Evaluation of spectrum and fluxes of the ChipIr facility for atmospheric neutron testing of electronics

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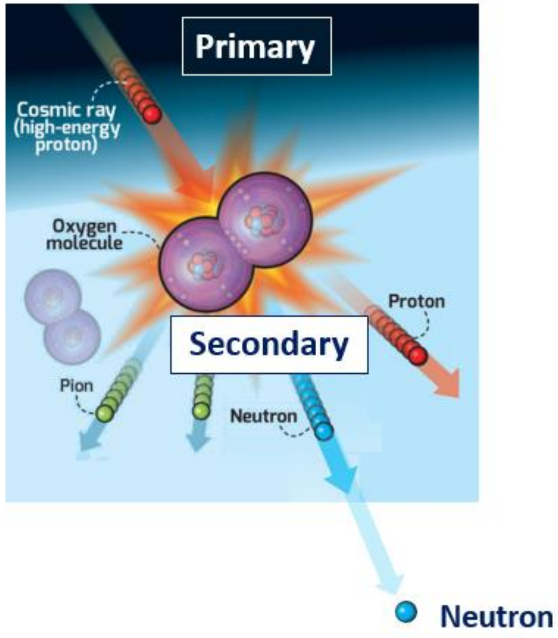
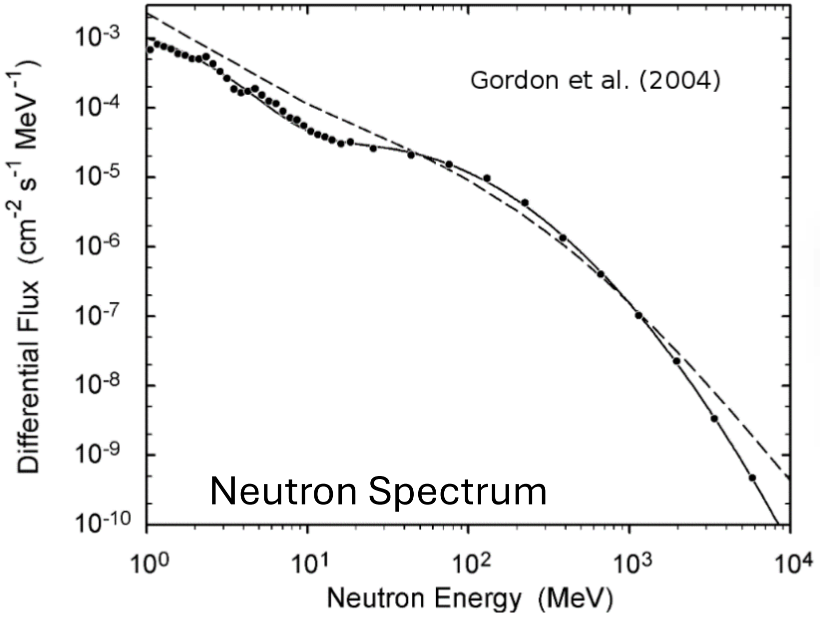
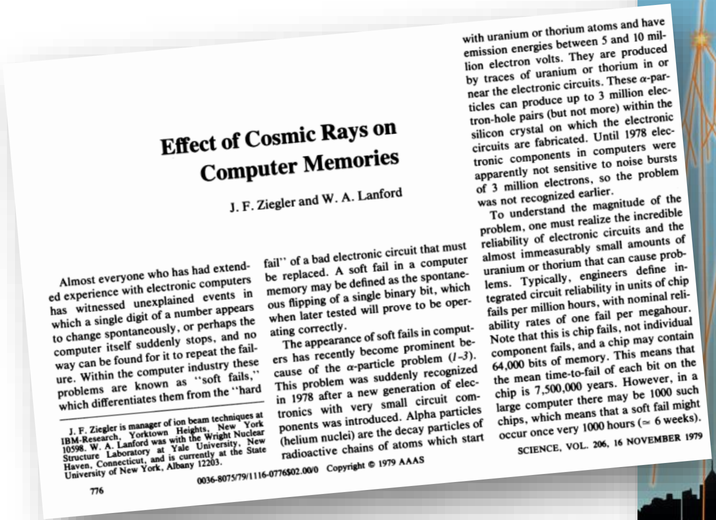
Science and Technology Facilities Council
ISIS Neutron and Muon Source

Sources of Radiation Causing Single Event Effects

A nuclear cascade takes place as the primary (galactic) cosmic rays interact with the atmosphere (predominantly nitrogen and oxygen) to create a shower of secondary particles extending down to aircraft altitudes and ground level.







Effect of Cosmic Rays on Computer Memories

J. F. Ziegler and W. A. Lanford

Almost everyone who has had extended experience with electronic computers has witnessed unexplained events in which a single digit of a number appears to change spontaneously, or perhaps the computer itself suddenly stops, and no way can be found for it to repeat the failure. Within the computer industry these problems are known as "soft fails," which differentiates them from the "hard fail" of a bad electronic circuit that must be replaced. A soft fail in a computer memory may be defined as the spontaneous flipping of a single binary bit, which when later tested will prove to be operating correctly.

The appearance of soft fails in computers has recently become prominent because of the α-particle problem (*1–3*). This problem was suddenly recognized in 1978 after a new generation of electronics with very small circuit components was introduced. Alpha particles (helium nuclei) are the decay particles of radioactive chains of atoms which start with uranium or thorium atoms and have emission energies between 5 and 10 million electron volts. They are produced by traces of uranium or thorium in or near the electronic circuits. These α-particles can produce up to 3 million electron-hole pairs (but not more) within the silicon crystal on which the electronic circuits are fabricated. Until 1978 electronic components in computers were apparently not sensitive to noise bursts of 3 million electrons, so the problem was not recognized earlier.

To understand the magnitude of the problem, one must realize the incredible reliability of electronic circuits and the almost immeasurably small amounts of uranium or thorium that can cause problems. Typically, engineers define integrated circuit reliability in units of chip fails per million hours, with nominal reliability rates of one fail per megahour. Note that this is chip fails, not individual component fails, and a chip may contain 64,000 bits of memory. This means that the mean time-to-fail of each bit on the chip is 7,500,000 years. However, in a large computer there may be 1000 such chips, which means that a soft fail might occur once very 1000 hours (≃ 6 weeks).

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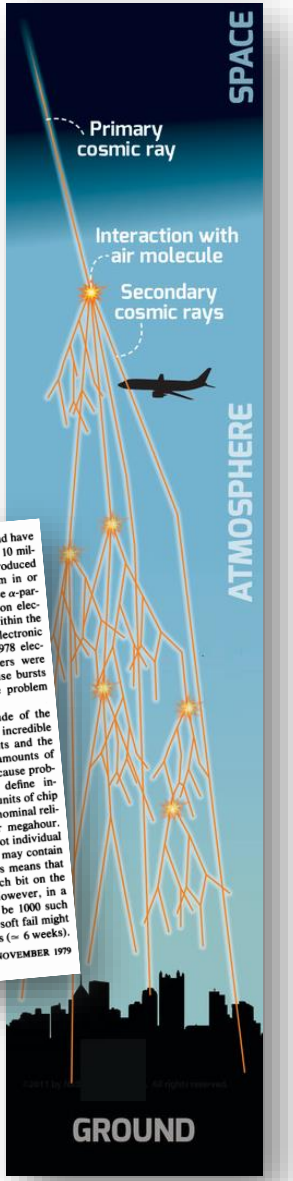


Ziegler and Langford in a landmark 1979 Science paper predicted that cosmic rays neutrons would cause major reliability problems at ground level (and aircraft altitudes).

Images: STFC/Ben Gilliland

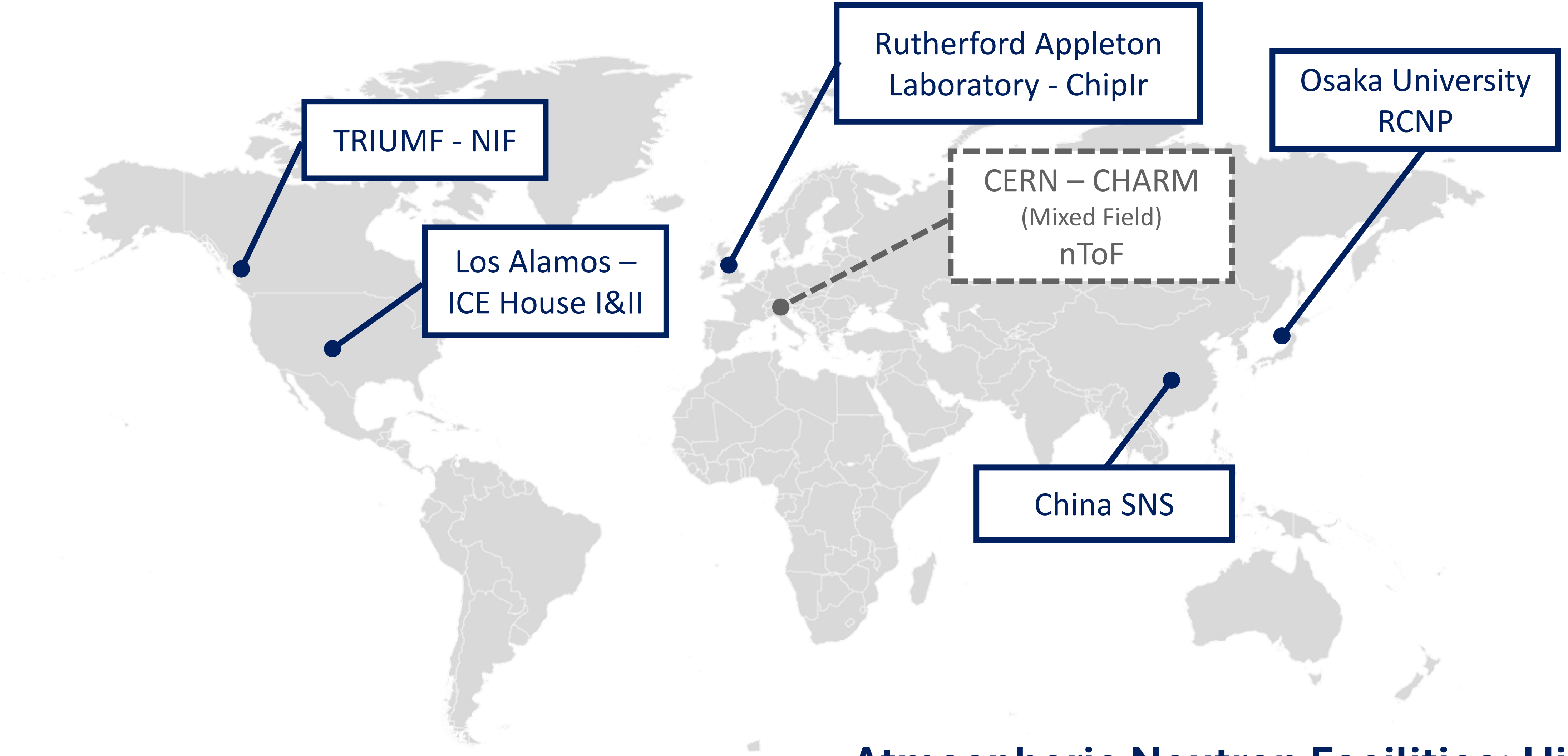
Industry Standards

JEDECS: JESD89A: Measurement and Reporting of Alpha Particle and Terrestrial Cosmic Ray-Induced Soft Errors in Semiconductor Devices
JEDECS: JEP151: Test Procedure for the Measurement of Terrestrial Cosmic Ray Induced Destructive Effects in Power Semiconductor Devices
IEC TR 62396 - Process management for avionics Atmospheric radiation effects

Important points:

- High-energy spallation sources are used for accelerated testing.
- When testing with a spallation neutron source, the SEUs recorded will be due primarily to the high energy (> 10 MeV) neutrons. The SEU contribution of the neutrons in the 1< E < 10 MeV is small.
- High-energy neutron SEE data cannot be used to predict alpha particle or low-energy neutron (i.e., thermal neutron), and vice versa.

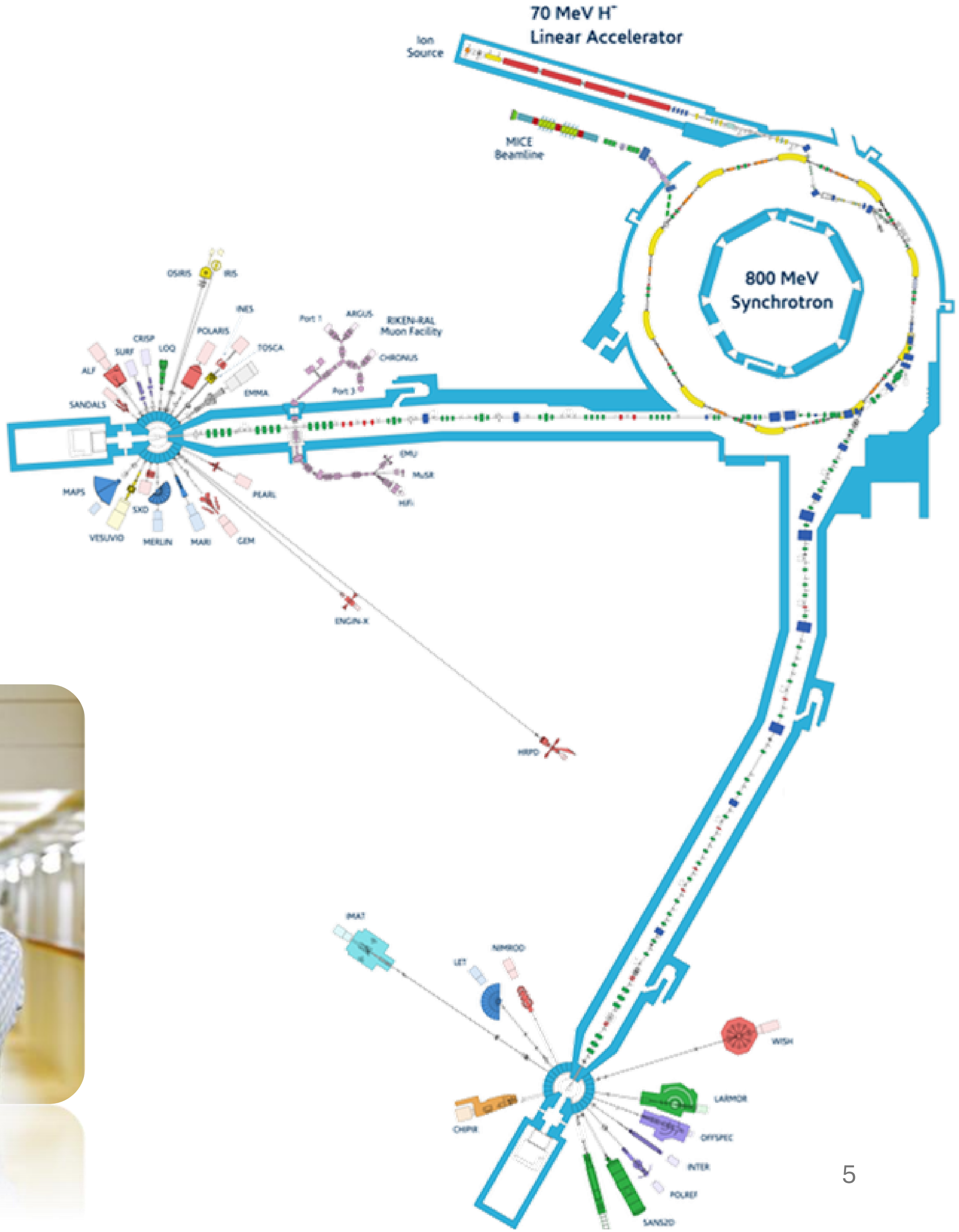
Spallation neutron Testing Facilities – Across the World



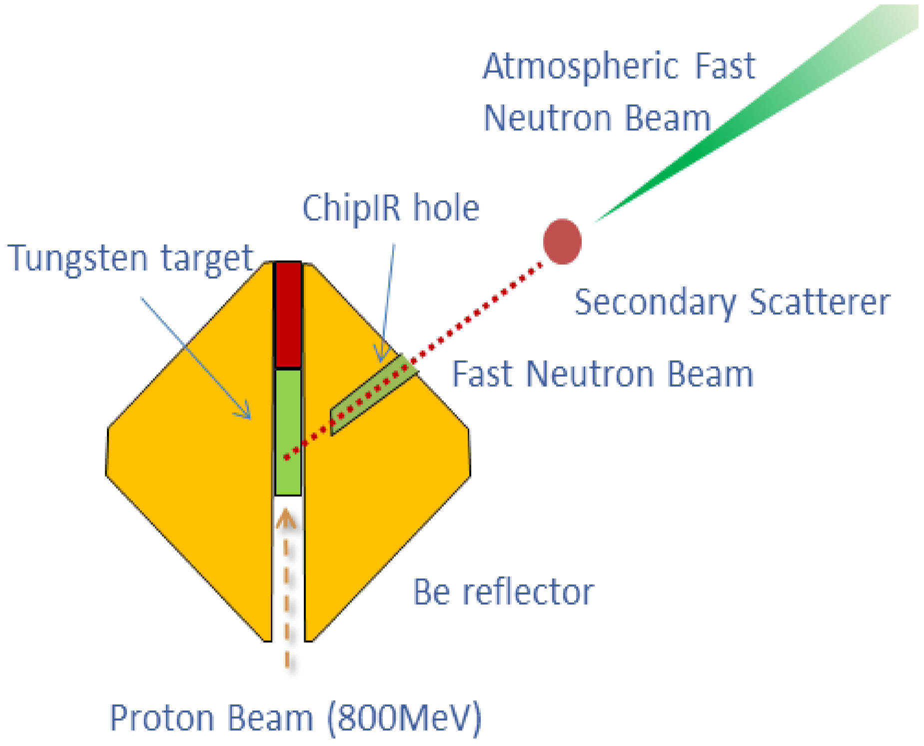
Atmospheric Neutron Facilities: High Energy (> 400MeV) & High Flux

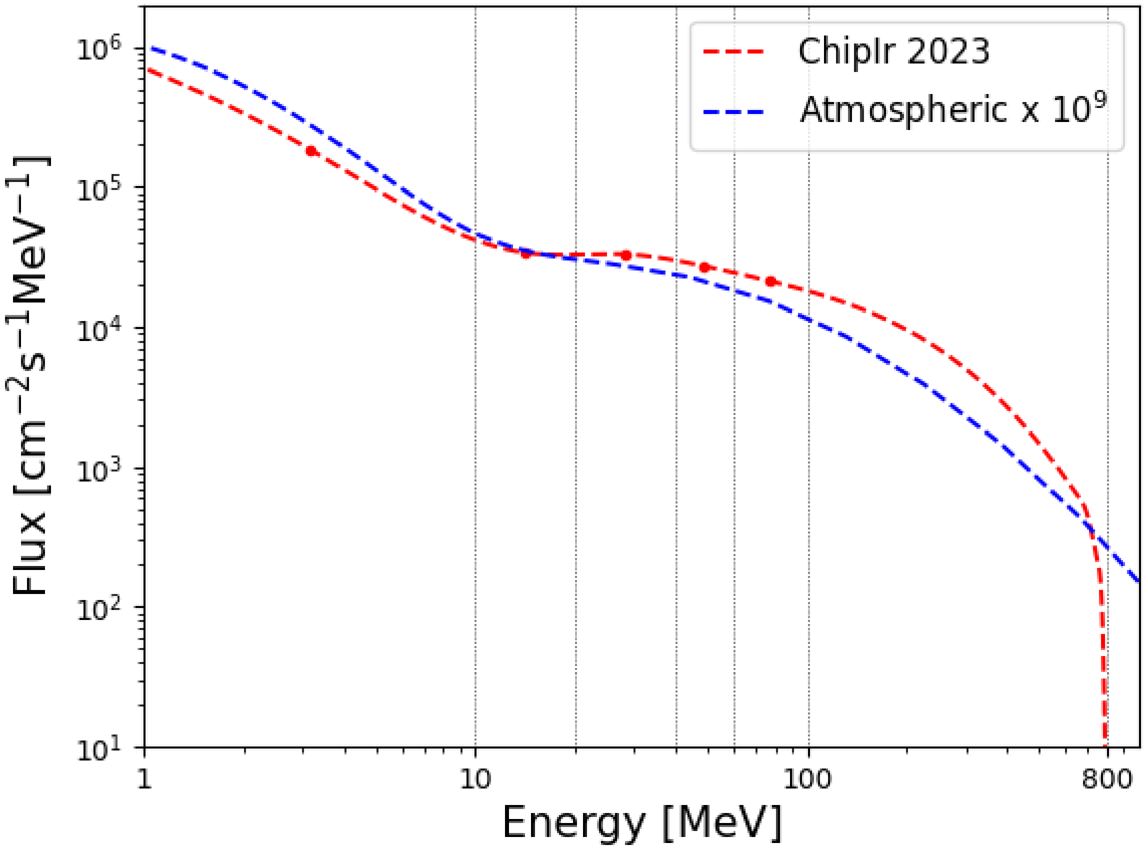
The ISIS neutron source

- 70 MeV Linac
- 800 Mev proton syncrotorn
- Two extraction lines
- Protons on tungsten targets
- Two target stations with moderators
- 30 neutron beamlines, 8 muon beamlines



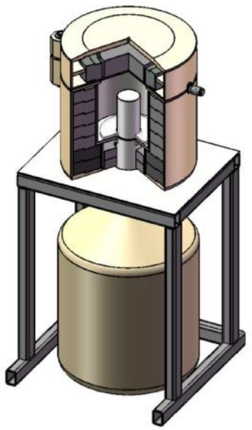
ChipIR: fast neutrons E >10 MeV





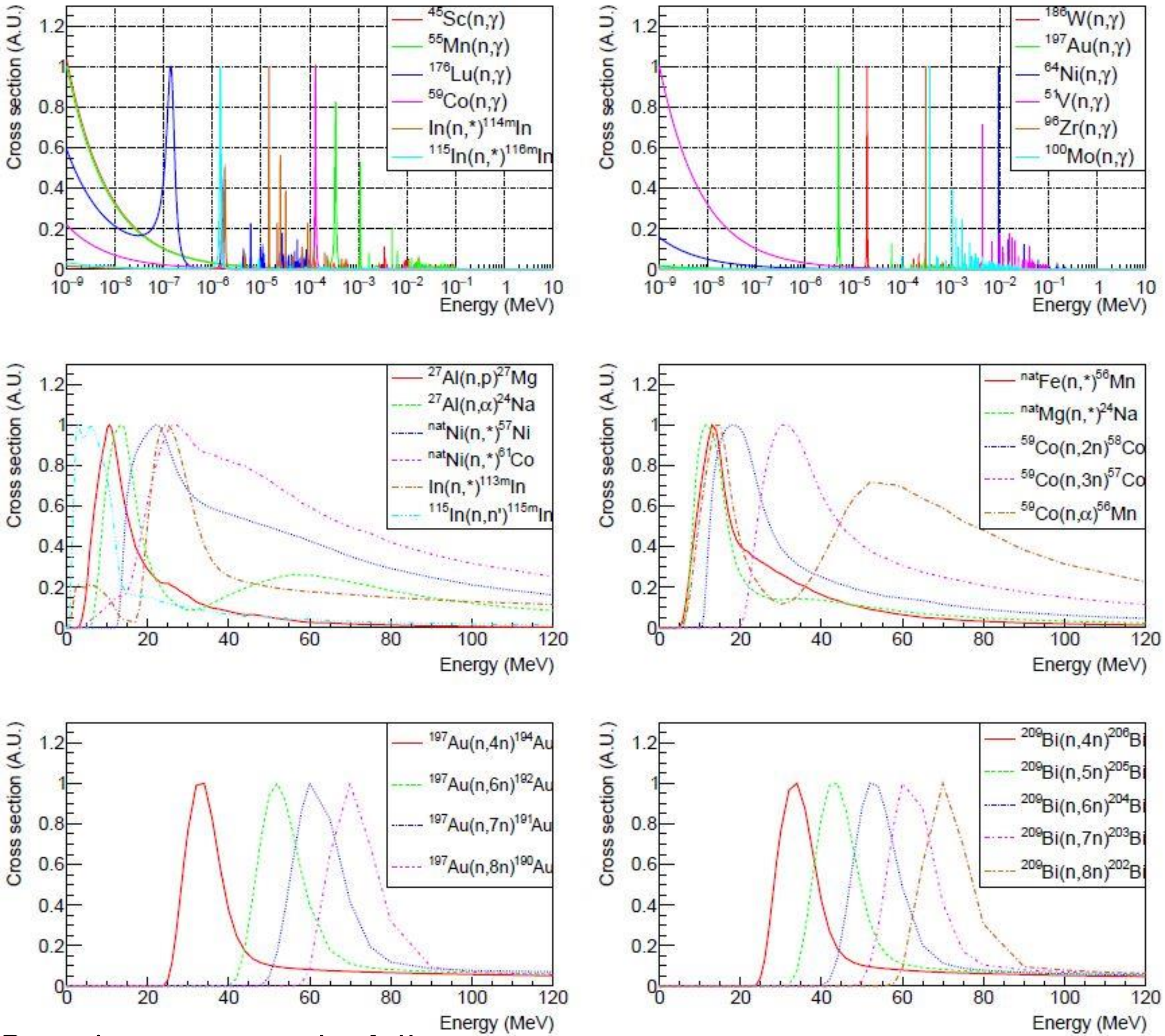
ChipIr Flux (>10 MeV) = 5.8 x 10^6 n $cm^{-2}s^{-1}$

Characterization with activation foils



Targets measured on a Germanium detector

- Multiple foils are selected to give multiple resonances and thresholds over the wide energy spectrum.
- Produced radionuclides need to have half lives of usable values
- Bi(n,xn) and Au (n,xn) are important for high-energy dosimetry.
- In general, measurements with E>20 MeV are sparse and with large errors



Reactions to cover the full energy range

Unfolding with statistical approach

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

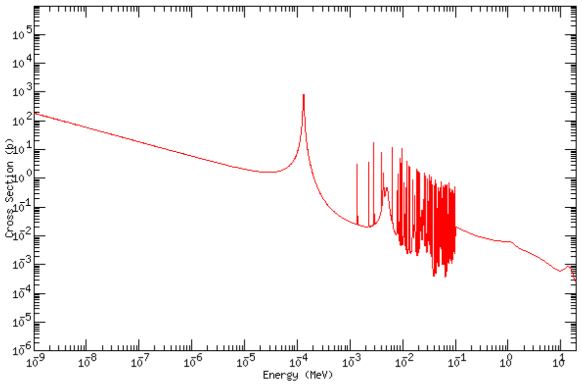
$$R = \mathcal{N} \int \sigma(E)\varphi(E)dE$$

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

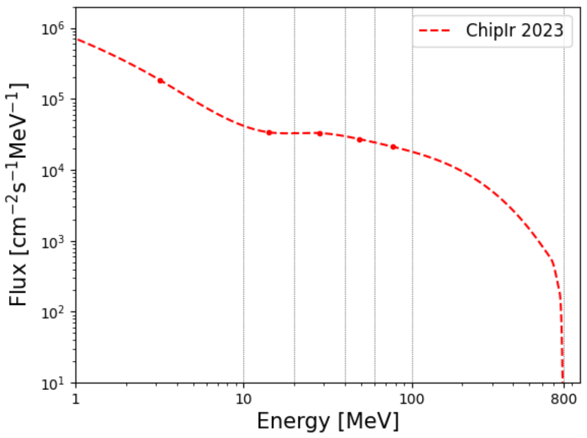
Activation Rates

Reaction	Rate (s^-1g^-1)	Uncertainty (s^-1g^-1)	Rate (s^-1g^-1)
45Sc(n,g)	1.52E+05	1.06E+04	(1.52±0.11)x10^5
51V(n,g)	2.73E+04	2.18E+03	(2.73±0.22)x10^4
55Mn(n,g)	6.56E+04	4.59E+03	(6.56±0.46)x10^4
64Ni(n,g)	8.19E+01	7.37E+00	(8.19±0.74)x10^1
96Zr(n,g)	1.35E+02	1.22E+01	(1.35±0.12)x10^2
100Mo(n,g)	2.91E+02	2.33E+01	(2.91±0.23)x10^2
115In(n,g)	5.58E+05	1.67E+04	(5.58±0.17)x10^5
176Lu(n,g)	1.60E+05	1.28E+04	(1.60±0.13)x10^5
186W(n,g)	4.13E+04	2.89E+03	(4.13±0.29)x10^4
197Au(n,g)	5.82E+05	3.49E+04	(5.82±0.35)x10^5
natMg(n,*)24Na	3.29E+03	1.65E+02	(3.29±0.16)x10^3
27Al(n,p)27Mg	2.01E+03	1.21E+02	(2.01±0.12)x10^3
27Al(n,a)24Na	2.81E+03	1.41E+02	(2.81±0.14)x10^3
natFe(n,*)56Mn	1.17E+03	7.02E+01	(1.17±0.07)x10^3
59Co(n,2n)58Co	7.41E+03	5.93E+02	(7.41±0.59)x10^3
59Co(n,3n)57Co	5.53E+03	3.87E+02	(5.53±0.39)x10^3
59Co(n,a)56Mn	1.01E+03	3.03E+01	(1.01±0.03)x10^3
natIn(n,*)113mIn	5.56E+02	2.78E+01	(5.56±0.28)x10^2
115In(n,n')115mIn	2.71E+03	1.08E+02	(2.71±0.11)x10^3
197Au(n,4n)194Au	2.56E+03	1.28E+02	(2.56±0.13)x10^3
197Au(n,6n)192Au	1.76E+03	1.06E+02	(1.76±0.11)x10^3
197Au(n,7n)191Au	1.39E+03	9.73E+01	(1.39±0.10)x10^3
197Au(n,8n)190Au	9.22E+02	5.53E+01	(9.22±0.55)x10^2
209Bi(n,4n)206Bi	2.51E+03	1.51E+02	(2.51±0.15)x10^3
209Bi(n,5n)205Bi	2.36E+03	1.65E+02	(2.36±0.17)x10^3
209Bi(n,6n)204Bi	1.68E+03	1.18E+02	(1.68±0.12)x10^3
209Bi(n,7n)203Bi	1.37E+03	9.59E+01	(1.37±0.10)x10^3
209Bi(n,8n)202Bi	1.22E+03	8.54E+01	(1.22±0.09)x10^3

cross sections

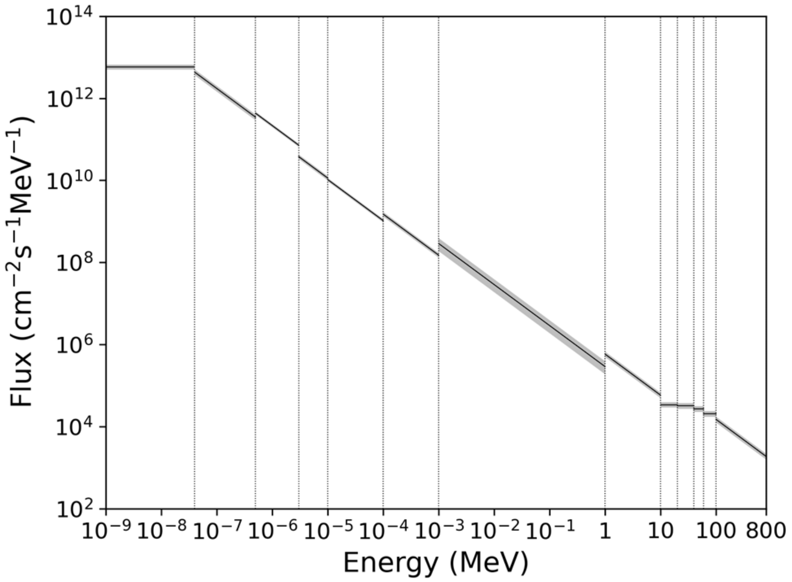


Neutron Flux



D. Chiesa et. al. "Bayesian statistics applied to neutron activation data for reactor flux spectrum analysis." *Annals of Nuclear Energy* 70 (2014): 157-168.

Results



INTEGRAL FLUXES OF ChipIr IN EACH ENERGY BIN. RESULTS CORRESPONDS TO THE ANALYSIS OF DATA OF 2023 WITH ACCELERATOR OPERATING AT 800 MeV AND 37 μA

E_{min} (MeV)	E_{max} (MeV)	Flux (cm^{-2}s^{-1})
10^{-9}	4×10^{-8}	$(2.26\pm0.33)\times10^5$
4×10^{-8}	5×10^{-7}	$(4.37\pm0.69)\times10^5$
5×10^{-7}	3×10^{-6}	$(3.87\pm0.36)\times10^5$
3×10^{-6}	10^{-5}	$(1.37\pm0.17)\times10^5$
10^{-5}	10^{-4}	$(2.40\pm0.23)\times10^5$
10^{-4}	10^{-3}	$(3.45\pm0.45)\times10^5$
10^{-3}	1	$(1.99\pm0.69)\times10^6$
1	10	$(1.34\pm0.20)\times10^6$
10	20	$(3.40\pm0.50)\times10^5$
20	40	$(6.49\pm1.05)\times10^5$
40	60	$(5.39\pm0.90)\times10^5$
60	100	$(8.26\pm1.34)\times10^5$
100	800	$(3.1\pm0.37)\times10^6$

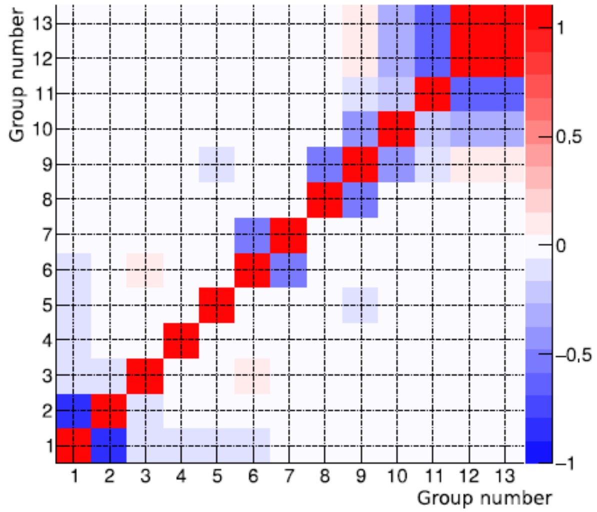
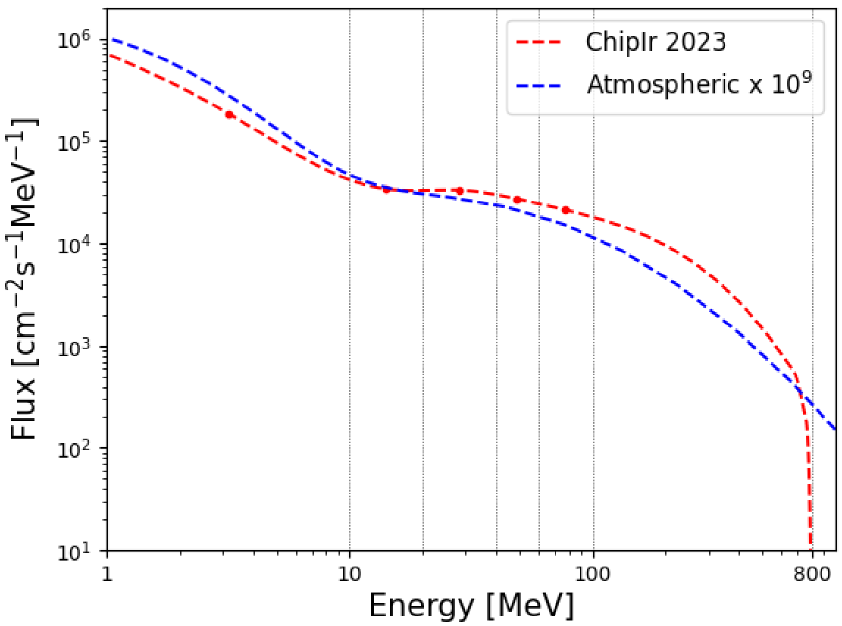
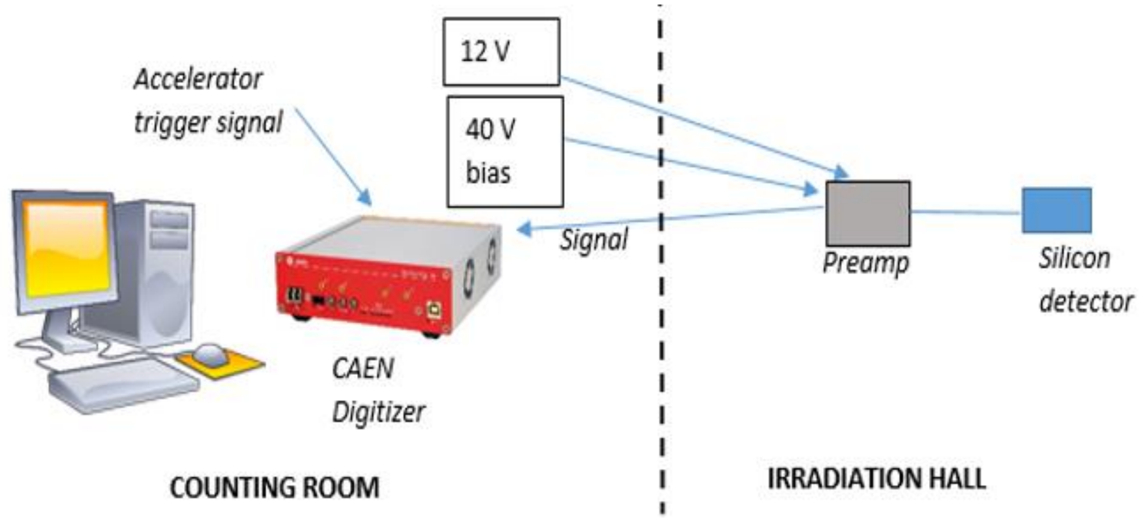


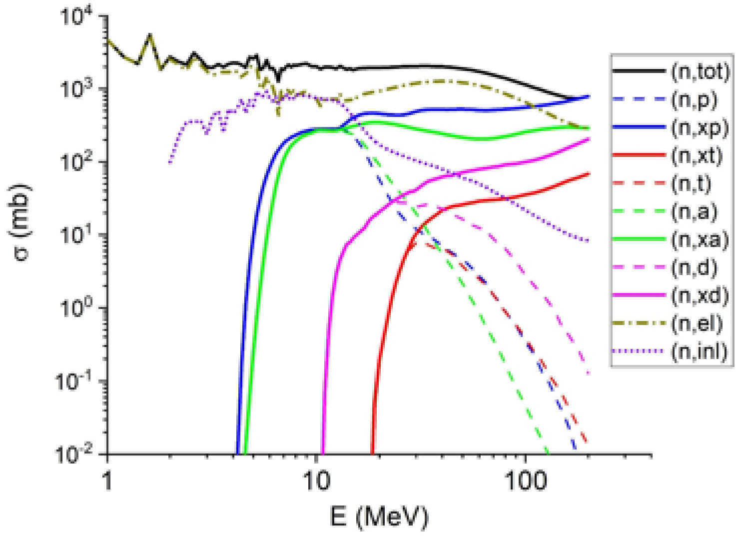
Fig. 6. Matrix of the correlations between energy groups for the reference unfolding result.



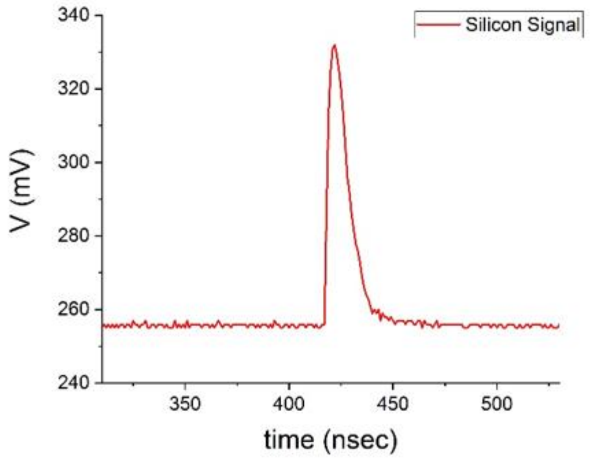
- The results on the left are the fluxes in a selected number of bins.
- Bins are chosen such to have at least one resonance or threshold.
- Statistical method allows to propagate the errors and to check the correlation between bins.
- A continuous spectrum (on the right) is presented by imposing continuity between the bins (but preserving the areas). The shape in the last bin is taken from Monte Carlo calculation.

Silicon Diodes and Diamond Detectors



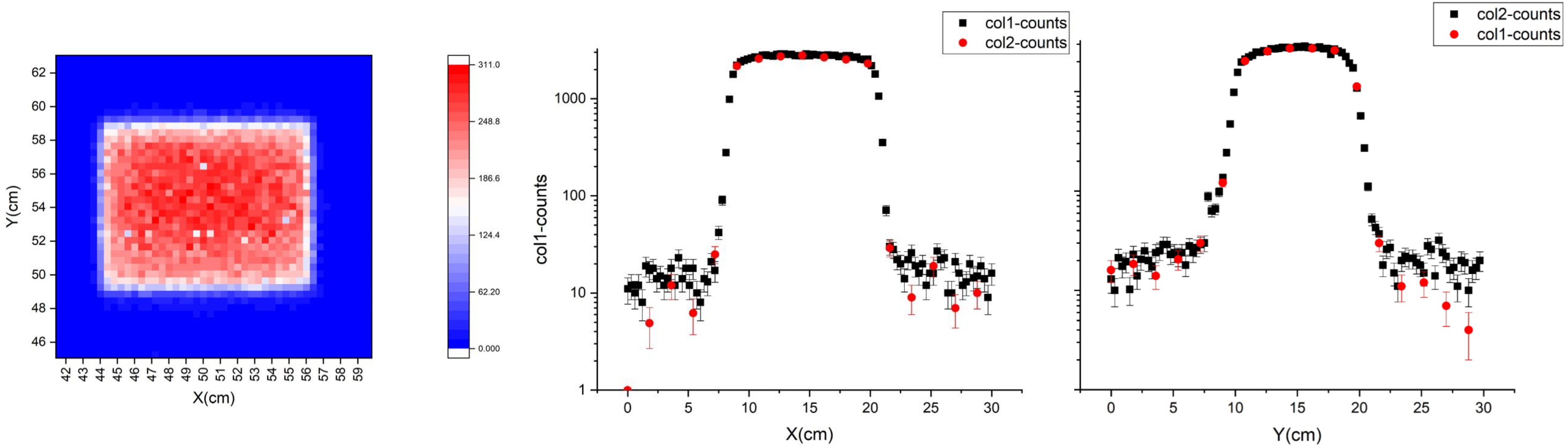


Neutron nuclear cross sections of Si-28 for the production of recoil and secondary radiation from the TENDL library



- Real time flux measurements.
- Event by event counting above threshold (E_{dep} > 10 MeV)
- Spectroscopic capabilities. Good energy resolution on deposited energy
- High mobility of free charges (→fast signal).
- Compact volumes (2 mm x 2mm x 140 um)

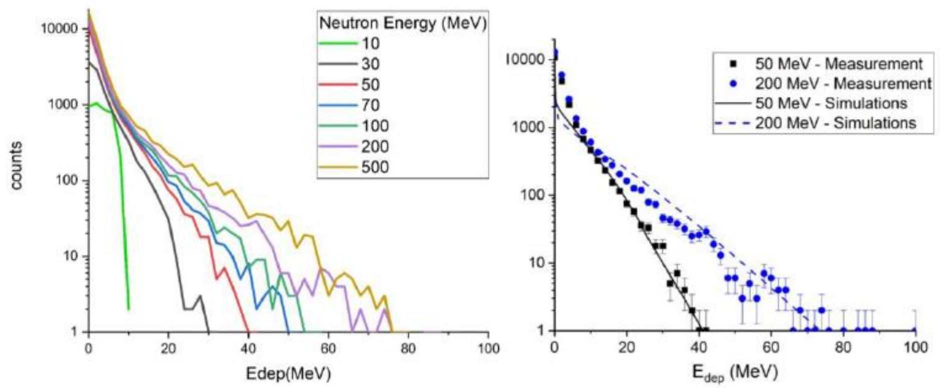
Beam profiles



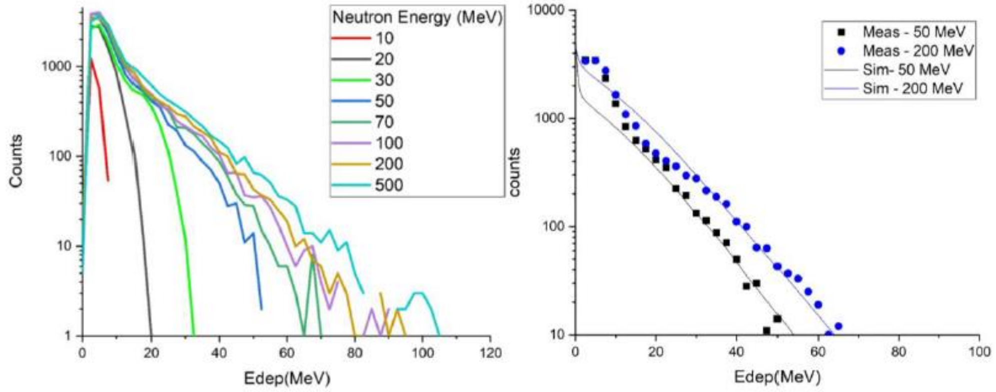
- Map of ChipIr beam in a typical configuration with jaws set at 10 × 10 cm.
- The step was 5 mm.
- The homogeneity is 9% from the average value.

Study of deposited energy

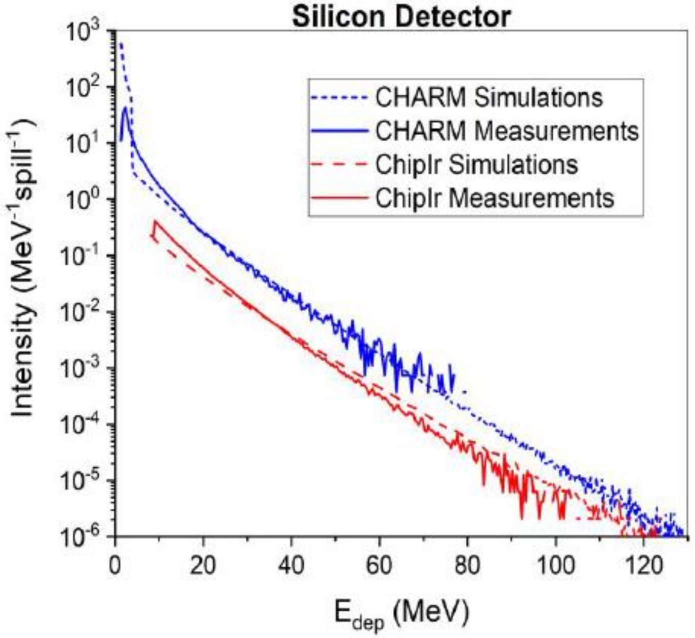
Silicon detector

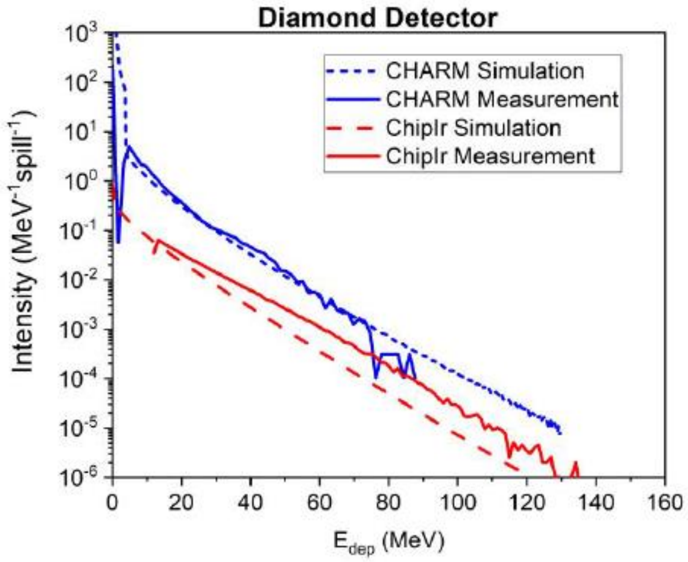


Diamond detector



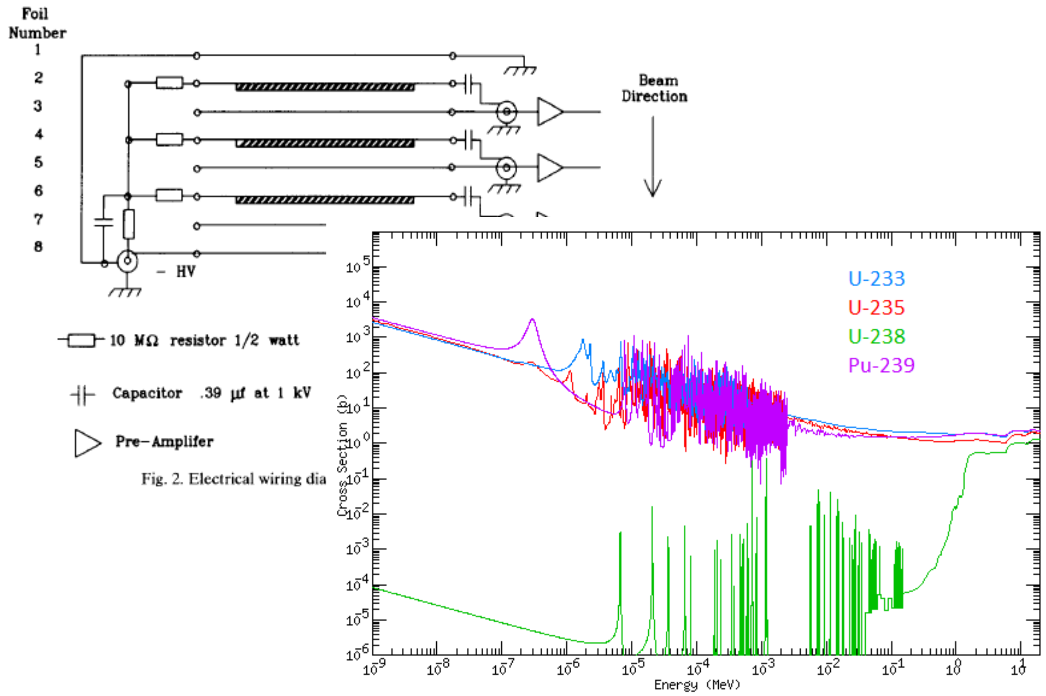
Data measured at nToF at CERN





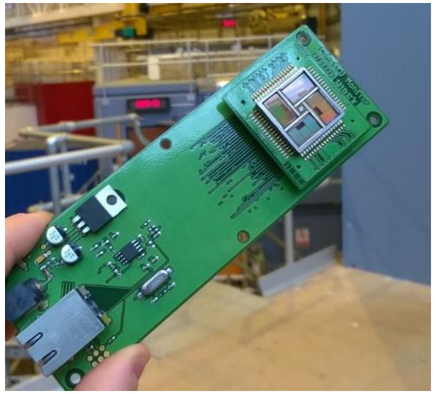
Data measured at ChipIR and CHARM

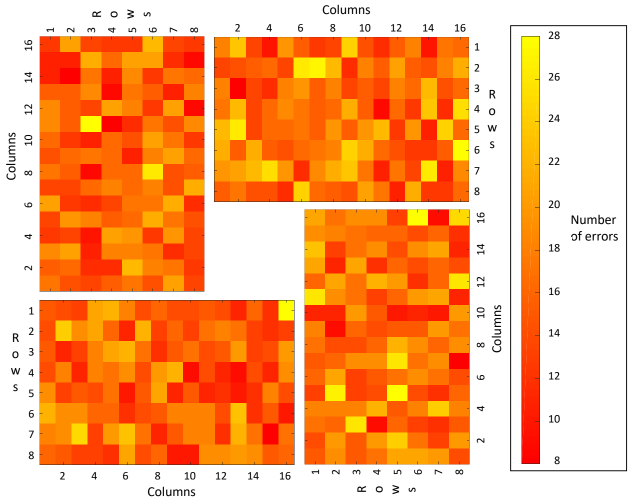
Other relevant high energy neutron detectors



Fission Chambers with ^{238}U

- Particularly useful where time of flight at high energy is available
- Has the advantage of the good knowledge of U cross sections





SRAM based detectors: bit flips

JEDEC Standard: A “reference chip” or “golden chip” with a relatively high soft error rate that is capable of withstanding a relatively high total dose level is recommended as part of the testing approach. Normal practice will be to perform testing on the “reference chip” before each test series in order to provide validation of the test equipment and as a secondary means of calibrating beam dosimetry of the facility.

Thank you

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