APEX Task I Progress Report
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I. Progress on Prerequisites for Proof-Of-Principle Liquid Wall Experiments on NSTX

Key issues to be addressed in proof-of-principle liquid wall experiments on NSTX are the following. The first is to explore the potentially beneficial effects of liquid metal walls, and CDX-U, LMMHD, PISCES, and other programs are funded by ALPS and APEX to develop concepts for exploring them. The second is to test integrated physics-technology liquid wall issues, and flowing liquid wall options have been proposed for NSTX. However, concerns such as flows in the presence of magnetic fields are still in the process of being addressed.

To explore plasma scrape off and edge properties due to reduced (or zero) particle and impurity recycling, probes and spectroscopic diagnostics will be used to obtain edge plasma parameters and measure impurity lines local to the lithium limiter/divertor in CDX-U. This will help determine the effects of large area liquid lithium surfaces on ST discharges.

To explore plasma core confinement due to improved plasma edge control, profile diagnostics (including Thomson scattering, tangential bolometer array, and multi-layer mirror array set for 135 Å LiIII line) on CDX-U will be used to determine the effects of large area liquid lithium surfaces on confinement and transport in ST discharges. Edge biasing experiments will be performed in CDX-U to study the effects of large area liquid lithium surfaces on H-modes in ST discharges.

To explore plasma heating and current drive efficiency (e.g., changes in coupling through scrape off layer, presence of ^{7}Li resonances, changes in radio frequency launcher, standoffs, shielding conditions, compatibility with helicity injection, etc.), fast wave experiments will be performed in CDX-U to investigate the effects of large area liquid lithium surfaces on radio frequency wave heating and coupling in ST discharges.

To explore plasma stability due to presence of nearby conducting liquid layer, experiments on LMMHD and other facilities will be performed first without plasmas to determine the practicality of high liquid lithium flow rates in the presence of magnetic fields.

To test hydrodynamic response, heating and vaporization of flowing liquid under plasma heat and particle loads, the effect of ST operation on lithium limiter/divertor target (eddy currents, vertical displacement events, etc.) will be investigated on CDX-U. Flowing liquid lithium as a plasma facing surface may not be compatible with carbon tiles or copper plates beneath them (including air or water cooling) in NSTX. Compatibility with coaxial helicity injection in NSTX and the restriction of divertor operation to single null NSTX are also issues that need to be addressed. Implementation of a flowing liquid wall in NSTX may have to wait for new center stack, which is planned for the end of FY03. While the original NSTX center stack will be preserved to retain the possibility of low aspect ratio operation, the new center stack is sufficiently early in its design phase to permit input that could make future implementation of liquid lithium walls more convenient.

For the magneto-hydrodynamic characterization of techniques for establishing, stabilizing and maintaining flowing liquid walls in response to fusion operational scenarios, schemes for startup and control for ST discharges will be developed on CDX-U.

For the development of diagnostics and instrumentation techniques, nozzle designs at will be studied at Sandia National Laboratories and elsewhere to accommodate penetrations and other flow considerations that will not interfere with heating and current drive systems, (including coaxial helicity injection), diagnostics, and configuration flexibility.

For the development of environmentally safe liquid wall systems, handling procedures and accident prevention techniques, failure mode analysis for liquid lithium use in CDX-U will address concerns (loss of vacuum, constraints on in-vessel cooling, etc.) common to ST's and other magnetic confinement devices.

In summary, the APEX program will develop and provide liquid wall technology systems that satisfy a set of operational conditions before installation in NSTX. NSTX could become a device to implement FLW capabilities that satisfy the operational conditions and contribute to the 10-year objective identified by FESAC of demonstrating spherical torus attractiveness over long pulse durations. The technical and programmatic issues that need resolution prior to implementation of FLW capabilities in NSTX are beginning to be addressed in new experiments.

II. Progress on Lithium Wall Options and Design Issues

As shown in the TFTR experiments, it is believed that a lithium surface at the plasma edge is adequate for improving plasma performance by reduced recycling and improved edge control. Thus, a stagnant lithium surface sprayed onto a compatible solid structural surface serves as the simplest configuration of a lithium wall. This option is only reasonable if the surface temperature resultant from the plasma surface heat load can be maintained below its melting temperature.

Several flowing liquid wall options are possible in NSTX. A straightforward option is an axi-symmetric flowing annular liquid film on the surface of the center stack, which forms a natural inboard divertor as the flow approaches the bottom of the center stack. An addition to this is a flowing liquid wall at the outboard divertor using a separated inlet manifold system.

An aggressive option is to cover the whole machine with flowing liquid walls. Separate inlet manifold systems will be provided for the outboard passive plate and the center stack, irrespectively. Other flowing lithium wall option includes a capillary porous flow on the outboard passive plates. Such an option provides a lithium surface that may be better to conform to the NSTX passive plate configurations with a lower lithium inventory.

One way to establish an annular flowing film on the center stack is to deliver the liquid through the pipes into a reservoir, which allows a stable flow being developed before discharged into the vacuum chamber. A 4-loops system is proposed at this juncture with 3 sectors per loop. This uses a total of 12 pipes. As presently envisioned, the pipes will penetrate through the existing diagnostics holes. All the liquid will be discharged to a catch basin before leaving the chamber. The catch basin also keeps the lithium short out the insulator ceramic break to be compatible with helicity injection, which need to be addressed later.

A large size of piping is needed to remove the liquid. There may have space problems particularly at the bottom of the chamber. As presently envisioned, 4-inch pipes are installed at 12 locations along a circumferential plane, while each exit pipe must clear out vacuum pumping ports and center stack and sneaks through the divertor supports.

There was a concern about splashing when these streams meet at the catch basin and this will require further evaluation. Other issues raised are:

(a) isolation between the CS and vacuum vessel,
(b) to what temperature the CS can be backed (350 C? and with what kind of liquid),
(c) freezing of lithium (and other liquids),
(d) elimination of the tiles from the CS/possible modification in designing the CS,
(e) mixing the flow steams of the OB and IB divertors makes OB flow characteristics depending on the IB flow,
(f) absence of helium ash and pumping, CHI, and start up issues,
(g) possible capillary porous flow on the OB passive plates,
(h) using Sn-Li instead of Flibe (at the later stage),
(i) Diagnostics involved.

III. Progress on Flowing Lithium Wall Analysis

A mathematical model and a new MHD code have been worked out to analyze multi-component MHD flows with the axial symmetry. The mathematical model includes all three components of the applied magnetic field, three velocity components as well as time and space (in the flow direction) variations of the applied field. The code can be applied to the analysis of MHD effects caused by the field gradients, transient effects and effects due to applied electric currents, such as active flow control. The present version of the code uses the cylindrical coordinates, however, it can be extended to different geometries including conventional Tokamak topology and NSTX central column. The code is not yet applicable to flows with no axial symmetry, flows with $Re_m>1$, multi-surface flows (droplet formation, splashing) or reverse or stagnant flows.

The code was applied to the analysis of MHD lithium flows over the NSTX inboard divertor region. Two cases were analyzed. In the first case, flow in a toroidal linearly varying magnetic field with or without applied electric current was considered. Changes in the flow thickness over the distance of 20 cm were calculated for one magnetic field component. In the calculations, the initial thickens was 2 cm and the initial velocity was 5 m/s. The result shows that under the NSTX conditions, the MHD drag due to the field gradient is insignificant to change any flow characteristics such as main velocity and film thickness.

In the second case, two components of the magnetic field were included in the analysis. The toroidal field is changed linearly over the distance of 50 cm as B_z=1.4-0.05x/L (variation is 3.5%) or B_z=1.4-0.14x/L (variation is 10%), while the radial one is kept constant of 0.02 T. The calculations show that the interaction between the induced current and the radial magnetic field results in a spiral-type motion, due to which a centrifugal force appears inside the fluid. If it is not balanced by another MHD force or by gravitation, the flow will develop a tendency toward a centrifugal instability. However, an applied small electric current of 0.64 kA/m^2 can easily suppresses this negative effect.

IV. Progress on Key Technical Issues and R&D Plan

A crucial issue for the use of liquid walls in fusion systems is their impact on the performance of the fusion plasma core. The liquid surfaces can impact the edge and core plasmas by releasing impurities through sputtering, recycling, and evaporation. Such impurities degrade fusion core performance through enhanced radiation loss and fuel dilution. On the other hand, the edge-plasma itself is affected by both the core plasma and the wall. The edge-plasma properties must be accurately determined to predict the coupling between the core plasma and the wall. Changes in the edge plasma temperature and gradient scale-lengths can also affect the stability of the core-edge plasma, *e.g.*, the L-H transitions, ELMs, and possibly disruptions. Presently, there is no effort allocated to Task I for addressing NSTX relevant PMI issues. However, heat transfer analysis has been performed to determine the expected maximum lithium surface temperature in the center stack and inboard divertor regions with respect to the projected heat load conditions.

Besides the aforementioned PMI issues, a successful deployment of liquid wall concepts to any plasma operating machines requires a number of technical issues to be addressed. The following is a preliminary list of key issues, grouped by areas that will have to be addressed in order to make it to become a viable technique. They are organized into six major areas: 1) magnetohydrodynamics concerning the establishment, maintenance and evacuation of the flowing liquid walls, 2) high heat load removal capability, 3) liquid motion under intense heating and abnormal conditions, 4) materials compatibility, 5) development of handling procedures and safety, and 6) diagnostics requirement. Technology objectives and requirements will be determined in response to the machine goals, while activities will be defined in support of these requirements.

V. Progress on proposed experiments in the liquid metal magnetohydrodynamic (LMMHD) toroidal facility

The APEX effort needs and is now developing a liquid metal MHD toroidal facility to provide “reality check” benchmark tests of free surface liquid metal MHD computer codes predicting flows in fusion-relevant toroidal or axisymmetric geometries. Experiments using magnetic field components restricted to the toroidal direction will include investigating diamagnetic drag forces, “CLiFF” concept mockup tests, trying schemes for electromagnetic adherence, pumping, and propulsion, and measuring instability onset thresholds and proposed stabilization methods. Later, with poloidal field coils added to the facility, poloidal direction mismatches will produce toroidal liquid motion or toroidal current and additional poloidal drag force, which will be studied in experiments. Finally, nonaxisymmetric effects can be directly studied.

Initial facility parameters are constrained by the limited available budget and by available equipment. The toroidal field (TF) coil torus will be constructed of 24 TARA water-cooled coils borrowed from MIT, and steadily powered at half the coils’ current rating via a convertor “power supply” borrowed from Princeton, providing a toroidal field ranging from 0.62 Tesla to 0.21 Tesla over the major radius range, $0.39\text{m} < R < 1.17\text{m}$. A support structure for the coils has been designed and is being fabricated.

The expected schedule includes completing the facility this fiscal year (FY2000) but with only the toroidal component of magnetic field and with limited toroidal extent of the flowing liquid metal.

VI. Additional Progress

The following progress has been made in Common Task B support of Task I goals. To assist in the characterization of NSTX operating conditions, predicted NSTX high beta EFIT equilibria and magnetic field components have been provided by PPPL personnel to the University of California at Los Angeles (UCLA) for determining an operating window for non-insulated lithium flow under these conditions. Information on the design and heat loads for NSTX plasma facing components has also been supplied to UCLA and ANL by ORNL and PPPL personnel. Time-dependent magnetic field components for NSTX discharges will be provided to UCLA after APEX meeting.

For the liquid metal experimental facility set up at UCLA, a power supply for the LMMHD coils was sent by PPPL to UCLA. Reports were also prepared on possibilities with TARA field coils, LN2 enhancement of coil performance, and LMMHD toroidal facility forces and torques.

Finally, to identify key issues and development of an R&D plan for implementing liquid walls in NSTX, a draft systems requirements document was prepared to describe issues which need to be addressed if NSTX decides to implement flowing liquid walls. The integration of CDX-U project and other ALPS/APEX programs for concept development to explore NSTX liquid wall issues has also begun.