# POWER OF ADS WITH LOW-ENERGY ACCELERATOR AND FISSIONABLE TARGET*

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Prospects and perspectives of ADS based on low-energy accelerator and fissile target design are considered in this paper. Fast reactor core which consists of fissionable target and booster, cooled by liquid metal, is proposed. Different reactor core structures are analyzed. Power in the ADS reactor is calculated.

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## INTRODUCTION

In ADS fission reaction occurs in subcritical reactor with additional (external) neutron source, generated in the target by accelerated charged particles beam.

Nowadays ADS utilization possibility is considered in nuclear power different areas:

- transmuting actinides and fission products [1 - 2];
- power generation [3 - 4];
- producing fissile materials [5];

Research in ADS field is carried out in many countries all over the world demonstration ADS plants are designed PDS-XADS, MYRRHA, MEGAPIE, HYPER, TEF, AFCI [6 - 10].

ADS cost and attributes are significantly defined by accelerator-driver characteristics. Proton beam with energy 1…2 GeV and power 10…75 MW [2] is necessary for long-lived transuranic elements transmutation. Such charged particles beams could only be obtained in the unique large expensive accelerators.

The possibility of accelerator with low particles beam parameters utilization in energy amplifier (ADS) is considered in this paper. In this case it is necessary to significantly amplify the neutron source in the reactor.

A proton linac is considered as a low-energy accelerator-driver [11], which characteristics are presented in the Tabl. 1.

It is worth to notice that accelerator parameters can be improved with optimization [13 - 17].

***Table 1***

| | |
|---|---|
| Output energy | 300 MeV |
| Average current | up to 5 mA |
| Duty factor | 10% |
| Frequency range of RFQ and DTL | 424…433 MHz |
| Beam power | 1.5 MW |

## 1. NEUTRON PRODUCING TARGET

The electronuclear neutron source intensity is defined by the expression

$$S = \frac{I_p m_0}{e},$$

where $I_p$ – average beam current, $m_0$ – neutron yield (average neutron number generating by an accelerated particle in the target), $e$ – accelerated particle charge.

Neutron yield from the target irradiated by charge particles depends on parameters of particle beam, target composition and it dimensions.

In ADS with targets of non fissile materials (Pb, Bi, etc.) the external neutron source intensity is specified by the spallation neutrons leakage from the target surface.

For small size targets a significant part of secondary particles that can induce nuclear fissions leave the target. For large size – radioactive capture of neutrons by the target plays an important role. Because of an anisotropy of non-elastic proton scattering the target length should in several times be greater than its radius, meanwhile the L value has weak influence on neutron yield if the following condition $L>D>\lambda_{in}$ is fulfilled. A great part of neutron leakage comes from the target face from the side of beam falling. So the neutron yield is maximal with some beam entry point deepening.

The optimal dimensions of cylindrical targets are presented in Tabl. 2, and neutron yields from these targets irradiated by the 300 MeV proton beam – in Fig. 1. The presented results were obtained with using GEANT-4.9.5 code.

***Table 2***

| Material | $D_{opt}$, cm | $Z_{opt}$, cm | $L_{opt}$, cm |
|---|---|---|---|
| Pb | 66 | 31 | 76 |
| Bi | 95 | 49 | 105 |
| W | 7 | 2 | 10 |
| Ta | 7 | 2 | 10 |

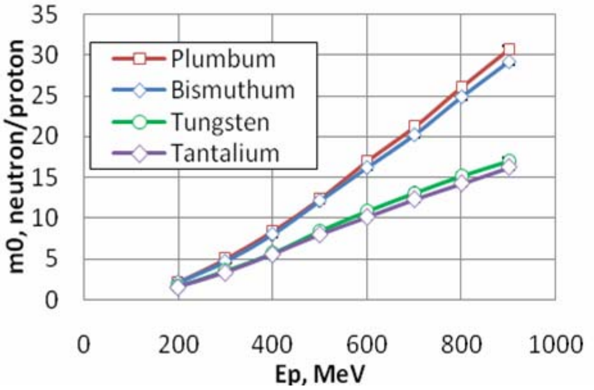

*Fig. 1. Neutron yield from target with the optimal sizes*

In ADS with fissionable targets (for example, U) as initial neutrons are to be considered only spallation neutrons, because the neutron multiplication due to fission reactions are accounted in neutronics calculation of the reactor core with the target as a part of it.

The spallation neutron yields in the infinite uranic target are presented in the Fig. 2 in dependence of the

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protons energy, and the dependence of spallation neutrons yield inside the target on its radius – in FIg. 3.

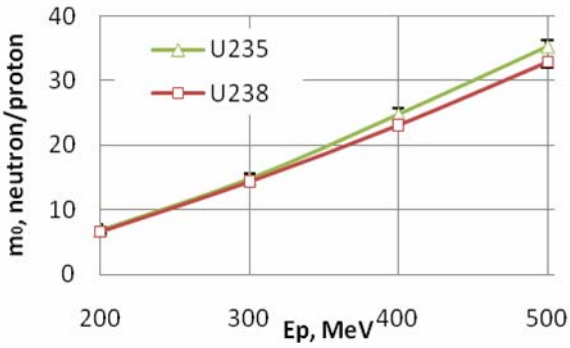

*Fig. 2. Neutron yields in the infinite uranic target (Geant 4.9.5)*

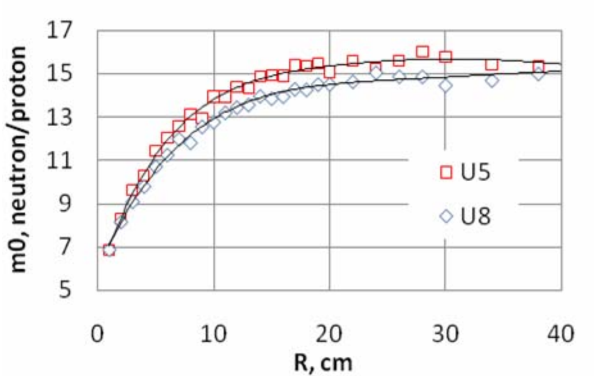

*Fig. 3. Dependence of spallation neutrons yield inside the target on its radius with 300 MeV proton beam (Geant 4.9.5)*

From the presented results it is followed that for an ADS with 300 MeV proton energy beam it is reasonable to use fissile targets.

## 2. SUBCRITICAL REACTOR

There are several factors influencing on ADS power with the given external neutron source intensity: reactor core subcritical level, external neutron source spatial localization, reactor core structure (homogenous, sections).

If the external neutron source spatial energy distribution corresponds to the fission neutrons distribution in the reactor core (reference source [18]), then the fission neutrons generation intensity is described by

$$Q_{f0} = S_0 \frac{k_{eff}}{1 - k_{eff}},$$

where $S_0$ – reference source intensity, $k_{\text{eff}} < 1$ – multiplication factor of the reactor core.

$k_{eff}$ value is chosen to provide nuclear safety. Nowadays for ADS $k_{eff}$ is admitted to be $k_{eff} \le 0.98$.

In order to maintain ADS power rate at a constant power level during reactor operation with decreasing $k_{eff}$ it's necessary to increase accelerator current. Reactivity reduction as a result of nuclear fuel burning and fission products is about 8% for thermal-neutron reactor and 1…3% for fast-neutron reactor. Thus, in ADS with fast-neutron reactor accelerator current variety during the operation period is significantly less than in ADS with thermal-neutron reactor. Consequently using fast core in ADS is more preferable.

In order to estimate the external neutron source spatial distribution influence on the reactor core power let introduce the amplification coefficient, which is equal to the ratio of the given neutron source generation intensity to reference neutrons source.

$$k_{\text{ampl}} = \frac{1 - k_{eff}}{k_{\text{eff}}} \cdot \left( \frac{Q_f}{Q_1} \right), \qquad (1)$$

$Q_f = \int\limits_V \int\limits_E \nu \Sigma_f \Phi dEdV$, $Q_1 = \int\limits_V \int\limits_E q_s dEdV$, $q_s(r,E)$ – external neutron source intensity, $\Sigma_f(r, E)$ – macroscopic fission cross-section, ν – average neutrons number born in a fission event, $\Phi(r,E)$ – neutron flux spatial energy distribution in the reactor core.

In homogenous reactor core case external neutron source localization in the reactor core center allows to increase source neutrons importance, because source neutrons leakage from the reactor core decreases. .

The dependence of the external neutron source amplification coefficient on its localization in the cylindrical fast reactor core ($k_{eff} = 0.98$) is presented in the Fig. 4 [18].

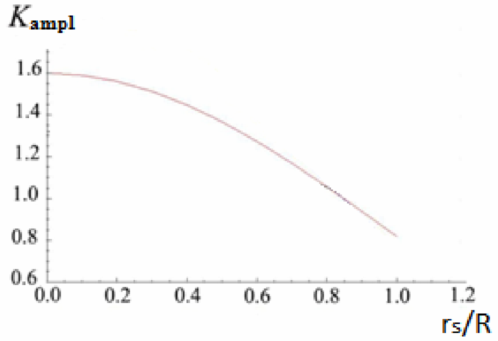

*Fig. 4.* $k_{\text{ampl}}$ *depends on source localization factor. R – reactor core radius,* $r_s$ *– external neutron source radius*

External neutron source localization in the center of the reactor core allows to increase the external neutron source generation intensity almost in 1.6 times. But taking into account that the fissionable target optimal size (the reactor core central part diameter) corresponds to $3\lambda_{in}$ (characteristic inelastic interaction lengths), this way of amplification doesn't seem to be fully realized.

The method aimed to ADS power amplification was proposed in several papers [17, 19, 20]. It is based on the reactor core sectioning (Fig. 5). The sectioned reactor core consists of two sections: fissionable target and subcritical booster with broken coupling between booster and target. Then the fissionable target is the first neutron multiplying cascade, and the booster – the second multiplying cascade.

Multiplication factor of the sectioned reactor core [21]:

$$k_{eff} = \frac{1}{2}\left( k_1 + k_2 + \sqrt{(k_1 - k_2)^2 + 4k_1 k_2 k_{12} k_{21}} \right),$$

where

$$k_i = k_{\infty i} P_{fiai},$$

$$k_{ij} = \frac{P_{fiaj}}{P_{fjaj}},$$

sections $i, j$: 1 – fissionable target, 2 – booster, $k_{\infty i}$– infinite multiplication factor for $i$-th section composition, $P_{fiaj}$ – probability for neutron born in section $i$ to be absorbed in section $j$.

Thermal power for the reactor core is defined by the formula

$$N_T = \frac{E_f Q_f}{\nu},$$

where $E_f$— energy released per a fuel nuclei fission.

For a sectioned reactor core $Q_f = Q_{f1} + Q_{f2}$,

where $$Q_{fi} = S_0 \frac{k_{0i}\left(\frac{1-k_j}{k_j}\right) + k_{0j}k_{ji}}{\left(\frac{1-k_j}{k_j}\right)\left(\frac{1-k_i}{k_i}\right) - k_{ij}k_{ji}},$$

$k_{0i} = \frac{P_{S0ai}}{P_{fiai}}$, $P_{S0ai}$ – probability for source neutrons to be absorbed in the section $i$.

Maximal external neutron source amplification in the sectioned reactor core can be achieved when the neutron coupling between booster and target is completely broken ( $k_{21} = 0$ ). In this case for the fissionable target with a reference source and $k_{eff} = k_1 = k_2 = 0.98$, $k_{\infty 1}=k_{\infty 2}=2.1$ it could be obtained $k_{ampl} = 27$.

Neutron coupling between booster and target break can be implemented by several ways.

1. Cascade fast-thermal reactor core: the inner section is fast and the outer is thermal [20]. The neutron coupling between booster and target is suppressed because of placing a “neutronics gate” (thermal neutrons absorber) between sections (Fig. 5).

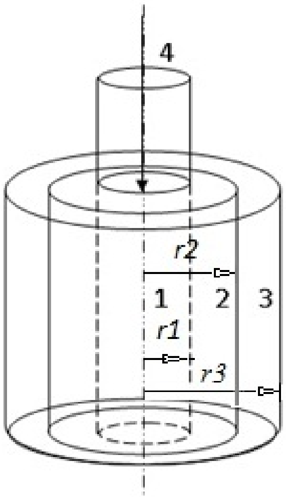

*Fig. 5. Cascade reactor core scheme.*
*1 – inner section, 2 – “gate”; 3 – outer section;*
*4 – charged particles beam*

But it real systems it is impossible to break neutron coupling completely because there are neutrons with rather high energies in the outer section, which can’t be absorbed in the “neutronics gate”. It should be noted that during ADS operating there is a significant $k_\infty$ changes due to fuel burnup and fission product build-up. This leads to $k_{eff}$ significant decrease.

2. Cascade reactor core with threshold fissionable target: the inner section consists of threshold fissile material, for example, $Np^{237}$, that allows to break neutron coupling more efficiently [17].

Transuranic threshold fissile elements are possible to utilize only in transmutation plants. Threshold fissile elements ($U^{238}$) usage in energy plants isn’t reasonable because in this case the fissionable target has a very low $k_{\infty 1}$ value.

3. Fast-fast cascade reactor core: inner and outer section with hard spectrum divided by a cylindrical gap (this gap can be named “geometrical gap” for convenience). Neutron coupling between inner and outer sections is suppressed at the expense of the ratio of the total neutron flux in the inner section to the outer section is in proportion to $R_1/R_2$ (in spherical case to $R_1^2 / R_2^2$ ).

Cascade reactor cores have rather strong power flux irregularity between sections, because in some cases ADS power is limited not by the external neutron source intensity but an acceptable specific power flux in the reactor core, which is defined under the heat engineering reliability condition. The mentioned limitation is occurred for reactor cores with “geometrical gap”, when the fuel volume fraction is rather small and $U^{235}$ enrichment in the fissionable target is greater than in the booster. In such reactor cores it is reasonable to use liquid metal coolant, that allows to increase maximal heat density up to 1180 MW/m$^3$ [22].

Heat density distributions for homogenous and cascade reactor cores with power 250 MW are presented in Fig. 6.

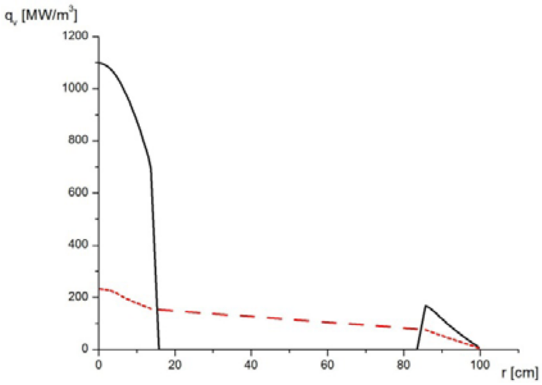

*Fig. 6. Dependence of heat density in the reactor core ($R_3$=100 см) on its radius. Solid line – cascade core, dashed line – homogenous*

The dependence of amplification coefficient, thermal power and peak-to-average ratio on $R_2/R_1$ for the reactor core ($k_{эф}$= 0.98) with outer diameter 2 m, height 1 m, the fissionable target diameter 0.28 m, composition is similar to reactor BN-600, but differs in $U^{235}$ enrichment (the fissionable target and booster enrichment vary from 14.4 to 95% in dependence of $R_2/R_1$). Neutronics calculations were performed with discrete coordinate method ($S_{16}$, 44 energy groups) using program SCALE. Initial neutrons yield in the fissionable target is 7.5 neutrons/proton. Results of the reactor core power characteristics calculation with the external neutron source intensity – 2.3 $10^{17}$ neutrons/c, which is provided by a low-energy accelerator (Tabl. 1) are presented in Tabl. 3.

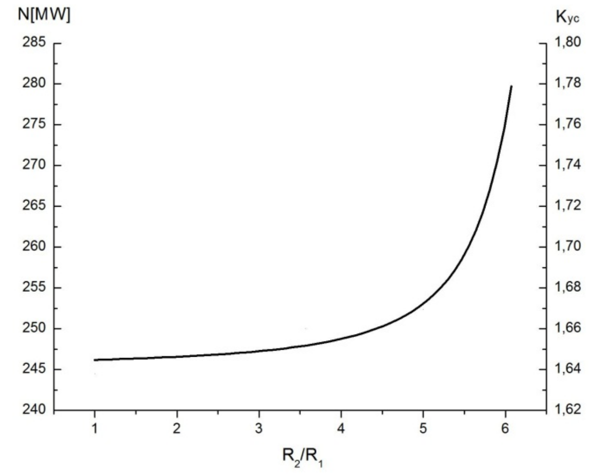

*Fig. 7. Dependence of the amplification coefficient and thermal power on $R_2/R_1$ in the reactor core ($R_3$=100 cm)*

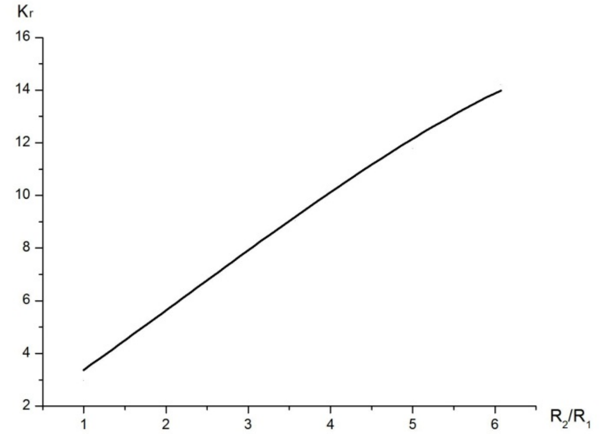

*Fig. 8. Dependence of the peak-to-average ratio on $R_2/R_1$ in the reactor core ($R_3$=100 cm)*

***Table 3***

| | $k_{ampl}$ | N[MW] | $q_v$ [MW/m$^3$] | $k_r$ |
|---|---|---|---|---|
| *R*=1 m homogenous | 1.62 | 245 | 232 | 2.97 |
| *R*=1 m cascade | 1.68 | 255 | 1098 | 11.8 |
| *R*=2 m homogenous | 1.56 | 228 | 56 | 3.1 |
| *R*=1 m cascade | 2.00 | 300 | 700 | 29.6 |

The homogenous reactor core with diameter 2 m and height 1 m has thermal power 245 MW, and the correspond cascade reactor core with maximal heat density – 255 MW. The cascade reactor core with bigger sizes (diameter 4 m, height 2 m) has thermal power 300 MW. Thus, for reactor cores with rather small sizes cascade scheme is not reasonable, it has advantage just for quite big reactor cores.

## CONCLUSIONS

ADS with low-energy accelerator-driver can be designed on the basis of fast reactor core, cooled by liquid metal.

The main characteristics of the energy ADS with diameter 2 m and height 1 m:

- proton beam parameters: current 5 mA, energy 300 MeV;
- external neutron source intensity: $2.3 \cdot 10^{17}$ н/с;
- multiplication factor of the reactor core: 0.98;
- external neutron source amplification coefficient: 2.0;
- thermal power: 250 MW.

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## МОЩНОСТЬ ЭЛЕКТРОЯДЕРНОЙ УСТАНОВКИ С НИЗКОЭНЕРГЕТИЧЕСКИМ УСКОРИТЕЛЕМ И РАЗМНОЖАЮЩЕЙ МИШЕНЬЮ

***А.Г. Головкина, И.В. Кудинович, Д.А. Овсянников***

Рассмотрены перспективы создания электроядерной установки на базе низкоэнергетического ускорителя и размножающей мишени. Предлагается использовать быструю активную зону, состоящую из размножающей мишени и бустера, охлаждаемых жидкометаллическим теплоносителем. Проанализированы различные варианты компоновки активной зоны, определена мощность энерговыделения в реакторе ЭЛЯУ.

## ПОТУЖНІСТЬ ЕЛЕКТРОЯДЕРНОЇ УСТАНОВКИ З НИЗЬКОЕНЕРГЕТИЧНИМ ПРИСКОРЮВАЧЕМ І РОЗМНОЖУЮЧОЮ МІШЕННЮ

***А.Г. Головкіна, І.В. Кудінович, Д.А. Овсянников***

Розглянуто перспективи створення електроядерної установки на базі низькоенергетичного прискорювача і розмножуючої мішені. Пропонується використовувати швидку активну зону, що складається з розмножуючої мішені і бустера, що охолоджуються рідиннометалевим теплоносієм. Проаналізовано різні варіанти компонування активної зони, визначена потужність енерговиділення в реакторі ЕЛЯУ.