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STUDY ON NEUTRONICS DESIGN OF AN ACCELERATOR DRIVEN SUBCRITICAL REACTOR

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Abstract

Thorium fueled Accelerator Driven Subcritical Reactors have been proposed as a more comprehensive alternative to conventional nuclear reactors for both energy production and for burning radioactive waste. Several new classes have been added by the authors to the GEANT4 simulation code, an extension which allows the state-of-the-art code to be used for the first time for nuclear reactor criticality calculations. In this paper we investigate the impact of the subcriticality and injected proton beam energy on the ADSR performance for novel ADSR configurations involving multiple accelerator drivers and associated neutron spallation targets within the reactor core.

COMPUTATION DETAILS

GEANT4 [1] provides an extensive set of hadronic physics models for energies up to 10 - 15 GeV, both for the intra-nuclear cascade region and for modelling of evaporation. There are many different (data based, parametrized and theory-driven) models using different approximations and each has its own applicable energy range. Monte Carlo codes usually come with their own physics models and the user is offered default selections. For example in the MC-NPX code, the Bertini model is used by default for nucleons and pions, while the ISABEL model is used for other particle types [2]. The Bertini model does not take into account the nuclear structure effects in the inelastic interactions during the intranuclear cascade and therefore the code modelling of interactions at energies much below 100 MeV is questionable [3]. This becomes an important issue when dealing with thick targets, as although the primary neutrons are produced by the high energy proton beam, these are relatively low energy neutrons which can produce further spallation processes inside the target leading to secondary neutrons.

Due to the vast range of applications, GEANT4 will not give the user any default physics models, the user themself has to work out what models to use for what processes. For the GEANT4 simulations, we selected the Liege intra-nuclear cascade model together with the independent evaporation/fission code ABLA. This model has been added recently to the GEANT4 code, as the INCL/ABLA model, and has been validated against experimental data for spallation processes in many different heavy elements [4]. This model is valid for proton, neutron, pion, deuteron and triton projectiles of energies up to 3 GeV and heavy target materials (Carbon - Uranium). It models the Woods-Saxon nuclear potential, Coulomb barrier, non-uniform time-step, pion and delta decay cross sections, delta decay, Pauli blocking and utility functions, making it an independent code. The Liege model is largely free of parameters and is preferred by validation and, compared to the other theoretical models available in GEANT4 (Binary and Bertini being currently the most widely used), it is more data driven [5].

However, the INCL/ABLA validation results presented at the IAEA benchmark for spallation reactions [6] show that, for energies lower than 100 MeV, the results of the Liege model are not so good as above this energy. This is because the model does not have pre-equilibrium: INCL cascade is directly "coupled" to equilibrium de-excitation handled by ABLA and therefore it does not describe well enough low energy reactions (where nuclear structure effects start to play their role). Above 100 MeV, INCL/ABLA works very nicely, being one of one of the best models available.

On the other hand, the other two models available in GEANT4, Bertini and Binary cascade, do incorporate the pre-equilibrium model. The Binary cascade model has been recently improved following a validation study against the TARC experiment data, in order to improve several shortcomings in applying these models to processes of interest in an ADSR [7]. All these recent developments have been considered and implemented in our code.

In the simulations presented in this paper, the Liege model was selected to simulate interactions for energies above 150 MeV, while for lower energies the Binary cascade model was selected. For neutron energies below 20 MeV, the high-precision models were selected. These models use the ENDF/B-VI [8], JENDL [9], MENDL-2 [10] and other data libraries [11]. The $S(\alpha,\beta)$ coefficient which takes into corrected treatment for neutron scattering on chemically bound elements in the thermal region has also been implemented in the GEANT4 physics list used for this study.

GEANT4 CODE DEVELOPMENT

While MCNPX is able to do reactor criticality calculations, GEANT4 is not. Being a code used for simulating experiments in particle and medical physics and space sciences, the particles are not tracked according to their "time of creation" and each particle will interact with existing matter (which is made from materials pre-defined in the simulation code) independently to the other particles that were created in any given event. This is an issue because if a spallation target is used to produce neutrons to convert

the existing ^{232}Th into ^{233}U, then in the simulation we must "allow" neutrons produced by each proton to be able to "act" on isotopes produced by previous proton events. Therefore the fact that in GEANT4 particles interact only with $pre-defined$ materials was also an issue for us.

GEANT4 provides an abstract base class which the user can use to create his own filter class:

class G4VSDFilter
{
public:
G4VSDFilter(G4String name);
virtual G4VSDFilter();
public:
virtual G4bool Accept(const G4Step*) const = 0;
......
}

and it is the Accept() function which will act as the corresponding filter.   Using this the user can create his/her own messenger class to define a /score/filter/< $user\ filter$ > command in the same way as it is done in the G4ScoreQuantityMessenger class.

Three new classes have been written and added to GEANT4: G4SDTimeFilter, G4SDParticleWithTimeFilter and G4SDParticleWithVolumeFilter. Another messenger class was created to count different particles and isotopes in specified geometry volumes and time intervals. This new version of GEANT4 is now able to count the number of neutrons and/or isotopes present inside the nuclear fuel for any input parameters: the proton beam size and energy, the fuel composition and finally the target size and material.

RESULTS

Spontaneous Fission Neutrons Impact on the ADSR Performance

Now that GEANT4 is able to count particles and isotopes in different time intervals, we can use the code for the first time to do estimates of the reactor criticality for different fuel compositions and proton beam characteristics.

The first attempts to implement a homogeneous reactor core geometry into the GEANT4 simulation code were shown in reference [12]. However a real reactor core is not homogeneous and therefore the fuel rods geometry had to be implemented next. Fig. 1 shows the GEANT4 simulation of an accelerator driven sub-critical reactor, having as input parameters a 1 GeV proton beam a 60 cm long Pb target and the reactor fuel rods surrounding the target.

As mentioned before, MCNPX is able to run simulations to predict the reactor criticality. MCNPX preliminary tests showed that the criticality should be 0.726 for 1% $^{233}UO_2$, 0.991 for 1.7% $^{233}UO_2$ and 1.02 for 1.8% $^{233}UO_2$.

MCNPX attempts to establish the criticality by generating neutrons with energies characteristic to a conventional reactor directly into the reactor fuel. The neutrons energy spectra used by MCNPX was implemented as input data into the GEANT4 code. The reactor criticality is defined as
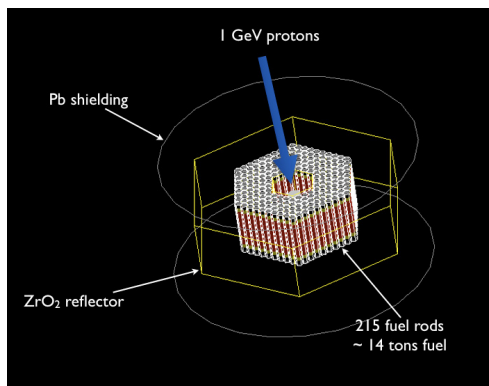

Figure 1:   Reactor geometry implementation into GEANT4.

the ration of the number of neutrons in one neutron generation to the number of neutrons in the previous generation. If the ratio is less than 1, i.e. the number of neutrons inside the core is decreasing in time, the reactor is said to be sub-critical.

A summary of the GEANT4 criticality results for different concentration of $^{233}UO_2$ inside the fuel is shown in Table 1.

Table 1: Criticality values for different concentrations of $^{233}UO_2$ inside the reactor fuel

Concentration	Criticality
0.2%	0.692
0.4%	0.703
0.6%	0.743
1.0%	0.764
1.4%	0.872
1.7%	0.947
1.8%	0.974
1.9%	> 1.

For a concentration of $^{233}UO_2$ greater than 1.9% the criticality exceeds the value of 1 and the reactor enters a super-critical regime.   The agreement of these two programs, despite the differences in the models used, gives confidence in their results.

Spallation Neutrons Impact on the ADSR Performance

An Accelerator Driven Subcritical Reactor (ADSR) consists of three parts: the accelerator, spallation neutron target and sub-critical reactor core. The spallation target is at the heart of any accelerator driven reactor. Because the ADSR is operated in a subcritical state, the target system has to provide the neutrons needed to sustain fission. These are generated by the spallation process resulting from high energy protons impacting the spallation target installed at the centre of the core. Therefore the target materials must have

high neutron production efficiency. One of the best candidate target material is lead or a lead/bismuth eutectic. However these spallation neutrons have an energy spectrum different from the one of the neutrons present in conventional reactors.

The energy spectra used by MCNPX to establish the criticality and the spallation neutrons energy spectra are shown in Fig. 2, both histograms being normalized to 1000 for direct comparison.
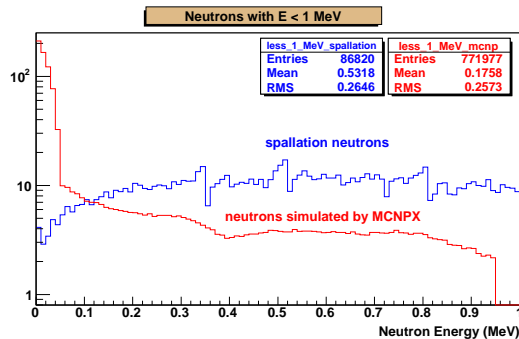

Figure 2: Energy spectra for neutrons with energy less than 1 MeV.

An ADSR relies upon these spallation neutrons to sustain fission, and different configurations were simulated, for different concentrations of $^{233}UO_2$, in order to find out at which level of $^{233}UO_2$ these spallation neutrons will start to have an impact on the ADSR performance. The spontaneous fission processes have to be switched off, so that the only fission processes that take place are those induced by the spallation neutrons and by the fission neutrons produced in these processes.

For a homogeneous reactor core, like the one described in [12], it was found that the reactor becomes critical for a $^{233}UO_2$ concentration of 6%. For the fuel rods geometry, the reactor was found to be sub-critical even for 90% $^{232}ThO_2$ and 10% $^{233}UO_2$.

Fig. 3 shows the time dependence of the number of neutrons inside the reactor core for the above configuration. The initial sudden drop in the number of neutrons is due to the fact that these neutrons are spallation neutrons produced by the 1 GeV proton beam. Once the "wrong energy" neutrons have escaped, the reactor criticality approaches the value of 0.9927.

When spallation neutrons are used to run the reactor, the criticality is reached only for 15% $^{233}UO_2$. However, as it has been shown in the previous subsection, the criticality is already reached at 1.9% $^{233}UO_2$ due to the spontaneous fission processes inside the reactor. Therefore the fact that at no point should the spallation neutrons cause an ADSR to become critical is an additional advantage.

CONCLUSION

GEANT4 and MCNPX predict the same reactor criticality values for identical fuel inside a conventional nuclear
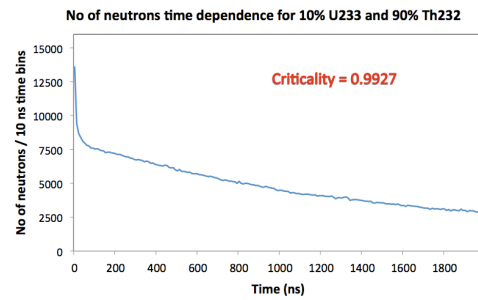

Figure 3: Number of neutrons time dependence.

reactor. Due to the different energy spectra of the spallation neutrons produced by the 1 GeV proton beam, the accelerator driven reactor remains subcritical even at high concentrations of $^{233}UO_2$.

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