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Beam and Target Optimization for Energy Production in Accelerator Driven Systems

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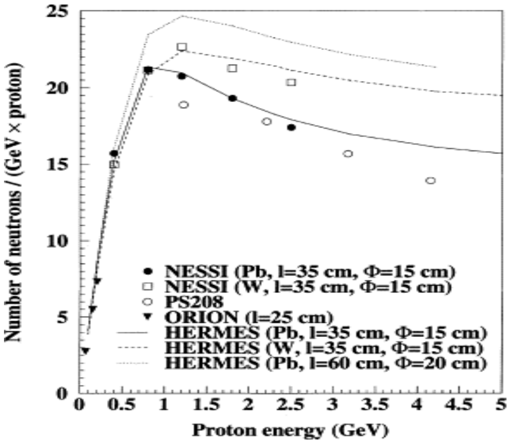
XXIV International Baldin Seminar, 17-22 September 2018, Dubna

ADS for transmutation and energy amplifier

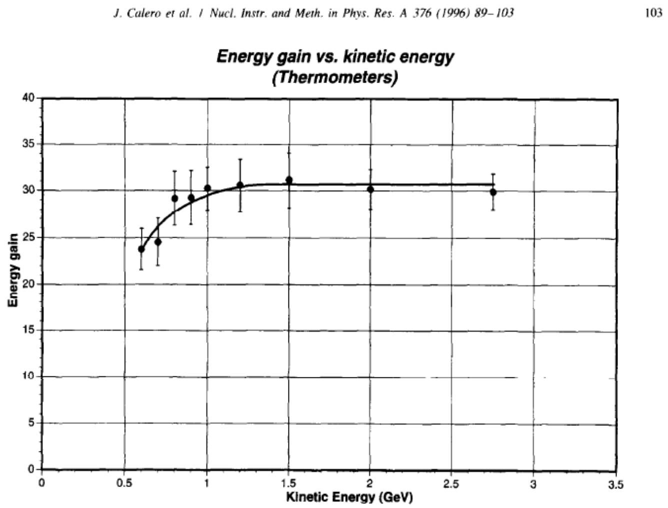
Transmutation of nuclear waste: project Omega (Japan), ATW (USA)
Concept of energy amplifier, experiments TARC and FEAT(CERN)
Project ESS (CERN)

Neutron yield from heavy metal targets



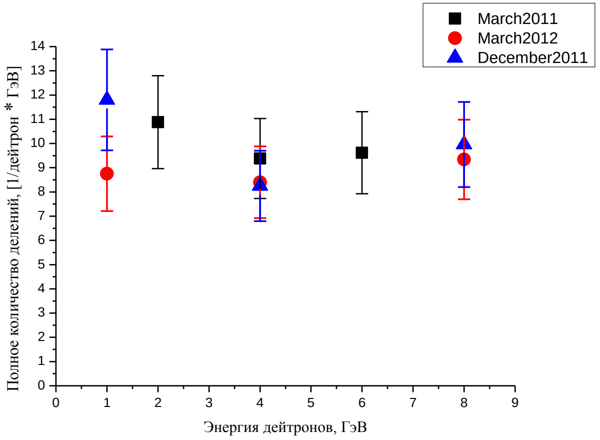
F. Carminati, C. Geles, R. Klapisch, J. P. Revol, Ch. Roche, J. A. Rubio, C. Rubbia,An Energy Amplifier for Cleaner and Inexhaustible Nuclear Production Driven by a Particle Beam Accelerator, CERN/AT/93-47 (ET) 1993

FEAT experiment (CERN)



J. Calero et al. / Nucl. Instr. and Meth. in Phys. Res. A 376 (1996) 89–103 103

Total number of fission in Quinta target irradiated with deuterons (measured with SSTD)



Energy gain for proton and ion beams

- **The energy gain factor G is the ratio of the produced electrical power Pprod to the power spent to accelerate the beam Pspent :**

$$G = \frac{P_{prod}}{P_{spent}}$$

- The energy deposited in the target is obtained through simulation with Geant4
- We present a method for the calculation of the energy spent to accelerate a given a given ion from the data about the energetic efficiency of the accelerator for a reference beam

Comparison of Geant4 simulation with experimental data

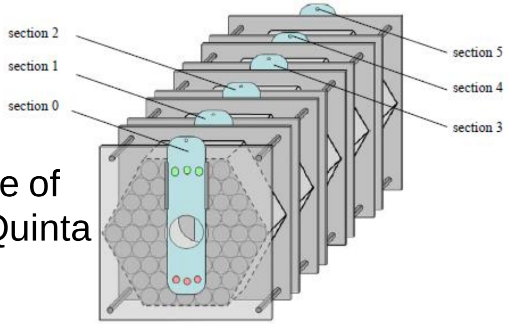
Neutron yield from extended Pb and U targets irradiated with proton beams

Average neutron yield per incident proton

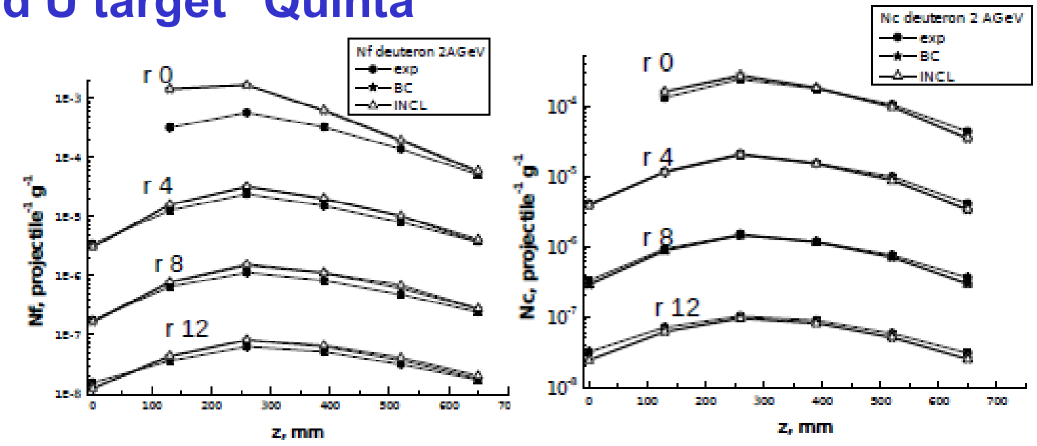
Beam energy, GeV	Pb target, length 35 cm, diameter 15 cm		U target, length 40 cm, diameter 8 cm	
	Exp	Sim	Exp	Sim
1.22	20.5	21.6	35.3	37.5
3.17	44	40.6	84.1	86.3
4.15	51	48.2	101	114.4

A. A. Baldin, A. I. Berlev, I. V. Kudashkin, G. Mogildea, M. Mogildea, M. Paraipan,S. I. Tyutyunikov, Simulation of Neutron Production in Heavy Metal Targets Using Geant4 Software, *Phys. Part. Nucl. 13 2 (2016) 391-402*

Fission and capture in extended U target "Quinta"



The scheme of the target Quinta



Experimental and simulated distribution of fission and capture in extended U target irradiated with deuteron 2 AGeV. The data are scaled with a factor of 0.1 from a radius to another.

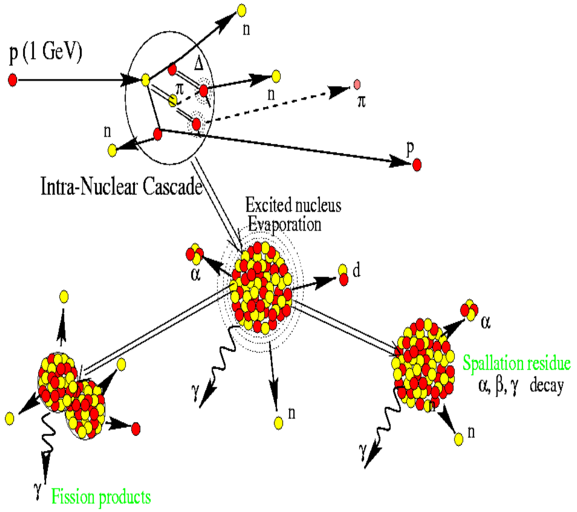
Total number of fission and capture in "Quinta"

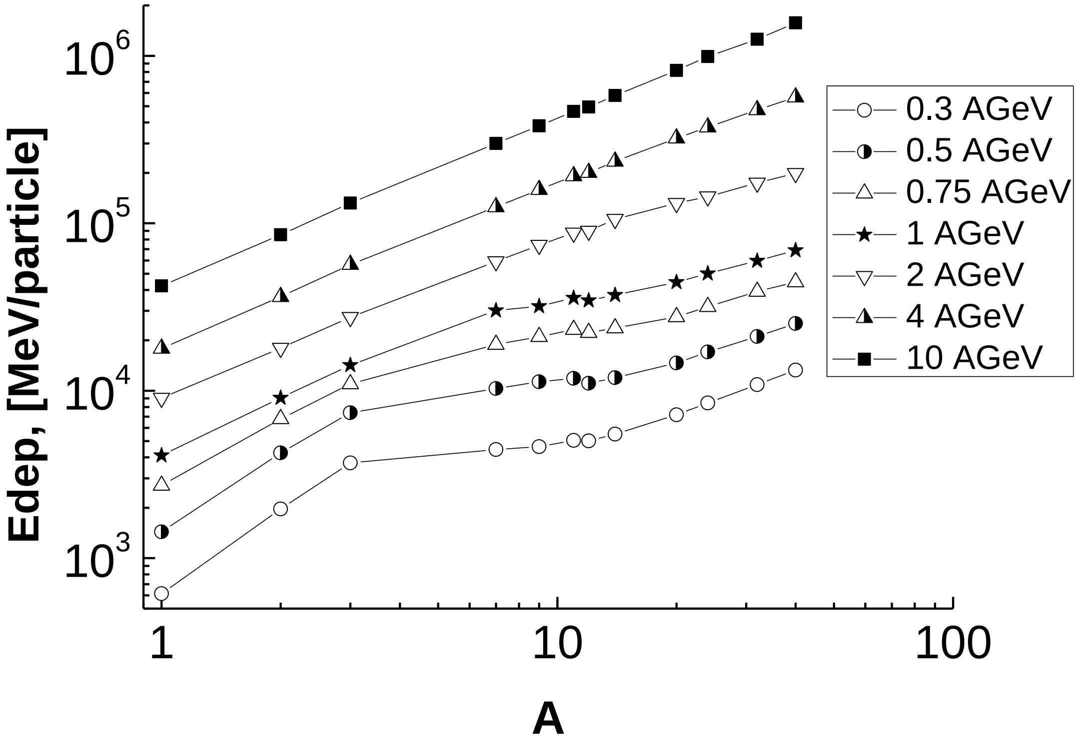
Projectile	Fission exp	Fission sim	Capture exp	Capture sim
D 2 AGeV	30.4	42.9	38.6	41.2
D 4 AGeV	68.1	74.1	74.8	78.1
C 2 AGeV	201.5	200.8	226.6	207.9
C 4 AGeV	410.9	389.4	422.7	406.1

*M. Paraipan,A. A. Baldin, A. I. Berlev, I. V. Kudashkin, G. Mogildea, M. Mogildea, S. I. Tyutyunikov***,** Comparison between deuteron and carbon beams at Quinta setup, *Baldin ISHEPP XXII, 2014*

The dependence of the integral energy released per projectile in quasi-infinite ^{nat}U target on projectile mass number (Geant4).

Beams of proton, deuteron, triton, ^{7}Li, ^{9}Be, ^{11}B, ^{12}C,^{14}N^{20}Ne, ^{24}Mg, ^{32}S, and ^{40}Ca with energies 0.3 - 10 AGeV in natural U.





Method for calculation of the energy spent and the energy gain of proton and ion beams

$$G = \frac{P_{prod}}{P_{spent}}$$

$$P_{prod} = \eta_{el} \cdot E_{dep} \cdot I_{beam}$$

$$P_{spent} = P_{beam} + P_{acc} = A \cdot E \cdot I_{beam} + P_{acc}$$

In synchrotron :

$$P_{acc} = \frac{A \cdot Z_0 \cdot p}{A_0 \cdot Z \cdot p_0} P_{acc\,0}$$

In linac :

$$P_{acc} = \frac{A \cdot Z_0 . E}{A_0 \cdot Z \cdot E_0} P_{acc\,0}$$

In cyclotron :

$$P_{acc} = \left(\frac{A \cdot Z_0 \cdot p}{A_0 \cdot Z \cdot p_0}\right)^2 P_{acc\,0}$$

G – the energy gain factor
P_{prod} – the electrical power produced
P_{spent} – the electrical power spent
η_{el} – the conversion coefficient from thermal to electrical power
E_{dep} - the energy released per incident particle
I_{beam} – the beam intensity
P_{beam} – the power transmitted to the particle beam
Z – the atomic number
A – the mass number
E–particle kinetic energy per nucleon
p – particle momentum
P_{acc} – the power spent for the functioning of the accelerator

The relative efficiency:

$$\varepsilon_r = \frac{G}{G_0} = \frac{P_{prod}}{P_{spent}} \frac{P_{spent0}}{P_{prod0}}$$

For a reference beam of protons with intensity I, final kinetic energy per nucleon E_0 and accelerator efficiency η_0 we have:

$$I \cdot E_0 = \eta_0 \cdot P_{spent}$$

In a synchrotron the energy consumption for the acceleration of a beam of particles with atomic number Z, mass number A, final energy per nucleon E, and the same beam intensity I is:

$$P_{spent}(Z, A, E, I) = A \cdot I \cdot E_0 \left[\frac{E}{E_0} + \frac{1}{Z} \frac{p}{p_0} \frac{1-\eta_0}{\eta_0} \right]$$

where p (p_0) is the particle (reference particle) momentum per nucleon.
The relative efficiency in a synchrotron becomes:

$$\varepsilon_r(Z, A, E) = \frac{E_{\mathrm{dep}}}{E_{\mathrm{dep0}}} \frac{1}{A\left[\eta_0 \frac{E}{E_0} + \frac{p(1-\eta_0)}{Z p_0}\right]}$$

The relative efficiency in a cyclotron is:

$$\varepsilon_r(Z, A, E) = \frac{E_{\mathrm{dep}}}{E_{\mathrm{dep0}}} \frac{1}{A\left[\eta_0 \frac{E}{E_0} + \frac{A}{Z^2} \frac{p^2(1-\eta_0)}{p_0^2}\right]}$$

The relative efficiency in a linac is:

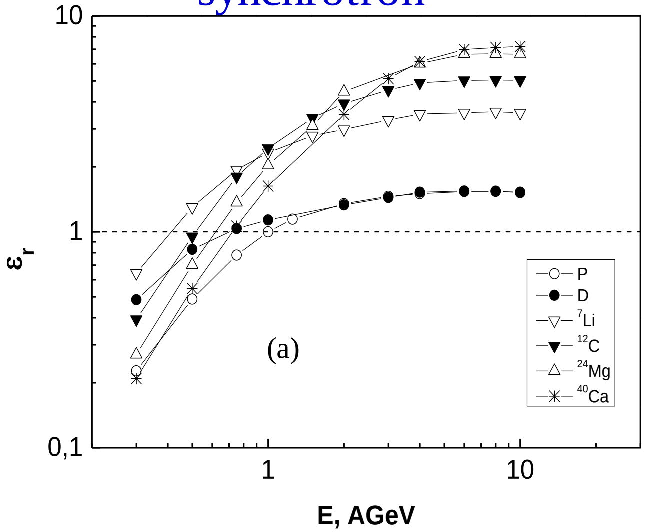
$$\varepsilon_r(Z, A, E) = \frac{E_{\mathrm{dep}}}{E_{\mathrm{dep0}}} \frac{Z \cdot E_0}{A \cdot E\left[\eta_0 Z + 1 - \eta_0\right]}$$

E_{dep} and E_{dep0} are the energies released obtained with the analyzed particle, respective the reference particle.

Energetic efficiency in natural U target

Beams of proton, deuteron, triton, ^{7}Li, ^{9}Be, ^{11}B, ^{12}C,^{14}N^{20}Ne, ^{24}Mg, ^{32}S, and ^{40}Ca with energies 0.3 - 10 AGeV in natural U.

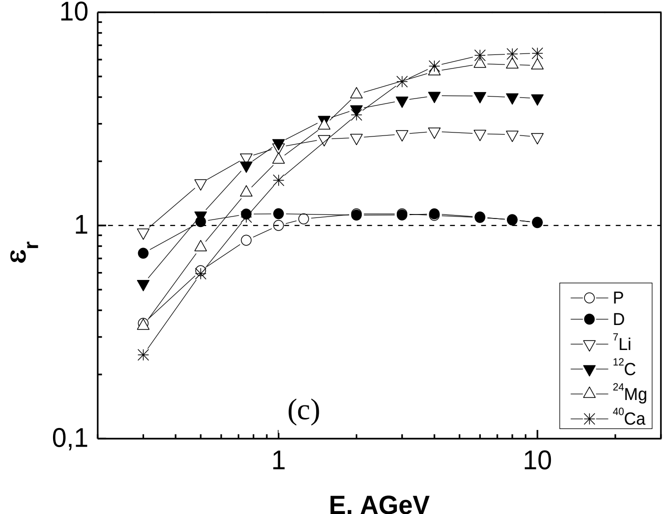
synchrotron



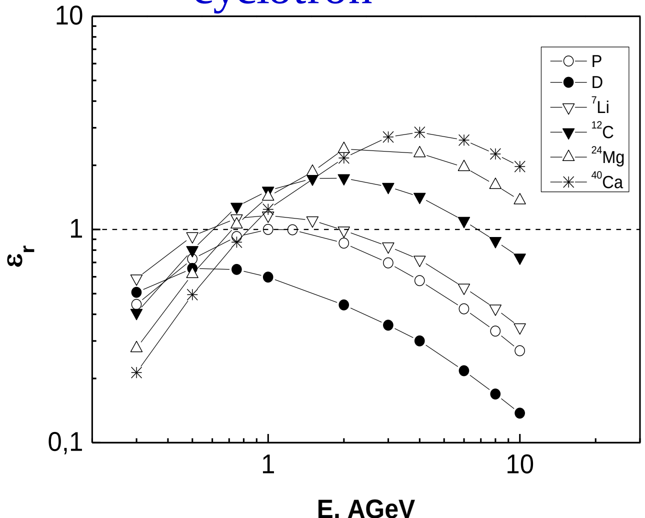
Relative (with respect to protons 1 GeV) ion efficiency as a function of beam energy for beams accelerated in a synchrotron, cyclotron, and a linear accelerator.

A. A. Baldin, A. I. Berlev, M. Paraipan, and S. I. Tyutyunnikov, Optimization of Accelerated Charged Particle Beam for ADS Energy Production, *Physics of Particles and Nuclei Letters, 2017, Vol. 14, No. 1, pp. 113–119*

linear accelerator

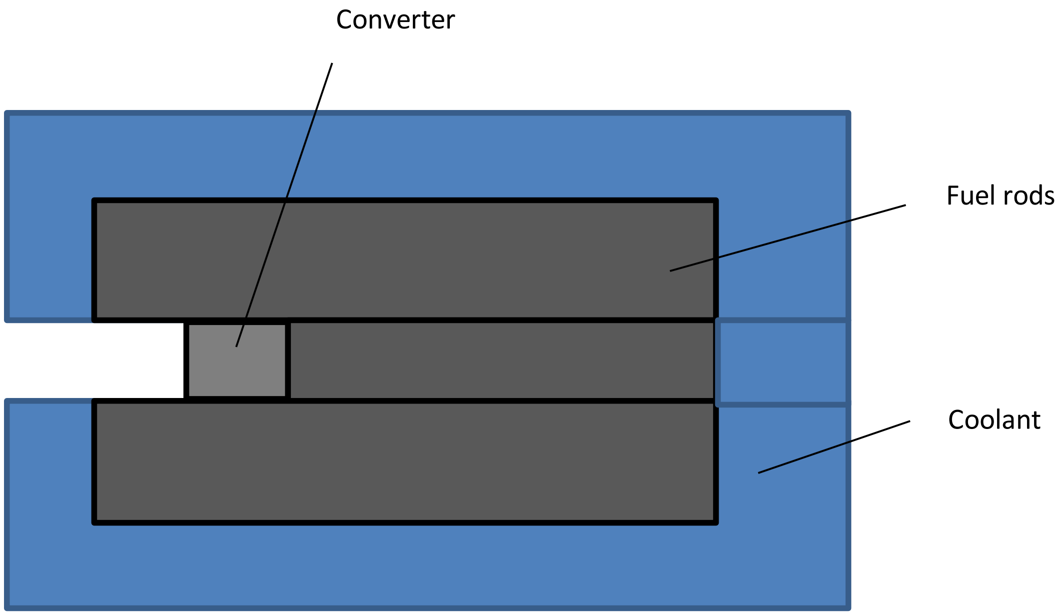


cyclotron



Target with different compositions and configurations

Fuel composition: metal (alloy U, Pu, Zr, Th), carbide, MOX
Bulk target or rods with radius 0.5-1 cm, distance between 1-5 cm
Target dimensions: radius 70-90 cm, length 100-150 cm
The level of enrichment properly chosen to obtain k_{eff} 0.96-0.97
Cooling with Pb, Pb-Bi eutectic (LBE), and Na



The energy deposited for different target configurations and different beams

Dimensions, cm	Material	Edep, MeV		
		Li-7 0.35 AGeV	Li-7 0.4AGeV	P 1.5 GeV
L120,R70,r0.5,d2	Metal U 11% Pu239	9.584e4	1.437e5	1.342e5
L140,R90,r1,d5	Metal U 14.7% U235	1.212e5	1.778e5	1.648e5
L150,R90, r0.5,d2	Metal U 9.2% Pu239	1.031e5	1.567e5	1.536e5
L150,R90, r0.5,d2	Carbid U 11.2% Pu239	9.276e4	1.457e5	1.375e5
L150,R90, r0.5,d2	MOX 12.3% Pu239	1.011e5	1.496e5	1.425e5
L150,R90, r0.5,d2	Metal Th 13.6% Pu239	9.423e4	1.429e5	1.381e5
L150,R90, r0.5,d2	Metal Th 18.8% U235	1.015e5	1.518e5	1.572e5

L – target length
R – target radius
r – rods radius
d – distance between rods

The coolant

Metallic target 14.7 % U235, L140-R90-r1-d5, irradiated with Li 0.35 AGeV and proton 1.5 GeV.

.

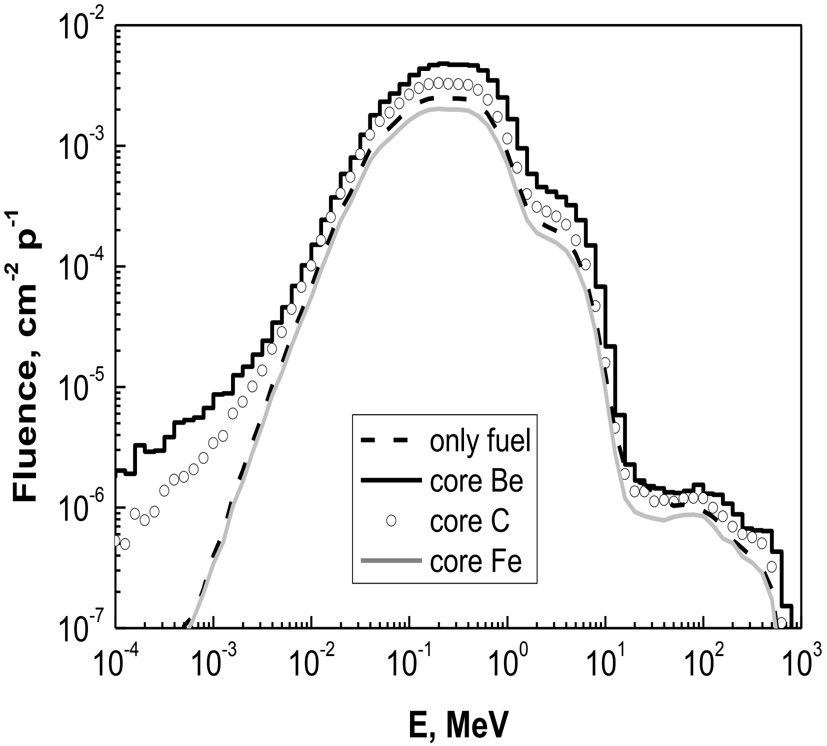
Ion	LBE	Pb	Na	Na + 20.5% U235	Na + layer 60 cm Pb
Li7	1.212e5	1.179e5	2.728e4	1.2289e5	1.173e5
Proton	2.146e5	2.037e5	5.028e4	2.165e5	2.101e5

The variation in actinide composition and the cooling with metals (Pb, LBE, Na) conserve the shapes of the neutron spectra and the ratio between the energies deposited by different ions.

Converter from different materials

Neutron yield from the converter and energy released in the enriched uranium target with the converter from different materials, irradiated with 0.5 AGeV ^{7}Li .

Core material	Core length, cm	Total neutron yield, particle^{-1}	Yield of neutrons with E>100 MeV, particle^{-1}	Deposited energy, MeV
fuel	10	34.4	1.49	$2.39 \cdot 10^5$
Li	70	5.7	2.64	$3.37 \cdot 10^5$
Be	**60**	**15.2**	**4.02**	**$5.06 \cdot 10^5$**
C	51	8.2	3.25	$3.06 \cdot 10^5$
Al	43	10.2	2.82	$2.78 \cdot 10^5$
Fe	16	14.5	2.12	$1.93 \cdot 10^5$



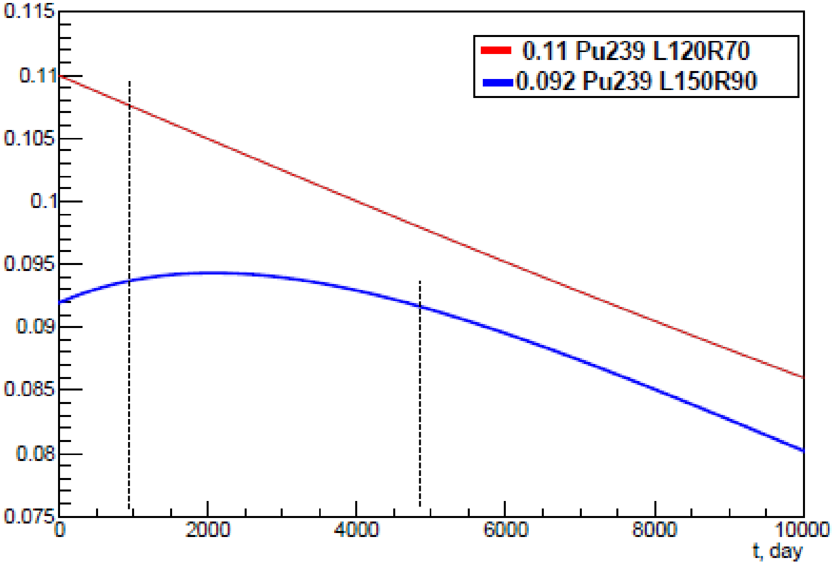
. Average neutron fluence in the enriched U target without a converter U, Be, C and Fe, irradiated by the 0.5 AGeV ^{7}Li beam.

Target converter from very low Z materials (Li, Be, C) increases the energy released for light ions at low energy 1.4-3 times.
The effect is higher in enriched target.

The choice of target dimensions

A target with higher dimensions and more compact packing ensures lower neutron leakage and the realization of the needed criticality coefficient with lower levels enrichment.

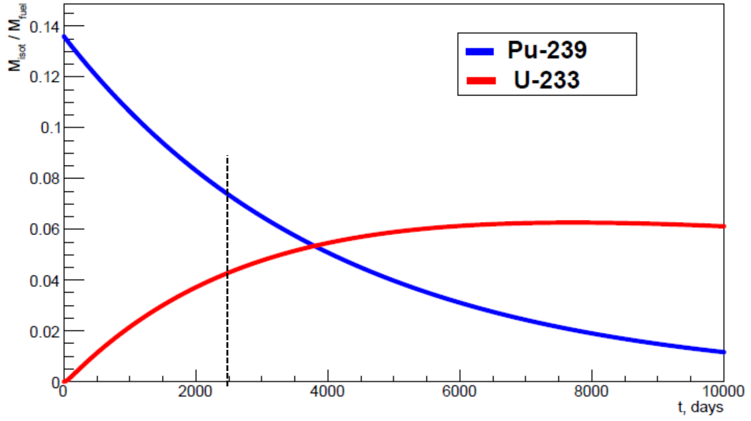
U-Pu metallic target



The time evolution of the Pu239 concentration for two initial levels of enrichment under irradiation with a beam of Li7, with intensity $1.25 \cdot 10^{16}$.

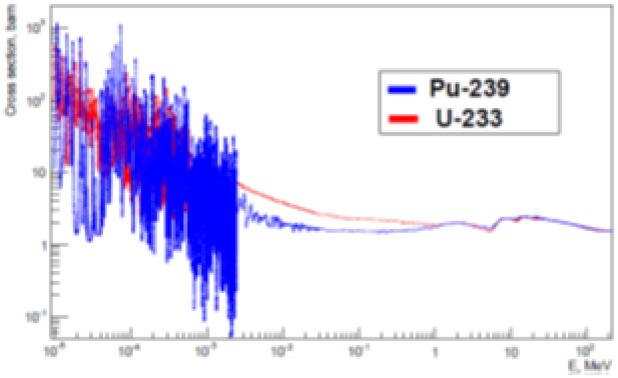
Thorium target

Metallic Th target with dimensions L150-R90-r0.5-d2 needs 13.6 % Pu239 for k_{eff} 0.96

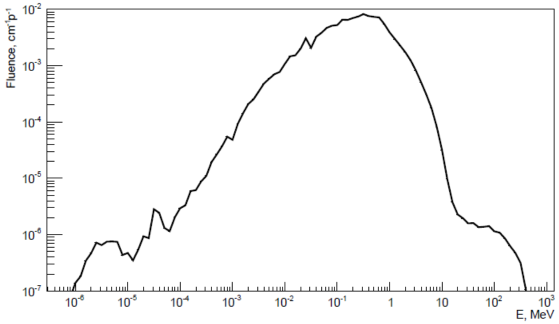


The time evolution of the Pu239 and U233 under irradiation with a beam of Li7, with intensity $1.25 \cdot 10^{16}$.

A thorium target needs a higher level of enrichment for the same geometry and a shorter period between refueling, comparing with uranium target.



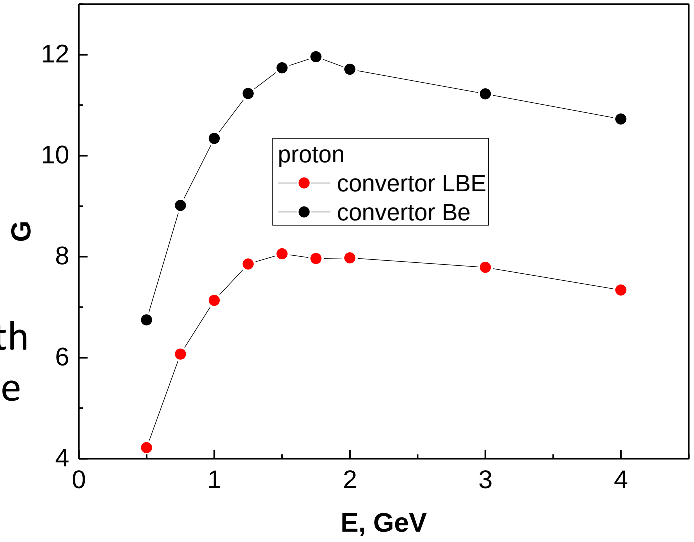
Fission cross section of neutrons in U233 and Pu239



Neutron spectrum under irradiation with Li-7

Mean fission cross section:
- 2.38 barn in U233
- 1.66 barn in Pu239

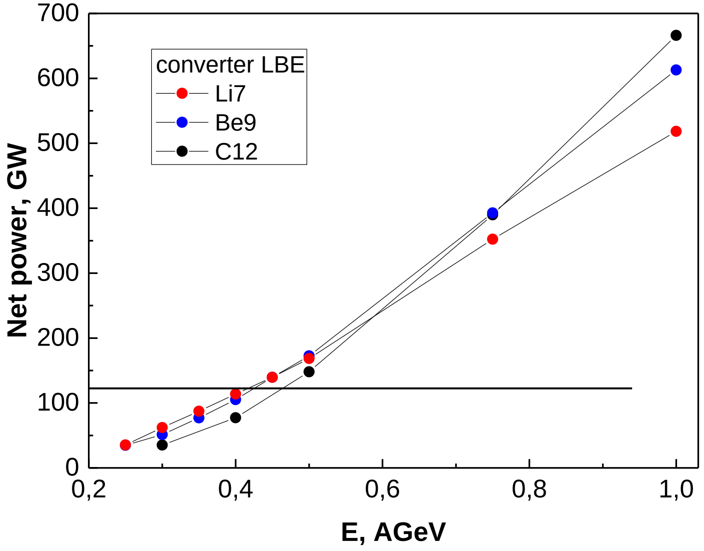
Energetic efficiency in U-Pu target



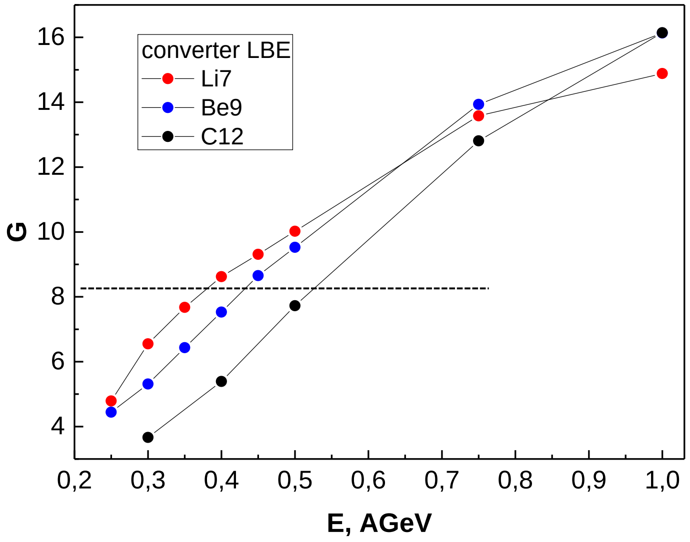
Energy gain for protons in target with converter LBE and Be

- metallic target with dimensions L150-R90-r0.5-d2
- linear accelerator (we used the data from European Spallation Source (ESS) project)
-reference particle proton 2.5 GeV
- the accelerator efficiency for the reference particle η 0.18
- the conversion coefficient from thermal to electrical power η_{el} 0.4

I_{beam} 1.25·10^{16}particles/s

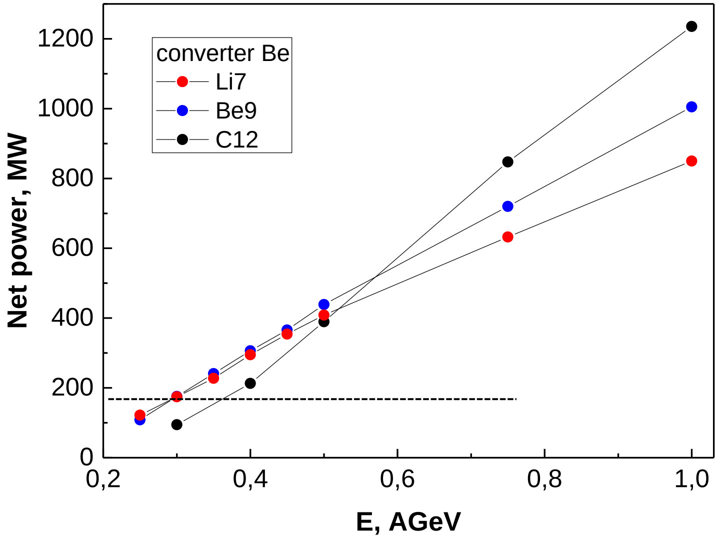


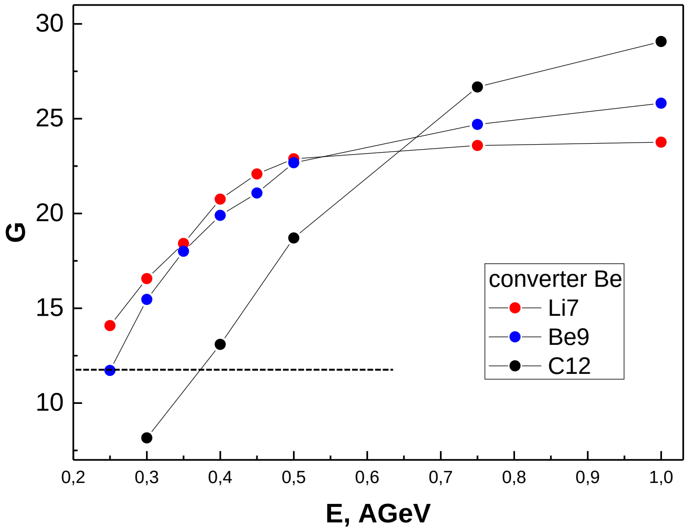
Net power production for light ions in target with converter LBE



Energy gain for light ions in target with converter LBE

Net power production and energy gain in target with converter Be





Net power production for light ions in target with converter Be

Energy gain for light ions in target with converter Be

Conclusions

The energetic efficiency depends on the beam and accelerator type. The optimal energy of proton beam is 2-3 GeV in synchrotron, 1.5 GeV in linac, and 1 GeV in cyclotron. Ions starting with Li, accelerated in linac or synchrotron have a higher energetic efficiency than protons. The optimal energy for ions increases with the ion mass.

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.

Convertors 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 refueling.

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 ^{11}B, and ^{12}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}Li beam with an energy of 0.3-0.35 AGeV and a target with converter of Be and cooling with Pb or LBE.

References

1. C. Rubbia et al., ” An Energy Amplifier for cleaner and inexhaustible nuclear energy production driven by a particle beam accelerator”. CERN/AT/93-47, November 1993

2. H. A. Abderrahim, P. Kupschua, E. Malambu, Ph. Benoit, K. Van Tichelen, B. Arien, F. Vermeersca, P. D’hondt, Y. Jongen, S. Ternier, D. Vandeplassche,” MYRRHA: A multipurpose accelerator driven system for research & development”, Nuclear Instruments and Methods in Physics Research A 463 (2001) 487–494

3. Kairat Ismailov, Masaki Saito, Hiroshi Sagara, Kenji Nishihara,” Feasibility of uranium spallation target in accelerator-driven system”, Progress in Nuclear Energy 53 (2011) 925-929

4. Pronskikh V., Mokhov N. V., Novitski I., Tyutyunikov S. I., "Energy production demonstartion for MW proton beams",12th Meeting on Shielding Aspects of Accelerators, Targets and Irradiation Facilities (SATIF-12), April 28-30, 2014, Fermi National Accelerator Laboratory, Batavia, Illinois, USA.

5. S.R. Hashemi-Nezhad , W. Westmeier, M. Zamani-Valasiadou, B. Thomauske, R. Brandt,” Optimal ion beam, target type and size for accelerator driven systems:Implications to the associated accelerator power”, Annals of Nuclear Energy 38 (2011) 1144–1155

6.Ridikas D., Mittig W., “Neutron production and energy generation by energetic projectiles: protons or deuterons?”, Nuclear Instruments and Methods in Physics Research A 418 (1998) 449-457

7. Кошкарев Д. Г., "Оптимальные ионы для ядерного реактора с нейтронной подсветкой", Журнал технической физики 2004, том 74, вып. 7;

8. A. A. Baldin, A. I. Berlev, M. Paraipan, and S. I. Tyutyunnikov, Optimization of Accelerated Charged Particle Beam for ADS Energy Production, Physics of Particles and Nuclei Letters, 2017, Vol. 14, No. 1, pp. 113–119

THANK YOU FOR ATTENTION !