SETUP OF AN INDUCTIVELY–HEATED PLASMA GENERATOR AND DIAGNOSTICS TO BUILD A HYBRID PLASMA SIMULATION FACILITY FOR COMPLEX SPACE ENVIRONMENT INVESTIGATIONS.
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Introduction: Plasma is the most common state in the universe; over 99% of the visible matter exists in the plasma state. As a result, it is essential to use ground test facilities for basic investigations to gather information about conditions in space before sending objects into it. Existing techniques cover only a specific area. Merging multiple devices extends investigation possibilities as well as enables new ones. The inductively-heated plasma generator IPG6-B – a collaborative research project of Baylor University, Texas, USA, and the University of Stuttgart, Germany – and its subsystems provides various environmental conditions for research in the fields of dusty plasma, catalysis, atmospheric entry and even terrestrial applications.

IPG6: IPG6 is a miniaturized inductively heated plasma generator (IPG) optimized for an operating frequency of 4MHz. It is based on the design of the plasma generators IPG3, 4 & 5, which have been developed for atmospheric entry simulation at the Institute of Space Systems (IRS) at the University of Stuttgart, Germany. IPGs couple power inductively into plasma. An induction coil, surrounding a discharge channel, produces a strong alternating electromagnetic field inside igniting the plasma, which is then exhausted into a vacuum chamber. In this way electrodeless plasma generation is possible which allows creating very pure plasmas even from chemical reactive gases, as no electrode erosion can take place.

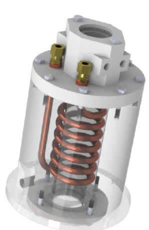

Figure 1: Inductively-Heated Plasma Generator (IPG)

Within the collaboration of IRS and the Center for Astrophysics, Space Physics and Engineering Research (CASPER) at Baylor University, Texas, two IPG6 test facilities have been set up. IPG6-S, in Stuttgart, has a power supply of 20 kW working at 4 MHz. IPG6-B, at Baylor University, has a 15 kW supply working at 13.56 MHz. Both generators have a discharge channel diameter of 40 mm and work with gas mass flow rates of less than 0.5 g/s. The pressure in the IPG6-S facility is several 100 Pa during operation, while the IPG6-B facility is capable of pressures as low as 2 Pa. Working gases used to date include air and argon. For future operation, hydrogen, helium, oxygen and carbon dioxide will also be considered.

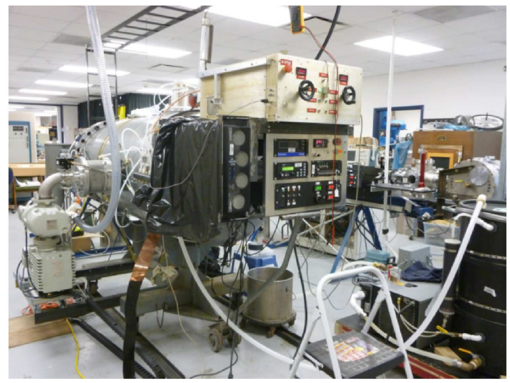

Figure 2: IPG6-B setup at CASPER Baylor University

Subsystems: The light gas gun (LGG) at Baylor will be used as a supplemental system of the IPG6-B facility. The LGG is a one stage dust accelerator that provides a dusty plasma where the particles as well as the plasma are accelerated and arranged to various angles of contingence. Particles of 0.6 to 2.4 mm size have been accelerated to about 780 m/s [1], with particles as small as 74 µm accelerated employing sabots to about 130 m/s [2]. A high-pressure chamber is filled with helium to about $8.27 \cdot 10^6$ Pa. The particles or sabot placed in a barrel are accelerated into a vacuum chamber of about 13 Pa by release of the gas. The target is aligned with the particles and hit first by the bypass. Velocities are measured using two laser curtains integrated into the barrel to record the fly through consecutively.

Setups with modifiable angles of the target allow for broader investigations covering not only frontal impacts. As a hybrid facility, the IPG6-B allows even variable angles of the plasma as conceivable.

To lower the atomic gas concentration a side-arm will be used as another subsystem of the IPG6-B. A diffusion tube will be connected as a side-arm at a right angle to the main flow tube. The dissociated species flow past the opening of the side-arm and reactants diffuse into the tube. Due to the surface reactions on the

walls the reactants are progressively removed from the gas phase, establishing a decreasing species concentration profile over the length of the side-arm tube.
Given these subsystems, the IPG6-B will be able to create a wide range of space and terrestrial environments.

Diagnostics: Diagnostics are an important component for experimental research. Dealing with the specific field of plasma it is necessary to have specially designed diagnostics equipment, which provide the required information during experiments. In a first step three diagnostic systems for IPG6-B are currently in development.

Calorimeter: In order to measure the total plasma power of the IPG6-B a cavity calorimeter has been developed consisting of a water-cooled copper cone. The plasma enters the cone and exchanges energy with the copper walls. Based on the increase of cooling water temperature, cooling water flow rate and plasma mass flow rate, the plasma power can be calculated, once energy losses have been considered.

Oxygen Sensor: VacuSEN is a miniaturized unique sensor system that was developed based on the space experiment FIPEX on ISS. It enables measurements of both the molecular and atomic oxygen concentrations inside the plasma chamber. The working principle is an amperometric solid electrolyte sensor that is able to measure a partial pressure down to $1 \cdot 10^{-6}$ mbar pO_2.

Due to the space driven miniaturization and reference free measurement principle, the robust ceramic sensor can be used for direct time resolved in-situ measurements.

Pitot Probe: In order to gather data about the pressure inside the vacuum chamber, which is influenced by the emitted plasma, a pitot probe is being developed for the IPG6-B. For the purpose of measuring in and near the extremely hot plasma stream, the pitot probe is a miniaturized and water-cooled pressure measurement instrument which can be attached at different positions. This enables the measurement of pressure profiles and helps to characterize the plasma and the conditions inside the vacuum chamber.

Potential Applications: IPG6-B offers many opportunities for investigations. At CASPER the following applications are of main interest.

Catalysis: Using the side-arm technology and the VacuSEN System gives the opportunity to collect data determining the oxygen amount along the side-arm. By placing a sample into the tube the change in oxygen concentration before and after the probe can be measured. Depending on the concentration, catalytic surface properties of the sample material can be calculated.

Atmospheric Entry: One of the most important investigations in human and unmanned space exploration is the field of atmospheric entry. Using heat shields, which resist the heat flux during entry, is vital for the success of any mission. Being capable of using various gases, even chemically reactive ones, the IPG6 test facility provides the opportunity to generate a high-enthalpy plasma of various compositions to simulate entries into different atmospheres eg. Earth and Mars.

Satellite Hardware: The large vacuum chamber and side-arm subsystem at IPG6-B are important assets to create low plasma densities, assuming a decrease of the plasma density with greater distance from the plasma source. The reproduction of plasma conditions, that have relevance for both aerothermodynamics and plasma environments in space, allows investigation of ambient plasma properties that are common in different orbits, eg. the Lower Earth Orbit (LEO), that is of interest for investigations of effects on satellite hardware.

Dusty Plasma: The Moon as well as comets and asteroids are promising targets for future exploration. The Moon has an extremely thin atmosphere of $1 \cdot 10^4$ molecules/m^3 during lunar day and $2 \cdot 10^5$ molecules/m^3 during lunar night [3]. The solar wind and impacts hit the surface almost unharmed, creating a hazardous environment for human missions with dust particle velocities up to of 2.7 km/s and a mean size of 60 to 80 µm in diameter. Plasma velocities of 300 to 700 km/s are common. Comets in the vicinity of the sun develop dust and plasma tails, at first coupled due to particle-molecule collisions in the tail before spreading due to solar radiation pressure. Nucleus ejecta velocities vary from 0.4 to 0.7 km/s [4]. The micro-meteoroids are linked with the plasma tail and thus have about the same velocity of 10 to 100 km/s as observed from Earth [5].

Terrestrial Applications: A final potential application of the IPG6-B test facility is the simulation of heat fluxes and dust impact at the divertor plate of tokamak nuclear fusion reactors. In this area there are still unsolved material issues, which need to be addressed for next step fusion reactors. IPGs are capable of creating the required high enthalpy hydrogen/helium plasmas which are found near the divertor plate. Further CASPER's Light Gas Gun (LGG), which will be attached to the test facility, can be used to accelerate dust particles to relevant velocities.

References:

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