THE PROBLEMS OF ACCELERATOR-DRIVER DESIGN FOR ADS

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Abstract

Main problems of accelerator-driver design for ADS are considered. Accelerator-driver should meet additional requirements in comparison with accelerators for other purposes: - high neutron production rate; - higher reliability; - continuous operation for more than 5000 hours; - possibility of accelerator parameters adjustment to regulate ADS power level. Different types of accelerators were analyzed taking into account the mentioned features and the fact that the most prospective way of ADS application nowadays is transmutation. It's shown that the most preferable accelerator type is proton linac. Also it's marked that for demonstration facilities accelerators with lower requirements and correspondingly cost can be used.

INTRODUCTION

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 [1]. 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 [2].

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.

THE CHOICE OF ACCELERATOR-DRIVER TYPE FOR ADS

There are three main accelerator types that are considered as drivers for ADS: proton [3] and electron linac [4] and cyclotrons [5]. 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 (Fig. 1) [3]. 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 (Fig. 2) [6], and even at the average current of 200 mA neutron flux does not exceed 10^{16} n/s.

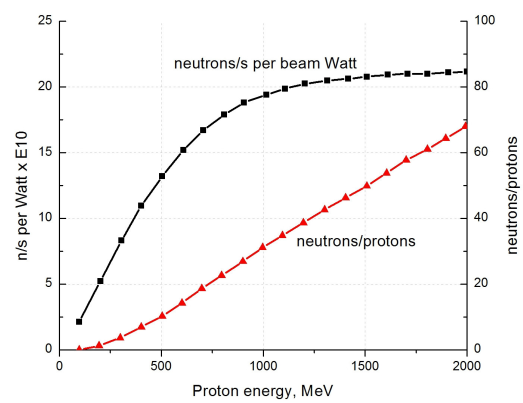

Figure 1: Neutrons/s per beam Watt, neutrons per proton, for a beam incident on axis of cylindrical W target 50-cm diam. x 100-cm long.

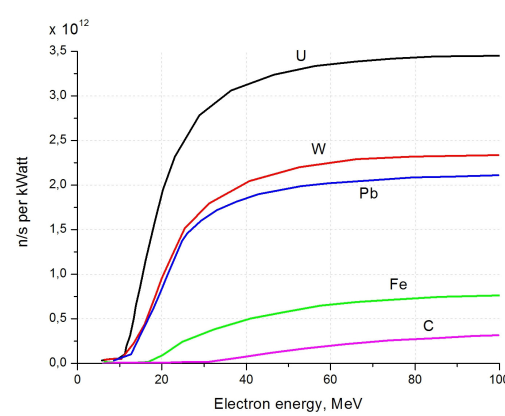

Figure 2: Neutrons/s per beam kWatt in photonuclear and photo fission reactions from Bremsstrahlung photons for an electron beam.

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ISBN 978-3-95450-181-6

In the energy and current range of ordinary proton and 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 [4], 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% [6].

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 [7].

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.

Deuteron linac isn't considered as ADS driver in this paper. Comparison of proton and deuteron beams as neutron producers was given in [8]. In range from 1 to 3.7 GeV under bombarding target the most essential difference are: (i) deuteron gives higher neutron yield by factor 1–1.15 than proton with the same energy; (ii) deuteron generates neutrons with smaller mean energy in comparison with proton. In the same time high energy d-linac design has essential additional problems in comparison with p-linac. So in this paper p-linac was decided to consider as an ADS driver. Conceptual scheme of proton accelerator proposed by Lawrence didn't change practically until the present time.

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.

NEUTRON PRODUCING TARGET

An electronuclear neutron source intensity is defined by the expression

$$S = \frac{I_p m_0}{e}, \tag{1}$$

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 proton beam of different energies — in Fig. 3. The presented results were obtained using GEANT-4.9.5 code. Possible targets construction is presented in [9].

Table 1: Optimal Dimensions of Cylindrical Not Fssile 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

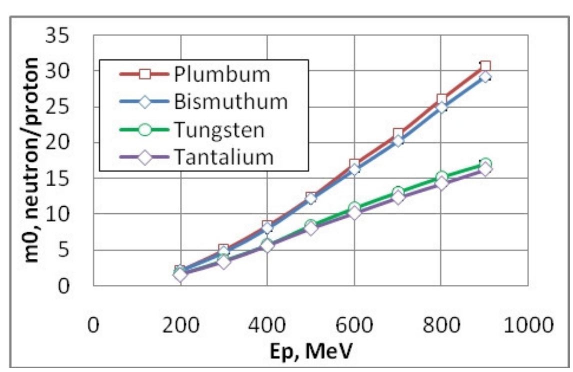

Figure 3: Neutron yield from target with the optimal sizes.

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

ISBN 978-3-95450-181-6

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 in dependence of the protons energy are approximately in twice more than for non fissile targets.

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

POSSIBLE CONTROL SCHEMES FOR ADS WITH PROTON LINAC

Thermal power for the reactor core is defined by the following formula [10]

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

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

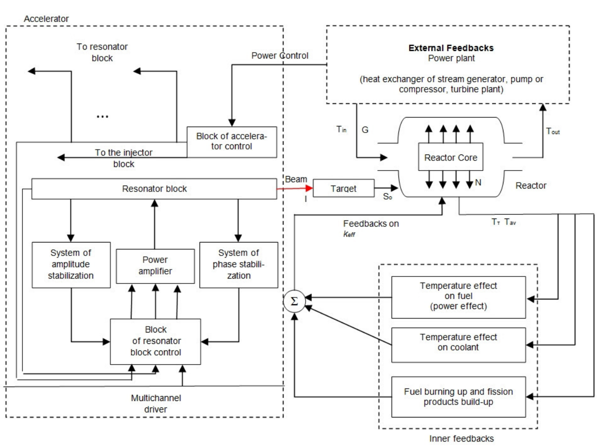

Figure 4: ADS structural scheme with feedbacks.

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.

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 [11].

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 isn't changed. 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.

Subcritical Reactor Feedbacks

The ADS subcritical reactor dynamics depends on outer and inner feedbacks (Fig. 4). 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.

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.

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ISBN 978-3-95450-181-6