Surface heat flux characterization on plasma-facing components in fusion energy relevant devices is of critical importance as we advance to higher power experiments, such as ITER. The divertor will need to withstand sustained heat flux during steady state operation and occasional bursts of intense heat flux from transient loss of confinement. The divertor is the region most at risk of suffering extensive damage from both heat and particle flux on relatively short timescales. The rest of the first wall will also need to withstand significant heating and particle flux that will affect the operation of the confined plasma over the long term use of the device. There has been an increasing focus on monitoring divertor heat fluxes with diagnostics such as IR cameras, which have advanced our understanding of heat flux profiles and their dependence on injected power and gas puffing (detachment). However, there has been less of a focus on monitoring heat flux at other locations in the device. A combined effort to monitor heat flux both at the divertor and at other lower heat flux intensity locations will provide a better assessment of both short and long term damage to plasma-facing components in tokamaks. In order to meet the challenges described in thrusts 11 and 14 of the ReNew report of designing materials and heat removal technologies for the plasma facing components, it is essential to have a thorough understanding of the exposure conditions that the materials will experience, one of the most important of which being the magnitude of the surface heat flux.

a. Progress since ReNew

IR cameras have been the principle diagnostic used for inferring surface heat flux, particularly in the divertor. Divertor heat fluxes for DIII-D, NSTX, and Alcator C-Mod have been measured and compared in order to develop a scaling relationship intended to predict the width of the heat flux profile near the strike point based upon plasma current, density, and magnetic field strength. These scaling relationships predict that the width of the heat flux profile near the strike point for higher current devices like ITER will likely be narrower than previously thought, which will lead to significantly higher peak heat flux. Studies such as these reinforce the point that surface heat flux will be one of the most critical concerns for PFCs as injected power increases. It is important to continue to improve our understanding and measurement of surface heat fluxes by adding additional independent heat flux diagnostics along with infrared techniques. The advanced divertor geometries being discussed for DIII-D and ADX intended for eventual use on FNSF provide an additional need to expand our heat flux diagnostics beyond IR cameras alone. The complex surfaces proposed for these divertors complicate the line-of-sight necessary for IR cameras by creating regions that may be shadowed from view and stray light from reflections. These areas require measurements near the tile surface with additional diagnostics such as thermocouples and Langmuir probes.

An effective model for surface heat flux characterization in a tokamak has been developed on the Alcator C-Mod experiment at MIT. Work by Brunner and LaBombard has demonstrated a successful method of integrating multiple heat flux and plasma diagnostics and achieving agreement in order to provide a higher level of confidence in the final measurements than could be achieved with any single diagnostic. Heat flux measurements were collected from an IR camera, an array of calorimeters, and an array of surface eroding thermocouples (SET). The SETs are able to give much higher time resolution for changes in surface temperature as compared to the calorimeters, while calorimeters provide valuable information about the total energy deposited on the tile surface. An array of embedded Langmuir probes (LP) was also utilized in order measure boundary plasma properties including plasma density, ion saturation...
current density, and electron temperature. The measurements from the LPs can be used to infer heat flux using the sheath power transmission factor (SPTF) while also providing useful measurements relevant to boundary plasma physics.

2. **Specific Proposal**

NSTX-U is planning to begin testing several of the SETs when they resume operation, which can then be compared with the heat flux measurements from IR cameras. There is an opportunity to implement a similar integrated suite of heat flux diagnostics on the DIII-D tokamak at both the divertor and the mid-plane limiter in order to perform more accurate surface heat flux measurements than have ever previously been achieved. Measurements at the mid-plane limiter would provide additional information regarding heat flux at regions of the inner wall other than the divertor. The introduction of one or more fully integrated diagnostic tiles at the divertor and at the mid-plane would allow for heat flux measurements to be taken from multiple diagnostics at the same spot simultaneously. These integrated “smart” tiles would contain calorimeters, SETs, and LPs. They could be assembled external to the device and then put in place of existing tiles during one of the semi-annual vents of the main chamber. By keeping these tiles within view of the IR camera, it is possible to use all four types of diagnostics together to achieve agreement on the surface heat flux. Once the method for constructing and installing these smart tiles has been optimized to a cost-effective level, they can be utilized more widely throughout the inner walls of the device. This could prove particularly advantageous when studying more complex confinement concepts such as the snowflake divertor configuration proposed for DIII-D and NSTX-U. These configurations produce multiple strike points, each of which needs to be studied in detail to better understand the extent to which these configurations are able to reduce peak heat flux. Developing an effective and economical diagnostic tile would allow them to be placed at various poloidal locations to study strike point configurations and at multiple toroidal locations to better diagnose symmetry around the device.

The same suite of heat flux diagnostics would also be valuable on linear plasma devices used in PMI studies, such as the Proto-MPEX experiment currently operating at ORNL. The purpose of Proto-MPEX is to study damage to materials in fusion energy relevant conditions and heat flux characterization at the tungsten target is an essential component of that work. A combined team from ORNL and UTK is already installing an IR camera on Proto-MPEX. Designing calorimeters and SETs for the experiment will improve the reliability of the measurement and provide a means of testing the various technologies for use in a diagnostic tile. Linear plasma devices like Proto-MPEX are an ideal platform for testing plasma and heat flux diagnostics before applying them to larger toroidal devices. The linear devices often have better controlled conditions, longer pulses, and more flexibility with testing new concepts compared to large tokamak experiments.

3. **Impact**

Much of the component technology needed for these diagnostic tiles has been utilized by others in the past and demonstrated to be effective. There is a great deal of expertise at various labs that have worked with one or more of these technologies and can provide valuable insight during this project including SNL (D. Buchenauer, J. Watkins, R. Nygren [See PMI Workshop 2015 White Paper], D. Youchison), MIT (B. LaBombard, D. Brunner), ORNL (T. Gray, E. Unterberg), LLNL (C. Lasnier, M. Makowski), UT-Knoxville (D. Donovan), and General Atomics (A. McLean).

This project has the potential to improve the fusion community’s understanding of surface heat flux conditions at multiple locations within DIII-D and will affect our scaling parameters for expected heat fluxes on ITER. This work will also benefit the Proto-MPEX experiment and will likely eventually become a critical class of diagnostics for use on a full-scale linear plasma stage for materials testing. This timing is ideal to act as scientists in the BPMIC group at DIII-D have stated the need for a better understanding of surface heat flux and Proto-MPEX is coming online and will soon require accurate target heat flux measurements.
4. References


8. V. A. Soukhanovskii, Presentation at Edge Coordinating Committee Fall 2014 Technical Meeting (2014).  