ОБЪЕДИНЕННЫЙ
ИНСТИТУТ
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E2-98-137

V.S.Barashenkov, I.A.Shelaev

ELECTRONUCLEAR AMPLIFIERS WITH LOW-ENERGY PROTON BEAMS

Submitted to «Атомная энергия»

1998

Though the idea of sub-critical electronuclear reactors has long been created (see, e.g., a review [1]), for several decades the electronuclear systems were considered only as breeders for a production of plutonium or U^{233} in targets with natural or depleted uranium or thorium and with a multiplication coefficient $K_{eff} \ll 1$. It was supposed that each such a breeder should supply by nuclear fuel several nuclear plants. Theoretical modeling and experiments have shown that an optimal energy of the bombarding particles is about 1 GeV because at other energies the "energy cost" of the produced neutron increases, especially due to a rapid growth of ionization losses at lower energies. For example, if the estimated energy spent at $E = 1$ GeV on the production of one neutron in a very large (practically infinite) natural uranium target is $E/N_n \simeq 9.6$ MeV, this value reaches already about 18 MeV at $E = 0.4$ GeV and 45 MeV at $E = 0.2$ GeV. A shifting to higher energies leads to a significant increase in capital cost of the accelerator.

The physical and economical estimations have shown that the electronuclear breeding is an excellent method to utilize the natural uranium and thorium [1]. However, progress on this way is restrained by a necessity to use accelerators with very intense beams ~ 100 mA when we encounter both a lot of pure technical problems and serious difficulties stimulated by the demand of the radiation safety.

The idea of using sub-critical systems has been rehabilitated by C. Rubbia who proposed to confine oneself to a closed scheme "one accelerator — one reactor" when the electronuclear setup, without no additional breeding, produces energy and incinerates its radioactive long-living waste. Such an approach allows one to reduce the beam intensity by an order and is not far to the region of the already assimilated proton currents. By that, as before, the energy of 1 GeV is considered as an optimal one. The recent experiment by Rubbia et al. with a reactor in a proton beam [4, 5] has confirmed that the relative (per an unity of the consumed energy) heat production and the neutron yield are maximal at 1 GeV indeed. However, in sub-critical systems the main contribution to the heat and neutron production is due to the low-energy fission and the ionization losses are not so important as in the case of small K_{eff}. For instance, at the bombarding proton energy $E = 100$ MeV where about 95 % of the energy is transformed into the ionization losses the relative energy gain $\Delta Q/E = |Q(E) - E|/E$ is, nevertheless, several times greater the unity. As it is seen from Fig. 1, a shifting from $E = 1$ GeV to $E = 0.5$ GeV decreases the value of $\Delta Q/E$ only about on 5%. A rapid abatement takes place only at $E = 0.2$ GeV.

In Fig. 1 typical values of the correction factor of the proton beam intensity $n(E) = Q(1GeV)/Q(E)$ compensating the decrease of the heat generation in comparison with that at $E = 1$ GeV are shown. Since, in contrast to the high energies, in the region of several hundred MeV the beam intensity can be enlarged in dozens times (especially by using of several beams for one target, see below), the use of low-energy accelerators in electronuclear setups seems advantageous.

The conclusion of the paper [4] that $E \approx 0.3$ GeV is a threshold for the spallation processes seems to be too rough. The number of spallation particles at those energies is indeed rather small, however, a generation of particles in the process of an evaporation of excited compound-nuclei which are created due to an absorption of fast particles developing in the target remains significant (for details see the monograph [6]). Due to a multiplication of these particles in internuclear cascades the relative heat production Q/E at $E = 0.2$ Gev is only two times lower than at $E = 1$ GeV. The conclusion of the paper [4] contradicts the numerous cascade calculations and the experimental measurements for thin and thick uranium and leaden targets.

[1] Such a conclusion was a results of a permanent seminar of specialists from several Russian and Ukrainian institutes which took place in Obninsk under leadership of P. L. Kirillov in early 70s. The seminar prepared a memorandum which initiated the regular investigation of the electronuclear problem in former Soviet Union and later on in Russia.

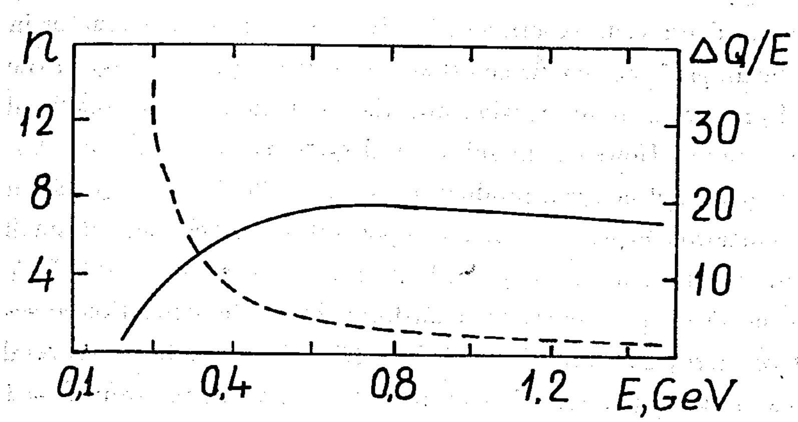

Fig. 1. *Dependence of the relative energy gain* $\Delta Q = |Q(E) - E|/E$ *(solid curve) and the correction factor of proton current* $n(E)$ *(dashed curve) on the bombarding proton energy E. The calculation have been done for the electronuclear system designed in JINR on the basis of the core of the impulse plutonium reactor IBR-30 [2, 3]. Coefficient of neutron multiplication* $K_{eff} = 0.943 \pm 0.003$.

An electronuclear setup combining the plutonium reactor and the proton accelerator with the energy $E = 0.66$ GeV and current 3.2 μA is beeing designed at JINR. Though the proton energy is one third smaller than the "optimal" one $E = 1$ GeV, the decrease of the energy gain is only 3 %. The use a quarter of the proton beam intensity by $K_{eff} = 0.94$ allows one to have a heat power about 10 kW [3] which can be removed by an aerial cooling. In order to avoid any alterations of the radioactive core of the available reactor the core in the new setup will be made of two identical parts disjoined by a steel plate with uranium-molybdenum insert in its center. This plane segment substitutes the revolving disk of the working now impulse reactor. The uranium (^{235}U) in the center of this detail is necessary to increase the coefficient K_{eff} of the setup. The

beam of the accelerated protons is brought into the edge of the segment.

Estimation of the thermal loads of various components of the designed setup have shown that they do not exceed the critical values and can be rapidly decreased by means of a decrease of the proton current. By the proposed value $K_{eff} = 0.94$ the setup is a safety sub-critical assembly and do not need a special system of emergency safeguard.

During several years in our Institute an accelerator system for an industrial electronuclear power plant with a thermal power 3 GW has been designed [7]. It includes 10 warm 28 MeV injector isochronous cyclotrons and an 240 MeV separated orbit cyclotron (SOC) with 10 floor superconducting magnet system and 12 rf cavities producing 10 separate 10 mA proton beams. Primary this SOC was assumed to be used as a booster for a main superconducting 1 GeV SOC. The developed idea to use low-energy proton beams in electronuclear setups allows one to manage without the later mashine. That four times decreases the complexity and the cost and of the accelerator system.

The 6 cm neighboring orbit separation at the final energy in injector cyclotrons is achieved by the application of 6 dees with 120 fkV amplitude of accelerating tension on each one. The warm rf cavities in the 240 MeV cyclotron are similar to the used at SIN. To excite the accelerating tension in a cavity one needs approximately 100 kW power without the beam load and 2 MW at the operating beam current. So, the efficiency of the rf power using is 95 %. The energy gain per turn is up to 6 MeV, so the turn separations are 5 cm and greater.

The bending and focusing of the proton beam in the 240 MeV SOC are provided by superconducting dipole and quadrupole magnets of synchrotron type with 25 mm apertures and low magnetic field formed by steel yokes [8]. For example, the field in a dipole magnet is 1.2 T. This type of SC magnets was successfully used in Dubna at the construction of JINR Nuclotron.

The superconducting magnets form a flat spiral magnetic road. In SOC there are 10 such roads placed on one another. The magnet structure has 16 FODO cells per turn. All superconducting magnets are assembled in 64 LHe cryostats placed between the rf cavities. Their estimated heat leaks of a cryostat is 10 W at LHe temperature, i.e. about 1 MW on the electrical system for all magnets or lower than 1 % of the total beam power.

The designed cyclotron facility is more compact than any linac, it is much cheaper and reliably in the operation. The division of the required very intensive beam into 10 separate channels at the start of the acceleration provides stable operation of the facility and its flexible control.

References

[1] V. G. Vasilkov et al. Atomic energy, **29**, p. 151.

[2] V. S. Barashenkov, A. Polanski, A. N. Sosnin. *Application of low-energy accelerators in electronuclear system.* JINR E2-97-304, Dubna (1997). Kerntechnik (in print).

[3] V. S. Barashenkov, et al. *Physical aspects of an electronuclear set-up on the basis of subcritical zone of the IBR-30 reactor and the 660 MeV proton phasotron.* JINR P2-98-14, Dubna, 1998.

[4] S. Andriamonie et al. Phys. Lett. B 348 (1995) 697.

[5] J Calero et al. NIM 376 (1996) 8.

[6] V. S. Barashenkov, V. D. Toneev. *Interaction of high energy particles and atomic nuclei with nuclei.* Moscow, 1972.

[7] I. A. Shelaev. *Superconducting Separated Orbit Cyclotron for Electronuclear Reactor.* JINR Rapid communication No. 5[62]-93.

[8] S. A. Averichev et al. JINR R9-78-11700, Dubna, 1978.