

Comparison of the efficiency of several controlled neutron sources

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Abstract

In this article, it is estimated the global efficiency of several controlled neutron sources, i.e. the ratio between the kinetic energy of neutrons generated by the neutron source and the necessary energy (thermal or more generally electric) to generate these neutrons. As the neutrons could only be used after thermalization, the neutrons energy being indifferent in that case, it is also determined the quantity of energy per neutron generated.

Comparisons will be made between these neutrons sources.

CONTENTS

	Page
1. Introduction	1
2. Determination of the efficiency of several controlled neutron sources	2
2.1 The basic amateur Fusor	2
2.2 Fusors from Universities	2
2.3 Professional Fusor	2
2.4 Alpha beam colliding Beryllium	2
2.5 D+ ions beam colliding a D2 gas	2
2.6 The HFR	3
2.7 The SINQ	4
2.8 The fusion reactor (in the future)	5
3. Conclusion	5
4. References	6

1. Introduction

The goal of this article is to determine or estimate the global efficiency (η) of several controlled neutrons sources, i.e. all except Alpha neutrons sources, Gamma neutron sources and Spontaneous fission neutrons sources. See [\[1\]](#) for a presentation of the different types of neutron sources. The global efficiency is, in general, equal to the product of the mechanical gain times the electrical efficiency. The energy necessary per neutron generated (E_{rn}) is also determined.

The first criterion (η) is important if the goal is to produce high energy neutrons. The second criterion (E_{rn}) is important if the goal is to produce thermalized neutrons. In that case, E_{rn} must be implicitly compared to the energy generated by a fission due to a thermalized neutron, i.e. about 200 MeV.

The neutron sources studied, from the least efficient to the most efficient (relatively to E_{rn}), are:

- The basic amateur Fusor
- Fusors from universities
- The professional Fusor
- Alpha beam colliding Beryllium

- D+ ions beam colliding a D2 gas
- The HFR
- The SINQ

2. Determination of the efficiency of several controlled neutron sources

2.1 The basic amateur Fusor

It is reminded that the Fusor is an Inertial Electrostatic Confinement equipment, fusing D-D ions and so generating neutrons at an energy $E_n=2.45$ MeV.

It is reminded that the two fusion interactions between Deuterium nuclei are:

$D+ + D+ \rightarrow T+ (+1.01 \text{ MeV}) + p (+3.03 \text{ MeV})$ (at 50%)

$D+ + D+ \rightarrow He3+ (+0.82 \text{ MeV}) + n (+2.45 \text{ MeV})$ (at 50%)

From [2], with a supply of 15 kV/ 60 mA supposed totally used (the paper does not give the active power consumption), it is generated at best a NPR (Neutrons Production Rate) of 300,000 n/s.

The maximum electric power consumed P_e is equal to $P_e = U \times I = 900 \text{ W}$.

The power generated in the form of kinetic energy of neutrons P_n is equal to:

$$P_n = NPR \times E_n \times 1E6 \times K = 1.18E-7 \text{ W}$$

with $K=1.602E-19$ (=charge of a proton) the constant to switch from eV to W, E_n being in MeV.

$$\text{The global efficiency } \eta = \frac{P_n}{P_e} = 1.31E-10$$

The energy required (E_n in MeV/n) per neutron is equal to $E_{rn} = \frac{P_e}{(NPR \times K \times 1E6)} = 1.87E10 \text{ MeV/n}$

2.2 Fusors from Universities

From data about the voltage V in kV, the intensity I in mA and NPR in [3] page 13, by applying the previous formulas it comes the following results, for the 3 best Fusors, working with Deuterium:

- University of Wisconsin 1, at $V=190 \text{ kV} / I=75 \text{ mA} / p=0.25 \text{ Pa} / NPR=2.4E8$
 $\eta=6.61E-9$ and $E_{rn}=3.71E8 \text{ MeV/n}$
- University of Missouri, at $V=24 \text{ kV} / I=29 \text{ mA} / p=0.05 \text{ Pa} / NPR=1.4E6$
 $\eta=7.89E-10$ and $E_{rn}=3.10E9 \text{ MeV/n}$
- University of Illinois, at $U=70 \text{ kV} / I=15 \text{ mA} / NPR=1.2E6$
 $\eta=4.49E-10$ and $E_{rn}=5.46E9 \text{ MeV/n}$

Note that the Fusor of the University of Wisconsin 1 is 50 times better, in term of E_{rn} , than the basic Fusor, mainly due to a much higher voltage.

2.3 Professional Fusor

An example of linear Fusor is taken from the NSD company [4], which technology is (simply) described in [5]. The sole fusion considered is the D-D one (even if D-T and T-T fusions are also possible).

- NSD-50: at $V=120 \text{ kV} / I=15 \text{ mA} / NPR=4E7 \text{ n/s}$
 $\eta=8.72E-9$ and $E_{rn}=2.81E8 \text{ MeV/n}$

Note that this linear Fusor has a better performance, in term of E_{rn} , than the best Fusor from Universities, with a lower voltage.

2.4 Alpha beam colliding Beryllium

An "AmBe" source is composed of Americium 241 which is an Alpha ($He4$ nucleus) emitter, mixed with Beryllium (see [1] page 12]. This source cannot be controlled and so is outside of the scope of this paper. However, let's suppose that the Alpha (α) be injected by an accelerator at the same energy as the Alphas particles emitted by Am-241, i.e. about 5.48 MeV. These accelerated Alpha particles will be slowed down in the Beryllium ($Be-9$), mainly by electrons. The calculation is presented below.

The two interactions between Alpha and $Be-9$ nuclei are:

$\alpha + \text{Be-9} \rightarrow n + \alpha + \text{Be-8}$

$\alpha + \text{Be-9} \rightarrow n + \text{C12} + \gamma$ (4.44 MeV)

For Alpha particles from Am-241 (at 5.48 MeV), the average neutron energy (E_n) is equal to 4.2 MeV ([1] page 12).

From [6], it is determined the "Total stopping power" of Alpha injected in Be-9 according to the kinetic energy of the Alpha. Note that the stopping power in [6] is given in MeV.cm²/g. The interesting stopping power dE/dx must be determined by multiplying this piece of data by the Be-9 density (1.848 g/cm³).

Along its path in the Be-9, the energy of the Alpha decreases. As the calculation is done by a program, this slowing down is simulated by small steps (i). For any Alpha energy found at a given step (i), it must be determined the interaction cross-section (from ENDF/B-VIII.0) and the speed of the Alpha particle. Knowing the number of Be-9 nuclei per m³ (123.6E21/cm³), the interaction frequency can be determined. Then it must be calculated the elementary probability of interaction (Prii). The Prii are calculated until to reach 200 keV, for which the interaction frequency is nil.

Let's call Pri ($\text{Pri} = \sum \text{Prii}$) the final probability of interaction of an Alpha injected at an initial energy $EA_{\text{initial}}=5.48$ MeV. The efficiency μ for the Alpha accelerator is supposed equal to 0.8. The global

efficiency is equal to $\eta = \frac{P_n}{P_e} = \frac{\text{Pri} \times E_n}{(EA_{\text{initial}} / \mu)}$ and the energy required (E_{rn} in MeV/n) per neutron is

equal to $E_{rn} = \frac{(EA_{\text{initial}} / \mu)}{\text{Pri}}$.

The main results are (the uncertainty of results being estimated to +/-30%.):

- The probability of interaction (Pri)=7.973E-5
Note: in [7], it is given, for an alpha-beryllium neutron source, 30 neutrons for 1E6 Alphas, so a probability of interaction of 3E-5. So, this calculation is perhaps a bit optimistic.
- The global efficiency (η)=4.89E-5
- The energy required per neutron (E_{rn})=8.59E4 MeV/n
- The slowing down distance (Dsd), covered by the Alpha before reaching 200 keV=27.3 microns

2.5 D+ ions beam colliding a D2 gas

In general, D+ ions are injected (by an accelerator) on a layer of Titanium, where Deuterium accumulates at the surface and is subject to fusions with D+ ions. The author did not find data about performances. So, instead, here it is proposed to inject D+ ions across D2 gas, where D+ ions fuse with D nuclei while there are slowed down, mainly by electrons. The calculation is presented below.

From [8], it is determined the "Total stopping power" in H2 gas according to the kinetic energy of protons. Moreover, the stopping power mainly stems from the Bethe formula, so it can be determined that the stopping power for D+ ions in D2 gas is about 1/0.47=2.13 faster than the stopping power for H+ ions in H2 gas, given in [8], for a given ion energy.

Note that the stopping power in [8] is given in MeV.cm²/g. The interesting stopping power dE/dx must be determined by multiplying this piece of data (from [8]) by the density of the hydrogen gas (H2), supposed at 1 atm / 0°C (=8,99E-5 g/cm³).

Along its path on the D2 gas, the energy of the D+ ion decreases. As the calculation is done by a program, this slowing down is simulated by small steps (i). For any D+ ion energy found at a given step (i), it must be determined the fusion cross-section (from ENDF/B-VIII.0) and the speed of the D+ ion. Knowing the number of D nuclei per m³, still for 1 atm / 0°C, the fusion frequency can also be determined. Then it must be calculated the elementary probability of fusion (Prfi). These Prfi are calculated until to reach 10 keV, for which the fusion frequency is negligible.

Now, due to the possible high kinetic energy of the D+ ion (called ED_{initial}), it must be taken into account the sharing of this energy between the He3 nucleus and the neutron (see §2.1).

It can be shown that the conservation of energy and momentum leads to a neutron energy equal to:

$E_{ni}=3/4.E_{Di} + 2.45$ MeV, with E_{Di} the current kinetic energy of the D+ ion in MeV, during it slowing down.

Finally the average neutron energy E_n will be calculated as $E_n = \frac{\sum Pr_{fi} \times E_{ni}}{\sum Pr_{fi}}$

Let's call Pr_f ($Pr_f = \sum Pr_{fi}$) the final probability of fusion of a D+ ion injected at an initial energy

$E_{D_initial}$, in MeV. The efficiency μ for the D+ ions accelerator is supposed equal to 0.8. As once on two

D-D fusions gives a neutron, the global efficiency is equal to $\eta = \frac{P_n}{P_e} = \frac{Pr_f \times 0.5 \times E_n}{(E_{D_initial} / \mu)}$ and the energy

required (E_{rn} in MeV/n) per neutron is equal to $E_{rn} = \frac{(E_{D_initial} / \mu)}{(Pr_f \times 0.5)}$

Below is a table which gives for a set of initial D+ ion energies ($E_{D_initial}$) in keV, the average neutron energy E_n (MeV), the probability of fusion (Pr_f), the global efficiency (η), the energy required per neutron (E_{rn}) in MeV/n and the slowing down distance (D_{sd}) in mm, covered by the ion before reaching 10 keV (if not fused before). The uncertainty of results is estimated to +/-30%.

$E_{D_initial}$ (keV)	E_n (MeV)	Pr_f	η	E_{rn} (MeV/n)	D_{sd} (mm)
30	2.468	1.198E-9	3.94E-8	6.26E7	0.3
100	2.507	8.588E-8	8.61E-7	2.91E6	1.3
300	2.614	1.778E-6	6.20E-6	4.22E5	5.7
1000	2.972	3.262E-5	3.88E-5	7.66E4	44.0
3000	3.885	2.700E-4	1.40E-4	2.78E4	311.2
5480	5.098	7.281E-4	2.71E-4	1.88E4	928.4
10000	7.365	2.398E-3	7.06E-4	1.04E4	2792.5

Note that at the same initial energy (5.48 MeV), this interaction is 4.6 better, in term of E_{rn} , than the Alpha-Be-9 interaction.

2.6 The HFR

The ILL (Institut Laue-Langevin) High Flux Reactor is a fission reactor aimed to produce a high flux of neutrons.

From [9] page 58, with $P_{th}=57$ MW of fusion power, it is able to generate $NPR=1E18$ n/s.

The average energy of fission neutrons is about 2 MeV.

So $\eta = \frac{P_n}{P_{th}} = \frac{NPR \times E_n \times 1E6 \times K}{P_{th}} = 5.62E-3$ and $E_{rn} = \frac{P_{th}}{(NPR \times K \times 1E6)} = 356$ MeV/n

2.7 The SINQ

The SINQ (Swiss Institute for Nuclear Research) is a continuous spallation neutron source. From [10], it can be seen that the protons are injected at 560 MeV with an intensity of 1 mA on a Pb-Bi target.

So the mechanical beam power is equal to $P_m=560E6 \times 1E-3=5.6E5$ W. The efficiency μ of the accelerator (P_m/P_e) is not given and supposed equal to $\mu=0.6$, which is relatively low because it is a complex

equipment. So $P_e = \frac{P_m}{\mu} = 9.33E5$ W

Each proton generates 10.4 neutrons per proton which average energy E_n is equal to 1.7 MeV.

$NPR = \frac{10.4 \times I}{K}$ and $P_n = NPR \times E_n \times 1E6 \times K = 10.4 \times I \times E_n \times 1E6 = 1.768E4$ W

So $\eta = \frac{P_n}{P_e} = 0.0189$ and $E_{rn} = \frac{P_e}{(NPR \times K \times 1E6)} = \frac{P_e}{(10.4 \times I \times 1E6)} = 89.7$ MeV/n

2.8 The fusion reactor (in the future)

There are mainly two types of fusion possible: either the D-T (Deuterium-Tritium) one and the D-D (Deuterium-Deuterium) one.

D-T fusion for a neutron source

As the Tritium is not available in nature, the Tritium must be supplied by a Lithium blanket.

So a neutron generated by a D-T fusion must, as a priority, be used to induce a reaction with Li6 to breed Tritium. As the TBR (Tritium Breeding Ratio) is slightly above 1 and, a priori, just sufficient to compensate the Tritium losses, it seems uncertain that it could exist a margin on the TBR to use neutrons for a neutron source. So this type of reactor is not considered.

D-D fusion for a neutron source

An example of D-D source of neutrons is given in [11]. It is used to breed a fission reactor, the set of both reactors (fusion/fission) being called a “hybrid reactor”.

The total consumed electrical power (P_e) is equal to 801.7 MWe, for the particles accelerators plus the cryogenic power for the superconducting coils and the UHV system.

The neutron power (P_n) is equal to 55.36 MW, with a proportion of 26 % of 14.06 MeV neutrons and 74 %

of 2.45 MeV neutrons. So the global efficiency $\eta = \frac{P_n}{P_e} = 0.069$

The mean energy per neutron is equal to 5.451 MeV

The NPR (Neutrons Production Rate) is equal to 6.339E19 n/s

The energy required (E_{rn} in MeV/n) per neutron is equal to $E_{rn} = \frac{P_e(W)}{(NPR \times K \times 1E6)} = 78.9 \text{ MeV/n}$

3 Conclusion

Below, a table groups several of the results obtained above.

Equipment	Injection energy (keV)	η	E_{rn} (MeV/n)
Basic amateur Fusor	15	1.31E-10	1.87E10
Fusor of the University of Wisconsin 1	190	6.61E-9	3.71E8
Professional Fusor (linear)	120	8.72E-9	2.81E8
Alpha beam colliding Beryllium	5480	4.89E-5	8.59E4
D+ ions beam colliding a D2 gas	5480	2.71E-4	1.88E4
The HFR (High Flux Reactor)	/	5.62E-3	356
The SINQ (Spallation neutron source)	560,000	0.0189	89.7
The D-D fusion reactor (in the future)	88	0.069	78.9

Currently, the best equipment, in term of energy required per neutron (E_{rn}), is the spallation neutron source. Note that $E_{rn}=89.7 \text{ MeV/n}$ for the SINQ is inferior to the energy generated by a fission due to a neutron, i.e. about 200 MeV. This explains the choice by Carlo Rubbia and his team of such way to breed in neutrons an “energy amplifier” or “accelerator-driven system”. See [12] for details.

The D-D fusion reactor would be a bit better than the spallation neutron source, but it is just a possibility for the future.

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