A PROTOTYPE BETA COMPENSATED REACTOR (BCR) DRIVEN BY ELECTRON ACCELERATOR

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ABSTRACT

An external neutron source is required to provide additional neutrons for a proper operation of a sub-critical system. Spallation neutron sources, though very effective in neutron production, are large, expensive and presently would involve certain difficulties in their operation (e.g. beam trips). In this paper we investigate the use of an external neutron source driven by an electron accelerator. The lower performance of the neutron source (compared to spallation based neutrons) could be balanced by a surrounding multiplier core, operating in a slightly undercritical regime with k_{eff} ~ 0.995 like in the case of a so-called Beta Compensated Reactor. An electron driver is rather cheap and compact machine that might bring many advantages in terms of reliability. An overall comparison between the electron-neutron converter and spallation process is done including a schematic layout for an electron driver coupled to nearly critical core with some preliminary calculations of the nuclear system parameters (k-effective, neutron fluxes, reactor power, etc…).

1. INTRODUCTION

Present critical nuclear reactors are unable to burn all long-lived nuclear waste produced and accumulated during last 40 years. Indeed, it would be extremely dangerous to operate standard PWR reactors with a high content of actinides in the fuel due to a very small number of delayed neutrons. Therefore, dedicated Accelerator Driven Systems (ADS) have been envisaged for nuclear waste transmutation. Coupling an external nuclear source (a proton accelerator inducing neutrons by spallation) to a sub-critical assembly enables to run safely the system even without any delayed neutrons. But until now, ADS have been facing a number of difficulties. The accelerator part by itself is a very long (300 to 500 meters) and quite expensive (150 to 300 MEuros) item [**1**] with extremely stringent requirements (less than one trip a month). Very high beam power is required if the nuclear assembly has to operate in a well undercritical regime (k_{eff} = 0.90 to 0.95). In addition, the nuclear part would demand long and extensive fuel development for fabrication and processing. In this paper an unusual system is described eliminating most of the problems encountered in conventional ADS. The accelerator is an electron machine, being cheaper, more reliable and more compact than high power proton linacs. Neutrons are produced in a uranium carbide target by photonuclear rather than spallation process.

Under operation, the nuclear assembly is slightly under-critical with an effective multiplication factor of k_{eff} = 0.995 to 0.997, but there is a dynamic feedback between the neutron flux measured and the intensity of the external source of neutrons to simulate the existence of delayed neutrons. The delayed neutrons which are not created in sufficient quantity in a fuel containing of minor actinides are supplemented by delayed neutrons coming from the external source in order to guarantee the controllability of the system and its safety. So, the whole system (under critical core plus external source having a suitable feedback) has the behavior of a critical system and control rods are used to control it like a traditional reactor. This kind of system is called Beta Compensated Reactor (BCR) after the fraction beta of delayed neutrons. A schematic layout and design of a small demonstrator (50 MWth) is proposed based on a high temperature reactor core using standard particle fuel with its neutronics and safety being analyzed and discussed. We note separately in this connection that an electron driven sub-critical facility IBR-30 with a multiplication factor of 200 have been operating successfully for nearly 30 years as a pulsed neutron source for nuclear measurements at JINR Dubna in Russia [**2**].

2. THE PHOTONUCLEAR PROCESS

Photonuclear reactions such as (γ,n) and (γ,2n) can be induced in any material by specific gamma rays exciting the Giant Dipolar Resonance (GDR) of the nuclei. (γ,fiss) may occur only in the case of actinides [**3**,**4**]. As an example, the GDR fission cross-section for ^{238}U is shown in Figure 1. A maximum fission probability of 160 mb can be obtained for photons having energy around 15 MeV. At that energy, the photoelectric as well as Compton and Rayleigh scattering cross sections are starting to fall off rapidly so the main contributions to gamma absorption are e^+e^- pair creation and the photonuclear reactions (γ,fiss), (γ,n) and (γ,2n). Although the absolute fission cross section is rather small (compared to normal fission with neutrons), its contribution is not negligible since even a pair creation reaction may in a thick target eventually lead to a fission through the resulting photon produced. In the same manner the neutrons produced by the (γ,n) and (γ,2n) photonuclear reactions as well as (γ,fiss) itself can in turn induce fission, this time by the regular (n,fiss) channel. Therefore, in a thick target, photonuclear processes may be a rather interesting way of creating an effective external source of neutrons.

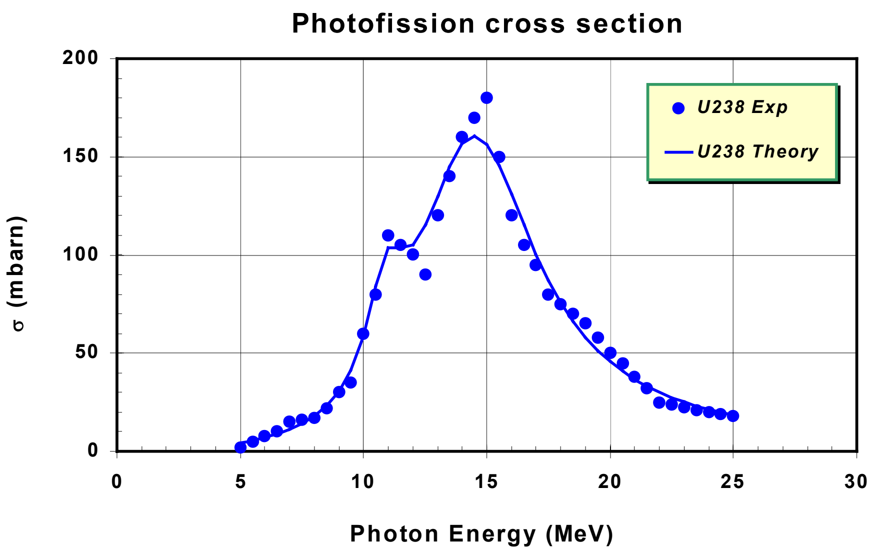

Figure 1. Photofission cross section for ^{238}U.

Unfortunately, the most common way for producing high gamma fluxes is the bremsstrahlung process radiated by passage of electrons through matter [**5**,**6**,**7**]. This process has a cross section rising linearly with energy. It will dominate the ionization process above a critical energy (around 20 MeV). But the resulting bremsstrahlung spectrum is widely spread in energy from zero up to the full initial electron energy. Although each single electron may ultimately produce as many as 40 photons, only a small fraction of them (a few percent) are "useful" photons lying in the GDR range (15 ± 5 MeV). Therefore, the overall efficiency is lower than what might be expected from the direct photonuclear process.

3. ESTIMATED NEUTRON YIELD & COST

The number of fissions per incident electron impinging on an infinite target can be calculated using the photofission cross section. It approximately follows a linear law with a threshold energy of about 8.5 MeV [**8**]:

$$(f/e-) = 1.9\,10^{-4}\ (E_{[\text{in MeV}]} - 8.5) \qquad (1)$$

For example, an electron of 100 MeV will induce 0.017 fissions. The neutron flux can then be estimated taking into account that each fission will release about $\nu_f = 3.4$ prompt neutrons in addition to the contribution of the direct photonuclear reactions (γ,n) and (γ,2n), which contribute nearly the same number of neutrons as the photofission process. The total number of neutrons produced for a 100 MeV electron is then (n/e-) = 0.11. In this case the neutron cost is about 900 MeV. This is much larger than the neutron produced by the spallation process (for example a 1 GeV proton on a lead target) where each proton can evaporate about 30 neutrons. The spallation neutron cost is around 30 MeV, i.e. 30 times cheaper than the photofission one. But, as it will be seen in the following discussion on the accelerator cost, the investment cost of a 100 MeV electron machine is about one order of magnitude lower than the 1 GeV proton one, which counterbalances the higher price paid for the neutron.

4. THE ELECTRON ACCELERATOR

An electron machine has many advantages over hadron accelerators. Because the electron rest energy is low, the particle is quite rapidly relativistic. So the electromagnetic structures are easy to design and no specific energy tuning is required in between the cavities. High accelerating gradients can be achieved making this type of machine rather cheap and compact. Two additional advantages are to be stressed: an extremely simple and very bright sources available and an easy radiation shielding and dismantling issue (no beam losses, no neutron production in the machine). Our reference design for the ADS/BCR is to choose a superconducting linac electron machine. This allows continuous (CW) beam operation and a very high efficiency (~100% RF to beam). A complete layout of the electron driver is shown in Figure 2. The gun is a standard 100 kV using a barium-oxide gridded cathode directly triggered at the working RF frequency. A specific structure is needed for the first cavity to properly capture the beam, a 100 keV electron being not fully relativistic. Four identical cryomodules containing each four β=1 elliptical cavities are sufficient to accelerate the particles up to the final energy of 250 MeV. The beam is then deviated and brought to the reactor vessel through a very simple transport line. The total cost amounts to 33 MEuros, not taking into account manpower and buildings. For redundancy and safety, one may also design two identical linacs each having half of the required beam current.

When comparing a photonuclear to spallation process, the neutron cost is higher while the accelerator cost is lower. Therefore, for the same neutron flux required, a higher electron intensity (and beam power) will be required due to the lower efficiency. Thus, above a given neutron flux, the spallation will be preferred while for the lower fluxes, the photonuclear process will tend to be much cheaper. This can be immediately seen from Figure 3 where for a given neutron flux, an electron machine as well as a proton accelerator have been cost effectively estimated. Note that this is only machine cost, which does not include manpower or buildings (which again are certainly cheaper for the electron machine). For fluxes exceeding 10^{17} n/s, the spallation process will start to appear more effective while below 10^{17} n/s, the photonuclear process is cheaper, even though the beam power required is higher. That is the reason why, aiming at a neutron source of the order of 10^{16} n/s, an electron accelerator has been selected for our baseline design.

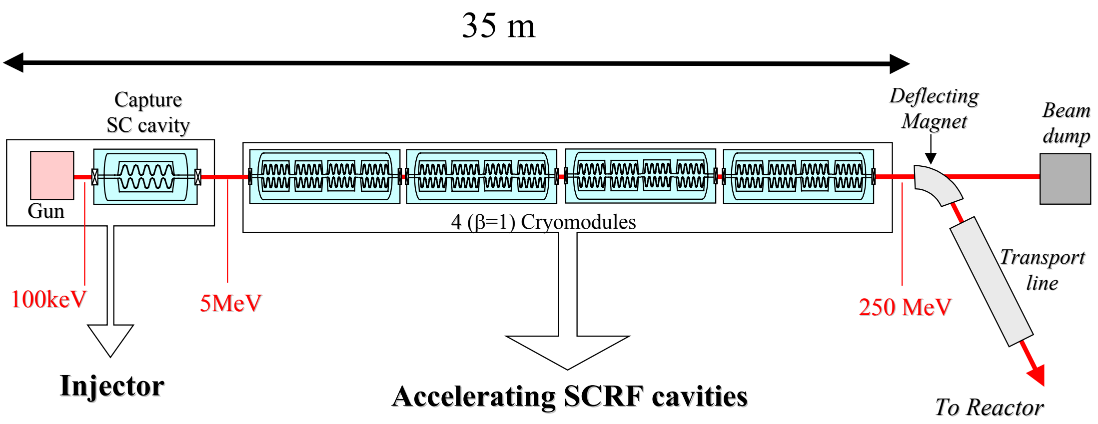

Figure 2. Layout of the electron accelerator for an ADS/BCR.

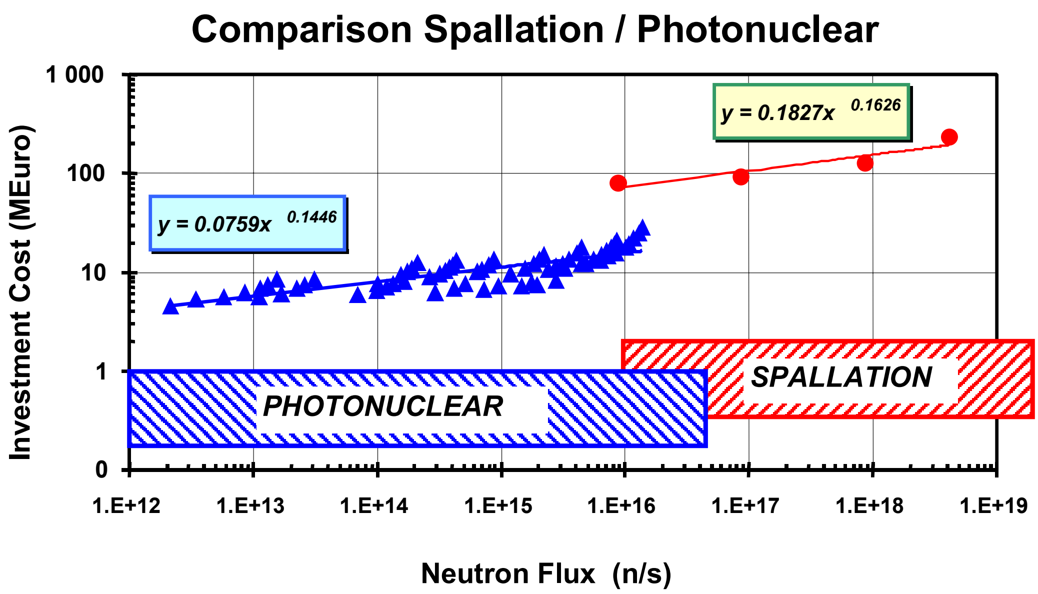

Figure 3. Spallation versus photonuclear process for neutron production.

5. MAJOR CHARACTERISTICS OF THE SUB-CRITICAL REACTOR

The proposed nuclear assembly is a sub-critical core based on the high-temperature gas-cooled technology. The gas turbine-modular helium-cooled reactor (GT-MHR) **[9]** (with an appropriate downscaling) is taken as a reference for our modeling. Conceptual design of GT-MHR was developed in a joint project of USA, Russia, France and Japan with the major interest in plutonium based fuel cycles in general and military plutonium destruction in particular **[9]**. We refer the reader to ref. **[9]** for further details on the technical characteristics of GT-MHR and refs. **[10,11]** for different performance estimates in the case of critical as well as sub-critical GT-MHRs. In brief, GT-MHR uses an annular graphite core and graphite inner and outer reflectors, giving a rather thermalized neutron spectrum, operates at high temperature without the need for fertile material and employs ceramic-coated fuel in a form of micro particles **[9].** It utilizes natural erbium as a burnable poison with the capture cross section having a resonance at a neutron energy such that ensures a strong negative temperature coefficient of reactivity. The lack of interaction of neutrons with the coolant (helium gas) means that temperature feedback is the only significant contributor to the power coefficient. GT-MHR **[9]** is an electric generation power plant (600 MW_{th}) that couples a critical reactor with an efficient (~ 47%) energy conversion system. A simplified model of the homogeneous sub-critical reactor core, cooled by helium gas, has been created using MCNP **[12]** geometry setup in 3D as shown in Figure 4.

MCNP was also used to obtain the k_{eff} eigenvalues and neutron fluxes. A single difference compared to a critical GT-MHR was to include an electron target for the neutron production located in the inner graphite reflector. The same MCNP code enhanced with photonuclear capability has been used to model neutron production with electrons **[13].** Both (γ,n), (γ,2n) and (γ,fiss) reactions were taken into account explicitly with a corresponding full secondary neutron transport.

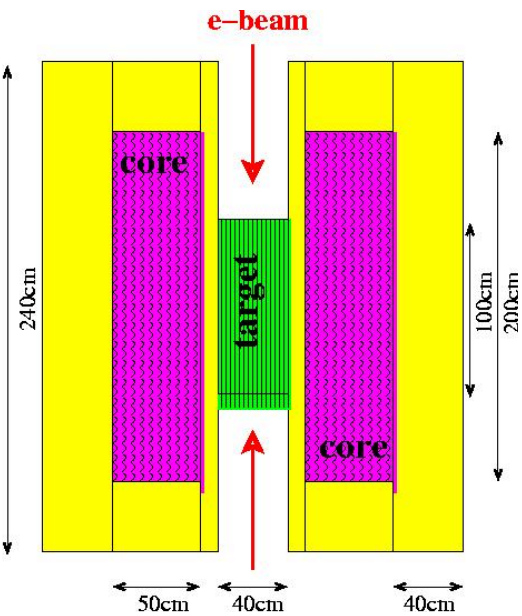

Figure 4. An annular core of a sub-critical gas cooled reactor driven by an electron accelerator. See Table I for details.

Table I. Basic core geometry and fuel parameters.

Active core size: - Height, cm - Outer radius, cm - Inner radius, cm	 200 80 30
Active core volume, m^3	3.456
Fuel : - Enriched uranium (%) - Initial fuel mass, kg	 20 487
Effective density, g/cm^3: - Electron target - Active core - Top/ inner/ bottom reflector - Side reflector	 1.25 1.41 1.45 1.82

6. RESULTS OF THE SIMULATION

The electron target (100 cm long and 40 cm diameter) is made of uranium carbide (^{238}UCx with M_u/M_c=1/1) (see Figure 4). An effective density of the target is chosen to be 1.25 g/cm^3 to optimize the beam energy deposition along the beam axis. For the same reason 250 MeV electron energy has been selected. The target is cooled by the same helium gas flow as the reactor itself. As an alternative, a separate cooling helium gas flow can be dedicated to the target, which could simplify the safety assessment. Almost 92% of the primary beam power is deposited in the target, while the rest of the energy is taken away by outgoing electrons, gammas and neutrons. In other words, the primary beam of 5 MW would result in ~ 37 W/cm^3 averaged power density in the target. The energy deposited by electrons is plotted in Figure 5 as a function of the target thickness with a beam spot diameter on the target as big as 20 cm. It is clear that further optimization of the target geometry and material is needed. On the other hand, our preliminary results presented above are already very promising.

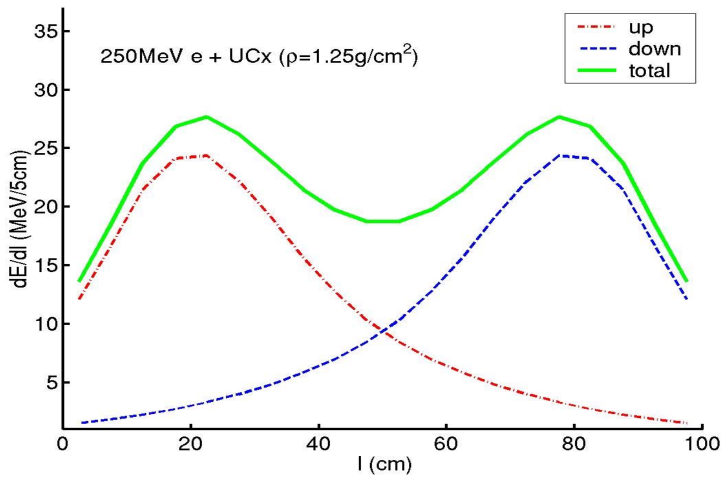

Figure 5. Energy deposition in the electron target by up and down electron beams at the incident energy of 250 MeV.

7. NEUTRONICS OF THE SYSTEM

In the case of the target presented in the previous subsection, each 250 MeV electron will roughly emit about 0.15 neutrons almost isotropically from the target surface. This neutron production rate results in an external neutron source intensity of the order of $2{\cdot}10^{16}$ n/s at 5 MW of the primary beam power (2x10 mA beam current). Note separately that most of these neutrons (~ 91%), being fast neutrons, have an energy lower than 5 MeV, i.e. external neutrons are to be used as efficiently as typical fission neutrons originating in the core.
Table II gives major neutronics characteristics of the sub-critical core (k_{eff} ~ 0.995), driven by two electron accelerators of 10 mA each.

Table II - Basic sub-critical reactor parameters.

Reactor power (density), MW_{th} (W/cm^3)	50 (14.5)
Multiplication coefficient	0.995
Neutron multiplication	200
Electron energy, MeV	250
Beam current (power), mA (MW)	2 x 10 (2 x 2.5)
Neutron yield, n/e^-	0.15
External neutrons, n/s	$1.88{\cdot}10^{16}$
Total neutrons, n/s	$3.76{\cdot}10^{18}$
Total fissions, fiss/s	$1.56{\cdot}10^{18}$
Neutron flux in the core, n/s cm^2	$2.2{\cdot}10^{14}$

It is clear that with the neutron multiplication factor of 200 the contribution to the total neutron flux by the external neutrons will be negligible (< 1%) as shown in Figure 6**.** The calculation results in the averaged neutron flux of the order of $2.2{\cdot}10^{14}$ $n/s{\cdot}cm^2$ in the active core region and 50 MW_{th} of fission power. Note that both in absolute value and energy distribution (~ 10% thermal) the resulting neutron spectrum is comparable to the typical GT-MHR spectra **[11]**.

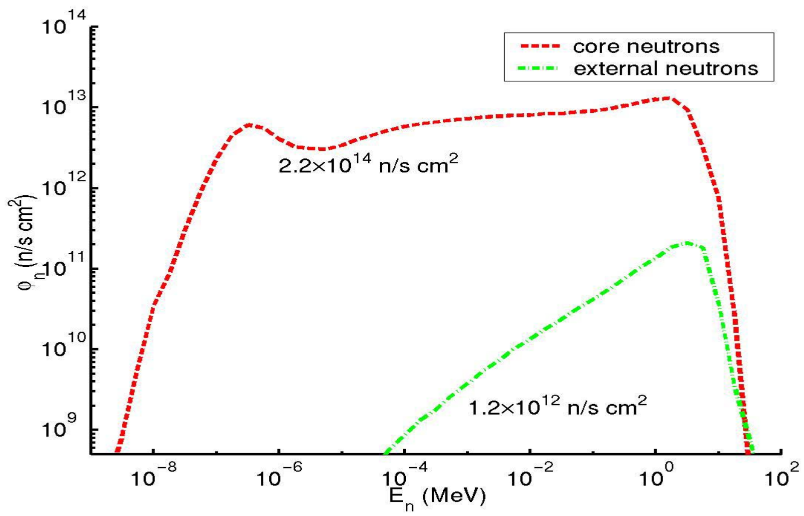

Figure 6. Averaged external neutron flux on the target surface compared to the averaged neutron flux over the active core volume.

8. THE CONTROL OF BCR

Incineration of minor actinides becomes rather difficult, if not impossible, in critical reactors as soon as their concentration exceeds a few percent of the fuel. The reason is the decrease of the delayed neutrons precisely due to the presence of these minor actinides. That results in shortening the period of the reactor and compromises its operation control. One solution usually considered in ADS systems is to operate very far from criticality ($k_{eff} = 0.95$). However, that requires a huge external source resulting in a huge and expensive proton accelerator. It has been shown here above (Figure 3) that only the spallation process would then be adequate for reaching these very high neutron fluxes. The approach presented here differs completely because the deficit of beta due to minor actinides is compensated by an external neutron source whose behavior simulates the evolution of the concentration of a group of precursors of delayed neutrons. The core operates on a level slightly under-critical but the whole system, including the external source and the feedback between the neutron flux and the accelerator power, behaves like a critical reactor. The large advantage is that the external neutron source is reduced by a factor 20 to 30 compared to more conventional ADS. This characteristics and the flexibility requested from the source to simulate a group of delayed neutrons makes possible the use of the photonuclear process for neutron production.

It must be noted that the coupling between neutron flux and the electron driver is permanent and that only the control rods make it suitable to control the power of the system as shown in Figure 7. The level of under criticality to which the core under operation is established is automatically fixed by the parameters of the coupling. -Another remark is that the thermal spectrum of a GT-MHR type core might be not effective for burning all minor actinides [**11**]. A faster spectrum would be more adequate, especially if one is aiming at deep burn-ups (like in a one through cycle). On the other hand, the design presented here is a demonstrator proposal namely to study only the coupling of an external neutron source based on the photonuclear process with a well-defined reactor core. It is clear that the incineration of minor actinides would request somewhat harder spectrum that would require further nuclear fuel and moderator development. This could be done at a later stage evolving from a typical GT-MHR towards a new concept of a gas cooled fast reactor dedicated to burn actinides.

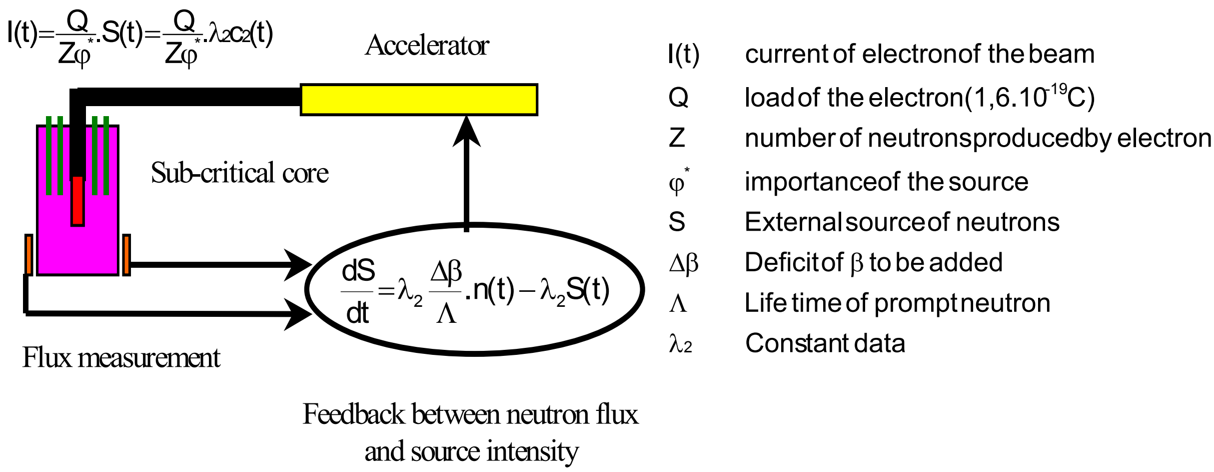

Figure 7. Principle of a Beta Compensated Reactor (BCR).

Below we list a number of advantages the BCR is offering (also see Figure 7):

- It makes use of the effectiveness of the very same feedback as those of critical reactors;
- It offers a flattened flux distribution that may be adjusted using control rods with different fuel enrichment zones. That solves the problem of sharpened flux encountered in many ADS systems having low multiplication coefficient;
- It relaxes the accelerator requirements and allows the use of photonuclear process for neutron production;
- It enhances the nuclear safety. The safety of BCR is improved compared to an equivalent critical reactor because, in addition to the traditional shutdown systems, the possibility of erasing a significant part of the delayed neutrons is added simply by turning off the beam. This ability to quickly reduce the neutron power with a reinforced reliability can give a definite advantage in the case of accident. The fact that the core is slightly under-critical also brings a certain margin of additional safety with respect to certain accidents of reactivity;
- It enables to run the system just as a usual nuclear reactor. The control and the behavior of BCR will be quite identical to a critical reactor. Criticality approach, power increase, burn-up compensation, control of the radial flux profile and possibly the follow-up of load will all be carried out by the absorbing control rods.

On the other hand, the BCR reactor will behave like an ADS system because the beta value results from an extrinsic process, while in a critical reactor the delayed neutrons are intrinsically brought by the fission itself. In order to ensure a permanent connection between the reactor power and the accelerator current, the reliability of the chain including the power measurement, the accelerator parameters and the command itself can be guaranteed to the desirable level by traditional process (redundancy of measurements and 2 out of 3 votes in operation). The same would apply for the correct operation of this chain and the emergency shutdown. One important incident may concern the loss of beam power from the accelerator. In that case, the core would experience an important power loss and consequently its temperature will start decreasing. The overall temperature reactivity coefficient (including the fast fuel component and the slower moderator one) of the proposed nuclear assembly have been calculated to be of the order of -1.3 pcm/K **[14]**. This rather low (compared to typical PWR reactors) but still negative value ensures the nuclear stability and also enables to work close enough to criticality without any fear to exceed it even in the case of a sudden failure of the accelerator system or in any other case of temperature change. Additional safety concerning that issue may be added by the target temperature control through a fully separated cooling system, i.e. independent from that of the core. In that case, the core temperature drop is highly reduced when the external neutron source is down. In order to prevent transients during operation, the accelerator current may be limited to a given maximum level (depending on the core power) with an emergency shutdown of the type beam intensity / primary flow active above the threshold. A passive safety component can be added to prevent fast changes in the beam power. It should be noticed that a beam stop should initiate an emergency shutdown and the fall of the control rods to guarantee safely the cold shutdown. Finally we add that more detailed both static and dynamic reactor investigations are still to be done and are in progress.

CONCLUSIONS

A non-conventional electron driven system (EDS) has been proposed based on the photonuclear processes, i.e. (γ,n), (γ,2n) and (γ,fiss) in particular. It includes an electron accelerator, neutron production target and a slightly under-critical (k_{eff} = 0.995) nuclear assembly, named "Beta Compensated Reactor" (BCR). Very encouraging preliminary calculations have been done using a GT-MHR high temperature reactor type core and coated particle fuel. Some safety issues have also been addressed and discussed. It is shown that a rather cheap 50 MWth demonstrator of that kind could be feasible with present technology. Further optimization study and safety issues in particular are in progress and will be reported elsewhere.

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