A New Inductively Driven Plasma Generator (IPG6) – Setup and Initial Experiments

Michael Dropmann, Georg Herdrich, René Laufer, Dominik Puckert, Hannes Fulge, Stefanos Fasoulas, Jimmy Schmoke, Mike Cook, Truell W. Hyde

***Abstract*—As part of the partnership between the Center for Astrophysics, Space Physics and Engineering Research (CASPER) at Baylor University and the Institute of Space Systems (IRS) at the University of Stuttgart, a new design for a modular, inductively driven plasma generator (IPG) is being developed and tested within CASPER and the IRS. The current IPG design is built on a well-established heritage of modular inductively driven plasma generators designed and operated at IRS. This latest IPG source enables the electrode less generation of high-enthalpy plasmas and will provide CASPER researchers with the ability to operate with various gases at plasma powers of approximately 15 kW. It will also provide minimized field losses and operation over a wide scope of parameters not possible using existing designs requiring flow-controlled stabilization.**

The setup of the two facilities in Stuttgart (IPG6-S) and at Baylor (IPG6-B) is described and results from first characterization with air plasma are presented. Further, the objectives of the test facilities will be described shortly.

***Index Terms*—Inductively Coupled Plasma Source, Space Plasma Environment, Man-made plasma**

I. INTRODUCTION

As part of a collaborative partnership between the Institute of Space Systems (IRS) at the University of Stuttgart, Germany, and the Center for Astrophysics, Space Physics and Engineering Research (CASPER) at Baylor University, Waco, Texas, USA, the establishment of two, new, independent plasma simulation facilities has been conducted [1]. The IRS device in Stuttgart (IPG6-S) is equipped with a miniaturized inductively driven high enthalpy plasma source that has its heritage from the IRS IPG3, IPG4 and IPG5 [2]. The facility at Baylor University (IPG6-B) is based on the same heritage but has several modifications over the Stuttgart device including a higher operating frequency and an improved injector design. Both designs are based on the experience with plasma wind tunnel facilities at IRS, which are mostly used for experiments concerning the atmospheric entry of spacecraft [3]. Subsequent research and development programs over the past two decades within the IRS facility have led to the development of the plasma diagnostics [4] and modeling tools necessary to properly utilize both facilities [5].

A primary driver behind the construction of the IPG within the CASPER lab is to provide CASPER researchers with the ability to examine dusty plasmas at higher powers and using gas mixtures currently unavailable within a standard Gaseous Electronic Conference (GEC) reference cell. The ability of the IPG to examine dusty plasmas formed employing gases or gas mixtures that would normally be destructive to an electrode driven design opens new opportunities within the field. Additionally, the ability to examine plasmas within a much larger volume and at higher powers than that afforded by a GEC cell should also provide new experimental regimes for study.

Similar IPG designs have already produced plasmas representative of the solar chromosphere. Plasma conditions that can be used to predict the charging of spacecraft within the solar wind or the interaction of a hydrogen plasma with lunar dust should also be possible. Additionally, the higher heat loads that can be produced within the IPG will aid in examination of the role that dust plays at the divertor region within a fusion reactor. In addition to the degradation created on the divertor by such heat loads, the inside of the divertor can also be subject to degradation due to high velocity dust particles produced at the reactor walls. The IPG will provide an opportunity to explore this question using the external dust accelerator described later in this paper. (For a more detailed description of the above, please see [6].)

Each of the above opens new experimental regimes within the field; although, it is difficult at this time to predict exactly what long-term impact the IPG might have on dusty plasmas in general, the future appears promising.

This paper is organized as follows. Section 2 describes the development and installation of the facilities in detail as well as initialization studies that have already been conducted while Section 3 will provide initial results of these studies. Section 4 will present analysis and conclusions to date.

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II. IPG6 TEST FACILITIES

The two similar inductively heated plasma wind tunnels mentioned above are noted in this paper as IPG6-S (in Stuttgart) and IPG6-B (at Baylor). Both facilities began operation in 2011 and are currently under characterization. A basic description of the physics behind the two facilities is following below.

A. *Theoretical Background*

Inductively heated plasma generators (IPG) basically work in the same manner as a transformer. An HF current is fed into a coil, which creates an oscillating magnetic field in the direction of the coil's centerline. This oscillating magnetic field induces an azimuthal electrical field, which in turn induces a voltage in a coil, which surrounds the magnetic field. In the case of the plasma generators described in this paper, the primary coil surrounds a quartz tube containing the plasma. The plasma is created inside the tube and represents a secondary coil with a single turn with the resulting ohmic heating of the gas producing the plasma. Since the plasma has a dampening effect on the coil's magnetic field, the plasma is primarily heated within a ring shaped region; in other words, there is less power coupling on the centerline of the discharge channel. The dampening of the magnetic field increases with increasing operating frequency. As a result, most IPGs working at high frequencies use small discharge channel diameters in order to maintain a high efficiency. In the current case, the IPG6 works at 4 MHz in Stuttgart while the IPG6-B runs at 13.56 MHz. In Stuttgart, this diameter has been chosen to be only 40 mm leading to a compact plasma generator design while at Baylor, 13.56 MHz was chosen to avoid conflict with local radio regulations. Further information on both the background and theoretical description for IPGs can be found in [7].

B. *Plasma Generator IPG6*

IPG6 is a small, inductively heated plasma generator operating at moderate power levels of up to 20 kW and at high operating frequencies of 4 MHz in the IPG6-S facility or 13.56 MHz in the IPG6-B facility respectively. Its external dimensions are approximately 230 mm in length and 130 mm in diameter. A schematic view of the working principle of IPG6 is shown in Fig. 1.

Plasma is injected through an azimuthal flow component, which provides a stabilizing effect on the plasma [8], into the discharge channel, which has a diameter of 40 mm and a wall thickness of 1.5 mm. The discharge channel consists of a quartz tube; this tube is able to cope with high plasma temperatures while still allowing limited optical access to the plasma. The tube itself is surrounded by a coil, which induces the strong electromagnetic fields needed to ignite the plasma. This coil is approximately 80 mm in length and has 5.5 turns. It is made of 8 mm copper tubing and is water-cooled internally. Additional cooling water circulates around the quartz tube cooling both the tube and the coil. This highly effective water-cooling process allows the plasma generator to cope with the high heat loads it experiences. Unfortunately, the cooling imposes an additional design challenge. The steep temperature gradient produced in the quartz tube leads to enormous thermo-mechanical tensions, posing structural integrity issues for the brittle quartz. Investigations have shown that these tensions can be minimalized using thin walled quartz tubes [9]. An added benefit is provided by the fact that the thinner the wall thickness, the closer the plasma discharge is to the coil, leading to a higher geometrical degree of efficiency. Due to the new casing design used by the IPG6, this instrument family offers greater flexibility concerning the induction coil. The length of the coil no longer must remain fixed, as is the case for IPG3, IPG4 and IPG5. As a result, coils having arbitrary length and numbers of turns can be utilized in the IPG6. Thus, the effects of different lengths and winding densities can be easily analyzed. The primary remaining limitation concerning coil impedance is simply that it must be compatible to the power supply used.

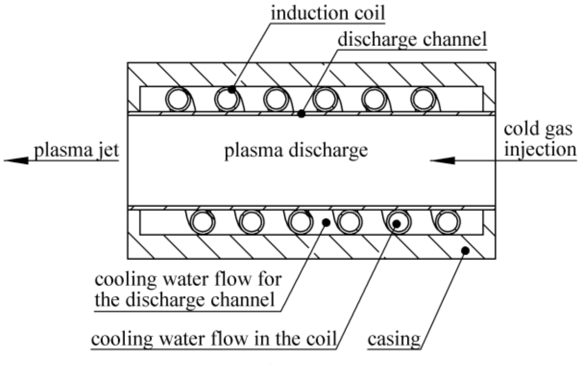

Fig. 1. Working principle of IPG6 as described in subsection B.

As mentioned previously, there are slight differences between the plasma generator design employed at the IPG6-S and IPG6-B facilities. For example, the gas injector design on the IPG6-B has been optimized and includes a window for optical observations of the plasma discharge. As part of the commissioning process, such modifications in the generator design are frequently conducted. As such, the collaboration between Stuttgart and Baylor allows for rapid design optimization between the two partners and facilities.

C. *Current Test Facility Setup*

The basic setup for both the IPG6-S and IPG6-B is similar. A schematic of the setups, showing the major subsystems, is given in Fig. 2 and Fig. 3 and a comparison of the subsystem parameters is given in Table 1. The IPG6-S employs a high energy power supply, Himmelwerk HGL 20-4B, which provides a high voltage DC supply feeding a Tetrode amplifier, which in turn amplifies a resonant circuit whose inductance is established by the IPG. In other words as is common with plasma systems, the operating frequency is load dependent and does not usually match the nominal frequency of 4 MHz. The anode current, respective of the power provided (which can be as large as 20 kW), is controlled by the screen grid voltage of the Tetrode. This ranges between 0 and 1.7 kV for a constant anode voltage of 8 kV. The IPG6-B is powered by a RF-Amplifier (SurePower® QL 15013 A). This amplifier operates

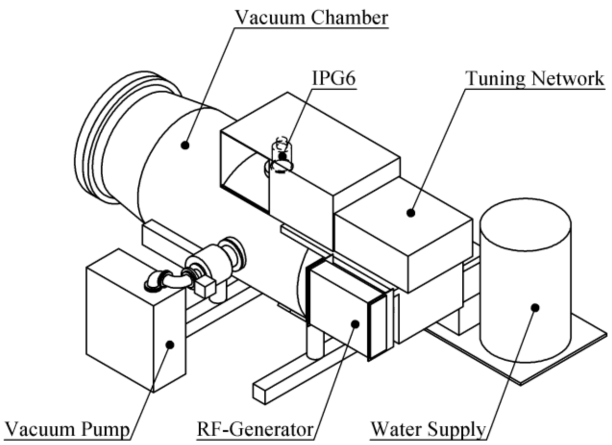

Fig. 2. Schematic setup of the IPG6-B facility showing its major subsystems. The single subsystems are described in subsection C.

at 13.56 MHz at powers up to 15 kW. Unlike the IPG6-S facility the operating frequency is fixed. In order to cope with the resulting impedance mismatch, an L-Type tuning network is operated between the amplifier and the IPG.

Both facilities use a closed cooling water circuit to cool the IPG, the power supply and any auxiliary equipment needing cooling. In both cases, the cooling water reservoir holds about 250 l of water and employs either a heat exchanger (IPG6-S) or a chiller (IPG6-B).

The vacuum system for the IPG6-S consists of a cylindrical vacuum chamber of 400 mm diameter and length and a rotary vane pump with a pumping speed of 400 m^3/h. The IPG6-B has a chamber of 2 m length and 1 m diameter. In this case, the IPG plasma head is perpendicular to the centerline due to the availability of ports. The vacuum system used consists of two stages; a rotary vane pump plus a roots pump, providing a total pumping speed of 160 m^3/h.

Gas is supplied by a pressure vessel and is controlled by a flow controller or needle valve.

A list of the major subsystems and the differences between the facilities is given in Table 1.

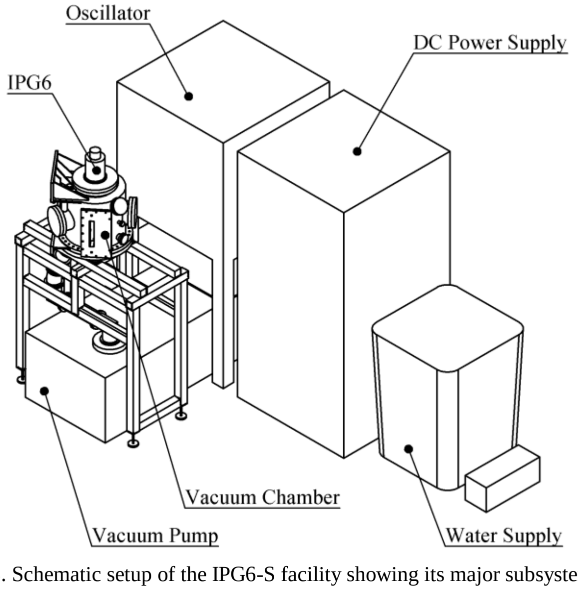

Fig. 3. Schematic setup of the IPG6-S facility showing its major subsystems. The single subsystems are described in subsection C.

TABLE I
SUBSYSTEMS OF THE IPG6 TEST FACILITIES

Subsystem	IPG6-S	IPG6-B
Plasma generator	IPG6	IPG6
Energy Supply	Himmelwerk HGL 20-4B P_{max}=20 kW f=approximately 4 Mhz (depends on IPG Impedance)	SurePower® QL 15013 A P_{max}=15 kW f=13.56 Mhz L-type tuning network
Vacuum chamber	Cylindrical chamber of 400 mm diameter and length	Cylindrical chamber of 1 m diameter and 2 m length
Vacuum pump	Rotary vain pump with a pumping speed of 400 m³/h Base pressure: approx. 3 Pa	Two stage vacuum system of a rotary vain pump and a roots pump with a total pumping speed of 160 m³/h Base pressure: approx. 1 Pa
Water cooling system	Closed circuit with 250 l water	Closed circuit with 250 l deionized water
Diagnostics	Injector pressure Chamber pressure Pitot probe Current monitor IPG cooling Cavity Calorimeter	Chamber pressure Pitot probe Cavity calorimeter Oxygen sensor system

D. Similar Test facilities

Several other institutions around the world operate inductively heated plasma generators. Facilities with powers ranging from a few kW to one MW are in use. Higher power facilities have larger discharge channel diameters and thus operate at lower frequencies (down to 500 kHz) while lower power facilities have smaller dimensions and operate at frequencies of up to 64 MHz. A list of currently active inductively heated plasma facilities and their operating parameters is given in Table 2.

E. Diagnostics and Additional Equipment

Currently several measurement systems are under development for use by the IPG6 facilities. Such diagnostics are necessary for both proper characterization of the plasma generator and to conduct the initial campaign of scientific experiments. In addition to the diagnostics listed below various electric parameters are measured. In case of IPG6-S these are screen grid voltage, anode current, anode power and operating frequency. In IPG6-B these are forward power, load power, reflected power and tuning network capacitor positions.

Cavity Calorimeter

A cavity calorimeter is an instrument commonly used to characterize the plasma generator both energetically and by performance. It works in a manner similar to a heat exchanger: Hot plasma enters the cavity cone through an entrance hole that is 50% larger in diameter than the quartz tube of the IPG6.

TABLE II
COMPARISON OF DIFFERENT INDUCTIVELY HEATED PLASMA GENERATORS (CURRENTLY ACTIVE)

Generator	Technical Specification				Operational Data			Ref
	P_{supply} [kW]	P_{anode} [kW]	F [MHz]	Ø [mm]	Working gas	Typical Flow Rate	Pressure [kPa]	
IRS, Stuttgart, Germany								
IPG3 to 5	375	-	0.5-1.5		N_2, O_2, H_2, Ar, CO_2, Air	<10 g/s	<1	[7]
IPG6-S	34	20	4		Ar, Air	<0.5 g/s	<0.5	-
CASPER, Waco, USA								
IPG6-B	15	-	13.56		Air, N_2, O_2 (H_2 planned)	<0.5 g/s	<0.5	-
IPM RAS, Moscow, Russia								
IPG1	60	30	11		Ar, CO_2, Air	1.2 g/s	100	[10]
IPG2	90	60	17		N_2, O_2, Air	2-3 g/s	5-100	
IPG3	1000	750	0.44		N_2, Air	8-11 g/s	1-30	
IPG4 IPM	100	80	1.76		N_2, O_2, H_2, Air, CO_2, Air, organic gas	2-5 g/s	1-100	
VKI, Brussels, Belgium								
Plasmatron	1200	-	0.4		Air, CO_2, Air	6 g/s	0.004-100	[11]
Minitorch	15	-	27		CO_2	1 g/s	2-100	
LAEPT, Clerment, Ferrant, France								
ICP T64	-	3	64		Ar, N_2, CO_2, Air, gas mixtures	0.2 g/s	-	[12]
CORIA, Rouen, France								
ICP torch 1	-	2	13.56		CO_2	0.1-0.3 slm	0.1-0.2	[13]
ICP torch 2	-	100	1.7		N_2, CO_2, Ar	18 l/min	2	[14]

Inside the cavity, the plasma stream transfers a majority of its power to the calorimeter walls and inner pipes through convection, radiation and recombination. This power is then transferred to the cooling water which flows through copper pipes on the outside of the cavity and helix-shaped pipes inside the cavity [15] and the recombined gas exits the calorimeter with a specific residual thermal and kinetic energy. Fig. 4 shows a cross-sectional drawing and the finished calorimeter.

The temperature of the cooling water is measured at both the inlet and exit. The volume flow rate is also measured. From the definition of the specific heat capacity, the calorimeter power P_{cal} can now be determined. The major portion of the power produced is absorbed by the calorimeter. Although residual thermal and kinetic power remains in the exiting flow of recombined gas, recent thermodynamic equilibrium models have shown this power to be minimal [15]. As such, it will be neglected in the following analysis.

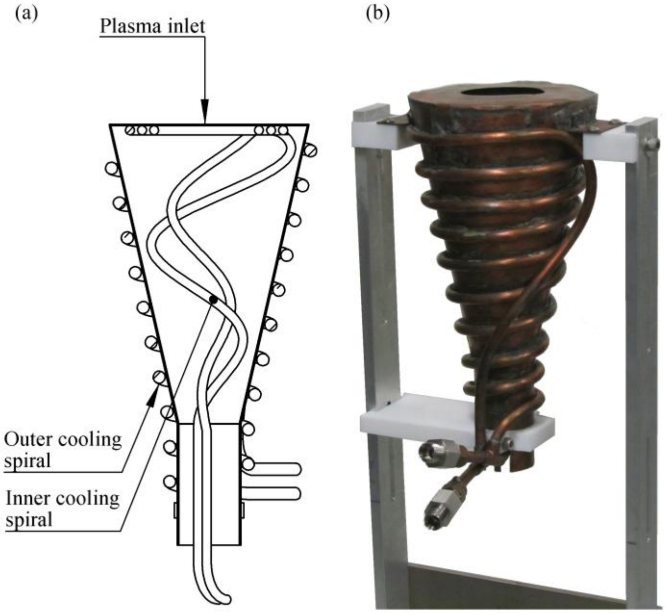

Figure 4. (a) Cross-sectional drawing and (b) finished calorimeter.

The specific enthalpy can be easily determined as the quotient of the calorimeter power and the mass flow rate of the gas:

$$h_{tot} = \frac{P_{cal}}{\dot{m}} \quad (1)$$

This value determines the average enthalpy of the plasma. The actual enthalpy varies over the radius and will be significantly higher in the center of the plasma jet.

Pitot Probe

The Pitot probe is a water-cooled tube which is inserted parallel to the flow direction (i.e., into the plasma jet) in order to determine the total pressure [16], [17]. Taking the static vacuum pressure into account the dynamic pressure and flow parameters like the velocity can be determined. A picture of the Pitot probe is given in Fig. 5.

Power Losses

In addition to the mentioned diagnostics the efficiency of the plasma generator can be estimated by measuring the cooling power of the discharge channel cooling. The water flow rate and the increase of its temperature are measured to determine

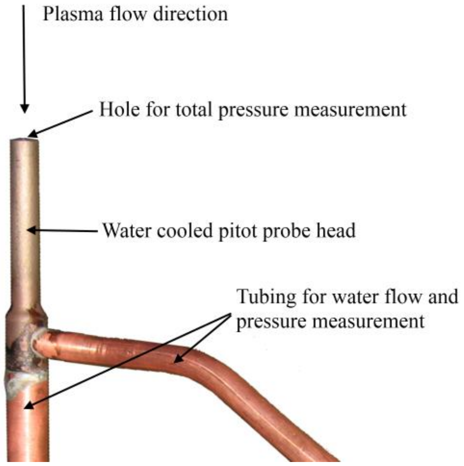

Figure 5. Water cooled miniaturized Pitot probe.

the thermal power losses. This data can be used to determine an upper boundary for the generator efficiency.

Light Gas Gun

It is planned to attach a dust accelerator, a so called Light Gas Gun (LGG), as additional subsystem to the IPG6-B facility. This LGG has already been tested independent from the IPG. It is capable to accelerate dust particles with diameters from only a few microns to projectiles up to a diameter of 2.4 mm driven by a pressurized gas. Velocities of several hundred meters per second have been measured, depending on particle size, used gas and pressure [18]. This will provide the opportunity to simulate conditions which include both plasma and high velocity dust impacts.

III. INITIAL RESULTS

Both test facilities have now begun operation and are currently under characterization. The IPG6-B facility has been operated with air, oxygen and nitrogen as working gas using mass flow rates of up to 300 mg/s and pressures of up to 400 Pa. The IPG6-S has been operated with air only over similar mass flow and pressure regimes. Fig. 6 shows the IPG6-B in operation.

Initial cavity calorimeter data obtained with the IPG6-S test facility [15] is presented in Fig. 7. Note that during these experiments the IPG6-S test facility used a vacuum system of only 16 m^3/h pumping speed. Consequently low mass flow rates have been used to keep the pressure levels low.

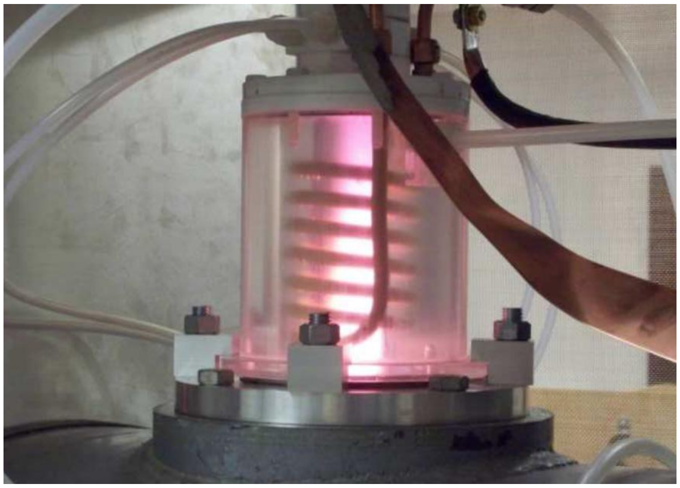

Fig. 6. IPG6-B during initial operations.

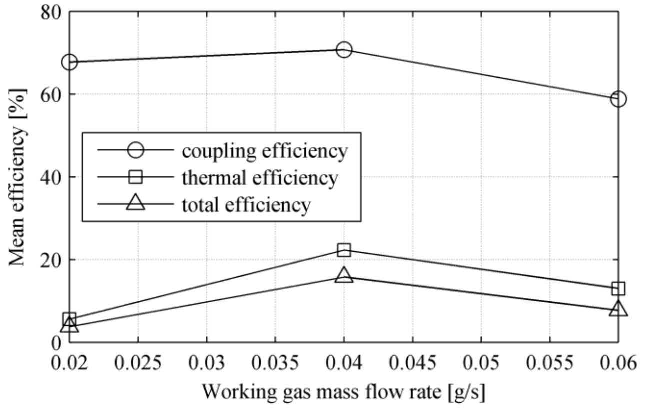

Fig. 7. The coupling efficiency, the thermal efficiency and the total efficiency are shown for mass flow rates from 0.02 g/s to 0.06 g/s in IPG6-S.

To obtain a measure of the performance of the plasma generator and the overall system, three efficiencies are introduced. The coupling efficiency characterizes how much energy is coupled from the electrical system to actual plasma generation:

$$\eta_{couple} = \frac{P_{cal} + P_{tube}}{P_{electrical}} \qquad (1)$$

P_{tube} is the power that is transferred from the plasma through the quartz tube and can be considered a power loss. Its extent determines the performance of the plasma generator itself. This is the thermal efficiency:

$$\eta_{th} = \frac{P_{cal}}{P_{cal} + P_{tube}} \qquad (2)$$

The net efficiency is the product of Eq. (1) and Eq. (2). Fig. 7 shows all efficiencies over the working gas flow rate for IPG6-S. The total efficiency shows a maximum of ~18% at 0.04 g/s. However it has to be considered that the cavity calorimeter is not ideal, which means that the real efficiency is higher, than the measured value. Further the position of the maximum will depend on the chamber pressure. In the presented results the chamber pressure was at 400 Pa at 0.02 g/s, 800 Pa at 0.04 g/s and 1200 Pa at 0.06 g/s. This pressure results from the maximum pumping speed of 16 m^3/h and is linear to the gas flow rate. In future experiments a stronger pump will be used to allow pressure control in a wide range. Thus the impact of the pressure on the efficiency can be analyzed independent from the mass flow rate. The coupling efficiency shows rather good values between 60% and 70% as well peaking at 0.04 g/s.

For IPG6-B no cavity calorimeter results have been obtained yet. Though in first tests the thermal power losses to the tube cooling have been determined. Comparing this power with the actual electrical input power an upper boundary for the efficiency can be calculated. These values are presented in Fig.

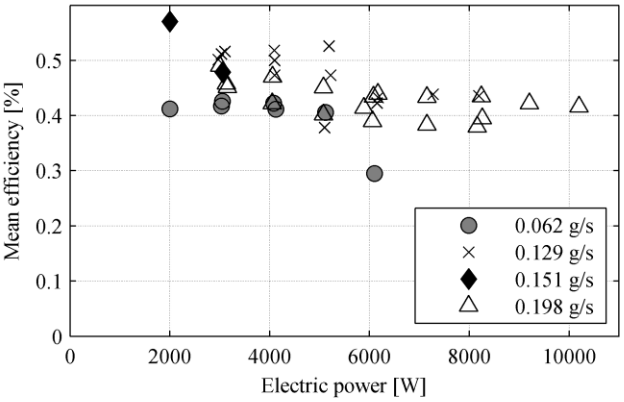

Fig. 8. Upper limit for IPG6-B efficiency for mass flow rates between 0.062 g/s and 0.198 g/s for powers up to 10 kW. The pressure is flow rate dependent and ranges from approximately 100 Pa at the low flow rate to 400 g/s at the high flow rate.

8 for different IPG input powers of up to 10 kW and gas mass flow rates from 0.06 g/s to 0.2 g/s with air as working gas. Note that this efficiency estimation does neither include electric losses between power supply and IPG nor field losses. The data shows efficiencies between 30% and 60%. The highest efficiency values are obtained for mass flow rates of 0.129 g/s and 0.151 g/s; here the pressure is approximately 200 Pa. The maximum tested power of 10 kW has only been reached at the highest used flow rate. At lower flow rates the experiments have been stopped at lower powers as discharges between the plasma generator and equipment in the vacuum chamber appeared.

An analysis of the efficiency's pressure dependency at constant flow rates has not been done yet. Though, it is expected that the pressure has strong influence on the results.

IV. CONCLUSIONS

The IPG6-S and the IPG6-B provide two miniaturized inductively driven plasma facilities that have been established at their various institutions. Both systems have successfully begun operation and are undergoing characterization. For the IPG6-S, initial characterization using air as the working gas have been conducted and presented. Initial results show mass specific enthalpies of more than 10 MJ/kg in air plasma. The installation of a new vacuum system is currently underway and will allow experiments over a wider pressure range and at higher mass flow rates.

The IPG6-B has undergone initial characterization tests as well employing air, oxygen and nitrogen as working gasses. For future applications the modification of the facility for operation with hydrogen is planned.

A Pitot probe and a cavity calorimeter have been constructed and tested in both the facilities. The integration of further diagnostics as well as a small dust accelerator is underway.

As both systems share many similarities, comparative experiments can be conducted allowing the cross-checking of results. Furthermore, equipped with different diagnostics, the facilities complement each other and make a wide field of research available. In the future the characterization of both plasma generators will be continued, especially including the use of various working gases.

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