BEAM POWER GAIN FOR MASSIVE URANIUM TARGET UNDER RELATIVISTIC PROTON, DEUTERON AND CARBON NUCLEI IRRADIATION

V.A. Voronko[1], *V.V. Sotnikov*[1], *A.A. Zhadan*[1],
I. Adam[2], *A.A. Baldin*[2], *A.I. Berlev*[2], *V.I. Furman*[2],
A.A. Solnyshkin[2], *S.I. Tyutyunnikov*[2],
K.V. Gusak[3], *I.V. Zhuk*[3]
P. Zhivkov[4]

[1]NSC Kharkov Institute of Physics and Technology, Kharkov, Ukraine;
[2]Joint Institute for Nuclear Research, Dubna, Russia;
[3]Joint Institute for Power and Nuclear Research, Minsk, Belarus;
[4]Institute of Nuclear Research and Nuclear Energy, Sofia, Bulgaria

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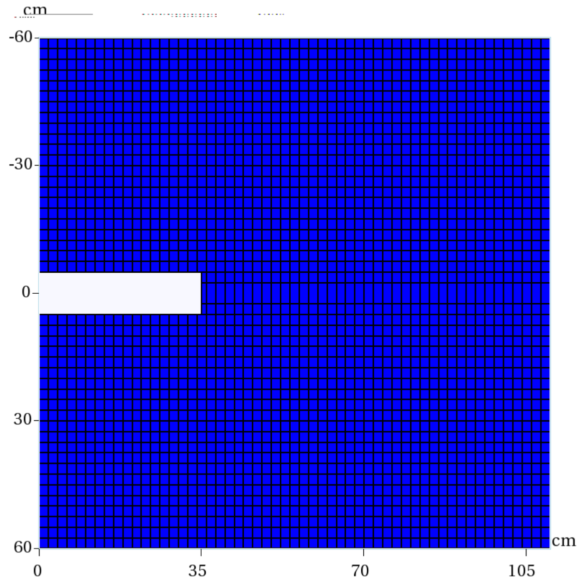
Introduction

The experimental study of the beam power gain for deep-subcritical uranium target assembly Quinta (mass of natural uranium 512 kg) under relativistic protons, deuterons and carbon nuclei irradiation is presented. The Quinta assembly was irradiated with 0.66 GeV protons, 1, 2, 4, and 8 GeV deuterons and 24, 48 GeV carbon nuclei from the Phasotron and Nuclotron accelerators at the Joint Institute for Nuclear Research (JINR), Dubna

Accelerator Driven System Concept

- Within the framework of the international project "Energy and Transmutation of RAW" a series of experiments aimed at the new ADS concept verification was carried out in 2011-2017 at the Nuclotron and Phasotron accelerators (JINR, Dubna). This system is intended for long-lived radioactive waste transmutation with simultaneous energy production.
- The basic physical idea of this approach is to use natural (depleted) uranium or thorium to create an ADS with a deep subcritical quasi-infinite (with negligible neutron leakage) multiplying target irradiated with protons, deuterons, or light nuclei with energy in the range 1…5 AGeV and possibly higher.
- In accordance with the experimental and theoretical results obtained over the last decades, such scheme can provide extremely hard neutron spectrum within the subcritical active core and ensure an effective burning of core material as well as spent nuclear fuel added to the initial core.

Quasi-infinite Uranium Target



R = 60 cm L= 110 cm

k_{eff} ~ 0.23

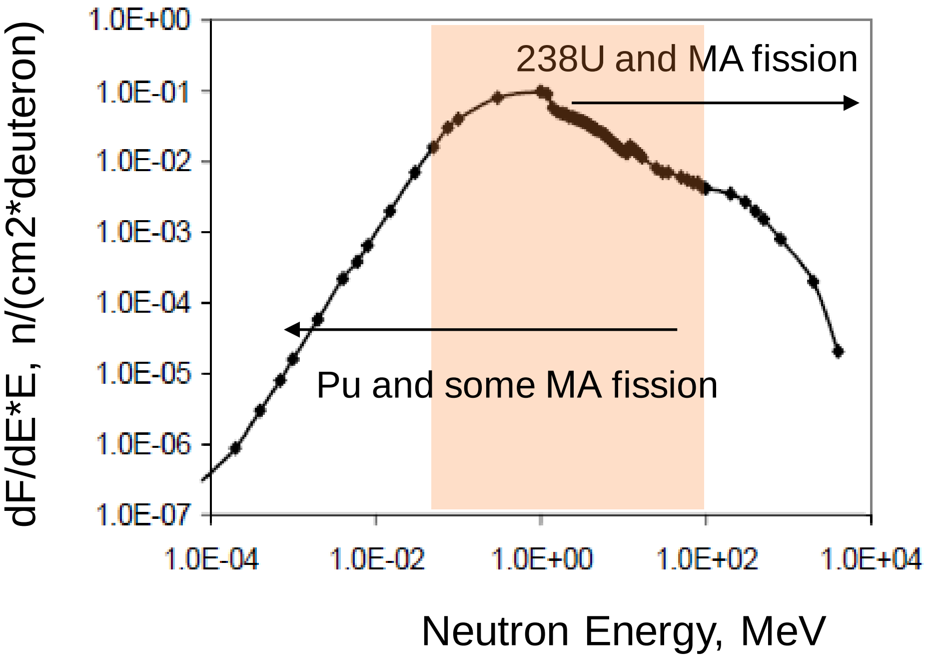
Neutron leakage from the uranium block surface < 7% (*V.S. Pronskich et al. // Annals of Nuclear Energy. 2017, v. 109, p. 692-697*)

Most of the neutrons in the neutron spectrum generated in the uranium target are concentrated in the energy range from tens of keV to ~ 100 MeV

238U(n,f) – neutron energy > 1 MeV

The neutron spectrum also contains a fast component, which is essential for transmutation via fast fission and other reactions.

Neutron spectrum in uranium target
MCNPx 8 GeV deuterons



Transmutation of Minor Actinides

Spent Nuclear Fuel (SNF) Content, g/t

$T_{1/2}$, years	Nuclide	VVER	RBMK	Nuclide	VVER	RBMK	$T_{1/2}$, years
	^{79}Se	5.9	3.5	^{237}Np	620	150	$2.1*10^6$
30	^{90}Sr	680	390	^{238}Pu	126	69	87.7
$1.5*10^6$	^{93}Zr	910	530	^{239}Pu	5330	2630	$2.4*10^4$
$2.1*10^5$	^{99}Tc	950	600	^{240}Pu	2420	2190	$5.56*10^3$
$6.5*10^6$	^{107}Pd	250	200	^{241}Pu	1470	710	14.4
105	^{126}Sn	22	15	^{242}Pu	580	510	$3.7.10^5$
$1.6*10^7$	^{129}I	220	140	^{241}Am	72	36	432
$2.3*10^6$	^{135}Cs	420	220	^{243}Am	10	74	737
30	^{137}Cs	1460	900	^{242}Cm	6.1	5.2	
87	^{151}Sm	15	4.0	^{244}Cm	46	8.1	18.1
				Minor Actinides			

In the fast neutron spectrum (> 1 MeV) the fission cross sections are 1-2 barn for all minor actinides. For fissile isotopes 239Pu and 241Pu the effective cross-section over the whole neutron spectrum will be an order higher. The possibility of transmutation and long-lived SNF fission fragments in such neutron spectra is also considered.

Beam Power Gain

From the point of view of the practical applicability of any ADS, the beam power gain of the beam of bombarding particles is crucial. For deep subcritical active core, studied in this project, the value of beam power gain, along with the maximum hard neutron spectrum, is determines the capabilities of the proposed ADS for SNF utilization with simultaneous energy production.

The beam power gain G can be determined by the following expression:

$$G = (E_p + n_f \cdot E_f) / E_p ,$$

where E_p *is the accelerated particle energy (GeV);*
n_f *is the uranium fission numbers in the uranium assembly per one accelerated particle;*
E_f *is the fission energy (0.197 GeV).*

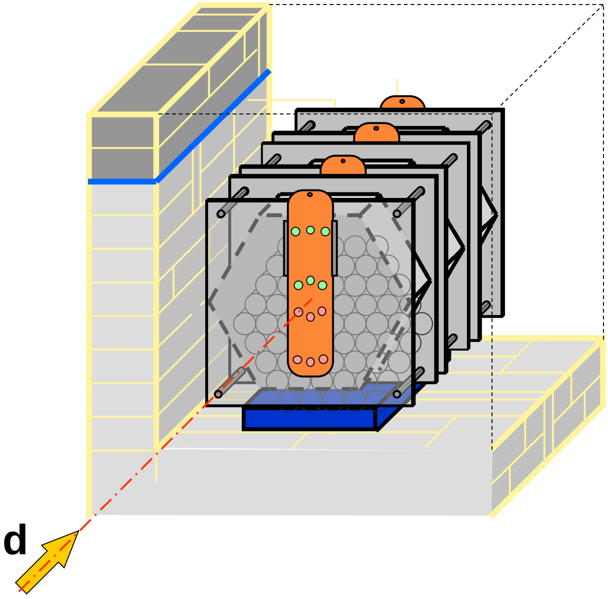
In this case, we assume that only a small fraction of the primary ion energy is out of the extended uranium target with γ-quanta, π^0 mesons and neutrons leakage. On the other hand, we take into account only the basic heat release due to the uranium fission, without taking into account other possible exothermic reactions on the secondary particles.

Experiment

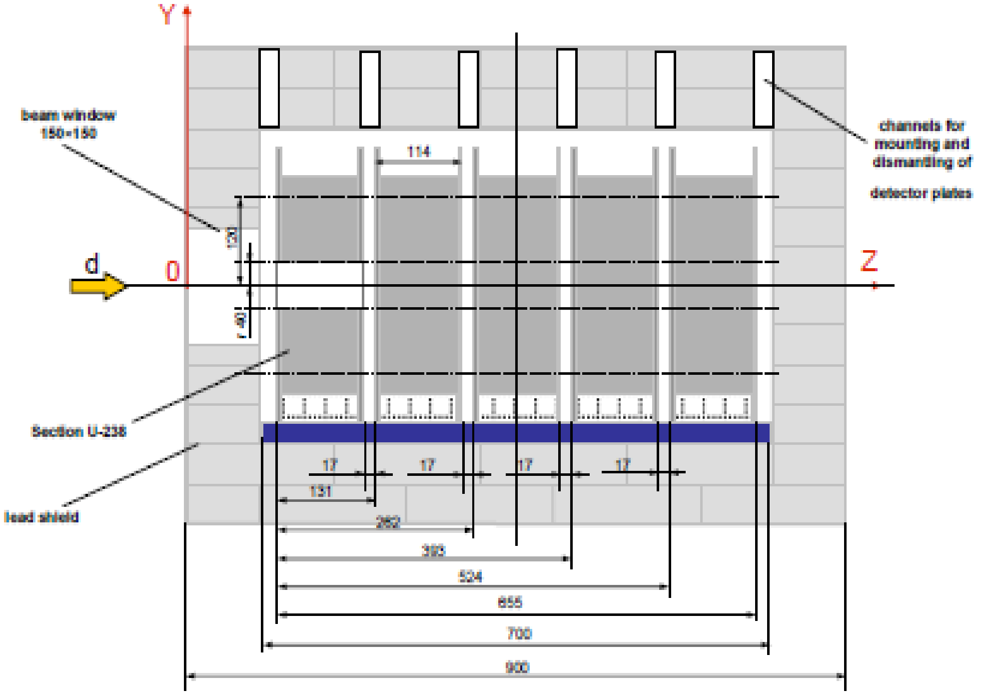
The experiments were carried out at the accelerators **«NUCLOTRON»** and **«PHASOTRON», JINR, Dubna.**

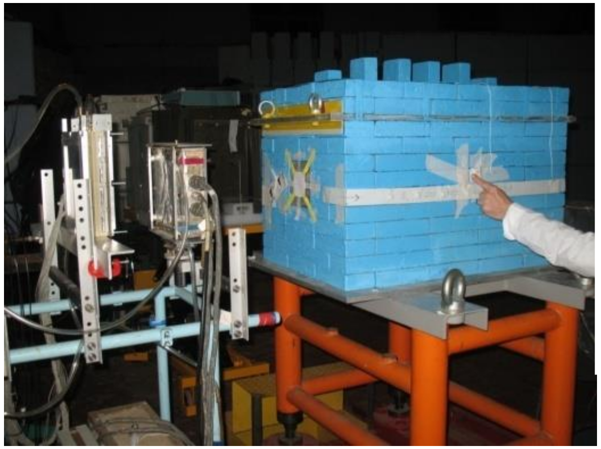
The TA Quinta was irradiated with 0.66 GeV protons, and deuterons and carbon nuclei with energy in the range 1…4 AGeV.

Target Assembly QUINTA



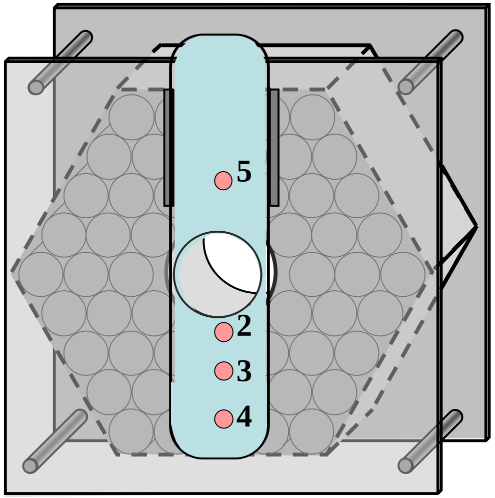
The uranium assembly length - 65 cm.
The lateral dimensions ~ 30 cm.
U mass - 512 kg.

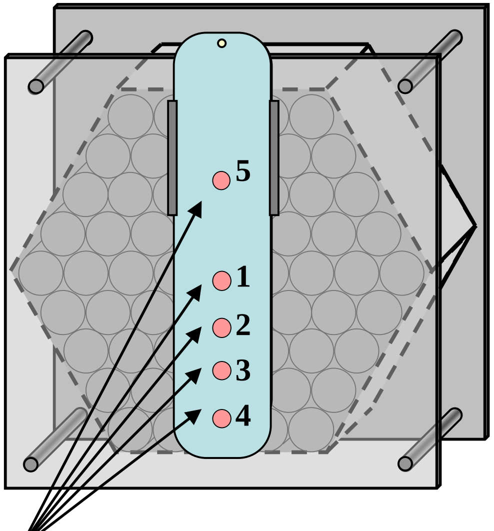


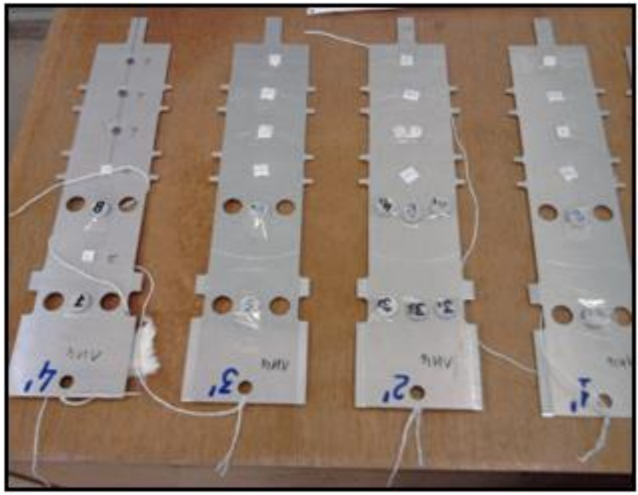


Location of the Detectors on the Detector Plates

Sections № 2,3,4,5







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Location of the detectors on the plate

The layout of the uranium foils location on the detector plate. Each plate have 5 positions at the different distances..

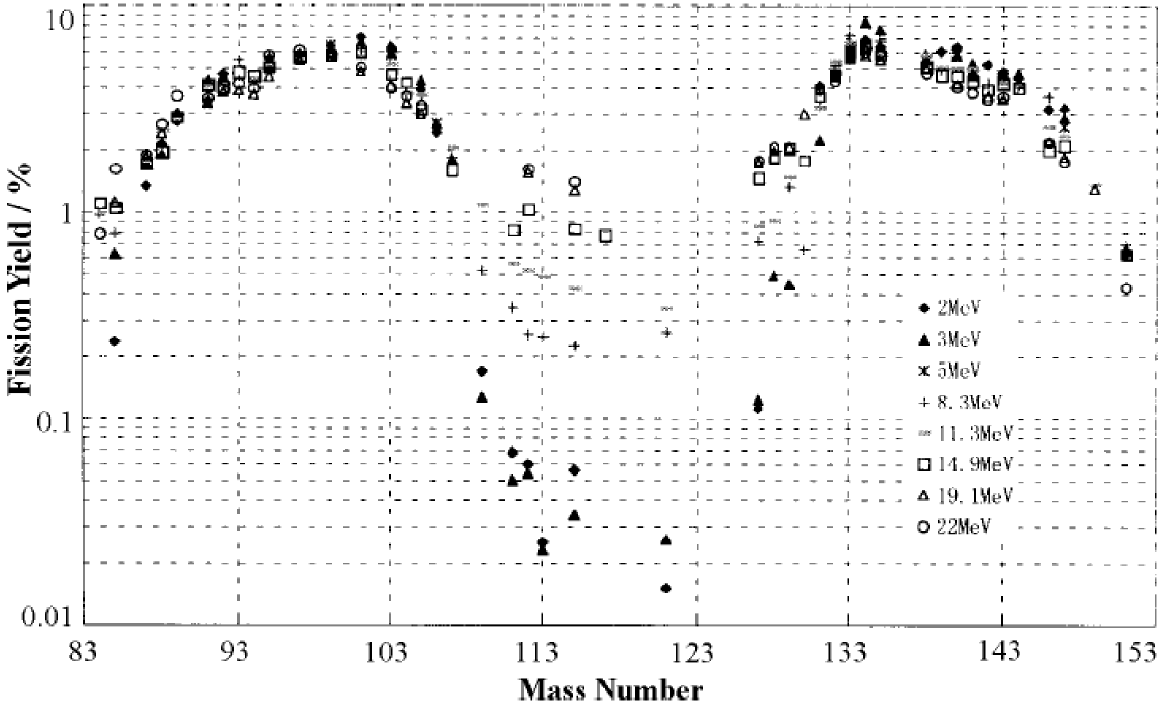
- ● **5** R = -80 mm
- ● **1** R = 0
- ● **2** R = 40 mm
- ● **3** R = 80 mm
- ● **4** R = 120 mm

Uranium detectors were fixed on the detector plates in dependence on the distance from primary beam axes – 0, 4, 8 and 12 cm.
The dimensions of the foils – diameter 8 mm, thickness 1 mm, weight 1 g.

For fission total number determination in the uranium target, we simultaneously used two techniques – activation and track.

Determination of the Fission Reaction Rates
Activation Technique

The fission number in the foils was determined by measuring the intensity of γ-lines at 743.36 keV (93% yield per decay), 364.49 keV (81.5%), 529.9 keV (87%), and 293.3 keV (42.8%), which accompany the β- decay of fission products 97Zr, 131I, 133I, and 143Ce, respectively. The γ-lines listed above are the most intense for these isotopes and, in addition, are isolated in the measured γ-spectra. The cumulative yields of these fission products do not greatly change (< 30%) in a wide range of neutron energies from fission spectrum to 60 MeV.



^{97}Zr (5.7%)
^{131}I (3.6%)
^{133}I (6.3%)
^{143}Ce(4.3%)

In the brackets there is a cumulative yield for fission spectrum and for 14 MeV neutrons

Beam Parameters
Total intensity of primary beams

Monitoring of deuteron, proton and ^{12}C nuclei beams was carried out by activation of aluminum and copper foils in the reactions

^{27}Al(d,x)^{24}Na, ^{27}Al(p,x)^{24}Na
^{27}Al(^{12}C,x)^{24}Na,
***^{64}Cu(d,x)^{24}Na* and *^{64}Cu(^{12}C,x)^{24}Na*.**

Cross sections of these reactions for given beam energy were chosen by averaging and interpolation of known experimental values

Next cross sections were used:

	Energy GeV	**CS (Al) mb**	**CS (Cu) mb**
p	**0.66**	**10.8**	**0.31**
d	**1**	**16.8**	**-**
	2	**15.4**	**3.8**
	4	**14.6**	**6.0**
	8	**14.0**	**6.3**
^{12}C	**24**	**19.4**	**9.5**
	48	**19.0**	**9.5**

Total intensities were 10^{12} - 10^{15} beam particles in different RUNs

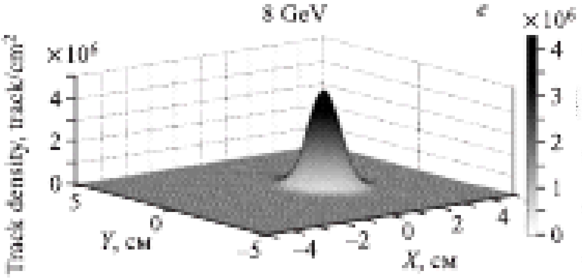
Beam Parameters

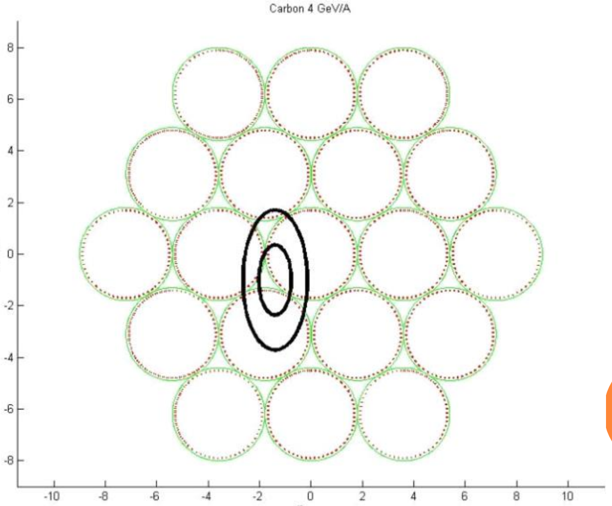
(I. Zhuk team from Belarus)

The beam positioning and beam shape were found using an array of fission track detectors by measuring ^{nat}Pb(d, f) fission track densities**.**

Track detectors were placed directly on the front of the targets along the X and Y axes of the Quinta assembly. The track densities from ^{nat}Pb(d, f) reactions were fitted to a Gaussian distribution function to obtain the beam profile.

These values used for compare measured reaction rates in different irradiation runs, for interpolation of the integral numbers of reactions and for simulate experiments by Codes.

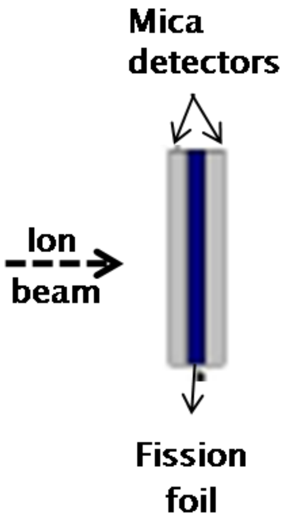


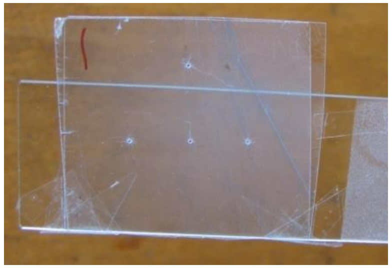


Determination of fission number of ^{238}U

Use of solid state nuclear track detector (SSNTD)

- The artificial mica was used as SSNTD. It has a high detection efficiency of fission fragments and it allows to exclude a recoil nucleus background in the hard spectrum of neutron field.
- Uranium foils was used as irradiator for SSNTD and as activation detector at the same time.
- SSNTD in pair with Pb-foils was used for determining of the beam parameters such as beam shape and size, beam center position on the target and total beam intensity.

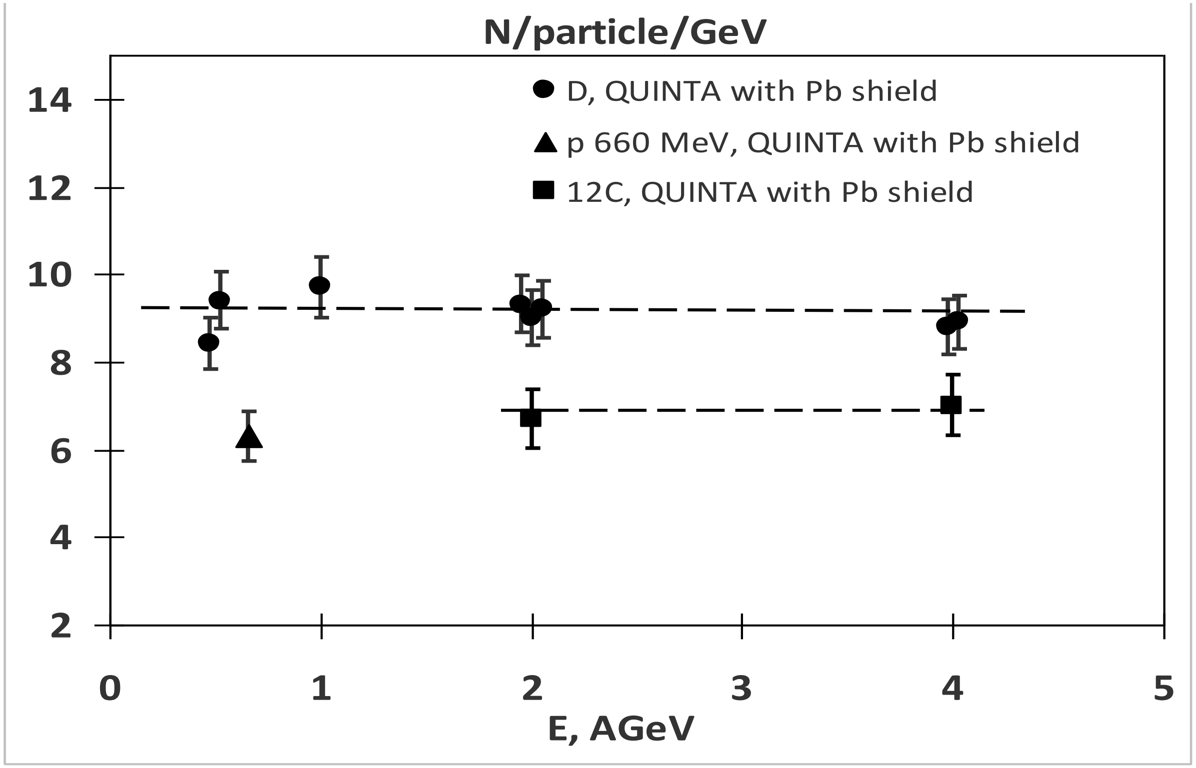




After the exposure the SSNTD are etched in hydrofluoric acid to make tracks “visible” in an optical microscope.

The technique was developed by I. Zhuk and A. Malikhin and was applied in fission reactions rate measurements in reactor systems

Total Integral Number of $^{nat}U(n,f)$ reactions over the volume of uranium target



N(D)/N(p 0.66 GeV) ≈ 1.46

N(D)/N(12C) ≈ 1.34

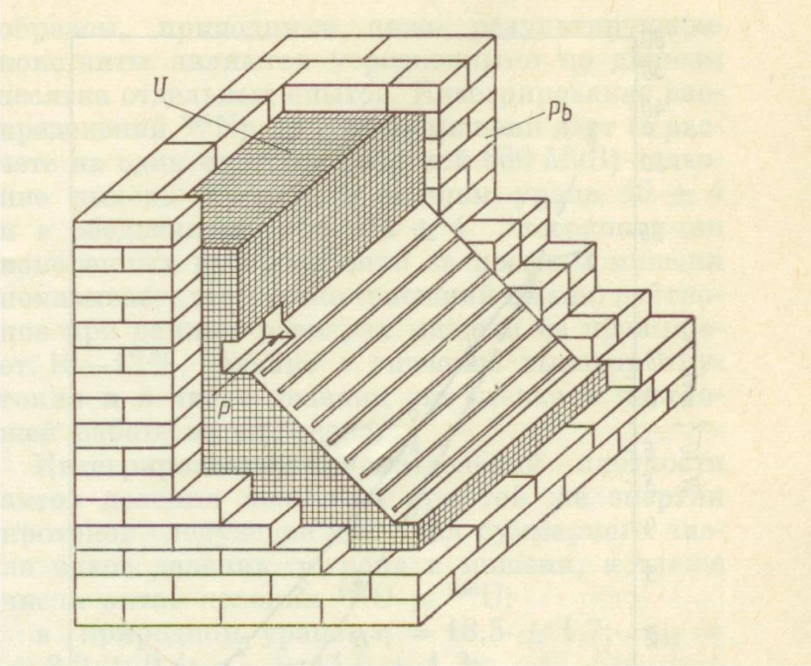
(per 1 particle and per1 GeV of energy)

The total number of fission in the volume of uranium target was determined by numerical integration of the measured uranium fission rate spatial distributions in the approximation of a cylindrical target with radius R = 140 mm (the vertical size of the uranium target sections).
The total number of fission for 1, 2, 4 and 8 GeV deutrons remains approximately constant within the limits of our errors (14%) (per 1 deuteron and per beam power).

Beam Power Gain of the Primary Particle Beam Under Relativistic Proton, Deuteron and Carbon Ions Irradiation

Beam (GeV)	**N_f per 1 particle**	**Beam Power Gain (G)**
p (0.66) (512 kg U)	4.1 ± 0.3	2.2
d (1)	8.9 ± 0.6	2.7
d (2)	19.4 ± 1.4	2.9
D (4)	37 ± 2	2.9
D (8)	71 ± 4	2.8
12C (24)	160 ± 20	2.3
12C (48)	340 ± 40	2.4

R.G. VASIL’KOV, V.I. GOL’DANSKII, B.A. PIMENOV, YU.N. POKOTILOVSKII, L.V. CHISTYAKOV. NEUTRON MULTI-PLICATION IN URANIUM BOMBARDED WITH 300…660 MEV PROTONS // *ATOMIC ENERGY. 1978, V. 44 (4), P. 377-384.*



General view of the part of uranium target in the lead blanket (it is shown the location of the channel system for detector location for proton beam input into target)

Mass of the target = 3.5 t

Linear dimensions: 56*56*64 cm^2.
Lead blanket thickness:10 cm

Fission total number:18.5±1.7
+ 3-4
R<6 cm (did not measured)

G = 9.2

Neutron leakage:11 – 12%

Beam Power Gain Of The Primary Particle Beam Under Relativistic Proton, Deuteron and Carbon Ions Irradiation

Beam (GeV)	N_f per1 particle	Beam Power Gain (G)	G∞ Estimation for 21 t ^{nat}U
p (0.66) (512 kg U)	4.1 ± 0.3	2.24	9
d(1)	8.9 ± 0.6	2.7	11
d (2)	19.4 ± 1.4	2.94	12
D (4)	37 ± 2	2.85	12
D (8)	71 ± 4	2.76	11
12C (24)	160 ± 20	2.33	9
12C (48)	340 ± 40	2.42	9
P (0.66) [R.G. Vasilkov et al] 3.5 t U (eq. 7 t U)	21.5 ± 2.1	9.2	-

G_{MIN} Required for the Energy Reproduction

The minimum beam power gain value G_{min} *required for the energy reproduction (grid power required to run the accelerator) is determined by the value of the electric to beam power conversion efficiency (the wall-plug efficiency)* η_{acc} *and the thermal to electric power conversion efficiency* η_{el}*:*

$$G_{\min} \cdot P_{beam} \geq \frac{P_{beam}}{\eta_{acc} \cdot \eta_{el}} \Rightarrow G_{\min} = (\eta_{acc} \cdot \eta_{el})^{-1},$$

where P_{beam} *is the power of primary ion beam.*

The thermal to electric power conversion efficiency η_{el} *can reach value ~ 45% (*η_{el} *=41% for sodium-cooled fast reactors BN-600,* η_{el} *= 42% for lead-cooled fast reactor "Brest").*

G_{MIN} Required for the Energy Reproduction

The coefficient η_{acc} *is different for different types of accelerators.*

In the class of high power accelerators for ADS applications the highest value

$$\boldsymbol{\eta_{acc} = 19.5\%}$$

was achieved for the PSI cyclotron with beam power of 1.4 MW, energy of 0.59 GeV and beam current of 2.4 mA.

With the beam power increasing the coefficient η_{acc} *increases. Thus, if the beam current increases to 5 mA at the PSI cyclotron, then the expected value of* η_{acc} *will be about*

$$\boldsymbol{\eta_{acc} \sim 25\%} \quad [1, 2]$$

It is also shown that the parameter optimization of the high-power accelerators for ADS makes it possible to reach

$$\boldsymbol{\eta_{acc} \sim 40\%} \quad [1, 3]$$

1. M. Seidel, A.C. Mezger. Performance of the PSI High Power Proton Accelerator // International Topical Meeting on Nuclear Research Applications and Utilization of Accelerators, Vienna. 2009.
2. M. Haj Tahar, F. Meot, S. Peggs. Energy Efficiency of High Power Accelerators for ADS Applications // Proceedings of IPAC2016, Busan, Korea. 2016, TUPOY044, p. 2001-2003.
3. Accelerator and Spallation Target Technologies for ADS Applications // Nuclear Energy Agency Report. 2005, №5421, © OECD, p. 92.

G_{MIN} Required for the Energy Reproduction

- Thus, for sufficiently powerful beams (P_{beam} > 3 MW) the beam power gain G_{min} required for the energy reproducing must be at least about

$$\mathbf{G_{min} \approx 9} \quad (\eta_{acc} = 0.25,\ \eta_{el} = 0.45)$$

- For more powerful beams (P_{beam} > 10…20 MW) it is possible to ensure energy reproduction even at

$$\mathbf{G_{min} \approx 6 - 7.5} \quad (\eta_{acc} = 0.3 - 0.4)$$

- It should be noted that it is necessary to distinguish the starting beam power gain and the corresponding equilibrium beam power gain, which is steady in the reactor core when ^{239}Pu equilibrium concentration is reached after a certain run-time of the ADS.
- In this paper the dependence of the starting beam power gain from the energy and the type of bombarding particles for TA Quinta (512 kg ^{nat}U) is experimentally investigated.

Discussion

The estimated G_∞ values satisfy the minimum requirements (**$G_{min} > 7$**) for energy reproduction (grid power required to run the accelerator).

At the same time, simulations for quasi-infinite targets give significantly lower beam power gain values.

For example, simulation with the MARS15 code (120 cm diameter uranium target with 110 cm length) gives the maximum

beam power gain value ~ 5.5

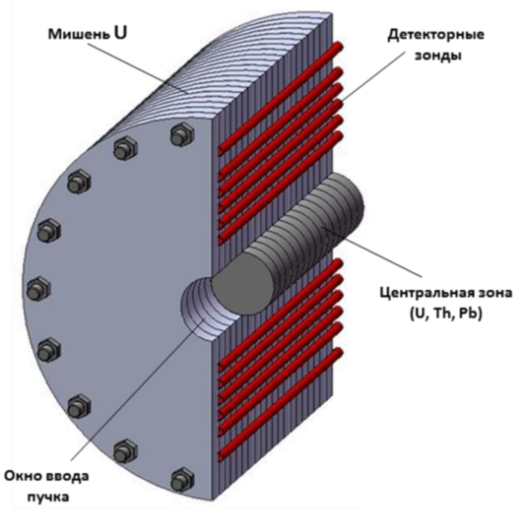
for protons with an energy of 2…4 GeV [*V.S. Pronskich et al*.].

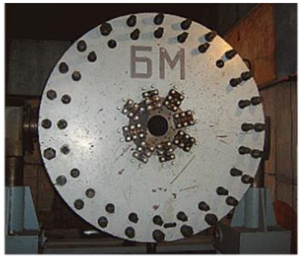
Simulation with the MCNPX 2.7e code [*P. Zhivkov et al.]* for the quasi-infinite *depleted* uranium target with a mass of ~ 22 tons, irradiated by protons and deuterons of 1, 6, 12 GeV, gives

beam power gain about 4.

If the beam power gain estimates **based on experimental data are correct**, a deep subcritical reactor with a quasi-infinite natural uranium target can be used for minor actinide transmutation with return of the spent energy back to the electrical mains. The neutron spectrum also contains a fast component, which is essential for transmutation via fast fission.

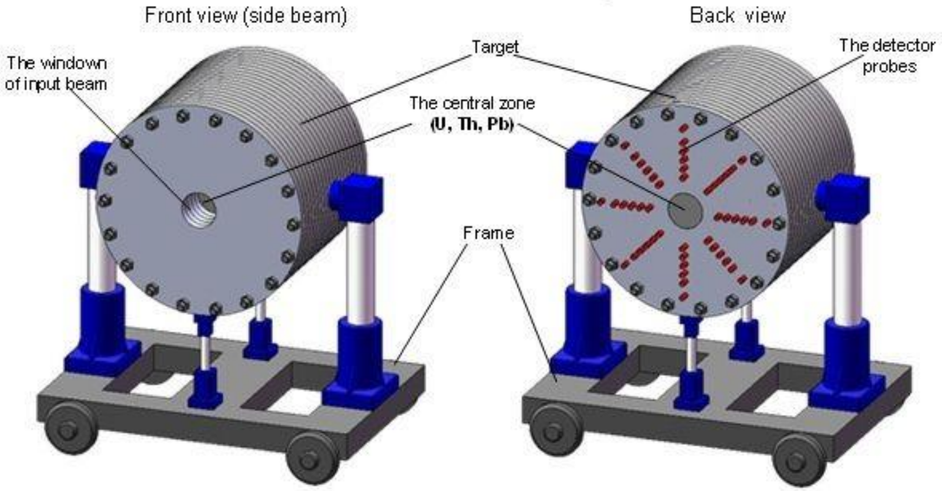
Quasi-Infinite Uranium Target "BURAN"(From Depleted Uranium)





Вид сзади

The target is in solid steel 10 cm thickness blanket . The mass of the assembly ≈ 21 t, diameter = 1.2 m, length = 1 m.



Conclusions

- The total number of the fission reaction (per beam power) in the volume of the uranium target Quinta for deuteron beams with energies from 1 to 8 GeV is independent of the beam energy within the limits of statistical errors (up to 7-10%).
- The total number of fission for deuterons is in 1.4 to 1.5 times greater than for protons with energy of 660 MeV at the same beam power.
- Comparing our experimental data obtained using proton and deuteron beams with the results of the [R.G. Vasilkov et al] experimental work it follows that the beam power gain for deuteron beams with 1…8 GeV energy can reach value about 12 for a quasi-infinite uranium target.
- In terms of further research, first of all, it is necessary to conduct experiments using the quasi-infinite uranium target “Buran”, JINR, Dubna (21 tons of depleted uranium with a replaceable central zone of the target), and to confirm the results R.G. Vasilkov et al with 660 MeV proton beam.

ХФТИ

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