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Conceptual design of accelerator driven systems with light ion beams

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Summary. — The superior energy efficiency of light ion beams instead of proton beams for energy production in accelerator driven systems (ADS) is demonstrated. The energy efficiency is characterized by the energy gain calculated as the ratio of the energy released in the target to the energy spent for the beam acceleration. The energy deposited in the target is obtained via Geant4 simulation. A method to calculate the energy spent for the beam acceleration by scaling from the data for a reference beam is presented. The influence of the target structure on the energy efficiency of 0.5 - 4 GeV proton beams and 0.25 1 AGeV light ion beams is studied. The target consists of rods with different composition (metal, oxide, carbide) and different levels of enrichment in order to implement the target with a criticality coefficient k_{eff} of 0.96 - 0.97, which ensure safe operation. The influence of the rod dimensions, the coolant and converter on the neutron spectrum and energy released are analysed.

1. – Introduction

The almost generalized opinion is that the optimal beam for ADS is represented by protons with energy around 1 GeV. However, we demonstrated in previous papers [1, 2] that ion beams can be more efficient for energy production in ADS than proton beams. This conclusion was obtained using the data about the energy released in quasi-infinite uranium target predicted through simulation with the code Geant4. In the present work the energy production in targets with more realistic structure is investigated. In the new set of simulations the target is an assembly of fuel rods with various composition and dimensions, immersed in a coolant bath. It was underlined in [1] that the most efficient way would be the acceleration of the beam in a synchrotron. Unfortunately the synchrotron cannot ensure the beam intensities necessary for ADS. Linear accelerators are more promising from this point of view. In this work the case when the beam is accelerated in a linac is investigated.

2. – Method to calculate the energy efficiency

The energy gain G defined as the ratio of the power produced in the target P_{prod} to the power spent to accelerate the beam P_{spent} is used as measure for the energy efficiency.

The power produced depends on the energy released in the target E_{rel} per incident particle, the beam intensity I_{beam}, and the conversion coefficient from thermal to electrical power η_{el}. An usual value of 0.4 for η_{el} was used in this work. The energy released in the target is obtained through simulation with the code Geant4. The predictive power of the code Geant4 was investigated in [3]. Here a detailed comparison between experimental data about the neutron yield from thin and thick metallic targets and the results of the simulation was performed. For integral values the agreement between experiment and simulation is good and we conclude that we can relay on the results of the simulation in the limit of 25 %.

The power spent to accelerate the beam is seen as a sum of two terms. One term represents the power transmitted to the beam P_{beam}. It depends on the ion mass number A, the final energy per nucleon E, and the beam intensity. The second term P_{acc} represents the power necessary to maintain the functioning of the accelerator. This term depends on the accelerator length, and scales as $A \cdot E/Z$, where Z is the atomic number of the ion.

In this way if the power spent P_{spent0} and the accelerator efficiency η_0 for a reference particle (with atomic number Z_0, mass number A_0, final energy per nucleon E_0) are known one can calculate the power spent for another particle. Assuming the same beam intensity the one gets:

$$P_{\rm spent} = P_{\rm beam} + P_{\rm acc} = A \cdot E_0 \cdot I_{\rm beam} + \frac{A \cdot Z_0 \cdot E}{A_0 \cdot Z \cdot E_0} P_{{\rm spent}_0}(1 - \eta_0) \tag{1}$$

Data from [4] were used for the reference particle: protons with energy 2.5 GeV, beam intensity $1.25 \cdot 10^{16}$ p/s, and total accelerator efficiency 0.18.

3. – Results and discussion

Proton beams with energy 0.5 - 4 GeV, and light ion beams (^{7}Li, ^{9}Be, ^{12}C) with energy 0.25 1 AGeV were used in simulation. The influence of the target geometry and composition on the neutron spectrum and on the ratio between the energy released by different ions was investigated. The following parameters were varied: the radius r of the fuel rods (between 0.5 - 1 cm), the length L of the rods (between 100 - 150 cm), the distance d between rods (between 1 - 5 cm), the total radius R of the fuel assembly (between 70 - 90 cm). Different compositions of the fuel were analysed: metal (U-Zr, U-Pu-Zr alloys), U-Pu-C, and U-Pu-O. In each case the level of enrichment was properly chosen in order to implement a target with k_{eff} 0.96 - 0.97. Some values for the energy deposited per incident particle for beams of ^{7}Li with energy 0.35 AGeV (E_{dep1}) and 0.45 AGeV (E_{dep2}), and protons with energy 1.5 GeV (E_{dep3}) are presented in table 1. The variations in target geometry or fuel composition do not change the shape of the neutron spectrum and preserve the ratio between the energy deposited by different ions.

The cooling with different metals: lead, lead bismuth eutectic (LBE), and sodium was also analysed. With lead or LBE as coolant one gets almost the same energy released, but sodium is a poor neutron reflector and the energy release is significantly lower. If we want to cool with Na it is necessary to use a higher level of enrichment, or a supplementary

TABLE I. – *The energy released per incident projectile for different target geometries and compositions. For the explanation of the notation see the text.*

Target dimensions cm	Composition	E_{dep1} [MeV/p]	E_{dep2} [MeV/p]	E_{dep3} [MeV/p]
L120R70r0.5d2	U-Pu-Zr 11 % ^{239}Pu	9.584e4	1.437e5	1.342e5
L150R90r0.5d2	U-Pu-Zr 9.2 % ^{239}Pu	1.031e5	1.567e5	1.536e5
L150R90r0.5d2	U-Pu-C 11.2 % ^{239}Pu	9.276e4	1.457e5	1.375e5
L150R90r0.5d2	U-Pu-O 12.3 % ^{239}Pu	1.011e5	1.496e5	1.425e5

layer of reflector. However, we remark that the cooling with metal conserves the ratio between the energy deposited by various ions.

The use of converters from very light materials (Li, Be) changes the shape of the neutron spectrum and increases the energy released with a factor of 1.4 - 3. The effect is more pronounced for light ions at low energy.

Apparently one has a large liberty for choosing the target geometry. However, targets with higher dimensions and closer packing diminish the neutron leakage and need lower level of enrichment. That allows longer period between refuelling and ensures a higher actinides burning. An example is presented in Fig. 1 which shows the time evolution of ^{239}Pu concentration for two targets which need different levels of enrichment in order to realize the same k_{eff}. If one chooses as criteria for refuelling the moment when the power produced decreases with 30% from the initial value (these moments are shown with vertical lines in the figure) one can see that the target with higher dimensions and lower level of enrichment can be irradiated without refuelling more than 10 years, but the other target needs less than tree years between refuelling.

The net power production and the energy gain for beams of ^{7}Li, ^{9}Be, and ^{12}C in targets with converter LBE and Be is presented in Fig. 2.

4. – Conclusions

Targets with various composition, cooled with metal (Pb, LBE, Na) maintain the shape of the neutron spectrum and the ratio between the energies deposited by different ions.

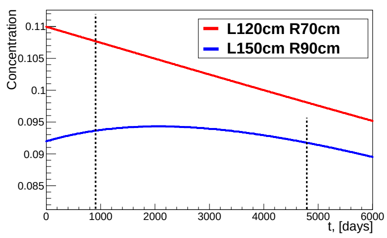

Fig. 1. – The time evolution of ^{239}Pu concentration for targets with different levels of enrichment, irradiated with beam of ^{7}Li with energy 0.35 AGeV, and beam intensity $1.25 \cdot 10^{16}$ p/s.

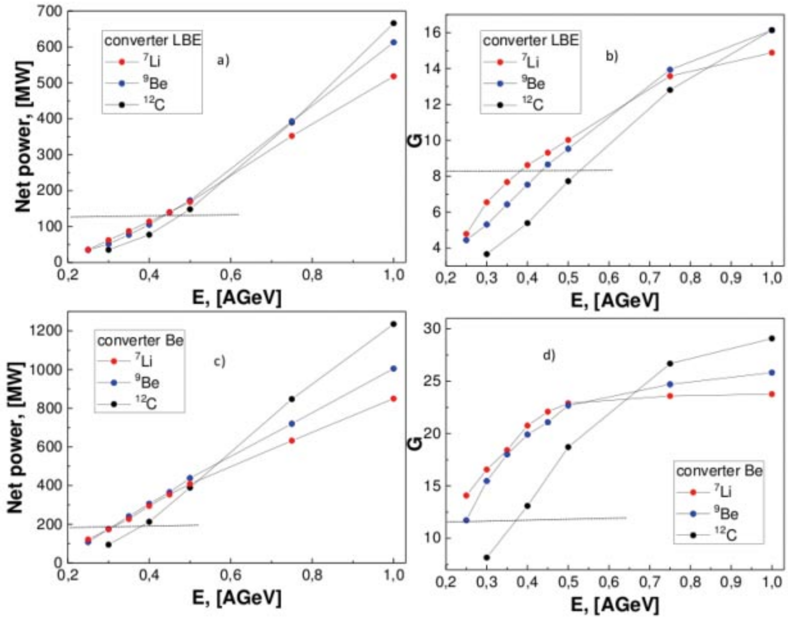

Fig. 2. – Net power production and energy gain in target with converter LBE (a,b) and converter Be (c,d). The corresponding values for 1.5 GeV protons are shown with horizontal lines.

Converters from light materials (Li, Be) produce a substantial increase of the energy deposited by light ions at low kinetic energy.

It is preferable to choose a compact packing and a target with dimensions large enough in order to obtain the needed value of k_{eff} at lower levels of enrichment. We can ensure in this way higher levels of actinide burning and large periods between refuelling. Light ions ^{7}Li and ^{9}Be with energy 0.3 - 0.4 AGeV realize the same energy release as a beam of proton 1.5 GeV. This allows one to obtain the same electrical power with lower energy consumption and an accelerator with 2 times lower dimensions. The acceleration of ^{12}C at 0.75 AGeV needs an accelerator with the same dimensions as for proton beam 1.5 GeV but produces a net electrical power about 5 times higher. The best solution from the point of view of the energy gain and miniaturization is the ^{7}Li beam with an energy of 0.3 - 0.35 AGeV, a target with converter of Be and cooling with Pb or LBE.

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