14.03.2016г.

Conceptual Design of Accelerator Driven Systems with Light Ion Beams

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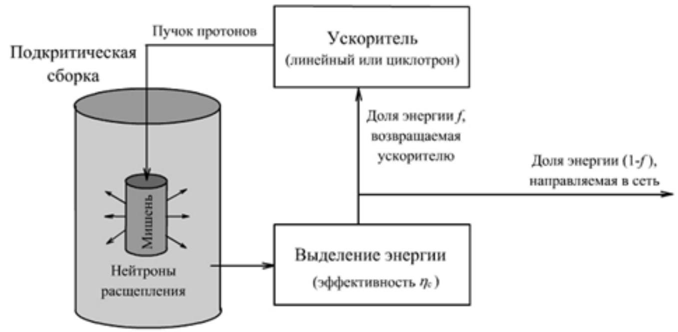
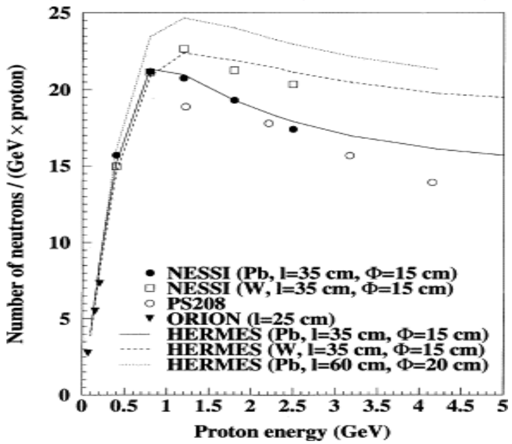
ADS for transmutation and energy amplifier

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

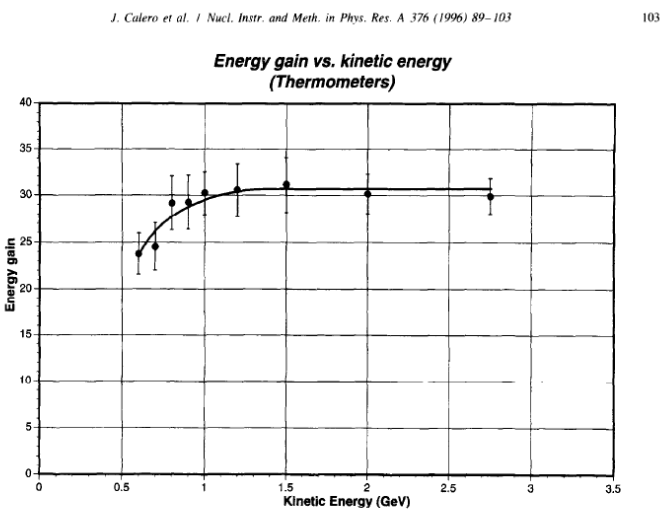


Neutron yield from heavy metal targets

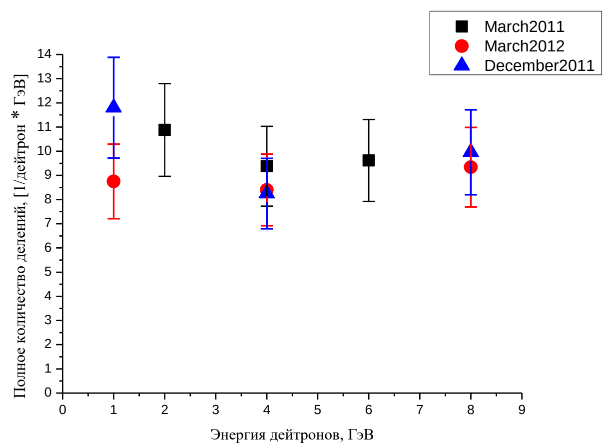


F. Carminati, C. Geles, R. Klapisch, J. P. Revol, Ch. Roche, J. A. Rubio, C. Rubbia,An Energy Amplifier for Cleaner and Inexhaustible Nuclear Production Driven by a Particle Beam Accelerator, CERN/AT/93-47 (ET) 1993

FEAT experiment (CERN)



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



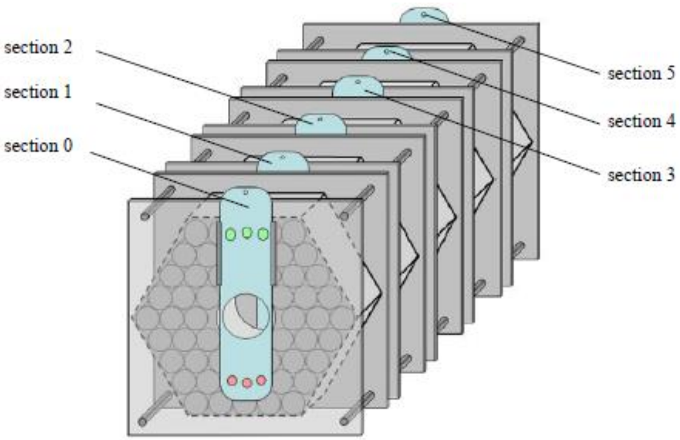
Energy gain for proton and ion beams

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

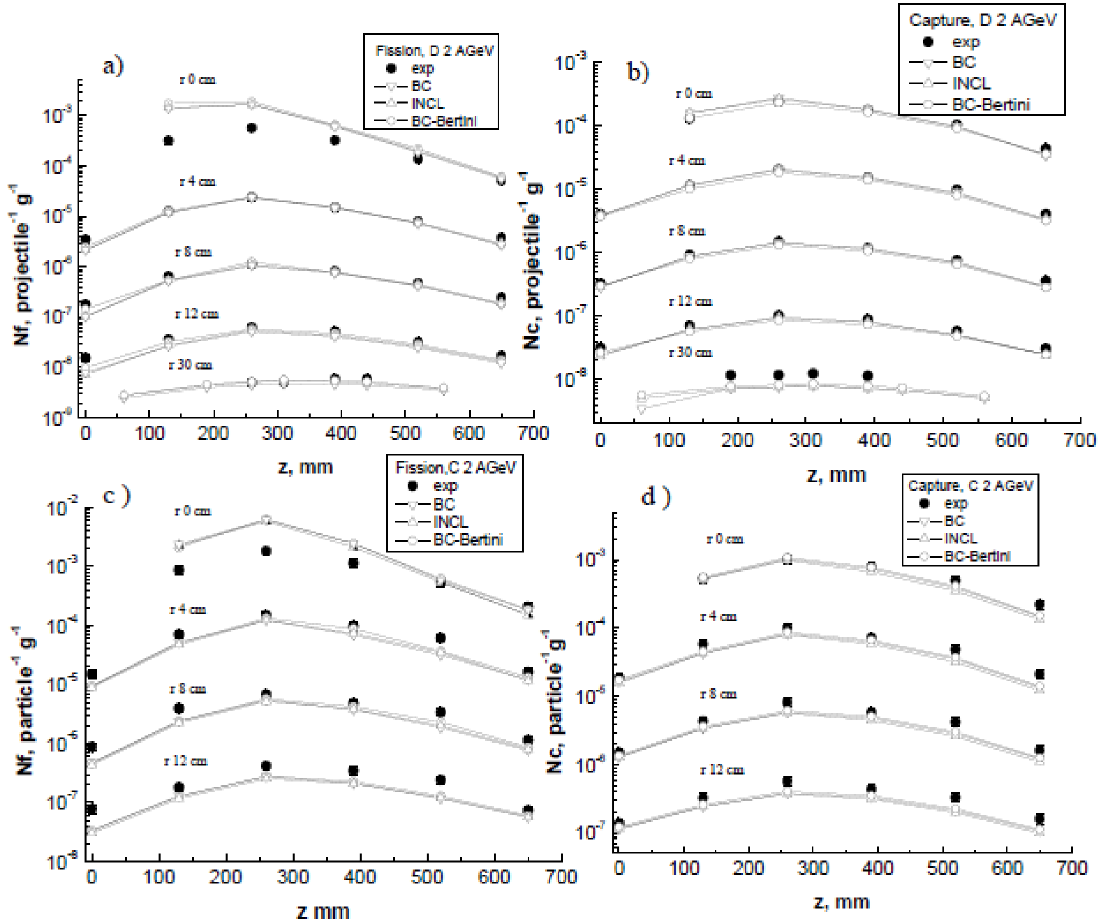
$$G = \frac{P_{prod}}{P_{spent}}$$

- 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 Geant simulation with experimental data obtained in extended U target



The scheme of the target Quinta



Experimental and simulated distribution of fission and capture in extended U target irradiated with deuteron 2 AGeV (up) and carbon 2 AGeV (down) Phys. Part. Nucl. 13 2 (2016) 391-402.

Comparison between Geant4, MCNPX, SHIELD

- **Fission, capture and neutron production in cylindrical natural U target**

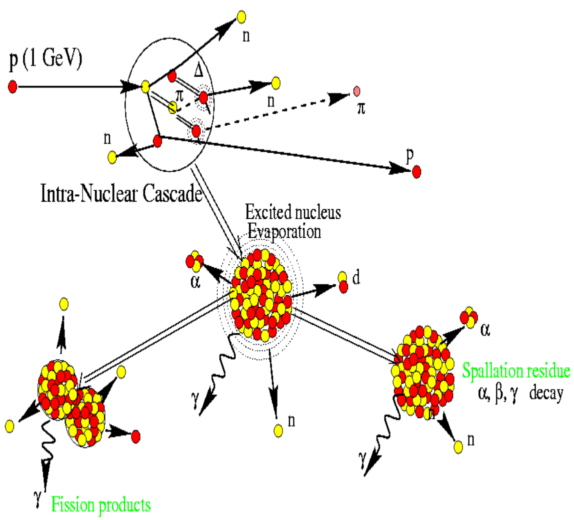
Target R15 cm, L 40 cm

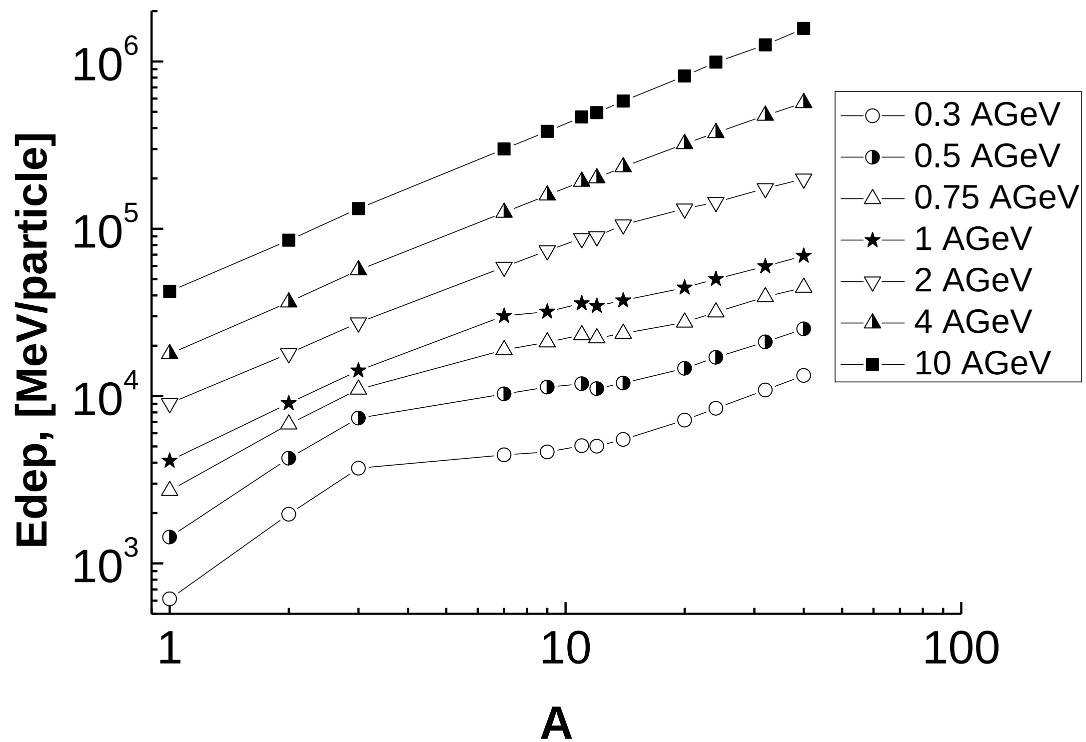
Ep, GeV	Neutron produced/part			Fissions/part			Captures/part		
	Geant4	SHIELD	MNCP	Geant4	SHIELD	MNCP	Geant4	SHIELD	MNCP
0.66	42	42	40	6.7	9.6	5	7.2	8.3	8
1	78	72	72	11	11.4	9	13.7	14.9	14
2	164	148	151	22.8	23	22	28.4	31	31
4	306	272	270	42.5	43	42	53.6	56	64

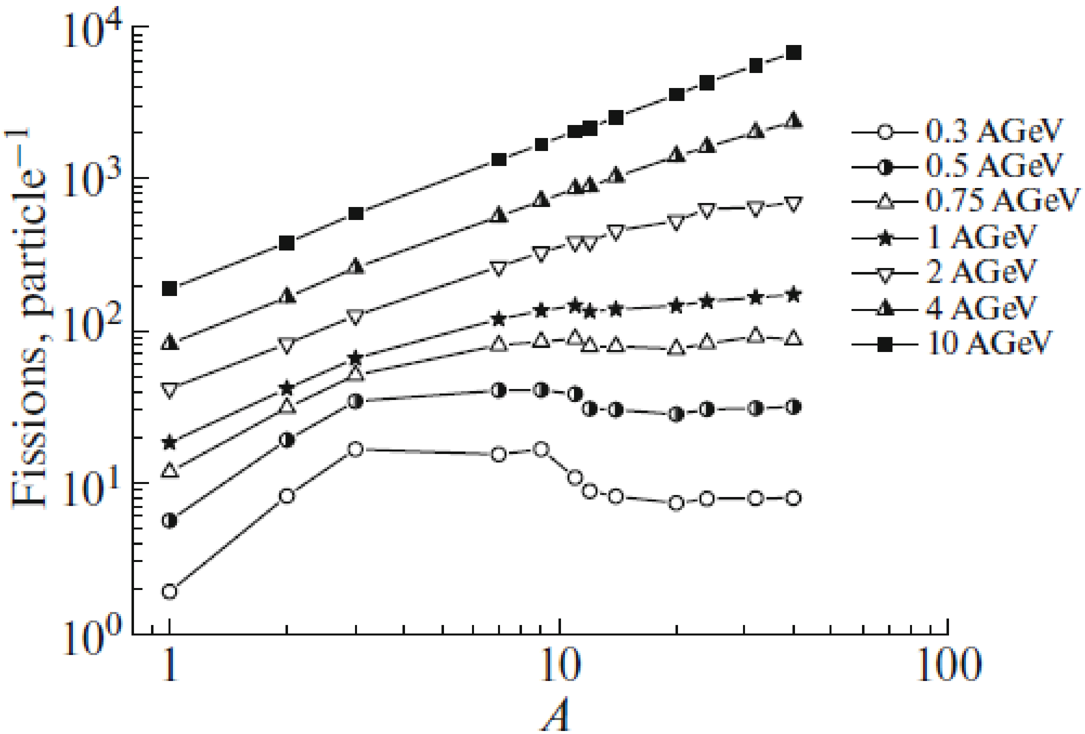
Target R 60 cm, L 160 cm

Ep, GeV	Neutron produced/part			Fissions/part			Captures/part		
	Geant4	SHIELD	MNCP	Geant4	SHIELD	MNCP	Geant4	SHIELD	MNCP
0.66	50	51	61	7.4	9.6	7	22	26	24
1	95	89	96	14.2	15	11	46	49	45
2	215	197	217	32	33	26	110	114	104
4	412	375	439	61	64	55	217	226	234

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

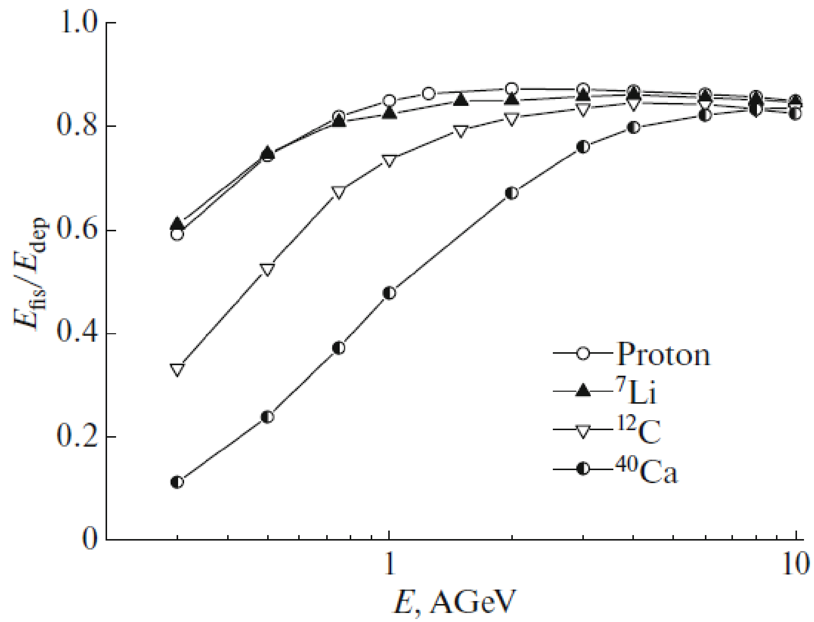






The dependence of the total number of fission on the projectile mass and energy.

The contribution of the fission to the total energy deposited as a function of the kinetic energy of the projectile.



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:

$$\varepsilon_r = \frac{G}{G_0} = \frac{P_{prod}}{P_{spent}} \frac{P_{spent\,0}}{P_{prod0}}$$

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

$$I \cdot E_o = \eta_o \cdot P_{spent}$$

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:

$$\varepsilon_r(Z, A, E) = \frac{E_{\text{dep}}}{E_{\text{dep0}}} \frac{1}{A\left[\eta_0 \frac{E}{E_0} + \frac{p(1-\eta_0)}{Zp_0} \right]}$$

The relative efficiency in a cyclotron is:

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

The relative efficiency in a linac is:

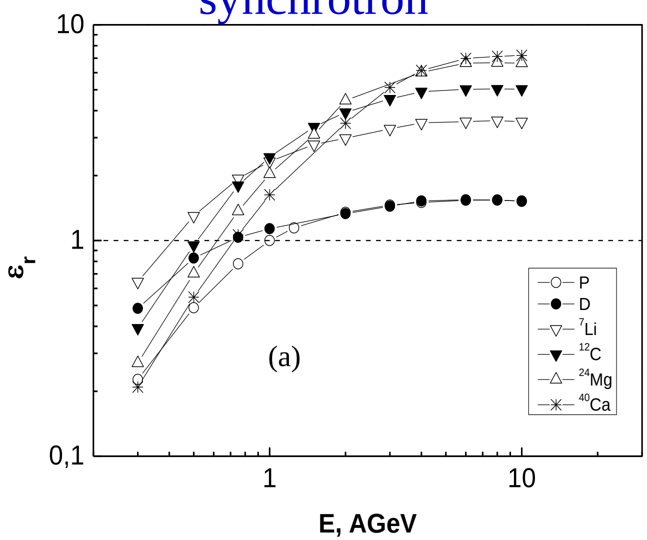
$$\varepsilon_r(Z, A, E) = \frac{E_{\text{dep}}}{E_{\text{dep0}}} \frac{Z \cdot E_0}{A \cdot E[\eta_0 Z + 1 - \eta_0]}$$

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.

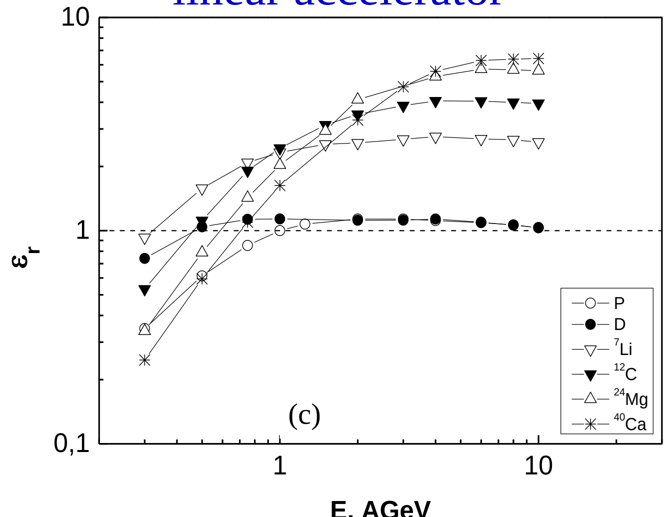
synchrotron



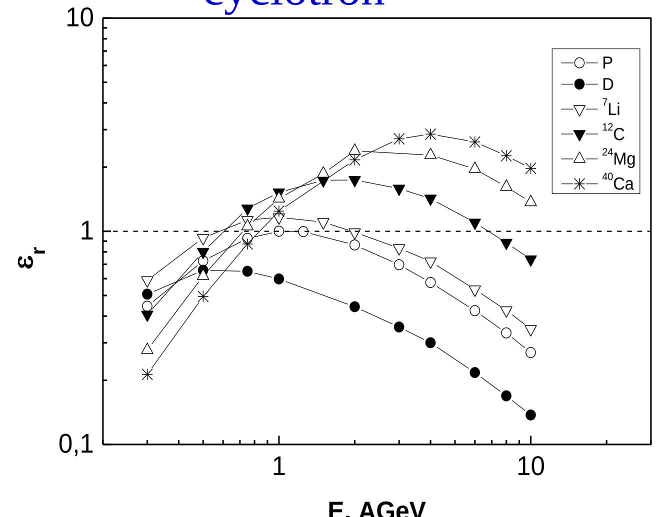
Relative (with respect to protons) ion efficiency as a function of beam energy for beams accelerated in a synchrotron, cyclotron, and a linear accelerator.

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

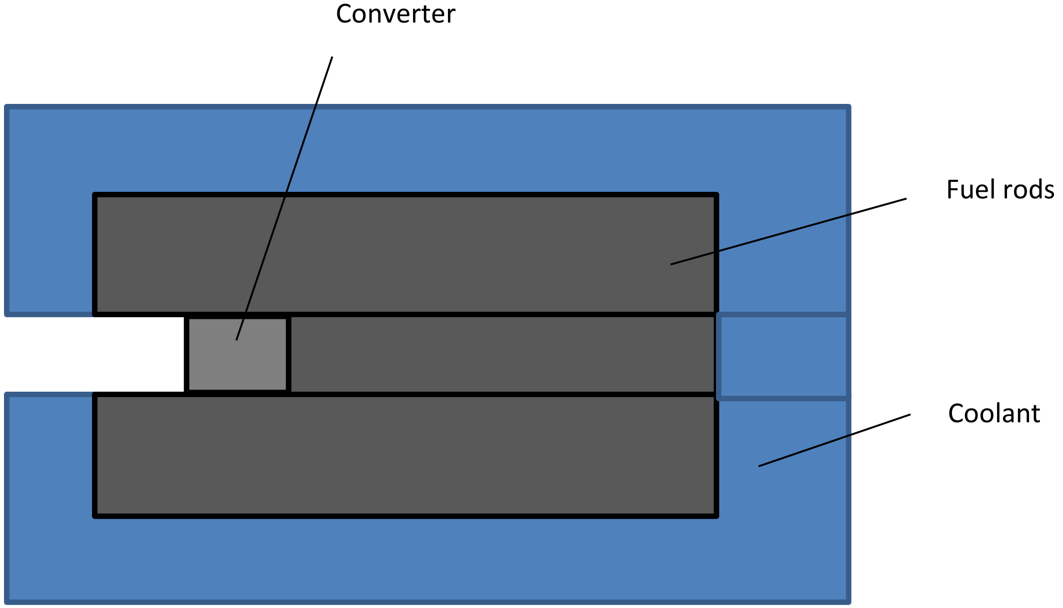


cyclotron



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 0.35AGeV	Li 0.45 AGeV	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

The cooling agent

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

.

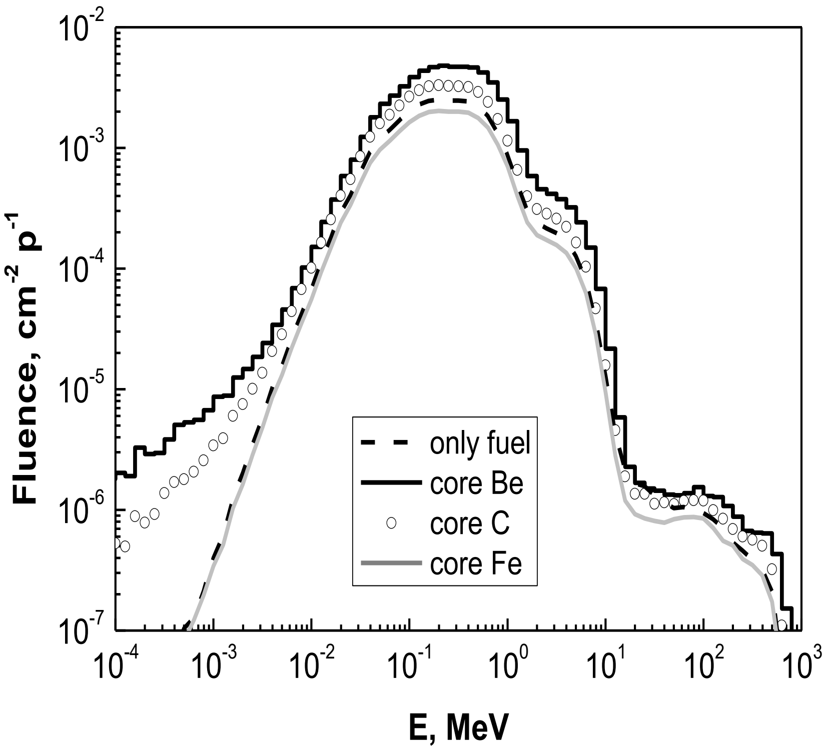
Ion	LBE	Pb	Na	Na + 20.5% U235	Na + layer 60 cm Pb
Li7	1.212e5	1.179e5	2.728e4	1.2289e5	1.173e5
Proton	2.146e5	2.037e5	5.028e4	2.165e5	2.101e5

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	$1.93 \cdot 10^5$

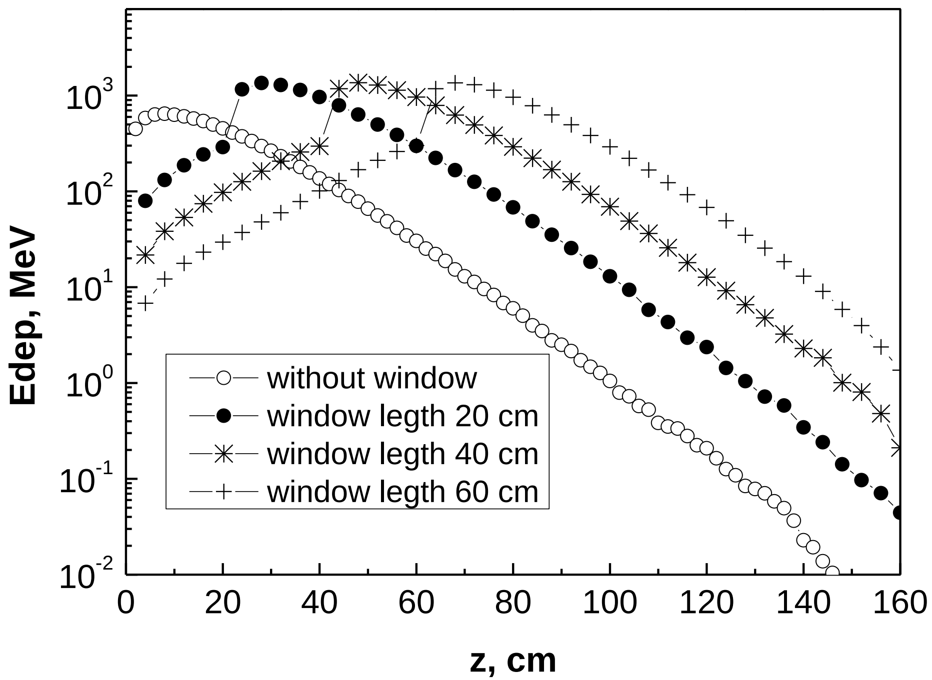


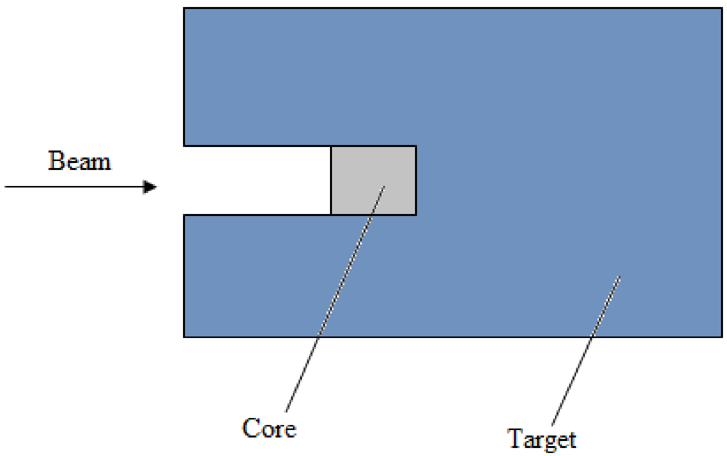
. Average neutron fluence in the enriched U target without a converter U, Be, C and Fe, irradiated by the 0.5 AGeV ^{7}Li beam.

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.

Optimal length of the beam window

The Z dependence of the energy released in ^{nat}U target (integrated on R) for a beam of protons with energy 2 GeV.



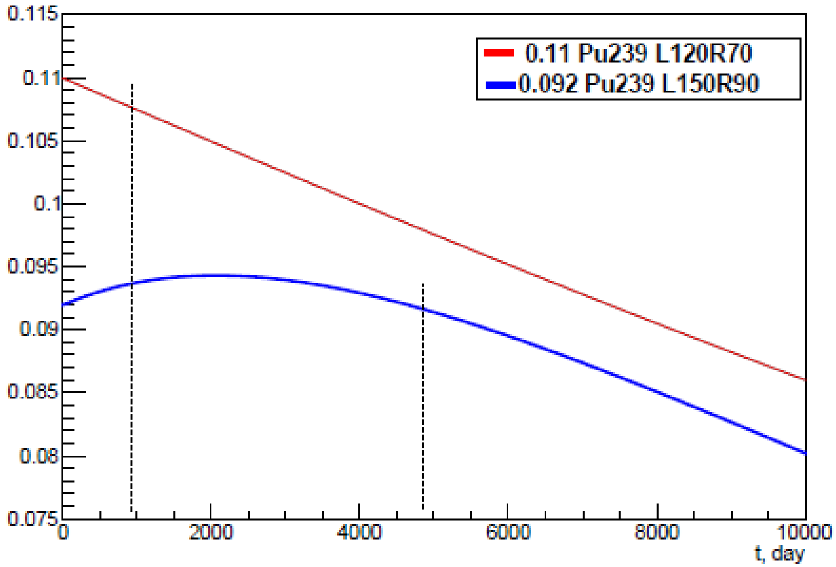


The deposited energy as a function of the beam window length in natural and enriched U targets.

	Deposited energy, MeV/p			
Window length, cm	0	20	**40**	60
^{nat}U target	$9.04 \cdot 10^{3}$	$1.03 \cdot 10^{4}$	**$1.07 \cdot 10^{4}$**	$1.08 \cdot 10^{4}$
Enriched U	$1.17 \cdot 10^{5}$	$1.93 \cdot 10^{5}$	**$2.64 \cdot 10^{5}$**	$2.83 \cdot 10^{5}$

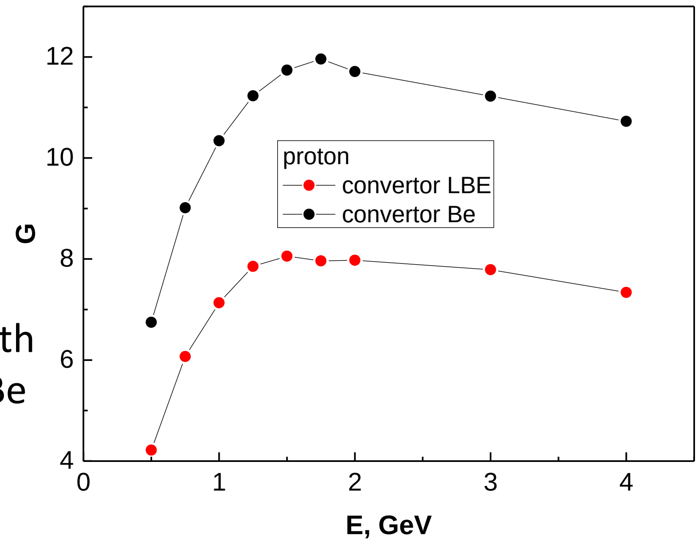
The choice of target dimensions

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.



The time evolution of the Pu239 concentration for two initial levels of enrichment.

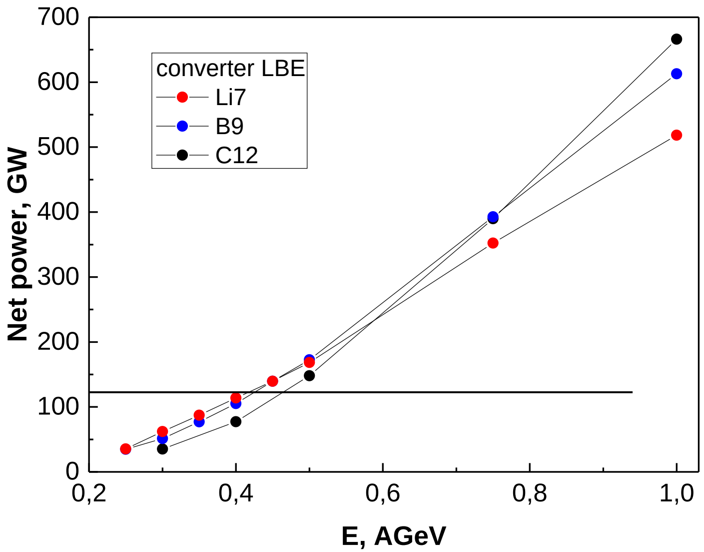
Energetic efficiency in U-Pu target



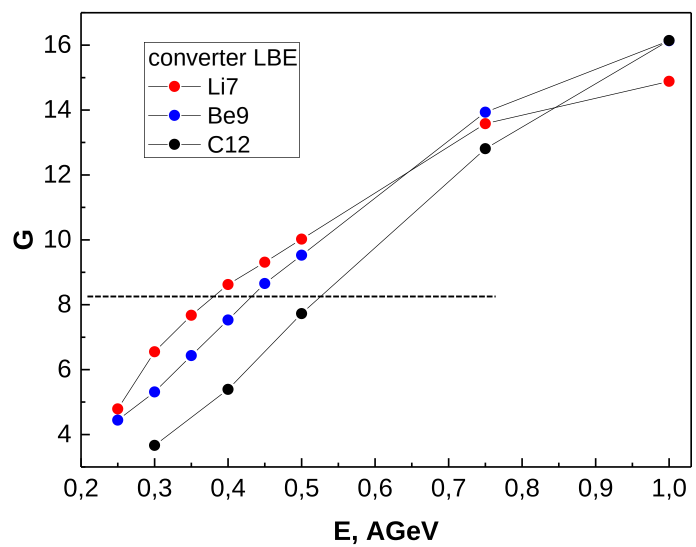
Energy gain for protons in target with converter LBE and Be

- 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

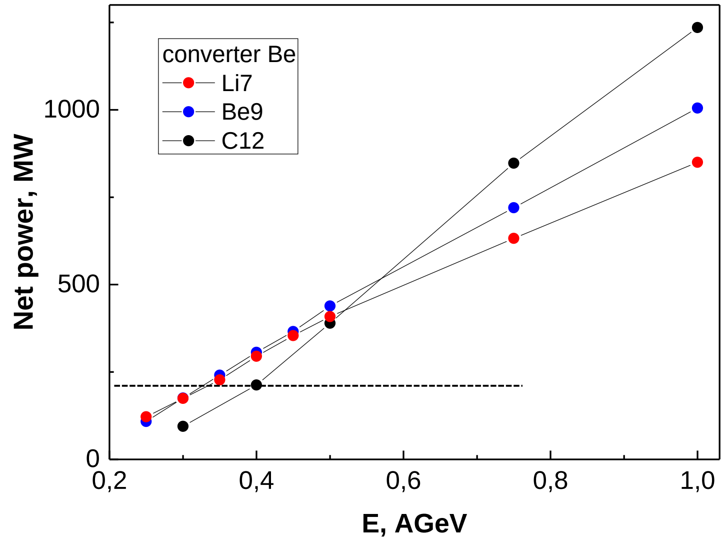


Net power production for light ions in target with converter LBE

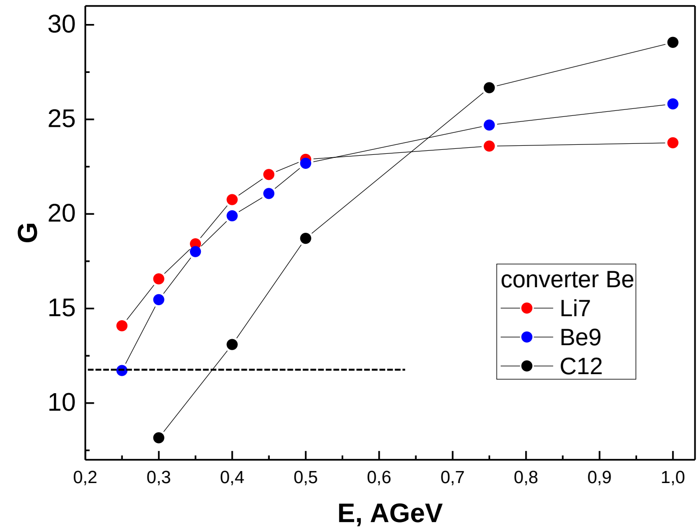


Energy gain for light ions in target with converter LBE

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. The optimal energy for ion beams depends on the type of the ion (1.5-2 AGeV for ^{7}Li, 2 AGeV for ^{12}C, 4 AGeV for ^{40}Ca) and the efficiency is significantly higher (more than 2 times) than for protons.

Targets with various composition, cooled with metal (Pb, LBE, Na) keep 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.

Ion beams present a superior energetic efficiency comparing with protons. 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.

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THANK YOU FOR ATTENTION !