MHD and Heat Transfer Analysis for Lithium Walls in NSTX – March 21 APEX Electronic Meeting

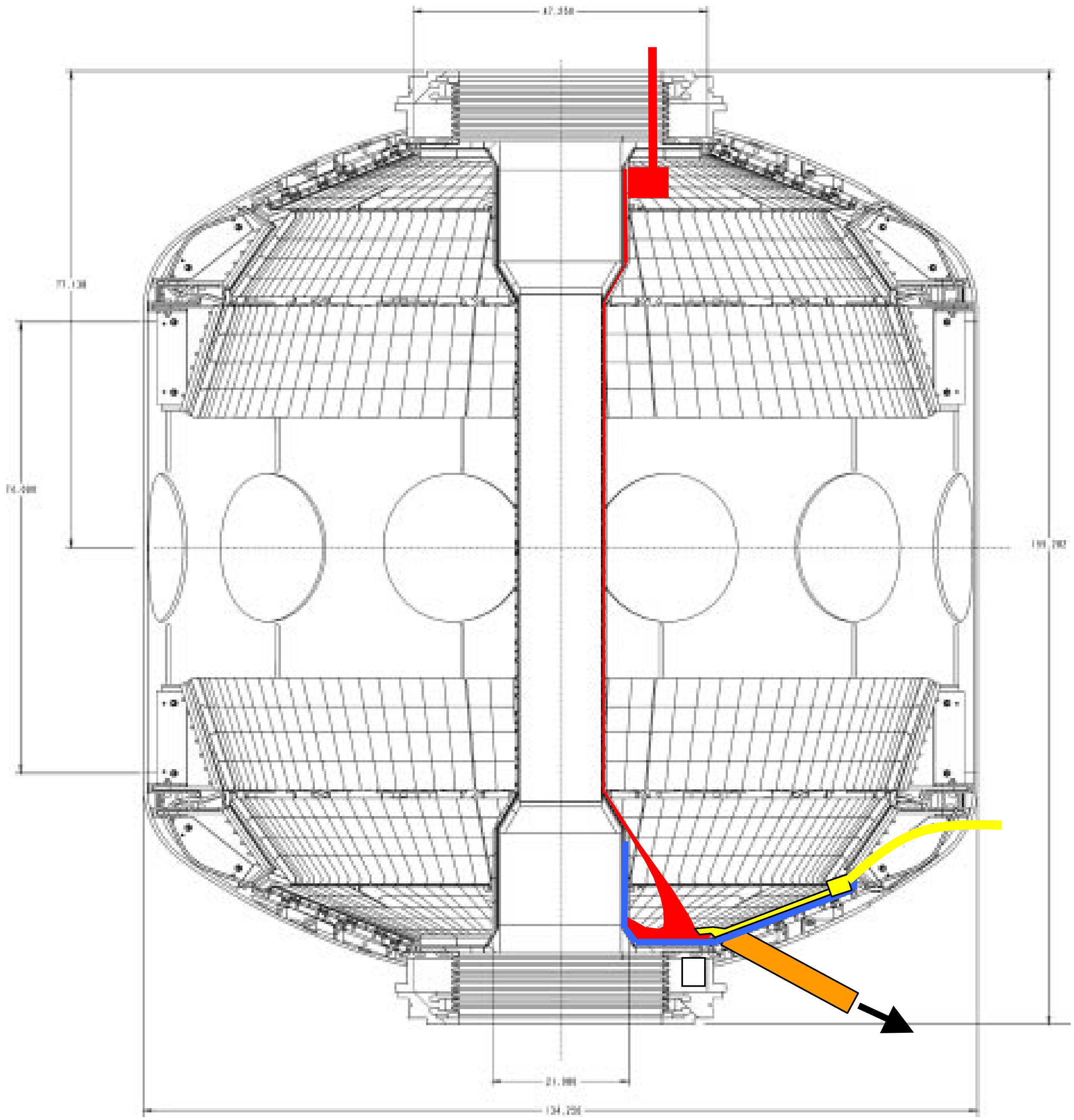
Presented by Alice Ying

Present Focus: ***Flowing lithium walls on NSTX center stack and inboard divertor***

Objectives of MHD and Heat Transfer Analysis

- **Identify the operating regimes that satisfy system requirements**
- **Define and understand issues that require further explorations**
- **Establish a database for design options**
- **Define meaningful experiments for R&D**

Flowing Liquid Wall on Center Stack and OB Divertor

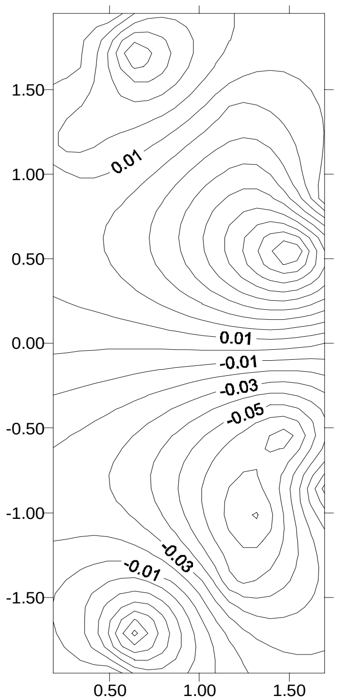


Spatial Variations of NSTX Magnetic Fields and Thermal Loads

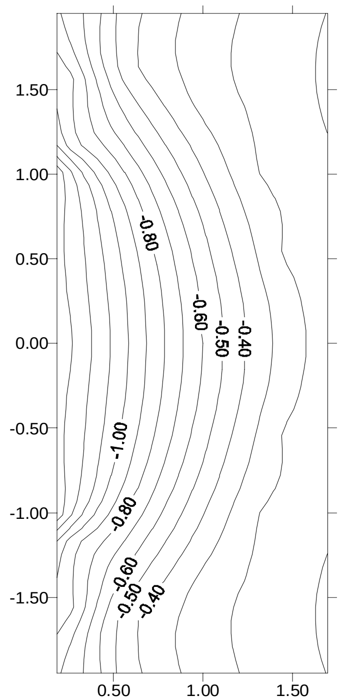
Some Observations of NSTX Magnetic Field Characteristics

(data from Douglass S.Darrow for discharges with beta of 10%)

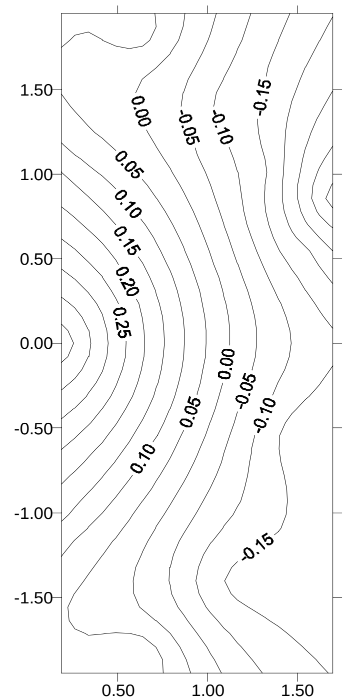
- ❑ 1/R dependence of the toroidal field (1.4 T on the surface of the center stack and 0.3 T on axis)
- ❑ A slight up-down asymmetry in the radial field distribution, since the poloidal field coil set is not exactly symmetric
- ❑ Radial field changes direction at the mid-plane
- ❑ Poloidal field can be 10 times higher than the radial field



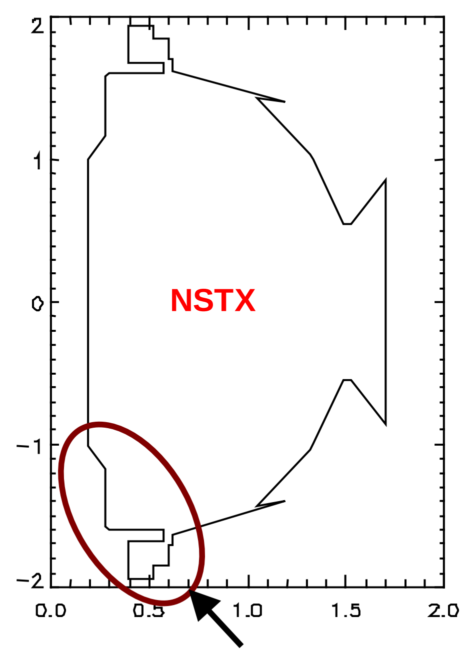
Normal radial field



Toroidal field



Poloidal field



Field gradient effect on flow expected

Developing a stable flowing liquid metal configuration across complicated magnetic fields (as in NSTX) is challenging

- **Damping of poloidal flow from normal B components δB**

  e.g. $\delta B \Rightarrow J_{toroidal} = V_p \delta B$
  JxB force opposing flow : $\sigma V_p \delta B^2$ (damping flow)

  A very stringent limit of $\delta B < 0.015$ T is required to maintain the flow characteristics (for ARIES-RS design parameters)

- **MHD jXB_p forces can also pull the Li off the surface**

  Again, $\delta B \Rightarrow J_{toroidal} = V_p \delta B$
  JxB force normal to surface: $\sigma V_p \delta B B_p$ (can pull Li off the surface)

- **Limiting field penetration requires that the magnetic Reynolds number of the fluid be greater than 1**

  - ❑ **Turbulent flow – MHD modeling becomes even more complicated!**
  - ❑ **Problems with the induced current**

- **For vertical instability, the eddy currents are toroidal**

  - don't want to impede the toroidal current paths (insulating sections problematic)

    Newton's third law implies that the plasma pushes back on the wall, which is an issue for a liquid wall for it can be easily deformed

  Toroidally segmented insulating breaks to impede toroidal conduction and reduce $J_{damping}$, but also reduce stabilizing eddy currents

NSTX Thermal loads (Original Requirements/Design Criteria)

Heating Power = 5 MW ?

Normal Operation, peak surface flux

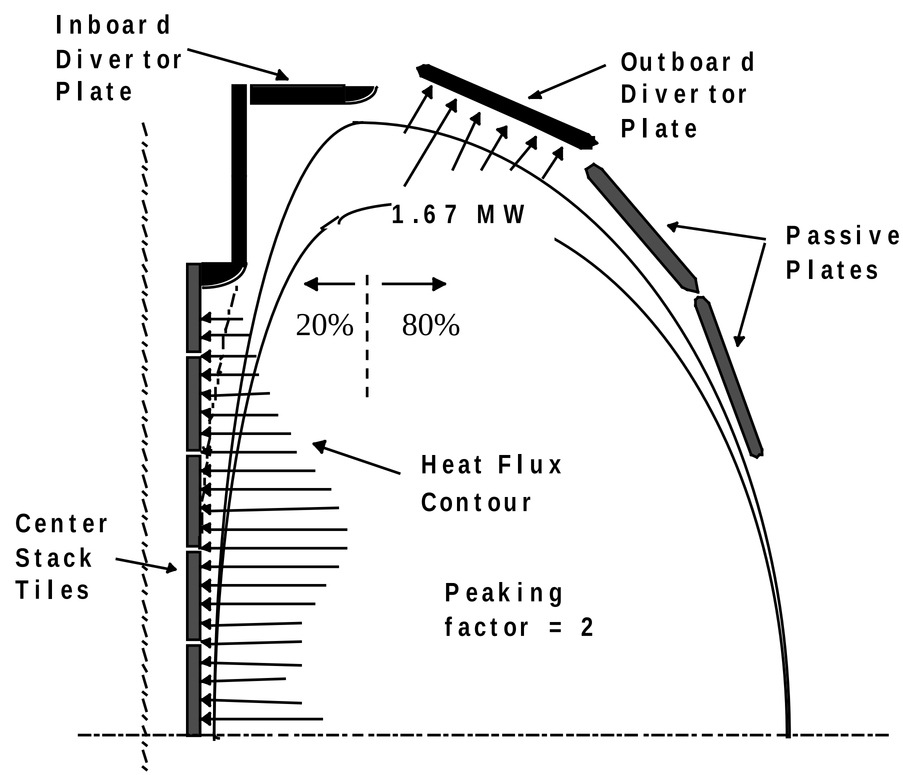
- **Center stack ~ 200 W/cm^2 peak**

- **Inboard divertor**
  ~ 700 W/cm^2 for single null

- **OB divertor**
  ~ 1100 W/cm^2 for $\lambda = 3$ cm
  ~ 1700 W/cm^2 for $\lambda = 1.5$ cm
  (peak from calc = 1400 W/cm^2)

- **Passive plates ~10 W/cm^2**

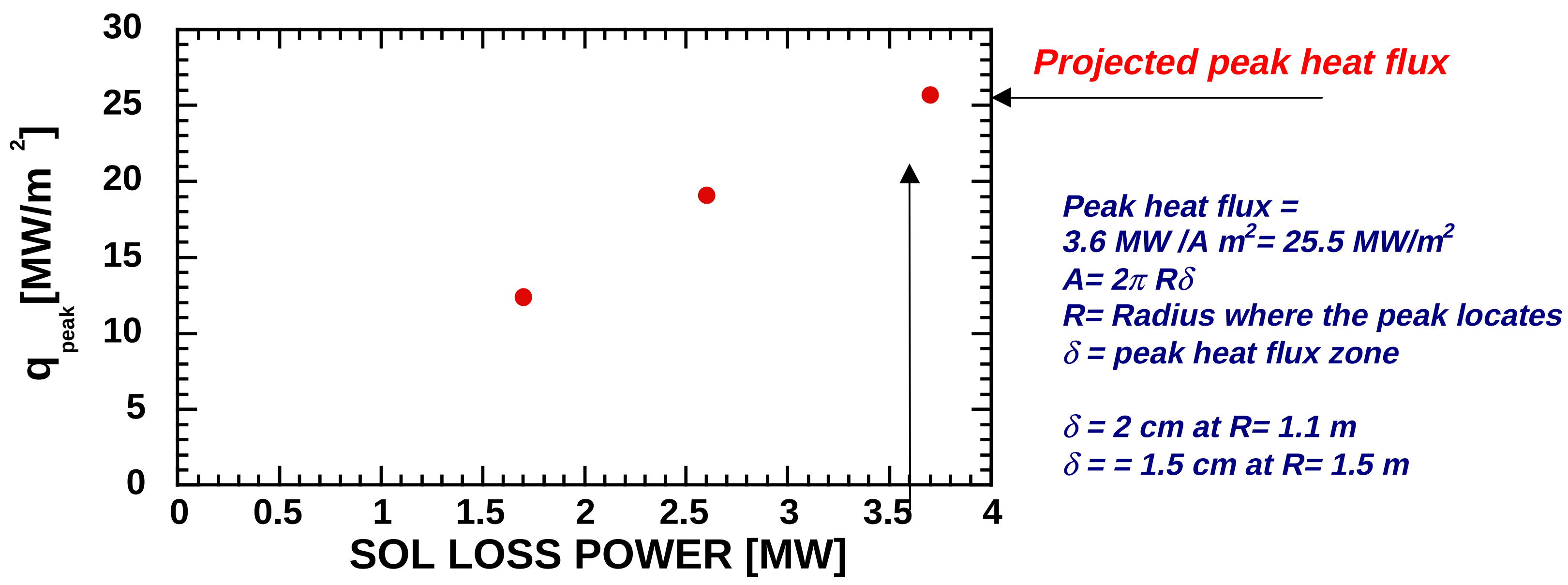
• **Disruption**
  - Peak surface flux: TBD



PEAK HEAT FLUX INCREASES LINEARLY WITH HEATING POWER (R. Maingi)

(divertor radiation power = 0.2 MW at P_{SOL} = 1.7 MW)

- **Peak heat flux occurs at outboard target**



- **Nominal operating point is 1.8 MW (Heating power = 5 MW); 3.6 MW operating point corresponds to heating power ~10 MW**

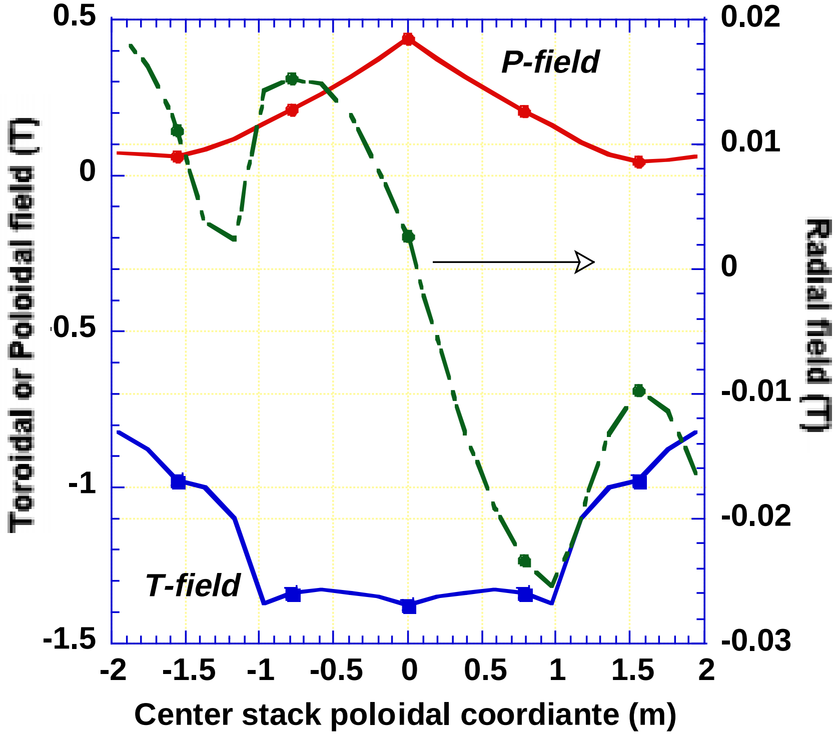
- **Peak heat flux decreases linearly with divertor radiation until plasma begins to detach from divertor (radiation ~ 1 MW)**

Flow Damping Occurs as a Result of the MHD Drag from the Radial field

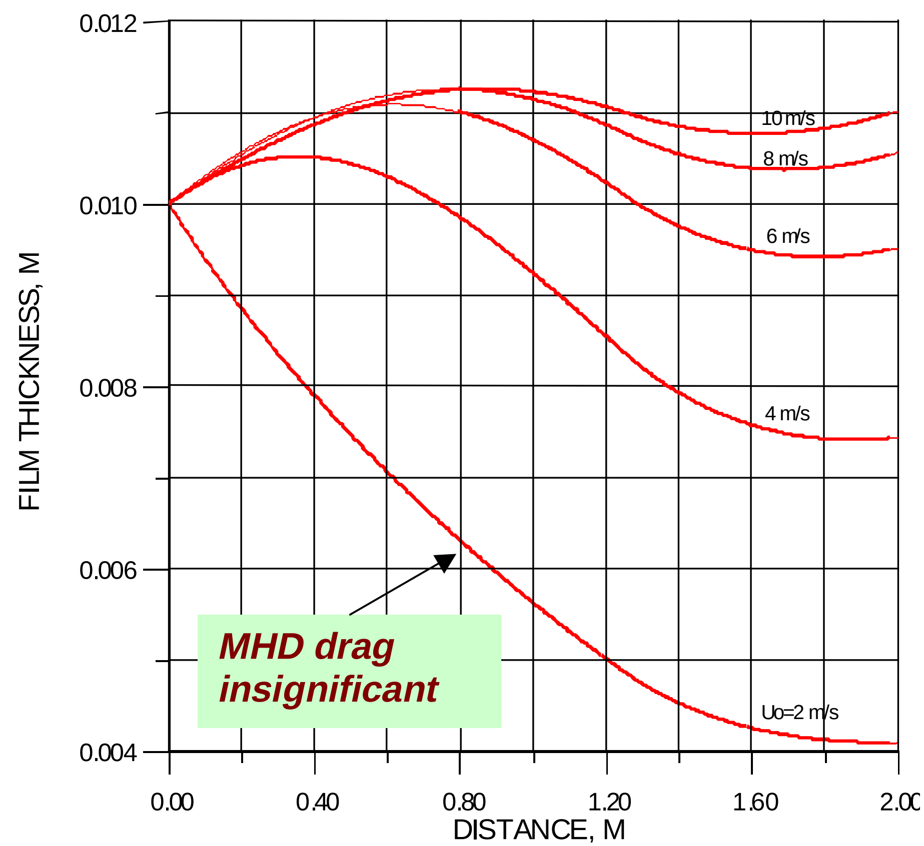
(The effect of the poloidal field on the flow characteristics is not yet taken into account, due to present modeling capability)

Initial film thickness = 1 cm

MHD drag appears acceptable, which results in about a ± 10% change in the flow thickness and the corresponding velocity at velocities of ~ 5 to 10 m/s



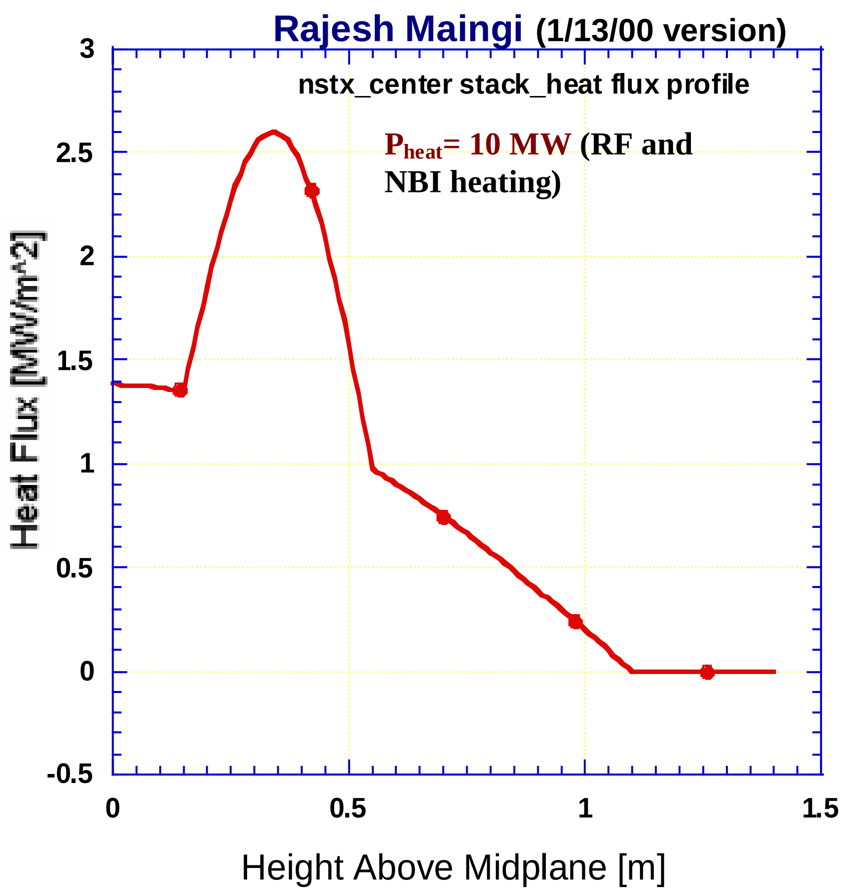
Film thickness varies as flowing lithium proceeds center stack downstream as a function of velocity



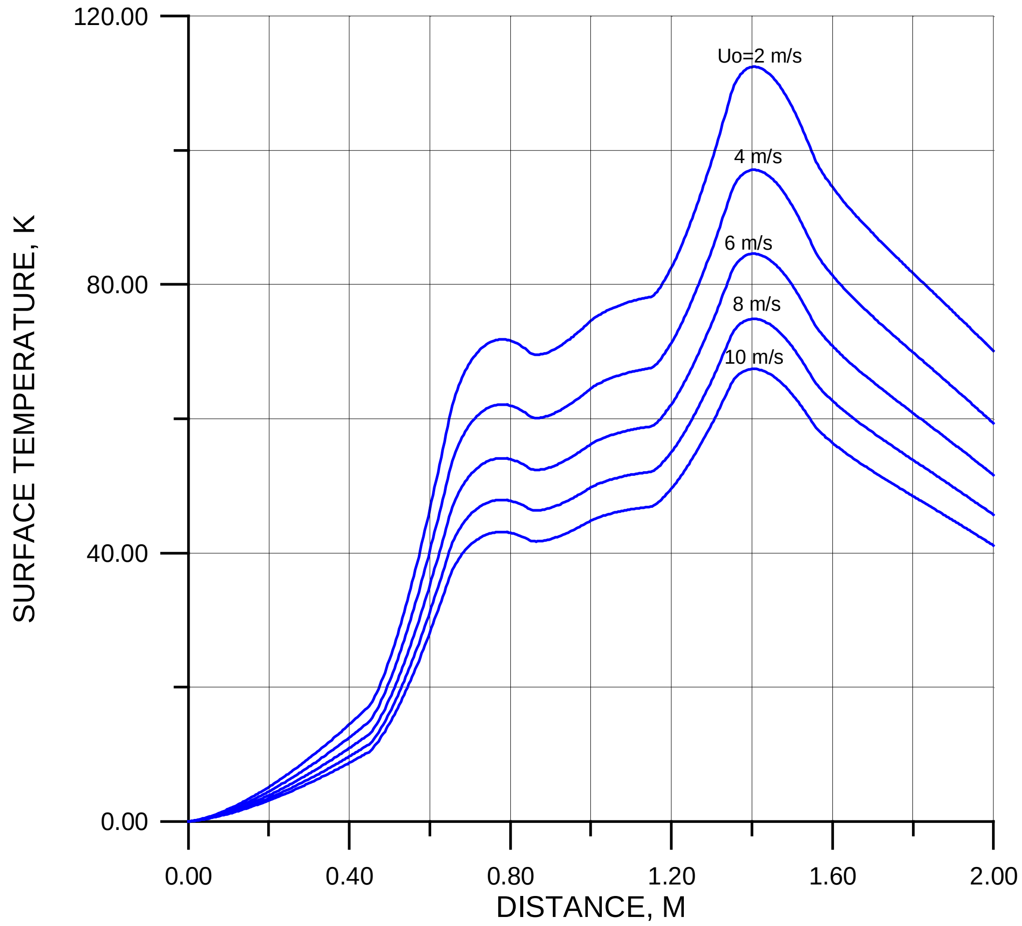
***Heat Transfer Capability-* During normal operation, lithium appears to have reasonable surface temperatures along NSTX center stack due to its high thermal conductivity (short flow path and manageable heat loads)**

Lithium melting temperature = 180.6 C

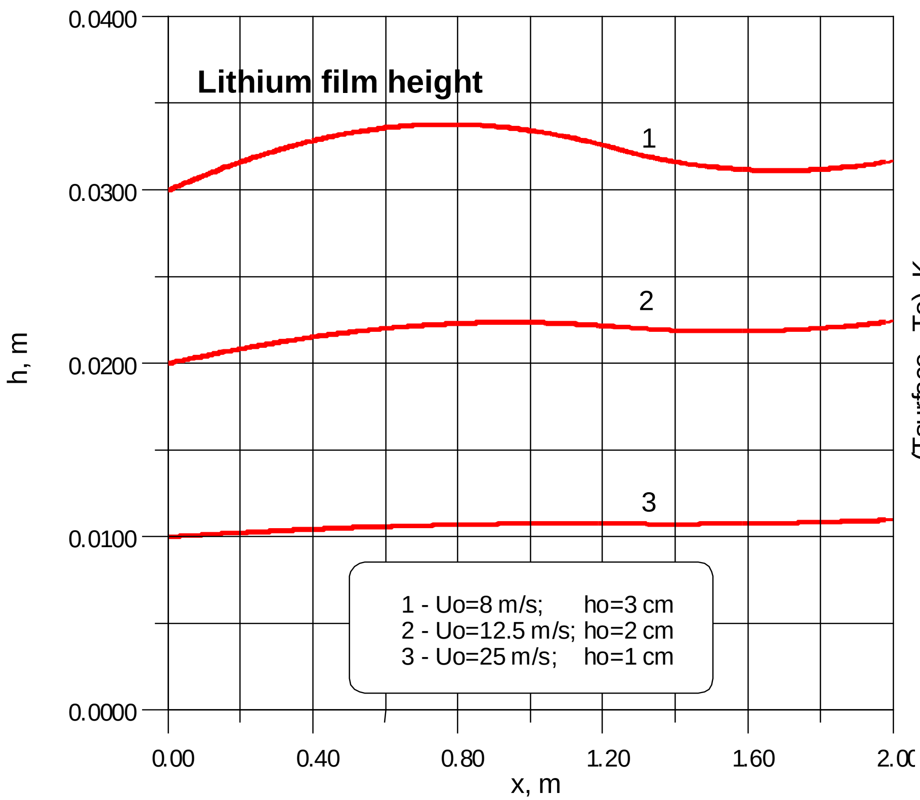
- **Predictable heat transfer (MHD-Laminarized Flow), but 2-D Turbulence may exist**
- **Laminarization reduces heat transfer**

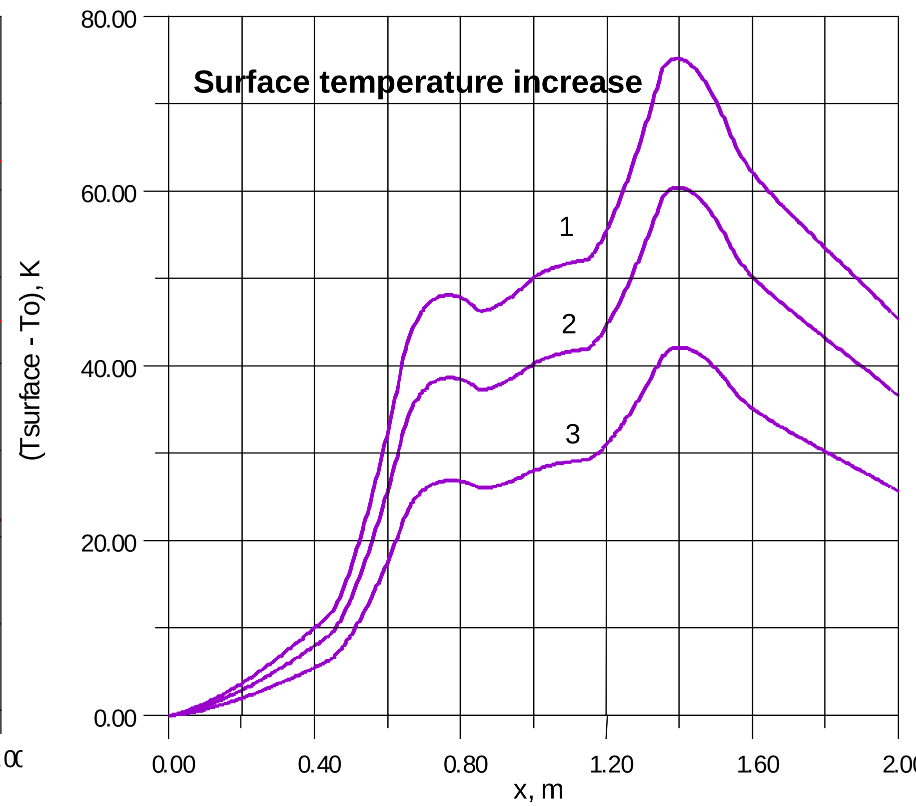


Lithium surface temperature increases as flow proceeds downstream as a function of lithium inlet velocity



To limit the field penetration for wall stabilization requires the operation of the flowing lithium wall with a Magnetic Reynolds number ($Re_m = \sigma\mu_o vh$) greater than 1 **[a much higher velocity than it is needed for heat transfer]**



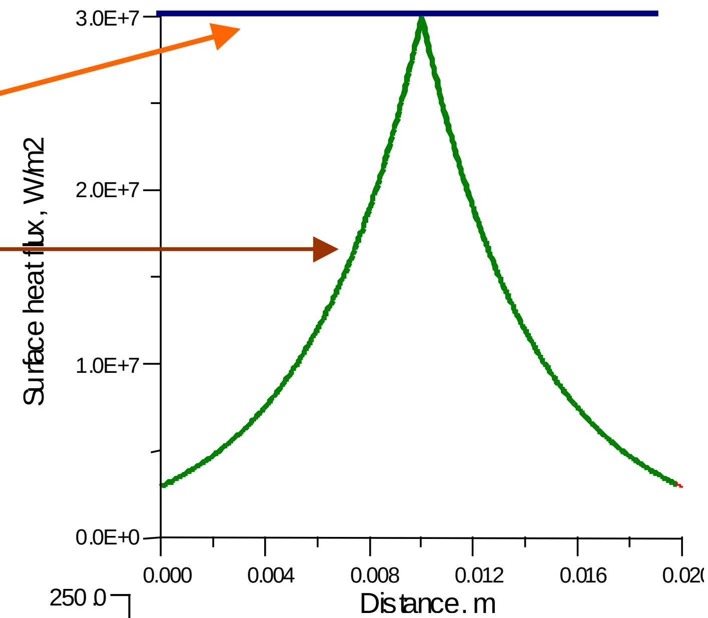


Note that:

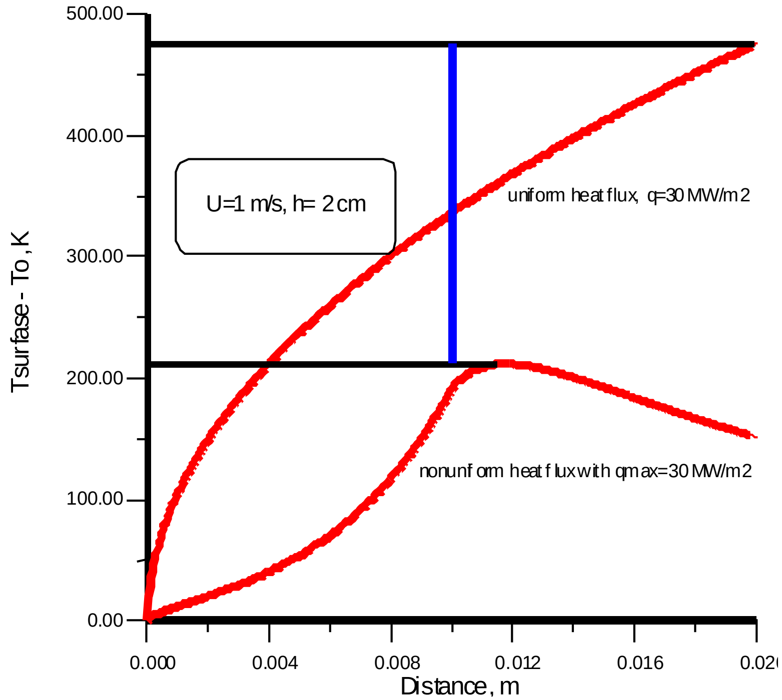
- **As developed, liquid metal magnetohydrodynamics mathematical formulation is valid with Re_m <<1**
- **As Re_m >1, the induced magnetic field is at about the same order of the applied magnetic field**

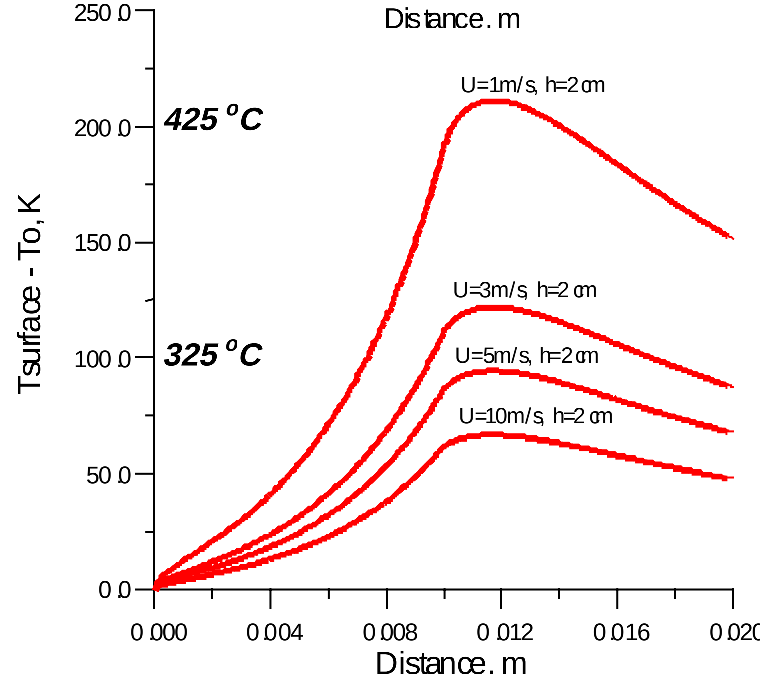
Lithium Surface Temperature Rises Under "Projected" Peak Heat Load Conditions

- ***A uniform heat flux distribution of 30 MW/m^2***
- ***A non-uniform heat flux distribution with a peak heat flux value of 30 MW/m^2***



Lithium velocity = 1 m/s
δ = heat flux zone = 2 cm
Peak heat flux = 30 MW/m^2





Plasma Liquid Surface Interactions in NSTX

- **What will be the maximum allowable flowing liquid wall temperatures in NSTX? (Preliminary Thoughts-Tom Rognlien)**
  - **At fixed density, impurity intrusion, and thus allowable wall temperature, is determined by (at least) two main effects:**

(1) Radial power flux

Projected heating power may be 2 times higher!

Reactor-sized slab: radial power flux = 0.12 MW/m2 (ITER)**

NSTX (4 MW, area = 30 m2): radial power flux = 0.12 MW/m**2**

Consequently, for this aspect of the problem, the two cases are the same.

(2) Axial lost time versus the radial diffusion time

NSTX would be better because of the shorter connection length and somewhat better flushing action.

Unique:

- ***Low-recycling edge density very dependent on edge fueling source***
- ***Need to evaluate sputtering and shielding for lower edge densities.***

- **How will local peak vaporization near the divertor region influence the maximum allowable surface temperature?**

Mechanisms to Evacuate the Lithium from the NSTX Chambers

Concerns:

- **Excessive MHD drag near the divertor region due to multi-component field effects**
- **Flow damping reduces heat removal capability**
- **May flood the chamber under high flow rate conditions**

If the combined inertia and hydrostatic head of the fluid is inadequate to move the liquid crossing the magnetic field (TBD):

Possible active evacuation mechanism

MHD pumping produced through jxB force by applying external currents

- **To apply radial currents to interact with the toroidal fields**
- **To use MHD propulsion from longitudinal currents interacting with decreasing toroidal field**

Key Research Elements for Deployment of Flowing Liquid Wall Tests in NSTX

- **Establishment and maintenance of stable flowing liquid walls in spatially and temporally varying magnetic fields**
- **Evacuation and removal of flowing liquid flows in regions with multi-complicated magnetic field components**
- **High heat removal capability without excessive concentrated vaporization and hot spots**
- **Electrical insulation requirements, material compatibility (liquid freezing, vacuum vessel baking temperature compatibility)**
- **CHI operational scenario**
- **Development of liquid handling and safety**
- **Plasma liquid wall interactions and plasma bulk interactions (gettering effects, conducting shell effects)**

Future Work

1. **Extension of the present 1.5 D MHD model to include multi-component magnetic fields is under way**

   Preliminary results based on 1.5 D of magnetohydrodynamics and heat transfer analysis have identified possible operating conditions for axisymmetric annular flowing lithium film for the NSTX center stack and inboard divertor.

   Further analysis will be performed for:

   - **flow in divertor region with prototypical toroidal field gradient and radial field**
   - **evacuation schemes**
   - **transient (or temporal effect) analysis**

   A porous capillary system may be used for the outboard passive plate.

2. **Potential issues concerning the implementation of the flowing liquid wall tests are being considered.**

   An R&D plan will be developed and reported on May meeting.

3. **Plasma edge analysis with a lower recycling edge density using the actual magnetic geometry of NSTX will provide guidance on the maximum allowable free surface temperatures.**