US-Japan Workshop on Plasma Surface Interactions and High Heat Flux Components
7-8jan2014, Sandia National Laboratories, Livermore, CA
SAND2014-1026C

Power exhaust, detailed thermal analysis and use of data from thermocouple arrays

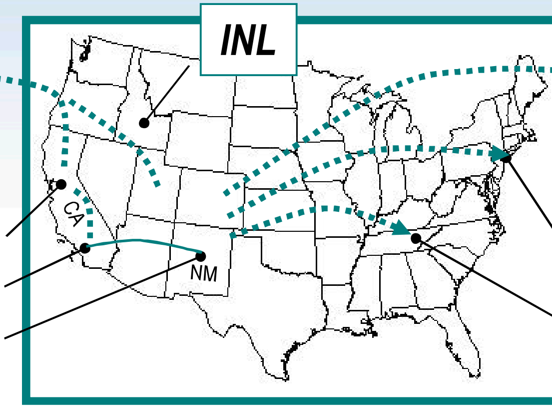
Richard Nygren
Sandia National Laboratories

- DEMO, Divertors and λ_q
- Two parameter strike point profile
- Thermal analysis of DIII-D tiles
- Use of thermocouple (TC) data to complement other edge measurements

Sandia National Laboratories is a multi program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Magnetic Fusion at Sandia

Collaborations with Japan, China, Korea, India



IPO, CEA France

Other EU collaborations

Livermore
La Jolla
Albuquerque

NSTX, PPPL
IP-ORNL

Sandia National Laboratories

Livermore California — **California Lab.**

Science & Technology — Albuquerque New Mexico

Physical & Eng. Sci.

Phys., Chem. & Nano Sci.

Puls… / **Radiation Sciences**

Hydrogen & Metallurgy Sci.
(Tom Felter, Mgr)

- PSI experiments
- TPE experiments with INL
- DiMES collaborations and probe support
- PSI Science Center
- PHENIX
- NSTX-U
- compact toroid with UCD
- DIII-D fast thermocouples
- DIII-D edge probes array – Watkins @ GA

Buchenauer
Kolasinski
Donovan
Whaley
Nygren-ABQ
(Youchison)

Rad.-Solid Int.
(Jon Custer, Mgr.)

- PSI experiments
- PSI collaborations
- **Ion Beam Lab**

Wampler
Van Deusen

~~Fusion Techn…~~

- ITER FW Design
- NSTX Liquid Li Div
- W armor
  He-cooled PFCs
  many SBIR/CRADA
- PHENIX

Ulrickson, 1352
Youchison
Nygren

Youchison, 1353

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HEAT power handling | BURNING PLASMA | TRITIUM self-sufficiency

Plasma Edge

HANDLE/HARVEST HEAT

PROTECT PLASMA

BREED/PROCESS/TRACK TRITIUM

Heat & Particles

ion damage

- Surface temperature
- Gradients: temp/stress

Morphology evolves!

Surface

He effects & neutrons

Bulk

- Material damage & modification
- T retention
- T permeation

- Cooling
- Pressure
- Thermal-hydraulics
- Thermal stress
- Cracking/failure
- Fab – Joining etc.

P F C

coolant

- Impurity source
- Erosion/redep.
- D/T recycling

PFC
SNL R&D

We analyze and test PFCs.

We have designed, built and deployed PFCs.

And we develop fundamental data in the Engineering Sciences on fluids and heat transfer*.

*presentation by Youchison

PMI
SNL R&D

We design, build and use probes and analyze tiles. We collaborate on plasma edge experiments.**

With various facilities, we study trapping of D/T/He; permeation of D/T and growth of W fuzz*.**

** Donovan, Nygren, (Watkins)

*** Kolansinski, Buchenauer, Cowgill, (Wampler)

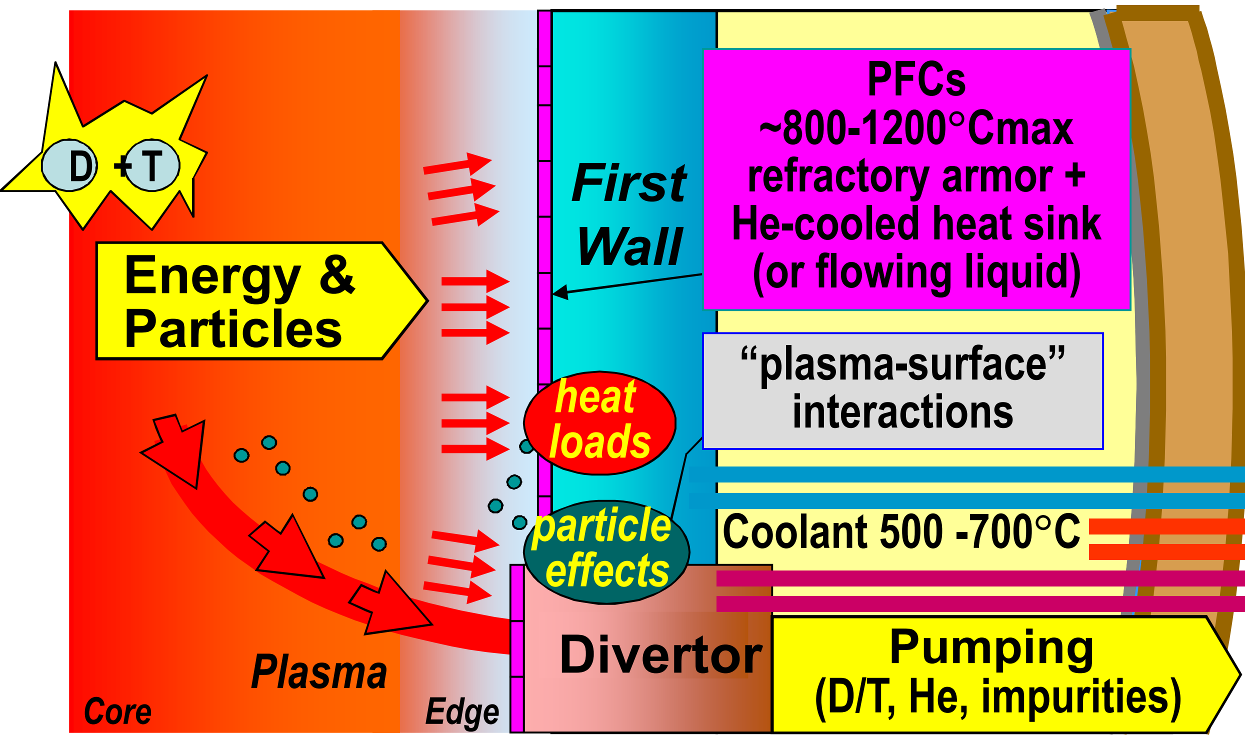
PFCs, DEMO, λ_q

We need robust and reliable components.

REACTOR Historic Preference:
solid refractory walls and
high temperature (He) coolant.

As we develop fusion, the distribution of heat on PFCs is a fundamental quantity and an active area of investigation in most large fusion devices.

For ITER and a D/D or D/T facility (FNSF, CFETR. DEMO), we must **understand** and **control** the **heat exhaust** and **significantly reduce heat loads** onto PFCs.



Youchison presentation Wednesday on micro-jet He cooling (scale issue)

PFCs, DEMO, λ_q

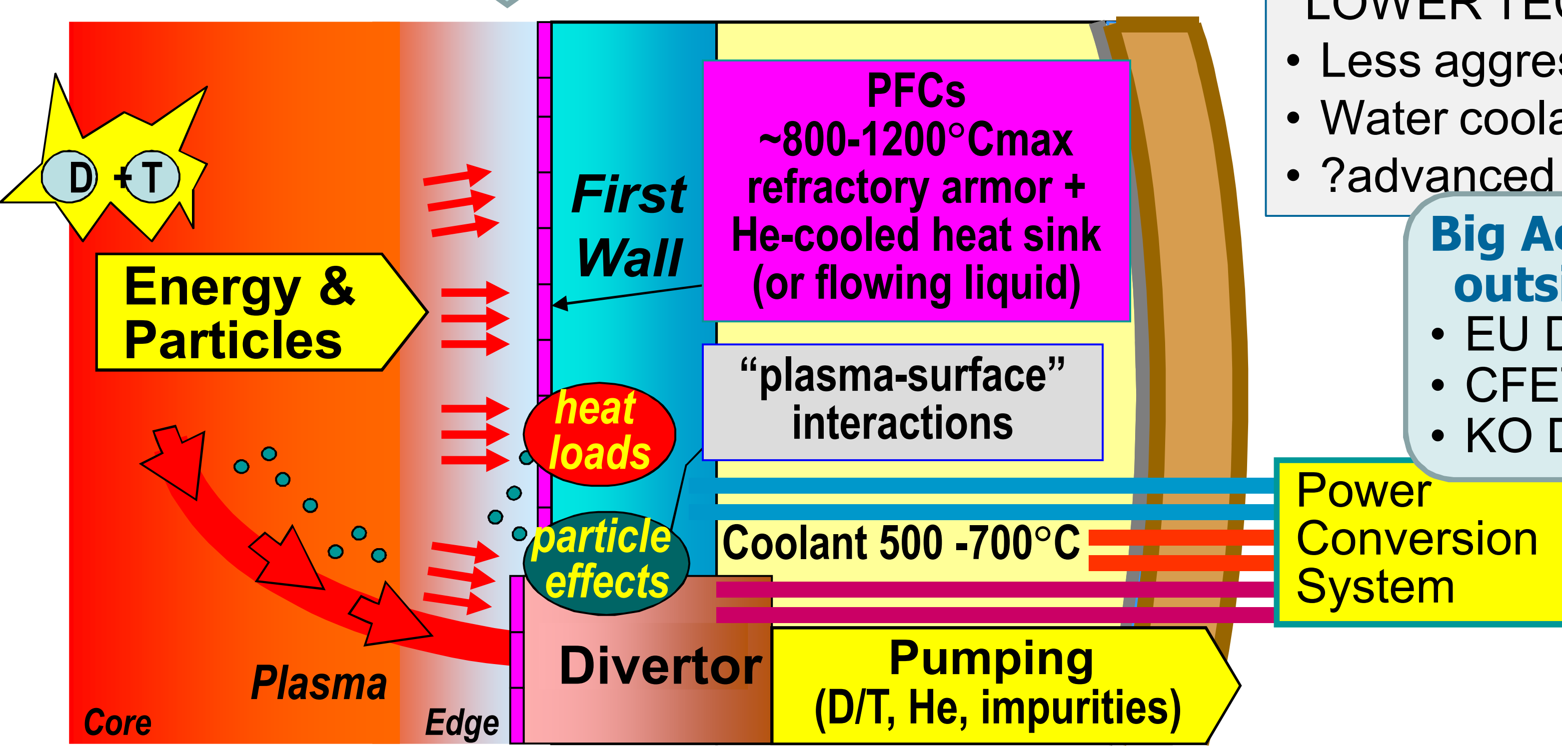
We need robust and reliable components.

REACTOR Historic Preference:
solid refractory walls and
high temperature (He) coolant.

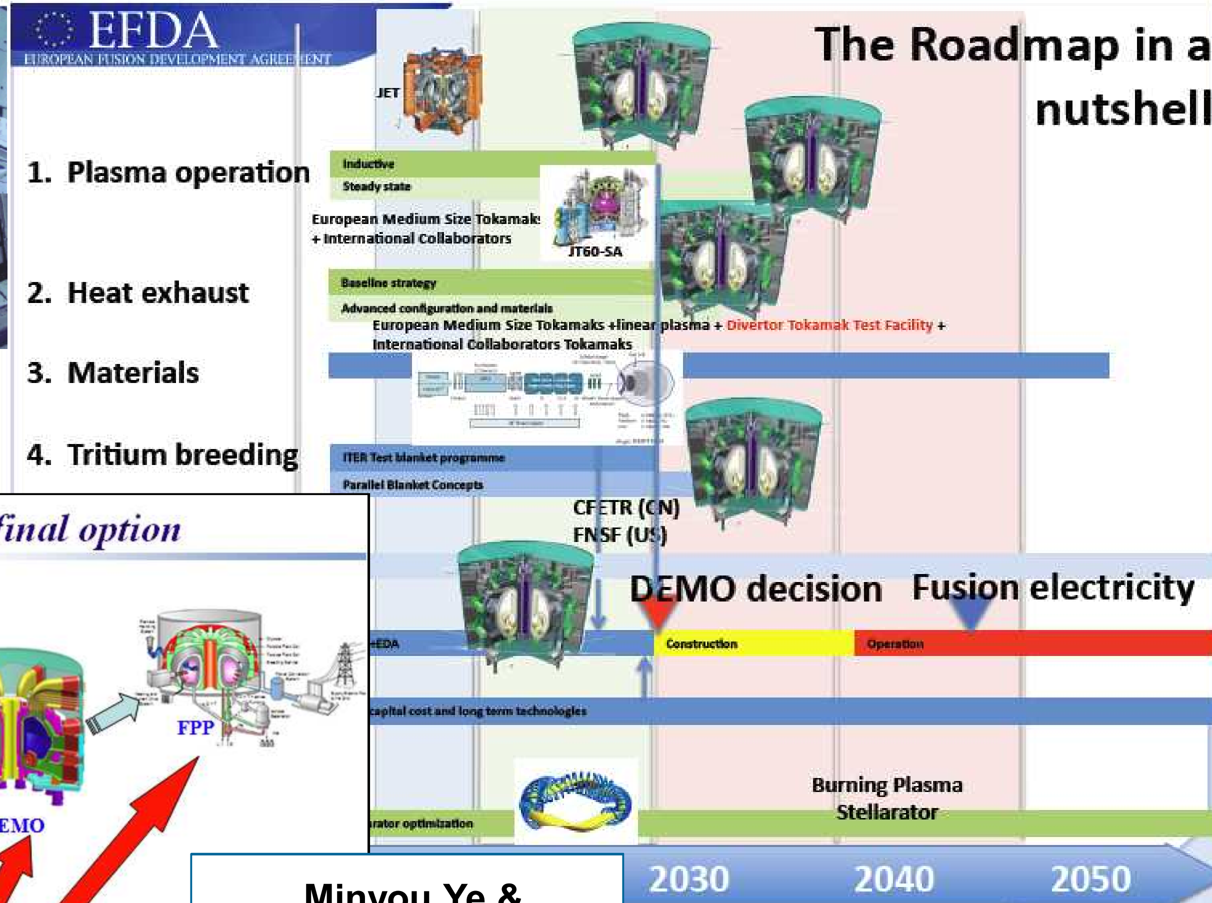
Big Concerns:
- High heat load with integrated FW
- Power distribution and scaling of λ_q
- Disruptions (tokamaks)
- Refractory lifetime and fabrication

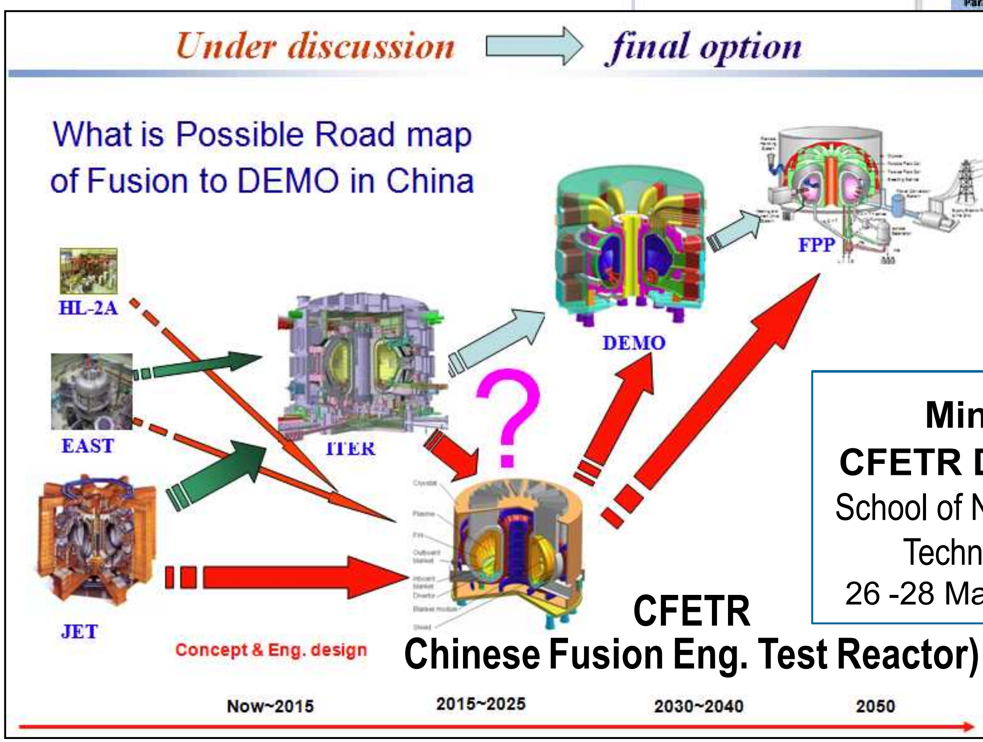
Recent DEMO/CTF Trend:
LOWER TECH OPTIONS
- Less aggressive physics
- Water coolant
- ?advanced divertor

Big Activities outside US/J:
- EU DEMO Study
- CFETR (PRC)
- KO DEMO (future)



ETR/DEMO Studies in EU and CH





Minyou Ye & CFETR Design Group
School of Nuclear Science & Technology, USTC
26 -28 March 2013, Kyoto

2011-14: two options
2015: proposal

Strike point profile

- DEMO, PFCs and λ_q
- Two parameter strike point profile
- Use of TC data to complement edge measurements
- Thermal analysis of DIII-D tiles

Analysis of a Multi-Machine Database on Divertor Heat Flux

APS-DPP Meeting, Salt Lake City 2011

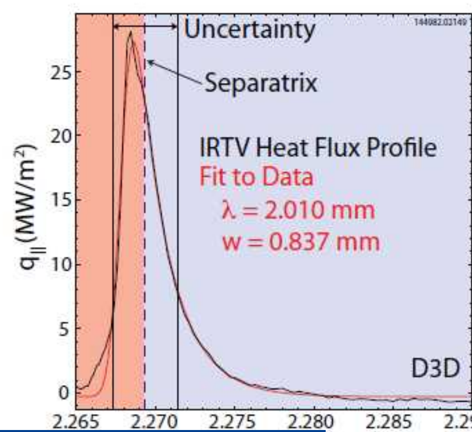
by
M.A. Makowski[1],
with
D. Elder[2], T.K. Gray[4], B.LaBombard[6], C.J. Lasnier[1], A.W. Leonard[3], R. Maingi[4], P.C. Stangeby[2], J.L. Terry[6], and J.G. Watkins[5]

The Eich Function is a Two-parameter, Semi-empirical Fit to the Entire Profile

- Eich* has developed a *two-parameter*, semi-empirical profile fit-function:

$$q_{\parallel}(s) = \frac{q_{\parallel,0}}{N\sqrt{\pi w_{pvt}^2}} \int_0^{\infty} e^{-(s-s')^2/w_{pvt}^2} e^{-s'/\lambda_{sol}} ds' + q_{bkg}$$

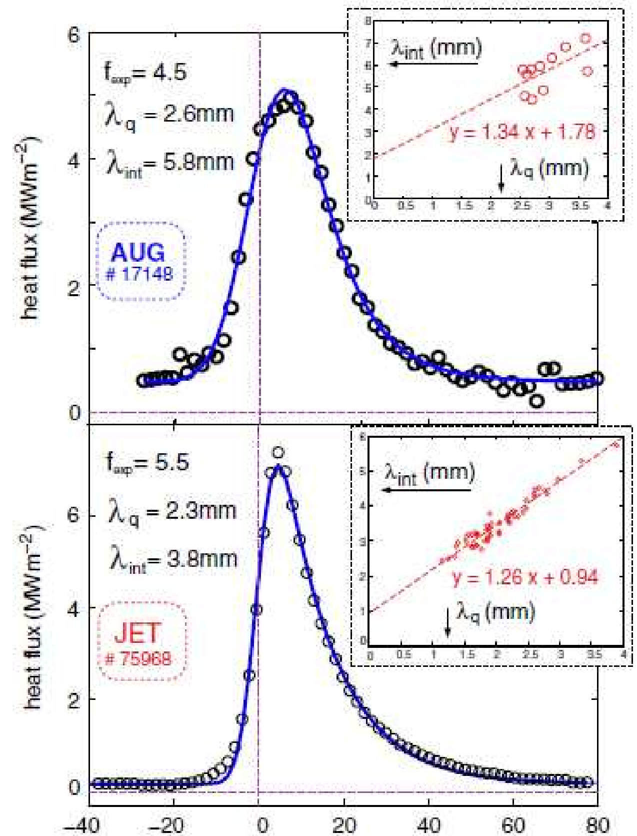
- The function is a convolution of a Gaussian and an Exponential
  - Gaussian: Characterized by w_{pvt} and models diffusion into the private flux and SOL regions
  - Exponential: Characterized by l_{sol} and models transport in the SOL



*T. Eich, accepted for publication, PRL.

DIII-D NATIONAL FUSION FACILITY

GENERAL ATOMICS



T. Eich, Sieglin, Scarabosio, Findamenski, Goldston, Herrmann, ASDEX Team, Inter-ELM Power Decay Length for JET and ASDEX Upgrade .... PRL 107, 215001 (2011)

Strike point profile

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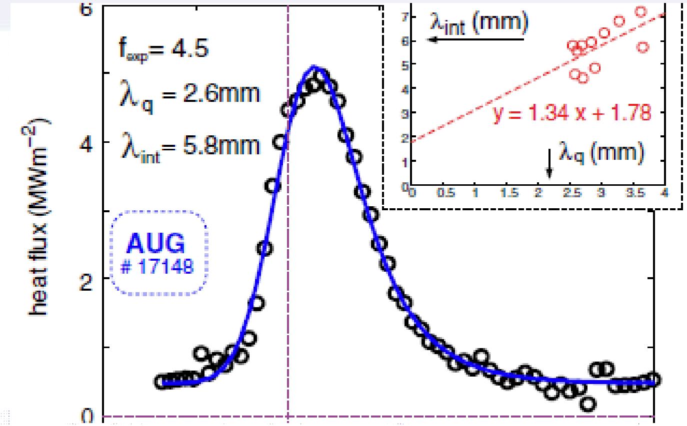
Main points:



- Private flux side steeper.
- Peak offset from strike point.
- Fit based on IR & probe data
- But the thermal profile (t>0) is broader than the heat load.

Example

Model for NSTX Liquid Li Divertor

Strike point profile

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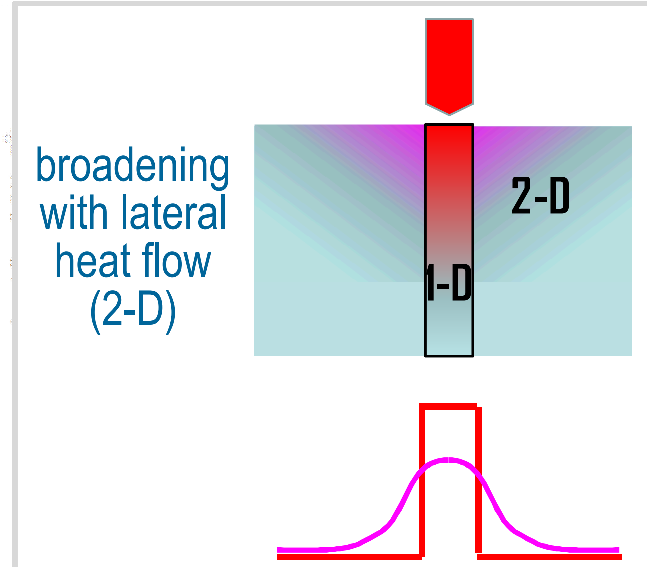

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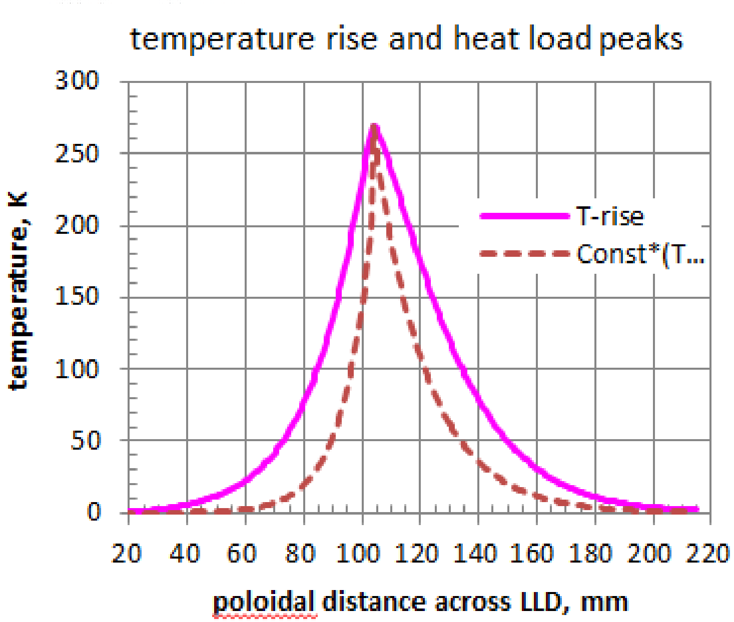


Example

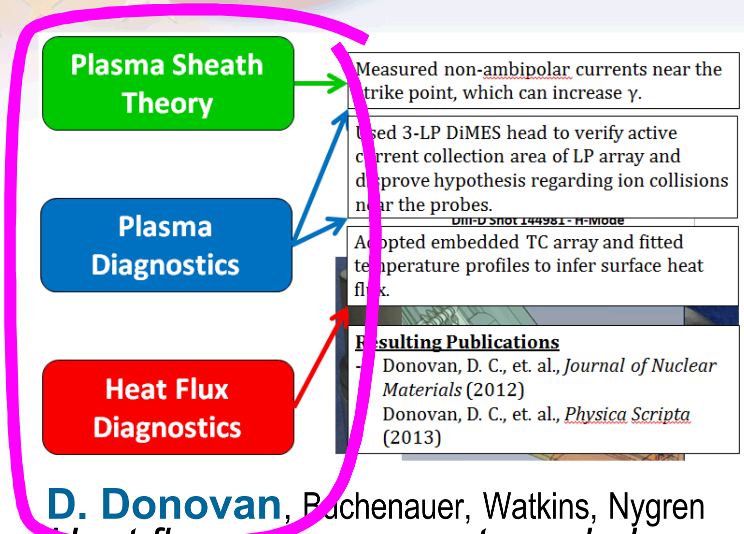
Model for NSTX Liquid Li Divertor

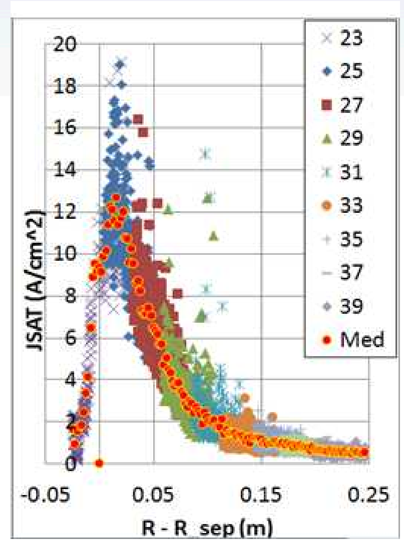
10 MW/m^2 peak heat load (input shape), normalized, and temperature rise (output). The temperature peak has broadened by ~2X near by end of shot.

The temperature profile progressively broadens due to **lateral heat conduction**, primarily in copper substrate, and is greatest at end of shot (temperatures highest).

This also happens in ATJ graphite (also Mo and W).

Strike point profile ⇦⇦⇦ IR thermal profile





D. Donovan, Buchenauer, Watkins, Nygren
Heat flux measurements and plasma boundary properties on DIII-D [this workshop]

DIII-D OPERATION

THEODOR (widely used 2-D code) uses IR data (middle of tile), assumes a uniform surface layer and uniform material, and delivers heat load versus distance along the divertor.

- Private flux side steeper.
- Peak offset from strike point.
- Fit based on IR & probe data
- But the thermal profile (t>0) is broader than the heat load.

2

A proper 2-D treatment (XY) handles this

- ***temp-dependent properties***
- ***uniform unchanging surface***
- ***“deep” Z projection***

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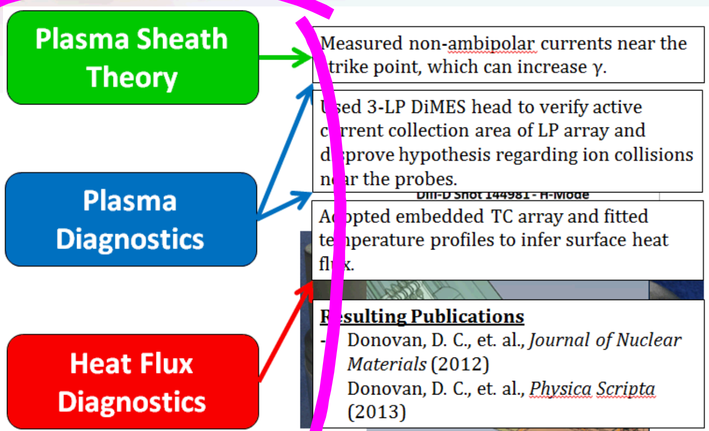
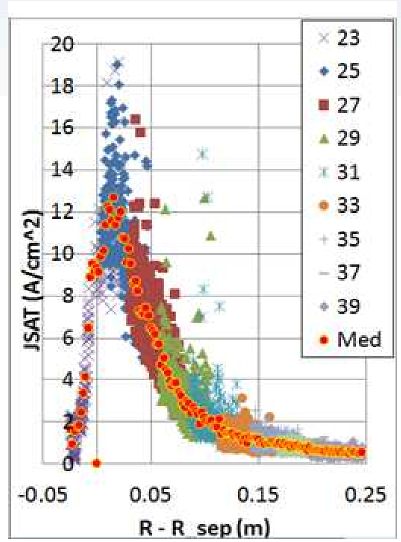
Strike point profile ◁◁◁ IR thermal profile





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A proper 2-D treatment (XY) handles this

- ***temp-dependent properties***
- ***uniform unchanging surface***
- ***"deep" Z projection***

Understand the limits of 2-D treatments.

Some advantages of TCs

1. not affected by these factors
2. independently determine heat flux (suitable conditions)
3. can be placed easily including points not seen by IRTV.

These factors affect the result: (3)

- *tile edges*
- *misalignments*
- *gaps*
- *varying properties (e.g, emissivity) of redeposited layers*
- *reflected hot spots*
- *camera motion*
- *...*

Use TCs to improve quick time automated processing for 2-D analysis of heat flux.

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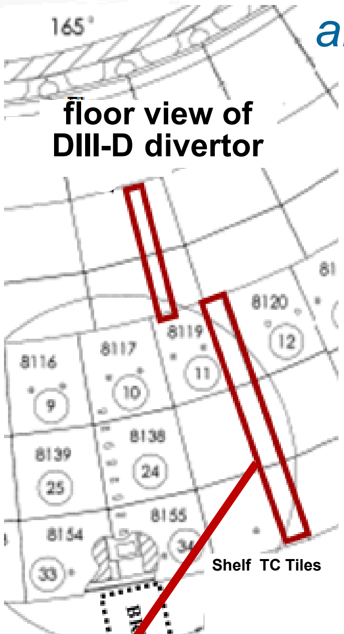
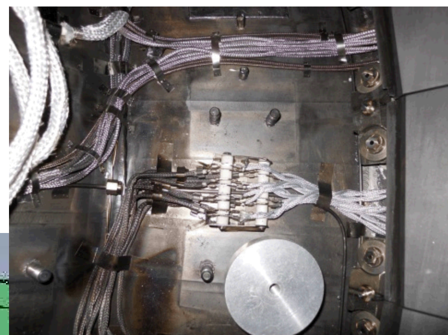
Use of Fast TC data

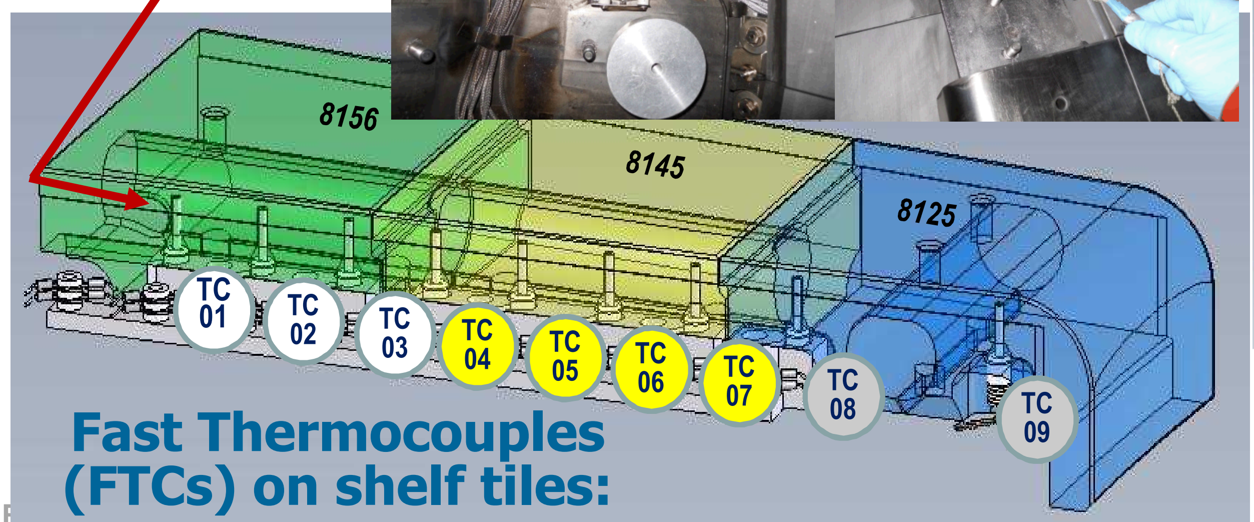
Sandia has a long relationship with DIII-D. We built, maintain and interpret data from the L-probe array and support DiMES.

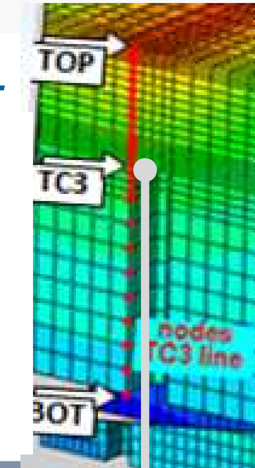
In 2013, SNL took stewardship of the Fast Thermocouple (FTC) array (installed by Schaffer and Taussig, GA) with 7 FTCs in floor tiles and 9 in shelf tiles.

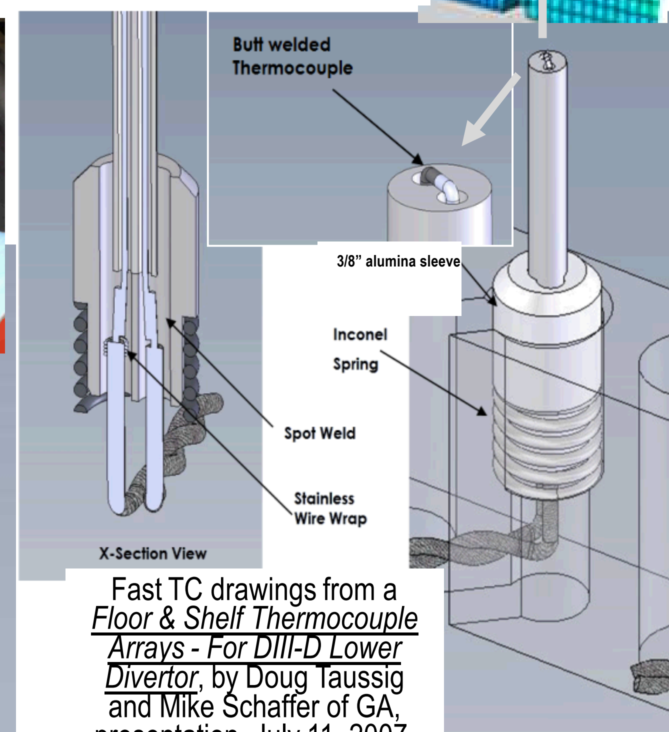
We have upgraded this array and are evaluating effective use of the data and providing analysis to support the investigation of heat exhaust in the plasma edge.











Fast TC drawings from a <u>*Floor & Shelf Thermocouple Arrays - For DIII-D Lower Divertor*</u>, by Doug Taussig and Mike Schaffer of GA, presentation, July 11, 2007.

Thermal analysis
for NSTX, NSTX-U and DIII-D

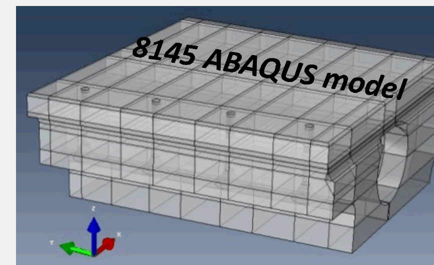
Main point in this presentation is role of 3-D thermal analyses.

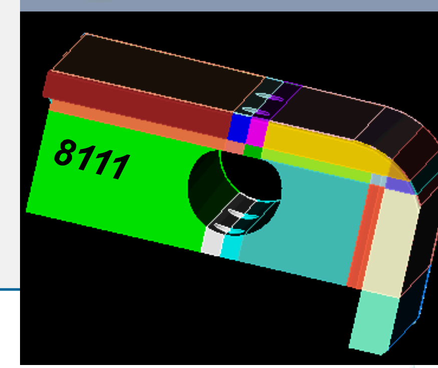
- Support plasma edge experiments
- Validate/guide 1-D & 2-D approaches,
  a) show effects of temperature dependence of materials properties,
  b) show importance of lateral heat flow *(thermal broadening)*
  subsequent slides
- Quantify 3-D effects
- Quantify limits for using FTC data
- Guide planning of experiments

Sheath physics experiments measured the relation* between heat and particle flux

- outer strike point on shelf
- diagnostics included
  IRTV
  FTCs
  diverter Thomson
  calorimeter probe
- thermal analyses in progress
- compare model using FTC data with fit from IR and calorimeter probe.

*sheath power transmission factor





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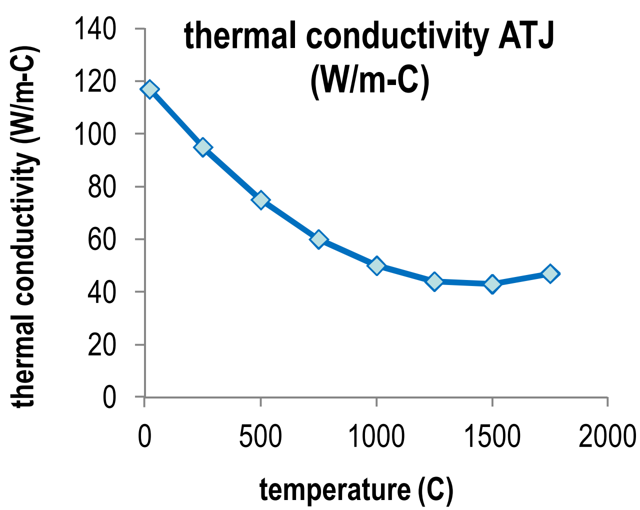
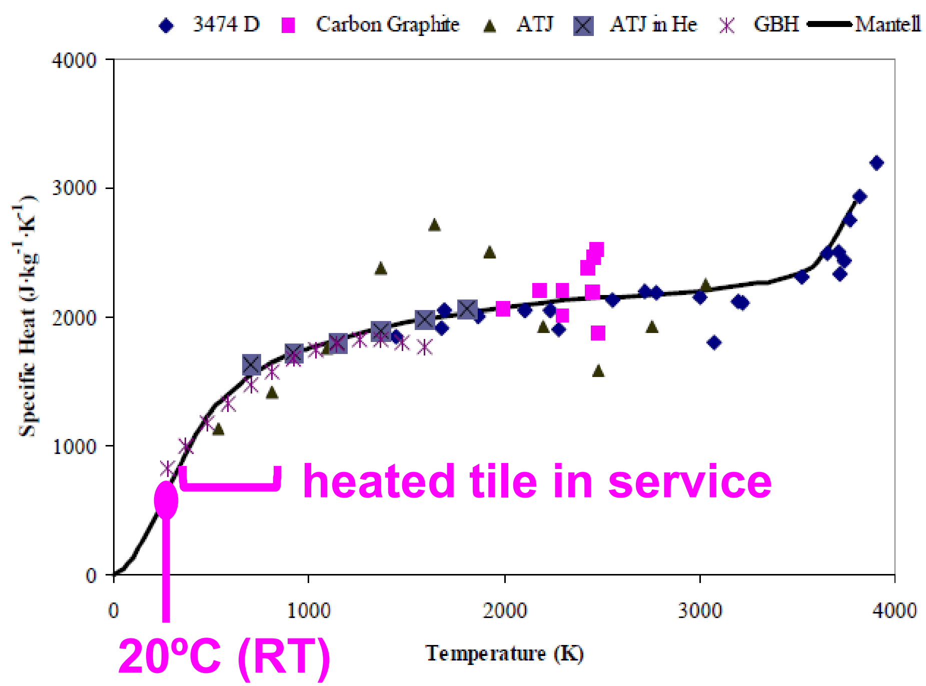


The large increase in ATJ's heat capacity above RT means that the upper portion of a tile, at higher temperatures, absorbs more heat than would be the case if only RT properties were used.



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Thermal analysis
for DIII-D

Filling the heat capacity in the upper region retards the flow of heat to the bottom of the tile (BOT).

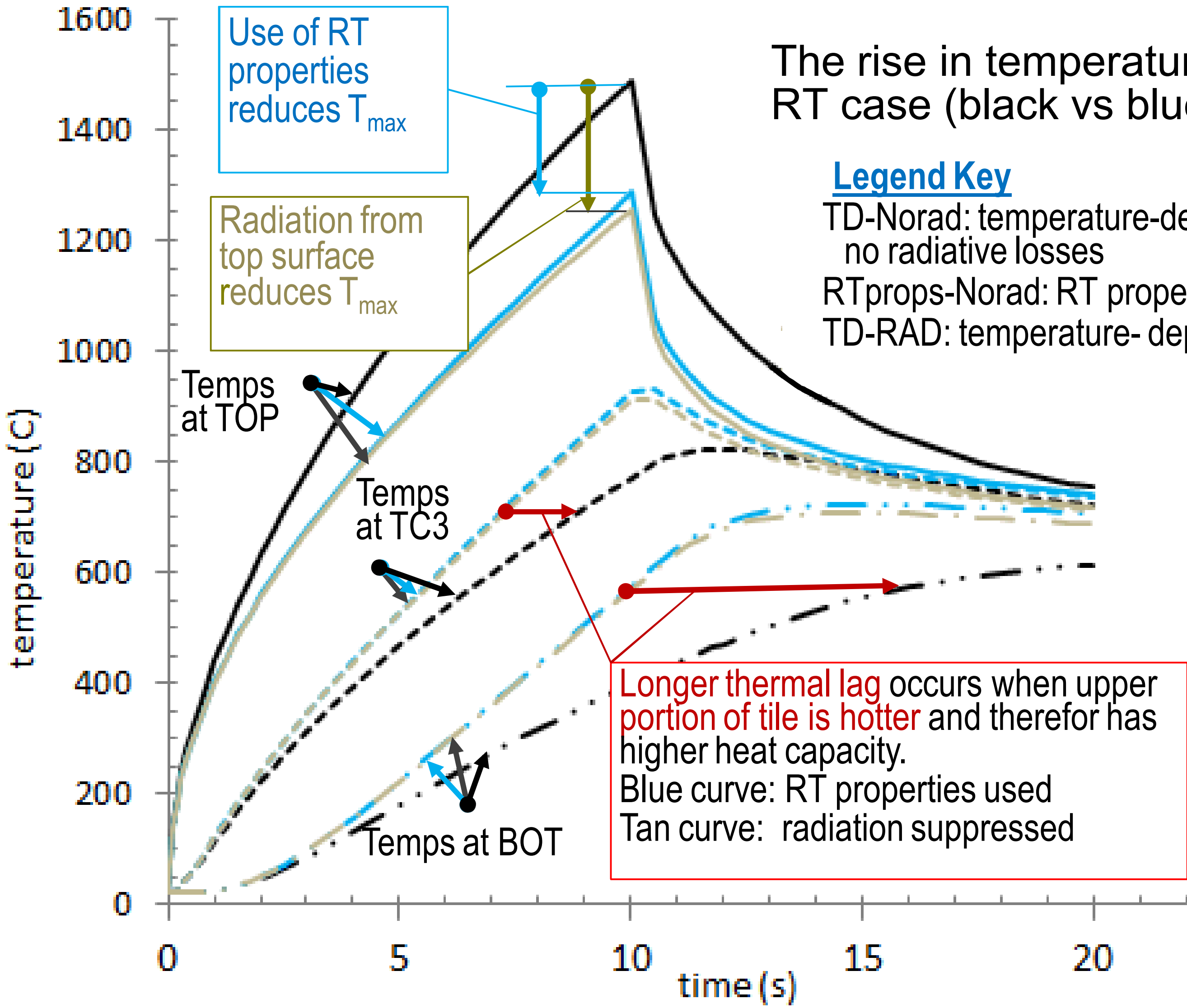
The rise in temperature there lags the RT case (black vs blue dash-dot lines).

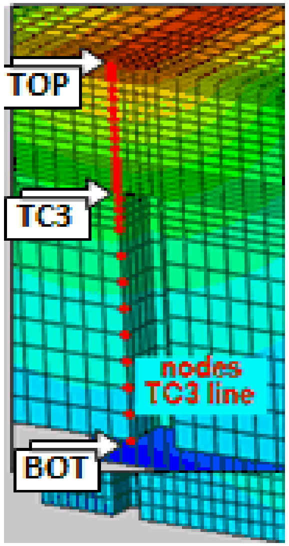
Legend Key

TD-Norad: temperature-dependent properties, no radiative losses

RTprops-Norad: RT properties, no rad. loss

TD-RAD: temperature- dependent, rad.loss





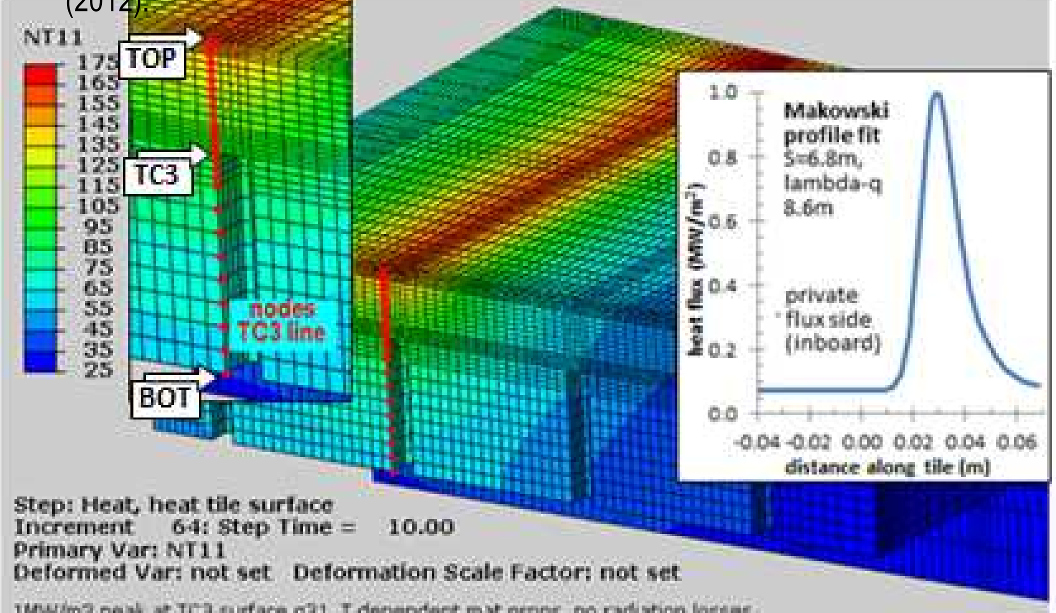
Thermal analysis
for DIII-D

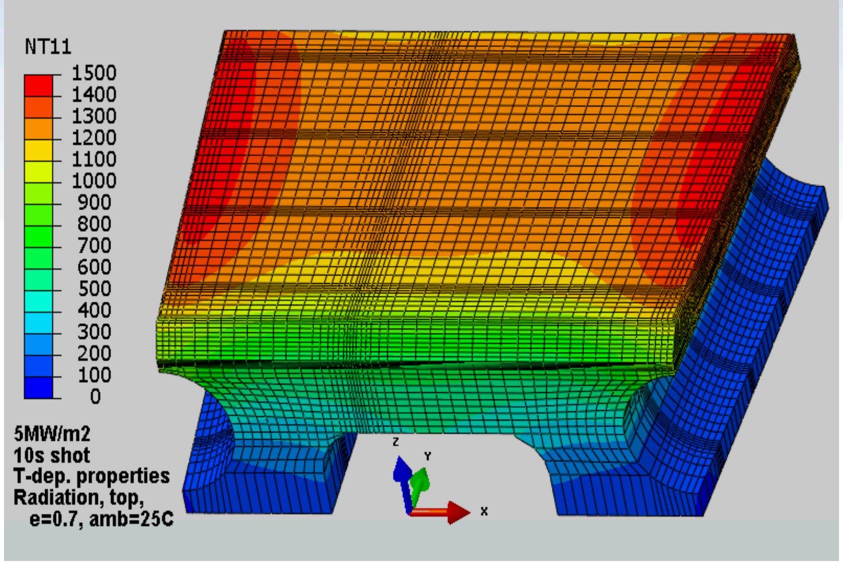
A cube with uniform heat load on top has "1-D" top-down heat flow. A 3-D model of a tile with a uniform surface heat load has 2&3-D effects.

T_{map} (below) shows nodes TOP, TC3, BOT and temperature distribution after 10s with the heat load profile (insert) centered on TC3.

The profile by Makowski et al[1] uses a two parameter fit (championed by Eich) and is based on IR data typical of H-mode shots.

[1] Makowski, Elder, Gray, LaBombard, Lasnier, et al., Phys. Plasmas 19, 056122 (2012).





(above) uniform heating, 5 MW/m^2, 10s, radiation from top surface. Pattern has 3-D effects from edges and feet.

Surface Heat Flux (MW/m²)	TOP Props (T), No Rad. (°C)	TC3 Props (T), No Rad. (°C)
1 uniform	310.0	205.4
1 peaked	157.0	99.4

T_{peak} of **157°C** in the peaked profile (left) is much below the **310°C** with 1 MW/m^2 uniform heating.

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Summary – Conclusion

Main point in this presentation is role of 3-D thermal analyses.

- Support plasma edge experiments
- Validate/guide 1-D & 2-D approaches,
  a) show effects of temperature dependence of materials properties,
  b) show importance of lateral heat flow *(thermal broadening)*
- Quantify 3-D effects of interest:
  strike point close to tile edge; long shots; surface maps corrected for varying emissivity.
- Quantify limits for use of FTC data,
  e.g., signal too small, complex shot history, etc.
- Produce data to guide planning of experiments,
  e.g., dwell times for strike point and sweep rates that give useful FTC data; thermal stresses for high power shots.

Comment on Status of HHFF

- SNL's HHF test program, flagship for the US, significantly influenced world programs. This capability, not supported now, may be lost.
- EB60 is in warm standby with users awaiting resolution to operate EB60.
- We promote HHFF as a national resource at SNL or elsewhere.
- We provide expertise in modeling, guidance on PFC development and continue our leadership roles.
- We will increase our domestic and international collaborations.

The latter are extremely important for the US program and SNL.

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