Amending the Reflected Shock Phase of the Lee Code

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Abstract. The radial reflected shock phase begin when the inward shock front (IS) which is collisional hits the central axis and a reflected shock (RS) is produced that moves radially outward. This phase ended and the pinch phase begins when the RS front meets the magnetic piston that continues to compress inward at the same time. The Lee code approximates the RS phase by taking an estimated constant RS speed as an expediency in the formulation of the code. This seemingly simplified approach has successfully accounted for the nonzero radius for the plasma pinched column. The plasma temperature obtained remains constant following the constant RS speed while the pressure assumed uniform from the RS to the magnetic piston. In this paper the physical mechanism when RS meeting the piston is considered. A point-to-point tracing of the RS speed according to the IS speed is carried out to obtain the RS speed as functions of position and time during its propagation towards the incoming piston. This is an important amendment to the Lee code, the results showed that the Lorentz force driven IS has considerable contribution to the RS speed. The plasma temperature variation during the RS phase is presented together with the RS speed vs time profiles. The plasma temperature vs radius profile from the axis of the pinch is also derived. The peaking of the plasma temperature near to the axis suggests that the pressure between the RS and the magnetic piston is not constant and reaches the maximum value very rapidly in a few nanoseconds. This rapid perturbation can be an important parameter in the consideration of the plasma focus pinch behavior and the subsequent breakup of plasma pinch due to the $m = 0$ instability.

INTRODUCTION

The Lee code (also known as Lee model) is a numerical model for plasma focus discharge based on empirical parameters. It was formulated by Lee in 1984 [1] based on Mather type [2] plasma focus device.The code couples the electrical circuits with the current sheath dynamics, thermodynamics of the shock-heated particles and the resulted in radiation emissions from the plasma pinch. It consists of multiple phases to accurately model the dynamics of the plasma focus. The model has been continuously checked and improved with experimental data obtained from different plasma focus facilities [3, 4, 5, 6, 7, 8, 9].]. It is found that this is one of the most powerful code as the code accounts for the energy-, charge- and mass-consistent, allows the inclusion of the effects of transit times of small disturbances, plasma self-absorption and the terms are correlated to anomalous resistances. Therefore it is widely used in designing and interpretation of plasma focus experiments [10, 11, 12, 13, 14, 15] and to provide diagnostic reference in different gases [12, 13, 14]. The model also features a module for neutron yield calculation [16, 17] and computes the scaling laws for various radiations [3, 16, 18, 19, 20, 21, 22, 23, 24, 25]. It is also being used as a reference for deuteron beam calculation [21, 22].

The Lee model consists of five phases [4, 5] that include the axial phase, radial inward shock phase, radial reflected shock phase, slow compression or pinch phase and expanded column phase. The axial phase uses the snowplow model [9], the radial phase that consists of radial inward shock phase and radial reflected shock phase uses the slug model [8] with thermodynamics. The pinch phase uses radiation coupled compression [4, 5, 7] and the snowplow model [9] is used in the expanded column phase.

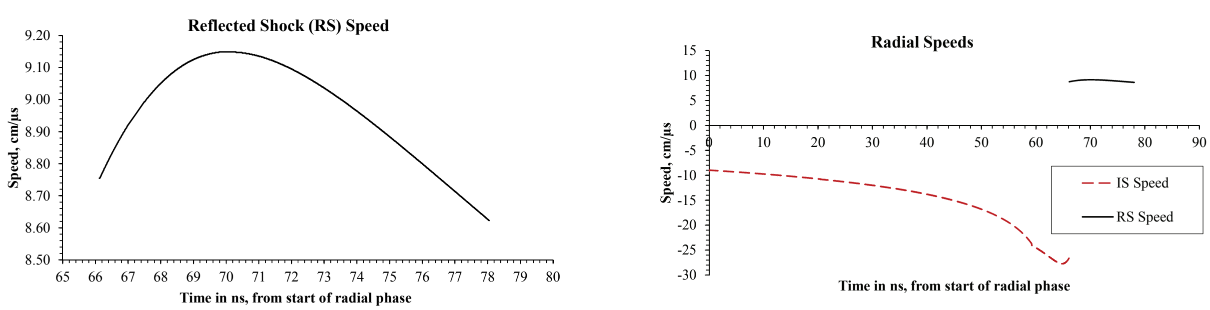
The radial reflected shock (RS) phase is the third phase of the five phases Lee model. This phase begins when the shock front which is collisional hits the axis and a reflected shock (RS) is produced that moves outward until it meets the incoming piston. The outward moving RS evolves depends on the historical speed of the inward flowed and the incoming magnetic piston; which the RS speed depends on the IS speed at the point where it passed through earlier. Even after the IS has coalesced on the axis the plasma flow at all points between the piston and the axis continues because the piston is still pushing inward to the axis. According to shock theory, in a cylindrical configuration the speed of RS as it leaves the axis is one third of the speed of the IS on-axis. The Lee code approximates the RS phase by taking RS speed and RS plasma temperature as constant as the RS propagates towards the incoming piston. As part of the continuous development of the code this paper considers a physical mechanism affecting the RS speed to compute a function of its propagation outward towards the magnetic piston. A spatial plasma temperature profile from the axis is derived.

COMPUTATION OF RS SPEED AT A POINT IN ITS PROPAGATION AND THE CORRESPONDING PLASMA TEMPERATURE AT THAT POINT AS THE RS PASSES

The RS speed in the RS phase is computed as a function of time, where the RS speed at current position is taken as

$$v_{RS} = v_{RS\,start}\left(\frac{v_{IS}}{v_{IS\,onaxis}}\right)$$

where $v_{RS\,start} = -1/3 v_{IS\,onaxis}$, $v_{IS\,onaxis}$ is radial inward shock speed on axis and v_{IS} is the speed of the radial IS when the IS was at the position of the RS. In the effort to obtain a good match for the position of the RS, in every 1 ns of IS traversal, the RS position is found to have advanced by 1/3 of its distant; therefore the RS speed is taken as 1/3 of the passed IS speed at the respective position. In practice it has been found that the RS speed does not deviate very much from the initial RS speed. Applying the Lee code for the radial phase, computation of the RS speed yield a curve as shown in FIGURE. 1a. The RS speed increases from 8.75 cm/μs at the beginning of RS phase to 9.19 cm/μs and subsequently slows down to 8.62 cm/μs. The total duration when the RS takes place is measured to be about 12 ns while the duration of the IS phase is 66 ns. The modified Lee code is used to plot the IS phase follow by the RS phase as shown FIGURE. 1b. The RS phase begins from the axis after IS hits the axis and ends on meeting the piston. The total traversed distant from the axis is about 1 mm. The RS speed versus it positions is plotted in FIGURE. 2.



(a) RS vs time. Time zero is the start of radial phase from modified Lee code.

(b) IS speed and RS speed vs time from modified Lee code.

FIGURE 1: Radial speed from modified Lee code.

For a practical and reasonable estimation, plasma temperature in RS phase in the Lee code is taken according to the RS speed, at about 7×10^6 K until the RS hits the axis whereby the plasma temperature then plunges to 4.8×10^6 (FIGURE. 3). The sudden increased in plasma temperature is computed considering the Bennett pressure balance. In other words at the point where the RS meets the piston there is this large plasma temperature drop which has no

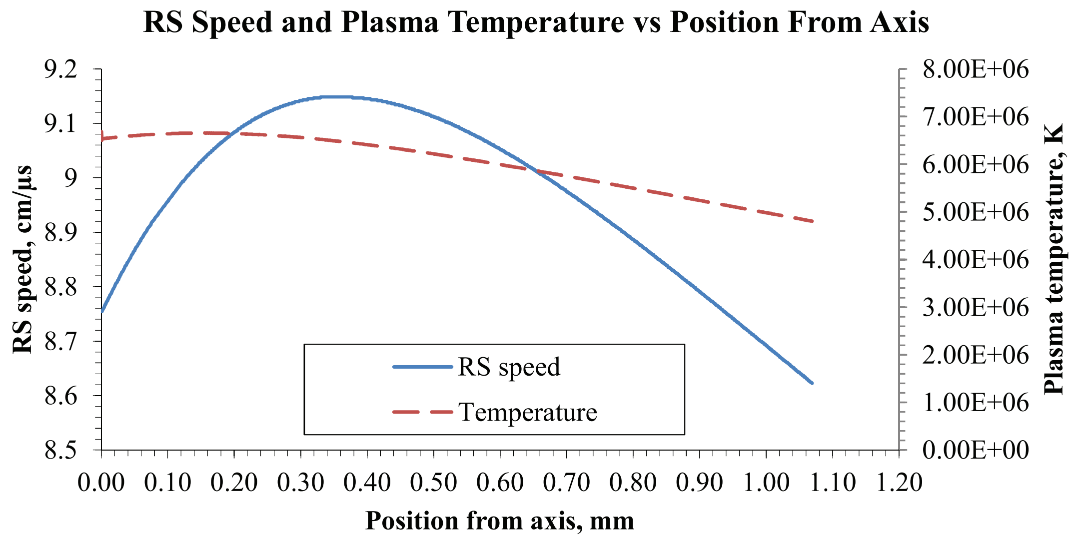


FIGURE 2: RS speed and plasma temperature vs position from axis from modified Lee code.

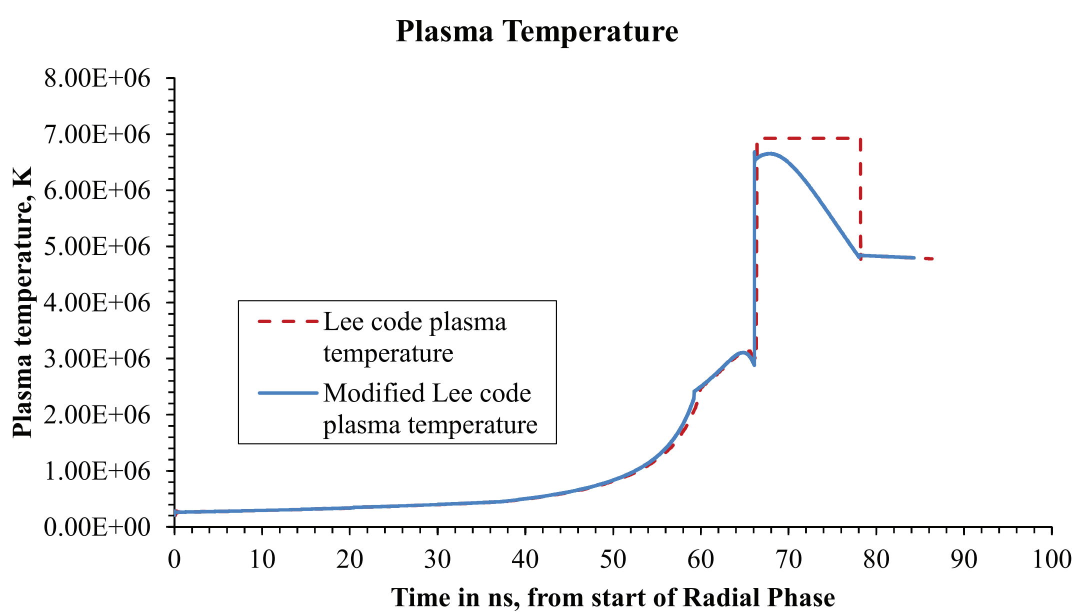


FIGURE 3: Plasma temperature vs time from Lee code and modified Lee code.

physical basis. This unrealistic plasma temperature behaviour is due to the assumption of a constant RS speed. In the present modification, the plasma temperature of RS (T_{RS}) is calculated for each position following this equation:

$$T_{RS} = T_{RS\,start}(T_{RS\,factor}/T_{RS\,start\,factor})(1 + CRS \times 10^7 \times t_{RS})$$

where $T_{RS\,start}$ is the plasma temperature at the start of RS, $T_{RS\,factor} = ((\gamma - 1)/\gamma^2)(v_{IS}^2/(1 + z))$ is the factor used to obtain plasma temperature at any given time for RS, z is the effective charge of the ions calculated from Corona model, $T_{RS\,start\,factor}$ is the initial value of the $T_{RS\,factor}$, t_{RS} is the time zero of the RS phase and CRS is the coefficient of RS which is adjustable. $(1 + CRS \times 10^7)$ is an empirical correction that is used in account for changes of the RS geometry from cylindrical to plane as it propagates outward. This factor is adjusted until the plasma temperature vs time profile becomes a smooth transition.

The modified Lee code is applied to a set of measured data from a 3 kJ plasma focus device. The standard procedure of Lee code is carried out to configure the numerical parameters for the setup. The computed current trace is fitted to the measured current trace and a good fit is obtained. The coefficient of CRS is adjusted to give the computed plasma temperature profile a smooth fit at the point where the RS meets the magnetic piston. This enable a smooth transition of RS phase to the pinch phase. The best value of CRS for this shot is determined as −2.35. The plasma temperature vs time profile using the modified code is presented in FIGURE. 3. It is observed that at the end of IS phase and the beginning of RS phase there is an abrupt change in plasma temperature from 3.5×10^6 K to 7×10^6 K (about double) at 66 ns. This is a correct depiction because as the IS hits the axis, particles are streaming in from all radial directions onto the axis. Computations show that the plasma is in a collisional regime; hence the particles stagnate and the streaming kinetic energy is converted into thermal energy. Thus, a sudden jump in plasma temperature is observed at the end of the IS phase. In the RS phase, we can see a rapid rise in plasma temperature near the axis and eventually decreases to about 4.85×10^6 K from 66 ns to 78 ns.

The detail of the RS speed and plasma temperature in the RS phase vs position from axis is shown in FIGURE. 2. Even though the RS speed and plasma temperature decrease as RS propagates outward from the axis, it is shown that a rapid peak is obtained before the RS meets the magnetic piston. When the numbers are studied in detail, the RS speed contributes minor effect to the overall plasma temperature term while the effective charge number is the major factor resulting to the plasma temperature calculated.

CONCLUSION

In this paper, the RS speed and plasma temperature are calculated point-by-point by considering the physical mechanism of the RS propagates towards the magnetic piston. The equation relating the RS speed to the speed of the IS on a point-by-point basis has been used to calculate the RS speed. The modified Lee code shows that the RS speed increases rapidly then decreases before RS hitting on the magnetic piston. The plasma temperature profile of the plasma during the RS phase also shows corresponding changes. Overall the RS plasma temperature term depends on the RS speed and the effective charge number. However the rapid increase of the plasma temperature near to the axis suggests that the pressure between the RS and the magnetic piston cannot be constant. The plasma plasma temperature increases in the region of about 0.3 mm from the axis and reaches to the maximum value in about 3 ns. This localized and rapid perturbation can be an important parameter in the consideration of the plasma focus pinch behaviour and the subsequent breakup of plasma pinch due to the $m = 0$ instability.

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