Numerical Calculation of a 2.8 kJ Plasma Focus Characteristics Using a Five-Phase Model

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Abstract

A radiative five-phase model for plasma focus (S. Lee model) (axial phase, inward radial phase, reflected shock phase, pinch phase and expanded phase) was applied to a 2.8 kJ plasma focus device to find the plasma parameters and the SXR radiation emitted from the plasma pinch at different gas pressures.

Fitting the model parameters, the calculated and measured current waveforms at 0.75 Torr of Argon were obtained and compared. The results were tabulated for the optimal operating conditions and compared with the same features of other different PF devices (NX2, PF1000, PF400, and DPF78).

1. Introduction

As known, the plasma focus is generated by applying a high-pulse voltage to a low-pressure gas between two coaxial electrodes, with a high energy density, intense beams of charge particles and radiation emission including SXR radiation, which could be used in radiography and microelectronics lithography.

Nowadays, the working PF devices operate in a wide range of energies, from tens of Joules to ones of MJ. Depending on the energy of the applied pulse voltage, the current in the pinch varies from tens of kA to several MA. It was shown that some of their parameters remain practically constant, such as the energy per unit mass, the axial and the radial speeds.

In the early stage of Mather type - PF devices, a simple three-phase model was developed to characterize their work, using a snow plow model in the axial phase and a slug model in the radial phase. Then, that model was modified to get a five-phase model, in which the radial phase is divided into three radial sub-phases in addition to two essential phases (axial, and expanded). The sub-phases are a radial inward shock phase, a radial reflected shock phase and a slow compression (radiative) phase [1-3].

This model is valid for many applications such as: the design of a cascading plasma focus; for estimating soft x-ray yield and for the purpose of developing a soft x-ray source (SXR) for microelectronics lithography.

The aim of this work is to use the visual basic program RADPFV5.13.9b written based on S Lee five-phase radiative model distributed during the last internet workshop on numerical plasma focus experiments to characterise our plasma focus device PF Sy1, in comparison with other PF devices [4].

2. Experimental setup

The structure of the plasma focus device which was constructed and operated locally is identical to UNU/ICTP PFF device fully described in [1] and the essential parts of the setup are shown in the Fig.1. Energy from the charger with specifications of 0-20 kV and 0-100 mA is stored in a 25 μF , 20kV capacitor which is charged to 15 kV and switched by means of a spark gap which is in turn switched by a high voltage negative pulse from a TV transformer triggering unit.

The focus action is characterized by a distinctive dip in the current signal and a spike in the voltage signal, which indicate a rapid magnetic compression. Fig. 1 shows a schematic diagram of the experimental setup. The ohmic voltage divider 1:100 and Rogowski coil were used to determine the voltage and current signals versus the time during the plasma focus process using a storage oscilloscope with 1:10 attenuator [2].

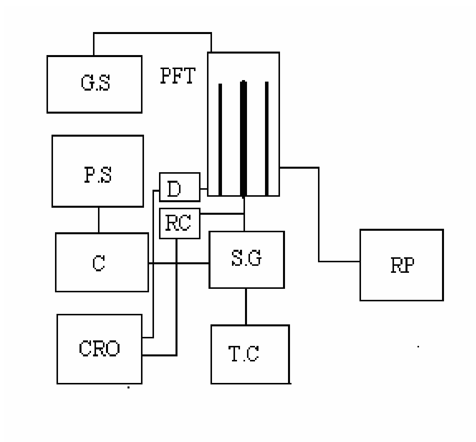

Fig.1 Experimental setup: PFT plasma focus tube, GS gas supplier, PS power supply, C bank capacitors, SG spark gap, TC triggering circuit, CRO storage oscilloscope, RP rotary pump, D- voltage divider, RC Rogowski coil.

3. Computational program

The theoretical model which allows predicting the plasma dynamics, the temperature, the density and the subsequent emission of particles and radiation, was demonstrated in details by [4, 5]. The two main generating equations of the model are: the circuit equation and the equation of motion.

The computation process was based on the plasma focus computation: 5-phase model by S Lee: RADPFV5.13.9b distributed during the last Internet – Workshop on Numerical Plasma Focus Experiments.

4. Results and discussion

Applying the program of RADPFV5.13.9b on our plasma focus devise under operating conditions in Ar at different pressures between 0.1 and 1.05 Torr with applied voltage of 15 kV, varying model parameters to obtain matching of computed and measured current waveforms for 0.75 Torr . Then the calculations should be continued for other values of pressure according to the parameters shown in Table.1 (bank, tube, operating parameters and model parameters). Thus, the following results were obtained:

a) Measured current waveform in L-C-R circuit for a short circuit case (Fig.2a), and measured voltage and current curves vs. the time (Fig 2b).
b) The calculated and measured current waveforms (Fig.3 a, b).
c) Normalized characteristic features of PF-Sy1 at optimal case for SXR radiation (p=0.55 Torr) (Fig.4).
d) Variation of SXR energy as line radiation and ion density vs. pressure (Fig.5).
e) Characteristic features of PF-Sy1 vs. the pressure (Table 2).
f) Comparison with other devices (Table 3).

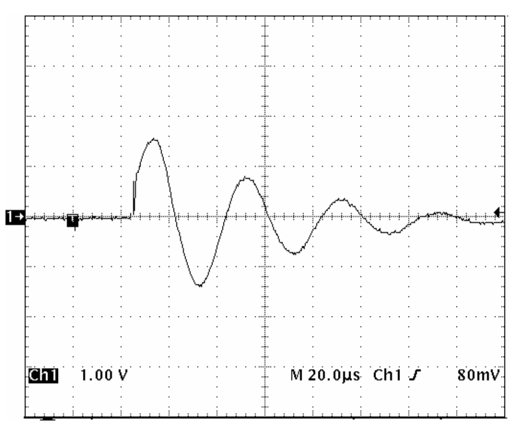

Fig. 2a Measured current waveform for L-C-R circuit at 3.75 Torr in Ar.

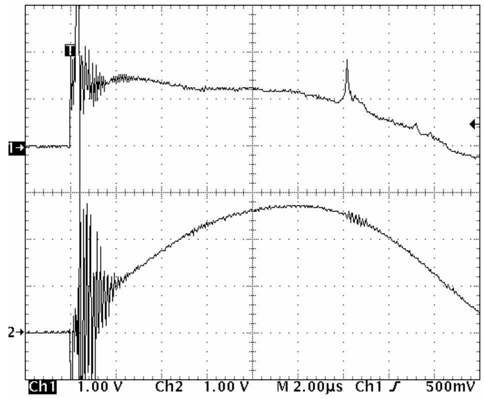

Fig. 2b Measured voltage (up) and current (down) curves in Ar at 0.75 Torr and 15 kV voltage.

Digitizing the measured current trace (from Fig 2b and matching it with the calculated current waveform by fitting the model parameters for 0.75 Torr, with given parameters for bank, tube and operating conditions shown in Tab. I) and then repeating the calculation for different pressures, we get the results shown in Fig. 3a.

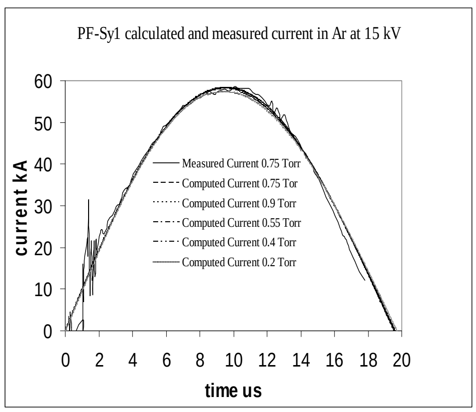

Fig. 3a Calculated and measured current waveforms at different Ar pressures (0.2-0.9 Torr).

As seen from Fig. 3a the current dip is not very strong. For this reason, it is necessary to enlarge the trace to see the dip more clearly as in Fig.3b.

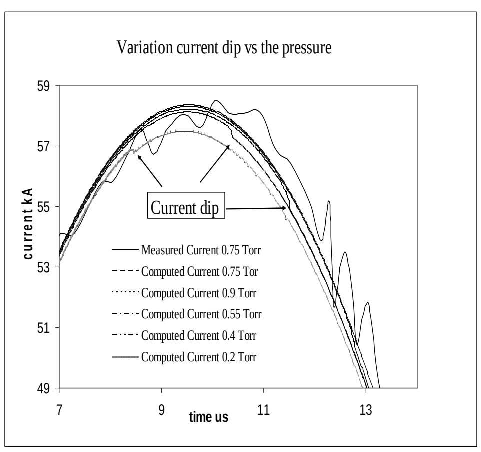

Fig. 3b After the enlargement the current dip vs. the time at different pressures is clear**.**

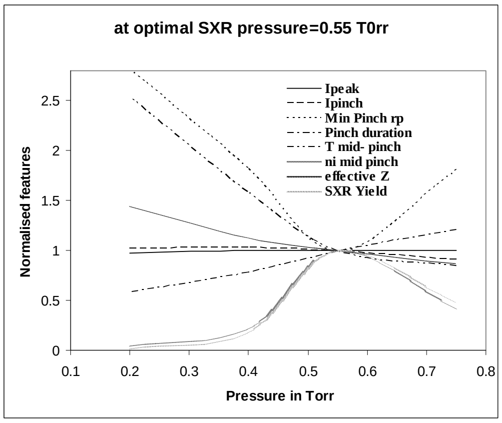

Fig. 4 Normalized features like I_{peak}, I_{pinch}, min r_p , pinch duration, temperature , ion density , effective charge number, and SXR yield vs. pressure in relation to 0.55 Torr as an optimal pressure for SXR.

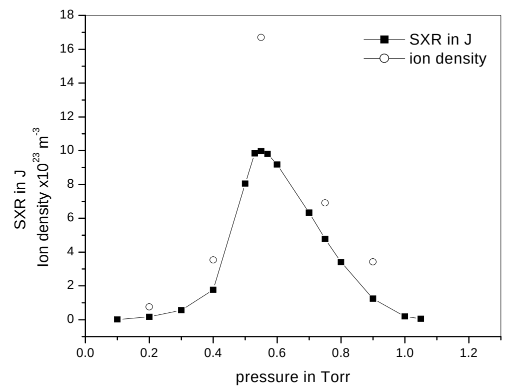

Fig. 5 SXR energy and ion density vs pressure.

From the calculation based on the measured current waveform in the case of a short circuit, the parameters such as: period T, inductance L_0, resistance r_0 and the maximum current I_0 could be found, after the determining factor f, using the following formulae:

$$I_0 = \pi C_0 V_0 (1+f)/T \ ;$$

where

$$L_0 = T^2/(4\pi^2 C_0) \ ; \ f = \frac{1}{n}\sum_n I_{n+1}/I_n \ ; \text{ and } r_0 = -\frac{2}{\pi}\ln(f)(L_0/C_0)^{1/2}$$

The results obtained are shown in Table 2a and 2b.

Comparison of PF-Sy1 characteristics with others PF devices like NX2 (Singapore), PF1000 (Poland), PF400 (Chile) and DPF78 (Germany) is shown in Table 3.

5. Conclusion

In this work we have applied RADV5.13.9b program to fit a computed current trace with a measured waveform varying the model parameters, given all bank, tube and operating parameters, in addition to that the current waveform was calculated at different pressures.

The parameters such as L_0, I_0 and r_0 were determined from the measured and calculated current waveform and compared between them.

Table I. Given bank, tube, operating parameters and model parameters at 0.75 Torr and applied voltage of 15 kV in Argon.

Bank and tube parameters	L_0 nH	C_0 uF	a cm	b cm	z_0 cm	r_0 $m\Omega$
	1525	25	0.95	3.2	16	10
Model parameters	massf	currf	massfr	Currfr		
	0. 1	0.7	0.15	0.7		
Operating parameters	V_0 kV	P_0 Torr	MW	A	At-1 mol-2	
	15	0.75	40	18	1	

Table 2a. Parameters from computed current waveform.

C_0 μF	V_0 kV	C_0*V_0	3*T μs	T μs	L_0 nH		f	I_0 kA	r_0 $m\Omega$
25	15	0.375	117.85	39.28	1565		0.938	58.1	10
Reversal ratio f	I_1	I_2	I_3	I_4	I_5	I_6			
	57.4	54.8	49.3	47.5	44.12	41.68			
	f_1	f_2	f_3	f_4	f_5				
	0.955	0.899	0.963	0.929	0.945				

Table 2b. Parameters from measured current waveform.

C_0 μF	V_0 kV	C_0*V_0	3*T μs	T μs	L_0 nH		f	I_0 kA	r_0 $m\Omega$
25	15	0.375	123.75	41.25	1726		0.813	51.75	34.6
Reversal ratio f	I_1	I_2	I_3	I_4	I_5	I_6			
	53.85	46.92	25.62	26.93	11.54	13.48			
	f_1	f_2	f_3	f_4	f_5				
	0.871	0.546	1.051	0.429	1.168				

Table 3. Comparison of PF-Sy1 with other PF devices.

Plasma focus device	PF-SY1	PF-Sy2	NX2	PF1000	PF400	DPF78
Stored Energy Eo in kJ	2.81	1.5	1.7	486	0.37	30.96
Pressure in Torr, Po	0.55	0.54	2.9	3.5	6.6	7.5
Anode radius a in cm	0.95	0.95	1.9	11.55	0.6	2.5
c=b/a	3.37	3.37	2.16	1.39	2.6	2
anode length z_o in cm	16	16	5	60	1.7	13.7
final pinch radius r_{min} in cm	0.023	0.0235	0.172	2.3	0.086	0.372
pinch length z_{max} in cm	1.74	1.71	2.79	18.9	0.85	3.66
pinch duration in ns	14.532	14.709	30.6	282	5.3	21.276
r_{min}/a	0.024	0.025	0.091	0.2	0.143	0.1488
z_{max}/a	1.83	1.8	1.47	1.64	1.42	1.464
I_{peak} in kA	58.2	82.5	369.4	1845	126	867.6
I_{peak}/a in kA/cm	61.26	86.84	194.42	160	210	347.04
$S=(I_{peak}/a)/(P_o^{1/2})$(kA/cm)/Torr$^{1/2}$	82.61	118.18	114	85.6	81.7	126.7
I_{pinch} in kA	38.6	38.9	142	784	81.3	437.4
I_{pinch}/I_{peak}	0.66	0.47	0.38	0.425	0.65	0.504
Peak induced voltage in kV	33.4	32.3	20.3	40.1	16.7	79.2
peak axial speed in cm/us	2.19	3.37	5.8	11.2	9	15.7
peak radial shock speed cm/us	13	13.4	20.6	16.4	34.3	36.2
peak radial piston speed cm/us	6.91	11.3	14.5	10.9	22.9	24.2
peak temperature in 10^6K	1.59	1.79	1.52	1.14	6.1	6.58
SXY yield in J	9.97	9.31	20.8	-	-	-

It was also shown the variations of normalized main properties of the plasma like I_{peak}, I_{pinch}, temperature and SXR yield and others versus the pressure in related to the case of optimal SXR and the variations of SXR and ion density with pressure.

The calculations have allowed comparing our PF device characteristics with other small and big PF devices.

References

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