A Numerical Study on the Ion Production in the INTI International University Plasma Focus Machine using Nitrogen Gas

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Abstract

In this paper, a numerical study on the production of ions beam and its energy in nitrogen gas using the Lee model code was carried out using the INTI International University plasma focus machine experimental current waveform results of 480 shots (120 shots at each pressure). It has been found that if the INTI International University plasma focus machine is to be used for material hardening the best results, from the viewpoint of ion beam energy will be obtained at 1 Torr.

Keywords: Numerical experiment, dense plasma focus, Nitrogen gas, Lee model code

Introduction

The dense plasma focus machine is a multiple radiation source of ions, electron, soft and hard x-rays, and neutrons, making it useful for several applications in many different fields such as surface hardening, lithography, radiography, imaging and etc.

In parallel with the laboratory work there has been extensive theoretical, analytical and numerical work on the plasma focus which could be traced back to the original one-fluid formulation of piston-like 'snowplow' model of Rosenbluth [1-5] to 2-D two-fluid MHD models [6] and three-fluid MHD models [7,8]. Kinetic models were extended to fully kinetic simulations [9-12] giving perhaps the most advanced simulations of the plasma focus at the expense of considerable theoretical sophistication and computing resources. On the other hand, simpler methods with varying degrees of utility had been used by others [13-20]. The Lee code [21-24] uses a relatively simple approach and yet is able to achieve the widest range of applications in plasma focus computations.

This paper gives one example of the applications of the Lee code to identify the optimum pressure for nitriding. To understand the performance of a plasma focus machine, the current trace [21], should be analysed because it contains information on the dynamic, electrodynamic, thermodynamic and radiation processes that occur in the various phases of the plasma focus [21-23]. One of the most important procedures therefore is to connect the numerical experiment [24] to the reality of the actual machine by fitting the computed current trace to a measured current trace. [21, 25-31].

Procedure for the numerical study

The machine parameters of the INTI International University plasma focus (denoted in this paper as INTI PF) is as follows. It is a conventional Mather type machine which is part of a network of 3kJ Mather type plasma machine known as the UNU/ICTP PFF (United Nations University/International Centre for Theoretical Physics Plasma Fusion Facility) [32]. It has a capacitance of 30μF, static inductance of 114nH; a circuit resistance of 13 mΩ. This machine has an anode length of 16 cm with a radius of 0.95 cm. The anode is surrounded by cathodes arranged in a circle having a radius of 3.2 cm measured from its center.

In a recent series of experiments over 480 shots, this machine was operated at various pressure of nitrogen gas from 0.5 -2 Torr. The measured current derivative was obtained with a coil and then integrated with respect to time to obtain the current trace. We then configure the Lee's 6 phase model code (version: RADPFV6.1) as the INTI PF by entering the bank parameters, tube parameters and operational parameters.

The computed total current waveform is fitted to the measured waveform by adjusting the model factors f_m, f_c, f_{mr} and f_{cr} one by one, till the computed waveform agrees with the measured waveform [32-36].

The mass swept-up factor f_m accounts for not only the porosity of the current sheet but also for the inclination of the moving current sheet-shock front structure, boundary layer effects, and all other unspecified effects which have effects equivalent to increasing or reducing the amount of mass in the moving structure, during the axial phase. The current factor f_c accounts for the fraction of current effectively flowing in the moving structure (due to all effects such as current shedding at or near the back-wall, and current sheet inclination). This defines the fraction of current effectively driving the structure, during the axial phase.

First, f_m, f_c are adjusted until (see Figure 1) the features (1) computed rising slope of the total current trace and (2) the rounding off of the peak current as well as (3) the peak current itself are in reasonable fit with the measured total current trace.

Then we continue to fit the radial f_{mr} and f_{cr} until features (4) the computed slope and (5) the depth of the dip agree with the measured. The mass swept-up factor f_{mr} takes into account all mechanisms which increase or reduce the amount of mass in the moving slug, during the radial phase. The current factor f_{cr} is the fraction of current effectively flowing in the moving piston forming the back of the slug (due to all effects). This defines the fraction of current effectively driving the radial slug. For the Lee Model 5-phase code the fitting ends here. For the Lee's 6 phase model code the Lee's 5 phase model is extended with a post –pinch phase of anomalous resistance. The good fit of the computed to the measured current waveforms assures that the code has been calibrated to the INTI PF focus machine including known mechanisms such as current sheath porosity and geometry and unknown machine effects such as random edge effects which are not incorporated in the coupled equations of the code but are incorporated through the resultant mass sweeping and effective current fractions.

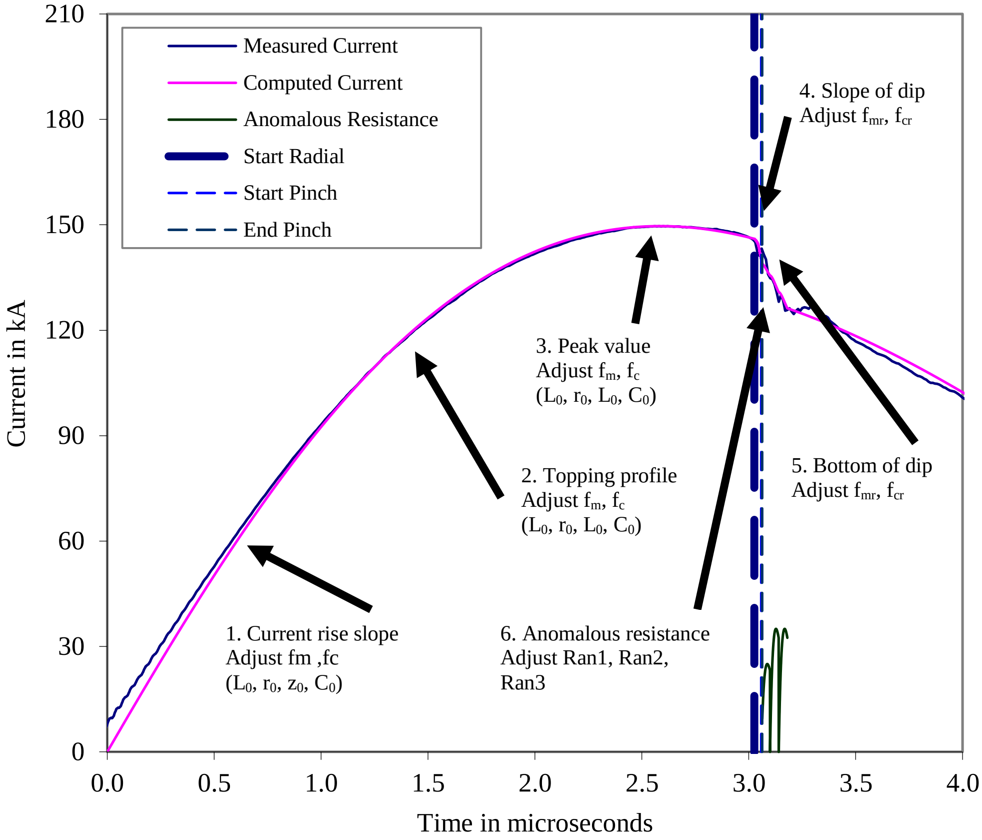

Figure 1 *The 6-point fitting of computed current trace to the measured current trace obtained from shot number 11 of the INTI International University Plasma focus machine operated at 12kV, 0.5 Torr in nitrogen gas. The fitting uses Lee Model 6-phase code.*

The machine, operation and fitted parameters for the fitting above are shown in Table 1.

Table 1 *Machine, operation and fitting parameters for the INTI International University Plasma focus machine used for fitting the numerical experimental current curve to the actual measured current curve. (Nitrogen at 0.5 Torr)*

Capacitance C_0 (μF)	30
Static inductance L_0 (nH)	114
Circuit resistance r_0 (mΩ)	13
Cathode radius ‘b’ (cm)	3.2
Anode radius ‘a’(cm)	0.95
Anode length ‘z_0’(cm)	16
Charging voltage V_0 (kV)	12
Fill gas pressure P_0 (Torr)	0.5
Fill gas(molecular weight)	28
Fill gas(atomic number)	7
Fill gas(molecule(2))	2
Axial phase mass factor, f_m	0.045
Axial phase current factor, f_c	0.53
Radial phase mass factor, f_{mr}	0.07
Radial phase current factor, f_{cr}	0.9

Results and discussion

The computed and measured current traces in Figure 1 show a good fit. The peak current computed is 150 kA and exhibits a radial phase start time of 3.025 µs for pinch duration of 4.463 ns with an all line yield of 3.13µJ (Note: All- line yield consists of the whole range of yields and covers a wide range of wavelengths such as ultra violet, soft X-ray, hard X –ray etc.) The fittings were carried out for all 120 shots for each pressure from 0.5 to 2 Torr and the computed values of the maximum temperature of the pinch, pinch duration, all- line yield, number of ions per shot and beam energy were obtained (Using the fitting parameters which were later input into Lee code model version: RADPFV5.15FIB

From the results, it can be noted that when the Pressure P_0 is increased the axial speed v_a decreases.

Similarly the radial shock speed v_s and the radial magnetic piston speed v_p also decreases. The decrease in the radial shock speed v_s causes a decrease in the temperature of the inward radial shock (the temperature depends on the shock speed to power of 2). This sets the stage for a decreased pinch temperature as pressure P_0 increases (see Figure 2). As these two radial speed decreases, the time required for the radial reflected shock increases and also the pinch duration increases [37,38]. This is shown in Figure 3 from the graph of pinch duration versus pressure.

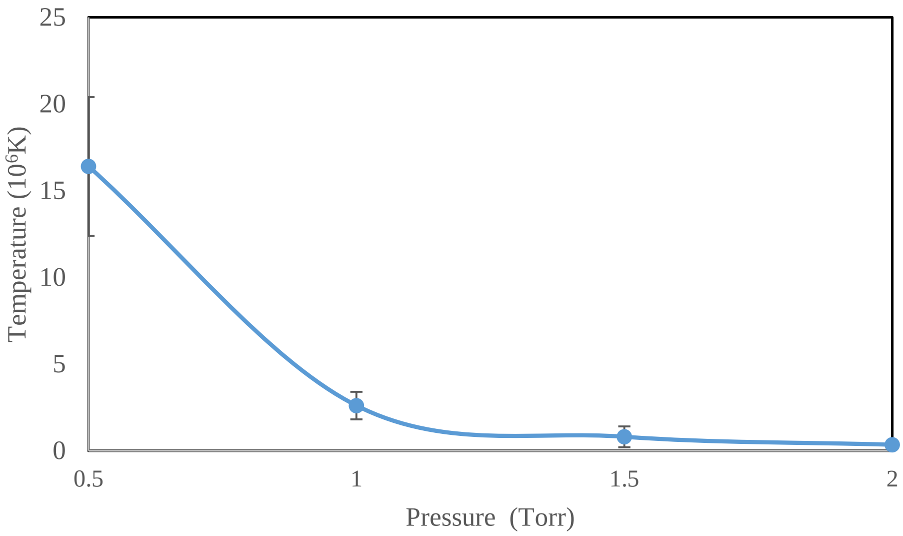

Figure 2 *Temperature of the plasma pinch versus Pressure of the 480 shots taken from measured current curve when they are fitted using the Lee's Model code.*

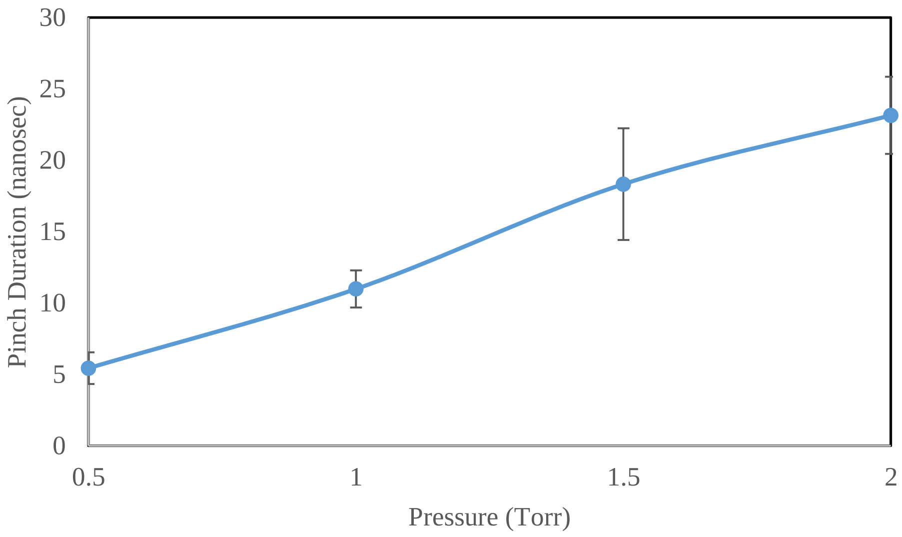

Figure 3 *Pinch duration versus Pressure of the 480 shots taken from measured current curve when they are fitted using the Lee's Model code.*

The ion beam exits the plasma focus pinch along its axis. It is assumed to be a narrow beam (having the same cross-section as the pinch) with little divergence; at least until it overtakes the post-pinch axial shock wave [39-41]. The curve of production of Ions versus pressure in the pinch is shown in Figure 4.

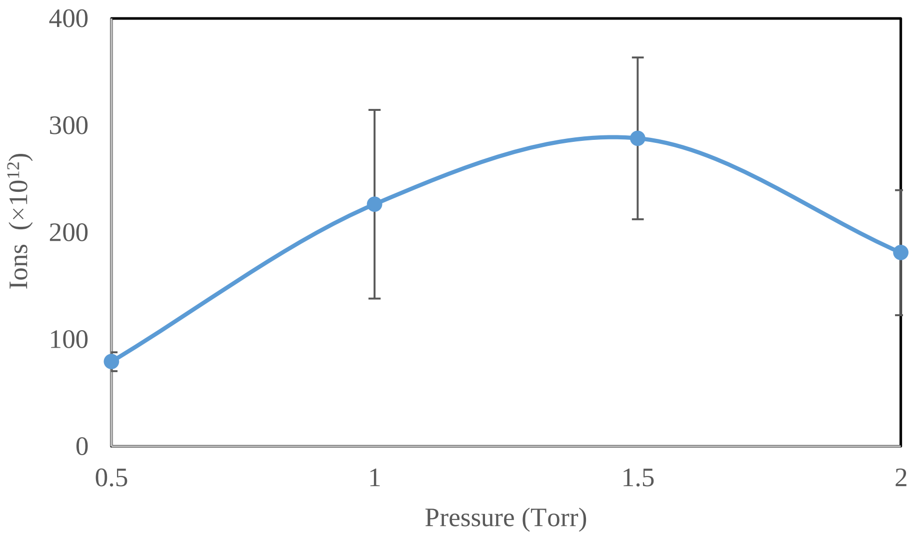

Figure 4 *Number of ions versus Pressure of the 480 shots taken from the Lee code fitted to each measured current curve.*

It should also be noted, that at higher pressure the energy per ion is less than at lower pressure. This can be seen in Figure 5, where the maximum ion beam energy is at 1 Torr whereas the maximum number of ions is at 1.5 Torr as shown in Figure 4.

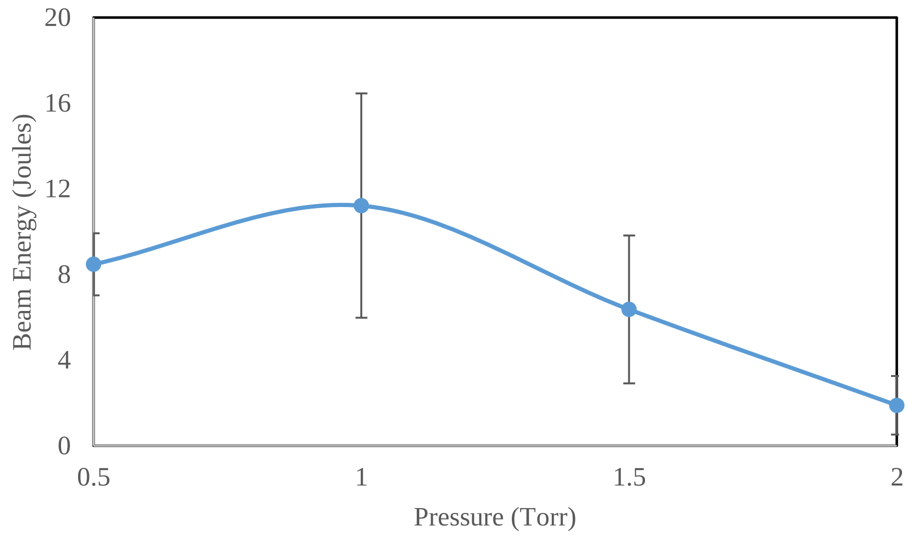

Figure 5 *Beam energy versus Pressure of the 480 shots.*

To study the all- line yield produced in nitrogen for the INTI International University plasma focus machine, it should be noted that the interaction between temperature and pinch density will produce a point where the maximum yield is produce. For INTI International University plasma focus machine this is obtained (by current fitting) at 1 Torr and the probably maximum all- line yield was 0.15 Joules as shown in Figure 6.

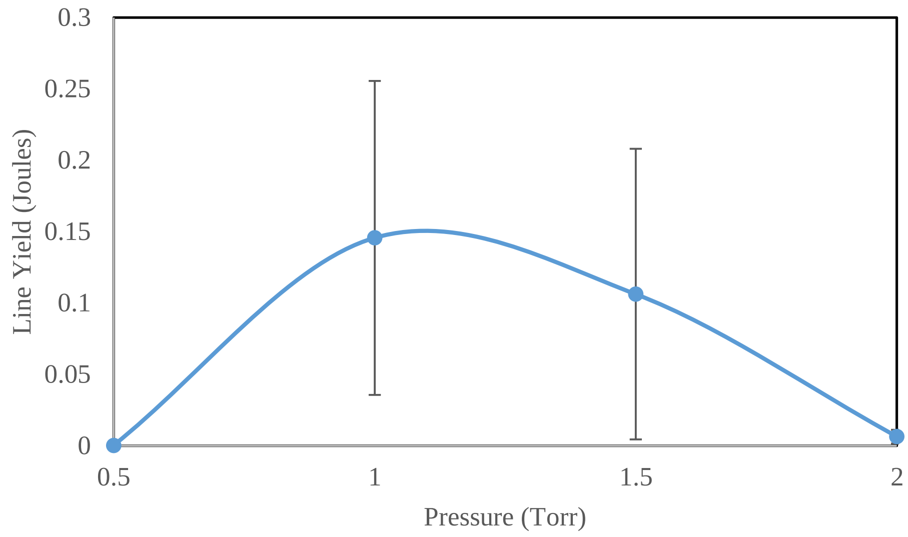

Figure 6 All Line Yield versus Pressure of the 480 shots taken from the Lee code fitted to each measured current curve.

Conclusion

From the Figures above, the Lee code reveals that when INTI International University plasma focus machine is operating, it will produce the maximum ion beam energy at 1 Torr. From this point of view, this may be a good operating pressure for the nitrating of materials as the device produces 16.5 Joules of ion energy at this pressure. This is in the process of being verified by analysis of the corresponding targets which were irradiated during these 480 shots.

The above presentation is an example of how the Lee model code is used to analyse measured current traces to give information of plasma properties and radiation yields.

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