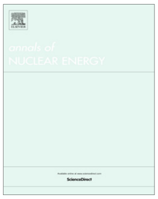
Annals of Nuclear Energy 105 (2017) 106–115

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene



Conceptual design of a hybrid fusion-fission reactor with intrinsic safety and optimized energy productivity

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ARTICLE INFO

Article history:
Received 20 August 2016
Received in revised form 16 February 2017
Accepted 25 February 2017

Keywords:
Hybrid fusion-fission
Dual blankets
Dense Plasma Focus
Subcritical
Safe reactor
Optimizing of energy productivity

ABSTRACT

A hybrid fission-fusion reactor with a Dense Plasma Focus (DPF) as a fusion core and the dual layer fissionable blanket as the energy multiplier were conceptually designed. A cylindrical DPF, energized by a 200 kJ bank energy, is considered to produce fusion neutron, and these neutrons drive the subcritical fission in the surrounding blankets. The emphasis has been placed on the safety and energy production with considering technical and economical limitations. Therefore, the $k_{eff\text{-}t}$ of the dual cylindrical blanket was defined and mathematically, specified. By applying the safety criterion ($k_{eff\text{-}t} \leq 0.95$), the geometrical and material parameters of the blanket optimizing the energy amplification were obtained. Finally, MCNPX code has been used to determine the detailed dimensions of the blankets and fuel rods.

1. Introduction

For the time being, the produced greenhouse gasses by fossil fuels, are becoming a global crisis. Hence the nuclear energy, which produces an average of 15 times less greenhouse gas (Lenzen, 2008; Beerten et al., 2009), is one of the most important energy sources. However, some hazard shortly may change this role, if not to be resolved. Safety, uranium resource constraints and radioactive wastes of fission reactors – which is the only economic method of nuclear energy production – are the main challenges. The fast breeder, the thorium-based fuel, the small nuclear power and the fusion reactors are some of the efforts to overcome these challenges.

The hybrid reactor concept introduced at the beginning of nuclear technology (Company CR and D, 1953; Imhoff et al., 1954) is one of the candidates to improve the exploitation of nuclear energy. The main idea of the hybrid concept, simply, is to use of fusion neutrons to activate a subcritical fission chain. In fact, a fusion facility which produces a steady state or pulse type neutrons is coated by a subcritical fissionable blanket. Such a combination can potentially be used to exploit fission energy in the safe conditions (Kotschenreuther et al., 2012; Leonard, 1973; Powell and Hahn, 1973; Wolkenhauer, 1974), breed fissionable fuel (Kulikov et al., 2016; Feng et al., 2016; Harms and Gordon, 1976; Stewart and Stacey, 2014; Manheimer, 1999, 2014; Hoffert, 2002) and dispose of radioactive wastes (Salvatores et al., 1998; Berwald and Duderstadt, 1979; Jiang et al., 2014; Siddique and Kim, 2014; Stacey, 2016; Velasquez et al., 2016). Up to 1975, studies were reviewed in Ref. Lidsky (1975), and an overview of some recent researches can be found in the Ref. Piera et al. (2010).

Generally speaking, at present, there are mainly two methods to achieve nuclear fusion reactions: Inertial Confinement Fusion (ICF) (Campbell, 1998; Paisner et al., 1994) and Magnetic Confinement Fusion (MCF) (Bertolini, 1993; Aymar, 0000). The realistic conditions such as temperature and pressure required to ignite nuclear fusion reactor are technically complex and economically expensive. An alternative method is pulsed power confinement fusion. Dense Plasma Focus (DPF) machine for high yield fusion; offer the potential for a cost-effective and efficient nuclear fusion reactor. The DPF thermonuclear driver with excellent plasma energy deposition and almost self-preheated plasma makes it attractive for a practical hybrid fusion-fission nuclear reactor design.

On the other hand, the neutron multiplication factor of blanket (k_{eff}) should be limited to 0.95 to achieve an inherent safe fission environment (Bertolini, 1993). Obviously, this condition restricts the production of neutron up to $20Y_{fus}$ in each pulse which Y_{fus} is the DPF yield. An interesting suggestion for increasing neutron production without passing the safety condition is to use of dual fissionable blankets in a way that the neutrons produced in the

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http://dx.doi.org/10.1016/j.anucene.2017.02.029
0306-4549/

inner layer can penetrate into the outer while those produced in the outer blanket cannot reach the inner one (Avery, 1958; Abalin, 1995; Daniel and Petrov, 1996). In this model, one fusion neutron will multiply in the first blanket, then the newly generated neutrons, multiply again in the second blanket.

This concept was used for a cylindrical geometry, although the symmetry of spherical form could give the best efficiency for using the fusion source neutrons (Daniel and Petrov, 1996) and very simpler calculations are needed to investigate it (Clausse et al., 2015), but in this work, a cylindrical geometry was chosen for its practical performance. In fact, fuel rode production for a cylindrical blanket is much easier than the spherical and refueling is too. Also, according to the DPF geometry, the cylindrical blanket is a more suitable choice.

The cylindrical configuration for a coupled twin blanket system has been analyzed by Barzilov et al. (1996) but by developing the amplification equations, a maximized and economized design were introduced here.

2. Fusion source designing

A DPF is a discharge machine which consists of two coaxial electrodes. It is opened at one end and closed with an insulator at the other end (Fig. 1). Excitation of bank energy creates hot, and dense short-lived magnetized plasma which is so called "pinch." The pinch itself goes through magnetic compression (thermonuclear phase) and the expansion (non-thermonuclear phase) process. If the filling gas is deuterium, both phases are involved in the neutrons production and electromagnetic radiations. The energetic beam of charged particles such as ions and electron are also produced in the DPF which is characteristic of non-thermonuclear or the beam target phase (Talaei et al., 2009; Nardi et al., 1988; Mather, 1965; Castillo-Mejía et al., 2001).

A DPF machine works in a pulse mode manner in which the frequency of operation depends on the system capacitor bank energy. However, in low and medium energies conditions, the relationship between stored energy and the outcome of PF can be characterized by $N_i \propto W^2, Y_p \propto W^2, Y_t \propto W^2$, where N_i is the deuterium ions, W is the stored bank energy, Y_p is the nuclear reaction yield, Y_t is the reaction yield on the external targets (Angeli et al., 2005; Brzosko et al., 2001).

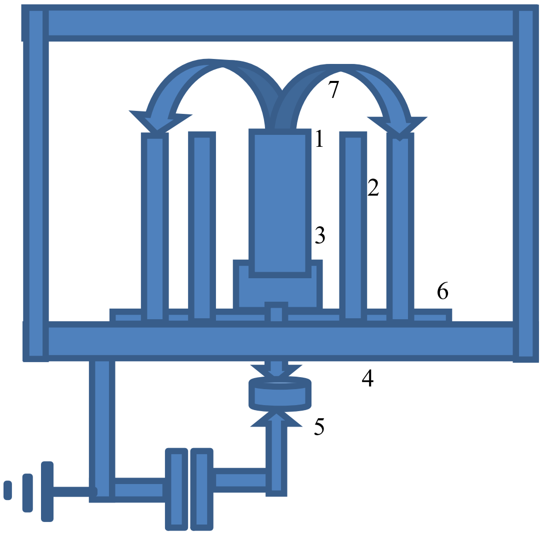

Fig. 1. (1) Anode electrode, (2) cathode electrodes, (3) the insulator, (4) spark gap, (5) capacitor bank, (6) vacuum chamber, and (7) plasma sheath.

A typical Mather type DPF Conceptual design has been discussed in Ref. Sadat Kiai et al. (2010). The first step in designing a DPF machine is to choose the capacitor bank energy and then calculate others parameters. When the PF machine is operating, it produces a plasma layer which is compressed by Lorentz magnetic force to build up a pinch at the middle of central electrode (the anode). At this point, two currents are built up; the ion motion away from the top of the anode and the electron motion in the opposite direction. The time varying of plasma inductance is given by the following

$$\left(\frac{dL_p}{dt}\right) = \frac{\mu_0}{2\pi}\left[\ln\left(\frac{b}{r_p}\right)V_a + \left(\frac{Z}{r_p}\right)V_r\right] \tag{1}$$

Here, b is the cathode radius, r_p is the pinch plasma radius, V_a is the axial plasma speed, Z is the pinch length, and V_r is the radial speed of the current sheath (Talaei et al., 2010). As we are interested in the numbers of ions produced in the pinch region, for this acquirement, first a diode model similar to the current density formula of Langmuir is used (Sadat Kiai et al., 2010) if we put Ø as an induced voltage into plasma column, $\varnothing = I_{max}(dL_p/dt)$ and

$$J_i = 1.86 \times \left(\frac{4}{9}\right)\varepsilon_0\sqrt{\frac{2\times e}{m_i}} \times \frac{\varnothing^{\frac{3}{2}}}{w^2} \tag{2}$$

where $I_{max} \approx V_0/\sqrt{L_0/C_0}\left(f^{\frac{\beta}{\pi}}\right)$, L_0 is the inductance of the external circuit, C_0 is the capacitor bank, f is a damping factor, β is an arctangent of an angle (Salvatores et al., 1998) ε_0 is the permittivity of free space, e is the electric charge, m_i is the mass of deuterium, and w is the width of the low conductivity plasma diode layer. The number of ejected and accelerated deuteron ions can be written as:

$$N_i = \pi\frac{r_p^2}{e}J_i\tau_p \tag{3}$$

where τ_p is the pinch life time.

The neutron yield is produced from the thermonuclear reactions during a cylindrical pinched plasma time, as the Lorentz force competes with the kinetic pressure from the gas and density. When temperature is sufficiently high, one can write;

$$Y_{th} = \frac{n_p^2}{2} < \sigma v >_{10keV} \pi r_p^2 d\tau \tag{4}$$

where n_p is the deuterons density in m^{-3}, $<\sigma v>_{10keV}$ the thermal collision rate in m^3/s, r_p the pinch radius, d is the pinch length, and τ the pinch life time. For a given plasma temperature, the thermal neutron yield for the DT fusion reactions is 100 times more than the DD reactions.

It should be noted that in PF devices, the output emissions have been assumed to come from several regions of micro size, hot and dense, inside the pinch column of a Plasma-Focus (PF) discharge. These miniature regions called "hotspots", and are separated in space and time (Fig. 2). The mentioned high temperature in Eq. (4) happens in these regions.

Hotspots were first observed by Cohen, et al. in the decade of 1960 (Cohen et al., 1968) but the mechanism of their formation has not been well understood today. Cohi, et al. proposed that the interaction between the electron beam and small, cold and dense plasma leads to formation hotspots (Choi et al., 1986). Later, it was suggested by Hirano, et al. that the hotspots far from the electrode face are generated by the interaction between the ion beam and the turbulent plasma, and electron beam interaction is the cause of nearer ones formation (Hirano et al., 1994).

However, the formation mechanism of hotspots is complex and there is no clear explanation for it but, the observations have shown that the size of them is about 10^{-4}–10^{-1} cm, their lifetime are about 1–50 ns and electron temperature in that regions could