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School on Physics, Technology and Applications of Accelerator Driven Systems (ADS)

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ADS Physics: Physics and Dynamics. Part II

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I.1. INTRODUCTION:
NEUTRONIC PECULIARITY of HYBRIDs

General prescription:

many important problems of the current NP could be solved if

- more neutrons were available per fission in reactor fuels (FR!)or if
- one might affect on characteristics of the overall neutron yield per fission (Hybrids!).

HYBRID's DEFINITION:

HYBRIDES = FISSIONABLE SYSTEM (NUCLEAR REACTOR) + SUPPLEMENTARY NEUTRON SOURCE

The question arrives:

is a niche for HYBRIDs in Nuclear Power seemed to be doubtfull because the cost of supplementary neutron production, additional energy consumption and the technology development efforts seem to be not (!) negligible?

One of the important attractive features of HYBRIDS (due to presence of an external neutron source via e.g. spallation of heavy nuclides by an intensive beam of the high-energy protons)
could be:

radical "enhancement" of OVERALL NEUTRON PRODUCTION potential compared with the corresponding critical reactor medium.

There are multiple EXAMPLEs of the supplementary neutron production via:

- *spallation;*
- *e-γ,γ-n;*
- *fusion "by-products";…..*

Generally, spallation (or other possible means such as fusion, electron beam braking, etc.) is much less effective than fission respecting both energy and neutron productions.

COMMENTS:

Doubts respecting this niche arise because:

One fission of a heavy nuclide is able producing in a (fast) reactor roughly

200MeV of thermal energy per fission plus about 3 fast neutrons.

Energy of one fission, being completely transformed into spallation, provides:

$$200\text{MeV}\times\eta_{Th}\times\eta_e\,(1-\varepsilon) \approx 200\times0.4\times0.5(1-0.5) =$$

20MeV of energy only,

where

> η_{Th} **- efficiency of transformation of thermal energy to electric one,**
> η_e **- the efficiency of transformation of electric energy into proton current energy in an accelerator,**
> ε **- the fraction of the kinetic energy of the incident proton spent for spallation (e.g. $\varepsilon \approx 0.5$ for the lead target)**

plus about 1 hard neutron in average:

$$200\text{MeV}\times\eta_{Th}\times\eta_e\, Z/E_p \approx 1$$

(Z is the number of the released neutrons ≅25 per proton of energy E_p = 1000 MeV in an "optimistic" evaluations).

Finally, it means that spallation "provides":

- 200 + 20 = - 180 MeV (it consumes energy!) per fission and 1 hard neutron×φ* of an "elevated" importance

I.2. PHYSICS BACKGROUND
GENERAL FEATURES.

I.2.A. Physics of external neutron sources

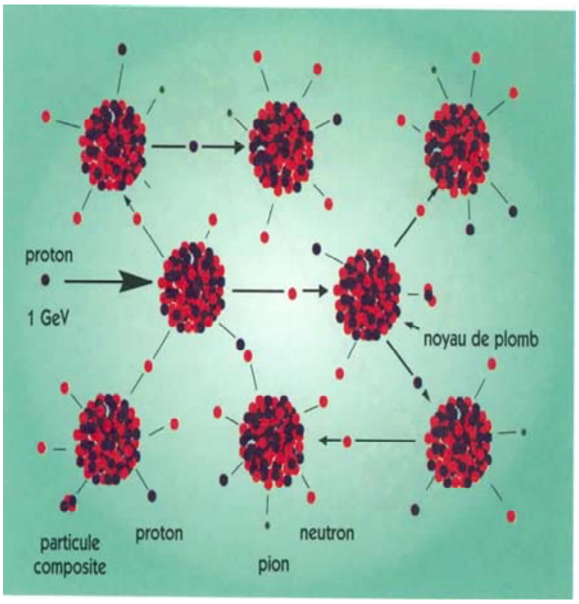
Spallation

- There is no precise definition of spallation. ↑ this term covers the interaction of high energy hadrons or light nuclei (from a few tens of MeV to a few GeV) with nuclear targets.

⇧ It corresponds to the reaction mechanism by which this high energy projectile pulls out of the target some nucleons and/or light particles, leaving a residual nucleus (spallation product)

⇧ Depending upon the conditions, the number of emitted light particles, and especially neutrons, may be quite large

⇧ This is of course the feature of outermost importance for the so-called ADS



The Spallation Process Details

◻ Cascade intranuclear

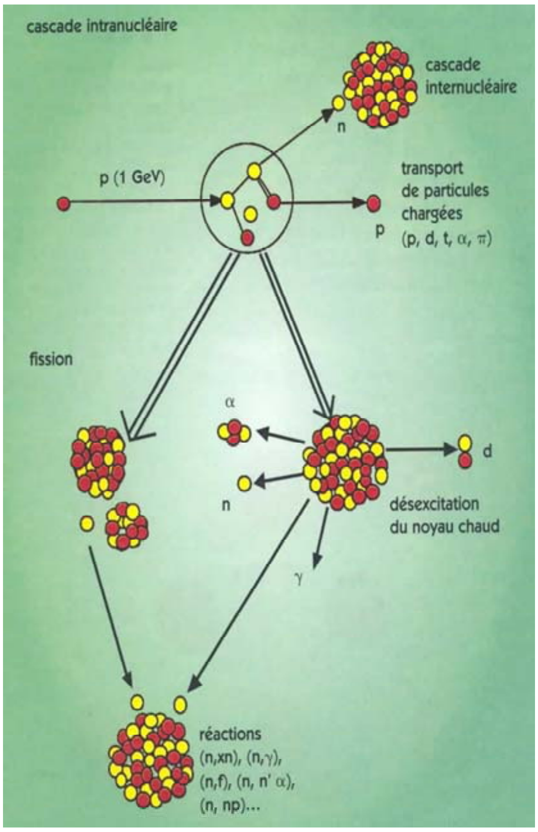
☆ Fast Direct Process:
- ⇧ Intra-Nuclear Cascade (nucleon-nucleon collisions)

🕐 Pre-Compound Stage:
- ⇧ Pre-Equilibrium
- ⇧ Multi-Fragmentation
- ⇧ Fermi Breakup

🕑 Compound Nuclei:
- ⇧ Evaporation (mostly neutrons)
- ⇧ High-Energy Fissions

🕒 Inter-Nuclear Cascade

🕓 Low-Energy Inelastic Reactions
- ⇧ (n,xn)
- ⇧ (n,nf)
- ⇧ etc...



The Spallation Process Features

- The relevant aspects of the spallation process are characterised by:

  - **Spallation Neutron Yield** (i.e. multiplicity of emitted neutrons)

    ➔ determines the requirement in terms of the accelerator power (current and energy of incident proton beam).

  - **Spallation Neutron Spectrum** (i.e. energy distribution of emitted neutrons)

    ➔ determines the damage and activation of the structural materials (design of the beam window and spallation target)

  - **Spallation Product Distributions**

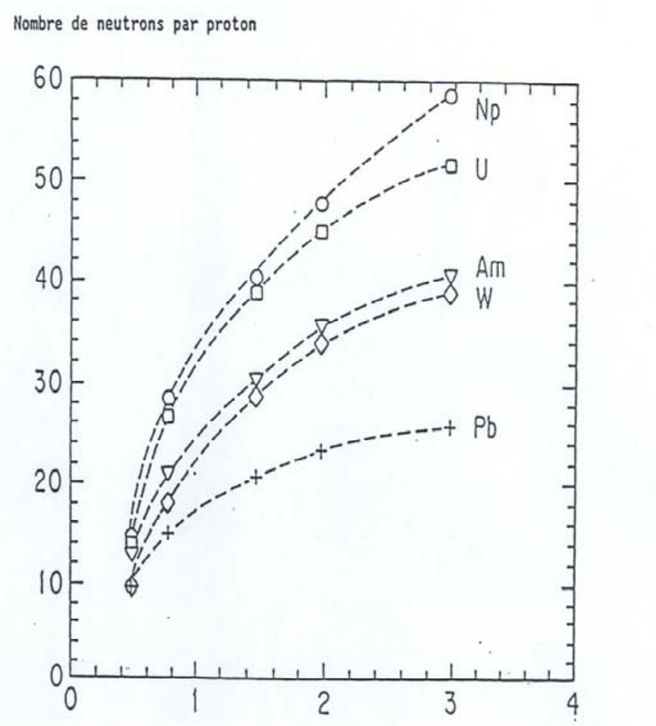
    ➔ determines the radiotoxicity of the residues (radioprotection requirements).

  - **Energy Deposition**

    ➔ determines the thermal-hydraulic requirements (cooling capabilities and nature of the spallation target).

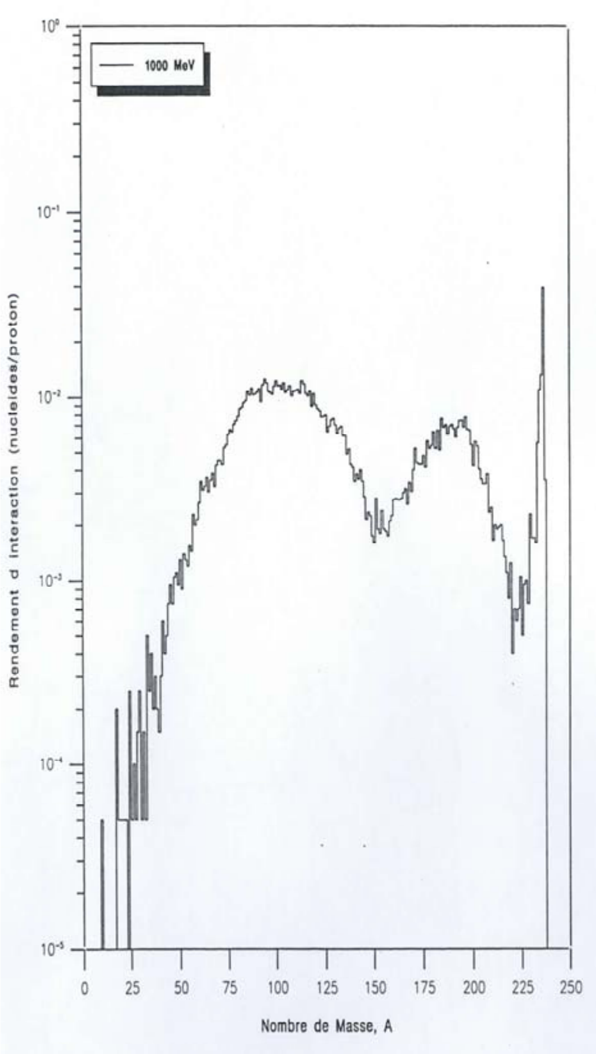
Spallation Neutron Yield

- The number of emitted neutrons varies as a function of the target nuclei and the energy of the incident particle ⇦ saturates around 2 GeV.
- Deuteron and triton projectiles produce more neutrons than protons in the energy range below 1-2 GeV ⇦ higher contamination of the accelerator.



I.2.B. Spallation source characteristics to be used in an ADS

Spallation Product Distribution



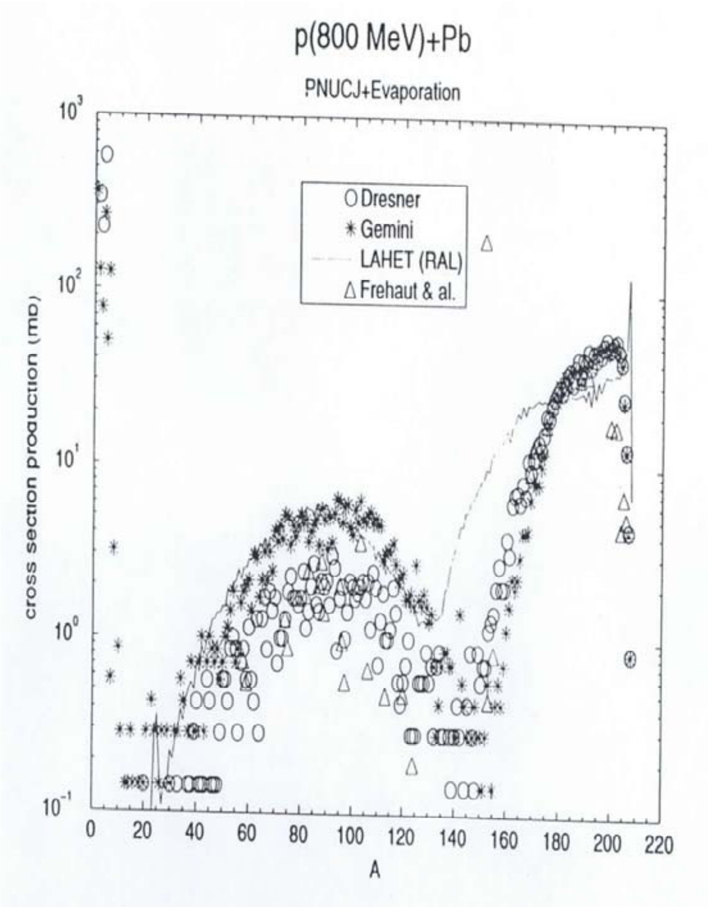
Spallation Product Distribution

- The spallation product distribution varies as a function of the target material and incident proton energy. It has a very characteristic shape:

  ⇦ At high masses it is characterized by the presence of two peaks corresponding to (i) the initial target nuclei and (ii) those obtained after evaporation

  ⇦ Narrow peaks corresponding to the evaporation of light nuclei such as (deuterons, tritons, ^{3}He and α)

  ⇦ An intermediate zone corresponding to nuclei produced by high-energy fissions



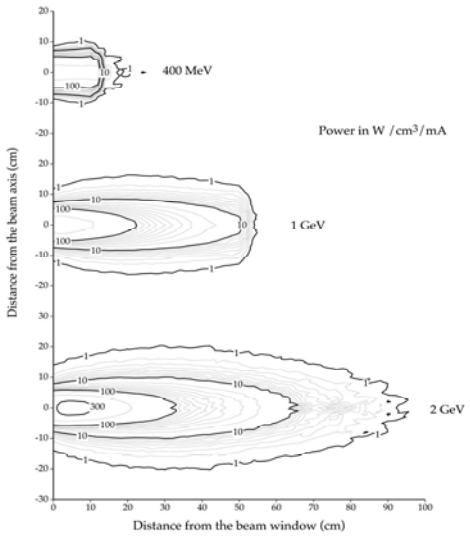
Energy Deposition

- Example of the heat deposition of a proton beam in a beam window and a Lead target

⇦ which takes into account not only the electromagnetic interactions, but all kind of nuclear reactions induced by both protons and the secondary generated particles (included neutrons down to an energy of 20 MeV) and gammas.

⇧ Increasing the energy of the incident particle affects considerably the power distribution in the Lead target. Indeed one can observe that, while the heat distribution in the axial direction extends considerably as the energy of the incident particle increases, it does not in the radial direction, which means that the proton tracks tend to be quite straight. ⇧ **Lorentz boost**

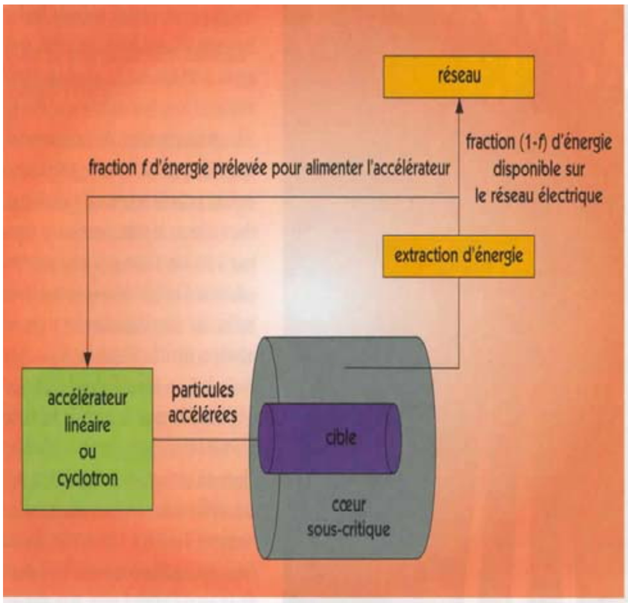
⇧ Heat deposition is largely contained within the range of the protons. But while at 400 MeV the energy deposit is exactly contained in the calculated range (16 cm), this is not entirely true at 1 GeV where the observed range is about 9% smaller than the calculated (r_{calc} = 58 cm, r_{obs} ~ 53 cm). At 2 GeV the difference is even more relevant (r_{calc} = 137 cm, r_{obs} ~ 95 cm). This can be explained by the rising fraction of nuclei interactions with increasing energy, which contribute to the heat deposition and shortens the effective proton range.



I.2.C. Physics of sub-critical systems

ADS-Schema

- In Accelerator-Driven Systems a *Sub-Critical blanket* surrounding the spallation target is *used to multiply the spallation neutrons*.



I.3. ADS NEUTRONICS. STATICS

Basic neutronics of ADS can be generally described by the neutron transport equation respecting the neutron flux Φ :

$$A\Phi = M\Phi + S\,, \tag{1}$$

where :

A the operator of the neutron consumption (neutron absorption and leakage),

M neutron production in a sub-critical medium,

S the neutron source, which can be either independent upon the medium power or dependent upon it (if one suggests to consume a part of power for external neutron production by spallation via an accelerator power supply).

An “external” neutron source can be presented as :

$$S = S_0\xi(r,E)\,,$$

where S_0 is total neutrons production rate and $\xi(r,E)$ is normalised ($\iint drdE\,\xi(r,E) = 1$) space-energy neutron distribution in the source.

If a source depends on total power W of an installation (expressed in fissions per time unit), then :

$$S_0 = \Gamma f W = \Gamma f \iint dr' dE' \Sigma_f (E', r') \Phi(E', r') \ ,$$

where :

f - fraction of the power being spent for spallation,

Γ the number of neutrons produced in an ADS if one fission can be completely transformed in proton beam.

Let us consider the *eigen value* type equation for the neutron importance Φ^*(related to K_{eff}) :

$$A^*\Phi^* = \frac{1}{K_{eff}} M^*\Phi^* \qquad (2)$$

Combining (1) and (2) one can get easily :

$$\frac{1}{K_{eff}} = 1 + \frac{\langle \Phi^*, S \rangle}{\langle \Phi^*, M\Phi \rangle} \qquad (3)$$

where :

$$\frac{\langle \Phi^*, S \rangle}{\langle \Phi^*, M\Phi \rangle} = \frac{S_0 / W}{\bar{\nu}} \times \frac{\bar{\Phi}^*_S}{\bar{\Phi}^*_F}$$

$\bar{\nu} = \dfrac{\iiint drdEdE' \ \chi(E) \nu \Sigma_f (r, E') \Phi(r, E')}{\iint drdE' \ \Sigma_f (r, E') \Phi(r, E')}$ - the averaged number of "secondary" neutrons;

$\bar{\Phi}^*_S = \dfrac{\iint drdE \xi(r, E) \Phi^*(r, E)}{\iint drdE \xi(r, E)} = \iint drdE \xi(r, E) \Phi^*(r, E)$ -

the averaged neutron importance of the "*external*" neutron source;

$$\overline{\Phi}_F^* = \frac{\iiint drdEdE' \, \Phi^*(r,E)\chi(E)\nu\Sigma_f(r,E')\Phi(r,E')}{\iiint dr' \, dEdE' \, \chi(E)\Sigma_f(r',E')\Phi(r',E')}$$ -

the averaged importance of neutrons produced by fission (or the importance of "*internally*" produced neutrons).

It is followed from (3):

$$f = \frac{\overline{\nu}}{\Gamma\varphi^*}\left(\frac{1}{K_{eff}} - 1\right), \qquad (4)$$

$\varphi^* = \overline{\Phi}_S^* / \overline{\Phi}_F^*$ - the ratio of the averaged importances of neutrons in the "*external*" and "*internal*" neutron sources correspondingly.

φ^* - the "*effectiveness of spallation neutrons*" of an ADS.

(4) defines the fraction of power f (consumed for spallation) to achieve "self-consistency" of a subcritical blanket (i.e. ability to support any desirable power like a critical system).

TWO cases:

1. f **does not** depend on power level and serves as the basic integral neutronic parameters of an ADS.
2. f **does** depend on power level – ACS (Accelerator-blanket coupled system)

Case 1: **The external source is independent upon the system power** (as in the "Energy Amplifier" of C.Rubbia's concept).

Equation (3) defines the nominal power level of this subcritical system:

$$W = \frac{S_0\varphi^*}{\overline{\nu}\left(\frac{1}{K_{eff}} - 1\right)} \; fissions/\sec, \qquad (4')$$

if S_0 is expressed in neutron/sec.

Case 2: **Kinetics (despite its sub-critical blanket nature) is similar to kinetics of a critical system which has a new group of "delayed" neutrons supplementary (in this case, spallation is a source of delayed neutron).**

Duration of these delays (t_{SP}) is defined by a technical choice of the process transforming fissions to spallation neutrons and can be regulated (optimised) within some reasonable interval.

In this case, power W *is defined as*:

$$\frac{dW(t)}{dt} = \frac{\rho(t) - \bar{\beta}(t)}{l(t)} W(t) + \alpha_1 \sum_j \lambda_j C_j + \alpha_2 f \Gamma W(t - t_{SP}) \ , \qquad (4'')$$

where α_1, α_2 are coefficients. Time dependent reactivity $\rho(t)$ takes into account both the initial subcriticality level and reactivity insertion during transients.

Similar to critical reactors, one can choose any power level depending on capability "withstanding" the given power production.

There is another version of the integral assessments of ADS neutronics by using the **multiplication coefficient K_S**

$$K_s = \frac{\langle M\Phi \rangle}{\langle A\Phi \rangle} \ , \qquad (5)$$

where $\langle \rangle$ means an integration over all domain of variables (angle-space, energy, time) of the operators, then :

$$\left(\frac{1}{K_s} - 1 \right) = \frac{S_0}{W\bar{\nu}} \qquad (6)$$

Equation (6) is “equivalent” to (4) and it gives the fraction f of medium power required for an ADS to support the given power. If one put $S_0 = f\Gamma W$, then :

$$f = \frac{\bar{\nu}}{\Gamma}\left(\frac{1}{K_S} - 1\right) \quad (7)$$

Comparing (7) and (4) one can get a relationship between the spallation neutron importance φ^* and the integral parameters of an ADS: $\boldsymbol{K_{eff}}$**,** $\boldsymbol{K_s}$:

$$\varphi^* = \frac{\left(\frac{1}{K_{eff}} - 1\right)}{\left(\frac{1}{K_S} - 1\right)} \quad (8)$$

COMMENTS:

The following relationships are very useful:

Fraction f **of energy defines the "*energy amplification*"** $\boldsymbol{K_W}$ (proposed by C. Rubbia) **- the ratio of ADS power and proton beam power :**

$$K_W = \frac{1}{f} = \frac{\Gamma\varphi^*}{\bar{\nu}\left(\frac{1}{K_{eff}} - 1\right)} = \frac{\Gamma}{\bar{\nu}\left(\frac{1}{K_S} - 1\right)} \quad (9)$$

- **the number of protons (**p**) per fission** :

$$p = \frac{f\,\Gamma}{z} = \frac{\bar{\nu}\left(\frac{1}{K_{eff}} - 1\right)}{\varphi^* z}$$

- **the number of protons (ζ) produced by an ADS per 1 Watt of power :**

$$\varsigma = \frac{\bar{\nu}\left(\frac{1}{K_{eff}} - 1\right)}{\varphi^{*} z} \times y \approx \frac{\bar{\nu}\left(\frac{1}{K_{eff}} - 1\right)}{\varphi^{*} z} \times 3.1 \times 10^{10}$$

where :

y is the number of fissions required for production of 1 Watt of power,

Z is the number of neutrons produced by one proton.

- **proton current (*I*) of an accelerator:**

$$I(mA) = \varsigma \times 1.6 \times 10^{-16} \approx \frac{\bar{\nu}\left(\frac{1}{K_{eff}} - 1\right)}{\varphi^{*} z} \times 5W, \tag{10}$$

where, ADS total power W is expressed in MW_{th}.

ADS and SAFETY REALATED PHYSICS

For a subcritical system (driving by an external source), the "*void power effect*" can be introduced as a potential change of the power (in relative units) when an ADS is voided.

$$\frac{\delta W}{W} = \frac{\delta K_{eff}}{K_{eff}^{2}\left(\frac{1}{K_{eff}} - 1\right)} + \frac{\delta\varphi^{*}}{\varphi^{*}} = \left(\frac{1}{1-K_{eff}}\right)\frac{\delta K_{eff}}{K_{eff}} + \frac{\delta\varphi^{*}}{\varphi^{*}} \qquad (11)$$

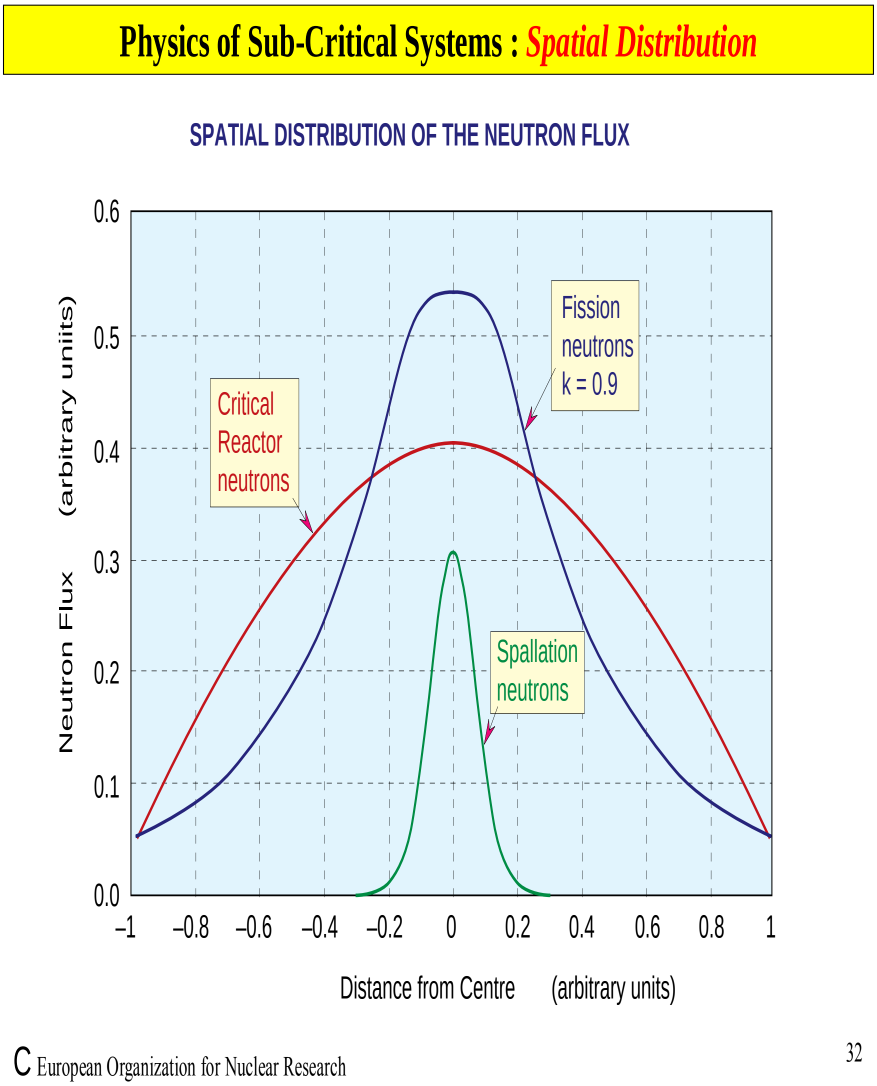
Void power effect = the "*reactivity void effect*" $(\delta K_{eff}/K_{eff})$+ the "external source importance void" $(\delta\varphi^{*}/\varphi^{*})$ effect.

$(\delta W/W)$ is rather sensitive to K_{eff} change in the vicinity of $K_{eff} = 1$.

Refering to K_S :

$$\frac{\delta W}{W} = \left(\frac{1}{1-K_S}\right)\frac{\delta K_S}{K_S}$$

On special neutron distribution in an ADS



I.4. DIVERSITY OF HYBRID SYSTEMS

I.4.1. **DEFINITIONS:** "ARTIFICIALLY ENHANCED" NEUTRONICS and CORE SUBCRITICALITY. ENERGY TRANSFER DIAGRAM.

Hybrid systems offer some promising options in resolving the current problems related to safety potential radical enhancement, transmutation of long-lived radioactive wastes, etc.

For generalization, one can call these hybrids as the nuclear fission systems with "**ART**ificially" **E**nhanced **N**eutronics (**ARTEN**) as the ***category of hybrids where an external neutron source is foreseen aiming to artificially improve the neutron yield and/or its characteristics*** *(e.g. time delay, energy spectra, etc)*.

ARTEN includes ADS, ACS, Fusion Driven System (FDS),….,etc.

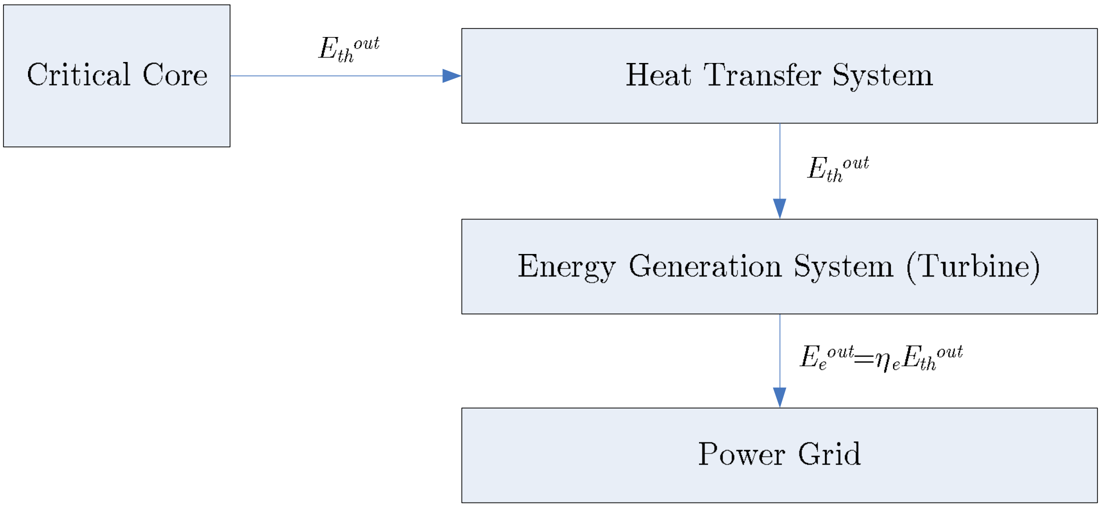
CRITICAL REACTORS

Thermal energy E_{th}^{out}, generated in the *reactor core* is transmitted by the *heat transfer system* to an *electric energy production device.*

The energy production device (e.g., turbine) transforms the heat to electricity with the transformation efficiency η_e

$$E_e^{out} = \eta_e E_{th}^{out}$$

which goes to the *power grid*.



Energy (power) transfer diagram for the critical system.

HYBRIDS WITH AN INDEPENDENT EXTERNAL NEUTRON SOURCE (ADS): ENERGY AMPLIFIER (EA)

"Energy amplifier" (EA) may be one of realistic types of ARTEN systems (Takahashi, 1995; Rubbia *et al*., 1995; Bowman, 1995).

"EA includes comprehensively all non-self sustaining "fissioning" cores, which are driven by an external neutron source provided by a charged particle accelerator and a neutron production target".

EA may be considered as a particular part of the ARTEN system with an "independent-source".

The subcritical blanket operates as an *neutron/energy amplifier*: the output thermal energy E_{th}^{out} of the core is equal to the energy E_b of the charged particle beam, originated from an *accelerator*, times the energy amplification coefficient G_b.

The energy E_e^{in} required for accelerator to create and to accelerate charged particles, is delivered from the power grid and it depends on the accelerator efficiency η_a:

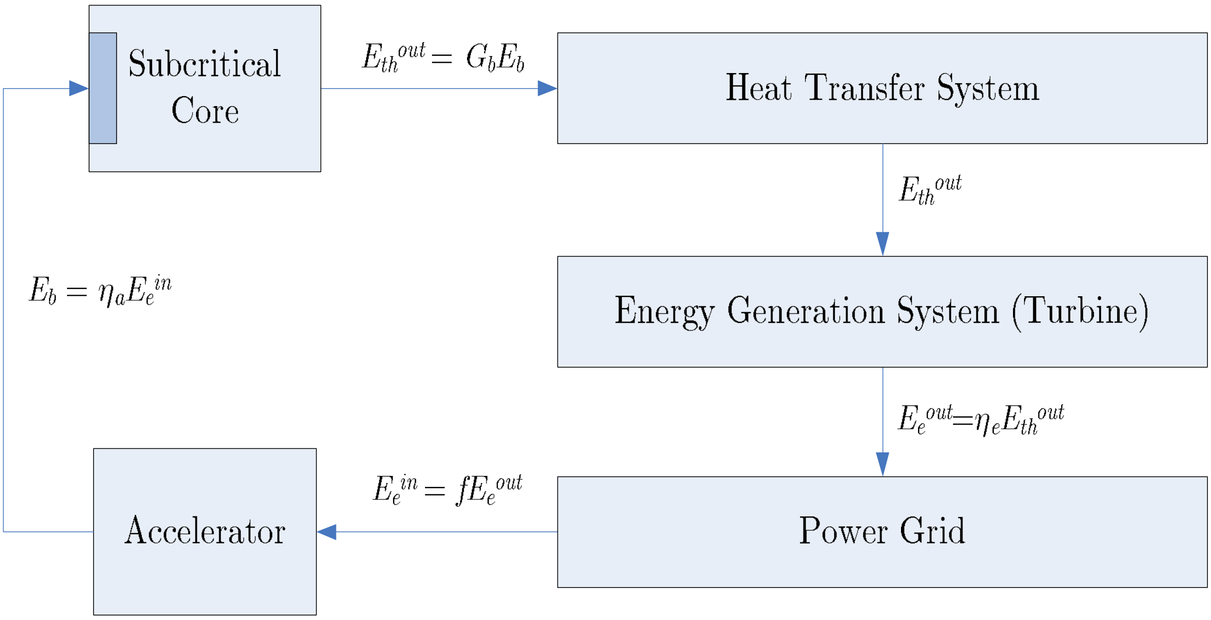
$$E_e^{in} = E_b \,/\, \eta_a .$$

Fraction f of produced electrical energy serving to feed the accelerator:

$$f = \frac{E_e^{in}}{E_e^{out}} = \frac{1}{\eta_e \eta_a G_b}.$$

Apparently, the total reactor power efficiency decreases, when compared with corresponding critical reactor, down to the value:

$$\eta_R^{EA(ADS)} = \eta_e \left(1 - f\right).$$



Energy transfer diagram for an EA (ADS).

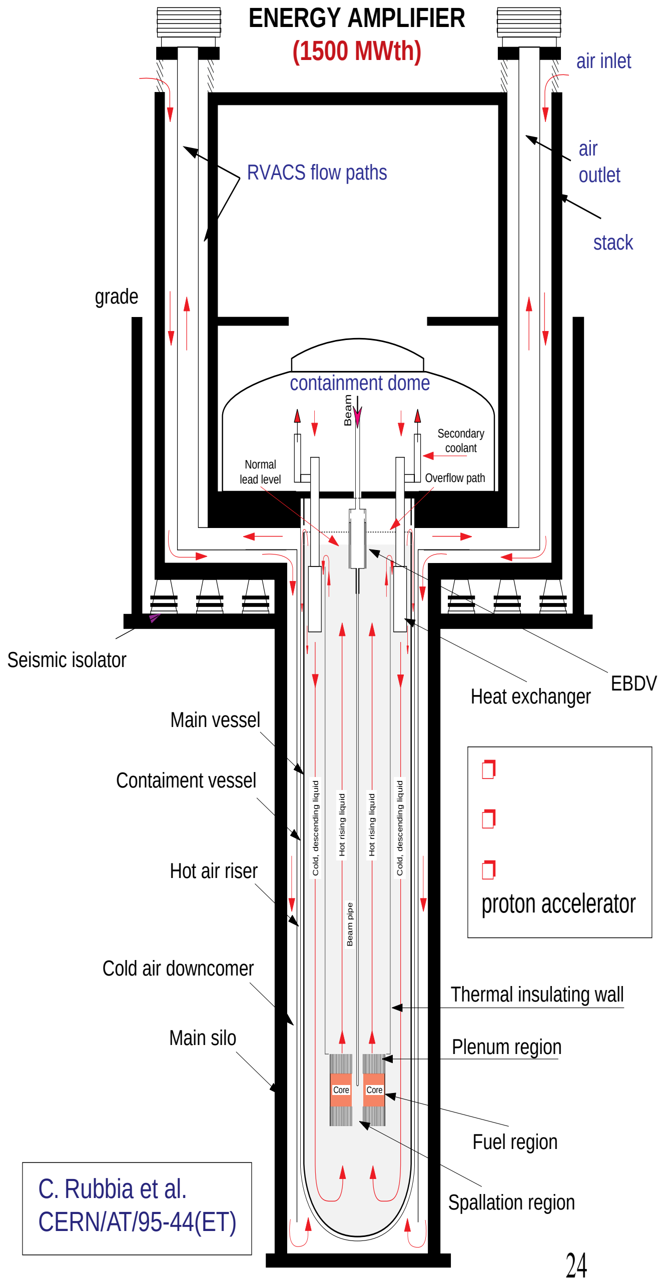
The Energy Amplifier Concept

➪*Method:* A high energy proton beam interacts in a molten lead (Pb-Bi) swimming pool. Neutrons are produced by the so-called spallation process. Lead is “transparent” to neutrons. Single phase coolant, b.p. ≈ 2000 °C

➪*TRU:* They are introduced, after separation, in the form of classic, well tested “fuel rods”. *Fast neutrons,* both from spallation and fission, drift to the TRU rods and fission them efficiently. A substantial amount of net power is produced (up to ≈ 1/3 of LWR), to pay for the operation.

➪*LLFF:* Neutrons leaking from the periphery of the core are used to transmute also LLFF (Tc^{99}, I^{129} ....)

➪*Safety:* The sub-criticality (k ≈ 0.95÷0.98) condition is guaranteed at all times.



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HYBRIDS WITH THE "COUPLED" EXTERNAL NEUTRON SOURCE: Accelerator-blanket Coupled Systems (ACS)

Delayed Enhanced Neutronics (DEN) concept

In the concept oriented towards an "artificial" delayed neutron production in order to enhance intrinsic safety (Delayed Enhanced Neutronics concept or, briefly, DEN), may be realized by direct transformation of a part of the fission energy into electricity and, finally, into supplementary neutron source by using one of the neutron production "mechanisms" **(spallation, bremsstrahlung-photonuclear, nuclear fusion, etc.).**

These supplementary neutrons can be naturally or artificially "delayed" when compared with **prompt** neutrons of fission. Such a system operates with increased total fraction of delayed neutrons. This fraction consists of the **delayed neutrons** of two kinds of origins:

- from fission product decay;

- from a supplementary neutron production "mechanism" with their particular neutron spectrum and spatial characteristics. Unlike the first kind, their delay depends on the engineering design of the installation and can be optimized by designers. These neutrons can be considered as a group of "artificially" created delayed neutrons.

Without supplementary neutrons, the blanket would remain subcritical. Together with these neutrons, it becomes "critical", i.e. the external neutron source produces a quantity of neutrons depending upon the neutron production of the basic mechanism (fission). These two mechanisms are "coupled".

Hence, this DEN-system can be referred to "coupled" ARTEN systems operating in a critical/self-sustaining mode and therefore achieving the increase of:

- **the *total neutron yield* per one fission in the hybrid as well as**

- **the *delayed neutron yield.***

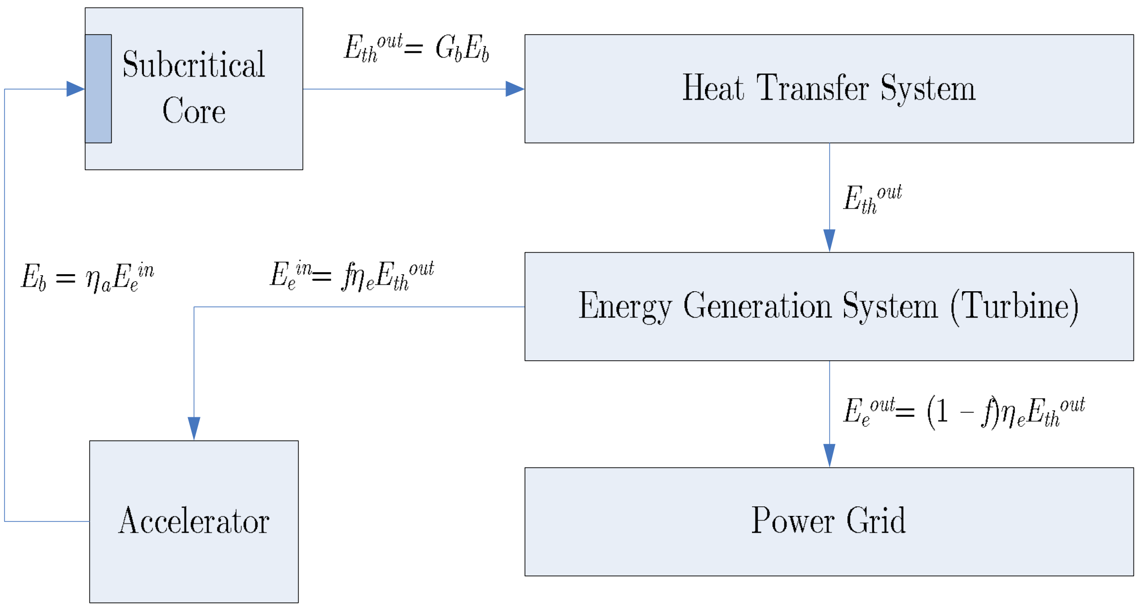
The physical background of this concept is rather simple: an intermediate process "hides" neutrons (of some neutron generation) temporarily to recover them later on. This allows slowing-down dangerous transients.

Unlike DEN, source-independent ADS power is much less sensitive to the thermo-hydraulic transients and

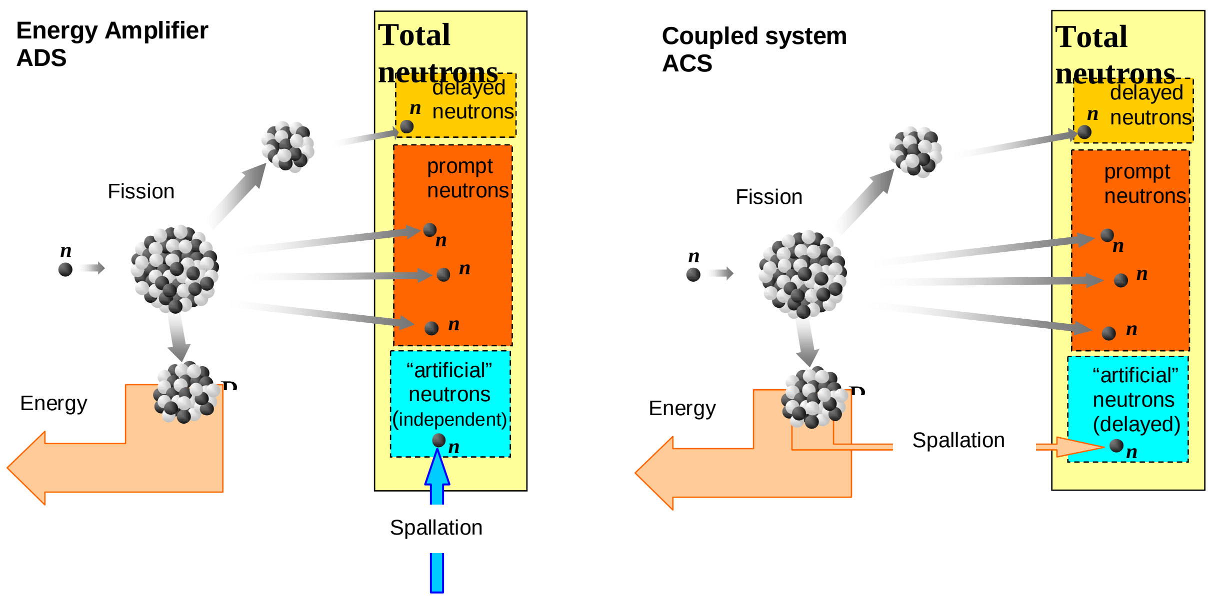
a forced intervention (by proton-beam cut-off) is the only mechanism of protection in multiple anticipated transients without scram.

ACCELERATOR COUPLED SYSTEMS (ACS)

The energy transfer diagram for ACS is similar to this one for the ADS. The only difference is that the power feeding the accelerator does not originate from independent power grid, but from energy generating by its own nuclear system.



Energy transfer diagram for an Accelerator Coupled System (ACS).



HYBRIDS WITH ALTERNATIVE NEUTRON SOURCES: FUSION DRIVEN SYSTEMS (FDS)

"Useful" fusion reactions:

- "pure D-D" fusion (two channels) presents altogether

$$4\mathrm{D} \rightarrow {}^{3}\mathrm{He} + \mathrm{T} + n(2.4MeV) + p + 7.3MeV$$

- "SCAT-D" multi- channels:

$$5\,\mathrm{D} \rightarrow {}^{3}\mathrm{He} + 2n(2.4, 14.1MeV) + \alpha + p + 24.9MeV$$

- "D-T" reaction:

$$\mathrm{D} + \mathrm{T} \rightarrow n(14.1MeV) + \alpha$$

with the total energy output: 17.6 MeV

Particularity of fusion reaction output

One has to take into account the neutron importance $\varphi^{*}_{\mathrm{Fus}}$ which reflects the difference between released neutrons and the "averaged" neutron worth in a fusion blanket as well as the "parasitic" neutron captures in a wall which separates domains of fusion and fission.

One of important parameters respecting Hybrid effectiveness:

$\epsilon_{\rm Fus}$ - energy released per one fusion neutron

"Pure D-D" reactions

produce <u>one</u> fast neutron per fusion. After transportation through the "first wall" which separates fusion and fission domains, a part of such neutrons (about 20%) is loosing. Entering the hybrid blanket, their importance $\varphi^*_{\rm Fus}$ does not exceed 1.2.

Hence: $\epsilon_{\rm Fus} = 7.3$ MeV/neutron, $\varphi^*_{\rm Fus} \approx 1.2$

"SCAT-D" reactions

produce <u>one</u> hard neutron (14.1 MeV) with the importance of $\varphi^*_{\rm Fus} = 1.8$ and <u>another</u> neutron similar to D-D reactions. In average, for both neutrons,

Hence: $\epsilon_{\rm Fus} = 12.45$ MeV/neutron, $\varphi^*_{\rm Fus} = 1.5$;

"*D-T*" reaction (T breeding is required as one of fuel components !)

produces one hard neutron (14.1 MeV) with the importance about

$$\varphi^* = 1.8$$

(i.e. the number of all incoming neutrons can be multiplied by this factor for the account of **(*n*,2*n*); (*n*,3*n*),** etc. reactions).

Two possible ways can be considered further on:

A

where about one neutron is consumed (!) for Tritium (**T**) breeding:

T is produced by ***(n,γ)*** exothermic (**4.8 MeV**) reaction on ^{6}Li.

Breeding requires one thermal neutron ($\varphi^*_b = 1$), thus,

$$\varphi^*_{Fus} = \varphi^* - \varphi^*_b = 1.8 - 1.0 = 1.8$$

Hence: $\epsilon_{\mathrm{Fus}} = 22.4 MeV / neutron, \varphi^*_{Fus} = 1.8$.

B

where ^{7}**Li** is used for **T**-breeding;

no neutron consumption is foreseen for breeding in this case:

$$^7\mathrm{Li} + n_f \rightarrow n' + \alpha + \mathrm{T},$$

where n_f and n' are a fast and the thermalized neutrons respectively.

The breeding reaction is endothermic.

Hence: $\epsilon_{\mathrm{Fus}} = 17.6 - 2.5 = 15.1; \varphi^*_{\mathrm{Fus}} = 1$

Neutron analysis. Fusion as an external neutron source.

Each fusion design consumes electrical energy E_{spent} for its needs and produces "output" energy E_{Fus} in the form of kinetic energy of charged and neutral particles.

If m as the ratio of the total consumed energy (E_{spent}) to the total output electric energy then,

denoting η_e as the efficiency of transformation of E_{Fus} to the electric energy in a fusion blanket, one get:

$$m = \frac{E_{spent}}{\eta_e E_{\mathrm{Fus}}}$$

$m = 1$

correspons to the "break-point" event and

$m > 1$

to the "negative" energy balance of a fusion installation.

Referring to one neutron in ones disposition:

$$m = \frac{\epsilon_{spent}}{\epsilon_{\mathrm{Fus}} \eta_e}.$$

COMMENTS:

At $m \geq 1$ (one consumes more than produces?!), there is no practical sense to use fusion for energy production, however, it may have a significant sense as a supplementary neutron source for a hybrid.

Let us evaluate thermal energy produced in a sub-critical core (blanket) when this core "received" one external neutron from domain of "fusion". This energy "accumulates" energy released due to fusion plus total energy of fission reactions in a subcritical blanket ($K_{\text{eff}} < 1$) possessing multiplication of neutrons:

$$\epsilon_t = \epsilon_{\text{Fus}} + \frac{K_{\text{eff}}}{(1 - K_{\text{eff}})} \frac{\varphi^*}{\overline{\nu} a_w} \epsilon_{\text{Fis}}$$

where $\overline{\nu}$ is the average number of the secondary neutrons per fission; φ^* is the importance of fusion neutrons; ϵ_{Fis} is fission energy;

a_w as the coefficient showing the neutron parasitic loss in the walls: it is the ratio of all fusion neutrons to all neutrons appeared in the blanket.

Taking into account the efficiency of transformation of thermal to electrical energy in a blanket, one gets

$$\epsilon_e = \epsilon_t \eta_e$$

Fraction of total electrical energy which has to be spent for the reproduction of one fusion neutron and to sustain the energy production can be assessed as

$$f_{\text{Fus}} = \frac{\epsilon_{spent}}{\epsilon_e} = m \frac{1}{1 + \frac{\varepsilon_{Fis}}{\varepsilon_{Fus}} \frac{K_{\text{eff}}}{(1 - K_{\text{eff}})} \frac{\varphi^*_{Fus}}{a_w \overline{\nu}}}$$

After neglecting with the first term in the denominator, one get:

$$f_{Fus} \approx \frac{1}{Y_{Fus} \frac{K_{\text{eff}}}{(1 - K_{\text{eff}})\overline{\nu}} \varepsilon_{Fis}} = \frac{1}{Y_{Fus}} \times \frac{1}{\varepsilon_{Fis} K_A}$$

where

the "effective" neutron yield Y_{Fus} in fusion per consumed energy:

$$Y_{Fus} = \frac{\varphi^*_{Fus}}{\varepsilon_{Fus} m a_w}$$

and

K_A is the coefficient of multiplication ("amplification") of fission energy in a sub-critical blanket:

$$K_A = \frac{K_{eff}}{(1 - K_{eff})\overline{\nu}}.$$

COMMENTS:

The fraction of power spent for the supplementary neutron source is inversely proportional to the effective neutron yield of this source and to the coefficient of power amplification in the blanket.

INTER-COMPARISON: ADS VERSUS FDS

One can conduct similar procedure of the assessment of energy which required for production of neutrons via spallation.

Total electrical energy which is produced by ADS core per one proton (Z is spallation neutron yield) :

$$\epsilon_e = \eta_a \left[\epsilon_{\mathrm{Sp}} + \frac{K_{\mathrm{eff}}}{(1 - K_{\mathrm{eff}})} \frac{Z \varphi^*_{\mathrm{Sp}}}{\overline{\nu}} \epsilon_{\mathrm{Fis}} \right],$$

where ϵ_{Sp} is energy released per one incident proton (for example, in the lead target, $\epsilon_{\mathrm{Sp}} \approx 0.5\epsilon_p$, ϵ_p is proton energy); φ^*_{Sp} is the importance of spallation neutrons.

For production of one proton, one has to spent ϵ_{spent} of energy, where $\epsilon_{spent} = \epsilon_p / \eta_a$ and η_a is the accelerator efficiency.

Finally, the fraction of total electrical energy which has to be spent for production of one proton and to sustain energy production in ADS:

$$f_{\mathrm{Sp}} = \frac{\epsilon_{spent}}{\epsilon_e} = \frac{1}{\eta_e \eta_a} \frac{1}{\left[\frac{\epsilon_{\mathrm{Sp}}}{\epsilon_p} + \frac{\epsilon_{\mathrm{Fis}}}{\epsilon_p} \frac{K_{\mathrm{eff}}}{(1 - K_{\mathrm{eff}})} \frac{Z \varphi^*_{\mathrm{Sp}}}{\overline{\nu}} \right]}$$

and, after neglecting with the first term in the denominator, one get, similar to the case of the fusion source:

$$f_{Sp} \approx \frac{1}{Y_{Sp} \frac{K_{eff}}{\left(1-K_{eff}\right)\overline{\nu}} \varepsilon_{Fis}} = \frac{1}{Y_{Sp}} \times \frac{1}{\varepsilon_{Fis} K_A}$$

the "effective" neutron yield Y_{Sp} of spallation per consumed energy is defined as

$$Y_{Sp} = \frac{Z\varphi^*_{Sp}}{\varepsilon_p \frac{1}{\eta_e \eta_a}}$$

Now, everything is ready to inter-compare fractions of energy consumption to create a neutron source by spallation or by fusion.

TABLE. **Required supplementary energy consumptions (*f*, %) in sub-critical hybrids supplied via spallation or via fusion reactions**

$$(K_{\text{eff}} = 0.9, \ \eta_e = \eta_a = 0.45, \ \overline{\nu} = 2.5).$$

Sources of supplementary neutrons in different Hybrids	Effective neutron yields **Y** $(\text{MeV})^{-1}$	f %		
FUSION ($a_w = 1.2$)	$m = 1$	$m = 1$	$m = 3$	$m = 10$
D-D	0.14	1.0	3.0	10
SCAT-D	0.10	1.4	4.2	14
D-T breeding on Li-6	0.030	4.1	8.2	41
D-T breeding on Li-7	0.055	2.5	7.5	25
SPALLATION				
Spallation by proton: $E_p = 1\text{GeV}$, lead target, $Z = 20\text{n/p}$, $\varphi^{*}_{\text{Sp}} = 1.3$	0.0053	$f = 26\%$		

COMMENTS

Fusion is able producing even more neutrons per power unit than spallation.

$$\frac{f_{\text{Sp}}}{f_{\text{Fus}}} = \frac{Y_{Fus}}{Y_{Sp}}.$$

The inter-comparison of Y-values demonstrates that the **effectiveness** of fusion for neutron production (when m $\rightarrow$ 1) is higher when compared with spallation and it is reducing when the m increases (see Table).

Certainly, the fraction of the fusion energy spent in a blanket will grow if

- less effective fusion reactions,
- there is higher neutron loss in the "walls",
- less beneficial economy of fusion sources ($m \geq 3$)

are used.

Conclusion

The neutron abundance of fusion reactions (particularly D-D reactions) per consumed energy is more rich potentially compared with the spallation sources.

When approaching to the "break-point" ($m = 1$), fusion source becomes more beneficial.

Even for significant core sub-criticality hybrids (e.g. Th-fuelled blankets), the required power (for the external neutron production) **could be assessed optimistically as only 3% of the total blanket power if D-D sources with $m = 3$ are foreseen to be used.**

The weakest potential is expected for D-T (breeding on Li-6) reaction.

I.5. Experimental validation of sub-critical core physics.

Review of Sub-Critical Core Experiments

- Highly specified experiments have been carried out to verify the fundamental physics principle of Accelerator-Driven Sub-Critical Systems:

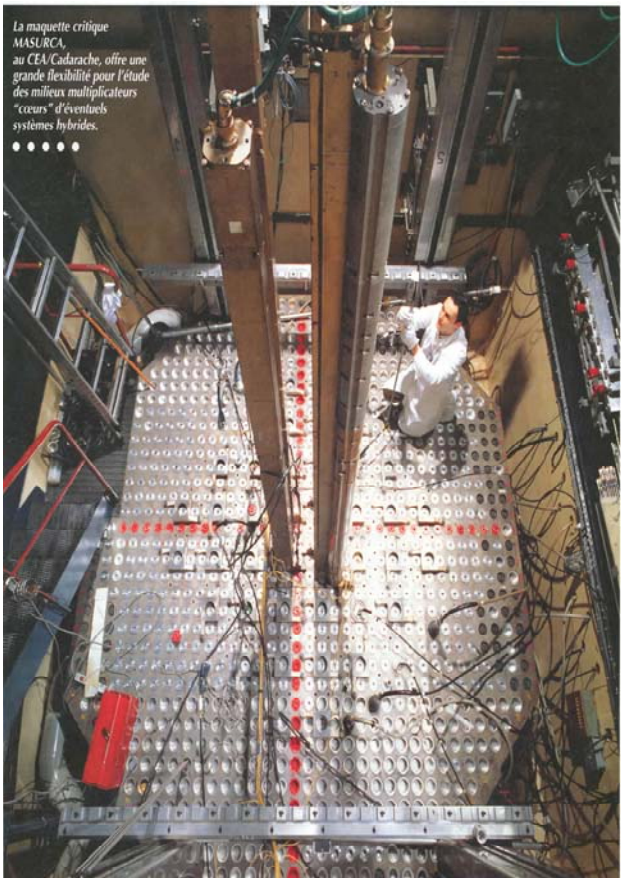
☆ The First Energy Amplifier Test (FEAT): S. Andriamonje et al. Physics Letters B 348 (1995) 697–709 and J. Calero et al. Nuclear Instruments and Methods A 376 (1996) 89–103;

The MUSE Experiment (MUltiplication de Source Externe): M. Salvatores et al., 2nd ADTT Conf., Kalmar, Sweden, June 1996;

The YELINA Experiment (ISTC-B-70): Institute of Radiation Physics & Chemistry Problems, National Academy of Sciences, Minsk, Belarus.

The MUSE Experimental Program –
in order to confirm the physical background, data-base parameters and techniques.

The MUSE Experiment



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As a result of the continuing interest in Accelerator Driven Systems (ADS) was realized in the MUSE-4 (**MU**ltiplication **S**ource Experiments)

The experimental programme was initiated in 2000 in the MASURCA facility at CEA Cadarache.

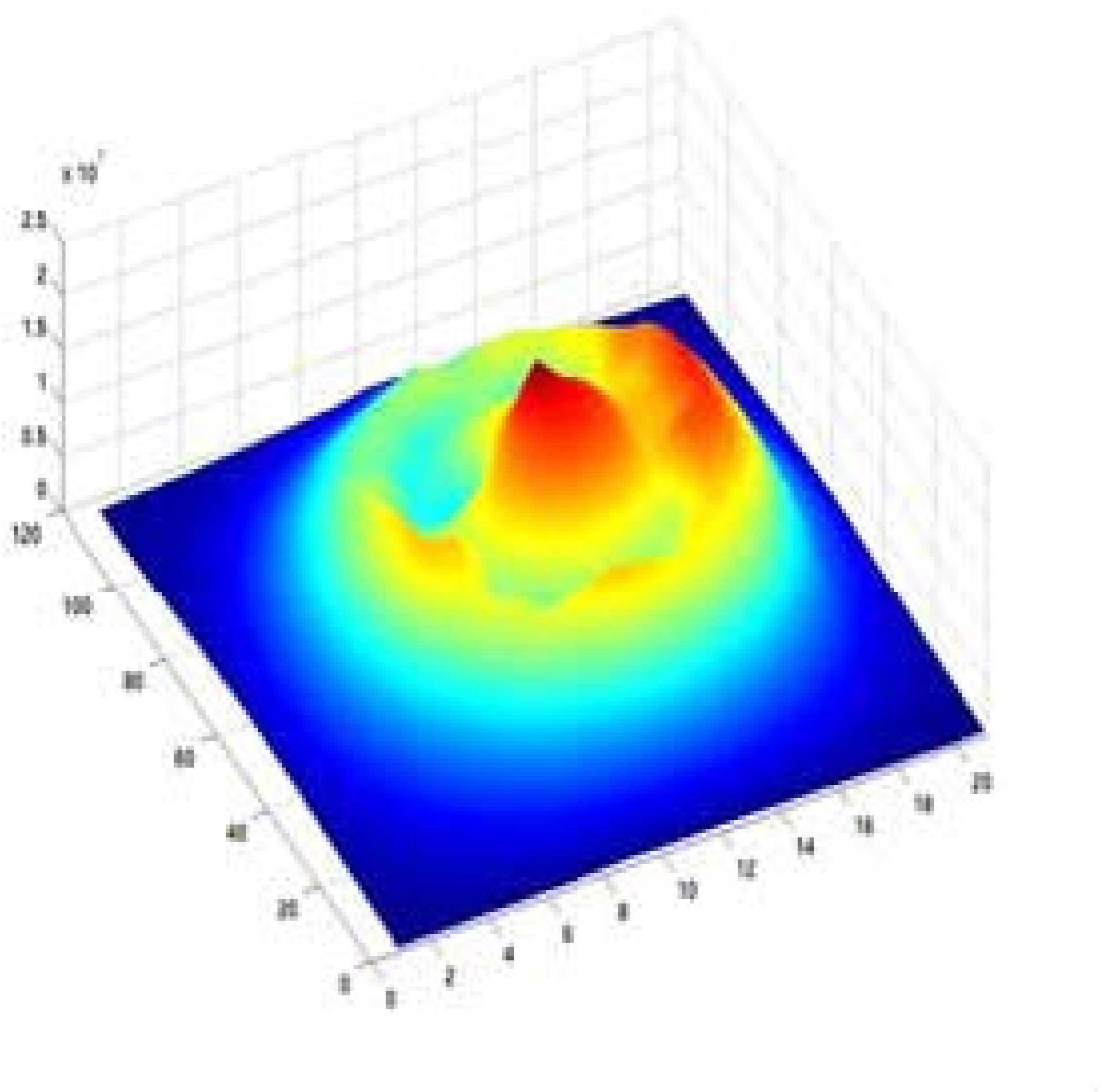
Finally, the MUSE-4 project covers the construction, characterisation and numerical analysis of a reactor which is representative of a fast spectrum MOX fuelled sodium cooled core.

The novelty and uniqueness of the MUSE-4 experiments is due to the inclusion of the GENEPI deuteron accelerator, which guides and focuses a deuteron beam onto a deuterium or tritium target in order to produce neutrons via the D(d,n)3He or the T(d,n)4He fusion reactions.

Several configurations have been analysed; a reference critical core followed by cores with varying degrees of sub-criticality (in which the neutron source due to GENEPI will act in a similar manner to that of the spallation source of a commercial ADS).

One of the objectives of the MUSE-4 project is to assess the applicability of deterministic neutronics packages such as **ERANOS** (developed primarily for critical fast reactor analyses) to ADS in general.

Fission Rate Map perturbation due to GENEPI



The YELINA Experiment