§2. Development of a Source Plasma for High Power Electromagnetic Plasma Accelerator

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The key for production of a fusion grade high temperature plasma is in technology of intensive energetic beam. The EM (electromagnetic) acceleration presents the most powerful tool in principle because the work is done on the neutral object so that achievement of the beam density as high as $10^3 \sim 10^4$ times to the usual electrostatic one must not be very difficult. Nevertheless, no such demonstration has ever appeared. We ascribe the reason to the fact that the velocity of the initial plasma produced just after ionization of the inlet gas is subsonic: papers [1,2] conclude that the EM force accelerates the super sonic plasma flow but chokes the subsonic. The key, therefore, is in development of the source based on the entropy acceleration, which is the most effective way to boost up the flow to super sonic. The problem of entropy acceleration is reduced to the design of the nozzle. Because our test system has shown to be robust enough as no remarkable damage is seen even ~800 kW power input, we are encouraged to figure out the ideal nozzle for high power plasma acceleration.

We studied the extended Navier-Stokes below under the steady state quasi-straight cylinder model bearing the Laval nozzle in mind.

$$m_i n \vec{v}_i \nabla \bullet \vec{v}_i = -\nabla p + \nabla \bullet \vec{\pi}_i + \vec{j} \times \vec{B} \quad \text{---(1)}$$
$$\nabla \bullet (n\vec{v}_i) = 0 \quad \text{----(2)}$$

A simple rearrangement of the equations above tells the fluid driving forces are gradients of cylinder cross-section A, temperature T, total arc current J and viscosity. Note that the Laval nozzle boosts up the fluid by changing the cross-section. As the most peculiar aspect of the system, we see the singularity in the velocity at the thermal speed: the singular velocity moves to sonic speed if the fluid behaves adiabatically as usual cold gases . In the case of the plasma, we believe that the constant temperature model must be the best because of huge thermal conduction through electrons. We pursued ample survey of parameters for to figure out the best construction. And we reached to the conclusion that the Laval nozzle is not very efficient but much simpler wall constricted thin arc must be the one. This comes from the fact that dynamic viscosity of the plasma has the value as large as $10^4 \sim 10^5$ times to that of a cold gas. We

aware that even in the Laval nozzle viscosity plays the major role in the throat where subsonic turns into super sonic flow. In one sense our system is made up by the throat only. Figure 1 shows how initial slightly subthermal flow is accelerated into super thermal in a very small distance.

Acceleration of stagnant cold gas in the reservoir to the plasma flow impinging into the channel with nearly thermal speed can be achieved by large temperature difference between the arc and the gas. We may say, therefore, that constricted arc channel has exactly the same function to the Laval nozzle.

For detail theoretical study, we separated the nozzle in two parts: [1] the fully ionized plasma zone inside the channel and [2] the dissociation and ionization zone adjacent to the gas inlet port. In the part [1] we assume the plasma temperature to be constant along the channel since thermal conductivity of electron is quite large. Under this simplification the Navier-Stokes has analytic solution, of which typical examples are shown in Fig.1. In the part [2] we assume that the law of mass action for dissociation and the Saha relation are valid for ionization process. Then integration of the region [2] becomes also possible provided the temperature distribution is a given function.

The actual ideal plasma ejector nozzle is not at our hand yet. However, the basic concept briefly stated above gives us a good insight. We are now designing a new system to be tested soon.
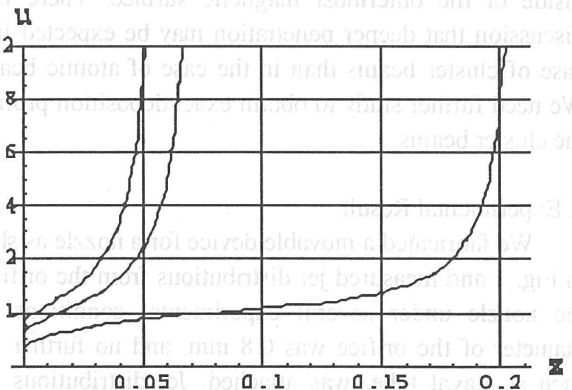

Fig.1. A plasma acceleration diagram by viscosity. **z** gives the relative distance of a channel 10 mm long and **u** the ratio of the flow to thermal speed. Initial sub thermal plasma is rapidly accelerated to super thermal in quite a small distance.

References :
[1] Hirano,K., Journal of Plasma and Fusion Research 69 (1993) 684
[2] Hirano,K., Journal of Plasma and Fusion Research 69 (1993) 806