

Light Ion Beams for Energy Production in ADS

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Abstract. A comparative study of the energy efficiency of proton beams with an energy from 0.5 GeV to 4 GeV and light ion beams (⁷Li, ⁹Be, ¹¹B, and ¹²C) with energies from 0.25 AGeV to 1 AGeV in natural and enriched quasi-infinite U target is presented. The numerical results on the particle transport and interaction are obtained using the code Geant4. The following target optimization issues are addressed: the beam window dimensions, and the possibility to use a core from low Z materials. The best solution for ADS from the point of view of the energy gain and miniaturization is obtained for ⁷Li or ⁹Be beam with an energy of 0.3–0.4 AGeV and a target with Be core.

1 Introduction

The use of proton beams for energy production in accelerator-driven systems (ADS) was extensively investigated and the general opinion is that optimal for ADS is a proton beam with energy ~ 1 GeV [1]. The possibility to use heavy ion beams was less analyzed and the conclusions of authors are contradictory [2]–[3]. Our results presented in [4] show that one can get a higher efficiency by accelerating heavier ions. In the present work we analyse in more detail the use of light ion beams at energies below 1 AGeV.

2 The energetic efficiency of the beam

The beam efficiency is described by the energy gain factor G calculated as the ratio of the produced electrical power P_{prod} to the power spent to accelerate the beam P_{spent} :

$$G = P_{\text{prod}}/P_{\text{spent}} . \quad (1)$$

The produced electrical power is:

$$P_{\text{prod}} = \eta_{\text{el}} \cdot E_{\text{dep}} \cdot I_{\text{beam}} , \quad (2)$$

where η_{el} represents the conversion coefficient from thermal to electrical power, E_{dep} is the energy deposited in the target, and I_{beam} is the beam intensity. The power spent for the beam acceleration P_{spent} is analysed as the sum of two terms. The first term P_{beam} represents the power transmitted to the

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beam. The second term P_{acc} contains the energy necessary to ensure the functioning of the accelerator (magnets, cooling system, etc.)

$$P_{\text{spent}} = P_{\text{beam}} + P_{\text{acc}} = A \cdot E \cdot I_{\text{beam}} + P_{\text{acc}}. \quad (3)$$

The term P_{acc} depends on the type of the accelerator used. In a synchrotron this term scales as:

$$P_{\text{acc}} = \frac{A \cdot Z_0 \cdot p}{A_0 \cdot Z \cdot p_0} P_{\text{acc}_0}. \quad (4)$$

In a linac P_{acc} scales as:

$$P_{\text{acc}} = \frac{A \cdot Z_0 \cdot E}{A_0 \cdot Z \cdot E_0} P_{\text{acc}_0} \quad (5)$$

and in a cyclotron:

$$P_{\text{acc}} = \left(\frac{A \cdot Z_0 \cdot p}{A_0 \cdot Z \cdot p_0} \right)^2 P_{\text{acc}_0}. \quad (6)$$

In formulas (3)–(6) A , Z , p and E are the mass number, the atomic number, the momentum per nucleon and the energy per nucleon of the analysed particle. The symbols with the subscript 0 represent the corresponding values for the reference particle. These formulas allow to calculate the power spent for any beam if we know the accelerator efficiency for a reference beam.

3 The energy produced in the target

The energy released in the target was calculated with the code Geant4. The hadronic inelastic interaction of protons, neutrons and pions was modelled with the Bertini cascade model. For neutrons with energies below 20 MeV high precision neutron models based on a detailed implementation of the data from ENDF (Evaluated Nuclear Data File) were used. The inelastic interaction of ions was modelled with the binary cascade model.

Cylindrical targets with dimensions large enough in order to ensure quasi-infinite conditions (the saturation of the energy deposited in both radial and longitudinal directions) were used. In the case of ^{238}U target the radius is 60 cm and the length 160 cm. The ^{238}U target has a low critical coefficient (0.48) and needs very high beam intensities for efficient power production. An enriched target with critical coefficient 0.96 ensures a safe exploitation and needs beam intensities 50 times lower. In such target (5.7 % ^{235}U) the quasi-infinite conditions are reached at higher dimensions. In this case a cylinder with radius 100 cm and length 200 cm was used. The influence of the the beam window length on the energy released was investigated. The presence of beam window increases the energy deposited by including the effect from backscattered particles. The simulation shows that the optimum length of the beam window is ~ 40 cm.

For ion beams at low energies the possibility to use low Z materials in the central part of the target was considered. Two phenomena with opposite effects concur in this case. On one side in a low Z material the energy loss through ionization decreases and the probability of inelastic interaction at higher energy per nucleon increases, generating higher multiplicity and a harder spectrum of the secondaries. On the other side a low mass number of the target diminishes the cross section. The overall result depends on which of these effects dominates. The simulation predicts that a core from very low Z materials (Li, Be, C) increases the energy released for light ions at low energies with a factor of 1.3–2. The maximum effect is obtained with a core of Be.

4 Results and discussion

The first set of simulations was performed in a ^{nat}U target irradiated with protons and ions with masses until ^{40}Ca and energies from 0.3 AGeV to 10 AGeV. The dependence of the energy released on the projectile mass and energy per nucleon is presented in figure 1a. The relative beam efficiency for different types of accelerators is also given (figure 1b-d). As reference beam we use protons with energy 1 GeV for which a value of 0.1 for the accelerator efficiency was assumed. When accelerated in a synchrotron or linac ion beams starting with 7Li demonstrate higher energetic efficiency than protons. The maximum efficiency for ions with higher masses is reached at higher energies. That does not represent a problem when the beam is accelerated in a synchrotron, but such energies are difficult to reach in a linear accelerator, needing accelerator lengths of a few km. Unfortunately, the beam intensities achieved in a synchrotron are by orders of magnitude lower than those necessary for ADS. Linear accelerators look more promising for obtaining the required beam intensity.

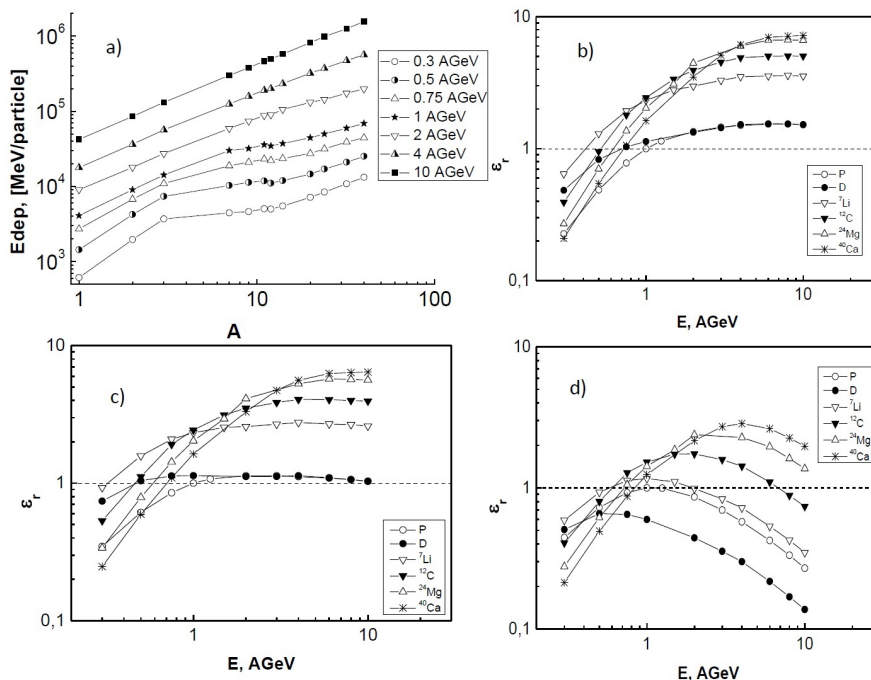


Figure 1. The energy released as function on the projectile type and energy (a), the relative efficiency for beams accelerated in a synchrotron (b), linear accelerator (c), and cyclotron (d)

For this reason in the second set of simulations we realized in enriched U target irradiated with light ions from 7Li to ^{12}C at low energies (0.3 AGeV–1 AGeV), accelerated in a linac. We use the data from the European Spallation Source (ESS) project for the reference particle (protons with final energy 2.5 GeV, beam intensity I_0 of $1.25 \cdot 10^{16}$ p/s, and a value of 0.18 for the accelerator efficiency). The total energy deposited per projectile, the energy gain and the net electrical power obtained with different beams at the same intensity I_0 are presented in table 1 for a target entirely from enriched U and with core of Be.

In target with Be core beams of 7Li or 9Be are equivalent from the point of view of the energy produced with a beam of 1.5 GeV protons (at maximum proton beam efficiency) but with higher energy gain and needing accelerator with lower dimensions.

Table 1. The energy released E_{dep} , the gain factor G and the net electrical power P_{el} produced in enriched U target irradiated with protons and light ions

P	Fuel				Core Be		
	E_{beam} AGeV	E_{dep} MeV	G	P_{el} MW	E_{dep} MeV	G	P_{el} MW
proton	1	1.09e5	7.3	75.6	1.25e5	8.64	88.1
	1.5	1.85e5	8.23	130.2	2.18e5	9.68	156.3
	2	2.49e5	8.32	175.6	2.94e5	9.8	211.2
${}^7\text{Li}$	0.3	8.49e4	6.06	56.7	1.79e5	12.8	132.1
	0.4	1.54e5	8.19	107.3	3.21e5	17.2	242.1
	0.5	2.39e5	10.3	172.9	4.65e5	19.9	353.1
	0.75	4.99e5	14.3	371.4	7.7e5	22	588.1
${}^9\text{Be}$	1	7.19e5	15.4	537.7	1.07e6	22.8	814.7
	0.4	1.5e5	7.39	120	3.34e5	16.5	267
${}^{11}\text{B}$	0.5	2.5e5	9.86	200	5.3e5	20.9	424
	0.5	2.26e5	8.17	158	5.21e5	18.9	417
${}^{12}\text{C}$	0.75	5.22e5	12.7	385.1	1.08e6	26.2	863
	0.3	5.5e4	3.3	30.8	1.22e5	7.4	84.7
${}^{12}\text{C}$	0.4	1.08e5	4.9	68.6	2.62e5	11.9	191.9
	0.5	1.93e5	7	32.5	4.68e5	17	352.1
	0.75	4.8e5	11.6	351.3	1.03e6	25	793.4
	1	8.07e5	14.7	601.7	1.5e6	27.3	1155.2

5 Conclusions

The optimal energy of proton beam depends on the accelerator type and is ~ 3 GeV in synchrotron, 1.5 GeV in linac, and 1 GeV in cyclotron. The optimal energy for ion beams depends on the type of the ion (1.5–2 AGeV for ${}^7\text{Li}$, 2 AGeV for ${}^{12}\text{C}$, 4 AGeV for ${}^{40}\text{Ca}$) and the efficiency is significantly higher (more than 2 times) than for protons.

Light ions ${}^7\text{Li}$ and ${}^9\text{Be}$ with energy 0.3–0.35 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 ${}^{11}\text{B}$, and ${}^{12}\text{C}$ at 0.7–0.75 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 ${}^7\text{Li}$ beam with an energy of 0.3 AGeV and a target with core of Be.

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