Theoretical Study of Pinching Effect in the Theta Pinch Plasma by Variation in Kinetic Pressure

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Abstract

In this paper we have used the snow plow model of plasma pinching has been used for the study of pinching effect in the theta pinch plasma. One of the parameter, kinetic pressures of plasma has been varied and its effecton the pinching effect is examined by the solution of differential equation of motion of imploded plasma by using the MATHEMATICA software.

Keywords: Theta pinch, Snow Plow Model, Equation of motion ,MATHEMATICA, Pinching effect, examined.

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INTRODUCTION

Plasmawas first discovered in 1879. Thomson identified the nature of the radiant matter in 1897. The American scientists Irving Langmuir and Lewis Tonks(Bittencourt JA. (2004) Fundamental of Plasma Physics.3rd Ed. New York, Springer – VerlagInc) were among the first who worked on plasma. It was Irving Langmuir who assigned the term "plasma" in 1928. Plasma word comes from the Greek which means something molded or fabricated (Chen F, 1983). The plasma is a matter similar to gaseous state in which some portion of the particles is ionized. The plasma is a quasineutral gas of charged and neutral particles which exhibit collective behavior. Plasma can be called quasineutral gas.

The collective behavior means motions of particles depend on indigenous conditions and as well as dependent on the state of plasma in distant region. In plasma state, charges move around while generating local concentrations of positive and negative charges which give rise to electric fields. Motion of charges also generates currents and hence magnetic fields.

Pinch Phenomenon

The pinch effect (Alsharea HO, et al. 1987) is defined as the self-radial constriction of flowing plasma or other electrically conductor carrying an electric current, caused by self-generated magnetic field. The constricting effect on the plasma or conductor is produced by the magnetic field pressure resulting from the current or by the Lorentz force produced by the current flowing in its own magnetic field. The conductor is usually plasma but could also be solid or liquid or metal as well. The pinch phenomenon in gases was first studied by Bennett and Tonks and named it as pinch effect. In 1933 when the neutron was being discovered, Willarad Bennett wrote his famous paper on the steady state pinch effect published in 1934 (Bostick, 1977). The pinch phenomenon may also be referred to as Bennett pinch, magnetic pinch or plasma pinch.A typical theta pinch device (LaPointe MR. (2000) Ohio Aerospace Institute, Brook Park, Ohio) consists of a linear vacuum vessel made of ceramic or glass enclosed by a single turn solenoid. The single turn solenoid is used to minimize the inductance of the system and hence to obtain the current for a given energy storage. A capacitor is used for electric potential bank source. This capacitor is (Freidberg J.(2012)) discharged from the external coil loop. The coil is used of a single turn for the sake of minimum inductance. This current induces the current in the plasma and produces axial magnetic field in the vacuum vessel. The plasma (Bittencourt, 2004). Fundamental of Plasma Physics. 3rd Ed. New York, Springer –VerlagInc) has diamagnetic property in nature therefore azimuthal current in the plasma is produced in such a direction that it opposes and cancels the magnetic field inside of the plasma causing of external coil loop. The difference of magnetic pressure inside and outside constricts the plasma. The phenomenon (Dolan et al.,1995) can also be explained in terms of JB force which acts radially inwards. As the current flows in azimuthal direction, the device developed is called theta pinch. This is shown in figure 1.

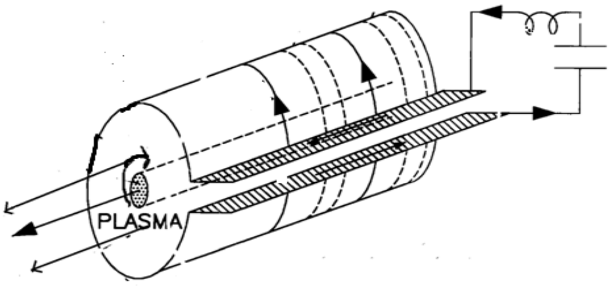


Figure 1

Snow Plow Model

When the current is passed through plasma the pinching starts due to the J B force which acts radially inwards by producing magnetic pressure (Deeba, 2008). This magnetic pressure resists against the kinetic pressure of plasma. The ratio of kinetic to magnetic pressure is termed as a (b), beta parameter. The radius of plasma reduces with time as magnetic pressure increases and value of b decreases. This type of pinching is known as dynamic pinching. The plasma in dynamic pinching (Lee ,1966) gets very high density and temperature. There is a simple model proposed by Rosenbluth in 1954 to explain the dynamic pinch which is called snow plow model shown in figure 2. In snow plow model it is supposed that plasma is fully ionized and it is an ideal conductor. There is no magnetic field inside the plasma due to its diamagnetic property (Inan U and Golkowskim, 2011). It is assumed that all gas particles are swept by plasma and concentrated in a thin shell. The plasma inwards radial force is due to the differences in magnetic fields on the inside and outside of the plasma sheet, this produces magnetic pressure equal to $B^2/2$ m_o .

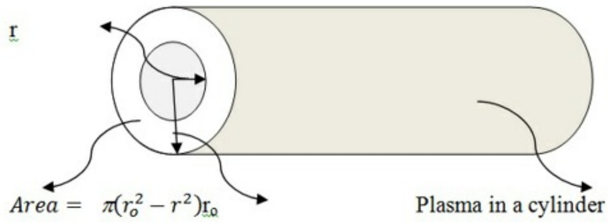


Figure 2: Snow Plow Model

The second law of Newton says that rate of change of momentum is force. The rate of change of momentum of plasma can be equated by the force of plasma magnetic pressure. This force sweeps the plasma radial inward direction.

$$\frac{d}{dt}\left[M\frac{dr}{dt}\right] = -2\pi r P_{mag}$$

where M is the mass per unit length of the plasma swept as it moves inward, P_{mag} the magnetic pressure generated , r_o is radius of cylinder and r represents radius of plasma and t time.

If p_m is denoted for initial mass density of the plasma then the mass it moves inward is given by

$$M = \pi \rho_m (r_o^2 - r^2)$$

When r is the initial radius of the plasma column. From equations 3.30 and 3.31 we get

$$\frac{d}{dt}\left[\pi\rho_m (r_o^2 - r^2)\frac{dr}{dt}\right] = -2\pi r P_{mag}$$

The theta pinch is investigated because it produces relatively pure high temperature ($T=10^5$ °k) plasma having electrons density ($n_e=10^{16}/cm^3$) (Lee, 1966). The concept of theta pinch was obtained from experimental theta pinch devices studied during the controlled fusion investigation (Lapointe, 2000). The initial theta pinch system was contained of an insulating cylindrical discharge cavity open at both end bounded by a single turn coil as shown in figure1. The external coil which is surrounded to the vessel is a single turn and it is attached to a high energy capacitor bank. The high voltage switch is connected to it. The inert gas is injected into the vessel and outer gas layers are partially ionized by a brief current pulse through the external discharge coil. The capacitor is then discharged to deliver a large amount of current in the single turn coil. The abruptly increasing current in the coil produces a sinusoidal axial magnetic field within the vessel. This induces an azimuthal current in the pre-ionized plasma as Faraday law of induction. The plasma is a diamagnetic and it opposes the magnetic field which is applied on it. Therefor induced current is in the direction which cancels the magnetic field in it. The difference of external and internal magnetic field produces magnetic pressure which constricts the plasma inward radial direction. In other words the induced current interacts with the axial magnetic field produced by the coil to produce inward radial Lorentz force JxB in the plasma. This produces a magnetic pressure and plasma starts to compress inward radial direction. When the plasma is compressed by magnetic pressure from self-generated magnetic field due to an azimuthal current, the magnetic field sweeps the mass of the plasma which forms a layer around the magnetic piston. The theoretical model which describes this form of plasma is called the snow plow model The differential equation can be derived for theta pinch imploded plasma as,

$$\frac{d^2x}{d\tau^2}=\frac{2x}{(1-x^2)}\left(\frac{dx}{d\tau}\right)^2-\frac{x\tau^2}{(1-x^2)}+\frac{2P_o \quad x^{1-2\Upsilon}\tau^2}{\mu_o I^2(1-x^2)}$$

Where P is kinetic pressure of plasma and I is current per unit length. Let length is unit for simplification. The equation depends on current and kinetic pressure of plasma and can be solved similarly numerically with the same boundary conditions with help of Mathematica.

Let consider the initial boundary conditions, when normalized time t is zero the normalized radius is maximum equal to 0.99 because there is no starting of pinching therefore velocity of imploded plasma is zero.

$$At \ \tau=0$$

$$x(0)=0.99$$

$$\frac{dx}{d\tau}(0)=0$$

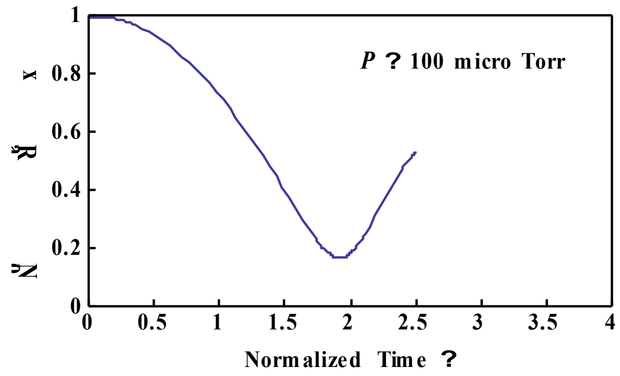
Where τ and x are normalized time and radius.

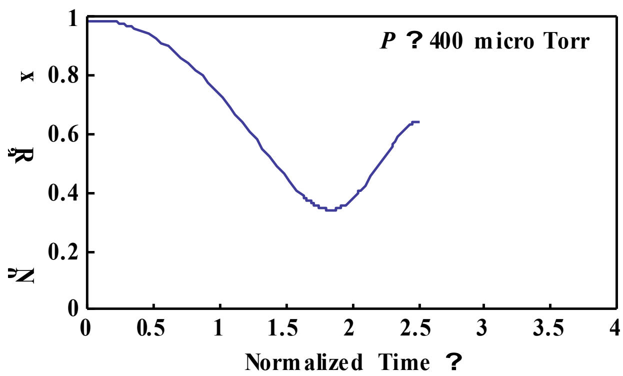
RESULTS AND DISCUSSION

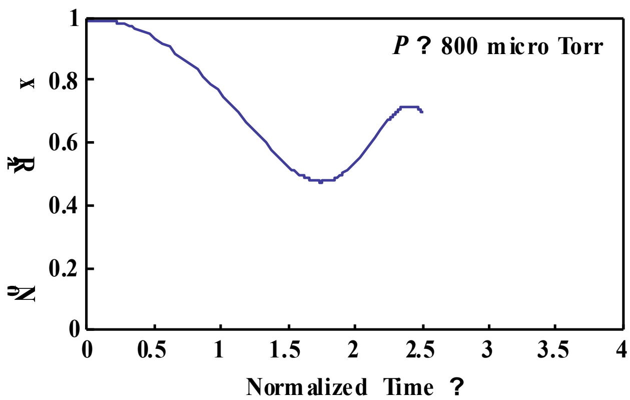
The differential equation of motion of acceleration of imploded plasma has been solved numerically. The results obtained numerically by varying pressure of plasma while by keeping applied current constant as 1KA has been plotted and are shown below in figure 3.

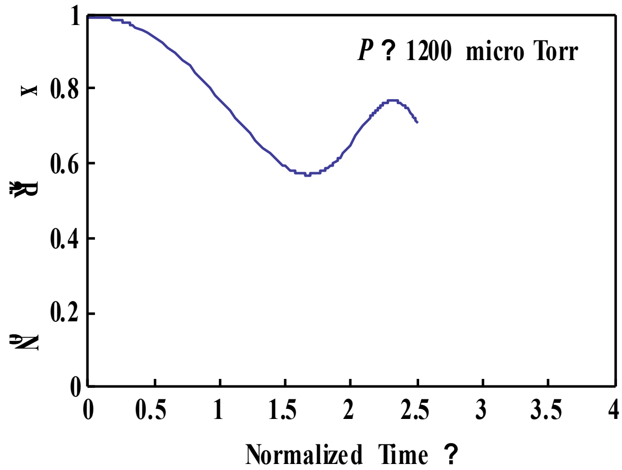
It has been observed from the plotted graphs that with increasing the Pressure, the normalized radius increases exponentially. This is because that by increasing the filling pressure, the pinch phenomenon increases and vice-versa. This can be explained as that when pressure of the plasma is increased leading to more ionization of the plasma causing internal induced plasma current which leads to generation of an internal axial magnetic field. The plasma is a conductor and diamagnetic in nature therefore induced current has such a direction that it cancels the internal magnetic field and due to the difference of external and internal magnetic pressure, the pinching starts. The induced current produces pre- heated plasma by ohmic heating. By increasing the temperature of the plasma its conductivity increases, therefore ohmic heating becomes less effective causing the reduction plasma temperature leading to increase in the normalized radius. The resistivity of a weakly ionized plasma, is dominated by electron-neutral collisions. As the pressure is increased, the frequency of these collisions increases, causing a commensurate rise in the pre ionized plasma's resistivity. During the inductive circumference of the current sheet, the plasma resistance increases with pressure.

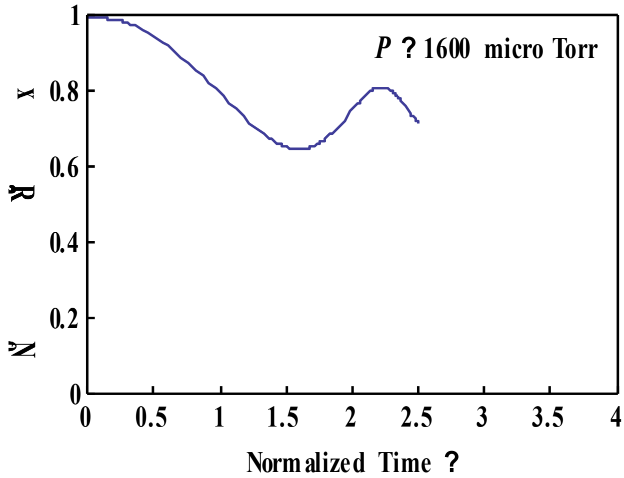
The plasma resistance decreases as the current sheet formation position moves axially towards the inlet of the theta-pinch which leads to decrease in the normalized radius of the plasma. The rising resistance in the plasma with increasing pressure also reduces the initial current rise rate, causing plasma currents at higher pressures to initially lag behind those at lower pressures. The effects of ionization greatly overwhelm this initial advantage within first microsecond with respect to the maximum total current achieved and the total current sheet strength; however the maximum in total current is shifted to later times for higher pressures.











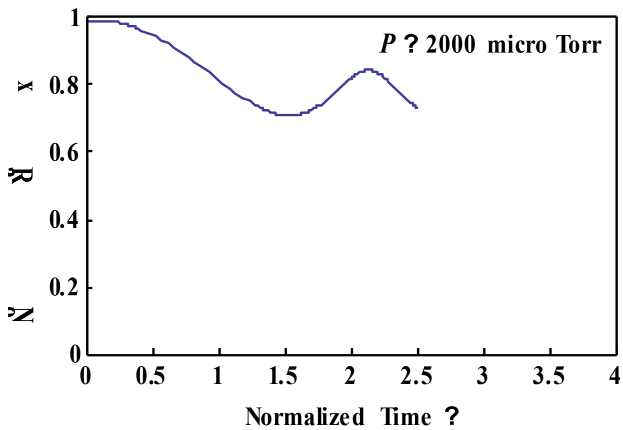


Figure 3: Variation of normalized radius with normalized time at different pressure.

CONCLUSION

In conclusion, the effect of variation of filling pressure on the normalized radius in a theta pinch is investigated numerically. It has been found that the rising resistance in the plasma with increasing pressure also reduces the initial current rise rate, causing plasma currents at higher pressures to initially lag behind those at lower pressures. The effects of ionization greatly overwhelm this initial advantage within first microsecond with respect to the maximum total current achieved and the total current sheet strength; however the maximum in total current is shifted to later times for higher pressures. By increasing the kinetic pressure of plasma the pinching effect reduces because magnetic pressure faces the more resistance by this for compression of the plasma.

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