UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

Istituto di Fisica del Plasma "Piero Caldirola"
Consiglio Nazionale delle Ricerche

INFN Istituto Nazionale di Fisica Nucleare

Fast neutron spectroscopy with diamonds on fusion plasma and short-pulse spallation neutron source

Outline

- Diamond detectors

- Diagnostic of fast neutrons beam at spallation neutron sources
  - Studying the SEE's: CHIPIR @ ISIS
  - ISIS-VESUVIO experiment description
  - n_TOF experiment description

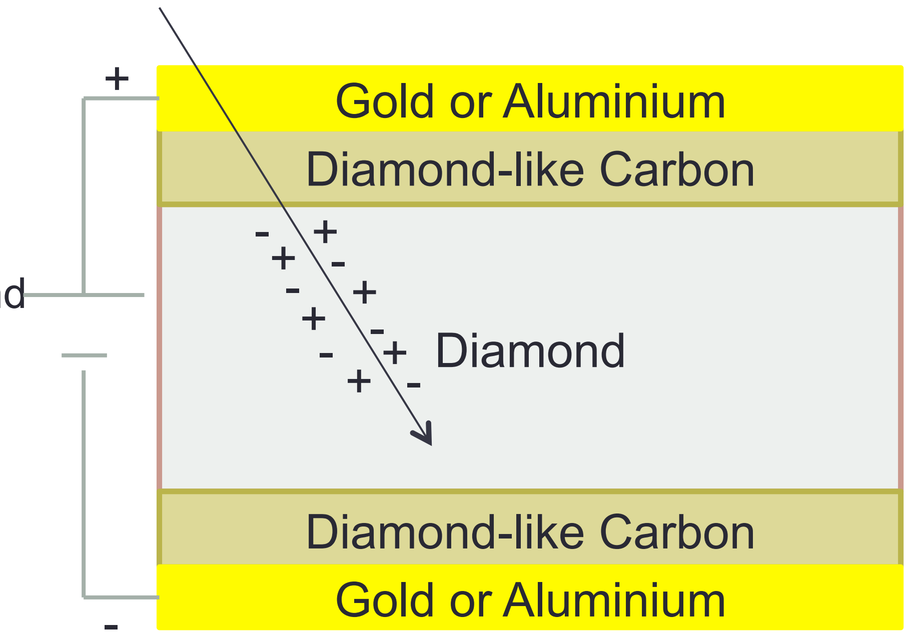
- Diagnostic on Fusion Plasmas
  - Neutron diagnostics of fusion plasmas
  - Development of a new SDD Matrix as a Vertical Neutron Spectrometer for JET
  - .

Diamond Detectors

- Radiation hardness.
- High mobility of free charges (→fast response, comparable to Si, Ge).
- Room temperature operation (E_g=5.5 eV)→ No Cooling.
- Compact volume solid state detector.

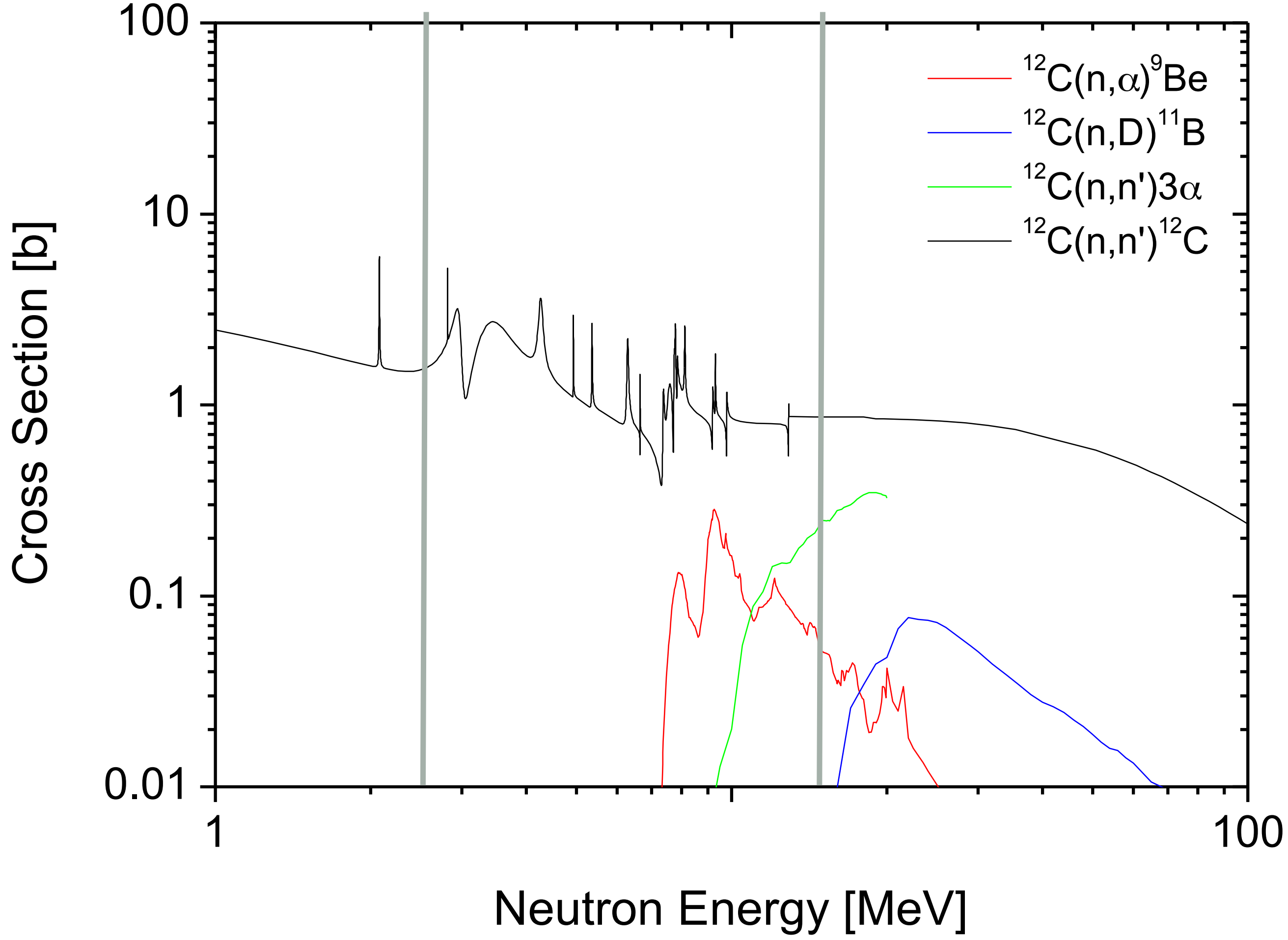
With the CVD technique diamonds can be produced with good energy resolution (<1%) and 100% charge collection efficiency.

A charged particle passes through the diamond and ionizes it, generating electron–hole pairs ($E_{e\text{-}h}$=13 eV)



Diamond Detectors Limited Technology

The n-^{12}C interaction cross section



→ Fast neutron detection is achieved by detecting charge particles produced via the reactions:

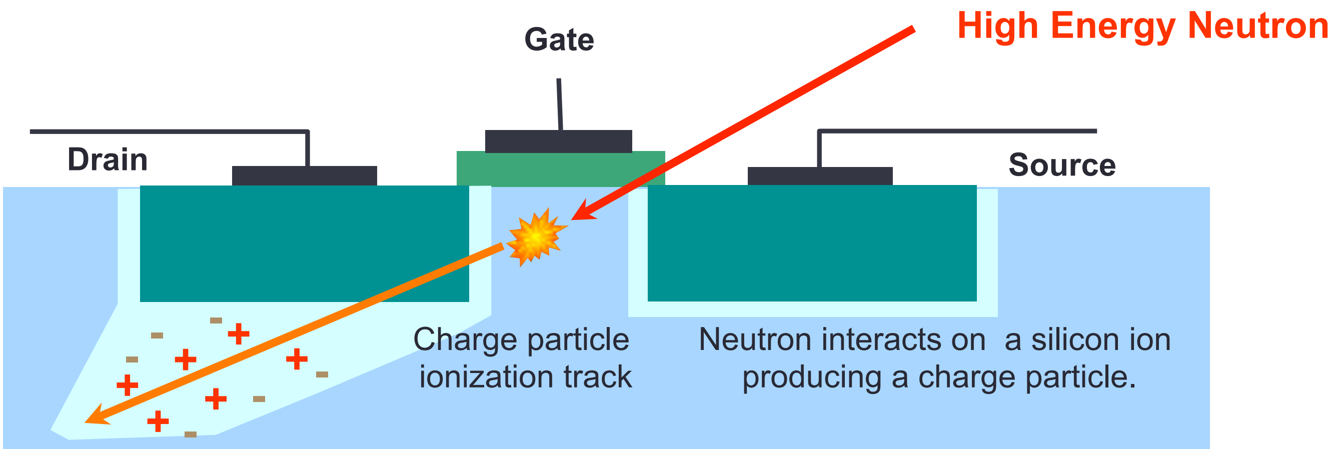
- ^{12}C(n,a)^{9}Be (Q_{value}=5.7 MeV, E_{thr}=6.17 MeV) good for 14 MeV neutron spectroscopy.
- ^{12}C(n,n')3α (Q_{value}= 7.23 MeV, E_{thr}=7 MeV)
- ^{12}C(n, D)^{11}B (Q_{value}= 13.7 MeV, E_{thr}=13.8 MeV)
- ^{12}C(n, n')^{12}C* only possible reaction for E_n=2.5 MeV

Diamond for spallation neutron sources

Single Event Effects (SEEs)

Different kind of errors (SEU, MEU) due to the interaction of a single ionizing particle.

→ Neutrons >1 MeV: dominant component at heights lower than 10 km.



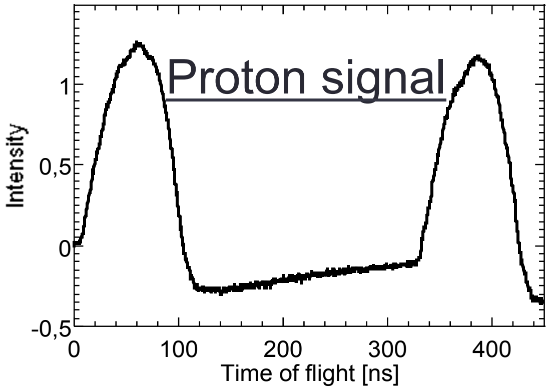
SEE cross section: $\sigma = \frac{\#SEE}{\phi}$

Beam line requirements:

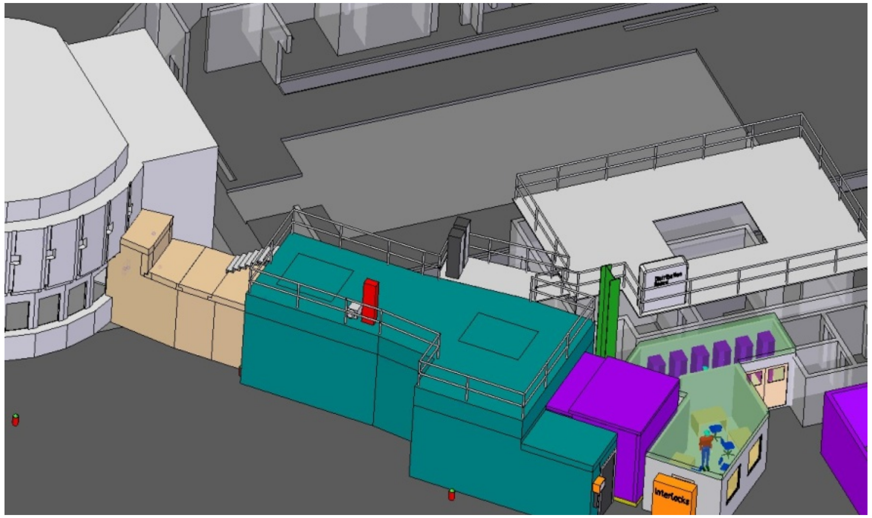
- "Atmospheric" neutron spectrum
- High flux (Φ_{atm}:10^{-5} $ncm^{-2}s^{-1}$)
- Beam uniformity

ISIS neutron source and CHIPIR

ISIS (RAL, Didcot, U.K.):spallation neutron source (800 MeV).

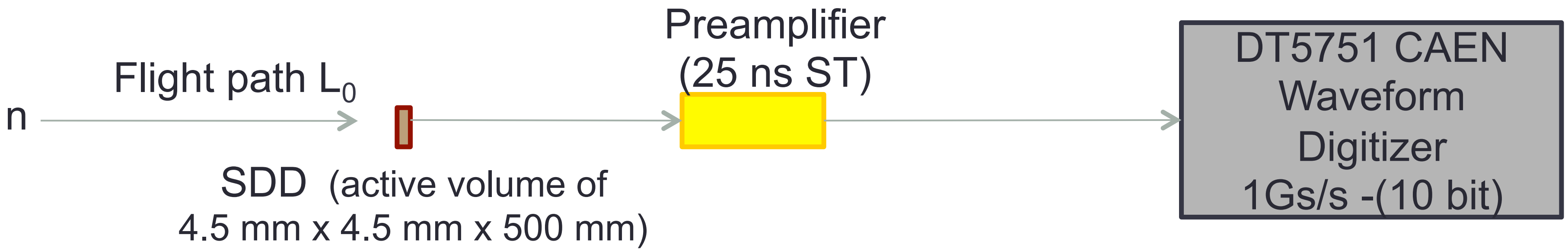


- Protons are accelerated by a synchrotron up to 800 MeV.
- Protons are produced into two bunches 70 ns wide and 322 ns apart.
- Protons produce neutrons via spallation reactions on a target.



$\Phi \approx 10^6$ n/cm^2/s above 10 MeV

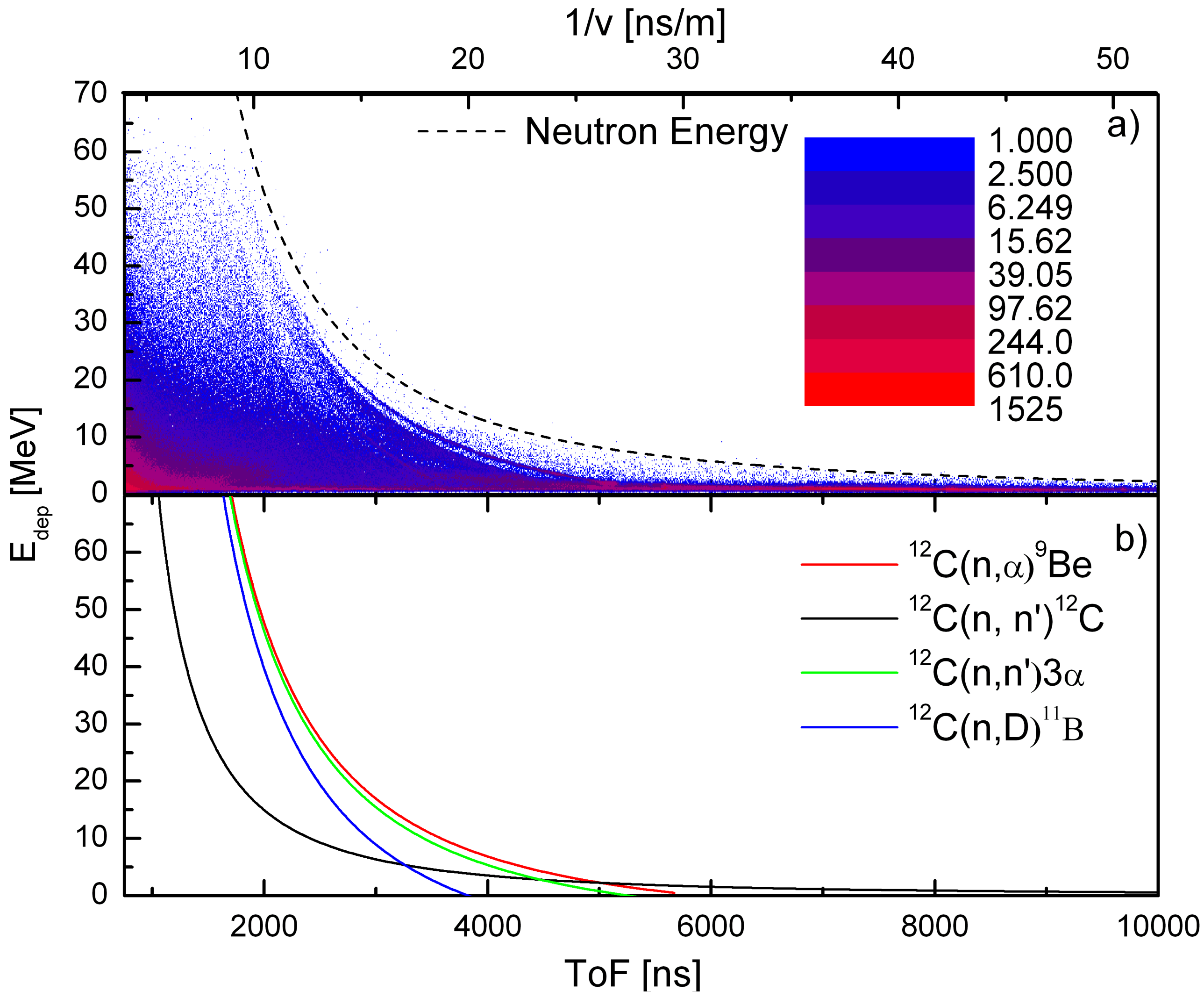
Single-crystal Diamond Detector measurements at spallation sources



- The waveforms obtained from SDDs were stored ***in coincidence*** with the t_0. The arrival time of a gamma-ray cascade, recognised in the recorded waveforms, gives the absolute time synchronization. → t_{ToF}

- ***Bi-parametric*** spectra were obtained off-line from the digitized waveforms through a custom analysis software.

Density plot at n_TOF



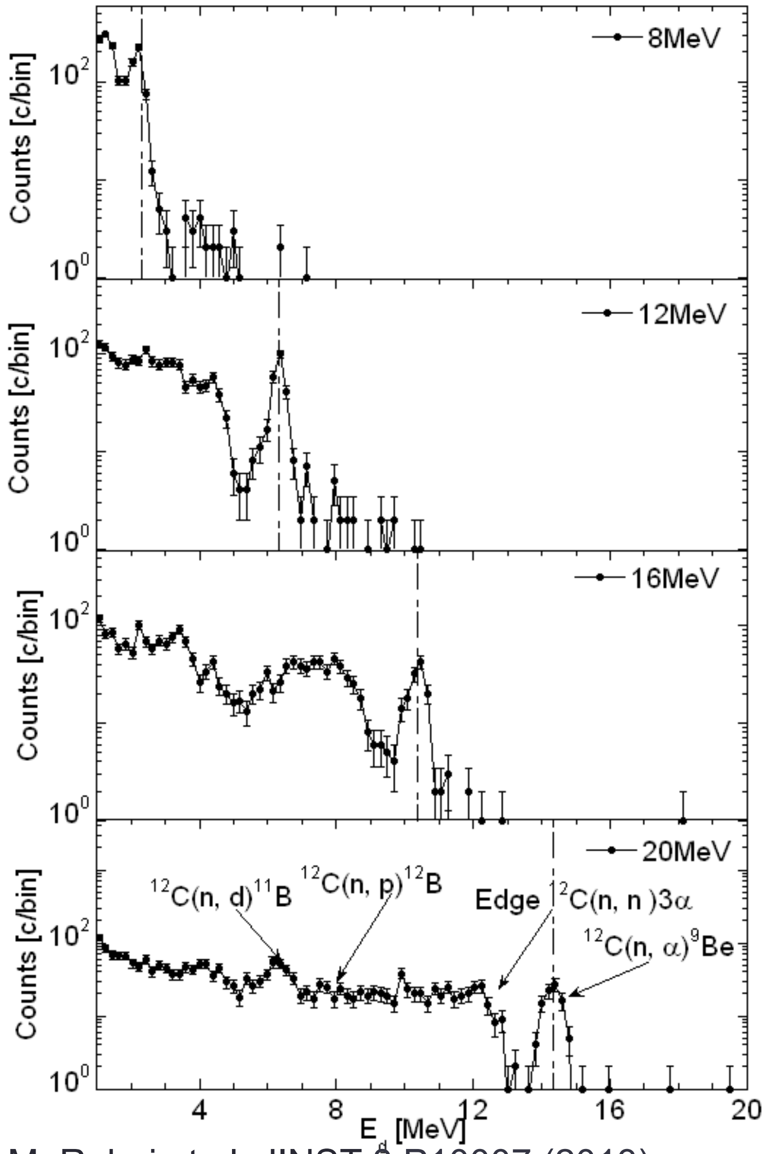
+ Shorter proton pulse (5ns FWHM).
+ Longer flight path (200 m)
→ Better E_n resolution.

Data acquisition time of 20 days and 6 hours.

→ mean frequency count of 0.63 cps.
→ peak-frequency count of 68 kHz.

M. Rebai et al. JINST 8 P10007 (2013)

PHS Spectra under 20 MeV



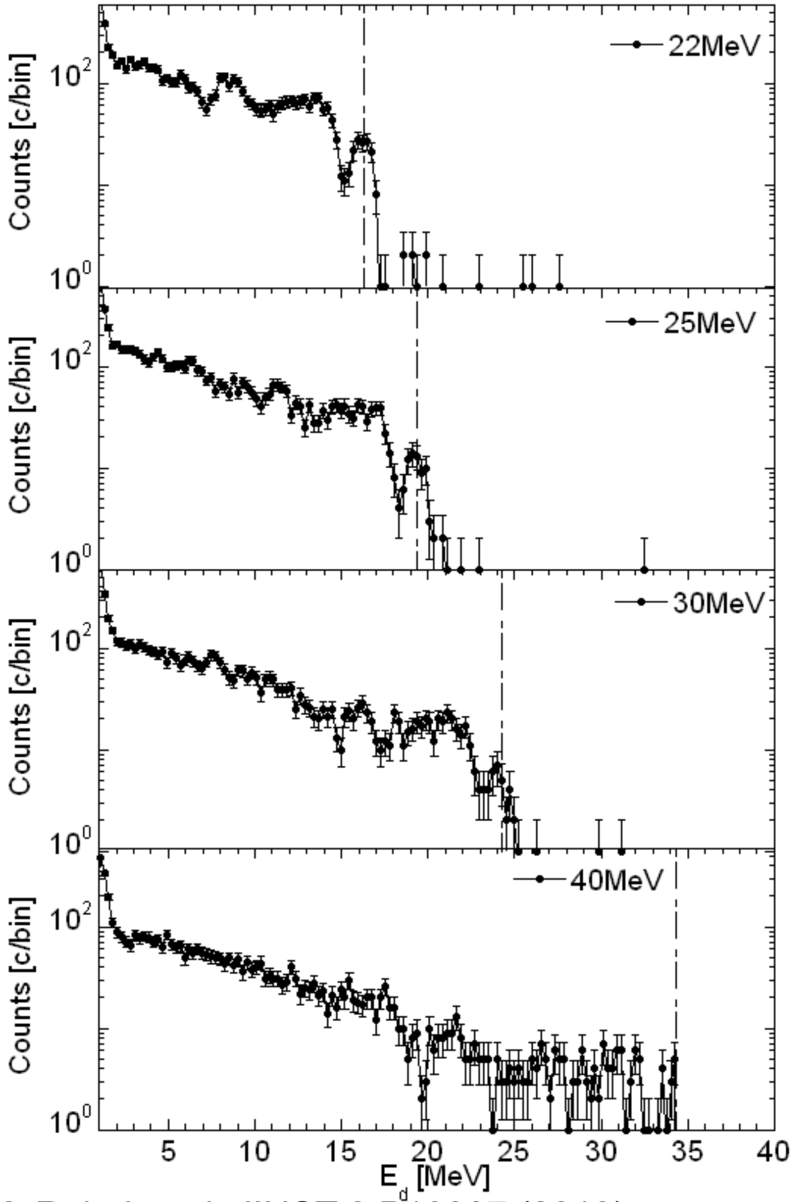
M. Rebai et al. JINST 8 P10007 (2013)

The vertical dashed line represent the position of the $^{12}C(n, \alpha)\,^{9}Be$ peak for the considered neutron energy. The peak is always visible as a well-separated peak at $E = E_n - 5.7$ MeV.

In the lower figure (E_n=20 MeV) the most important n-^{12}C reactions are reported. The uncertainty of the neutron energy is about 100 keV, 200 keV, 300 keV and 400 keV for the four energy values, due to the constant binning in TOF.

The other reaction channels and carbon recoil give rise to a continuum spectrum at lower energies, except the peak of the $^{12}C(n, d)\,^{11}B$ visible at E_n = 20 MeV.

PHS Spectra above 20 MeV



M. Rebai et al. JINST 8 P10007 (2013)

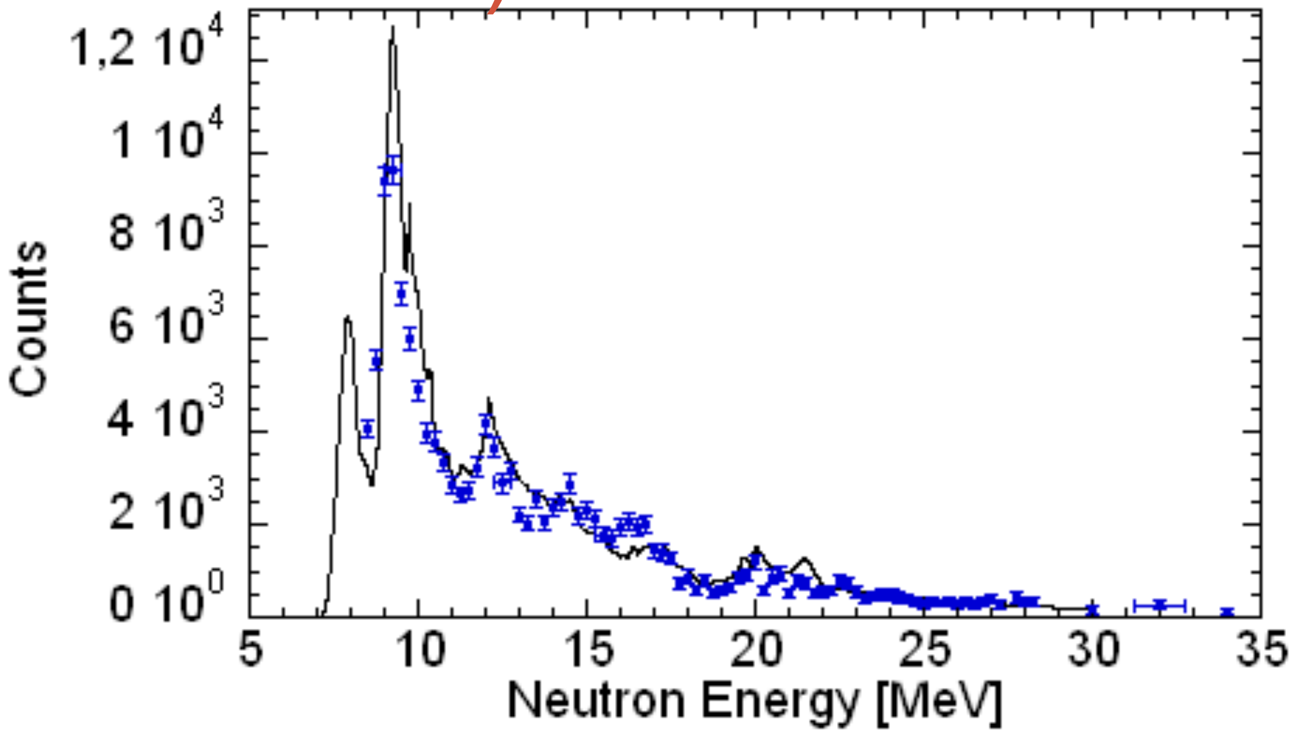
Spectra of the energy deposited in the detector for selected neutron energies above 20 MeV.

The dashed line represent the position of the $^{12}C(n, a)\,^{9}Be$ peak for the considered neutron energy.

The uncertainty in E_n is about 1.25 MeV.

The response function was measured successfully up to 40 MeV. In the future we plan to measure above 40 MeV with a low gain electronic chain.

Comparison with calculations: (the n-α reaction)



Total number of counts in the n-α peak at different neutron energies is reported with blue dots.

The full line is the expected number of counts calculated using:

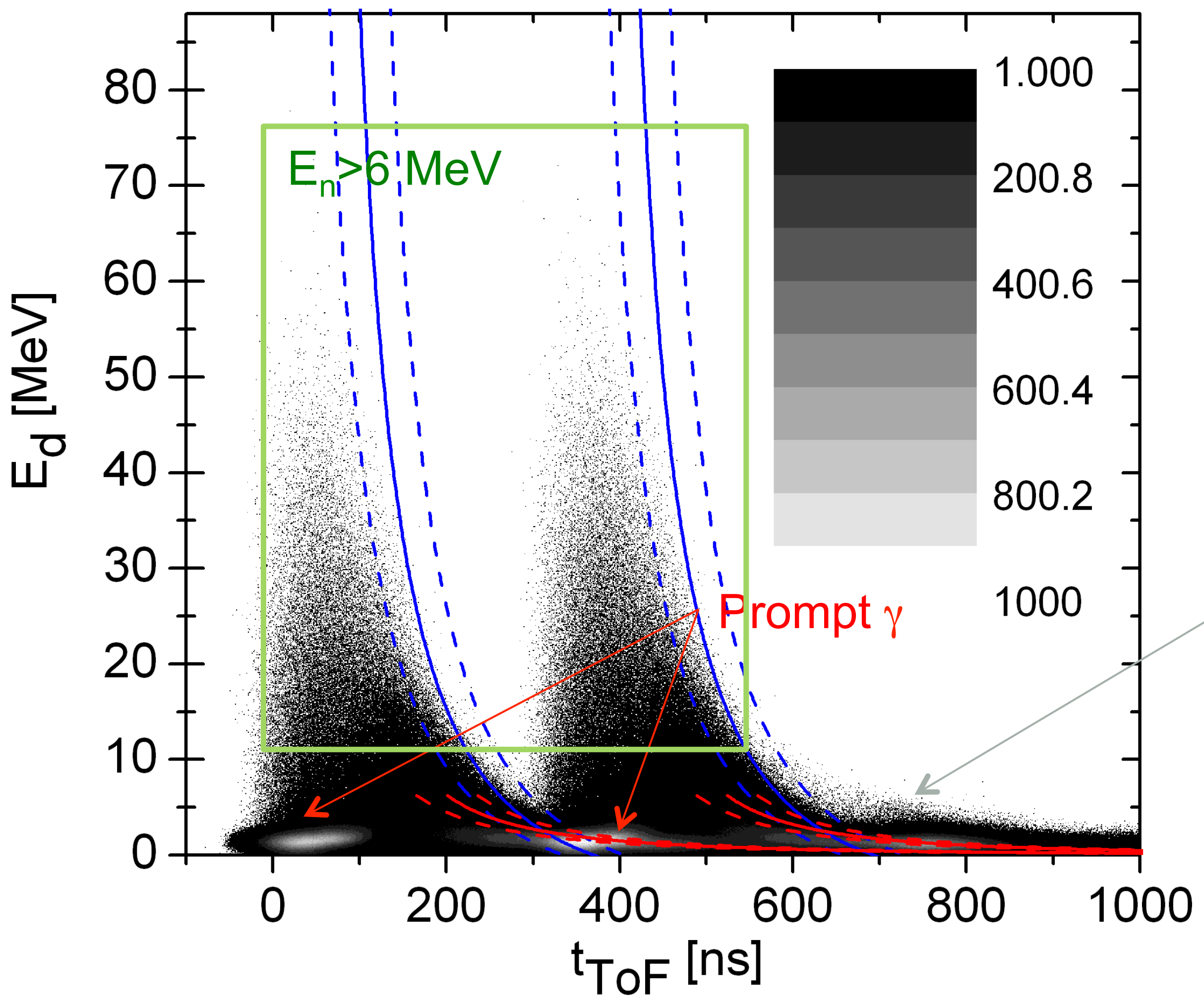
$$c = \sigma(E)[cm^2]\cdot\phi[n/b](E)\cdot\left(\frac{N_A\cdot\rho\cdot z}{A}\right)\cdot\left(\frac{A_{beam}}{A_{det}}\right)\cdot N_b\cdot\varepsilon$$

Number of bursts

Efficiency =5*10^5

M. Rebai et al. JINST 8 P10007 (2013)

Event density plot at ISIS-VESUVIO

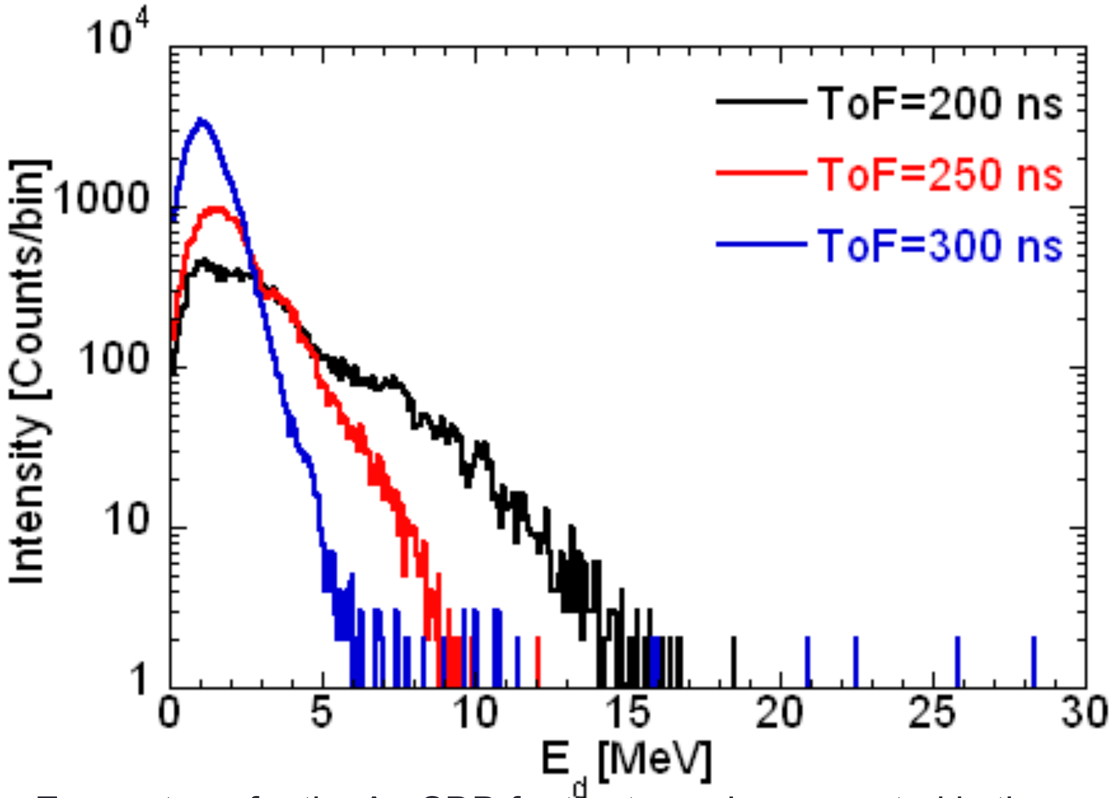


Flight path: 12.5 m
Peak Rate: 1 MHz.

Events due to the interaction of 3.5 MeV neutron which release energy via elastic recoil on the ^{12}C nucleus.

M. Rebai et al., JINST 7 C05015 (2012).

PH spectra for different t_{ToF}



E_d spectrum for the Au-SDD for the t_{ToF} values reported in the legend. The t_{ToF} bin width is 5 ns. The E_d bin width is 0.089 MeV.

The t_{ToF} values correspond to an (average) neutron energy equal to :
E_n=21.1 MeV (t_{ToF}=200 ns), E_n=13.3 MeV (t_{ToF}=250 ns), E_n=9.2 MeV (t_{ToF}=300 ns).

M. Rebai et al., JINST 7 C05015 (2012).

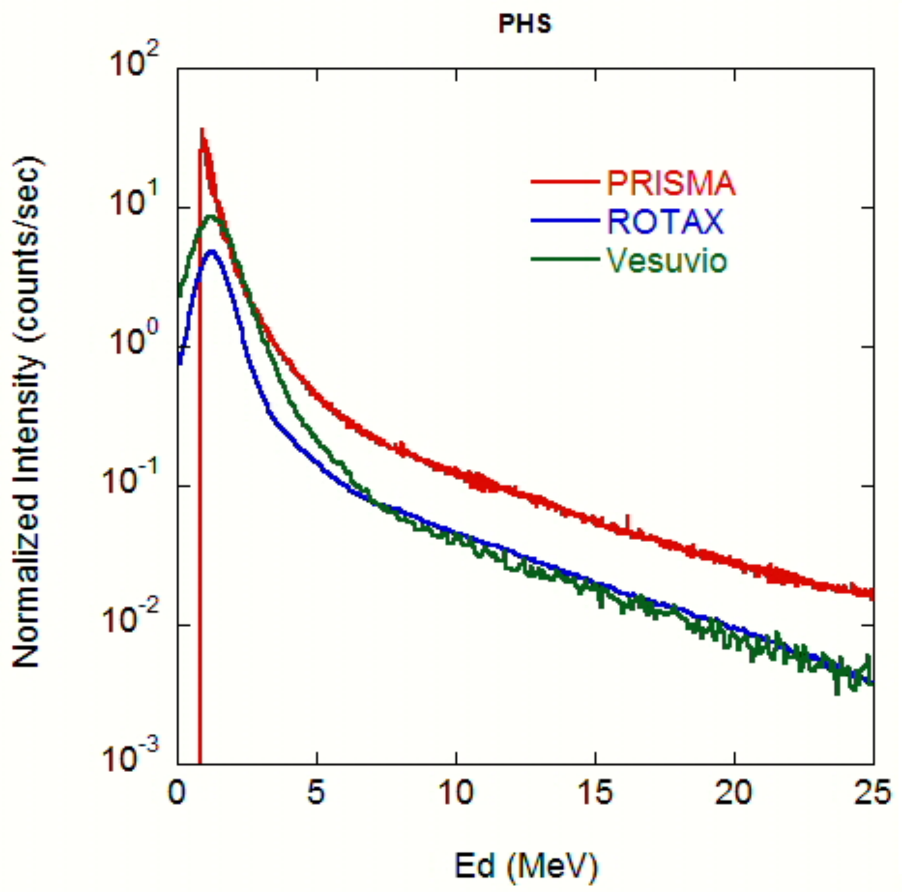
→ clear correlation between average E_n and maximum E_d.

Measurements at high-rates (>100 MHz) with SDDs at ISIS is possible.

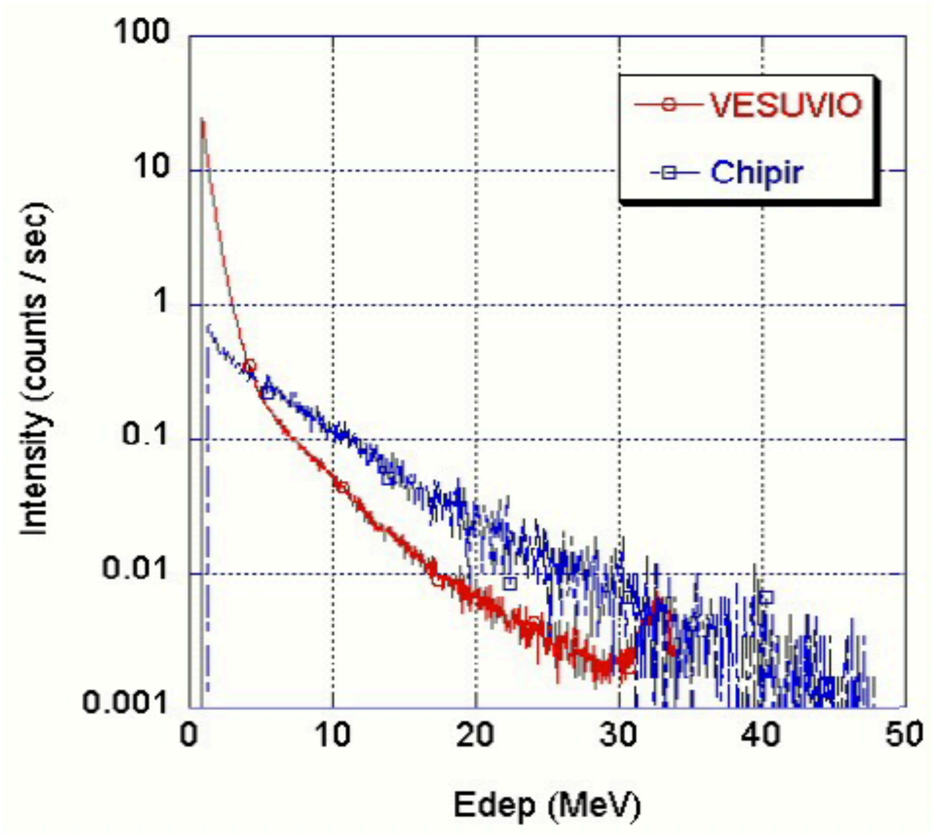
BUT at ISIS is impossible to study the response function (short flight path and temporal structure of the beam).

→ ***n_TOF***
The interpretation of the ISIS results by using n_TOF data is in progress.

PHS measured on different beam-lines



PRELIMINARY



- Prisma has more fast neutrons: it’s closer (8m)

Diamond for fusion plasmas diagnostics

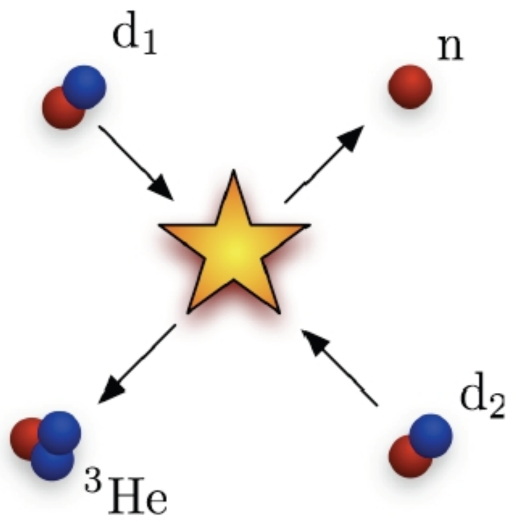
Neutron emission in fusion plasmas

Neutron production

Neutrons are produced by fusion reactions

d +d → n + ^{3}He

d + t → n + α



In a **cold plasma** ($E_{reactants}$ ≈ 0)

E_n = 2.45 MeV for DD reaction

E_n = 14.0 MeV for DT reaction

The neutron energy depends on the **energy of the reactants:**

$$E_{\mathrm{n}} = \frac{1}{2} m_{\mathrm{n}} v_{\mathrm{cm}}^2 + \frac{m_{\mathrm{R}}}{m_{\mathrm{n}} + m_{\mathrm{R}}}(Q+K) + v_{\mathrm{cm}} \cos(\theta) \left(\frac{2 m_{\mathrm{n}} m_{\mathrm{R}}}{m_{\mathrm{n}} + m_{\mathrm{R}}}(Q+K) \right)^{1/2}$$

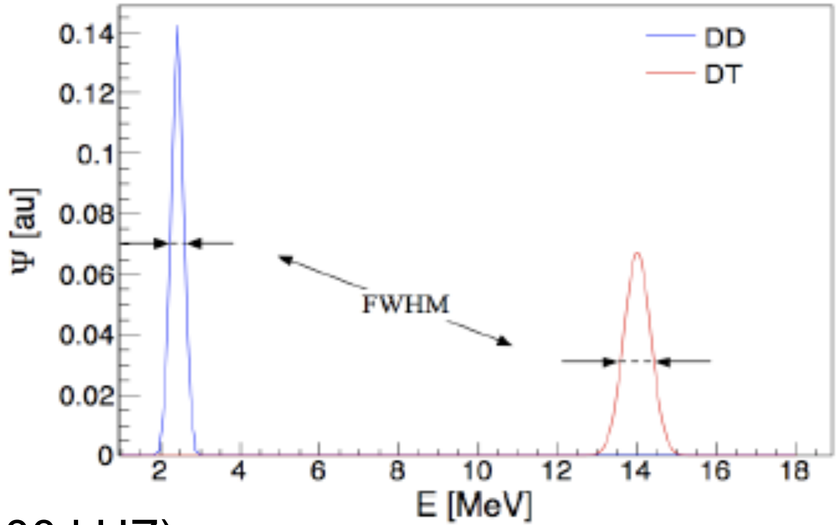
Neutron emission spectroscopy in fusion plasmas

In a plasma in thermal equilibrium, the particles are distributed according to a Maxwellian distribution Neutron spectrum is well approximated as a Gaussian centered at 2.45 MeV (or 14.0 MeV) and with FWHM (W)

Ion Temperature T_i

$W = 82.5 \cdot \sqrt{T}$ for DD emission

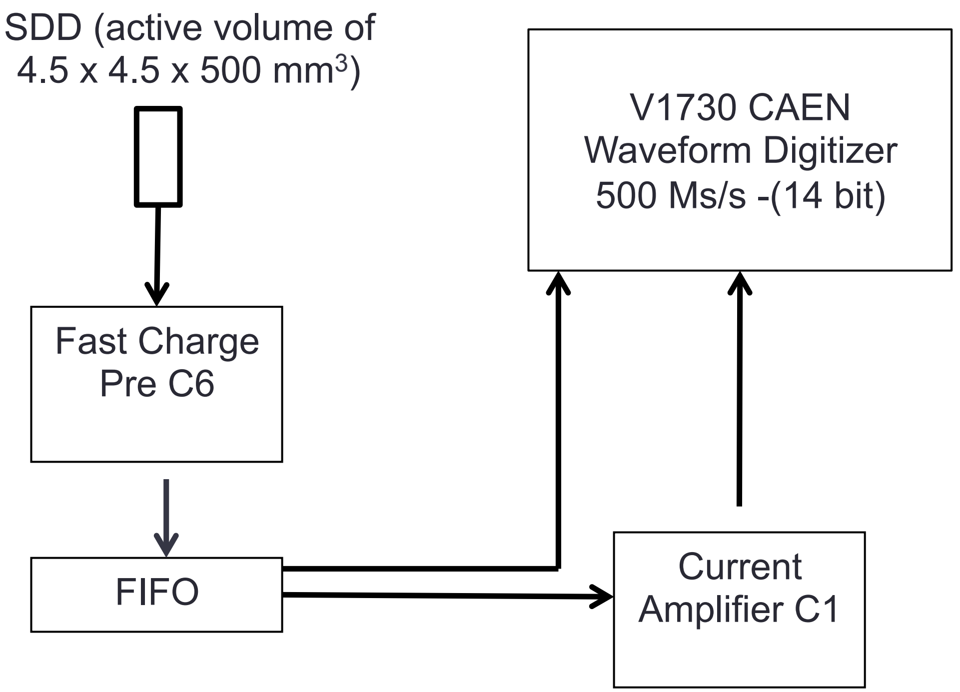
$W = 177 \cdot \sqrt{T}$ for DT emission

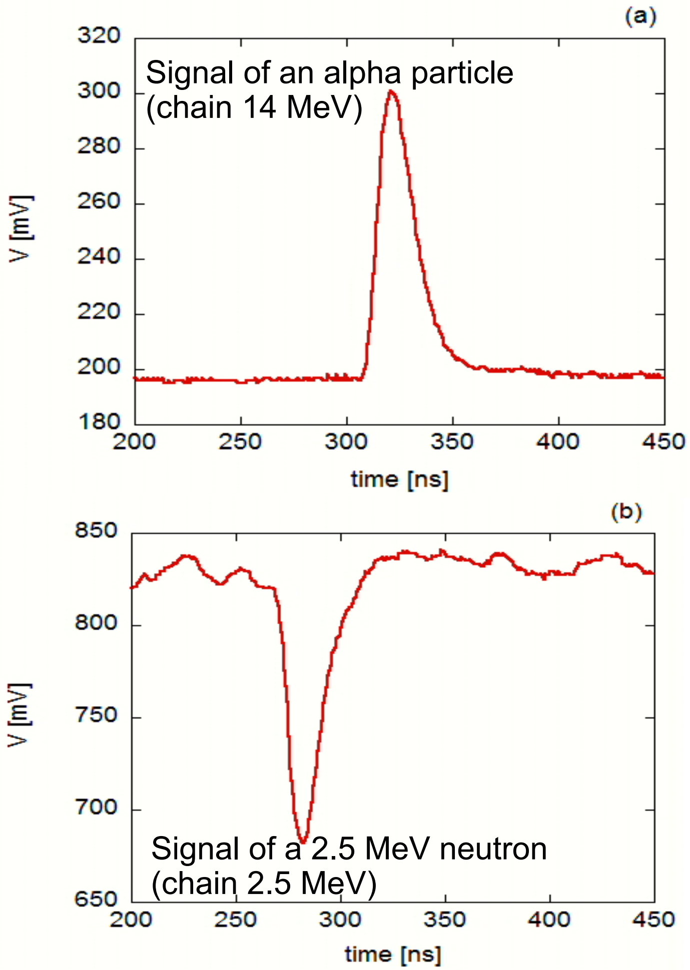


Need for dedicated spectrometers:
Energy resolution ($\Delta E_n/E_n$<5%)
Time resolution (count rate capability >100 kHZ)

NES spectrometers installed at JET:
MPR (Magnetic proton recoil) for 14 MeV neutrons
TOFOR (Time of flight optimized rate) for 2.5 MeV neutrons

Read-out electronics for simultaneous measurements of 14 and 2.5 MeV neutrons



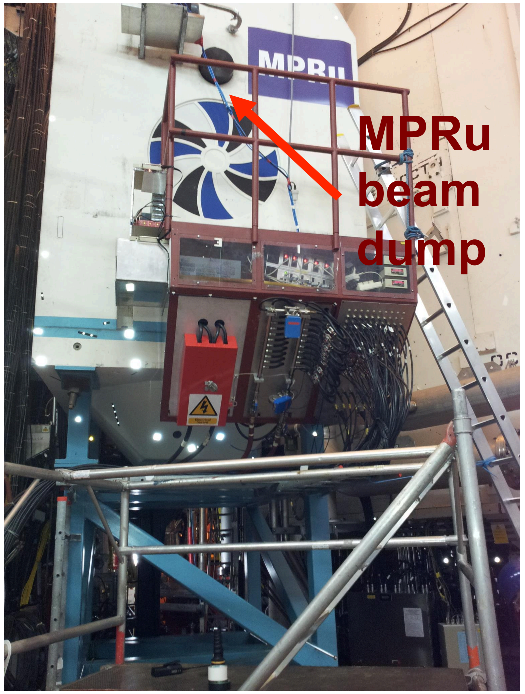


- Fast charge preamplifier (CIVIDEC C6)

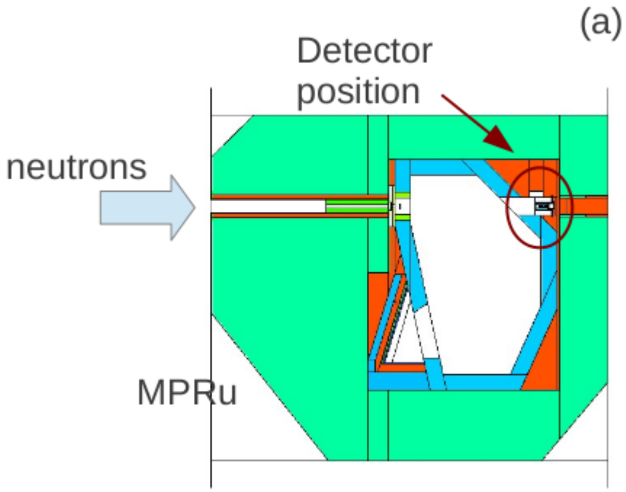
- Second amplification stage for 2.5 MeV neutrons.

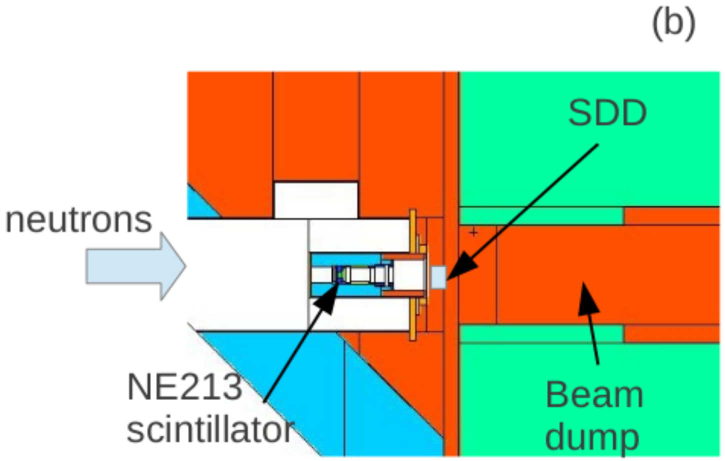
- DAQ with FPGA providing list mode data (time, deposited neutron energy)

SDD prototype installation at JET

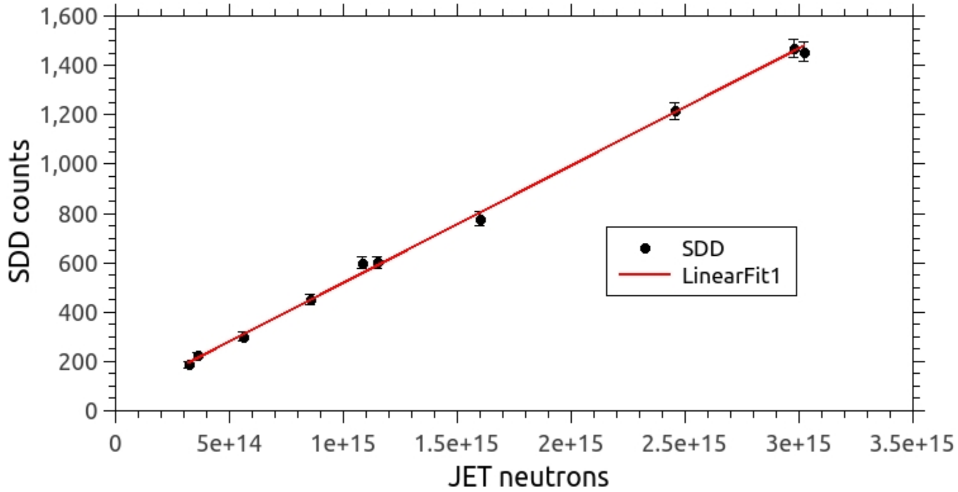


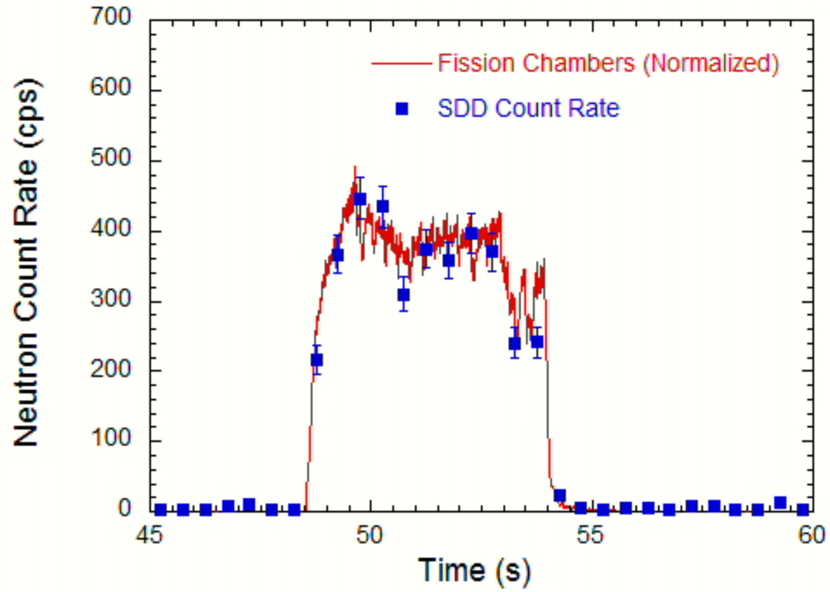
Diamond Detector installed at JET behind the MPRu beam dump.





Results at JET I





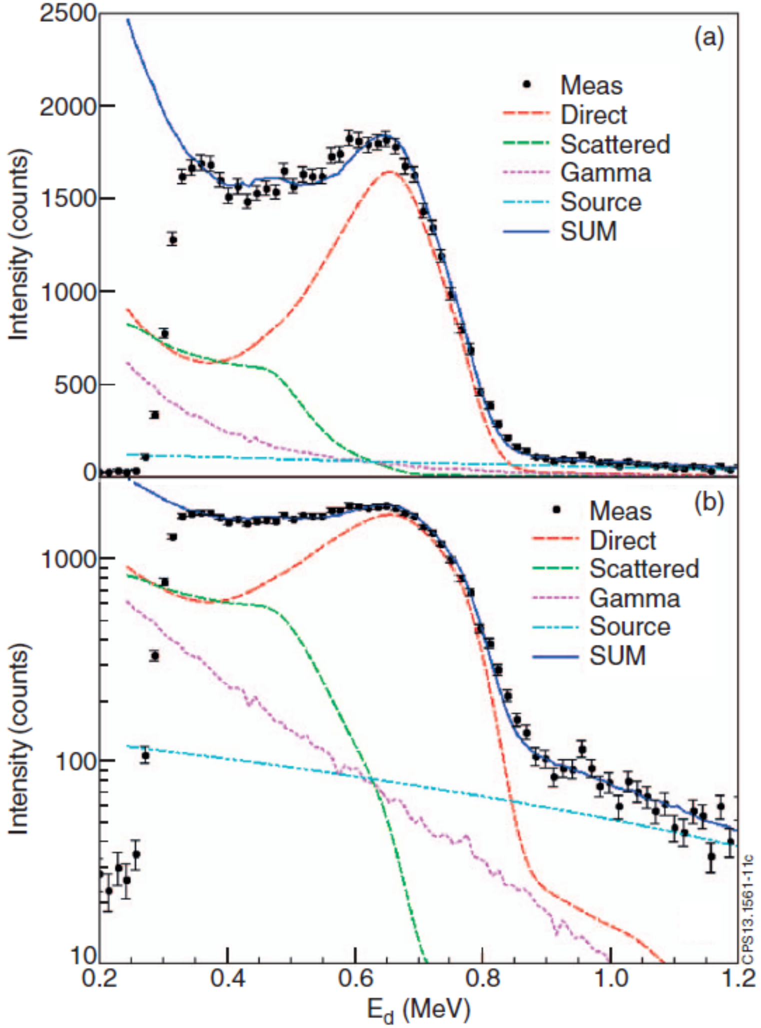
Discharge 84476

2.5 MeV measured during JET discharges

- SDD counts vs fission chambers
- Every point is one discharge

Neutron time trace in good agreement with other JET diagnostics

Results at JET II



Cazzaniga et al. Rev. Sci. Instrum. **85**, 043506 (2014)

- NBI neutron spectrum from TOFOR used for convolution with response functions.
- Broaden 5% for detector energy resolution.
- Alpha source counts normalized to the acquisition time.
- **Scattered neutron** spectrum used for convolution with response functions. Total area is a free parameter → **It's 30% respect to direct neutrons (MCNP says 37%)**
- **Gamma-rays** spectrum used af imput. Responce calculated with tally F8 by MCNP. Total area is a free parameter → **It's 19% respect to direct neutrons (consistent with NE213 measurements)**

The Technology Exchange - your portal into technology that has been developed as part of the ESA Space Programme and the Fusion Technology Transfer Action

Diamond Detector Matrix

Abstract

A 12-pixels diamond based neutron spectrometer matrix has been built in a collaboration between the two CNR institutes IFP (Institute of Plasma Physics, Milan) and ISM (Institute of the Structure of Matter, Rome). The spectrometer is equipped with fast electronics and digital acquisition, which for the first time allows combined fast neutron spectroscopy (>1 MeV) with good energy resolution (<3% at 14 MeV) and high count-rate capability in excess of 1 MHz.

Description

A 12-pixel diamond-based neutron spectrometer matrix has been developed and built in a collaboration between two Italian research institutes within the VNS enhancement project. This new spectrometer allows for spectroscopic analysis of fast neutrons to be undertaken where both a good energy resolution and high count-rate can be achieved. Each pixel is made of a single crystal diamond of area 4x4x0.5 mm3 and is grown using the Chemical Vapor Deposition (CVD) technique.

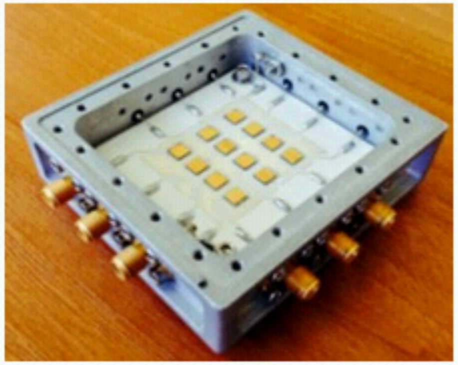
The diamond matrix will be used to take high energy resolution measurements of the 14MeV neutron spectra created in Deuterium-Tritium plasmas within the JET tokamak. Moreover, the diamond matrix is also capable of measuring 2.5 MV neutron spectra from D plasma with limited energy resolution. Each pixel is completely independent of the others.

The new detector features the advantages of being compact, insensitive to magnetic field and radiation resistant, which makes it ideal for use on neutron cameras of future burning plasma experiments such as ITER or DEMO.

No patent has been made on this instrument.

Innovations and advantages of the offer

- Fast neutron spectroscopy with combined good energy resolution (<3% at 14MeV) and high count-rate (in excess of 1MHz).
- Compact



CATEGORY
Sensors & Measuring Techniques

REFERENCE NO.
TDF0009

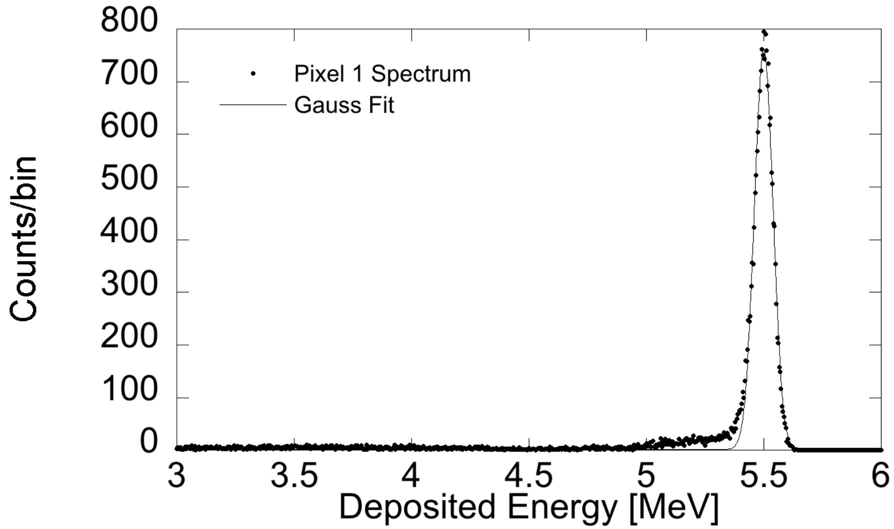
Could this technology benefit your business? Please contact Matthew Edwards STFC Innovations (UK)

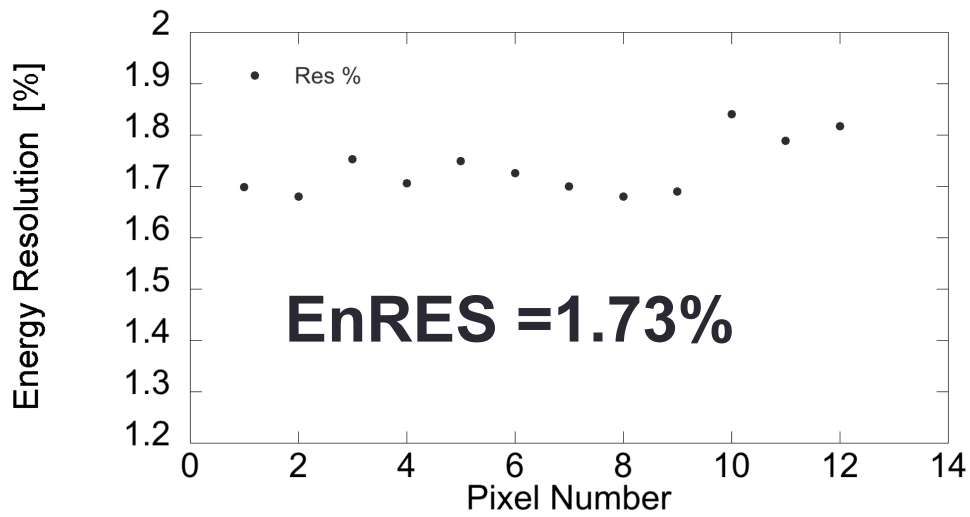
PRINTABLE VERSION
TDF0009 - Diamond Detector Matrix

DISCUSSION

Alpha particle calibration

Characterization with ^{241}Am (5.5 MeV alphas) in vacuum.





Calibrations with alphas indicated a very uniform response in term of pulse height and resolution from the 12 pixels.

Neutron calibration

The SDD Matrix full set up (preamps, cables, DAQ…) was calibrated using neutrons at different facilities:

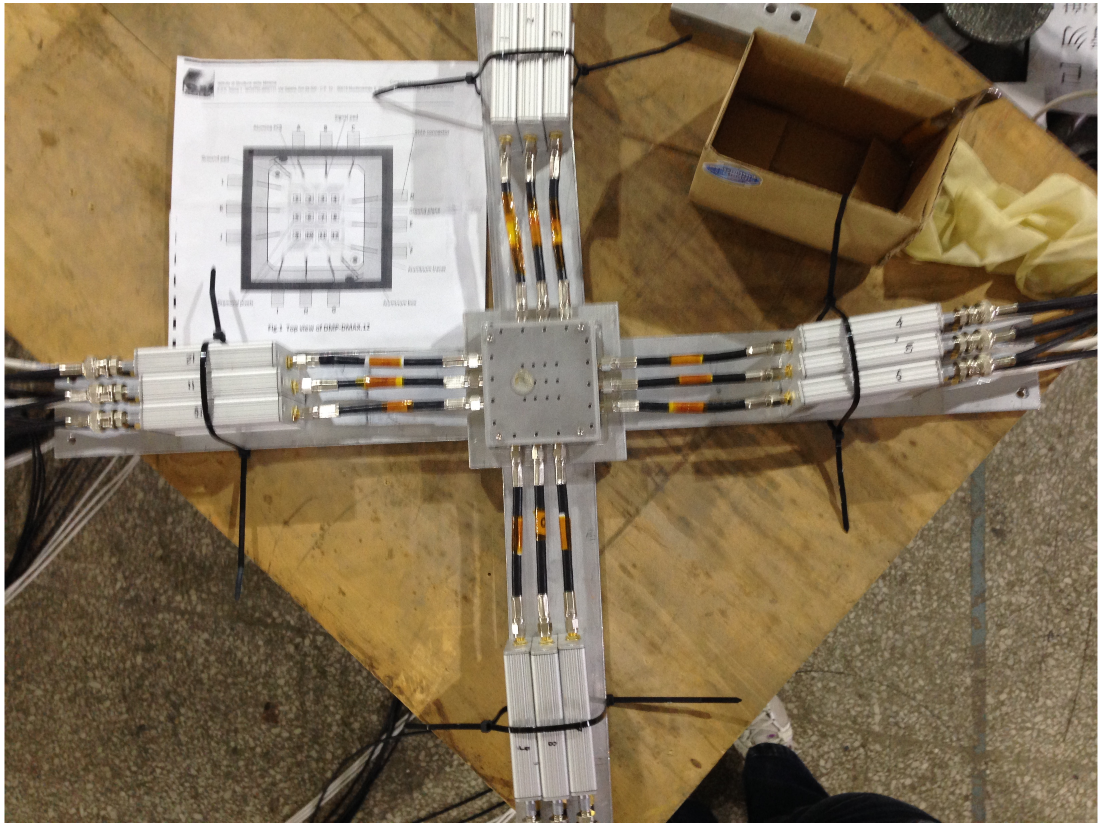
-FNG with 14 MeV neutrons (December 2014)

-Institute of Heavy Ion Physics (Peking University) with neutrons)

- From 1.5 to 2.5 MeV
- From 13 to 20 MeV

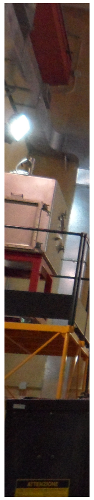
(March 2015)

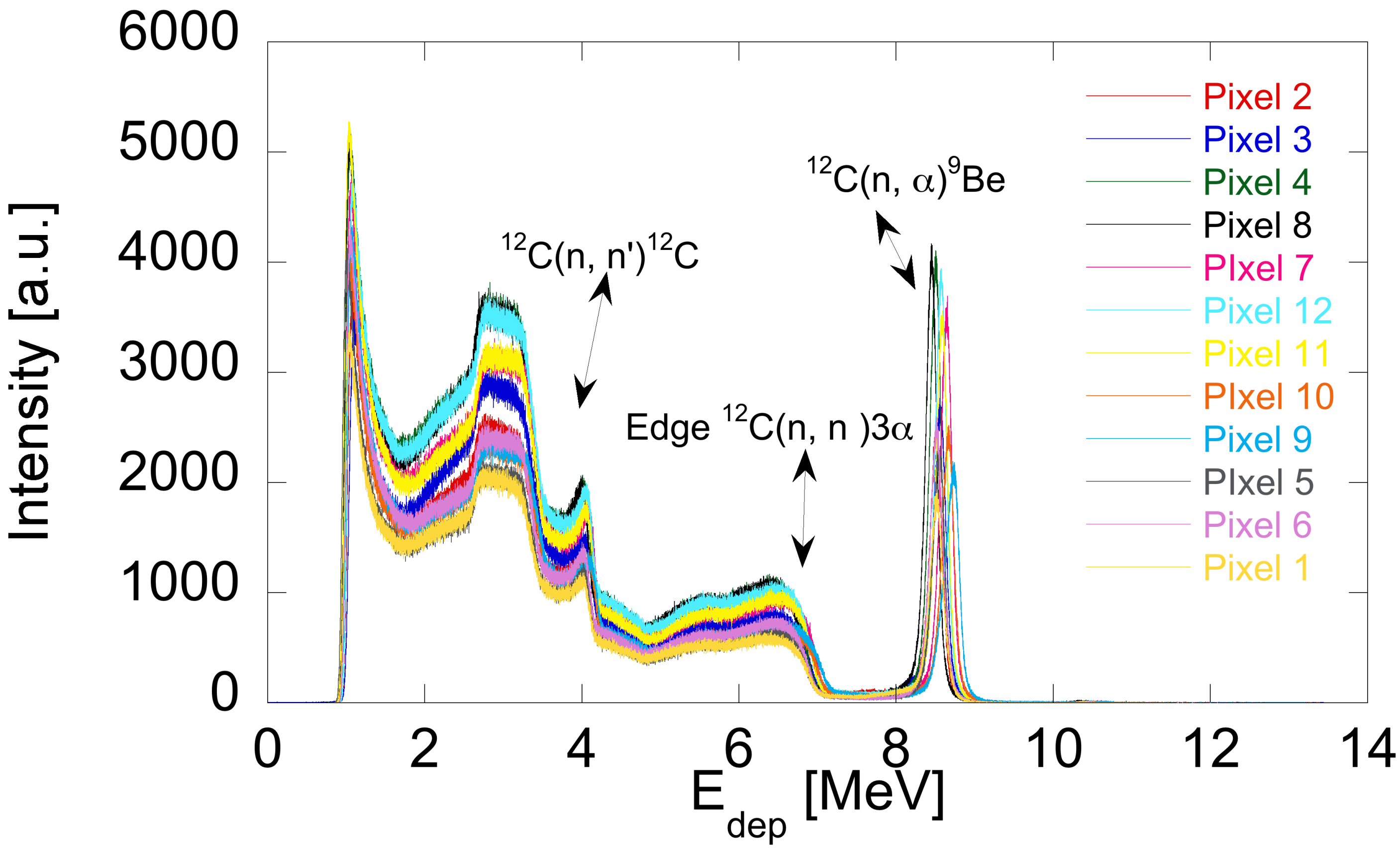
At the CN here in Legnaro a single pixel prototype has been measured with En from 2.5 to 3.8 MeV in April 2015.



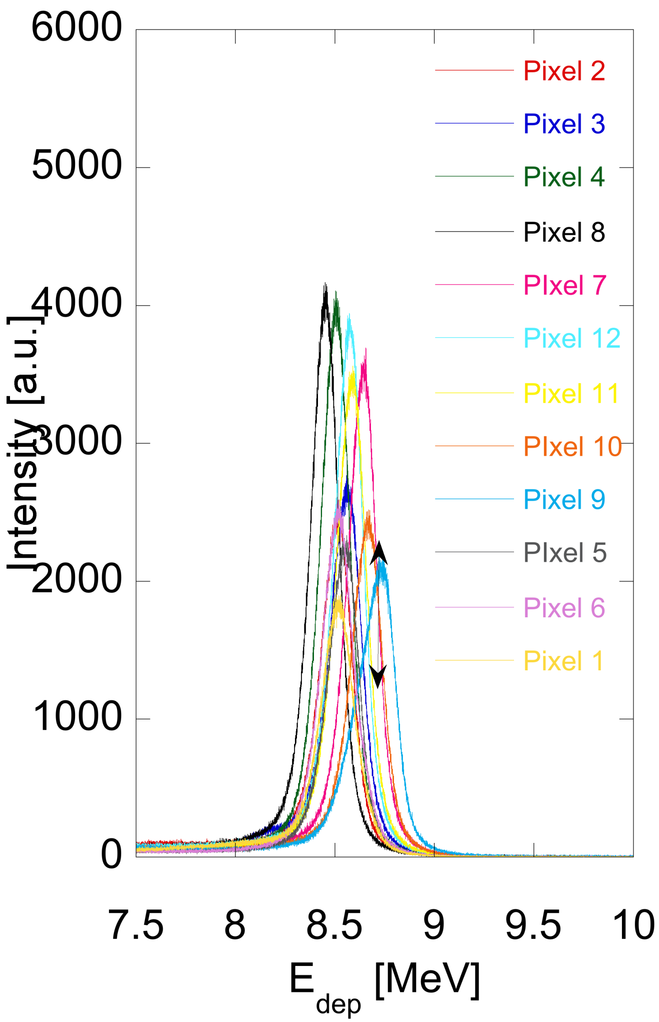
SDD Matrix with the front-end electronics mounted on the aluminum support.

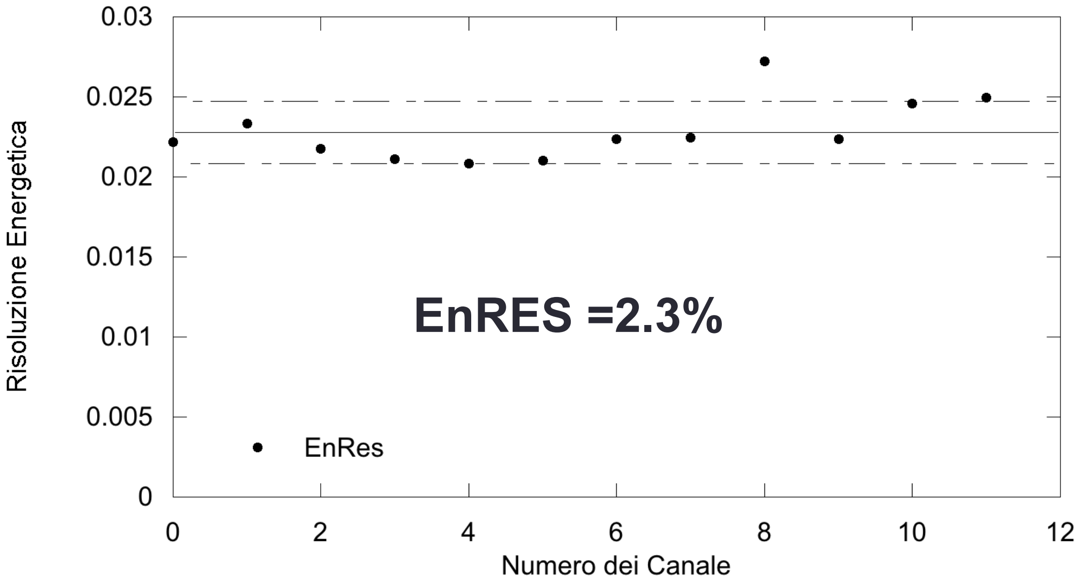
14 MeV neutron calibration at FNG





14 MeV neutron calibration at FNG

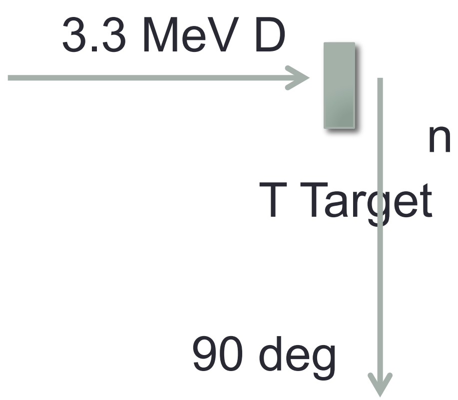




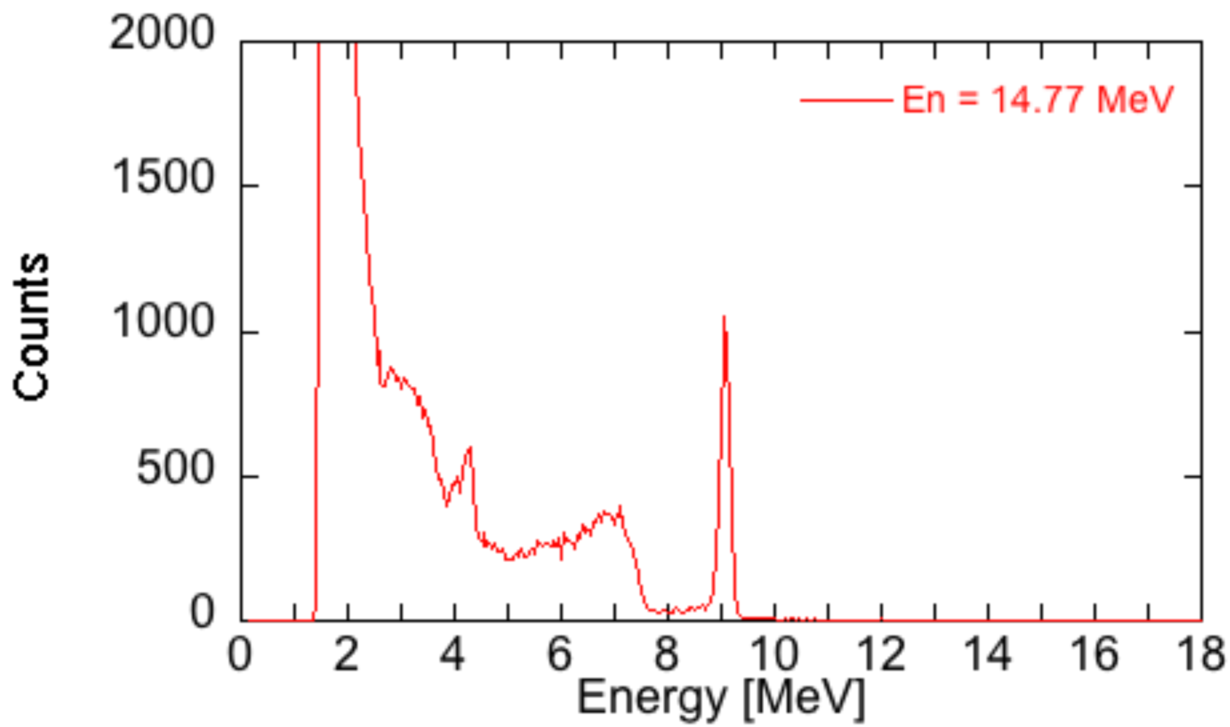
12 pixels response is very uniform

Detector response at different neutron energies

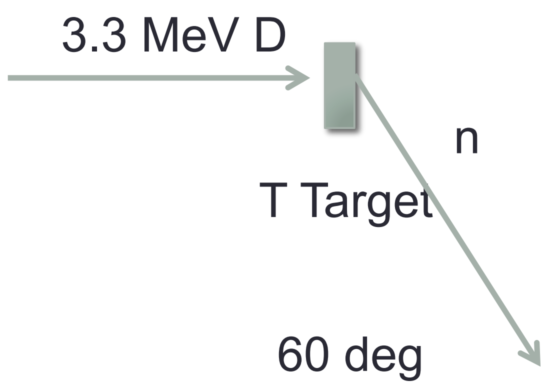
Detector response at different neutron energies

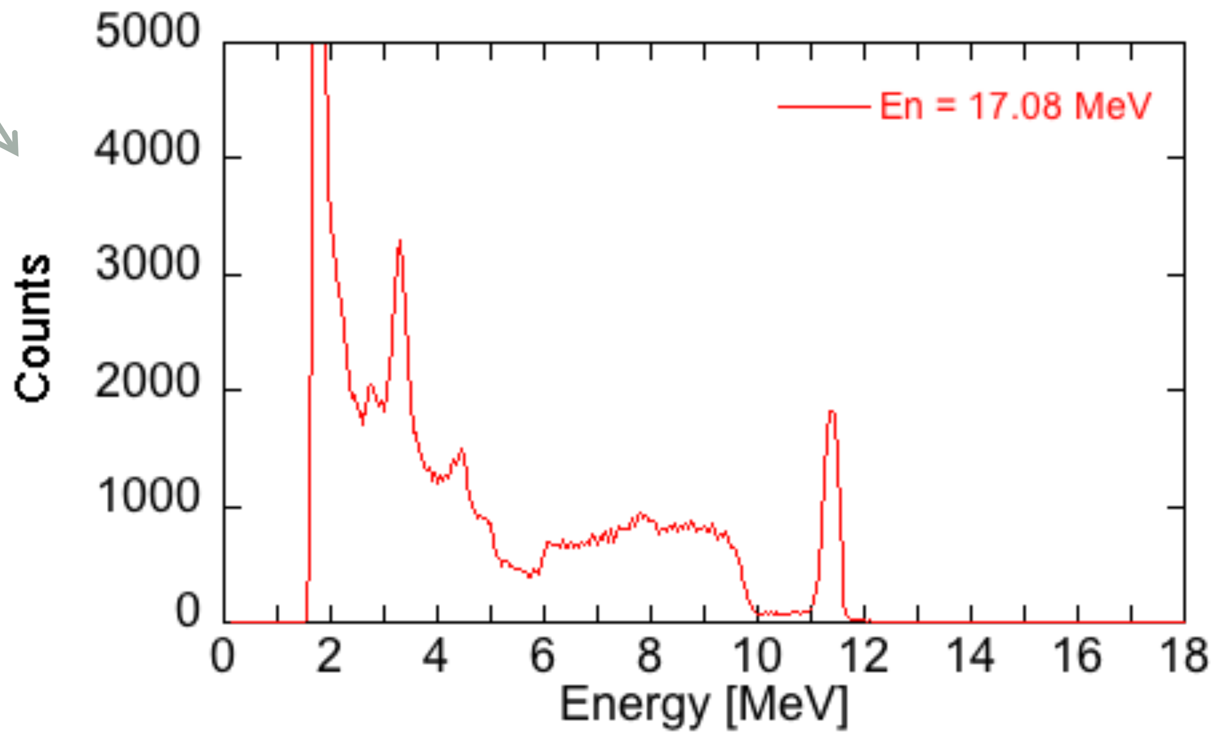


220 keV



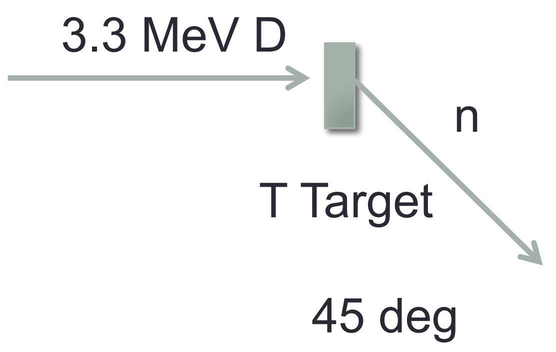
Detector response at different neutron energies

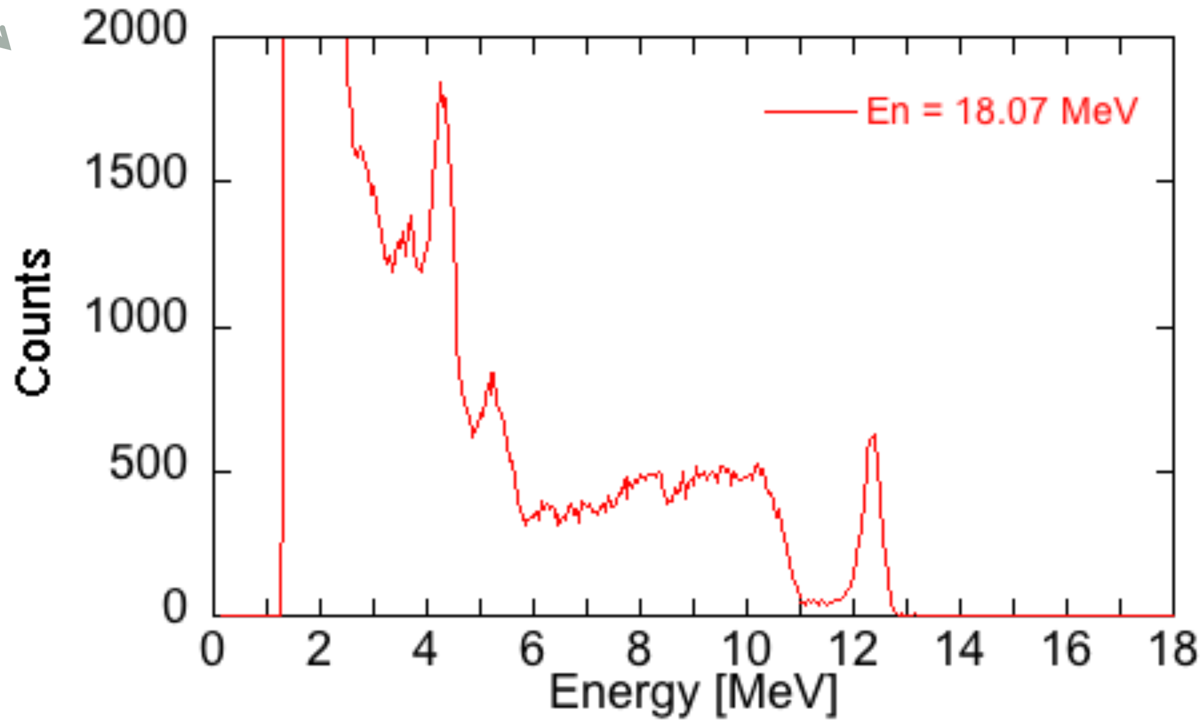




FWHM 296 keV

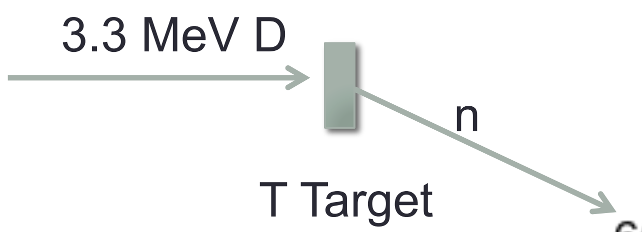
Detector response at different neutron energies





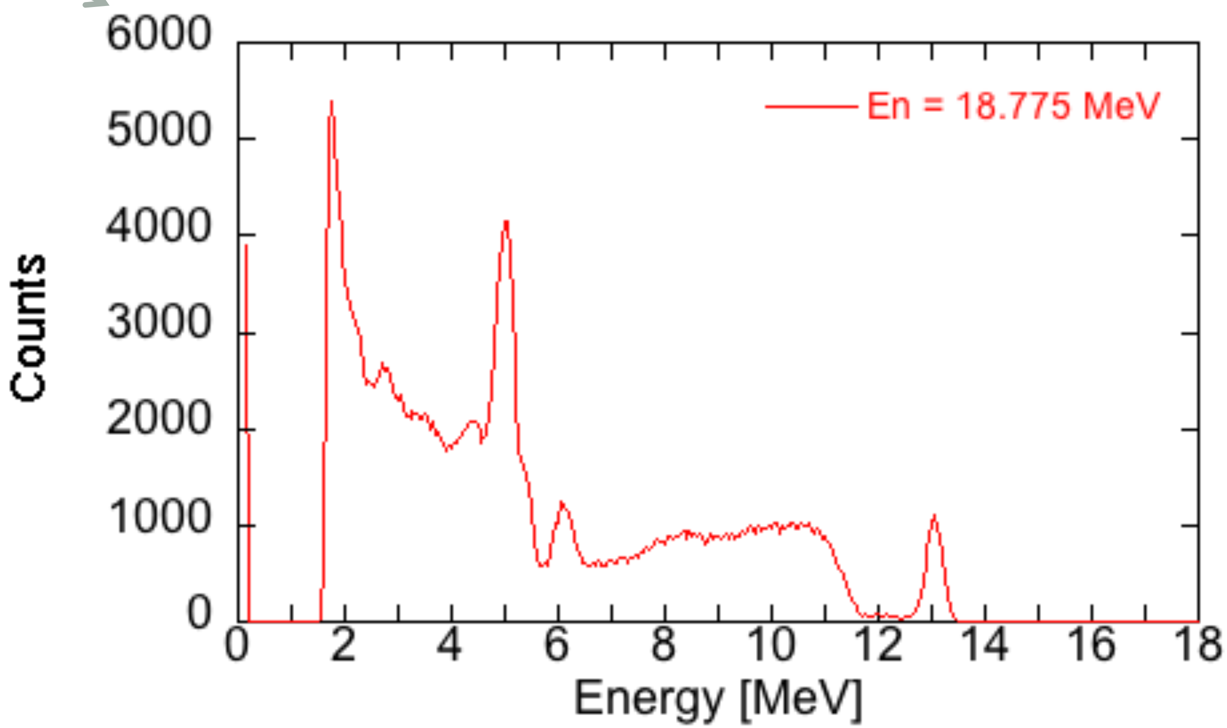
FWHM 415 keV

Detector response at different neutron energies

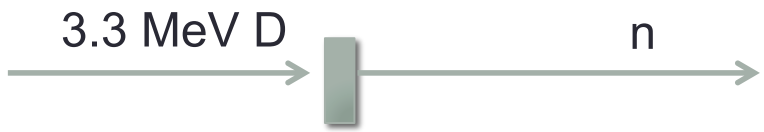


30 deg

FWHM 361 keV



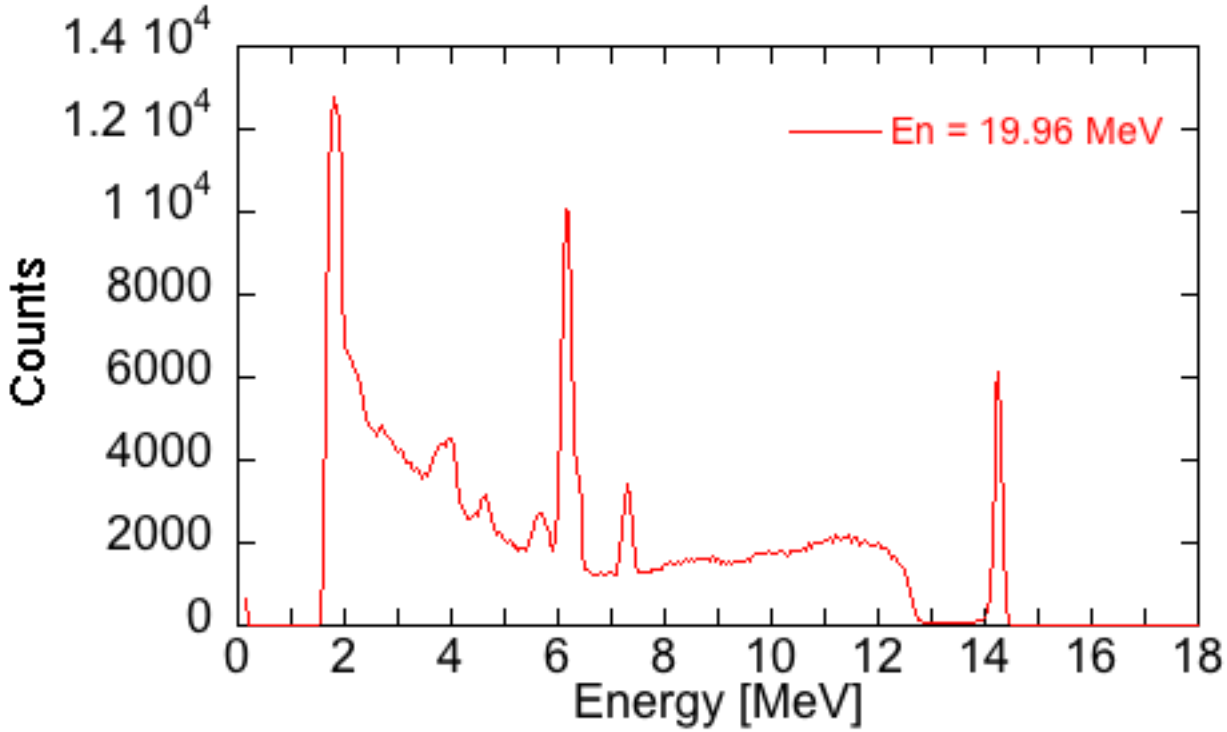
Detector response at different neutron energies



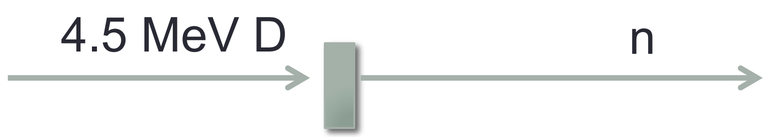
T Target

0 deg

FWHM 180 keV



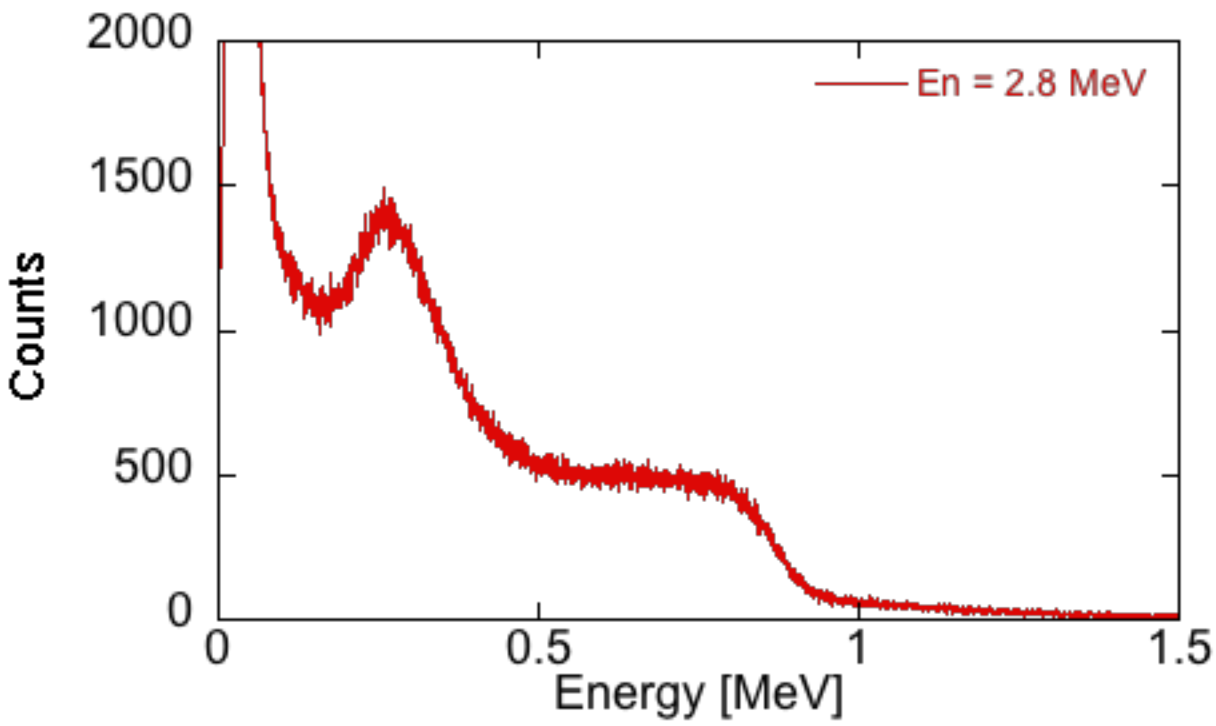
Detector response at different neutron energies



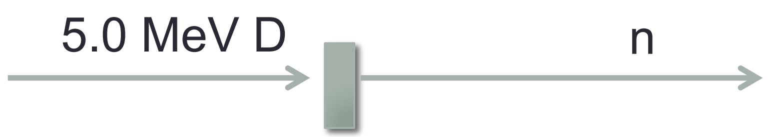
Li Target

0 deg

Equivalent FWHM 78 keV



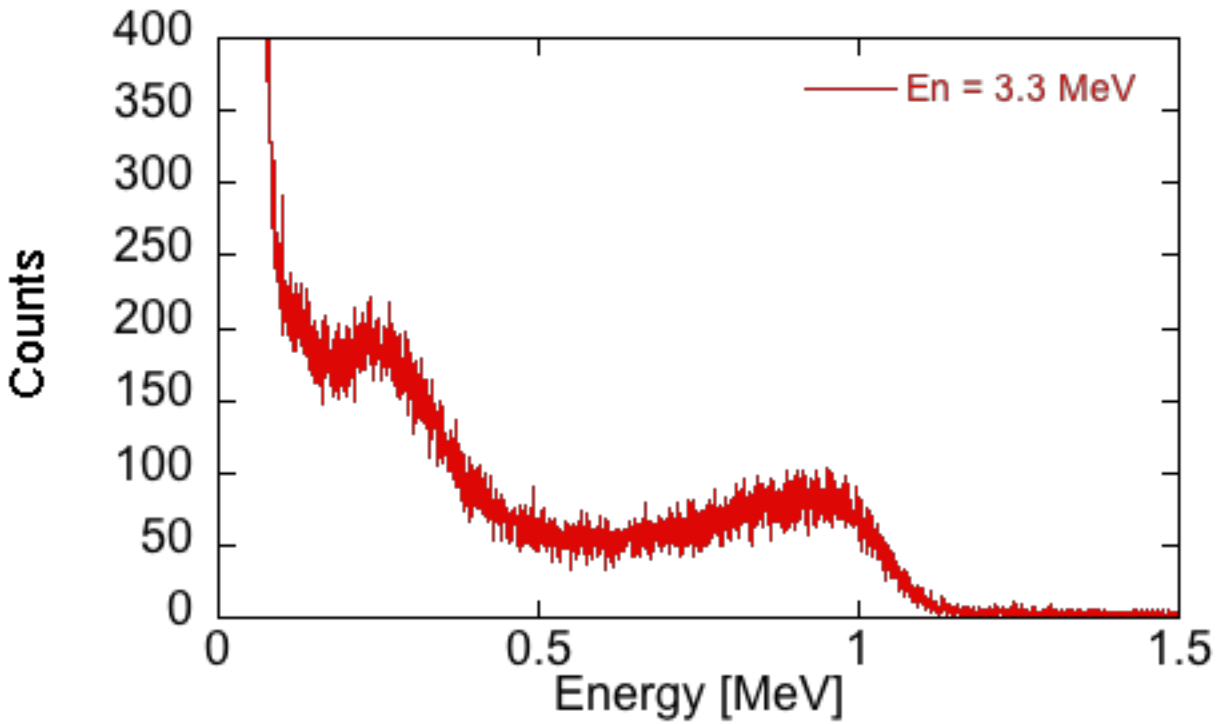
Detector response at different neutron energies



Li Target

0 deg

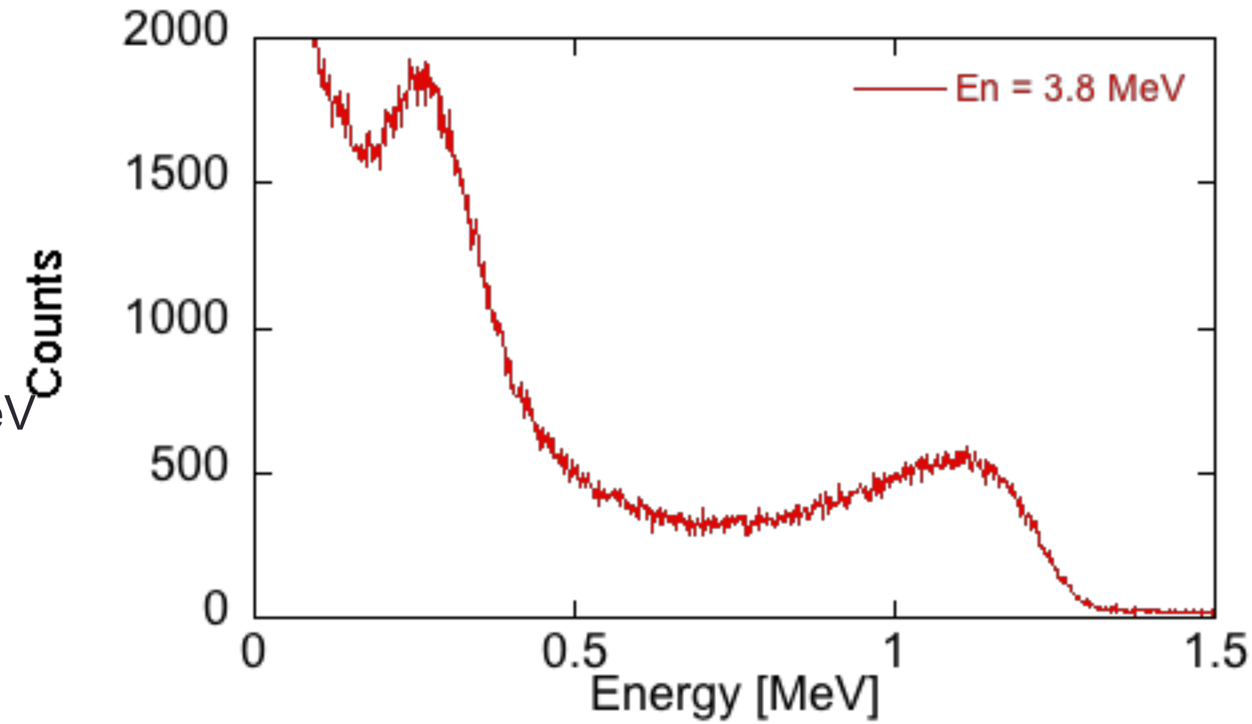
Equivalent FWHM 80 keV



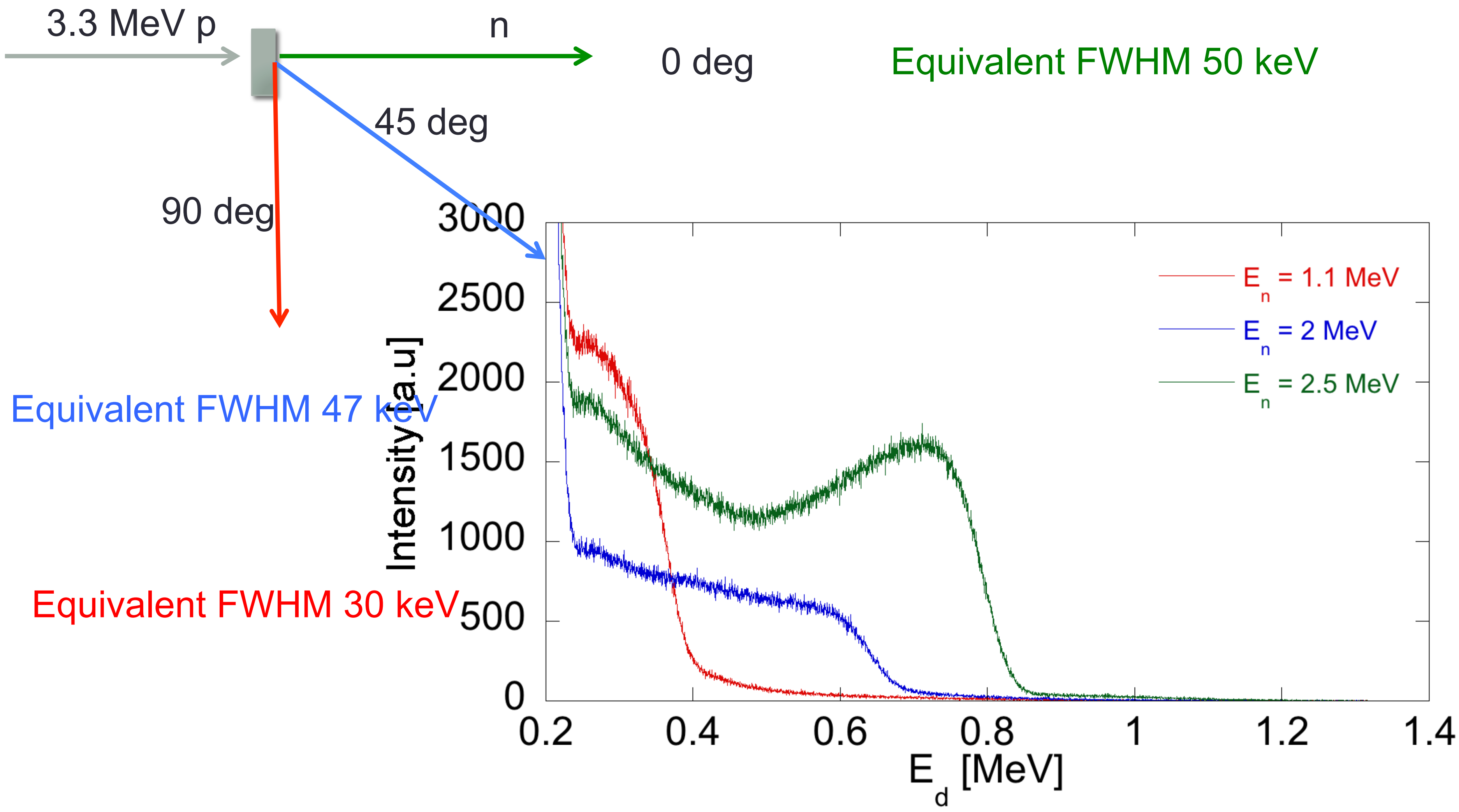
Detector response at different neutron energies

0 deg

Equivalent FWHM 70 keV

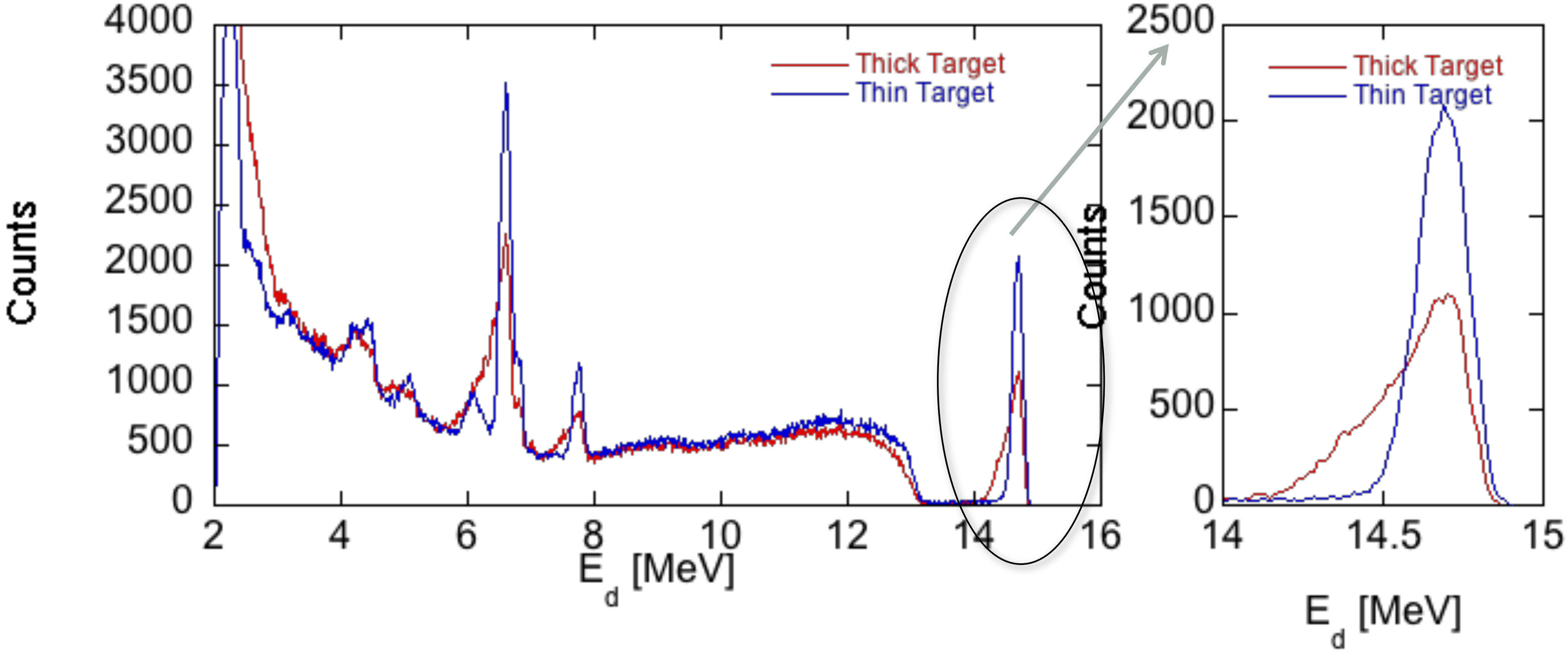


Detector response at different neutron energies



Measurement at 20 MeV with different T targets

At 0 degrees, the deuterium slowing down in the target is greater if a thick target is use



Conclusions and perspectives

- Fast neutron measurements have been successfully performed at the ISIS-neutron source. The test revealed the SDD capability to measure fast neutrons at **high rates**, but a complete comprehension of the data needs the study of the SDD response to quasi-moenergetic neutrons.

- The **response** of two SDD detectors to **quasi-monochromatic** neutrons of energies in excess of 1 MeV has been successfully measured at the n_TOF beam line via a bi-parametric method (good energy resolution).

- For the next DT JET campaign **a matrix of 12 diamonds** was realized, calibrated and installed at JET as a vertical neutron spectrometer.

- Combined high energy resolution (<1%@14MeV) and High Count rate capability (1MHz) have been demonstrated