Divertor Physics Experiment

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Mission

Study the physics of heat-flux mitigation and plasma-material interaction in fusion-relevant plasma and surface conditions

I. Research Summary

The goals of this facility are two-fold:

1) Understand in a detailed manner the physics of heat-flux mitigation in fusion-relevant conditions, including both the partial and total detachment of the plasma from the material target that is observed under some conditions in toroidal fusion devices, as well as the vapor shielding process that may be available with liquid-metal as a plasma-facing material. This is difficult to undertake in the tokamak or stellarator environment because of limited access for diagnostics and limited control over the scrape-off layer plasma, as well as limited control and characterization of the surfaces with which the plasma interacts. After many years of study on tokamaks, the processes of heat-flux mitigation remain poorly understood and ineffectively modeled. [Wischmeier et al., 2011]

A full set of detailed plasma diagnostics will be installed on this device, capable of measuring radiation from the atoms and ions of plasma-facing materials as well as atoms and ions of hydrogen and materials introduced to enhance radiative losses. Detailed measurements of all loss channels for particles, momentum and energy will be made, for example combining extensive spatially resolved UV spectroscopic measurements with measurements of charge-exchange particle and momentum loss. It will be possible to perform thorough physics investigations over a wide range of fusion-relevant parameters. Important features of detached regimes, such as the ability to pump He exhaust, the evolution and transport of dust from solid plasma-facing materials, and the evolution and transport of vapor from liquids will also be examined.

2) Understand in a detailed manner the surface physics of materials interacting with plasmas carrying hundreds of megawatts/m^2 of parallel heat flux. We are interested both in high-Z materials such as tungsten, and low-Z liquids, such as lithium. Indeed medium-Z liquids such as tin or gallium may be of interest. Key issues include the physics of plasma-facing materials under intense heat fluxes (steady parallel heat flux of hundreds of MW/m^2) and the erosion and redeposition mechanisms for both solid and liquid plasma-facing materials. Key goals for these studies include predictive capability for erosion and redeposition of solids and liquids, and for the production of dust and evaporated or sputtered liquids.

II. Facility Description

Currently operating linear plasma devices for studying plasma-material interactions are designed to produce relatively low temperature plasmas, up to ~ 10 eV, and to deliver up to a few tens of MW/ m^2 of parallel heat flux to a target through a combination of kinetic flow energy of the low-temperature plasma and electrical biasing of the target. This is representative neither of the magnitude nor of the mechanism of heat delivery in a fusion plasma device, in which hundreds of MW/m^2 of heat flows intially from the upstream plasma towards the divertor target by parallel electron thermal conduction. It has been shown that, in heat-flux mitigated conditions, as the plasma approaches the target convective heat flux takes over from conductive and radiation extracts power from the plasma [Leonard et al., 1998]. It is the physics of this class of phenomenon that we need to study in much greater detail in Goal 1, where we examine the effect of plasma facing materials on the plasma. For example, what controls the position of the radiation front and its stability? As a result, how does changing the radiating species affect the locus and effectiveness of detachment? How do impurities flow upstream towards the main plasma, taking into account not only flow friction and diffusion, but also the parallel thermal force? How important is radiation upstream of the point where conduction is overtaken by convection? None of this physics is accessible in a device dominated everywhere by convective flow, but is accessible in a device with high upstream temperature. This sets a device requirement for upstream plasma temperature > 100 eV, and for appropriate plasma collisionality, density > 10^{19}/m^3.

Goal 2, in which the focus is on the effect of the plasma on the material surface, requires delivery of realistic parallel heat fluxes, which translate at the target into particle impingement rates as a function of particle energies. A device with high parallel power flux and high upstream temperature has a wide range of capabilities for varying the plasma temperature and particle flux at the divertor target. For any given target temperature and angle to the field lines, a device delivering 100's of MW/m^2 of parallel heat flux provides 10x the particle flux and plasma density of one that delivers 10's of MW/m^2.

It is remarkable that even the scrape-off-layer parameters of toroidal plasmas are difficult to reproduce in the core of other plasma devices. Indeed the only non-toroidal device that can currently produce such parameters is the Gas Dynamic Trap. This is an axisymmetric magnetic mirror device with a high ratio of magnetic field in the mirror to that in the main plasma. It uses off-perpendicular neutral beams for plasma heating. The GDT device located in Novosibirsk, Russia (figure 1) has shown remarkable stability, both microscopic and macroscopic, and has already produced the plasma parameters needed for this application.

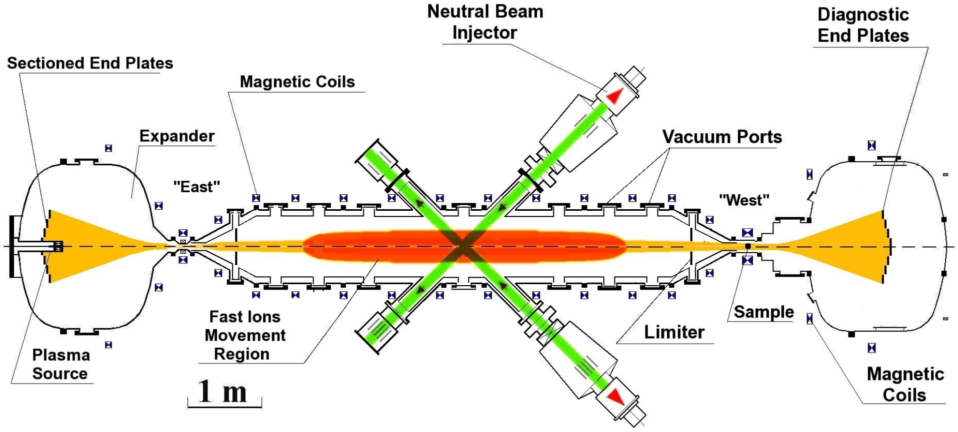

Figure 1: GDT device layout for heat-flux test. A divertor simulator would be equipped with a high-field solenoid to transport the hot plasma from the mirror throat to the target.

Detailed discussions have been undertaken with the Novosibirsk group, and they have performed specific experiments to examine the issue of parallel heat flux from the GDT, for application to plasma-material interactions. [Soldatkina et al., 2013, figure 1]. Heat fluxes up to 250 MW/m^2 and particle fluxes up to $10^{24}/m^2$sec have been measured on a molybdenum target placed in the mirror throat of the Novosibirsk GDT, with upstream electron temperature of 140 eV and density of 2 $10^{19}/m^3$, using 4 – 5 MW of injected neutral beam heating.

III. Facility Impact Beyond FES Mission

There are two major areas of potential impact beyond the OFES mission and outside of fusion energy.

1) There are many applications that require the management of high heat fluxes, such as electrodes in RF wave generators or even rocket nozzles. Advances in high-heat flux technology could have wide impact.

2) The GDT has the potential to provide an intense neutron source [Molvik et al., 2010] for both fusion and non-fusion applications.

IV. Scientific Community Considerations

This option was examined at PPPL during FY2011, using discretionary funds. While the need for the basic physics understanding of both the effects of the plasma on materials and the effects of materials on the plasma are well known and documented in ReNeW Thrusts 9 – 11 and in the Rosner Panel report, this particular approach to acquiring the necessary knowledge has not had wide discussion. However, OFES has recently provided a white paper on a Materials Facilities Initiative to the FESAC sub-panel, and it is clearly appropriate to consider a device of these capabilities in the context of the remark there that, “Some research and development on the power source for the plasma-material interaction facility is required”.

V. Context of the Facility in the World Effort

The most powerful device in the world devoted to plasma-material interaction today is Magnum-PSI in the Netherlands. It is designed to provide tens of MW/m^2 of parallel heat flux with a plasma temperature in the range of 10 eV. Since electron thermal conduction scales as $T_e^{7/2}$ these parameters are far from those required to study the physics through which parallel conduction first dominates, and then heat and momentum are extracted from the divertor plasma. Furthermore, in order to understand the effects of the plasma on materials in relevant regimes, high absolute parallel heat flux and associated high particle flux are necessary to study the surface physics of erosion and redeposition at realistic field-line angles.

The Gas Dynamic Trap at Novosibirsk today can provide the necessary plasma parameters, $T_e > 100$ eV and $n_e > 10^{19}/m^3$, but limited to 5msec pulses by the pulse length of its neutral beams and by its neutral pumping capacity. Alexander Ivanov, Deputy Director of the Budker Institute, has confirmed that the Institute and its GDT group are very interested in collaboration on the development of steady-state capability for GDT devices. This fits very well with the Institute’s programmatic objectives.

One should recognize that experiments on this facility will support research on tokamaks, but cannot supplant such research. For example, while the parallel transport physics can be arranged to be similar to that of a tokamak scrape-off-layer, including such effects as the parallel thermal force, it is likely that cross-field transport of heat, particles and momentum will be different. Also the transport and subsequent management of dust and evaporated liquids in a toroidal device will be significantly different from that in a linear device. Finally, and perhaps most importantly, the effect on the upstream plasma of detachment or vapor shielding at the divertor target has no fundamental reason to be similar between a gas dynamic trap and a toroidal device. Indeed the intrinsic parallel electric field in the core of the GDT makes it likely to be more robust against impurity influx.

VI. Construction Cost Estimate

While the present Novosibirsk GDT produces the needed electron temperature, density and heat flux, its pulse-length capability is limited to about 5 msec, both by its neutral beam system and by its use of ballast tanks for neutral pumping. An implementation of a GDT for simulating a tokamak divertor would need to be capable of steady-state operation, using much longer beam pulses and perhaps additional means of plasma heating, as well as active pumping. Based on preliminary discussions with the Novosibirsk group, it appears that such a facility could be constructed for a cost in the range of $50-100M, but clearly much more work is needed to provide an accurate cost estimate.

VII. Readiness of the Facility Concepts

There is no reason to doubt that the present GDT plasma parameters can be sustained in steady-state, with appropriate beam sources and active pumping. There is also no reason to doubt that the very high heat flux provided by the GDT at high plasma temperature can be used to simulate the scrape-off layer of a toroidal plasma. During the Conceptual Design phase of such a device, nonetheless, one would want to perform validating experiments on the existing GDT at Novosibirsk, such as extending the mirror field with a long solenoid and showing that the high heat flux is transported along B to a remote target with low incidence angle. One could also perform experiments examining heat flux mitigation, for example with nitrogen gas puffing, to confirm that the physical processes of interest are clearly visible as expected.

References

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