Sheath Power Transmission and Divertor Probe Analysis

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Summary

- SPTF Calculations using Embedded Thermocouples
  - 1D Heat Flux Analysis
  - Radiated Heat Flux Measurements using Bolometry
- Comparison of ECH vs NBI Heating
- Recent Activities with Sandia – DIII-D Collaboration
  - In-Vessel Maintenance
  - Contributions to Experiments
  - Hardware Upgrades

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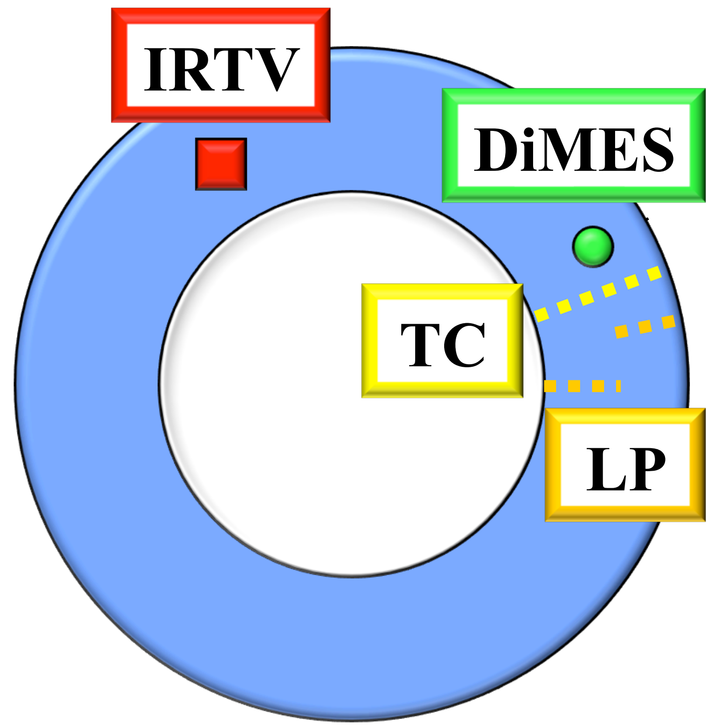
Embedded thermocouples provide alternate method of measuring heat flux

- Array of 16 thermocouples embedded 1 cm below the surface of the tiles
- Embedded TC's are located on the floor and divertor shelf and separated from the Langmuir probe array by a toroidal angle of less than 20 degrees
  - IR camera is 120 degrees from the LP array
- Previous SPTF measurements on DIII-D indicating values of 1 to 2 near the outer strike point were determined using heat flux from the IR camera



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Heat flux is inferred from temperature profile measured by embedded TC's

- $$\Delta T = \frac{q_0 t}{\rho c l} + \frac{q_0 l}{K}\left\{\frac{3x^2 - l^2}{6l^2} - \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}e^{-\kappa n^2 \pi^2 i/l^2}\cos\frac{n\pi x}{l}\right\}$$
- 1D Heat Equation* used to convert TC temperature profile into surface heat flux (*ρ* = density, *c* = specific heat capacity, *K* = thermal conductivity)
  - Assumes constant heat flux (q_0) at the surface ($x=l$), negligible contribution from the lateral directions, and no heat flow at rear boundary ($x=0$)
  - q_0 is varied to obtain the best agreement
- TC analysis is best for shots with constant magnitude of heat flux and constant strike point position

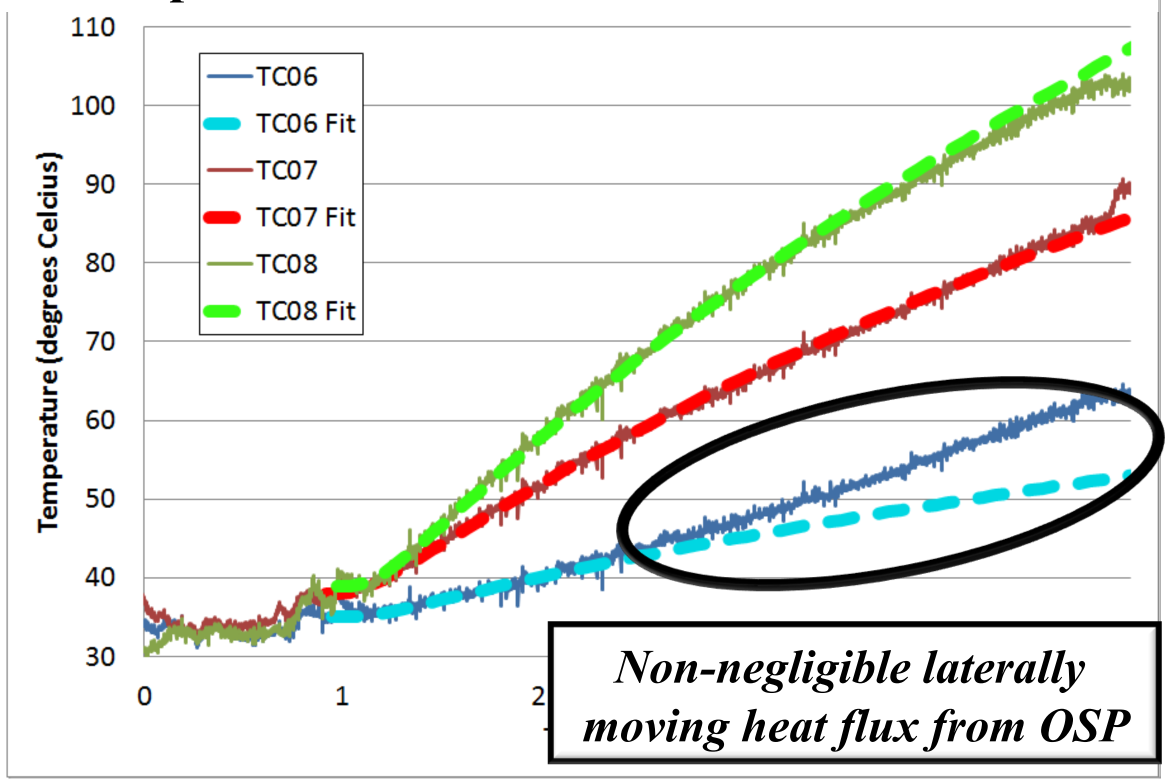
* Carslaw, Jaeger, *Conduction of Heat in Solids*, 1959

TC analysis performed on shots intended for DiMES sample exposures

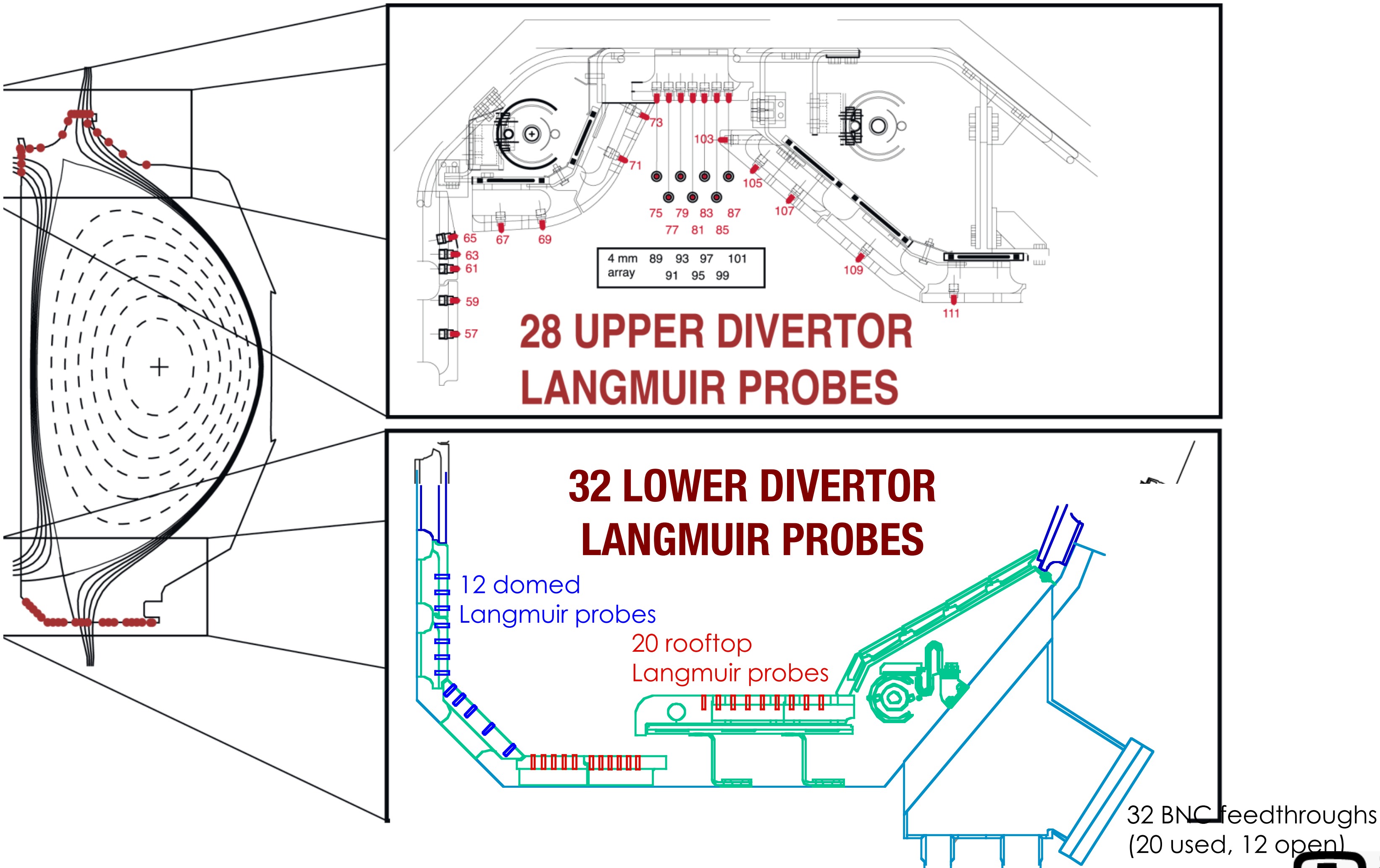
- Several L-mode shots were performed with small strike point sweeps for LP analysis
- The subsequent shots had the same conditions, but maintained a constant strike point position, ideal for TC analysis
- Temperature profiles from 3 TC's closest to the OSP shown

Plasma Heating	Input Power	Plasma Current	Core Density
NBI	2.1 MW	1 MA	$2.6\text{x}10^{13}$ cm^{-3}

Temperature Profiles of TC's Nearest to OSP



SNL has 60 Target Plate Langmuir probes in DIII-D



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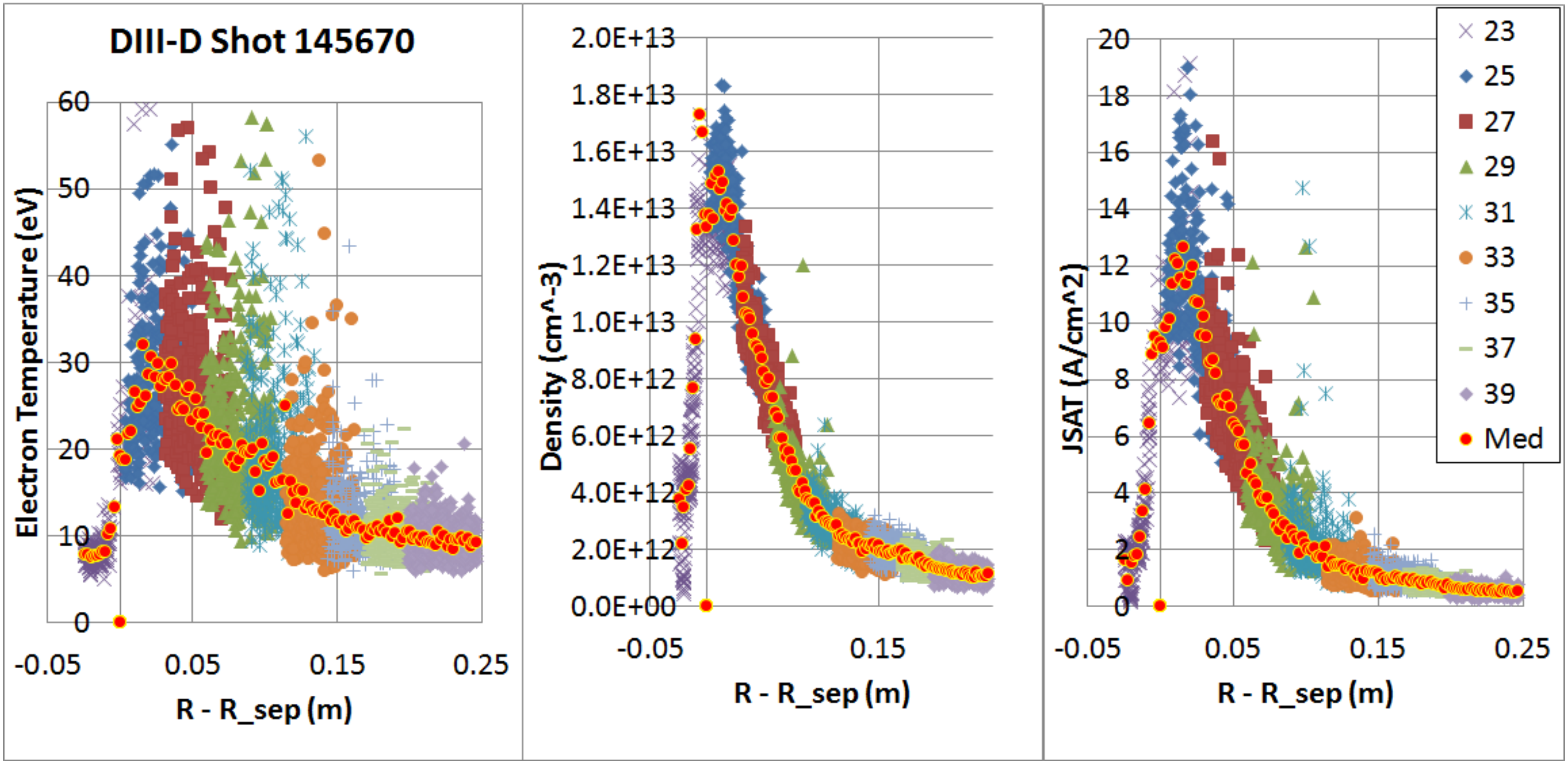
OSP swept over LP array to obtain T_e, density, and J_{sat} profiles, plotted with median values



Sheath Power Transmission Factor (SPTF) from Collisionless Sheath Theory

- SPTF (γ) *:

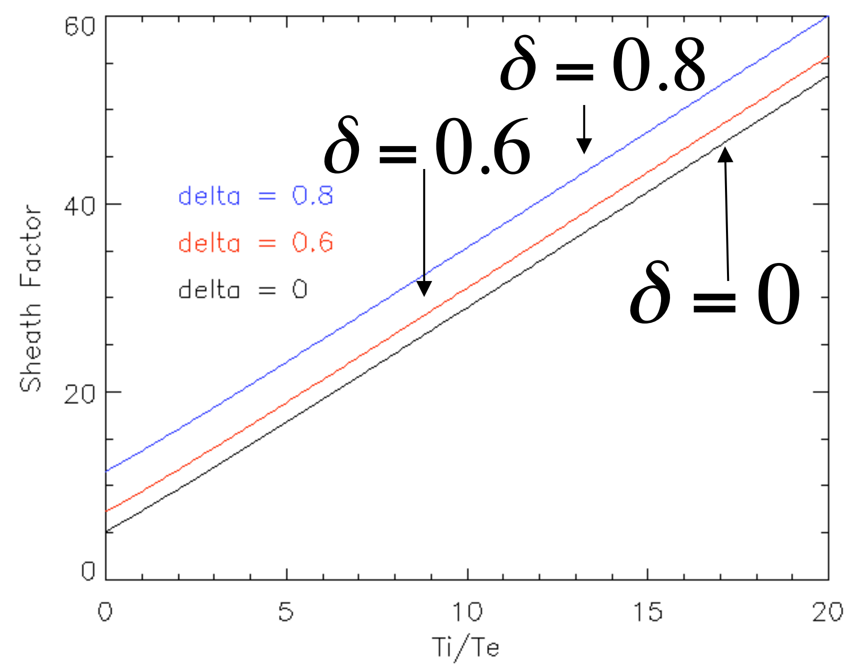
$$\gamma \approx \frac{2.5 \cdot T_i}{T_e} + \frac{2}{1-\delta_e} - 0.5 \cdot \ln\left[(2\pi \cdot \frac{m_e}{m_i})(1+\frac{T_i}{T_e})(1-\delta_e)^{-2}\right]$$

- The lowest theoretical value of the SPTF that can be obtained occurs when T_i/T_e and the secondary emission coefficient (δ_e) are both approaching zero

  $\gamma_{min} \approx 5$ for Deuterium plasmas

- For Deuterium plasma with $T_i/T_e \approx 1$ and $\delta_e = 0$, the SPTF should be ~7

Sheath Factor Profiles



* Stangeby, P. C., *The Plasma Boundary of Magnetic Fusion Devices*, 2000

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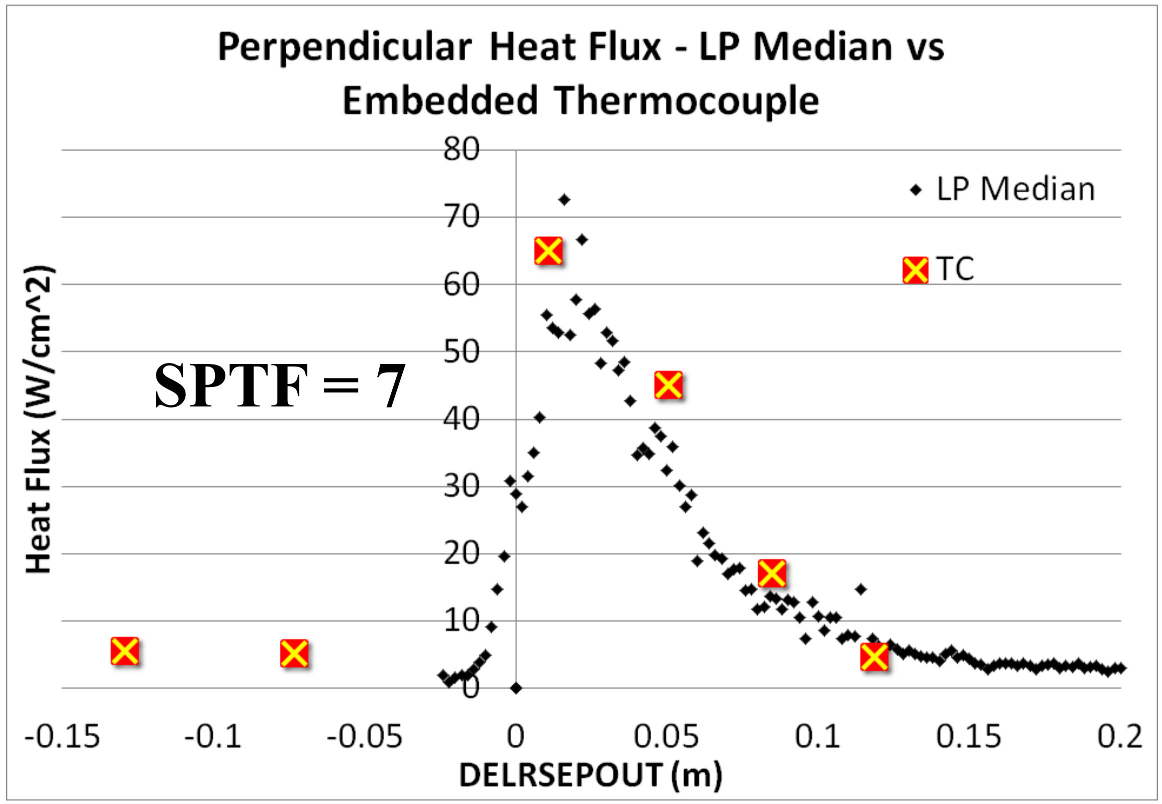
Good agreement between LP and TC data near the OSP using a SPTF of 7

- Electron temperature (T_e) and ion saturation current density (j_{sat}^+) from the LP used to determine heat flux using the SPTF (γ)

$$q = \gamma \cdot kT_e \cdot j_{sat}^+$$

- Scrape off layer currents can cause SPTF values greater than 7
- The correction factor for the SPTF due to SOL currents for these shots was less than 10%



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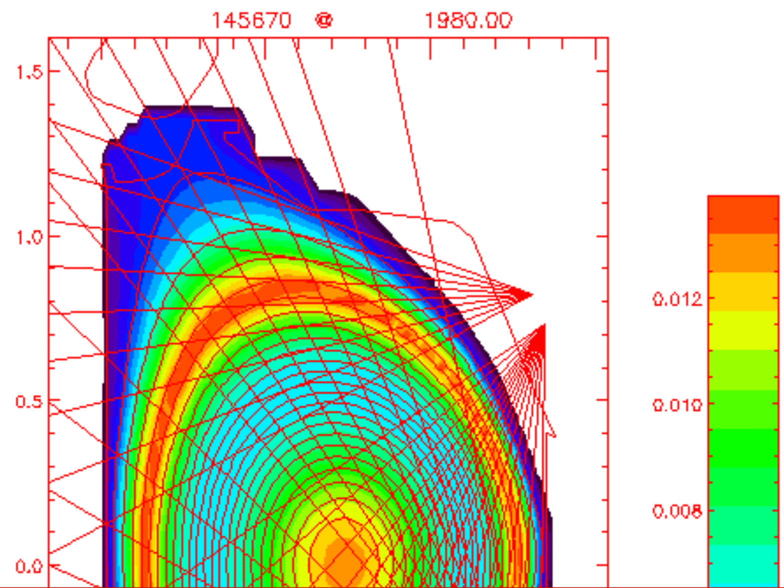
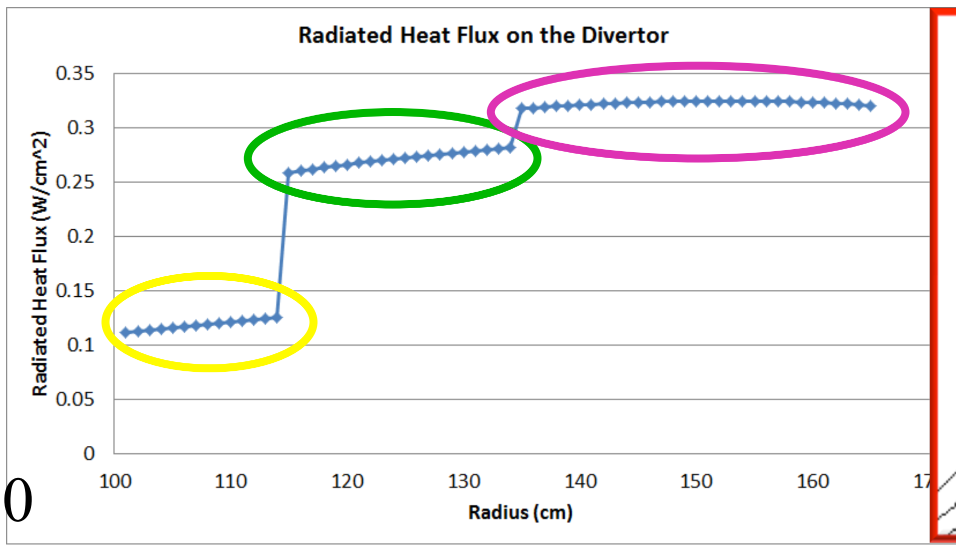
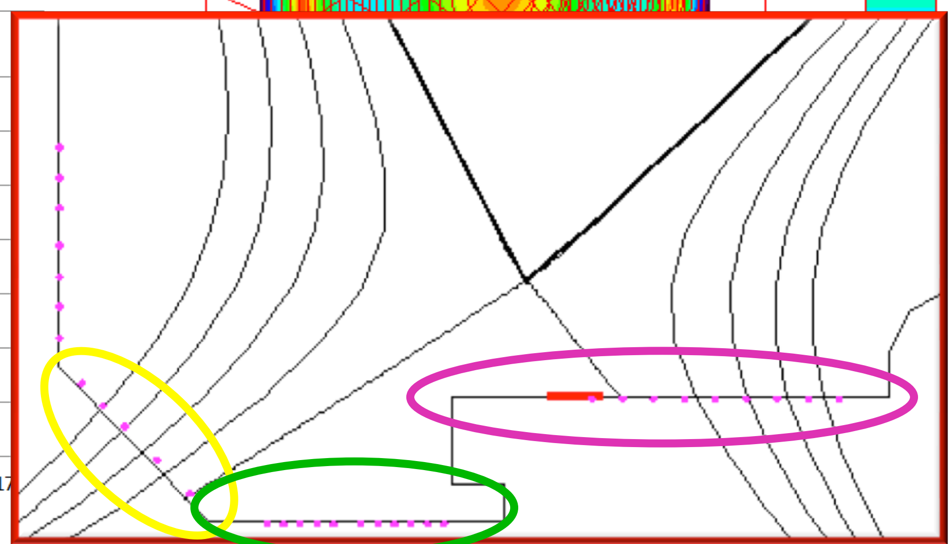
Radiated heat flux at the divertor not significant for these shots

- Radiated heat flux at the divertor is not detected by LP but would affect the TC temperature profiles
- Radiated heat flux is measured using bolometry
- Maximum radiated heat flux at the divertor for these shots is less than 0.35 W/cm^2

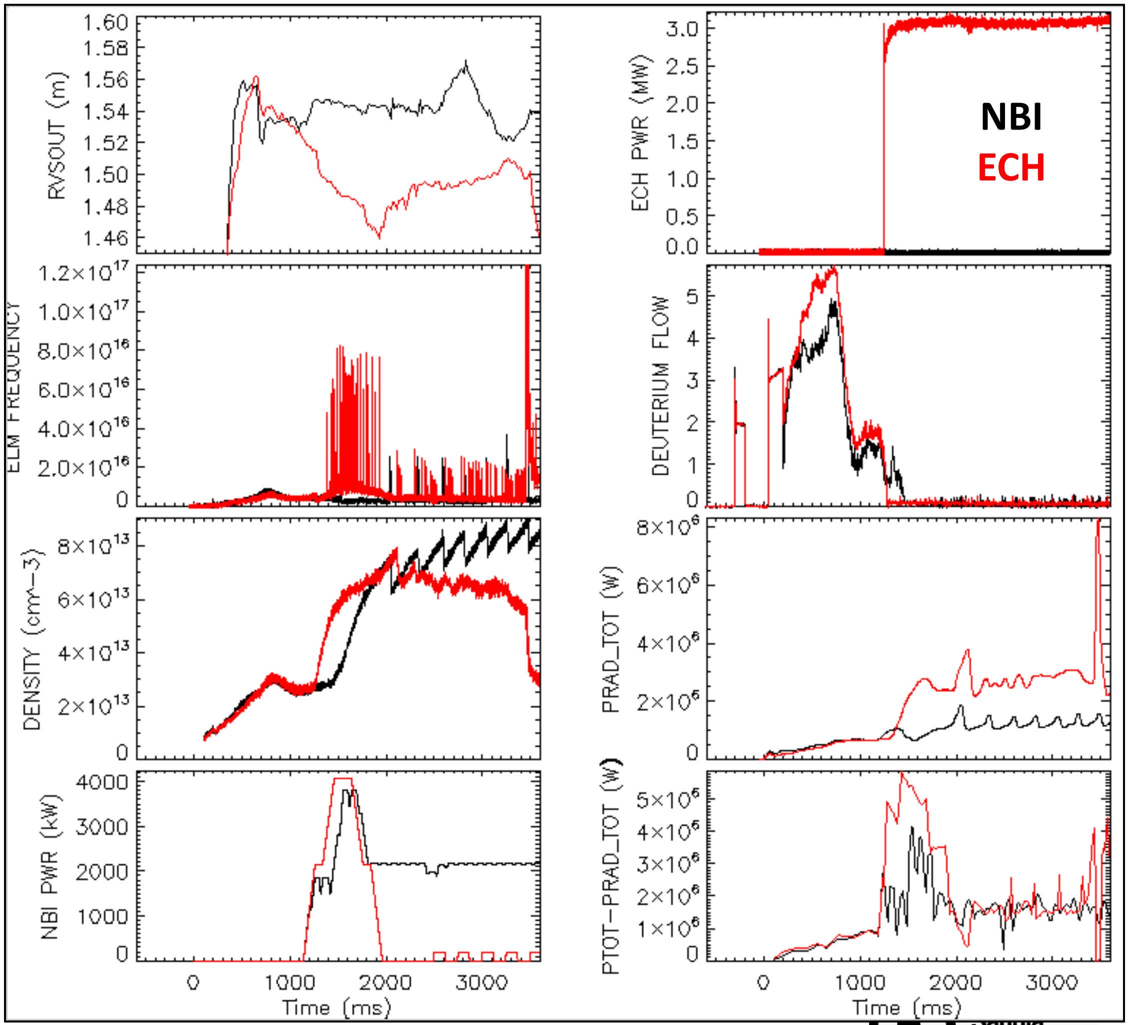






ECH vs NBI Comparisons

- Neutral Beam Injection (NBI) injects hot neutrals, heat background plasma through collisions
- Electron Cyclotron Heating (ECH) heats only the plasma electrons, heats the rest of the plasma through collisions
- Comparisons were made to determine if NBI was creating a large population of hot ions thereby by changing T_i/T_e
- Core density diverged by th end of the shot
- NBI injected 2 MW, while ECH injected 3 MW
- ECH radiated twice as much power
- Net power crossing the separatrix (Total – Radiated) was the same for both shots



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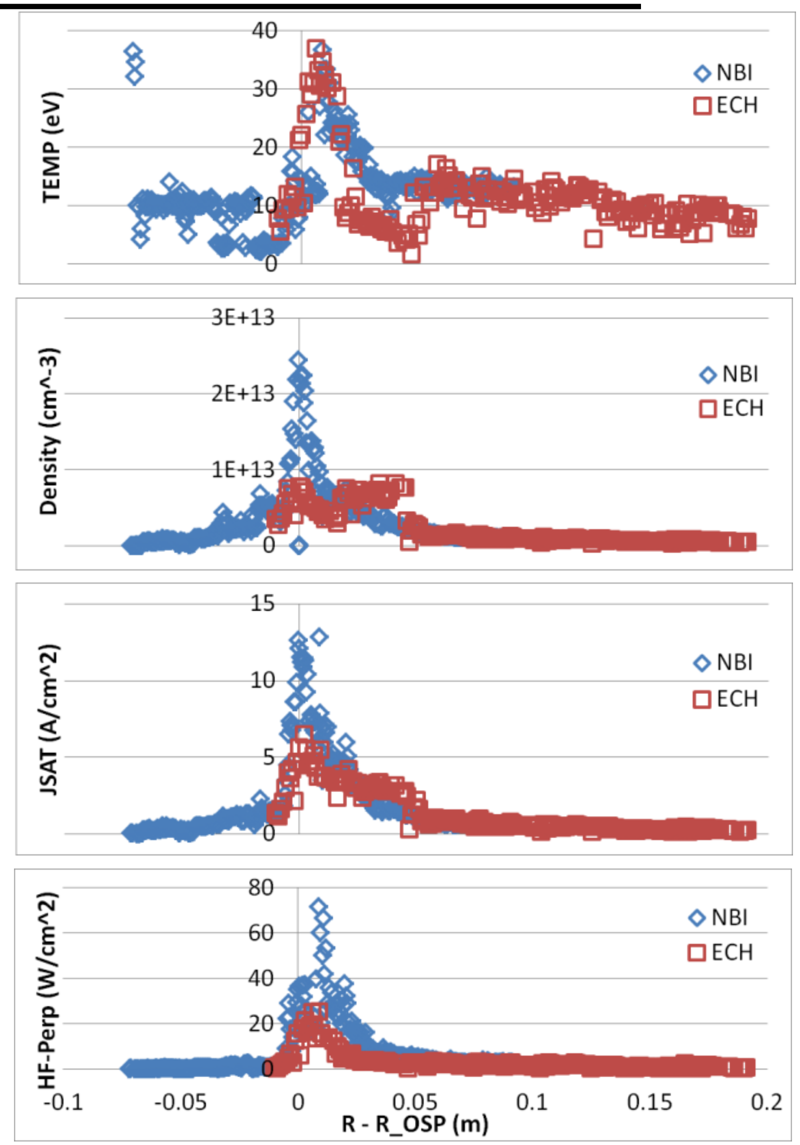
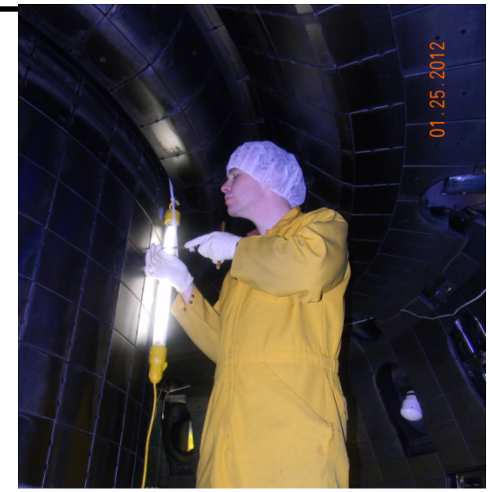
LP data demonstrated similarities between ECH and NBI

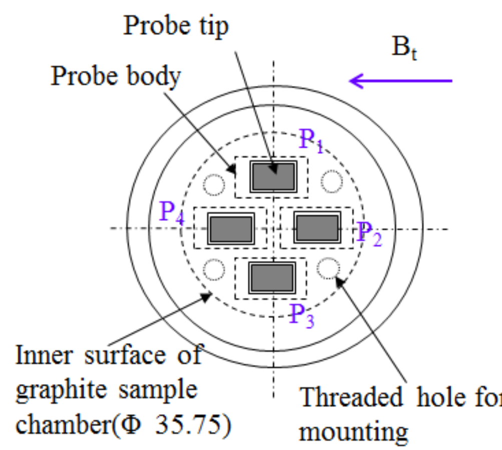
- Same T_e for ECH and NBI near OSP
- Density and J_{sat} for the ECH shot were nearly half that for the NBI shot, resulting in half the perpendicular q_0
- X-point for the ECH shot was 5 cm lower than for the NBI shot causing a 50% larger flux expansion
- 50% flux expansion is consistent with a 50% drop in density at the OSP
- No IR camera or TC data for these shots prevented any SPTF calculation
- ECH and NBI producing similar plasma conditions at divertor, but ECH radiates 50% more power than NBI
- Further comparisons need to be made with better matching of plasma conditions and x-point height, along with data from IR camera and TC's



Recent developments in Sandia - DIII-D Collaboration

- Divertor measurements are critical to understanding PMI and boundary physics issues
- Support for DIII-D divertor probe array moved to SNL-CA
  - Jon Watkins transferred to Dept 8252, but remains at DIII-D
- Sandia-Livermore personnel joined the in-vessel teams during the last vent
  - LP's were replaced and repaired on the divertor, inner wall, and ceiling
    - Detachment studies depend highly on the proper functioning of the inner wall probes
- Plasma measurements conducted for Moly erosion experiments on divertor probe array
  - DiMES samples made by SNL
  - Experimental measurements compared with model results done in collaboration with Jeff Brooks and Peter Stangeby
- SNL is working with Gwangwu Zhong (SWIP) to test design issues for the ITER Langmuir probes using DiMES
  - Issues tested are robustness, optimum orientation of annealed pyrolitic graphite, comparison of proud vs. flat probe geometry





Top View Sketch (from plasma side, in scale)

An upgrade of the Langmuir probe data acquisition system is in progress

- Replace aging CAMAC systems
  - Although CAMAC systems still operate in the tokamak environment, these systems are obsolete, difficult to keep in repair, and are required to operate in a harsh environment. Lack of suitable high voltage isolators required operating with all data acquisition electronics at vessel potential which increases the risk of damage.
- Add more probes and study longer tokamak shots
  - More channels and longer sample windows needed
- Send data to control room and use modern electronics
  - Fiber links acquired to send signals to control room
  - New digitizers acquired with 64 data channels, 10x faster sample rate, and 4x longer time window
  - Embedded link calibration circuit
  - Designed and tested new system, already in limited use, completion in FY12

Questions?

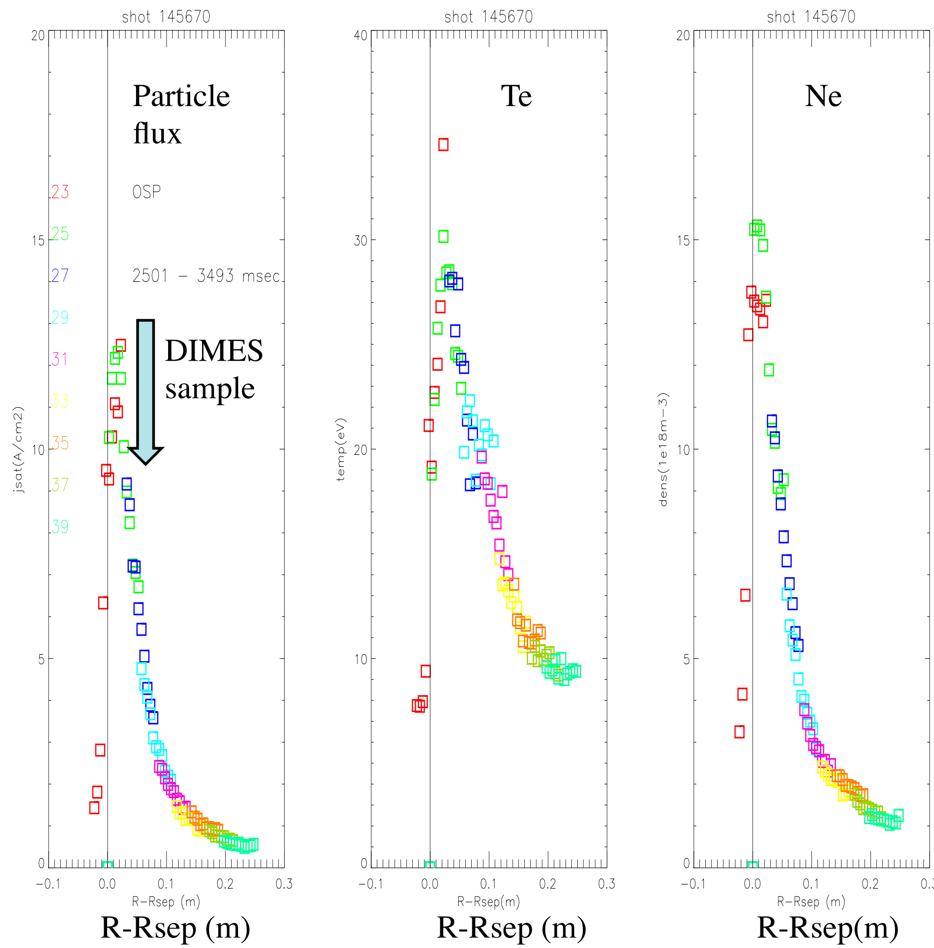
Tests of divertor geometry effect on target heat flux yielded surprising results

- Larger major radius strike point expected to reduce heat flux at target through larger deposited area
- Langmuir probes and IRTV were used to test concept
- The heat flux was actually lower at smaller radii because of increased particle flux and recycling – at larger radii the recycling was reduced and the plasma electron temperature was increased -> measured peak heat flux was higher

Molybdenum erosion measured by SNL

- DIMES samples made for tests by SNL
- Target plate plasma conditions measured by Langmuir probes
- Moly erosion measured by surface analysis
- Experimental measurements compared with model results done in collaboration with Jeff Brooks and Peter Stangeby

Langmuir probe profiles for Moly erosion experiment



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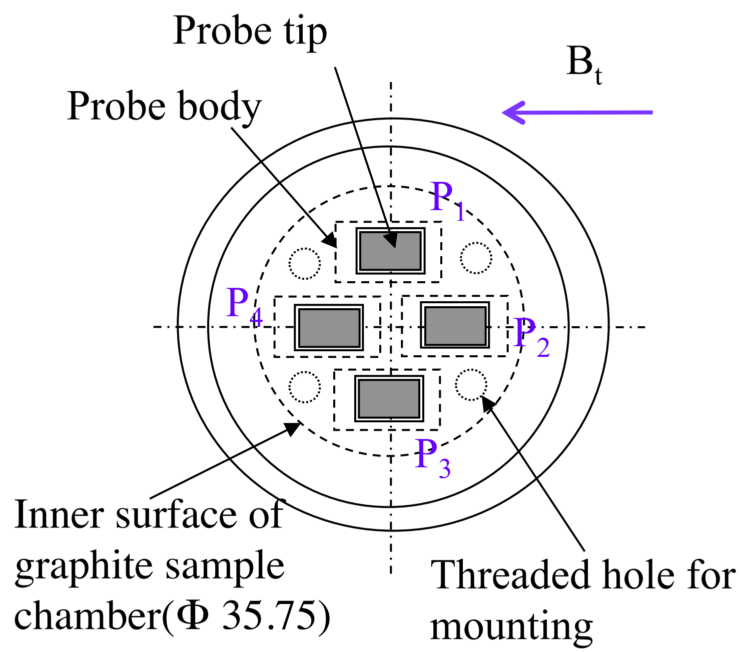
SNL consulting on ITER Langmuir probe design

- Gwangwu Zhong (SWIP) is collaborating with SNL at DIII-D on DIMES to test design issues for the ITER Langmuir probes
- Issues such as the robustness and optimum orientation of annealed Pyrolytic Graphite and comparison of proud to flat probe geometry will be tested

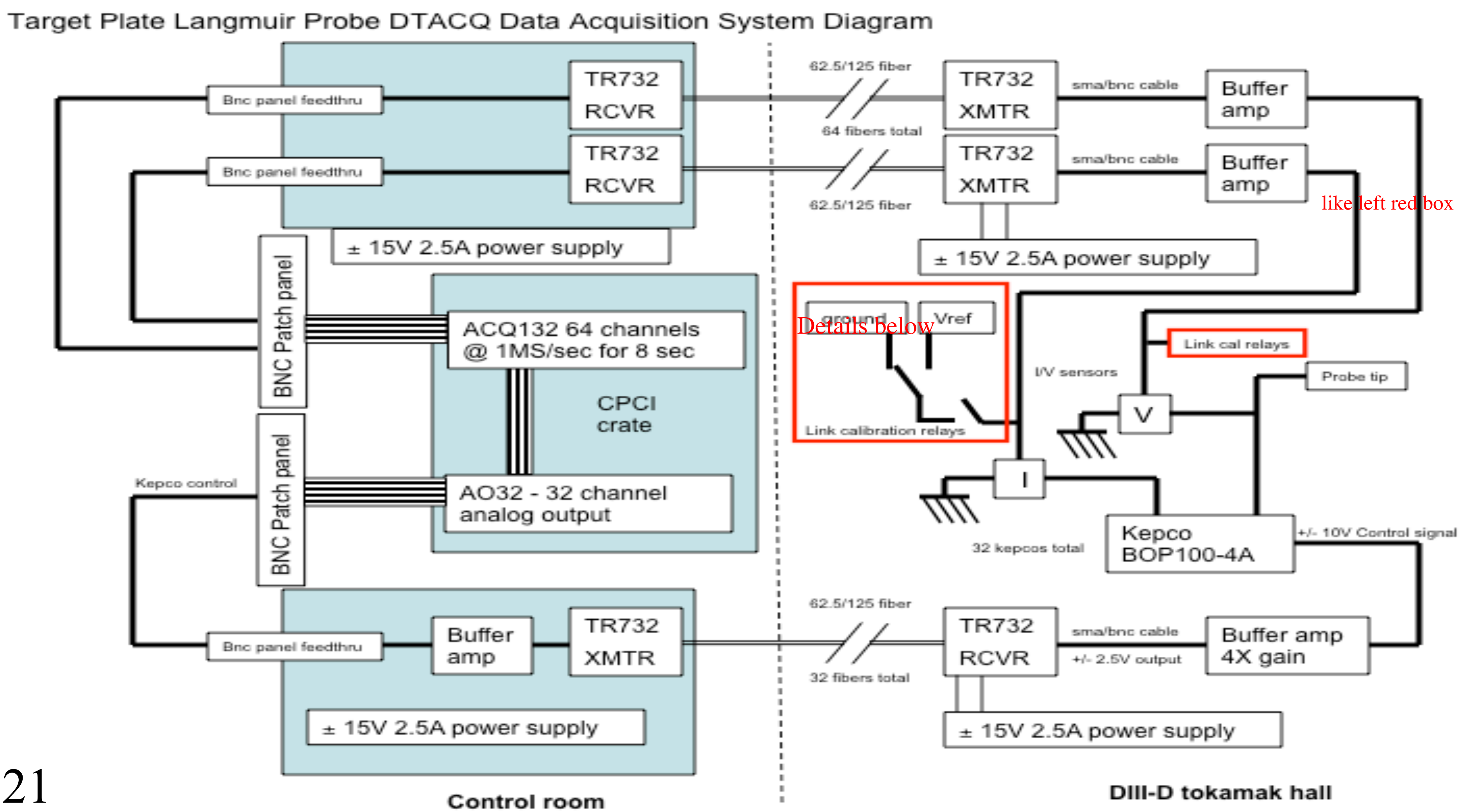


Top View Sketch (from plasma side, in scale)

New data acquisition system improves capabilities

- Increased number of channels from 48 to 64
- Increased sample rate from 100 kS/sec to 1Msample/second
- Increased data window from 2.3 sec to 8 seconds
- Increased power supply control channels from 24 to 32 channels
- Embedded reference signals allows calibration of all data signals and power supply control signals carried over fiber links

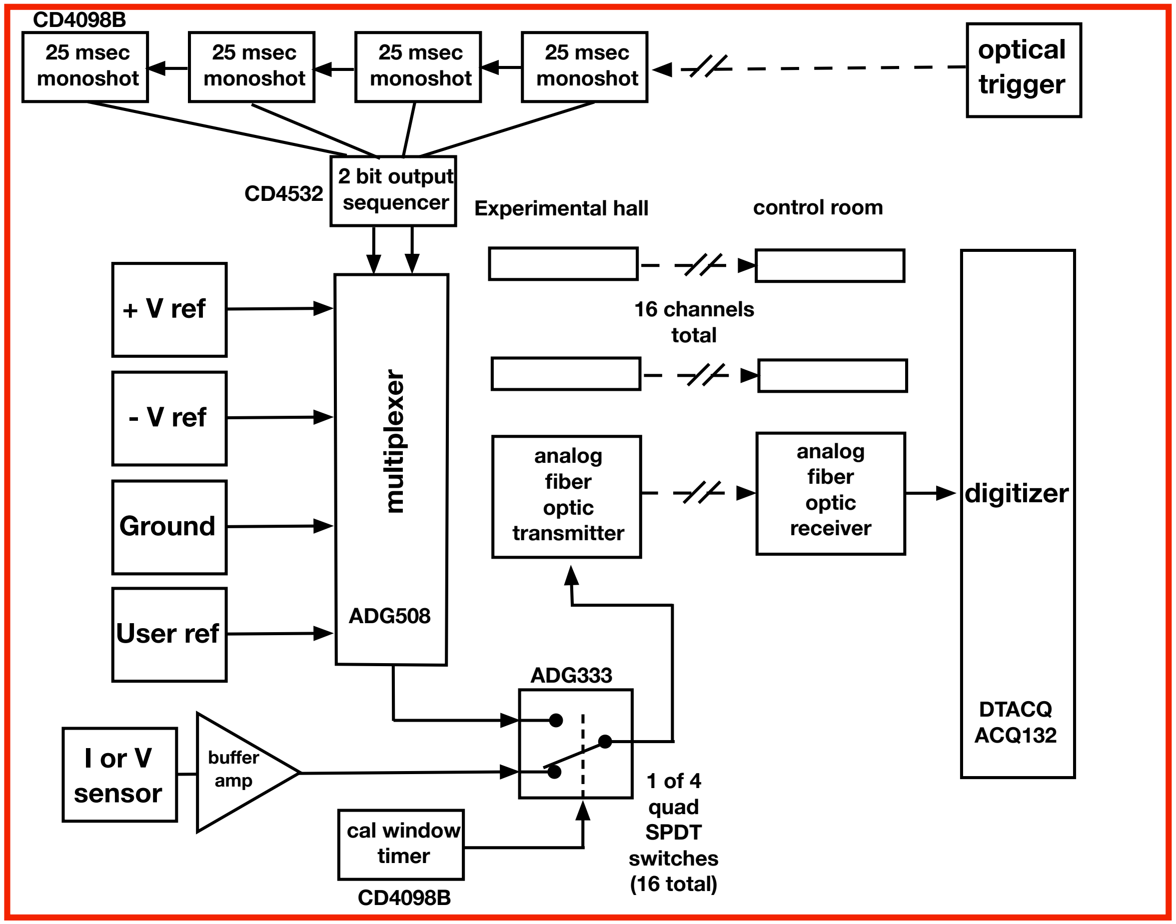
Diagram of New Langmuir probe DAQ system



New calibration technique enables use of fiber links and modern data acquisition electronics

- This diagram shows the main elements of the calibration circuit
- Each circuit board sends a sequence of reference voltage signals over 16 fiber optic links before the tokamak shot (one channel shown)
- After the calibration signals are sent, the normal Langmuir probe signals are transmitted over the links.

Items in red box are details from red boxes in diagram above



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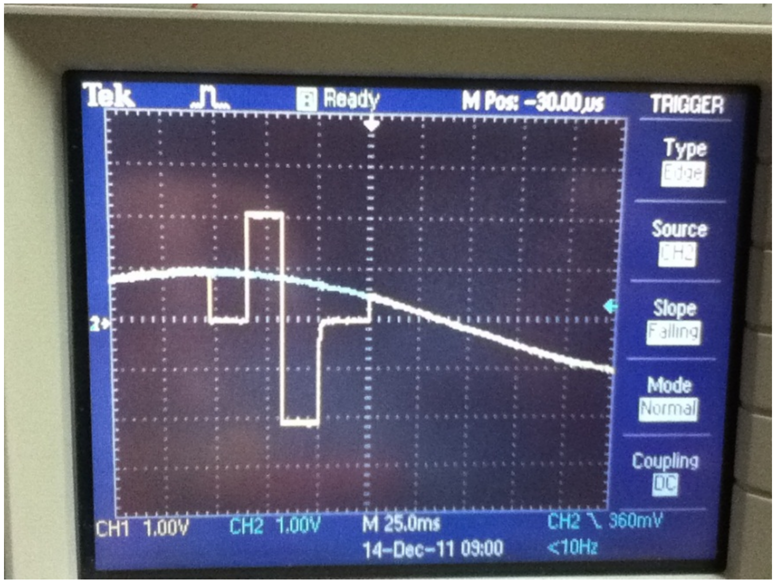
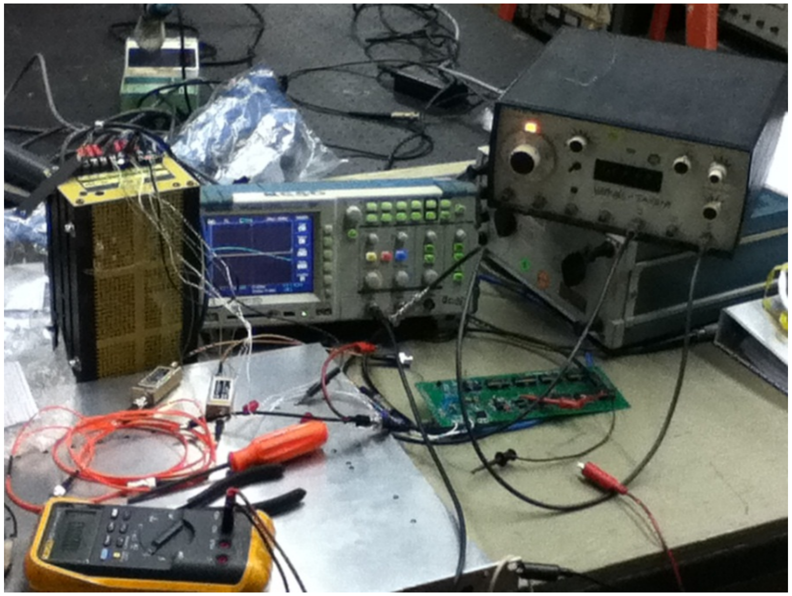
Prototype tests show proper circuit performance

- Traces from bench test of the calibration circuit show input data signal (blue) to fiber optic transmitter and output (yellow) from fiber optic receiver with calibration signal embedded.





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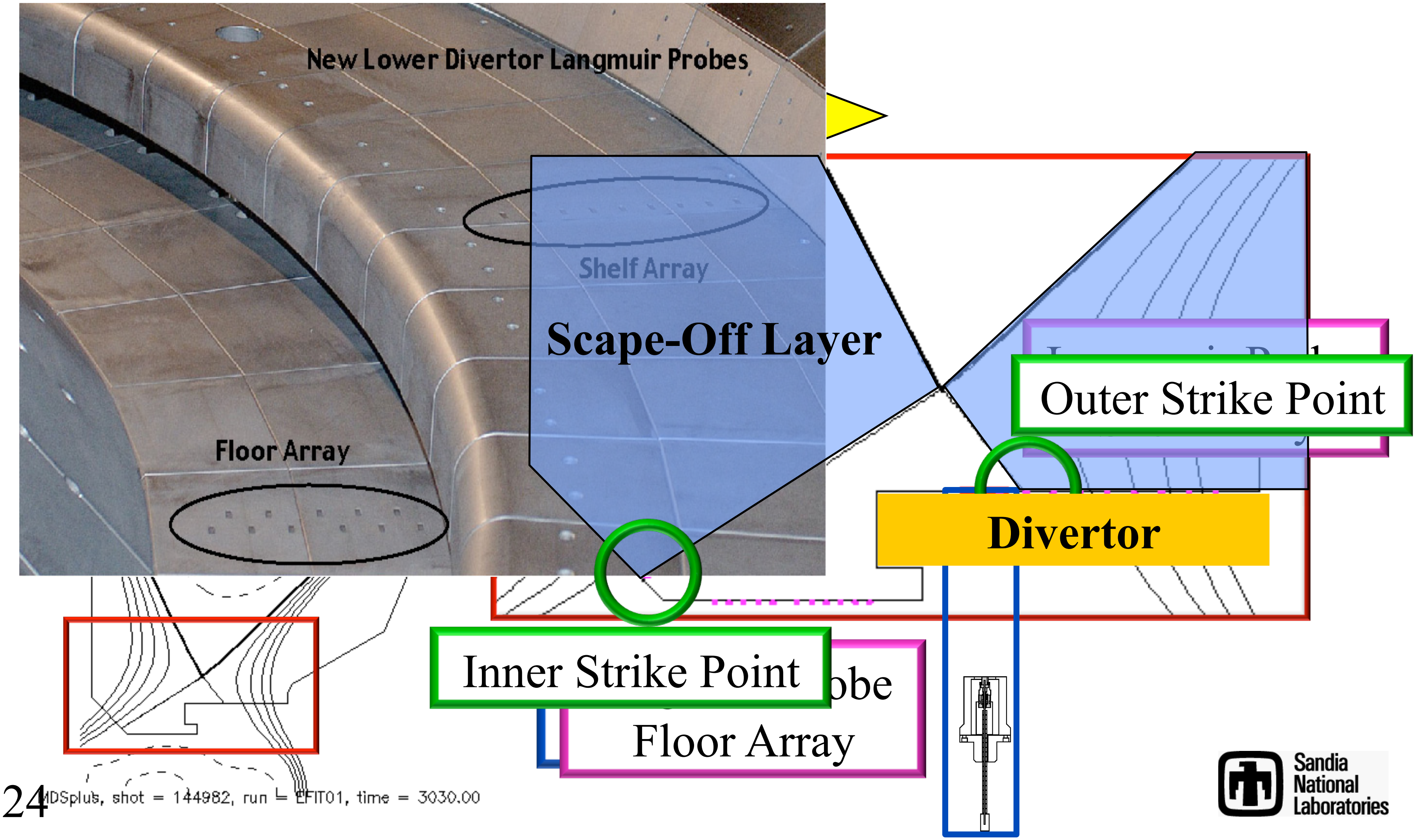
Cross-section of DIII-D Tokamak



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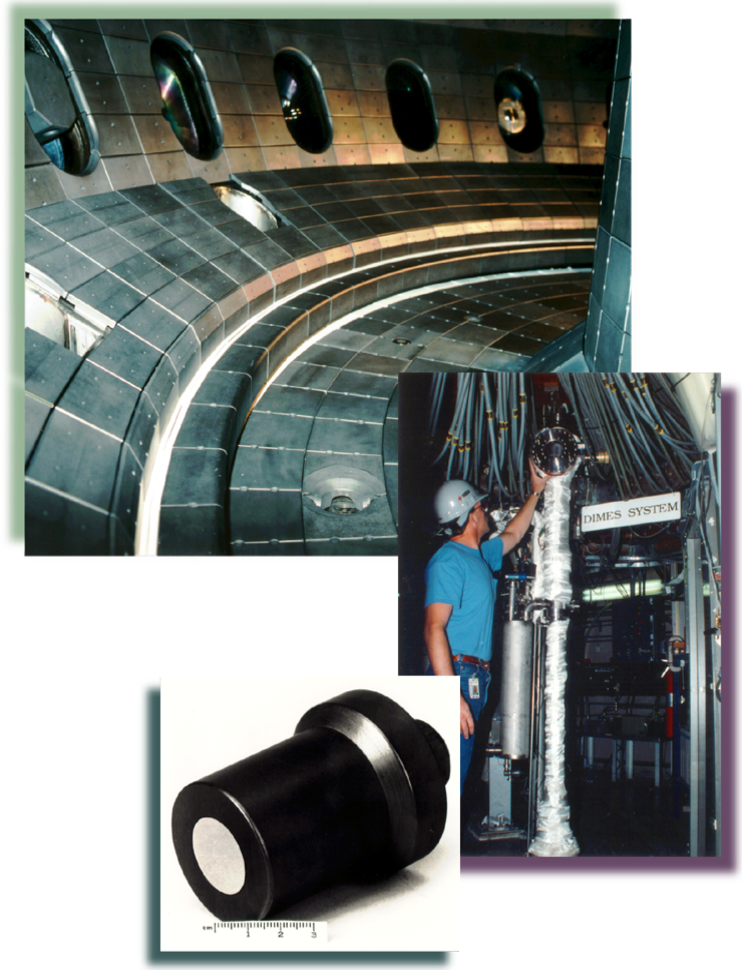
Divertor Materials Evaluation System (DiMES)

- DiMES head is retractable and is equipped with its own gate valve and pump
- Different DiMES heads can be inserted and removed without disturbing the rest of the vacuum
- Various DiMES heads have been designed and utilized
  - Active Measurements
    - Langmuir Probes
    - Calorimeter Probes
  - Passive Measurements
    - Materials Exposure Studies



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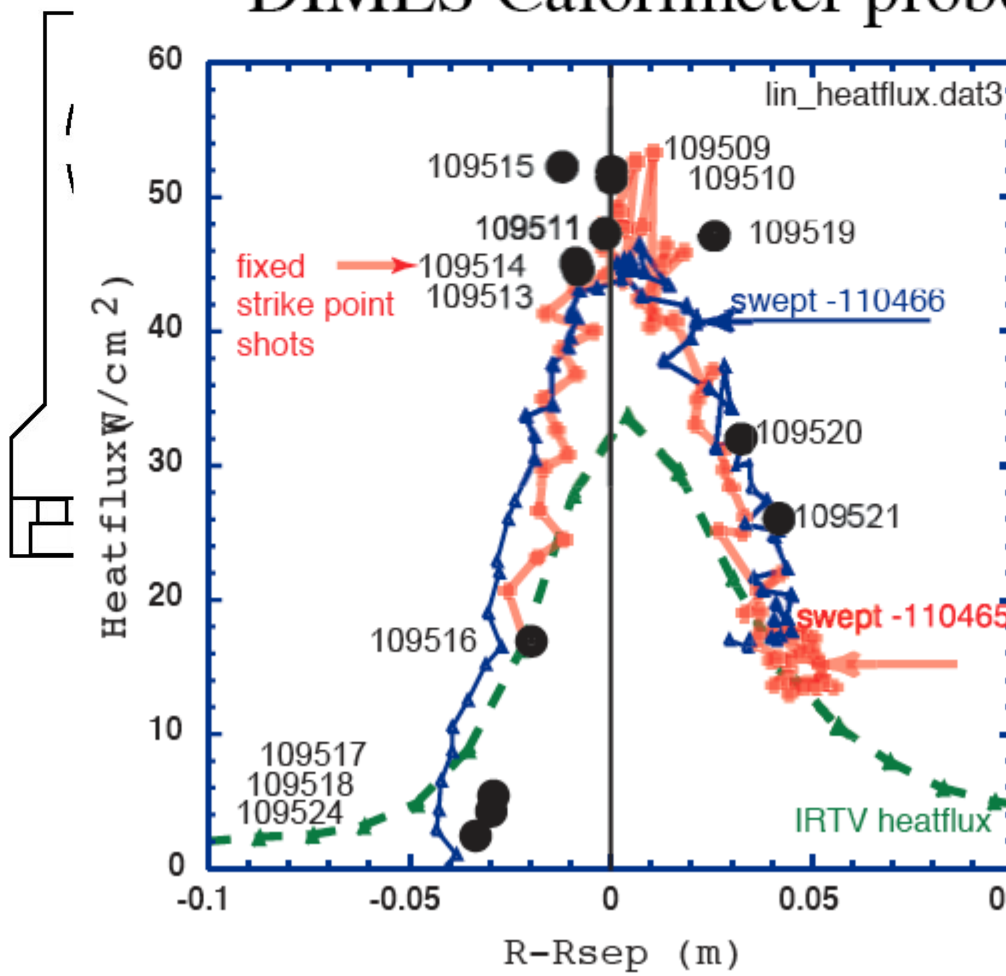
Calorimeter Probe installed in DiMES head by Jon Watkins of SNL

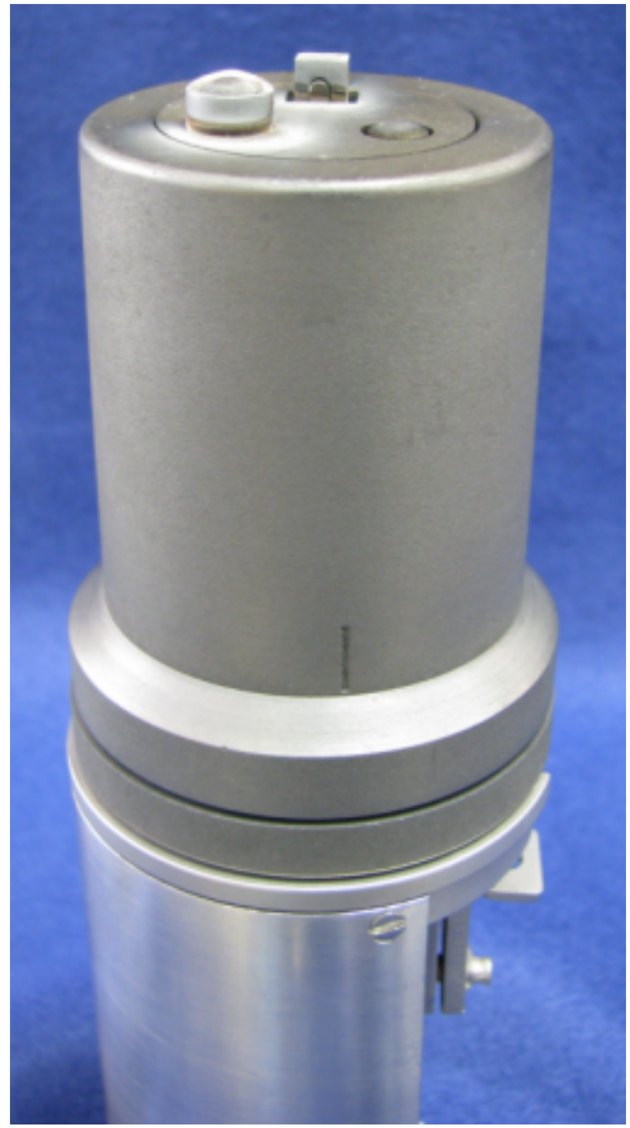
- Calorimeter probe used to collect heat flux measurements
- Compared against measurements of Infrared camera
  - IR camera field of view capable of sweeping across entire floor
  - Calorimeter measured higher heat flux than IR camera
  - IR camera measurements' spatial resolution can often be too course, which potentially leaves out peaks in the heat flux resulting in a lower heat flux profile than actual

Heat Flux Profiles using DIMES Calorimeter probe



DiMES Langmuir Probe Studies

- Applied voltage on the LP is varied sinusoidally and the collected current is measured to provide:
  - Electron Temperature (T_e)
  - Plasma Floating Potential (V_f)
  - Plasma Density (n_p)
- DiMES head is composed of graphite, ~5 cm outer diameter
- Elevated Dome and Planar Probes utilize BN shielding to control exposed area
- Each probe has equal collection area (0.04 cm^2)
- Each probe is equally spaced around a 0.95 cm radius circle to avoid shadowing of one probe on another



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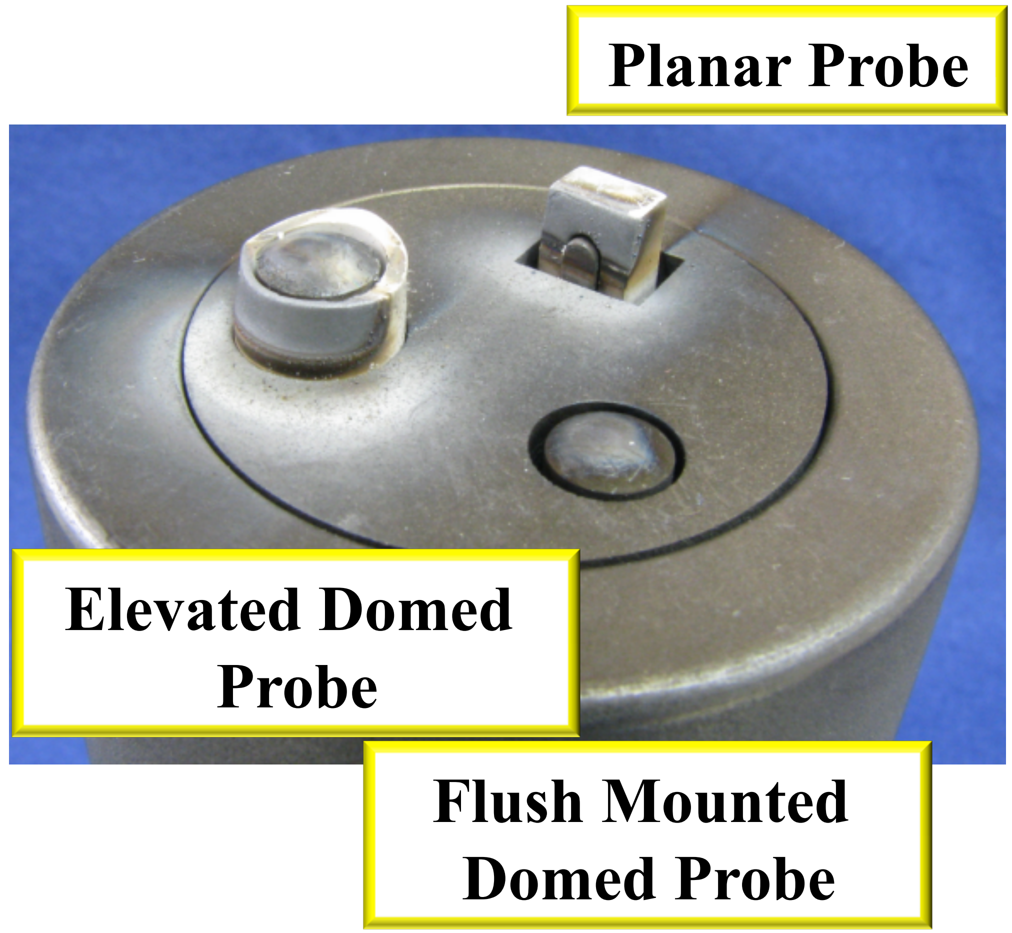
DiMES Langmuir Probe Studies

- Flush Mounted Domed Probe is designed to be similar to other probes in the LP array
- Elevated Domed Probe height is 0.5 cm, which is above the magnetic sheath height (~0.14 cm)
  - Elevated above magnetic sheath in order to determine extent that flux of cold ions from collisional effects in the sheath affect the measurements on the probe
- Planar Probe height is 0.22 cm, intended to be mainly within the sheath
  - Planar face is oriented normal to the magnetic field to mitigate influence of cross field currents reaching the probe
- The three-probe DiMES head can be used to determine the reliability of measurements on the standard domed probes in the rest of the LP network by isolating interfering plasma characteristics for separate study



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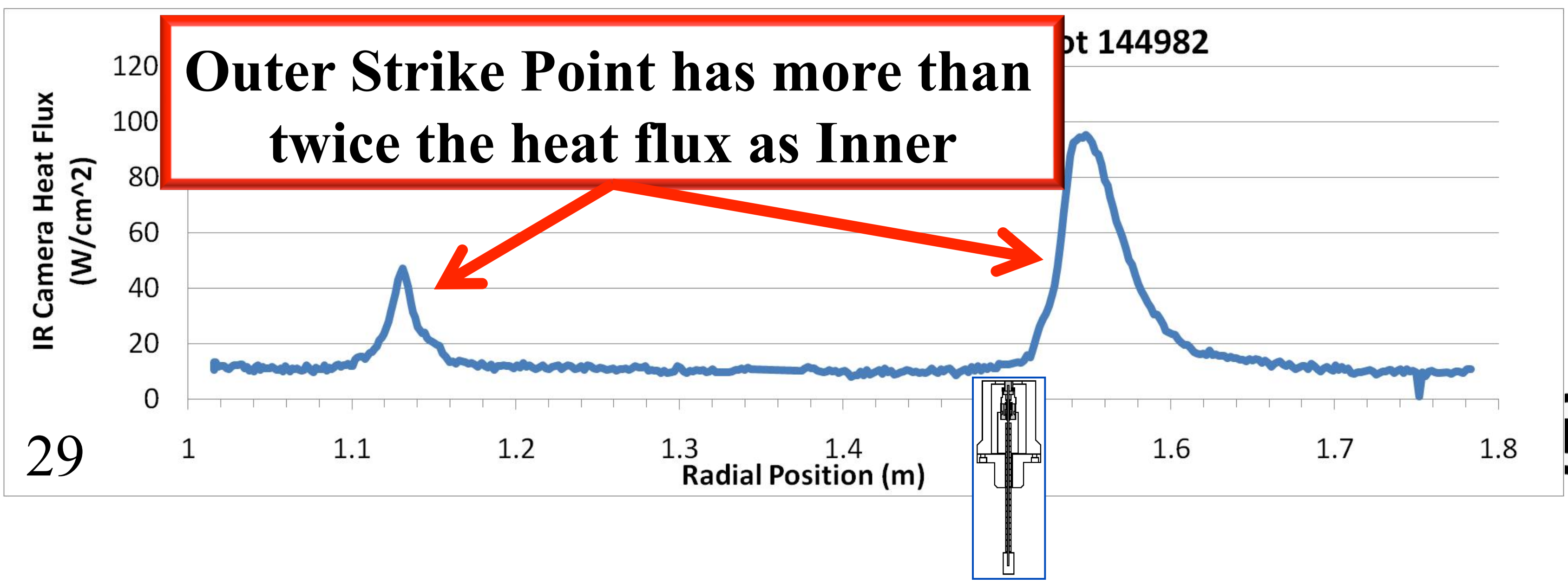
Sheath and the Sheath Power Transmission Factor (SPTF)

- The sheath is a positively charged region between the plasma and vessel walls.
- The SPTF (γ) is needed to properly correlate the particle flux measured by the LP to the heat flux measured by the IR camera

$$\gamma \equiv (Q)/(k \cdot T_e \cdot j^+ / e)$$

- The heat flux (Q) (W/cm^2) is typically measured using the IR Camera
- The electron temperature (kT_e) (eV) and ion saturation current (j+) (A/cm^2) are measured using Langmuir Probes



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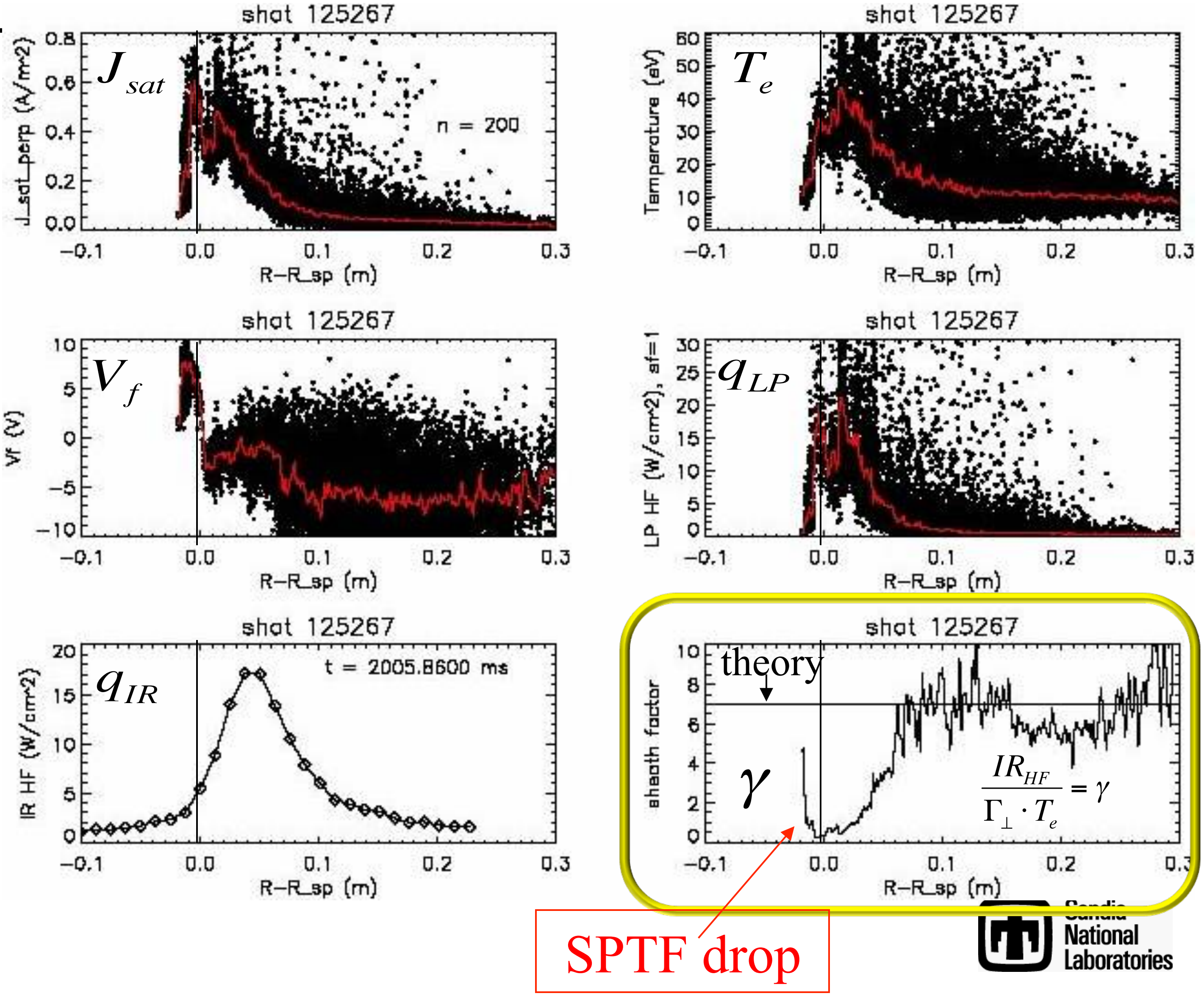
Sheath factor theory has problems near the strike point

- The sheath factor profile is too low at the strike point, typically ~1-2
- Scrape-off layer values of sheath factor agree with theory prediction of ~7.
- New high power pyrolitic graphite Langmuir probes (with lower surface temperature) get the same heat flux answer as before.



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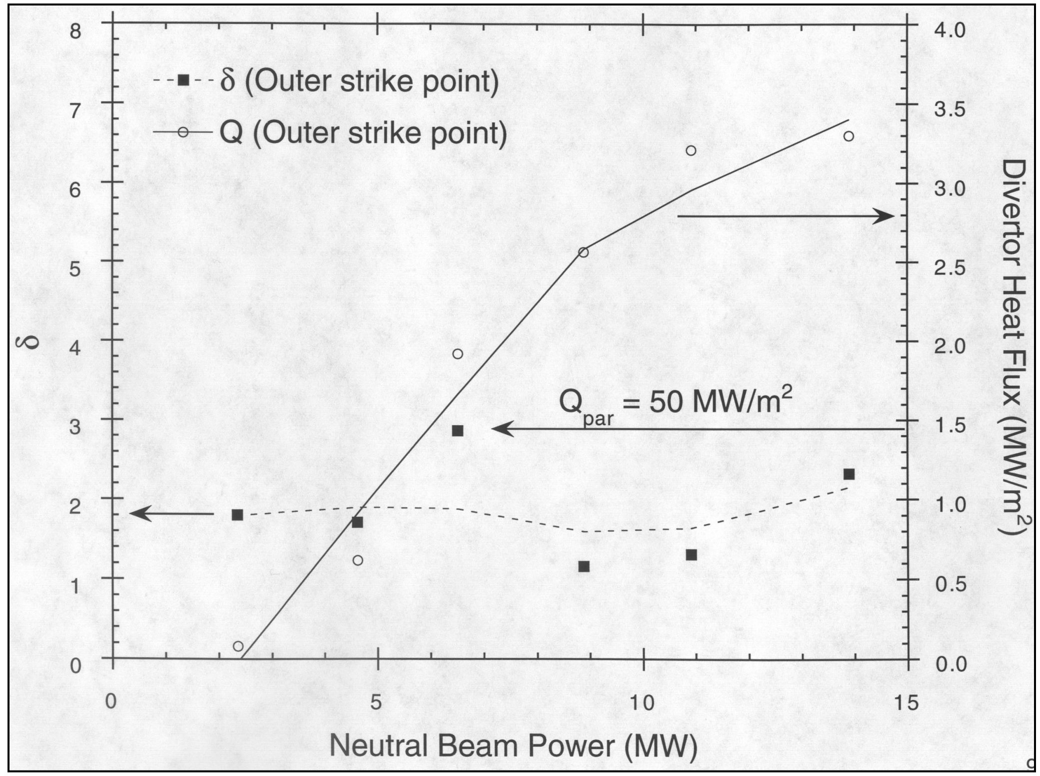
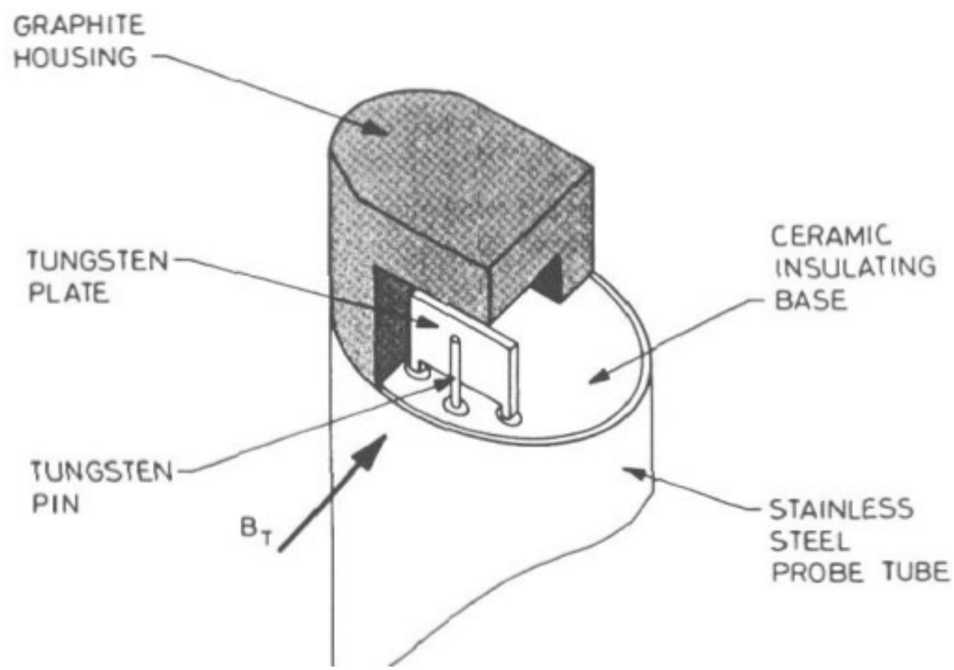
Sheath Power Transmission Factor

- SPTF remains roughly constant at the strike point (~1-2) as injected power and divertor heat flux are increased, even for high density plasmas
- γ approaching 1-2 are difficult to understand for divertor plasmas
  - Is the measured **ion flux** larger than expected for the probe A_p?
  - Is interpretation of the probe characteristics not giving $\boldsymbol{T_e}$ correctly?
  - Is the measured **heat flux (IR)** too low (unknown emissivity?)



Future Plans – New DiMES Head

- DiMES offers a unique platform on which new probe designs can be implemented during a DIII-D campaign without disrupting the rest of the experiment
- Pin-plate probe design (Stangeby, 1995) is currently being considered to more accurately measure the electron temperature in the presence of a magnetic field
  - Magnetic field makes measurements above the floating potential suspect
  - Unrealistically high values of T_e are obtained due to the magnetic field interfering with electron current at probe
  - Floating pin in front of the principal LP plate allows direct measurement of the plasma potential
  - More of the I-V trace can then be used, allowing for a more accurate calculation of T_e as well as the SPTF



Stangeby, P. C., Plasma Physics and Controlled Fusion, 37, 1337-1347 (1995)

Future Plans – Alternate Methods of Measuring Heat Flux

- Heat flux is currently measured using IR camera
  - IR camera is typically very reliable, but may not able to capture the full heat flux due to relatively course spatial resolution
  - Low measurement of heat flux will result in a low value calculated for the SPTF
- New thermocouple network has been installed below the divertor tiles
  - Combined with thermal conductivity modeling, the TC network can be used to determine heat flux on tiles
- Calorimeter probe head on the DiMES diagnostic has demonstrated higher values of the heat flux than the IR camera
- Heat flux can be measured using the thermocouples or the calorimeter and used in conjunction with the Langmuir measurements to provide independent means of measuring the SPTF in order to determine the reason for low SPTF values