# ON ACCELERATOR DRIVEN SUBCRITICAL REACTOR POWER GAIN

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*Abstract*

The accelerator driven system (ADS) with subcritical reactor is considered. Such systems demonstrate high safety, due to the fact, that the reactor operates at sub-critical level. The problem of the reactor power rate maximisation on fixed values of effective multiplication factor and the external neutron source (neutron generating target) intensity is studied. In this paper the main attention is paid to the reactor core optimisation. Some ways of ADS power rate gain and optimised reactor core parameters are proposed.

## INTRODUCTION

Since the early 1990's, accelerator driven systems (ADS - subcritical reactors with external neutron source generated by proton accelerators through a spallation target) have been proposed [1] for addressing certain missions in advanced nuclear fuel cycles. Institutes throughout the world have conducted numerous programs evaluating the role of ADS in nuclear waste transmutation and energy production. The interest is induced by a number of ADS different applications, for example:

- Transmuting selected isotopes present in nuclear waste (e.g., actinides, fission products) to reduce the burden these isotopes place on geologic repositories.
- Generating electricity and/or process heat.
- Producing fissile materials for subsequent use in critical or sub-critical systems by irradiating fertile elements.

There are needed high energy proton beams for transmutation problems. Such beams could be obtained only inlarge and expensive accelerators. So using them in ADS designed for power generation isn'teconomical effective. There should be used cheaper accelerators with lower output beam energy, so some other ways to increase reactor power rate are needed to be find.

## EXTERNAL NEUTRON SOURCE AMPLIFICATION

In the general case the neutron flux $\Phi(r, E)$ in subcritical reactor is described by equation:

$$\mathbf{M}\Phi(r, E) = -\mathbf{M_1}\Phi(r, E) - q(r, E),$$
$$r \in V, E_T \leq E \leq E_f; \qquad (1)$$

$$\Phi(r_S, E) = 0, r_S \in S,$$

where $\mathbf{M}$ - operator describes transport, slowing-down and absorbation of neutrons,

$M_1$ - operator describes fission neutron source,

$q(r, E)$ - intensity of the external neutron source,

$E_t$ - thermal neutron energy;

$E_f$ - fission neutron energy

The multiplication factor of the reactor core $k_{\text{eff}}$ does not depend on the external neutron source intensity and it is defined for critical fictitious system by equation:

$$\mathbf{M}\Phi_0(r, E) = -\frac{1}{k_{\text{eff}}}\mathbf{M_1}\Phi_0(r, E), \qquad (2)$$
$$\Phi_0(r_S, E) = 0, r_S \in S$$

Eq. (2) can be written as:

$$\mathbf{M}\Phi_0(r, E) = -\mathbf{M_1}\Phi_0(r, E) - \frac{1 - k_{\text{eff}}}{k_{\text{eff}}}\mathbf{M_1}\Phi_0(r, E). \quad (3)$$

Equations (1) and (3) are the same if spatial and energy distribution of the external source is:

$$q(r, E) = \frac{1 - k_{\text{eff}}}{k_{\text{eff}}}\mathbf{M_1}\Phi_0(r, E), \qquad (4)$$

where $\Phi_0(r, E)$ is the solution of Eq. (3).

A source with the spatial and energy distribution given by Eq. (4) is called a reference source [3].

The full intense of the external neutron source is defined by

$$Q_1 = \int\limits_V \int\limits_{E_T}^{E_f} q(r, E)dEdV,$$

and fission neutron generation intensity for sub-critical system:

$$Q_f = \int\limits_V \int\limits_{E_T}^{E_f} \mathbf{M_1}\Phi(r, E)dEdV.$$

Then thermal power rate of reactor ($N_0$) is:

$$N_0 = \frac{P_f Q_f}{\nu},$$

where $P_f$ - energy, released per fission, $\nu$ - mean number of neutrons per fission.

The relation of $Q_f$ and $Q_1$ for reference source is:

$$\left(\frac{Q_f}{Q_1}\right)_{\text{ref}} = \frac{k_{\text{eff}}}{1 - k_{\text{eff}}} \qquad (5)$$

In case of arbitrary spatial and energy distribution of external neutron source the efficiency of its amplification in the core can be estimated:

$$k_{\text{ampl}} = \left(\frac{Q_f}{Q_1}\right) \bigg/ \left(\frac{Q_f}{Q_1}\right)_{\text{ref}}$$

and according to Eq.(5) :

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

In order to maintain ADS power rate at a constant power level during reactor operation with decreasing $k_{\text{eff}}$ 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 [2]. 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.

## NEUTRON-PRODUCING TARGET

Neutron yield from the target depends on parameters of the charged particles beam, target composition and dimensions.

Yields of neutrons (number of neurons which escape from the target) for finite targets depend on both beam characteristics and target dimensions. When dimensions are small a substantial part of secondary particles capable to induce fission with additional neutron production escapes form the target without interaction. At the same time in large target neutron radiative capture plays an important role.

For cylindrical target an optimal diameter with respect to neutron yield corresponds to few (2-3) characteristic inelastic interaction lengths $\lambda_{in}$. Due to anisotropy in particle production for inelastic proton scatterings in the lab frame (most of particles are produced in forward direction), the target length L should be somewhat larger than its radius, at the same time value of L has minor effect on the neutron multiplicity provided $L > D > \lambda_{in}$. Substantial part of neutrons escapes through the front butt-end of the target block, so neutron yield is maximal for comparatively small deepening of the beam injection point $z_0 \approx 0.3\lambda_{in}$.

In table 1 we present calculated values for optimal dimensions of cylindrical target, it also represents maximum neutron yields for them obtained via GEANT-4 [4].

Table 1: Optimized target diameter D (cm), target length L (cm), penetration beam deepening Z (cm) and relative neutron yield N (neutron/protons) in dependence of protons energy.

| *Ep,* | Pb | | | | Ta | | | |
|---|---|---|---|---|---|---|---|---|
| **МэВ** | **D** | **L** | **Z** | **N** | **D** | **L** | **Z** | **N** |
| 200 | 16.1 | 20 | 8.1 | 2.12 | 5.20 | 7 | 2.0 | 1.60 |
| 300 | 17.6 | 22 | 7.8 | 4.98 | 6.80 | 10 | 2.0 | 3.37 |
| 400 | 18.5 | 23 | 7.4 | 8.38 | 8.50 | 13 | 2.1 | 5.63 |
| 500 | 18.9 | 24 | 6.6 | 12.4 | 9.40 | 15 | 2.0 | 8.04 |
| 600 | 19.4 | 26 | 6.5 | 17.0 | 10.3 | 17 | 2.0 | 10.2 |
| 700 | 19.6 | 27 | 6.2 | 21.2 | 10.6 | 17 | 1.8 | 12.3 |

| | U | | | | Bi | | | |
|---|---|---|---|---|---|---|---|---|
| 800 | 20.0 | 28 | 6.0 | 26.1 | 11.0 | 18 | 1.7 | 14.2 |
| 900 | 20.3 | 28 | 5.8 | 30.7 | 11.3 | 19 | 1.6 | 16.2 |
| 200 | 16.1 | 20 | 8.1 | 7.34 | 16.1 | 20 | 8.1 | 2.09 |
| 300 | 17.6 | 22 | 7.8 | 15.36 | 17.6 | 22 | 7.8 | 4.67 |
| 400 | 18.5 | 23 | 7.4 | 25.05 | 18.5 | 23 | 7.4 | 8.01 |
| 500 | 18.9 | 24 | 6.6 | 35.61 | 18.9 | 24 | 6.6 | 12.2 |
| 600 | 19.4 | 26 | 6.5 | 47.08 | 19.4 | 26 | 6.5 | 16.2 |
| 700 | 19.6 | 27 | 6.2 | 58.27 | 19.6 | 27 | 6.2 | 20.3 |
| 800 | 20.0 | 28 | 6.0 | 68.72 | 20.0 | 28 | 6.0 | 24.9 |
| 900 | 20.3 | 28 | 5.8 | 78.27 | 20.3 | 28 | 5.8 | 29.3 |

## SPATIAL LOCALISATION OF EXTERNAL NEUTRON SOURCE

Intensity of the electronuclear neutron source

$$Q_1 = \frac{I_p m_0}{e} \qquad (6)$$

with $I_p$ standing for an average current of accelerator, $m_0$ – average neutron yield out of the target per single accelerated beam particle, e – charge of the accelerated particle.

It is possible to reduce intensity of external neutron source locating one in the center of the core and hence decrease neutron leakage.

Spatial localization of external neutron source (radius $r_{source}$) in the center of the core (radius $R_{core}$) can be characterized by source localization factor $\bar{a}$.

$$\bar{a} = \frac{r_{source}}{R_{core}}$$

Analytical dependence of $k_{ampl}\left(\bar{a}\right)$ [5] for fast-neutron core is shown in fig.1.
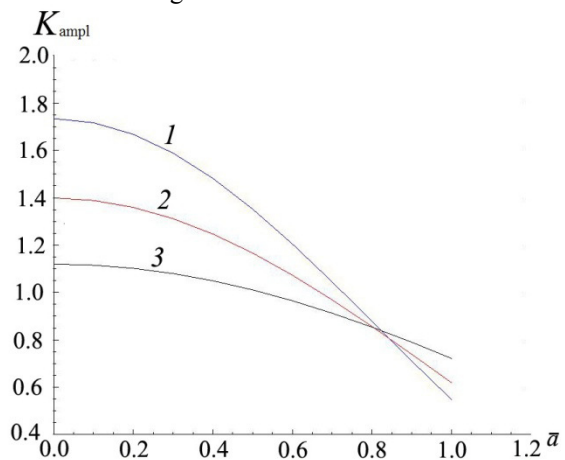


Figure 1: $k_{\text{ampl}}$ depend on source localisation factor, 1 - spherical geometry, 2 - cylindrical, 3 - slab.

## CASCADE REACTOR CORES

In works [3], [6] it's proposed to amplify external neutron source using coupling fast-thermal core zones (cascade core). Fast-thermal cascade core consists of inner subcritical section in fast neutrons with additional

neutron source and outer subcritical section in fast or thermal neutrons. The neutron feedback of inner and outer sections could be broken using neutron gate (thermal neutron absorber).
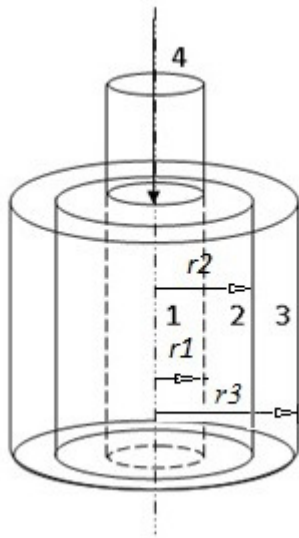


Figure 2: Cascade reactor core scheme. 1- inner section, 2- neutron gate, 3- outer section, 4 – charged particles beam.

In real cascade core it's impossible to break neutron feedback completely, because there is a lot of high energy neutrons in the outer zone, which couldn't be absorbed by the "neutron" gate and come into the inner section [2]. It can be avoided by using the second gate type: "geometrical" gate in cylindrical core (void gap $\Delta r = r_2 - r_1$). In this case both coupling zones could be fast.

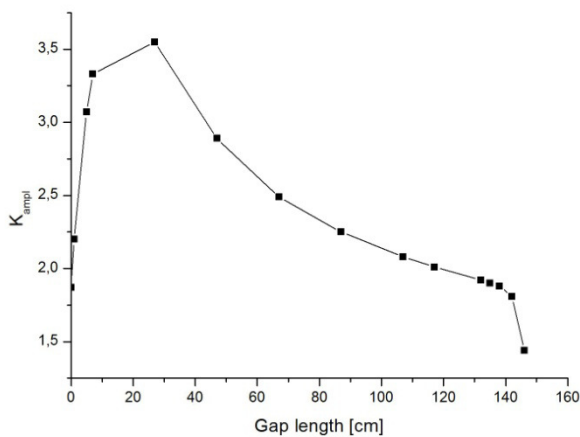In fig. 3 it's shown dependence $k_{ampl}(\Delta r)$ for fast cascade core with $r_3=150\ cm$.



Figure 3: Dependence of $k_{ampl}$ on gap length for cylindrical geometry.

## RESULTS

Thus, ADS power rate could be increase by several ways:

- localization of spatial distribution of external neutron source in the reactor core;
- optimization of spallation target size;
- using of coupling fast-neutron reactors (cascade core with "geometrical" gate).

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