A Single-crystal Diamond Detector Matrix for DT plasma diagnostic

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Outline:

- Neutron diagnostics of fusion plasmas
- Single-crystal diamond detectors (SDD) for neutron spectroscopy
- Development of a new SDD Matrix as a Vertical Neutron Spectrometer for JET
- Results: Energy Resolution and pixels uniformity under alphas and neutrons irradiation.
- Conclusions and perspectives

Neutron emission in fusion plasmas

Neutron production

Neutrons are produced by fusion reactions

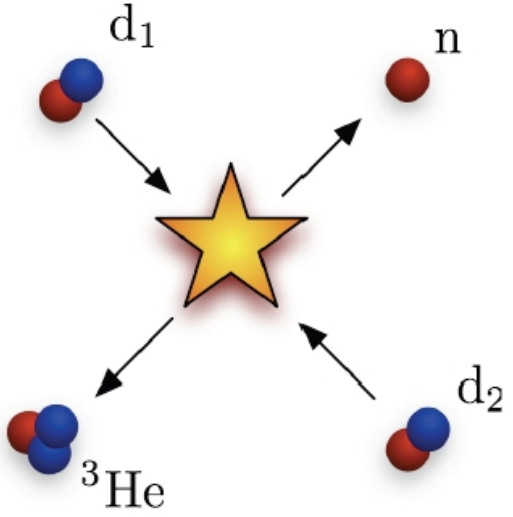
d +d → n + ^{3}He

d + t → n + α

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

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:**

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

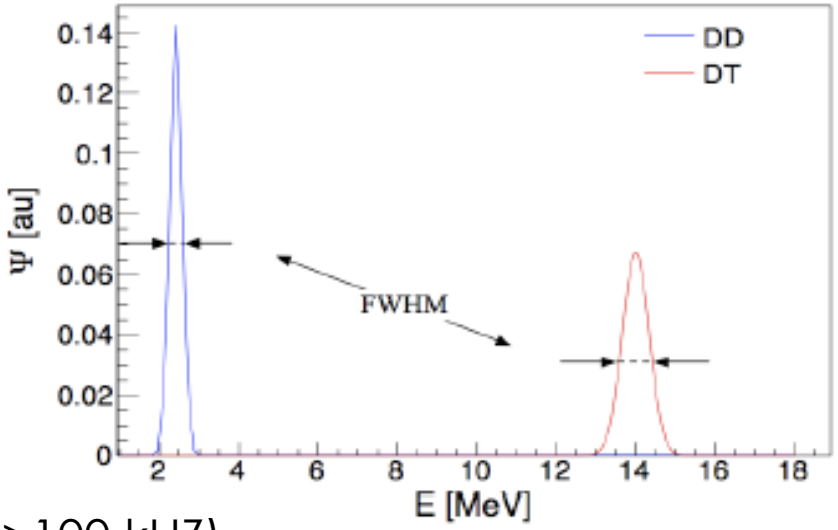
Neutron emission spectroscopy in fusion plasmas

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)

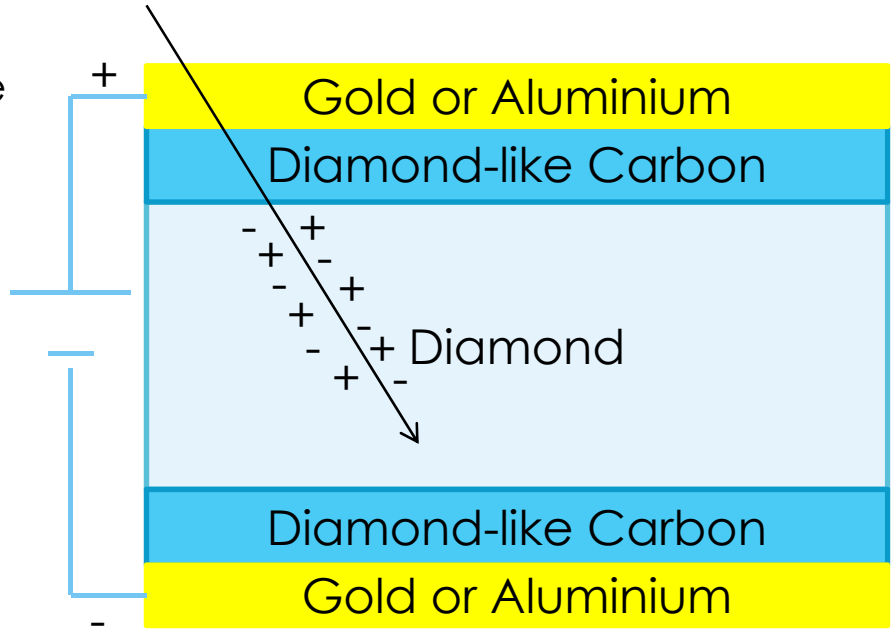
NES spectrometers installed at JET:
MPR (Magnetic proton recoil) for 14 MeV neutrons
TOFOR (Time of flight optimized rate) for 2.5 MeV neutrons

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.

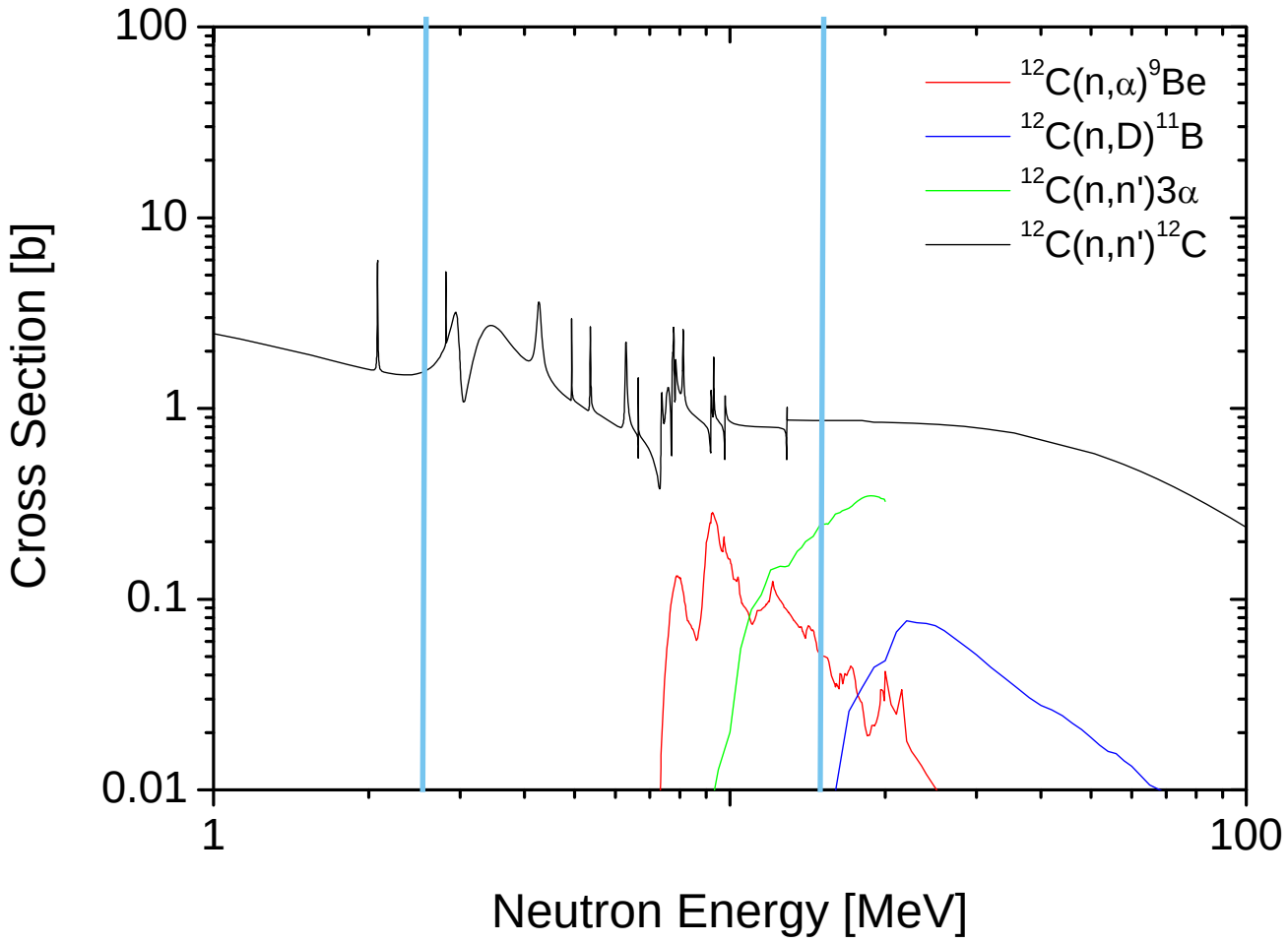
With the CVD technique diamonds can be produced with good energy resolution (<1%) and 100% charge collection efficiency.

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



Diamond Detectors Limited Technology

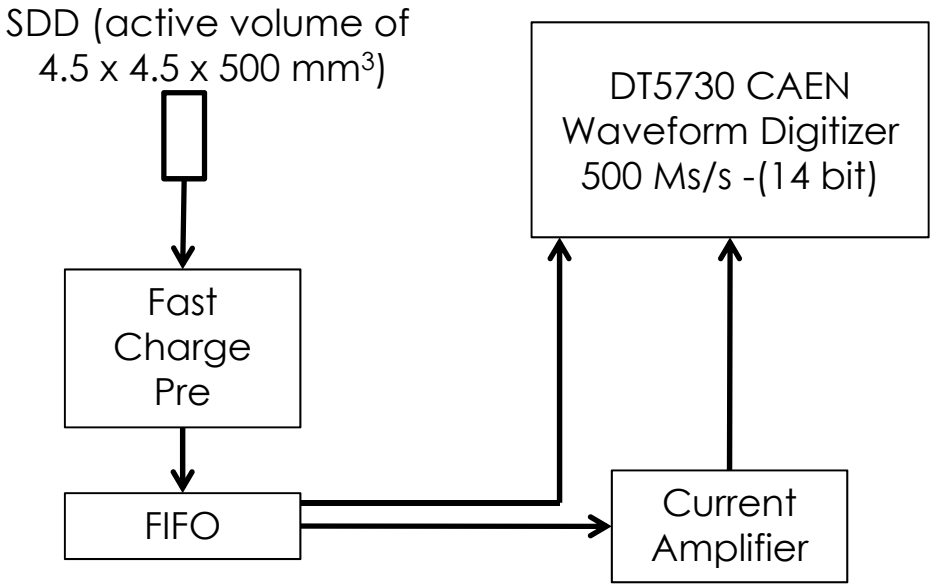
The n-^{12}C interaction cross section



→ 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')3a (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 fro 2.5 MeV neutrons.

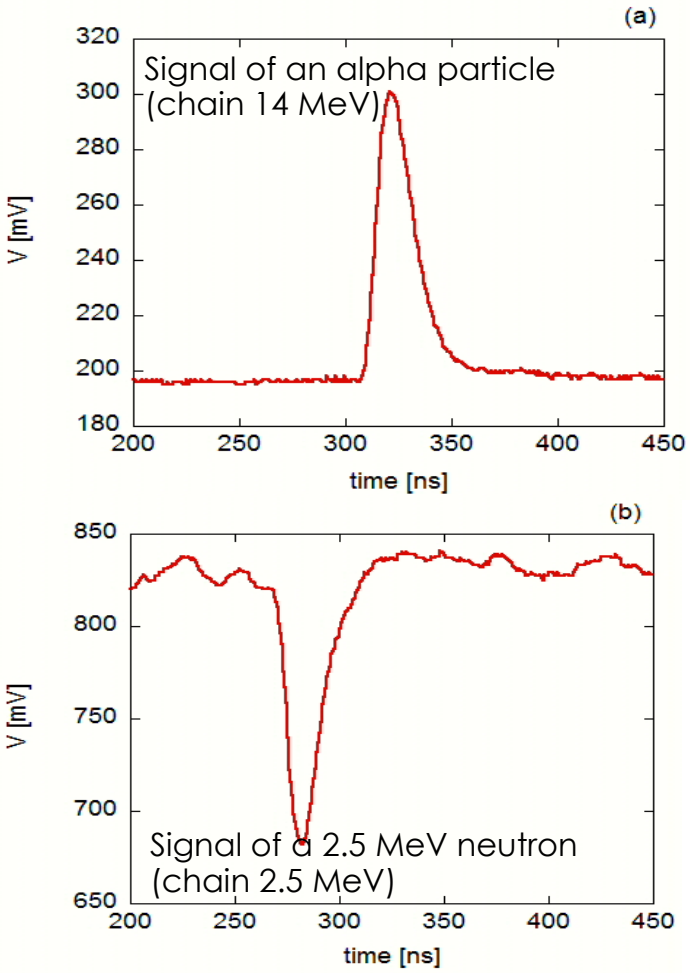
SDD Electronics for simultaneous measurements of 2.5 and 14 MeV neutrons



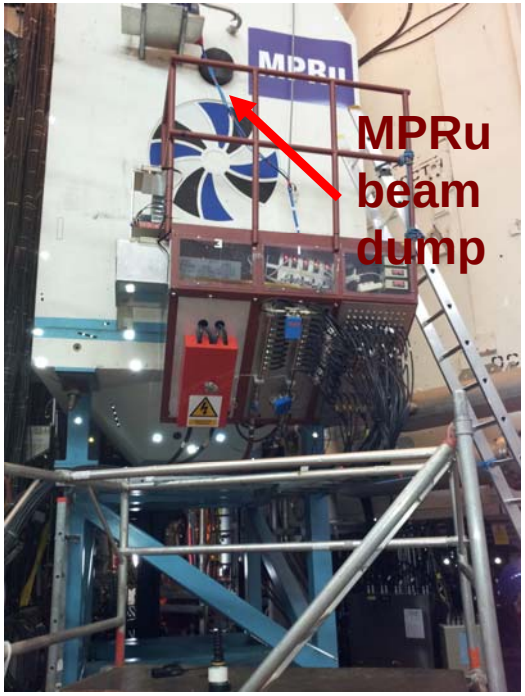
- Fast charge preamplifier (CIVIDEC C6)

- Second amplification stage for 2.5 MeV neutrons.

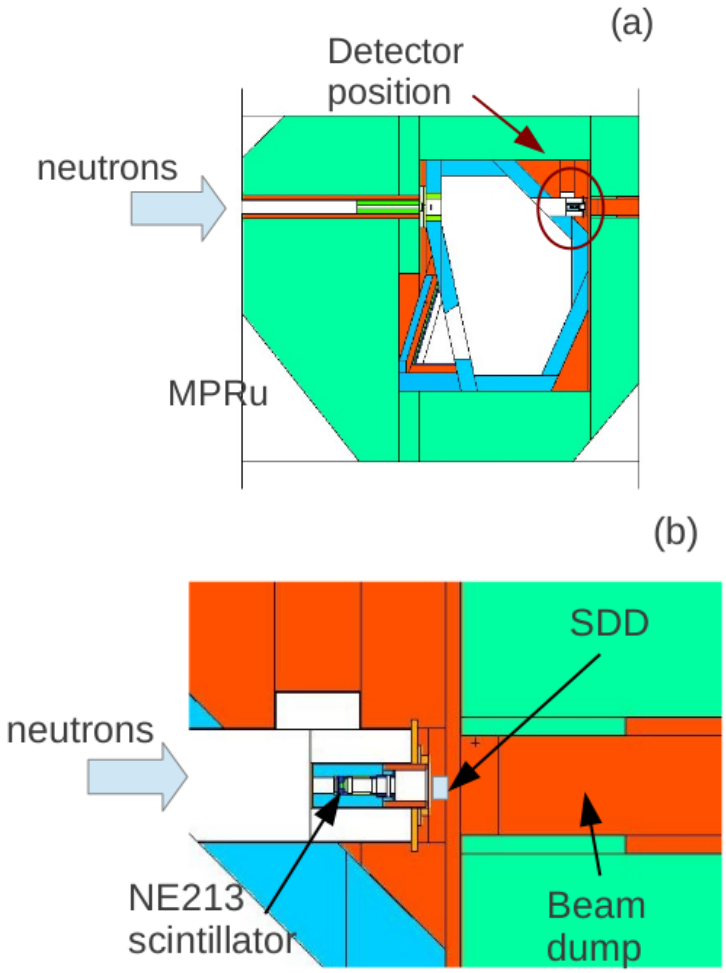
- DAQ with FPGA providing list mode data (time, deposited neutron energy)



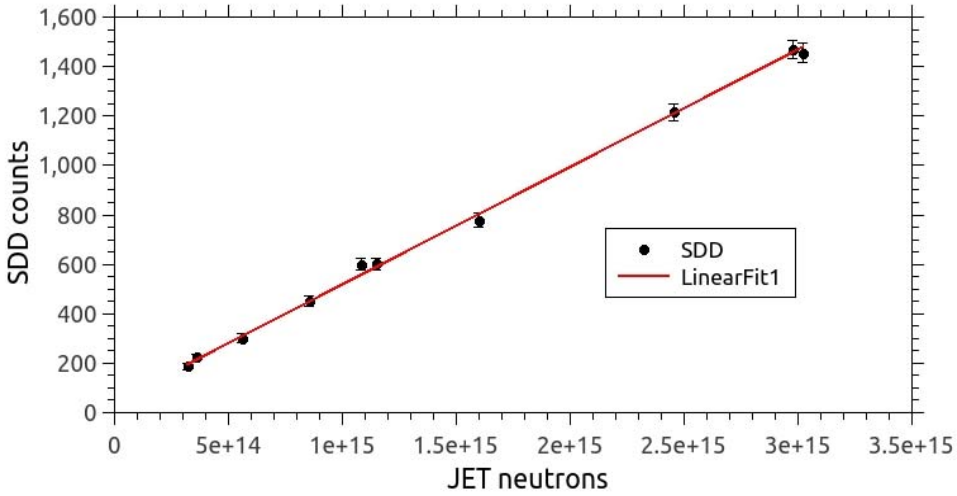
SDD prototype installation at JET

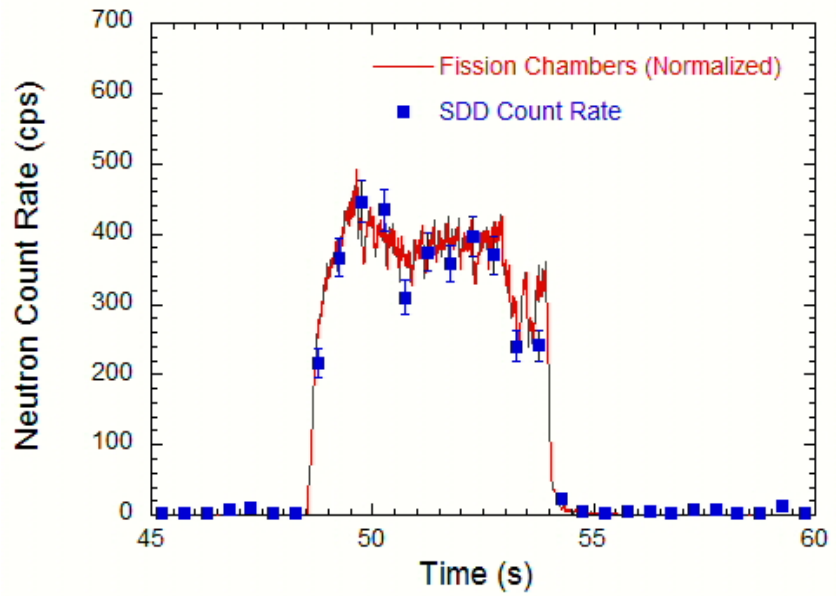


Diamond Detector installed at JET behind the MPRu beam dump.



Results at JET I





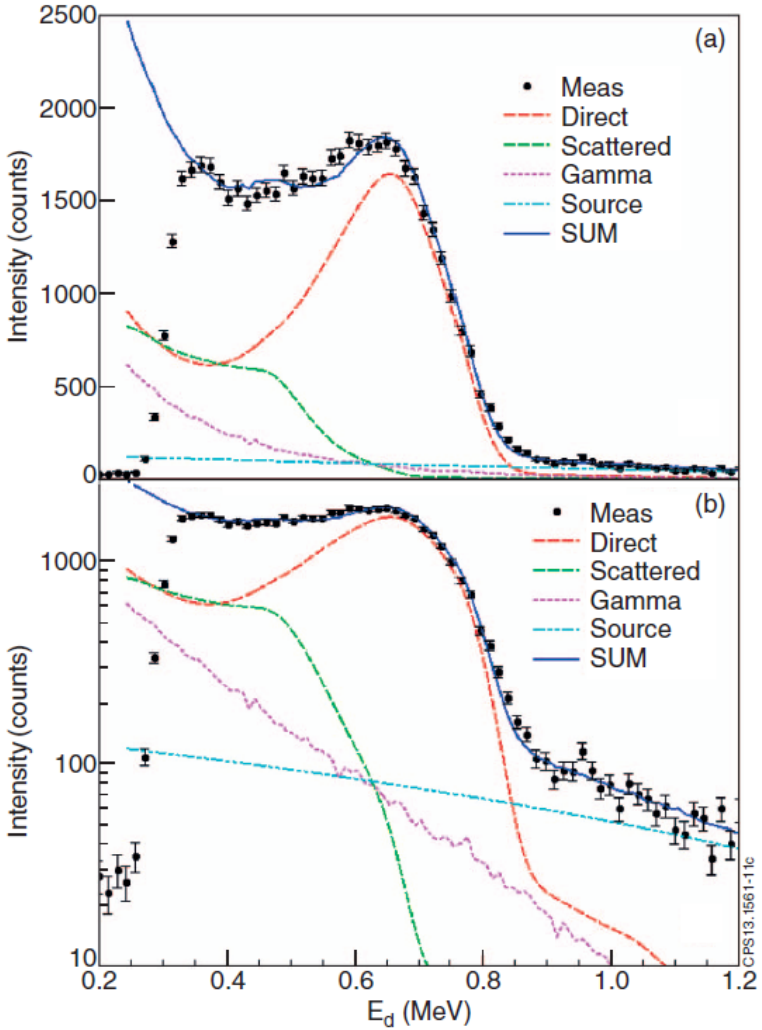
Discharge 84476

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

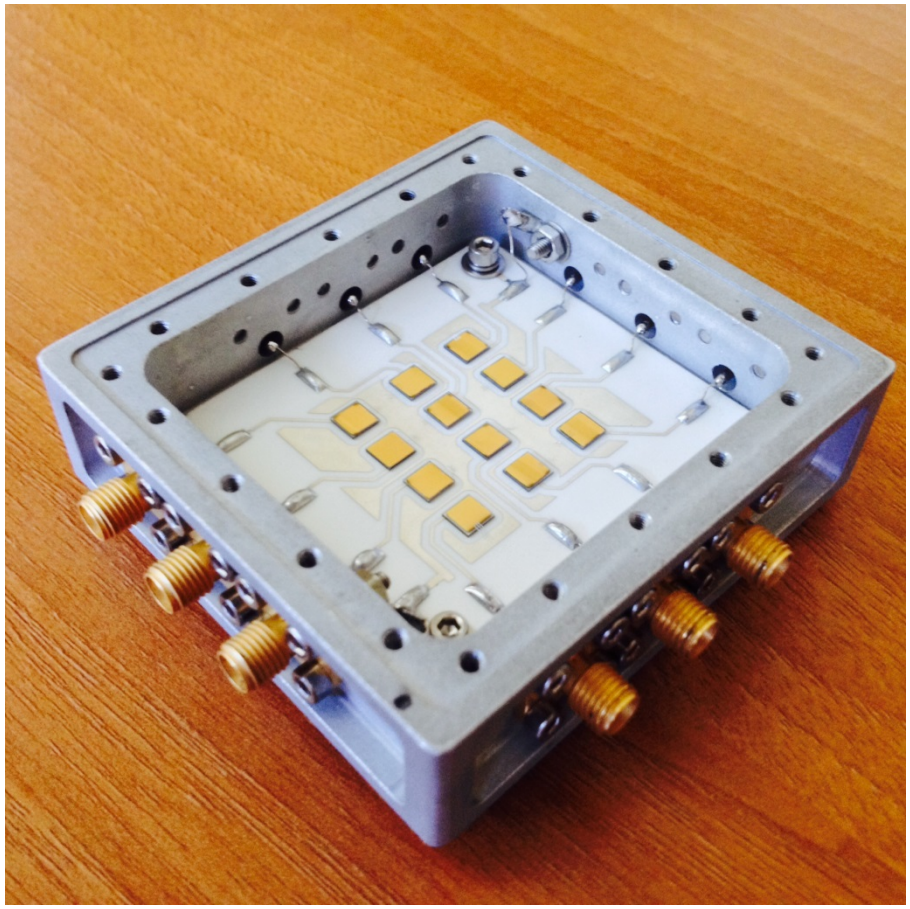
Results at JET II



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)**

VNS Project 12 Pixel SDD Matrix



12 Pixels equipped with 12 standard SMA connectors.

The Single Cristal CVD Diamond is produced by the Element Six Ltd

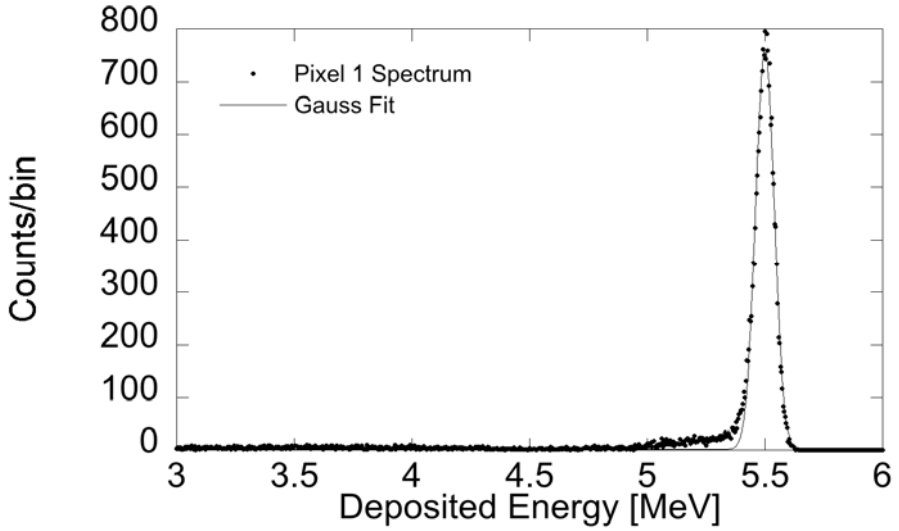
Thickness: 0.5 mm
Area: 4.5x4.5 mm^2

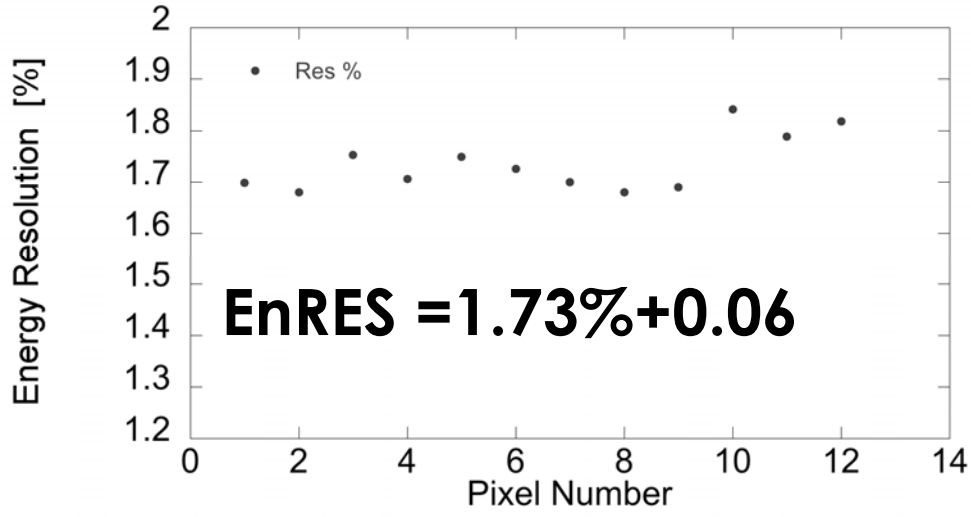
The samples are glued with a Silver Paste onto a PCB board (Al_2O_3, 99.6%).

Detector produced by CNR

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.

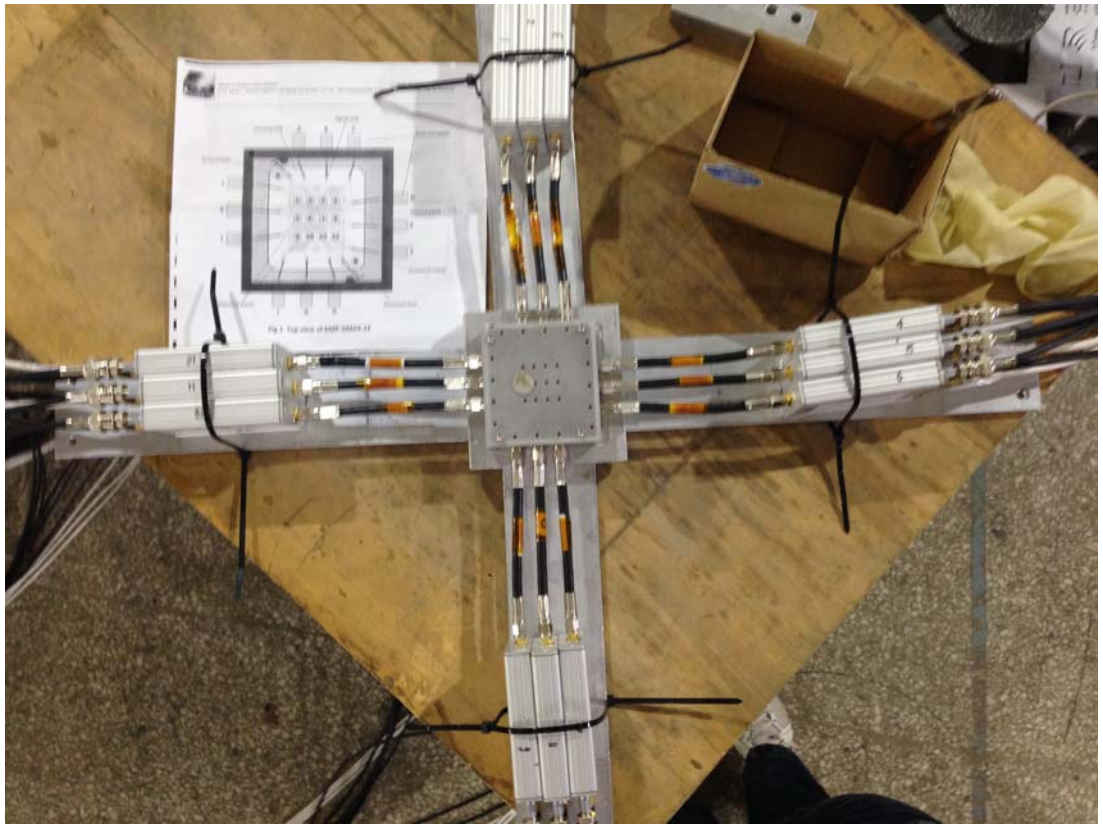
Neutron calibration

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

- FNG with 14 MeV neutrons (December 2014)

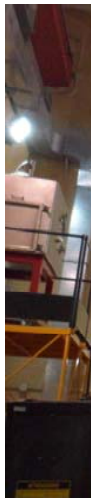
- Institute of Heavy Ion Physics (Pecking University) with neutrons)
  - From 1.5 to 2.5 MeV
  - From 13 to 20 MeV (March 2015)

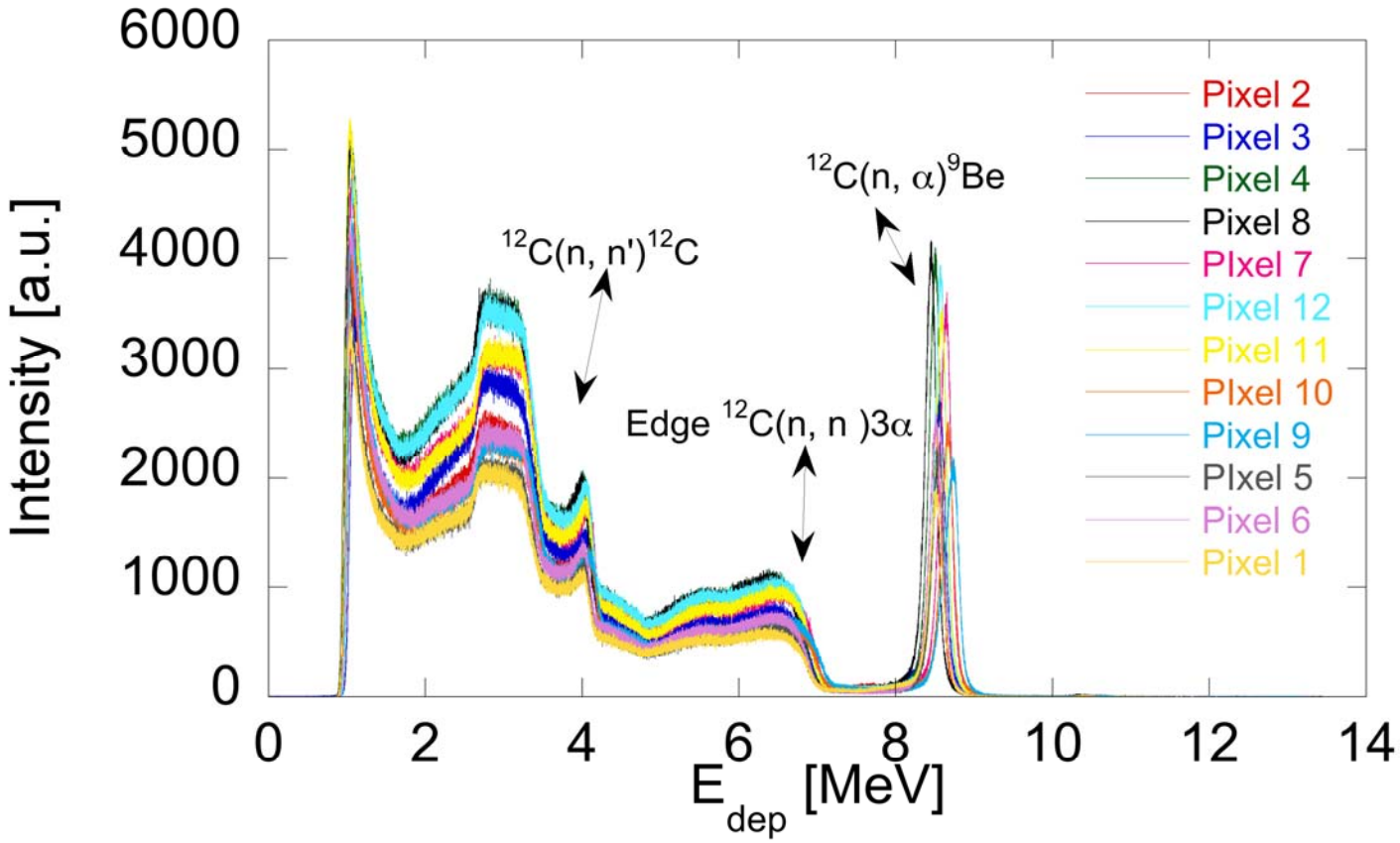
At the CN here in Legnaro a single pixel prototype has been measured with En from 2.5 to 3.8 MeV in April 2015.



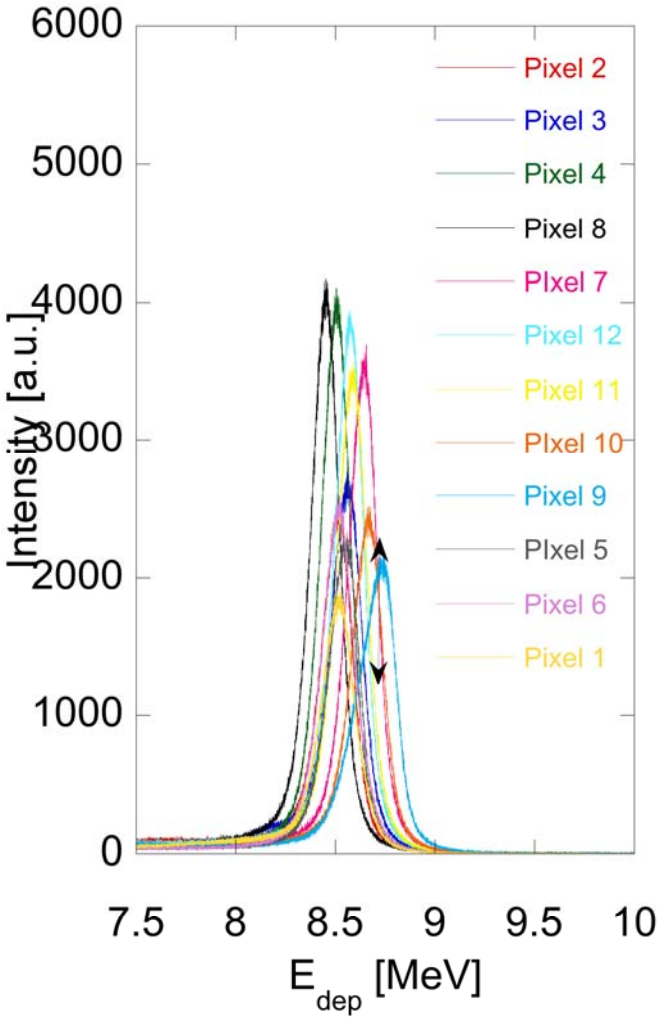
SDD Matrix with the front-end electronics mounted on the aluminum support.

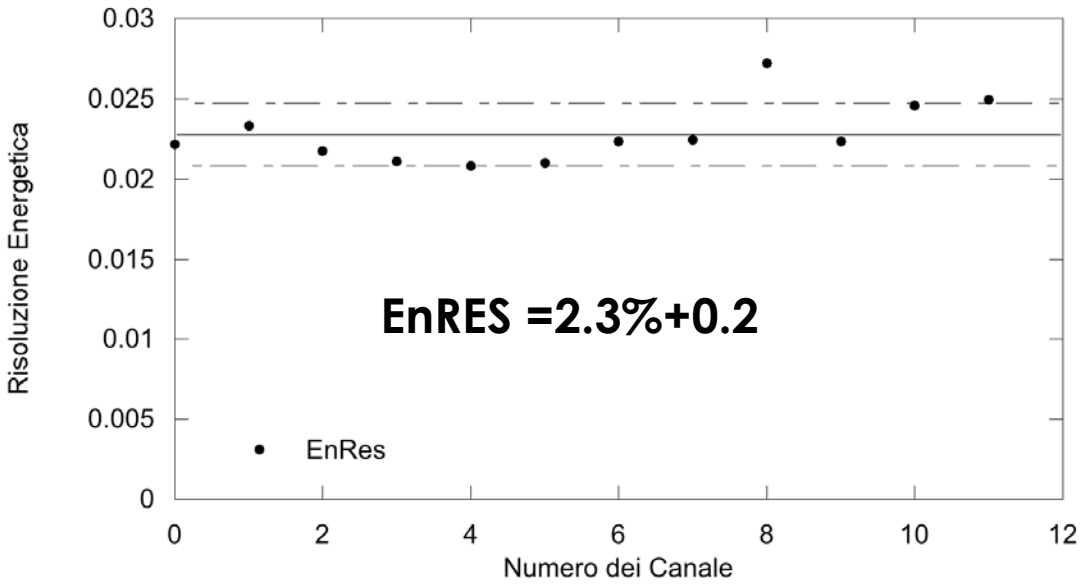
14 MeV neutron calibration at FNG





14 MeV neutron calibration at FNG





12 pixels response is very uniform

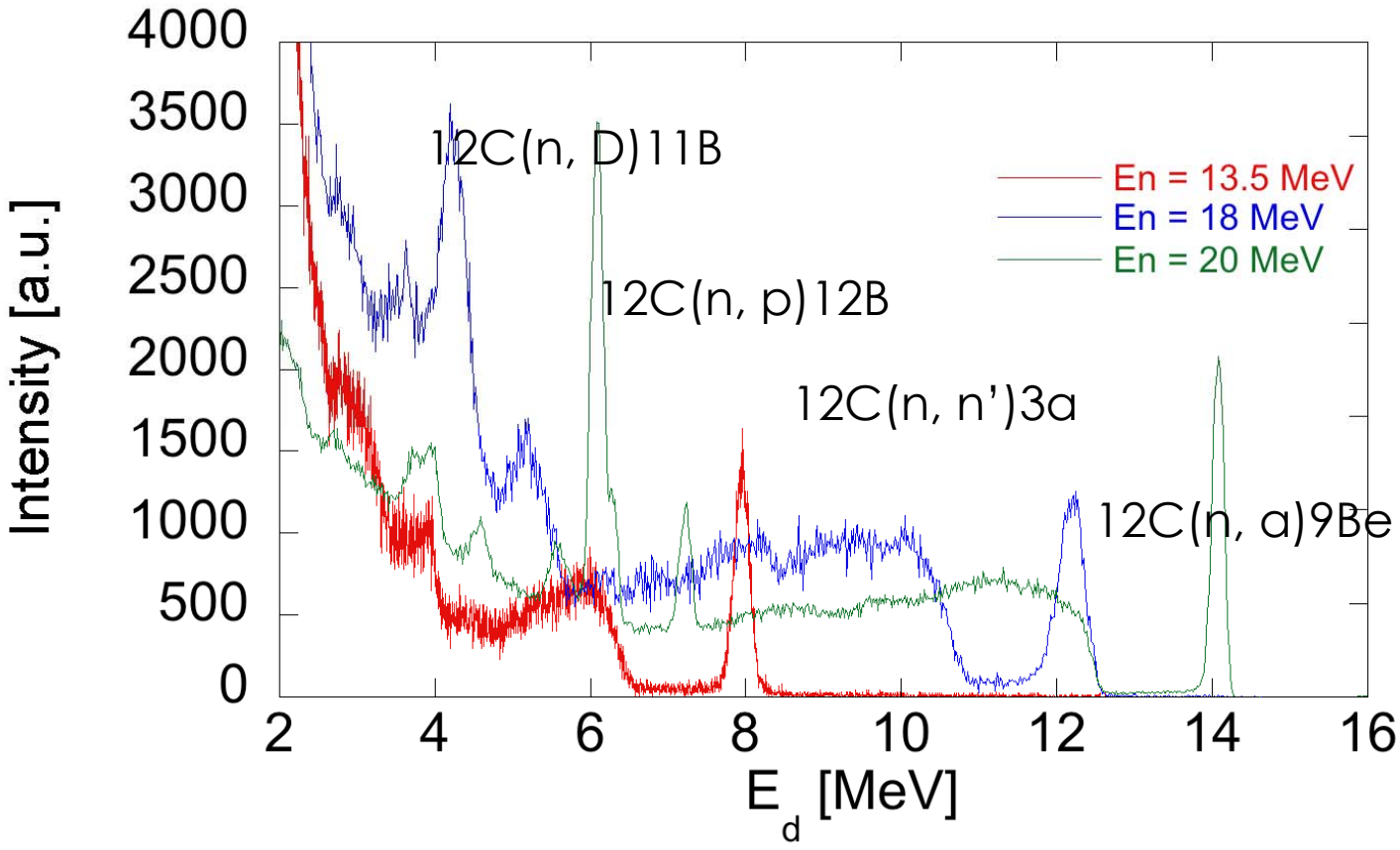
Results between 12 - 20 MeV

3.3 MeV D on Tritium target at:

- -110 deg
- -60 deg
- -0 deg

For pixel #5

FWHM= 176 keV @ 20 MeV neutron Resolution around 1.3%.



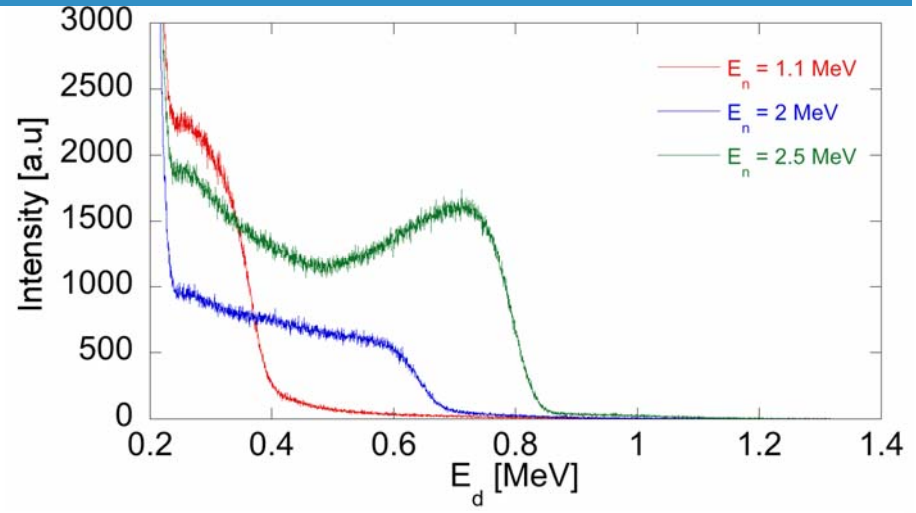
Results between 1.5 - 4 MeV

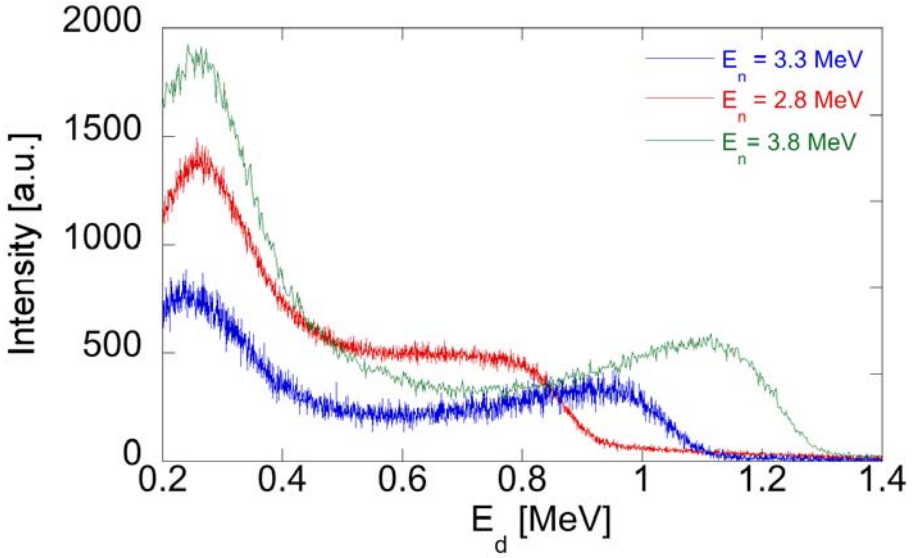
3.3 MeV p on Tritium target at
- 0 degrees
- 45 degrees
- 90 degrees

For pixel #5

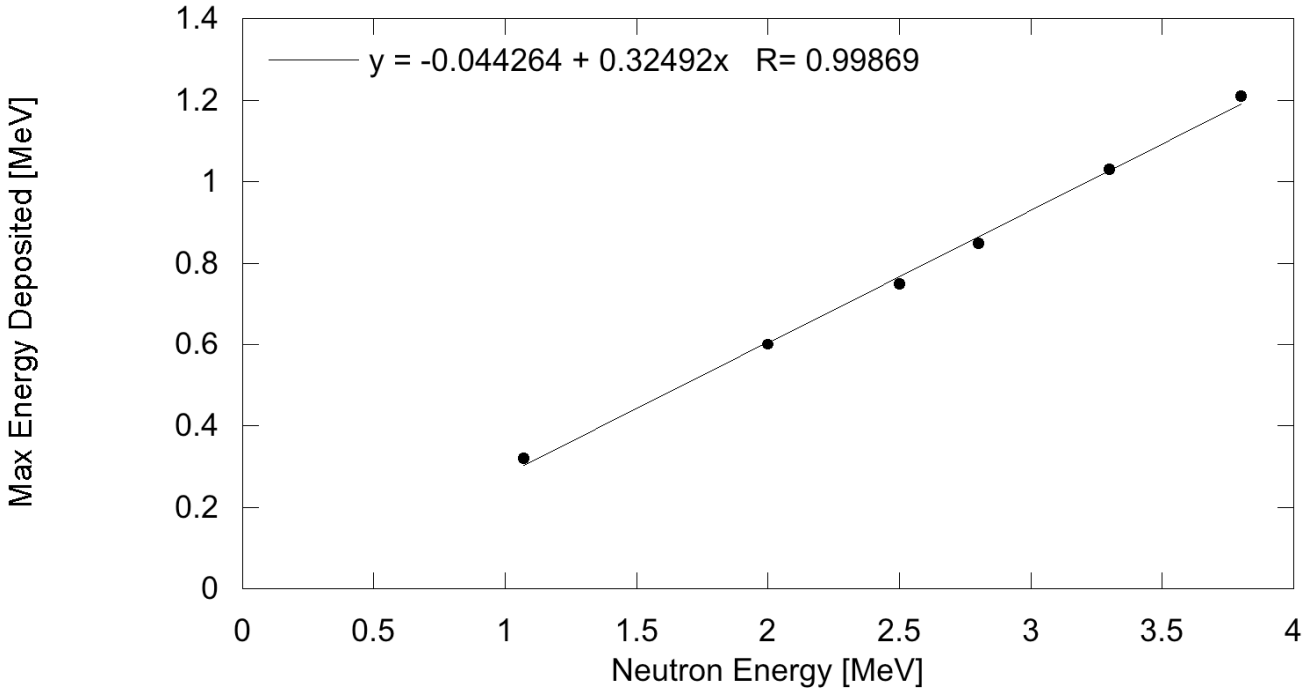
Resolution @ 2.5 MeV around 6%

p on Lithium target at 0 degrees proton energy:
- 4.5 MeV
- 5 MeV
- 5.5 MeV



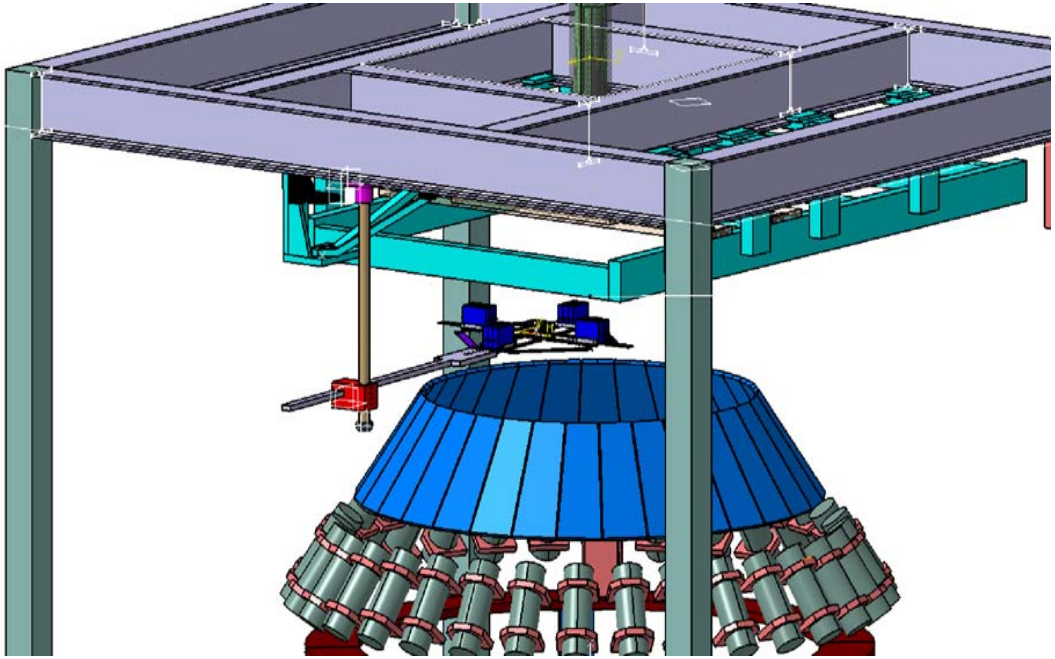


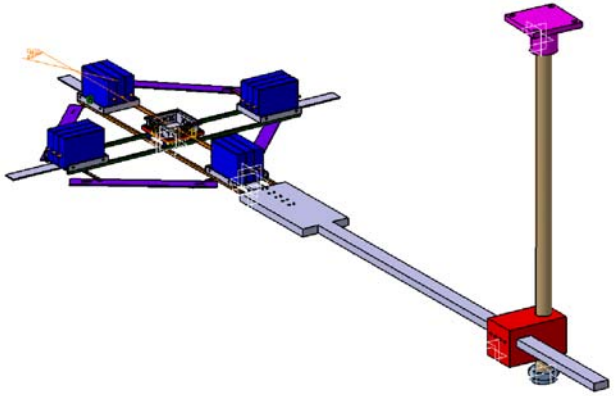
Results between 1.5 - 4 MeV: linearity



Relationship between the maximum energy deposited into the detector via elastic scattering on 12 C and the neutron energy

Installation at JET: June 2015





The SDD Matrix will be installed at JET on a vertical line of sight (just above the TOFOR spectrometer):
→ the detector will be ready to measure the neutron spectrum during the next DD campaign in winter 2015/16.

Conclusions

- Measurement performed at JET with a Single-crystal Diamond Detector (SDD) demonstrated the capability of such a detector to be a plasma diagnostic.
- A Matrix of 12 Single-crystal Diamond Detector has been realized as a Vertical Neutron Spectrometer for JET.
- Calibrations with 14 MeV neutrons at FNG measured an energy resolution of 2.3%, with a good reprodubility.
- Each pixel response was successfully measured with neutrons from 1.5 to 4 MeV and from 13 to 20 MeV: the full detector response function will be evaluated.
- In June 2015 the SDD matrix will be installed as a diagnostic for the JET campaign.
- SDD is very interesting for use in the future ITER Radial Neutron Camera where one can combine neutron emissivity and spectroscopy measurements.

Thank you!

A Single-crystal Diamond Detector Matrix for DT plasma diagnostic

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