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Research Article

Neutron yield and ion production with respect to cathode radius in spherical plasma focus

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Abstract: The effect of the cathode radius variation (from 11.5 cm to 17 cm) on neutron yield, discharge current, plasma temperature, and ion properties (velocity, energy, and density) are investigated in this study using the developed spherical plasma focus model and the results are reported in this paper. Peak discharge current and peak beam-ion properties decrease with increasing the cathode radius. Maximum plasma temperature (22.34 eV) and maximum beam-target neutron yield (1.18×10^{13}) are achieved using the cathode with 15 cm radius. The longest pinch duration for all calculations is also achieved using 15 cm cathode radius. It is found that the optimum cathode radius is 15 cm in terms of the neutron yield, plasma temperature and beam-ion properties in spherical plasma focus device.

Keywords: *Beam-ion, Cathode, Neutron yield, Plasma focus*

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1. INTRODUCTION

Plasma focus (PF) as pulsed devices are used to produce the pinch, which is hot and dense plasma. Pinch is produced between electrodes by gas discharge. Electron and ion beams can also be accelerated to high energies by plasma focus devices to produce neutrons, ions, and x-rays using deuterium (D), tritium (T), or a mixture of D-T gases.

The optimum length and shape of the plasma focus electrodes are investigated to see their effects on the plasma dynamics so that the optimized plasma focus devices can be built in terms of the electrode length and radius in addition to the optimum electrode shapes to produce higher neutrons, x-rays, or ions efficiently [1-6]. While Hill and Hubs [1] decreased waist diameter of the cathode to improve neutron yield, Wong et al. [2] used tapered anode for x-ray investigation. Borthakur et al. [3] studied the effect of the electrode's diameters and separation on detection efficiency of vacuum photodiodes in plasma focus device. Two different cathodes were designed and tested [4] for x-ray yield and it is found that cathode design and electrode separation have considerable effect on the x-ray yield. Hayati et al. [5] used a different approach in that they used artificial neural network to optimize anode shape for higher x-ray yield.

Thermonuclear and beam-target neutron production mechanisms are the two widely accepted ways to produce neutrons in plasma focus devices. While interaction of the thermal deuterons under maximum compression produces thermal neutrons (thermonuclear neutron production), beam-target neutrons are produced through fusion reactions with the accelerated ion beams that interact with thermal deuterons under diode voltage. Neutron yield and energy of neutrons are anisotropic which leads to the dominant beam-target neutron production compared to thermonuclear neutron production in plasma focus devices, which is also the case in this study with spherical plasma focus device [6-8].

Tubular and squirrel cage cathodes are mostly used cathode designs in plasma focus devices. Both of these designs have their advantages and disadvantages. Smaller plasma focus devices can be build using tubular cathode but plasma focus with tubular cathode produces less pinch current compared to squirrel cage design. Impurities is also increased if tubular cathode is used in PF devices. Increased impurities cause radiation loss which is also the reason of less neutron production in tubular cathodes compared to squirrel cage cathodes. Changing cathode design from tubular to squirrel cage results in better neutron production. Squirrel cage cathode compose of a number of rods which is one of important design parameters to optimize plasma focus such that when the number of rods in squirrel cage cathode are decreased, the impurities and instabilities are increased because of the runaway electrons in addition to slower movement of Current Sheath (CS). In addition to type of cathode designs, the radius of the cathode also influences the CS dynamics and instabilities such that large energy densities and intense radiations result from a cathode with a small radius, and slower plasma movement is due to a cathode with a large radius [9,10].

A miniature plasma focus device is used with two different cathode designs, which are tubular and squirrel cage cathodes, to investigate the neutron yield. While tubular cathode produced 1.82×10^5 neutrons per shot at 4 mbar, squirrel cage cathode produced 1.15×10^6 neutrons per shot at 6 mbar. It can be seen that it is possible to increase neutron yield by using squirrel cage cathode in plasma focus devices [11].

In addition to the cathode design, anode length is also an important parameter for neutron yield. Increasing anode length increases neutron yield until some optimum anode length. Beyond this optimum point, increasing anode length results in decreasing neutron yield. When anode length is too short, the current sheath will not reach sufficient velocity for good focus action. Similarly, when anode length is too large, the current sheath become unstable for focusing. Therefore, departure from optimum anode length leads to a decrease in neutron yield due to poor focusing [12].

In the previous works, a model for spherical plasma focus (SPF) is developed and validated [13,14], spherical plasma focus device is optimized for neutron yield [15] and the effect of spherical cathode radius on plasma dynamics is studied [16]. Now this cathode variation effect is investigated for neutron yield and ion properties in this study.

The main objective here is to investigate the cathode radius effect (ranging from 11.5 cm to 17 cm with 0.5 cm increment) on neutron yield, plasma temperature, discharge current, and beam-ion properties (velocity, energy and density) in SPF device using developed SPF model [13,14].

2. SPHERICAL PLASMA FOCUS MODEL

Since the developed model and model validation are given in detail in previous works [13, 14], a brief description of model is mentioned in this paper.

Modeled spherical plasma focus device has two concentric electrodes. The developed model uses shock wave equations and snow plow model and couple them with equivalent circuit model to describe SPF device [13, 14]. The model has 4 phases which are rundown phase I, rundown phase II, reflected shock phase, and radiative phase.

Gas discharge between electrodes creates the current sheath between electrodes which is the beginning of rundown phase I. This phase ends and the second phase (rundown phase II) starts when CS reaches equator point of device. Then shock front hits axis of device which starts reflected shock phase. Then shock front reflects towards CS. This phase then ends and the last phase (radiative phase) begins when reflected shock front reaches the coming CS. Compression of plasma column in this phase continues until the maximum compression. At this point in the SPF, plasma disruption occurs and ends radiative phase.

Figure 1 shows configuration and equivalent circuit model for the SPF. In the circuit model, V_0 is charging voltage, C_0 represents the capacitor bank. L_0 and r_0 represent circuit inductance and resistance. L_p and r_p represent the plasma inductance and resistance.

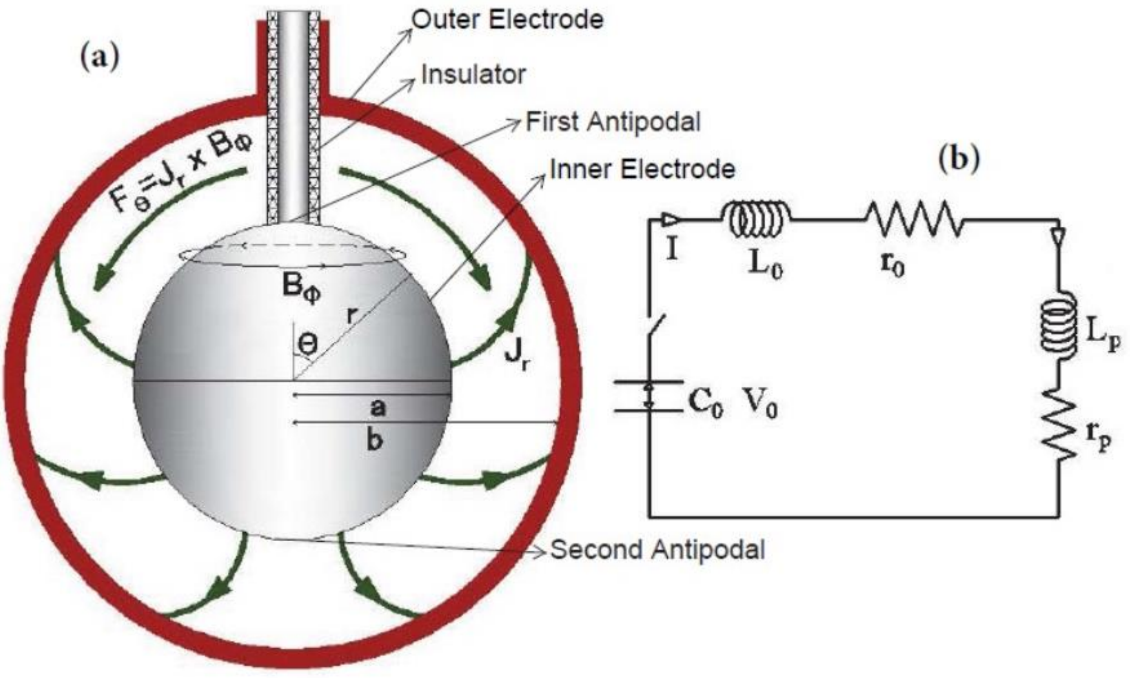

Figure 1. (a) Spherical plasma focus device configuration (b) Equivalent circuit model of SPF

2.1 Governing Equations

Derivation of the model equations is explained and given in the previous works [13, 14]. Therefore, only the final equations with brief explanations are given here.

The magnetic pressure on the CS results in a change in the momentum of the CS. Therefore, this momentum change is set equal to the magnetic pressure to form a balance equation which is then solved for $\ddot{\theta}$ that is the equation of motion for the CS. This equation of motion is calculated for all phases as follows [13,14]:

Equation of motion for rundown phase I:

$$\ddot{\theta} = \frac{\alpha^2 I^2}{r sin\theta \, (cos\theta_0 - cos\theta)} - \frac{\dot{\theta}^2 sin\theta}{cos\theta_0 - cos\theta} \tag{1}$$

Equation of motion for rundown phase II and reflected phase:

$$\ddot{\theta} = \frac{\alpha^2 I^2}{r cos(\theta - \pi/2)(cos\theta_0 - cos\theta)} - \frac{\dot{\theta}^2 sin\theta}{cos\theta_0 - cos\theta} \tag{2}$$

where $\alpha = \frac{3\mu_0 f_c^2 \ln\left(\frac{b}{a}\right)}{8\pi^2 \rho f_m (b^3 - a^3)}$ is a scaling parameters that consist of constant values. I is discharge current, r is the distance for plasma parameter calculations, θ is angle of the motion, θ_0 is an angle corresponding to the insulator volume, μ_0 is permeability of free space, f_c and f_m are current and mass fraction, a is inner and b is outer electrode radius, ρ represents initial gas density.

For the last phase (radiative phase), radiation terms are taken into account and there is a third force on the CS due to radiation emissions. In this phase, the momentum change of the current sheath is because of the magnetic pressure on the current sheath and radiation emission, which leads to the following equation as the equation of the motion for radiative phase:

$$\ddot{\theta} = \frac{\alpha^2 I^2}{r cos(\theta - \pi/2)} - \frac{sin\theta \, \dot{\theta}^2}{C} - \frac{3QA}{2\pi \rho f_m (b^3 - a^3) r C} \tag{3}$$

where $C = cos\theta_0 - cos\theta$ and A is plasma column surface area.

Equation for neutron yield:

$$Y = N_b N_i V_{col} \sigma v_b \tag{4}$$

where N_b and N_i are beam-ion number density and plasma-ion number density, V_{col} is the pinch volume, σ is cross section for DT reaction, v_b is beam-ion velocity.

Plasma-ion number density:

$$N_i = N_0 f_m \frac{2}{1 + cos\theta} \tag{5}$$

Beam-ion number density:

$$N_b = \frac{f_i L \, I^2 f_c^2}{2eUV_{col}} \tag{6}$$

Where f_i represents how much pinch inductive energy is converted into beam kinetic energy, N_0 is ambient gas number density, *e* is the elementary charge, and *U* is diode voltage, *L* is plasma inductance.

3. RESULTS AND DISCUSSION

In this work, a spherical plasma focus with 432 µF capacitor bank energy is simulated using 25 kV charging voltage, 14.3 Torr D-T gas pressure (equal amount of D-T mixture) and 36 nH external inductance. The inner electrode (anode) radius of the SPF device is 8 cm. The outer electrode (cathode) radius is changed from 11.5 to 17 cm using 0.5 cm increment so that its effect on neutron yield and ions can be investigated. The lines in the figures below are also plotted with the same order.

While figure 2 [16] shows the discharge currents for the selected cathode radii, figure 3 shows the maximum (peak) currents and dip discharge currents with respect to cathode radius variation. In figure 2, only 4 cathode radii are plotted so that the lines can be seen clearly but the change of the discharge currents with respect to cathode radius can be seen clearly both in figure 2 and figure 3. Discharge current for 11.5 cm cathode radius reaches the maximum value of 1508 kA. Increasing cathode radius results in decreasing both peak currents and dip currents in spherical plasma focus device.

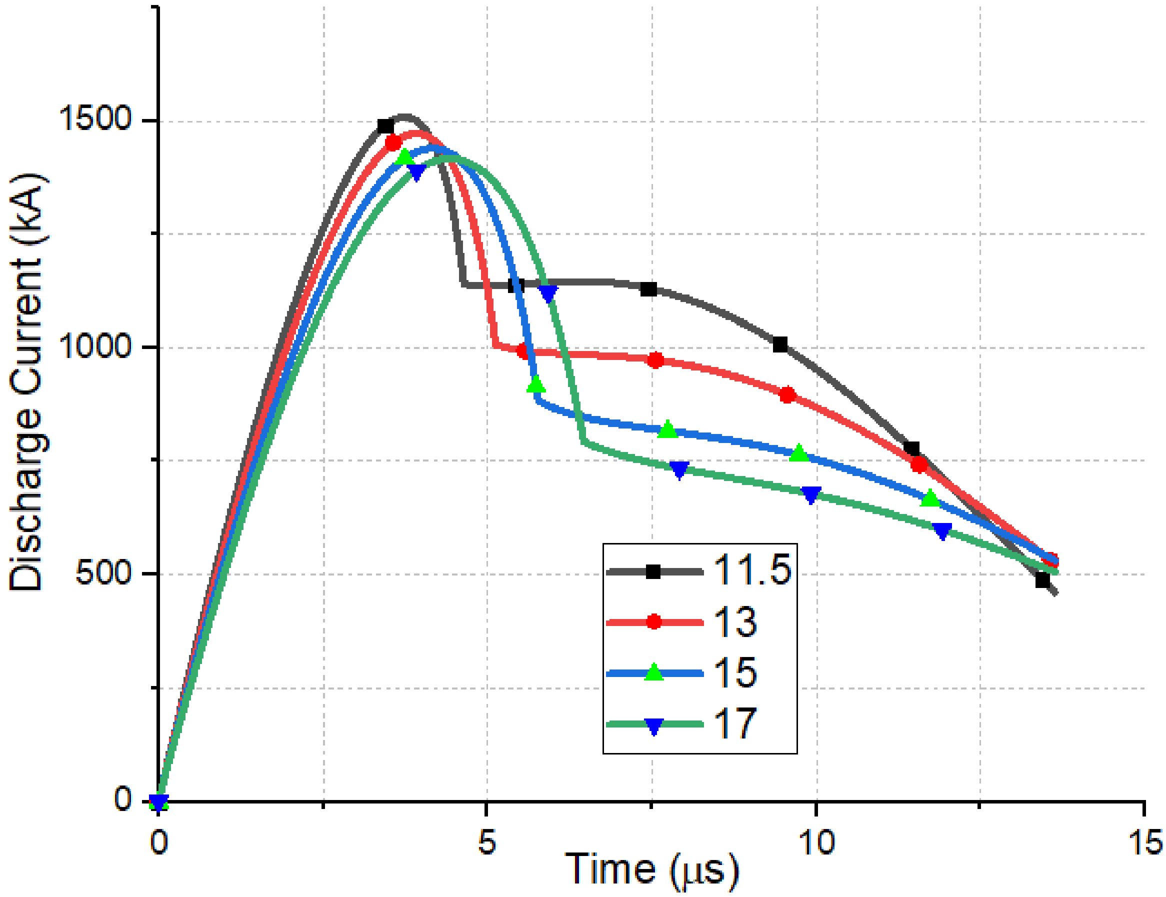

Figure 2. Discharge currents for different cathode radii [16]

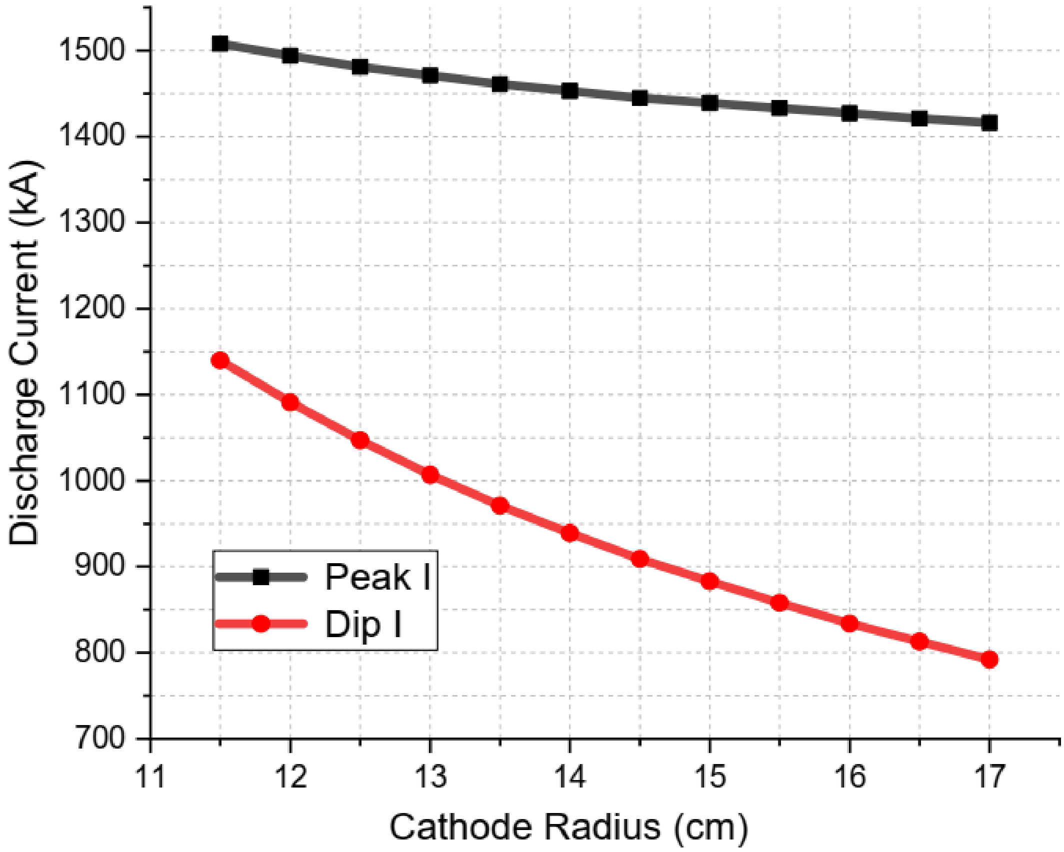

Figure 3. Peak and dip discharge currents with respect to cathode radius in the spherical plasma focus device

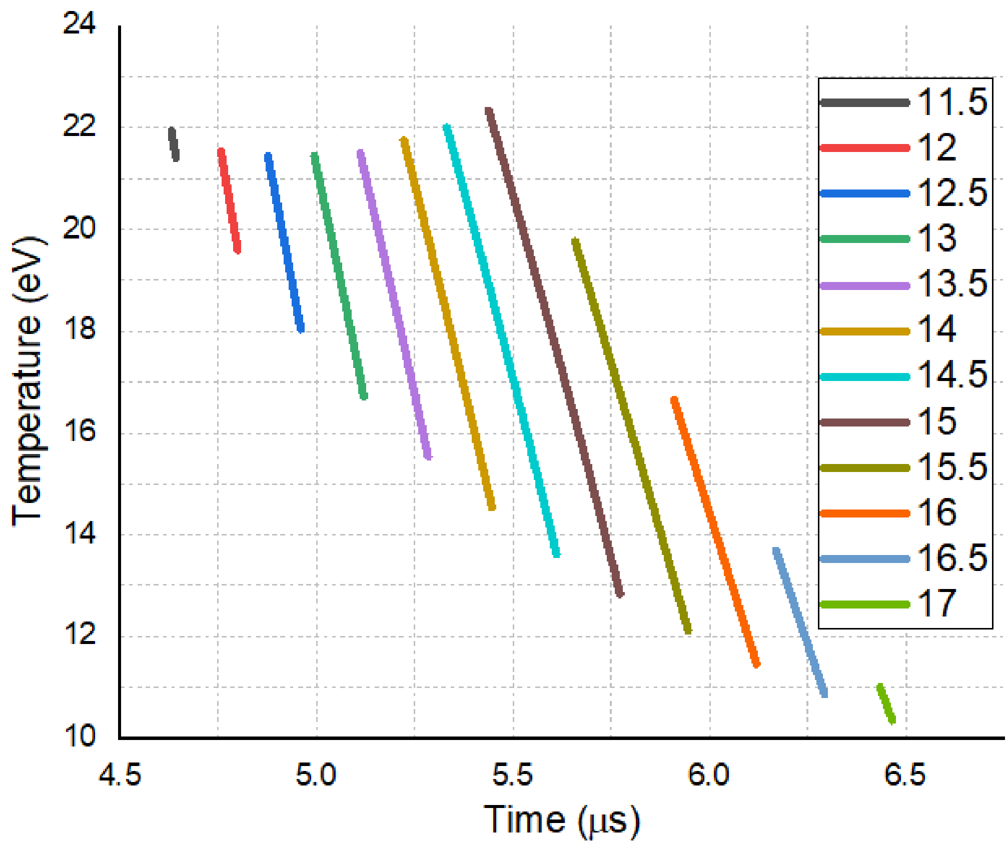

Figure 4. Plasma temperature for various cathode radii

The cathode variation has different effect on plasma temperature which can be seen in figure 4. Increasing cathode radius from 11.5 cm to 13 cm decreases the peak plasma temperature but then peak plasma temperature starts to increase with increasing the cathode radius from 13 cm to 15 cm. Plasma temperature reaches the peak value of 22.34 eV using a cathode with 15 cm radius. Increasing the cathode radius beyond 15 cm causes plasma temperature to drop suddenly. Therefore, it can be deduced that 15 cm cathode radius is optimum cathode radius in terms of temperature.

Figure 5 and figure 6 show beam-ion velocity and corresponding beam-ion energy. Beam-ions are accelerated under diode voltage. Since increasing the cathode radius decreases the discharge current which results in a decrease in diode voltage, increasing the cathode radius decreases the beam-ion velocity and beam-ion energy.

Even though maximum beam-ion velocity (226.95 cm/μs) and beam-ion energy (53.79 keV) are obtained using cathode with 11.5 cm radius, a cathode with 15 cm radius has longer pinch duration which makes 15 cm cathode radius the optimum cathode in terms of the beam-ion velocity and beam-ion energy. Increasing cathode radius beyond 15 cm results in short pinch duration with lower beam-ion velocity and energy. Maximum beam-ion velocity and beam-ion energy for the cathode with 15 cm radius are 207.39 cm/μs and 44.92 keV.

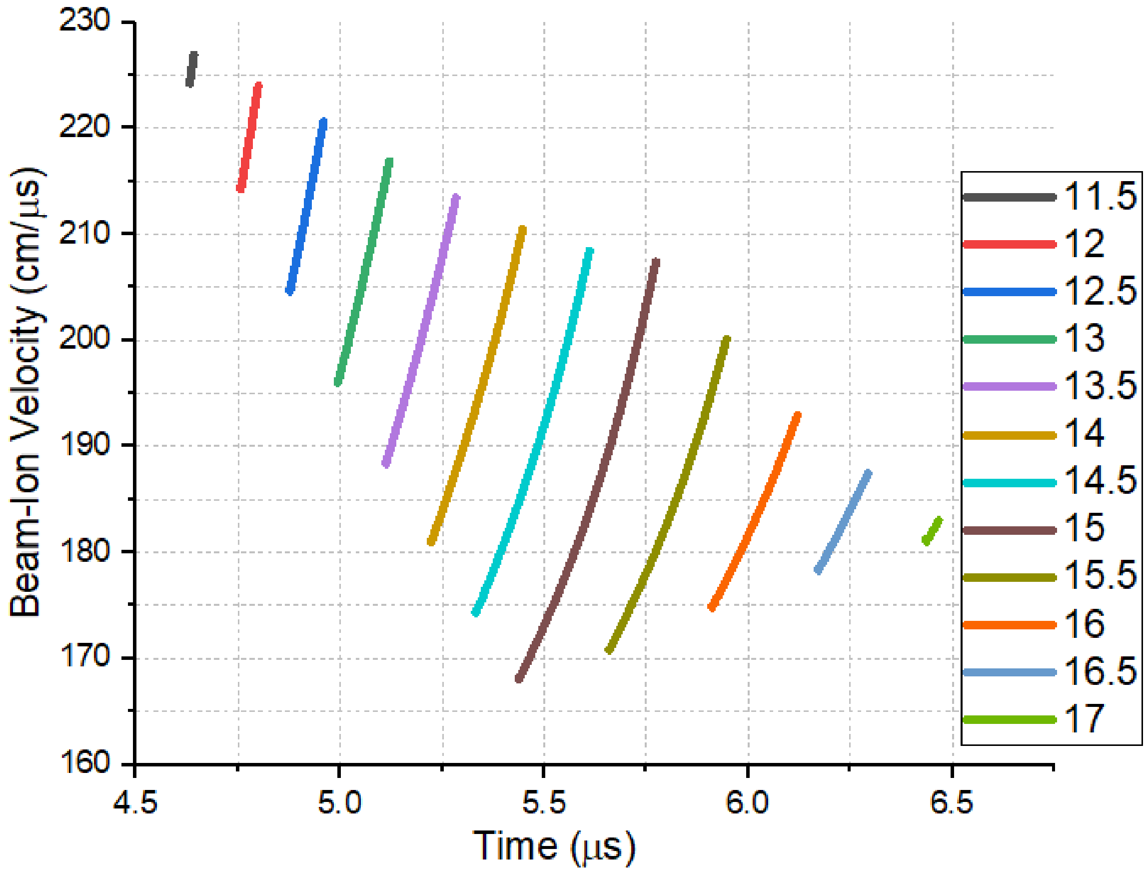

Figure 5. Beam-ion velocity for various cathode radii

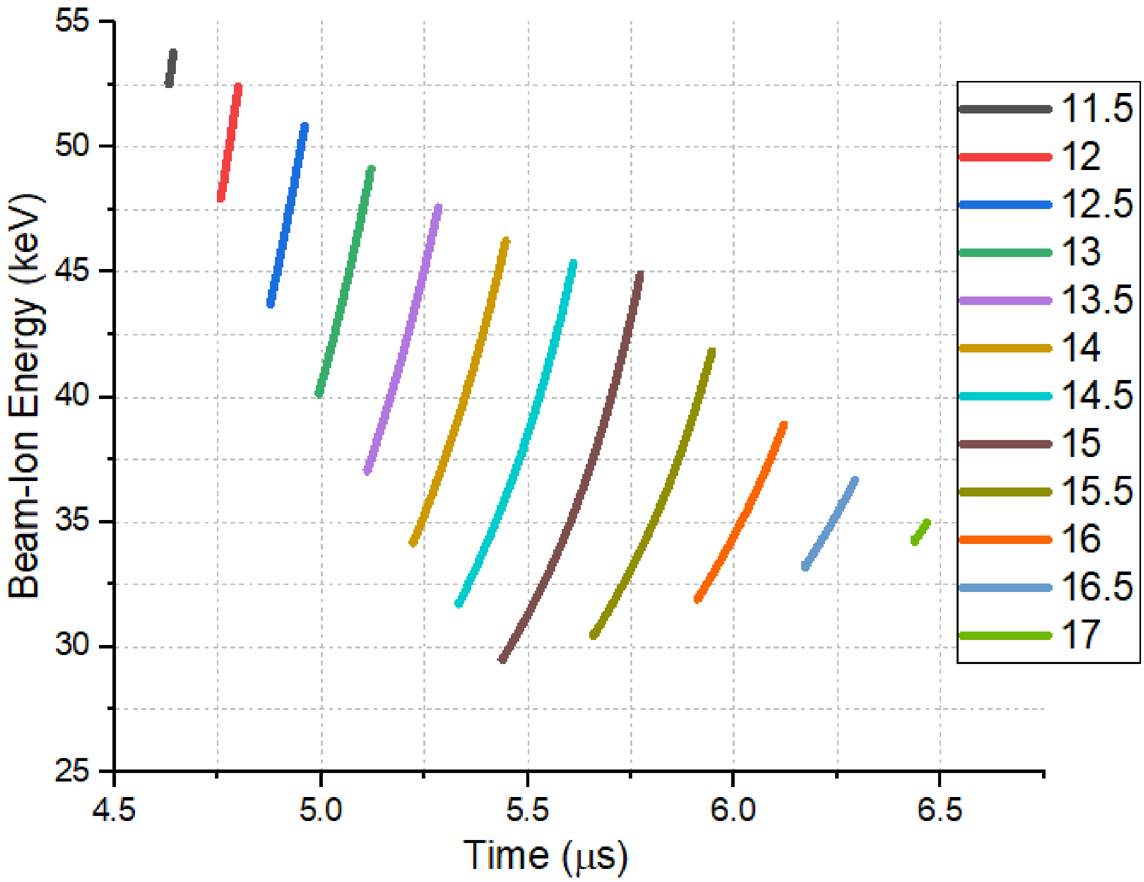

Figure 6. Beam-ion energy for various cathode radii

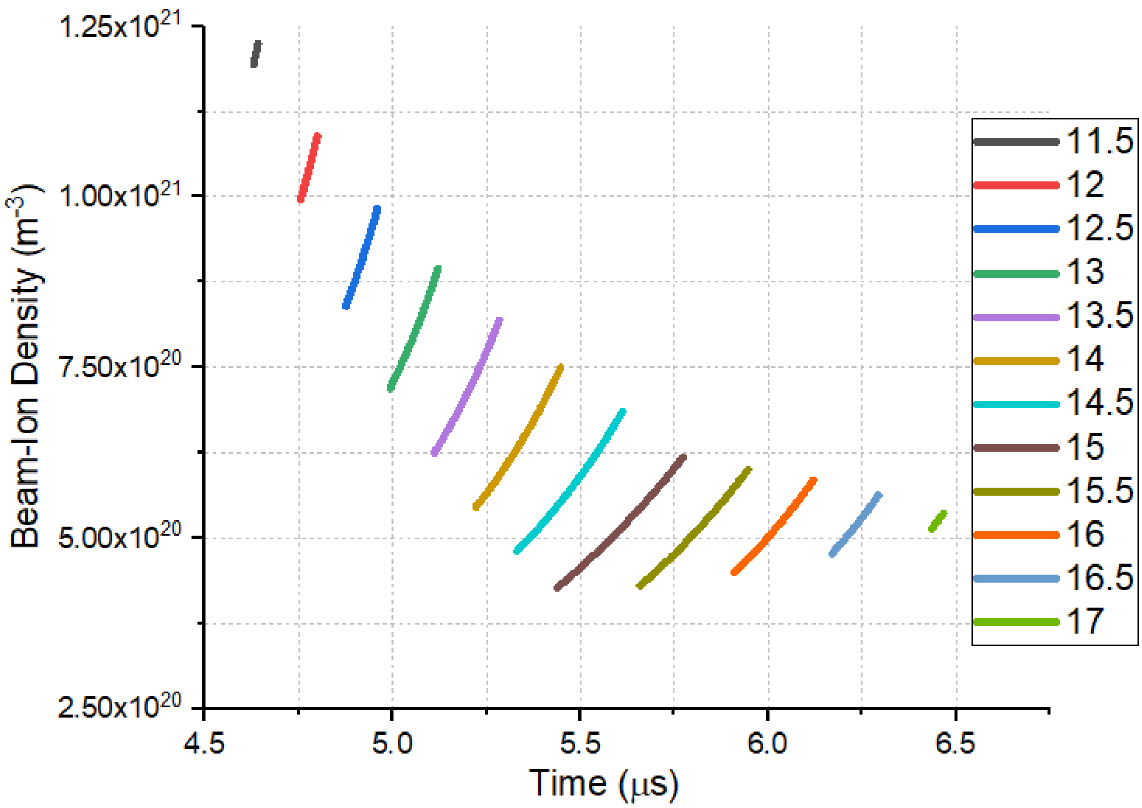

Figure 7. Beam-ion density for various cathode radii

The effect of cathode radius variation on beam-ion density (figure 7) is similar to beam-ion velocity and beam-ion energy. Beam-ion density reaches the maximum of 1.23×10^{21} m^{-3} using 11.5 cm cathode radius. Beam-ion density decreases with increasing cathode radius. Rate of beam-ion density decrease starts to slow down after 15 cm cathode radius and pinch duration is the longest using the cathode with 15 cm radius. The maximum beam-ion density for 15 cm cathode radius is 6.19×10^{20} m^{-3}.

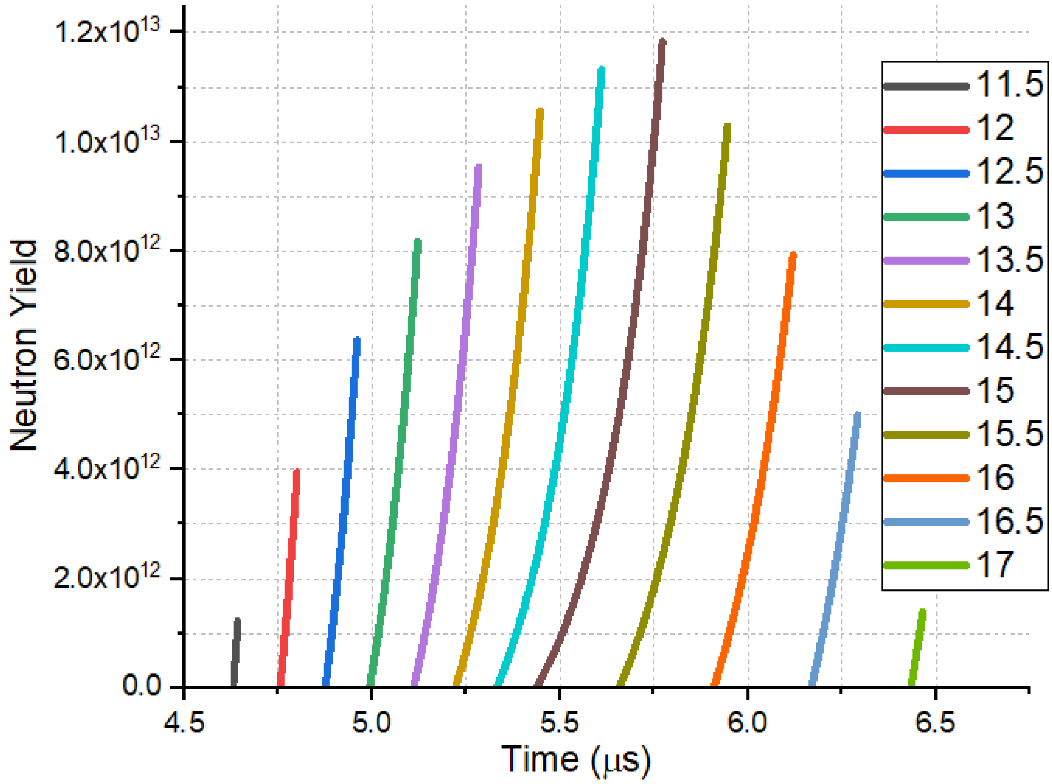

Figure 8. Beam-target neutron yield for various cathode radii

Figure 8 shows the beam-target neutron yield in SPF device. Increasing cathode radius starts to increase neutron yield until the cathode with 15 cm radius. Increasing the cathode radius beyond 15 cm results in decreasing the neutron yield. It can be concluded that 15 cm cathode radius is the optimum cathode radius in terms of beam-target neutron production. Beam-target neutron yield reaches maximum value of 1.18×10^{13} neutrons for 15 cm cathode radius. It also has longest pinch duration.

5. CONCLUSION

A spherical plasma focus device is simulated in this work with different cathode radii ranging from 11.5 cm to 17 cm. It is found that increasing the cathode radius decreases the discharge current, beam-ion velocity, beam-ion energy and beam-ion density but maximum plasma temperature and beam-target neutron yield is obtained using the cathode with 15 cm radius. The longest pinch duration is also obtained with 15 cm cathode radius for all calculations. In this study, neutron yield of 1.18×10^{13} and plasma temperature of 22.34 eV are calculated with 15 cm cathode radius. Considering all these calculations, it can be concluded that the cathode with 15 cm radius is the optimum value for SPF under given conditions.

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