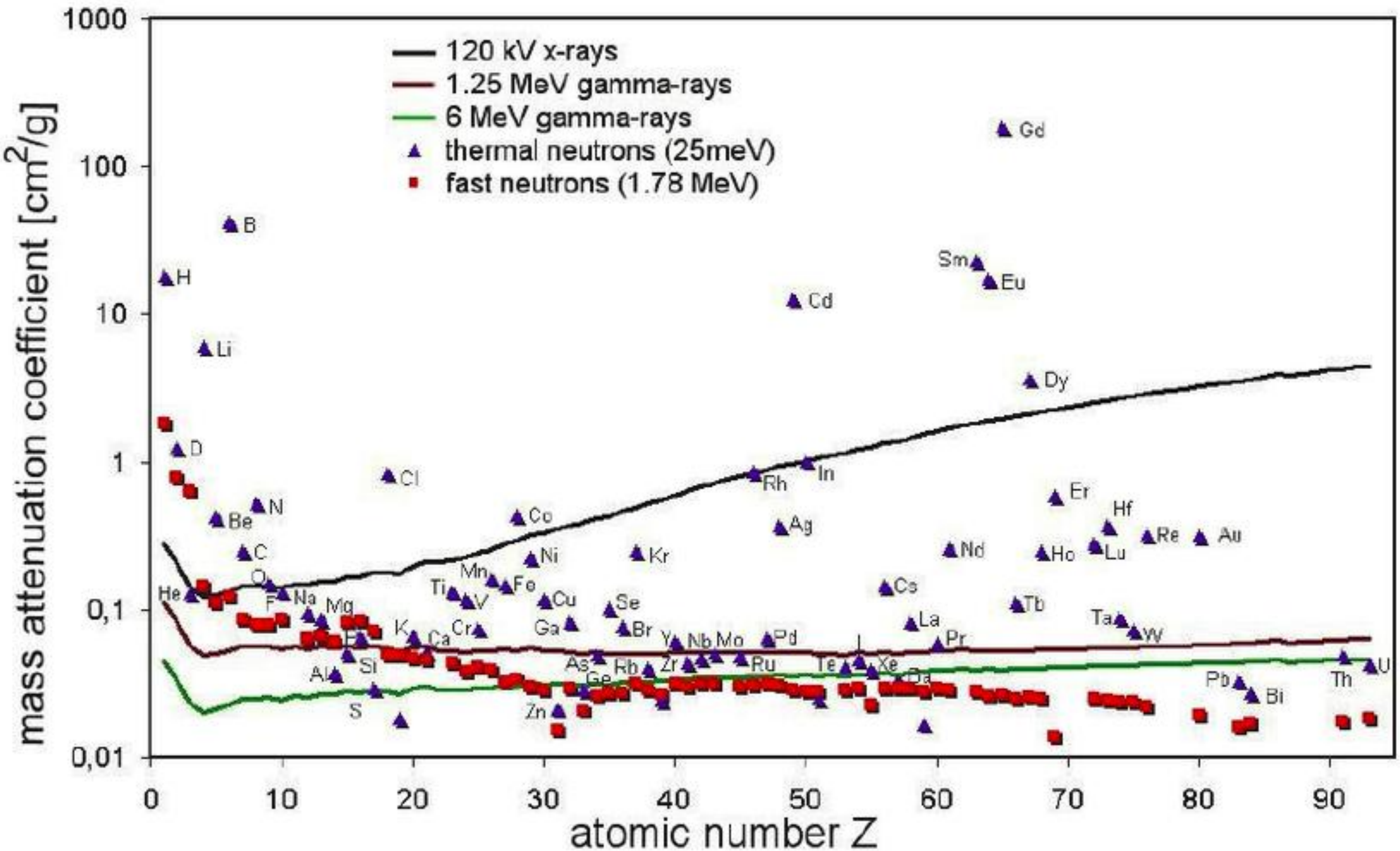


10^8 neutrons per stroke

Neutron radiation enevironment in extreme conditions: lightning

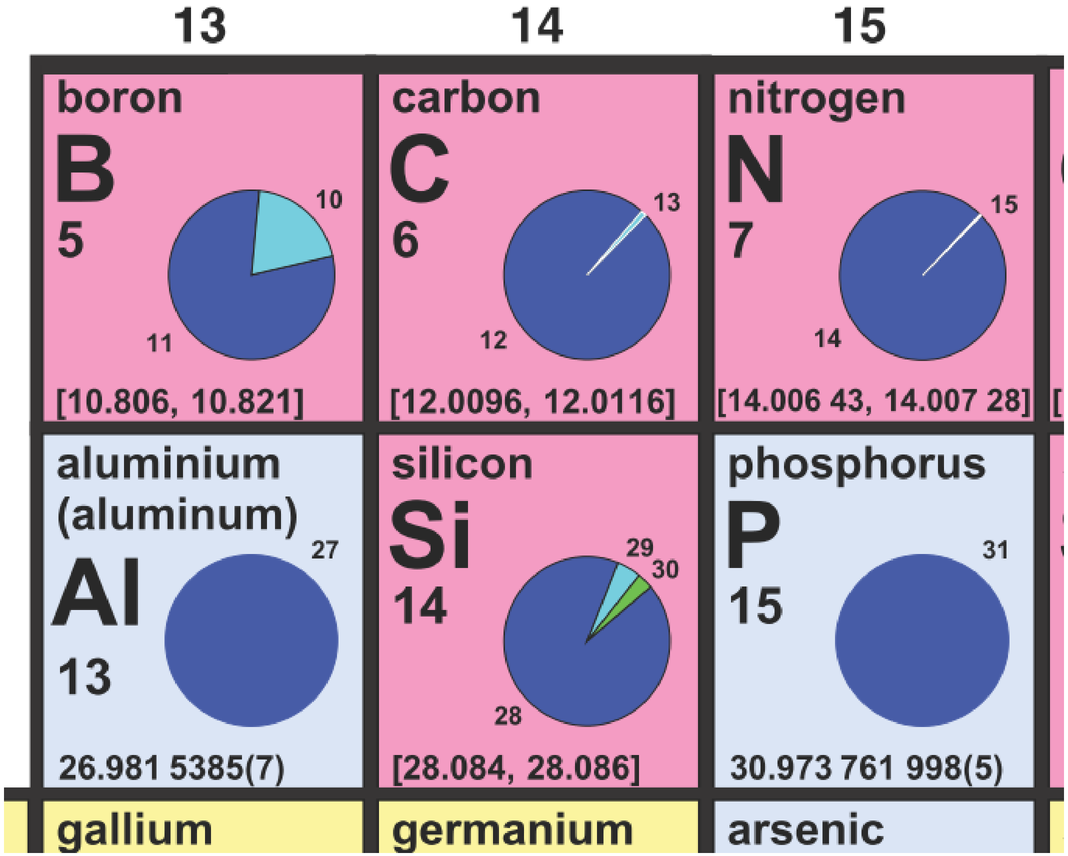


Interaction of MeV neutrons with materials: penetration



MeV neutrons and silicon

Natural silicon atoms are composed of three isotopes, ^{28}Si (abundance: 92.23%), ^{29}Si (abundance: 4.67%) and ^{30}Si (abundance: 3.10%).



~~M~~meV neutrons and silicon - Absorption in 30 silicon, industrially relevant for thermal neutron trasmutation doping

$$^{30}Si + n \rightarrow {}^{31}Si \rightarrow (\beta^-)\,{}^{31}P$$

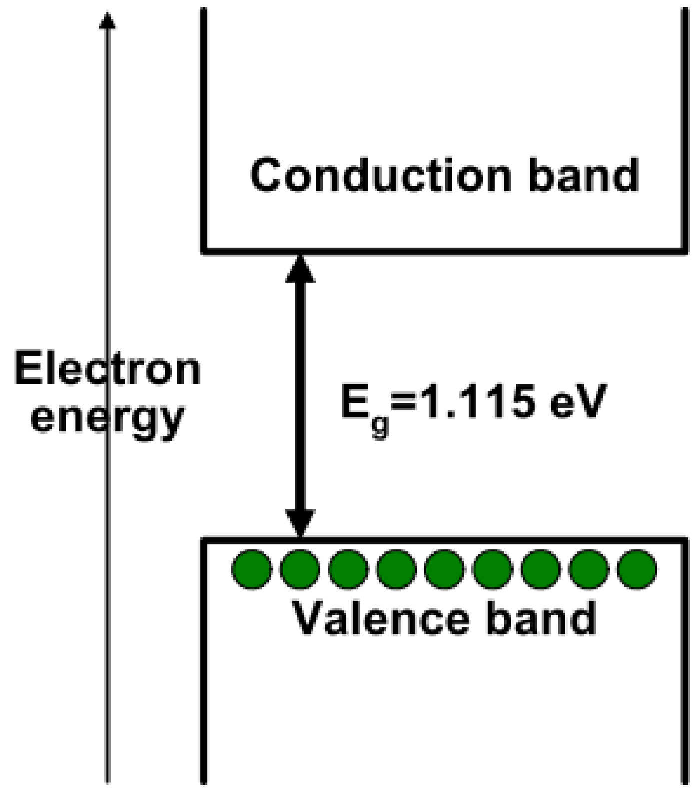
Neutron Trasmutation Doping is defined as the process by which neutron irradiation creates the impurity in an intrinsic or extrinsic semiconductor to increase its value for various uses .

irradiation of Si with thermal neutrons results only in a single nuclear reaction and the short half-life of ^{31}Si of only 2.62 h are parameters of crucial importance with respect to the use of the NTD doping technique on an industrial scale.

Absorption in 30 silicon, industrially relevant for thermal neutron trasmutation doping

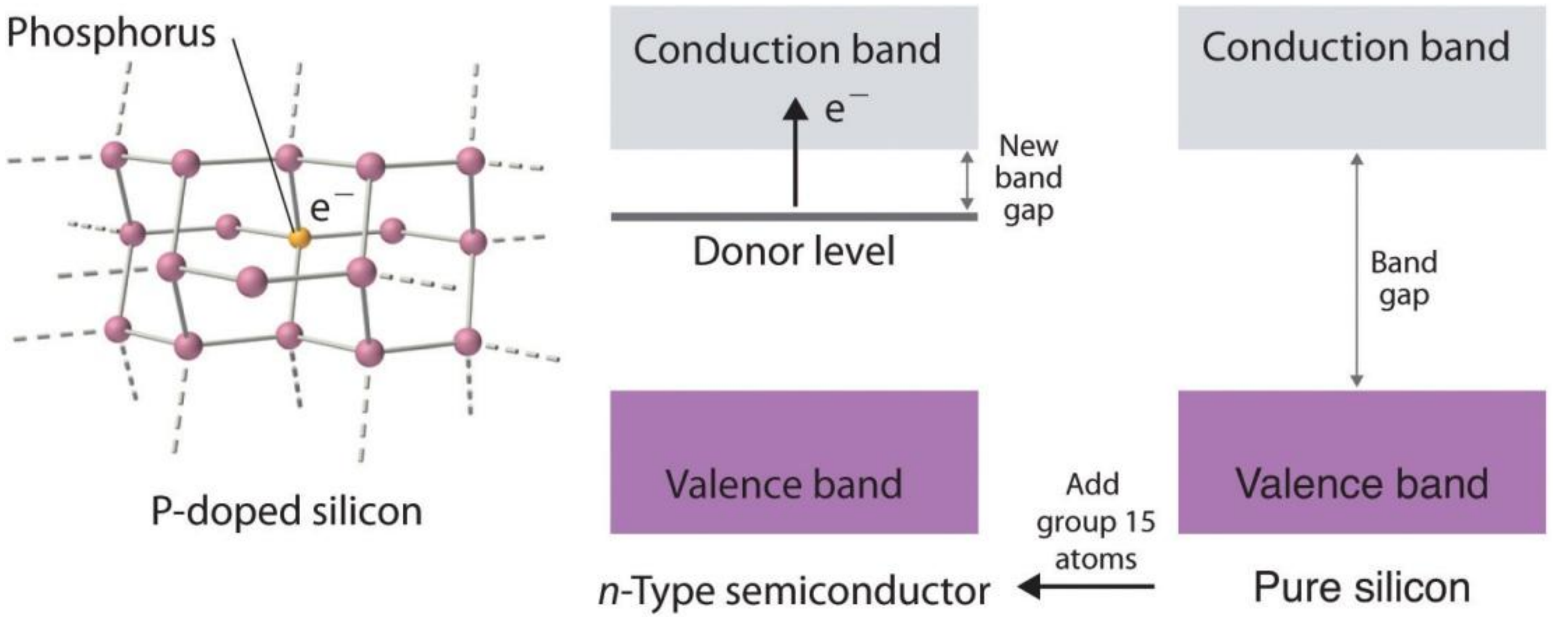
So what?

Electron bands in silicon



Absorption in 30 silicon, industrially relevant for thermal neutron trasmutation doping

Electron bands in silicon doped with phosphorous: many more electrons ready to enhance conductivity! High power electronics!

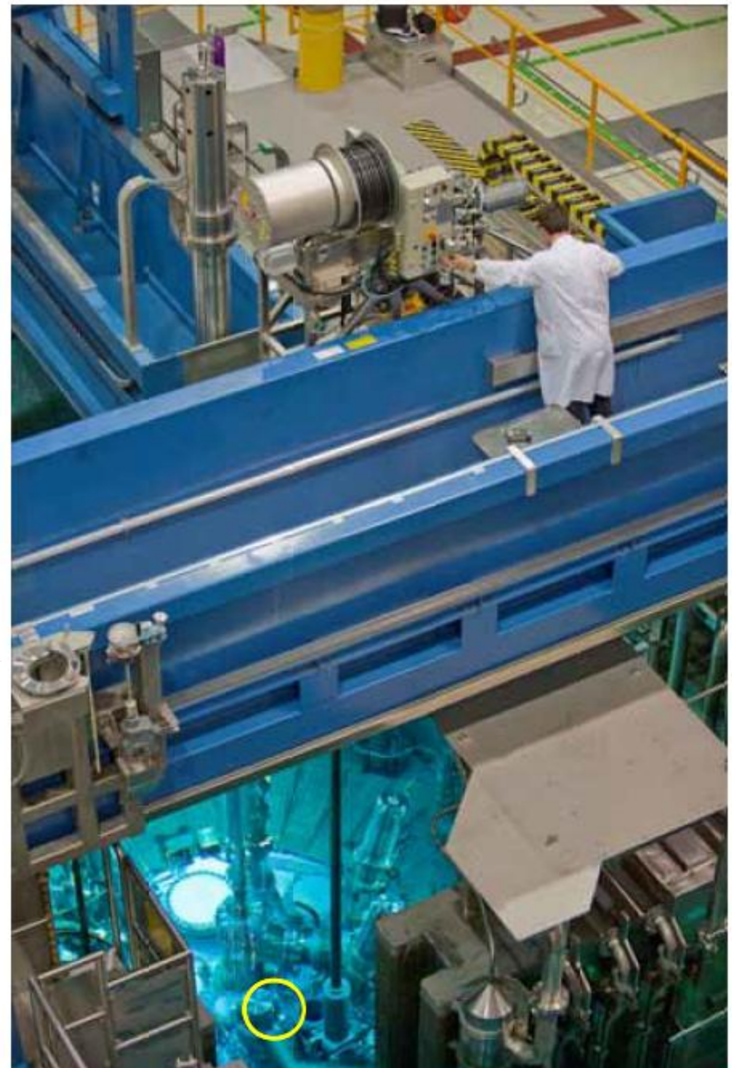


Absorption in 30 silicon, industrially relevant for thermal neutron trasmutation doping

The demand for high power semiconductors increases rapidly according to the rapid increase of alternative and much wider use of ‘green energy’ technologies.

Absorption in 30 silicon, industrially relevant for thermal neutron trasmutation doping

Where and how?



(Ingot Etching) → (Initial Resistivity Measurement) → (Ship to a Reactor) → (Storage under suitable conditions e.g. no contact with stainless steel from storage racks) → (Neutron Irradiation and Decay of Induced Radioactivity) → (Cleaning and Residual Radioactivity Measurements) → (Ship Back) → (Heat Treatment) → (Resistivity Measurement) → (Feedback of Measured Resistivity to the Reactor).

Research Neutron Source Heinz Maier-Leibnitz (FRM II)
Technical University of Munich

- Home
- About us +
- The Neutron Source +
- Research
- **Industry & Medicine** –
- Radioisotope production +
- **Silicon doping**
- Analysis with neutrons
- Non-destructive testing and material development

Home › Industry & Medicine › Silicon doping

Silicon doping

The silicon doping system (SDA) is the only purely commercial production facility at the FRM II. It is used for the doping of high purity silicon that is instrumental in the semiconductor industry, for example for high- power electronics such as long-range DC power transmission, or in the automotive industry.

Silicon mono crystal for the semiconductor industry. (Photo: Siltronic)

Pure silicon is a very poor conductor of electricity. However, it is industrially viable for semiconductors when it contains a small amount of impurities (such as phosphorus). The introduction of these impurities is called doping. At the research neutron source, doping is achieved using neutrons. The silicon crystal is placed in the irradiation position and subjected to a well-defined thermal

Interaction of MeV neutrons with materials

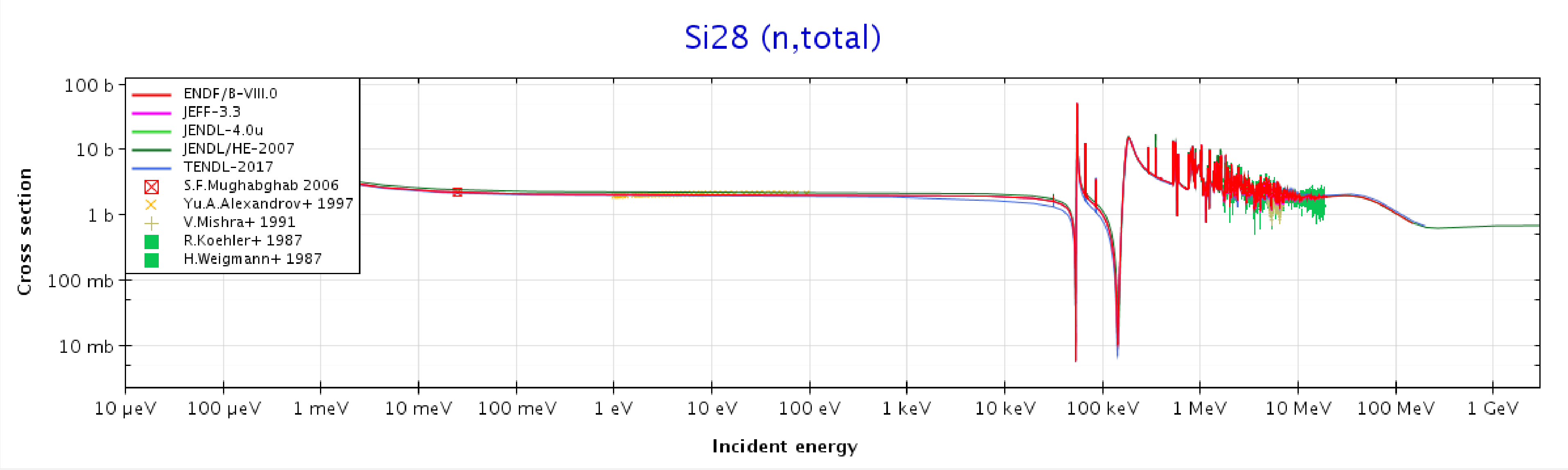
$$
\begin{aligned}
n + {}^{28}Si &\rightarrow p + {}^{28}Al \longrightarrow 1 \\
&\rightarrow n + \alpha + {}^{24}Mg \longrightarrow 2 \\
&\rightarrow n + p + {}^{27}Al \longrightarrow 3 \\
&\rightarrow \alpha + {}^{25}Mg \longrightarrow 4 \\
&\rightarrow {}^{3}He + {}^{26}Mg \longrightarrow 5 \\
&\rightarrow 2\alpha + {}^{21}Ne \longrightarrow 6 \\
&\rightarrow \gamma + {}^{29}Si \longrightarrow 7 \\
&\rightarrow etc.
\end{aligned}
$$

Information Technology relevant materials

Production of directly ionizing particles

Interaction of MeV neutrons with materials

$$
\begin{aligned}
n + {}^{28}Si &\rightarrow p + {}^{28}Al \longrightarrow 1 \\
&\rightarrow n + \alpha + {}^{24}Mg \longrightarrow 2 \\
&\rightarrow n + p + {}^{27}Al \longrightarrow 3 \\
&\rightarrow \alpha + {}^{25}Mg \longrightarrow 4 \\
&\rightarrow {}^{3}He + {}^{26}Mg \longrightarrow 5 \\
&\rightarrow 2\alpha + {}^{21}Ne \longrightarrow 6 \\
&\rightarrow \gamma + {}^{29}Si \longrightarrow 7 \\
&\rightarrow etc
\end{aligned}
$$



A problem has been detected and windows has been shut down to prevent damage to your computer.

The problem seems to be caused by the following file: SPCMDCON.SYS

PAGE_FAULT_IN_NONPAGED_AREA

If this is the first time you've seen this Stop error screen, restart your computer. If this screen appears again, follow these steps:

Check to make sure any new hardware or software is properly installed. If this is a new installation, ask your hardware or software manufacturer for any windows updates you might need.

If problems continue, disable or remove any newly installed hardware or software. Disable BIOS memory options such as caching or shadowing. If you need to use Safe Mode to remove or disable components, restart your computer, press F8 to select Advanced Startup Options, and then select Safe Mode.

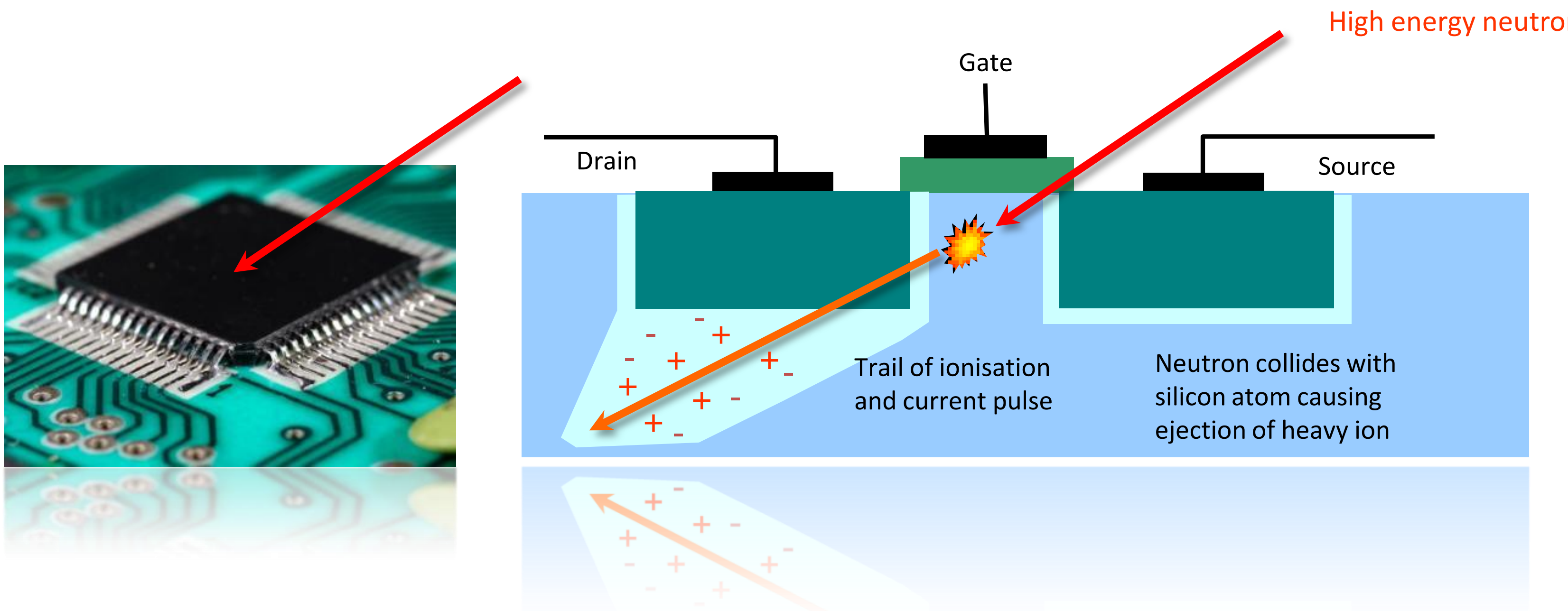
Technical information:

*** STOP: 0x00000050 (0xFD3094C2,0x00000001,0xFBFE7617,0x00000000)

*** SPCMDCON.SYS - Address FBFE7617 base at FBFE5000, DateStamp 3d6dd67c

Single Event Effects

A Single Event Effect (SEE) is when a highly energetic particle (neutron), present in the environment, strikes sensitive regions of an electronic device disrupting its correct operation

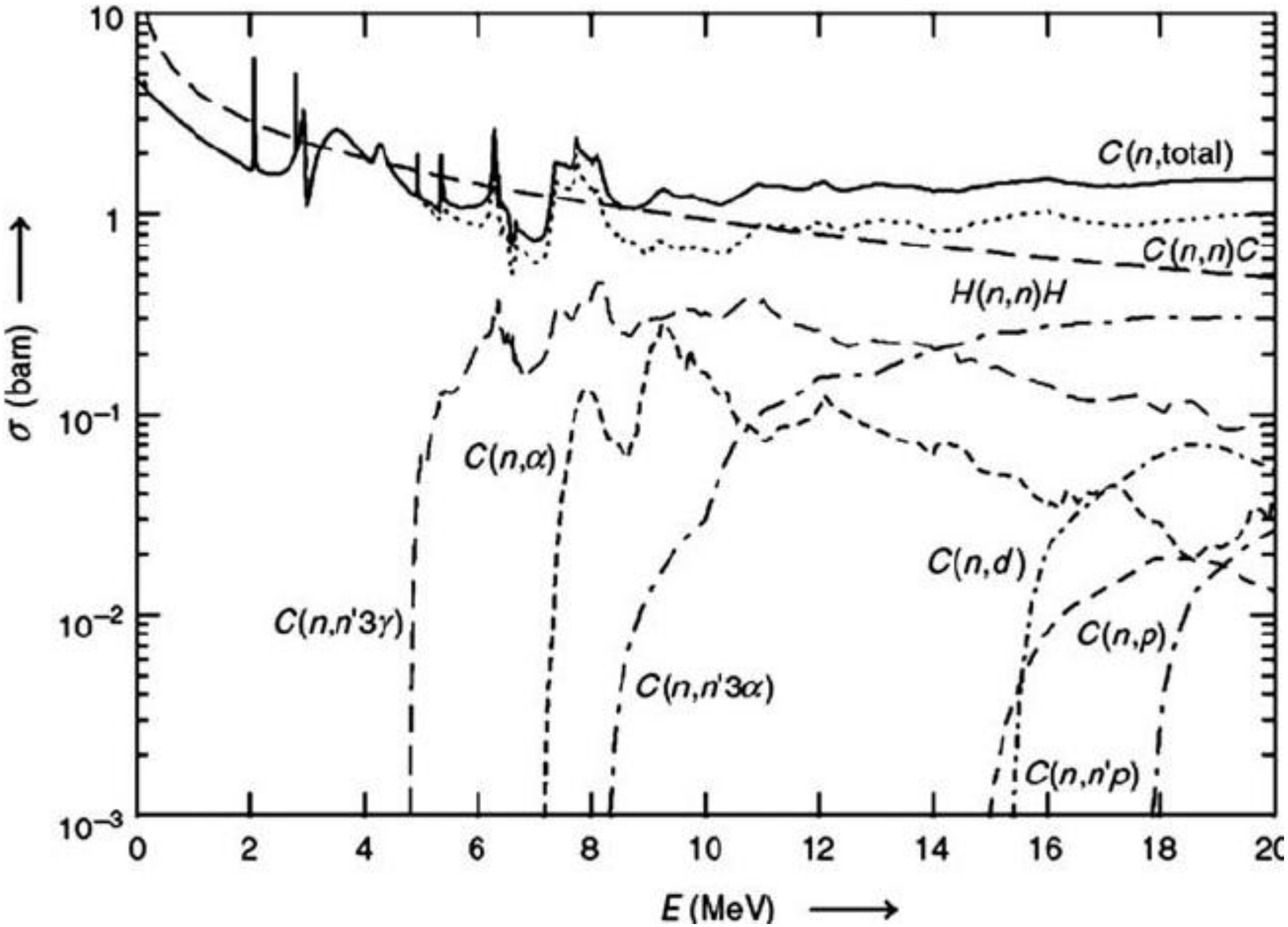


Interaction of MeV neutrons with materials: Displacement damage

-Becomes relevant at high fluences (about 10^{10} n /cm^2)
- MeV neutrons produce atomic displacement cascades and transmutation nuclear reactions within the materials.

-Transmutation nuclear reactions yield the formation of impurities (e.g. H, He atoms).
- Atomic displacement cascades produce point structure defects (vacancies, interstitials).
- Then, diffusion processes lead to the formation of the final microstructure

Interaction of MeV neutrons with materials: Displacement damage



Elastic scattering and charged particle-out reactions for carbon (Mazrou et al, Rad Prot Dos- 2010)

Interaction of MeV neutrons with materials: Displacement damage

Elastic collisions mostly responsible for damage in metals and semiconductors

They lead to production of vacancies and self-intersticial atoms, and rearrangements around lattice sites

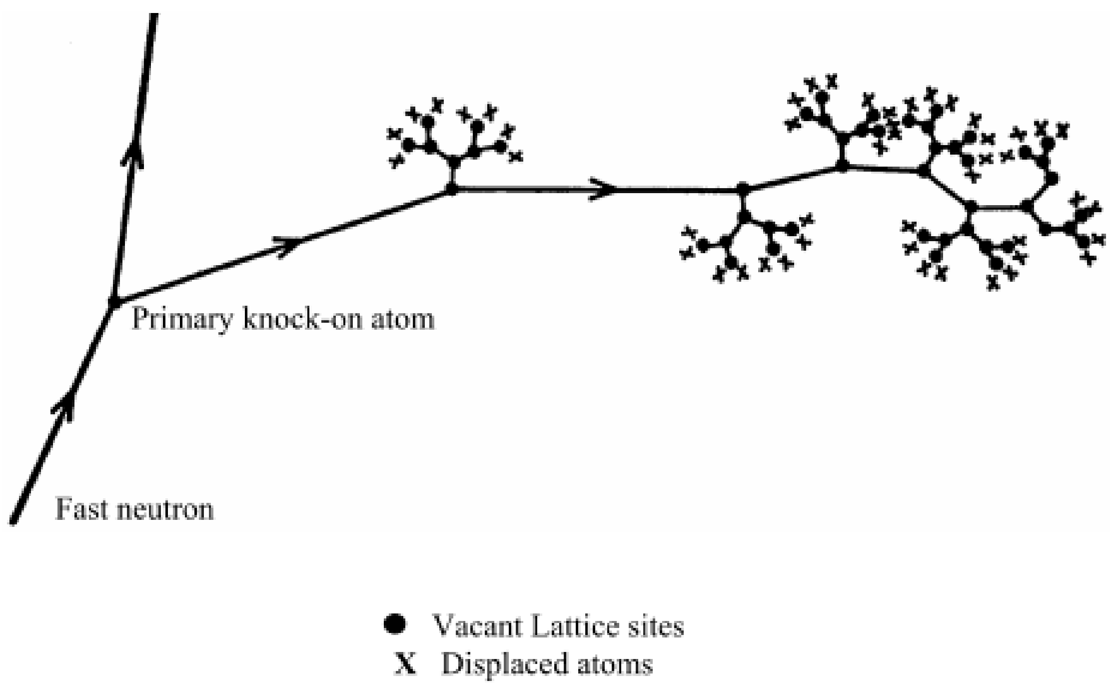
Atomic displacement start: Primary Knock on Atom (PKA)= any target atom struck by the fast neutron

Many PKAs recoil with energies much far in excess of lattice bonding energies, leaving their lattice sites and displace additional atoms in secondary recoil events, eventually resulting in a cascade

Localised regions of lattice become highly disturbed, containing high concentration of defects and excess lattice energy

Interaction of MeV neutrons with materials: Displacement damage

About 0.2 ps from the creation of a PKA the «ballistic» cascade ends
At this time all atoms in the cascade have been set into motion!
Local thermal spike lasting few ps before heat dissipates around, promoting additional rearrangement



Final microstructure formed within microseconds

Simmons 1965, UK Env. Ag. TR P3-080 2002

Interaction of MeV neutrons with materials: Displacement damage

The final microstructure results from a balance between radiation damage and thermal annealing

- Key radiation damage parameters:
- Accumulated damage (in dpa)
- Damage rate (in dpa/s, or dpa/y)
- Rate of production of impurities (e.g. He/dpa, H/dpa ratios)
- Temperature

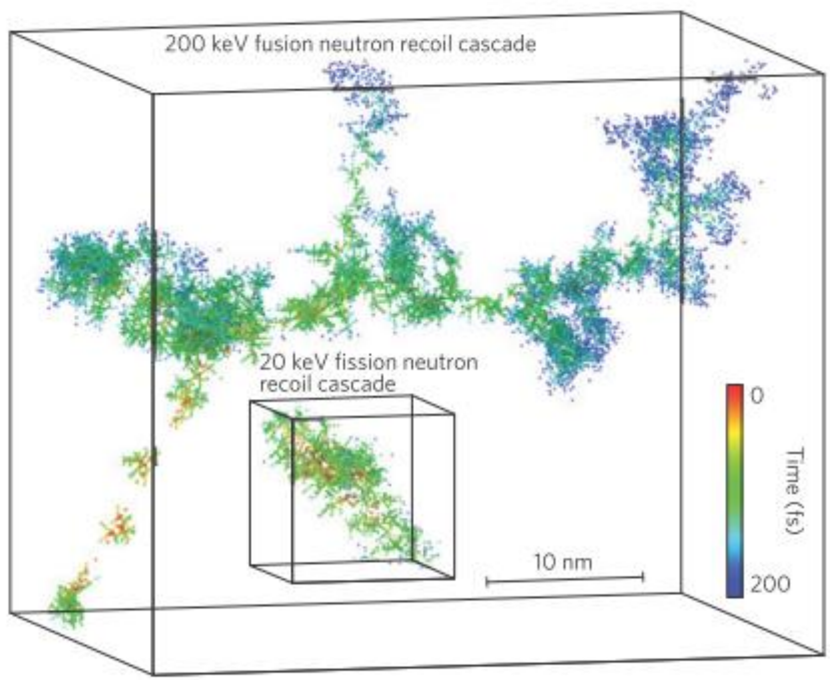


Figure 2 | Evolution of a typical morphology cascade in pure iron triggered by a 20 keV fission and a 200 keV fusion neutron calculated by means of molecular dynamics. The colours of the atoms correspond to the times

dpa = number of displacements per atom

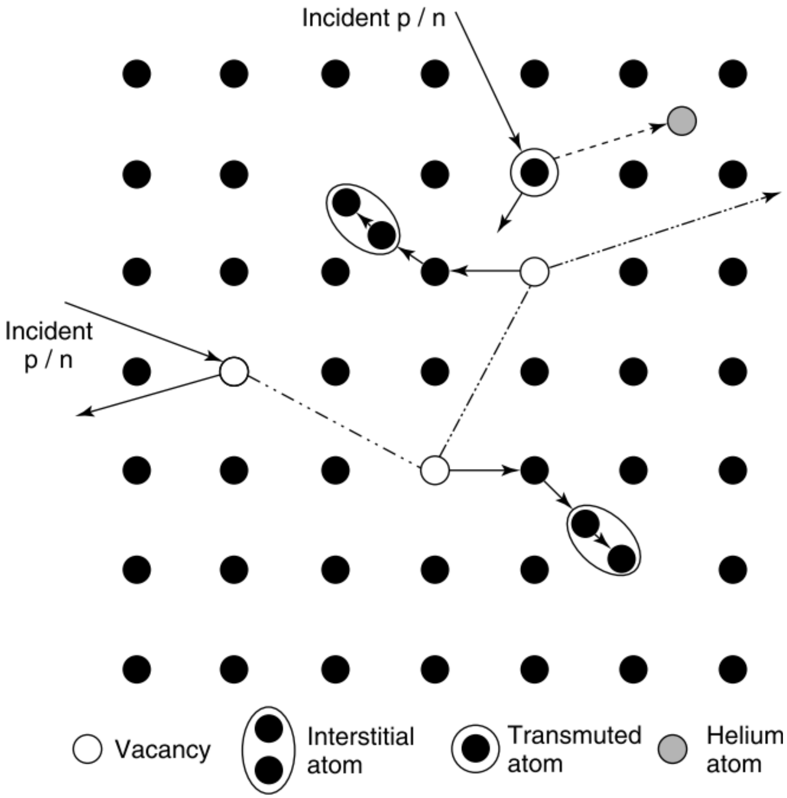
Moeaslang et al, Nat Phys 2016

Evolution of the Properties

- Chemical composition:
- Change in the chemical composition
- Physical properties:
- Decrease of electrical conductivity (low temperatures)
- Decrease of thermal conductivity (ceramic materials)
- Mechanical properties:
- Hardening (H)
- Loss of ductility (LD)
- Loss of fracture toughness
- Loss of creep strength
- Dimensions:
- Swelling, irradiation creep, irradiation growth
- Environmental effects:
- Irradiation-assisted stress corrosion cracking
- Radioactivity:
- Activation effects

Ref. Baluc (CRPP)

Interaction of MeV neutrons with materials: Displacement damage

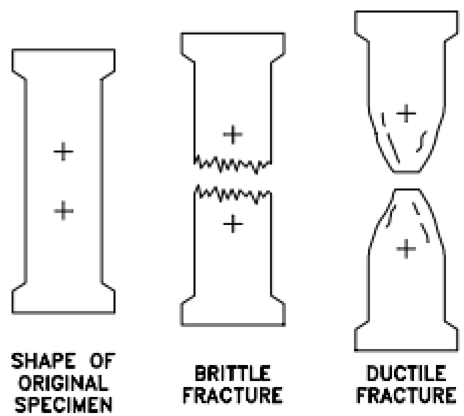


From Filges et al, 2009

TABLE 1

General Effects of Fast-Neutron Irradiation on Metals

Property Increases	Property Decreases
Yield strength	Ductility
Tensile strength	Stress-rupture strength
NDT temperature	Density
Young's Modulus (slight)	Impact strength
Hardness	Thermal conductivity
High-temperature creep rate (during irradiation)	



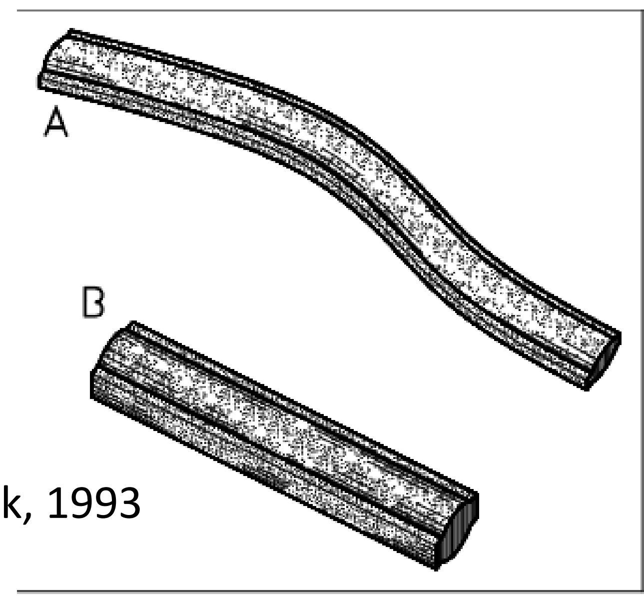


Figure 6 (a) Growth of Uranium Rod; (b) Uranium Rod Size Dummy

From DOE Handbook, 1993

Recall: a measure of the irradiation load to a material is the total dpa number (displacements per atom)

Hystorical note: Wigner's disease

As early as 1942, in Fermi's reports on the operation of the uranium-graphite reactor, E. P. Wigner pointed out that the intense fluxes of high energy neutrons created in the fission events would cause the displacement of carbon atoms from their equilibrium positions in the graphite lattice.

For every fission reaction, neutrons with MeV energies would transfer part of their energy into the graphite lattice destruction,

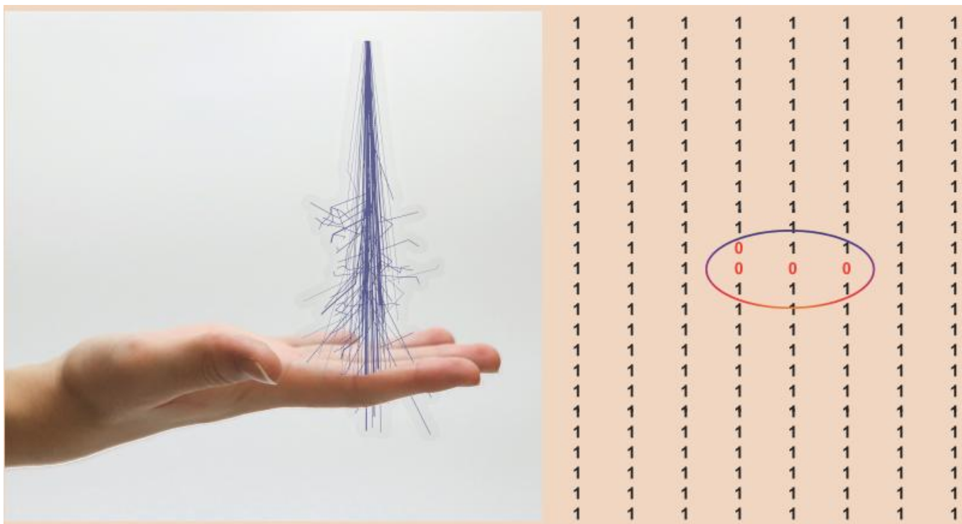
The swelling and distortion of graphite under the bombardment of fast neutrons from nuclear fission was called the "Wigner disease", and led to intense activity on solid state physics and materials research

Instruments for MeV irradiation

- Science case, business case, proposal
- Scope of the instrument
- Requirements & Solutions
- Design & Construction
- SOUP

MeV irradiation of electronic chips: ChipIr

Science, business case

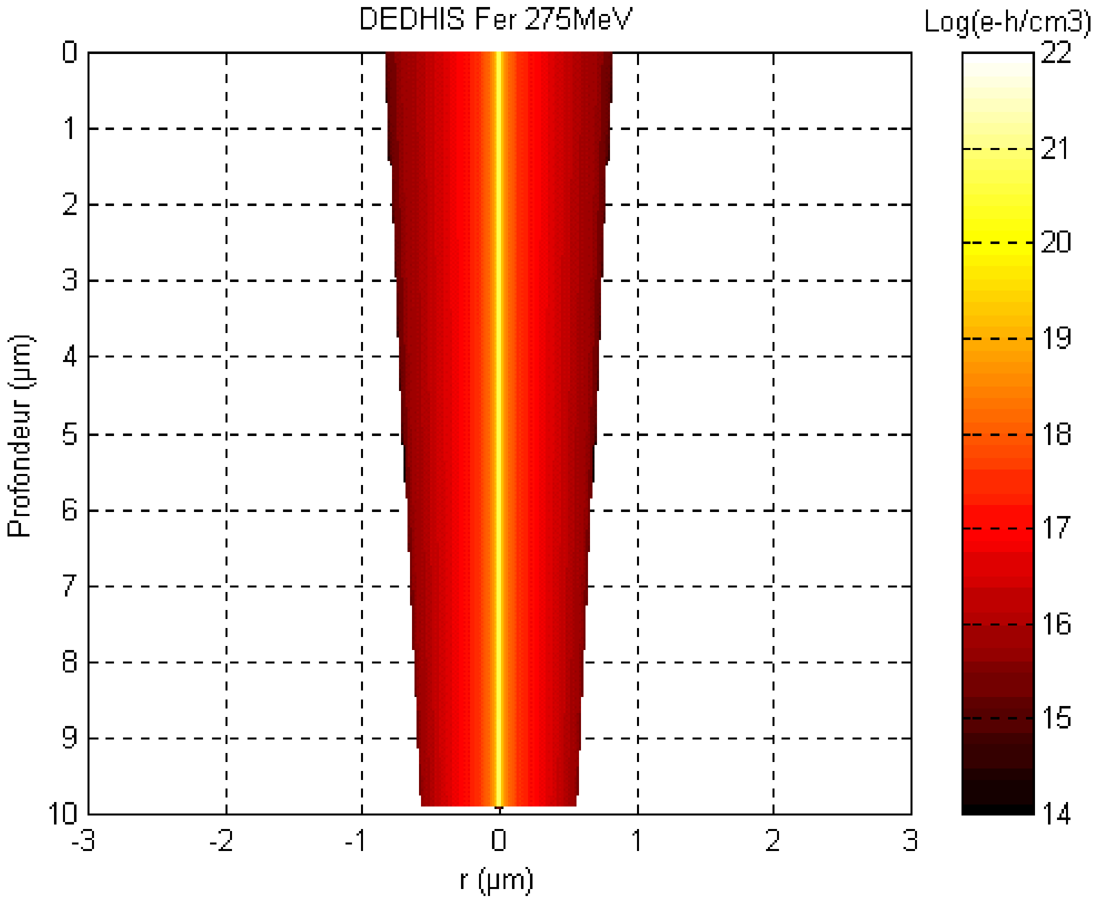


1979: Effect of a single alpha particle on a 64 kb DRAM

This class of malfunctions is termed SINGLE EVENT EFFECTS (SEE)

Slides and images adapted from C. Frost, and: RS, C. Andreani, G. Gorini, Il Nuovo Saggiatore 2017

Simulated heavy ion e-h track in Si



Electron-Hole density (cm^{-3})

Fe ions 275 MeV
Linear Energy Transfer=24 $MeVcm^2/mg$

LET metrics in Si:

1 $MeVcm^2/mg$

$6.4 \cdot 10^4$ e-h pairs/µm

10 fC/µm

P. Foulliat, EWRHE 2004

Chip Irradiation

One Failure in time (FIT) equals one failure per billion hours

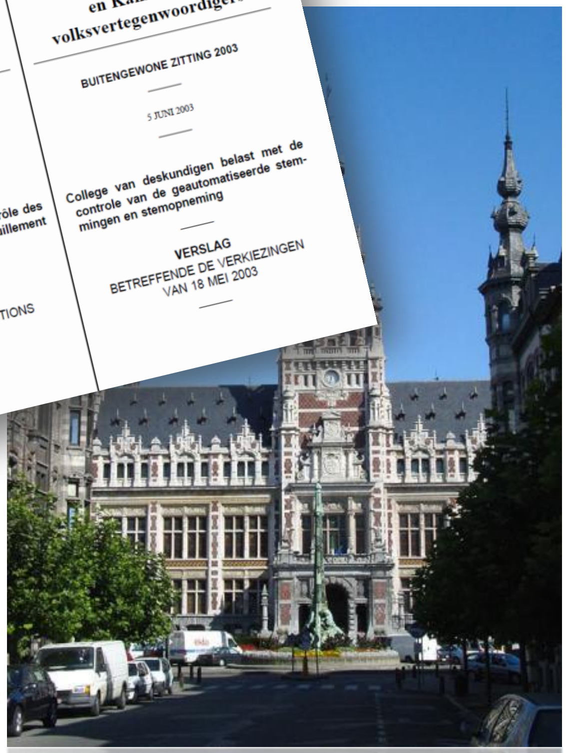
Reliability in advanced ICs is improving down to some **10-100 FIT**

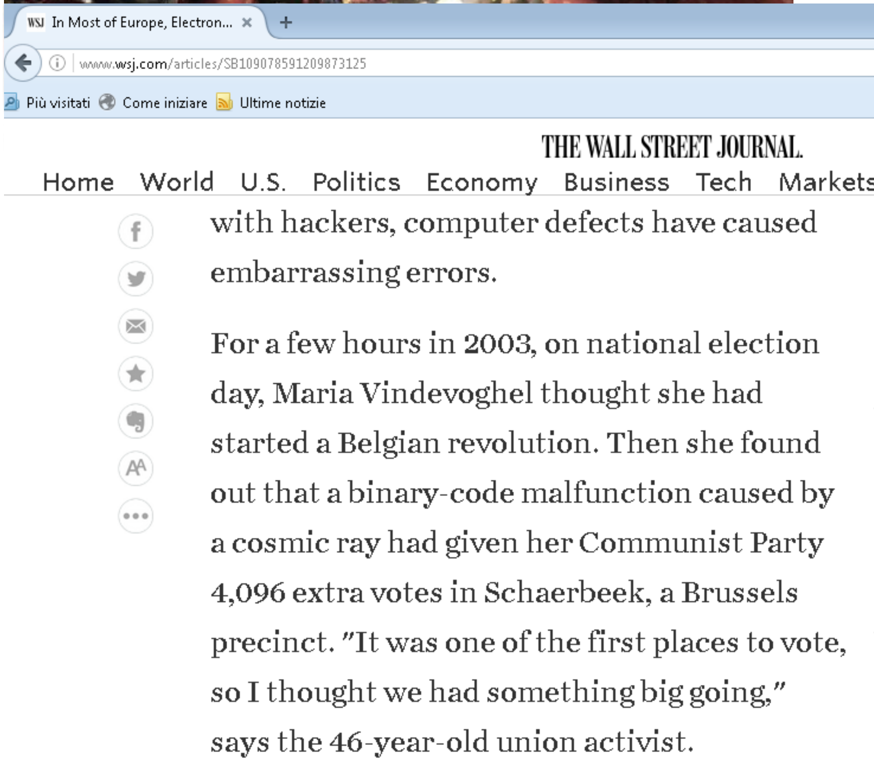
- SEE at sea level is dominated by **Soft Errors (SE)** leading to the
- **Soft Error Rate (SER)** figure of merit;
- if not properly mitigated, SER may reach **10^5 FIT**

Critical charge of the order of 10 fC/µm


3- 7/1 (Sénat)
DOC 51 0001/2 (Chambre)
Sénat et Chambre des représentants de Belgique
SESSION EXTRAORDINAIRE DE 2003
5 JUIN 2003
Collège d'experts chargés du contrôle des systèmes de vote et de dépouillement automatisés
RAPPORT
CONCERNANT LES ÉLECTIONS DU 18 MAI 2003

3- 7/1 (Senaat)
DOC 51 0001/2 (Kamer)
Belgische Senaat en Kamer van volksvertegenwoordigers
BUITENGEWONE ZITTING 2003
5 JUNI 2003
College van deskundigen belast met de controle van de geautomatiseerde stemmingen en stemopneming
VERSLAG
BETREFFENDE DE VERKIEZINGEN VAN 18 MEI 2003



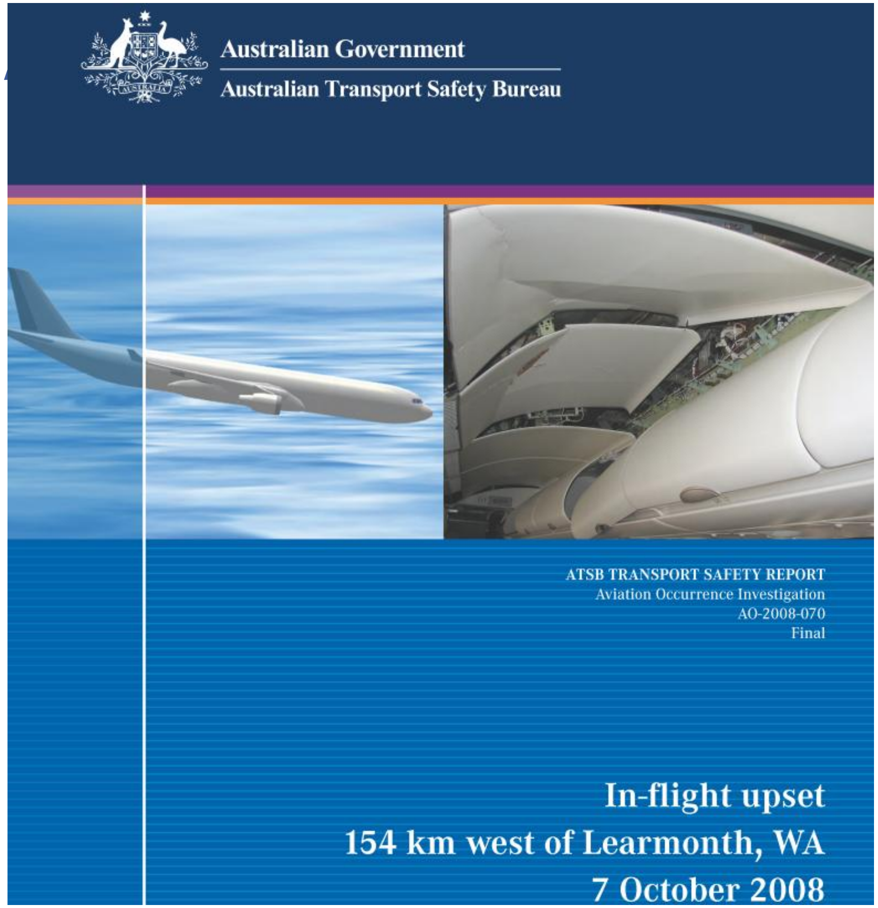


with hackers, computer defects have caused embarrassing errors.

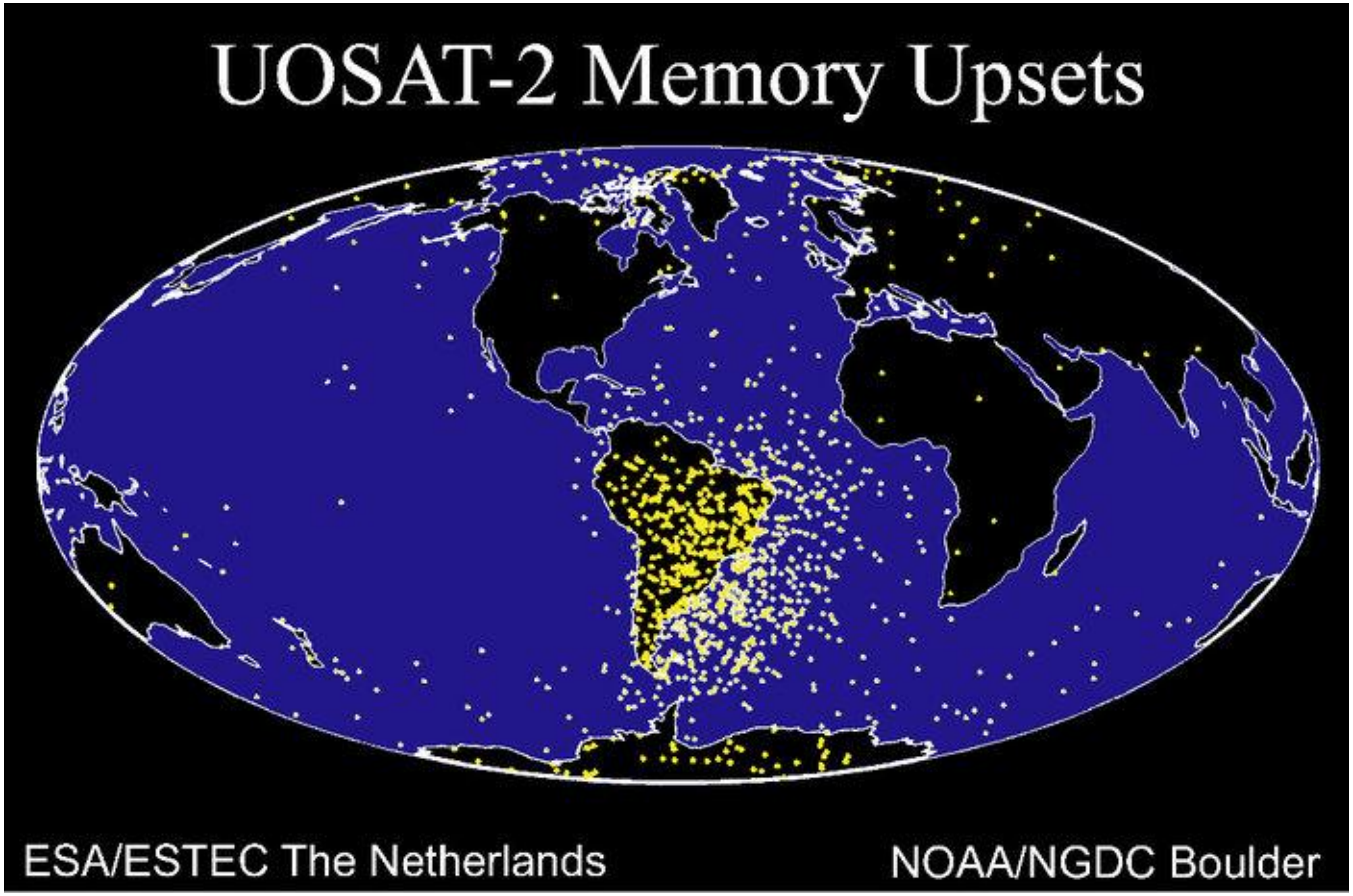
For a few hours in 2003, on national election day, Maria Vindevoghel thought she had started a Belgian revolution. Then she found out that a binary-code malfunction caused by a cosmic ray had given her Communist Party 4,096 extra votes in Schaerbeek, a Brussels precinct. "It was one of the first places to vote, so I thought we had something big going," says the 46-year-old union activist.

Schaerbeek, Belgium, May 2003

4096 (2^{12}) votes added to an electronic voting machine



“The investigation team is **evaluating the relevance, if any**, of SEEs to the ADIRU fault that resulted in spikes being produced in ADIRU parameters.”



Failure in electronics of a satellite across the South Atlantic Anomaly

This means if the same vendor uses the 1M gate SRAM-based FPGA safety system in 500,000 vehicles, we can multiply the number of upsets (1.05E-4) by the number of vehicles/systems on the road to arrive at a total of 52.5 upsets per day for the population. This translates to an upset every 27.4 minutes, or 2,187,500,000 FITs. Since these are firm

Actel

Reliability Considerations for Automotive FPGAs

White Paper

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White Paper: UltraScale Devices

WP462 (v1.0) February 26, 2015

UltraScale Devices Maximize Design Integrity with Industry-Leading SEU Resilience and Mitigation

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APPLIED PHYSICS LETTERS **92**, 114101 (2008)

Facility for fast neutron irradiation tests of electronics at the ISIS spallation neutron source

C. Andreani,[1] A. Pietropaolo,[1,a)] A. Salsano,[1] G. Gorini,[2] M. Tardocchi,[2] A. Paccagnella,[3] S. Gerardin,[3] C. D. Frost,[4] S. Ansell,[4] and S. P. Platt[5]
[1]*Centro NAST, Università degli Studi di Roma Tor Vergata, Italy*
[2]*Dipartimento di Fisica "G. Occhialini," Università degli Studi di Milano-Bicocca, Italy*
[3]*Dipartimento di Ingegneria dell'Informazione, Università di Padova, Italy*
[4]*ISIS Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 0QX, United Kingdom*
[5]*School of Computing, Engineering and Physical Sciences, University of Central Lancashire, Preston, Lancs. PR1 2HE, United Kingdom*

(Received 22 January 2008; accepted 25 February 2008; published online 20 March 2008)

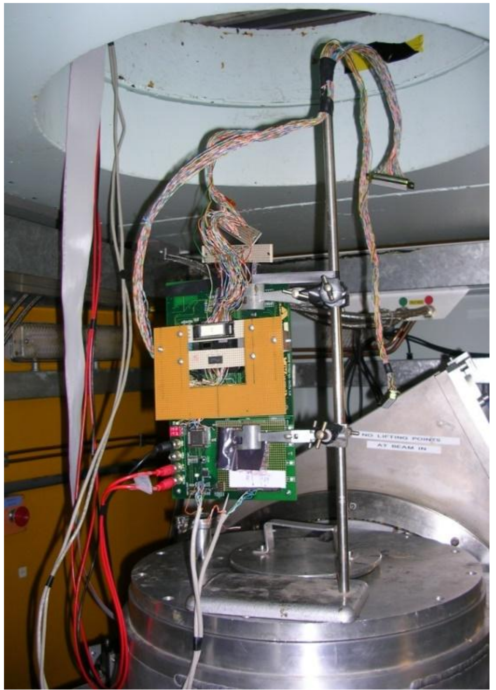
The VESUVIO beam line at the ISIS spallation neutron source was set up for neutron irradiation tests in the neutron energy range above 10 MeV. The neutron flux and energy spectrum were shown, in benchmark activation measurements, to provide a neutron spectrum similar to the ambient one at sea level, but with an enhancement in intensity of a factor of 10^7. Such conditions are suitable for accelerated testing of electronic components, as was demonstrated here by measurements of soft error rates in recent technology field programable gate arrays. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2897309]

from eV to MeV

-Within Italy- UK collaboration on instrumentats for eV-to-MeV neutrons, the Italian team proposed in 2006 a test experiment for irradiation of electronic chips on VESUVIO

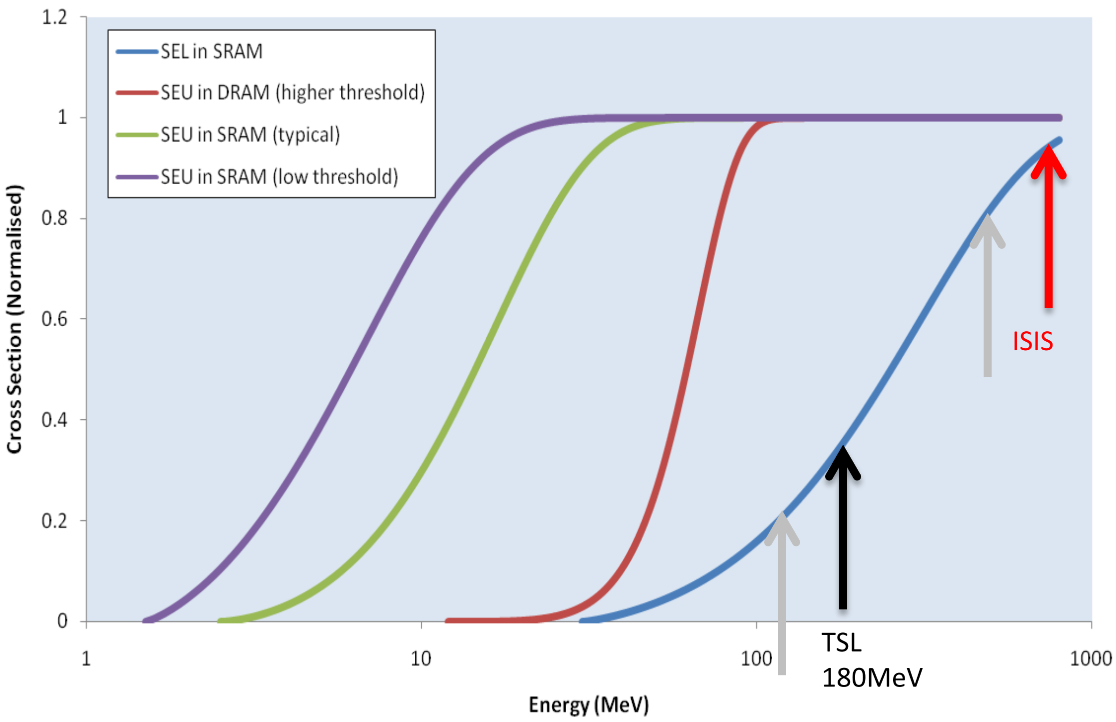
-This paved the way to the construction of ChipIr

- The user programme on irradiation continued on VESUVIO and moved to ChipIr



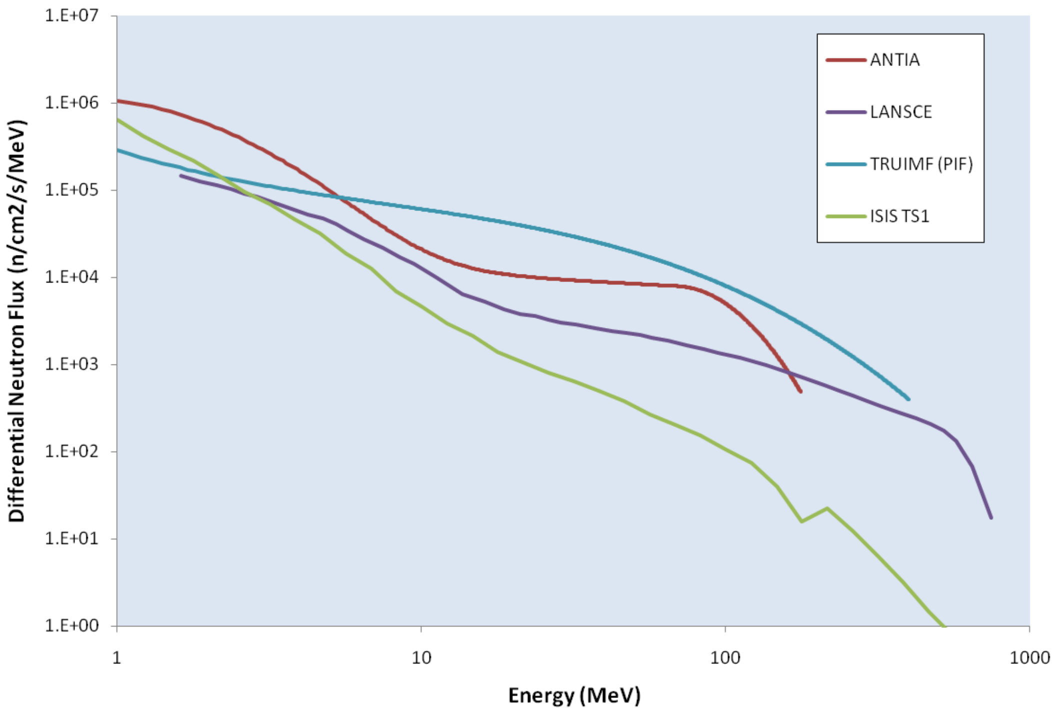
Device Cross Sections

European 'Energy Gap'



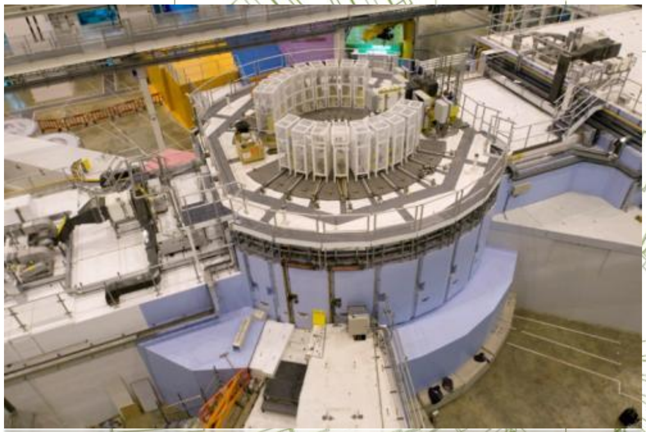
Sources:
Y.Yahagi et al, Proc Int. Rel. Phys. Sym. IEEE, 2004, 669-670;
A.Hands et al IEEE Trans Nuc Sci , 56, 2009, 2026-2034;
C.S.Dyer IEEE Trans Nucl. Sci. 51, 2004, 2817-2824

Accelerated SEE Testing using Accelerator Sources- Requirement: 1 hour at test facility = 114 years in real environment



Source	Flux (>10MeV)
Anita (Sweden)	9.31×10^{6}
LANSCE (USA)	4.58×10^{5}
TRIUMPF (Canada)	2.61×10^{5}
ISIS –VESUVIO (UK)	5.82×10^{4}
PNPI (Russia)	10^{5}(?)

Fast Neutron Beam – W1

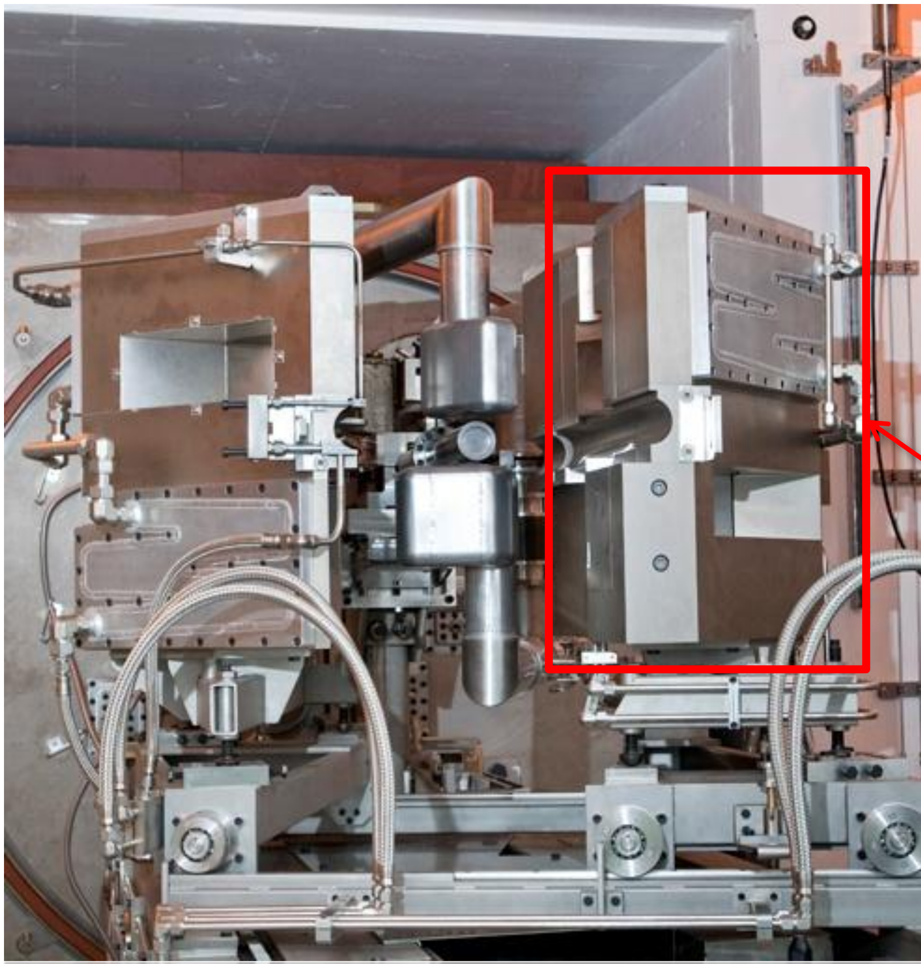


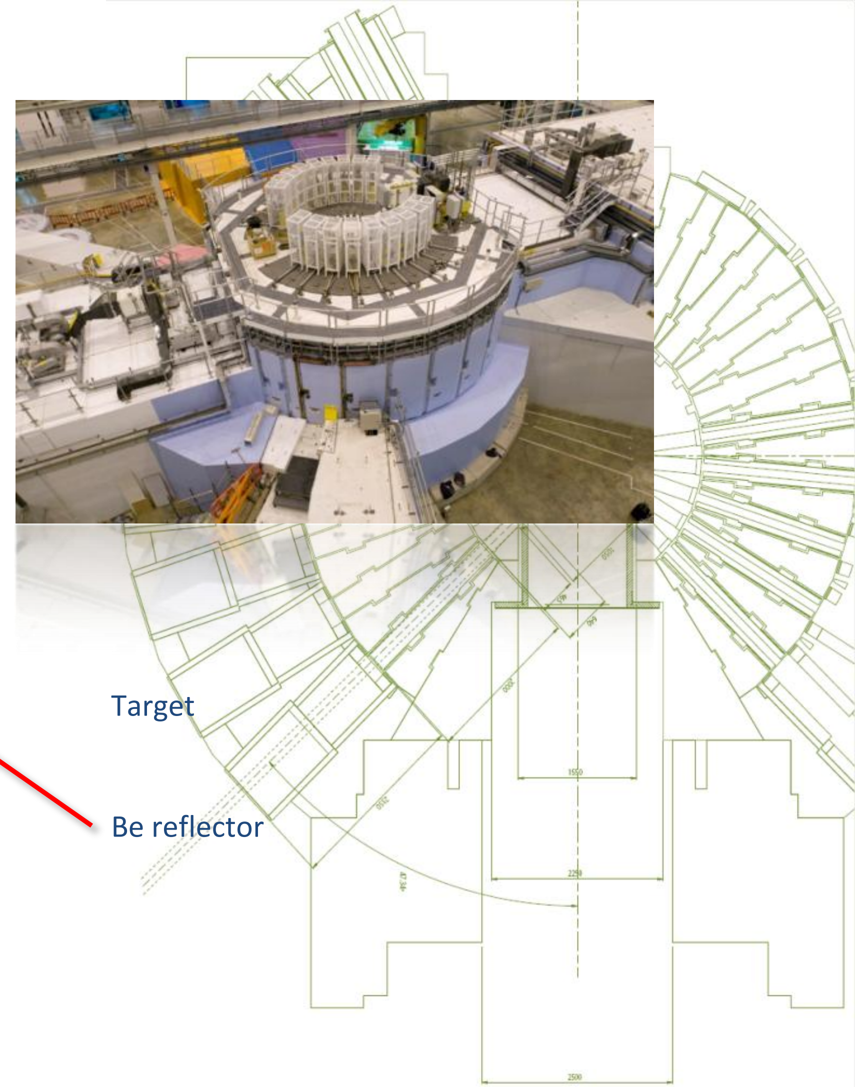
TS2 Provides Opportunity to Build ChipIr Instrument

Design and construction started in 2007- now in operation

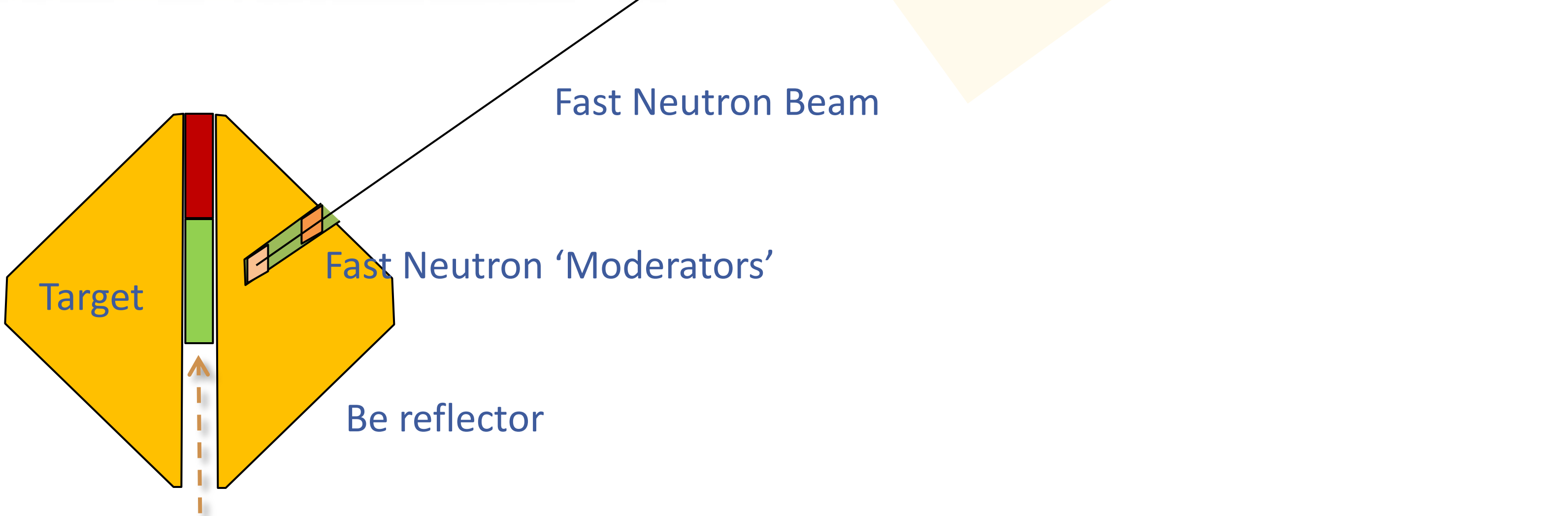
- Strategic European Facility
- Optimise flux and spectrum
- Closed European ‘’Energy Gap’
- Builds on 25 years of providing ‘user facilities’
- STFC-CNR agreements

Fast Neutrons from Target Complex





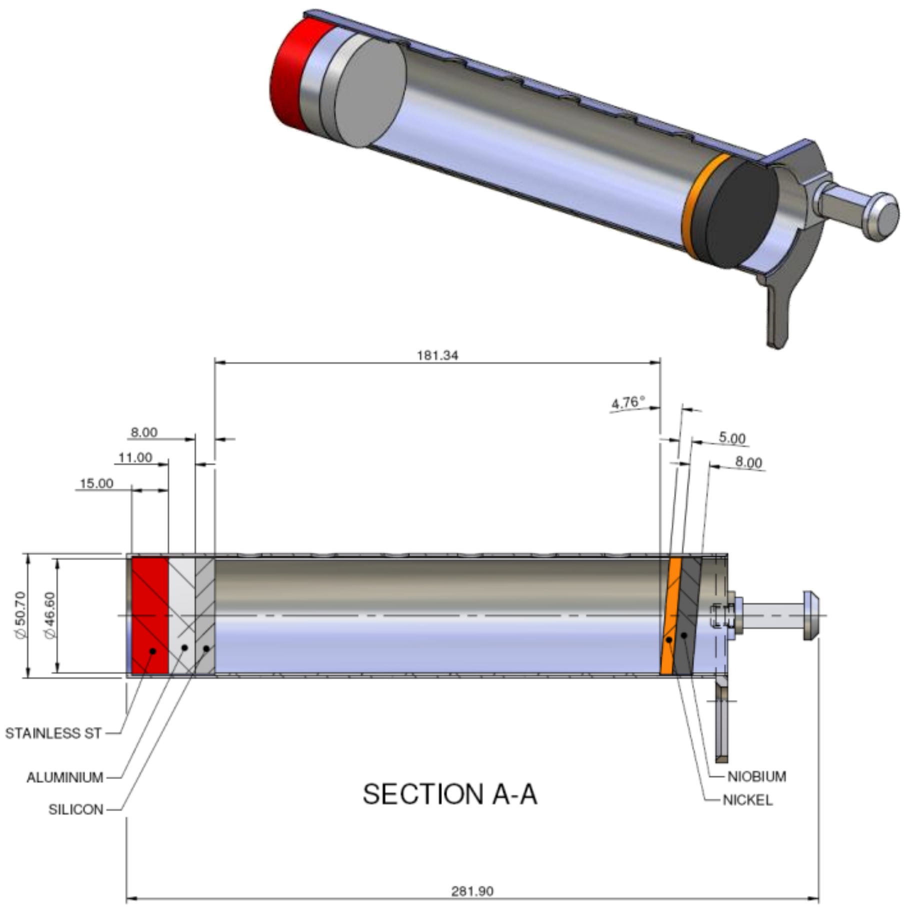
Fast Neutron Beam – W1



Fast Neutrons from Target Complex

Fast Neutron Moderator

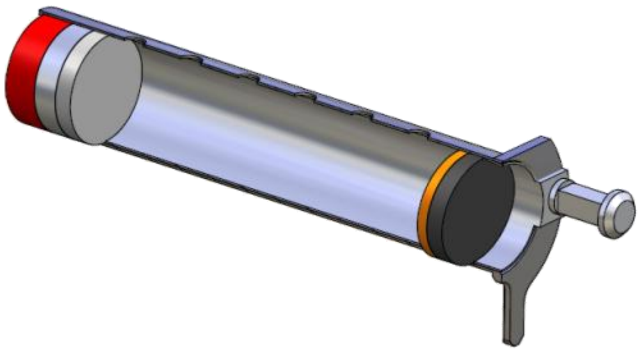
- Inserts into ‘hole’ in Be reflector



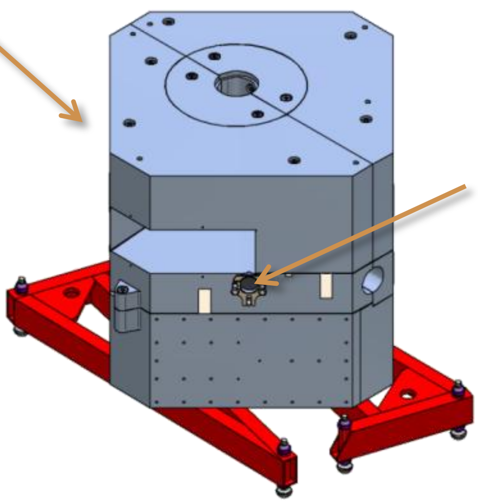
Fast Neutrons from Target Complex

Fast Neutron Moderator

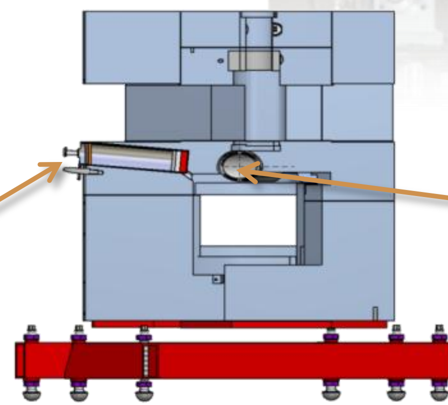
- Inserts into ‘hole’ in Be reflector



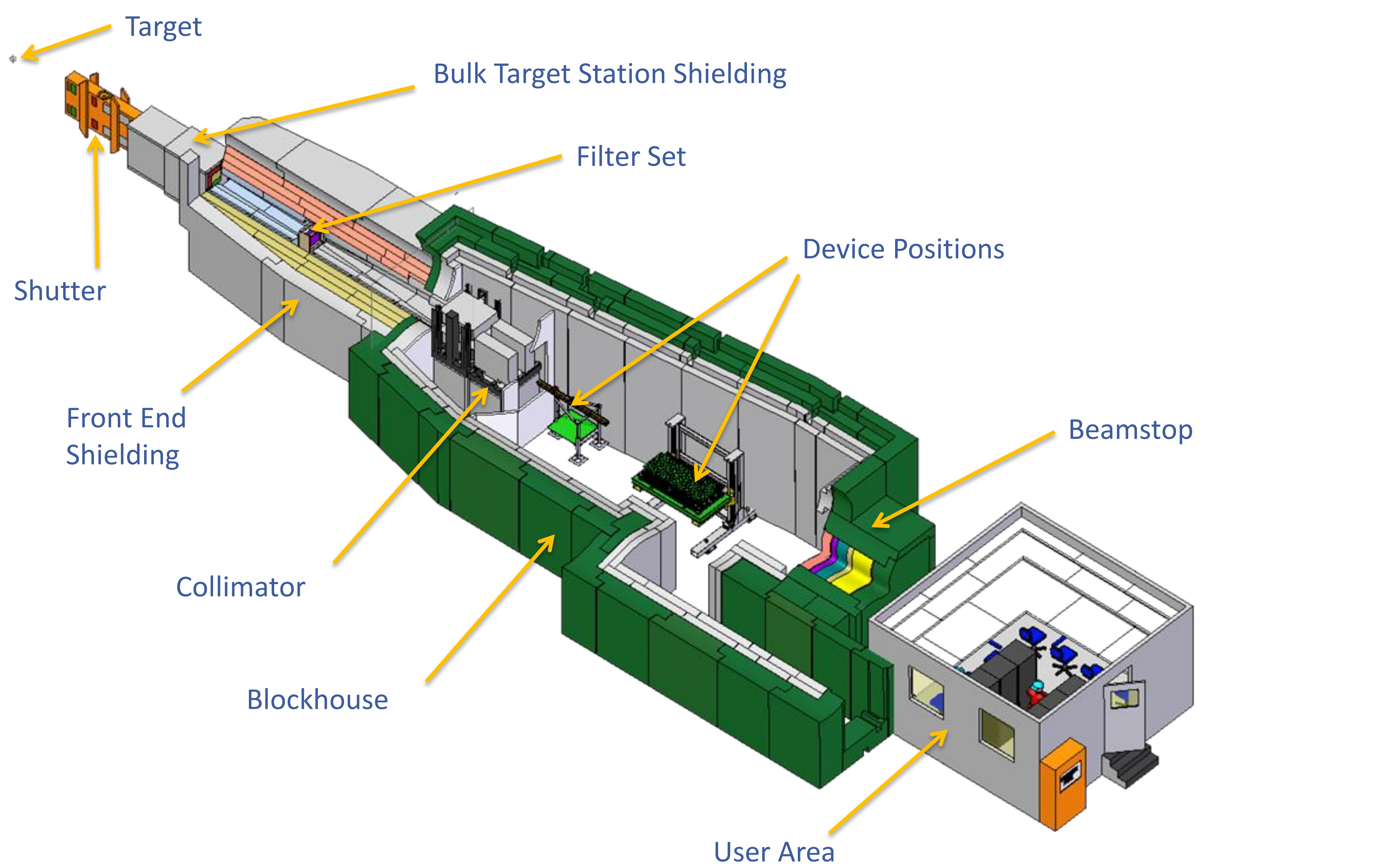
Direction of Beam



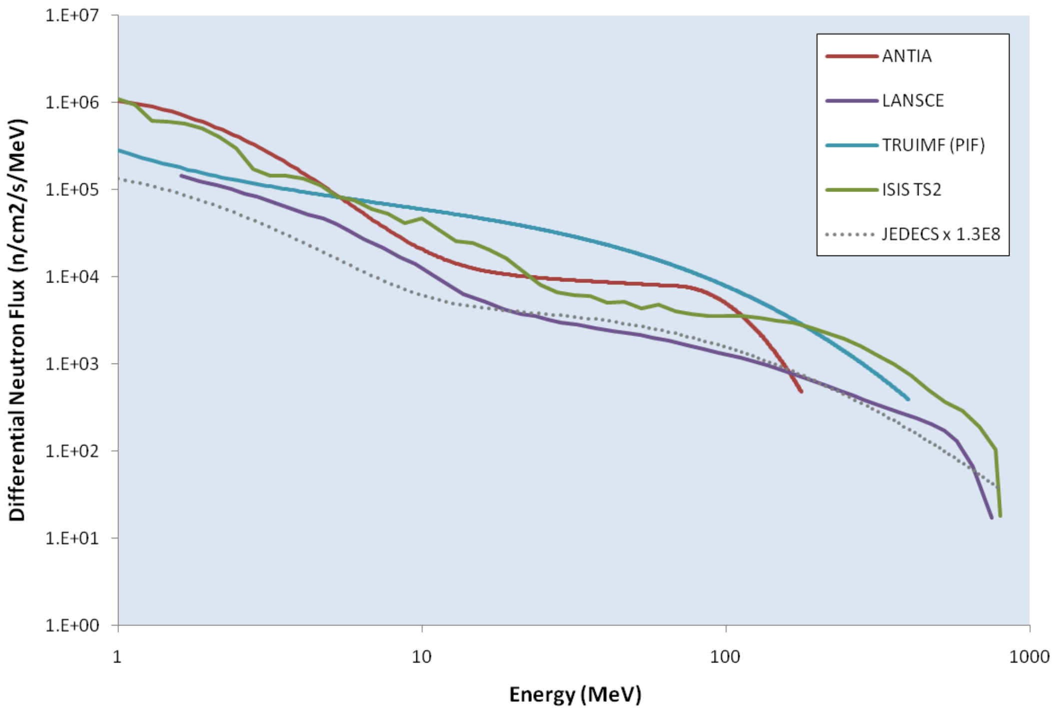
ChipIr Moderator View Port



Target


Target
Bulk Target Station Shielding
Filter Set
Device Positions
Shutter
Front End
Shielding
Beamstop
Collimator
Blockhouse
User Area

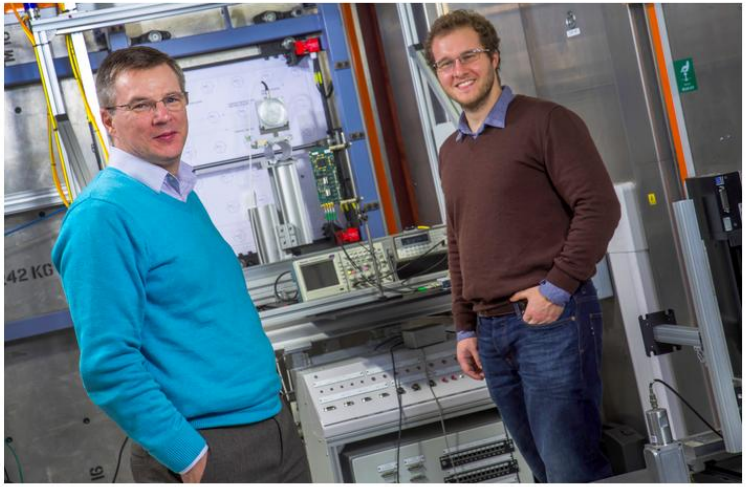
Accelerated SEE Testing using Accelerator Sources



LANSCE	$4.6x10^5$ n/cm²/s	800Mev
TRIUMF	$2.6x10^6$ n/cm²/s	500MeV
ISIS TS1	$5.8x10^4$ n/cm²/s	800MeV
TSL ANITA	$9.3x10^5$ n/cm²/s	174MeV
ISIS TS2- ChipIr	$>1x10^6$ n/cm²/s	800MeV

https://www.isis.stfc.ac.uk/Pages/ChipIR.aspx

ChipIr user programme



The ChipIr team Dr Chris Frost and Dr Carlo Cazzaniga

2 minutes irradiation of a CCD for ESA balloon exp (E. Grosso, Msci thesis, Tor Vergata)

AIP ADVANCES **8**, 025013 (2018)

Fast neutron irradiation tests of flash memories used in space environment at the ISIS spallation neutron source

C. Andreani,[1,2,3,4] R. Senesi,[1,2,3,4,a] A. Paccagnella,[5] M. Bagatin,[5] S. Gerardin,[5] C. Cazzaniga,[6] C. D. Frost,[6] P. Picozza,[1,2,7] G. Gorini,[8] R. Mancini,[9] and M. Sarno[9]

FAST NEUTRON IRRADIATION FACILITIES FOR ELECTRONICS AND MATERIALS

NEW OPPORTUNITIES AT SPALLATION SOURCES IN EUROPE

ROBERTO SENESI[1,2,3], GIUSEPPE GORINI[4,5,3], CARLA ANDREANI[1,2,3]

Il Nuovo Saggiatore, SIF 2017

Displacement damage instrumentation- The Irradiation Module at ESS

R Senesi[1,2], F Masi[3] , G Gorini[3] , G Scionti[4], C Vasi[2], Y Bessler[5], M Kickulies[6], Y Lee[6], R Linander[6], D Lyngh[6] , V Santoro[6] and L Zanini[6]

[1] Università degli Studi di Roma "Tor Vergata", Dipartimento di Fisica, Centro NAST, Roma, Italy
[2] CNR- IPCF, Sezione di Messina, Messina, Italy
[3] Università degli Studi di Milano-Bicocca, Milano, Italy
[4] Università della Calabria, Dipartimento di Fisica, Rende, Italy
[5] Forschungszentrum Jülich GmbH, Jülich, Germany
[6] European Spallation Source ERIC, Lund, Sweden

Consiglio Nazionale delle Ricerche

Within the italian (through CNR) in-Kind contribution to ESS construction

Displacement damage instrumentation- Irradiation Module at ESS

- Respond to the need of data following irradiation under unprecedented neutron energy, time structure, flux
- One main existing facility: STIP at SINQ , a module in the spallation target- mixed proton-neutron field

SINQ Target Irradiation Program (STIP)

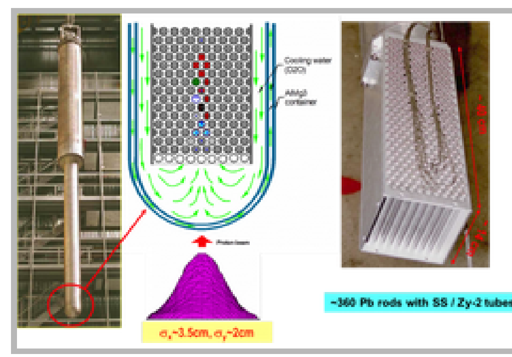
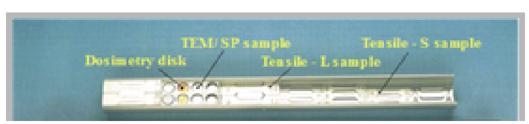


Figure 1: SINQ target as irradiation facility

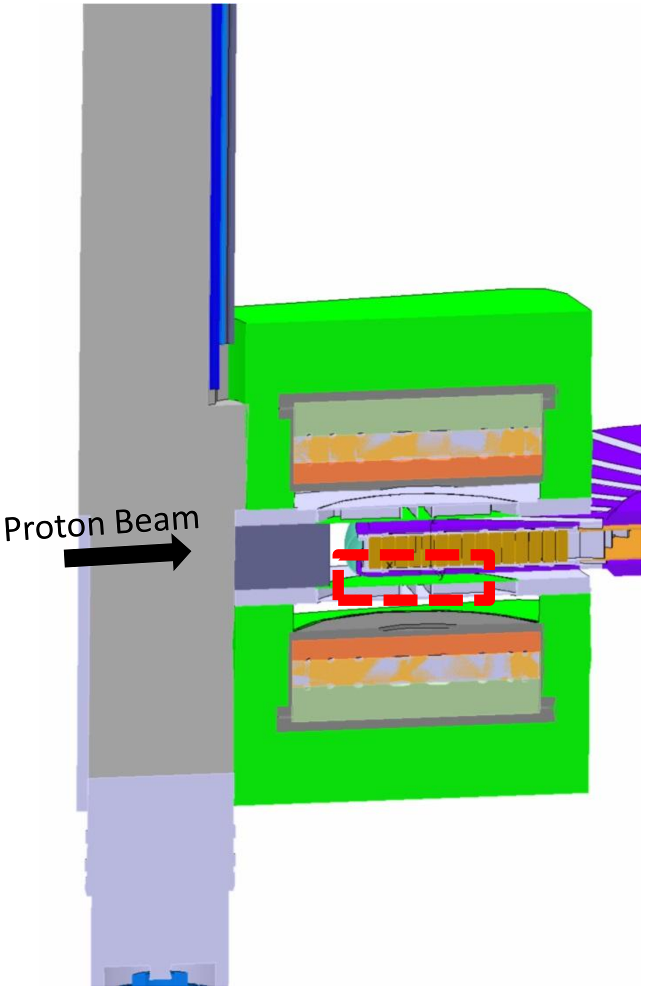
The unique **S**INQ **T**arget **I**rradiation **P**rogram (STIP) is using SINQ targets (Figure 1) as an irradiation device and is operated as a user facility in collaboration between LNM and the NUM Division. Various miniature type specimens (Figure 2) are irradiated in a real environment of a spallation target with high energy protons and spallation neutrons. The irradiation dose can reach about 15 dpa (in Fe) per year, accom-



Displacement damage instrumentation- The Irradiation Module at ESS

- Science case, business case, *proposal*
- Scope of the instrument
- Requirements & Solutions
- Design & Construction
- ~~SOUP~~

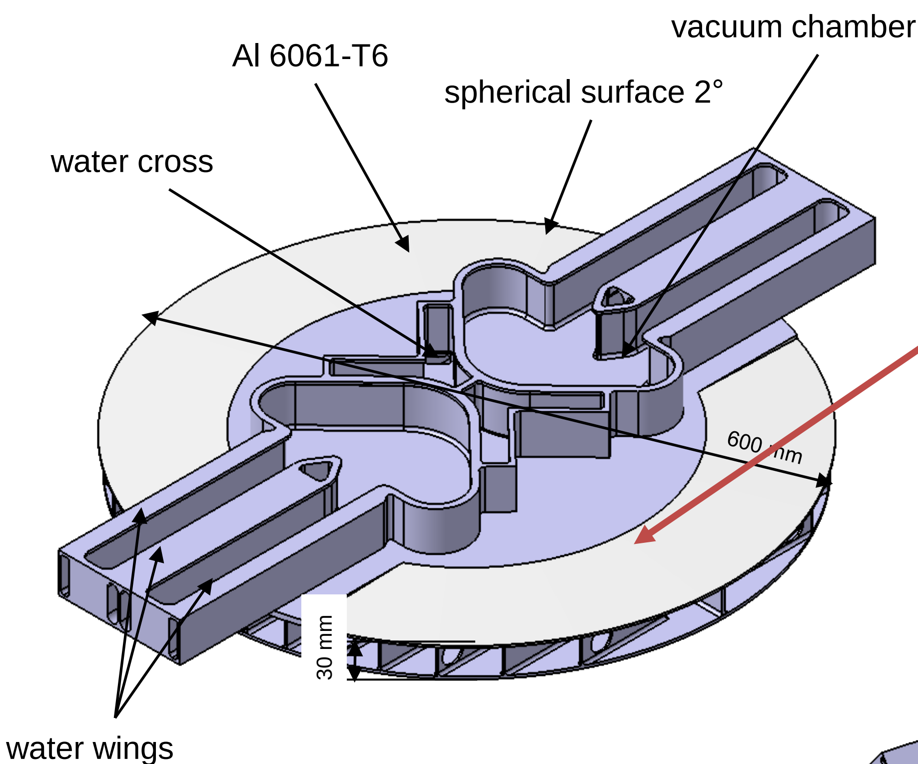
Interface: IRRADIATION MODULE is located inside Moderator Reflector plug



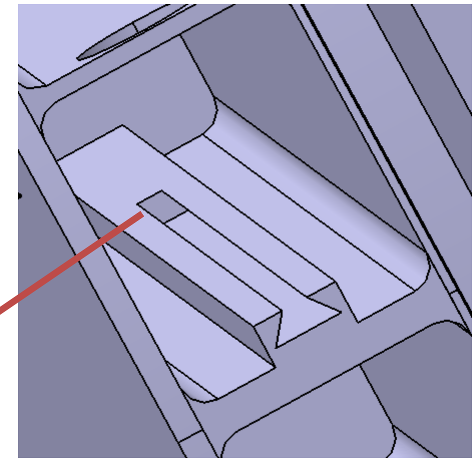
- Location for the module – many choices possible, final decision is inside water moderator close to surface.
- Interface handled via close collaboration with FZ Juelich
  - *Neutron flux in the range of interest*
  - *Impact on moderator's performance*
  - *Radiation damage (dpa)*
  - *Gas (H, He) production*
  - *Heat load*
  - *Activation*

Y. Bessler- FZJ

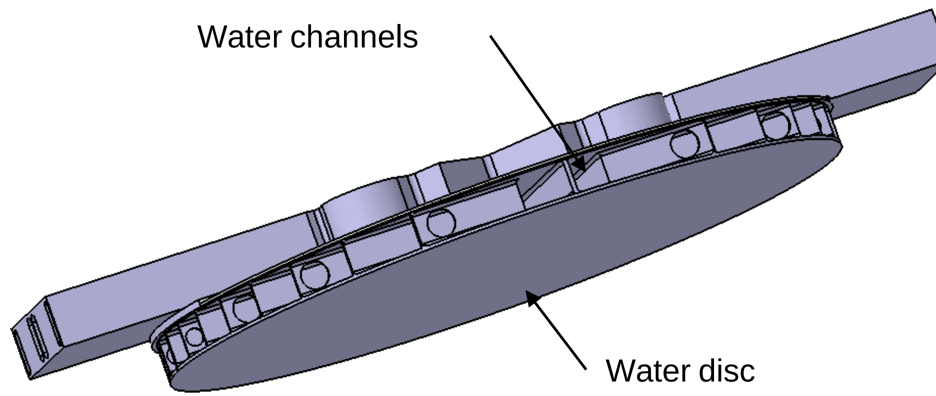
Location of Irradiation Module



view from reflector



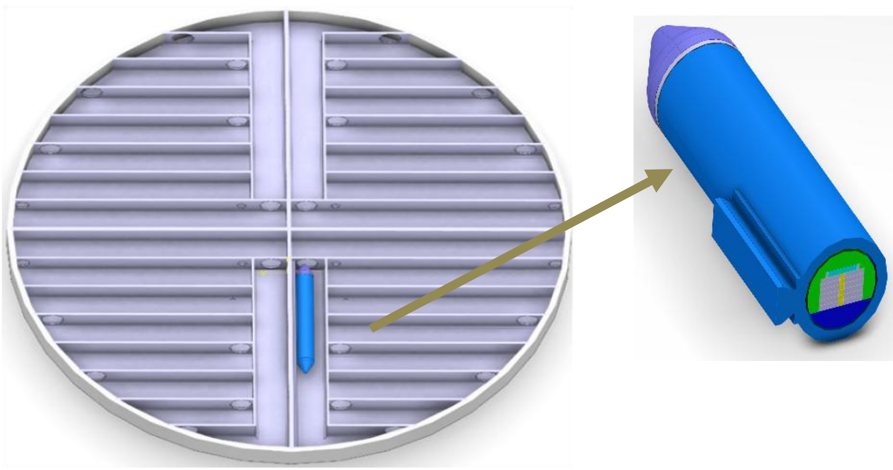
"dovetail" guide for irradiation modules



view from target

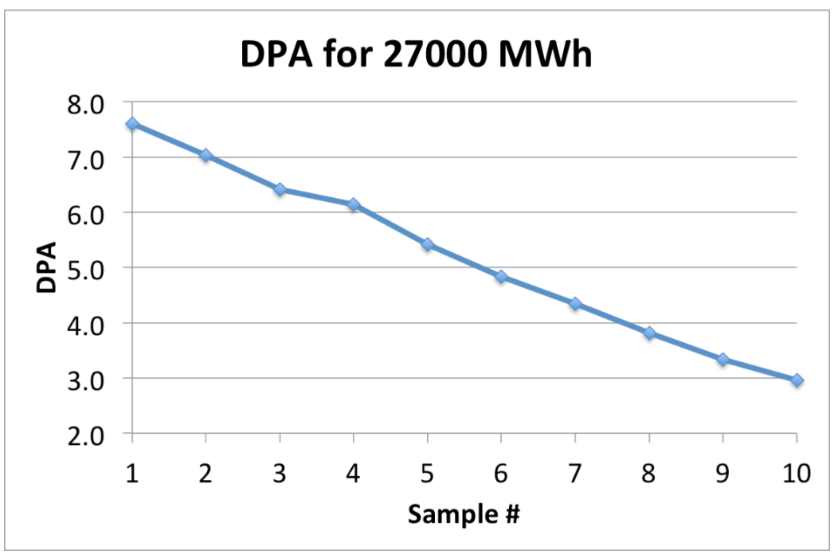
→made from one full block

IRRADIATION MODULE is located inside the thermal Moderator



Equipment	Lifetime (MW-h)	Basis for the lifetime limit
Target Wheel	125,000	• 10 dpa in 316L SS target vessel
MR Plug	25,000	• 40 dpa or 10^{23} n/cm^2 thermal (E_{th}<0.625 eV) neutron fluence in Al

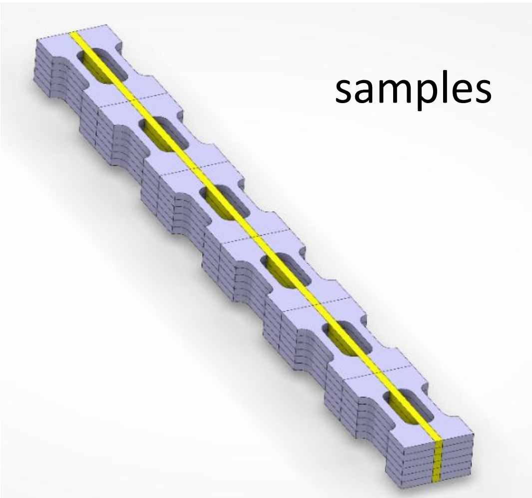
- The helium to dpa ratios are 14.01 (571 MeV), 13.14 (1.3 GeV) and 15.6 (2.0 GeV) [He-appm/dpa]

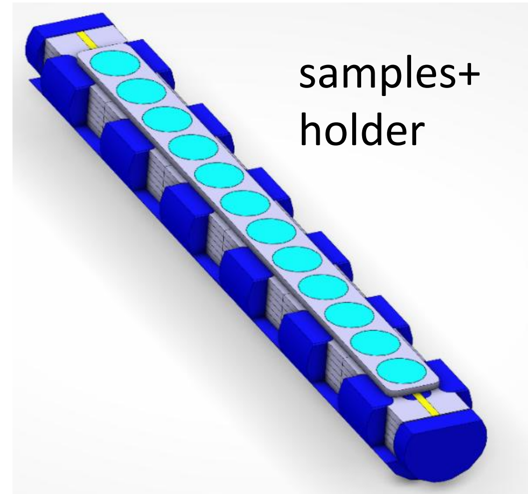


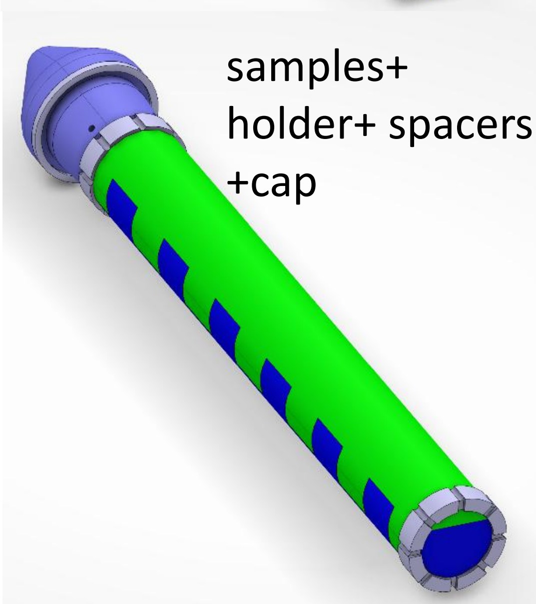
- Maximum damage: 7.6 DPA
  - Ideal Module: Maximum 13.5 DPA for 27000 MWh
- Helium to Damage ratio: 15.6 He-appm/dpa
- Neutron fluxes in the module region ~10^{14} n/cm^2/s

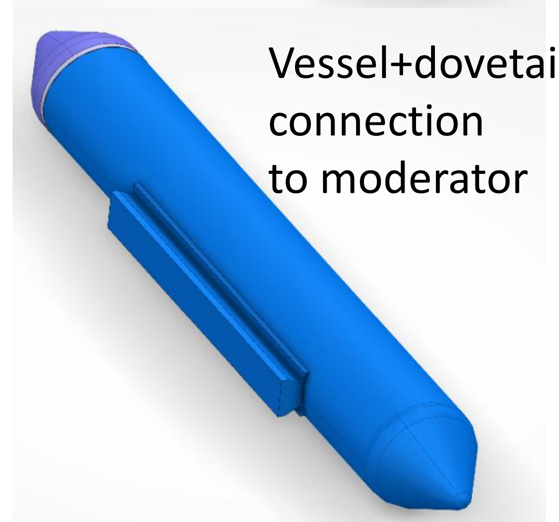
Data from Y. Lee, G.Scionti

IRRADIATION MODULE is located inside the thermal Moderator







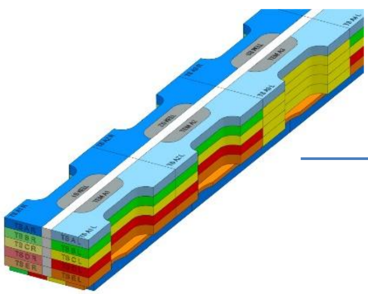


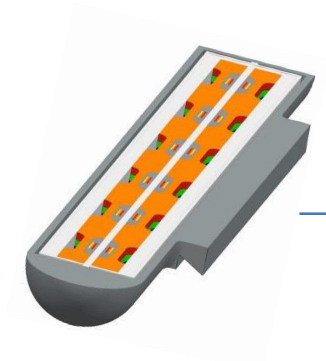
Interface : ESS Materials' Division (Y.Lee) for samples specifications

InKind: ESS construction Phase

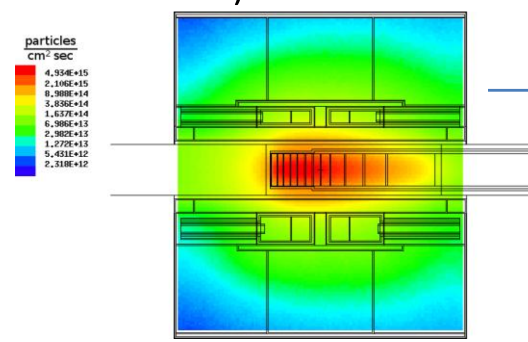
ESS operation Phase

Samples specification to fit
ESS programme on spallation materials

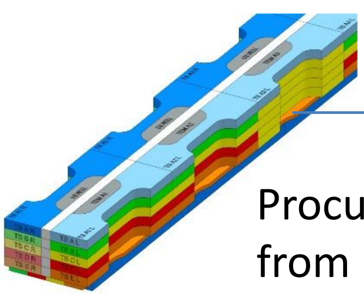




Neutrons (0.1 MeV
to 2.0 GeV)



Post Irradiation Examination on irradiated and unirradiated samples

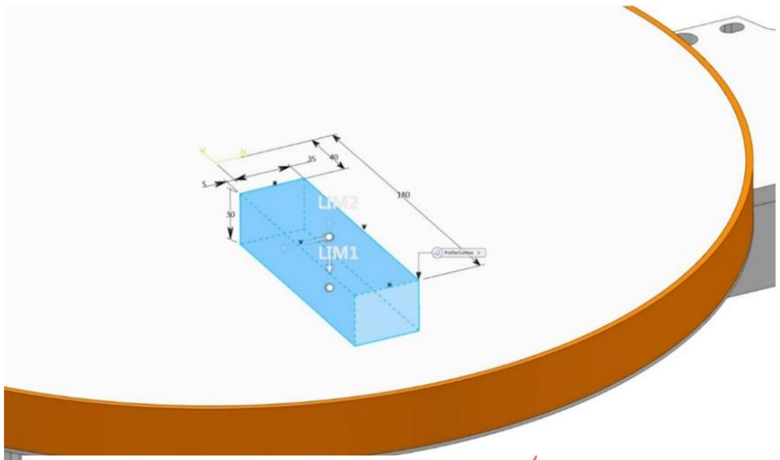


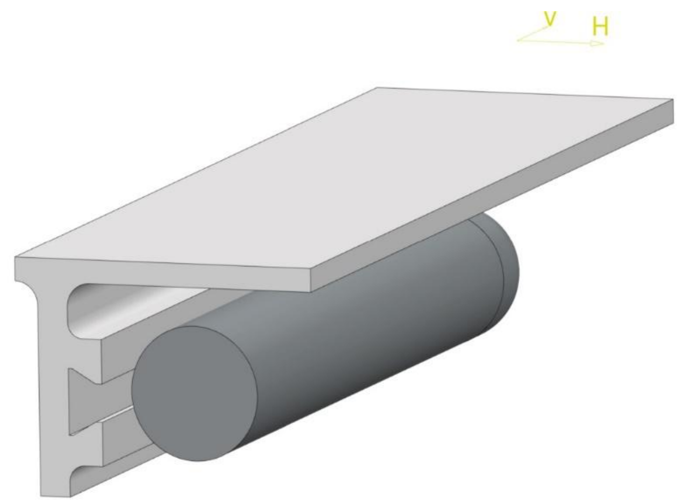
Procurement of special samples- EUROFERs from Karlsruhe Institute of Technology
Establish contacts between ESS and potential partners for PIE (Karlsruhe, Culham..)

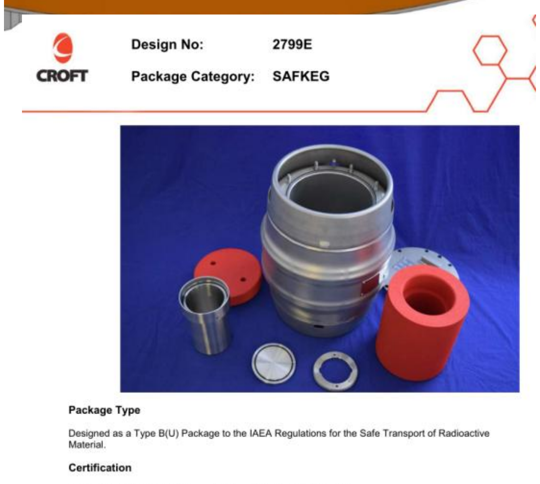
Work done in collaboration with Y. Lee

Interface with Remote Handling

In order to carry out Post Irradiation Examination, irradiated samples have to be extracted from the module.






CROFT

Design No: 2799E

Package Category: SAFKEG

Package Type

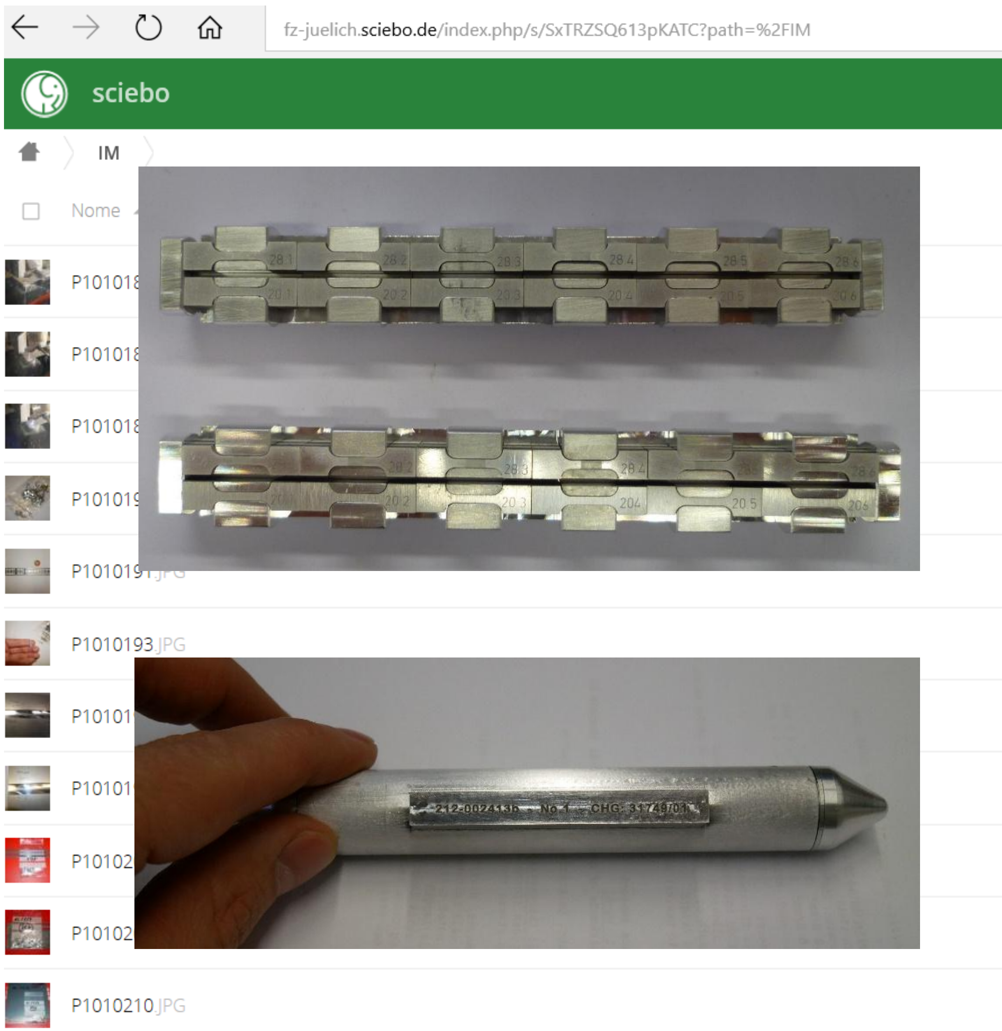
Designed as a Type B(U) Package to the IAEA Regulations for the Safe Transport of Radioactive Material.

Certification

Certified as a Type B(U) package by the UK Competent Authority.

Procedures for removing samples require collaboration with Remote Handling Group and Partners .

Manufacturing and assembly pictures



Final assembly by CNR-FZJ-ESS on November 7 2017 at FZJ

Manufacturing and assembly pictures

Nonferrous Metal	Ferrous Metal
Al6061-T6	Invar
Al5754-NET-O	Stainless Steel 316L
Al6061-T6 with Al4047 filler	EUROFER97
Al6061-T6 and Al5754-O hybrid	F82H

Not for a user community, but data relevant for spallation materials science

- The work unit completion is the integration of the module into the thermal moderator. NOTE: scientific value (data) will be garnered (data collected) after irradiation and Post Irradiation Examination (>2025+)

Suggested literature

- Displacement damage
- *R.S. Averback and T. Diaz de la Rubia, Displacement Damage in Irradiated Metals and Semiconductors, Solid State Physics, Volume 51 (1998)*
- *Detlef Filges and Frank Goldenbaum, Handbook of Spallation Research, Wiley (2009)*
- *https://www.psi.ch/lnm/sinq-target-irradiation-program-stip*
- *ESS webpages*
- SEE effects on electronics
- *https://www.isis.stfc.ac.uk/Pages/ChipIR.aspx*
- *R. Jones, A. Chugg, Radiation damage - Neutron time bomb, Electronics Systems and Software (Volume: 4, Issue: 6, Dec. 2006)*

Thank you (for flying with us)!
Questions?