Limiter Heat Flux Measurements in the HSX Stellarator

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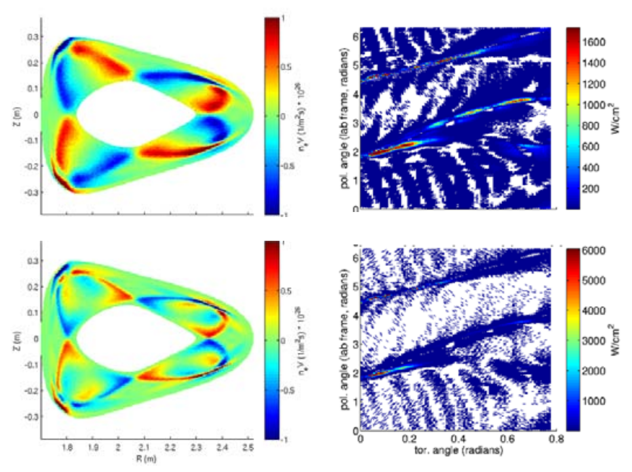
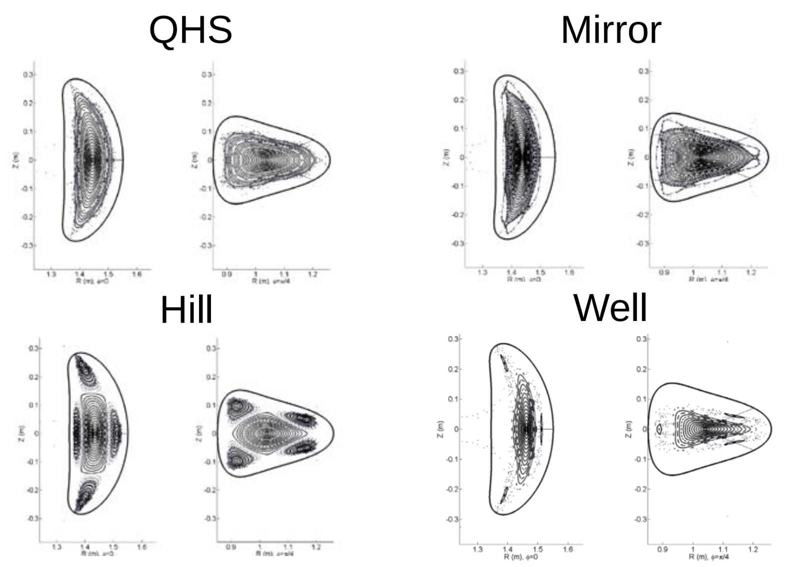
Motivation

- What is the role of perpendicular heat transport in the HSX edge?
- Divertor heat flux measurements are a common technique to infer edge heat transport information [1,2]
- HSX does not have a conventional divertor, but it currently has one limiter and a second is being constructed
- IR measurements of the limiter will be used to study edge heat transport in HSX:
  - Is there clear structure in the heat flux footprint? (suggests low $X_{\perp}$)
  - Is the heat flux footprint blurry/spread out? (suggests large $X_{\perp}$)
  - Does the heat flux footprint agree with connection length profiles from field line following?
  - Does the heat flux footprint agree with predictions from EMC3-EIRENE [3]?
  - How does the footprint change with radial limiter position, various plasma parameters (ne, Te) and magnetic configuration?



EMC3-EIRENE simulations for HSX courtesy of A. Bader.[3] They depict flows (left) and heat flux (right) for $D_{\perp}$=1.0 (top) and $D_{\perp}$ = 0.25 (bottom). In these simulations, $X_{\perp}$=3$D_{\perp}$.



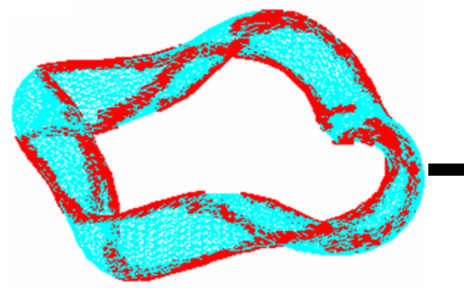
Preliminary IR Measurements

- Determine which type of measurements are possible and feasible in HSX using the current IR camera
  - Preliminary measurement locations:
    - Vessel wall at predicted strike point locations
    - Internal magnetic diagnostic array located ~ 1cm outside LCFS
- Strike point measurements are inconclusive because camera cannot resolve small temperature rise
- Magnetic diagnostic measurements are encouraging since structure and temperature rise are clear

Current HSX camera specifications

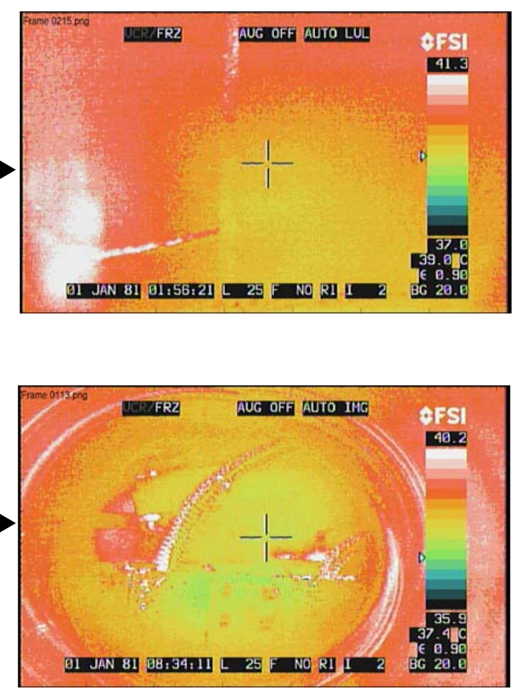
Measurable range	3.6-5 μm
Refresh rate	60 Hz
Precision	0.1 °C
Accuracy	± 2°C

Predicted Strike Points

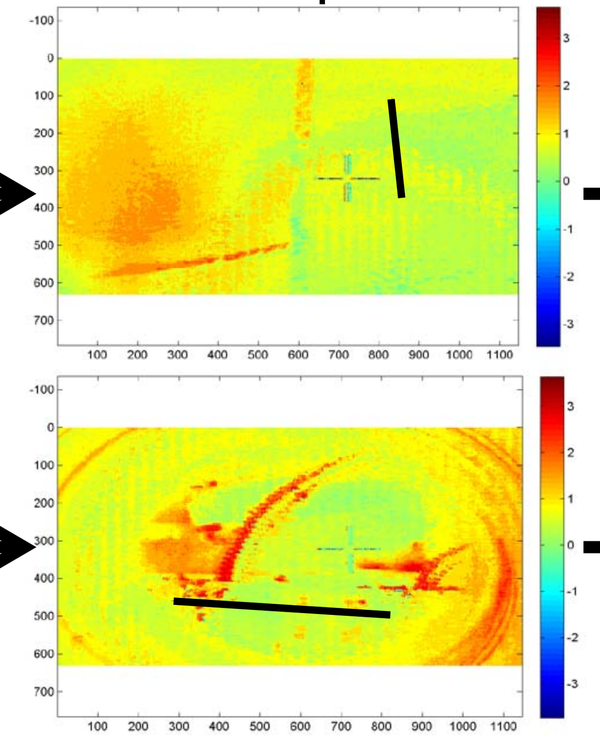


Magnetic Diagnostics

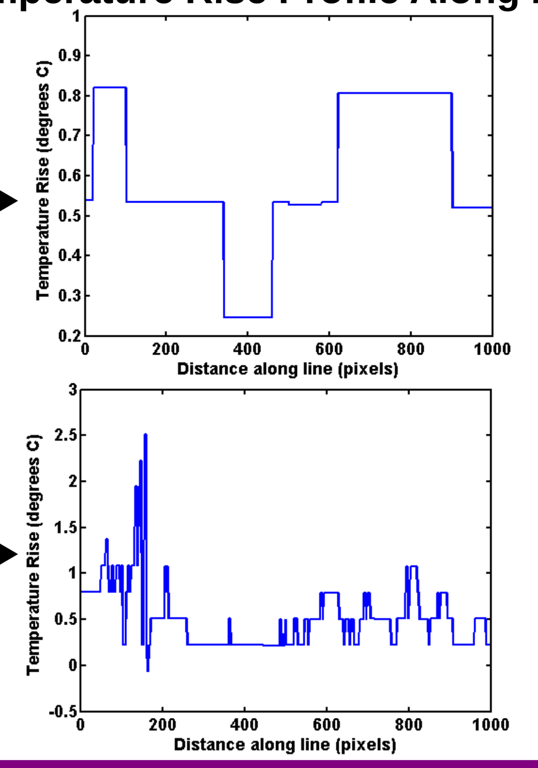
Unprocessed IR Image



Calculated Temperature Rise

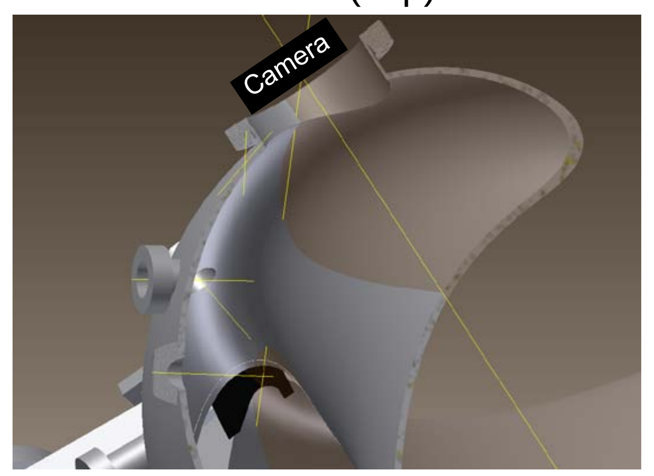


Temperature Rise Profile Along Line

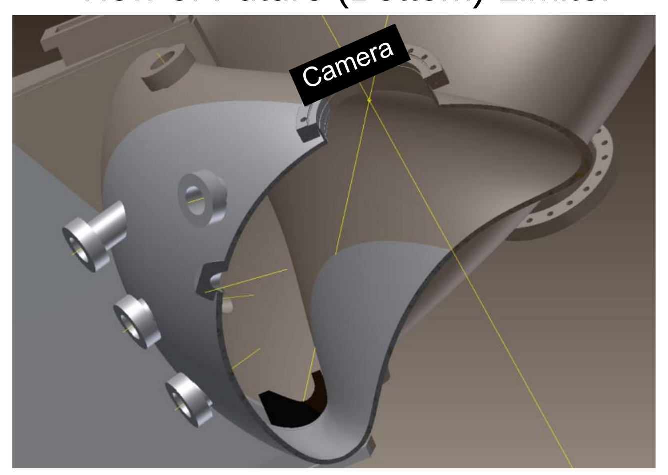


Planned Experiments

View of Current (Top) Limiter



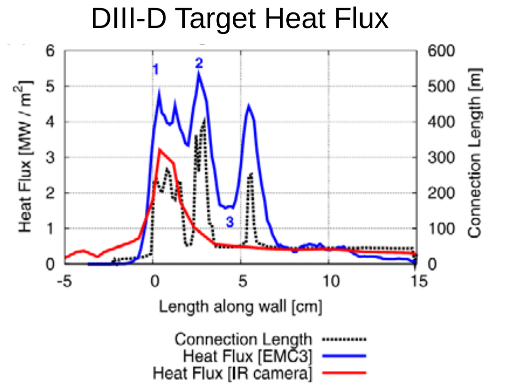
View of Future (Bottom) Limiter



AutoDesk Inventor view of current limiter (top) and future limiter (bottom) from selected 6 inch port. There is no direct line of sight to either limiter, so a mirror system is being designed.

- Design mirror system to provide view of limiter from selected port
- Make IR measurements of side view of the limiter
- Use bench calibrated emissivity and window transmission to determine actual temperature rise
- Use thermal modeling (SolidWorks) to determine steady-state heat flux from temperature rise
- If a faster IR camera is acquired, determine heat flux directly from time-resolved IR measurements
- How closely does the heat flux follow the connection length profile?
- Does the heat flux measurement agree with EMC3-EIRENE predictions?
  - If so, we can use a minimization technique to find the value of $X_{\perp}$ that provides the best agreement between the measurement and the prediction
  - If not, why?
    - Full 360 degree simulations of EMC3-EIRENE may be necessary to capture effects of toroidally localized limiter
- Look for parameter dependence of heat flux footprint in several magnetic configurations of:
  - Edge ne
  - Edge Te
  - Limiter position

An example of the measurement and model comparisons made at DIII-D [4] we plan to complete at HSX.



Preliminary Calculations

- Are heat flux measurements feasible in HSX?
- Where can we make heat flux measurements?
  - Predicted strike points?
  - HSX Limiter?
- Used worst-case scenario calculations to predict temperature rise of various cases
- The following assumptions were made:
  - 96 kW of ECRH heating power
  - Plasma absorbs 25% of this power (a conservative assumption)
  - Plasma radiates 15 kW of the absorbed power
  - This leaves roughly 10 kW to be deposited on the strike points/limiter
  - The limiter and strike points are heated evenly over their surface area
  - The heat deposition takes place during 50 ms

Stainless Steel

Emissivity	0.55
Heat capacity	0.5 J/g/°C
Thermal diffusivity	4.2 mm^2/s
Density	7600 kg/m^3

Graphite

Emissivity	0.7
Heat capacity	0.71 J/g/°C
Thermal diffusivity	3.6 mm^2/s
Density	2.1 g/cm^3

Heat equation:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T$$

L, the characteristic distance heat can travel:

$$L \approx \sqrt{\alpha t}$$

Blackbody temperature rise during 50 ms plasma shot:

$$\Delta T_{blackbody} = \frac{mE}{c}$$

Actual temperature rise:

$$\Delta T_{actual} = \varepsilon * \Delta T_{blackbody}$$

Predicted Strike Points

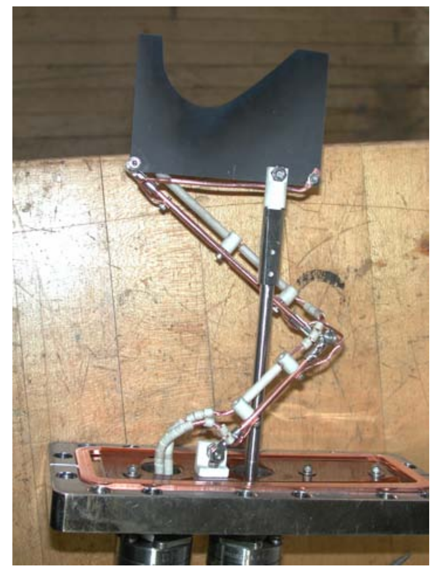
Surface Area	Area (m^2)	Mass (kg)	Blackbody Rise (°C)	Actual Rise (°C)
5 %	0.525	1.827	0.547	0.301
10 %	1.05	3.655	0.274	0.151
25 %	2.625	9.137	0.109	0.060
50 %	5.25	18.27	0.055	0.030

Graphite Limiter

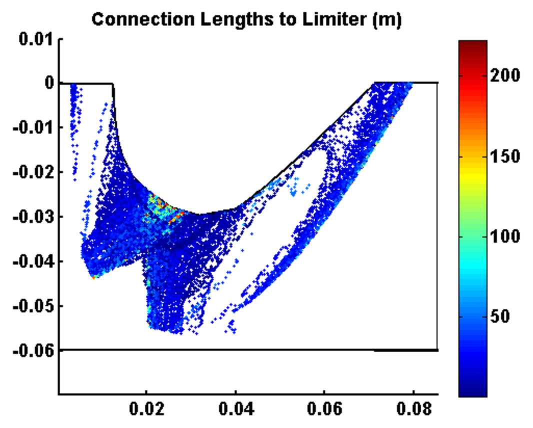
Area (cm^2)	Mass (g)	Blackbody Rise (°C)	Actual Rise (°C)
40	3.528	88.98	62.28

HSX Graphite Limiter

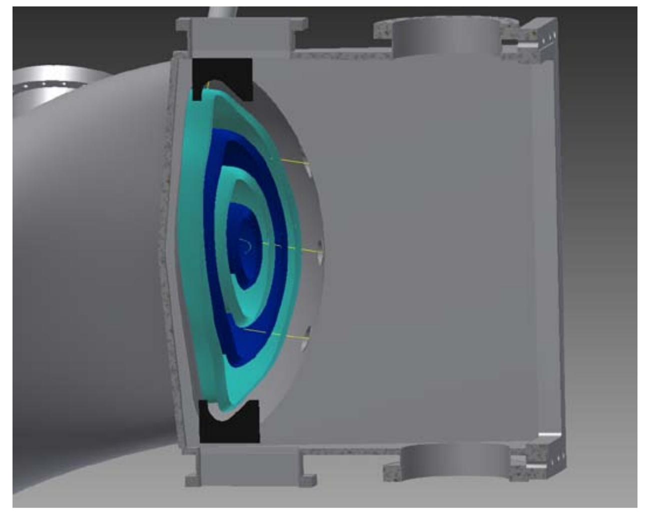
- HSX currently has a single graphite limiter that was designed to sit 1 cm outside the LCFS in the QHS configuration
- This limiter is designed to intercept approximately 45% of field lines in this configuration
- A new limiter is currently being constructed to be:
  - Larger
  - Easier to view with IR camera from available ports
  - On a linear drive
    - Fully retractable
    - Able to be inserted up to several cm into the confined plasma
  - Equipped with nearby ports for future pumping, spectroscopy, or electrical experiments
- AutoDesk Inventor is being used to design the new limiter and the optical system (i.e. the camera position and mirror geometry and location)



Current HSX limiter designed by C. Clark. It measures approximately 8.5 by 6 cm. It can be completely retracted and inserted up to several cm into the confined plasma.



Field line following connection lengths for current limiter as designed in QHS configuration.



AutoDesk Inventor design of HSX vacuum vessel and QHS flux surfaces. This is the helical cut where the current limiter is located (top) and where the second limiter will be inserted (at same location on bottom). Since space is available, the new limiter will be larger to provide more viewing area.

References

1. M. W. Jakubowski et al. “Overview of the results on divertor heat loads in RMP controlled H-mode plasmas on DIII-D.” Nucl. Fusion **49** (2009).
2. V. A. Soukhanovskii et al. “Divertor heat flux mitigation in high-performance H-mode discharges in the National Spherical Torus Experiment.” Nucl. Fusion **40** **(**2009).
3. Y. Feng et al. “3D edge modeling and island divertor physics.” Contrb. Plasma Physics. **44** (2004).
4. A. Bader et al. “Simulations of edge configurations in quasi-helically symmetric geometry using EMC3-EIRENE.” Nucl. Fusion **53** (2013).
5. H. Frerichs et al. “Three-dimensional edge transport simulations for DIII-D plasmas with resonant magnetic perturbations.” Nucl. Fusion **50** (2010).

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