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Feasibility study of a hybrid subcritical fission system driven by Plasma-Focus fusion neutrons

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ABSTRACT

A feasibility analysis of a hybrid fusion–fission system consisting of a two-stage spherical subcritical cascade driven by a Plasma Focus device is presented. The analysis is based on the one-group neutron diffusion equation, which was appropriately cast to assess the neutronic amplification of a spherical configuration. A design chart was produced to estimate the optimum dimensions of the fissile shells required to achieve different levels of neutron amplification. It is found that cascades driven by Plasma Focus of tens of kJ are feasible. The results were corroborated by means of Monte Carlo calculations.

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1. Introduction

The concept of hybrid nuclear reactors combining fusion and fission processes was first proposed in the decade of 1950 (see references in Nifenecker et al., 2003) and was reactivated later in the 70s (Bethe, 1979). After that, the interest in the hybrid idea waned, not so much because of technical difficulties but for lack of economic incentive. This remained so until the last two decades, during which the interest in hybrids has again increased for their possible application in energy production, either using Uranium fuel or combining breeder systems with Thorium fuel cycles, and also for the destruction of nuclear waste (Abalin et al., 1995; Gerstner, 2009; Freidberg and Kadak, 2009; Kotschenreuther et al., 2009).

The central concept of hybrids is to surround a fusion source of neutrons with fissile fuel configured in such a way that the whole system is subcritical. The neutrons injected by the source, usually as a train of pulses, are then multiplied by fissions, generating a total energy that in principle should be larger than the input energy required for the fusion process. The most popular neutron drivers that were proposed are spallation targets pumped by proton or electron accelerators, called Accelerator Driven Systems, ADS (Nifenecker et al., 2003). In the last decade has been a renewed interest in ADS systems, including experimental validations (Shahbunder et al., 2010), comprehensive physical (Wang et al., 2013) and economic analysis (Steer et al., 2012; Gulik and Tkaczyk, 2014). Very recently the commissioning of a zero power experimental subcritical facility has been reported in India (Sinha et al., 2015). Also, based on the theory of ADS an isotope source driven subcritical battery was proposed (Wang and He, 2014).

It is generally accepted that for security and control reasons, the effective multiplication factor of a subcritical driven system should be limited to about 0.98 for fast-neutron reactors and 0.95 for thermal reactors (Nifenecker et al., 2003). This limitation, in principle, imposes an upper bound to the amplification factor. In order to increase the amplification without compromising the subcritical condition, the concept of cascade reactors was introduced as early as the 50s (Borst, 1957; Avery, 1958; Dubovskii, 1959) and reactivated in the 90s by Daniel and Petrov (1996) and Barzilov et al. (1996). Recently, control and safety issues of specific cascade configurations were analyzed using Monte Carlo methods, in spherical (Kolesov and Khoruzhii, 2003) and cylindrical geometries (Gulevich et al., 2007). Essentially a cascade or diode subcritical reactor consists of two multiplying sections (generally separated spatially) with asymmetric coupling, in such a way that neutrons produced in the first section easily penetrate the second while those produced in the second have little influence over the first.

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On the neutron source side, the alternatives to accelerators or laser induced neutrons are fusion neutron sources. For example, Moiseenko et al. (2010) proposed a stellarator-mirror driven reactor. The work reported here is focused on assessing the feasibility of hybrid fusion–fission systems driven by Plasma Focus (PF) neutron sources. PF devices are special types of dense z-pinch discharges that are very efficient, both technically and economically, in producing neutron pulses within certain modest ranges, when operating with Deuterium or Deuterium–Tritium gases (Bernard et al., 1998; Moreno et al., 2002; Soto et al., 2008; Soto et al., 2010). Essentially, a PF is a high-voltage pulsed discharge in a gas at low pressure induced between two coaxial cylindrical electrodes separated by an insulator. The discharge starts over the insulator surface producing a plasma sheath that comes off and is accelerated axially by the magnetic field auto generated by the current. After the current sheath runs over the upper end of the central electrode, the plasma is compressed in a small region, called focus or pinch, where peaks of high density and temperature are achieved. When the gas is Deuterium or mixtures of Deuterium and Tritium, fusion nuclear reactions are produced in the pinch generating neutrons pulses. The neutron yield depends on several design and operating parameters, namely, pinch current, filling pressure, geometrical dimensions of the electrodes, among others. In general terms, when most parameters are optimized, the peak neutron yield is roughly proportional to the square of the energy stored in the capacitors. With Deuterium, the peak yield ranges from 10^4 neutrons per shot for table top devices operating at tens of joules (Soto et al., 2008) to 10^{11} neutrons per shot for several cubic-meter devices operating around 1 MJ (Schdmidt et al., 2002). The neutron yield increases in two orders of magnitude using Deuterium–Tritium mixtures (Mather, 1971). There are a few studies that entertained the idea of using a PF device as the seed of neutrons for a hybrid fusion–fission system (Gribkov and Tyagunov, 1983; Zoita and Lungu, 2001). Those studies analyzed the simplest array of a single subcritical region hosting a PF device, concluding that, achieving break-even conditions would require energies as high as 10 MJ capable of deliver currents of 20 MA in 1 μs to produce pulses of 10^{18} neutrons. Alas, that sort of figure is out of the range of the current technology. In effect, although since their invention 50 years ago several projects were carried out to push higher the upper energy limit of PF facilities, the neutron production ceases to increase beyond 1 MJ (Nukulin and Polukhin, 2007; Lee, 2009).

In this article, the feasibility of hybrid systems driven by PF neutron pulses is revisited. The analysis starts from the model of a two-stage cascade presented by Barzilov et al. (1996), which is here specified for a spherical geometry, deriving a set of equations to assess the neutronic amplification in terms of the geometric parameters. The occurrence of optimum configurations is determined here for two spherical fission blankets, varying the size of each region while keeping constant the total volume of the system. Finally a search is conducted for an 8%-enriched Uranium cascade by means of Monte Carlo calculations, determining the feasibility range for hybrid break-even using the current PF technology.

2. Model of subcritical fission cascades

Barzilov et al. (1996) showed that a multiplicative set of two coupled subcritical regions driven by periodic neutron pulses can be reasonably represented by the one-group neutron diffusion equation in each region. Accordingly, those authors wrote a set of ordinary differential equations in terms of the multiplication factors of each region and the neutron transfer between regions. Let us revisit that set of equations starting from the one-group diffusion equation, that is:

$$\frac{\partial n}{\partial t} - Dv\nabla^2 n = -\Sigma_a vn + \overline{\upsilon}\Sigma_f vn + S \tag{1}$$

where $n(x,t)$ is the neutron density, v is the average neutron velocity, D is the diffusion constant, Σ_a and Σ_f are the absorption and fission macroscopic cross sections, $\overline{\upsilon}$ is the average number of neutrons produced per fission, and S is an external source.

Furthermore, let us assume that the spatial dependence of the neutronic density can be described by the Helmholtz equation (Hetrick, 1971):

$$\nabla^2 n + B^2 n = 0 \tag{2}$$

where B^2 is an effective geometrical buckling. This is a strong assumption that should only be taken as an approximation in order to produce an analytical expression of the neutronic amplification in terms of geometric parameters. Therefore, the results will need to be corroborated by Monte Carlo calculations.

The train of periodic pulses injected by the sources will lead to a sustained oscillatory regime of n. In each region, substituting the spatial variation in the diffusion term in Eq. (1) according to Eq. (2), and then integrating over a temporal cycle with its periodic boundary conditions and over the volume, yields:

$$\left(\frac{DB^2+\Sigma_a}{\overline{\upsilon}\Sigma_f} - 1\right)F = \iint S\,dt\,dV \tag{3}$$

where

$$F = \overline{\upsilon}\Sigma_f \iint vn\,dt\,dV \tag{4}$$

is the number of fission neutrons produced in the region during the cycle.

Note that the time derivative would give values of the neutron density at the beginning and end of the cycle. However, these are identical in the permanent oscillatory regime and therefore cancel because the reactor process is periodic.

Now, let us consider the special coupled case of a cascade, consisting of a core region 1 hosting an external neutron source, which is completely surrounded by a multiplicative blanket region 2. The coupling is not symmetric, that is, all the neutrons leaking from region 1 arrive in region 2, whereas only a fraction of those produced in the latter penetrates the former. Then, for regions 1 and 2, Eq. (3) boils down to:

$$\left(\frac{DB^2+\Sigma_a}{\overline{\upsilon}\Sigma_f} - 1\right)_1 F_1 - c\left(\frac{DB^2}{\overline{\upsilon}\Sigma_f}\right)_2 F_2 = S \tag{5}$$

$$-\left(\frac{DB^2}{\overline{\upsilon}\Sigma_f}\right)_1 F_1 + \left(\frac{DB^2+\Sigma_a}{\overline{\upsilon}\Sigma_f} - 1\right)_2 F_2 = 0 \tag{6}$$

Note that the coupling coefficient c should ensure that the whole system is subcritical. The total effective multiplication factor of the system, k, can be determined by multiplying the fission term by a factor $1/k$ (Zweifel, 1973), that is:

$$\left(\frac{DB^2+\Sigma_a}{\overline{\upsilon}\Sigma_f} - \frac{1}{k}\right)_1 F_1 - c\left(\frac{DB^2}{\overline{\upsilon}\Sigma_f}\right)_2 F_2 = 0 \tag{7}$$

$$-\left(\frac{DB^2}{\overline{\upsilon}\Sigma_f}\right)_1 F_1 + \left(\frac{DB^2+\Sigma_a}{\overline{\upsilon}\Sigma_f} - \frac{1}{k}\right)_2 F_2 = 0 \tag{8}$$

which has a non-trivial solution if the following condition is satisfied:

$$\left(\frac{DB^2+\Sigma_a}{\overline{\upsilon}\Sigma_f} - \frac{1}{k}\right)_1 \left(\frac{DB^2+\Sigma_a}{\overline{\upsilon}\Sigma_f} - \frac{1}{k}\right)_2 - c\left(\frac{DB^2}{\overline{\upsilon}\Sigma_f}\right)_1 \left(\frac{DB^2}{\overline{\upsilon}\Sigma_f}\right)_2 = 0 \tag{9}$$

Eqs. (5)–(9) are equivalent to the Barzilov et al. set, although the approximation of the leakage term given by Eq. (2) provides a more direct mean to introduce the geometry of the system in the analysis.

Using Eqs. (5, 6 and 9), and taking into account that the infinite multiplication factors of each region i are given by

$$k_{\infty i} = \frac{\bar{\nu}_i \Sigma_{fi}}{\Sigma_{ai}} \tag{10}$$

and that the no-leakage probability for region i is given by:

$$p_i = \left(\frac{D_i B_i^2}{\Sigma_{ai}} + 1 \right)^{-1} \tag{11}$$

then the total number of fission neutrons per neutron inserted by the source, from now on called the amplification factor M, can be written as:

$$M = \frac{F_1 + F_2}{S} = \left(\frac{1}{p_2 k_{\infty 2}} + \frac{1}{p_1 k_{\infty 1}} - \frac{1}{k_{\infty 1}} - 1 \right) \frac{1}{\Delta} \tag{12}$$

where:

$$\Delta = \left(\frac{1}{p_1 k_{\infty 1}} - 1 \right) \left(\frac{1}{p_2 k_{\infty 2}} - 1 \right) - c \frac{1}{k_{\infty 1}} \times \frac{1}{k_{\infty 2}} \left(\frac{1}{p_1} - 1 \right) \left(\frac{1}{p_2} - 1 \right) \tag{13}$$

and

$$c = \frac{\left(\frac{1}{p_1} - \frac{k_{\infty 1}}{k} \right) \left(\frac{1}{p_2} - \frac{k_{\infty 2}}{k} \right)}{\left(\frac{1}{p_1} - 1 \right) \left(\frac{1}{p_2} - 1 \right)} \tag{14}$$

3. Subcritical spherical cascade

In general the condition of perfect cascade, with null feedback from the blanket (region 2) to the central region (region 1), is difficult to achieve. Two methods were proposed in accelerator-driven systems (Nifenecker et al., 2003), namely, by means of selective absorbers and by special geometric arrangements. The first method is to produce a sort of neutronic greenhouse effect, consisting of a central fast-neutron multiplier with strong thermal-neutron absorption properties and a thermal blanket medium. The fast neutrons generated in medium 1 that reach medium 2 are then slowed down and multiplied, but the slow neutrons from medium 2 could not reach medium 1 without being immediately absorbed by the thermal absorber. In turn, the geometric method takes advantage of the dependence of the neutron leakage on the relative geometrical arrangement of the two regions. In the present study the latter method will be applied.

Let us consider a central sphere with radius r_1 surrounded by a spherical multiplicative shell with internal radius r_2 and external radius r_3 (Fig. 1). From any leakage point at the inner wall of the external shell, only those neutrons with directions contained in the cone tangent to the inner sphere with vertex in the leakage point reaches the core region 1 (Fig. 1). The solid angle defined by this cone is given by:

$$\Omega = 2\pi \left(1 - \frac{\sqrt{r_2^2 - r_1^2}}{r_2} \right) \tag{15}$$

Since the total solid angle of leakage is 2π, the coupling coefficient c results:

$$c = 1 - \sqrt{1 - \left(\frac{r_1}{r_2} \right)^2} \tag{16}$$

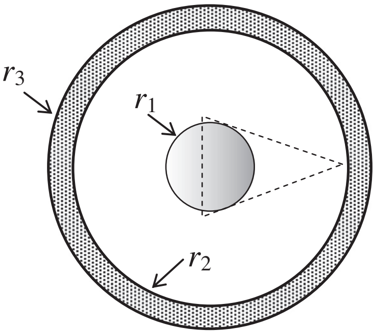

Fig. 1. Diagram of a spherical cascade consisting of a central multiplicative core surrounded by a spherical multiplicative shell.

The symmetry of the problem is useful to estimate the buckling parameter B_i of each region. For the inner sphere (Reuss, 2008):

$$B_1 = \frac{\pi}{r_1} \tag{17}$$

and for the spherical shell (Mattingly, 2002):

$$B_2 = \frac{\pi}{r_3 - r_2} \tag{18}$$

The no-leakage probabilities (Eq. (11)) can be written then as:

$$p_1 = \frac{1}{1 + R_1^{-2}} \tag{19}$$

$$p_2 = \frac{1}{1 + (R_3 - R_2)^{-2}} \tag{20}$$

where R_i is the radius r_i in units of the diffusion length times π, that is:

$$R_i = \frac{r_i}{\pi \sqrt{D/\Sigma_a}} \tag{21}$$

Actually, if moderation effects are involved, the migration length would be more appropriate to apply, to account for the slowing down of the neutrons (Stacey, 2001). Nevertheless, even if the material is the same, the diffusion or migration lengths can differ from one region to the other, since the energy spectrum can be different. Alternatively, a few energy-groups model could have being used from the start, but it would have obscured the simplicity of the analysis that is offered for the purpose of guidance in the search of optimum configurations using Monte Carlo calculations. For the sake of simplicity in the search for design patterns, all nuclear properties will be considered identical in both regions in what follows.

In order to draw a consistent path towards feasible designs of subcritical fission cascades driven by PF sources, let us consider a system with total effective multiplicative factor $k = 0.95$ and $k_\infty = 1.18$ in both regions as has been said in the last paragraph. This value of k_∞ corresponds to 8%-enriched metallic Uranium, calculated with the Monte Carlo code MCNP5 (Briesmeister, 2000). Using the geometric relations of the spherical configuration, the amplification factor M of the cascade can be estimated in terms of the radii R_i. Assuming then $k_\infty = 1.18$ and $k = 0.95$ the amplification factor is solely determined by only two geometrical dimensions. This is due to the fact that the value of the effective multiplication factor of the system, k, reduces in one degree of freedom the set of equations.

An interesting design problem is the variation of M keeping constant the total volume V of the multiplicative regions, which in units of diffusion length times π is given by:

$$V = \frac{4}{3}\pi \left(R_1^3 - R_2^3 + R_3^3 \right) \tag{22}$$

Fig. 2 shows the variation of the amplification factor with the radius of the inner sphere for three different volumes *V*. It can be seen that there is an optimum distribution of the material which corresponds to the competition between the multiplication power of each region and the geometrical back coupling. It should be stressed that in all cases the effective multiplication factor of the system is kept at $k = 0.95$ in order to ensure safe subcritical conditions.

4. Monte Carlo calculations

In order to corroborate the results of the analytical model, Monte Carlo calculations were performed using the MNCP5 code (Briesmeister, 2000). A system consisting of two spherical concentric regions of 8%-enriched Uranium was tuned to maintain the total effective multiplication factor $k = 0.95$. The inner core was modelled allowing a central void region to host a PF discharge chamber, which is simulated by a point neutron source of 14.1 MeV (see Fig. 3).

Fig. 4 shows the amplification factor obtained following the same procedure as Fig. 2, that is, keeping the total volume of Uranium constant and the effective multiplication factor $k = 0.95$. It can be seen that similar curves as the analytical approximation are obtained, with an optimum configuration for each volume. The reference length that makes the maxima of *M* of Figs. 2 and 4 correspond to each other can be estimated by assuming an effective solid dimensionless radius R_1 equal to the thickness of the inner sphere of Fig. 3, which gives $\pi\sqrt{D/\Sigma_a} \approx 14\,\mathrm{cm}$. Using this value, the dimensionless volumes plotted for the analytical approximation in Fig. 2 corresponds to the volumes of the Monte Carlo calculations shown in Fig. 4. It can be seen that the analytical approximation gives a conservative assessment of the amplification factor, which in this case is about 30% lower than the MCNP predictions. Nevertheless, it is worth noting that the general trend of increasing optima is reproduced.

The optimum geometrical configurations for given volumes of fissile material that gives the maximum amplification factor were also calculated using MCNP. Fig. 5 shows the combinations of optimum radii corresponding to each material volume, together with the corresponding amplification factor *M*.

5. Energy balance of a fusion–fission hybrid driven by Plasma-Focus sources

It is known that the optimum neutron yield of a PF operating with Deuterium is approximately given by $10^7\,\mathrm{kJ}^{-2}\,E_{PF}{}^2$, where E_{PF} is the stored energy in the capacitor (Bernard et al., 1998; Lee, 2009; Soto et al., 2010). For a mixture 50% Deuterium and 50% Tritium, given the larger cross section of the D-T fusion reaction, an increment in two orders of magnitude is expected (Mather, 1971). Thus, let us assume that the neutron source is a PF device of charging energy E_{PF}, operating with a gas mixture of Deuterium and Tritium. Under optimum conditions, the neutron yield of per pulse is given by:

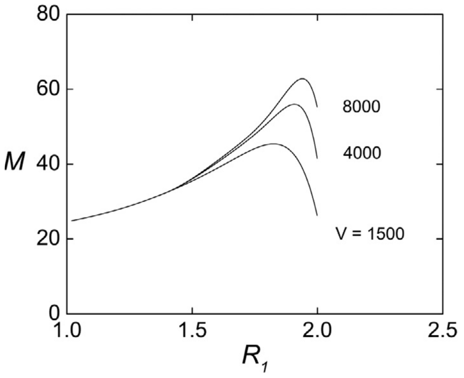

Fig. 2. Amplification factor of the spherical cascade for different volumes of 8%-enriched Uranium ($k_\infty = 1.18$) calculated with the analytical approximation given by Eqs. (12)–(14). All dimensions are given in units of the diffusion length times π. The effective multiplication factor of the whole system is in all cases $k = 0.95$.

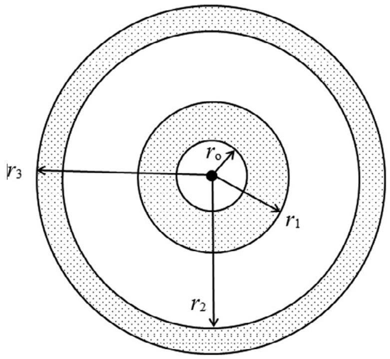

Fig. 3. Diagram of the configuration of the spherical cascade used in the Monte Carlo calculations.

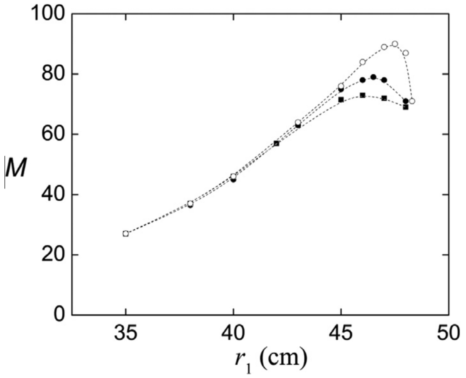

Fig. 4. Monte Carlo calculations of the amplification factor of the spherical cascade for different volumes of 8%-enriched Uranium: 4.2 m^3 (■), 11.3 m^3 (●) and 22.6 m^3 (○). The effective multiplication factor of the whole system is in all cases $k = 0.95$ and the radius of the central void region for the location of the Plasma-Focus source is $r_o = 20$ cm.

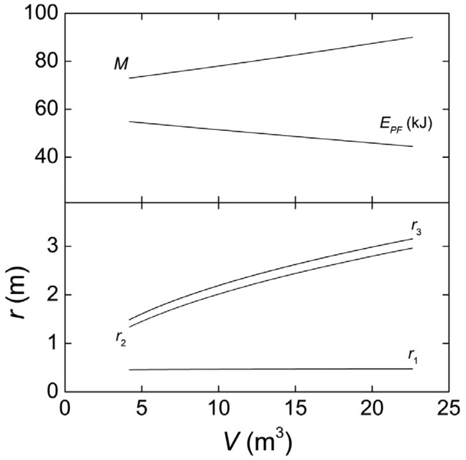

Fig. 5. Optimum amplification factor, PF break-even energy, and geometrical parameters of the spherical cascade as functions of the volume of 8%-enriched Uranium, calculated with MCNP5.

$$Y(E_{PF}) \cong 10^9\ \mathrm{kJ}^{-2}\ E_{PF}^2 \tag{23}$$

The number of fissions produced by Y is then $(M/\bar{\upsilon})Y(E_{PF})$. Considering that the fissile fuel is U^{235} (193 MeV $\cong$ 3 10^{-14} kJ per fission, $\bar{\upsilon} \cong 2.43$), the fission energy produced in each shot is:

$$E_f \cong 1.23\ 10^{-5}\ \mathrm{kJ}^{-1}\ E_{PF}^2 M \tag{24}$$

Now, only a small part of the energy of the capacitor bank is consumed in the pinch to produce the thermal conditions for fusion reactions. A reasonable figure of this fraction is about 5% (González et al., 2009). In that case, the fusion–fission break-even condition satisfies:

$$0.05\ E_{PF} \cong 1.23\ 10^{-5}\ \mathrm{kJ}^{-1}\ E_{PF}^2 M \tag{25}$$

Therefore, the *PF* energy required for hybrid break-even is given by:

$$E_{PF} \cong \frac{4000\ \mathrm{kJ}}{M} \tag{26}$$

Fig. 5 shows that the energy of the Plasma Focus required for break-even in the optimum spherical configurations for the range of volumes considered in the MCNP calculations is about 50 kJ, which is within the range provided by the current technology. Moreover, the reactor external radius is about 2 m, which is also a feasible figure.

6. Conclusions

The feasibility of a hybrid fusion–fission system consisting of a two-stage spherical subcritical cascade driven by a Dense Plasma Focus was studied. An analytical model based on the one-group neutron diffusion equation was developed to estimate the amplification achieved per source's neutron knowing the neutronic parameters of each region. The conditions for energy break-even for this hybrid concept were assessed. It was found that in principle the concept is feasible given the current Plasma-Focus technology. The results were corroborated by means of Monte Carlo calculations and a design chart was produced for assessing the optimum configuration of the spherical cascade to achieve different levels of neutron amplification.

The present novel analysis of PF-driven two-region reactors is valuable regarding that the technology of PF neutron sources, in spite of its limited neutron yield, is currently more advanced than their counterparts based in inertial fusion. The remaining challenge is to increase the discharge rate of PF devices of tens of kJ in order to achieve reasonable power outputs.

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