

## **ON THE SUPPLEMENTARY FEEDBACK EFFECT SPECIFIC FOR ACCELERATOR COUPLED SYSTEMS (ACS)**

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### **Abstract**

In this work a new approach to the realization of an Accelerator Coupled hybrid System (ACS) is proposed. A significant improvement of the feedback effect due to the particularities of the neutron production in a spallation target is expected. In a present study we explain the principle of the system functioning, advantages and disadvantages of the proposed concept. The quantitative analysis of the innovative ACS operation is based on a generalized point kinetics approach. In the frame of this simplified model we show that the particular dependence of the spallation neutron yield allows creating a supplementary negative feedback effect (Doppler-like). The implementation of this concept should compensate, at some extent, eventual feedback degradation in the cores dedicated to transmute nuclear waste.

## Introduction

In general, nuclear systems, devoted to the Minor Actinide (MA) transmutation, may suffer from the significant degradation of safety characteristics. In particular, such important parameter as delayed neutron fraction can decrease by several times compared to the conventional nuclear reactors. Another serious problem, arising in such systems, is the reduction of Doppler effect - the fastest and the most important temperature feedback effect in the reactor core. This degradation of safety properties makes the control of such systems rather delicate.

An innovative solution aiming to handle the above problem has been proposed recently and consists of the artificial enhancement of system neutronics: an external neutron source added to the core permits the system to operate in a sub-critical mode (so-called hybrid nuclear reactor). In Accelerator Driven Systems (ADS) [1], where a sub-critical core serves only to amplify the incident beam energy, a large sub-criticality margin ( $k_{eff} \sim 0.95-0.97$ ) mitigates the negative consequences of the degradation of safety parameters. However, this significant sub-criticality level requires a powerful and expensive particle accelerator. Another way to deal with the problem is to employ the concept of the Accelerator Coupled System (ACS) [2]. In this case an external neutron source, coupled directly to the core power and artificially or naturally delayed, can compensate the decrease of delayed neutron fraction. In this case less powerful (and consequently, less expensive) particle accelerators may be applied. On the other hand, the ACS inherits some properties of a critical nuclear system. In particular, degradation of feedback effects, e.g. Doppler, makes possible power and temperature excursions in the case of unprotected reactivity insertion.

In present work we propose a new approach for the realization of ACS, where a significant improvement of the feedback effect is expected due to the modification of the accelerator-core coupling mode and due to the particularities of the neutron production in a spallation target.

## Generalities of hybrid systems

In principle, core sub-criticality will improve the safety, in particularly, when feedback effects, the delayed neutron fraction or other safety related parameters are degraded due to presence of long-lived actinides subjected to transmutation. There are at least two different ways of functioning of a sub-critical core in combination with an external neutron source. In brief, this source can be independent on neutron (energy) production in cores (as in Accelerator Driven System – ADS), or it can depend on neutron (energy) production in cores and in this way becomes “coupled” or “coordinated” by core power level (e.g., Accelerator Coupled System – ACS [2]). Each combination opens some new opportunities related to the safety improvement. Major features of the ADS and ACS are summarized below.

In the case of ADS an *independent* mechanism of supplementary neutron production is employed to achieve the desired power level, and the accelerator power is supplied via independent energy grid.

In the case of ACS a “source of artificially delayed neutrons” consumes a part of in-core released energy. In this way the external neutron source becomes “coupled” with the core power level. As a result, the supplementary neutron creation will be delayed to the time required for fission energy transfer from the core to a chosen neutron production mechanism (e.g., spallation, *bremsstrahlung*-photonuclear, nuclear fusion, etc.). In other words, this intermediate process “hides” neutrons (of some neutron generation) temporarily to recover them later. This allows increasing the neutron life time artificially and to slow-down dangerous transients [3].

If compared to the conventional critical reactors, this particular property of the ACS can improve the reactor dynamics significantly. Moreover, the ACS operates in a critical mode and, therefore, in contrast to the ADS, takes advantages of favourable temperature feedbacks, which might exist in these systems [3].

It is known that in terms of safety the ADS is *inherently* more favourable (compared with the similar critical reactor) regarding reactivity accidents, where core sub-criticality mitigates consequences of the reactivity insertion. On the other hand, a system functioning in a critical regime (including ACS) is *intrinsically* safer in the case of thermo-hydraulic type of transients. Therefore, it would be rather attractive to combine these inherent advantages of both ADS and ACS in a single installation. In other words, one needs to realize a system, for which during *unprotected transients*

(a) the intensity of an external neutron source decreases with the decrease of core power,

(b) the intensity of an external neutron source remains stable or even decreases with the increase of core power, and

(c) conditions a) and b) have to be *intrinsic*.

One of possible solutions to merge the above advantages is presented in the following Section. It is based on the physical processes taking place in the neutron production target, what makes our approach inherent.

### Accelerator-core coupling modes in the case of ACS

Traditionally, it is assumed that in hybrid systems the current of proton accelerator is the coupling parameter, which one can vary to change the neutron source intensity. In the case of ACS, at least two modes of coupling between external neutron source and core could be envisaged:

1. When it is supposed to modify the intensity of an external neutron source  $Q$  by varying the proton beam current  $I_p$  at a fixed nominal value of the proton energy, namely

$$I_p = I_{p,0} P^{out} / P_0^{out}. \quad (1)$$

Here  $P^{out}$  is the output power of the installation, and subscript “0” denotes nominal values of the corresponding variables. Hereafter this method of the “accelerator-core” coupling is designated as “*I-mode*” coupling.

2. When any *change of an output power leads to a proportional change of the proton energy*  $\varepsilon_p$  at a fixed nominal value of the proton current, namely

$$\varepsilon_p = \varepsilon_{p,0} P^{out} / P_0^{out}. \quad (2)$$

This coupling method is denoted as “*E-mode*” coupling.

In this work we propose *to utilize the proton energy as coupling parameter (E-mode ACS)*. The difference between the *E-* and *I-*modes, we would like to make use of, is based on a *non-linear*

behaviour of the neutron yield  $Y_n$  with respect to the proton energy  $\varepsilon_p$  variation (hereafter “ $Y_n$ -effect”).

Indeed, as it is shown in a number of studies, when the energy of incident protons becomes higher than, say,  $\sim 1$  GeV, the neutron yield normalized per incident proton energy becomes nearly constant and even slightly decreases with proton energy (see Refs. [4-6] and Refs. therein). There are two major reasons for this decrease of neutron production efficiency with energy increase: (a) opening of new reaction channels, (b) escape of high energy particles from the spallation target with finite geometry.

This neutron production dependence is illustrated qualitatively in Fig. 1. The neutron yield, after protons passed the reaction threshold [zone (1')], grows rather rapidly with energy [zone (1'')]; above a certain value of  $\varepsilon_p$ , this dependence has a moderated quasi-linear behaviour [zone (2)]. So, there is a value of proton energy  $\varepsilon_p^{optimum}$  which is optimal with respect to the neutron economy, i.e. the neutron yield per one incident proton and per consumed energy reaches its maximal value. Therefore, it is generally considered that there is no sense to increase the energy of protons further than  $\varepsilon_p^{optimum}$  since the production of neutrons in the spallation target becomes less efficient if compared with the equivalent increase of the proton current (i.e., the accelerator power being constant).

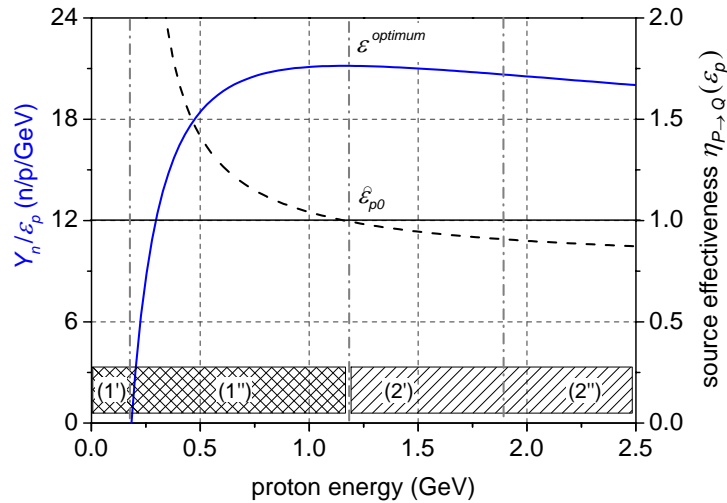


Figure 1. The dependence of the spallation neutron yield  $Y_n(\varepsilon_p)/\varepsilon_p$  (solid line) and that of the source effectiveness  $\eta_{P \rightarrow Q}(\varepsilon_p)$  (dash line). Also see the text for details.

Quantitatively, the  $Y_n$ -effect as a function of proton energy can be described by an empirical formula proposed in Ref. [6] in the units of neutron yield per one incident proton interacting with a thick heavy metal target:

$$Y_n(\varepsilon_p) = -a + b(\varepsilon_p)^\alpha, \quad (3)$$

where the parameters  $a, b \geq 0$ ,  $0 \leq \alpha \leq 1$  can be fitted to the experimental data depending on the target geometry and material. This particular dependence of the neutron yield on target geometry and

material should not be neglected. Furthermore, one should make use of these particular situations. Indeed, our preliminary estimates have shown that some optimization on the geometry of the spallation target might strengthen further the  $Y_n$ -effect. More quantitative calculations in this context are needed.

### Principle of the operation – DENNY concept

In this work, we propose to utilize this particularity of neutron production to form a quasi-linear dependence (the  $Y_n$ -effect) between energy production in the core and external neutron production in the spallation target aiming to get an auto-regulating behaviour of the ensemble “accelerator – sub-critical core”. A proposed system ( $E$ -mode coupled ACS) would have the kinetics of a critical system with artificial group of delayed neutrons as in the case of the “standard” ACS. In addition, its external neutron production would contain the supplementary feedback, tending to stabilize the installation power in its nominal state.

To elucidate this statement, let us remind that the ACS may be considered as a *critical* system with two types of neutrons contributing to the *global* neutron balance: “core neutrons” and “source neutrons”. Despite the fact that this separation of neutrons is relatively artificial, it reflects their origin and, therefore, corresponding neutron production feedbacks existing in each case. In the same context, the  $Y_n$ -effect can be compared to the Doppler feedback effect but for the external source neutrons. Similarly as the Doppler feedback effect, the  $Y_n$ -effect is intrinsic. It would be quite advantageous for the system safety to have this supplementary feedback acting on the entire neutron balance if the “standard” core feedbacks are degraded and can not play their self-stabilizing role indispensable for the inherent system safety.

The advantage of the above realization of a coupled hybrid system can be illustrated by the “neutron production versus core power” (Fig. 2a) as well as by the “core power versus accelerator power” (Fig. 2b) diagrams during unprotected accidents. We note the equivalence between Fig. 2a ( $E$ -mode ACS) and Fig. 1 for the neutron yield  $Y_n$  dependence, which is possible to make use of only in the case of  $E$ -coupling. According to the new concept (proposed  $E$ -mode ACS), the power (and temperature) excursion would be less important than in the “standard”  $I$ -mode ACS, what is clearly seen from Fig. 2b. The system with an accelerator coupled to the core in the  $E$ -mode will be named also “DENNY” (Delayed Enhanced Neutronics with Non-linear neutron Yield) in the present work. Below we propose the principle of DENNY functioning.

Let us consider the  $E$ -mode ACS with a pre-defined sub-criticality level  $r_0 = (1 - k_{eff,0}) / k_{eff,0}$  and a fraction  $f < 1$  of the produced core power, which is used to drive an external neutron source. The external neutrons are created in the spallation target by incident protons accelerated up to the energy  $\varepsilon_p$ . It is preferable to choose the nominal proton energy  $\varepsilon_{p,0} > \varepsilon_p^{optimum}$  in order to avoid an eventual instability of the DENNY power with respect to negative reactivity insertions (power decrease). Hence the proton energy has to be chosen as follows:  $\varepsilon_{p,0} = \varepsilon_p^{optimum} + \Delta\varepsilon_m$  (region 2” in Fig. 1). Here the margin  $\Delta\varepsilon_m$  [zone (2’) in Fig. 1] makes the system more stable with respect to negative reactivity insertions. This is valid if during the system operation the proton energy remains beyond the optimal energy, i.e. the condition  $\varepsilon_p \geq \varepsilon_p^{optimum}$  is fulfilled.

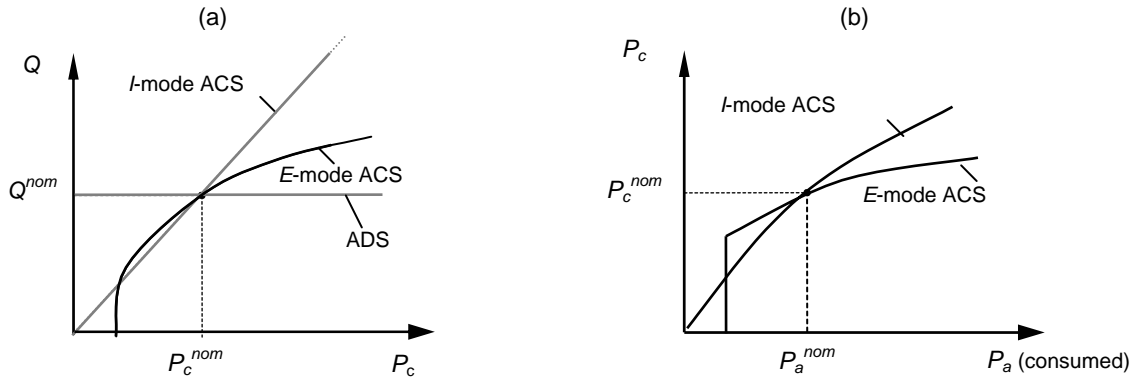


Figure 2. Diagrams of the intrinsic dependences: of (a) the neutron production  $Q$  on the core power  $P$ , and (b) of the equilibrium core power  $P_c$  on the accelerator power  $P_a$  for different concepts of a hybrid system.

The nominal values of proton current ( $I_{p,0}$ ) as well as of the fraction of accelerator feed power ( $f_0$ ) are chosen in the way to sustain the power level  $P_0$  in a nominal state:  $I_{p,0} \propto r_0 P_0$ . The value of the proton current is fixed over all period of the  $E$ -mode ACS functioning. On the contrary, the fraction  $f$  may be adjusted to compensate eventual reactivity swing (e.g., due to burn-up). In other words, for the proton energy we write:

$$\varepsilon_p = \varepsilon_{p,0} \frac{fP}{f_0 P_0}. \quad (4)$$

Above we explained schematically the principle of the DENNY functioning, where some details are omitted with a view to simplify our description (for example, we suppose that accelerator efficiency is identical for all proton energies, importance of source neutrons does not depend on proton energy, etc.). Detailed description of a hybrid system based on the  $E$ -mode coupling is outside the scope of this paper. However, in order to give some quantitative illustration of the main principle, a simplified model of the system operation with the  $E$ -coupling is presented below.

## Results and discussion

Let us study the response of the  $E$ -mode ACS on an accidental reactivity insertion in order to describe qualitatively the influence of the  $Y_n$ -effect on its kinetics. A new equilibrium power level  $\bar{P}$  of the system after insertion of the reactivity  $\Delta\rho_{ext}$  can be found from generalized reactivity-power balance equation [2, 7, 8] (following from the stationary kinetic equation):

$$\Delta\rho_{ext} - r_0 + \Delta\rho_{feedback}(\bar{P}) + r_0 Q(\bar{P})/\bar{P} = 0, \quad (5)$$

where the term  $Q(P) = P_0 Y_n(\varepsilon_p(P))/Y_n(\varepsilon_{p,0})$  describes the external source and the proton energy  $\varepsilon_p$  was already defined in Eq. (4). In *this* context the last term in Eq. (5) may be considered as a “source (feedback) reactivity”, i.e.  $\rho_{source} = r_0 Q(\bar{P})/\bar{P}$ . Eq. (5) together with the feedback model and neutron

yield dependence describes equilibrium states of the  $E$ -mode ACS after reactivity transients. In this case, a new power level  $\bar{P}$  after the reactivity transients will be determined not only by the core feedback but also by the ability of the external source to produce sufficient neutrons to sustain this power.

Eq. (5) is non-linear with respect to the variable  $\bar{P}$  and can be solved numerically. However, linearization of Eq. (5) allows us to characterize the  $Y_n$ -effect analytically with respect to the infinitesimal power fluctuation. Introducing normalized power reactivity coefficients  $A \equiv P_0(d\rho_{feedback}(P_0)/dP_0)$  and  $B \equiv P_0(d\rho_{source}(P_0)/dP_0)$  we rewrite Eq. (5) in the linearized form:

$$\delta\rho_{ext} + \delta\bar{P}(A+B)/P_0 = 0. \quad (6)$$

Taking into account that  $Q(P_0) = P_0$  (being the initial condition) and after some modifications, one obtains the following expression for the parameter  $B$ :

$$B = r_0 P_0 \left[ \frac{d}{dP_0} \left( \frac{Q(P_0)}{P_0} \right) \right] = -r_0 (1 - \eta_{P \rightarrow Q}(P_0)) \quad (7)$$

with the function  $\eta_{P \rightarrow Q}(P) \equiv dQ/dP$  being a measure of the local source effectiveness, i.e. a source response due to an infinitesimal power change in a nominal state. With respect to the global neutron balance in the  $E$ -mode ACS, Eq. (7) demonstrates that the parameter  $B$  may be considered as a coefficient, being a measure of the supplementary neutron production feedback, which is present in the system due to the  $Y_n$ -effect. As it follows from Eq. (7), coefficient  $B$  is proportional to the nominal sub-criticality level  $r_0$  and depends on the  $\eta_{P \rightarrow Q}(P_0)$  functional behaviour.

A non-linear neutron production influences the equilibrium power level, and its effectiveness [ $\eta_{P \rightarrow Q}(P_0)$ ] will depend on the choice of the nominal proton energy  $\varepsilon_{p0}$ . The  $Y_n$ -effect increases the asymptotical power if  $\varepsilon_{p0} < \varepsilon_p^{optimum}$  [region (1) in Fig. 1] and, contrary, it reduces the power growth if  $\varepsilon_{p0} \geq \varepsilon_p^{optimum}$  [region (2) in Fig. 1]. In fact, we can see from Eq. (7) that, if the condition  $(\delta Q / \delta P) < 1$  is fulfilled, the external neutron source is not able to support the increasing power, what will limit the consequent power growth  $\Delta\bar{P} = \bar{P} - P_0$ .

Let us suppose for simplicity that  $f = f_0$ . In this case the function  $\eta_{P \rightarrow Q}$  can be expressed as follows:

$$\eta_{P \rightarrow Q}(\varepsilon_p) = \left( \frac{\varepsilon_p}{Y_n(\varepsilon_p)} \right) \left( \frac{dY_n(\varepsilon_p)}{d\varepsilon_p} \right) \quad (8)$$

As it follows from Eq. (3) and Eq. (8) at  $\hat{\varepsilon}_{p0} = (a/[1-\alpha]b)^{1/\alpha}$ , the function  $\eta_{P \rightarrow Q}(\hat{\varepsilon}_{p0}) = 1$ . This energy point defines the limit between the “destabilizing” area of the  $Y_n$ -effect (amplification of  $\Delta\bar{P}$ , similar to positive feedback) at  $\varepsilon_{p,0} < \hat{\varepsilon}_{p,0}$  and the “stabilizing” domain of the  $Y_n$ -effect (suppression

of  $\bar{\Delta P}$ , similar to negative feedbacks) at  $\varepsilon_{p,0} \geq \hat{\varepsilon}_{p,0}$  (Fig. 1.). It is important to note that in the present case  $\hat{\varepsilon}_{p,0}$  is equal to the optimum energy  $\varepsilon_p^{optimum}$  with respect to the neutron economy.

What is the real gain of the proposed DENNY concept? Below we perform a comparative analysis in the case of ACS with the *I*-mode coupling and *E*-mode coupling, what results in a linear  $Q(P)$  dependence and non-linear  $Q(P)$  dependence correspondingly (see Fig. 2a). The effectiveness of the  $Y_n$ -effect for the safety improvement can be described by the *transient suppression parameter*  $D$ . It is defined as a ratio of asymptotic power values of the *E*-coupled and *I*-coupled systems after a certain reactivity insertion transient, namely

$$D = \bar{P}^{(E-mode)} / \bar{P}^{(I-mode)}. \quad (8)$$

If  $D < 1$ , it signifies that the  $Y_n$ -effect stabilizes the system. The  $D$ -values at different  $r_0$  and  $\Delta\rho_{ext}$  for the linear model of in-core feedback are presented in Fig. 3a. For a quantitative comparison we had to define the parameters in Eq. (3), which we took from [6], namely  $a = 8.2$ ,  $b = 29.3$  and  $\alpha = 0.75$ . According to the discussion in the previous Section we choose the nominal energy value  $\varepsilon_{p,0} = 1.6$  GeV (greater than  $\hat{\varepsilon}_{p,0} = 1.16$  GeV) for our comparative analysis, from which the following conclusions are drawn:

- stabilizing role of the  $Y_n$ -effect increases when both  $r_0$  and  $\Delta\rho_{ext}$  increase. This effect can be quite significant (up to 27 % at  $r_0 = 15\beta$ ) even in the case of a “good” in-core feedback ( $A = -488$  pcm). A further growth of  $\Delta\rho_{ext}$  leads to the saturation of such a tendency;
- the augmentation of the nominal proton energy  $\varepsilon_{p,0}$  enhances the stabilizing impact of  $Y_n$ -effect due to the reduction of the source effectiveness  $\eta_{p \rightarrow Q}(\varepsilon_{p,0})$ .

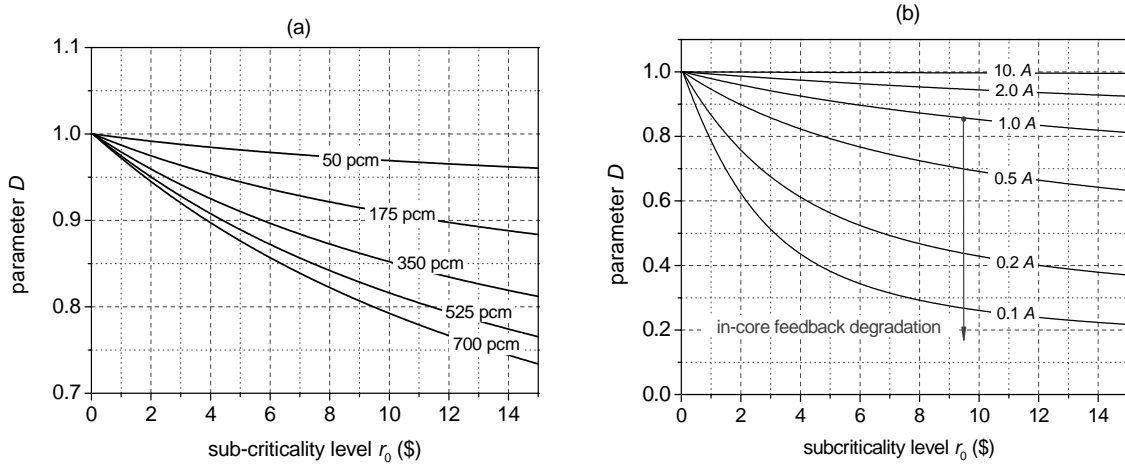


Figure 3. Transient suppression parameter  $D$  as a function of the sub-criticality level  $r_0$ : (a) at different values of the inserted reactivity  $\Delta\rho_{ext}$  (feedback coefficient  $A = -488$  pcm), (b) at different values of the parameter  $A$  (the inserted reactivity  $\Delta\rho_{ext} = 350$  pcm);  $\beta = 350$  pcm.



Parameter  $D$  depends also on the feedback coefficient  $A$ , defined earlier in this work. It should be reminded that this parameter reflects both the in-core feedback effects and thermo-hydraulics of the system. Fig. 3b demonstrates that the impact of the  $Y_n$  -effect on power stabilization increases when the absolute value of the feedback coefficient  $A$  decreases. This dependence of the transient suppression parameter  $D$  on parameter  $A$  is expectable. Indeed, if  $A \rightarrow 0$ , i.e. in-core feedback effects are absent, the  $Y_n$  -effect becomes the only feedback effect, influencing the system.

## Conclusions

In present work a new approach for the realization of an Accelerator Coupled hybrid System (ACS) was proposed and nominated as DENNY system (Delayed Enhanced Neutronics with Non-linear neutron Yield). The concept is based on the particularity of neutron production forming a quasi-linear dependence between energy production (coupled to the proton energy) in the core and the external neutron yield  $Y_n$  in the spallation target ( $Y_n$ -effect). This particular dependence provides an auto-regulating behaviour of the ensemble “accelerator – sub-critical core”. A proposed system has the kinetics of a critical system with artificial group of delayed neutrons as in the case of the “standard” ACS. In addition, its external neutron production contains the supplementary feedback, able to stabilize the installation power in its nominal state.

We showed that a significant improvement of the feedback effect due to this particular coupling between an accelerator and sub-critical core (denoted as  $E$ -mode coupling) could be achieved. The proposed  $Y_n$ -effect can be compared to the Doppler feedback effect but for the external source neutrons. Similarly as Doppler effect, the  $Y_n$ -effect is intrinsic. Finally, our qualitative estimates show that the implementation of this concept could compensate eventual feedback degradation in the cores dedicated to transmute nuclear waste. Further and more quantitative analysis in this context is urgently needed. These studies should equally include the feasibility estimates to answer if the  $E$ -mode ACS could be realised in practice.

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