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

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## Abstract

In this work a new approach to the realisation 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 the present study, we explain the principles of system functioning as well as the advantages and disadvantages of the proposed concept. The quantitative analysis of the innovative ACS operation is based on a generalised point kinetics approach. In the framework of this simplified model, we show that the particular dependence of the spallation neutron yield allows for the creation of a supplementary negative feedback effect (Doppler-like). Implementation of this concept should compensate, to some extent, the eventual feedback degradation in the cores dedicated to the transmutation of nuclear waste.

## Introduction

In general, nuclear systems devoted to minor actinide (MA) transmutation may suffer from significant degradation of safety characteristics. In particular, such important parameters as delayed neutron fraction can decrease by several times compared to conventional nuclear reactors. Another serious problem arising in such systems is the reduction of the Doppler effect – the fastest and 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 to handle the above problem was proposed recently and consists of the artificial enhancement of system neutronics, which involves an external neutron source added to the core permitting the system to operate in subcritical mode (so-called hybrid nuclear reactor). In an accelerator-driven system (ADS) [1] where a subcritical core serves only to amplify the incident beam energy, a large subcriticality margin ($k_{eff}$ ~0.95-0.97) mitigates the negative consequences of the degradation of safety parameters. However, this significant subcriticality 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]. With an ACS, an external neutron source, which is coupled directly to the core power and is artificially or naturally delayed, can compensate the decrease of delayed neutron fraction. In this case, less powerful (and thus less expensive) particle accelerators may be applied. On the other hand, the ACS inherits some properties of a critical nuclear system. In particular, the degradation of feedback effects (e.g. Doppler) makes power and temperature excursions possible in the case of unprotected reactivity insertion.

In the present work, we propose a new approach for the realisation 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 neutron production in a spallation target.

## Generalities of hybrid systems

In principle, core subcriticality will improve safety when feedback effects, the delayed neutron fraction or other safety-related parameters are degraded due to the presence of long-lived actinides that are subjected to transmutation. There are at least two different ways a subcritical core can function in combination with an external neutron source. In brief, this source can be independent of neutron (energy) production in the core [as in accelerator-driven systems (ADS)]. Or, the source can depend on neutron (energy) production in the core and in this way become “coupled” or “co-ordinated” by core power level [as in accelerator-coupled system (ACS [2])]. Each combination opens some new opportunities related to safety improvement. Major features of ADS and ACS are summarised below.

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

In the case of ACS, a source of “artificially delayed neutrons” consumes a portion 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 time required for fission energy transfer from the core to a chosen neutron production mechanism (e.g. spallation, nuclear fusion, *bremsstrahlung*-photonuclear, etc.). In other words, this intermediate process temporarily “hides” neutrons (of some neutron generation) in order to recover them later. This allows for the artificial increasing of neutron lifetime and for the slow down of dangerous transients [3].

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

In terms of safety, ADS is *inherently* more favourable (compared with similar critical reactor) in regards to reactivity accidents where core subcriticality mitigates consequences of 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 transients. Therefore, it would be attractive to combine the inherent advantages of both ADS and ACS in a single installation. In other words, one needs to realise a system where the following occurs 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.

c) Conditions a) and b) must be *intrinsic*.

One possible solution 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, which makes our approach inherent.

## Accelerator-core coupling modes in ACS

Traditionally, it is assumed that in hybrid systems the current of a 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 the external neutron source and the 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:

$$I_p = I_{p,0} \, P^{out} / P_0^{out} \tag{1}$$

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

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

$$e_p = e_{p,0} \, P^{out} / P_0^{out} \tag{2}$$

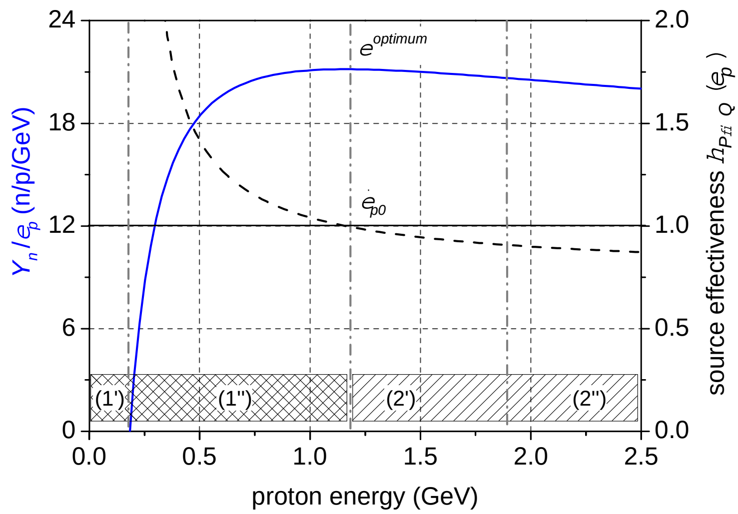
This coupling method is hereafter denoted as "*E*-mode" coupling.

In this work we propose *to utilise the proton energy as a coupling parameter* (*E*-mode ACS). The difference between *E*-mode and *I*-mode, of which we would like to make use, is based on the *non-linear behaviour of neutron yield* $Y_n$ *with respect to the proton energy* $e_p$ *variation* (hereafter the "$Y_n$-effect").

As shown in a number of studies, when the energy of incident protons becomes higher than ~1 GeV, for example, the neutron yield normalised per incident proton energy becomes nearly constant and even slightly decreases with proton energy (see Refs. [4-6] and references contained therein). There are two major reasons for this decrease of neutron production efficiency with energy increase - 1) opening of new reaction channels and 2) escape of high-energy particles from the spallation target with finite geometry.

This neutron production dependence is illustrated qualitatively in Figure 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)]. Thus, there is a value of proton energy $\varepsilon_p^{optimum}$, which is optimal with respect to neutron economy (i.e. neutron yield per one incident proton and per consumed energy reaches its maximal value). Therefore, it is generally considered nonsensical to increase the energy of protons beyond $\varepsilon_p^{optimum}$ since the production of neutrons in the spallation target becomes less efficient compared with the equivalent increase of the proton current (accelerator power being constant).

**Figure 1. Dependence of the spallation neutron yield $Y_n$ ($\varepsilon_p$) / $\varepsilon_p$ (solid line) and that of the source effectiveness $\eta_{P \to Q}$ ($\varepsilon_p$) (dash line)**




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

$$Y_n(\varepsilon_p) = -a + b(\varepsilon_p)^{\alpha} \tag{3}$$

where parameters $a$, $b \geq 0$ and $0 \leq \alpha \leq 1$ 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 optimisation on the geometry of the spallation target might further strengthen the $Y_n$-effect. More quantitative calculations in this context are needed.

## Principle of the operation – DENNY concept

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

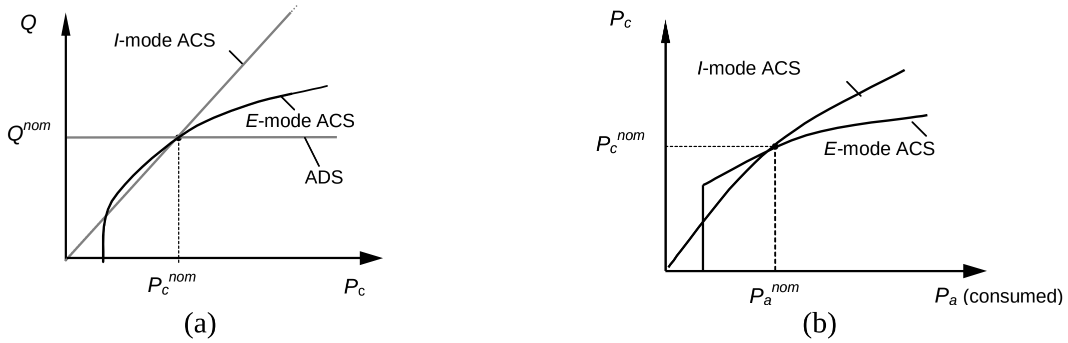
To elucidate this statement, we recall that ACS may be considered as a *critical* system with two types of neutrons contributing to the *global* neutron balance – "core neutrons" and "source neutrons". Despite the fact that this separation of neutrons is relatively artificial, it reflects their origin and, thus, the corresponding neutron production feedback for 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 with the Doppler feedback effect, the $Y_n$-effect is intrinsic. It would be quite advantageous for system safety to have this supplementary feedback acting on the entire neutron balance if the "standard" core feedback is degraded and cannot play a self-stabilising role, which is indispensable for inherent system safety.

The advantage of the above realisation of a coupled hybrid system can be illustrated by the "neutron production versus core power" [Figure 2(a)] as well as by the "core power versus accelerator power" [Figure 2(b)] diagrams during unprotected accidents. We note the equivalence between Figure 2(a) (*E*-mode ACS) and Figure 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, which is clearly seen in Figure 2(b). For the present work, the system with an accelerator coupled to the core in *E*-mode is named DENNY (delayed enhanced neutronics with non-linear neutron yield). Below we propose the principle of DENNY functioning.

Let us consider the *E*-mode ACS with a pre-defined subcriticality level $\rho_0 = (1 - k_{eff,0}) / k_{eff,0}$ and a fraction $f < 1$ of the produced core power, which is used to drive an external neutron source. 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 must be chosen as follows: $\varepsilon_{p,0} = \varepsilon^{optimum} + \Delta\varepsilon_m$ [zone (2") in Figure 1]. Here the margin $\Delta\varepsilon_m$ [zone (2') in Figure 1] makes the system more stable with respect to negative reactivity insertions. This is valid if during system operation the proton energy remains beyond the optimal energy, i.e. the condition $\varepsilon_p \geq \varepsilon^{optimum}$ is fulfilled.

**Figure 2. Diagrams of intrinsic dependences**

*(a) Neutron production Q dependence on core power P and (b) equilibrium core power $P_c$ dependence on accelerator power $P_a$ for different concepts of a hybrid system*




The nominal values of proton current ($I_{p,0}$) and of fraction of accelerator feed power ($f_0$) are chosen in such a way to sustain the power level $P_0$ in a nominal state ($I_{p0} \quad \rho_0 P_0$). The value of the proton current is fixed over all periods 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 proton energy we write:

$$\varepsilon_p = \varepsilon_{p,0} \frac{fP}{f_0 P_0} \tag{4}$$

Above we explained schematically the principle of DENNY functioning where some details are omitted with a view to simplify the 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. A detailed description of a hybrid system based on the *E*-mode coupling is outside the scope of this paper. However, in order to provide some quantitative illustration of the main principles, a simplified model of system operation with *E*-coupling is presented below.

## Results and discussion

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

$$\Delta\rho_{ext} - \rho_0 + \Delta\rho_{feedback}(\overline{P}) + \rho_0 Q(\overline{P})/\overline{P} = 0 \tag{5}$$

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 "source (feedback) reactivity" [i.e. $\rho_{source} = \rho_0 Q(\overline{P})/\overline{P}$]. Equation (5) together with the feedback model and the neutron yield dependence describes the equilibrium states of the *E*-mode ACS after reactivity transients. In this case, a new power level $\overline{P}$ after the reactivity transients will be determined not only by core feedback but also by the ability of the external source to produce sufficient neutrons to sustain this power.

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

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

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 $B$:

$$B = \rho_0 P_0 \left[ \frac{d}{dP_0} \left( \frac{Q(P_0)}{P_0} \right) \right] = -\rho_0 \left(1 - \eta_{P\to Q}(P_0)\right) \tag{7}$$

with the function $\eta_{P\to Q}(P) \equiv dQ/dP$ 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 parameter $B$ may be considered as a coefficient, being a measured supplementary neutron production feedback and arising in the system due to the $Y_n$-effect. As it follows from Eq. (7), coefficient $B$ is proportional to the nominal subcriticality level $\rho_0$ and depends on the $\eta_{P\to Q}(P_0)$ functional behaviour.

Non-linear neutron production influences the equilibrium power level and its effectiveness $[\eta_{P\to Q}(P_0)]$ will depend on the choice of the nominal proton energy $\varepsilon_{p0}$. The $Y_n$-effect increases the asymptotical power if $\varepsilon_{p,0} < \varepsilon_p^{optimum}$ [zone (1) in Figure 1] and, on the contrary, it reduces power growth if $\varepsilon_{p,0} \geq \varepsilon_p^{optimum}$ [zone (2) in Figure 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, which will limit the consequential power growth $\Delta\bar{P} = \bar{P} - P_0$.

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

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

As it follows from Eq. (3) and Eq. (8), at $\hat{\varepsilon}_{p0} = \left(\alpha / \left[(1-\alpha)\beta\right]\right)^{1/\alpha}$ the function $\eta_{P\to Q}(\hat{\varepsilon}_{p0}) = 1$. This energy point defines the limit between the "destabilising" 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 "stabilising" domain of the $Y_n$-effect (suppression of $\Delta\bar{P}$, similar to negative feedback) at $\varepsilon_{p,0} \geq \hat{\varepsilon}_{p,0}$ (Figure 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 neutron economy.

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

$$D = \overline{P}^{\,(E-mode)} \Big/ \overline{P}^{\,(I-mode)} \tag{9}$$

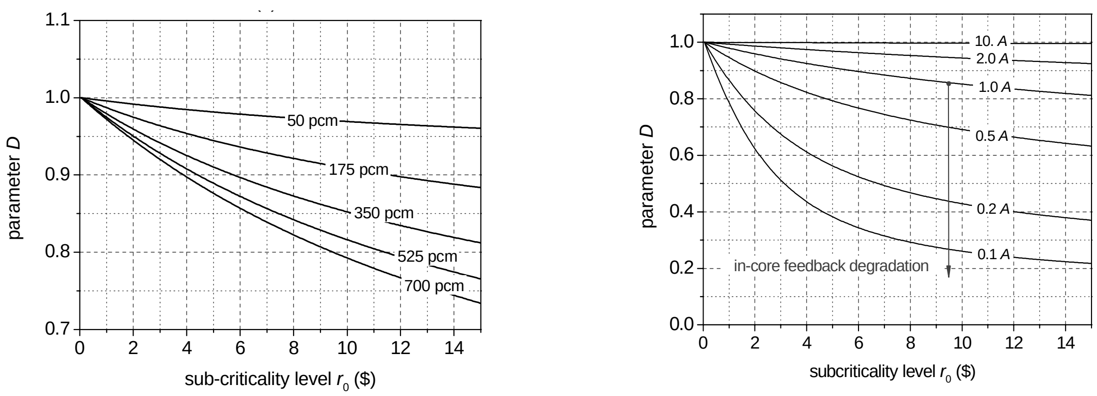
If $D < 1$, it signifies that the $Y_n$-effect stabilises the system. The *D*-values at different $r_0$ and $\Delta\rho_{ext}$ for the linear model of in-core feedback are presented in Figure 3(a). For a quantitative comparison we defined the parameters in Eq. (3), which we took from Ref. [6], namely $a = 8.2$, $b = 29.3$ and $\alpha = 0.75$. According to the discussion in the previous section, we chose 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 were drawn:

- The stabilising 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 "good" in-core feedback ($A$ = -488 pcm). Further growth of $\Delta\rho_{ext}$ leads to the saturation of such a tendency.

- Augmentation of the nominal proton energy $\varepsilon_{p,0}$ enhances the stabilising impact of the $Y_n$-effect due to the reduction of the source effectiveness $\eta_{P\to Q}(\varepsilon_{p0})$.

**Figure 3. Transient suppression parameter *D* as a function of subcriticality 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*




(a) (b)

Parameter *D* depends also on the feedback coefficient *A*, defined earlier in this work. We recall that this parameter reflects both the in-core feedback effects and the thermo-hydraulics of the system. Figure 3(b) demonstrates that the impact of the $Y_n$-effect on power stabilisation increases when the absolute value of feedback coefficient *A* decreases. This dependence of the transient suppression parameter *D* on parameter *A* was predictable. Indeed, if $A \to 0$, i.e. in-core feedback effects are absent, the $Y_n$*-effect becomes the only feedback effect, exiting in the system.*

## Conclusions

In the present work, a new approach for the realisation of an accelerator-coupled hybrid system (ACS) was proposed and nominated as the DENNY system (delayed enhanced neutronics with non-linear neutron yield). This 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 auto-regulating behaviour of the ensemble "accelerator-subcritical core". The proposed system has the kinetics of a critical system with an artificial group of delayed neutrons as with the "standard" ACS. In addition, its external neutron production contains supplementary feedback, which is able to stabilise the installation power in its nominal state.

We showed that significant improvement of the feedback effect due to this particular coupling between an accelerator and a subcritical core (*E*-mode coupling) could be achieved. The proposed $Y_n$-effect can be compared to the Doppler feedback effect but for external source neutrons. Similar to the Doppler effect, the $Y_n$-effect is intrinsic. Lastly, our qualitative estimates showed that implementation of this concept could compensate eventual feedback degradation in cores dedicated to the transmutation of nuclear waste. Further and more quantitative analysis is urgently needed. Such further studies should include feasibility estimates to show whether the *E*-mode ACS could be realised in practice.

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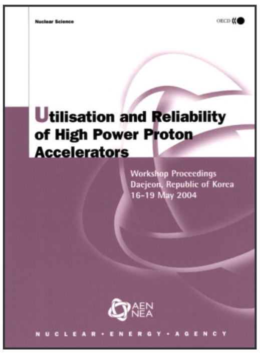
## TABLE OF CONTENTS

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