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Development of Gas Tunnel Type High Power Plasma Jet†

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Abstract

A new type of high power plasma jet were developed and its fundamental characteristics were clarified.

High energy density plasma beam can be generated in a "gas tunnel" produced by a strong vortex flow with a high flow rate. And it can be ejected as a high power plasma jet from the torch. It is easier to obtain extremely high power plasma jet with this "gas tunnel type" than with the conventional type.

The characteristics of the gas tunnel type of plasma jet are follows;

1) high voltage,
2) high thermal efficiency,
3) high energy density.

KEY WORDS: (Plasma Jet) (Gas Tunnel) (Vortex Flow) (High Power) (High Voltage)

1. Introduction

The plasma jet, currently being put to various industrial applications, was not developed until the late 1950s[1,2,3]. In the initial stage of studies, water was employed as the working fluid, causing excessive consumption of electrodes, making it hard to obtain stable plasma. For this reason, it was not tried as a new high temperature heat source, being confined within the range of academic research.

However, in the studies on arc, various stabilization methods were designed. And the studies[4] on an energy transfer were carried out, resulting the advanced applications of the arc to the engineering fields. For example, the inert gas sealded arc using tungsten electrodes (TIG arc), which makes it easy to obtain stable plasma, had already found applications in welding. And, a high temperature, high velocity plasma jet obtained by fitting a water-cooled copper nozzle to the top of this TIG arc torch was tried to apply to the cutting of metal materials[5,6]. The plasma ejected from the torch by generating an arc between the electrode and the nozzle electrode, constricted by the nozzle wall and the working gas, is called "plasma jet". This plasma jet is characterized by being a high temperature heat source with high energy density as well as an extremely high velocity.

The remarkable progress made with the plasma jet since then has allowed versatile engineering applications including melting and processing (cutting, welding, metallizing, etc.) of metal materials, and high temperature chemical reaction[7,8,9,10,11,12,13].

The plasma jet, due to its easy operation in addition to reduced heat generating costs, high power, high temperature and high thermal efficiency, would be certainly applied in an ever widening range of fields. However, with the conventional plasma jet it was difficult to obtain any higher output due to such problems as the damage of electrodes. The plasma jet most generally used has an output of only 100 kW or less.

In this study, we attempted to obtain a high temperature, high energy density, high power plasma jet by generating a plasma beam in a "gas tunnel" designed to provide extremely powerful thermal pinch effects, and investigated its basic characteristics.

2. Experimental Apparatus

Figure 1 shows the block diagram of the experimental apparatus for the high power plasma jet. Power was provided by six DC power sources with a rated current of 1500A and load voltage of 50 V, allowing both serial and parallel arrangement by simply switching over the wiring. A maximum 450 kW output can be obtained by using these power sources.

Figure 2 is a sectional view of the high power plasma jet developed for this study. In this figure, (A) is the

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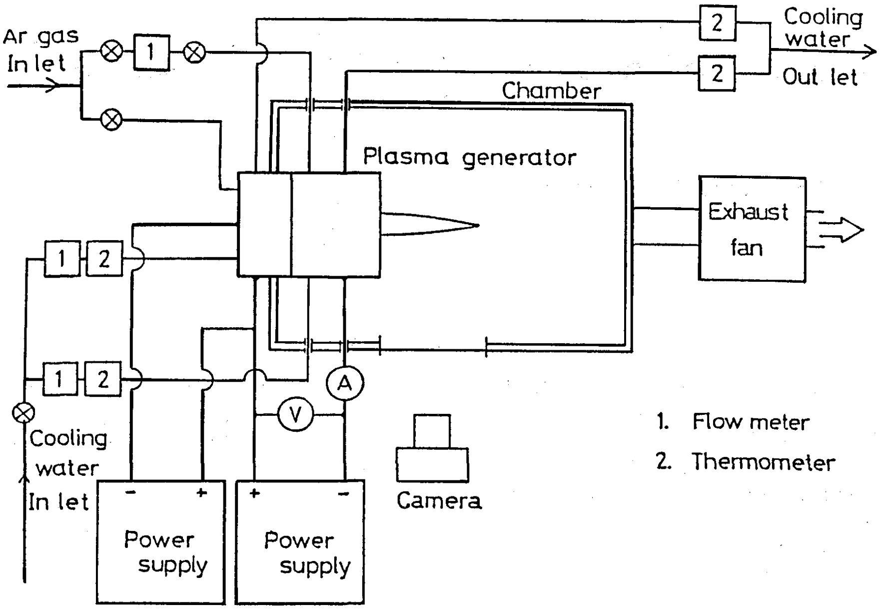

Fig. 1 Block diagram of experimental apparatus for high power plasma jet.

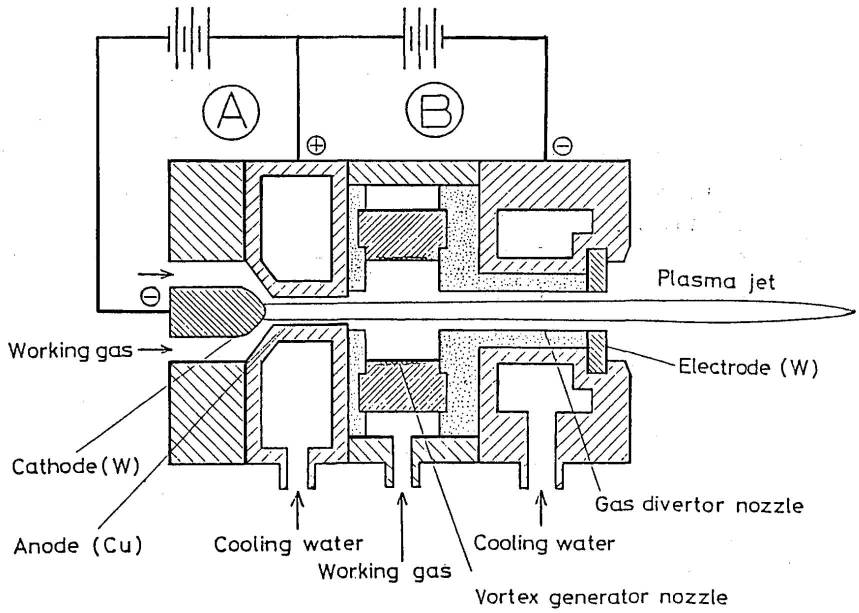

Fig. 2 Schematic diagram of plasma jet generator.

plasma jet gun for igniting the high power plasma jet, which features a similar construction and function as that of the conventional plasma jet. (B) is the gas tunnel generator, consisting of the vortex generator and gas divertor nozzle (electrode). This vortex generator, provided with numerous small holes in its circumference, forms a vortex with excellent axial symmetry. The large volume of gas ejected from these small holes (vortex generator nozzle) is provided with radial velocity by the gas divertor nozzle, forming the radial pressure distribution with an sharp gradient inside the vortex chamber. This forms a sort of gaseous wall, i.e. "gas wall", which generates a low-vacuum (vortex) gas tunnel in the vicinity of its inner central axis[14,15]. Discharge inside this gas tunnel is called "gas tunnel discharge".

The plasma jet is generated as follows. Argon gas is fed into the water-cooled plasma jet generator in order to form the gas tunnel at the central axis of the vortex generating unit. Then, the plasma jet is initiated and led into the gas tunnel by the conventional method; on applying high voltage between the two electrodes, a high current flows, starting the gas tunnel discharge, generating the high energy, high power plasma jet.

In this study, the gas divertor nozzle (electrode) was used as cathode; but by changing the power source wiring, it may also be used as anode. The voltage between electrodes varies depending on the inner diameter of the gas divertor nozzle, the length of the vortex chamber, gas flow rate and pressure level of the vortex working gas. Incidentally, in this study, the distance between electrodes was kept a constant 4.6 cm.

Compared to the conventional plasma jet, the plasma jet generated by this method guarantees a high energy plasma column with optimum stability and an extremely high electrical potential gradient, due to the formation of the gas tunnel by a strong vortex.

3. Basic Characteristics of the High Power Plasma Jet

3.1 Current-voltage characteristics

The current-voltage characteristics of the conventional plasma jet, though varying depending on the gas flow rate, the torch shape, the type of the gas used etc., generally show decreasing voltage characteristics. Under high current, it shows constant-voltage characteristics, the voltage being about 50 V. The gas tunnel (discharge) type plasma jet developed through this study, however, shows current-voltage characteristics as shown in **Fig. 3**, in which the voltage tends to increase from a fairly low-current range; voltage increases linearly with the increase in current. The figure shows an example of argon as working gas, gas flow rate of 400 ℓ/min and gas divertor nozzle diameter of 8 mm; at the current level of 900 A, voltage exceeds 200 V. The electrical potential gradient of the plasma jet is estimated to be about 45 V/cm. The current-voltage characteristics of the conventional plasma jet when using argon as working gas is also shown in Fig. 3, where the voltage is as low as 40-50 V and electrical potential gradient is 20 V/cm or less, presenting typical drooping characteristics.

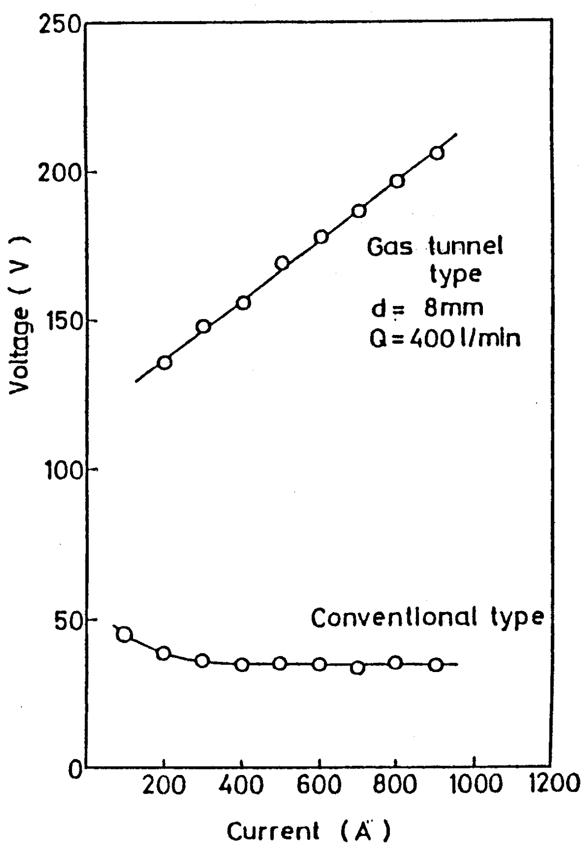

Fig. 3 Current-voltage characteristics of plasma jet.

Figure 4 shows the voltage characteristics when gas divertor nozzle diameter varies. The gas flow rate at this time is a constant 400 ℓ/min. The figure shows voltage at the current level of 500 A and 1000 A – at both values, as nozzle diameter decreases, the voltage shows a sudden rise, since the thermal pinch effect of the strong vortex is enhanced as the gas divertor nozzle diameter decreases. As a consequence, the plasma jet diameter is reduced, while the electrical potential gradient is increased. If gas divertor nozzle diameter remains constant, linear current-voltage characteristics as shown in Fig. 3 are obtained.

The correlation between gas flow rate and arc voltage is shown in **Fig. 5** for gas divertor nozzle diameter of 8 mm and current level of 200 A and 400 A. As gas flow rate increases, the plasma jet voltage increases linearly at either current level. The increase rate of voltage to gas flow rate, dV/dQ, remains constant, independent from current level, at 12.5 V/(100 ℓ/min). The fact that the voltage rises as gas flow rate increases is due to the enhanced thermal pinch effects of the strong vortex, just as when the gas divertor nozzle diameter is reduced.

3.2 Shape of the plasma jet

The high power plasma jet increases in output as the current increases, raising the plasma light luminance signifi-

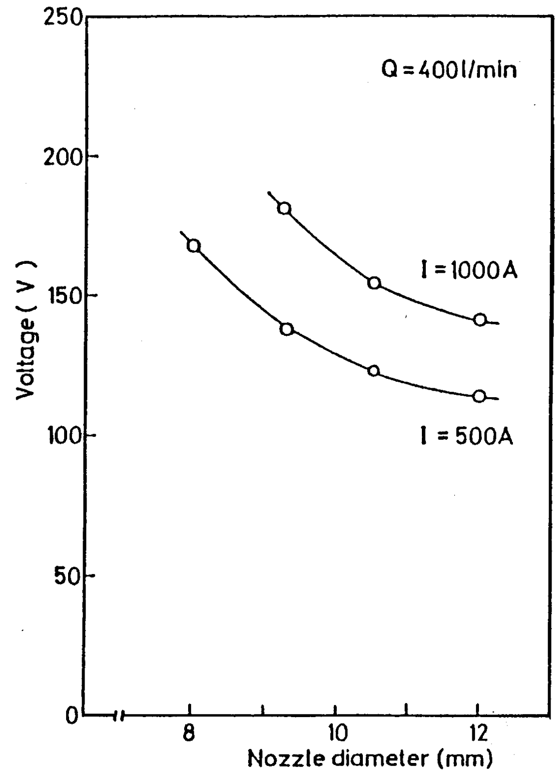

Fig. 4 Dependences of voltage on nozzle diameter.

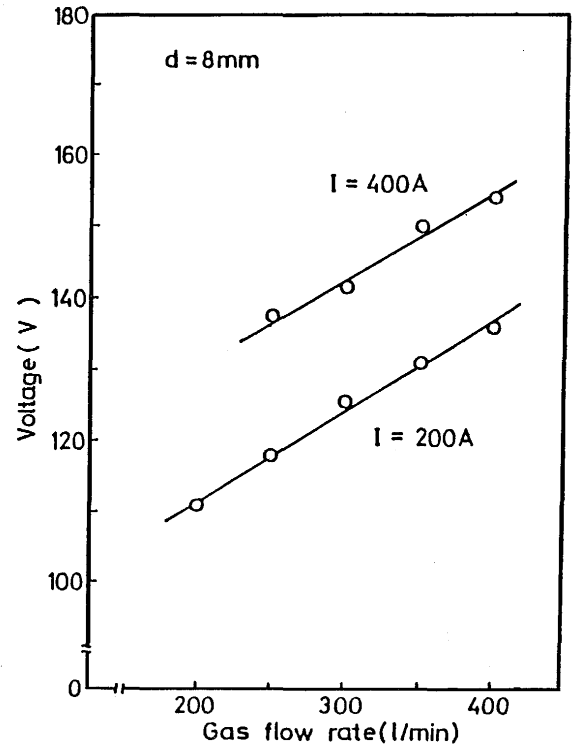

Fig. 5 Dependences of voltage on working gas flow rate.

cantly higher. Therefore, to take a photograph of the plasma jet, we used very strong filters. The shape of the plasma jet was found with this photo, and its length and diameter were respectively determined by the size of the highly luminous white core flame. Due to this measurement of the length and diameter, was investigated the effect of the thermal pinch by the strong vortex with a big flow rate.

Figure 6 shows the correlation obtained between the length and diameter of the plasma jet and the current, when gas divertor nozzle diameter is 8 mm and gas flow rate is a constant 400 ℓ/min. As current increases, the length of the plasma jet increases linearly at the rate of about 6 mm per 100 A; at higher current levels, a plasma jet as long as 50 mm or more can be obtained. The conventional plasma jet is about 30 mm when input is 50 kW, but this plasma jet was 43 mm long, almost 1.5 times longer, at the same input; this appears due to high temperature plasma ejection, and the thermal efficiency is enhanced as explained below.

The plasma jet diameter is also shown in Fig. 6, which shows that below 300 A, as the current is raised, the diameter gradually increases, while at a higher current level, the plasma jet attains the diameter of 7 mm, slightly smaller than the gas divertor nozzle diameter of 8 mm, remaining almost constant in relation to the increase in current. This is due to the remarkable thermal pinch effect of the strong vortex.

3.3 Thermal efficiency of the plasma jet

The electrical input for the plasma jet is given by the following equation:

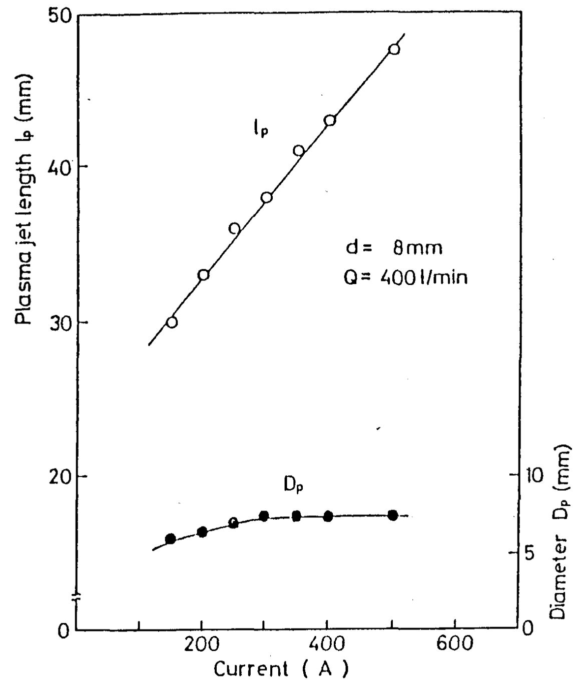

Fig. 6 Dependences of plasma jet length and its diameter on current.

$$P = IV = I(V_a + V_k + V_p)$$

where, I; current, V; voltage, V_a; anode drop voltage, V_k; cathode drop voltage and V_p; the so-called arc column voltage.

The electrical input for this plasma jet is ejected to the outside as the thermal energy of the plasma jet, except energy loss at the electrode and thermal loss into the torch wall from plasma column. The torch thermal loss can be experimentally determined by the temperature rise and the flow rate in the cooling water. The thermal efficiency of the plasma jet is determined by ((electrical input − torch thermal loss)/electrical input) × 100%. In this case, the input of the plasma jet gun is zero after generating the high power plasma jet produced by the gas tunnel discharge.

Figure 7 shows the thermal efficiency of the high power plasma jet at varying current levels. These results are with the gas divertor nozzle diameter of 10.5 mm and gas flow rate of 400 ℓ/min; in that case, the thermal efficiency reaches a maximum at the current level of 300 A, gradually decreasing as the current rises.

Under the experimental condition range, the thermal efficiency of the high power plasma jet of this study proved to be 80% or more, an extremely high value. This is due to the fact that the thermal loss was largely suppressed by the vortex flow with radial velocity, and that the plasma jet diameter was reduced by the thermal pinch effect of the strong vortex.

Figure 8 shows thermal loss at varying current levels of the torch during the measurement of the thermal ef-

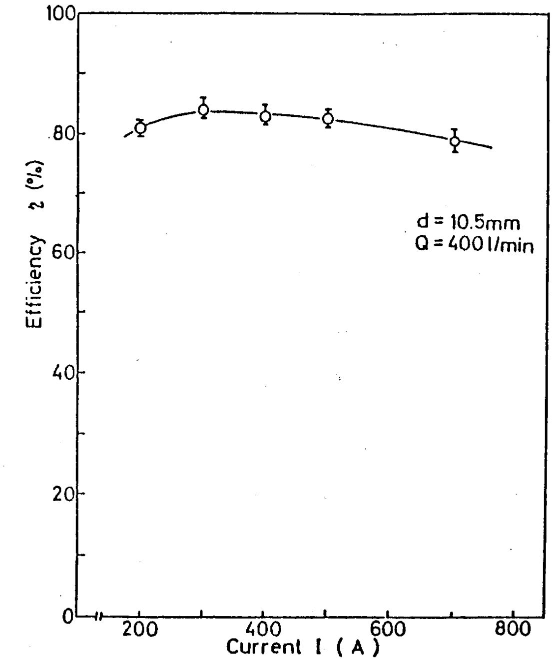

Fig. 7 Dependence of thermal efficiency of plasma jet on current.

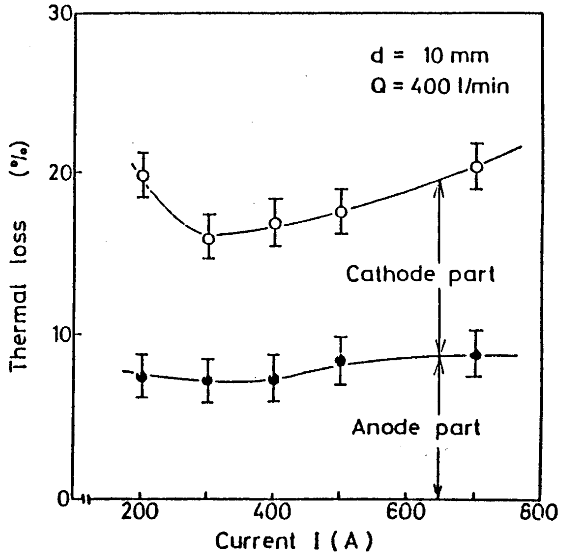

Fig. 8 Characteristics of thermal loss from plasma jet against current.

ficiency shown in Fig. 7. The thermal loss of the torch comprises that of anode and cathode, the minimum being about 16% at 300 A. The high power plasma jet uses inverse polarity – the nozzle electrode of the plasma jet gun as anode and the gas divertor nozzle electrode as cathode – as shown in Fig. 2. In this case, the thermal loss of a cathode part is large compared to the case of positive polarity because the cathode is located at the torch exit and given a large thermal load from the plasma jet, resulting in thermal loss more or less balanced between anode and cathode, for an extra design advantage.

Compared to the thermal efficiency (40 – 50%) of the conventional plasma jet, the high power plasma jet has nearly twice the thermal efficiency.

4. Discussion

In order to clarify the characteristics of the high power plasma jet developed in this study, comparison was made with the conventional plasma jet, the results are shown in **Table 1**. The experiments carried out in this study have clearly shown the high power plasma jet to have high electrical potential gradient, high thermal efficiency and high energy density. These phenomena have been attained by suppressed the plasma jet through thermal pinch effects and the protection of the electrode by means of the special strong vortex.

Table 1 Performances of high power plasma jet as compared with conventional plasma jet

	High power plasma jet	Conventional plasma jet
Electrical potential gradient	40 ~ 50 V/cm	10 ~ 20 V/cm
Output	200 kW	< 100 kW
Plasma temperature	20000 K	10000 K
Thermal efficiency	80%	50%

The plasma jet obtained by gas tunnel discharge, unlike the conventional plasma jet, is a high voltage type with an extremely large electrical potential difference, which allows extremely high power to be obtained. Moreover, by introducing the multi-stage layout, a super-high-power plasma jet generator capable of producing as high as several MW may also be feasible.

The thermal pinch effects of the special strong vortex constricts the plasma jet, resulting in high temperature and longer plasma. Moreover, since the loss in radial thermal conductivity is suppressed, thermal efficiency extremely higher than that of the conventional plasma jet is guaranteed, which should prove to be highly advantageous in actual application.

The high power plasma jet developed in this study features extremely optimum stability, making versatile engineering applications possible by taking advantage of the characteristics of such a high power plasma jet.

The use of this high power plasma jet featuring extremely high temperature and high energy density should prove to be highly efficient (higher velocity and greater efficiency than the conventional plasma jet) for melting metals with high melting points, melting ceramics and other insulating materials with high melting points, refining metals, and the like. Moreover, by using a large volume of working gas, any sort of high temperature gas or reduction gas may be directly and easily obtained in a large quantity without using the current method of passing it through heat exchangers.

Far higher quality and work efficiency can be attained in processing, surface treatment or metallizing of materials, if applied to metal materials with high melting points or various non-metal materials, such as ceramics, etc. The high temperature chemical reaction based on the high temperature of the plasma jet may also open roads to its application to the production of various synthetic substances, formation of crystals, production of spherical powders of high-purity alumina, degrading of poisonous substrances, etc.

5. Conclusions

The high power plasma jet obtained by the gas tunnel discharge developed through this study is characterized by an extremely high electrical potential gradient due to the high thermal pinch effect of the strong vortex, also featuring positive current-voltage characteristics. This in turn makes it extremely easy to give the plasma jet higher power. Besides, this gas tunnel discharge can be made in multiple stages, bringing about the possibility of a device to generate a super-high-power plasma jet or several MW.

This gas tunnel type plasma jet also has optimum stability; the plasma jet can be constricted through the thermal pinch effects of the special strong vortex, realizing higher temperature and longer plasma. This vortex suppresses the loss in the radial thermal conductivity, having extremely high termal efficiency when compared to the conventional plasma jet.

By making the best of the characteristics of the high power plasma jet, experimentally clarified through this study, the high power plasma jet may be used in a far wider range of applications as a high temperature heat source. And this plasma jet featuring high energy density will make possible its use in various new fields impenetrable for the conventional plasma jet.

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