Single crystal CVD diamond neutron detectors in a p-type/intrinsic/metal layered structure

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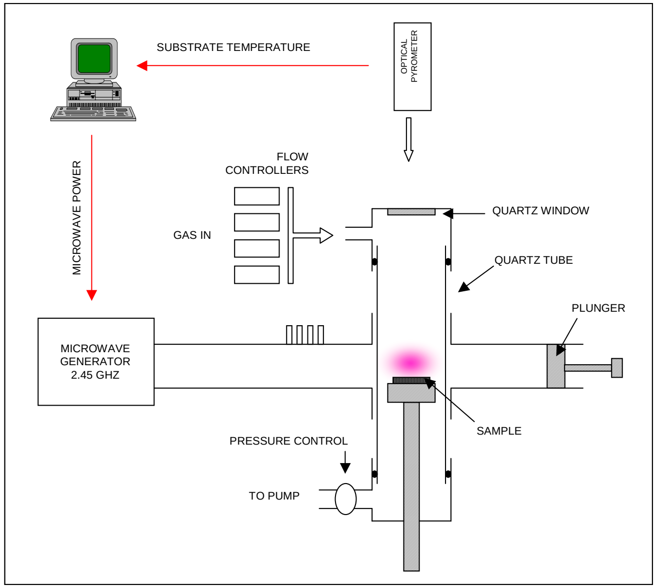
Outline

- ***Growth and device fabrication***
- ***Main application***
- ***Neutron detection***
- ***Radiation hardness***
- ***Results at JET***
- ***Conclusions***

Device fabrication



Typical growth parameters

Plasma composition	***99% H_2- 1% CH_4,***
Temperature	***650 – 800 °C***
Microwave power	***600 - 1300 W***
Pressure	***100 - 150 mbar***
Gas flow rate	***100 sccm***

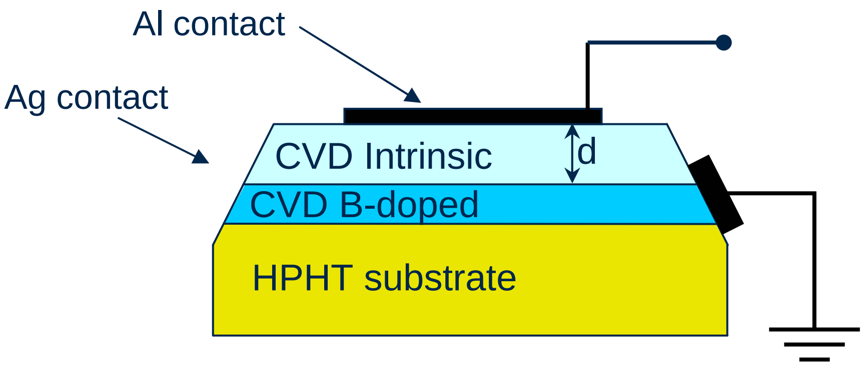
Doping

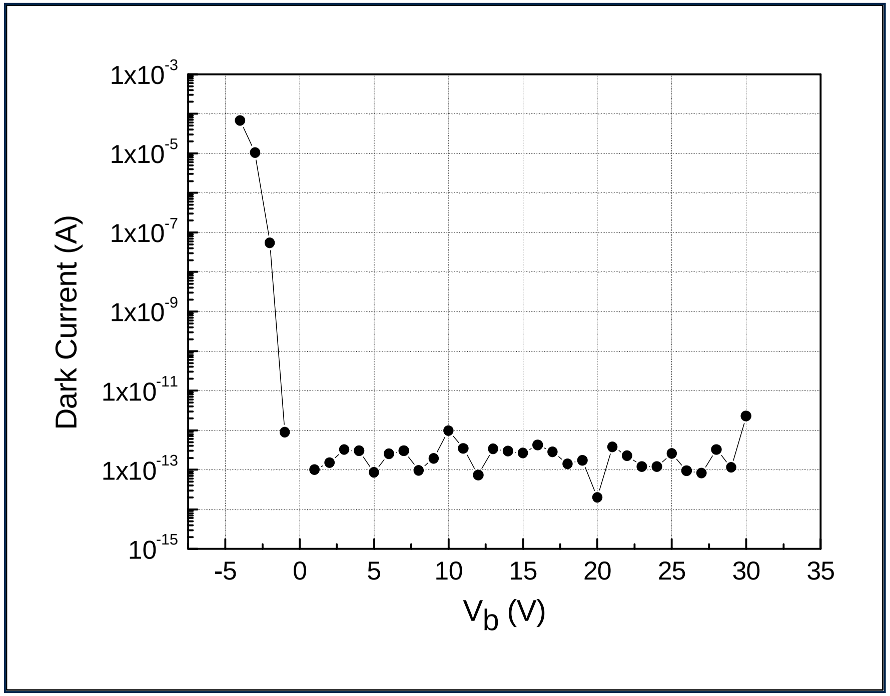
- ✓ ***B_2H_6 10 ppm***

Substrates

- ✓ ***(100) HPHT type Ib 4×4 mm²***

Device fabrication

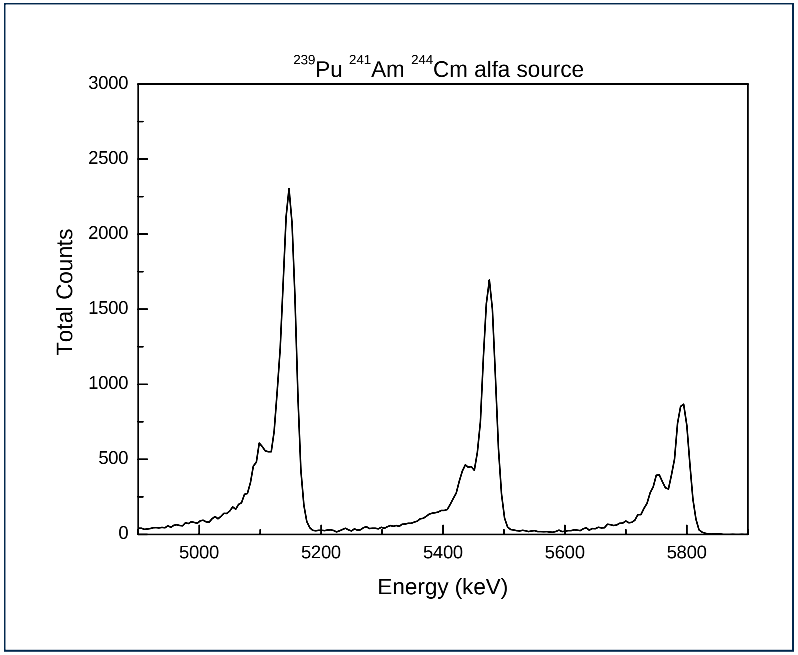


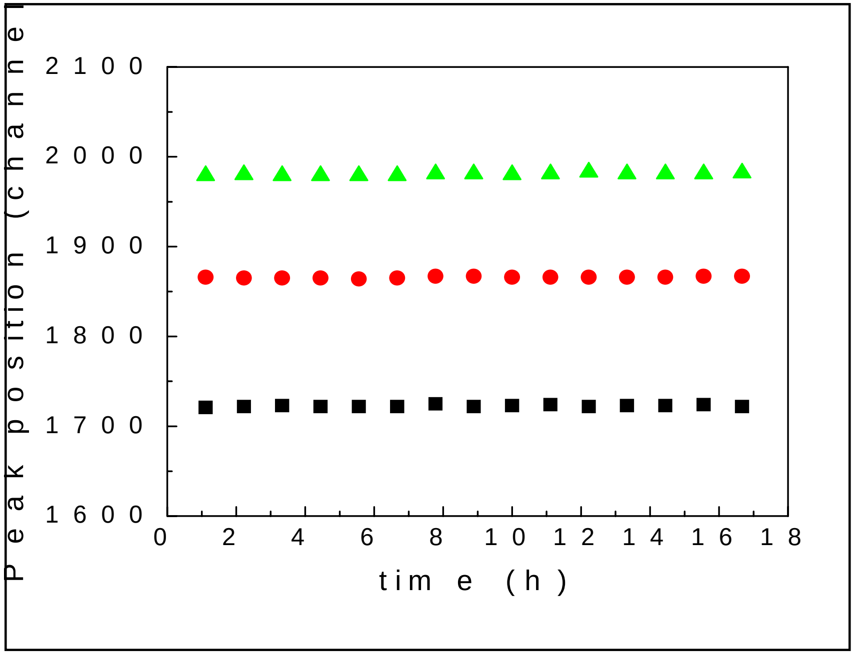


α particles test

Triple α source (^{239}Pu, ^{241}Am, ^{244}Cm)

emitting 5.16 MeV, 5.48 MeV and 5.80 MeV α-particles





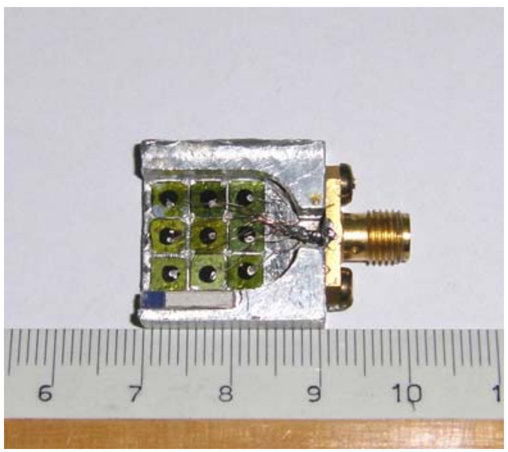
- ✓ *100 % charge collection efficiency*
- ✓ *100 % detection efficiency*
- ✓ *0.6-1.8 % energy resolution*
- ✓ *No pumping (priming) effects*
- ✓ *Long term stability*

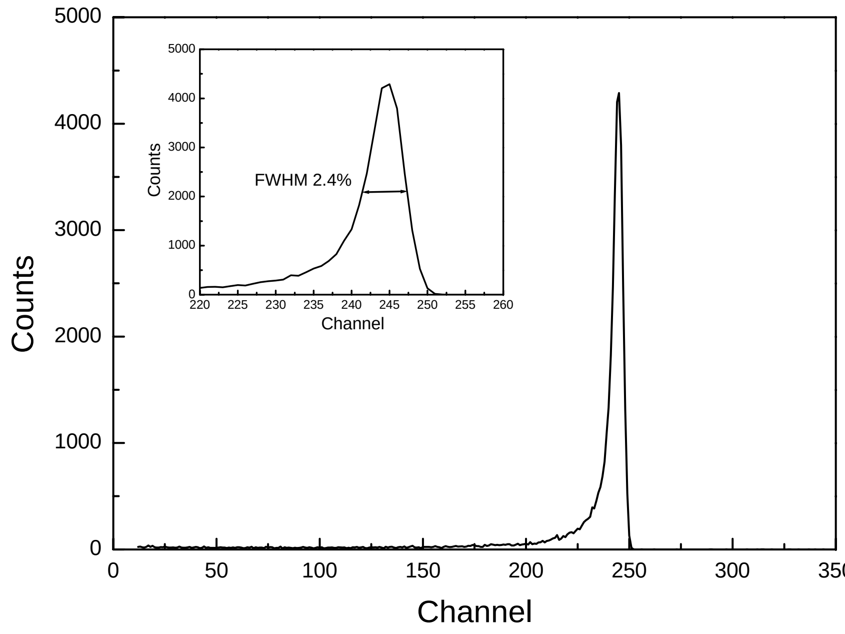
More than 50 detectors realized, all with very similar performance

Mosaic detectors

In low neutron flux environments a higher sensitivity is needed → Large area detectors!

Once the reproducibility of the detectors fabrication is achieved, it is possible to obtain large sensitive area detectors by connecting many samples in parallel (mosaic detector).





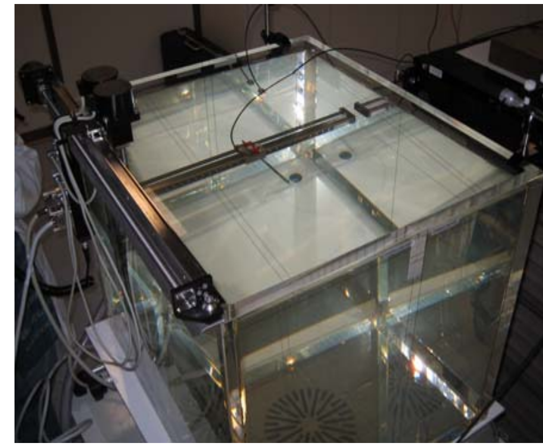
Nine diamond detectors connected in parallel and tested under α particles irradiation

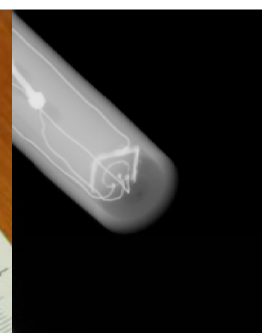
Sensitivity increased by a factor 9

Resolution: 2.4% (FWHM)

Radiotherapy dosimeters

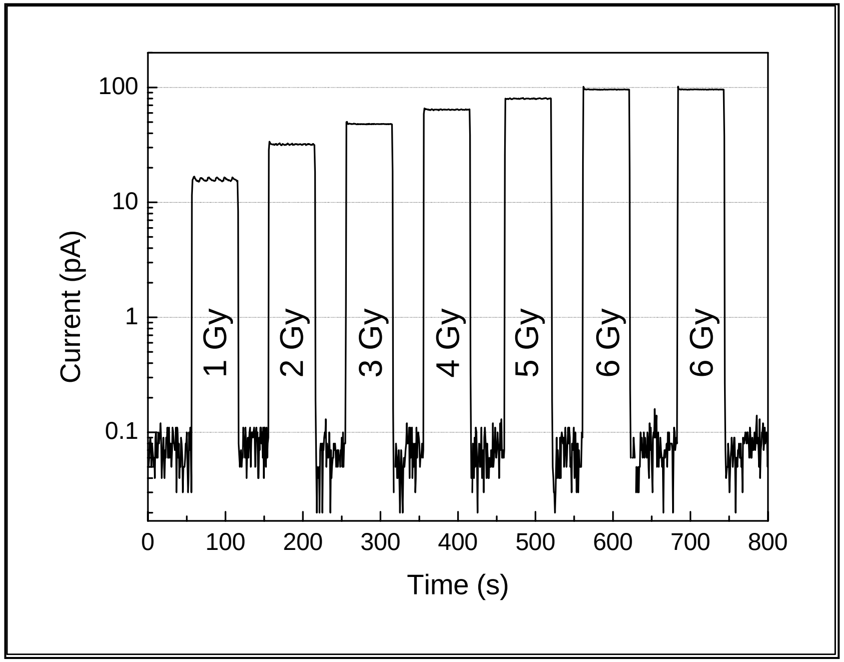
Test performed at S. Filippo Neri Hospital in Rome

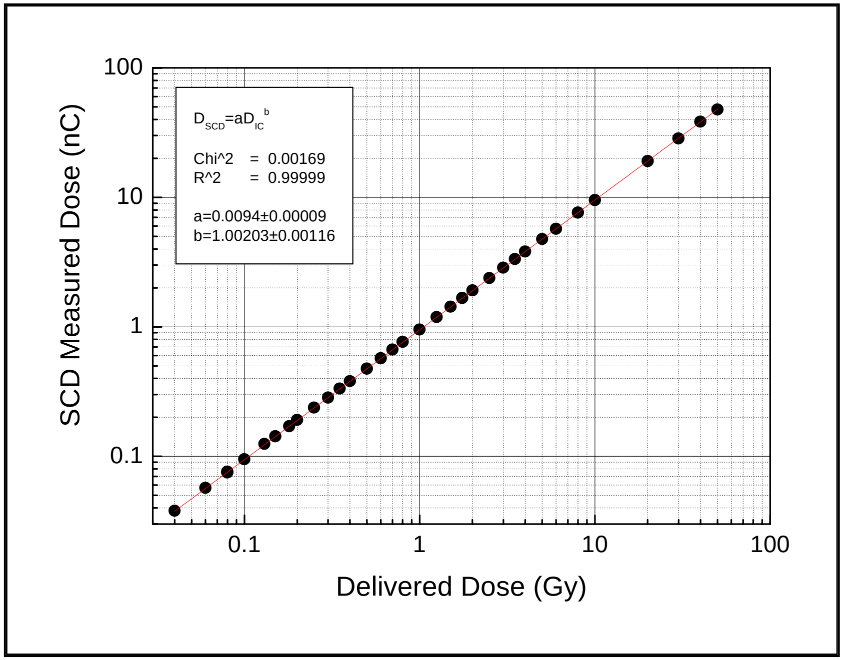




- ✓ *PMMA and epoxy resin waterproof housing*
- ✓ *No applied bias voltage*

Radiotherapy dosimeters

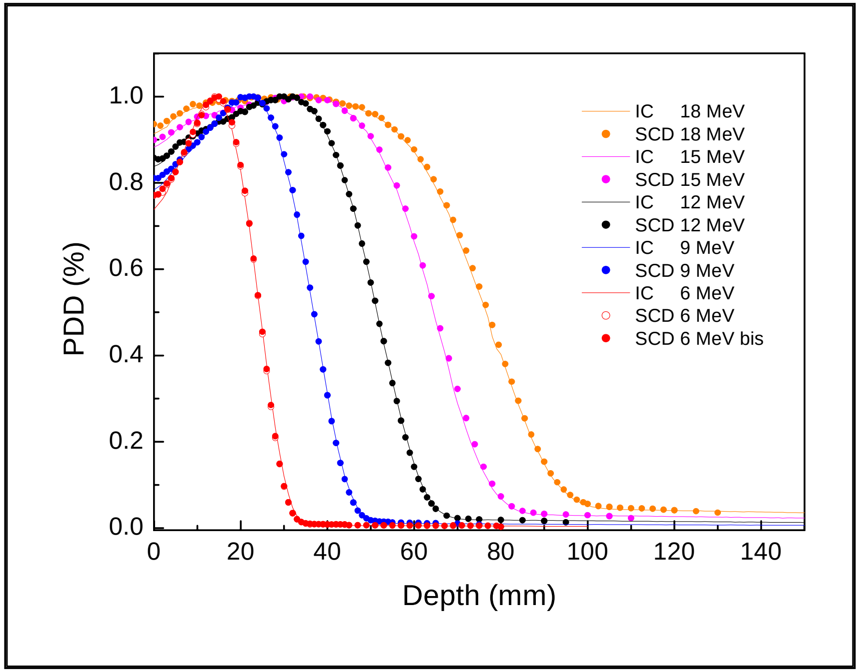


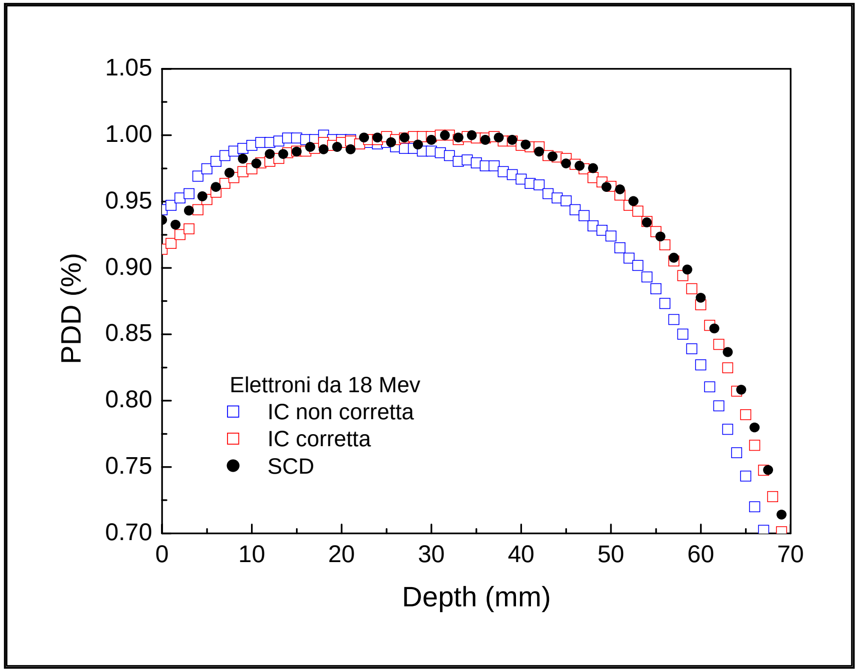


- **0 bias voltage operation**
- **No persistent photocurrent**
- **Excellent linearity**
- **Sensitivity 1 – 4 nC/Gy**

Radiotherapy dosimeters

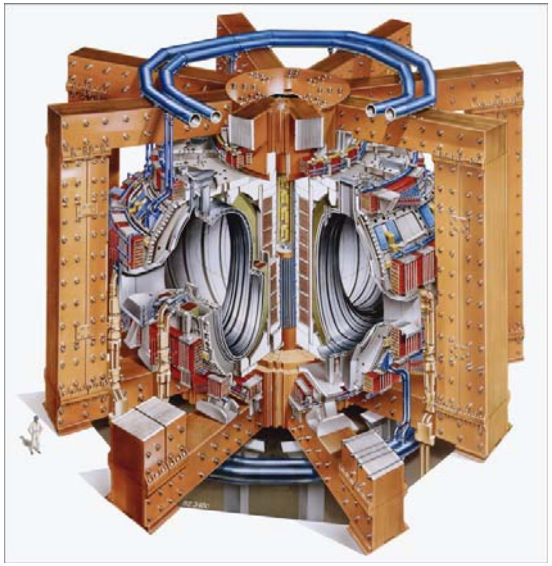
Depth dose profiles in water



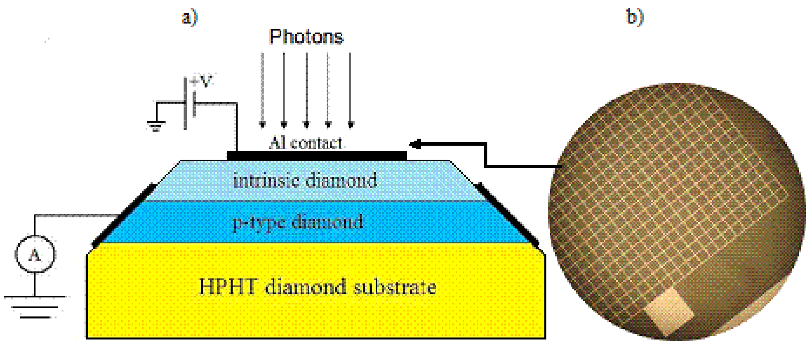


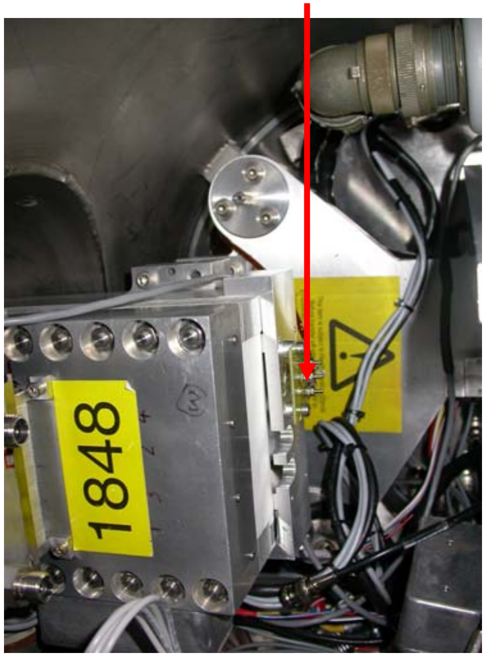
- **No need of software corrections!**

UV – VUV detectors



Joint European Torus (JET)
Chulam (UK)

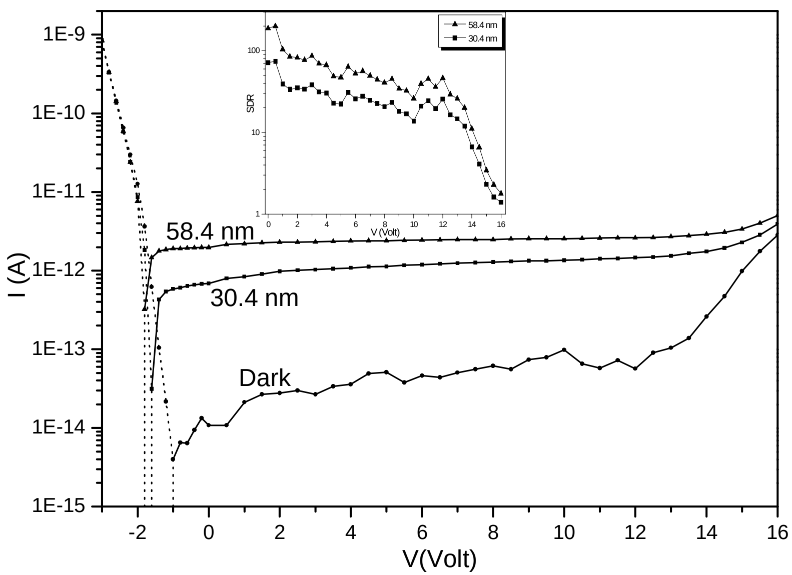




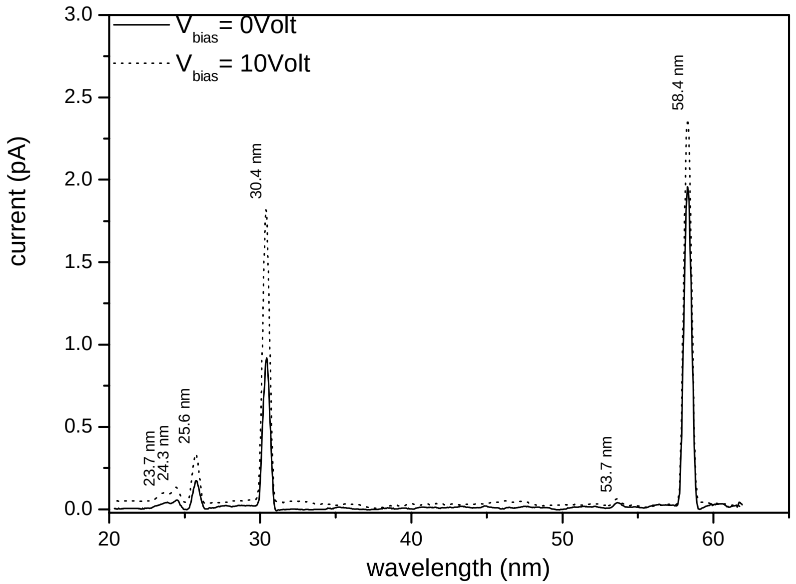
In November 2007 a CVD diamond detector was installed at JET and connected to the main on-line data acquisition system

Since then it is continuously operating

VUV measure at JET

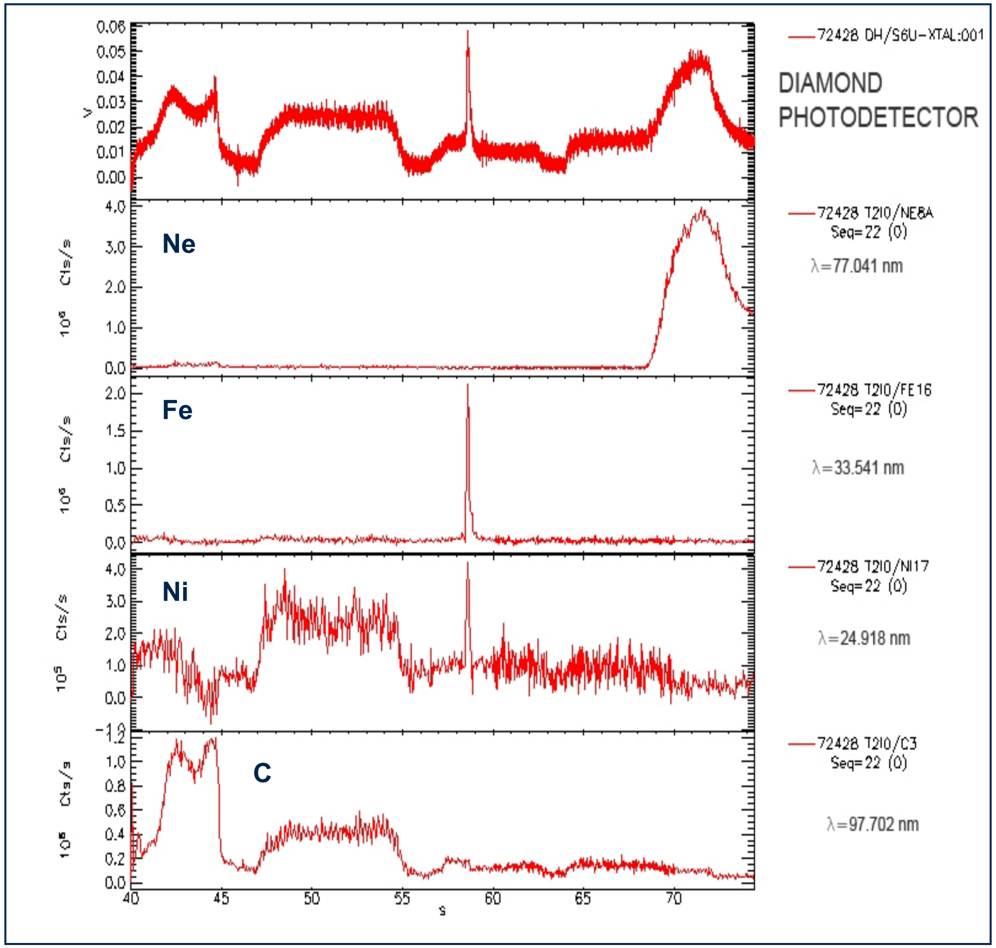


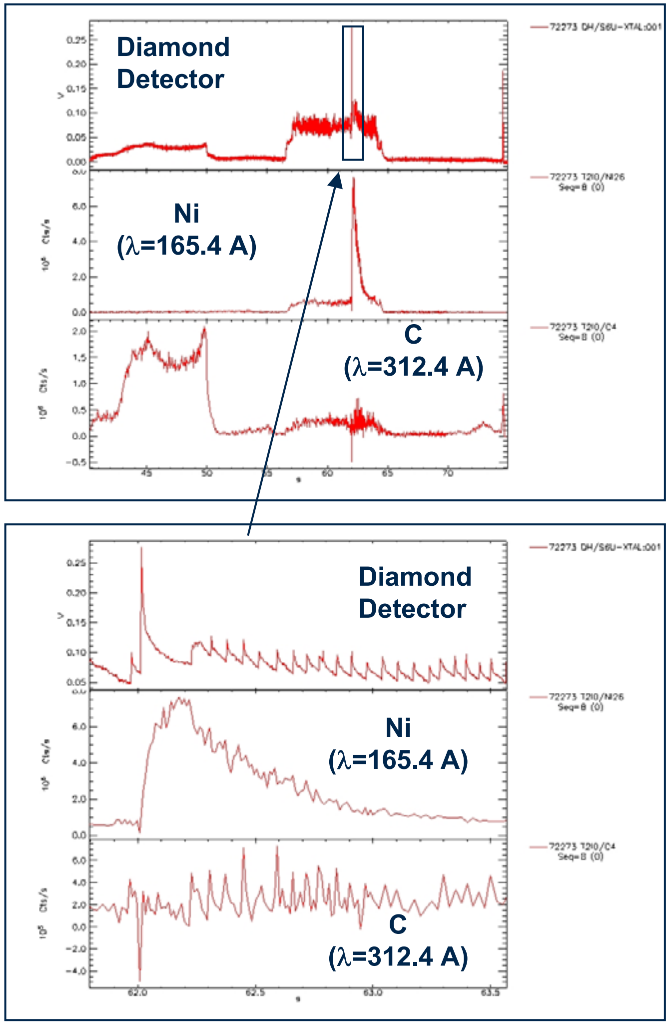
I-V curve of SCD VUV detector



He spectrum acquired by the SCD detector

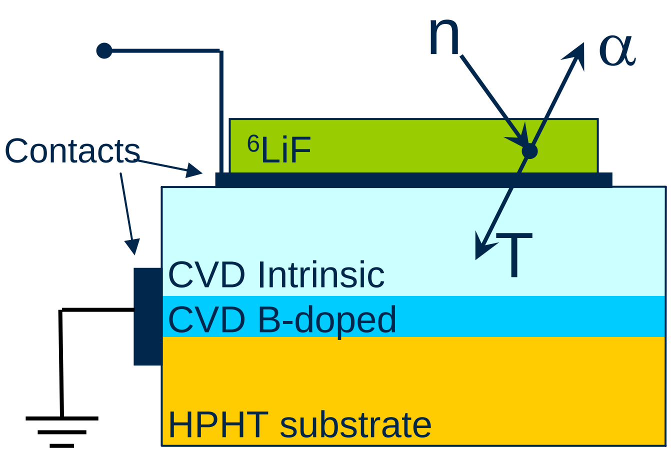
VUV measure at JET





Neutron detectors

Thermal Neutrons

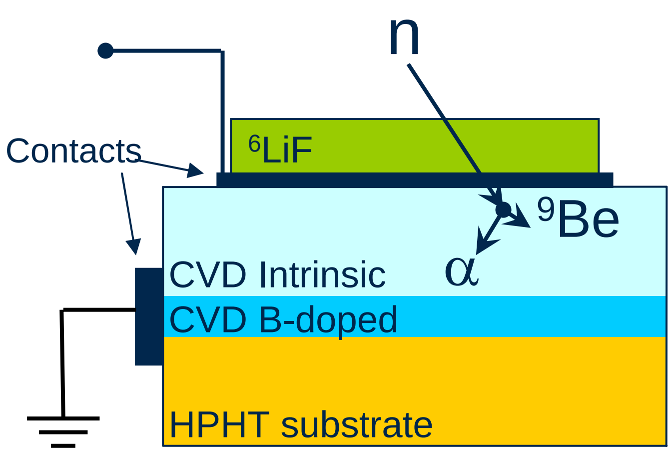


neutrons interact with ^{6}Li in the 95 % enriched ^{6}LiF layer:

n + ^{6}Li → Tritium + α + 4.8 Mev

T (2.73 MeV) and α (2.06 MeV) are emitted at 180°, so only either the T or the α particle is detected

Fast Neutrons



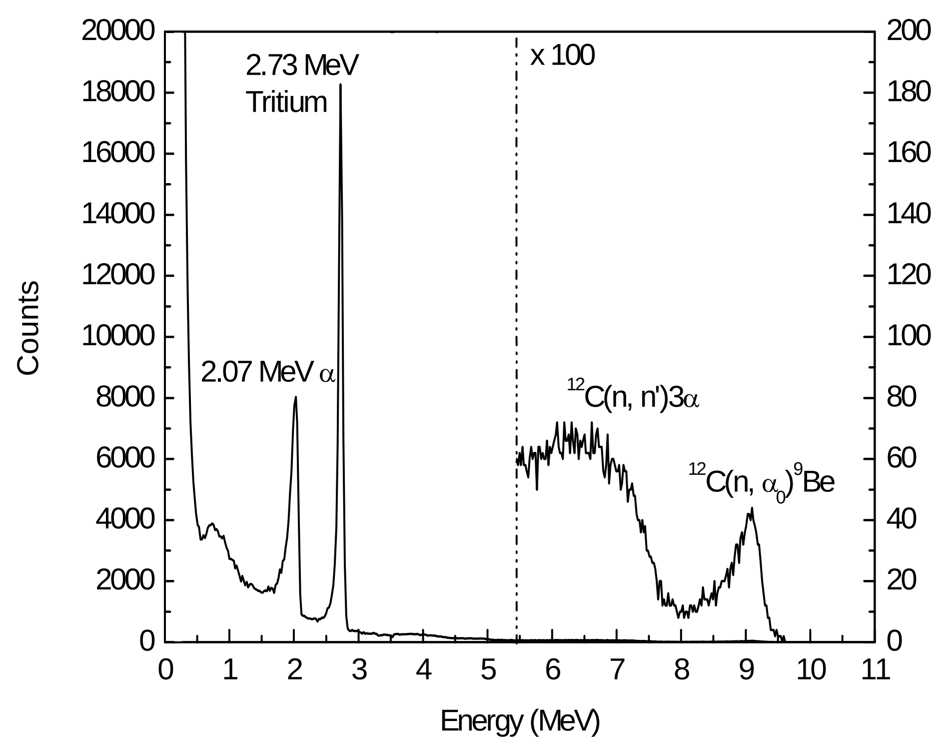
neutrons directly interact with ^{12}C in the diamond sensing layer:

n + ^{12}C → α + ^{9}Be – 5.7 MeV

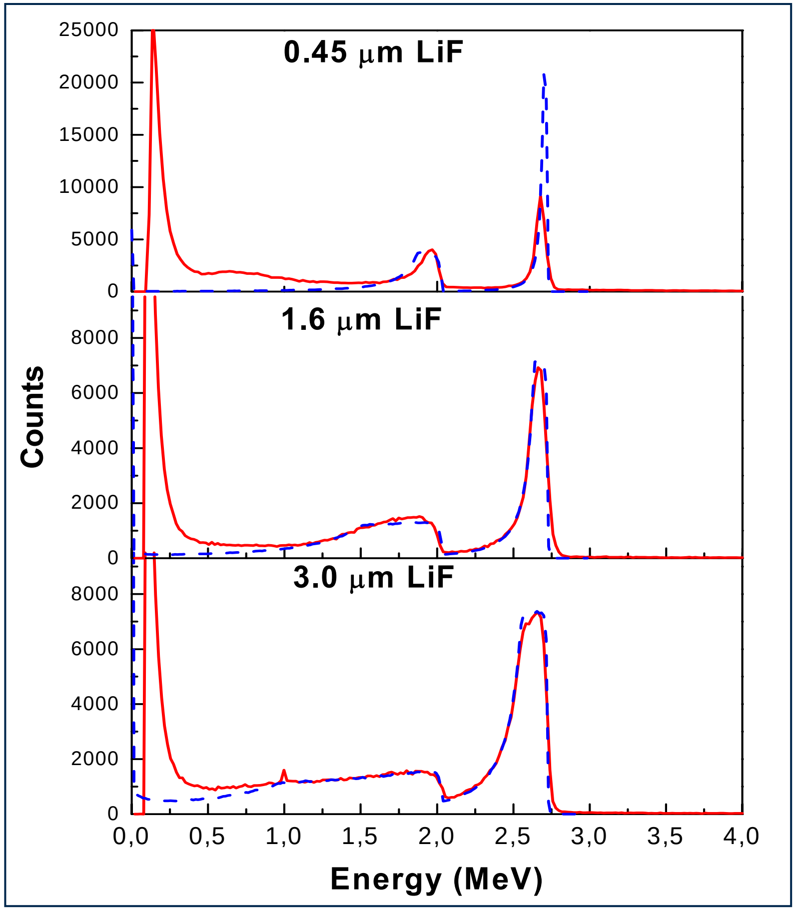
(for 14.1 MeV neutrons) with α and Be having a total energy of 8.4 MeV

Neutron detectors

- Thermal neutrons where produced by slowing down a fraction of the 14.8 MeV neutrons produced at FNG by a 10 cm PMMA moderator
- Both the 2.06 Mev α and the 2.73 MeV Tritium peaks originated by thermal neutrons interactions are clearly resolved
- The width of the two peaks is due to the energy loss of the produced particles inside the LiF layer. In particular, the 2.06 MeV α peak is broader than the Tritium peak due to the higher stopping power of α particles in LiF
- The 9.1 MeV $^{12}C(n, \alpha_0)^9Be$ reaction peak can be noticed as well, demonstrating the possibility of simultaneous detection of thermal and fast neutrons



Neutron detectors: spectra simulations



experimental (red) and simulated (blue) thermal neutron spectra

Amplitude (only adjustable parameter) chosen to match the simulated and experimental a-particle peak intensity.

Very good agreement

simulation can be used to predict the detector behaviour for any ^{6}LiF layer thickness.

2.73 MeV tritium peak for 0.45 μm ^{6}LiF : equal simulated and experimental peak area (i.e. total counts).

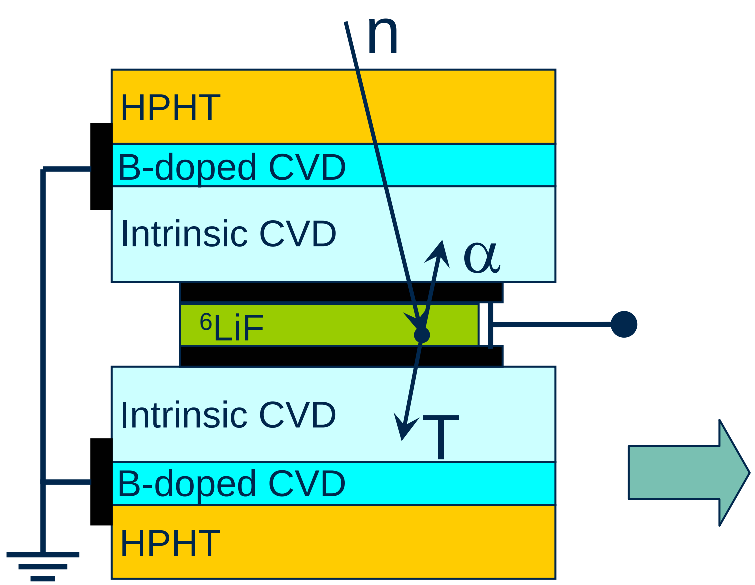
real peak wider (and less intense) because of the broadening produced by detector inhomogeneities and by noise (not taken into account)

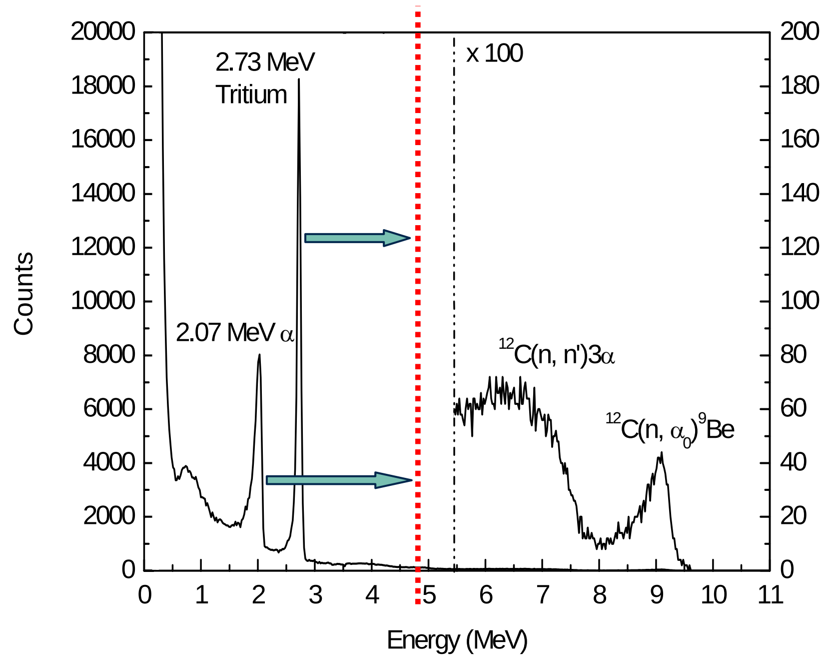
Sandwich detectors

A low energies background, due to low energy reactions, is always observed, especially in presence of high γ fluxes.

This effect is much more detrimental when a converter whose reaction products have low energy is used

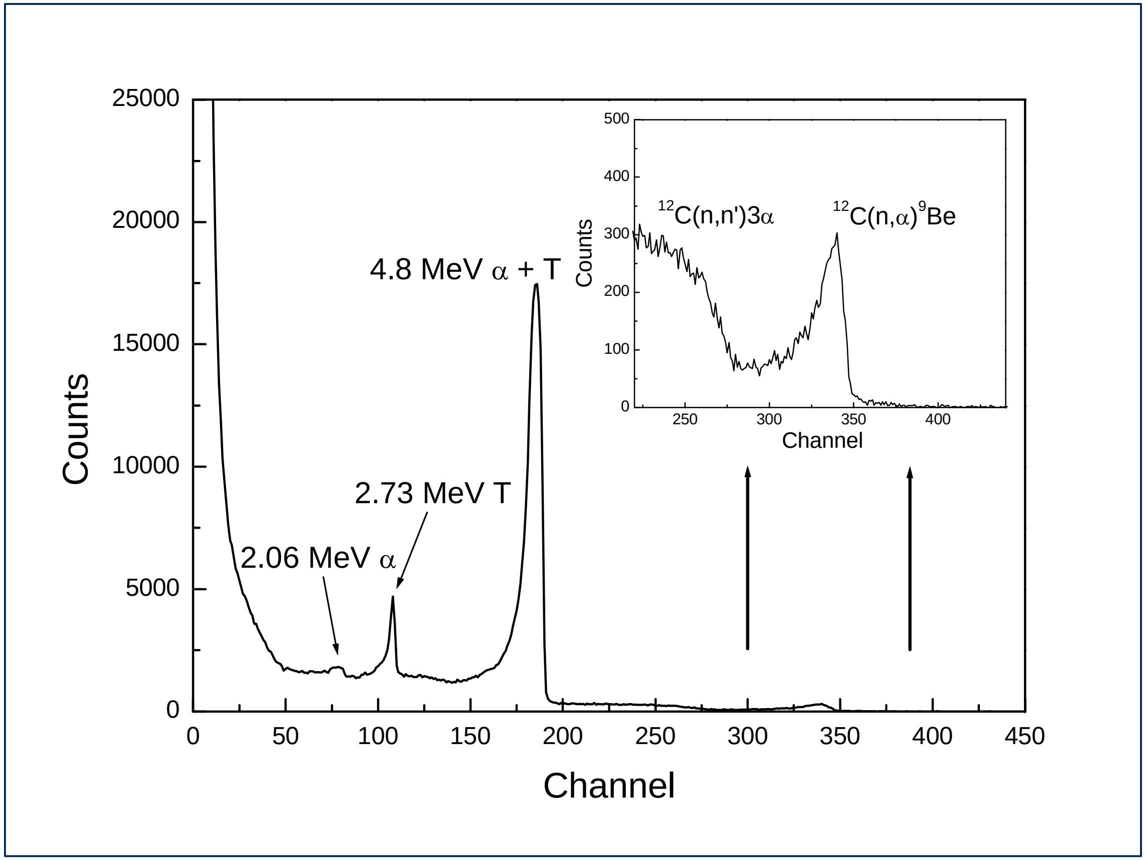
A higher energy peak would allow a better discrimination between thermal neutrons and other ionizing radiations (e.g γ and protons).





- The α particle and the tritium ion are simultaneously detected at 4.8 MeV (E_T+E_α)
- The effective sensitive thickness to fast neutrons is given by the sum of the two intrinsic CVD layers

"Sandwich" configuration

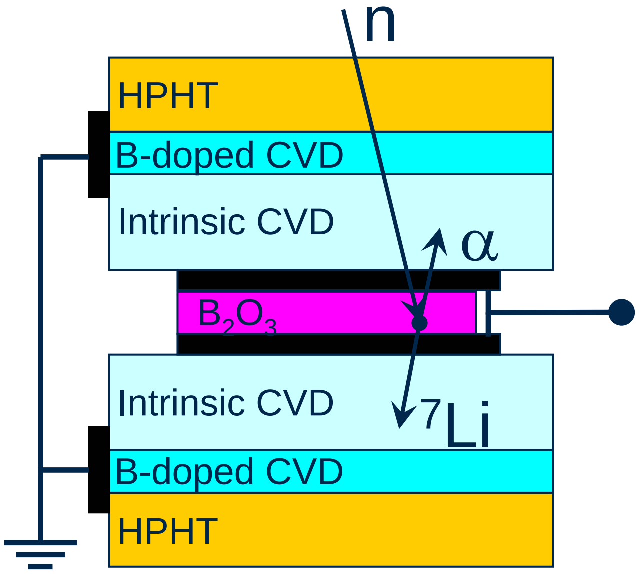


An intense α + T peak is observed at 4.8 MeV

Residual 2.73 MeV and 2.06 MeV peaks are observed (peak integral about a factor 15 lower).
These peaks are due to a slight misalignment of the two sandwiched samples.

^{10}B converter

- ✓ Deposition of B_2O_3 or BN or B …
- ✓ About 20% of ^{10}B in natural Boron
- ✓ Low energy reaction products
- ✓ Higher stopping power of the reaction products

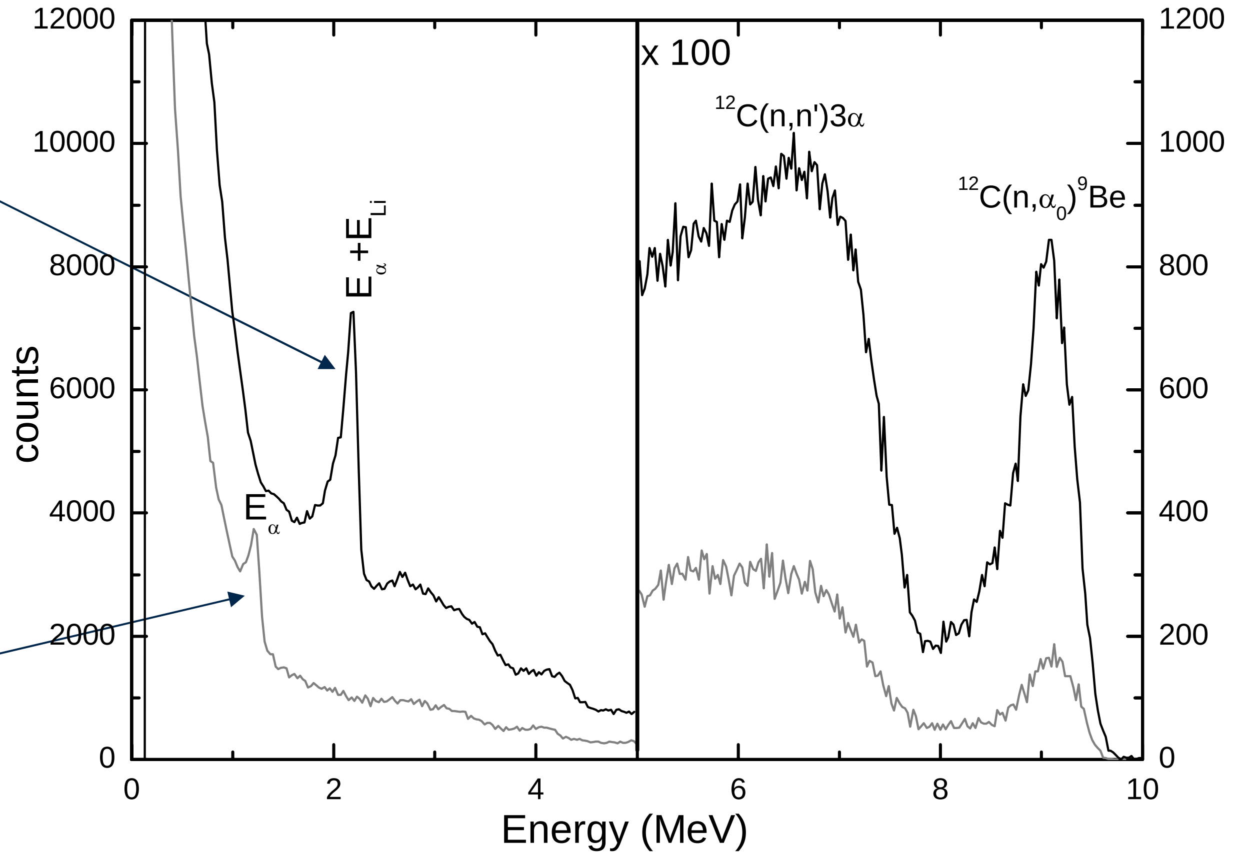


$$^{10}B + n \Rightarrow \alpha\ (1.47MeV) + {}^{7}Li(0.84MeV)$$

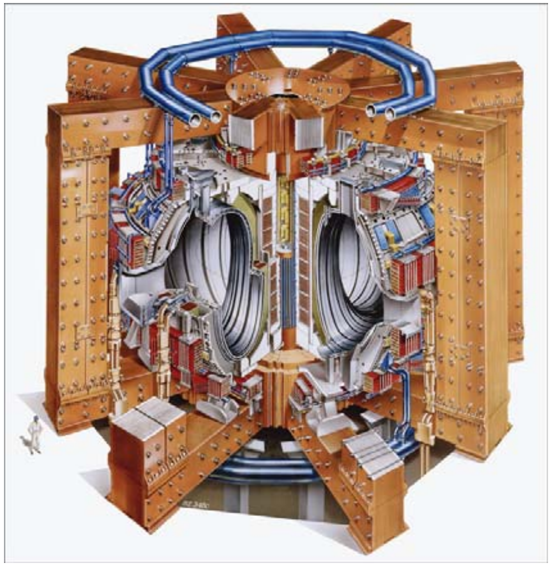
^{10}B converter

Sandwich configuration

Single detector configuration



Radiation Hadness



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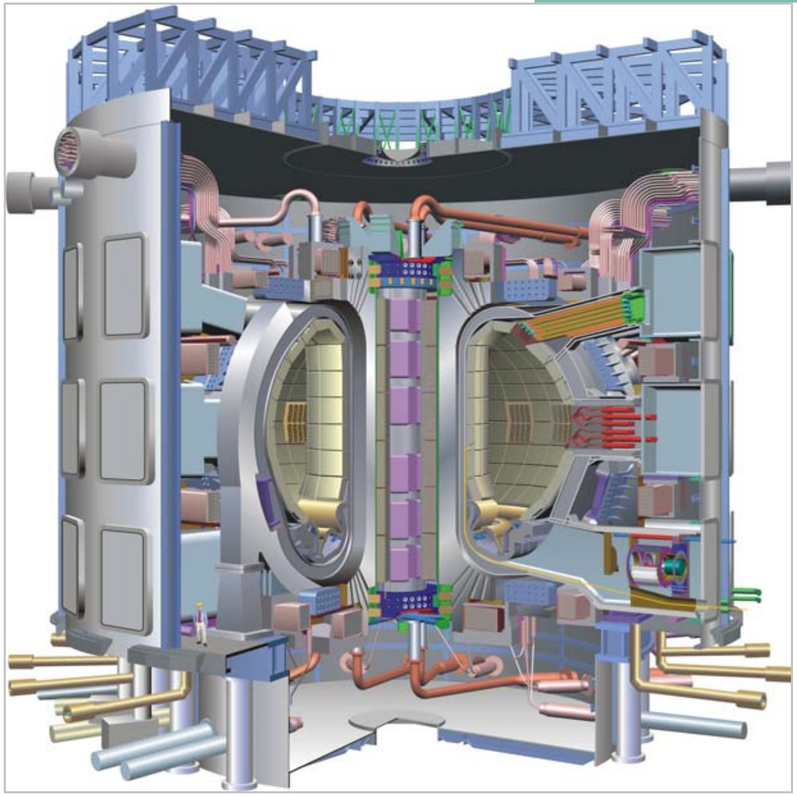


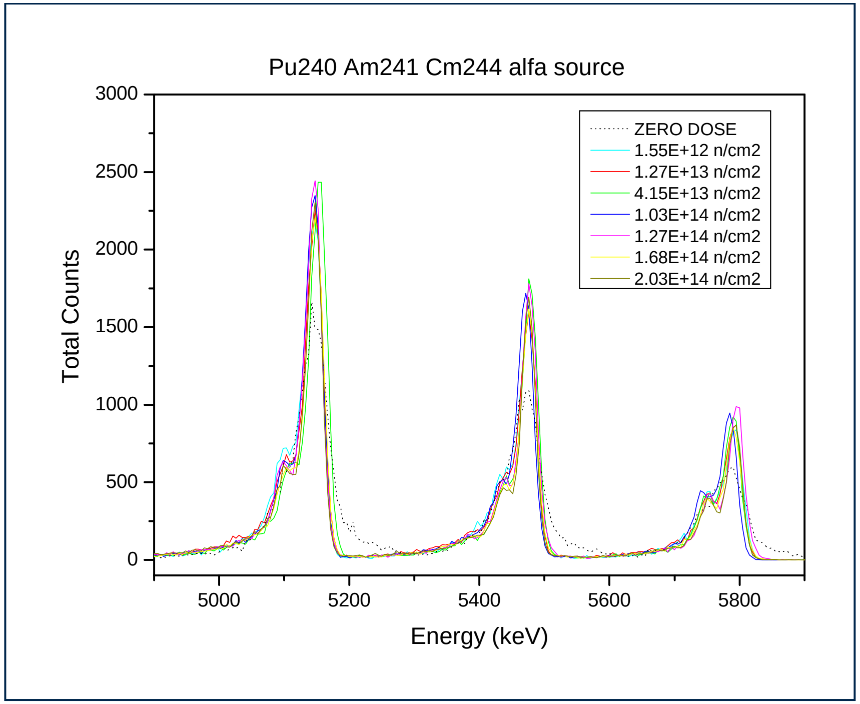
ITER

Si detectors are replaced approximately after 1 year at JET (if working with tritium).
At ITER the 14MeV neutron flux will be too high for conventional detectors:
$1x10^{14}$ neutron/cm^2 RADIATION HARDNESS REQUIRED

Radiation hardness

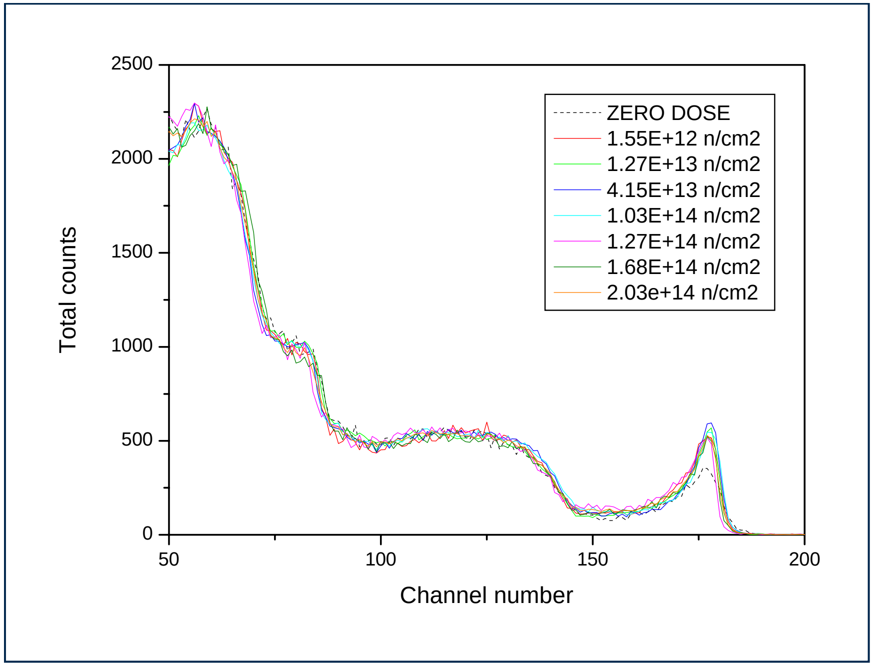
Test performed at the Frascati Neutron Generator (FNG)

Multi-step irradiations with 14.8 Mev Neutrons were performed. At the end of each step both the neutron detection and alpha particle detection spectra are acquired



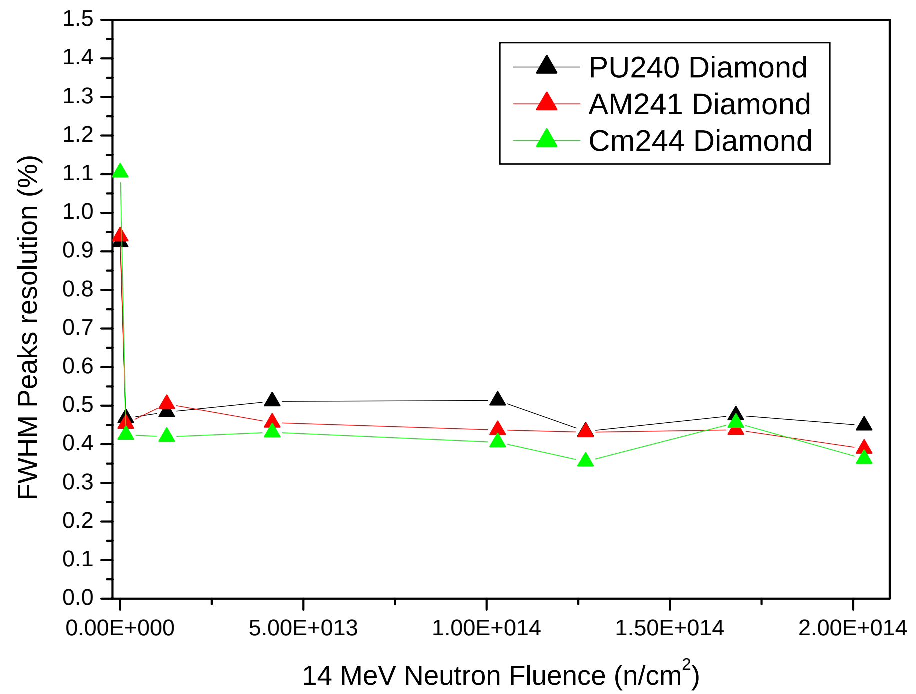
α particles spectra after sequential 14 MeV fast neutrons irradiations

Maximum delivered fluence = 5*10[14]



14 MeV Neutrons spectra after sequential irradiations

Radiation hardnes



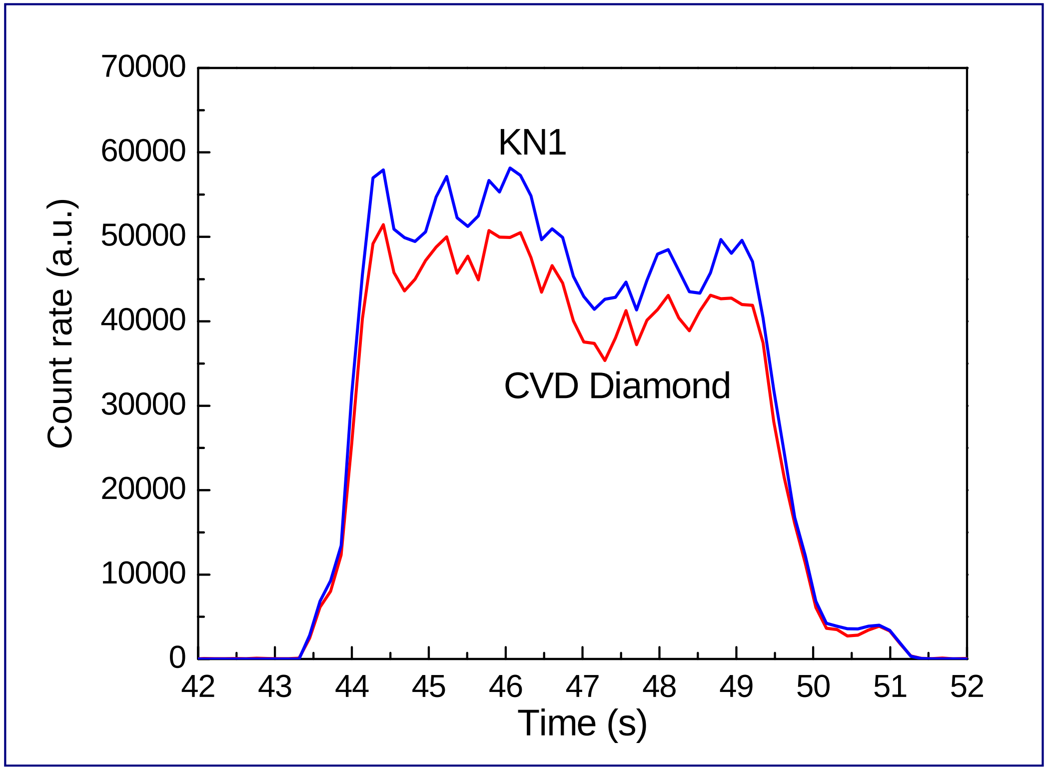
Detector resolution vs total 14 MeV neutron fluence

Resolution still better than 1% after irradiation with $5*10^{14}$ neutrons/cm^2

Neutron detection (JET)

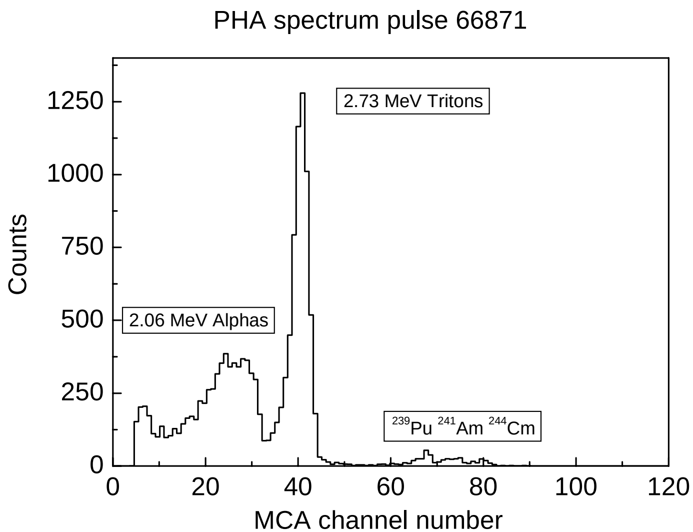
In FEBRUARY 2006 two CVD diamond detectors were installed at JET and connected to the main on-line data acquisition system

Since then they are continuously working in normal operating conditions



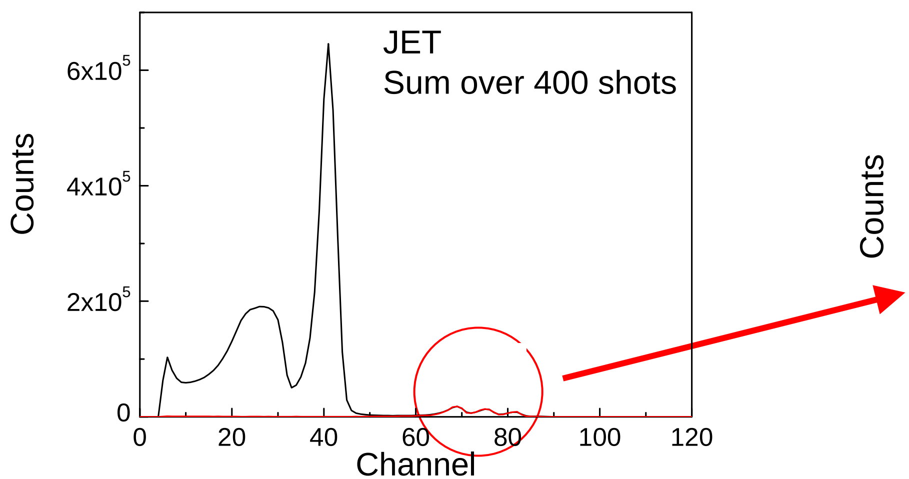
Comparison of time dependent neutron emission measured by a CVD diamond and KN1 system during a JET pulse.

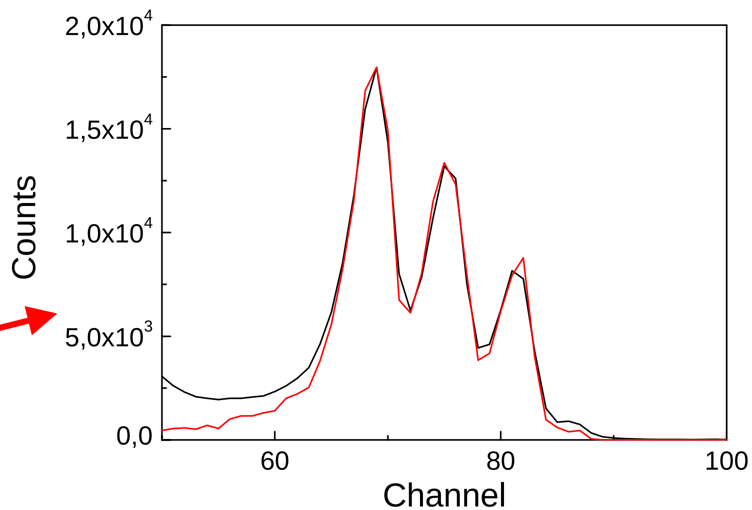
Response and stability (JET)



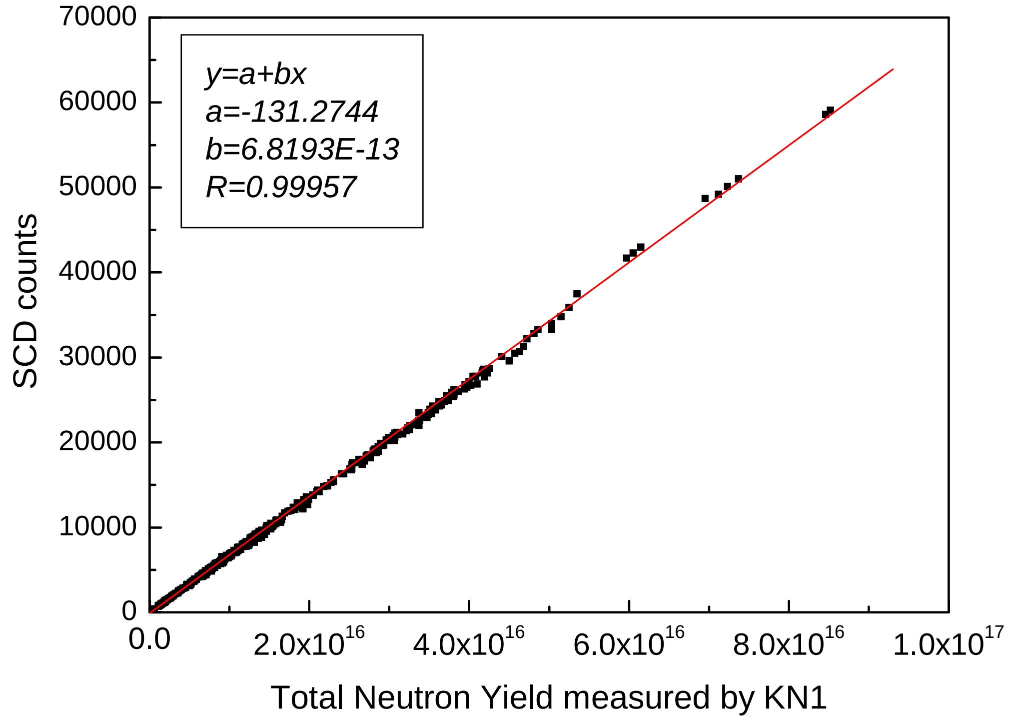
Pulse Height Spectra

- ***Thermal neutrons were properly detected and both 2.06 MeV α particles and 2.73 MeV Tritium peaks are clearly visible***
- ***The resolution is comparable with that obtained in the FNG laboratory tests***
- ***The response stability and reproducibility over more than 400 shots is surprisingly good !***





Neutron detection (JET)



Comparison between CVD diamond detectors and KN1 JET acquisition system (official monitor) over 400 JET shots.

Extremely stable performance over more than 2 year of uninterrupted operation

Conclusions

- *Diamond based neutron detectors a p-type/intrinsic/metal have been successfully fabricated and tested*
- *The reproducibility of the fabrication process is shown to be good enough to produce multiple detector devices*
- *Very good agreement of experimental data with theoretical simulation*
- *Radiation hardness to 14 MeV neutrons at least up to fluence of $5*10^{14}$ n/cm^2 was measured.*
- *Stability and reliability during 2 year of uninterrupted operation at JET was demonstrated*

Thank You!