Technological parameters of the discharger intended for the polymer recycling

H Li, S Garelina, M Kazaryan

1Department of Equipment Engineering, Shenyang Ligong University, 6 Nanping Central Road, 110159, Shenyang, China
2Department of Mechanics and Engineering Graphics, Federal State Military Educational institution of Higher Education "Academy of Civil Defense Ministry of the Russian Federation for Civil Defense, Emergencies and Elimination of Consequences of Natural Disasters, 3 Teatralny Proezd, 109012, Moscow, Russian Federation
3Department of Optics, PN Lebedev Physical Institute of the Russian Academy of Sciences, 53 Leninsky Avenue, Moscow 119991, Russian Federation

1E-mail: syitlhd@mail.ru

Abstract. Theoretical justification of technological and constructive parameters of a discharger included into high-voltage pulse-periodic reactor for plasma-chemical recycling of polymer wastes is presented in the work. Geometric dimensions, gas flow rate, capacity of the discharge power supply, productivity, and the pulse frequency of the discharger have been determined. Operating conditions of the discharger were calculated for polyethylene, polyvinylchloride and polyethylene terephthalate (concentrations $10^{14}$, $10^{15}$, and $10^{16}$ \(\text{cm}^{-3}\)) in inert gas atmosphere (atoms concentrations of $10^{17}$, $10^{18}$, and $10^{19}$ \(\text{cm}^{-3}\)). For the polymers the maximum permissible discharge duration was calculated for the conditions taking into account the realization of the gas flow rate less 10 m/s: discharger power rating of 5 kW (range of capacities of industrial power supplies for metal vapor lasers), the frequency of the discharges at 2 Hz, and discharger’s dimensions of 0.5 m. The obtained results can significantly reduce experimental studies and allow the creation of a plasma-chemical reactor for polymer wastes recycling.

1. Introduction

Gross production and ubiquitous use of polymers has resulted in accumulation of polymer-based wastes for the past 60 years. More than 300 million tons of polymers are generated annually in the world [1,2]. Most polymers have a negative impact on the environment [3,4], since they do not biodegrade for centuries although today there are polymers which decompose under the influence of biotic factors [5]. Landfills or burning are still the most common ways to eliminate polymer waste in the most countries of the world [6,7]. According to [8], only 9% of polymer wastes are recycled, 12% are burned, and 79% of wastes are sent to landfills and dumps or remained in the natural environment. The use of land for dumps poses a threat to environmental safety; therefore it will be terminated eventually due to the lack of space and ever-increasing cost [9]. The main factor inhibiting widespread use of burning is the formation of toxic fumes and fly ash emissions [10]. There are strict regulatory requirements for the natural environment quality that do not allow the practical implementation of the polymer burning method in the developed countries.

Despite the development of a various physical and chemical methods for recycling of polymeric waste [11], until now the transfer of waste into ready-to-use products is a great challenge for scientists.
and practitioners. Moreover, it was showed that the reuse of polymeric waste is not the most effective method for solving the problem of their removal from the environment [6], it is more rational to utilize them on the basis of low-cost methods.

Plasma-chemical technologies for waste recycling have introduced relatively recently since they process various polymer wastes and dangerous chlorine-containing organic compounds [12]. Plasma-chemical methods provide high temperatures and high energy densities in conjunction with ionization of the medium. Based on the selective heading of the energy flow and appropriate external parameters for the components activation in chemically reaction mixture may ensure obtaining the desired products as well as hydrogen release [13-15]. Besides, plasma technologies provide eco-friendly recycling of raw materials without the formation of resins, dioxins, and aerosols, as well as the complete recovery of all carbon from the waste material, where the recycling degree reaches 99.7 % [14]. Apart from hydrogen production, recycling of polymeric wastes can be accompanied by the formation of carbides and chlorides. However, despite the profitable side, polymer waste recycling by plasma-chemical methods is not still developed and requires more experimental and theoretical data on plasma-chemical processes taking place in reactors.

For the transforming of polymer wastes into hydrogen and other marketable products, it is more preferable to use non-equilibrium plasma due to lower energy costs, richer reaction capabilities and simplified technological scheme. We chose a high-voltage pulse-periodic discharging process that is widely used in chemical-compound-lasers [16] and exhibits efficiency similar to that of other plasma creating discharges currently used in non-equilibrium plasma chemistry for dissociating of chemical compounds.

The objective of this work is theoretical justification of technological and constructive parameters of the discharger setting and the operation mode of the reactor for polymer wastes recycling with the production of hydrogen and other marketable products.

2. Simulative experiment

Figure 1 shows a discharger that fits to the proposed reactor objective [17]. Nearly equal values of a, b, and c are used in Figure 1 for simplicity only. Based on analysis of the operating mode of a high-voltage pulse-periodic discharge in metal-vapour-lasers [16], we choose following conditions and parameter values for our mathematical model: the inert gas (helium) as a carrier of polymer waste and reagent molecules flow in the discharger; calcium as the reagent; 1500 K for the gas temperature; 30% for the discharge efficiency coefficient η; $10^{14}$, $10^{15}$, and $10^{16}$ cm$^{-3}$ for the concentration of recycling substances, $n$; $10^{17}$, $10^{18}$, and $10^{19}$ cm$^{-3}$ for the concentration of inert gas, $n_g$.

![Figure 1. Schematic images of the discharge device: 1 – electrodes, 2 – dielectric walls, u – gas flow rate](image_url)
Such conditions establish thermally equilibrium in the active zone of proposed plasma-chemical reactor, which simplifies our simulative experiment based on the proposed physico-mathematical model.

Since both excitation and dissociation of the association products cause energy losses, we use minimization of those energy losses for estimating the efficiency of proposed discharger. We also assume that the minimum time $\tau_{a\,\text{min}}$ and $\tau_{D\,\text{min}}$ of bulk association (recombination rate) of atoms and their diffusion onto the electrodes and walls of discharger exceeds by 10 times the residence time $t = \frac{c}{u}$ of the recycling-substance molecules within the discharge device: $\tau_{a\,\text{min}} = \tau_{D\,\text{min}} = 10\,t$.

Equation (1) determines the characteristic time of association as:

$$\tau_a = \frac{1}{\alpha n_Y n_X},$$

where $\alpha$ is the association coefficient, $n_X$ and $n_Y$ are concentration of polymer molecules (X) associated with each other and with the reagent atoms (Y) added into the discharge device, as a result of dissociation. Calculation was carried out for the condition: $n_X = n_{C2}, n_Y = n_{Cir}$.

The characteristic time and diffusion coefficient of the X-atoms in the discharger are reduce to [18]

$$\tau_D = \frac{\Lambda^2}{D},$$

$$D = \frac{3}{16n_g (\frac{r_g}{2} + r)^2} \left(2kT \frac{m_g + m}{\pi m_g m} \right)^{1/2}$$

where $D$ is the diffusion coefficient of the X-atoms within the inert gas; $\Lambda$ is the characteristic diffusion length such that $\Lambda^2 = \tau_D D$; $m_g$ and $r_g$ are the mass and the radius of the inert gas atoms, respectively; $T$ is the temperature of the inert gas; $m$ and $r$ are the mass and the radius of the X-atoms.

The pumping volumetric flow rate $\nu$ of the gas mixture is reduced to:

$$\nu = SU = \frac{cs}{0.1\tau_{a\,\text{min}}},$$

where $S=ab$ – a cross section of the gas flow.

The coefficient $\eta$ of discharging efficiency is calculated as the ratio of the energy $Q$ needed for breaking all chemical bonds of the recycling substance molecule to the energy introduced into the discharger per such molecule. Knowing the pumping volumetric flow rate of the gas mixture $\nu$, the energy $Q$, one can calculate the required capacity $W$ of power source, the rate $P$ of recycling, and the frequency $f$ of discharge pulses

$$W = \frac{\nu n Q}{\eta},$$

$$P = \nu n M,$$

$$f \geq f_{\text{min}} = \frac{W\eta Vn Q}{},$$

where $M$ is the mass of recycling substance molecules and $V$ is the volume of discharge gap. We use the equations (1) to (6) for simulating discharging process applicable to the recycling of polymeric wastes, such as polyethylene, polyvinylchloride, and polyethylene terephthalate.
The concentration of calcium atoms $n_{Ca}$ needed for a particular recycling substance can be written as

$$n_{Ca} = \theta n,$$

(7)

where $\theta$ determines the maximum number of Ca atoms that could react with an atom formed as a result of dissociation of polymer molecules. The value of $\theta$ is 3 for polyethylene terephthalate, 0.5 for polyethylene, and 1.5 for polyvinylchloride [17].

We use the equation (1), $\alpha = 2.98 \times 10^8 \text{cm}^2/\text{s}$ as an estimated value of the association coefficient $\alpha$, $n_Y = n_{Ca}$, and $n_Y = n_{Ca}$ for estimating the numerical value of the recombination rate $\tau_{D \min}$ of Ca and C$_2$ atoms at a temperature of 1500 K, according to [17]. The value of $\tau_{D \min}$ was calculated from the equation (2) for the hydrogen atom.

3. Results and discussion

Tables 1 and 2 display results of our simulative experiment with discharging in the plasma-chemical reactor.

| Table 1. Parameters of the discharger$^a$. |
|---------------------------------------------|
| # | $n_g$ | $n_i$ | $c_r$ | $u_i$ | $W_i$ | $f_r$ | $c_r$ | $u_i$ | $W_i$ | $f_r$ |
|----|-------|-------|------|------|------|------|------|------|------|------|
| 1  | 1 × 10$^{-17}$ | 1 × 10$^{-14}$ | 16.61 | 2.47 | 383771 | 0.149 | 9.59 | 4.29 | 456596 | 0.447 | 6.78 | 6.06 | 1440243 | 0.894 |
| 2  | 1 × 10$^{-17}$ | 1 × 10$^{-13}$ | 5.25 | 7.83 | 1213593 | 1.49 | 3.03 | 13.55 | 443882 | 4.47 | 2.14 | 19.17 | 455444 | 8.94 |
| 3  | 1 × 10$^{-17}$ | 1 × 10$^{-16}$ | 1.66 | 24.75 | 3837719 | 14.9 | 0.96 | 42.86 | 456596 | 4.47 | 0.68 | 60.62 | 1440243 | 89.4 |
| 4  | 1 × 10$^{-18}$ | 1 × 10$^{-14}$ | 1.66 | 2.47 | 3838 | 1.49 | 0.96 | 4.29 | 4566 | 4.47 | 0.68 | 6.06 | 1440 | 8.94 |
| 5  | 1 × 10$^{-18}$ | 1 × 10$^{-15}$ | 0.53 | 7.83 | 12136 | 14.9 | 0.30 | 13.55 | 4439 | 4.47 | 0.21 | 19.17 | 45544 | 8.94 |
| 6  | 1 × 10$^{-18}$ | 1 × 10$^{-16}$ | 0.17 | 24.75 | 38377 | 149 | 0.1 | 42.86 | 45660 | 4.47 | 0.07 | 60.62 | 144024 | 89.4 |
| 7  | 1 × 10$^{-19}$ | 1 × 10$^{-14}$ | 0.17 | 2.47 | 38 | 149 | 0.1 | 4.29 | 46 | 4.47 | 0.07 | 6.062 | 144 | 89.4 |
| 8  | 1 × 10$^{-19}$ | 1 × 10$^{-15}$ | 0.05 | 7.83 | 121 | 149 | 0.03 | 13.55 | 144 | 4.47 | 0.02 | 19.17 | 455 | 89.4 |
| 9  | 1 × 10$^{-19}$ | 1 × 10$^{-16}$ | 0.02 | 24.75 | 384 | 1490 | 0.01 | 42.86 | 457 | 4.470 | 0.007 | 60.62 | 1440 | 8940 |

$a$ $n$ and $n_g$ – concentrations of the recycling substances and inert gas, $c_r$ – length and $u$ – gas flow rate, $W$ – the capacity of power supply, $f_r$ – frequency of the discharge pulses.

According to data from table 1, the value of the gas flow rate $u$ lies in the range from 2.47 to 60.62 m/s for polyethylene, from 4.29 to 42.86 m/s for polyvinylchloride, and from 6.78 to 60.62 m/s for polyethylene terephthalate. Several tens m/s rate of permanent flow is difficult to achieve in the closed reaction chamber. However, significant reduction of the gas flow rate can be achieved by using periodic pulsed-discharges. In this case the length of the discharger can be significantly increased in comparison with the transverse dimensions. Then the duration $t_{dis}$ of the discharge can be $t_{dis} = \tau_g$ and $t_{dis} = \tau_D$ while the residence time of recycled molecules can be increased, $t = k \tau_{min}$, $k \geq 1$, in order to minimize the energy loss due to dissociation and excitation of molecules formed during association of dissociation products with each other and with the reagent.

Further, the productivity of the reactor was estimated for a separate power supply (table 2). For example, for the conditions of $n_g = 1 \times 10^{-18}$ cm$^3$ and $n = 1 \times 10^{-16}$ cm$^3$ the capacity of power supply is 38377 J/s (table 1). Then according to table 2 the productivity of the reactor under these conditions will be found: 1.31 kg of CaCl$_2$, 0.08 kg of H$_2$, will be obtained per an hour; this will require 0.82 kg of Ca. Thus, the productivity of polyethylene recycling is 0.57 kg/h. For the same conditions, the capacity of the plasma-chemical reactor for the polyvinyl chloride recycling is 1.47 kg/h.

We received the following productivity for the power supply capacity of 50 kW: 0.74, 1.6 and 1.11 kg/h, respectively for polyethylene, polyvinylchloride and polyethylene terephthalate.
It should be noted that the composition of the recycling products includes hydrogen. According to our calculations, about 1727 MJ of electricity is required to produce 1 kg of chemically pure hydrogen during recycling of polyethylene compared to the calculations in [19], where about 200 MJ of electricity gave 1 kg of hydrogen using the industrial electrolyzers. Thus, if the efficiency of electric energy introduced into the discharge, is increased from 0.3 to 0.9 (energy costs will decrease to 576 MJ per kg of hydrogen), and take into account that the recycling of polyethylene is combined with the destruction of polymer waste and the possibility of obtaining valuable carbides (for example, silicon carbide), it is necessary to consider the plasma-chemical technology for producing hydrogen from polymer wastes, as an important and promising one.

Table 2. Output of polymer recycling products and reagent costs, kg/h.

| # | \( n_\text{g} \) cm\(^{-3} \) | \( n_\text{s} \) cm\(^{-3} \) | Polyethylene | Polyvinylchloride | Polyethylene terephthalate |
|---|---|---|---|---|---|
| CaC\(_2\) | H\(_2\) | Ca | CaC\(_2\) | H\(_2\) | CaCl\(_2\) | Ca | CaC\(_2\) | H\(_2\) | CO | Ca |
| 1 | 1-10\(^{-7}\) | 1-10\(^{-14}\) | 13.08 | 0.82 | 8.17 | 15.1 | 0.71 | 13.08 | 14.17 | 32.03 | 1.33 | 18.66 | 20.03 |
| 2 | 1-10\(^{-7}\) | 1-10\(^{-15}\) | 41.35 | 2.58 | 25.83 | 47.75 | 2.24 | 41.35 | 44.8 | 101.3 | 4.22 | 59.01 | 63.35 |
| 3 | 1-10\(^{-7}\) | 1-10\(^{-16}\) | 130.8 | 8.16 | 81.68 | 151 | 7.07 | 130.8 | 141.7 | 320.3 | 13.33 | 186.6 | 200.3 |
| 4 | 1-10\(^{-8}\) | 1-10\(^{-14}\) | 0.13 | 0.008 | 0.08 | 0.15 | 0.007 | 0.13 | 0.14 | 0.32 | 0.01 | 0.19 | 0.20 |
| 5 | 1-10\(^{-8}\) | 1-10\(^{-15}\) | 0.41 | 0.03 | 0.26 | 0.48 | 0.02 | 0.41 | 0.45 | 1.013 | 0.04 | 0.59 | 0.634 |
| 6 | 1-10\(^{-8}\) | 1-10\(^{-16}\) | 1.31 | 0.08 | 0.82 | 1.51 | 0.07 | 1.31 | 1.42 | 3.20 | 0.13 | 1.87 | 2.00 |
| 7 | 1-10\(^{-9}\) | 1-10\(^{-14}\) | 0.001 | 8.10\(^5\) | 8.10\(^4\) | 0.002 | 7.10\(^3\) | 0.001 | 7.10\(^2\) | 0.001 | 1.10\(^4\) | 0.002 | 0.002 |
| 8 | 1-10\(^{-9}\) | 1-10\(^{-15}\) | 0.004 | 3.10\(^4\) | 0.003 | 0.005 | 2.10\(^3\) | 0.004 | 0.004 | 0.01 | 4.10\(^4\) | 0.006 | 0.006 |
| 9 | 1-10\(^{-9}\) | 1-10\(^{-16}\) | 0.01 | 8.10\(^4\) | 0.008 | 0.015 | 7.10\(^3\) | 0.013 | 0.014 | 0.03 | 0.001 | 0.02 | 0.02 |

n and \( n_\text{g} \) - concentrations of the recycling substances and inert gas.

The optimal dimensions of the discharger \((a, b)\) shown in Table 3 are estimated by

\[
a = b = \left( \frac{W_{\text{re}}n}{u_{\text{re}}nQ} \right)^{1/2},
\]

where \( n_\text{g} = 10^{18} \text{ cm}^{-3} \) and \( n = 10^{16} \text{ cm}^{-3} \), the required gas flow rate through the discharger \( u = 1 \text{ m/s} \), the required discharger length \( c \) of 0.5 m and the capacity of the pulse-periodic discharge power supply \( W \) of 5 kW.

Power supplies for the pulsed-periodic discharges meet power supplies Russian industry manufactures for the copper vapor lasers [17]. The energy of 2.5 kJ in each pulse is achieved at a discharge frequency \( f \) of 2 Hz with such power supplies. The \( t_{\text{dis,max}} \) values are obtained and shown in the Table 3 for the maximum permissible discharge duration of \( t_{\text{dis,max}} = 0.1 \tau_w \).

Table 3. The required values of the transverse dimension \( a, b \) of the discharger, the maximum permissible discharge duration \( t_{\text{dis,max}} \).

| Recycling substance | \( a = b \) m | \( t_{\text{dis,max}} \) \( \mu \text{s} \) |
|---------------------|-------------|----------------|
| Polyethylene        | 0.30        | 6711           |
| Polyvinylchloride   | 0.21        | 2237           |
| Polyethylene terephthalate | 0.10 | 1119           |

Commutation of energy on the order of 1 kJ is known as a serious technical problem, therefore rotary arresters are considered as the most suitable switches. According to [20, 21] the following switching parameters are reached: switching voltage from 25 to 40 kV, pulse duration from 50 to 1000 ns, pulse frequency from 50 to 400 Hz, switching energy from 19 to 1000 J. The values of the maximum permissible discharge duration (table 3) can significantly reduce the energy commutated in one pulse by switching to a discharge excited by a pulse train with a total number up to 100 pulses or more.
The results show that by adjusting the gas flow rate through the discharger and changing the concentration of the recycling substance molecules, the same discharger with transverse dimensions of about 10x10 cm can be used for recycling of all the considered polymer wastes.

4. Conclusion
In the work we theoretically justified technological and constructive parameters of the discharger setting the operation mode of the reactor for polymer wastes recycling with the production of hydrogen and other marketable products. It has been revealed that the conditions of reactor operation are characterized by the values of gas flow rates from 1 to 10 m/s, that can be implemented in a closed reaction chamber, and power supply capacities about 5 kW, which lie in the range of capacities of industrial power supplies of lasers at self-limited transitions. We determine geometric dimensions of reactor, capacity of the discharge power supply, gas flow rate, productivity, and the pulse frequency of the discharge device. Operating conditions of the discharger is calculated for polyethylene, polyvinylchloride, and polyethylene terephthalate (concentrations of $10^{14}$, $10^{15}$ and $10^{16}$ cm$^{-3}$) in the atmosphere of inert gas atoms (concentrations of $10^{17}$, $10^{18}$ and $10^{19}$ cm$^{-3}$).

The maximum permissible discharge durations are 6711, 2237 and 1119 μs for polyethylene, polyvinylchloride and polyethylene terephthalate, respectively. The values are calculated for the condition of 1 m/s gas flow rate and 2 Hz frequency of pulsed-periodic discharge in the device that does not exceed 0.5 m in size and works with 5 kW power supply that meets ones produced for copper vapor lasers.

Thus, all prerequisites exist for establishing design and manufacturing an experimental sample of plasma-chemical recycling reactor for decomposing polymer wastes and producing hydrogen.

The proposed technology also enables polymer waste recycling with reduced energy consumption. This technology uses energy released during the process of association of dissociation products with each other and with the reagent for partial dissociation of the recycling substance molecules.

The proposed technology can be used in large-capacity plants recycling various polymeric wastes. Such plants should use modular units because of a limited power of industrial power supplies for pulsed-periodic discharge lasers on self-limited transitions.

References
[1] Huan S J (1995) Polymer waste management—biodegradation, incineration, and recycling. J. Macromol. Sci. A, 32, 4 593
[2] Plastic waste: ecological and human health impacts (2011) Science for Environment Policy. In-depth Reports. DG Environment Alert Service, European Comission.
[3] Andrady A (1994) Assessment of environmental biodegradation of synthetic polymers. Polym. Rev. 34 25
[4] Oehlmann J, Oehlmann, Schulte-Oehlmann U, Kloas W, Jagnytsch O, Lutz I, Kusk K O, Wollenberger L, Santos E M, Paull G C, Van Look K J W and Tyler C R (2009) A critical analysis of the biological impacts of plasticizers on wildlife. Philos. Trans. R. Soc. B. 364 2047
[5] Swift G and Wiles D (2004) Degradable polymers and plastics in landfill sites. Encycl. Polym. Sci. Technol. 9 40
[6] Saleem J, Riaz M A and McKay G (2018) Oil sorbents from plastic wastes and polymers: A review. J. Hazard. Mater. 341 424
[7] Zhou C, Fang W, Xu W, Cao A and Wang R (2014) Characteristics and the recovery potential of plastic wastes obtained from landfill mining. J. Clean. Prod. 80 80
[8] Geyer R, Jambeck J R and Law K L (2017) There are 8.3 billion tons of plastic in the world Sci. Adv. 3,7 1700782
[9] Bazargan A, Hui C W and McKay G (2013) Porous carbons from plastic waste. in: Porous Carbons – Hyperbranched Polymers – Polymer Solvation. Long T, Voit B, Okay O (eds) Adv. Polym. Sci. 266. (Springer, Cham) pp.1-25
[10] Siddique R, Khatib J and Kaur I (2008) Use of recycled plastic in concrete: a review. *Waste Manage.* **28** 1835–1852

[11] Hamad K, Kaseem M and Deri F (2013) Recycling of waste from polymer materials: An overview of the recent works, *Polym. Degrad. Stabi.* **98** 2801

[12] Punčochář M, Raj B and Chatterjee P K (2012) Development of process for disposal of plastic waste using plasma pyrolysis technology and option for energy recovery. *Procedia Engineer.* **42** 420

[13] Pitea D, Lasagni M and Collina E (1994) Innovative thermal technologies for treating or destroying hazardous organic wastes. in *Technologies for Environmental Cleanup: Toxic and Hazardous Waste Management.* Avogadro A, Ragaini RC (eds) (Springer, Dordrecht) pp.57-100

[14] Mossé A L, Savchenko G É, Vlasov V A, Karengin A G, Karengin A A and Levashov A V (2013) Plasma plant for processing of wastes: design variants and technological application. *J. Eng. Phys. Thermophy.* **86** 651

[15] Messerle V E, Mosse A L and Ustimenko A B (2016) Plasma gasification of carbonaceous wastes: thermodynamic analysis and experiment. *Thermophys. Aeromech.* **23** 613

[16] Batenin V M, Buchanov V V, Boichenko A M, Kazaryan M A, Klimovskii I I and Molodykh E I (2017) *High-brightness Metal Vapour Lasers. Volume I: Physical Fundamentals and Mathematical Models* (CRC Press and Taylor & Francis Group) p.542

[17] Bulychev N A, Kazaryan M A, Sachkov V I and Feofanov I N 2014 Calculation of kinetics constants of two-atom molecules in plasma, in Proc. All-Rus. Workshop “Physical and Technocal Aspects of Materials and Technologies Sciences in Nuclear Industry”, June 15-19 2014, Zvenigorod, pp.115-116 [in Russian]

[18] McDaniel E W (1964) *Collision Phenomena in Ionized Gases* (NewYork: John Wiley and Sons)

[19] Tarasov B P and Lototsky M V (2006) Hydrogen for energy release: problems and perspectives. *Alternative Energy and Ecology,* **8,**40** 72 [in Russian]

[20] Bickes C, Bochkov V D, K Frank and O B Frants (1997) Development of sealed-off pseudospark switches for pulsed power, in *Proc. XIIth Int. Conf. on Gas Discharges and Their Applications,* Greifswald, Germany, September 8-12 1997, vol.1. pp. 218-221.

[21] Bogolyubov E P, Bochkov V D, Veretennikov V A and Vekhoreva L T (1998) A powerful soft X-Ray source for X-Ray lithography based on plasma focusing. *Physica Scripta.* **57** 488