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Effect of Gas Type on Characteristics of Ion Beam Emitted by Plasma Focus

This research aims to make a comparison between the features of the ion beam emitted by NX2 dense plasma focus device when using hydrogen and neon gases. Firstly, the characteristics of plasma focus were determined when the pressure of the gas used was changed. Secondly, the ion beam characteristics (flux, energy, power, and current and ions number) were studied. The results showed the effect of the difference in atomic number on the characteristics of the ion beam.

Keywords: Dense plasma focus; Z-pinch; Ion beam; Lee code
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1. Introduction

The term Z-pinch refers to a distinct class of magnetically driven or confined plasma in which a current passes through a plasma cylinder parallel to the axial or z direction, and the interaction between the angular self-magnetic field and the internal radial axial current results a J × B force or the magnetic force. This force can be used dynamically to break a hollow plasma cylinder or quasi-static to confine the plasma through the pinch effect [1].

Plasma focus is a form of Z-pinch, as it is obtained by discharging energy stored in a capacitor bank through a vacuum chamber containing an array of electrodes to form a layer of plasma at the bottom of the chamber to move toward the top of the chamber using Lorentz force to form at the end of the focusing process a small column of very dense plasma, or what is called the Pinch [2,3]. Two different types have been developed for plasma focus devices: Mather type [4] and the Filippov type [5] as shown in Fig. (1). These two types differ from each other in geometric dimensions and this effects on the stages of evolution plasma focus starting from the moment of discharge.

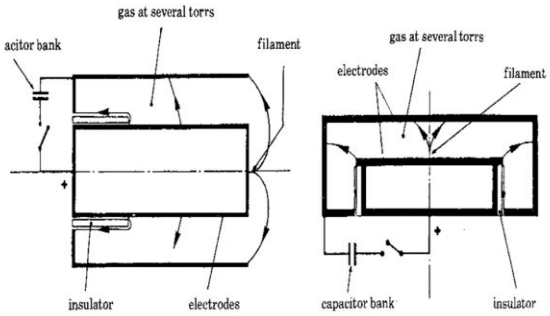

Fig. (1) Plasma focus: Mather type (left), Filippov type (right) [5]

Since the discovery of plasma focus in The sixties of the twentieth century, a large number of studies have been conducted to understand the physical behavior of this phenomenon [6] and to study the properties of emitting ion beams [7] and soft x-rays [8] and also the possibility of benefiting from it in practical fields. Indeed, plasma focus has opened the way to a large number of applications, such as the synthesis materials [9] and the deposition thin films [10] and the obtaining of short-lived radioactive isotopes [11] by taking advantage of emitting ion beams from the collapse of the plasma pinch, and this prompted the study of the properties of these ion beams and their relationship to the operational factors of plasma focus, such as the device energy, its geometric composition, the energy of the capacitor bank, and type of gas used in the operating process. For this purpose, in this research, we conducted a numerical study on the correlation of the characteristics of ion beam emitting by the NX2 dense plasma focus device with the type of gas used in the operating processژ.

2. Dense Plasma Focus Device NX2

This device is considered one of the best dense plasma focus devices in the world for its operational features. This device was designed at NTU NIE Nan Yang University - Singapore according to the Mather type [12]. It is a modified version of the NX PF plasma focus device, as it is distinguished by higher values of current and operating frequency. It operates according to the pulse-periodic mode, with a frequency 1-20 Hz, an operating capacity 1.6-3.3 kJ, and a discharge current of 190-510 kA.

The discharge chamber and electrodes are made of copper or steel, and the anode has a hollow end whose dimensions can be changed. Its diameter ranges from 23 to 40 mm and its length is 25-70 mm.

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As for the cathode, it is in the form of a group of 8 to 12 rods, with a thickness of 10 mm, a length of 50 mm, and a diameter of 100-800 mm. In some experiments, the top of the anode was conical in shape, or titanium or FeCo was added to it. The insulating material between the anode and the cathode is a quartz disc or a Pyrex glass tube. A variety of gases are used to operate this device: hydrogen, deuterium, helium, argon, neon, a mixture of argon and oxygen with a pressure range of 0.7-20 mbar. This device was used as a source of soft x-ray for lithography [13], in addition to a source of neutrons, deuterons, and electron beams, which in turn are used in the synthesis of FeCo nanoparticles, and nanocrystalline thin films of titanium dioxide (TiO_2) [14].

Parameters of NX2 dense plasma focus device include the following:

Operating parameters: operation Power E_0=2.7 kJ, operating voltage V_0=14 kV, operating pressure P_0 is variable, and working gases are H_2 and Ne

Capacitor bank parameters: Inductance of circuit L_0=20 nH, capacitance C=28 μF, and resistance r_0=2.3 mΩ

Tube parameters: anode radius a=1.9 cm, cathode radius b=4.1 cm, and anode length Z_0=5 cm

3. Results and Discussion

Tow gases were studied: hydrogen and neon. Where we first found the parameters of the plasma focus and their change with increasing pressure of the studied gas until the value after which focusing does not occur. These parameters are: maximum current (I_{peak}), pinch current (I_{pinch}), maximum temperature of the pinch (T_{pinch}), v_a, v_s and v_p are the values of the axial velocity, shock wave velocity, and piston speed, respectively, r_{min} is the minimum radius of the pinch, z_{max} is the maximum length of the pinch, pinch duration, V_{max} is maximum value of the voltage generated within the pinch, n_i is the ion density. These parameters were determined because of their effect on the formed pinch and thus on the emitted ion beam after its collapse. Numerical experiments were carried out using Lee code and the results were as follows:

a- Characteristics of plasma focus when using hydrogen gas (tables 1 and 2)

b- Characteristics of plasma focus when using Neon gas (tables 3 and 4)

From the previous results, it can be noted that the decrease in the value of the pressure necessary to complete the focusing process of neon due to the increase in the atomic number of the gas used. The value of the total current flowing within the plasma increases during the entire focusing process and with increasing gas pressure, noting a difference in its percentage of the capacitor bank discharge current, where in the case of hydrogen it constitutes on average 62%, neon. 70.9%.

Table (1) Characteristics of plasma focus when using hydrogen gas

P Torr	I_{peak} kA	I_{pinch} kA	T_{pinch} 10^6 K	v_a cm/μs	v_s cm/μs	v_p cm/μs
1	233	140	6.7	19.7	52.7	36.5
2	270	162	4.5	16.3	43.2	29.9
3	293	175	3.5	14.5	38.2	26.3
4	310	185	2.9	13.4	35.0	24.0
5	323	192	2.5	12.5	32.5	22.3
6	334	197	2.2	11.8	30.6	21.0
7	343	202	2.0	11.3	29.0	19.9
8	350	206	1.8	10.8	27.7	19.0
9	356	209	1.6	10.5	26.5	18.2
10	362	211	1.5	10.1	25.5	17.5
11	367	213	1.4	9.8	24.6	16.9
12	371	215	1.3	9.5	23.8	16.3
13	375	217	1.2	9.3	23.1	15.8
14	379	218	1.2	9.1	22.4	15.3
15	382	219	1.1	8.9	21.8	14.9
16	385	220	1.0	8.7	21.2	14.5
17	387	221	1.0	8.5	20.7	14.1
18	389	221	0.9	8.3	20.2	13.8
19	391	221	0.9	8.2	19.7	13.5

Table (2) Continued Characteristics of plasma focus when using hydrogen gas

P Torr	amin cm	zmax cm	pinch duration ns	Vmax kV	ni (10^{23})/m^3
1	0.30	2.9	11.7	36	0.9
2	0.30	2.9	14.3	34	1.9
3	0.30	2.9	16.2	32	2.8
4	0.30	2.9	17.8	31	3.7
5	0.31	2.9	19.2	30	4.6
6	0.31	2.9	20.4	29	5.4
7	0.31	2.9	21.6	28	6.3
8	0.31	2.9	22.6	27	7.2
9	0.31	2.9	23.6	26	8.0
10	0.31	2.9	24.6	26	8.8
11	0.31	2.9	25.6	25	9.7
12	0.31	2.9	26.5	24	10.5
13	0.31	2.9	27.4	24	11.3
14	0.31	2.9	28.3	23	12
15	0.32	2.9	29.1	22	12.8
16	0.32	2.9	29.9	22	13.5
17	0.32	2.9	30.8	21	14.3
18	0.32	2.9	31.6	21	15.0
19	0.32	2.9	32.5	20	15.7

Table (3) Characteristics of plasma focus when using neon gas

P Torr	I_{peak} kA	I_{pinch} kA	T_{pinch} 10^6 K	v_a cm/μs	v_s cm/μs	v_p cm/μs
0.5	323	185	9.3	12.5	12.5	25.9
1	362	204	5.9	10.1	10.1	20.8
1.5	382	211	4.4	8.9	8.9	18.0
2.0	393	213	3.4	8.0	8.0	16.7
2.5	401	212	2.7	7.4	7.4	15.8
3	406	209	2.2	6.9	6.9	15.0
3.5	411	205	1.8	6.5	6.5	14.1
4	415	200	1.5	6.2	6.2	13.4
4.5	418	195	1.3	5.9	5.9	12.7
5	421	188	1.1	5.6	5.6	12.0
5.5	423	181	0.9	5.4	5.4	11.2
6	426	174	0.8	5.2	5.2	10.5
6.5	428	165	0.7	5.0	5.0	9.8
7	429	157	0.6	4.8	4.8	9.2

Table (4) Continued Characteristics of plasma focus when using neon gas

P Torr	a_{min} cm	z_{max} cm	pinch duration ns	V_{max} kV	n_i $(10^{23})/m^3$
0.5	0.23	2.9	15.7	43	0.8
1	0.23	2.9	18.8	39	1.6
1.5	0.22	2.9	20.7	37	2.5
2	0.21	2.8	21.3	35	4.0
2.5	0.18	2.8	21.0	35	6.6
3	0.14	2.9	24.5	34	12.5
3.5	0.16	2.9	26.7	33	12.3
4	0.17	2.9	29.3	31	11.3
4.5	0.18	2.8	31.5	29	11.3
5	0.18	2.8	34.1	27	12.9
5.5	0.18	2.8	38.3	25	14.5
6	0.18	2.7	42.1	22	15.9
6.5	0.18	2.7	46.1	20	17.0
7	0.18	2.7	49.2	17	18.0

In the case of hydrogen, we notice that the pinch current increases steadily with the increase in gas pressure as a result of the increase in the total current. We also notice a peak for this current in the case of neon, corresponding to pressure values of 2 Torr .

The temperature of the formed plasma core decreases with increasing pressure, with higher values observed in the cases of neon.

We notice a decrease in the values of axial velocity, the shock wave velocity, and the magnetic piston velocity with increasing pressure, due to the increase in gas density and thus a decrease the movement plasma layer speed, axially and radially

Here we can distinguish the absence of the pinching effect in the cases of hydrogen, as we notice that the pinch's radius continues to increase with increasing pressure, while in the cases of neon we notice a smaller radius at pressure values 3 Torr. No change was observed in Pinch's length and its stability was approximately 2.9 cm for the gases studied. The pinch duration increases with increasing pressure due to the continued pumping of energy from the capacitor bank until the discharging process ends.

We noticed a decrease in the value of induced voltage as the gas pressure increases. This is due to the decrease in the value of the energy arriving from the capacitor bank to pinching stage due to the loss of a large portion of it in the ionization process when the gas pressure increases. We noticed an increase in ions density within the pinch as a natural result of increasing gas pressure.

The characteristics of ion beam emitted by NX2 plasma focus device:

A series of numerical experiments were conducted using Lee code in order to study the change in the characteristics of ion beam emitted by NX2 device with a change in type and pressure of the operating gas according to the following:

The flux of hydrogen ions increases steadily with increasing pressure, starting from $6.6x10^{27}$ ions/m^2.s at 1 Torr until $1.9x10^{28}$ ions/m^2.s at 19 Torr. The flux of neon ions shows similar behavior in that there is a maximum flux value of $6.8x10^{27}$ ions/m^2.s at 3 Torr (Fig. 2).

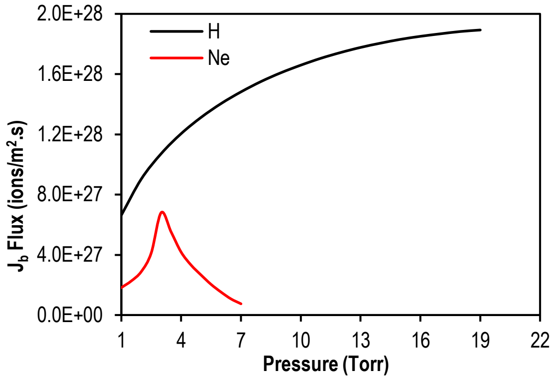

Fig. (2) Ion beam flux from the NX2 device

The energy of the hydrogen ion beam increases with increasing pressure until reaching a maximum value of 194.2 J for hydrogen. The results showed that in the case of neon, the ions beam energy increased until reaching a maximum value for neon, 141.1 J at 3.5 Torr, and then it decreased with continue increasing the pressure. This maximum value of ions beam energy in the case of neon is related to the occurrence pinching effect, that is, the smallest radius of the pinch, thus trapping a larger amount of energy within the plasma column and thus increasing the energy of the resulting ion beam after the collapse of pinch (Fig. 3).

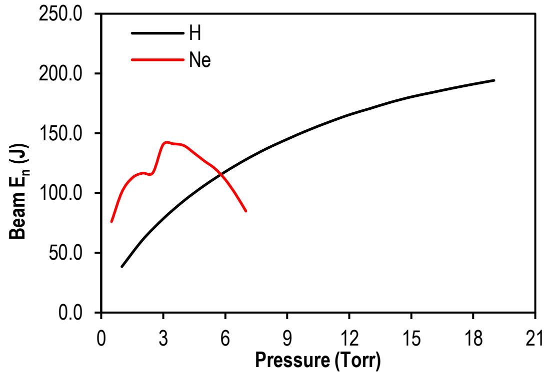

Fig. (3) Ion beam energy from the NX2 device

The results showed that the ion current in hydrogen was within the range 30.3-98 kA, and in neon we notice a peak of 56 kA corresponding to a pressure 3 Torr. We notice a decrease in the value of the current with noble gases (Fig. 4).

Numerical experiments showed that there is a maximum value for the ion beam power for each of the gases studied according to the following: hydrogen $6.2x10^9$ W at 10 Torr, neon $5.6x10^9$ W at 2.5 Torr. We believe that the presence of a maximum value for ion beam power at a specific pressure value depending on the type of gas represents the optimal condition for generating the ion beam from plasma, as ideal factors are available that give the highest power (Fig. 5).

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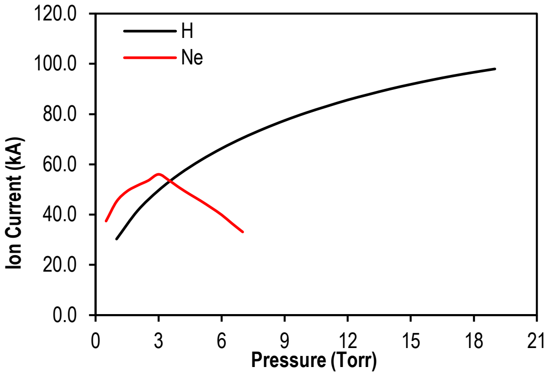

Fig. (4) Ion beam current from the NX2 device

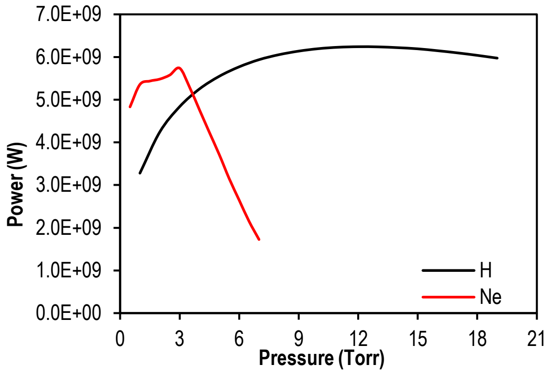

Fig. (5) Ion beam Power emitted by the NX2 device

The results showed that the ions number increased with pressure increasing gas, reaching the highest value at the highest pressure value, about 2×10^{16} ions for hydrogen and 1.3×10^{15} ions for neon. We notice a decrease in the value of the ions number in the case of neon due to the increase in atomic number and the need for greater energy for the ionization process (Fig. 6).

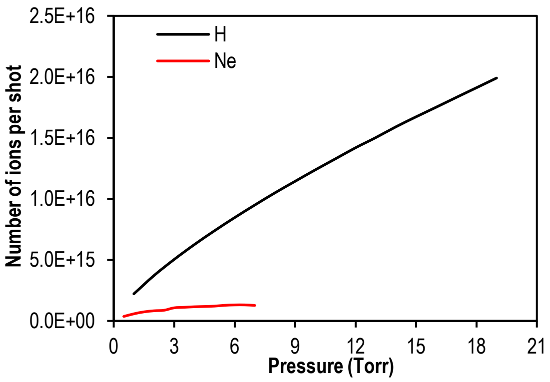

Fig. (6) Ions Number emitted by the NX2 device

4. Conclusions

The results obtained showed the effect of gas type used in the dense plasma focus device on ion beam characteristics, as it can be observed that the number of emitted hydrogen ions compared to neon increases due to the lower atomic number of hydrogen compared to neon and thus greater ionization occurs.

The results also showed the occurrence of a pinching effect in the case of neon gas, which affected the ion beam energy, and the absence of this effect in the case of hydrogen gas. The occurrence of this effect can be considered by expanding the study to include other noble gases.

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