Some Unsolved Physics and Diagnostic Issues in Divertor Physics

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with many thanks to

The DIII-D
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Edge Physics Team

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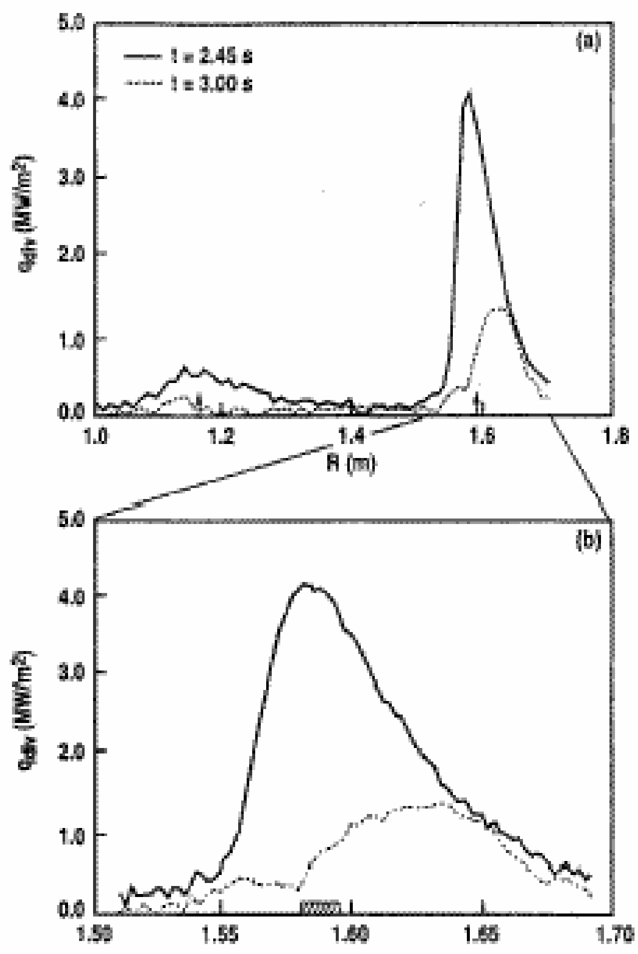
5. High density SAPP (detached) divertor studies on DIII-D: significant physics and diagnostic issues need to be resolved.

6. Conclusions.

1. Detached Divertor as ITER Solution for Handling Power Exhaust

About a decade ago – thanks as much/more to DIII-D edge research as that on any tokamak – the detached divertor state was identified as the solution for the ITER power handling problem.

DIII-D. Received heat flux on divertor target.
As <n_e> is raised by gas puffing, the heat flux received on the divertor decreases substantially:



Nucl Fusion 37 (1997) 321.

2.The recent ‘opening up’ of tokamak edge physics issues.

- **Since then a number of unanticipated, major effects have shown up in divertor tokamak edge research:**

  - **tritium retention found in DT JET at unexpectedly high levels and at unexpected locations**

  - **fast, intermittent, ‘blobby’, non-diffusive cross-field transport**

  - **strong plasma-wall contact**

  - **narrow target power profiles (on JET)**

  - **fast parallel flows far from targets**

  - **large scale convection patterns for impurities**

- **Undoubtedly many parts of our earlier picture remain correct.**

- **The task is to verify which parts and to continue to identify the controlling physics in the edge.**

- **This has motivated the Simple-as-Possible Plasma (SAPP) studies recently undertaken on DIII-D.**

3. The SAPP Approach

1. **Start with simplest possible conditions, e.g. no ELMs, no detachment.**

2. **Operate as comprehensive a set of edge diagnostics as possible.**

3. **Run many repeat shots.**

4. **Do not put aside *any* diagnostic unless it is known to be mis-functioning.**

5. **Bring *all* of the measurements into mutual, detailed comparison with an interpretive edge code, such as OEDGE.**

6. **If most of the data are matched by the code, then probably the controlling physics has been correctly identified and quantitatively characterized.**

7. ***All* outstanding discrepancies to be flagged for further investigation as potentially containing important information.**

8. **Proceed to more complex regimes, e.g. detachment.**

Is L-Mode actually simpler than H-Mode?

- **ELMs in H-modes make the already challenging 2D edge problem more difficult by making the edge also time dependant….**

- **…however, the main SOL of L-mode plasmas extends further out toward the main wall than for (between-ELM) H-mode plasmas, due to higher levels of intermittent turbulence.**

- **The ELM is itself an intermittent cross-field transport event that can also cause plasma-wall contact.**

- **Thus, with regard to plasma-wall interaction with the main chamber, L-modes and H-modes both have their complexities.**

- **The focus here, however, is on the divertor, where the removal of the strong time-dependence of ELMs is definitely a helpful simplification.**

The OEDGE Interpretive Edge Code

- OEDGE = Onion-Skin Modeling (OSM) + EIRENE + DIVIMP for edge analysis
- Monte Carlo codes are used to make most of the comparisons with experimental data.
- EIRENE is a neutral hydrogen M C code.
- DIVIMP is an impurity neutral/ion M C sputtering/transport code.
- The M C codes require a "plasma background" into which to launch particles – provided by OSM.
- As much as possible, empirical data is used as input to OSM.
- *Prescription-based OSM mode*: 2D 'fields' of n_e, T_e, etc. directly specified from measurements.
- *Model-based OSM*: solves the 1-D plasma (fluid) conservation equations along the magnetic field, using across-B boundary conditions from experiment to produce a 2-D solution for the edge plasma. $D_\perp$ and $\chi_\perp$ not required as input.

SAPP Studies on the DIII-D Tokamak

- **Sets of identical, low density, L–mode, lower single-null divertor shots with 1 MW total input power.**

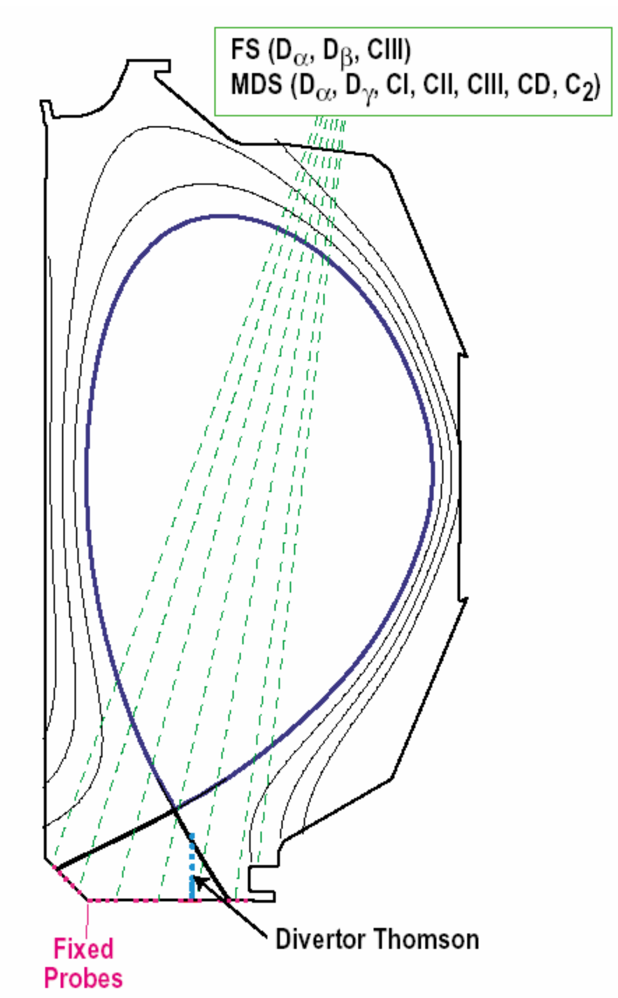
- **10 shots at low density,** n_e **= 2.5x10^{19} m^{-3}**
  (attached)

- **3 shots at medium density,** n_e **= 3.5x10^{19} m^{-3}**

- **4 shots at high density,** n_e **= 4.4x10^{19} m^{-3}**
  (detached)

Diagnostics used in the SAPP Divertor Studies

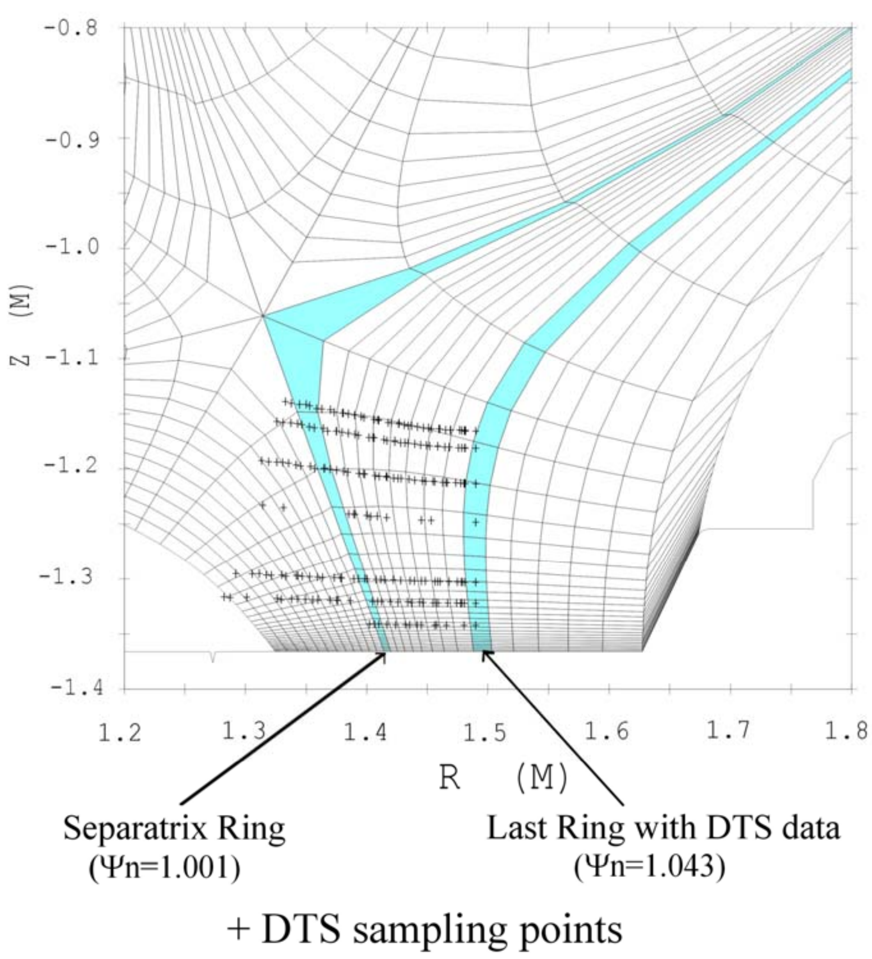
- **Target Langmuir probe measurements of I_{sat} and T_e**
- **Divertor Thomson System (DTS) measurements of the 2D distribution of n_e and T_e near the target.**
- **Calibrated spectroscopic measurements of various hydrogenic and carbon lines measured by FS (Filterscopes) and MDS (Multi-chord Divertor Spectrometer).**



The OSM used for analysis of SAPP

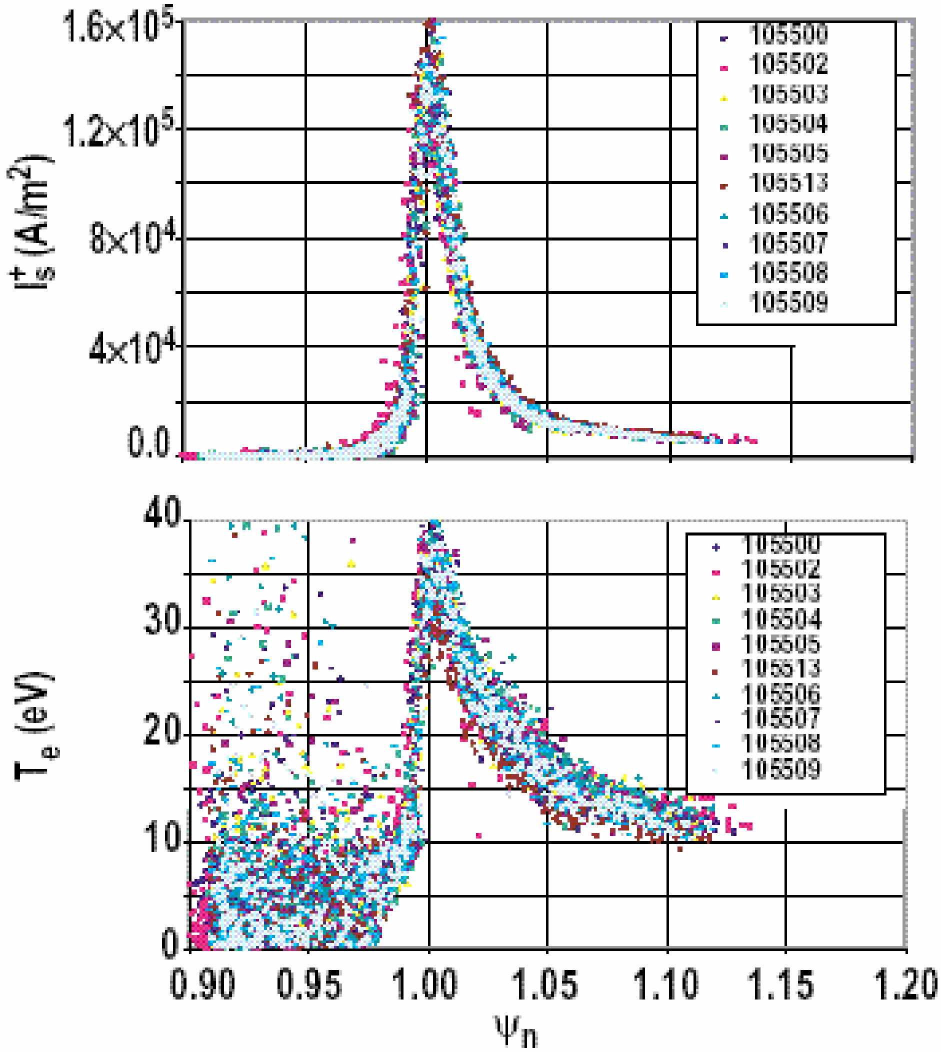
- ***Model-based OSM*** **used to analyze attached SAPP.**
- ***Prescription-based OSM*** **used to analyze detached SAPP.**
- **The 2D n_e and T_e spatial distributions for each of the different SAPP densities provided by DTS.**
- **The flux of D^+ striking the targets taken from Langmuir probe I^+_{sat}.**

Grid showing 'computational rings' and DTS locations:



4. Low density SAPP divertor

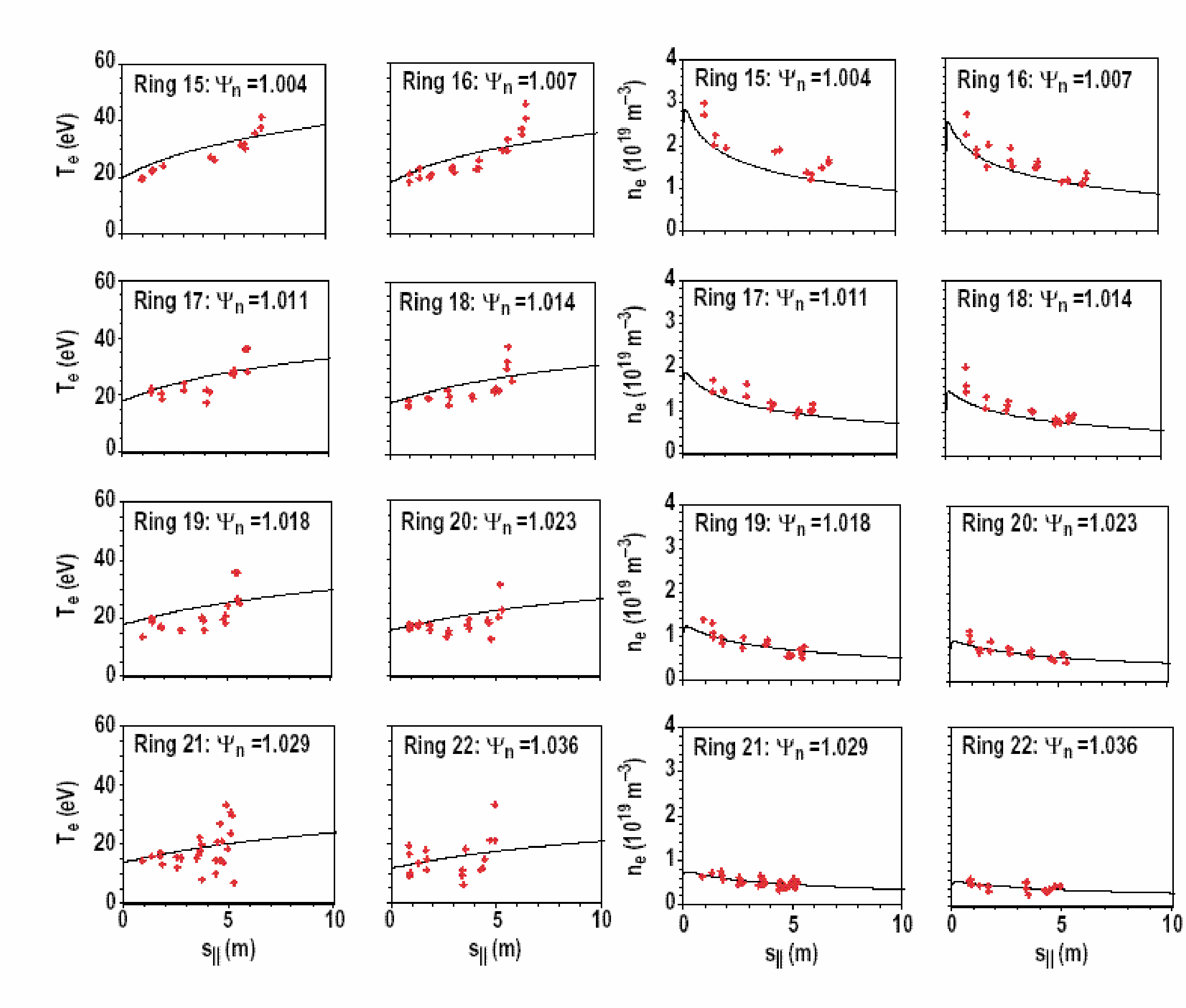
Langmuir probe measurements across the outer divertor target:



Low Density SAPP

Model-based OSM **used boundary conditions across target:**
I^{+}_{sat} and T_e from compromise between DTS and probe values.

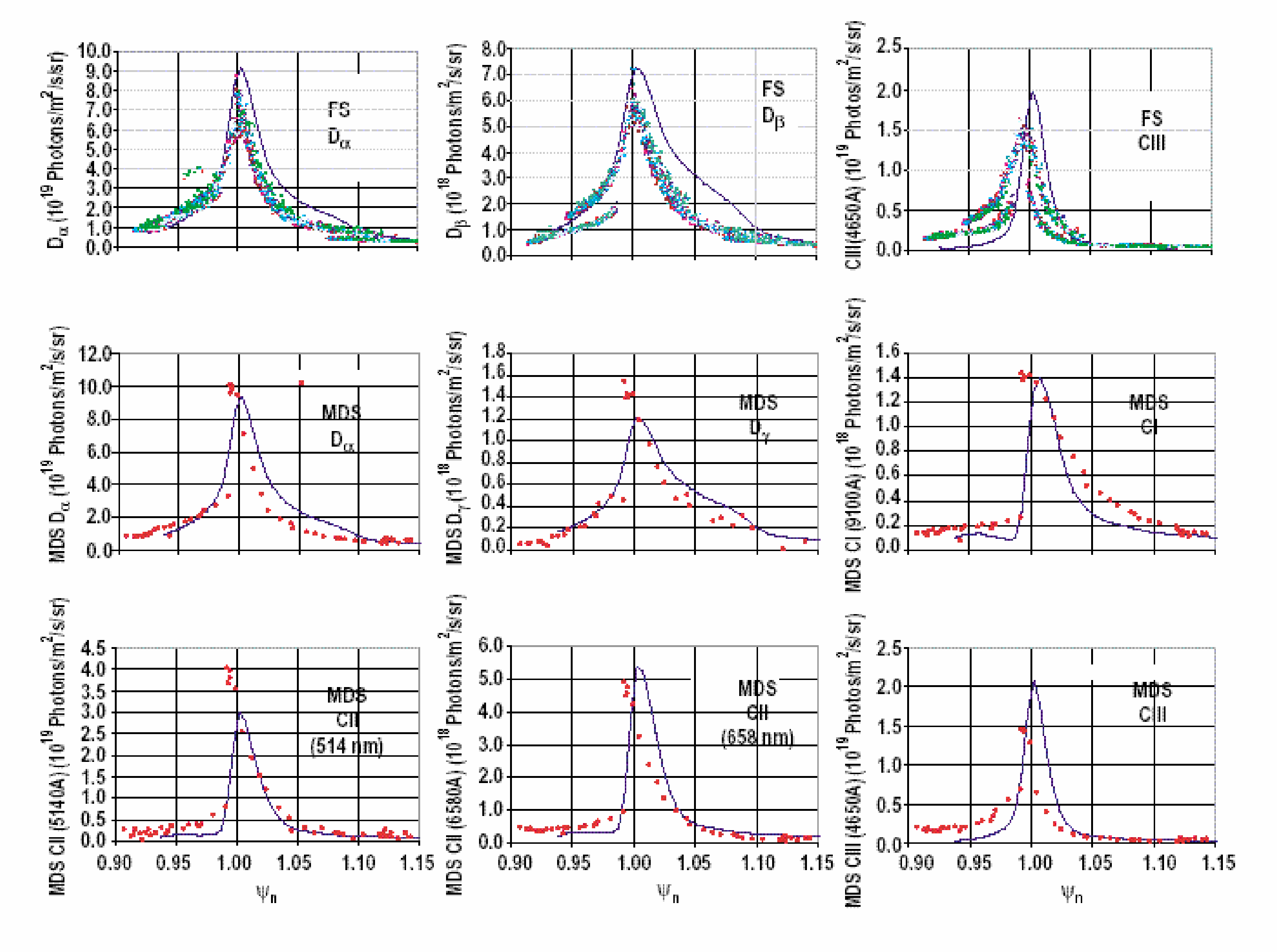
Profiles of $n_e(s_{||})$ and $T_e(s_{||})$ for the computational rings for which there are DTS data:



Line: OSM code. Points: DTS.

Good agreement indicates the controlling physics is reasonably in hand for attached plasmas.

OEDGE (EIRENE and DIVIMP) calculates good matches to the spatial distributions of D_α, D_β, D_γ, CI, CII, CIII measured by the absolutely-calibrated FS and MDS, evidently indicating that much of the controlling physics for the low density, attached SAPP has been correctly identified.



We can therefore conclude, that at least for the very simplest plasma conditions

– *attached*

- and at least for the region near the divertor

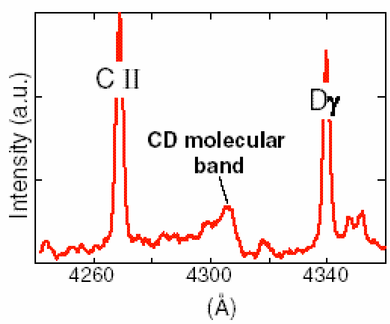
- that much of the controlling physics is evidently understood, has been correctly characterized quantitatively, and has been correctly incorporated in the code-modeling.

but……

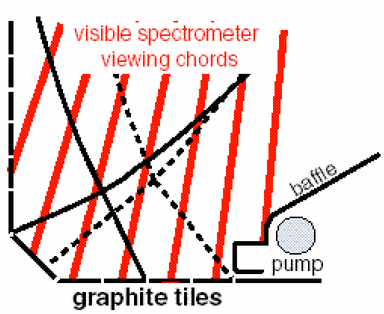
DIVIMP assumed physical sputtering only – no chemical sputtering!

Why assume no chemical sputtering in the modeling?

Spectroscopy is used to reveal the cause & magnitude of carbon erosion in DIII-D lower divertor plasma



DIII-D Lower Divertor Spectroscopy



Chemical Erosion

$$Y_{chem} = \frac{\Gamma_{C_xD_y}}{\Gamma_{D^+}} = \frac{B_{CD}\cdot(D/XB)_{CD_4}}{B_{D_\gamma}\cdot(S/XB)_{D_\gamma}} \propto \frac{B_{CD}}{B_{D_\gamma}}$$

"Total" Carbon Ion Source

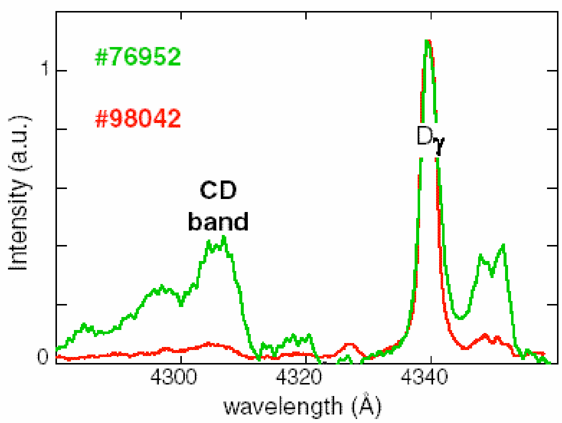
$$Y_{C,total} = \frac{\Gamma_{C^{+1}}}{\Gamma_{D^+}} = \frac{B_{CII}\cdot(S/XB)_{CII}}{B_D\cdot(S/XB)_D} \propto \frac{B_{CII}}{B_D}$$

- Only adjacent wavelength transitions used.
- Assumes 100% D recycling ~ D^+ flux.
- Relies on calculated "loss events per photon" ratios to convert to yield.
  - Must have knowledge of T_e and n_e.

Reduction of Divertor Carbon Sources in DIII-D, D. Whyte, PSI-14 May 2000 #4

Dennis Whyte
14th International Conference on Plasma Surface Interactions
May 2000

Carbon erosion has been substantially reduced in the lower divertor from 1993 to 1999



Attached ELMy H-mode discharges nearly identical

Date	1993	1999
n_e ($10^{19} m^{-3}$)	5.5 - 7	6.8
P_{inj} (MW)	7	6.6
W (MJ)	1.1-1.2	1.1
Γ_i (10^{22} $s^{-1} m^{-2}$)	1.8-2.5	3
$T_{e,OSP}$(eV)	25-35	26

Reduction of Divertor Carbon Sources in DIII-D, D. Whyte, PSI-14 May 2000 #5

Dennis Whyte
14th International Conference on Plasma Surface Interactions
May 2000

Chemical sputtering of carbon at divertor targets in DIII-D has apparently disappeared.

- **How is this possible? prolonged plasma conditioning? years' of boronizations?**
- **Do we really believe it?**
- **Major practical implications for ITER.**
- **Not all the evidence is consistent: high resolution spectroscopy used to measure the CI line width and shift showed:**

1. **a width ($T_{eff} \sim 1$ eV) consistent with physical sputtering and not consistent with chemical (~ 3 eV)**
2. **a shift (~ 0.005 nm) consistent with chemical sputtering but not consistent with physical (~ 0.02 nm).**

????

there's another, perhaps more important anomaly:

The sheath heat transmission coefficient

- **One of the most basic aspects of the plasma-solid interaction is the ratio of particle to heat flux, transferred from the plasma to an electrically floating solid surface.**

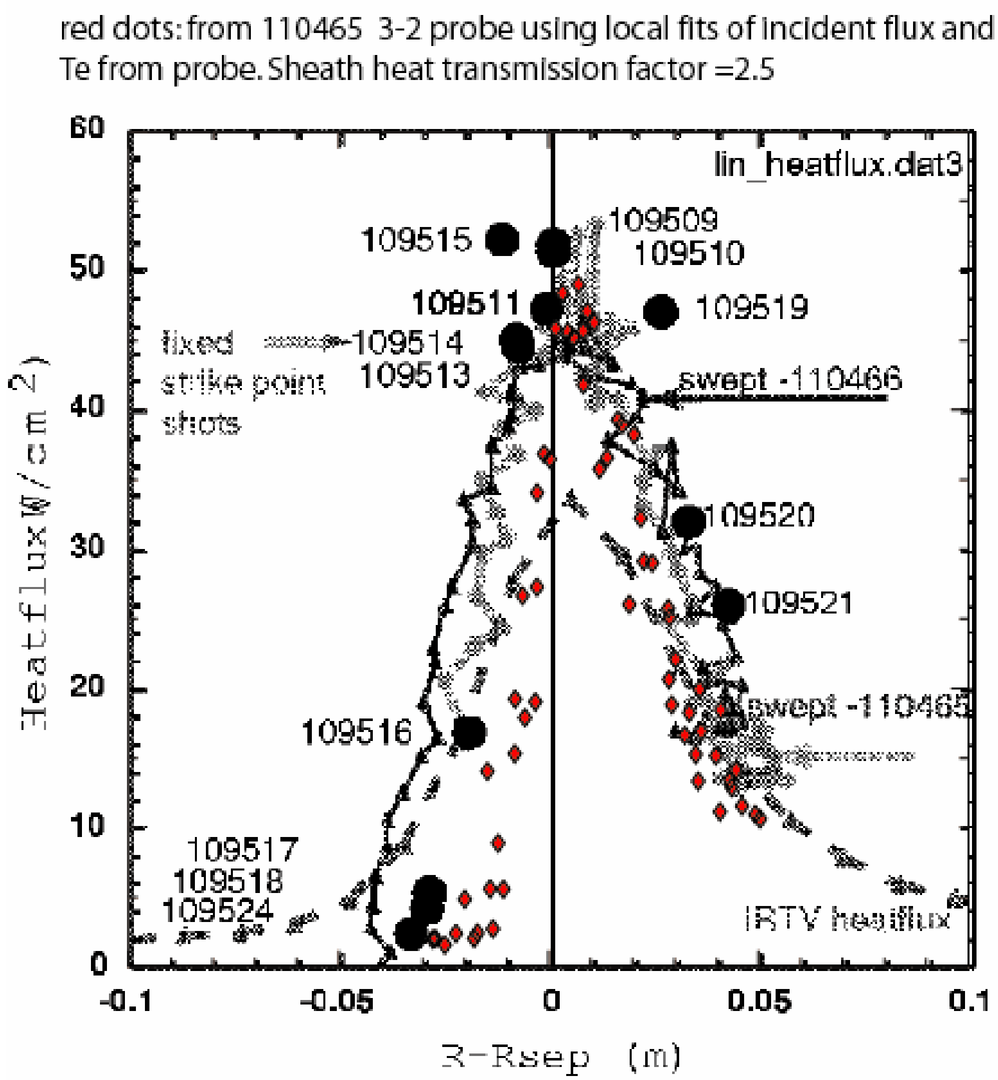
- **Using 'textbook' Debye sheath theory – dating back to Langmuir – we expect to find that:**

$$\frac{\textbf{power flux density}}{\textbf{particle flux density}} \sim \frac{7\,kT\,I^{+}_{sat}}{I^{+}_{sat}}$$

$\gamma \equiv$ sheath heat transmission coefficient ~ 7
roughly: 2 each for thermal part of e and i
+ 3 for sheath potential drop

- *But experimentally we find γ << 7:*

Heat flux density received at outer target for low density SAPP conditions.

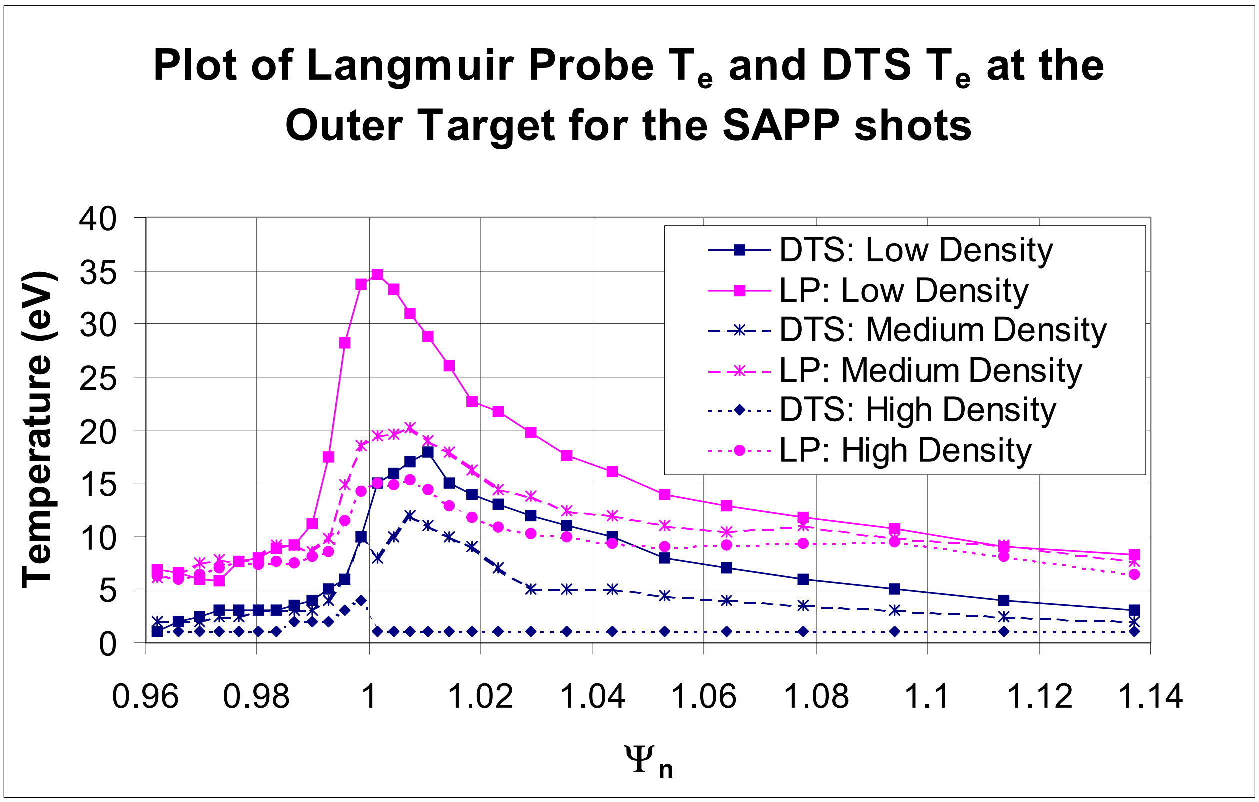


Calorimeter probe on DIII-D (Jon Watkins) (black), IRTV (dashed) and Langmuir probe (I^{+}_{sat}, T_e) with γ= 2.5 (red).

A problem first identified ~ 15 years ago.
We still do not have an explanation.

and there's indication of another anomaly:

T_e measured by the Langmuir probes in the outer divertor target and measured by DTS for the location nearest the target surface, differ by up to ~ 2X for the low density SAPP shots, increasing to *enormous* discrepancies with increasing n_e .



Conclude

Attached SAPP divertor:

**A substantial part of the controlling physics is evidently in hand,
however, 2 critically important, unresolved issues identified:**

1. **Is chemical sputtering absent or not?**

2. **Do we understand sheath physics in the environment of tokamak divertors?**

turning to the….

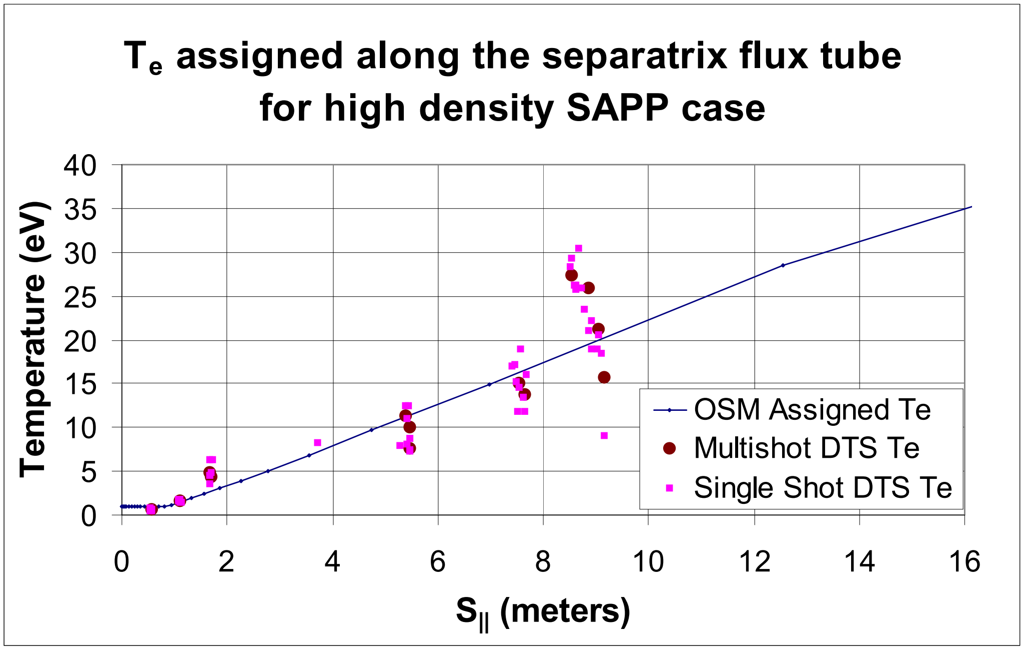
5. Detached (high density) SAPP divertor:

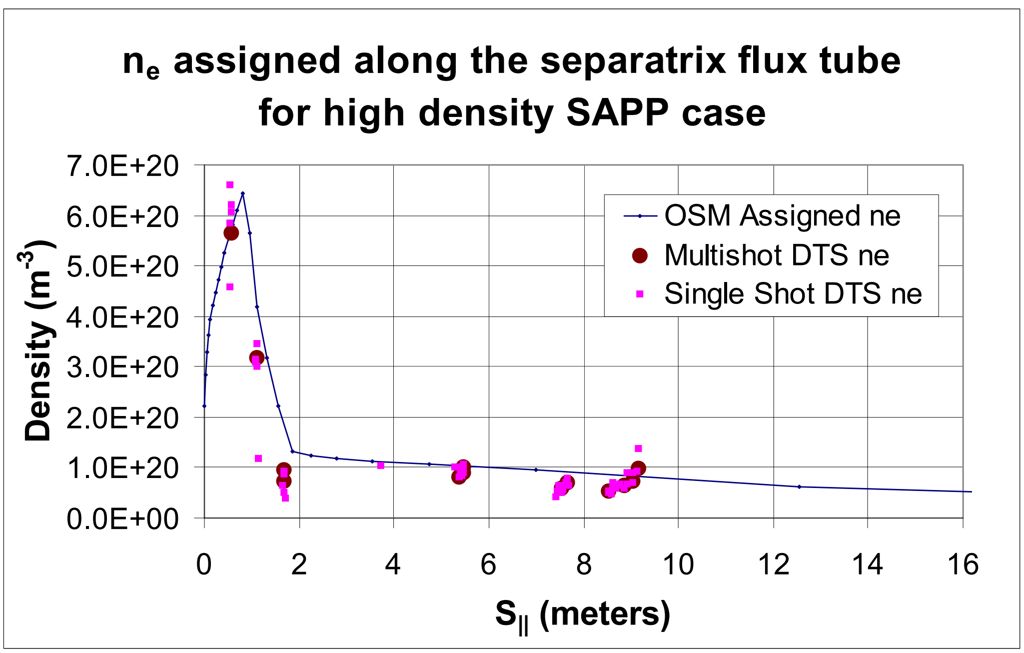
significant physics and diagnostic issues.

Detached SAPP Divertor

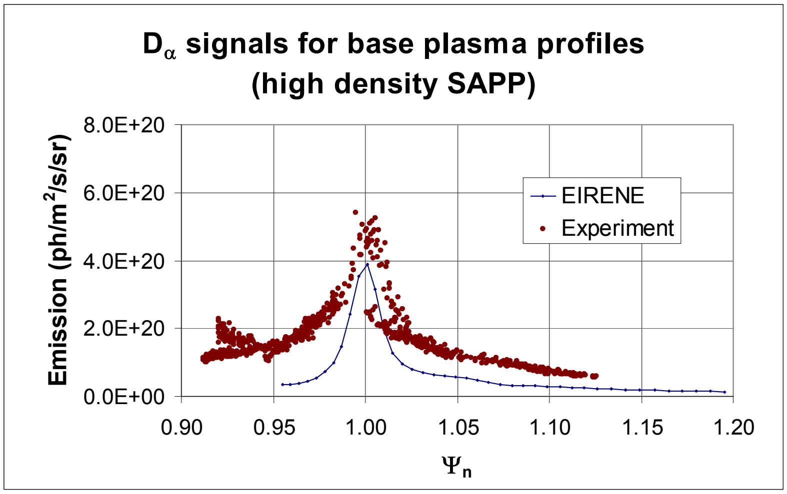
Prescription-based OSM **used in analysis. The 2D 'fields' of n_e and T_e assigned from DTS.**

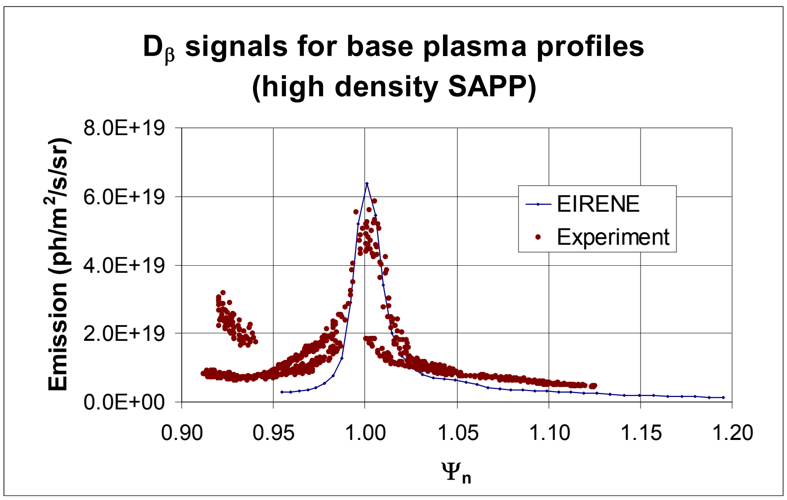
Separatrix Plasma for High Density SAPP:

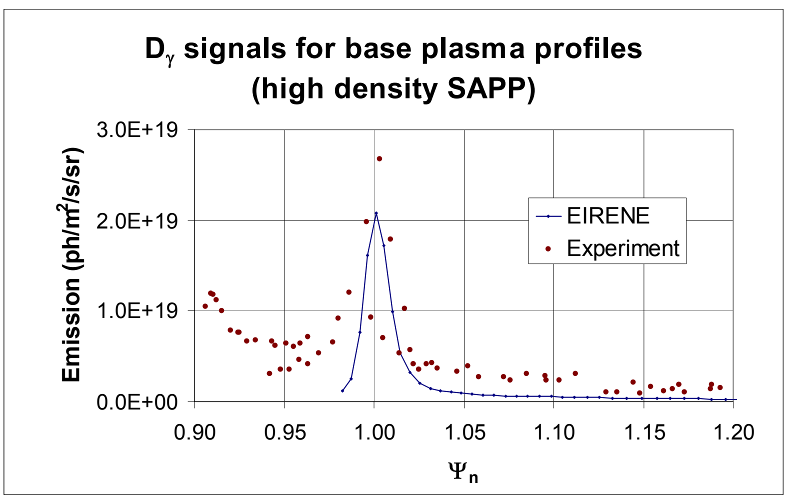




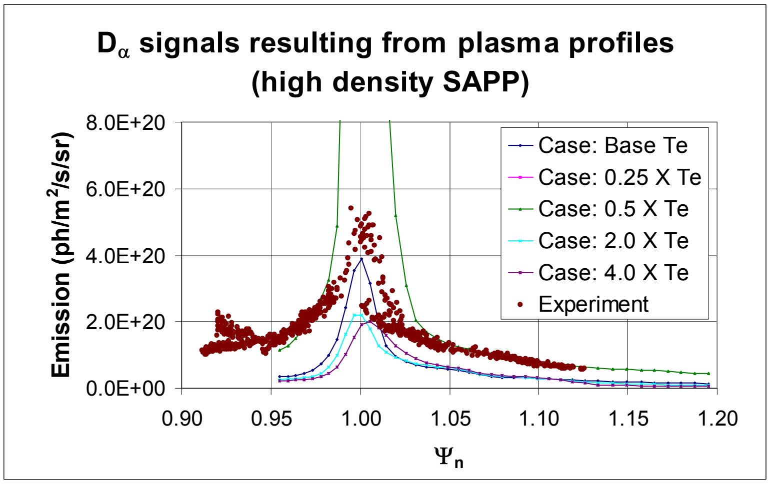
Detached SAPP: very good agreement between code (EIRENE) and measured D_α, D_β, D_γ

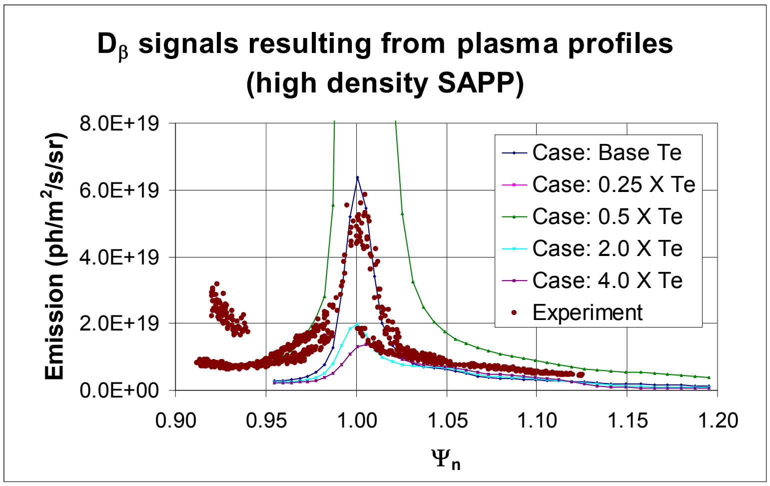


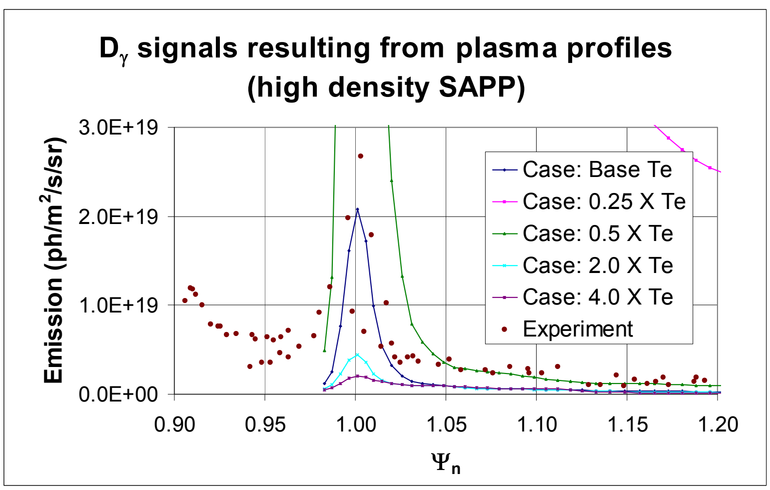




D_α, D_β, D_γ is a highly sensitive T_e 'thermometer' for detached plasmas



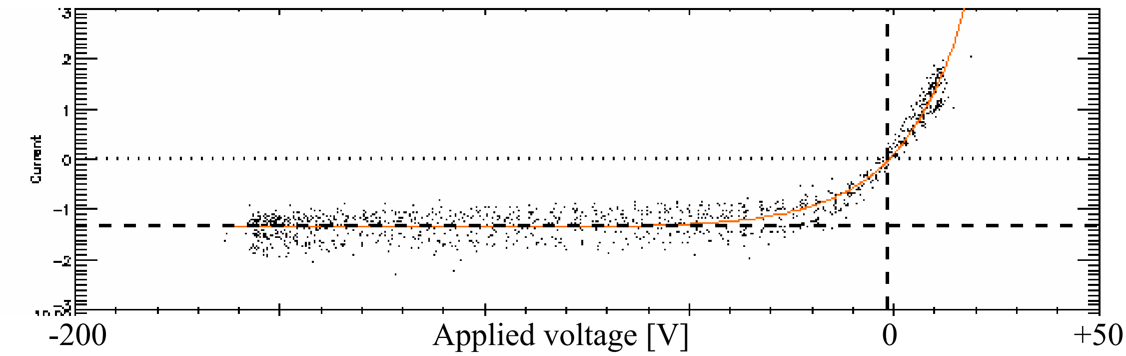




The very low $T_e \sim 1$ eV measured by Thomson is thus closely confirmed.

But, we have this big problem: Langmuir probe T_e is ~ 15 eV!

- **The probe I-V characteristics look 'textbook':**



- **How can we justify simply ignoring the probe data?**

"4. Do not put aside any diagnostic unless it is known to be mis-functioning.

……….

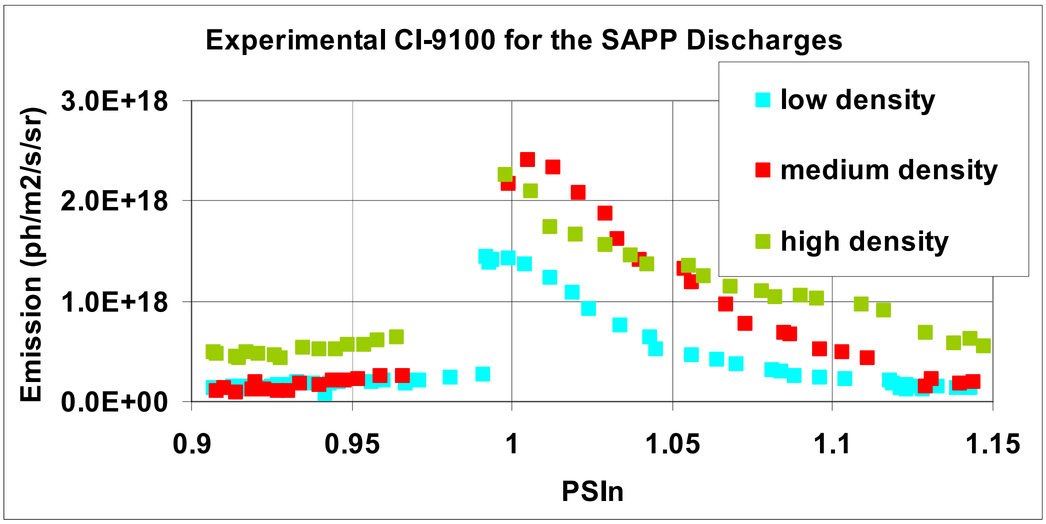
7. Any outstanding discrepancies to be flagged for further investigation as potentially containing important information."

- **Langmuir probes – particularly when they are built into the target, as here – involve such fundamental physics of plasma-solid contact that if we can't resolve this anomaly, how sure are we that we understand basic plasma-solid interaction in tokamaks? particularly for detachment – the ITER solution?**

- **One critically important part of the probe I-V characteristic seems ~ok: the measurement of charged particle flux density onto a solid surface from a contacting plasma, I_{sat}. The good agreement for D_α, D_β, D_γ is (almost) as much a test of the I_{sat} values as of the DTS T_e.**

A second major problem: we can't explain the source of carbon at the detached target.

- **The CI intensity is ~ as strong for high density SAPP as for the lower densities, implying that there is still a strong C-source:**

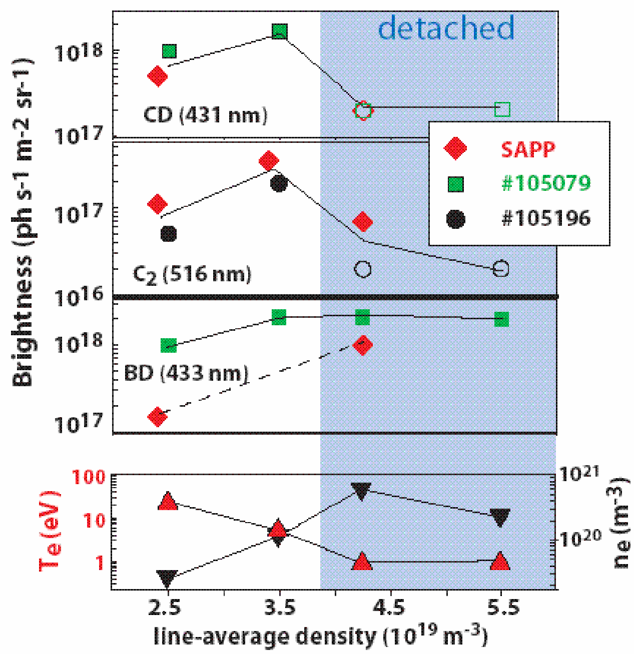


- **What source mechanism?**

- **Physical sputtering? If T_e is ~ 1 eV, then physical sputtering is not possible.**

- **Chemical sputtering? Lab-measured chemical sputtering yields also decrease strongly for low D^+ impact energy, although they remain finite.**

- **However, the spectroscopic indicators of chemical sputtering, C-D and C-C molecular band emission, essentially disappear for high density SAPP, next:**



- HC brightness decreases to or below detection limits (open symbols) in detachment.
- BD behavior significant:
  - Must radiate in detached plasma (MFP ~1 mm)
  - Verifies $T_e \sim 1$ eV to sustain BD emission.
  - Ultra-low T_e cannot be cause of extinction of HC emission, since $E_{th} \sim$ identical between BD & CD.

Carbon Workshop, Sept. 2003, Whyte 13

Dennis Whyte
10th international workshop on carbon, 17-19 Sept 2003, Juelich Germany.

Is there a Two-Temperature Electron Population?

- **For $\underline{B} = 0$ plasmas, the entire IV characteristic of a Langmuir probe can be used to extract T_e, however, for $\underline{B} \neq 0$ plasmas, the part for $V_{probe} > V_{floating}$ is distorted (Bohm, 1940's) and we still (!) don't know how to use this part. We therefore use only the part for $V_{probe} < V_{floating}$:**

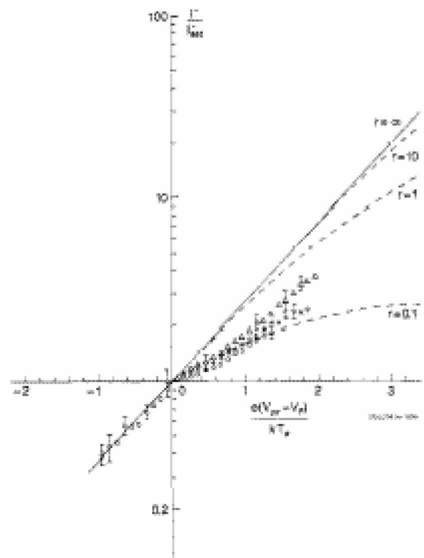


FIG. 3—Ratio of I^-/I^-_{sat} experimental results obtained on JET (○ = shot 3068, * = shot 3024, △ = shots 3757, 5411 and 5546) as a function of the normalized probe potential $e(V_{pr} - V_F)/kT_e$. Negative values (○) correspond to all analysed shots (Table 1). A comparison with the values predicted by the simple theory is shown for different values of the reduction factor r.

JET. Tagle, Stangeby, et al, PPCF 29 (1987) 297.

- **Problem: we are only sampling the high energy tail of the electron distribution and if it is non-Maxwellian… oh, oh!**

- **Consider a 2-Maxwellian distribution with $T_{cold} = 1$ eV and $T_{hot} = 15$ eV. Then, even if $n_{hot}/n_{cold} \sim$ a few %, the hot electrons will dominate the electron flux to the probe, for $V_{probe} < V_{floating}$, and so probe will give $T_e = T_{hot}$.**

- **Could this explain the discrepancy here?**

Are the two anomalies related?

- **Could a 2-T_e population explain the source of C?**

- **If a small (few %), hot component dominates the probe's electron collection for $V_{probe} < V_{floating}$, then these hot electrons would presumably also set the ~floating sheath potential drop that exists across the divertor target, i.e. $\Delta V_{sheath} \sim 3kT_{hot} \sim 45$ eV.**

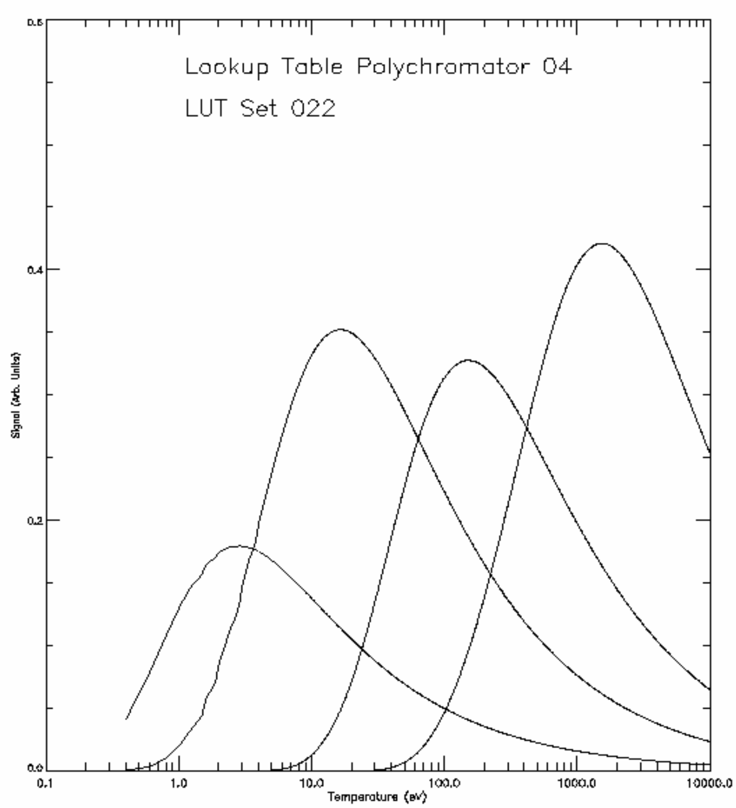
- **The D^+ ions, accelerated through ΔV_{sheath}, might then have enough impact energy to cause physical sputtering, explaining the observed C-source.**

Possibility of Two-T_e Electrons in Detached Plasmas

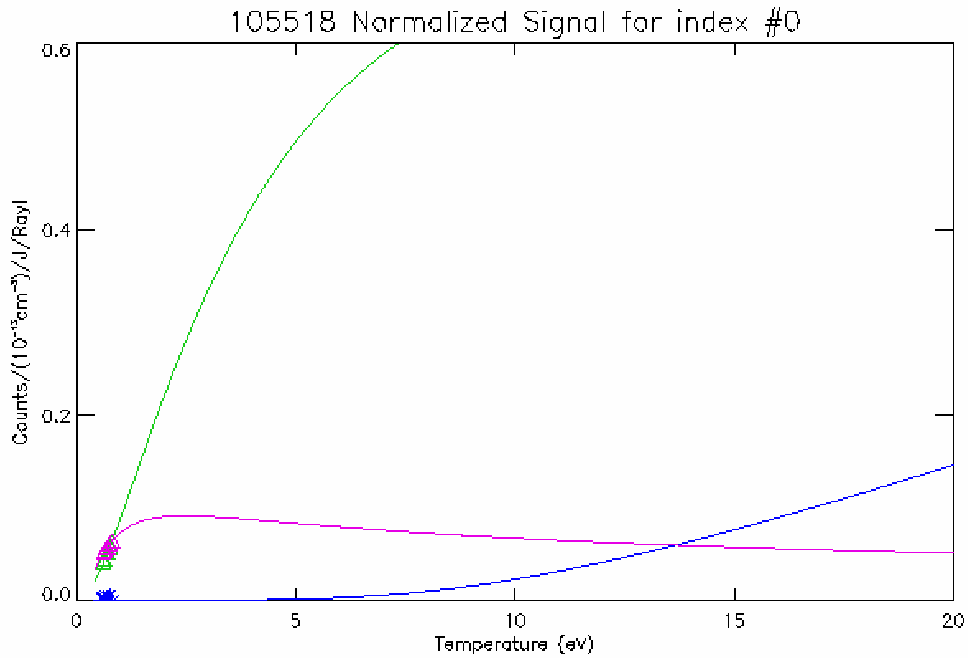
- **The extremely strong collisionality of detached plasmas seems to rule out the possibility of a 2 T_e distribution.**
  $\lambda_{ee} \sim 10^{16}\ T_e^2/n_e$.
  For 15 eV electrons and $n_e = 6\text{x}10^{20}\ m^{-3}$, $\lambda_{ee} \sim 4$ mm.

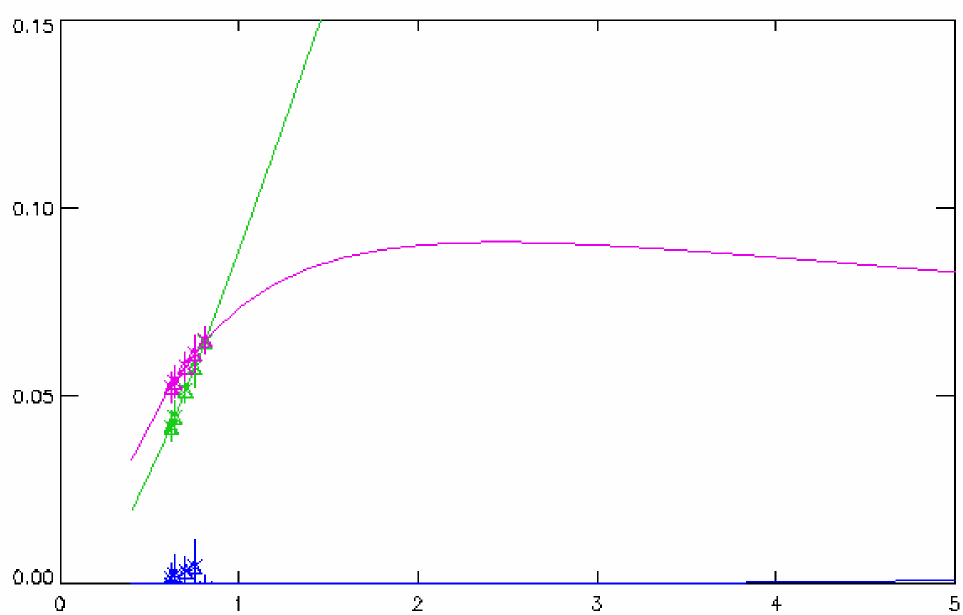
- **Nevertheless, if somehow a small (few %), hot component were present, could Thomson detect it?**

- **DIII-D's DTS uses a Nd:YAG laser (20Hz, 1J, 15 ns, 1064 nm). Scattered photons recorded by a polychrometer; intereference filters centered at 1062 nm, 1056 nm, 1046, 1022 nm:**



Expected counts for each filter, as a function of T_e: continuous lines.
Points: for high density SAPP, location closest to the divertor target.





Finding a Hot Electron Minority in the DTS Data

- **There are only significant numbers of counts in the first 2 filters, indicating that most of the electrons have T_e ~ 0.8 eV.**

- **There may be some counts in the 3rd filter, but the error bars are also consistent with zero counts.**

- **With the present system one can only say that if a 15 eV component is present, it is < ~4% of the total – which is not adequate to resolve the T_e discrepancy.**

- **Improvements and extensions to the DTS could significantly increase the ability to detect small, energetic components of the electron population.**

A missing piece of critical information:
T_{D+} in the divertor.

- **After n_e and T_e, the most important divertor quantity that we need to know about is T_{D+} .**

- **While there are a number of ways that n_e and T_e are regularly measured in divertors – directly and indirectly – measurements of T_{D+} are scarce to non-existent.**

- **The ion temperature can play an important role in the sputtering source at the divertor targets. It is also the quantity with the largest influence in the parallel force balance for impurity ions where the two strongest forces are usually the ion temperature gradient force and the frictional force (coupling to the D^+-flow).**

- **Another possible explanation of the C-source in detached SAPP is that $T_{D+} >> T_e$ and so the D^+ energy – even without sheath acceleration – is enough to cause physical sputtering.**

Measuring T_{D+} from D_α line shape

- **In principle, analysis of D_α line shape can give T_{D+}, however, interpretation is usually difficult/unconvincing.**
- **Fortunately, it can be simpler and more convincing for cold, dense, detached plasmas.**
- **1996 APS:**
  "Ion Temperature Measurements in the DIII-D Divertor"
  H.H. Brooks, R.C. Isler, G.R. McKee, S. Tugarinov

"Doppler ion temperature lend confirmation to Divertor Thomson measurements of $T_e \sim 1$ eV in detached plasmas."

This is a diagnostic that we need to more fully exploit.

Extracting More Information from the Divertor Thomson

- **The DIII-D Divertor Thomson is the only one operating in any divertor tokamak.** ***This unique, powerful diagnostic ought to be fully exploited.***

- **Supplementing the interference filters with a high dispersion resolving instrument such as a Fabry-Perot would substantially extend the measuring capability of the DIII-D DTS:**

  1. **The ability to detect the presence of a small component of fast electrons – which may be causing the C-source – would be increased.**

  2. **For the high n_e, low T_e of detachment, collective scattering contributes to the scattered Thomson light as $\alpha = 1/k\lambda_{Debye}$ approaches 1. For $n_e = 6 \times 10^{20}$ m^{-3} and $T_e = 0.8$ eV, $\alpha \sim 0.6$. For high values of α, the DTS analysis method based on interference filters results in errors in measuring n_e and T_e (~20% at $\alpha = 0.8$). A Fabry-Perot would deal with this problem – and would also provide a 2nd, independent measurement of n_e (from *shape* of scattered profile, separate from the *intensity*).**

  3. **At high values of α, measurements of T_{D+} are possible (also of Z_{eff}). Thus, with sweeping, 2D mapping of T_{D+} throughout the divertor.**

The Detached Plasma State
– the ITER divertor solution -
is relatively
'unknown territory'

- i-n momentum collisions exert strong frictional drag on parallel plasma flows

- volume recombination

- very high neutral density $\Rightarrow$ radiation trapping

- extremely high ee, ii collisionality.
  $n_e = 6\text{x}10^{20}$ m^{-3}, T_e = 0.8 eV (= T_i ?), B = 1.5 T (DIII-D):
  $\lambda_{ee} \sim \lambda_{ii} \sim 10^{-5}$ m short!
  $\tau_{ee} \sim 10^{-11}$ s $\tau_{ii} \sim 10^{-9}$ s short!
  $\omega_e\tau_{ee} \sim 2$ $\omega_i\tau_{ii} \sim 0.1$ small!
  electrical resistivity $\eta_{||} \sim 10^{-3}$ Ωm high!

- If, in fact, T_i is this low, then the ions are ~ *non-magnetized* – and the plasma doesn't flow along $\underline{B}$ to the targets! However, our interpretation of the probe I_{sat} to give the D^+ flux onto the target – thus the neutral recycling source strength – assumes v || $\underline{B}$. How, then, to explain the good agreement with the D_α, D_β, D_γ? Is T_i really this low? Even if it's not here, what about more strongly detached plasmas, e.g. for ITER?

- For such high $\eta_{||}$, ohmic heating will be strong for even small $j_{||}$. The probes draw $j_{||} \sim j_{sat} \sim 4\text{x}10^5$ A/m^2, thus $P_\Omega \sim 10^8$ W/m^2; does this explain the high $T_{e,probe}$? Natural currents flow to the targets – thermoelectric, Pfirsch-Schlutter; is the resulting P_Ω important?

Conclusions

- **For the simplest, attached divertor conditions, much of the controlling physics is evidently in hand, but at least 2 issues of critical importance remain to be resolved: (a) chemical sputtering, (b) sheath physics.**

- **The ITER design is based on divertor detachment.**

- **While a number of the important processes involved in detachment have been identified, the detached plasma state is still 'unknown territory', comparatively speaking.**

- **Greatly improved diagnosis is required for detached plasmas:**

    - **We need to know how to interpret existing diagnostics, e.g. probes**

    - **We need to extend existing diagnostics to extract their full potential, e.g. Thomson**

    - **We need new diagnostics, e.g. flow speeds, in the divertor**

- **We need to develop better understanding of the controlling physics of detachment.**

An unusual - possibly unique - plasma condition is involved in divertor detachment and we don't understand enough about it.