Agenzia nazionale per le nuove tecnologie,
l’energia e lo sviluppo economico sostenibile

Upgrade of the accelerator-driven Frascati Neutron Generator: α/n correlation measurements for the installation of a trigger system

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Phd in Accelerator Physics

Introduction

I have performed the research activity of my PhD at the Frascati Neutron Generator (FNG) at the Enea in Frascati.

FNG is a machine that produces fusion neutrons inducing D-T, principally, or D-D fusion reaction accelerating deuterium ions.

Now the machine only works continuously allowing to perform only measurements of efficiency for particles detectors. So, it is not possible to execute measurements event per event or to study the time response of a detector. There is no reference time and so it is impossible to tag the particle beam. To do this it is necessary to have a pulsated source.

There are two ways to achieve this:

1. Create a pulsated source but this requires a total rebuilt of the machine;
2. Having a clear knowledge of where the neutron will be when the alpha particle will be detected and so a tagging between neutrons and alpha particles will be mandatory.

The main goal of my PhD was to verify the feasibility of this kind of trigger system. To do this it is necessary to verify if the neutrons and the alpha particles maintain their spatial correlation between them and so if they are still tagged between one another when the α particle is detected. To study this a series of Monte Carlo simulations have been executed. The code chosen for them was FLUKA-INFN. So, I had to reproduce correctly the FNG fusion spectrum.

My PhD work mainly focused on the reproduction of the FNG spectrum on FLUKA and in the measurements of the α/n spatial correlation to study the tagging of the two particles.

The Frascati Neutron Generator (FNG)

FNG is a machine that starts its activity in 1992 to make measurement with fusion neutrons.

Deuterium nuclei are accelerated up to an energy of 260 keV.

The collision with a titanium-tritium target triggers the fusion reactions with neutrons production.

It is possible to have also DD reactions.

The neutrons are produced at FNG with the following reactions:

$$\boxed{D + T \longrightarrow He^4\ (3.5\ MeV) + n\ (14.1\ MeV)} \longrightarrow$$

For the tagging I will focus mainly on this reaction

$$D + D \longrightarrow He^3\ (0.82\ MeV) + n\ (3.2\ MeV)$$

For the DT reaction is obtained a yield of $\Phi_n \sim 10^{11}$ n/s and for the DD one of $\Phi_n \sim 10^9$ n/s with a current of 1 mA.

The FLUKA Software

FLUKA is a Monte Carlo code written in the ’80s in collaboration with CERN and INFN of Milan. It can simulate a wide range of particles in an energy range going from 10^{-5} eV to 20 PeV.

However, FLUKA misses the deuterium-tritium and deuterium-deuterium fusion cross sections. So, to reproduce the FNG fusion spectrum it is necessary to use an external source that estimates it.

A source that calculated the neutrons fusion spectrum already exists but for another Monte Carlo code, MCNP, and was written in a different language. However, this source only estimated the neutron spectrum and no the alpha and helium-3 one.

First, I wrote a source for the fusion neutrons generation in the language of FLUKA.

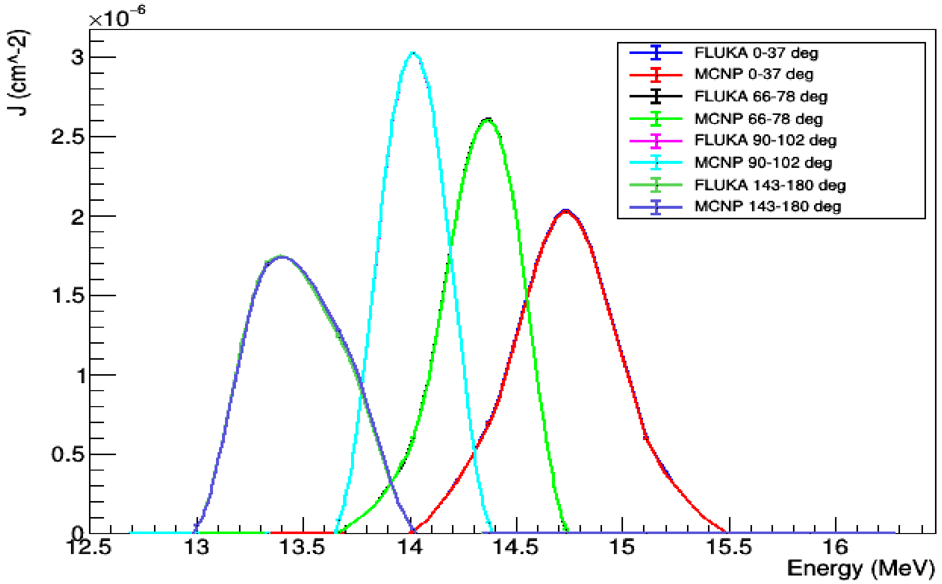
Second, I validate the FLUKA source comparing with the MCNP one for the neutrons, because this was already experimentally validated at FNG.

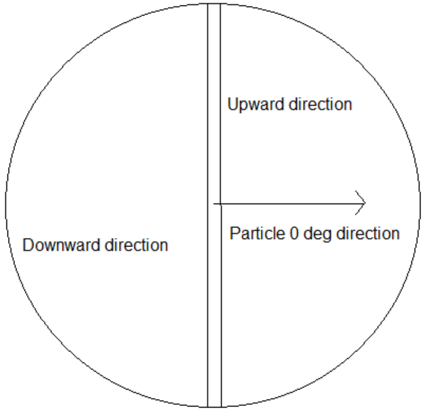
Third, I add the possibility to produce alpha and helium-3 particles.

Fourth, I gave the chance to have the transport of both fusion products at the same time in a single history.

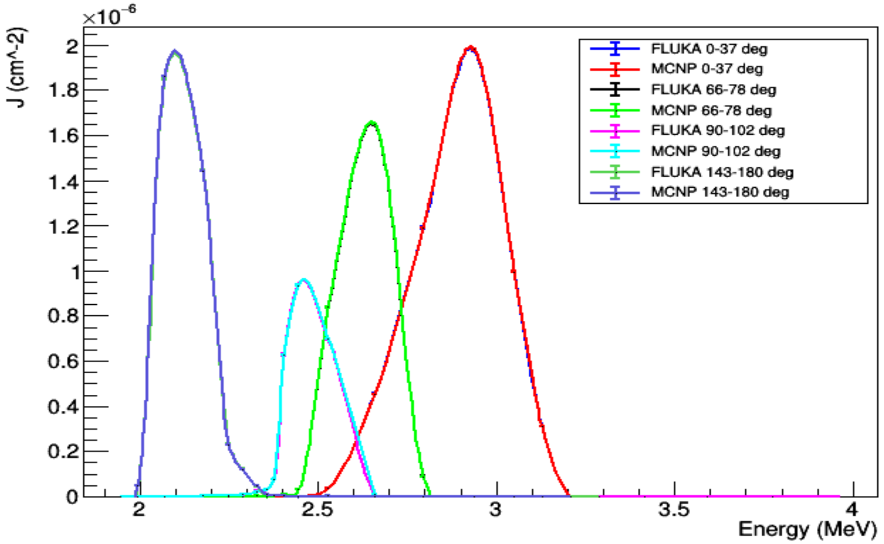
Comparison between FLUKA and MCNP, Hemisphere

Hemisphere simulations D-T reaction:



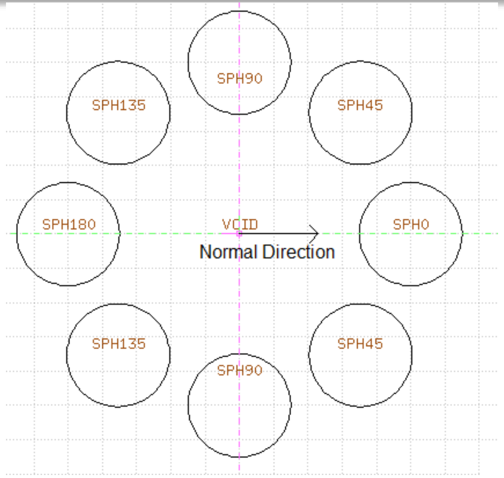


Hemisphere simulations D-D reaction:

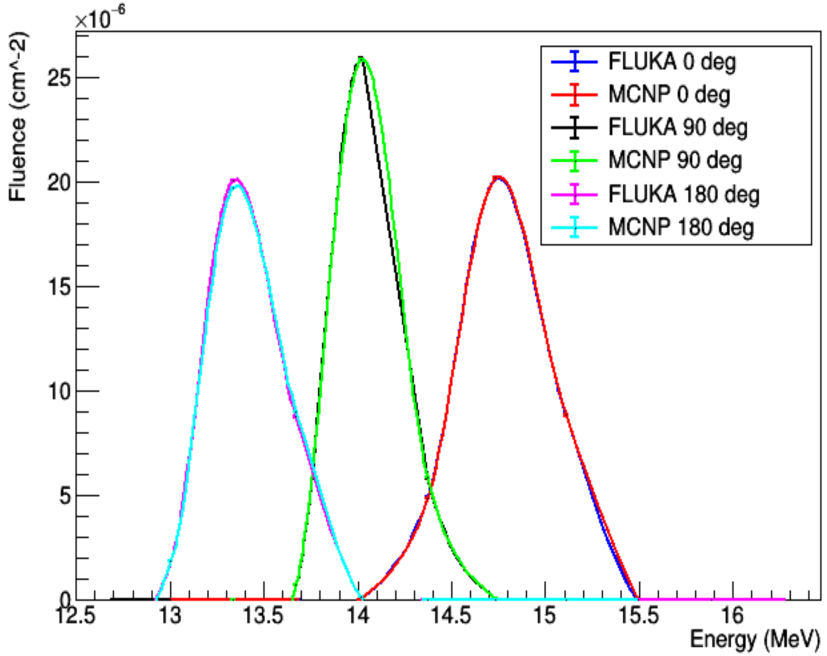


Comparison between FLUKA and MCNP, Sphere DT

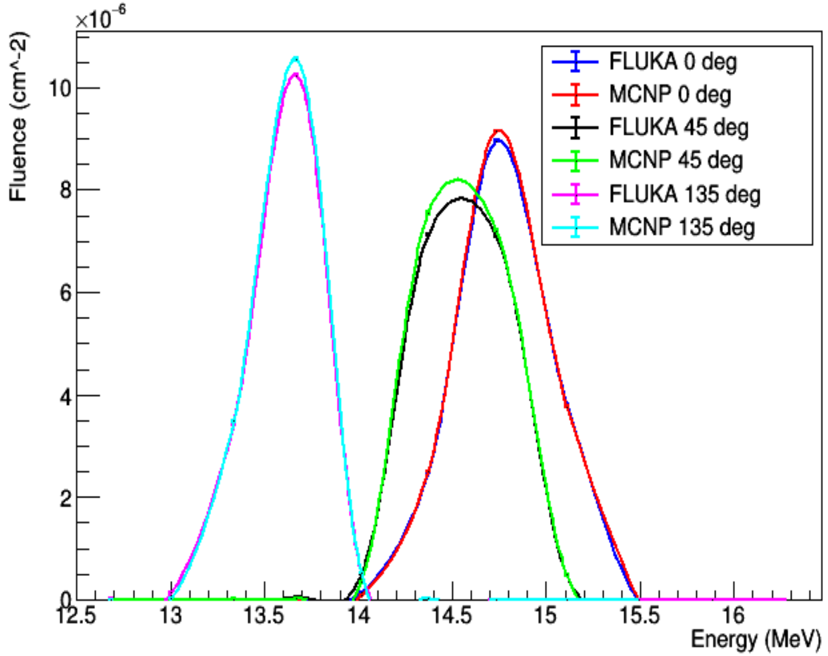
Sphere simulations, D-T reaction:



Vacuum

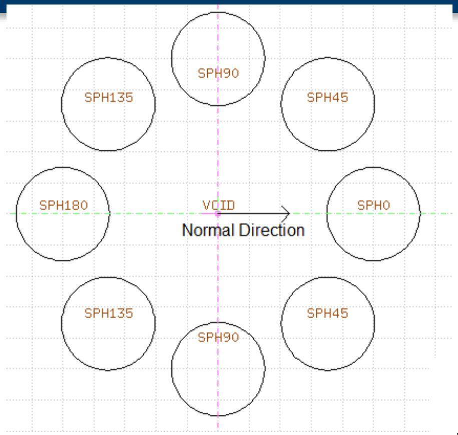


Lead

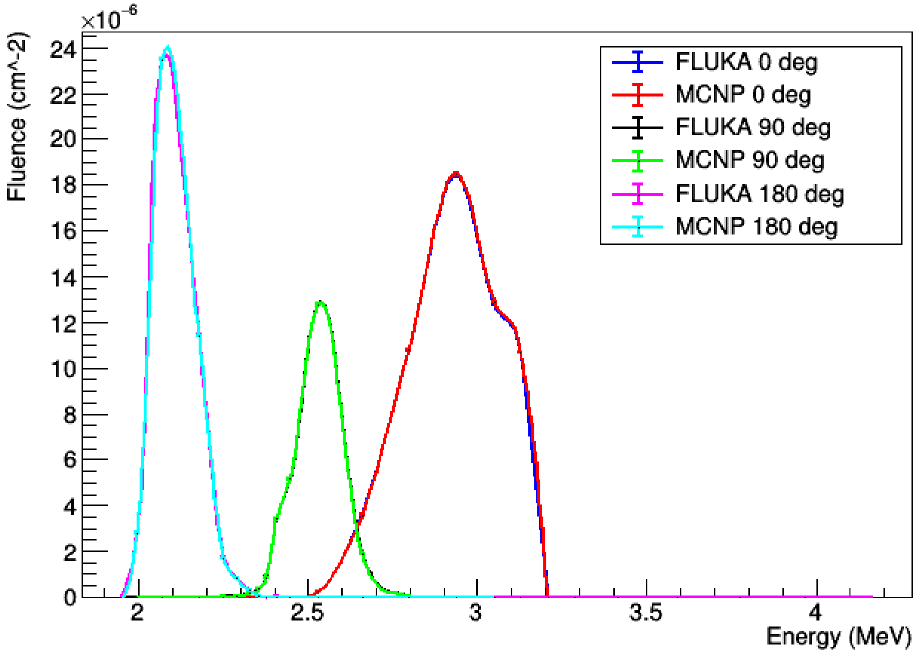


Comparison between FLUKA and MCNP, Sphere DD

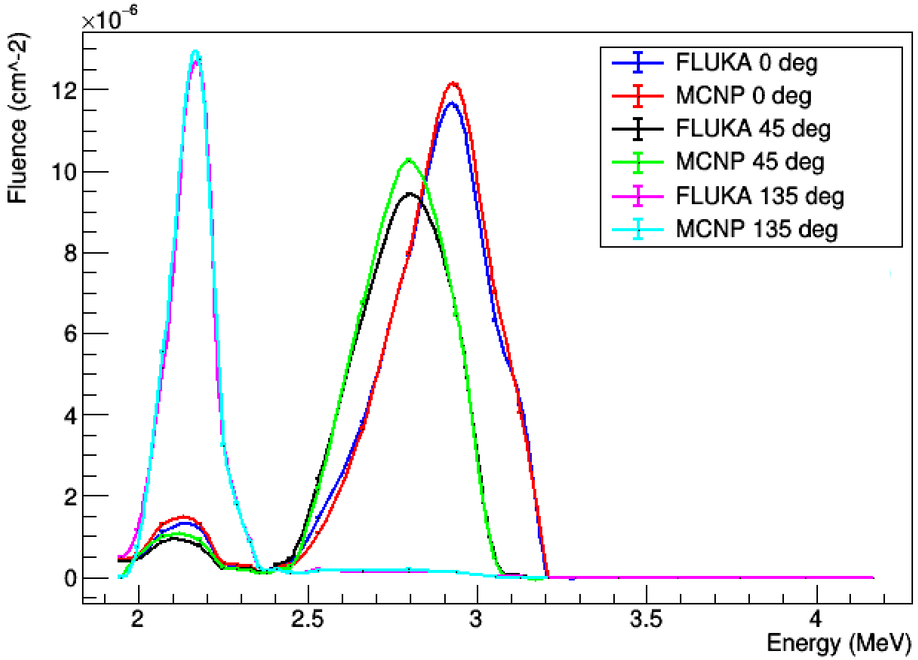
Sphere simulations D-D reaction:



Vacuum



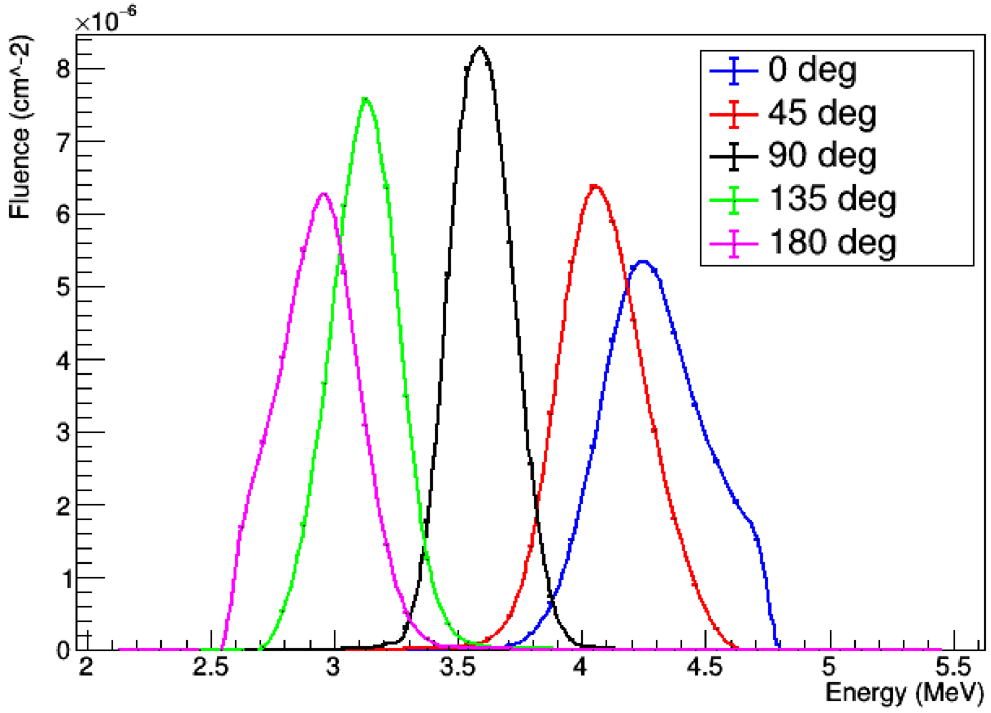
Lead



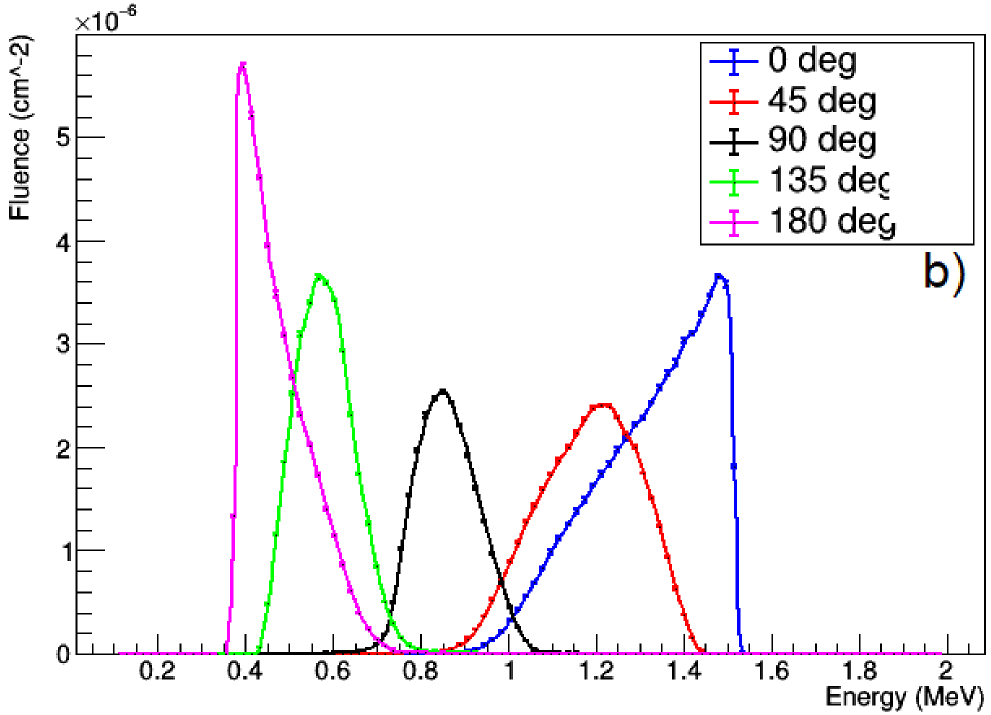
The Emission of Alpha/Helium-3 Particles

Spectra calculated with FLUKA.

Alpha particles spectrum, DT reaction



Helium-3 particles spectrum, DD reaction



The First Version of the Source

The first version of the FNG Source produces the fusion neutron spectrum for both DT and DD reactions as the MCNP one.

Moreover the FLUKA source is able to reproduce the alpha/helium-3 particle spectrum. Also, it can gave to the main program both fusion products allowing FLUKA to simulate both particles at the same time.

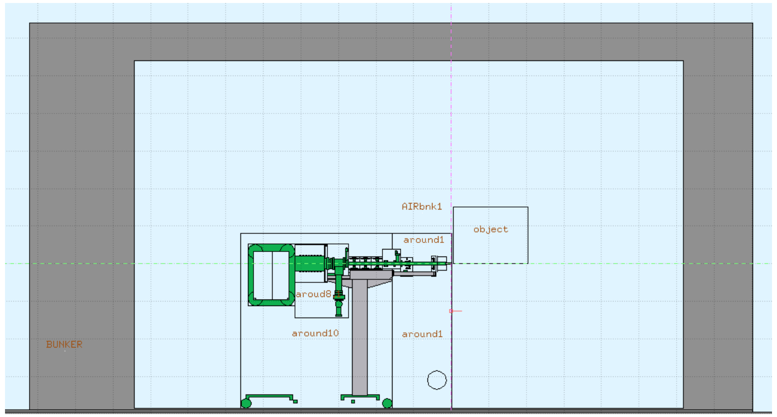
Now the starting point of the source is fixed and so the depth of target crossed by the particles is chosen arbitrary by the user. This version of the source is called *All_Sim* source.

WHASOU(1)=deuteron beam energy
WHASOU(2)=Tritium/Titanium or Deterium/Titanium atomic ratio
WHASOU(3)= x coordinate
WHASOU(4)= y coordinate
WHASOU(5)= z coordinate
WHASOU(6)=deuteron beam width
WHASOU(7)=flag, 1 for D-T reaction, 2 for D-D solid reaction
WHASOU(8)=starting cell
WHASOU(9)=flag, 0 for neutron, 1 for positive eions (alpha or helium-3)
WHASOU(10)=flag, 0 for single particle simulation, 1 for dual one. If DT neutron and alpha and if DD neutron and helium-3

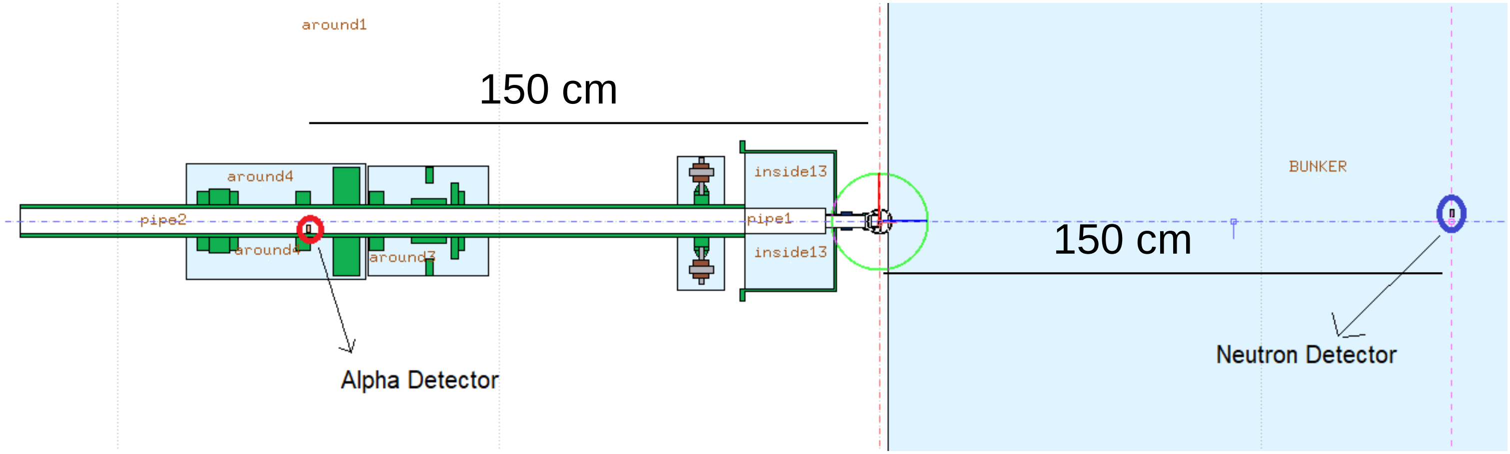
SOURCE		#1: 0.26	#2: 1.4	#3: 0
	sdum:	#4: 0.001	#5: 0	#6: 0.5
		#7: 1	#8: 1	#9: 0
		#10: 1	#11:	#12:
		#13:	#14:	#15:
		#16:	#17:	#18:

FNG modeling

The geometry of the FNG machine and bunker was represented in FLUKA.



From that I extracted the part of geometry that I need and then I added the detectors for the alpha particles and the neutrons. The one for the alpha particles is an approximation of the real one installed at FNG.



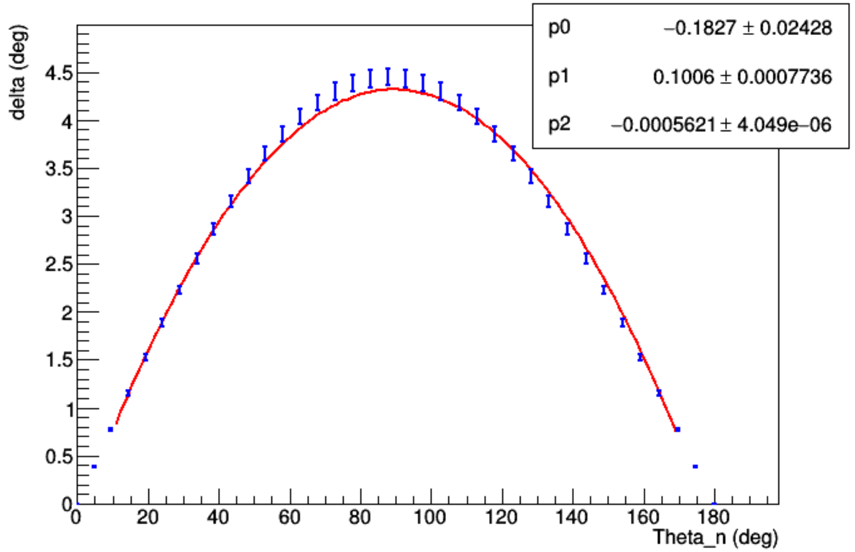
Spatial Correlation Study

There are various factors that could destroy the α/n spatial correlation.

If the D-T reaction happens in a rest frame the two particles would be emitted back-to-back. Since the deuteron has a no zero kinetic energy it will be a little discrepancy between them.

Other elements that could decrease the spatial correlation could be:

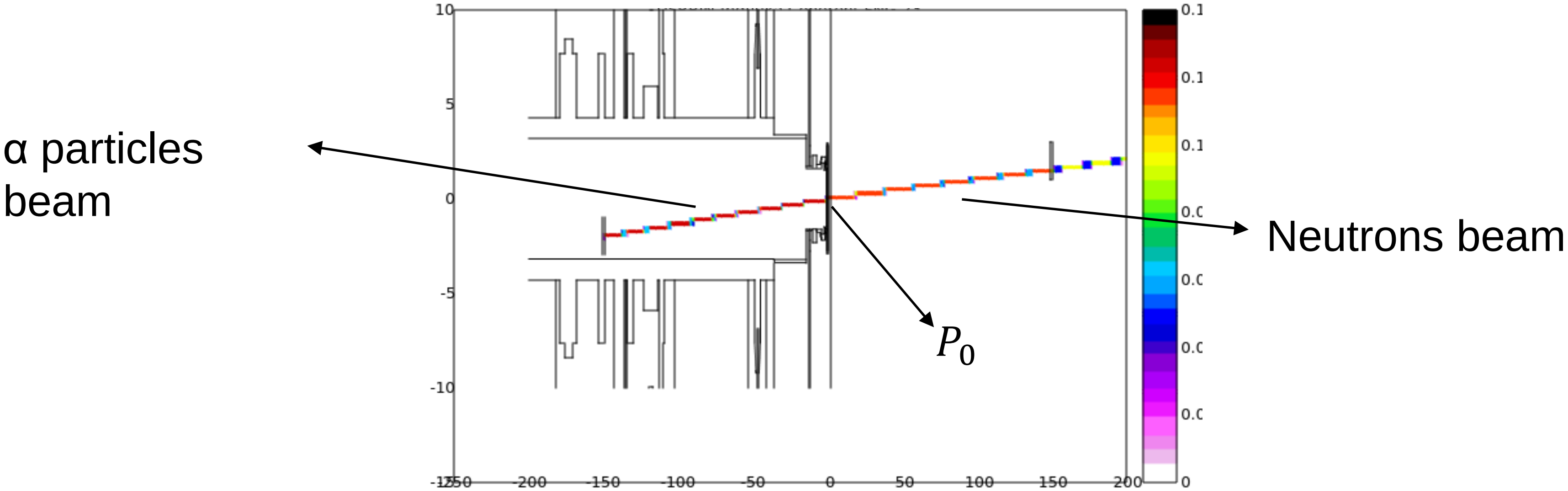
- The structure of the machine deviating the neutrons;
- The target deviating the alpha particle;
- Scattering of the alpha on the beam pipe internal walls;
- Scattering of the neutrons with air.



$$\delta \cong -5.62 \cdot 10^{-4} * \theta_n^2 + 0.1006 * \theta_n + 0.18$$

Results with the Collimated Source (I)

To study the deflection due to the machine structure and the target, I wrote a focalized source. In vacuum the efficiency of the detectors and the spatial correlation is 100%. Surrounding the FNG geometry with vacuum any decrease would come from this factor.

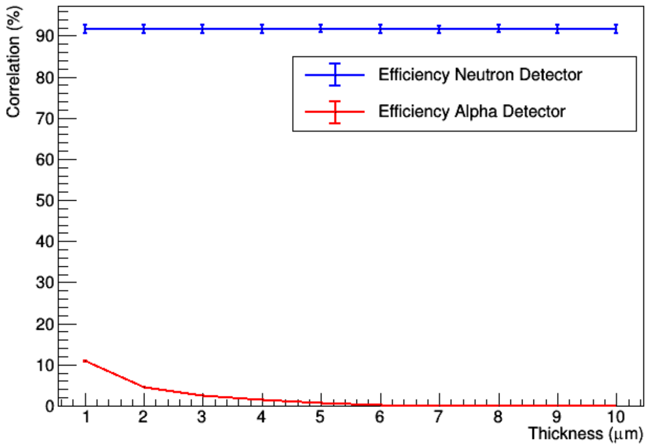


With 0 μm of target crossed the results are the following:

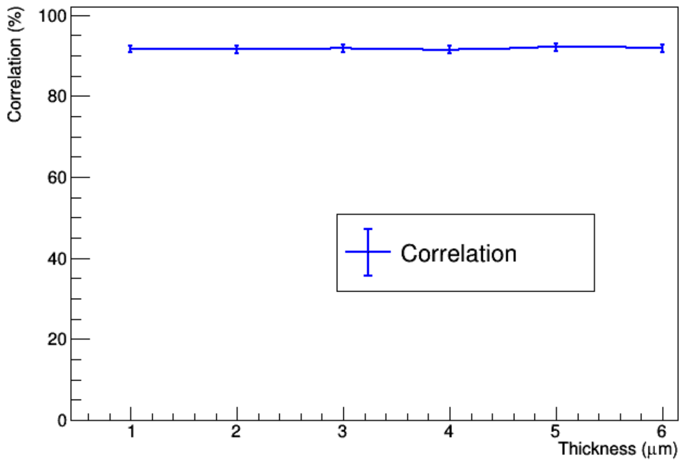
$$Eff_{Alp} = 100\ \% \qquad Eff_{Neu} \cong 91.63\ \% \qquad Corr \cong 91.63\ \%$$

Results with the Collimated Source II

The efficiency of the neutron detector is not affected by the thickness of target crossed. The alphas' one, on the contrary, drops to zero over 6 μm.



The coherence between the two particles remains constant independently to the efficiency of the alpha detector.

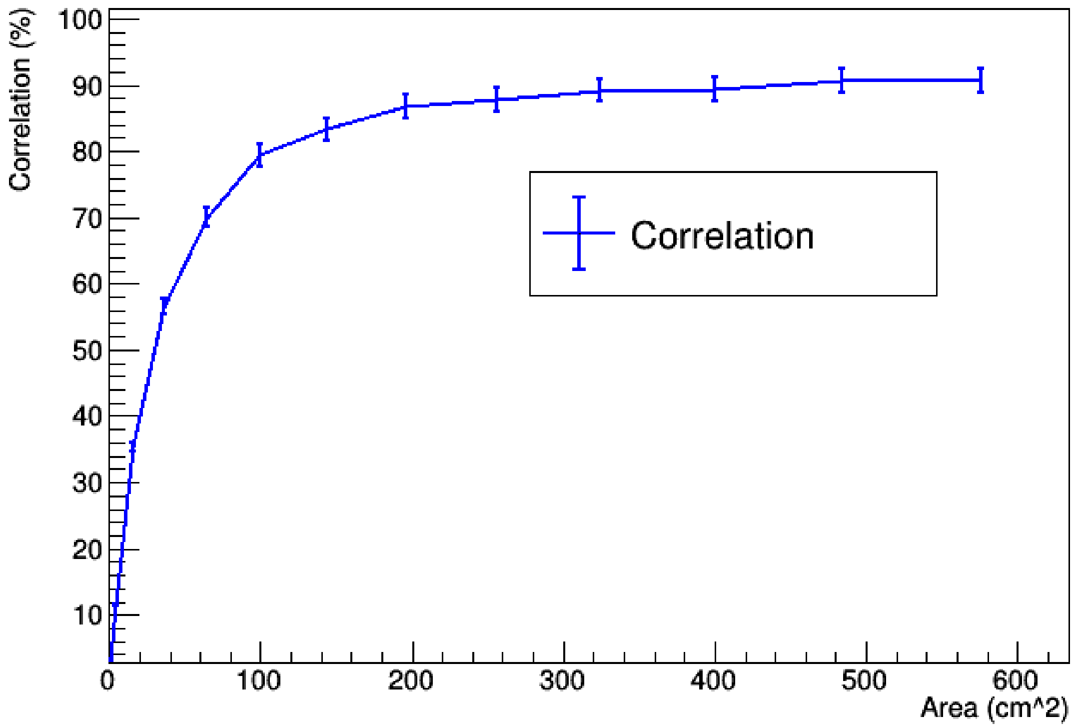


Spatial Correlation Shift

Using the actual FNG source the first results give a correlation of $Corr \cong 3.23\ \%$. So, it seems that the neutrons are scattered away from the detector.

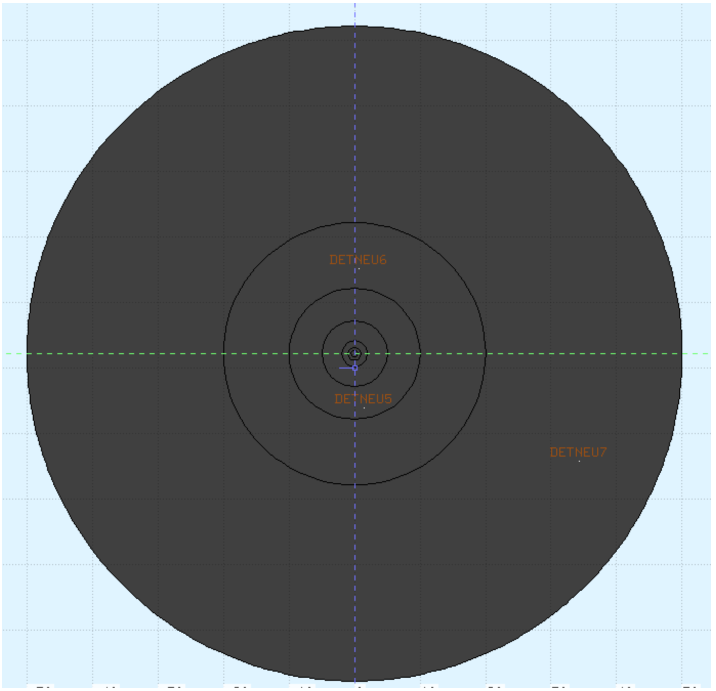
To see how much this happens, I run a series of simulations increasing its size.

I created a specific user scoring routine to measure the α/n spatial correlation.



The Neutron Detection Region

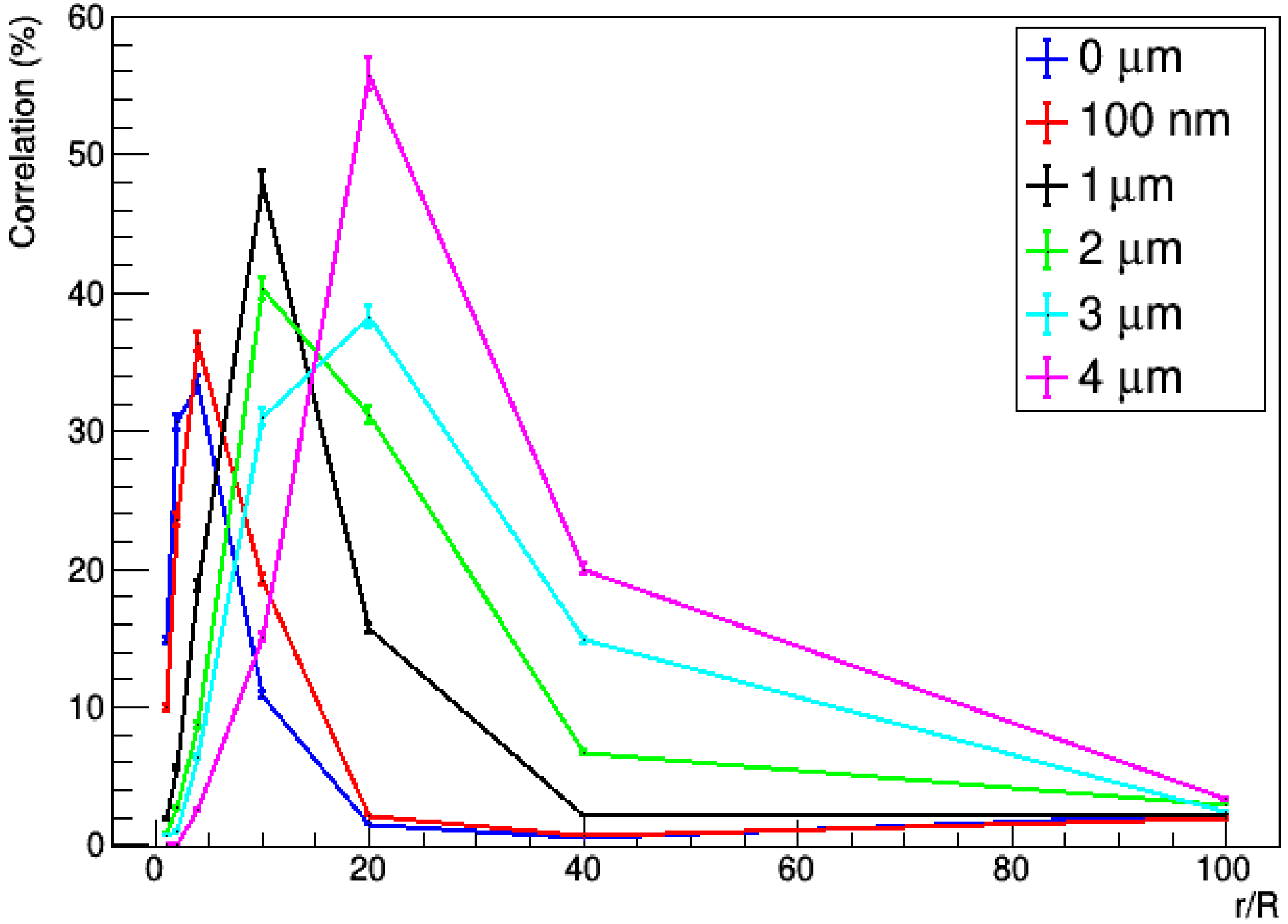
To detect how far from the central region the neutrons are deflected, I put a series of concentric regions around the central one. The radius of the central region is $R_{core} = 0.5$ cm. I will plot the spatial correlation data as a function of the r_{ext}/R_{core} ratio. For example, when I will show that a certain spatial correlation corresponds to a value of r_{ext}/R_{core} =10, I will mean that I am counting all the neutrons detected in the region between $r_{int} = 2$ cm and $r_{ext} = 5$ cm.



r_{int} (cm)	r_{ext} (cm)	r_{ext}/R_{core}
0	0.5 (=R_{core})	1
0.5	1	2
1	2	4
2	5	10
5	10	20
10	20	40
20	50	100

The α/n Spatial Correlation for Various Range

Energy threshold 2.3 ÷ 3.2 MeV



The Second Version of the Source

During the α/n spatial correlation measurements, I decided to rework the source.

Now the transport in the target of the deuteron is recorded and the thickness of target crossed by the particles is no more arbitrary chosen by the user. The starting point of the particle now is where the fusion reaction happens.

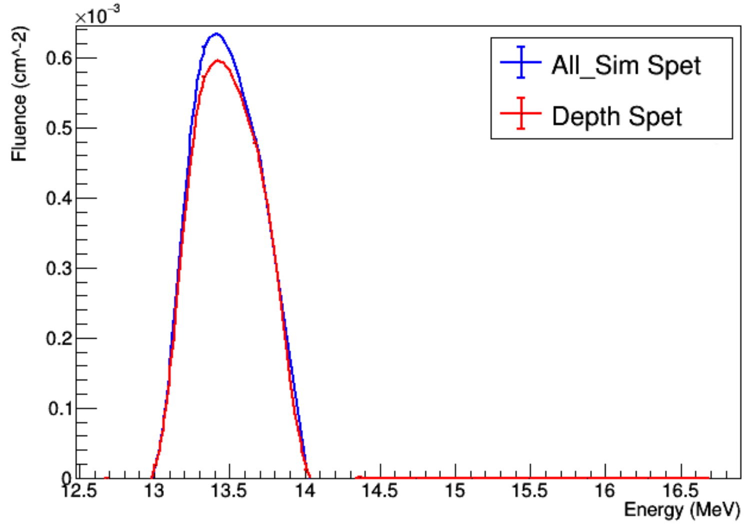
The second version of the source is called *Depth* source.

WHASOU(1)=deuteron beam energy
WHASOU(2)=Tritium/Titanium or Deterium/Titanium atomic ratio
WHASOU(3)=target thickness (um)
WHASOU(4)=targer radius (cm)
WHASOU(5)= x coordinate (cm)
WHASOU(6)= y coordinate (cm)
WHASOU(7)= z coordinate (cm)
WHASOU(8)=deuteron beam radius (cm)
WHASOU(9)=flag, 1 for D-T reaction, 2 for D-D reaction
WHASOU(10)=flag, 0 for neutron, 1 for positive ions (alpha or helium-3)
WHASOU(11)=flag, 0 for single particle simulation, 1 for dual one. If DT neutron and alpha and if DD neutron and helium-3

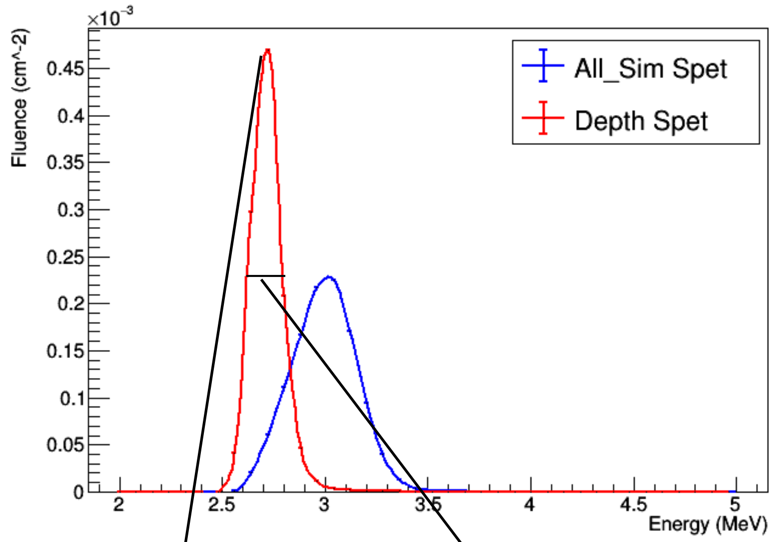
SOURCE	#1: 0.26	#2: 1.4	#3: 10
sdum:	#4: 1.5	#5: 0	#6: 500
	#7: 0	#8: 0.5	#9: 1
	#10: 0	#11: 1	#12:
	#13:	#14:	#15:
	#16:	#17:	#18:

Alpha Particles and Neutron Spectra with the Depth Source

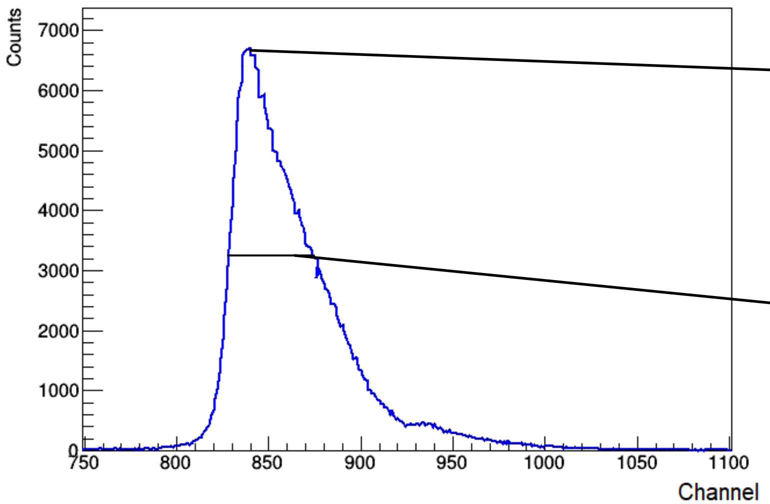
Neutron Spectrum



Alpha Particles Spectrum



Alpha Particles Experimental Spectrum



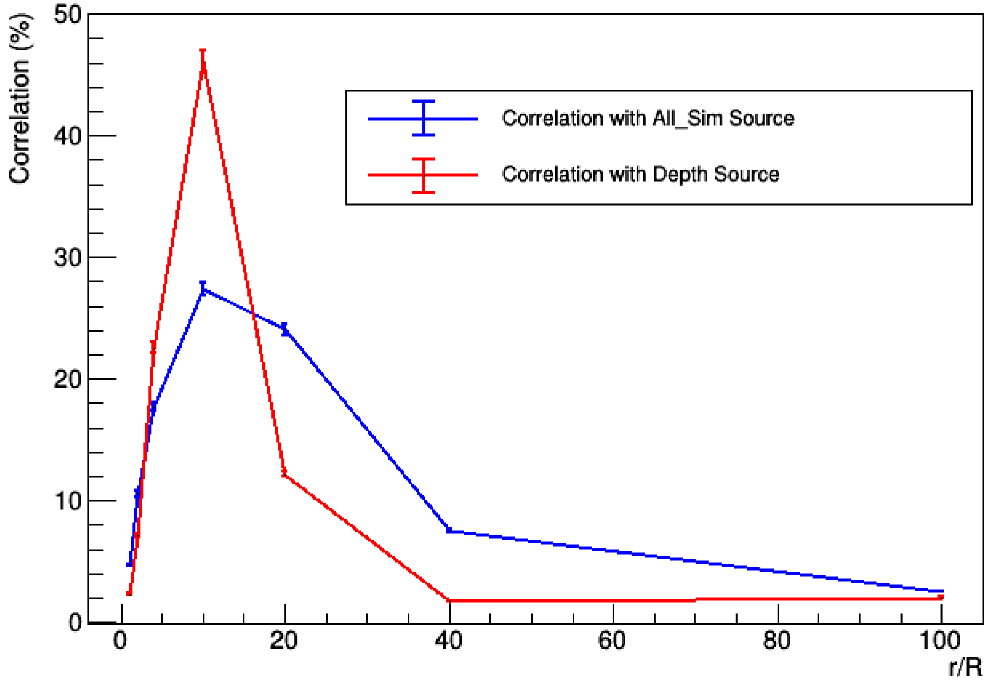
$E_{peak} \cong 2.7$ MeV

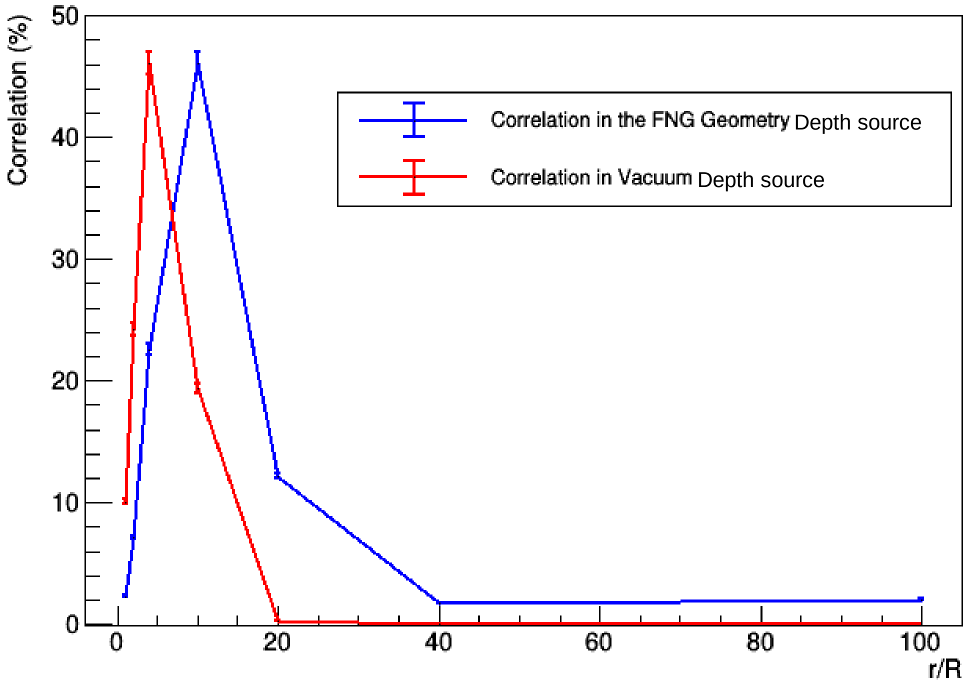
$FWHM_{MC} = 1.7 \pm 0.1$ MeV

$FWHM_{Exp} = 1.5 \pm 0.1$ MeV

The α/n Spatial Correlation with the Depth Source

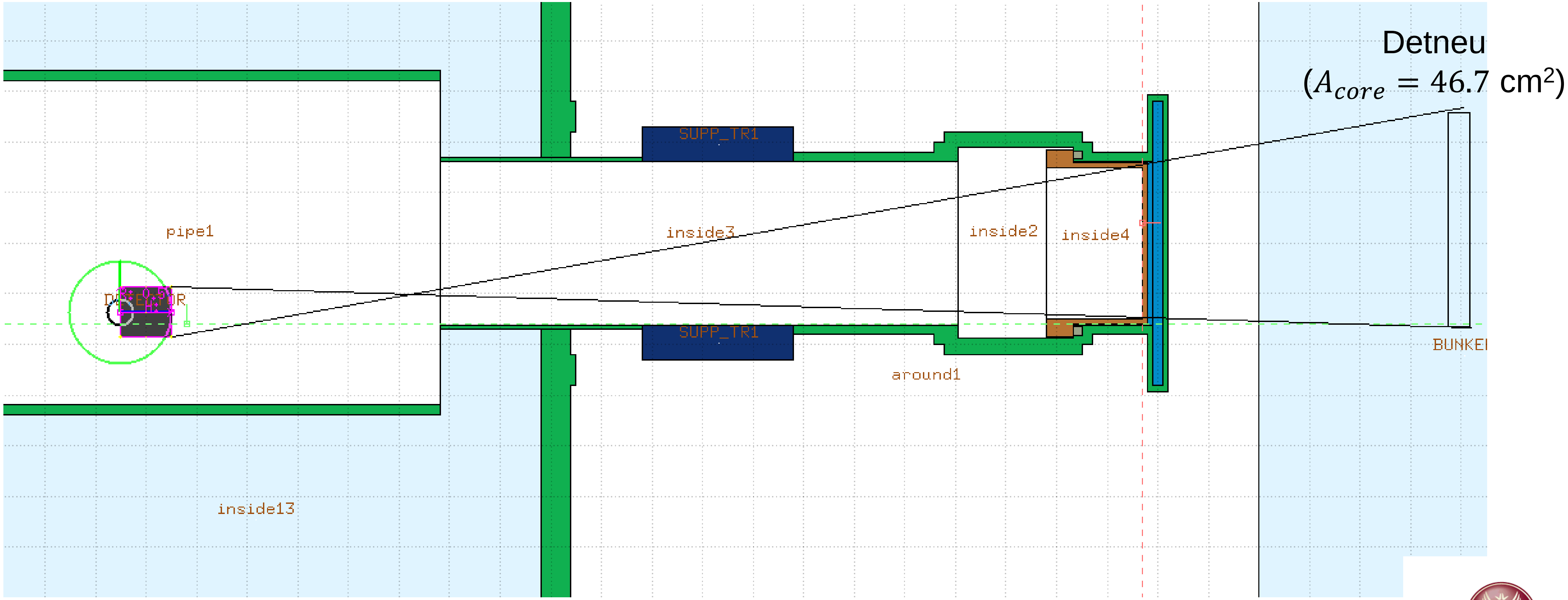
The α/n spatial correlation is calculated using the *Depth* source. The *All_Sim* source results are averaged over the thicknesses of target crossed from 0 μm to 4 μm. The energy threshold for all of the runs is $2.3 \div 3.2$ MeV. Then, there is a confrontation using the *Depth* source between the results in vacuum and in the FNG environment.





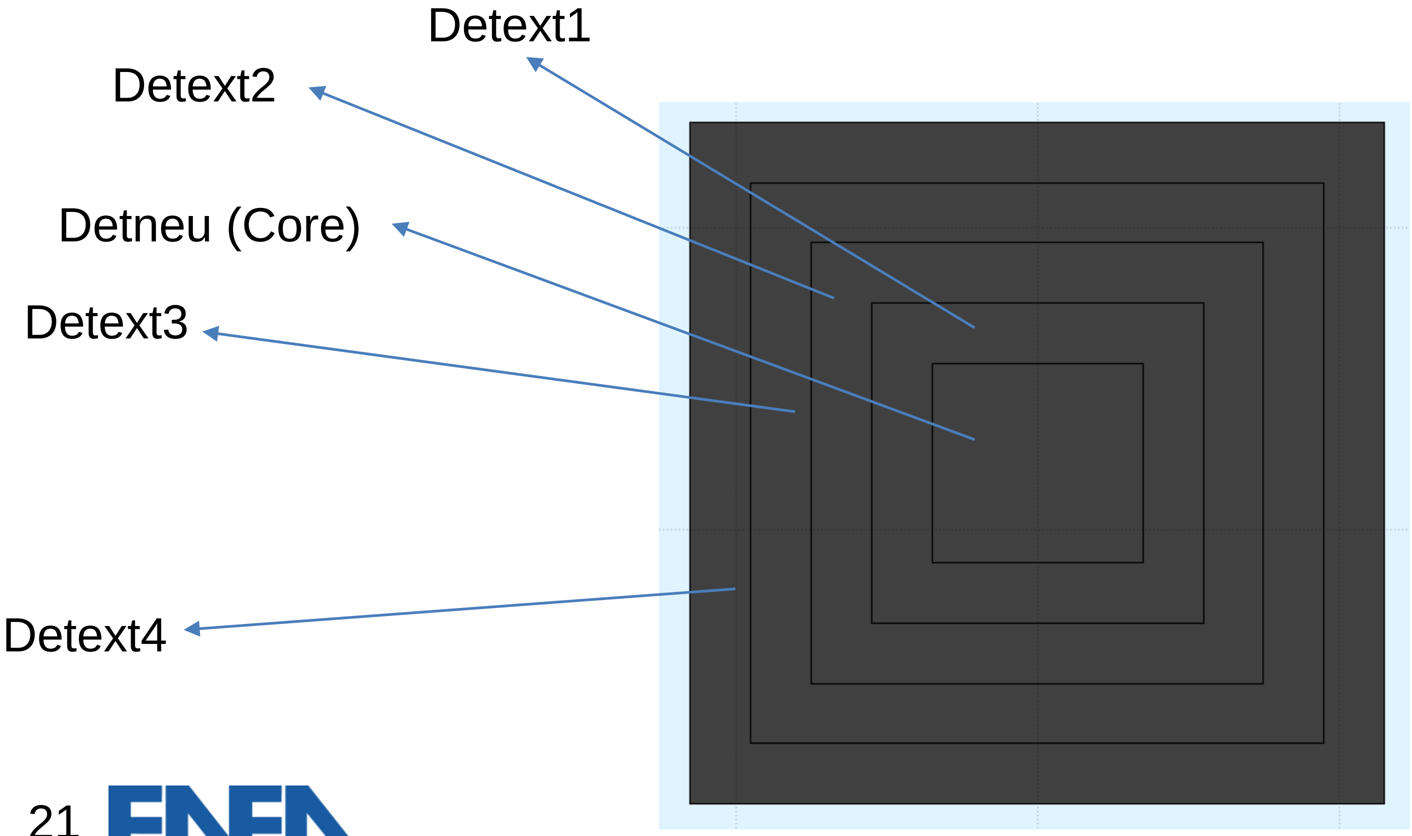
Origin of the Spatial Correlation Shift

The spatial correlation shift observed is due to the different point of origin of the particles. At different position will correspond a different angle of incidence on the neutron detector. This will correspond in a much bigger area for the neutron detector. Figure not in scale.



New Neutron Detection Region

The new configuration of the neutrons detection region. I put a big central region and 4 outer region to observe how much the neutrons lose their spatial correlation with their respective alpha particles. The detector for these is now squared with dimension 0.5×0.5 cm². This configuration has been named Ext Configuration. The area of the central region is $A_{core} = 46.2$ cm². I will plot the spatial correlation data as a function of the a_{ext}/A_{core} ratio. For example, when I will show that a certain spatial correlation corresponds to a value of $a_{ext}/A_{core} = 2.524$, I will mean that I am counting all the neutrons detected in the region between $a_{int} = 46.2$ cm² and $a_{ext} = 116.6$ cm².

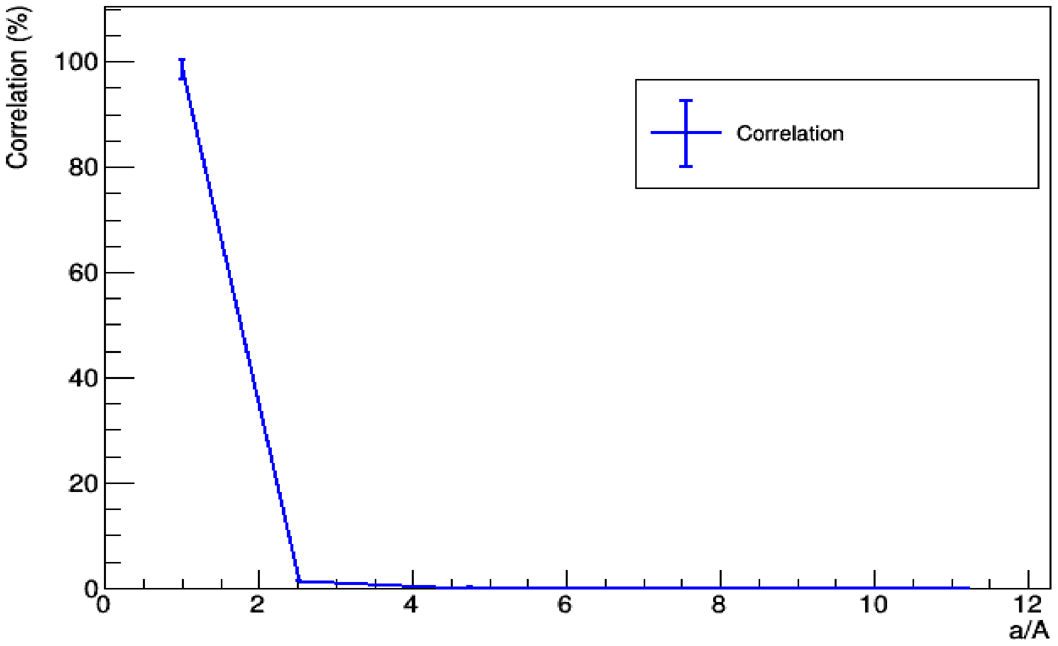


a_{int} (cm²)	a_{ext} (cm²)	a_{ext}/A_{core}
0	46.2 (=A_{core})	1
46.2	116.6	2.524
116.6	219	4.74
219	353.4	7.649
353.4	519.8	11.251

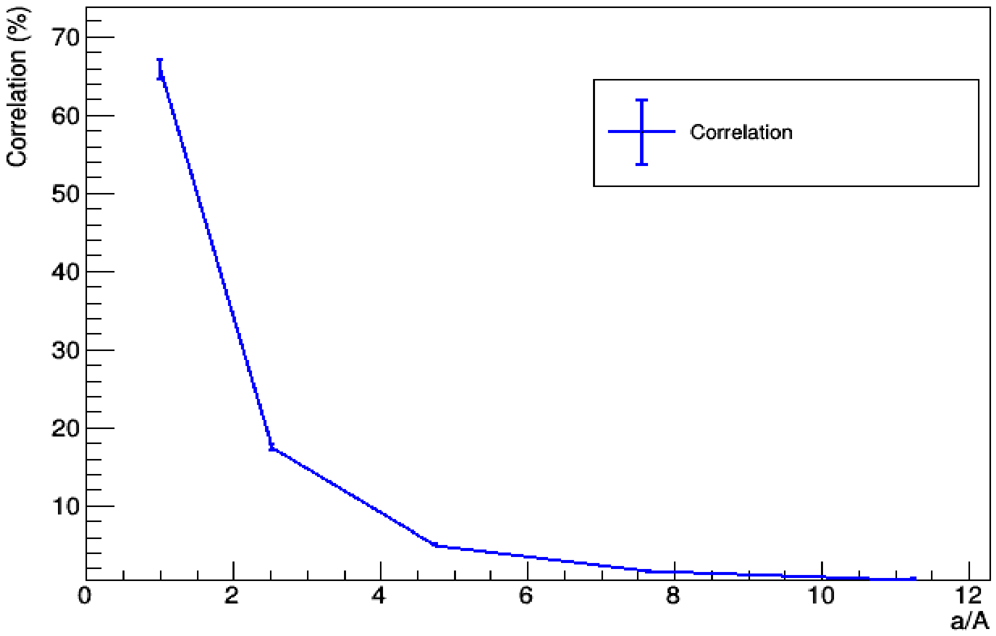
The α/n Spatial Correlation in Ext Configuration

The α/n spatial correlation as a function of the a_{ext}/A_{core} ratio for the Ext Configuration. On the left, results from the simulation in vacuum. On the right, the results in the FNG environment.

Vacuum



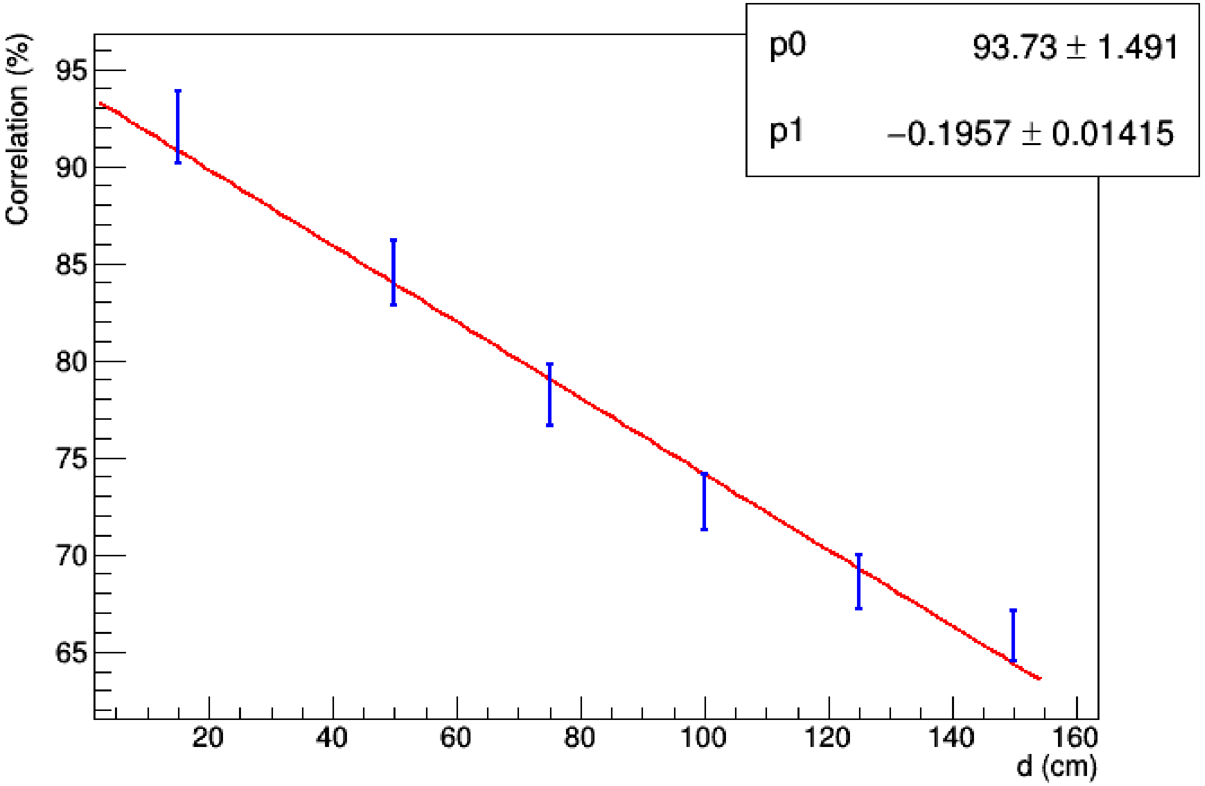
FNG Environment



The Decrease of α/n Spatial Correlation due to the Neutron Scattering with Air

To study if the spatial correlation decreases due to the neutrons scattering with air, I run a series of simulations moving closer to the target the neutron detection region. Its dimensions were rescaled to respect the a_{ext}/A_{core} ratio given before.

The α/n spatial correlation in the central region for the Ext Configuration as a function of the distance from the source origin point. The decrease is linear.



Conclusions and Future Perspectives

- Starting from the MCNP source, the new one for FLUKA was written and validated;

- Adding the possibly to reproduce the alpha and helium-3 spectra and with the simultaneous emission, I was able to create a source code that reproduce the whole FNG spectrum and allowed me to study the α/n spatial correlation;

- The first studies about the α/n spatial correlation lead to the result that even in vacuum it was not conserved;

- Considering the source extended and no more point-like allowed me to give a more realistic estimation of the α/n spatial correlation, finding that it is conserved in ~ 66 % of the cases with a neutron detector of ~ 46.2 cm^2;

- The one before represents the best result for the tagging detection of the alpha particles and neutrons and so would be the starting point for the development of a neutron detector;

- Placing the neutron detection region at various distances from the target leads to the result that the neutron scattering with air was responsible of the decrease of the α/n spatial correlation;

- A series of dedicated experimental measurements to verify the simulations were scheduled to begin by February 2020 but the Covid-19 outbreak forced FNG to several months of shutdown and also the entrance to the Frascati research centre was forbidden to external workers until late September 2020. So, making impossible to carry out the experiments.

Thanks for the Attention!!!

Thesis Planned Experimental Measurements

The FNG acquisition system for neutron counting is composed from a silicon detector for the associated alpha particle, a fission chambers and a NE 213 scintillator. The data are collected by a multichannel analyser DAQ. This system only allows time-integrated measurement of the charge spectra. This does not permit, for example, the acquisition of a single waveform in real time.

To overcome this limitation, it has been thought to use a new acquisition system with a CAEN digitizer. This will allow to do measurements of the energy spectra and of single waveforms in real time for detector diagnostics and neutrons-discrimination.

The detector for the neutrons thought to be used was a NE 213 scintillator. With this the tagging of neutrons and alpha particles could be studied in an experimental way too and the results of the simulations could be verified and eventually validated.