CYBERNETICS AND PHYSICS, VOL. 5, NO. 2, 2016 , 52–58

THE PROBLEM OF ADS POWER-LEVEL MAINTENANCE

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Abstract

Scheme of subcritical reactor driving by proton accelerator is considered. The choice between proton and electron linac as an ADS driver for transmutation purposes is discussed. Principal scheme of ADS control system is presented.

Key words

Accelerator driven systems, subcritical reactor, ADS control, proton linac.

1 Introduction

Accelerator driven systems (ADS) is a new type of reactor which produces power even though it remains sub-critical throughout its life (Carminati and et al, 1993). The additional neutron supply, necessary to maintain nuclear reaction, comes from the interaction of an accelerated charged particle beam with a target. ADS can find a usage in nuclear power engineering for transmutation of long-lived radioactive waste, energy production and breeding new fissionable elements (Kudinovich, Ovsyannikov, Svistunov and Golovkina, 2014). The main advantage of ADS is high nuclear safety, because uncontrolled spontaneous chain fission reaction is eliminated.

In contrast to traditional critical reactors, where the control on reactor power rate is fulfilled with neutron absorbing rods, in ADS subcritical reactor is controlled by charged particle accelerator. Reactivity coefficient decreases as a result of nuclear fuel burning and fission products and actinide accumulation during reactor operation. So to maintain fixed ADS power-level dynamics of subcritical reactor driven by accelerator should be investigated.

ADS is most perspective for effective actinide transmutation, because it allows safely load large amount of transuranic elements to the reactor core in contrast to traditional critical reactors. However, it should be noted that construction of high power ADS will require to use accelerators also with high beam power not less than 10 MW. It is obvious, that such facilities are very expensive and the necessity of their construction as the alternative to fast reactors requires serious justification.

Nowadays R&D activities on ADS are focused on demonstration and experimental low-power facilities construction and also design of industrial ADS conceptual projects. In this paper the possibility of low-power ADS construction based on the proton linac is considered. The choice of such accelerator type as an ADS driver is justified. Also the problem of subcritical reactor control via accelerator is discussed.

2 The Choice of Accelerator-Driver Type for ADS

There are three main accelerator types that are considered as drivers for ADS: proton (Lawrence, 1995) and electron linac (Batskikh, Bekhtev, Boiko, Elian and Mitshenko, 1991) and cyclotrons (Alenitskii, Vorozhtsov, Dolya and et al, 2010). In the majority of works devoted to the transmutation of nuclear waste using ADS RF proton accelerator is considered as a driver. It can be explained by the fact that neutron production per watt of beam power for heavy elements targets (Pb, W, U etc) reaches a plateau just above energy 1 GeV (Figure 1) (Lawrence, 1995). That allows achieve necessary for transmutation neutron fluxes $10^{17} \div 10^{18}$ n/s with the beam power 10 MW. At energy 1 GeV, it corresponds to a relatively low average current of 10 mA. For electron beam, neutron yield growth as a result of photo-nuclear reaction practically stops at energy of 50-60 MeV (Figure 2) (Mittal, Nimje, Mondal and et al, 2010), and even at the average current of 200 mA neutron flux does not exceed 10^{16} n/s.

In the energy and current range of ordinary proton and

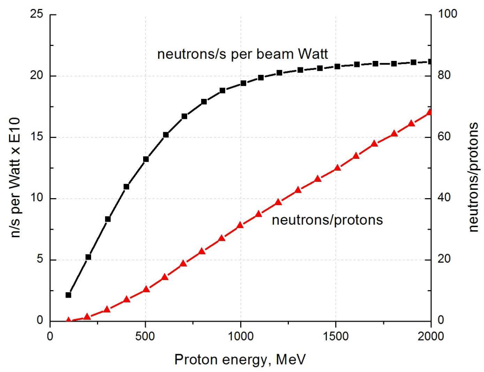

Figure 1. Neutrons/s per beam Watt, neutrons per proton, for a beam incident on axis of cylindrical W target 50-cm diam. x 100-cm long.

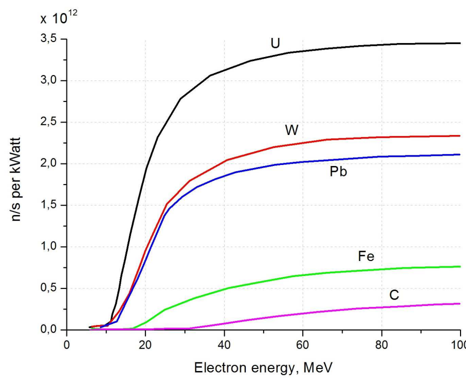

Figure 2. Neutrons/s per beam kWatt in photonuclear and photo fission reactions from Bremsstrahlung photons for an electron beam.

electron accelerators for industrial applications (50–100 MeV, the average current of 5-10 mA), the cost of one beam Watt for p-linac is 6–8 times higher than for e-linac. However the construction of e-linac providing neutron flux 10^{18} n/s by photo-nuclear reactions will require the output energy of 50 MeV with an average current of 10 A. Such accelerator would be far more difficult to create than p-linac with beam energy of 1 GeV and average current of 5-10 mA. It is shown, for example, in (Batskikh et al., 1991), where electron linac with an output energy of 100 MeV, the average current of 0.1 A and an accelerating system of racetrack microtron (RTM) type is offered as ADS driver. The authors expect to get 98% efficiency for RF power. Total efficiency, of course, will not exceed 40-50% (Mittal et al., 2010).

The proof of possibility to construct proton linear accelerator with an energy of 1 GeV and average current of 2–3 mA is SNS accelerator working at ORNL Laboratory since 2006 (Holtkamp, 2006).

There are also ideas to design accelerator-driver based on several circular RF accelerators. But even JINR offer to create cyclotron complex with an output energy of 600 MeV and a current of 10 mA looks not realistic, because in modern cyclotrons the output current is limited by 2 mA. It will take years of research to increase this limit to 5 times.

So in this paper was decided to consider p-linac as an ADS driver. The concept of a linear proton accelerator is shown in Figure 3.

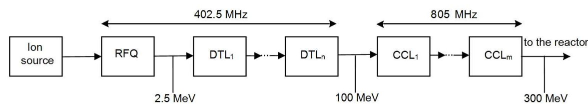

Figure 3. Principle scheme of considered accelerator

To accelerate particles to energy 2–3 MeV RFQ resonator, which allows to carry out almost 100% capture of particles in the acceleration, is used; to accelerate protons from 3 to 100 MeV — resonator with Alvarez-type drift tube with an additional beam focusing by quadrupole lenses, located in drift-tubes (not necessary in every one). The frequency of accelerating field can be 432, 350 or 216 MHz in the depenance of impulse current value. After the energy of 200 MeV is reached the further acceleration can be carried out in resonators with higher working frequency, for example, 864, 700 or 432 MHz. The accelerator length can be reduced at the expense of isochronous turn of the beam through 180° at the definite energy level. If account for an average accelerating field gradient of 3 MeV/m in prospect, then the length of accelerating tract will be 400–500 m. In the Figure 4 relatively compact possible ADS scheme is presented (Golovkina, Kudinovich, Ovsyannikov and Bogdanov, 2014).

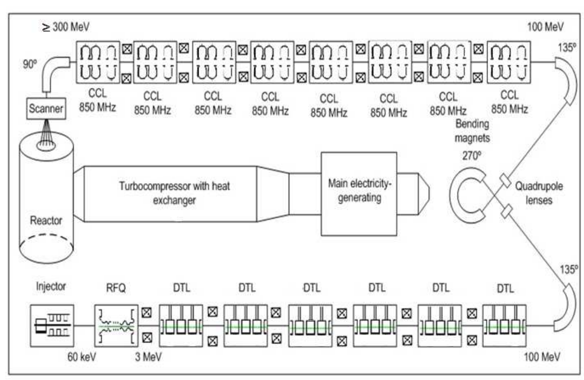

Figure 4. Possible ADS with proton linac scheme.

3 Neutron Producing Target

An electronuclear neutron source intensity is defined by the expression

$$S = \frac{I_p m_0}{e}, \quad (1)$$

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 Table 1, and neutron yields from these targets irradiated by the 300 MeV proton beam — in Figure 5. The presented results were obtained using GEANT-4.9.5 code (Svistunov, Kudinovich, Golovkina and et al., 2014).

Table 1. Optimal dimensions of cylindrical not fissile targets

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

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 Figure 6 in dependence of the protons energy, and the dependence of spallation neutrons yield inside the target on its radius in Figure 7.

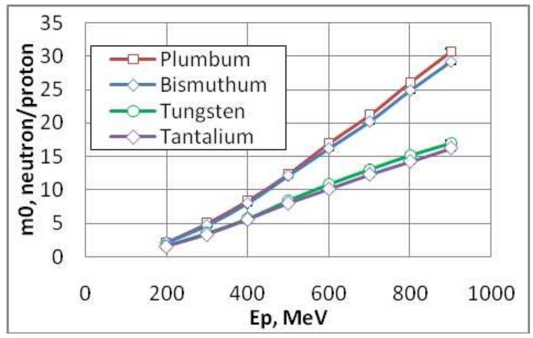

Figure 5. Neutron yield from target with the optimal sizes

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

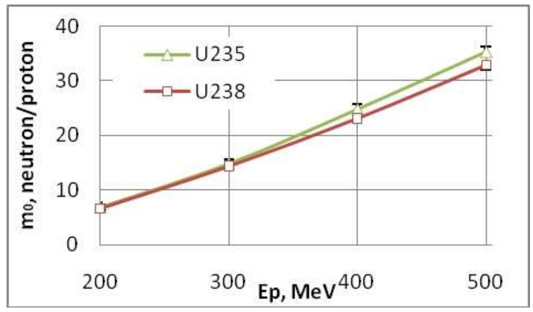

Figure 6. Neutron yields in the infinite uranic target (Geant 4.9.5).

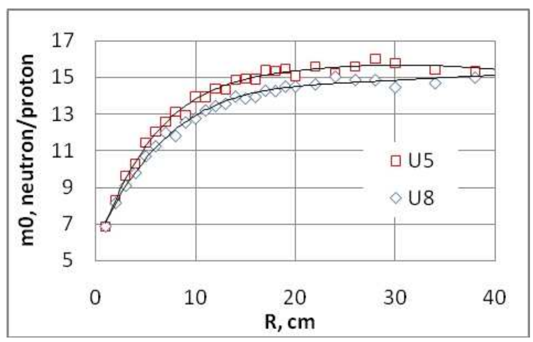

Figure 7. Dependence of spallation neutrons yield inside the target on its radius with 300 MeV proton beam (Geant 4.9.5).

4 Possible Control Schemes for ADS with Proton Linac

Thermal power for the reactor core is defined by the following formula (Golovkina, Kudinovich, Ovsyannikov and Bogdanov, 2014)

$$N_T = \frac{E_f S k_{\text{ef}}}{\nu(1 - k_{\text{ef}})}, \quad (2)$$

where E_f — energy, released per a fuel nuclei fission, k_{ef} — effective multiplication factor, S external neutron source generation intensity defined by (1).

In traditional nuclear reactors k_{ef} and the core are maintained critical by control system with neutron-absorbing rods which are mechanically introduced and withdrawed from the core. In ADS for the nuclear safety reasons neutron-absorbing rods are not used, that eliminate the possibility of accidents with unauthorized multiplication factor growth. So durting ADS operation external neutron source intensity should be variable to compensate possible reactivity changes. Reactivity is determined by the physical characteristics of the core and depends on the temperature, reactor fuel burn up and the accumulation of fission products and actinides.

4.1 ADS Power Level Regulation

The ADS power level control can be realized by variation of external neutron source generation intensity which depends on the average accelerator current and charged particles beam energy (Svistunov, Kudinovich and Golovkina, 2014).

The average current regulation is possible because of pulse current value or pulse repetition rate variation.

Pulse current can be increased by rising current at the exit of plasma ion source (for example, because of increasing the emissive aperture diameter), but the beam emittance grows meanwhile, system of beam formation for injection to the acceleration channel gets more complicated, transient processes in resonators and beam dynamics change. That is the accelerator design and adjustment becomes more complicated in comparison to accelerator with fixed output parameters.

Increasing of average current by increasing pulse repetition rate is a simpler decision because particle dynamics in accelerating tract doesn't change. The effect is achieved due to the control system of RF and injector feed lines.

Increasing of proton energy can be fulfilled by activating additional resonators at the end of the accelerating channel. In should be noted that when the resonators are turned off, the beam output characteristics will get worse.

Thus, the most suitable way to control ADS is the accelerator average current variation by pulse repetition rate change.

It should be noted that because of additional resonators high quality factor the transient processes in them will have quite large duration. As well known, the process of RF electrical field amplitude stabilization is characterized by the following expression:

$$E = E_\infty \left(1 - \exp(-t/\tau)\right),$$

where $\tau = Q/\pi f$ — magnitude which characterize transient (taking into account generator impact); t — time, Q — quality factor, E_∞ — steady value of rf field in resonator (for $t \to \infty$). The field stabilization time can be comparable with the current pulse duration or exceed it in several times. This can lead to the additional short pulsations of source neutron power.

4.2 Subcritical Reactor Feedbacks

The ADS subcritical reactor dynamics depends on outer and inner feedbacks (Figure 8). The inner feedbacks are determined by the reactor core physical characteristics, the external ones reflect the reactor connection with the power plant (coolant flow, coolant temperature at the entrance).

For stable ADS working at the constant power level, the reactor core should have the negative fuel and coolant temperature inner feedback and the negative mean reactivity coefficient. These conditions ensure the reactor self-control and the average temperature maintenance.

5 ADS Parameters Change in Time in Steady State Operation Mode

The ADS reactor core power level change is described by the point kinetics equations for subcritical reactor with the external neutron source:

$$\begin{aligned} \frac{dN(t)}{dt} &= \frac{\rho - \beta}{l} N(t) + \sum_{i=1}^{6} \lambda_i C_i(t) + q(t), \\ \frac{dC_i(t)}{dt} &= \frac{\beta_i}{l} N(t) - \lambda C_i(t), \\ N(0) &= N^{\text{ini}},\ C_i(0) = C_i^{\text{ini}}. \end{aligned} \quad (3)$$

Here $N(t)$ — reactor core power level (W), C_i — power of nucleus sources, bearing delayed neutrons, β — effective part of delayed neutrons; λ_i — decay constant for nucleus, bearing delayed neutrons; l_0 — average prompt life time; $\rho = (k_{\text{ef}} - 1)/k_{\text{ef}}$ — reactivity coefficient, determined by Doppler effect; $l = l_0 // k_{\text{ef}}$, $Q(t)$ — external neutron source intensity.

The average prompt lifetime depends on neutron energy spectra in the reactor core and changes from $5 \cdot 10^{-7}$ sec (for fast reactors) to $5 \cdot 10^{-4}$ sec (for thermal reactors). The effective part of delayed neutrons is $\beta = 0.0068$ for ^{235}U.

ADS subcritical reactor kinetics depends on accelerator current pulse period and duration $q(t)$ (Figure 9). If pulse period considerably less than the average prompt lifetime in the reactor, then the neutron source can be

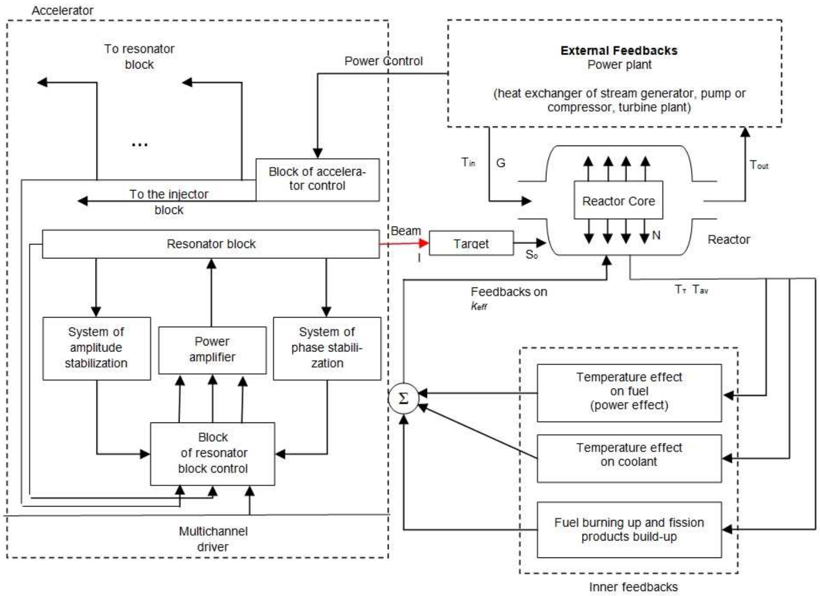

Figure 8. ADS structural scheme with feedbacks

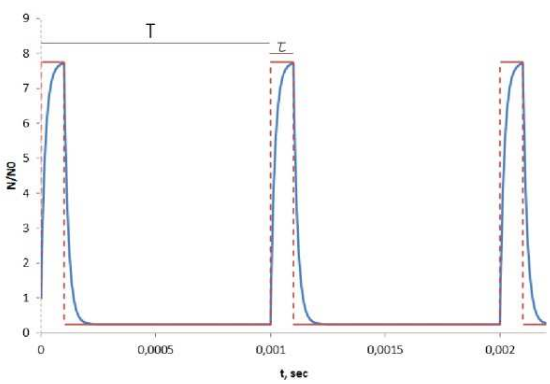

Figure 9. ADS structural scheme with feedbacks

treated constant with the intensity equals to the average (time) value of $q(t)$. This condition is fulfilled in cyclotrons.

The micro pulses period in the linear accelerator ($T = 5 \cdot 10^{-9}$ sec) is considerably less than the prompt life time. However the macro pulses period of the accelerator proposed for ADS ($T = 5 \cdot 10^{-3}$ sec) exceed the prompt lifetime in the reactor. Thus, the additional neutron source intensity in ADS with linac can be described as the sequence of rectangular pulses with a period and pulse duration corresponding to the accelerator current period and macro-pulse duration and with pulse amplitude corresponding to the average current value in the macro-pulse:

$$q_{\text{av}} = \frac{Q^{\max}\tau}{T}.$$

Inner feedbacks specify the dependence of power level dynamics in the reactor core on the fuel elements temperature. Because of reactor core heat capacity the time constant, characterizing the fuel rods temperature change, is not less than 0.01 sec. Thus, the subcritical reactor dynamics taking into account the influence of inner feedbacks can be described by quasi-static approximation for prompt neutrons — instantaneous step approximation (Keepin, 1965). In this case the system, describing the ADS subcritical reactor dynamics with external neutron source looks like (Golovkina, Kudinovich and Ovsyannikov, 2014):

$$\begin{aligned}
&N(t) = \frac{(\lambda C_i(t) + q)\, l}{\beta - \rho(t)},\\
&\frac{dC_i(t)}{dt} = \frac{\beta N(t)}{l} - \lambda C_i(t),\\
&\rho(t) = \rho_{\text{av}} + \alpha_T \left(\widehat{T}_T(t) - T_T\right),\\
&M_{TH} C_{TH} \frac{dT_{TH}(t)}{dt} = 2G C_{TH}(t)\,(T - T_{TH}(t)) +\\
&+ hS\left(\mu \widehat{T}_T(t) - T_{TH}(t)\right), \qquad (4)\\
&M_T C_T \frac{dT_T(t)}{dt} = N(t) - hS\left(\mu \widehat{T}_T(t) - T_{TH}(t)\right).\\
&C_i(0) = C_i^{\text{ini}},\ \rho(0) = \rho^{\text{ini}},\ T_{TH}(0) = T_{TH},\\
&\widehat{T}_T(0) = T_{TH}.
\end{aligned}$$

where ${}_T$ — the fuel elements in the reactor core mass; ${}_{TH}$ — the coolant mass, ${}_T$ — fuel elements temperature; $\hat{T}_T$ — fuel rod temperature on its surface, μ — conversion factor; T_{TH} — coolant temperature, N — reactor thermal power; G — coolant mass flow; S —

fuel elements heat exchange area, α_T — Doppler coefficient (fuel), h — heat-transfer coefficient, $Q = pq$ — average source intensity, p — normalization coefficient.

In Figure 10 and 11 as an example, calculation results of reactivity and power rate change during fast subcritical reactor start-up are presented (Golovkina, Kudinovich, Ovsyannikov and Svistunov, 2014). It should be noted that fuel temperature remains constant after reactor start up due to fuel elements thermal inertia.

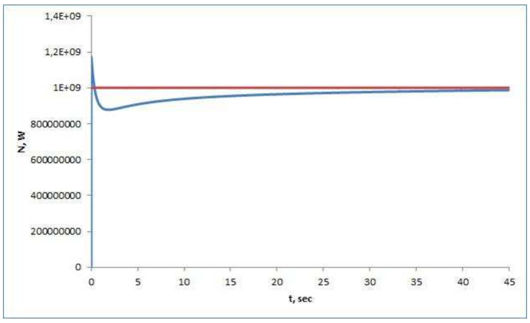

Figure 10. The ADS reactor power level change in time

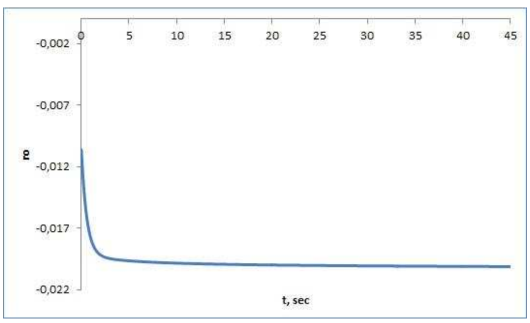

Figure 11. The reactivity coefficient change in time

6 Conclusion

To maintain ADS power-level it is necessary to regulate the external neutron source intensity and therefore charged particles beam characteristics. The most convenient way to control ADS is the average current variation by pulse repetition rate change. This control scheme doesn't depend on the used type of accelerator-driver, but it's shown that proton linac is more preferable for this purpose.

In the steady ADS operation condition neutron flux density in the reactor core changes periodically with a period corresponding to the impulse period in accelerator. The fuel elements temperature is almost constant in time because of their thermal inertia. At the ADS start-up, driven by linac with the constant average current, a short-time power surge higher the power rating level is possible, but the fuel temperature doesn't exceed its rated value.

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