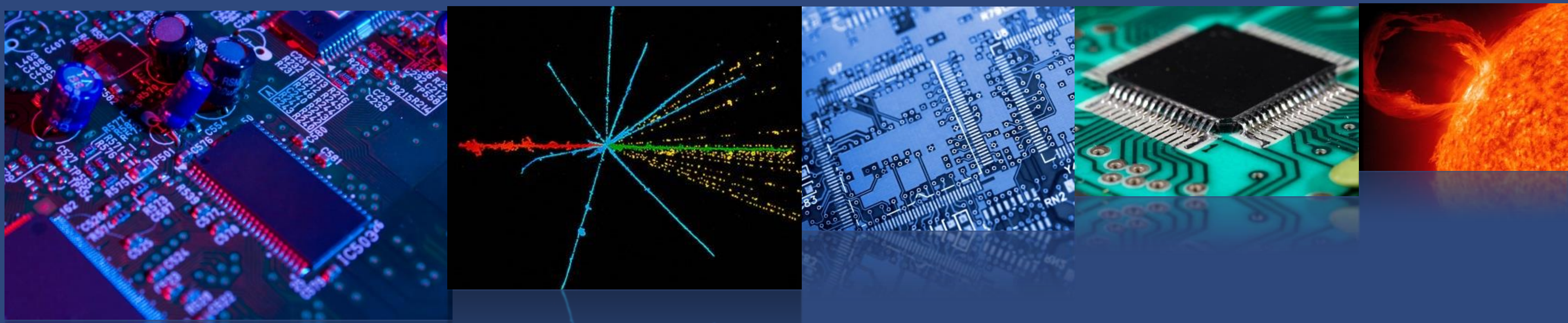
Design, characterization and commissioning of an atmospheric neutron beamline for the irradiation of microelectronics



Carlo Cazzaniga

STFC, Rutherford Appleton Laboratory, UK

carlo.cazzaniga@stfc.ac.uk

Can alien invaders change government?

Schaerbeek, Belgium

May 18th 2003, 22:30

“worried about the influence of Martians on these elections….
unless the cosmic rays affect our lists in a positive way!”

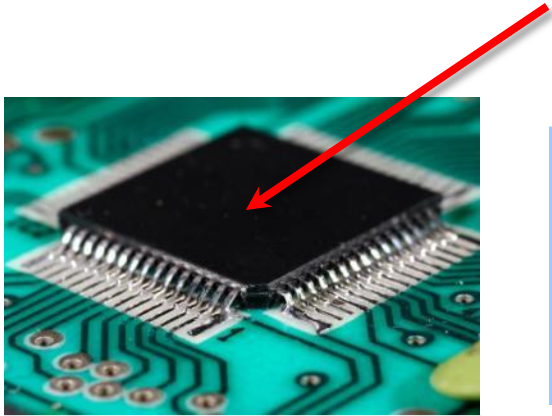
4096 (2^{12}) votes added to an electronic voting machine

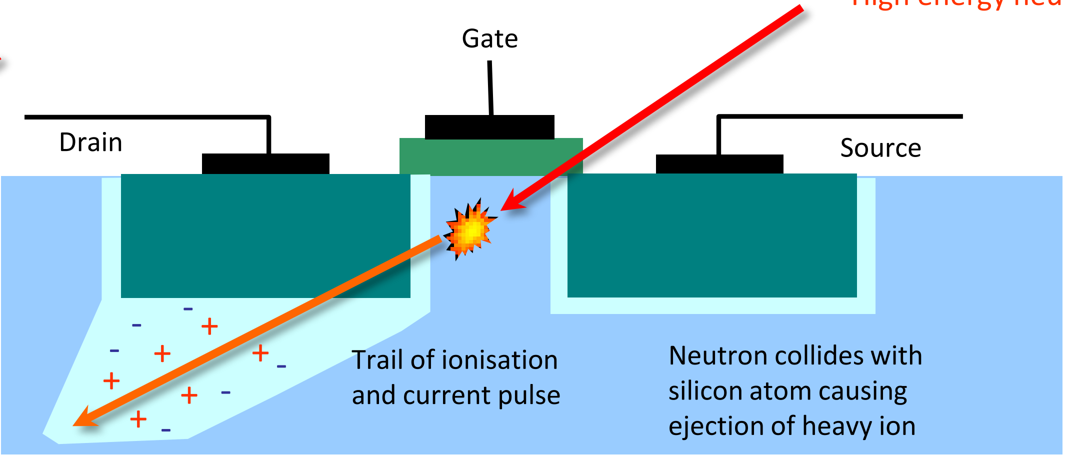
0	0	0	0	0	1	0	0	0	1	1	0	0	1	1	0	1

4096

Science & Technology Facilities Council
ISIS

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

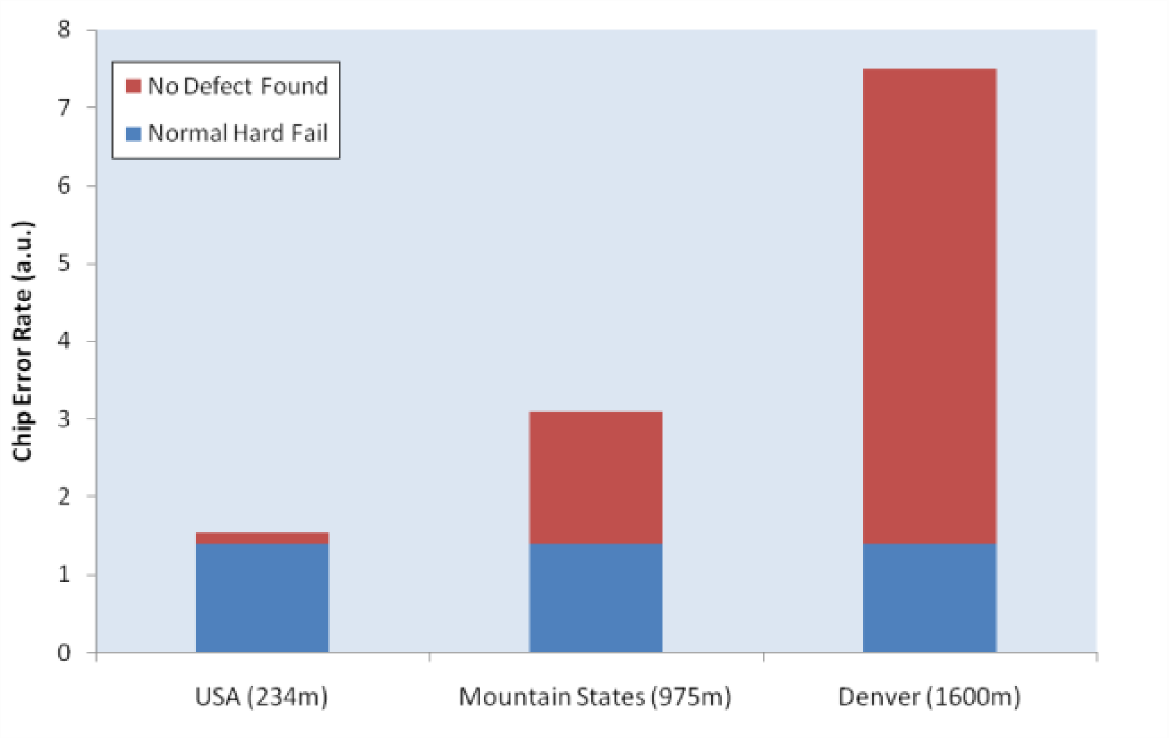


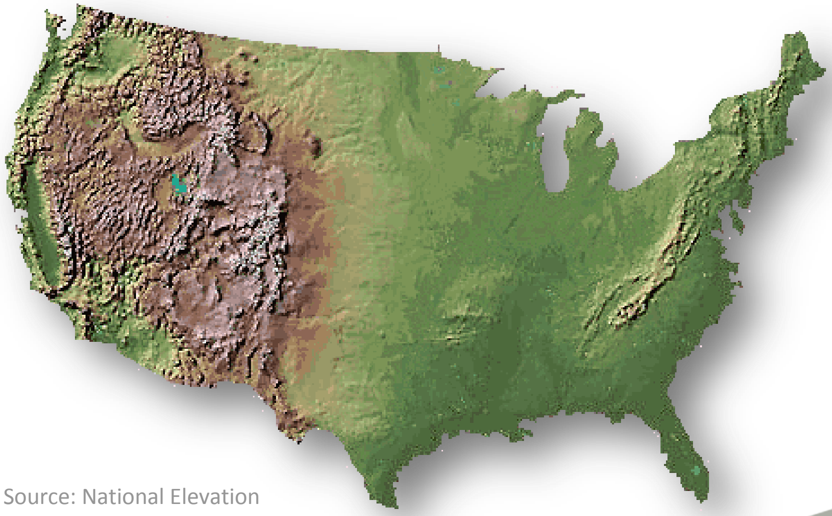


High energy neutron

Trail of ionisation and current pulse

Neutron collides with silicon atom causing ejection of heavy ion





Source: National Elevation
Dataset: USGS

Reproduced from J.F.Ziegler et al IBM. J. Res. Develop. 40, 1996, p3

Science & Technology Facilities Council
ISIS

‘Real-world Incident’

7th October 2008 at 04:40:26
Flight Qantus QF72
Singapore to Perth

Travel News

'Cosmic rays' may have hit Qantas plane off Australia's northwest coast

By Ben Packham | Herald Sun | November 19, 2009 12:01am

- Two terrifying dives by Qantas Airbus
- Flight attendant, passengers injured
- Cosmic rays from space may be to blame

COSMIC rays may have been responsible for a near disaster involving a Qantas jet off Australia's northwest coast.

Safety investigators have isolated the cause of two terrifying dives by the Airbus A330-303 to an onboard computer.

But the computer itself, fitted to about 900 aircraft worldwide, was found to be in perfect working order, the Herald Sun reports.

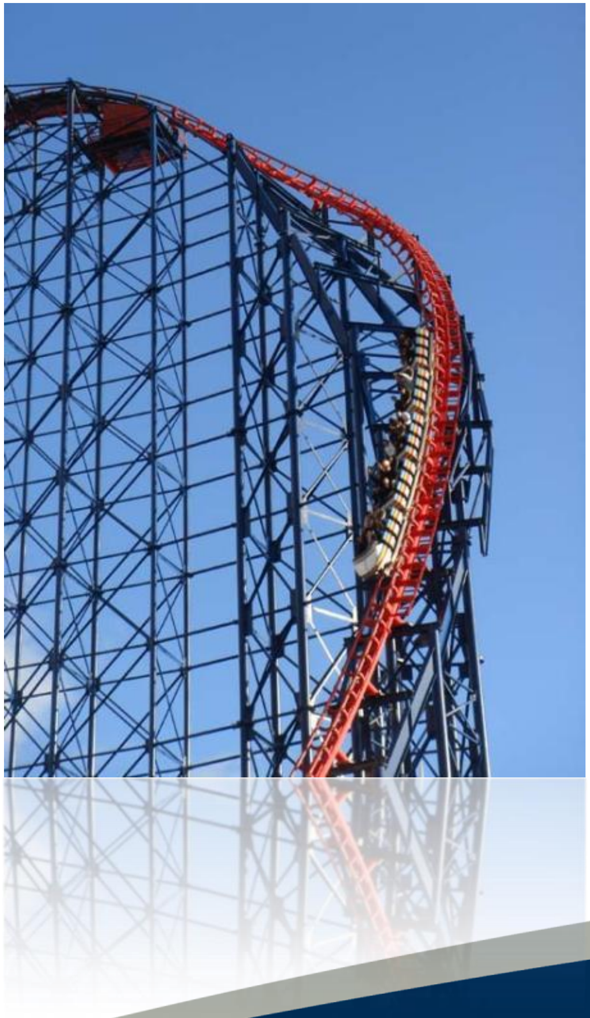
A flight attendant and 11 passengers were seriously injured and many others experienced minor injuries in a near-miss on October 8 last year.

The aircraft's nose pitched violently downward twice in rapid succession, diving 650ft and 400ft, throwing unsecured passengers and luggage around the cabin / File

An Australian Transport Safety Bureau report into the incident found at least six passengers' seatbelts came unfastened during the event.

ATSB probe Qantas jet

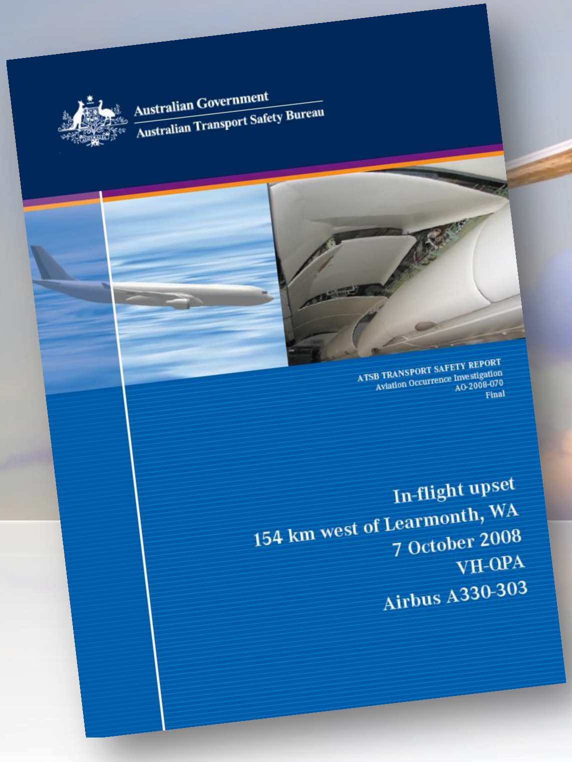
Science & Technology Facilities Council
ISIS



Equivalent of 3 Blackpool Rollercoasters

ATSB TRANSPORT SAFETY REPORT Aviation Occurrence Investigation
AO-2008-070
Final

ATSB TRANSPORT SAFETY REPORT Aviation Occurrence Investigation
AO-2008-070
Final

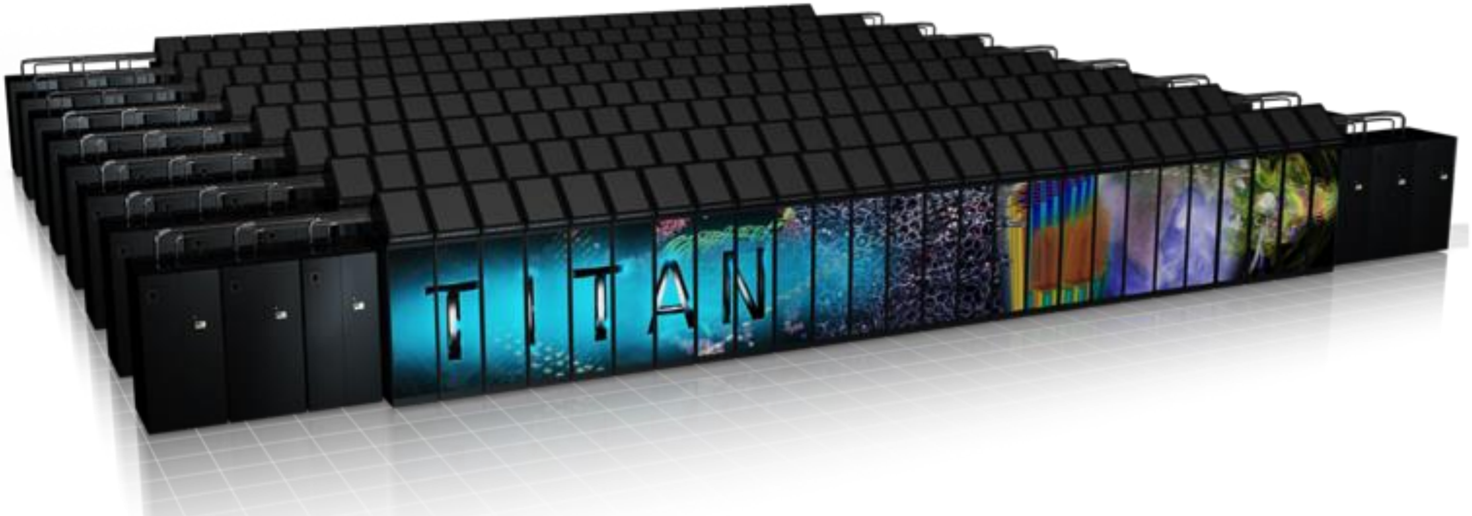


Australian Government
Australian Transport Safety Bureau

ATSB TRANSPORT SAFETY REPORT
Aviation Occurrence Investigation
AO-2008-070
Final

In-flight upset
154 km west of Learmonth, WA
7 October 2008
VH-QPA
Airbus A330-303

ATSB TRANSPORT SAFETY REPORT Aviation Occurrence Investigation
AO-2008-070
Final



Work at ISIS reported at RADECS 2013 (Oxford)

The control circuitry (scheduler) on a GPU can be corrupted by radiation, with severe repercussions on its reliability

High probability of having a GPU corrupted…

…Titan personnel: “we have 1 error every 10 minutes”

Consumer

Low Reliability

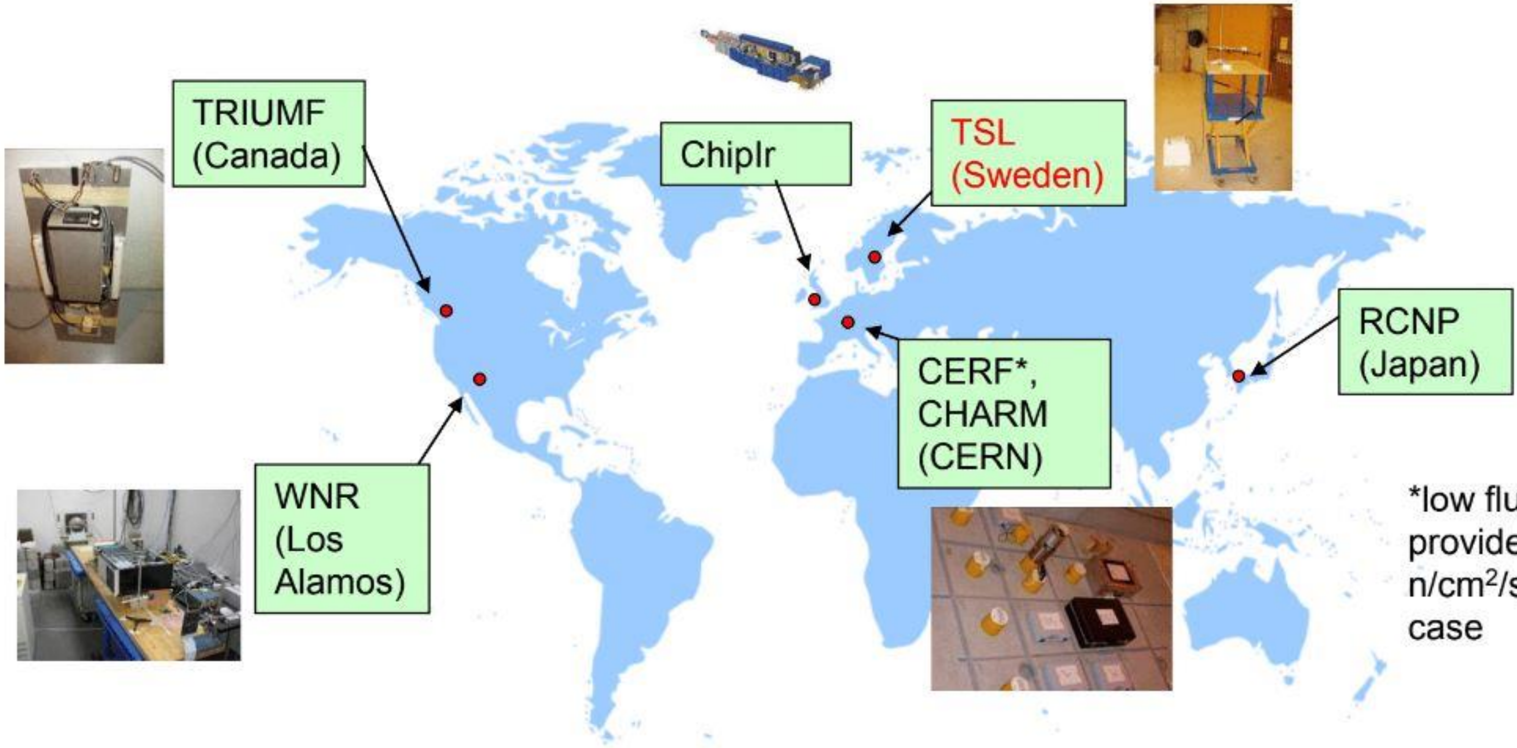
Communications

High Reliability

Critical

What can we do? Neutron test!

- Few appropriate facilities worldwide:



TRIUMF (Canada)

ChipIr

TSL (Sweden)

WNR (Los Alamos)

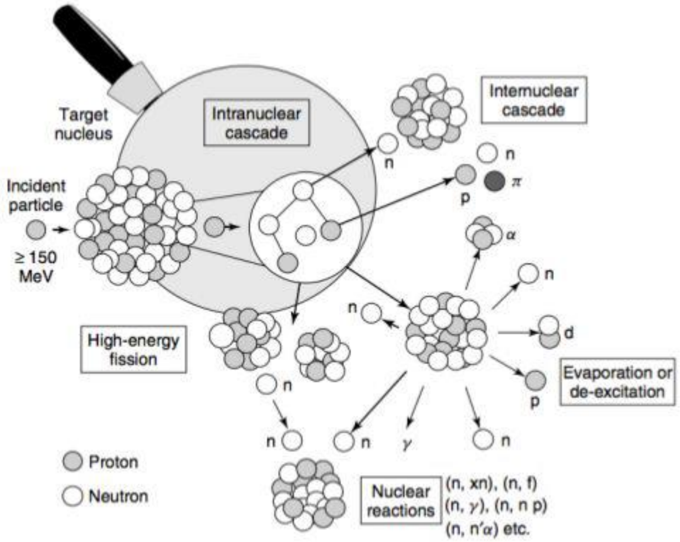
CERF*, CHARM (CERN)

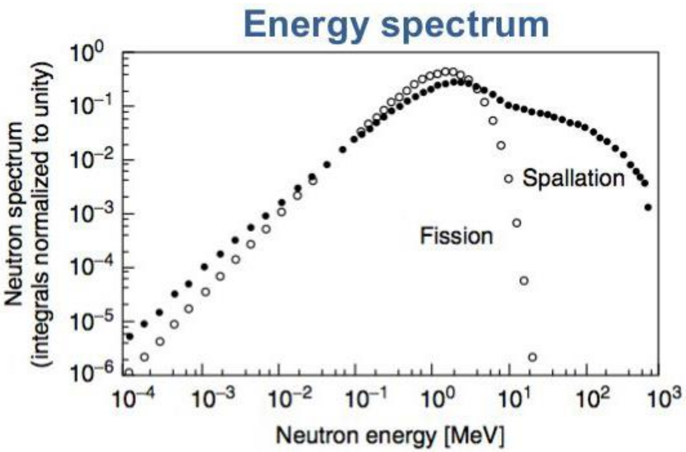
RCNP (Japan)

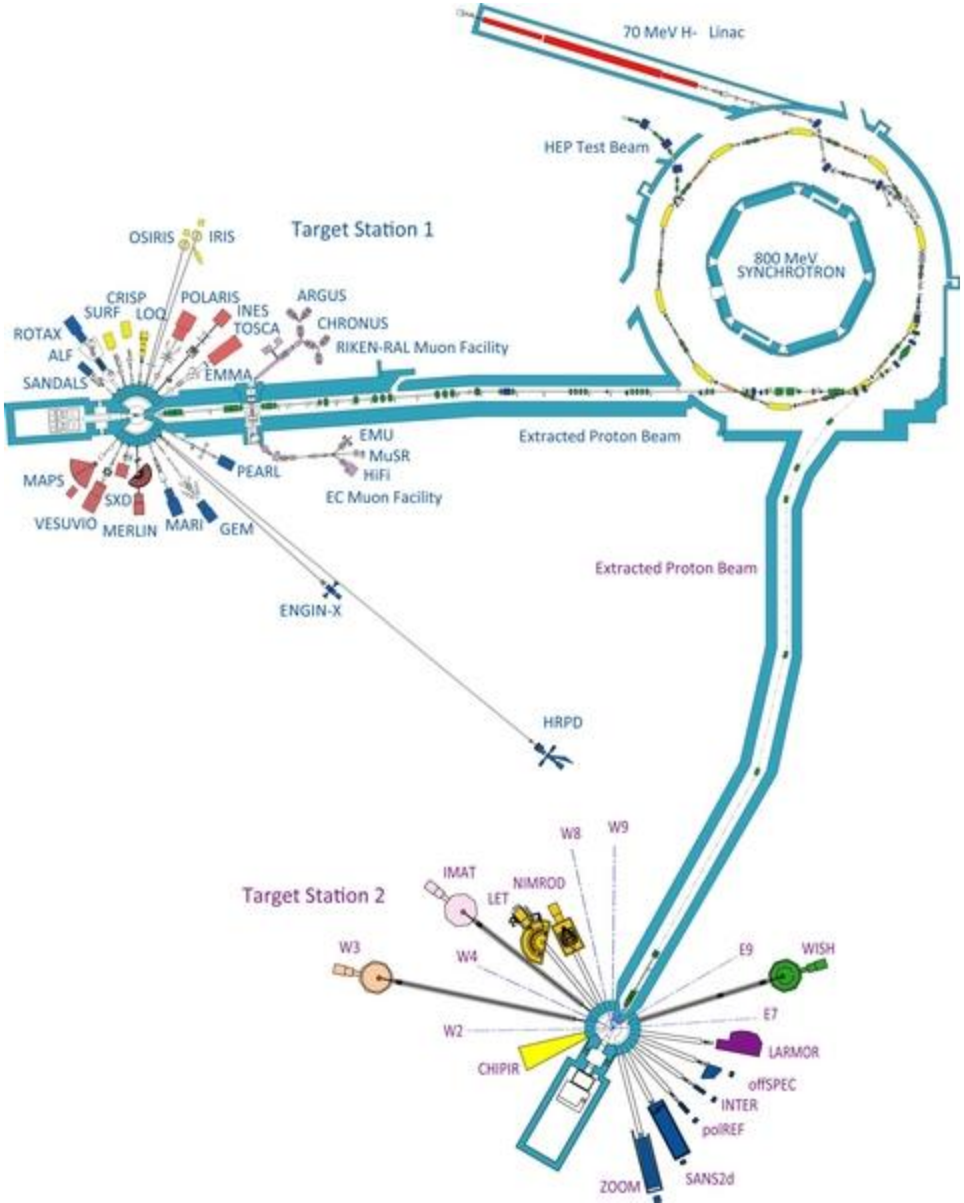
*low flux (can’t provide 10^5 n/cm^2/s) worst case

The facility at RAL

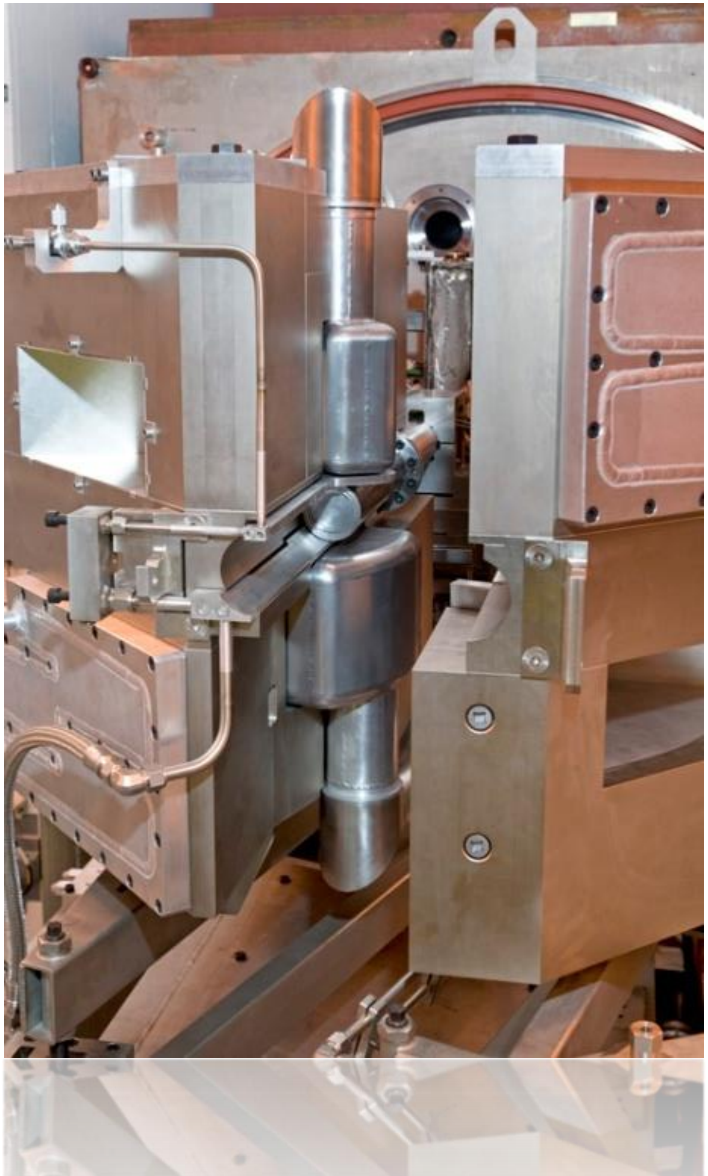
The spallation neutron source at RAL

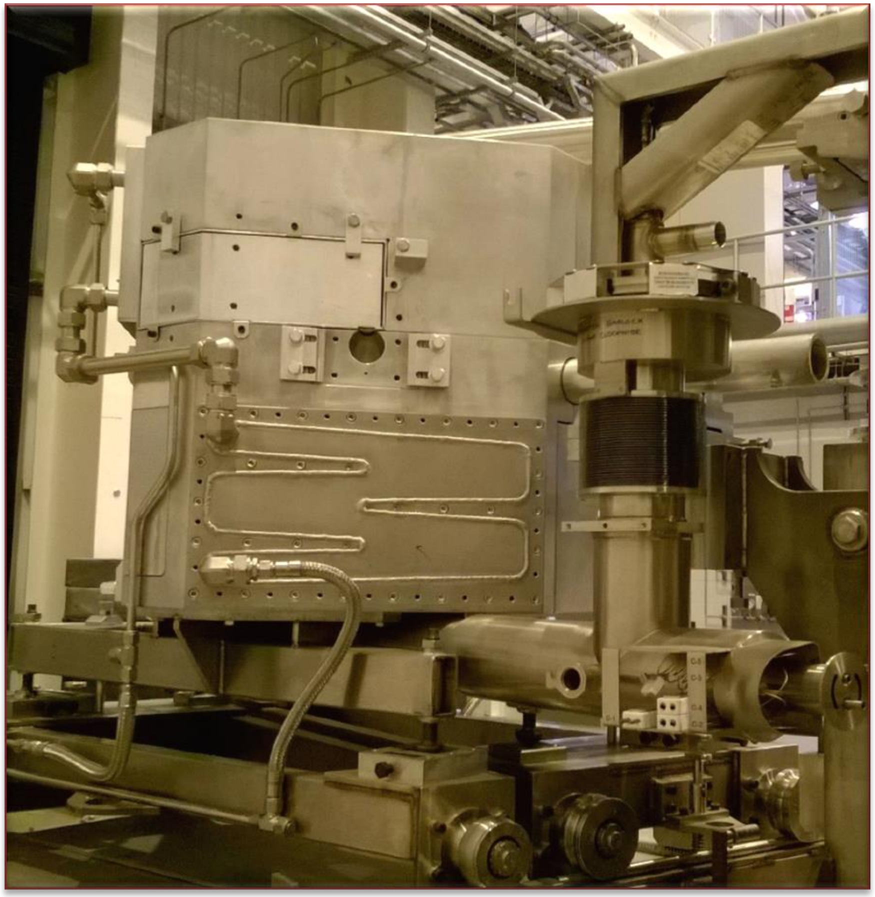






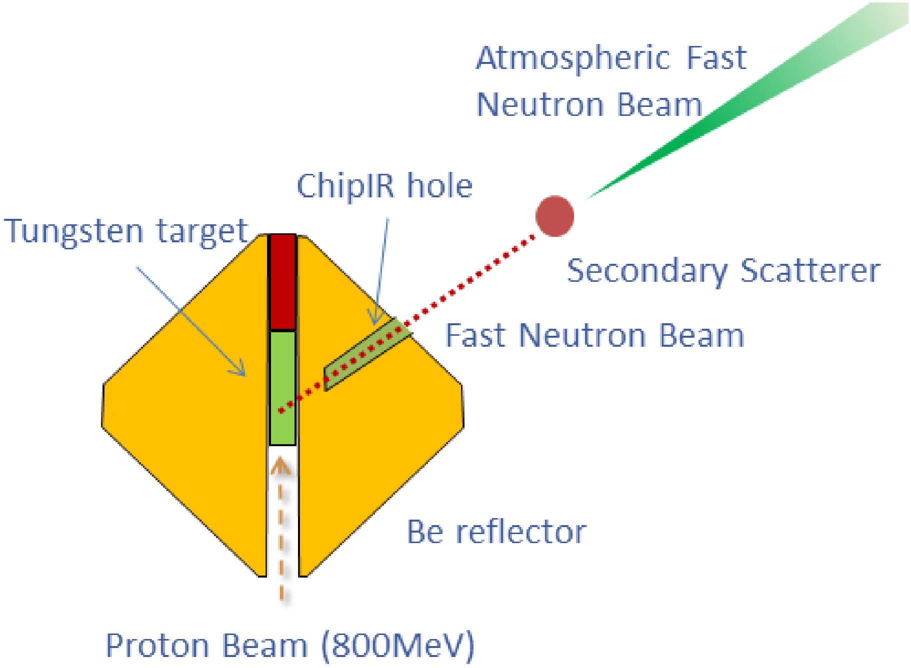
The Target

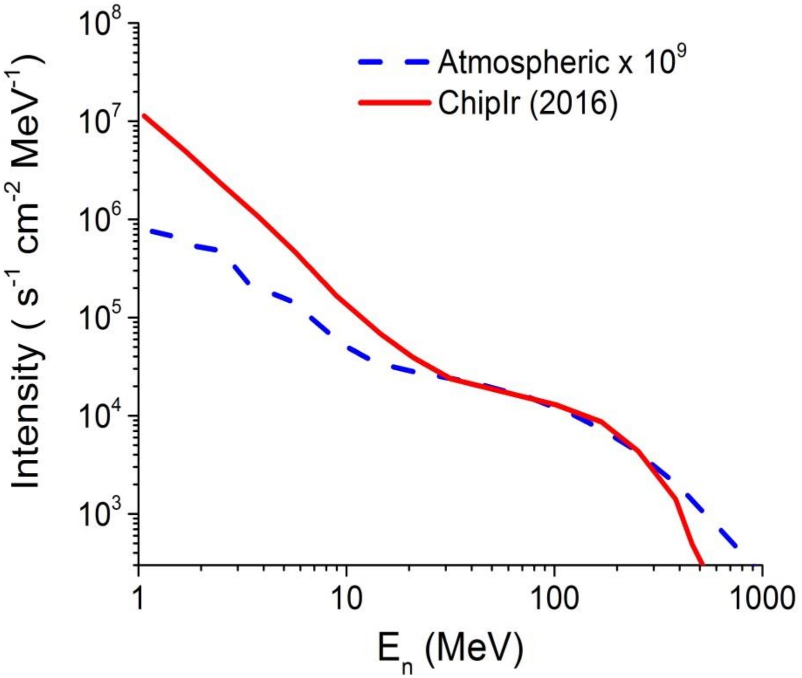




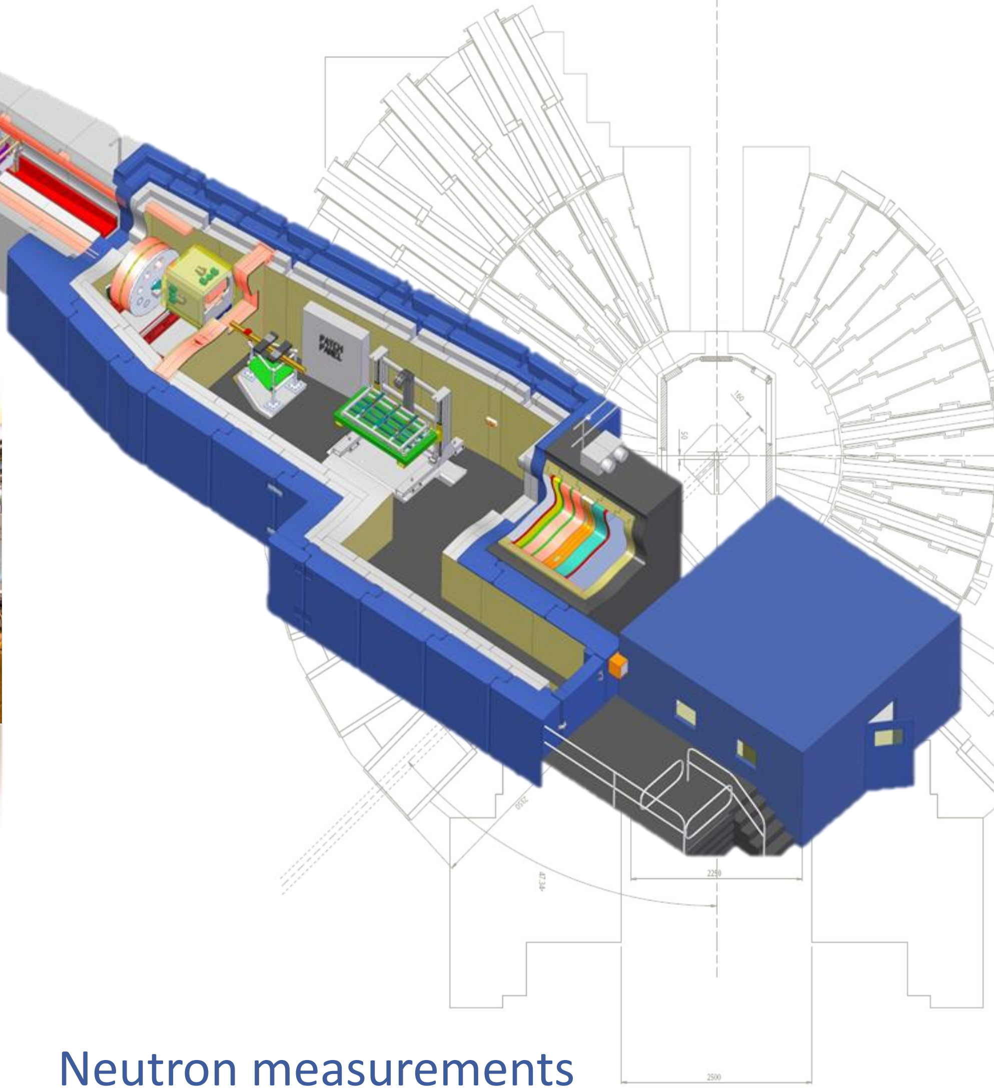
ChipIr

Fast neutron transport Optimized on the basis of Monte Carlo calculations





Fast Neutron Beam



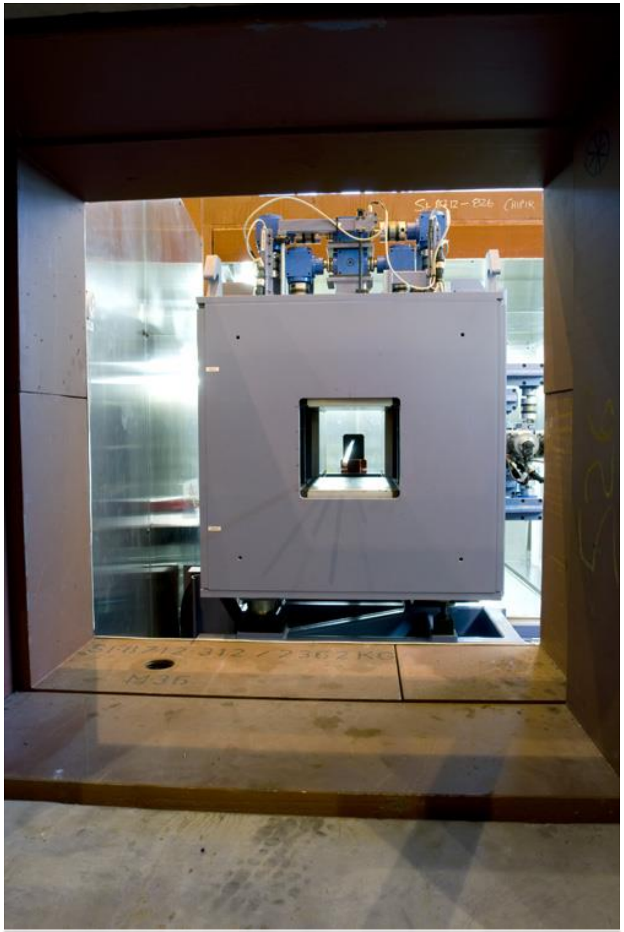
State-of-the-Art Instrument

- Optimised flux and spectrum
- Collimators and filters
- Two irradiation position

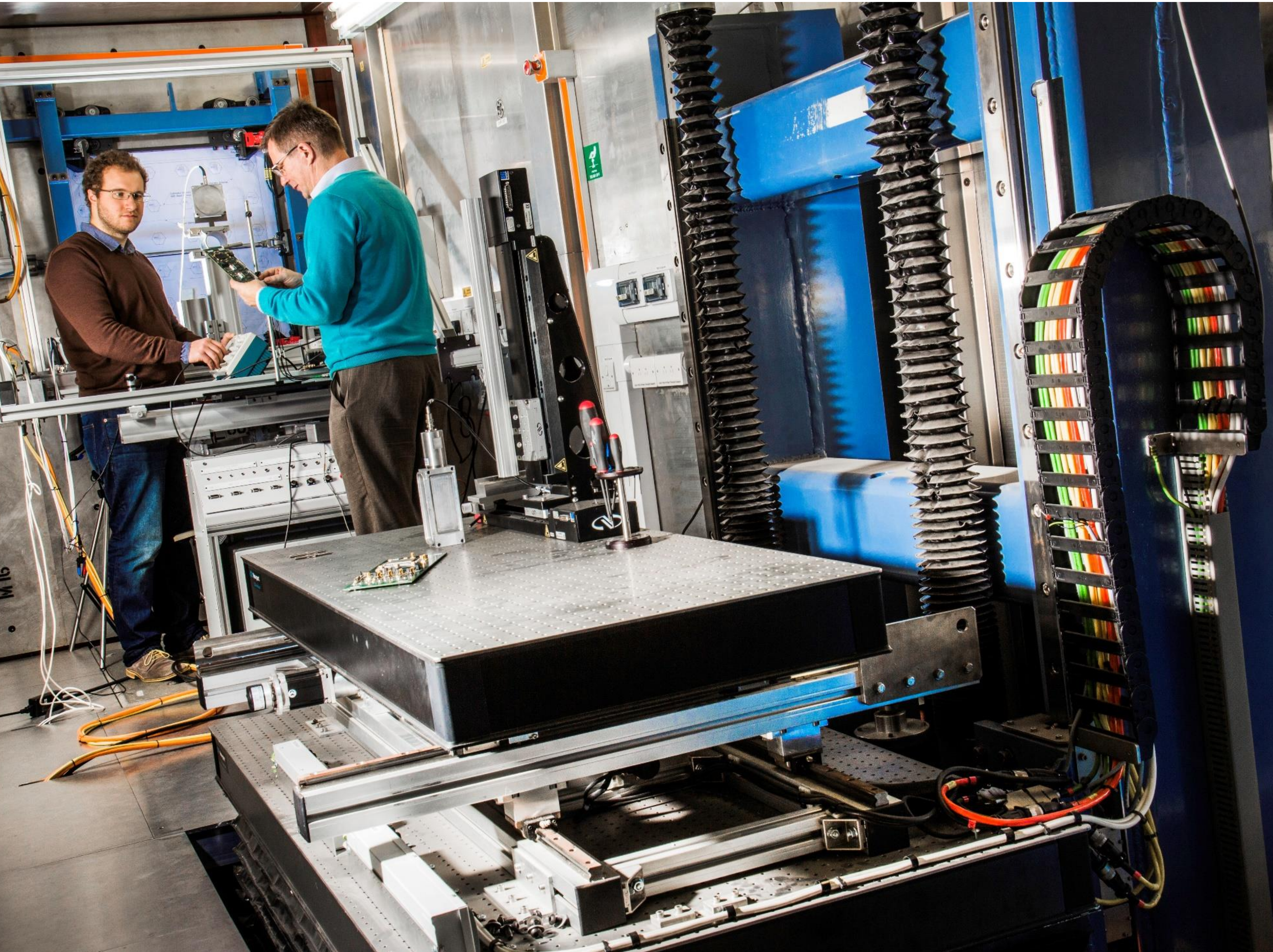
Neutron measurements

- Flux and spectrum
- Profiles and maps
- Different configuration of the beamline (eg. 800 MeV and 700MeV)

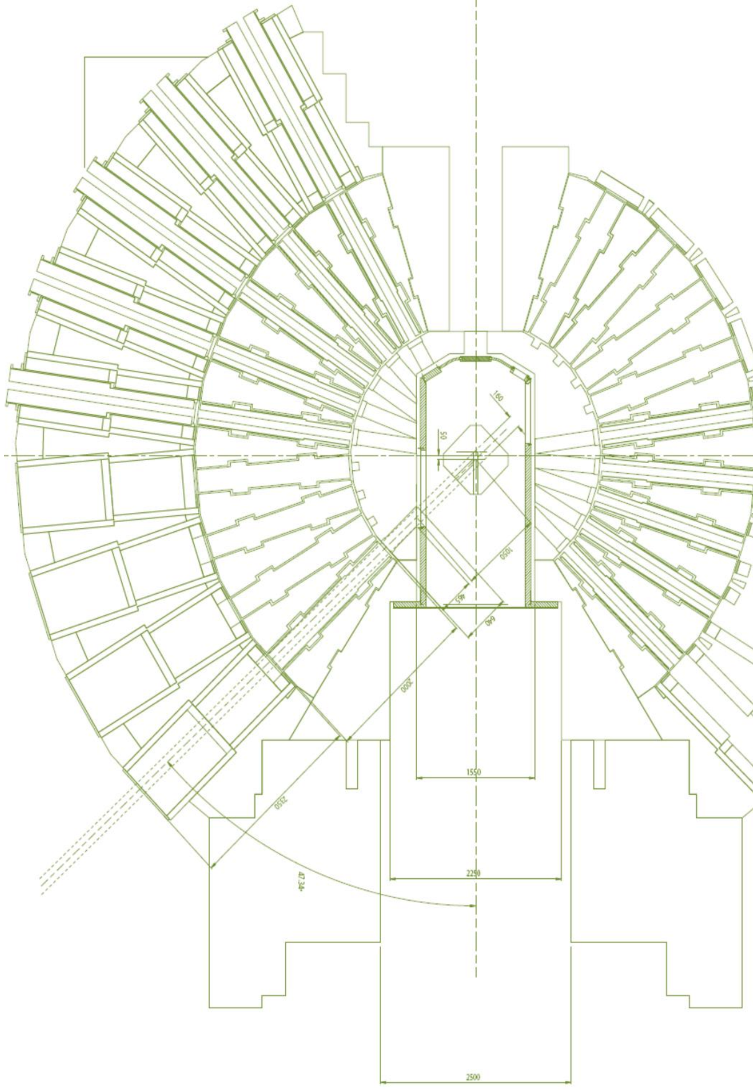
Build



Build

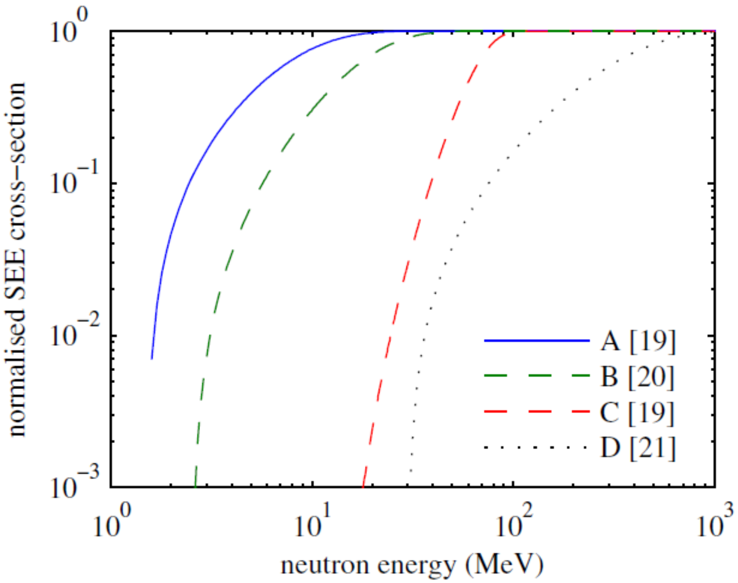


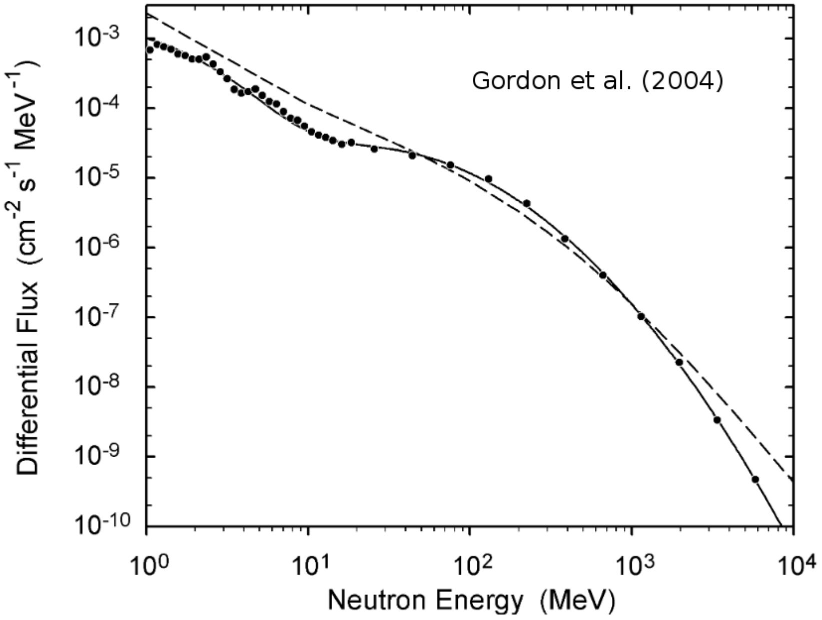
NEUTRON MEASUREMENTS



Spectrum, why is it important?

SELECTED SEE CROSS-SECTION FUNCTIONS





Neutron Spectrum

$$SER = \int \sigma_{SEE}(E) \left(\frac{d\phi(E)}{dE} \right) dE$$

Spectrum measurements: Activation foils

Step 1: find good reactions…

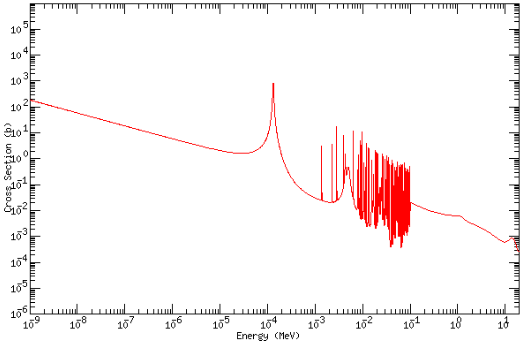
- Samples containing known amount of elements are irradiated and radioactive isotopes are produced by neutron activation reactions.
- Experimental measurement of the ***Activation Rate (R).***

$$R = N\int \sigma(E)\varphi(E)dE$$

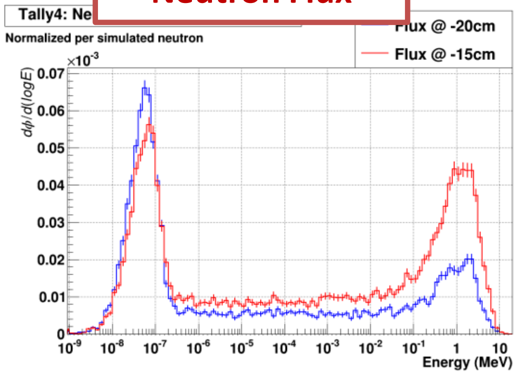
N = number of precursor isotopes
σ(E) = activation cross section
φ(E) = neutron flux

^{60}Co Activation Rate

^{59}Co (n,γ) cross section

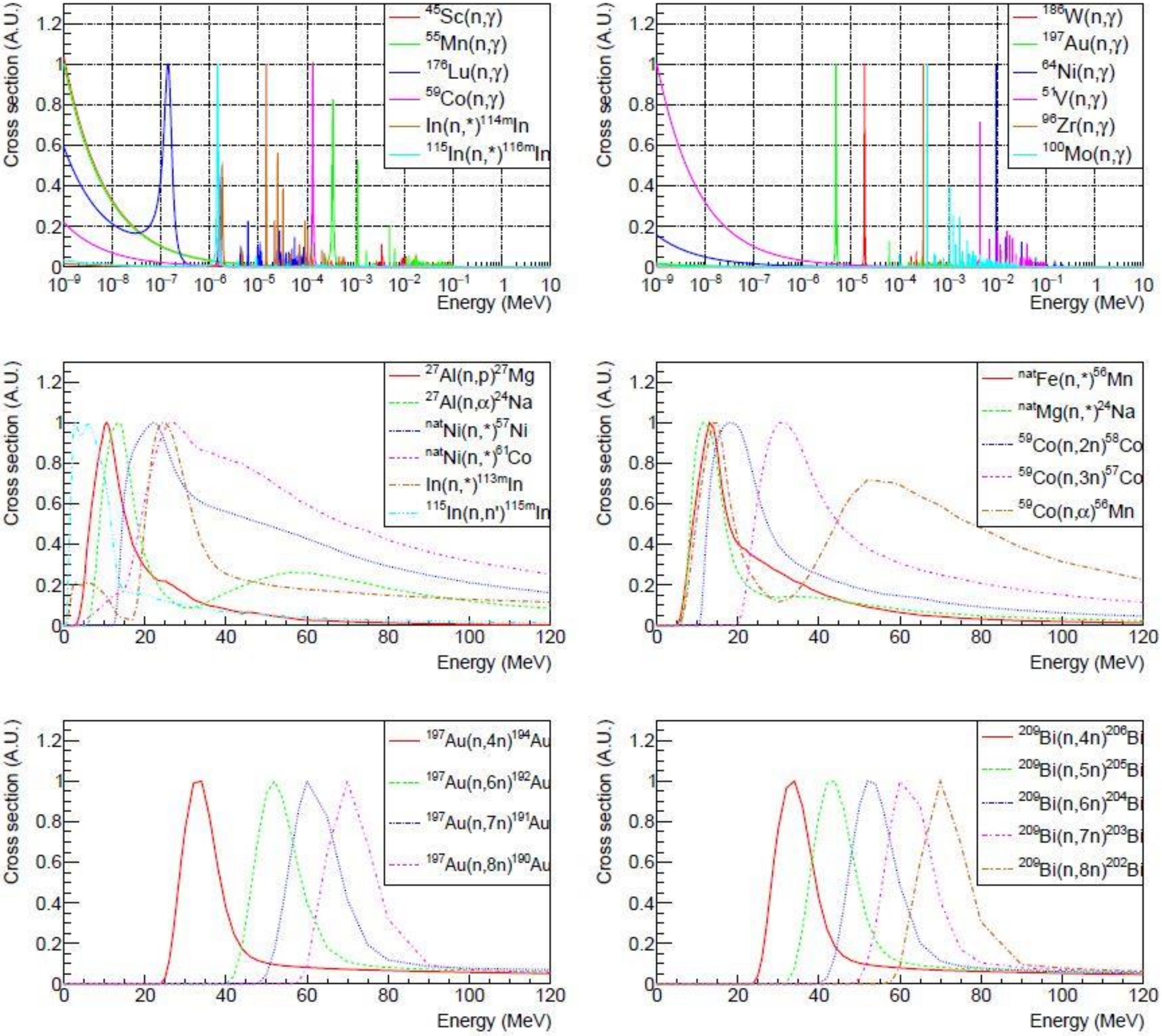


Neutron Flux

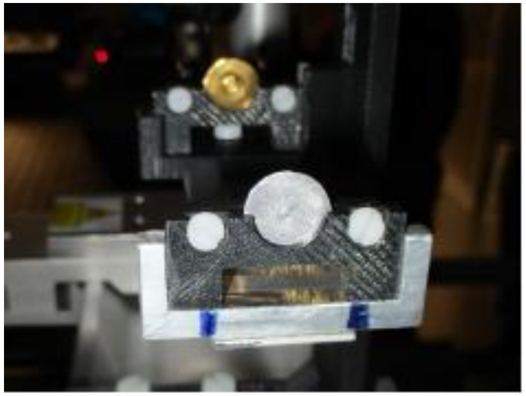


And good energy binning…

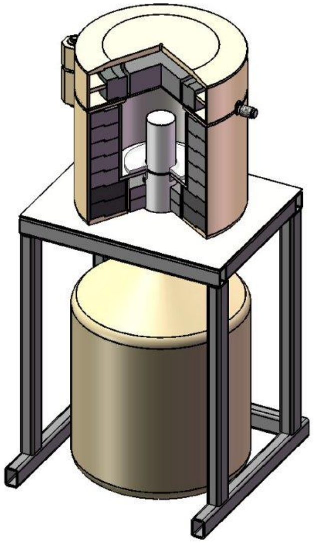
$$R_j = N_j\sum_{i=1}^{n}\sigma_{ij}\phi_i$$


Cross section (A.U.)
Energy (MeV)
^{45}Sc(n,γ)
^{55}Mn(n,γ)
^{176}Lu(n,γ)
^{59}Co(n,γ)
In(n,*)^{114m}In
^{115}In(n,*)^{116m}In
^{186}W(n,γ)
^{197}Au(n,γ)
^{64}Ni(n,γ)
^{51}V(n,γ)
^{96}Zr(n,γ)
^{100}Mo(n,γ)
^{27}Al(n,p)^{27}Mg
^{27}Al(n,α)^{24}Na
^{nat}Ni(n,*)^{57}Ni
^{nat}Ni(n,*)^{61}Co
In(n,*)^{113m}In
^{115}In(n,n')^{115m}In
^{nat}Fe(n,*)^{56}Mn
^{nat}Mg(n,*)^{24}Na
^{59}Co(n,2n)^{58}Co
^{59}Co(n,3n)^{57}Co
^{59}Co(n,α)^{56}Mn
^{197}Au(n,4n)^{194}Au
^{197}Au(n,6n)^{192}Au
^{197}Au(n,7n)^{191}Au
^{197}Au(n,8n)^{190}Au
^{209}Bi(n,4n)^{206}Bi
^{209}Bi(n,5n)^{205}Bi
^{209}Bi(n,6n)^{204}Bi
^{209}Bi(n,7n)^{203}Bi
^{209}Bi(n,8n)^{202}Bi
0
0.2
0.4
0.6
0.8
1
1.2
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
0
20
40
60
80
100
120

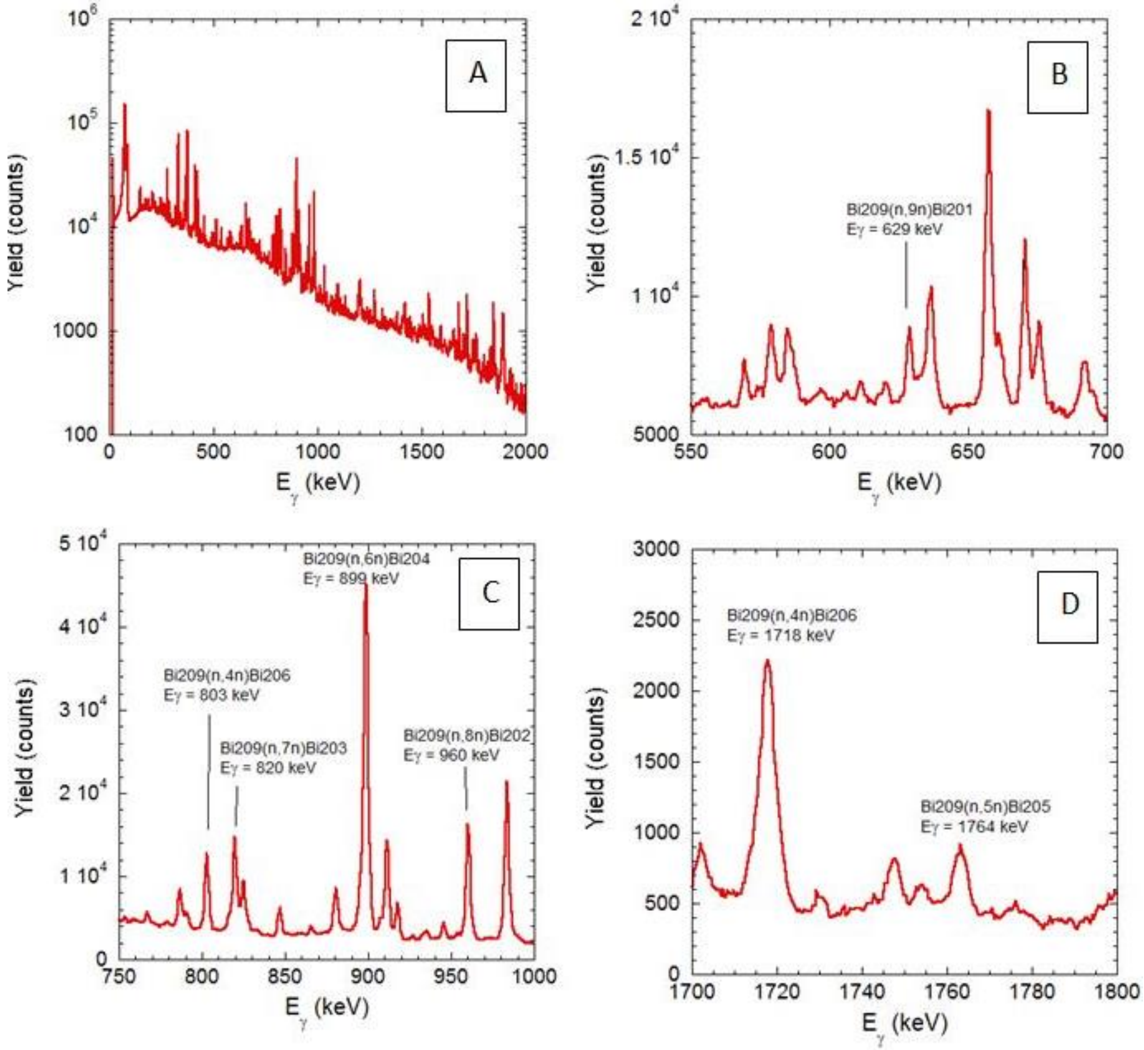
Step 2: Measure the activation gamma lines



Targets irradiated on the beam line



Targets measured on a Germanium detector



Step 3: Calculate the activation rates

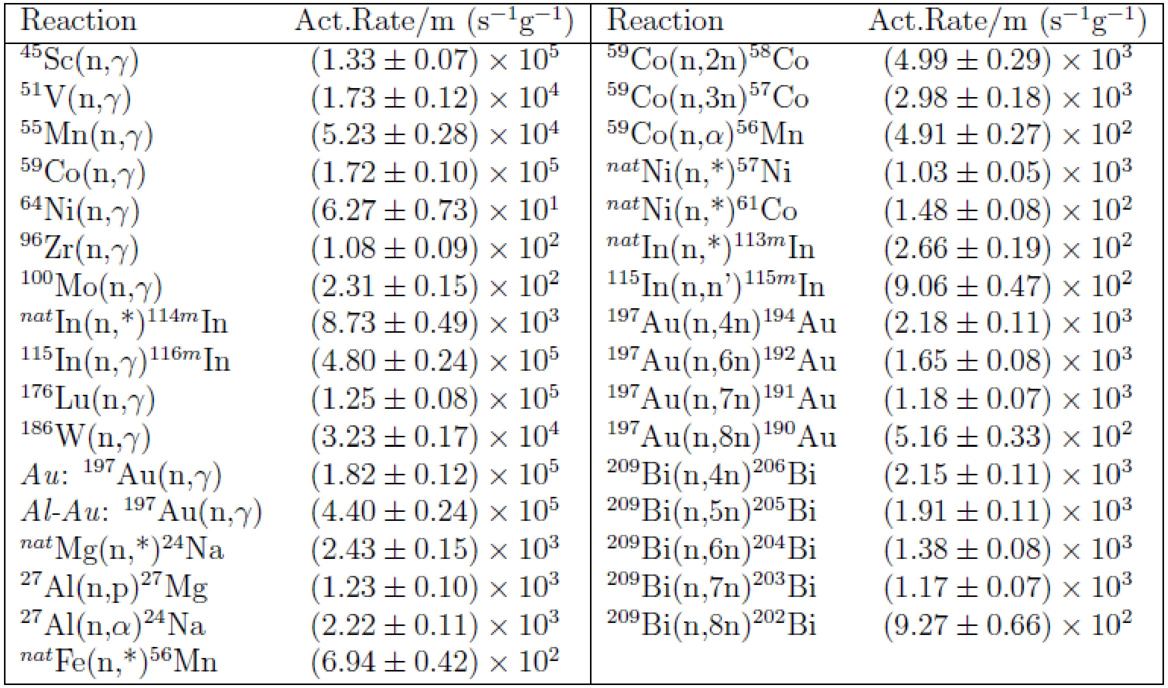
During irradiation:

$$\boxed{dN = R\,dt - N\lambda\,dt}$$

Activity after irradiation:

$$\boxed{A(t) = R\left(1 - e^{-\lambda t_{irr}}\right)e^{-\lambda t}}$$

λ = decay constant



Reaction	Act.Rate/m ($s^{-1}g^{-1}$)	Reaction	Act.Rate/m ($s^{-1}g^{-1}$)
^{45}Sc(n,γ)	$(1.33 \pm 0.07) \times 10^5$	^{59}Co(n,2n)^{58}Co	$(4.99 \pm 0.29) \times 10^3$
^{51}V(n,γ)	$(1.73 \pm 0.12) \times 10^4$	^{59}Co(n,3n)^{57}Co	$(2.98 \pm 0.18) \times 10^3$
^{55}Mn(n,γ)	$(5.23 \pm 0.28) \times 10^4$	^{59}Co(n,α)^{56}Mn	$(4.91 \pm 0.27) \times 10^2$
^{59}Co(n,γ)	$(1.72 \pm 0.10) \times 10^5$	^{nat}Ni(n,*)^{57}Ni	$(1.03 \pm 0.05) \times 10^3$
^{64}Ni(n,γ)	$(6.27 \pm 0.73) \times 10^1$	^{nat}Ni(n,*)^{61}Co	$(1.48 \pm 0.08) \times 10^2$
^{96}Zr(n,γ)	$(1.08 \pm 0.09) \times 10^2$	^{nat}In(n,*)^{113m}In	$(2.66 \pm 0.19) \times 10^2$
^{100}Mo(n,γ)	$(2.31 \pm 0.15) \times 10^2$	^{115}In(n,n')^{115m}In	$(9.06 \pm 0.47) \times 10^2$
^{nat}In(n,*)^{114m}In	$(8.73 \pm 0.49) \times 10^3$	^{197}Au(n,4n)^{194}Au	$(2.18 \pm 0.11) \times 10^3$
^{115}In(n,γ)^{116m}In	$(4.80 \pm 0.24) \times 10^5$	^{197}Au(n,6n)^{192}Au	$(1.65 \pm 0.08) \times 10^3$
^{176}Lu(n,γ)	$(1.25 \pm 0.08) \times 10^5$	^{197}Au(n,7n)^{191}Au	$(1.18 \pm 0.07) \times 10^3$
^{186}W(n,γ)	$(3.23 \pm 0.17) \times 10^4$	^{197}Au(n,8n)^{190}Au	$(5.16 \pm 0.33) \times 10^2$
Au: ^{197}Au(n,γ)	$(1.82 \pm 0.12) \times 10^5$	^{209}Bi(n,4n)^{206}Bi	$(2.15 \pm 0.11) \times 10^3$
Al-Au: ^{197}Au(n,γ)	$(4.40 \pm 0.24) \times 10^5$	^{209}Bi(n,5n)^{205}Bi	$(1.91 \pm 0.11) \times 10^3$
^{nat}Mg(n,*)^{24}Na	$(2.43 \pm 0.15) \times 10^3$	^{209}Bi(n,6n)^{204}Bi	$(1.38 \pm 0.08) \times 10^3$
^{27}Al(n,p)^{27}Mg	$(1.23 \pm 0.10) \times 10^3$	^{209}Bi(n,7n)^{203}Bi	$(1.17 \pm 0.07) \times 10^3$
^{27}Al(n,α)^{24}Na	$(2.22 \pm 0.11) \times 10^3$	^{209}Bi(n,8n)^{202}Bi	$(9.27 \pm 0.66) \times 10^2$
^{nat}Fe(n,*)^{56}Mn	$(6.94 \pm 0.42) \times 10^2$		

Measured activation rates

decays expected to occur during the measurement:

$$\boxed{n_{dec} = \frac{R}{\lambda}\left(1 - e^{-\lambda t_{irr}}\right)e^{-\lambda t_{wait}}\left(1 - e^{-\lambda t_{meas}}\right)}$$

Step 4: Unfolding and results

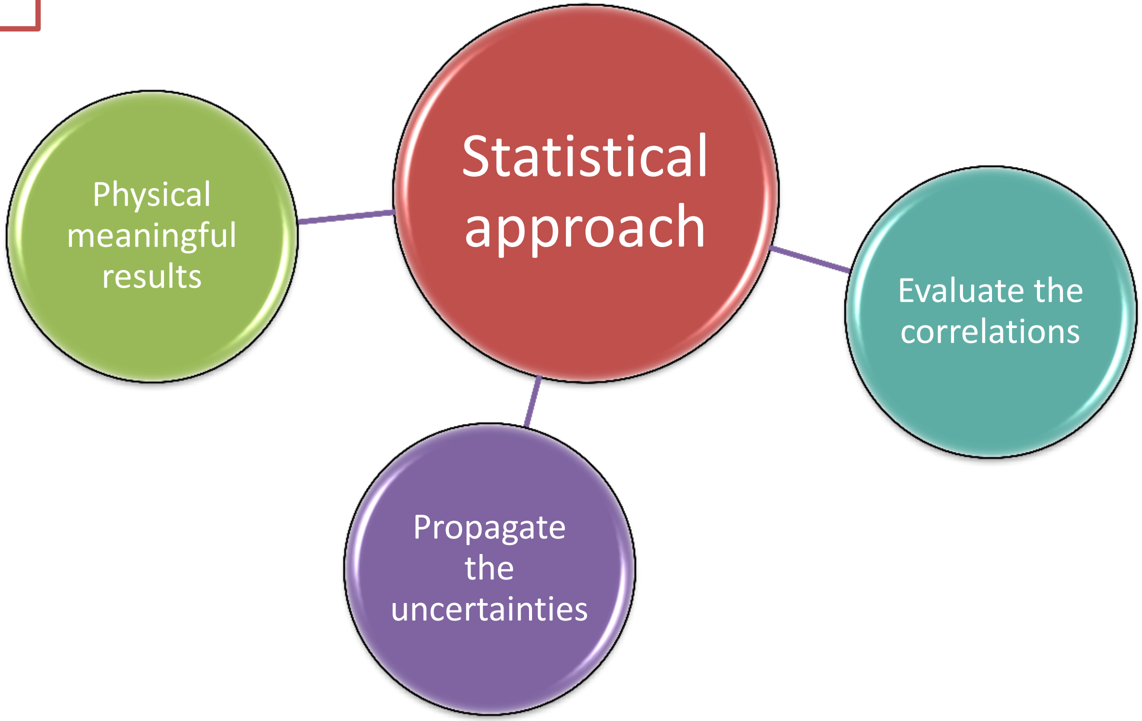
$$R_j = N_j \sum_{i=1}^{n} \sigma_{ij} \phi_i$$

$$\begin{cases} \frac{R_A}{N_A} = \sigma_{1A}\Phi_1 + \sigma_{2A}\Phi_2 + \sigma_{3A}\Phi_3 \\ \frac{R_B}{N_B} = \sigma_{1B}\Phi_1 + \sigma_{2B}\Phi_2 + \sigma_{3B}\Phi_3 \\ \frac{R_C}{N_C} = \sigma_{1C}\Phi_1 + \sigma_{2C}\Phi_2 + \sigma_{3C}\Phi_3 \end{cases}$$

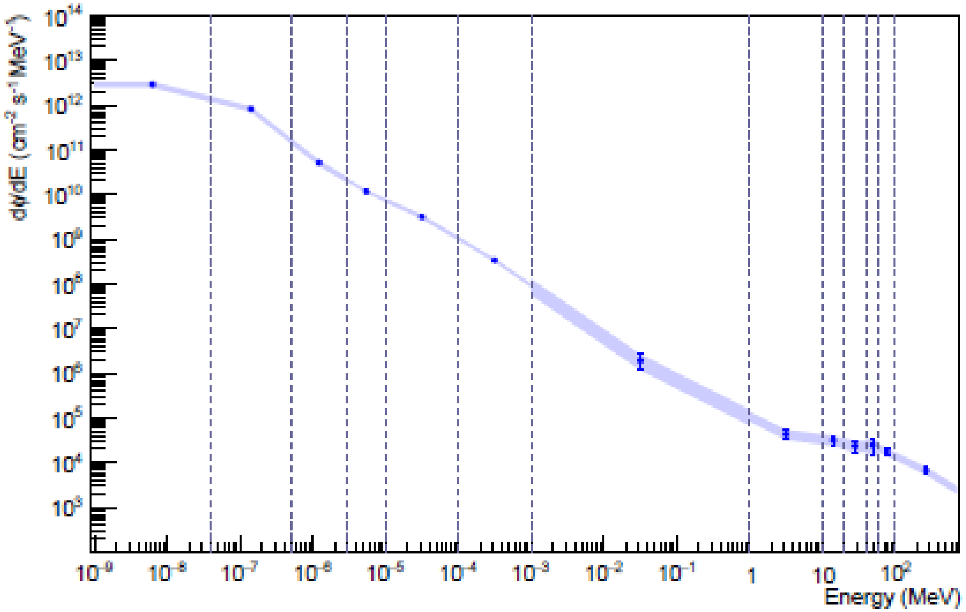
R_X/N_X = activation rate per precursor isotope X

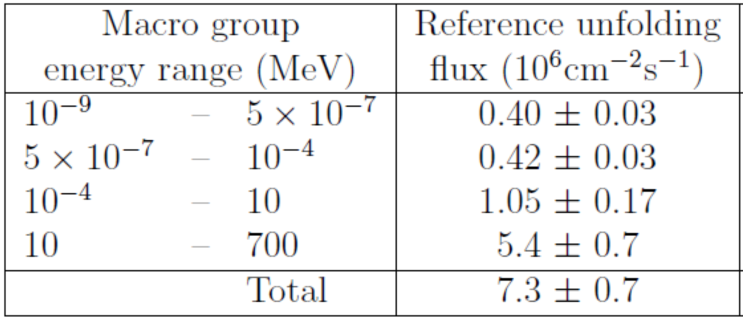
$\sigma_{iX}(E)$ = activation cross section of isotope X in the *i-th* energy group

Example of the linear system in the case of 3 activated isotopes and 3 energy groups

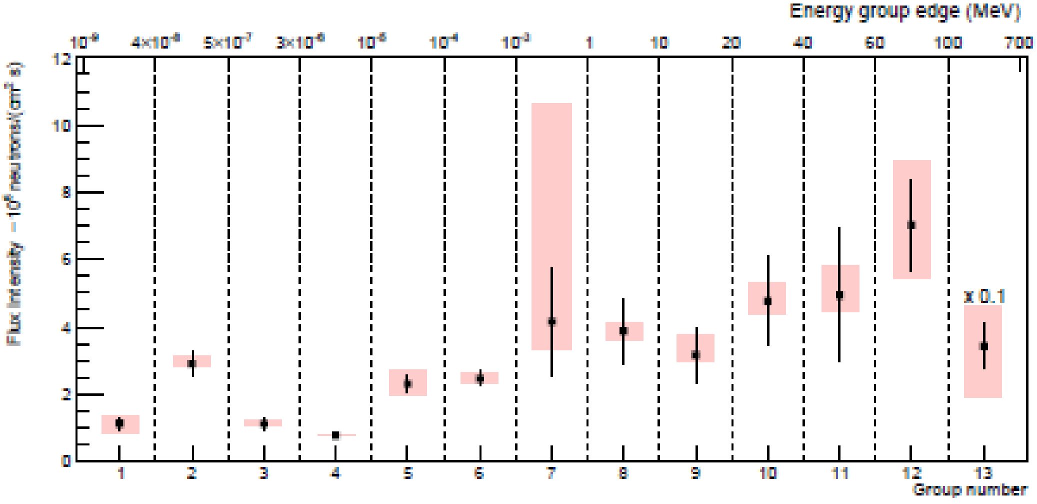


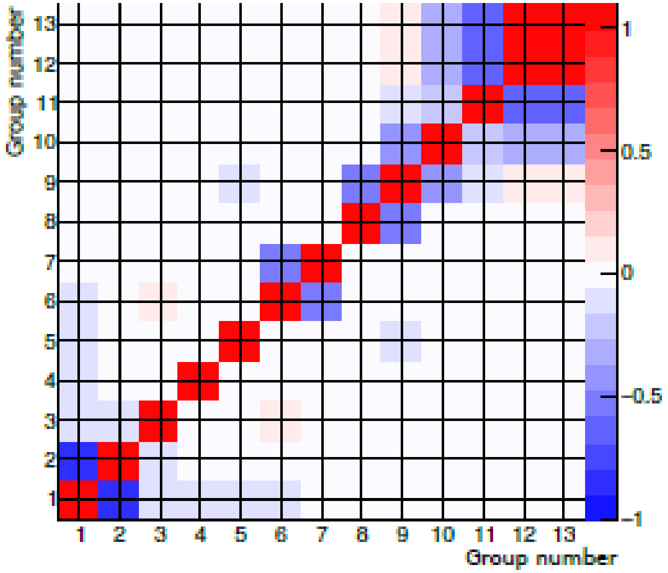
Step 4: Unfolding and results



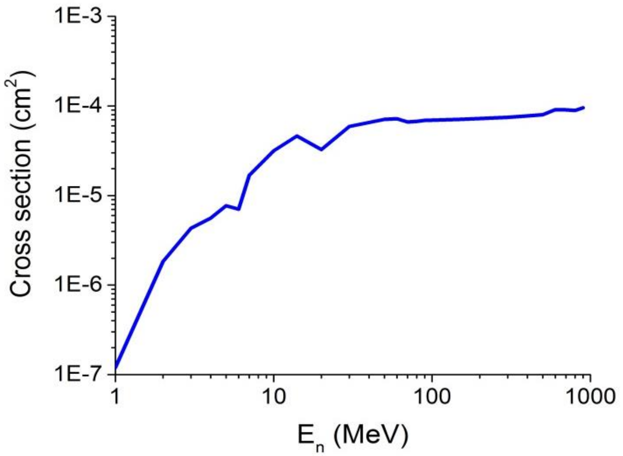


Macro group energy range (MeV)	Reference unfolding flux (10^6cm^{-2}s^{-1})
10^{-9} – 5×10^{-7}	0.40 ± 0.03
5×10^{-7} – 10^{-4}	0.42 ± 0.03
10^{-4} – 10	1.05 ± 0.17
10 – 700	5.4 ± 0.7
Total	7.3 ± 0.7

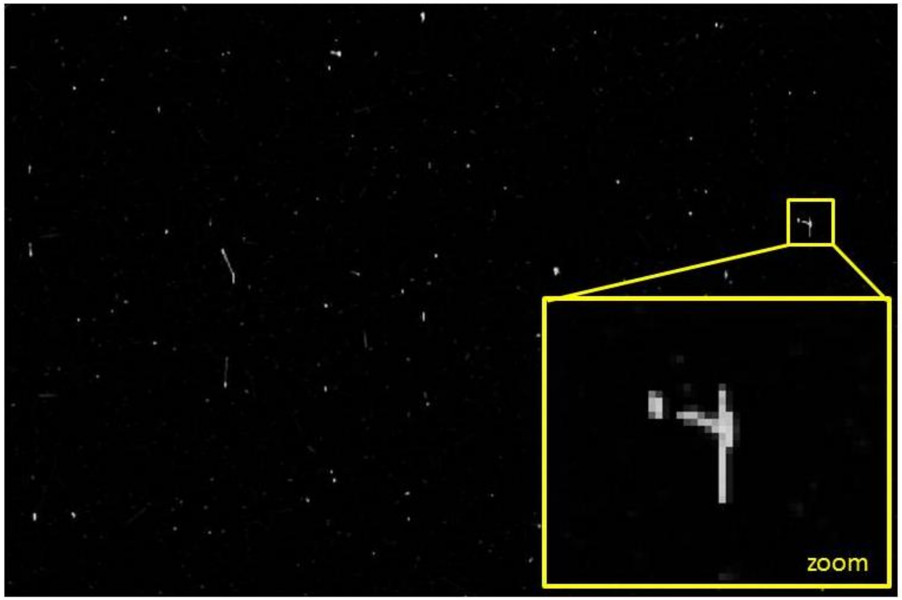




ISEEM measurements

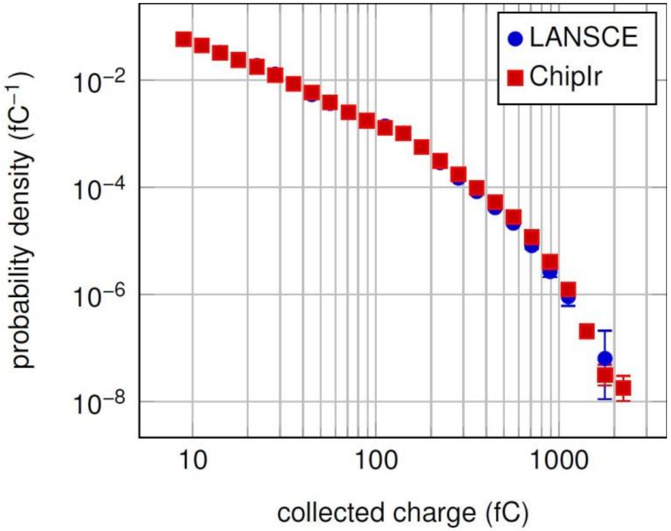


Cross section of the ISEEM to fast neutrons as a function of neutron energy



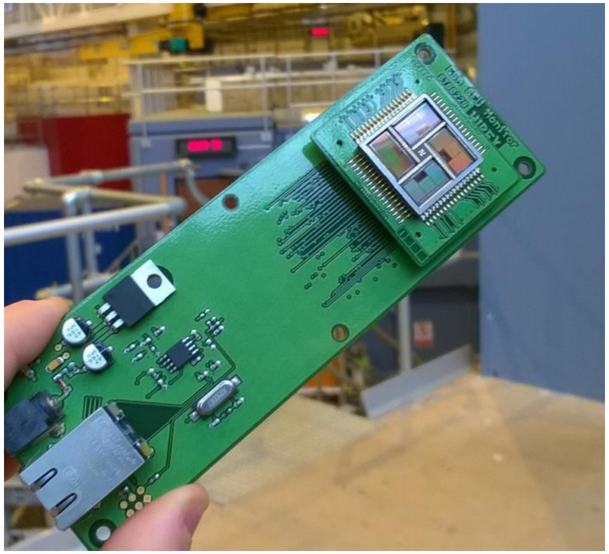
LANSCE equivalent flux
(E_n>10 MeV)

$4.9 \cdot 10^6$ n cm^{-2} s^{-1}

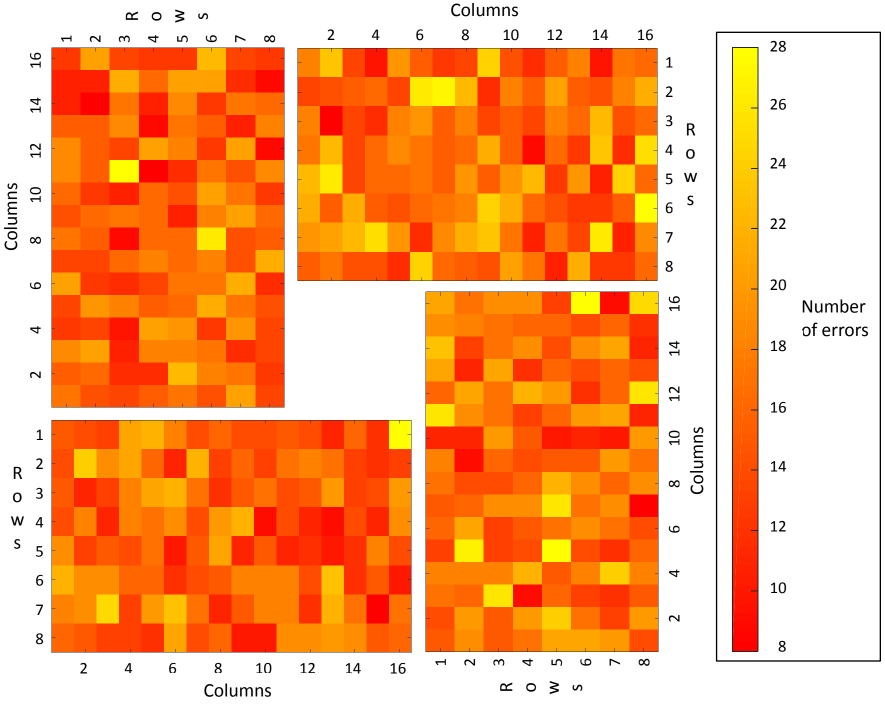


ChipIr and LANSCE collected charge spectra of the ISEEM detector normalized to the area above 8 fC.

SEU in SRAMs



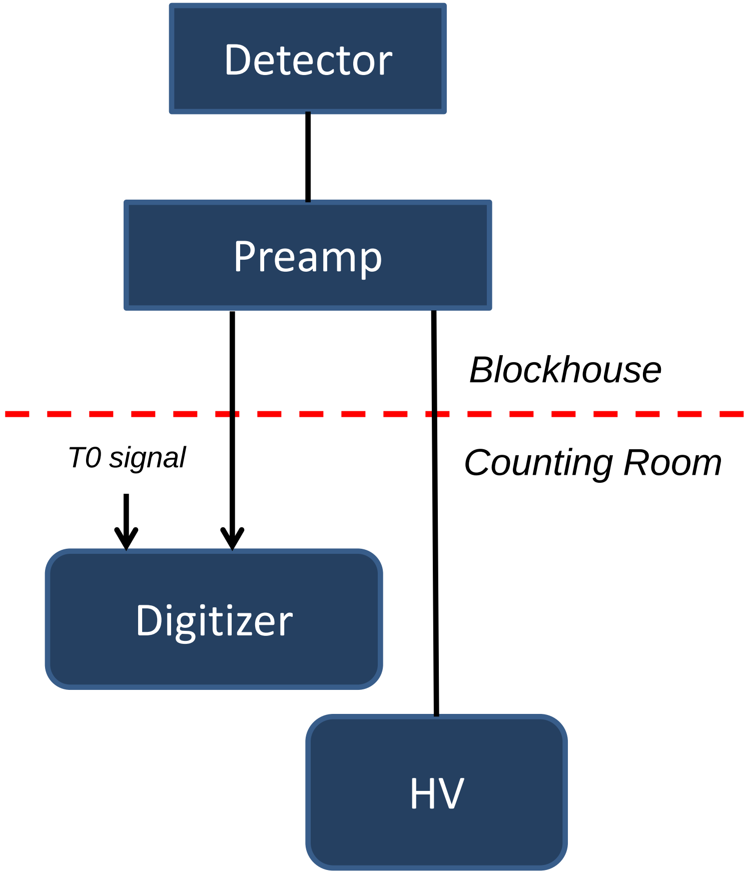
SEU monitor developed by ESA



- 4 x 4 Mbit = 16 Mbit
- **On ChipIr we measure an error rate of 2.05 errors/sec**
- This gives an average cross section (E>20 MeV) of about $2 \cdot 10^{-14}$ cm^2

	Flux (E> 10MeV)	**SER measured**	**SER expected**
ChipIr	$5.6 \cdot 10^{6}$ s^{-1}cm^{-2}	2.05 errors/s	2.13 errors/s
ANITA	$1 \cdot 10^{6}$ s^{-1}cm^{-2}	0.42 errors/s	0.38 errors/s
PROBA-II	≈ 10^{2} s^{-1}cm^{-2}	$2.44 \cdot 10^{-5}$ errors/s	$3.25 \cdot 10^{-5}$ errors/s

Deposited Energy Measurements



Detector

Preamp

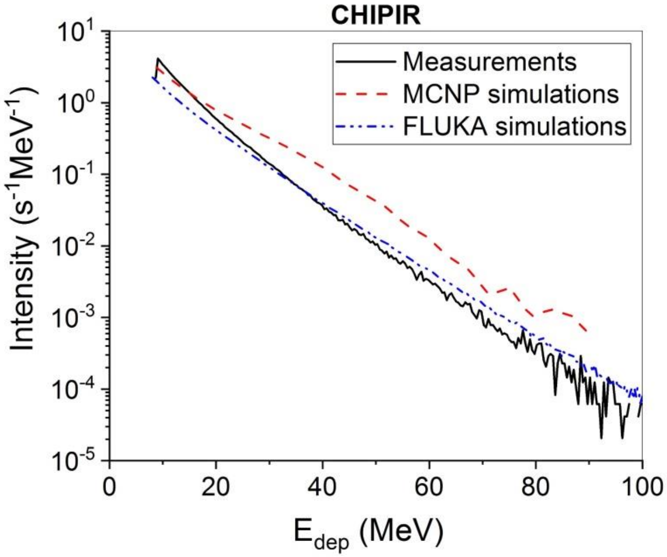
Blockhouse

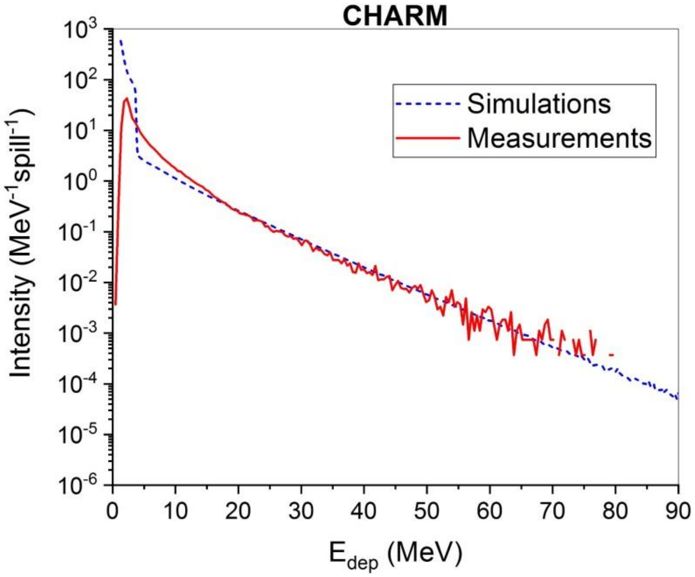
T0 signal

Counting Room

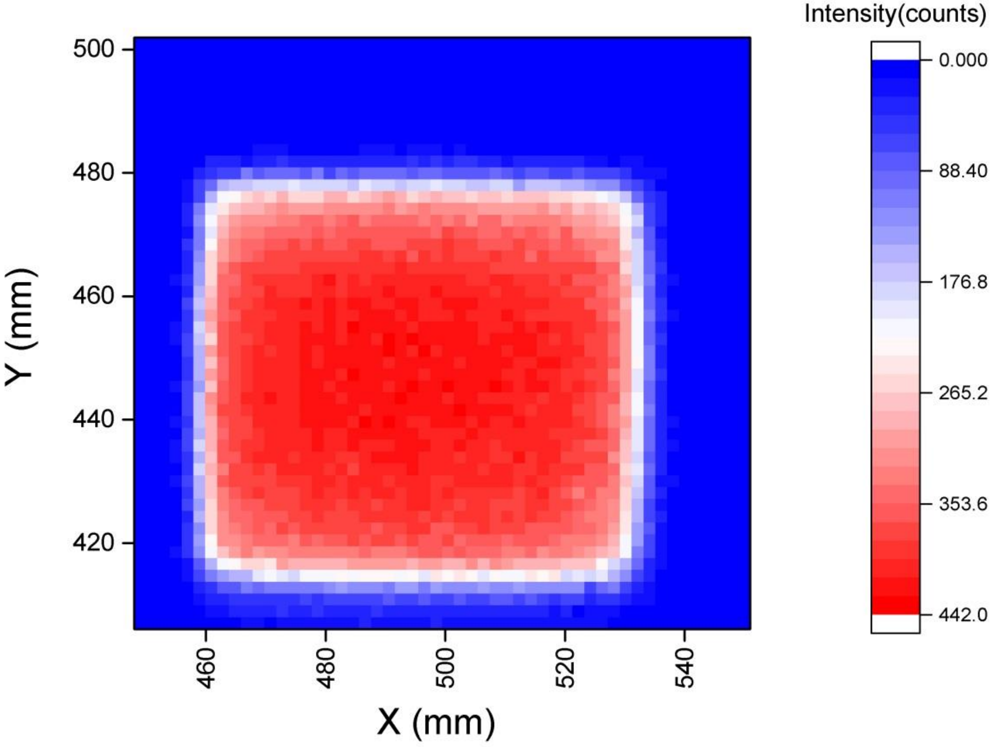
Digitizer

HV

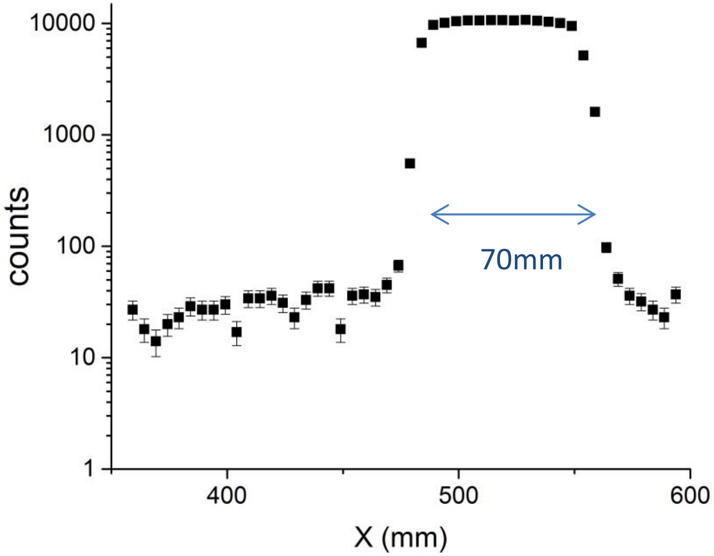


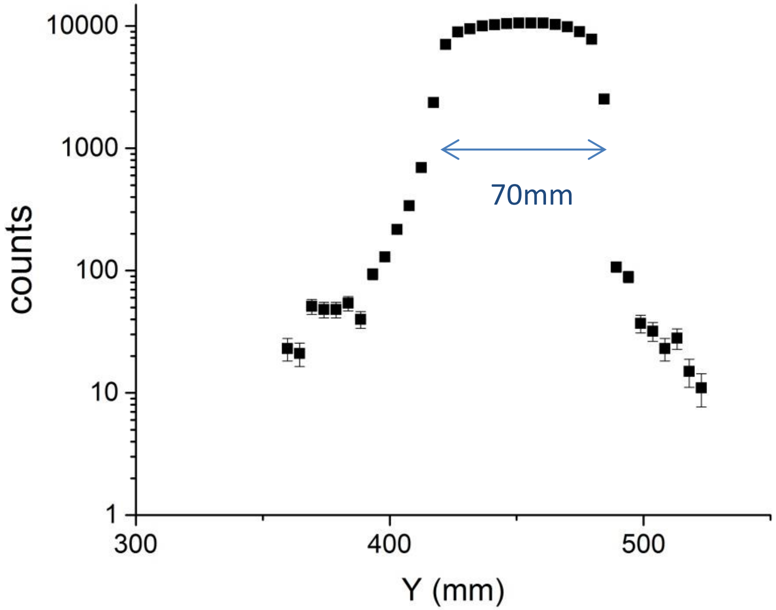


Maps and Profiles of a 70 x 70 mm^2 beam

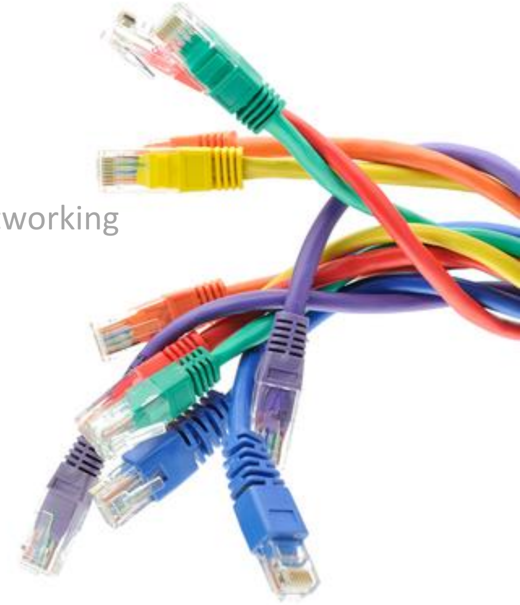


Map is measured with a diamond detector with 2 mm accuracy





ESA: SRAM for space applications.

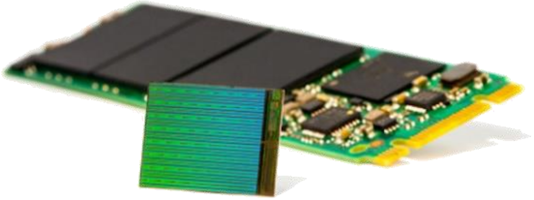


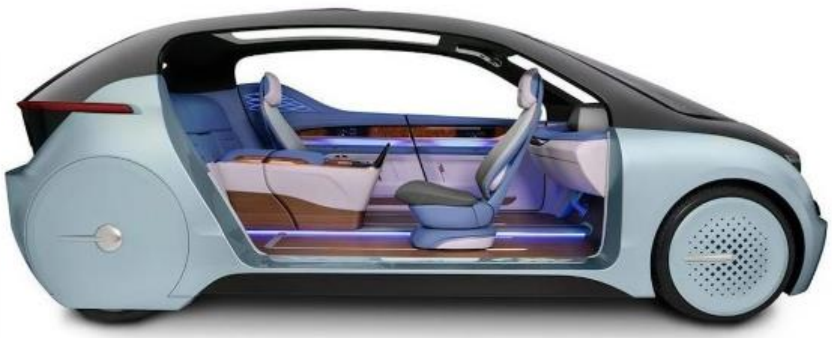
technology for networking systems.

Success examples of ChipIr user experiments.

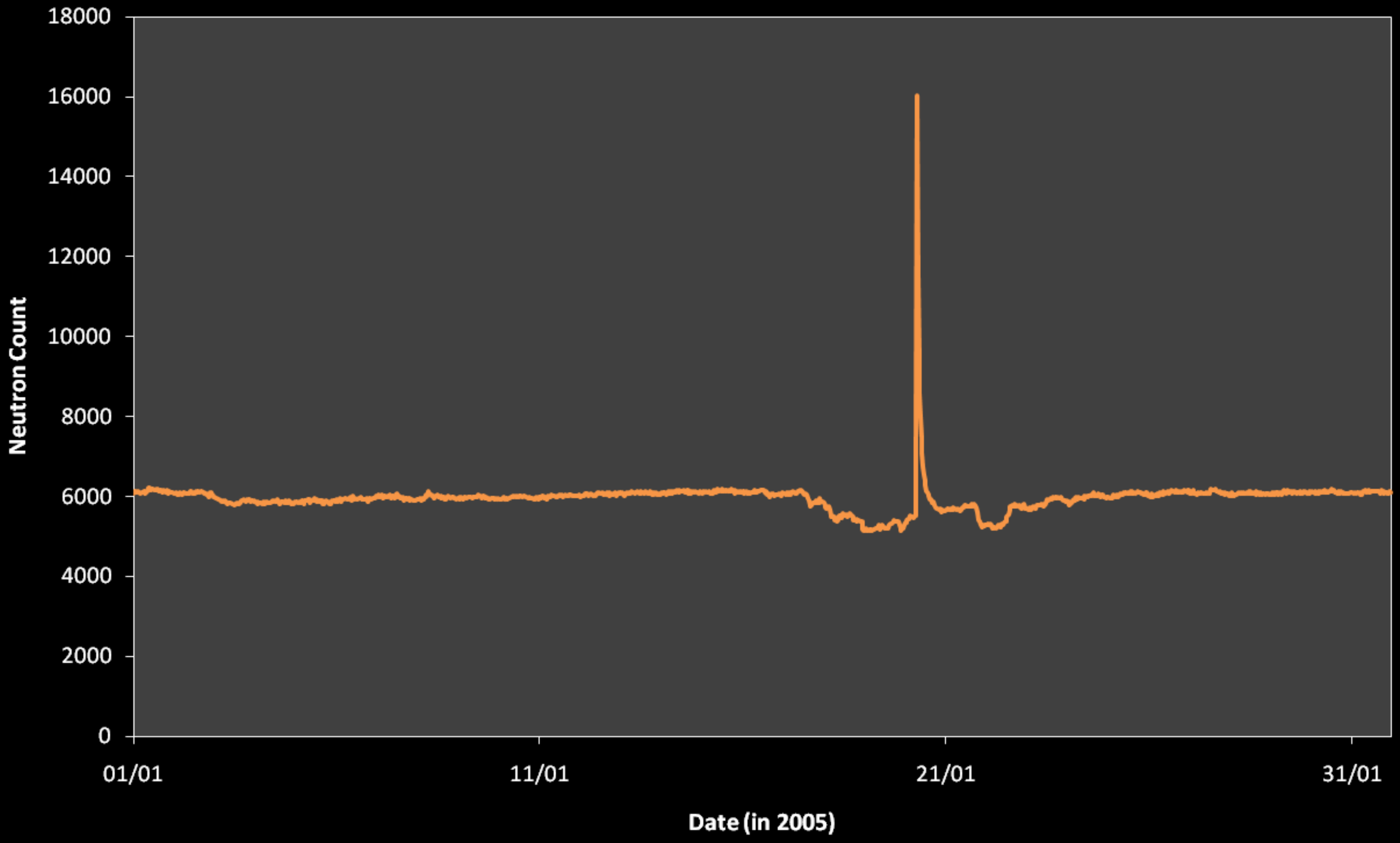
Power MOSFETS for renewables.

3D NAND Flash Memory,

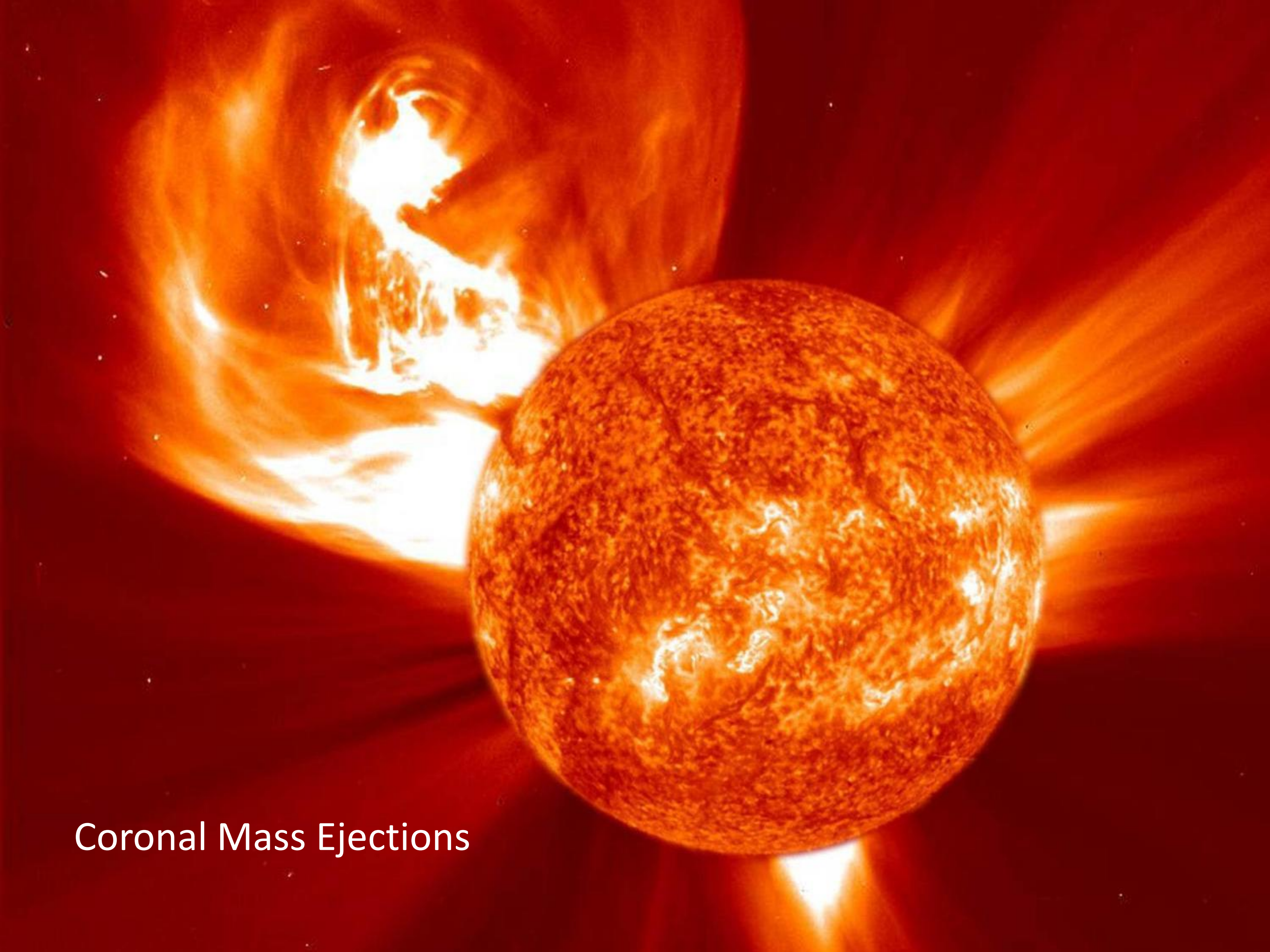




GPUs for self-driving cars.



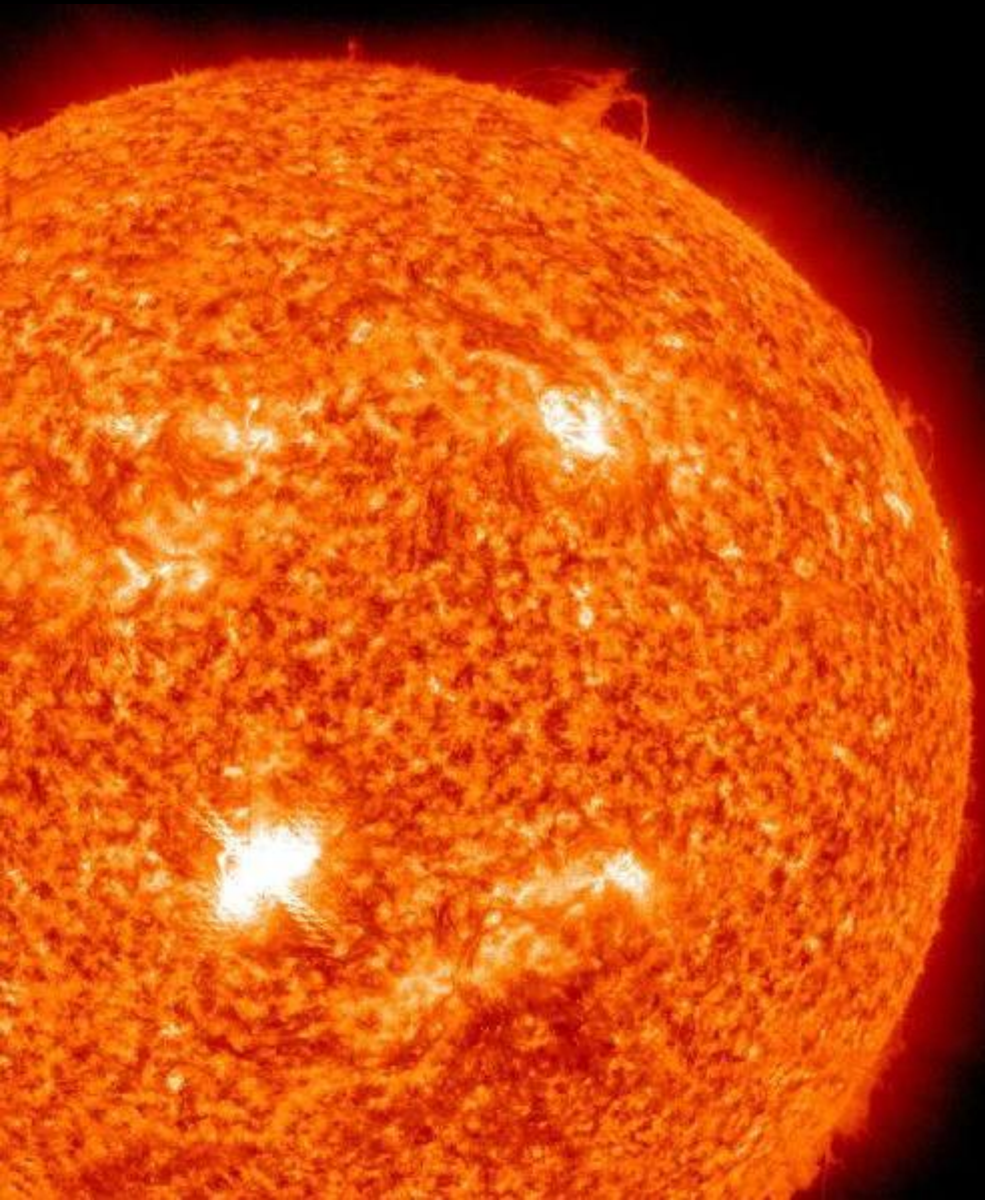
Thank you for listening

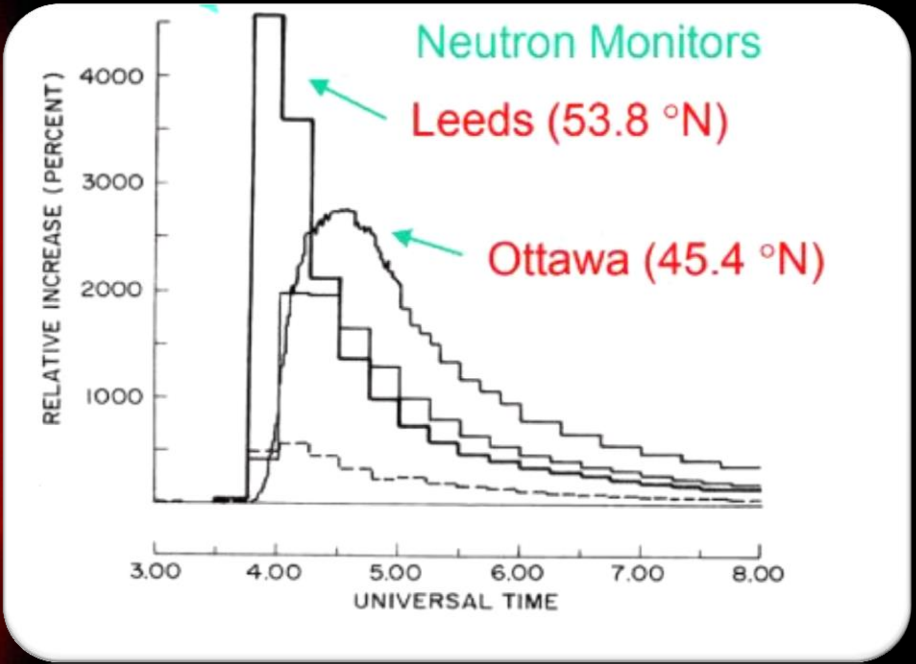


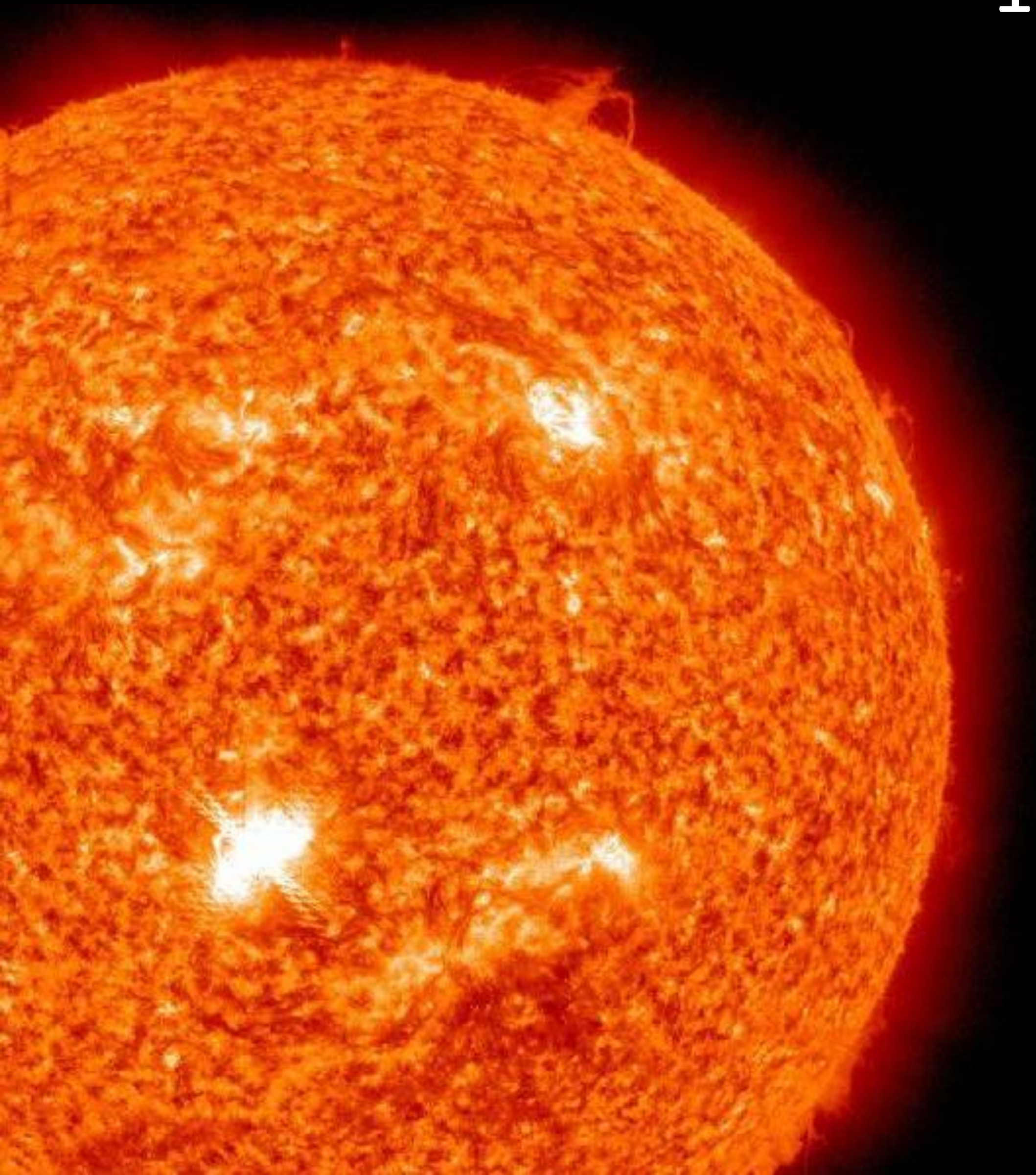
Coronal Mass Ejections

1956 Event

Largest event in electronics era







1859 ‘Carrington’ Event

Largest event in last 150 years

The recurrence statistics of an event with similar magnitude and impact to a Carrington event is poor, but improving. Various studies indicate that a recurrence period of 1-in-100 to 200 years is reasonable…

Royal Academy of Engineering
Extreme space weather:
impacts on engineered systems and infrastructure