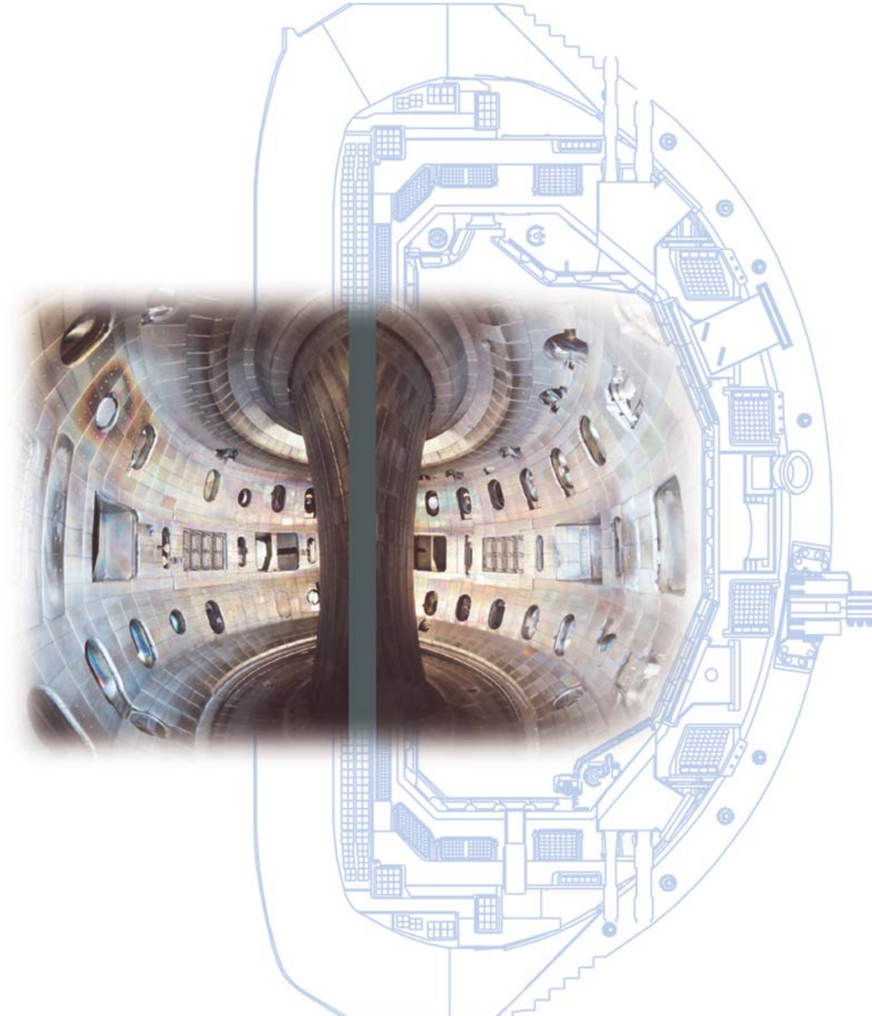
Comparative study of C I line profiles resulting from methane puffing in the DIII-D divertor with those from surface sputtering

by
N.H. Brooks, R.C. Isler, W.P. West,
C.P.C. Wong, A.G. Mclean, and
D. L. Rudakov



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DIII-D
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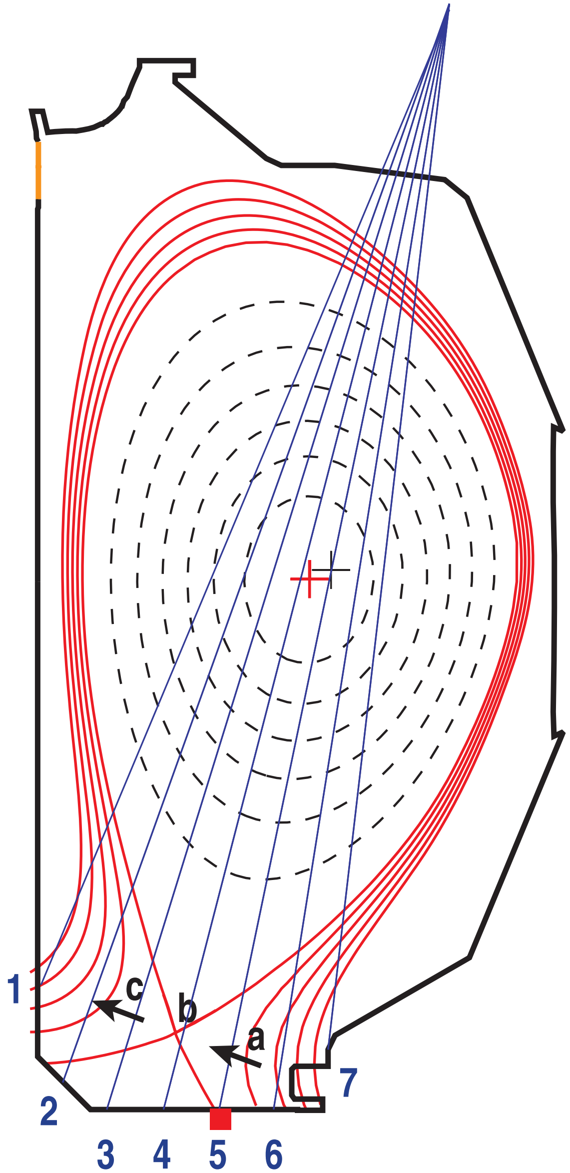
GENERAL ATOMICS

165-05/jy

Outline

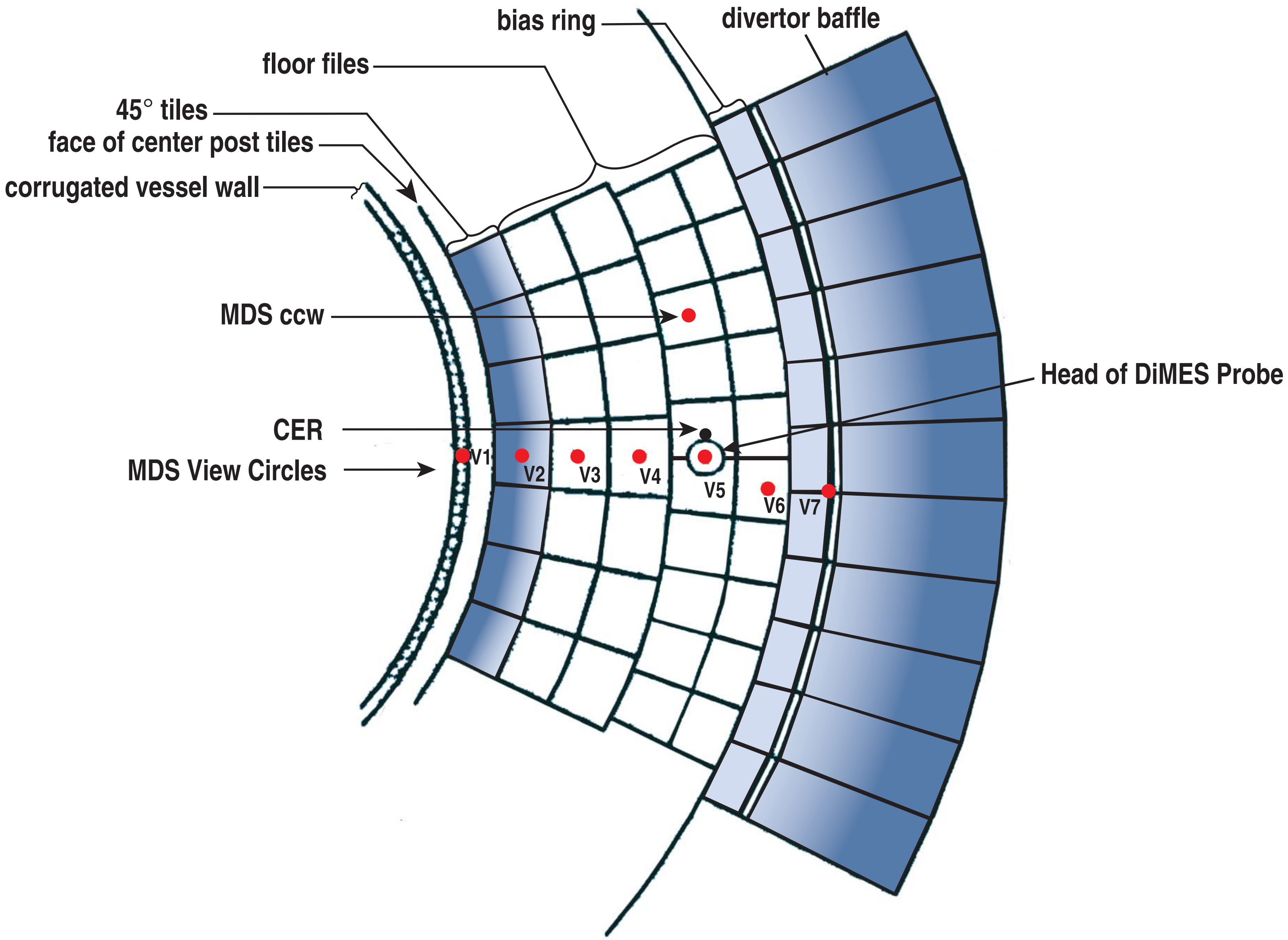
- **Both passive and, more recently, active DiMES samples have been exposed to divertor plasma at the outer strike point (OSP)**
  - *In-situ* divertor behavior of carbon flakes, gaseous methane, and amorphous C-H / -D films has been imaged, and recorded spectroscopically
- **Molecular spectroscopy (CH and C_2 bands)**
  - formation of an a:C-H film observed during CH_4 puffing
  - transformation of film seen in shots w/o puffing
- **Atomic spectroscopy (C I line profile)**
  - decomposition of asymmetric profile sheds light on sputtering mechanisms

Spectrometer views of lower single-null magnetic configuration in divertor-sample-exposure experiments



- Typically, OSP swept onto the DiMES sample and held stationary for several seconds
- High-resolution, multichord divertor spectrometer (MDS) equipped with poloidal fan of viewchords
- Medium-resolution spectrometer (Reticon CER) has single vertical viewchord
- Dα, Dβ, C III, and He II monitored with spectral filter / photomultiplier combinations over similar fan of viewchords

Toroidal Geometry of MDS View Chords



Summary of initial findings from porous plug experiment

- **a:C-H film forms on surface of porous plug during CH_4 methane injection**

- **energetic D^+ flux causes rapid isotopic replacement of H by D**

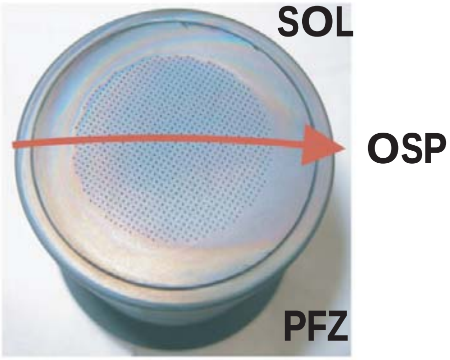
- **Total C° influx is sum of direct and indirect components: CH_4 gas puff and re-erosion of a: C-H film**

- **Chemical sputtering dominates erosion of bare graphite tiles at outer strike point in low-power, attached L-mode plasmas, based on C I line shape analysis.**
  — Contradictory conclusion reached by U of T group (**CP1.0014**), based on CII-normalized, CD-photon-yield method

Puffing methane gas through a porous plug locally changes the balance of erosion and redeposition

Pre-Exposure

Post-Exposure



Top View

Side View

- 1,004 holes of 0.25 dia mm diameter in ATJ graphite plate
- Flow ~4 sccm, to approximate in-situ chemical sputtering rate
- Gas reservoir, valve, and p-transducers all contained within graphite plug
- Brownish film indicates net deposition locally over plug
- Significantly greater deposition downstream on PFZ side

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See Davis CP1.00014 - this session

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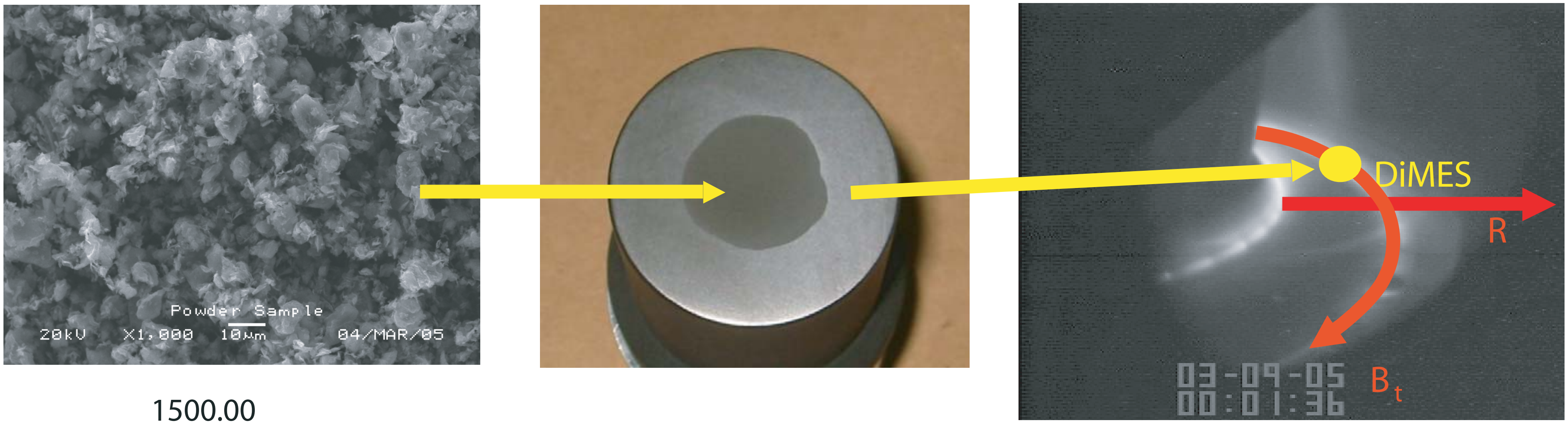
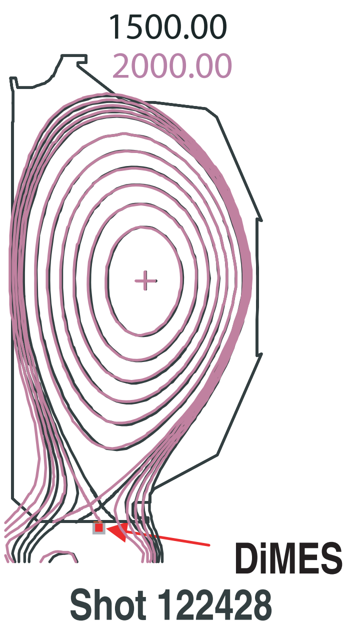
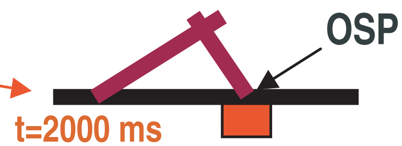
Dust DiMES Summary

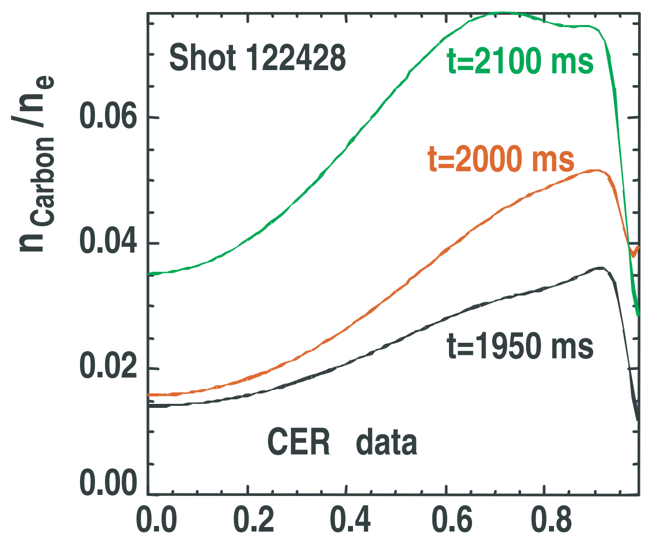
About 25 mg of 5 – 10 μm size carbon dust was introduced in DIII–D divertor





When OSP was swept over DiMES, about 1-2% of the total carbon content of the dust penetrated into the core raising core carbon content by about a factor of 2





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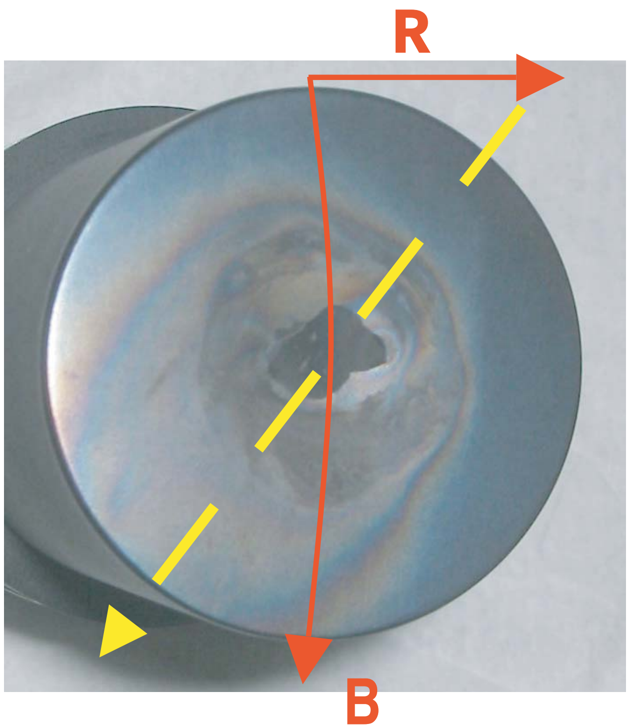
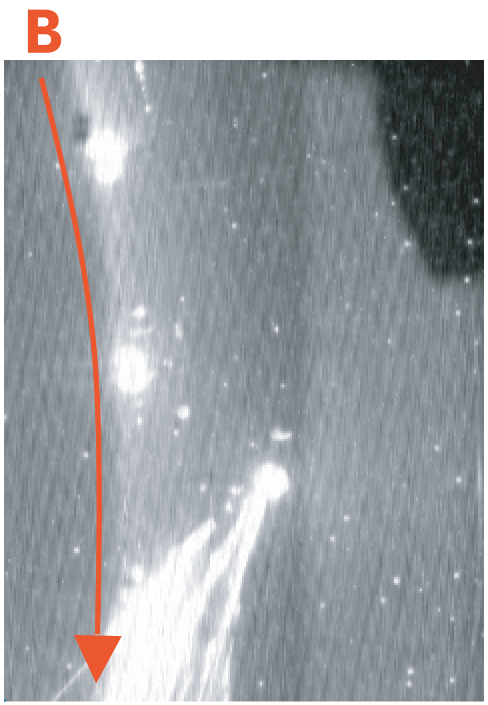
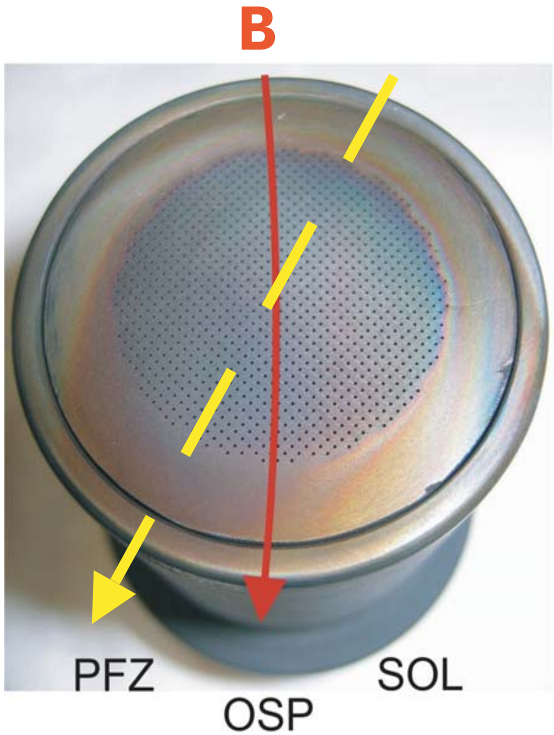
Dust Holder and PPI DiMES Head had Similar Deposition!



Dust DiMES



Dust tracks



PPI

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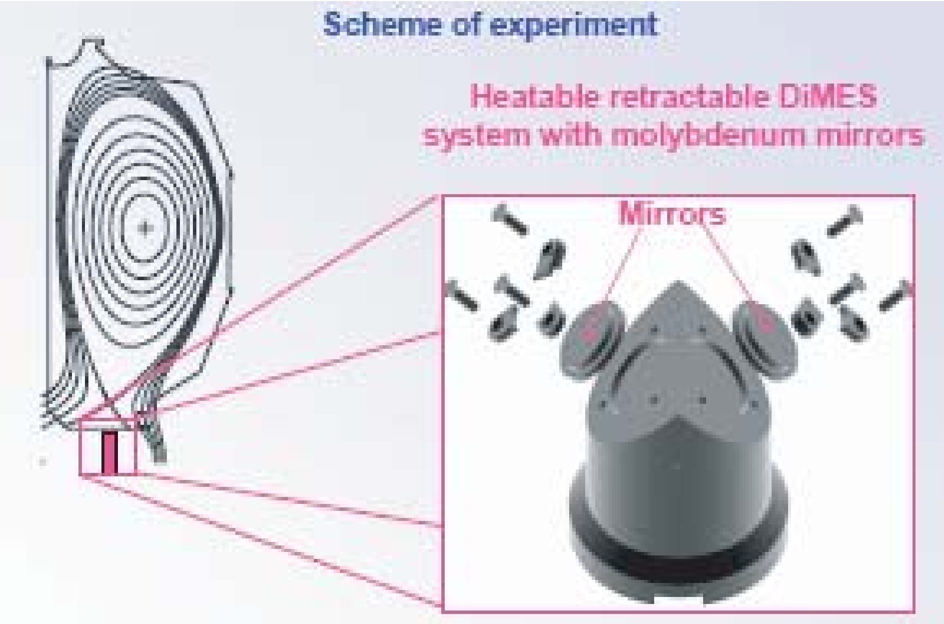
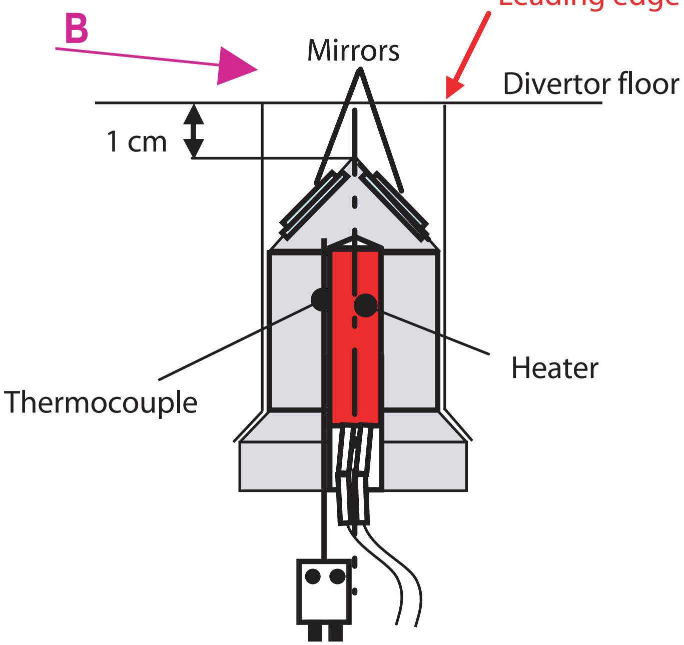
First Tests of ITER-relevant Diagnostic Mirrors in DIII–D

Presented orally this morning by Rudakov in B03.0007





- A set of two mirrors was exposed in a piggyback mode over two days to 72 plasma discharges with varying parameters for a total of 435 plasma seconds
- DiMES was in the outer SOL in some shots and in private flux zone (PFZ) in others
- Significant semi-transparent deposits appeared on the mirror closest to the leading edge of the floor tile

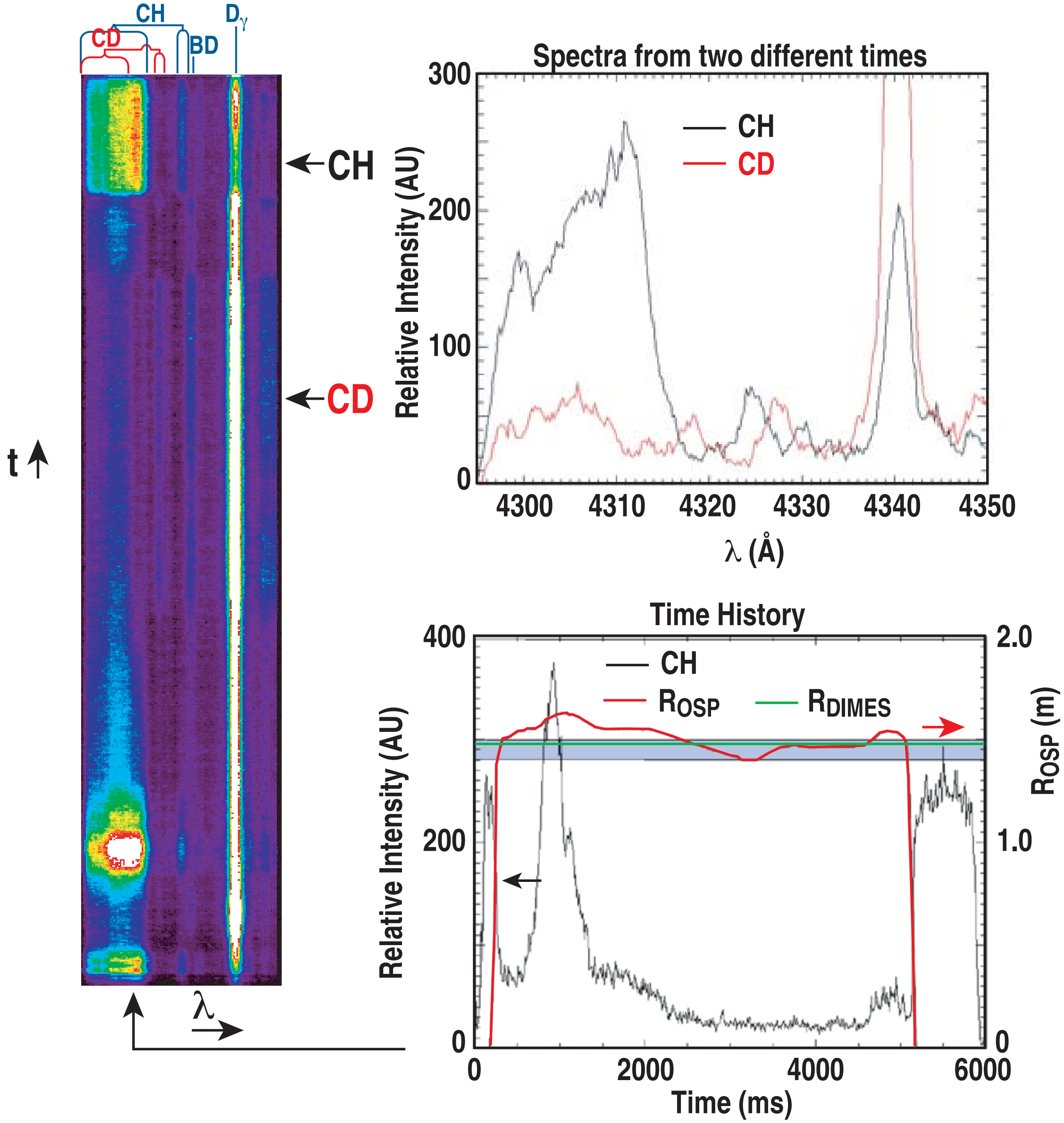
Before exposure

After exposure

Conclusions from molecular spectroscopy

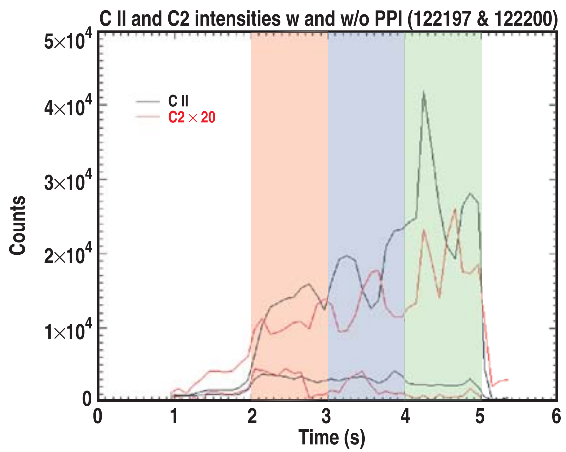
- CH_4 puffing causes net deposition locally on face of porous plug
- Determination of CD photon yield from gas injection complicated by secondary source of sputtered HCs
- Energetic D^+ flux causes rapid isotopic exchange and hardening of film (that is, a reduced chemical sputtering rate)
- *In-situ* film formation provides unique capability to study film evolution under strike point conditions

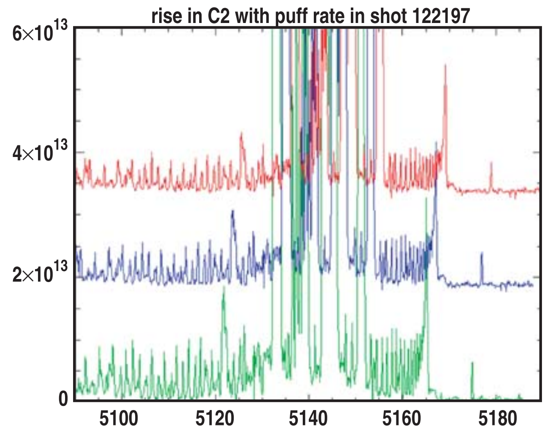
$A^2\Delta - X^2\Sigma$ band of CH/CD easily identified in CER view upstream of DiMES

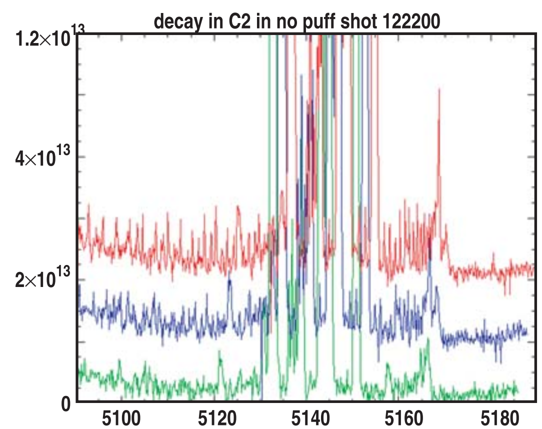


- CH dominates early and late in shot, when CH_4 cloud can expand unimpeded toward toroidally displaced viewchord
- Only CD visible during dwell of OSP on DiMES, due to plasma plugging of neutral efflux from holes
- In contrast, CH dominates in MDS view of DiMES surface during dwell of OSP
- Plasma flow entrains ionic fragments of CH_4, carrying HC fragments back to DiMES surface

Bright C_2 bands are visible in view of the porous plug







- During shot with puff, C II ion and C_2 band intensities mimic temporal history of CH_4 injection
- During shot w/o puff, C II and C_2 decay continuously during dwell on OSP
- Spectra integrated over 1-sec intervals give clearer picture
- Chemical erosion rate during OFF shot decays to level approaching that seen upstream of puff location

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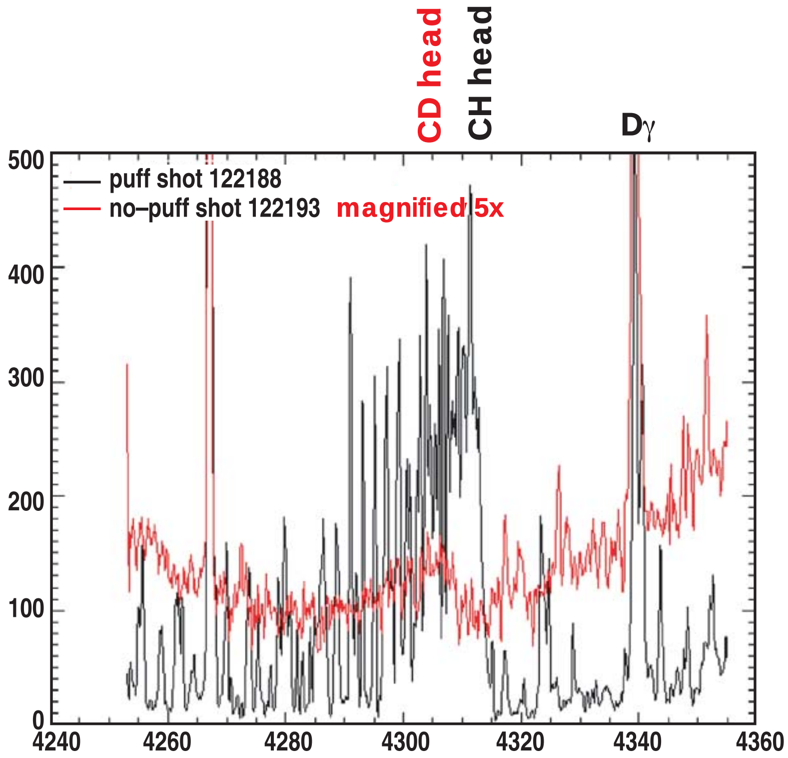
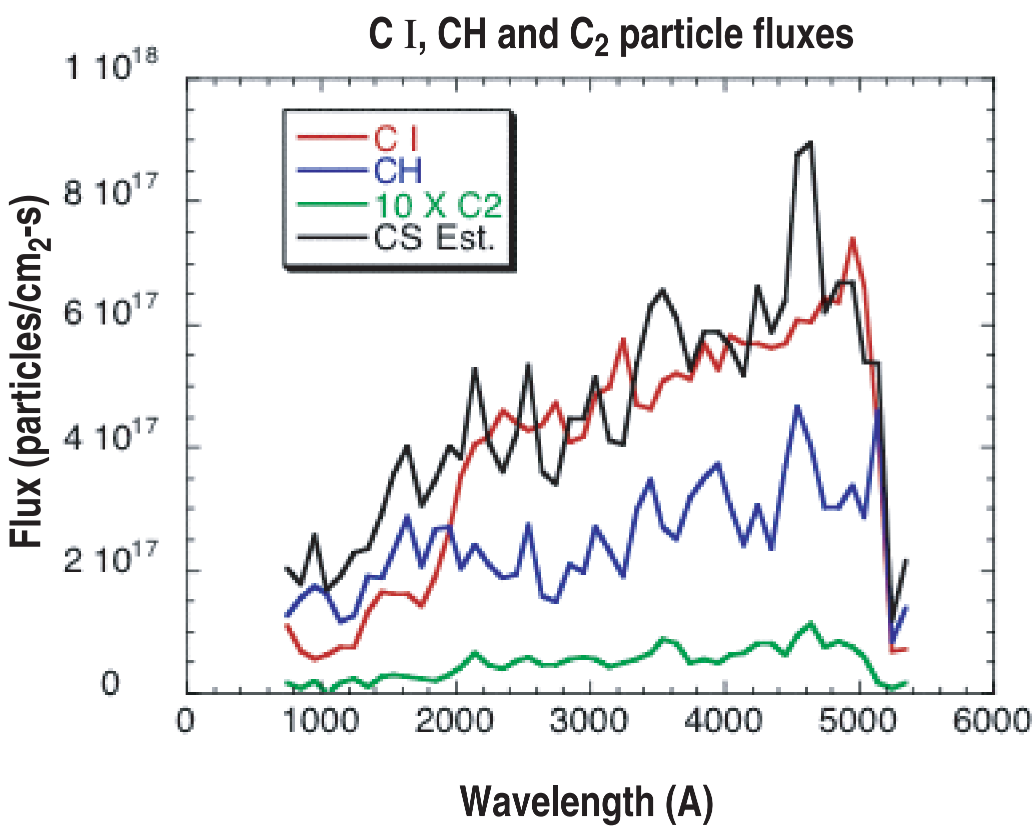
D+ flux to outer strike point promotes rapid isotopic exchange of D for H in film



- D^+ flow rate onto DiMES is an order-of-magnitude larger than CH^4 injection rate (1.4e18 /s).
- CH band dominates during shot with puffing; replaced by weak CD band on shot without puffing.
- CD band intensity too weak to deduce time history in no-puff shot
- Isotopic exchange and degassing of a:C-H film occur in no-puff shots
- How much of C I and C II light comes directly from breakup of CH_4? How much indirectly, from sputtering of a:C–H film ?

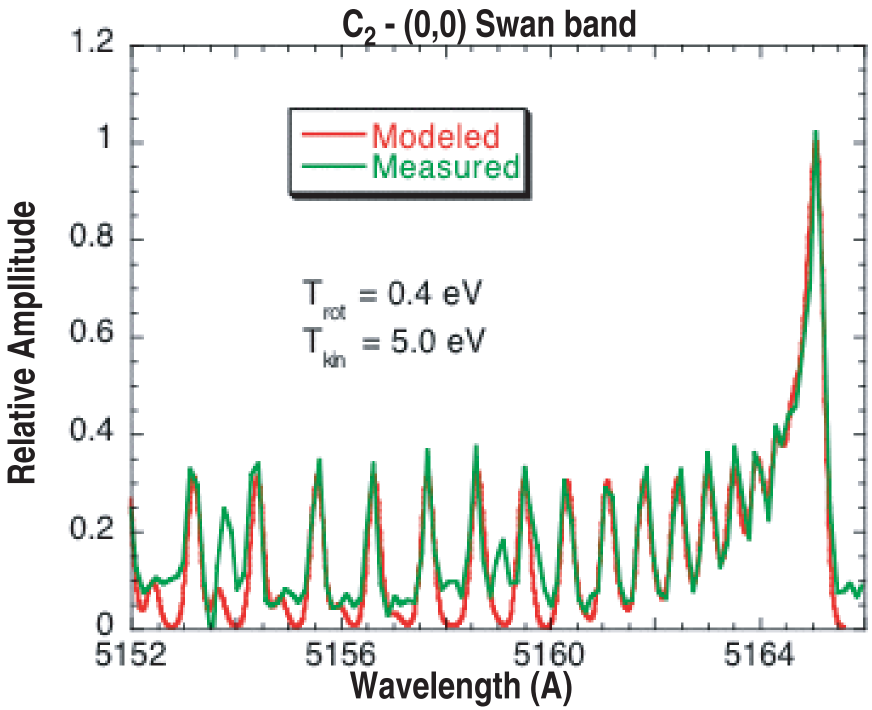
In the puff, all the C I flux can be ascribed to HC breakup

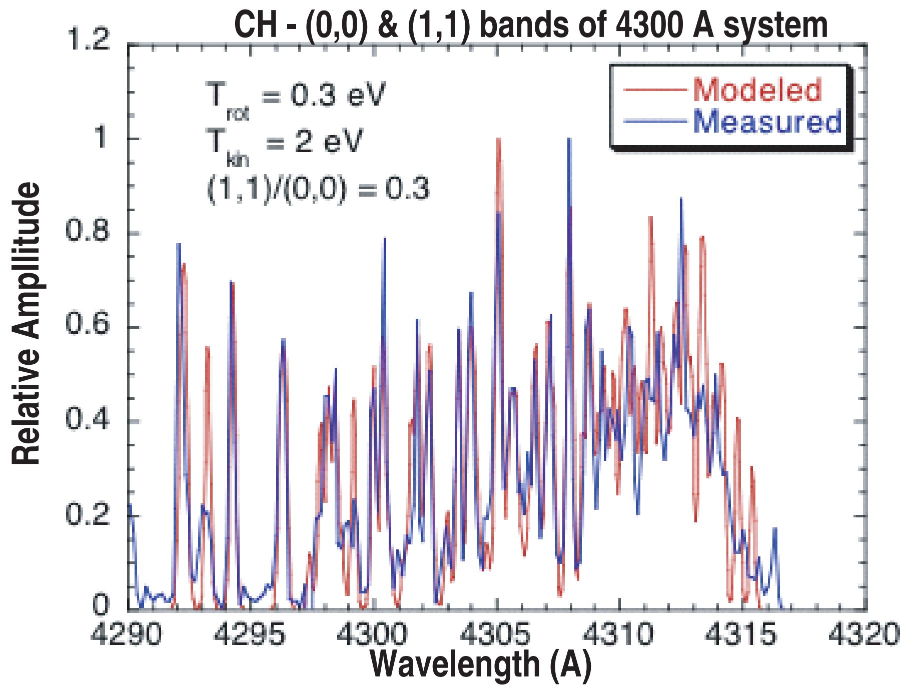
- **The measured CH and C_2 fluxes are sufficient to explain the C I influx, using the expression** $\Gamma_{mol} = 52 \times \Gamma_{C_2} + (\Gamma_{CD} - 8 \times \Gamma_{C_2})$
  - The 1st term accounts for C_2D_y and C_3D_y; the 2nd for CH_4



- **The relative sizes of the direct and indirect HC sources (puffed CH4 versus eroded HCs) can not be reliably determined from this data**

Least square fits to synthetic spectra of C_2 and CH bands yield T_{rot} and T_{kin}

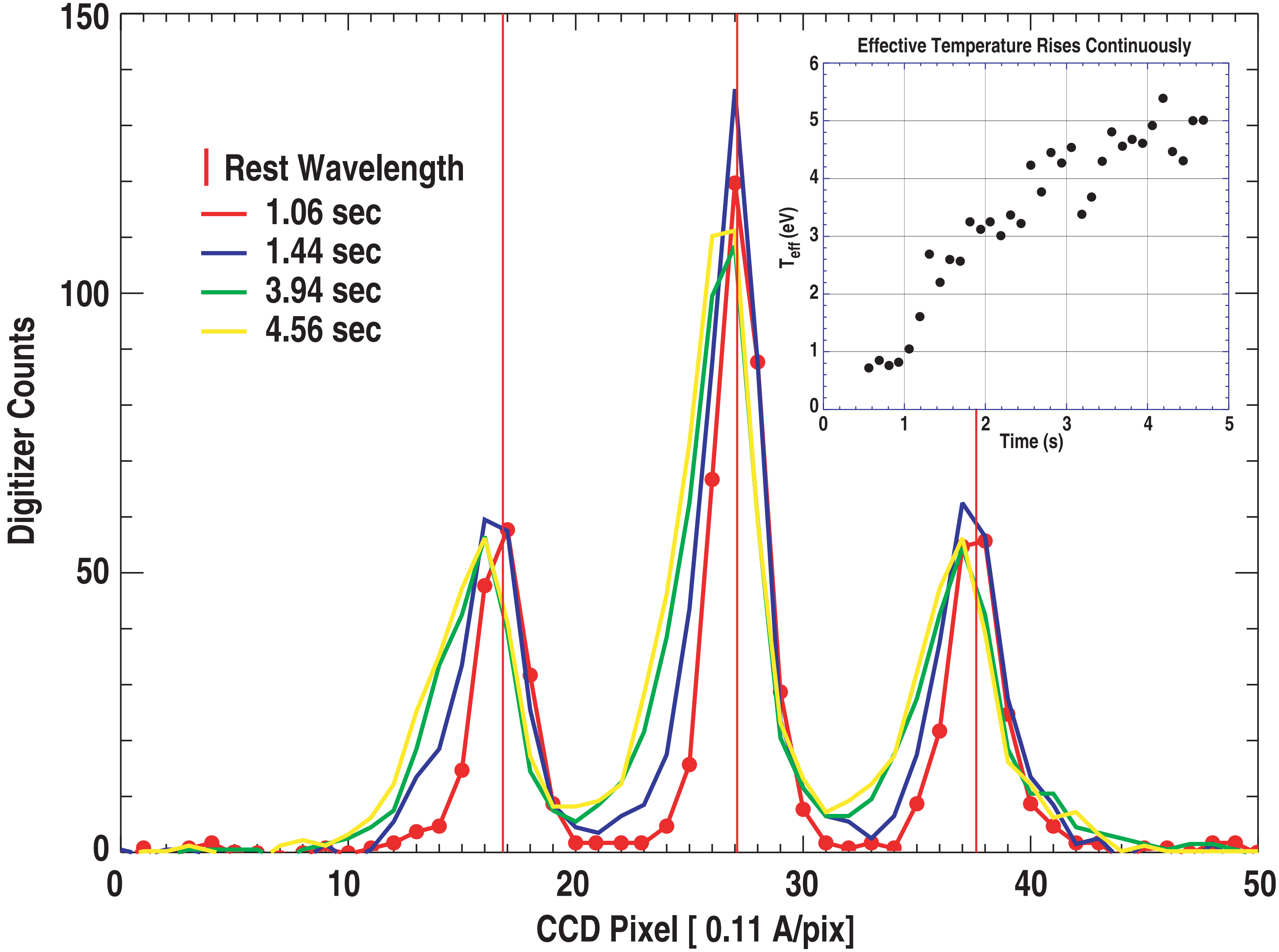




Overview of C I Profile Analysis

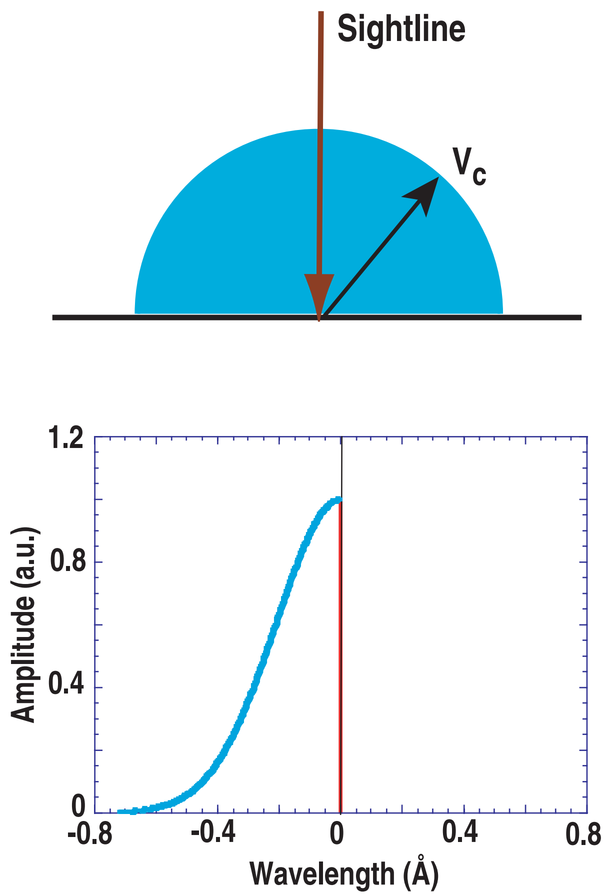
- **Analysis of C I spectral line shapes gives an independent way to distinguish carbon release mechanisms**
  - Asymmetry and λ–shift observed in C I 9095 line
  - Effective C I temperatures cluster in ranges 0.8-1.2 and 5-8 eV, according to which sputtering mechanism dominates
  - Physical sputtering causes λ–shift which increases with mass and energy of incident ions
  - Both chemical sputtering and recombination give rise to symmetric line
- **Relative importance of physical and chemical sputtering supported by flux measurements of C I, C_2 and CD in the DIII–D divertor**

Physical Sputtering Broadens C I Line Profile Preferentially on Blue Side of Rest Wavelength

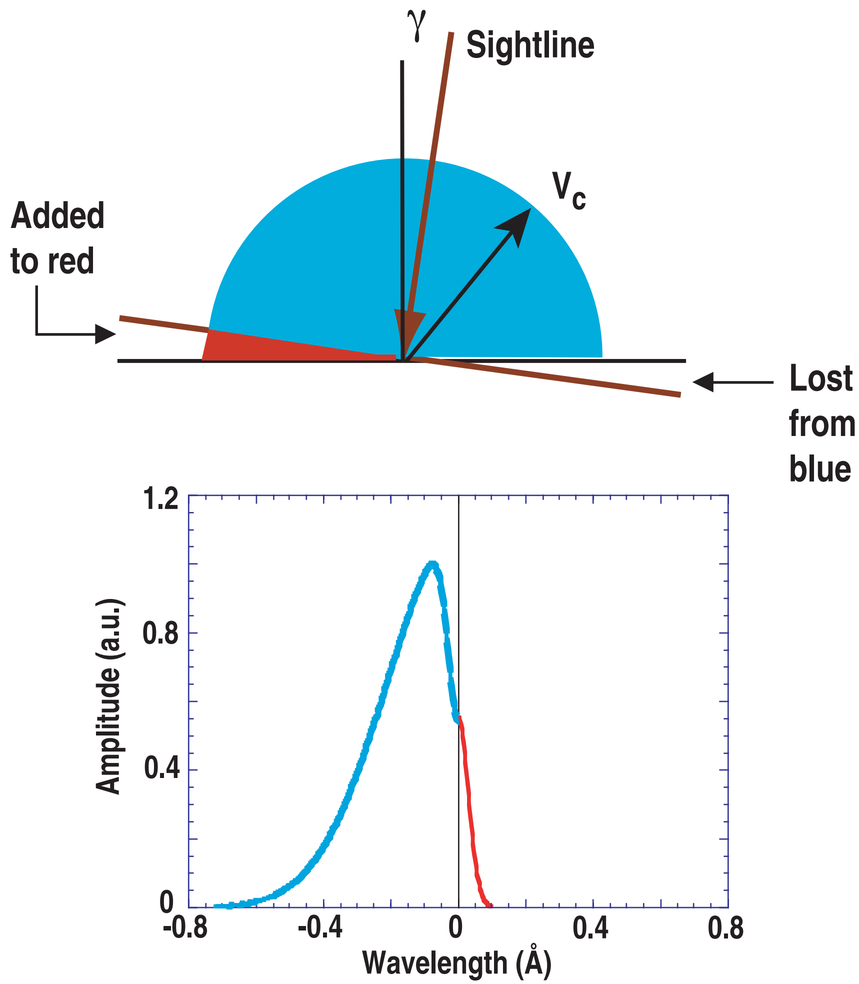


With Physical Sputtering, Hemispheric Velocity Distributions Give Rise to Asymmetric Spectral Profiles

Normal View



Angled View



Details of Profile Analysis

- Maximum entropy technique used to deconvolve source profile from measured one
- Source profile fit with analytically constrained, asymmetric and symmetric components by a non-linear, least squares method
  - Asymmetric part represented by a modified Thompson velocity distribution mapped to λ space

$$f(E)dE = \frac{E}{(E + U_0)^3} h(\theta)G(E)dE$$

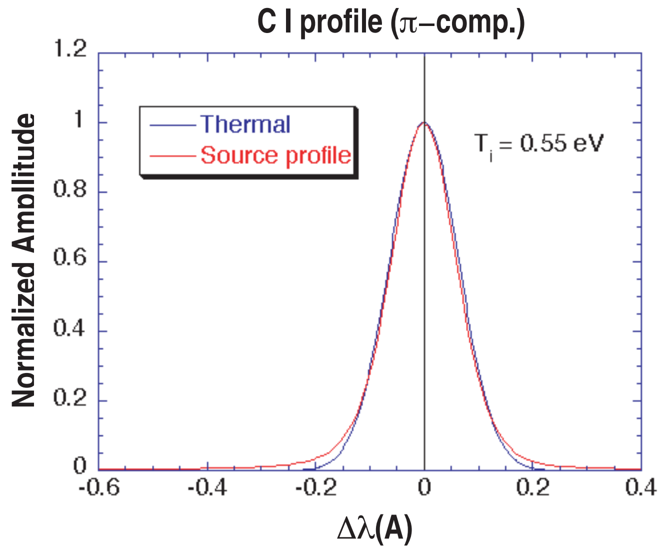
where $h(\theta) = \cos^{\alpha}(\theta - \delta)$

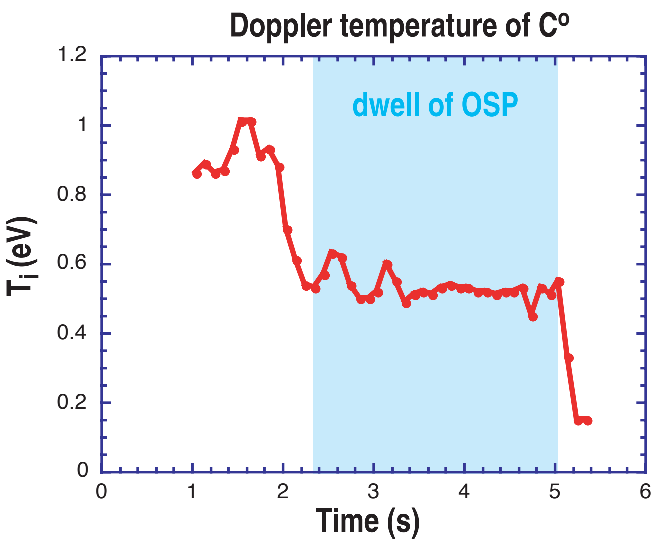
  - Symmetric part described by single (or double) Gaussian
- In absence of λ fiducial from argon lamp, centroid of profile from detached, inner strike point used to locate λ_o

Conclusions from C I atomic spectroscopy

- T_{eff} from C I profiles are ordered by size according to carbon source: breakup of HCs < sublimation of dust < physical sputtering
- Puffing experiment contradicts T_{eff} predictions from modeling of CH_4 breakup dynamics
- Consistent with empirical finding by Isler of low T_{eff} when C influx dominated by chemical sputtering
- Is C I emission in porous plug experiment dominated by direct source (CH_4 breakup), or indirect source (sputtering of a:C-H film) ?

In puff, C I line profile is well-fit by Gaussian. T_{Dop} ~ 0.6 eV





- **Gaussian fits source profile, despite Frank-Condon creation mechanism of C atoms from CD, and C_2**
  - — Source profile obtained by deconvolution of instrumental function from measured data

- **Measured T_{Dop} is much lower than 3-4 eV suggested by modeling of fragmentation sequence for CH_4**
  - — Bumps in T_{Dop} trace during dwell caused by strike point movement

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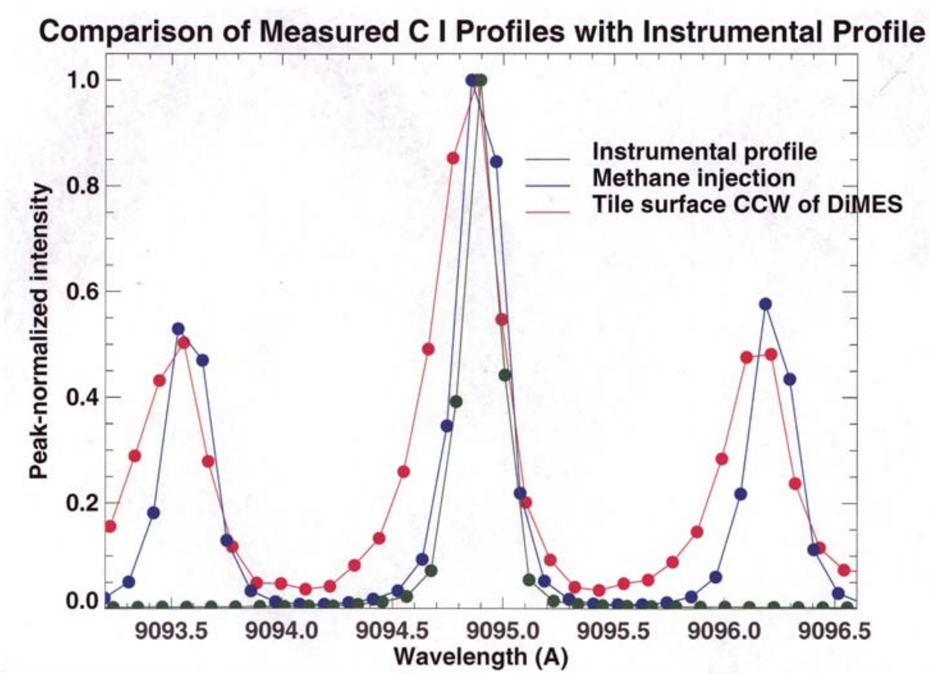
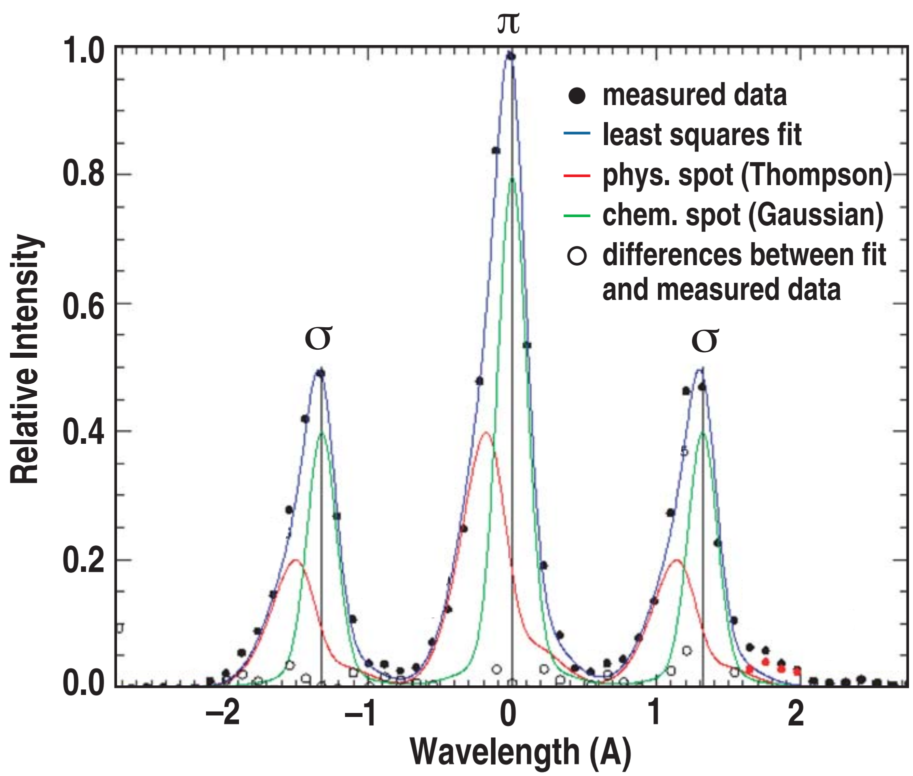
Normalized profile of C I upstream of porous plug is broadened asymmetrically w.r.t. profile on plug



- CH_4 puff gives rise to symmetric profile only slightly broader than instrumental, $T_{C\ I}$ ~ 0.55 eV
- Graphite sputtering produces asymmetric broadening on blue side of profile
- Graphite flakes produce symmetric profile (not shown) with $T_{C\ I}$ ~ 1 eV

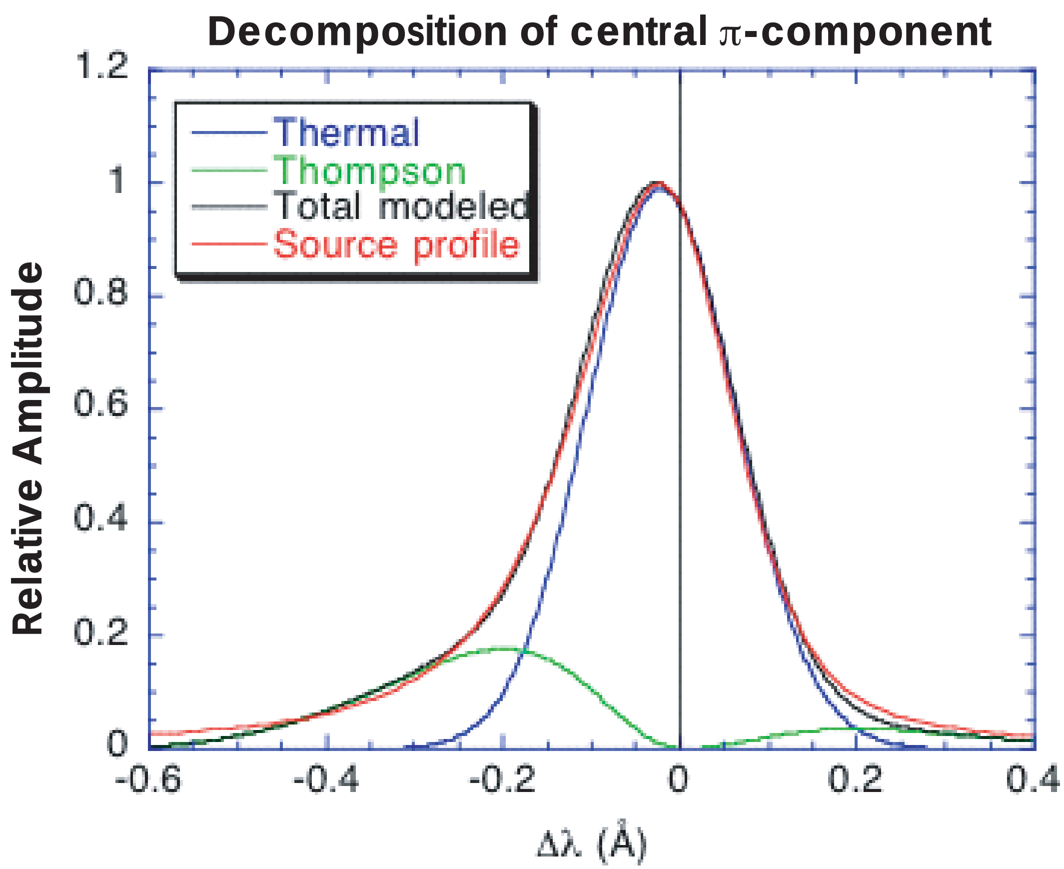
Upstream of DiMES, chemical sputtering makes dominant contribution to atomic C flux at OSP

- T_i of Gaussian taken from C I profile through CH_4 puff, instead of being left as independent fit parameter
- Shoulder on Thompson profile due to indirectly observed light; its contribution is mirrored about λ_o of each Zeeman component
- Best fit obtained with effective tile reflectivity of 15% and incident ion energy of 150 eV



Least squares fitting of the deconvoluted C I source profile

- **Best fit obtained with T_{Dop} = 0.9 eV, E_{impact} = 150 eV, R_{eff} = 20%**
  - 80% of C flux due to chemical sputtering, based on integrated areas under Thermal and Thompson profiles



Summary of initial findings from porous plug experiment

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