FES Joule Milestone 2009
First Quarter Report
December 22, 2008

Annual Target: Conduct experiments on major fusion facilities to develop understanding of particle control and hydrogenic fuel retention in tokamaks. In FY09, FES will identify the fundamental processes governing particle balance by systematically investigating a combination of divertor geometries, particle exhaust capabilities, and wall materials. Alcator C-mod operates with high-Z metal walls, NSTX is pursuing the use of lithium surfaces in the divertor, and DIII-D continues operating with all graphite walls. Edge diagnostics measuring the heat and particle flux to walls and divertor surfaces, coupled with plasma profile data and material surface analysis, will provide input for validating simulation codes. The results achieved will be used to improve extrapolations to planned ITER operation.

Quarter 1 Milestone

Develop a preliminary research plan, coordinated among the three facilities, in order to accomplish the required experiments on particle control and hydrogenic fuel retention, towards the goal of understanding particle balance.

Completion of 1st Quarter Milestone

The three tokamak facilities have made excellent progress on preparations to carry out particle control and hydrogenic fuel retention experiments and analysis for this milestone. The facilities have cooperated to develop research methods and analysis plans that allow for accurate and quantitative comparisons between the different tokamaks which have different plasma-facing wall materials.

The milestone goal is to better understand the differences between different plasma-facing wall materials, divertor topology, and exhaust methods. This milestone highlights that the wall materials on the three US devices have widely different characteristics as far as their interaction with hydrogenic fuels. The refractory metal wall (tungsten and molybdenum) used in C-Mod are characterized by very high diffusivity of the H, yet low solubility. Therefore the retention characteristics tend to be governed by implantation, diffusion and bulk trapping. Conversely, the graphite materials in DIII-D and NSTX exhibit extremely low H diffusivity, yet high solubility at room temperature. In this case the retention is typically dominated by the transport of the carbon to form layers that grow and hold fuel; a process called codeposition. Therefore the science focus for carbon is primarily to understand the transport of the carbon, and to develop methods to remove the codeposits. In the case of lithium, as used to cover the divertor graphite in NSTX, the lithium purposely acts as a strong H particle sink in order to obtain plasma particle control.

The opportunity of the milestone is to bring together the experiments and facility capabilities of the three US machines to understand the large range of behaviors of these different wall materials for H fuel control and retention. Each facility has unique and strong capabilities in this area. For example, DIII-D and C-Mod can use cryogenic pumping for particle exhaust. NSTX will use the wall coating itself, lithium, to provide active pumping due to its strong affinity to H. NSTX has the ability to freshly coat the divertor graphite with lithium between discharges, which adds considerable flexibility to controlling and testing the effective wall pumping of H by the lithium. The measurement challenge is that the wall materials present a significantly larger fuel reservoir than the plasma. The scientific challenge is that the plasma is predominately self –fuelled by the wall, that is the recycling flux at the wall is much larger than the external sources and sinks supplied by fuelling and active pumping. Therefore one requires accurate particle accounting measurements, recycling fluxes, and material transport to understand the complex wall-plasma fuelling picture.

The milestone will cover three broad topics, which are all necessary to understand H particle control and fuel retention:

- Measurements and modeling of the edge plasma and plasma transport
- Particle balance measurements
- Measurements and changing the properties of the plasma walls

In the area of *Measurements and Modeling of the Edge Plasma and Plasma Transport*, the ability to measure the plasma recycling flux at the surfaces allows us to understand the relationship between incident ion flux and fuel retention. Boundary plasma transport patterns, which includes both the H fuel and impurity / wall species, will be diagnosed by edge plasma diagnostics (e.g. Mach probes, spectroscopy) and plasma fluid modeling (e.g. UEDGE). Divertor strikepoint sweeping can obtain ion flux profiles to the target plates using fixed Langmuir probes. Reciprocating probes in the edge plasma provide “upstream” plasma parameters, estimates of main-wall flux, and flow measurements if Mach probes are employed. Another method of obtaining plasma flow measurements is active or passive visible spectroscopy using the Doppler shift or by imaging of injected impurities. The brightness of H atomic lines can be interpreted to diagnose recycling fuel flux densities over most of the plasma surface area. All of these boundary plasma measurements are necessary to properly constrain use in interpretive or predictive edge models, which themselves can be seen as important diagnostic tools. To complement this extensive set of diagnostics on C-MOD, DIII-D, and NSTX is a suite of US and international edge codes and H transport in materials models that can be used for analysis. These modeling codes will be used to help interpret the data and to aid in extrapolations. The extent to which these codes will be applied will be determined in more detail as research planning continues and initial results are seen.

In the area of *Particle Balance Measurements and Modeling*, the goal is to obtain as accurate particle balance as possible in order to understand the dynamic uptake and release of H fuel from the wall. Dynamic particle balance uses calibrated pumping speeds, pressure measurements and plasma density to determine real-time total particle inventory. This has the distinct advantage of providing insight as to how the evolving nature of the plasma characteristics (confinement, divertor plasma temperature, etc.) affects particle control. However, accuracy is typically the difficulty with dynamic particle balance since one is examining small relative differences of large sources and sinks. In some experimental conditions, the accuracy can be significantly improved by using "static" particle balance, i.e. operating without external vacuum pumping during the discharge (i.e. turbo pump gate valves close), such that the H gas released after tokamak shots comes is kept in the vacuum vessel for accurate particle accounting. This has the additional advantage that one can perform gas mass spectroscopy on the recovered gas to ensure that impurity gases do not confuse particle accounting of the fuel. Also, if internal cryopumping is used, the pump can be regenerated, i.e. release the frozen gases, into the un-pumped vacuum vessel in order to accurately account for the integral of active pumping source during the shot. Conversely, the disadvantage of the "closed-pump" technique is that it can often preclude plasma-heating schemes, especially neutral beam injection, which limits the operational window for the plasma. This is overcome if radio-frequency (RF) heating can be used since no particle source is involved. In the case of Lithium coating, as used in NSTX, an interesting experimental control is the quantity of lithium, since this represents a way to control the effective pumping capacity of the wall.

In the area of *Measurements and changing the properties of the plasma walls*, an important boundary plasma tool is the ability to distinguish net changes in actual material properties at the wall. Both DIII-D and C-Mod have a material diagnostic "station" which allow for exposure and diagnosis of materials in contact with the boundary plasma. The DiMES system on DIII-D allows for material exposure in the divertor, while the SSS (Surface Science Station) system on C-Mod can expose and diagnose materials in the SOL and during wall conditioning. NSTX has the ability to monitor net C and Li film deposition in-situ with quartz microbalances and may install a material probe. Besides material probes, the injection of "tracer" impurities, or different H isotopes, can lead to insights on material transport and particle control. On DIII-D, ^{13}C tracers are used to effectively map carbon transport patterns. DIII-D is exploring the possibility of using baking in air or oxygen to control the fuel inventory in the carbon wall. In NSTX, the ability to control lithium injection into the plasma and wall is used. On C-Mod, boronization films and H to D evolution are used as diagnostic tools. In addition, disruption heating is used as a method to recover retained fuel in C-Mod

Research Planning

Research planning forums with wide national and international input were completed in December 2008 for the NSTX and DIII-D facilities in December 2008. Alcator C-Mod will have its research forum in early 2009. The planning activities include proposals for experiments that are relevant to the 2009 Joule milestone. The proposed experiments on all three facilities are oriented towards exploiting the joint capabilities of the three devices as much as possible. This strategy helps to assure that we gain maximum scientific insight as to particle control in our comparisons of results and modeling efforts foreseen across the devices. January 2009 will be a period of experimental planning at each facility, and will include discussions between the facilities.

Experiments in several broad areas have been presented, which will be discussed in the first part of 2009. (Run time has not yet been allocated to these areas).

1. Dynamic versus static particle balance (All)

2. Retention studies using variable particle exhaust and plasma conditions (All)

3. Control of fuel (C-Mod: disruptions, boronization, DIII-D: baking, baking with air, boronization, NSTX: baking)

4. Edge plasma flux and flow diagnosis (All)

5. Material probe diagnosis (C-Mod: Mo/W tile analysis + SSS, DIII-D: DiMES, 13-C tracer tile analysis, NSTX: quartz micro-balance, dust)

6. Fuel control with air baking, cryopumping, and boronization.

7. Modeling of fuel transport, retention and release.

Research capabilities

We have identified several appropriate diagnostic measures and facility capabilities that will be instituted across devices in various degrees for the milestone. These are organized in Table 1,indicating the strong overlap in measurement capabilities across the devices despite their significant difference in plasma-facing materials.

Facility	**Alcator C-Mod**	**DIII-D**	**NSTX**
Particle Balance			
Dynamic particle balance	Yes	Yes	Yes
Static particle balance	Yes	Yes	Yes
Exhaust gas mass spectroscopy	Yes	Yes	Yes
Post-shot cryopump regeneration	Yes	Yes	N/A
Shot-to-shot lithium coating	N/A	N/A	Yes
RF heating (no particle source)	Yes	Yes	Yes
Neutral beam post-shot isolation	N/A	Yes	Yes
Air baking to remove codeposits	N/A	Yes[#]	N/A
Boundary plasma			
Divertor Langmuir probes	Yes	Yes	Yes
Divertor & wall H-alpha	Yes	Yes	Yes
Boundary flow: Mach probes and Doppler-shift spectroscopy	Yes	Yes	Yes
Material exposure probes	Yes	Yes	Yes*
Impurity "tracer" injection	Yes	Yes	Yes

** In-situ quartz microbalance*

 # If approved following laboratory tests

***Table 1 Facility diagnostic capabilities relevant to the 2009 Joule milestone**.*