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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.

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:

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

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:

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