14.03.2016г.

LIGHT ION BEAMS FOR ENERGY PRODUCTION IN ACCELERATOR DRIVEN SYSTEMS

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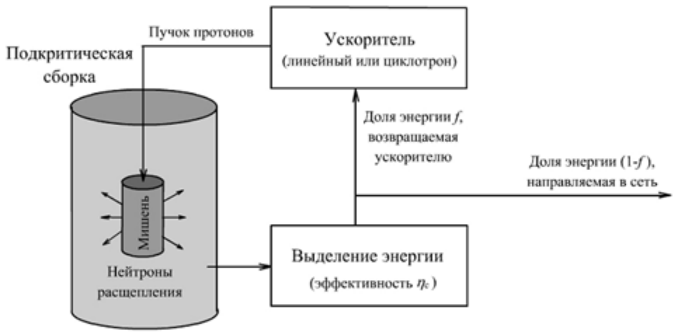
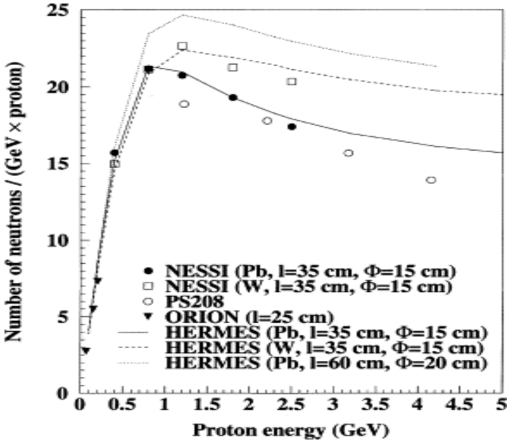
MMCP July 3-7 2017, Dubna

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)

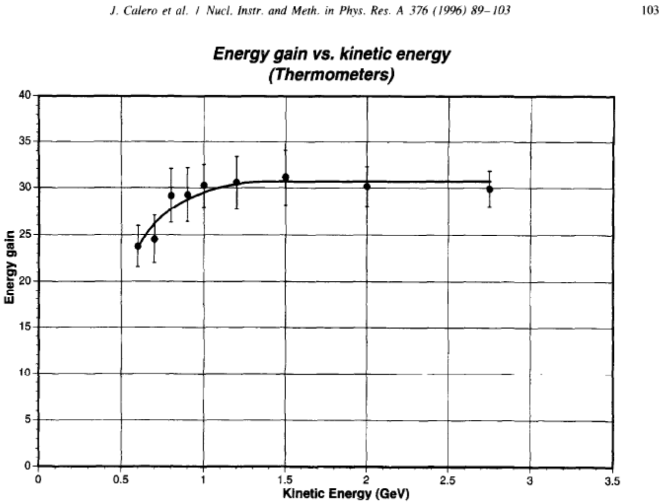


Neutron yield from heavy metal targets



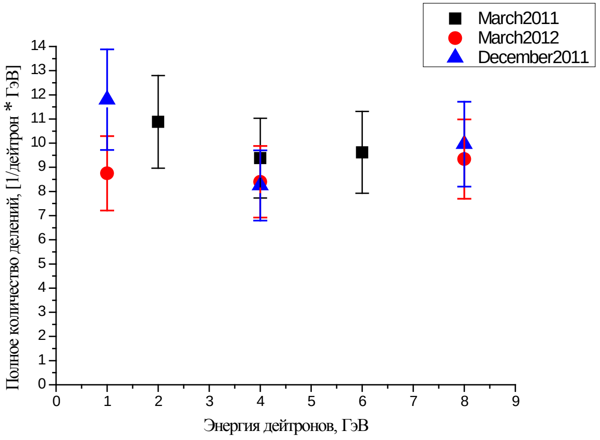
F. Carminati, C. Geles, R. Klapisch, J. P. Revol, Ch. Roche, J. A. Rubio, C. Rubbia, An Energy Amplifier for Cleaner and Inexhaustible Nuclear Production Driven by a Particle Beam Accelerator, CERN/AT/93-47 (ET) 1993

FEAT experiment (CERN)


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

Energy gain vs. kinetic energy
(Thermometers)

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



Energy gain for proton and ion beams

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 are analyzed.

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

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

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

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

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

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

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

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:

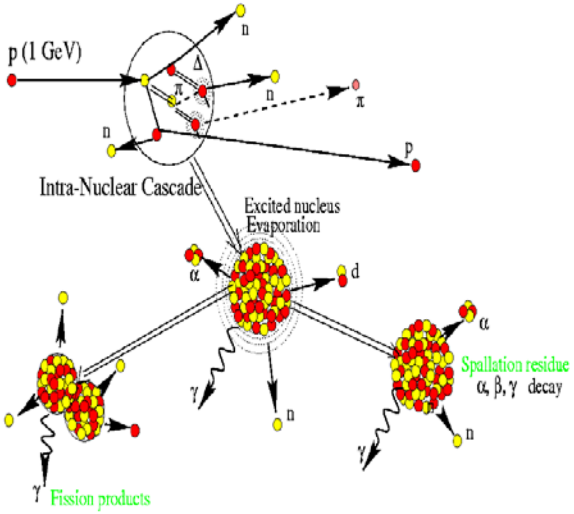
$$\varepsilon_r(Z, A, E) = \frac{E_{\mathrm{dep}}}{E_{\mathrm{dep0}}} \frac{1}{A\left[\eta_0 \frac{E}{E_0} + \frac{A}{Z^2} \frac{p^2(1-\eta_0)}{p_0^2} \right]}$$

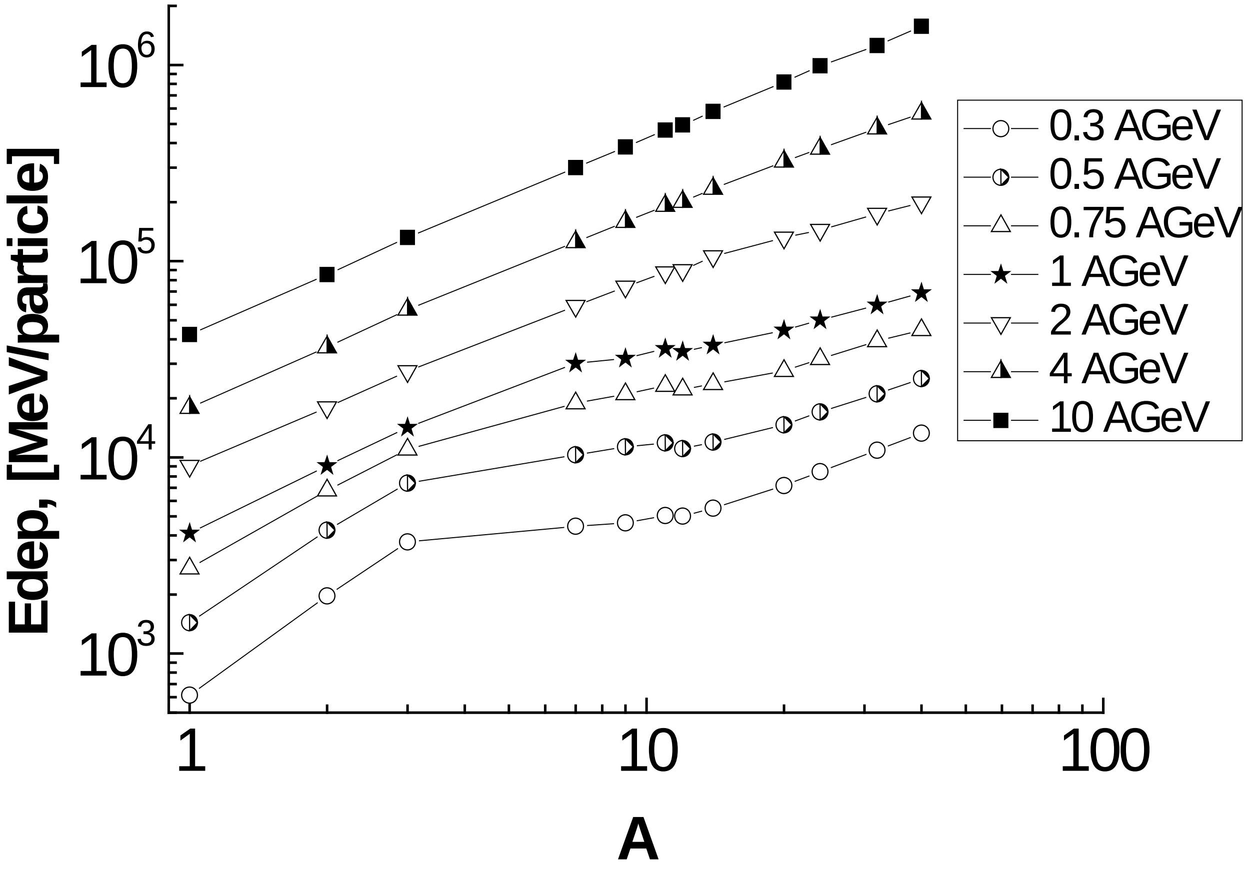
The relative efficiency in a linac is:

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

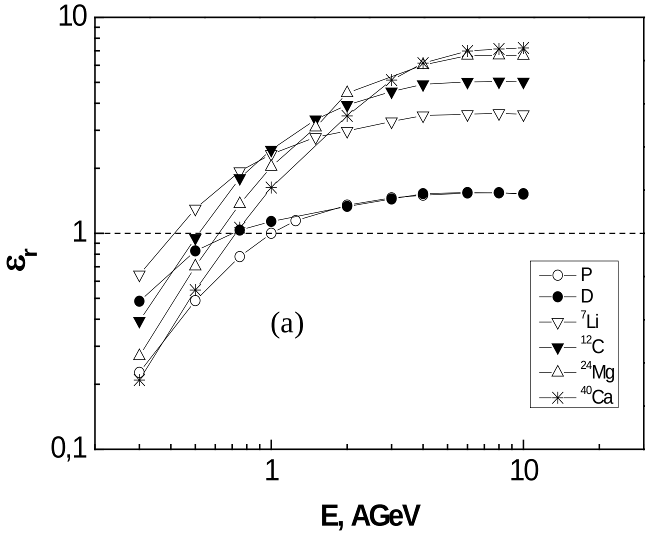
E_{dep} and E_{dep0} are the energies released obtained with the analyzed particle, respective the reference particle.

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





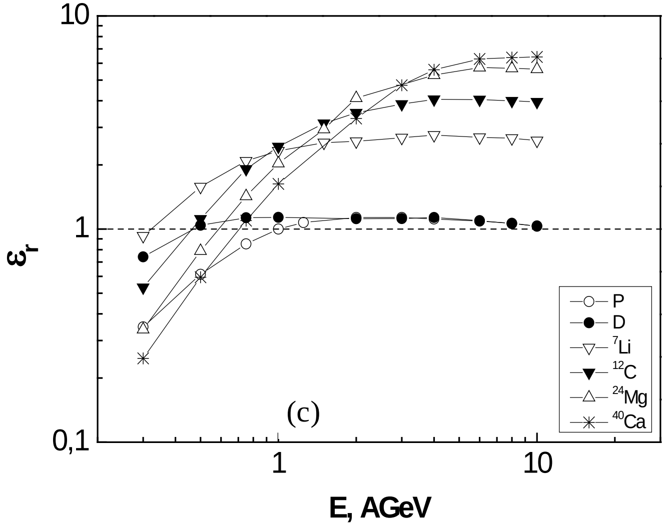
synchrotron



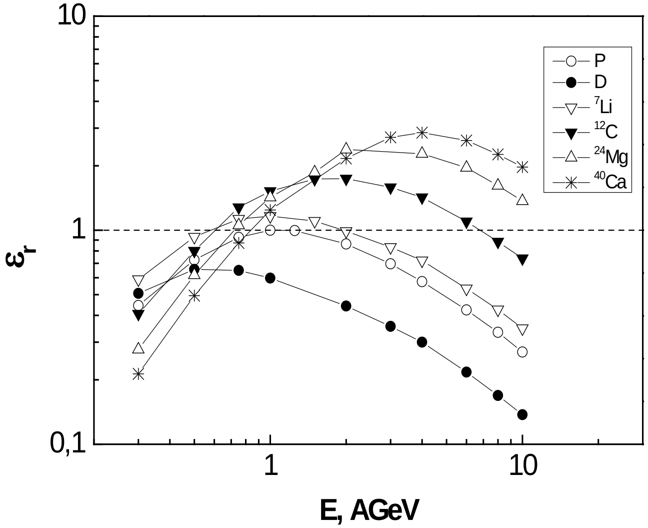
Relative (with respect to protons) ion efficiency as a function of beam energy for beams accelerated in a synchrotron, cyclotron, and a linear accelerator.

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



Power production in enriched U target

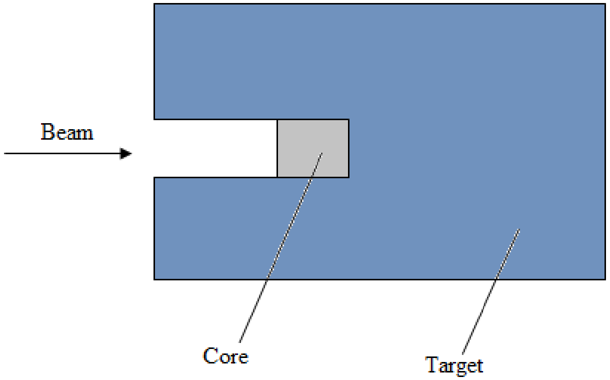
- target U(5.7 % 235) L 200 cm, R 100 cm, beam windows length 40 cm.
- linear accelerator (we used the data from European Spallation Source (ESS) project)
- reference particle proton 2.5 GeV
- the accelerator efficiency for the reference particle η 0.18
- the conversion coefficient from thermal to electrical power η_{el} 0.4

I_{beam} 1.25·10^{16} particles/s

Energy released, gain factor and net electrical power produced in target with k_{eff} 0.96

Particle	E_{beam} , AGeV	Fuel		
		E_{dep}, MeV	G	Net power, MW
proton	1	1.09·10^5	7.3	75.6
	1.5	**1.85·10^5**	**8.23**	**130.2**
	2	2.49·10^5	8.32	175.6
^{7}Li	0.3	8.49·10^4	6.06	56.7
	0.4	**1.53·10^5**	**8.19**	**107.3**
	0.5	**2.39·10^5**	**10.3**	**172.9**
	0.75	4.99·10^5	14.3	371.4
	1	7.19·10^5	15.4	537.7
^{9}Be	0.4	1.5·10^5	7.39	120
	0.5	**2.5·10^5**	**9.86**	**200**
^{12}C	0.3	5.5·10^4	3.3	30.8
	0.4	1.08·10^5	4.9	68.6
	0.5	1.93·10^5	7	132.5
	0.75	**4.8·10^5**	**11.6**	**351.3**

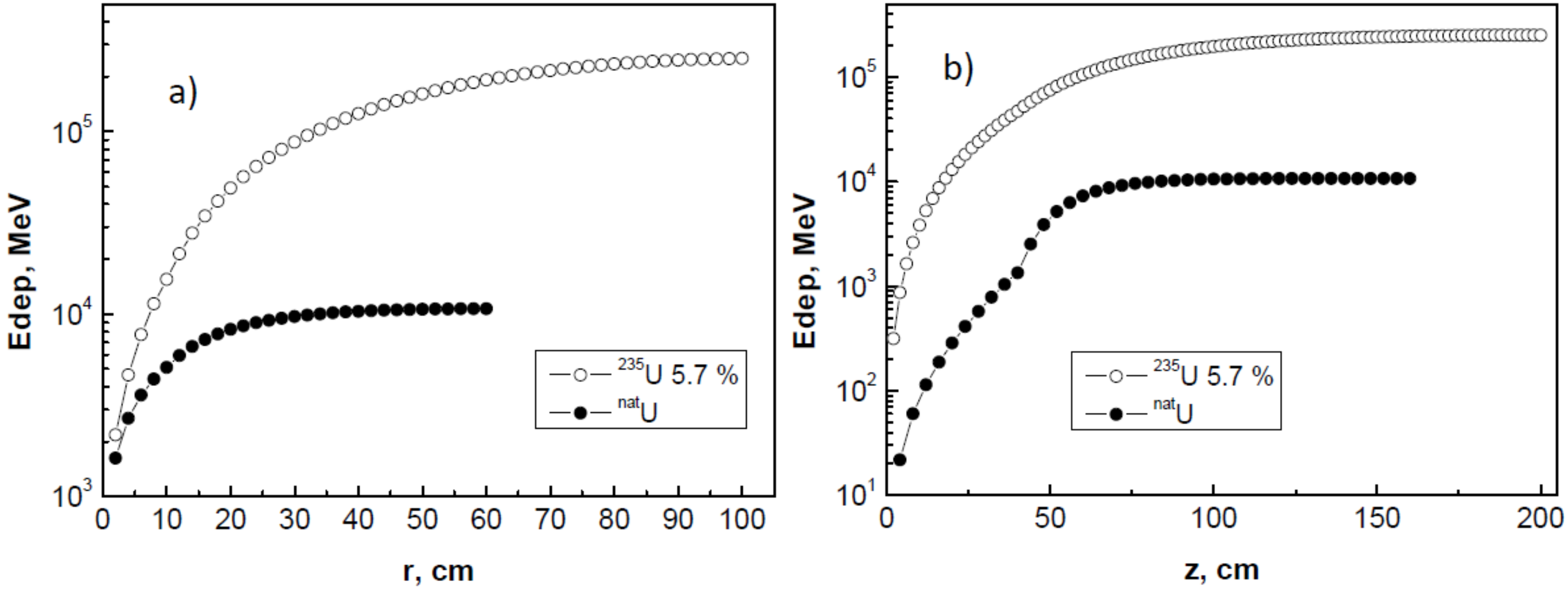
Target optimization



1. **Target dimensions and material**
2. **Dimensions of the beam window**
3. **Core**

^{nat}U target L 160 cm R 60 cm - k_{eff} 0.48
enriched U target (5.7 % ^{235}U) L 200 cm R 100 cm - k_{eff} 0.96

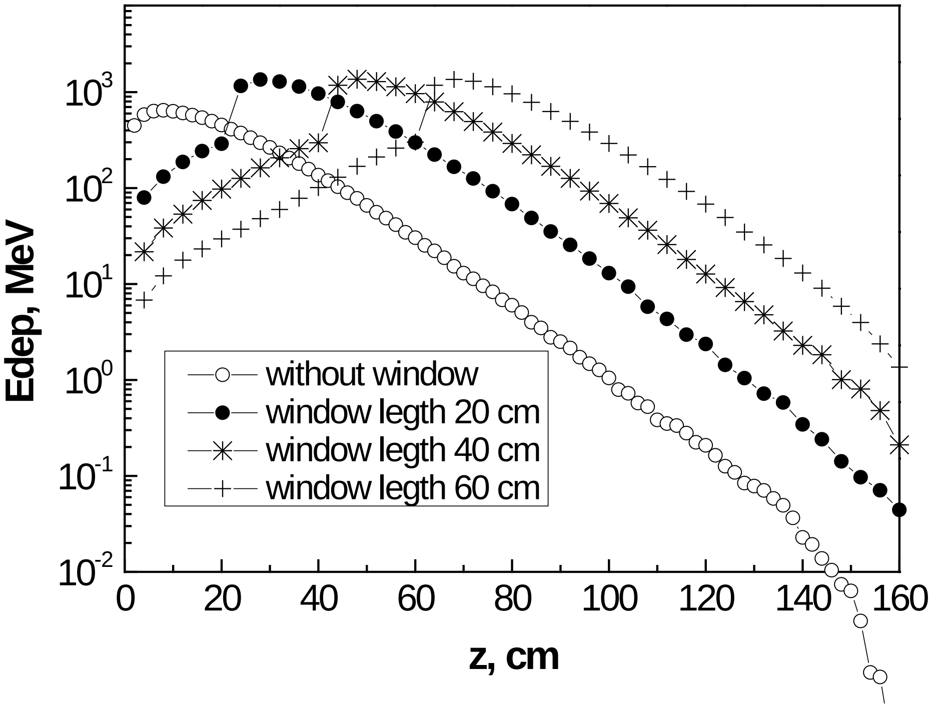
In enriched target the quasi-infinite conditions are reached at higher dimensions.

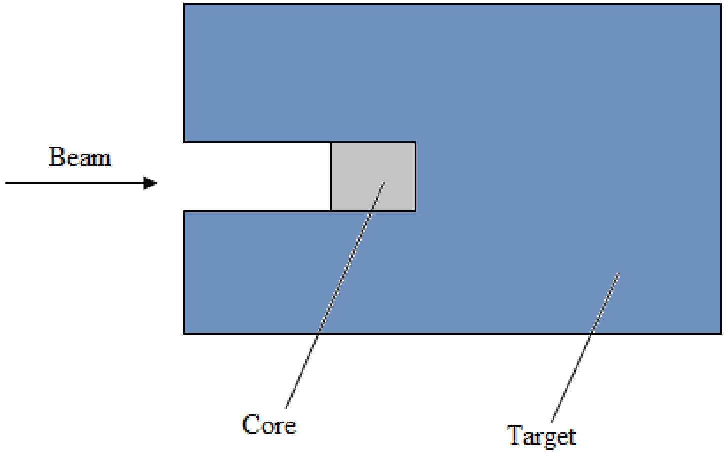


The energy released in the target Edep (integrated on Z and R) as a function of the target (a) radius and (b) length for a ^{nat}U and enriched U targets irradiated with 2 GeV protons.

2. 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.





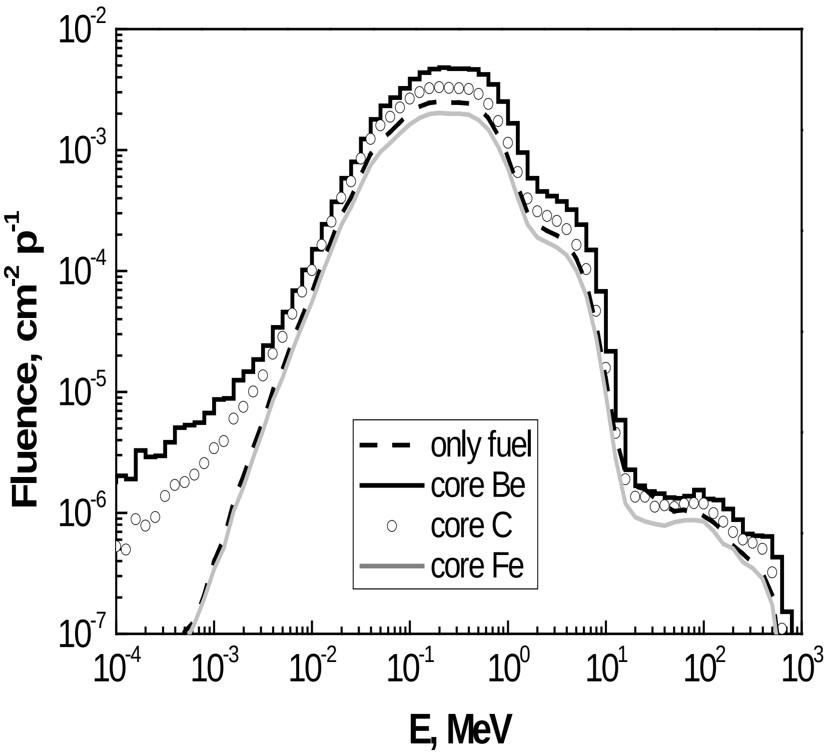
The deposited energy as a function of the beam window length in natural and enriched U targets.

	Deposited energy, MeV/p			
Window length, cm	0	20	**40**	60
^{nat}U target	$9.04\cdot10^{3}$	$1.03\cdot10^{4}$	**$1.07\cdot10^{4}$**	$1.08\cdot10^{4}$
Enriched U	$1.17\cdot10^{5}$	$1.93\cdot10^{5}$	**$2.64\cdot10^{5}$**	$2.83\cdot10^{5}$

3.Core from different materials

Neutron yield from the core and energy released in the enriched uranium target with the core 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	$2.39\cdot10^{5}$
Li	70	5.7	2.64	$3.37\cdot10^{5}$
Be	**60**	**15.2**	**4.02**	**$5.06\cdot10^{5}$**
C	51	8.2	3.25	$3.06\cdot10^{5}$
Al	43	10.2	2.82	$2.78\cdot10^{5}$
Fe	16	14.5	2.12	$1.93\cdot10^{5}$



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

Target core from very low Z materials (Li, Be, C) increases the energy released for light ions at low energy 1.4-2 times.

The effect depends on beam window length and is higher in enriched target.

The energy released for targets with core from Be (radius 10 cm, length 24 cm) and different lengths of the beam window irradiated with ^{7}Li 0.3 AGeV.

Beam window length, [cm]	**natural U target** Edep [MeV/part]		**U target (5.7 % ^{235}U)** Edep [MeV/part]	
	only U	core Be (coreBe/onlyU)	only U	core Be (coreBe/onlyU)
0	$4.23\cdot10^{3}$	$6.99\cdot10^{3}$ **(1.65)**	$3.09\cdot10^{4}$	$1.2\cdot10^{5}$ **(3.88)**
20	$5.02\cdot10^{3}$	$7.35\cdot10^{3}$ **(1.46)**	$5.97\cdot10^{4}$	$1.49\cdot10^{5}$ **(2.5)**
40	$5.28\cdot10^{3}$	$7.52\cdot10^{3}$ **(1.42)**	$8.49\cdot10^{4}$	$1.8\cdot10^{5}$ **(2.12)**

Energy released, gain factor and net electrical power produced in target with Be core

Particle	E_{beam} , AGeV	Core Be		
		E_{dep}, MeV	G	Net power, MW
proton	1	$1.25\cdot10^{5}$	8.64	88.1
	1.5	**$2.18\cdot10^{5}$**	**9.68**	**156.3**
	2	$2.94\cdot10^{5}$	9.8	211.2
^{7}Li	**0.3**	**$1.79\cdot10^{5}$**	**12.8**	**132.1**
	0.4	**$3.21\cdot10^{5}$**	**17.2**	**242.1**
	0.5	$4.65\cdot10^{5}$	19.9	353.1
	0.75	$7.7\cdot10^{5}$	22	588.1
	1	$1.07\cdot10^{6}$	22.8	814.7
^{9}Be	**0.4**	**$3.34\cdot10^{5}$**	**16.5**	**267**
	0.5	$5.3\cdot10^{5}$	20.9	424
^{11}B	**0.4**	**$3.21\cdot10^{5}$**	**14.6**	**256**
	0.5	$5.21\cdot10^{5}$	18.9	417
	0.75	$1.08\cdot10^{6}$	26.2	863
^{12}C	0.3	$1.22\cdot10^{5}$	7.4	84.7
	0.4	**$2.62\cdot10^{5}$**	**11.9**	**191.9**
	0.5	$4.68\cdot10^{5}$	17	352.1
	0.75	$1.03\cdot10^{6}$	25	793.4
	1	$1.5\cdot10^{6}$	27.3	1155.2

Conclusions

The optimal energy of proton beam 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}Li, 2 AGeV for ^{12}C, 4 AGeV for ^{40}Ca) and the efficiency is significantly higher (more than 2 times) than for protons.

The optimal length of the beam window is 1/5-1/4 from the target length.

The core from low Z materials (Li, Be and C) increases the deposited energy by a factor of 1.3 -2 for light ions with the energy below 0.5 AGeV.

Light ions ^{7}Li and ^{9}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}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 AGeV and a target with core of Be.

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