POLITECNICO DI MILANO

Passive detectors (nuclear track detectors) – part 2: Applications for neutrons

4th ARDENT Workshop: CTU, Prague, Czech Rep.

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Date: 25/03/2015

This research project has been supported by the Marie Curie Initial Training Network Fellowship of the European Community's Seventh Framework Programme under Grant Agreement PITN-GA-4 2011-289198-ARDENT

Outline

- Overview of Neutron Physics in CR-39 detectors
- Concept of Dose calculations from LET_{nc} (mean LET) spectra
- Neutron dosimetry: State of the art & the innovative approach
- Other applications for neutrons spectrometry
- Conclusion

Overview of Neutron Physics

Classification of neutrons by energy

Thermal:	E < 1 eV (0.025 eV)
Epithermal:	1 eV < E < 10 keV
Fast:	> 10 keV ← Our applications of the CR-39 as dosimeter

Neutron sources	*Neutron energies*
Reactors	neutrons in the few keV to several MeV
Fusion reactions	14 MeV
Large accelerators	Hundreds of MeV

Ref: Principles of Radiation Interaction, 22.101, fall 2006, MIT open courseware

Overview of Neutron Physics

Energy Deposition by Neutrons:

- Neutrons are generated over a wide range of energies by a variety of different processes
- Like photons, neutrons are uncharged and do not interact with orbital electrons
- Neutrons can travel considerable distances through matter without interacting
- Neutrons will interact with atomic nuclei through several mechanisms:
    - Elastic scatter
    - Inelastic scatter
    - Non-elastic scatter
    - Neutron capture
    - Spallation

Ref: Principles of Radiation Interaction, 22.101, fall 2006, MIT open courseware

Overview of Neutron Physics

Neutron Interactions

Elastic scatter: The most important process for slowing down of neutrons.

- Total kinetic energy is conserved
- E lost by the neutron is transferred to the recoiling particle.
- Maximum energy transfer occurs with a head-on collision.
- Elastic scatter cross sections depend on energy and material.

$$Q_{\max} = \frac{4mME_n}{(M+m)^2}$$

TABLE 9.4. Maximum Fraction of Energy Lost, Q_{max}/E_n from Eq. (9.3), by Neutron in Single Elastic Collision with Various Nuclei

Nucleus	Q_{max}/E_n
$^{1}_{1}H$	1.000
$^{2}_{1}H$	0.889
$^{4}_{2}He$	0.640
$^{9}_{4}Be$	0.360
$^{12}_{6}C$	0.284
$^{16}_{8}O$	0.221
$^{56}_{26}Fe$	0.069
$^{118}_{50}Sn$	0.033
$^{238}_{92}U$	0.017

Ref: Principles of Radiation Interaction, 22.101, fall 2006, MIT open courseware

Overview of Neutron Physics

Inelastic scatter

- The neutron is absorbed and then re-emitted
- The nucleus absorbs some energy internally and is left in an excited state.

  e.g., $^{14}N(n,n')^{14}N$ $E_\gamma = \sim 10$ MeV

- De-excitation emits a gamma ray.
- In tissue, inelastic scatter reactions can occur in carbon, nitrogen and oxygen.

Nonelastic scatter

- Differs from inelastic scattering in that a secondary particle that is not a neutron is emitted after the capture of the initial neutron.

  e.g., $^{12}C(n,\alpha)^{9}Be$ $E_\gamma = 1.75$ MeV

- Energy is transferred to the tissue by the alpha particle and the de-excitation gamma ray.

Ref: Principles of Radiation Interaction, 22.101, fall 2006, MIT open courseware

Overview of Neutron Physics

Neutron capture

- Same as nonelastic scatter, but by definition, neutron capture occurs only at low neutron energies (thermal energy range is < 0.025 eV).
- Capture leads to the disappearance of the neutron.
- Neutron capture accounts for a significant fraction of the energy transferred to tissue by neutrons in the low energy ranges.

e.g., $^{14}N(n,p)^{14}C$ $\quad Q = 0.626$ MeV $\quad E_p = 0.58$ MeV

$^{1}H(n,\gamma)^{2}H$ $\quad Q = 2.2$ MeV $\quad E_\gamma = 2.2$ MeV

- The hydrogen capture reaction is the major contributor to dose in tissue from thermal neutrons. Because the gamma is fairly energetic, the dose to tissue will depend on the volume of tissue irradiated.
- Boron Neutron Capture

$$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{4}_{2}He + ^{7}_{3}Li + 0.48\,MeV\,\gamma \qquad Q = 2.31\text{ MeV}$$

$E_\alpha = 1.47$ MeV

$E_{Li} = 0.84$ MeV

Ref: Principles of Radiation Interaction, 22.101, fall 2006, MIT open courseware

Overview of Neutron Physics

Spallation

- In this process, after the neutron is captured, the nucleus fragments into several parts. Only important at neutron energies in excess on 100 MeV. (cross sections are higher at 400-500 MeV).

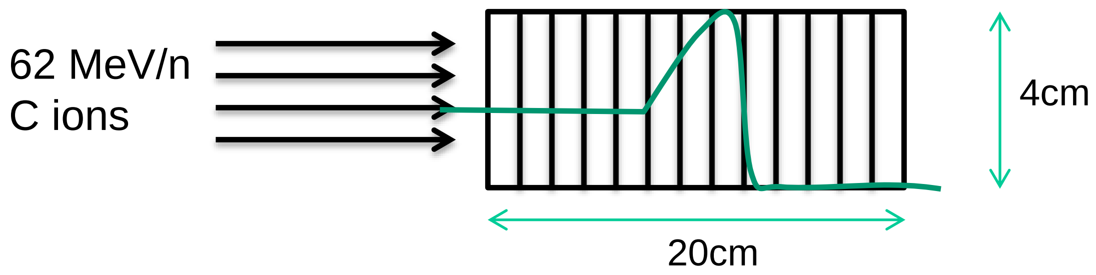
- The dose to tissue comes from the several neutrons and de-excitation gamma rays which are emitted.

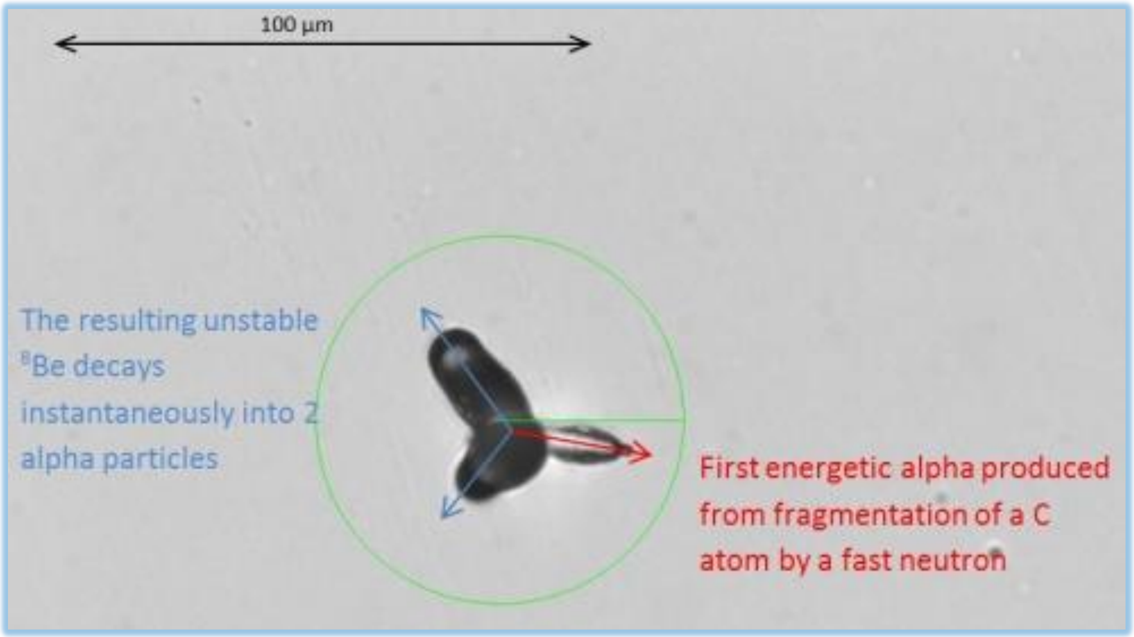
Ref: Principles of Radiation Interaction, 22.101, fall 2006, MIT open courseware

For neutron detection using CR-39 detectors, the nuclear interactions involved are:

- Elastic scattering – recoil nuclei (mainly protons for our application)
- Non-elastic scattering – (n,p) or (n,α) reactions
- Spallation (fragmentation of the C and O atoms in the radiator into secondary hadrons and neutrons, due to highly energetic primary neutrons)

Overview of Neutron Physics





N.B: I've seen this kind of tracks only 2 times in the past 3 years of experiments in different neutron/proton/carbon beams

Neutron dosimetry with CR-39 detectors

Neutron Cross section on C and H

Chemical composition:

PMMA: $(C_5 0_2 H_8)_n$

CR-39: $(C_6 0_8 H)_n$

C compensates for reduction in neutron cross section on H at $E_n > 10$MeV

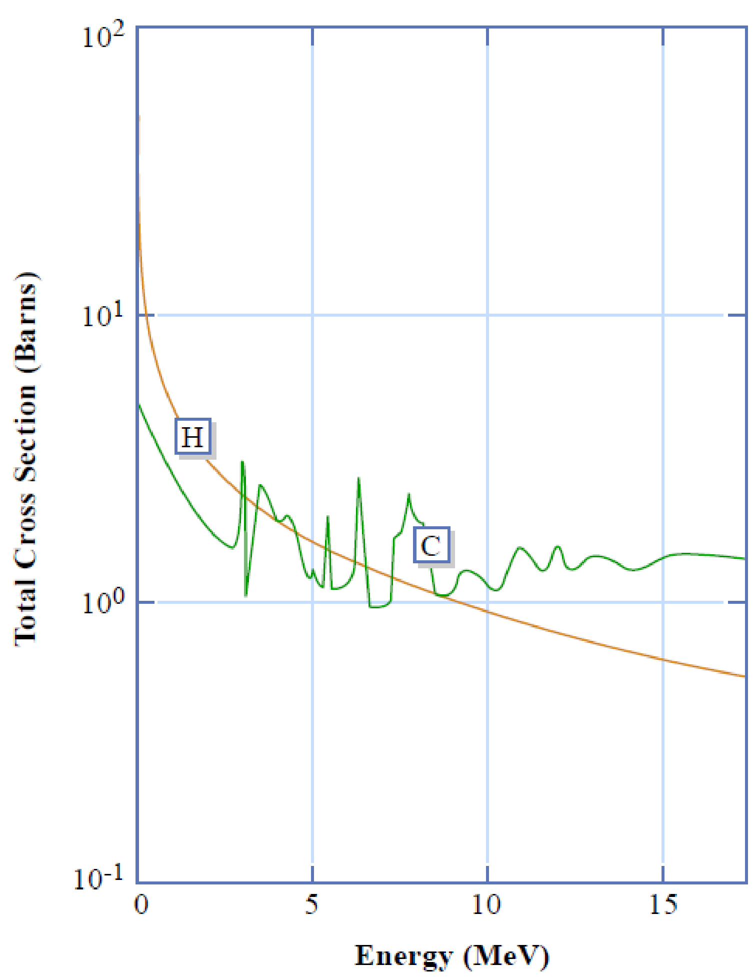


Figure by MIT OCW.

Correlation between LET and Energy

Stopping power (-dE/dx) gives the energy **lost** by a charged particle in a medium.
LET gives the energy **absorbed** in the target.
Secondary δ-electrons can transport a fraction of the energy **out of the target volume**.

- Particularly true with heavy charged particles if the target is small compared with the ranges of the secondary electrons (delta rays).
- On the biological scale, the target dimensions are on the order of microns (cells), nanometers (chromatin), or angstroms (DNA).

Restricted stopping power

$$LET_{\Delta} = -\left(\frac{dE}{dx}\right)_{\Delta}$$

- Energy transfers > Δ = 100eV are considered as imparted to **δ-electrons**.
- The symbol LET_{∞} denotes the **unrestricted stopping power**.
- LET is commonly found in the biological literature with no subscript. It is assumed that the unrestricted stopping power is implied.

Ref: Principles of Radiation Interaction, 22.101, fall 2006, MIT open courseware

Correlation between LET and Energy

Examples:

Radiation	Typical LET values
1.2 MeV ^{60}Co gamma	0.3 keV/μm
250 kVp x rays	2 keV/μm
10 MeV protons	4.7 keV/μm
150 MeV protons	0.5 keV/μm
14 MeV neutrons	12 keV/μm
Heavy charged particles	100-2000 keV/μm
2.5 MeV alpha particles	166 keV/μm
2 GeV Fe ions	1,000 keV/μm

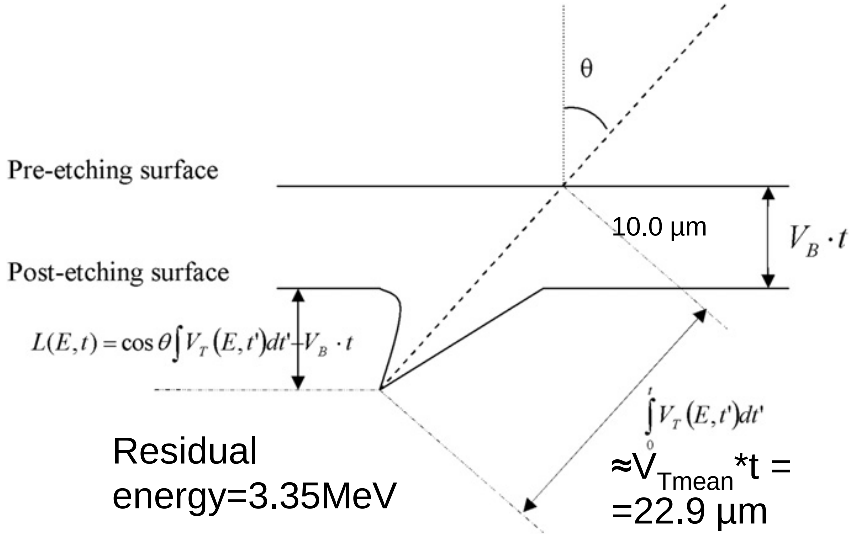
Ref: Principles of Radiation Interaction, 22.101, fall 2006, MIT open courseware

$$\frac{dE}{dx} \approx \rho \left(2\, MeV cm^2 g^{-1} \right) \frac{Z^2}{\beta^2}$$

Ref: S. Tavernier, Experimental Techniques in Nuclear and Particle Physics

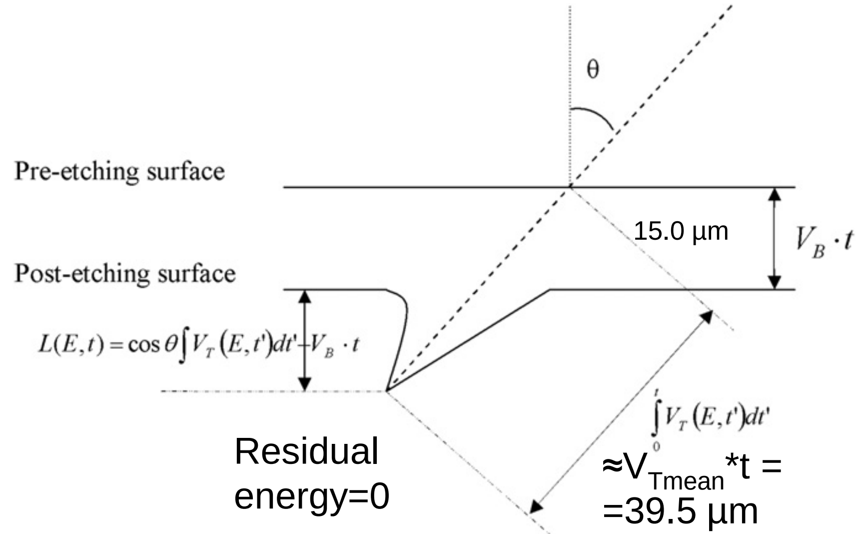
What is LET_{nc} measured in CR-39?

Etching time 60 min
Alpha energy 6.1 MeV (Cf-252)



$$LET_{nc} = \frac{E_i - E_r}{x} = \frac{6100 - 3350}{22.9} = 120\left[{keV}/{\mu m}\right]$$

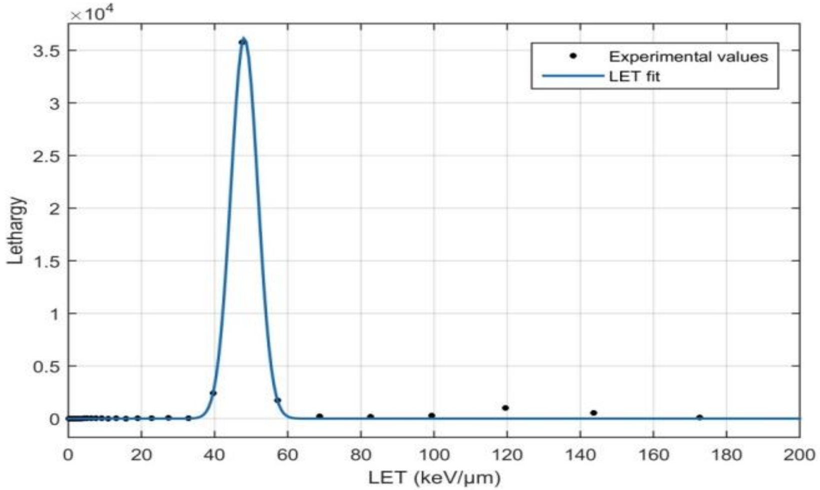
Etching time 90 min
Alpha energy 6.1 MeV (Cf-252)



$$LET_{nc} = \frac{E_i - E_r}{x} = \frac{6100 - 0}{39.5} = 154\left[{keV}/{\mu m}\right]$$

LET_{nc} is the calculated from the V ratio (V_t /Vb) and is an approximation of the lineal energy of the impinging ion

Dose calculations from the LET_{nc} spectra



Example of an LET_{nc} spectrum measured in a carbon beam

The dose equivalent can according to [14] be calculated as the sum of all track energy depositions, weighted by Q,

$$H = \sum_i D_i Q(L_i)$$

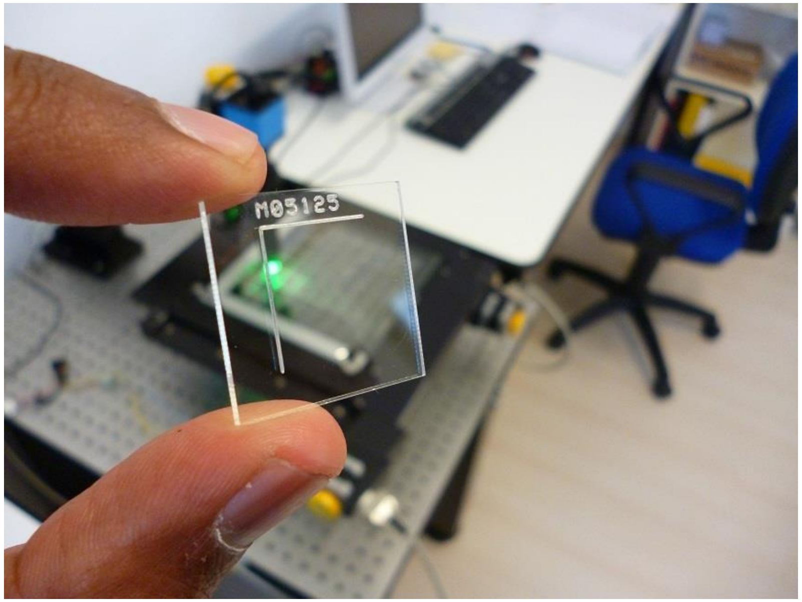
where

$$Q(L) = \begin{cases} 1 & L < 10 \text{ keV}/\mu\text{m} \\ 0.32L - 2.2 & L \in [10, 100] \text{ keV}/\mu\text{m} \\ 300/\sqrt{L} & L > 100 \text{ keV}/\mu\text{m} \end{cases}$$

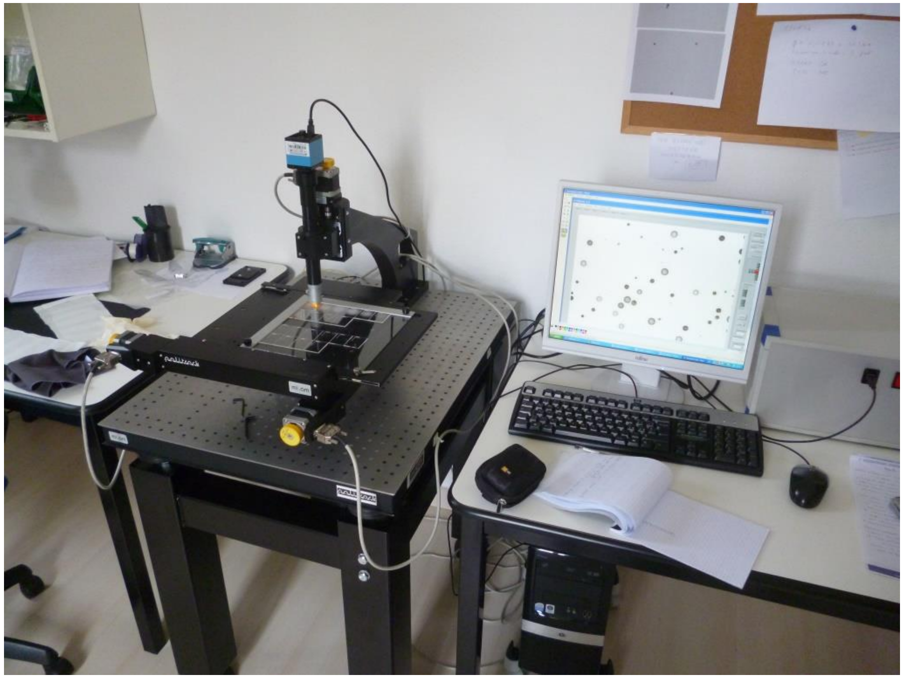
and L is the unrestricted Linear Energy Transfer (LET) in water.

ICRP, 1991

Politrack® instrument

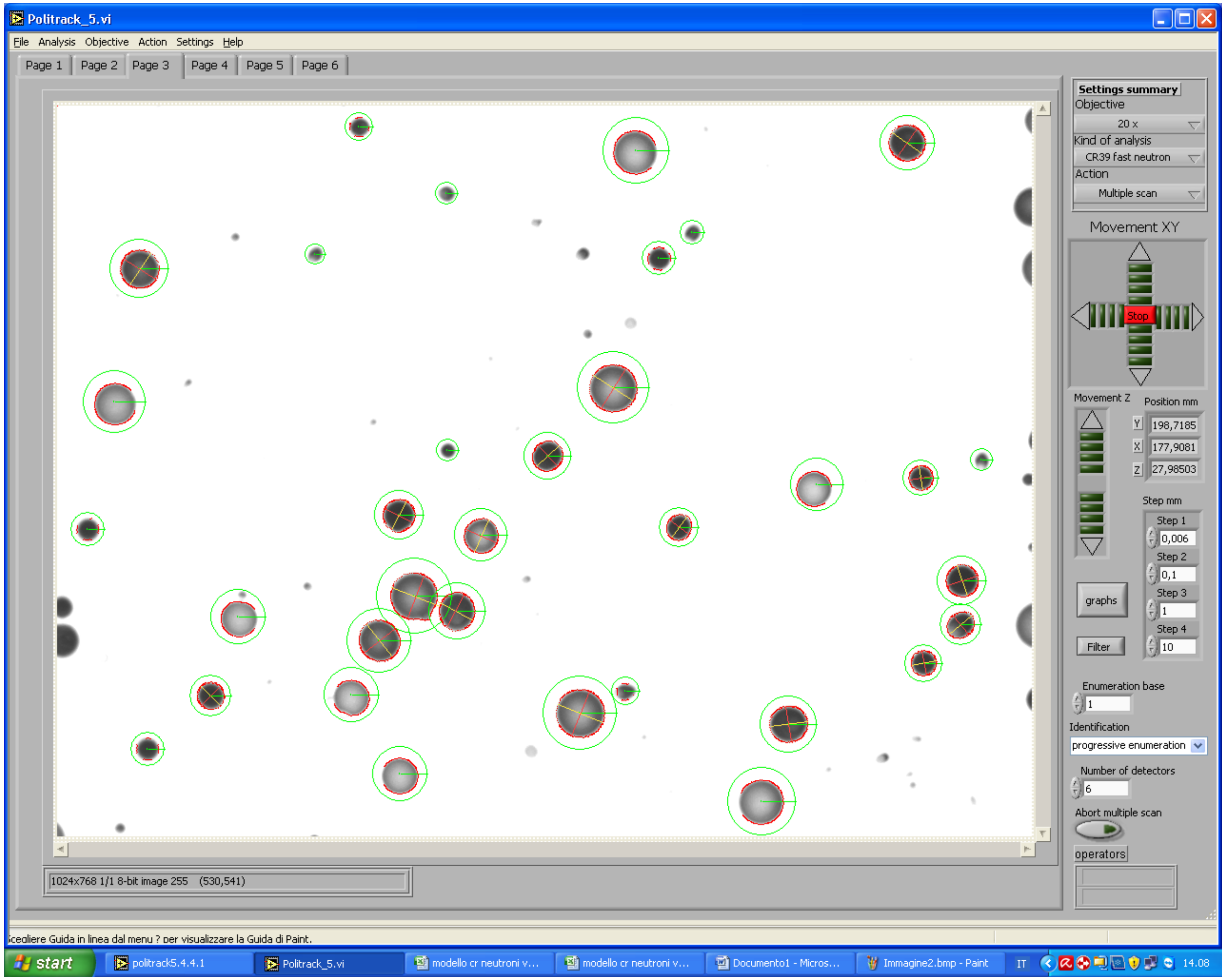


CR-39 ® detector from RTP

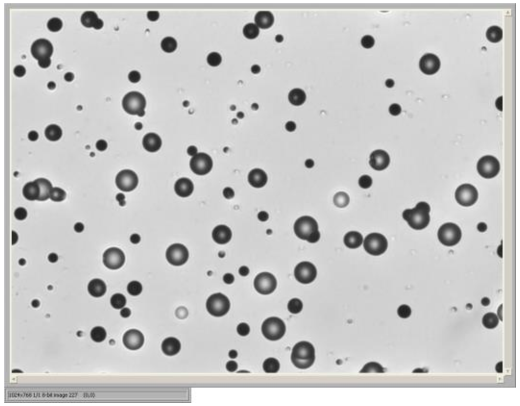


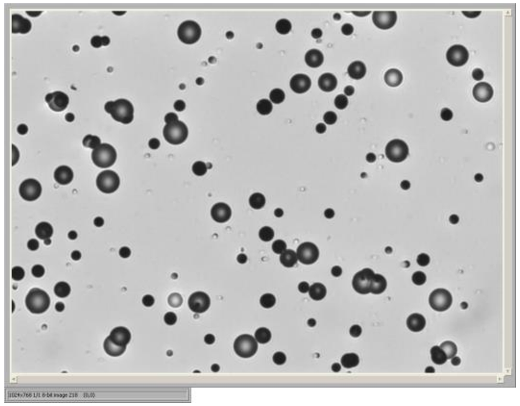
Politrack® instrument

Politrack® instrument

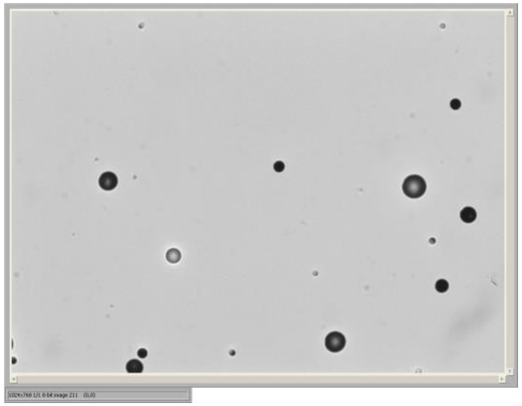


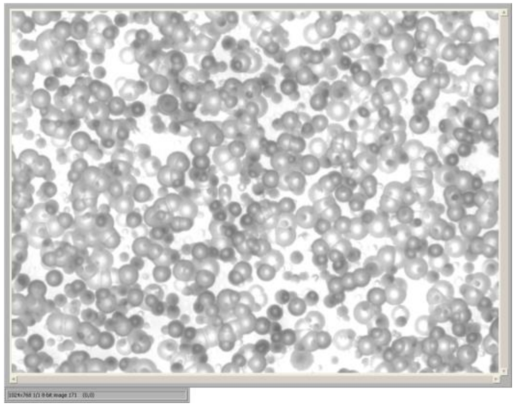
Politrack® instrument





A few examples of frames on a CR-39 detector

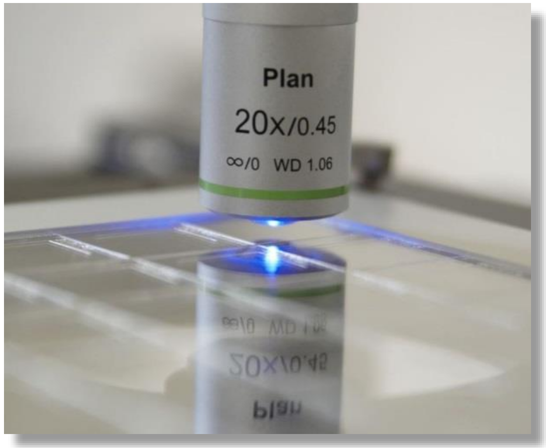




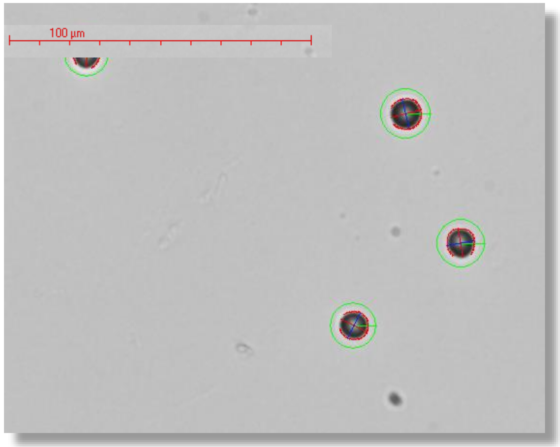
Totally saturated detector

CR-39 detector analysis with Politrack®

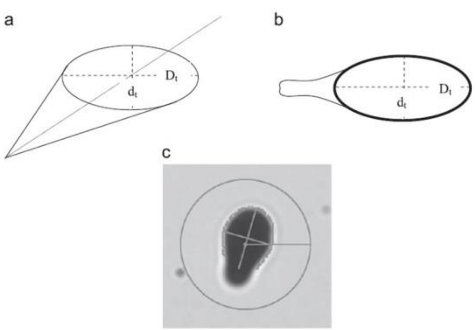
- Automatic counting and geometrical analysis of the tracks by POLITRACK (a)
- Track filtering (account for dust particles or surface defects) (b)
- V_t and LET_{nc} and impinging angle determination (c)
- LET_{nc} distribution (d)



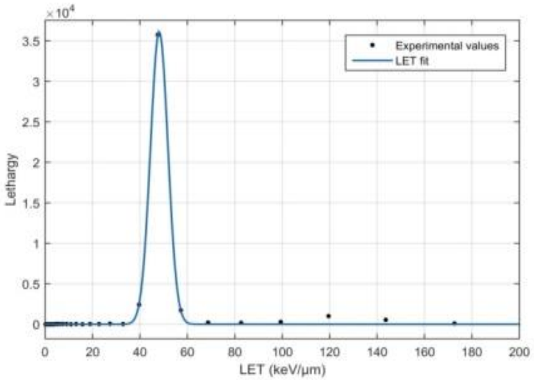
(a)



(b)



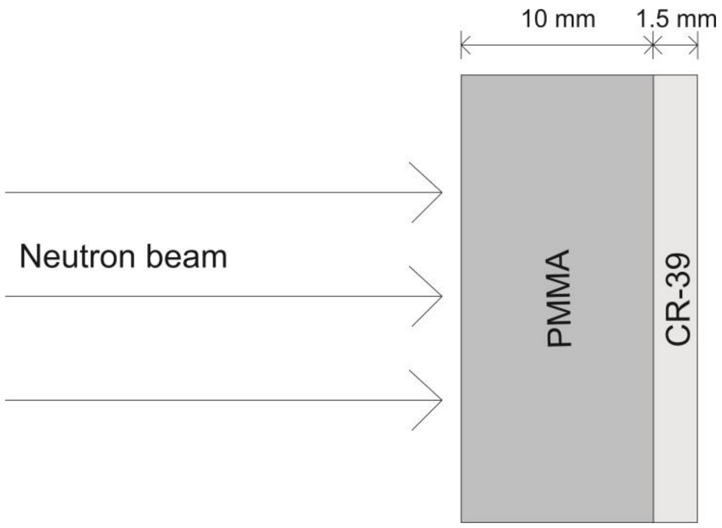
(c)



(d)

- Dose Calculation => $$H = \frac{1}{\rho . A} \cdot 1.602 \cdot 10^{-6} \cdot \sum_{i=1}^{n} \frac{\overline{LET}_i}{\cos \vartheta_i} \cdot Q\left(\overline{LET}_i\right)$$

Neutron dosimetry with CR-39 detectors

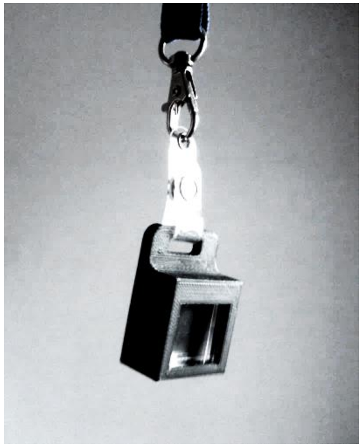


In the PMMA radiator, the type of secondary particles produced is strongly dependent on the neutron beam energy (E_n):

E_n < 10 MeV : (n,p) reactions

E_n > 10 MeV : (n,p) reactions
+ (n,α) reactions
+ (n,d) reactions
+ (n,t) reactions

http://www.oecd-nea.org/janis/

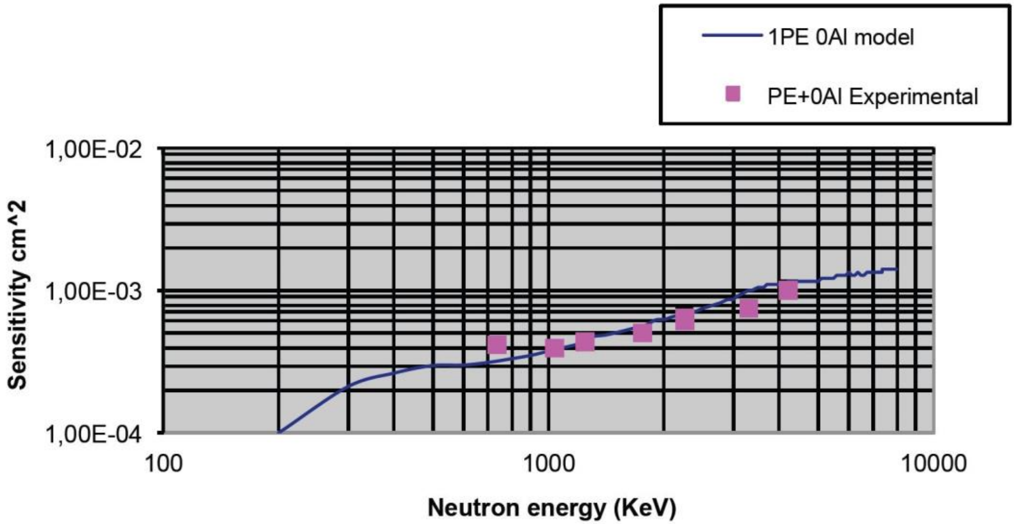


Fragmentation of O and C atoms occur due to inelastic scattering and spallation reactions when E_n > 10 MeV

State of the Art

Most of the present European dosimetry services (IRSN France, LANDAUER Europe, PSI Switzerland, ENEA Bologna in Italy) correlate the neutron dose with the track density.

This results in a detector sensitivity that can vary by a factor 10 according to the neutron energy. Thus a prior knowledge of the energy composition of the neutron field is required.



M. Caresana et al.

Novel approach

- Our approach is based on the capability of CR-39 to evaluate the average Linear Energy Transfer (LET) and the possibility to assess the dose from the average LET. (*M. Caresana et al.*)

- The results is that when using this approach the detector response is more stable on a wide neutron energy range.

Beam	Measured Dose (mSv)	Reference Dose(mSv)	Detector Response
PTB 565 KeV	1.79	3.67	0.49
PTB 8 MeV	1.75	4.90	0.36
PTB 14 MeV	3.49	6.90	0.51
PTB 19 MeV	1.84	2.90	0.64
iThemba 66 MeV 0°	2.38	4.44	0.54
iThemba 66 MeV 16°	1.72	3.20	0.54
iThemba 100 MeV 0°	1.52	2.36	0.64
iThemba 100 MeV 16°	1.75	2.83	0.62
Average Sensitivity			0.54 ± 0.09

- No or little prior knowledge of the neutron field is needed with this technique. The neutron field can thus be investigated directly with the average LET measurements done using the CR-39 detectors, acting as a low-resolution spectrometer.

Dose measurement in a simulated workplace field at CERF facility at CERN

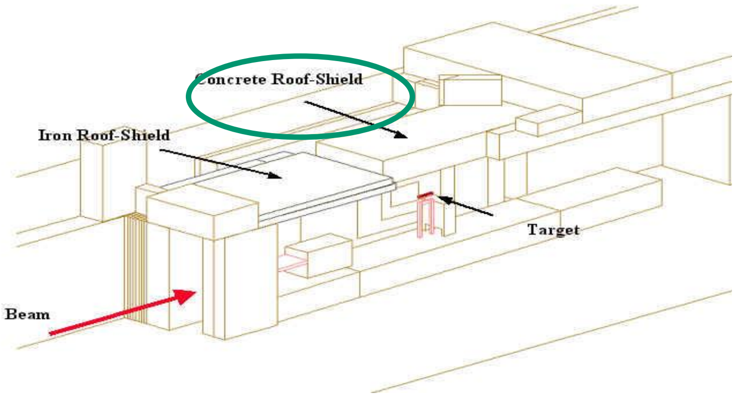


Fig 1a. *CERF irradiation facility*

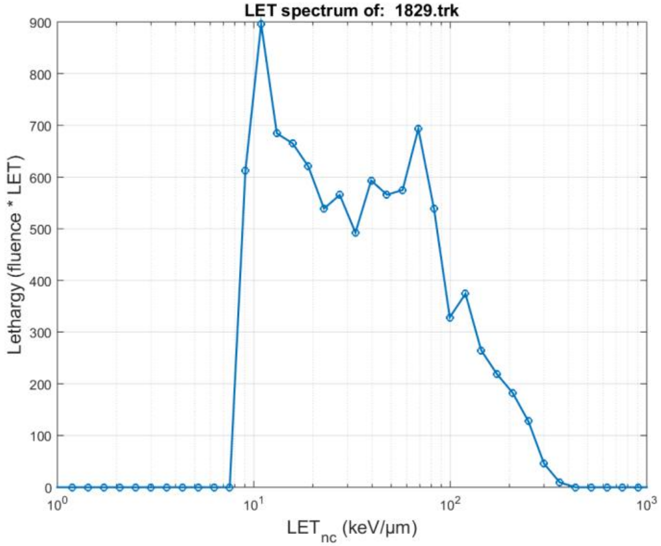


Fig 2a. *LET* distribution measured for the position CT 5

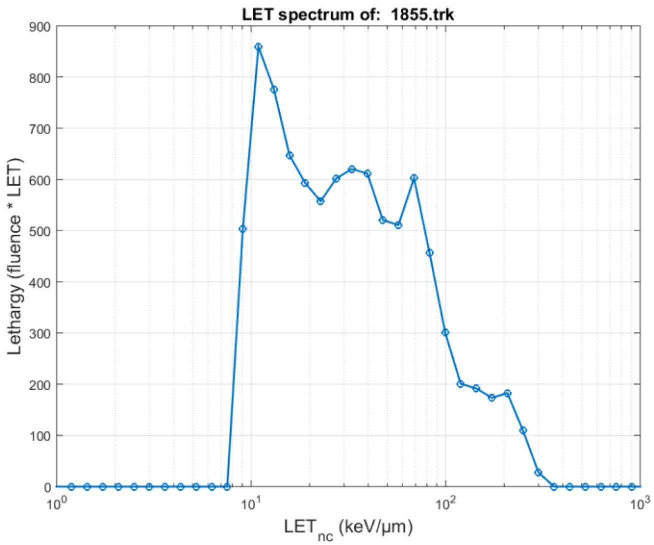
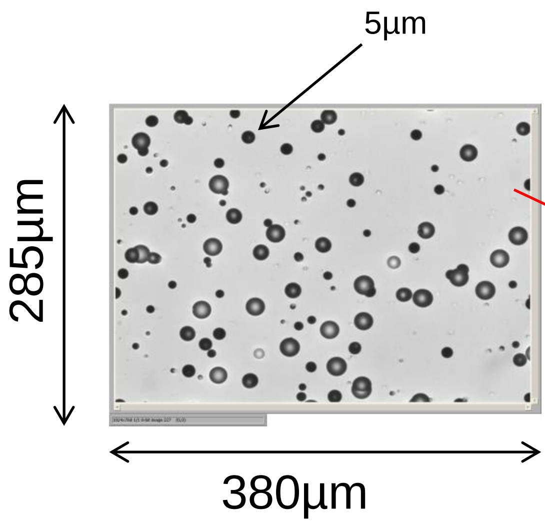


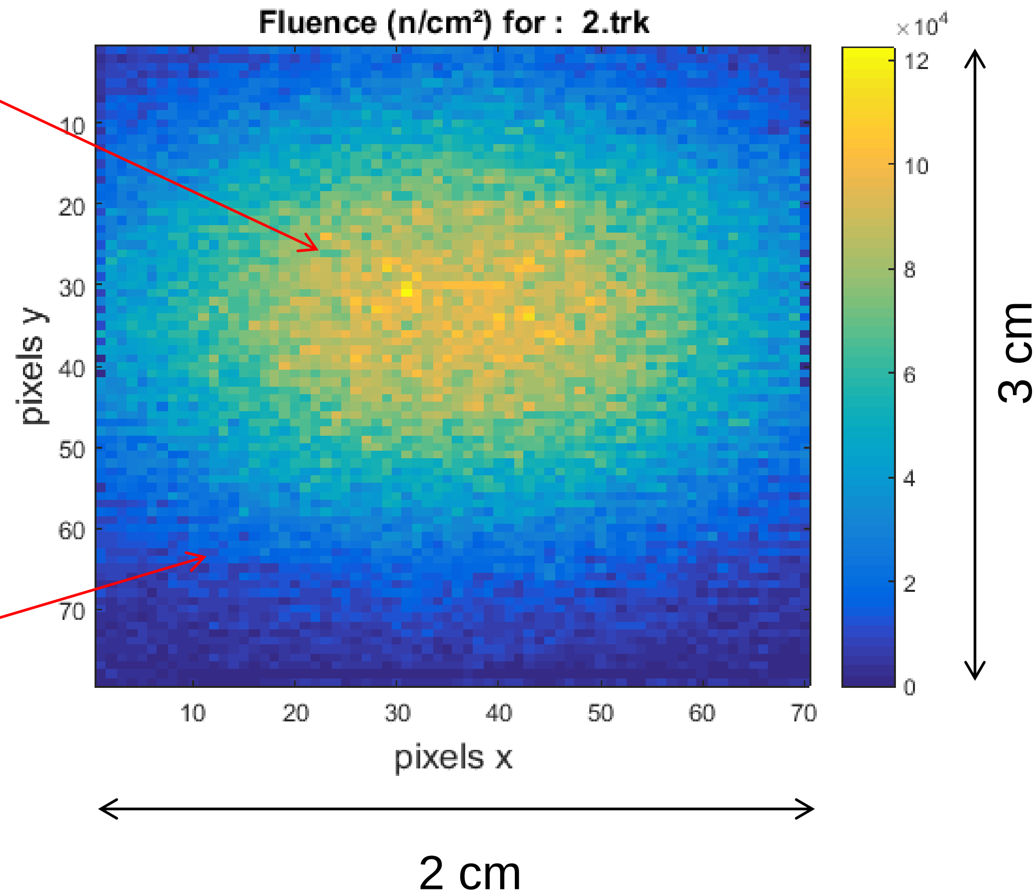
Fig 2b. *LET* distribution measured for the position CT12

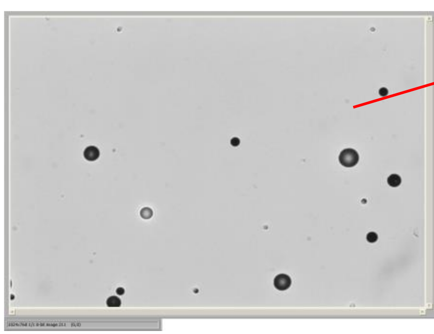
Position	Reference Dose (mSv)	Measured Dose in CR-39 (mSv)
CT-5	5.17	3.8 ± 1.4
CT-12	4.85	4.1 ± 0.5

Testing the spectrometric capabilities of the Politrack®



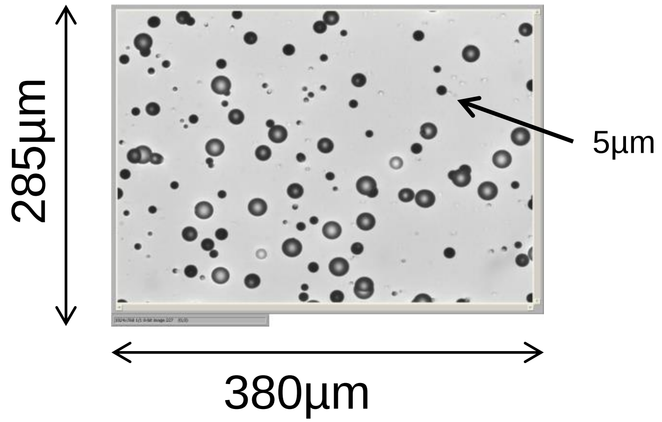
CR-39 surface reconstruction from track parameters

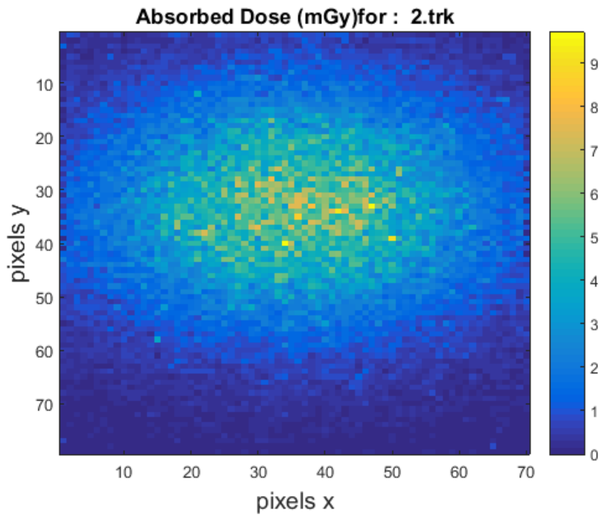




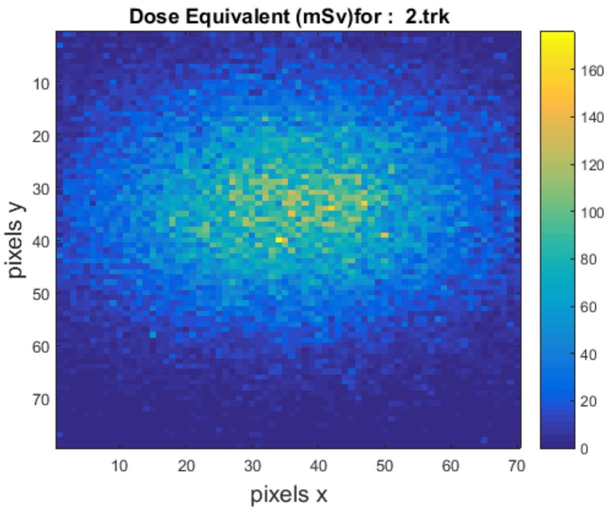
Testing the spectrometric capabilities of the Politrack®

- Spatial resolution: 0.37 µm
- Pixel/Frame size : 285 µm * 380 µm
- Sensitive area : 70 * 79 pixels/frames (2 * 3 cm)





2D distribution of the Absorbed dose (mGy)



2D distribution of the Dose Equivalent (mSv)

Applications for neutron spectrometry using CR-39 track detectors

$$D + T \rightarrow n\,(14.1\ \text{MeV}) + \alpha\,(3.5\ \text{MeV}).$$

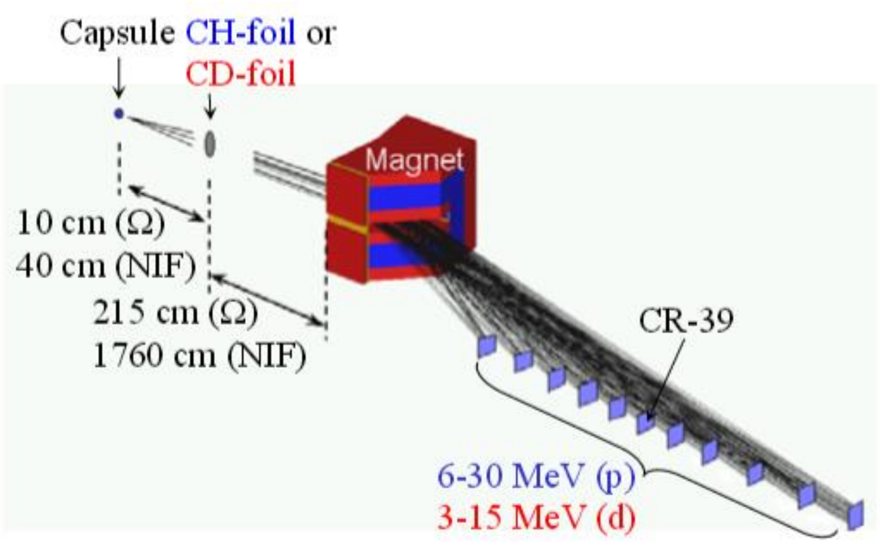
Primary reactions

$$n + D \rightarrow n'\,(1.6\text{-}14.1\ \text{MeV}) + D'\,(<12.5\ \text{MeV})$$
$$n + T \rightarrow n'\,(3.5\text{-}14.1\ \text{MeV}) + T'\,(<10.6\ \text{MeV}).$$

Secondary reactions

$$D' + T \rightarrow \alpha\,(0.1\text{-}18.1\ \text{MeV}) + n''\,(12.0\text{-}30.1\ \text{MeV})$$
$$T' + D \rightarrow \alpha\,(<19.0\ \text{MeV}) + n''\,(9.2 - 28.2\ \text{MeV}).$$

Tertiary reactions



Magnetic Recoil Spectrometer at OMEGA laser facility, Laboratory for Laser Energetics, Rochester, NY

Ref: Frenje JA. et al., *First measurements of the absolute neutron spectrum using the magnetic recoil spectrometer at OMEGA*. Rev Sci Instrum. 2008 Oct;79(10):10E502. doi: 10.1063/1.2956837.

Conclusion

- CR-39 is acts as a low resolution spectrometer and a dosimeter at the same time
- A relatively low cost
- It is insensitive to stray radiation such as intense gamma rays pulses which are parasites to all active detection instruments
- It's limits however are it's insensitivity to hadrons having a low-LET or high angle of incidence on the detector; thus reducing the response of the detector