Characterization of High-Energy Neutron Beamlines Using Silicon and Diamond Detectors

Carlo Cazzaniga

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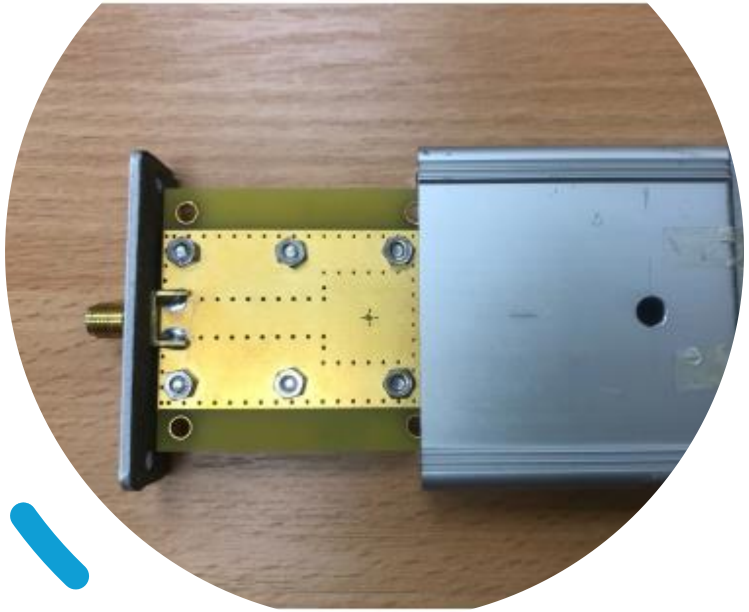
ISIS Neutron and Muon Source

Motivation

- Need for precise **<u>characterization of high-energy neutron and mixed fields</u>**.
- **<u>Benchmarking</u>** Monte Carlo transport models.
- Need for real time **<u>beam monitors</u>**.



<u>Solution:</u>

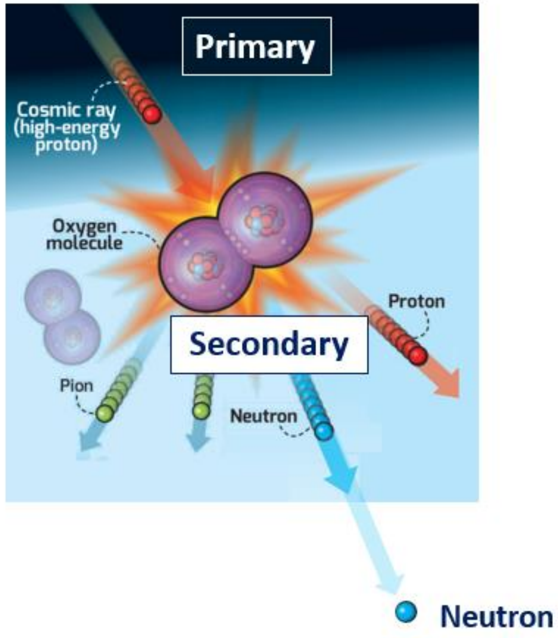
Solid-state detectors (Si, diamond) = compact, fast, gamma-insensitive solutions.

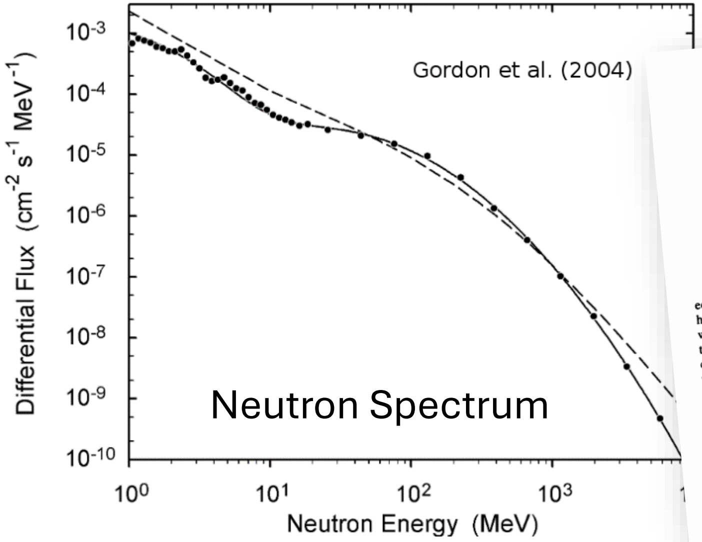
<u>Applications:</u>

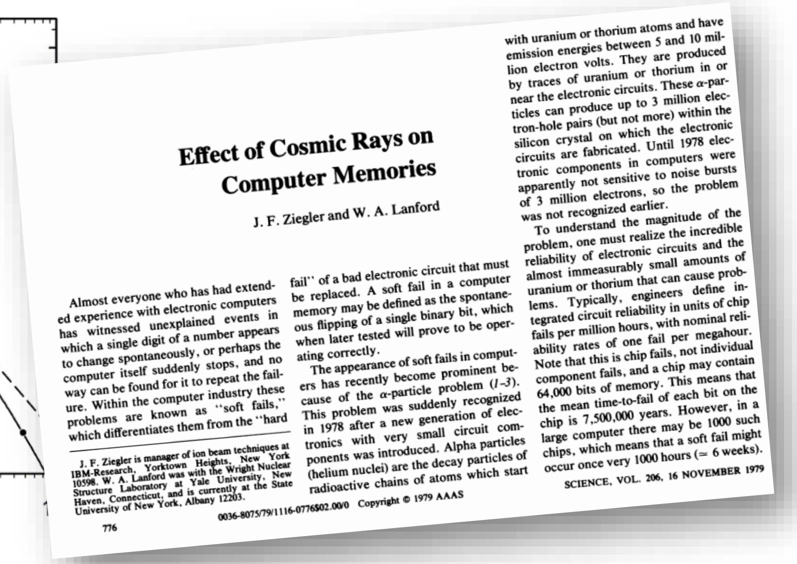
- **Single Event Effects (SEE)** testing in microelectronics
- **Fusion diagnostics** (14 MeV neutrons)

Application: Atmospheric neutrons

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).

J. F. Ziegler is manager of ion beam techniques at IBM-Research, Yorktown Heights, New York 10598. W. A. Lanford was with the Wright Nuclear Structure Laboratory at Yale University, New Haven, Connecticut, and is currently at the State University of New York, Albany 12203.

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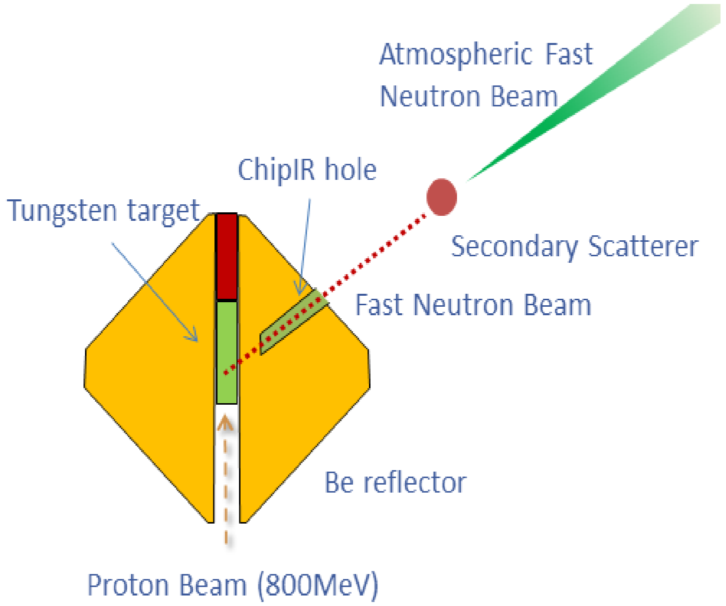
Need measurements over a wide energy range

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

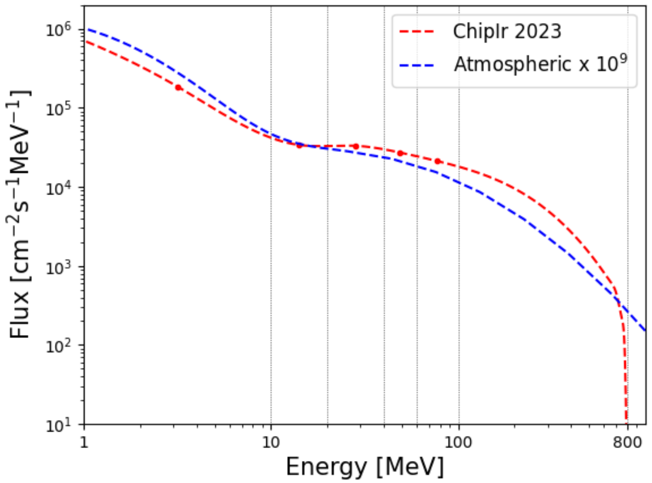
Facility: ChipIR

High energy protons on tungsten target produce **fast-neutron spectrum** that go up to the proton energy (of 800MeV at ISIS); a much broader, higher energy spectrum than can be obtained from fission reactors sources

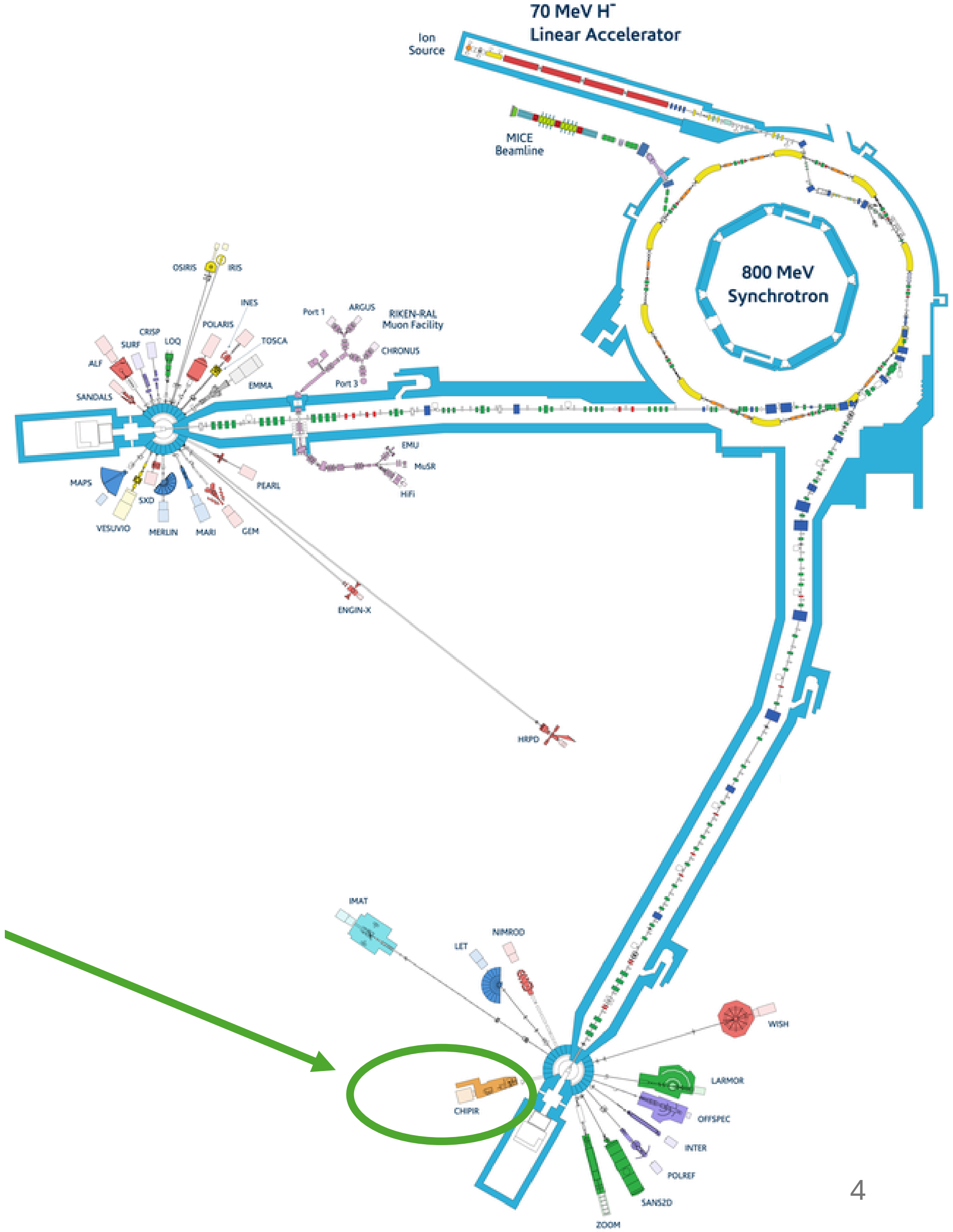


ChipIR

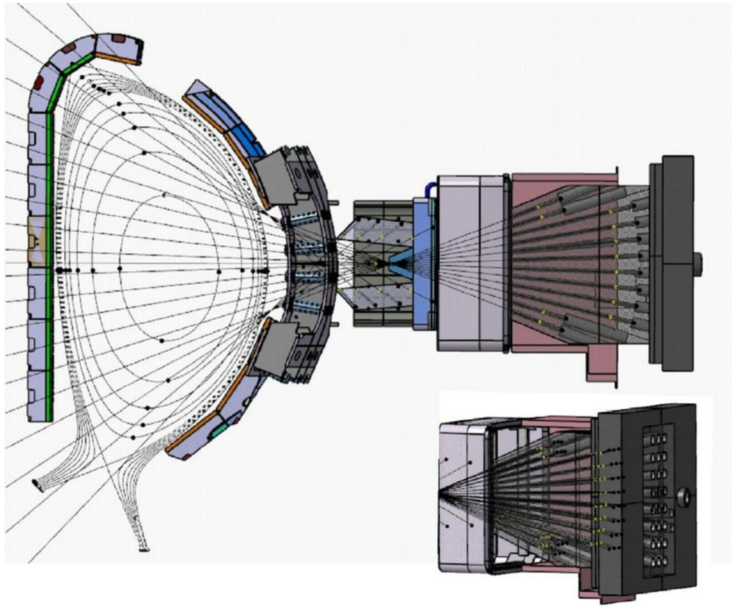
Atmospheric neutrons

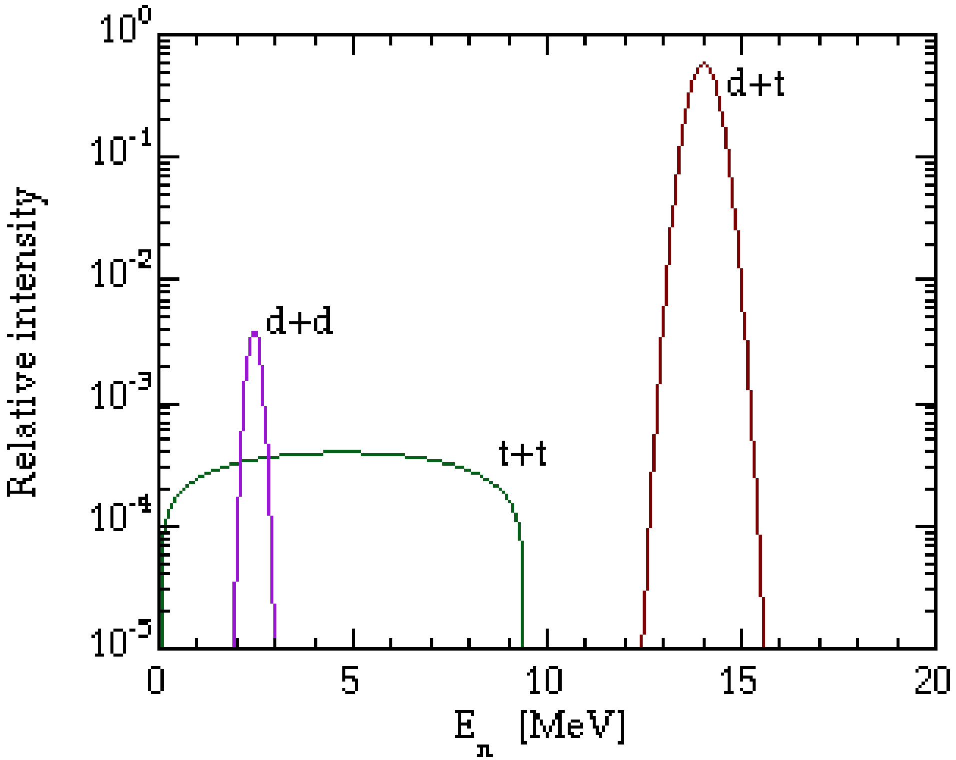


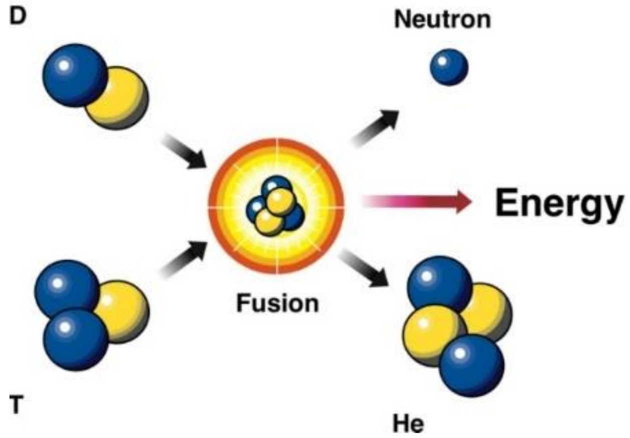
ChipIr Flux (>10 MeV) = 5.8 x 10^6 n $cm^{-2}s^{-1}$



Application: Nuclear fusion







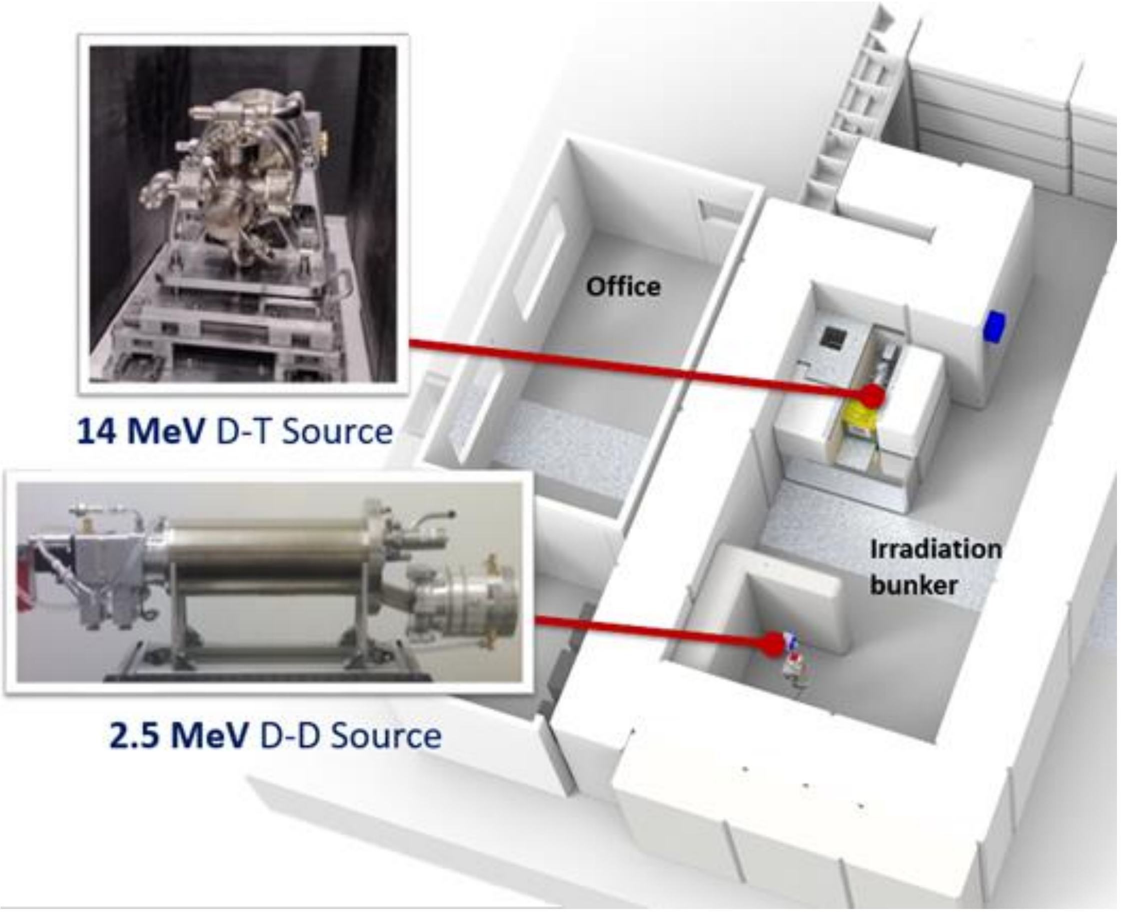
Need **high-resolution spectroscopy** for plasma diagnostics

- Nuclear fusion yield (intensity of the neutron emission line)
- Plasma temperature and fast ions energy distribution (doppler broadening)

Facility: NILE

- Produce **2.5 MeV and 14 MeV neutrons** via compact generators.
- **Complement ChipIr** electronics irradiation experiments to study single-event-effect.
- Support development and testing of fast neutron detectors.
- Able to operate **independent of ISIS** beamtime cycles.

Need high-resolution spectroscopy for the characterization of neutron fields



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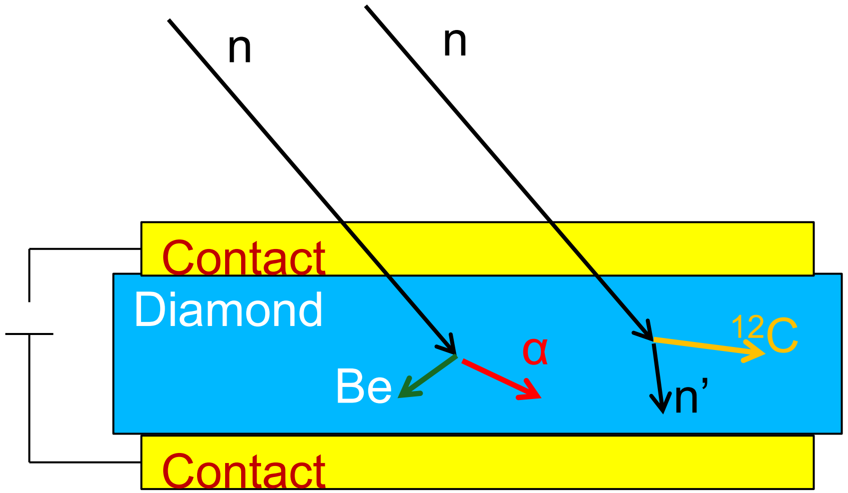
Detector Technologies



Both Silicon and Diamond detector

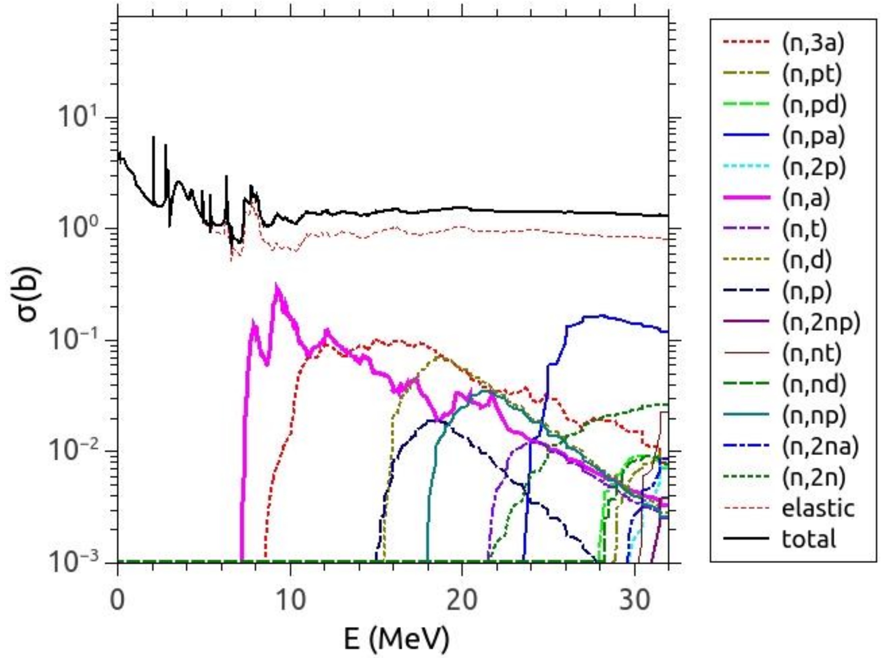
- High mobility of free charges (→fast response, short signals).
- Good energy resolution on deposited energy
- Room temperature operation (E_g=5.5 eV)→ No Cooling.
- Compact volume solid state detector.

Silicon detectors

- 2×2×0.14 mm^3 PIN diode (Micron)
- Stable, no polarization, fast charge collection
- Used for high energy neutrons and hadrons

Diamond detectors

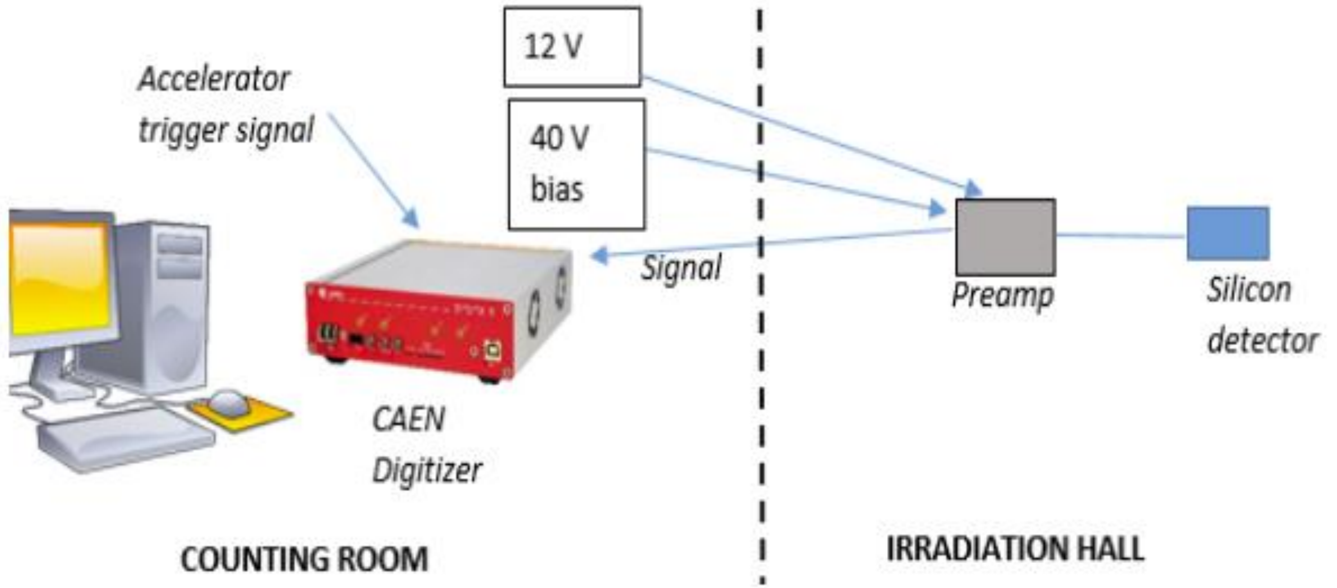
- Chemical Vapour Deposition, single-crystal, 300–500 μm thick
- Radiation hard (to >10^{16} n/cm^2), low γ sensitivity
- Polarization effects possible at much lower fluences
- Used for 14 MeV DT spectroscopy (8.3 MeV peak from $^{12}C(n,\alpha)^9Be$)

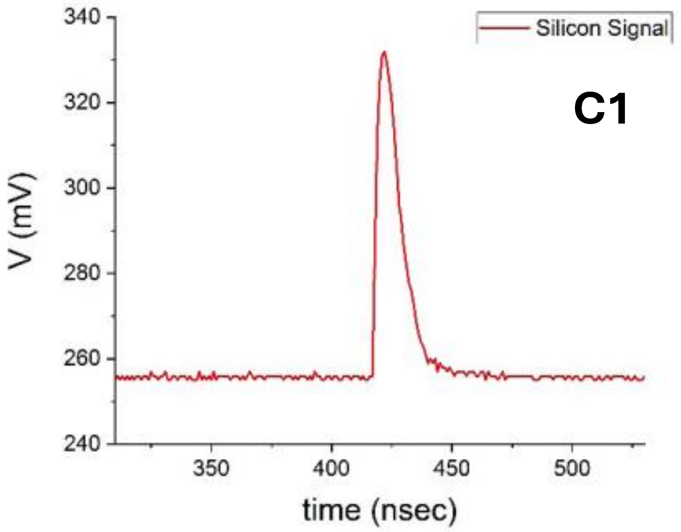


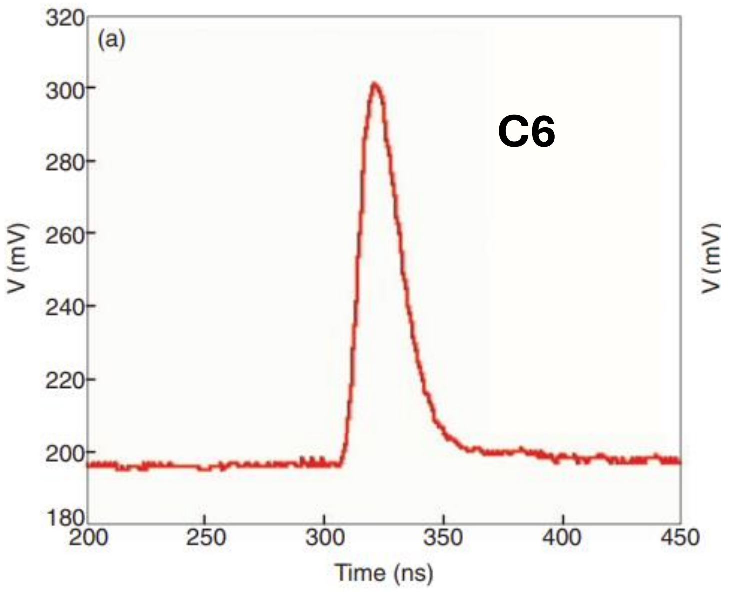
Carbon Cross Sections

Electronics and Acquisition

- **Cividec C1 (current) or C6 (fast integrating) preamps**, 2 GHz bandwidth or 10 ns shaping
- **CAEN 1 GS/s digitizers** record *all* waveforms (oscilloscope mode)
- Required because high instantaneous rates prevent classical shaping amplifiers
- Enables **event-by-event** ToF + pulse-area analysis

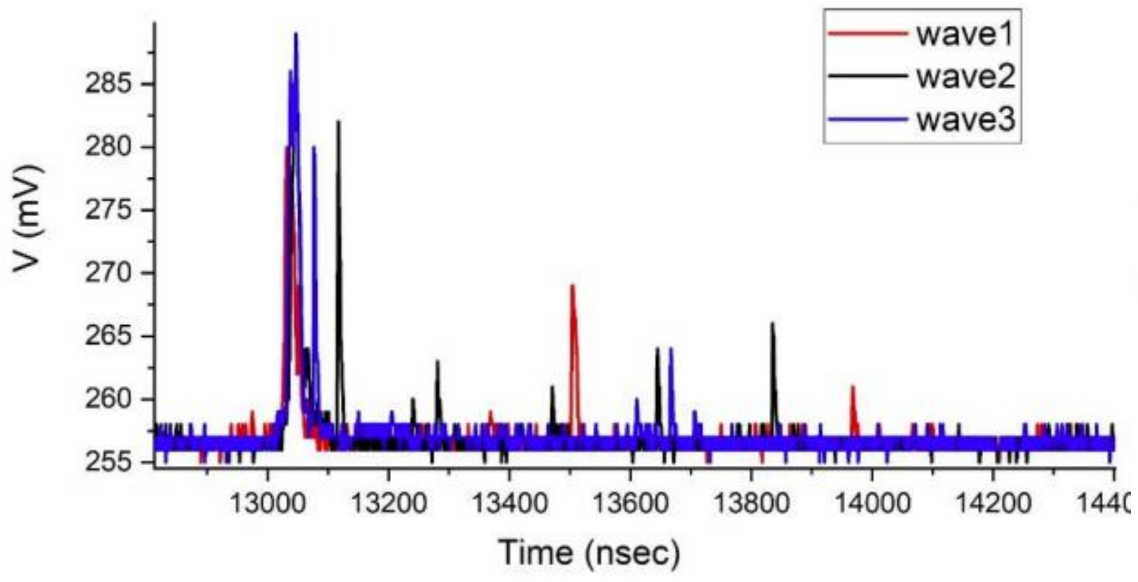


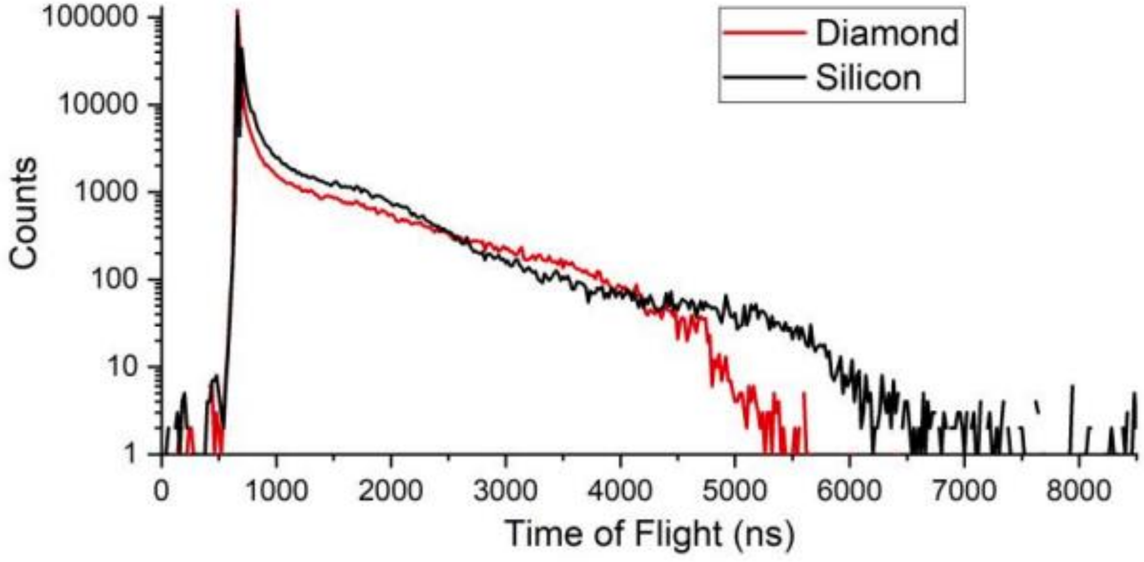




nTOF: Using ToF to Extract Response Functions

- Short pulse (4 ns) + 200 m → direct neutron energy measurement
- Response functions extracted for selected neutron energies (10–500 MeV)
- Silicon and diamond measured response curves (Fig. 5)
- **Purpose:** build **monoenergetic response functions** for benchmarking FLUKA/GEANT4.

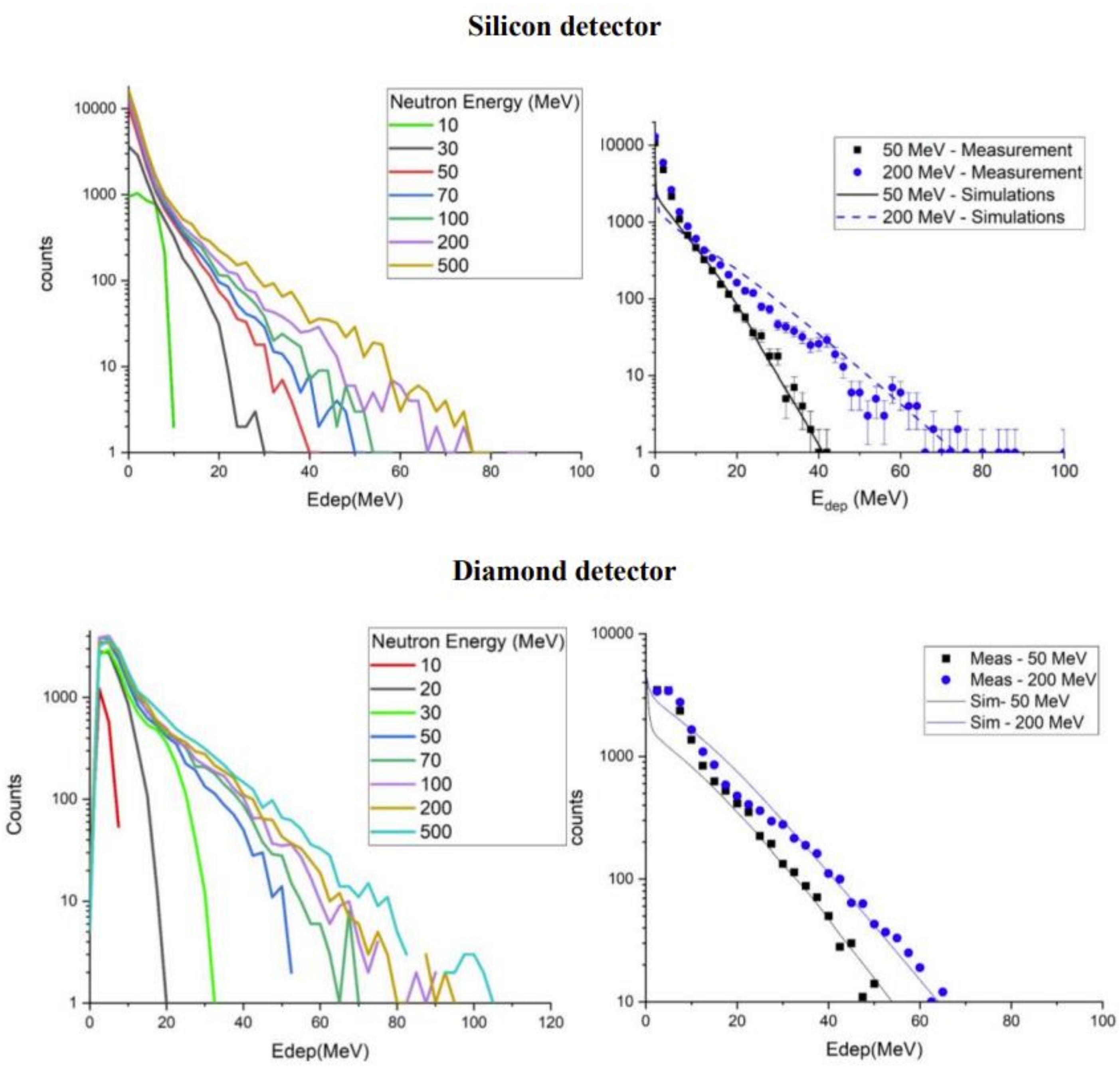




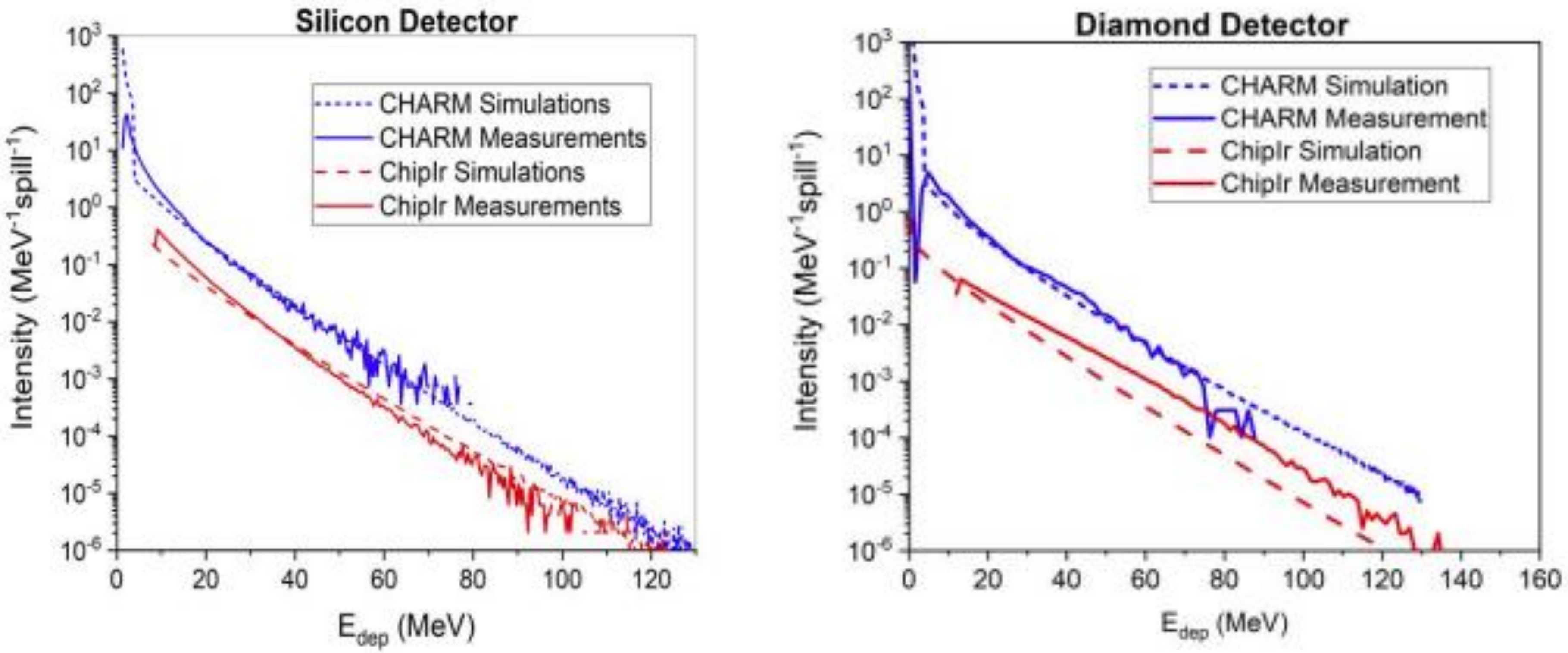
Fast Neutron Response

Event-by-event response functions measured at nTOF (10–500 MeV) capture the full range of neutron–silicon/diamond interactions, including elastic scattering, inelastic channels, and (n,p)/(n,α) reactions.

Excellent agreement between measured and simulated responses validates the detector models and enables accurate reconstruction of high-energy neutron fields.



Application: Beamline Characterization at ChipIr & CHARM

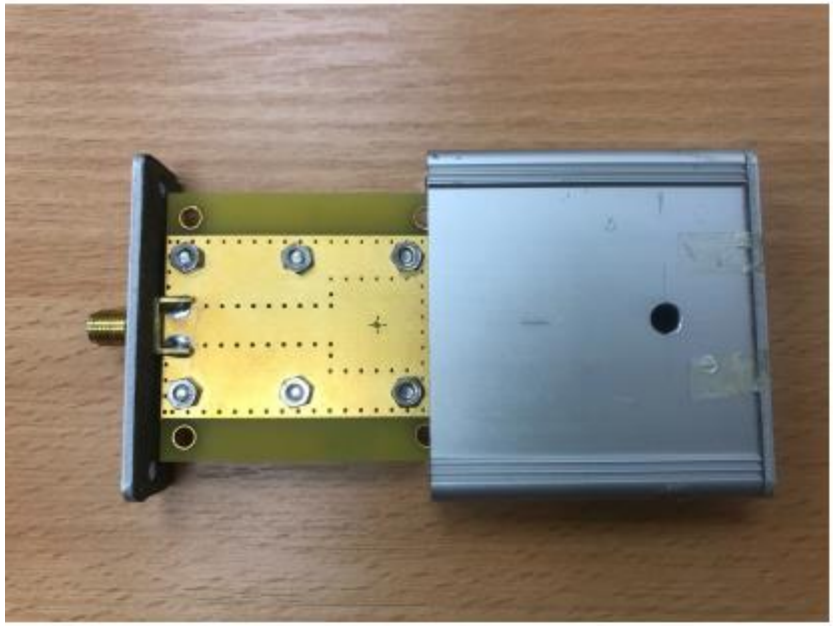


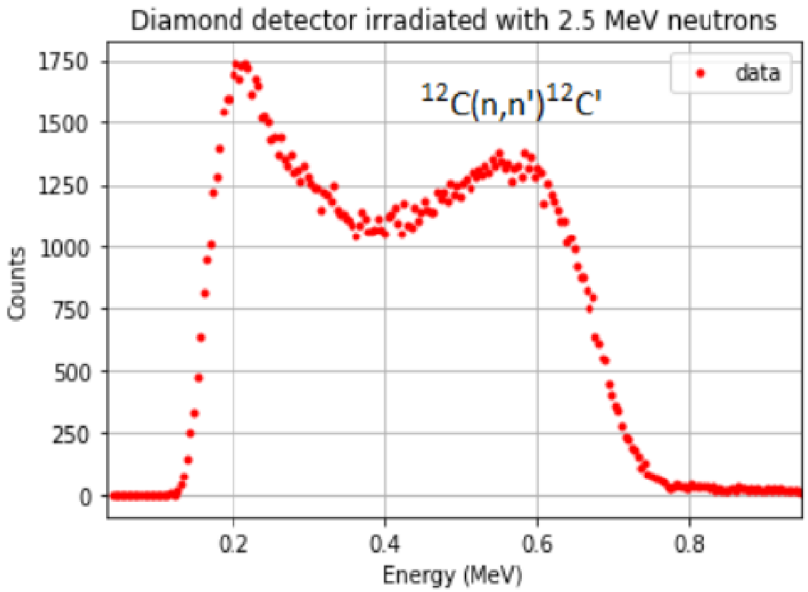
- Measured deposited-energy spectra at both facilities show excellent agreement with FLUKA simulations, validating the neutron and mixed-field models used for SEE testing.

- Response functions derived at nTOF enable accurate reconstruction of the high-energy neutron fields, allowing cross-calibration

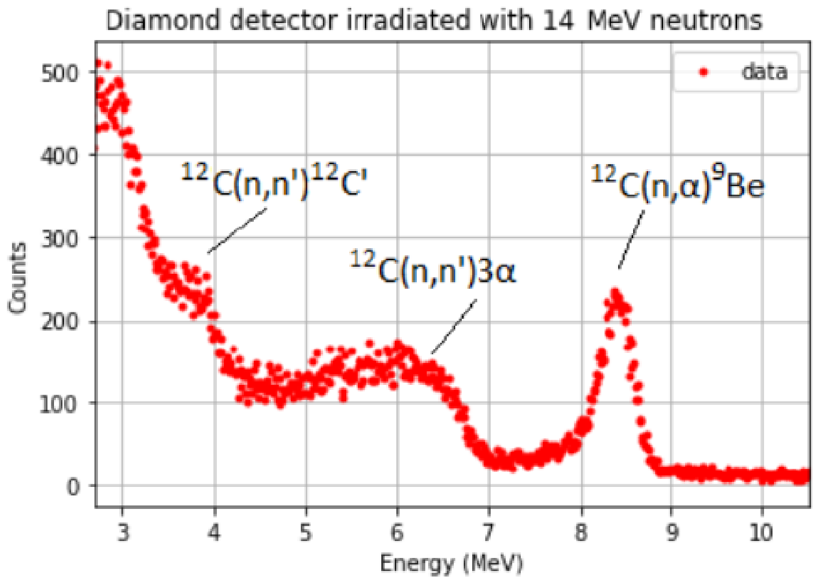
High Resolution Spectroscopy with a diamond detector

Single-crystal diamond grown by chemical vapor deposition of size 500 um x 4.5 mm x 4.5 mm.



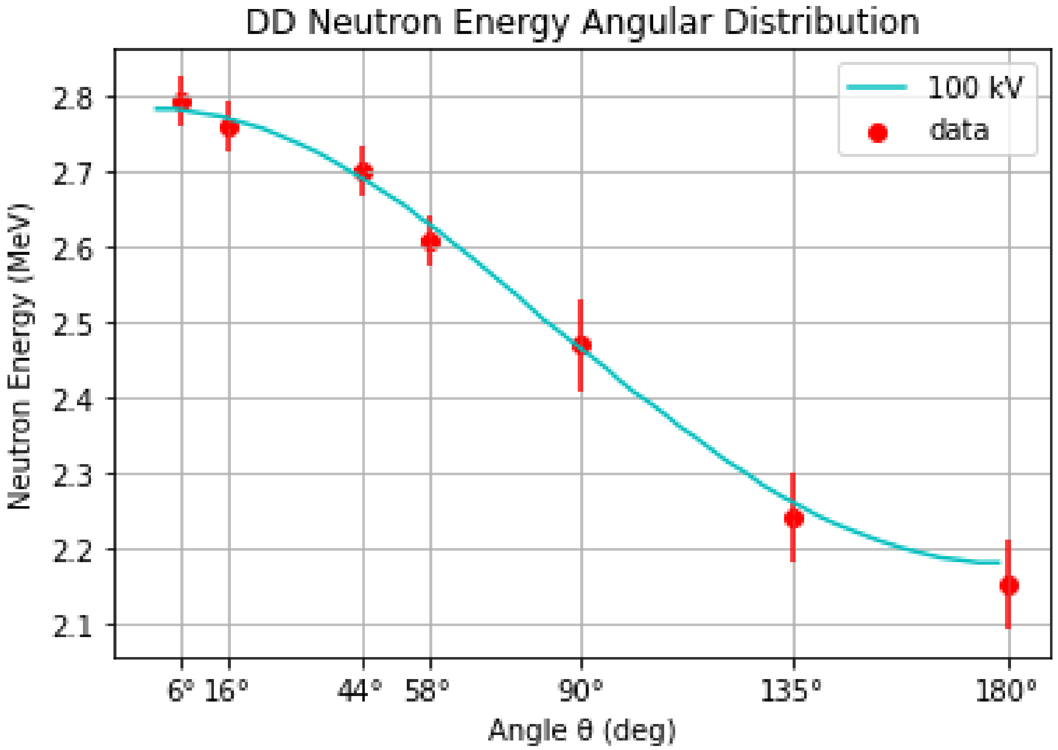


2.5 MeV



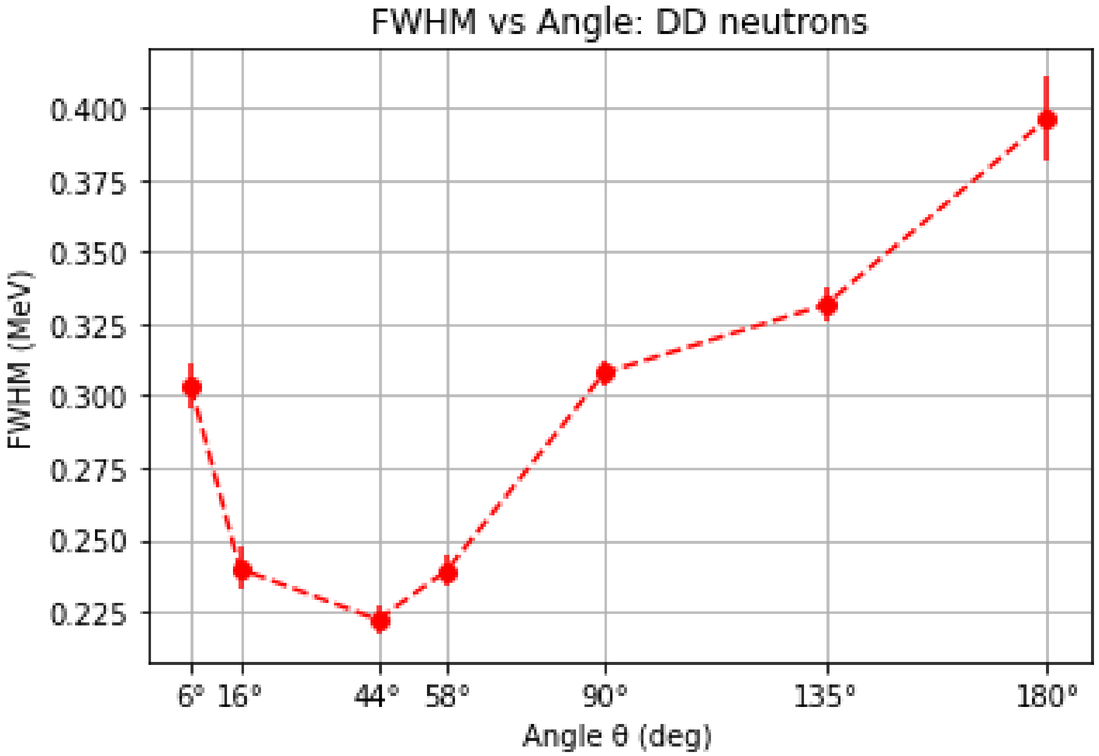
14 MeV

Application: NILE characterization
2.5 MeV high-resolution spectroscopy



Neutron Energy

Analytical curve from kinematics



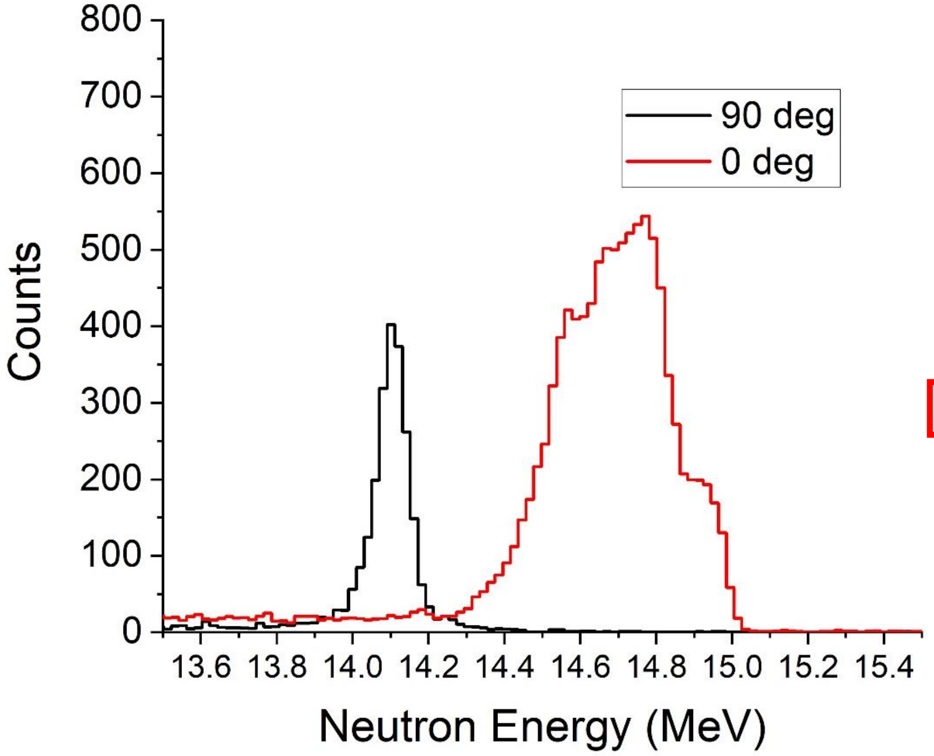
Broadening

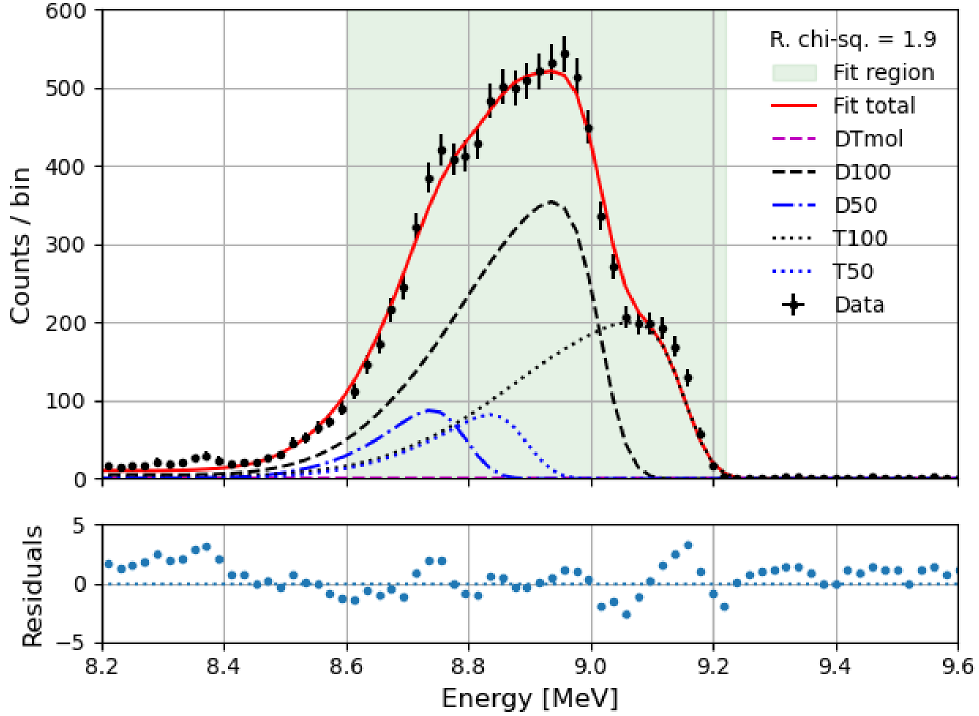
Due to multiple effects:

- Geometry/solid angle
- Thickness of the target/kinematics
- Purity of the beam

Application: NILE characterization
14 MeV high-resolution spectroscopy

Neutron peaks measured thanks to n,α reaction



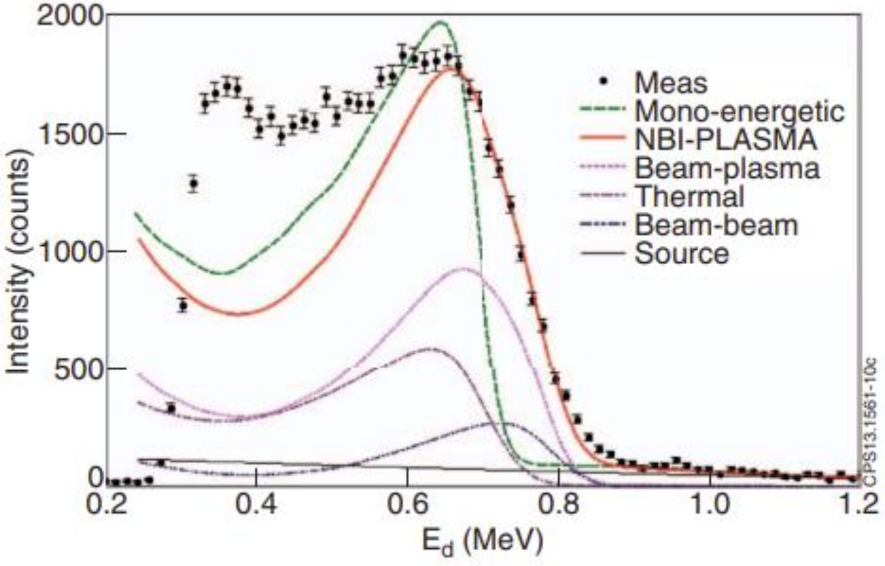


- Sharpest peak is at 90 deg because of kinematics
- Broadening of peak at 0 deg is due to kinematics and different species in the ion beam, D_2, T_2 DT, D, T

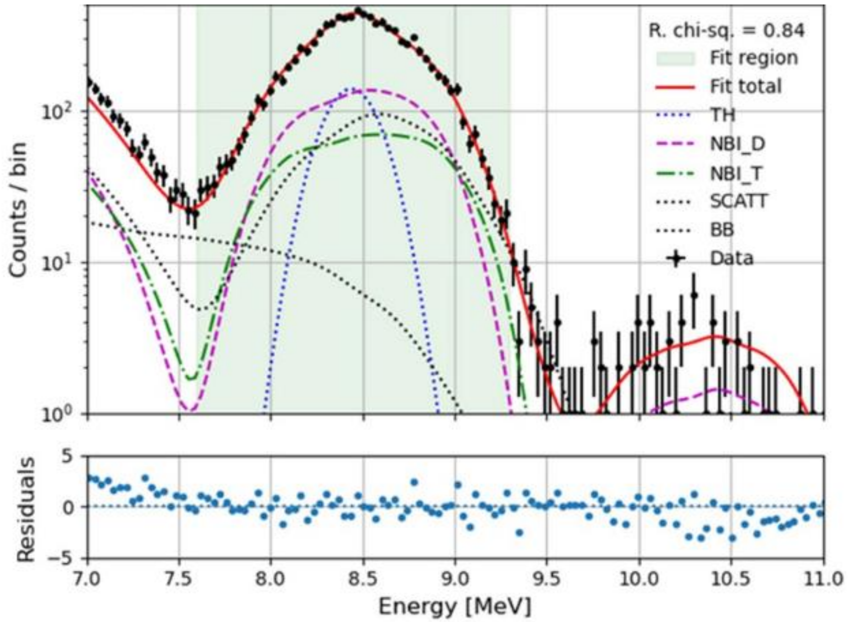
Diamond detector deployed at tokamaks

- Diamond detectors are now successfully deployed as plasma diagnostics at tokamaks thanks to high-resolution spectroscopy
- Doppler broadening of neutron line due to plasma temperature, beam-plasma kinematics, high energy ions

DD plasmas 2.5 MeV

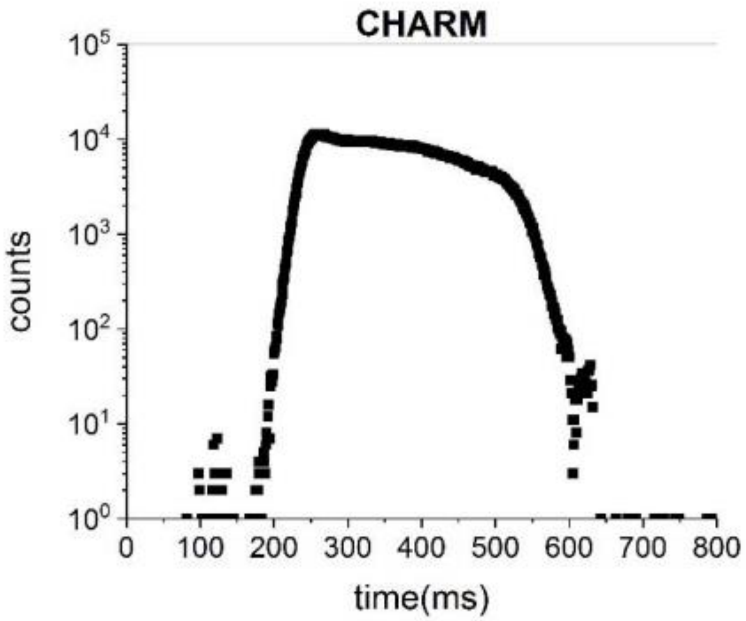


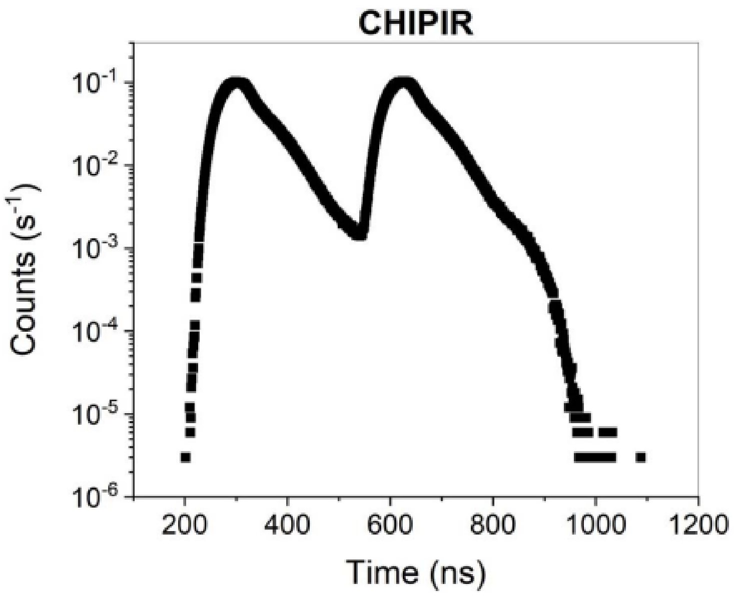
DT plasmas 2.5 MeV



Time Structure Measurement

- The fast digitizer allows event-by-event timestamping.
- CHARM shows a **long, flat 350 ms spill**, characteristic of slow extraction from the PS.
- ChipIr shows the **two 70 ns proton bunches, 360** ns apart.
- Understanding the time structure is essential for:
  - evaluating **pile-up probability**
  - estimating **dead-time corrections**

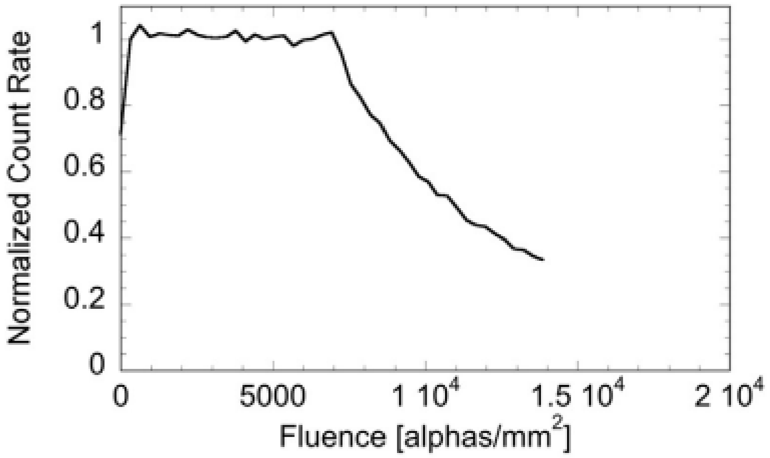


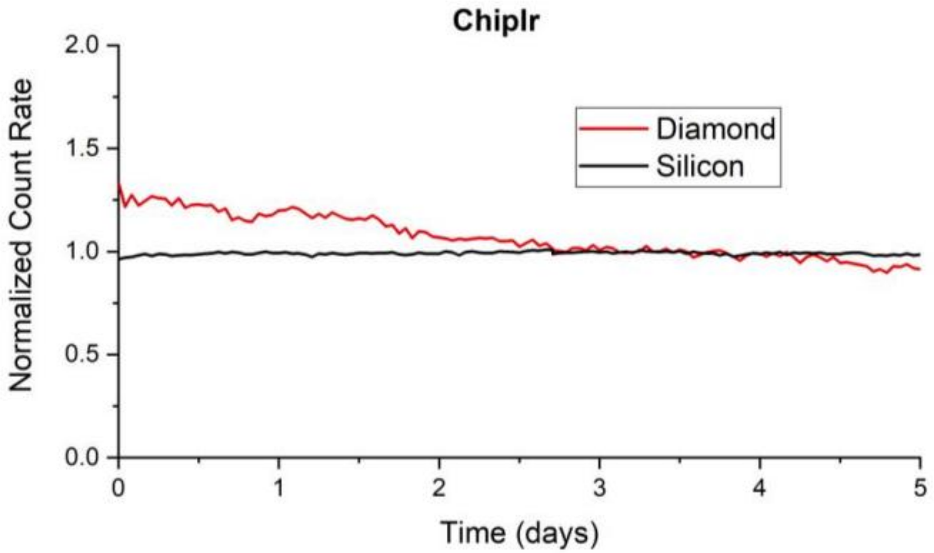


Polarization effects in diamonds

- Single-crystal CVD diamonds contain a small fraction of **defects, impurities and trapping centers**.
- Quality of contacts metallization is also important:
- Under sustained flux, charge carriers created by neutron-induced ionization become **trapped**, creating internal space-charge regions.
- This modifies the internal electric field, leading to **Reduced charge-collection efficiency (CCE)**

Alpha particles

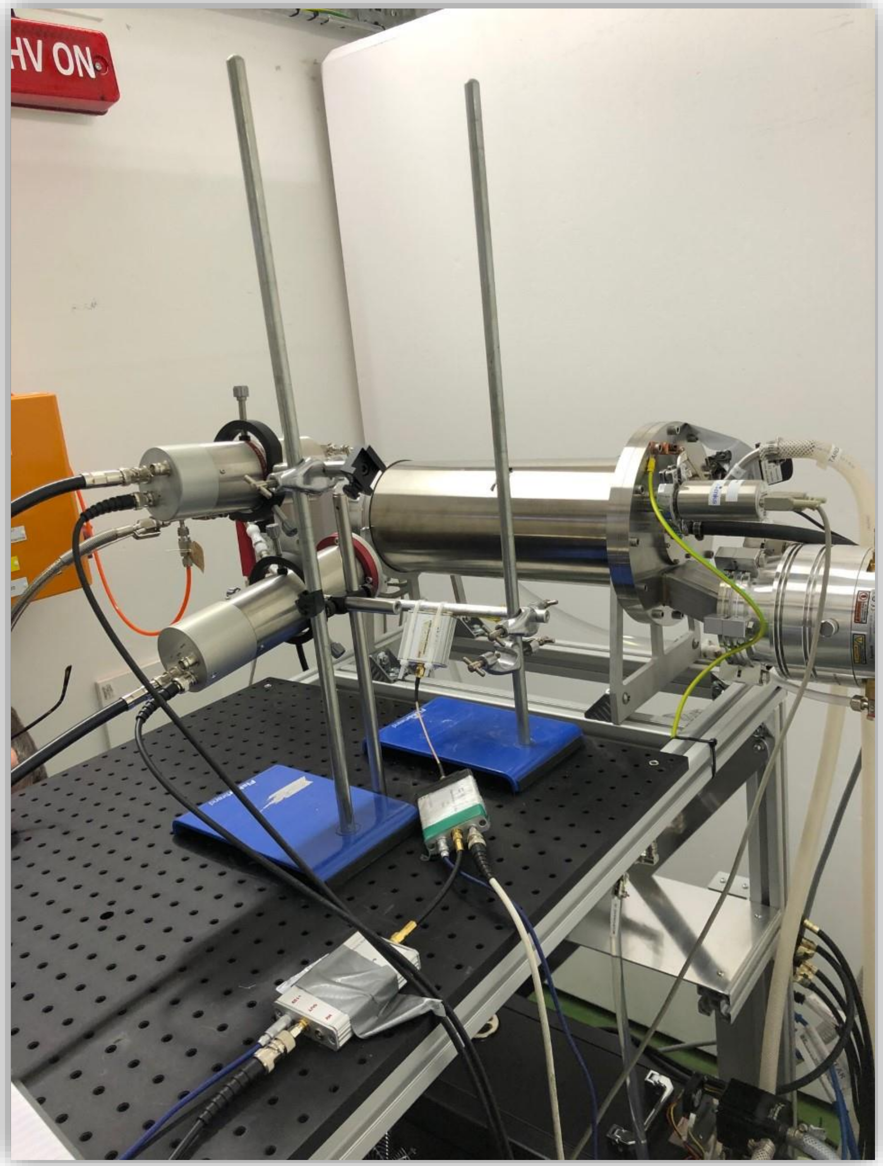




Other Neutron Measurements

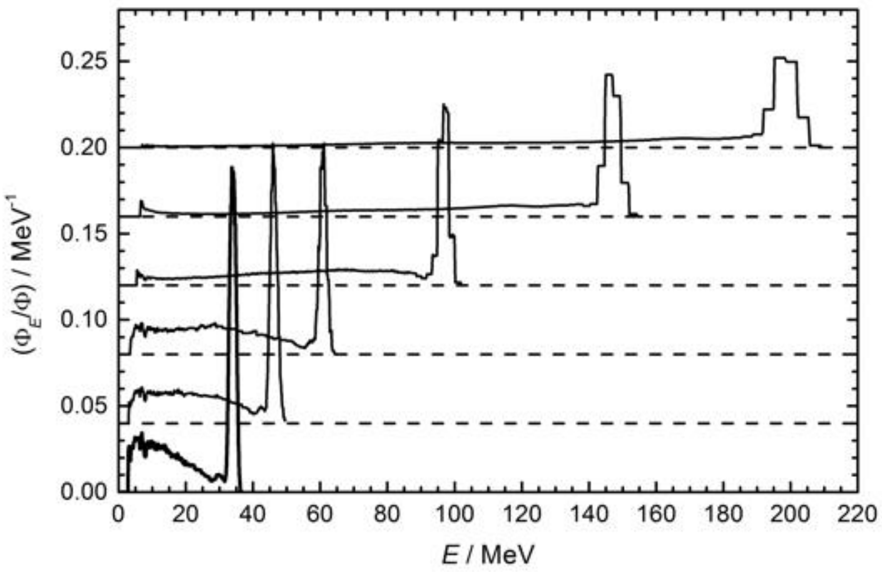
	Absolute flux	Beam monitoring	Neutron Spectroscopy	Gamma/neutron discrimination
Activation foils	**Primary**			
Fission Chamber	Secondary	**Primary**		
Diamond Detectors	Secondary	Secondary	**Primary**	
EJ276 scintillator	Secondary	Secondary		**Primary**
7CLYC scintillator	Secondary		Secondary	Secondary
SRAM monitors	Secondary	Secondary		

Summary of measurement requirements and systems for the dosimetry of compact generators.



Next project: high energy neutrons at iThemba LABS

- The project will evaluate neutron fluxes, spectra, and beam uniformity at energies **from 50 to 200 MeV**.
- **Silicon and diamond detectors** will be used for their **well-known neutron energy response** combined with fast signals that allow for time of flight measurements.
- Activation foils will measure neutron flux and energy distribution with direct reference to nuclear cross sections. SRAM-based detectors will monitor Single Event Upsets to measure neutron flux and beam profiles, aiding cross calibration with existing facilities like ChipIR.
- This comprehensive approach ensures robust testing and **confidence for using ithemba beams for microelectronics testing application**.



Conclusions

- **Silicon and diamond** detectors enable **event-by-event** measurements of high-energy neutron and mixed fields.
- nTOF provides monoenergetic response functions, allowing accurate benchmarking of FLUKA and GEANT4 models.
- Atmospheric neutron spectra reconstructed with these response functions show excellent agreement (≈10% in 20–80 MeV).
- **Silicon shows stable operation across all facilities** (no polarization effects); diamond offers superior radiation hardness but is sensitive to polarization in high instantaneous flux environments.
- **Diamond enables high-resolution spectroscopy at 2.5 and 14 MeV** for fusion diagnostics and complements spallation-based beam characterization.