Recent Results on Carbon Erosion, Migration and Re-deposition in DIII-D Tokamak using DiMES

D. Rudakov, J. Boedo, E. Hollmann, R. Moyer, A. Pigarov ***University of California, San Diego***

W. Jacob, K. Krieger ***Max-Planck-Institut fuer Plasmaphysik***

A. Litnovsky, V. Philipps, P. Wienhold ***Forschungszentrum Jülich***

W. West, C. Wong, N. Brooks ***General Atomics***

A. McLean, P. Stangeby ***University of Toronto***

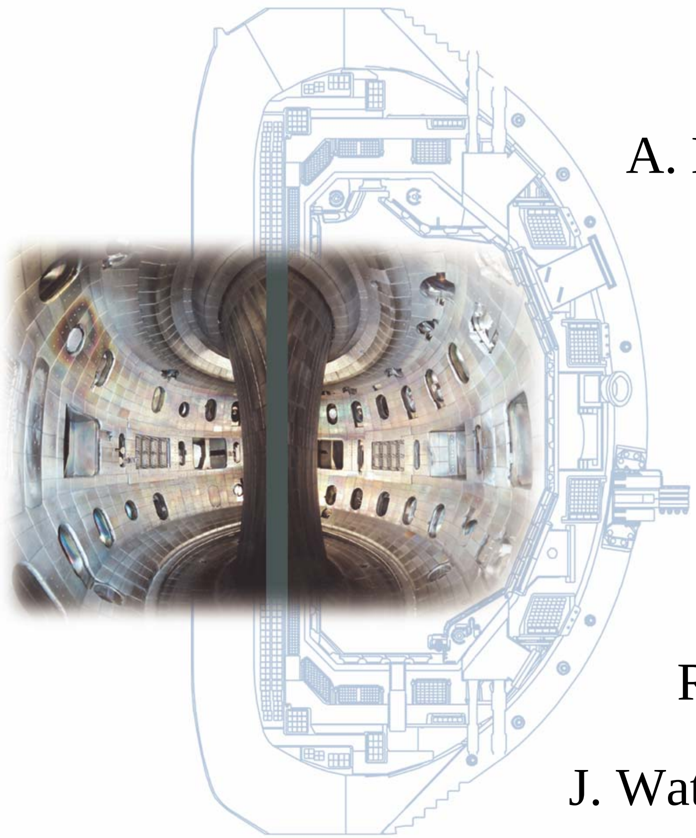
W. Solomon ***Princeton Plasma Physics Laboratory***

G. De Temmerman ***Institute of Physics, University of Basel***

R. Bastasz , J. Whaley ***Sandia National Laboratories, Livermore***

J. Watkins, W. Wampler ***Sandia National Laboratories, Albuquerque***

S. Allen, M. Fenstermacher, M. Groth, C. Lasnier ***Lawrence Livermore National Laboratory***



DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

Presented at the PFMC-11 Workshop
October 10-12, 2006, Greifswald, Germany

Summary

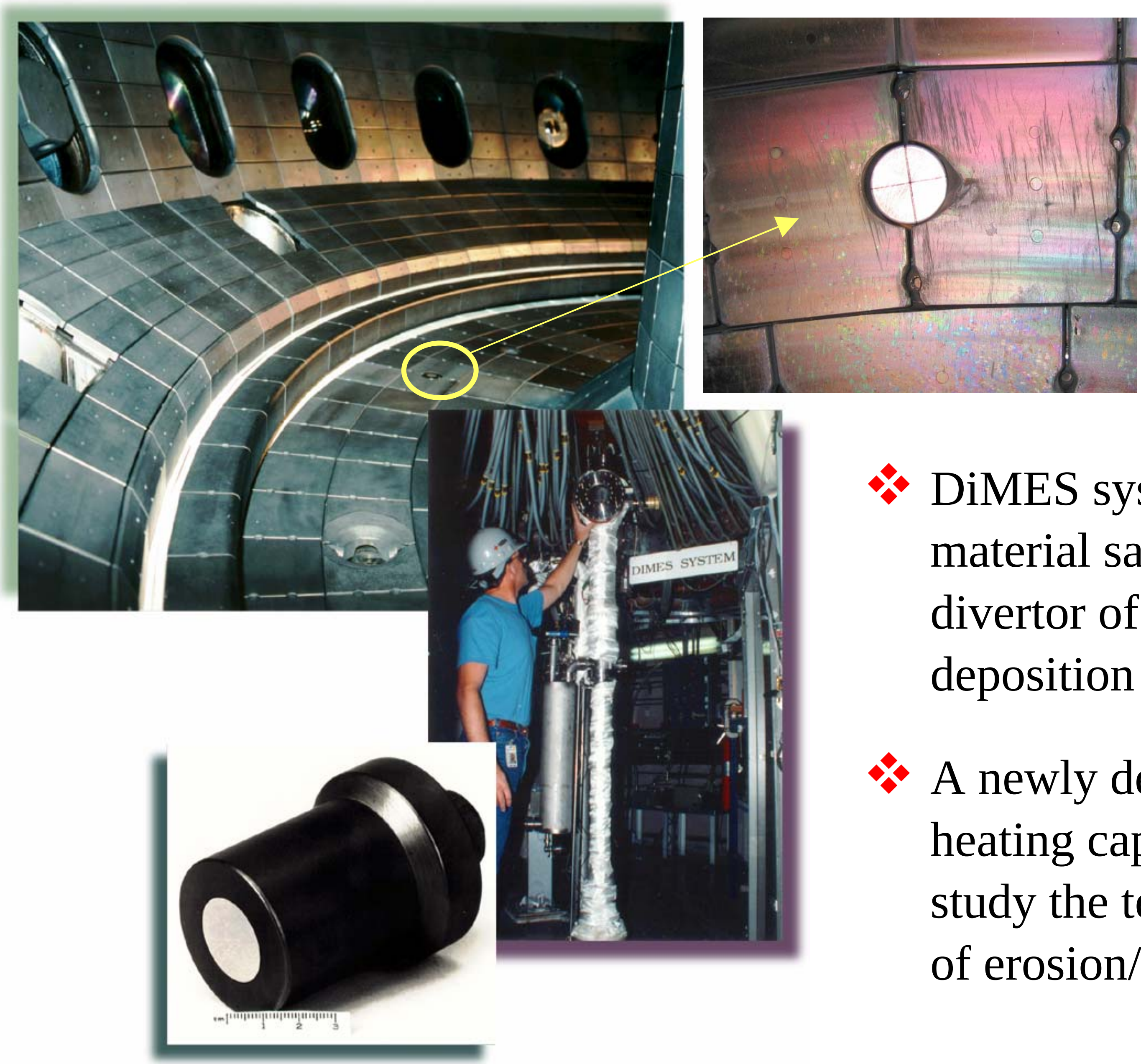
Part I: Temperature dependence of carbon erosion and re-deposition

- At 200° C we observed net carbon erosion at a rate of ~ 3 nm/sec from a plasma-facing surface under detached conditions, where normally net deposition is observed
- At 200° C carbon deposition down a simulated tile gap was reduced by about a factor of 2 - 4 and D co-deposition by an order of magnitude compared to those at room temperature
- Carbon deposition was observed on molybdenum mirrors recessed below the divertor floor at room temperature and was suppressed at elevated temperature between 90-175°C

Part II: Migration of artificially introduced carbon dust in the divertor

- Micron size carbon dust introduced in the lower divertor of DIII-D penetrated core plasma raising the core carbon density by a factor of 2-3
- The amount of C that penetrated the core plasma following the dust injection was equal to 1.5-2 % of the total dust carbon content (equivalent to a few million of dust particles)
- Experimentally observed dust trajectories can be explained by combination of ion drag force, E×B drifts, and reflections from PFC surface corrugations

Divertor Material Evaluation System - DiMES



- DiMES system is used to insert material samples in the lower divertor of DIII-D for erosion and deposition studies
- A newly developed *in situ* sample heating capability allows us to study the temperature dependence of erosion/deposition

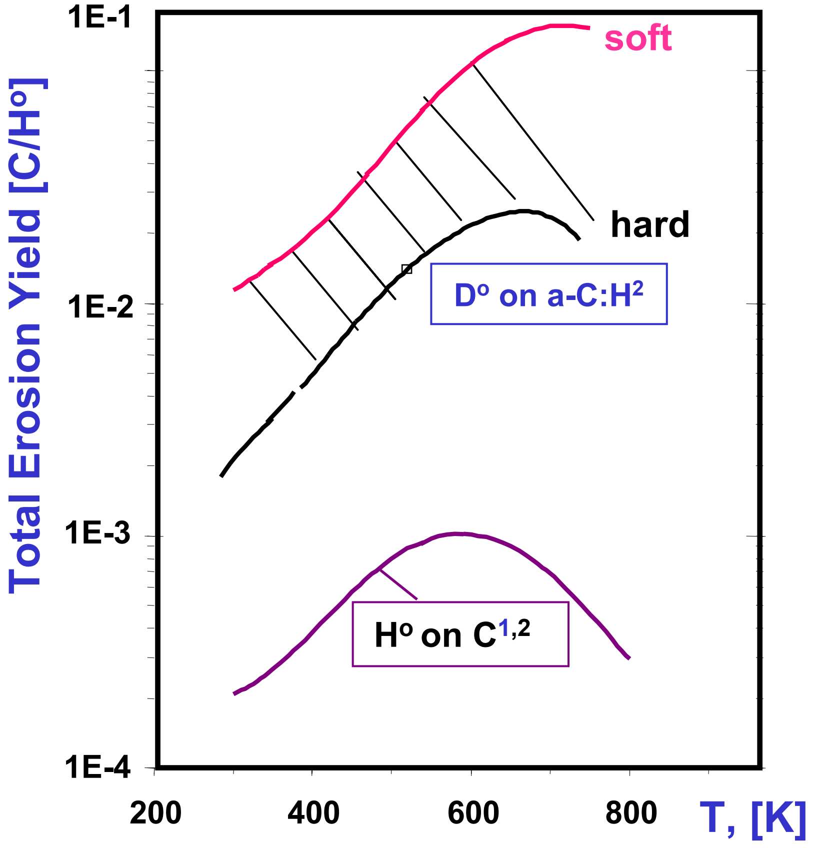
Part I

Temperature dependence of carbon erosion and re-deposition in DIII-D divertor

Motivation:

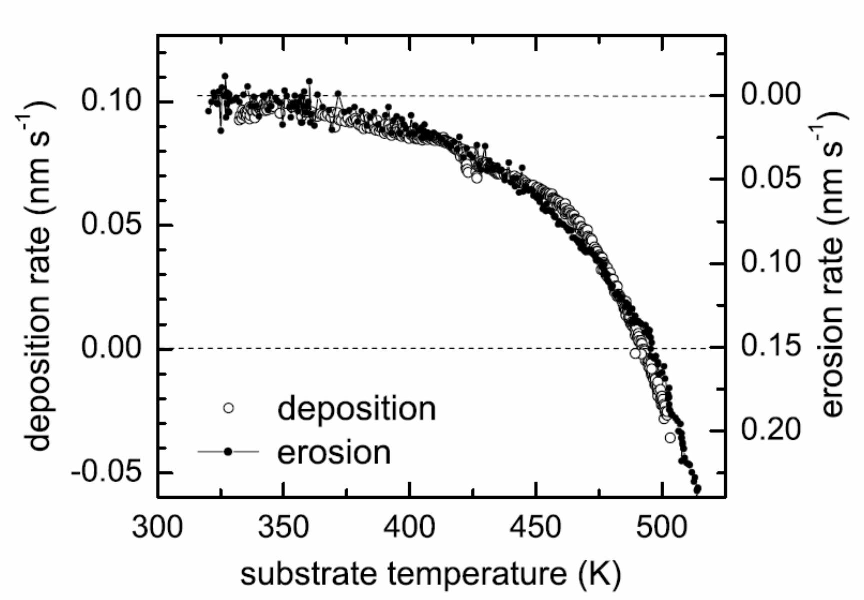
- Chemical erosion rate of carbon and hydrocarbon films by hydrogen/deuterium is known to increases with surface temperature
- Experiments with thermal ion beams have shown that the chemical erosion rate of carbon peaks at about 400°C
- Transition from net erosion to net depositrion was observed in low-temperature methane plasmas between 200-300°C

Erosion by atomic H and D (0.2 eV)



[1]J.W. Davis et al, JNM 155-157(1988), 234

[2]E. Vietzke et al. Fus. Technol. 15 (1989), 108



W. Jacob, J. Nucl. Mater. 337-339, 839 (2005)

Studies of C deposition and D co-deposition in a simulated tile gap - Tile Gap DiMES

Originally proposed by Wolfgang Jacob
Max-Planck-Institut fuer Plasmaphysik, Germany

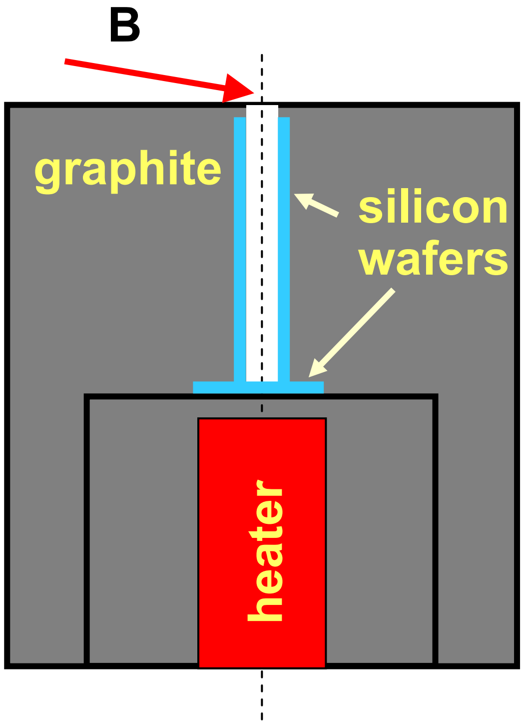
Motivation

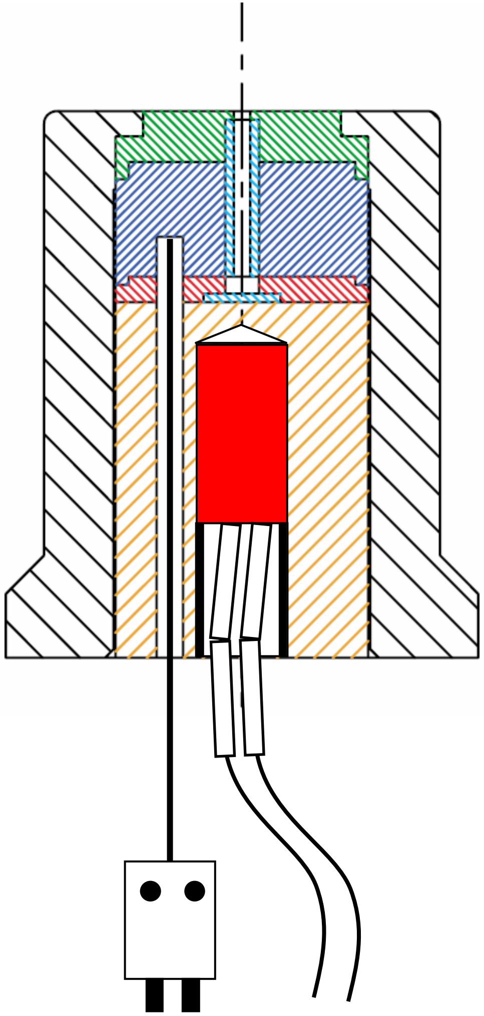
- Tritium co-deposition/retention is one of the most critical issues for ITER
- High-priority ITPA topic
- One of the most troublesome carbon deposition regions for trapping tritium are the narrow tile gaps since such regions are not accessible to many of the proposed T-recovery methods
- In DIII-D co-deposition of deuterium (as a proxy for tritium) can be studied in a simulated tile gap using DiMES
- Altering the tile temperature may affect C deposition and D co-deposition rates

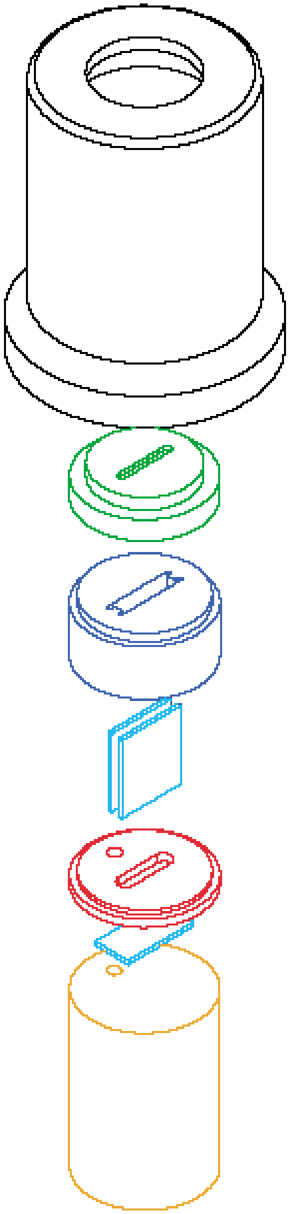
Tile Gap DiMES experimental concept and design

Concept features:

- radially oriented gap
- deposition on the silicon wafers
- defined geometry for modeling of the deposition profile

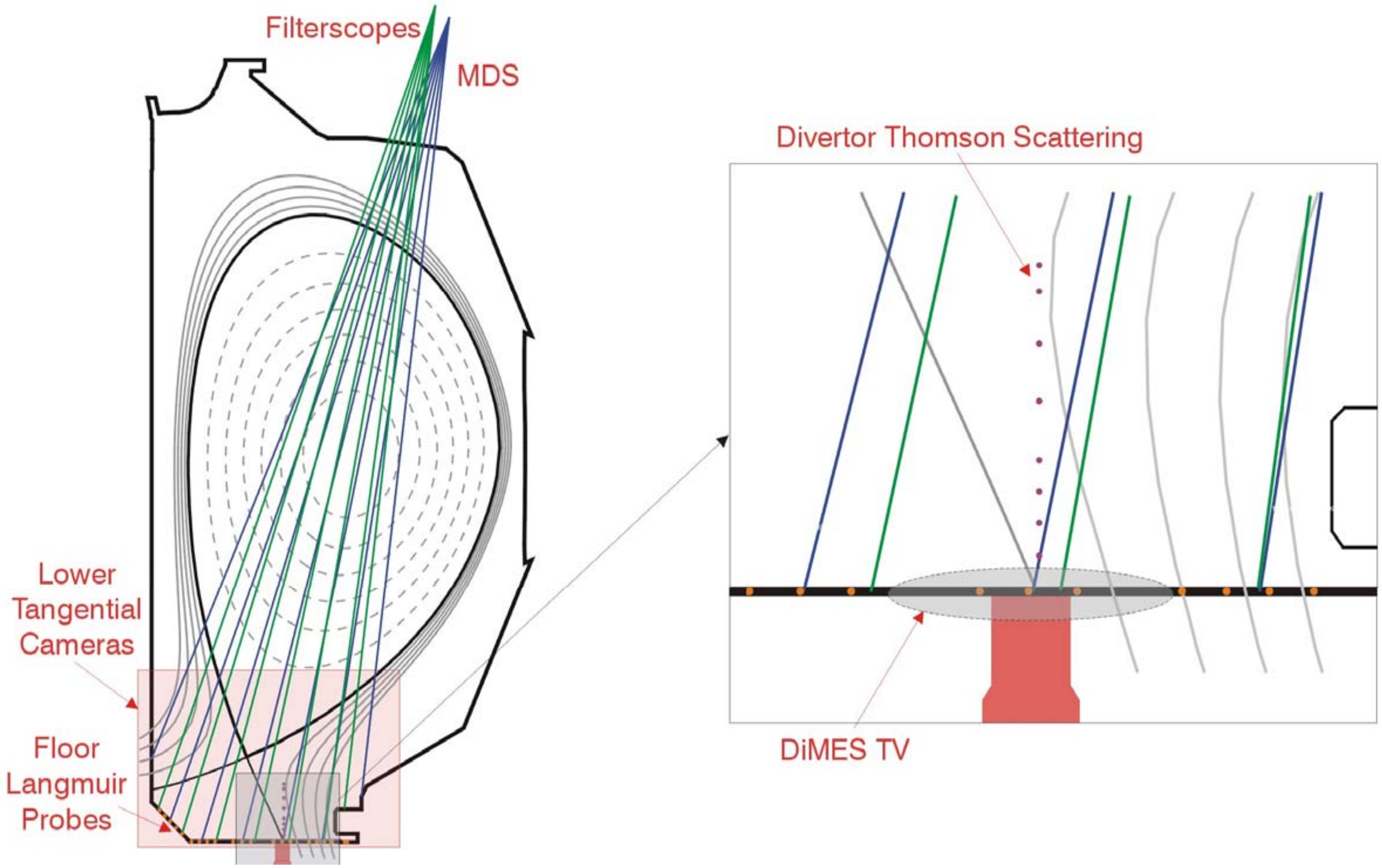






Built in heater and thermocouple for *in situ* temperature control

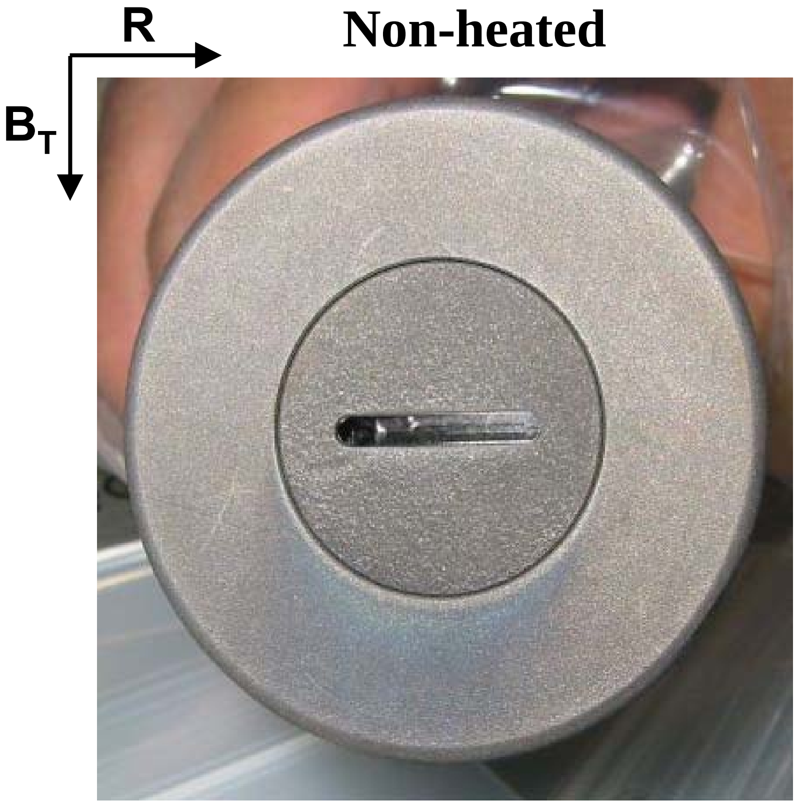
Two exposures at different temperatures were performed



- Lower Single Null Simple-As-Possible Plasma (SAPP) shape
- DiMES located near the detached Outer Strike Point (OSP)
- Two exposures were performed, first at ~ 30º C, second at 200º C
- Each exposure was to 9 highly reproducible high-density L mode discharges for a total exposure time of about 32 seconds

Non-heated versus heated exposures: plasma-facing surface

Non-heated



- There were visible signs of plasma contact on the sample face upon removal, most likely deposits
- No net erosion/deposition measurements were available

Heated

- No visible signs of plasma contact on the sample face upon removal
- A graphite button with implanted Si marker was built into the sample face to measure net erosion/deposition on the plasma-facing surface

A high erosion rate was measured on the heated sample

● IBA locations

IBA data courtesy of Bill Wampler

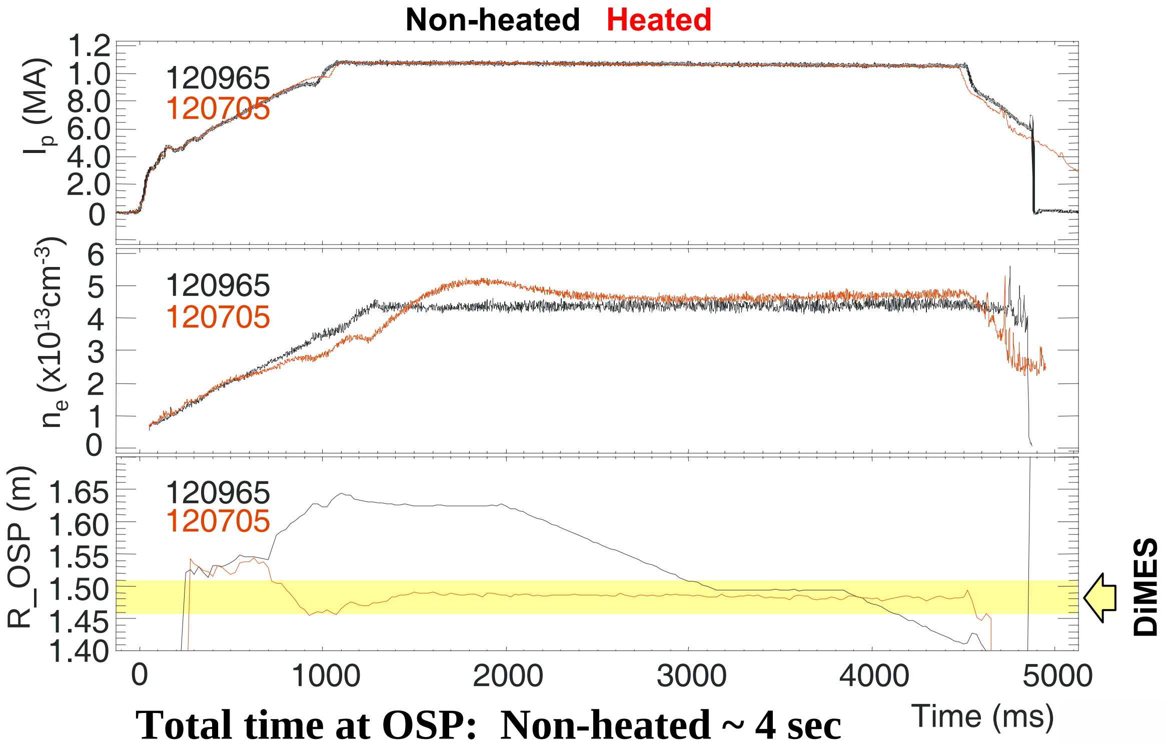
- Ion Beam Analysis (IBA) at SNL Albuquerque has shown a total net erosion of about 90 ± 4 nm on the depth marked button from heated exposure
- This corresponds to a net erosion rate of ~ 3 nm/sec = 1.2 µm / ITER shot = 9 cm / burn year – rather high!
- We did not have erosion/deposition measurements on the non-heated sample, but it looked like there was some net deposition

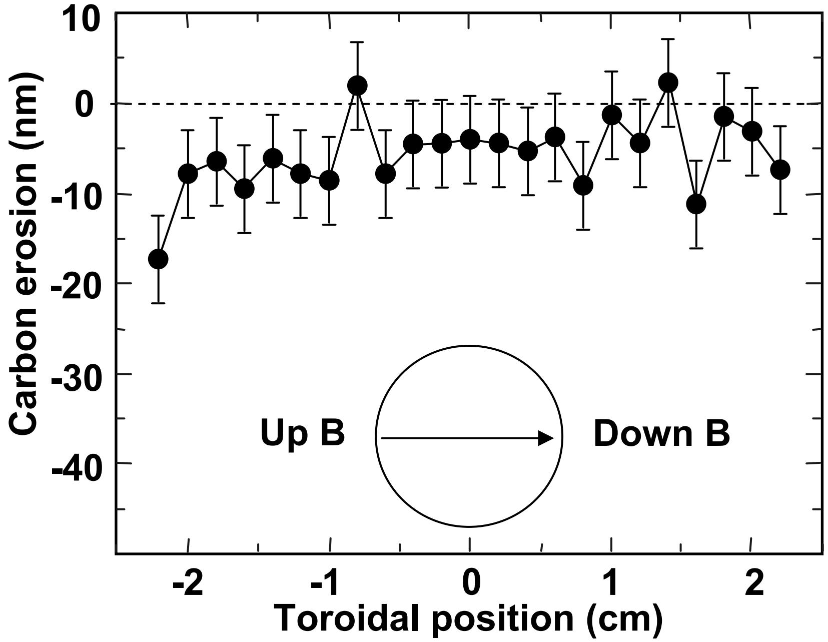
Potentially bad news for ITER:
surface erosion of C is strongly increased at elevated temperature

DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

No net erosion observed with detachment at room temperature

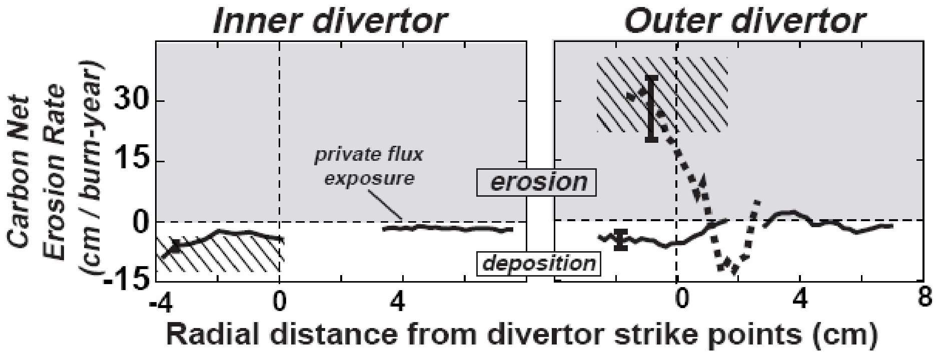
- A depth-marked DiMES sample exposed later to 7 comparable high-density SAPP L-mode discharges (but with OSP sweeps) showed no measurable erosion





Total time at OSP: Non-heated ~ 4 sec

Heated ~ 32 sec

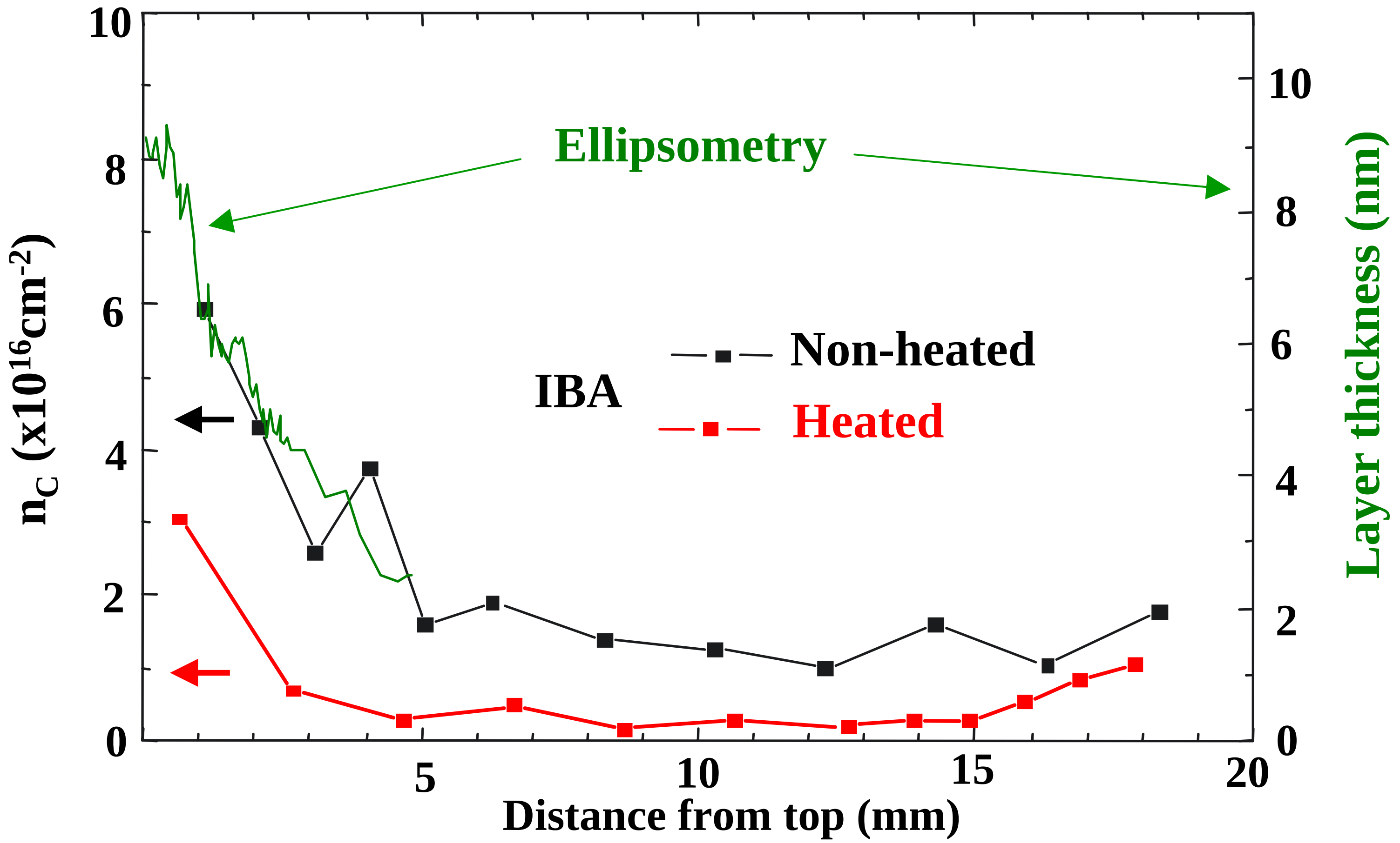


- Previous DiMES experiments in detached H-mode showed net deposition around OSP and in the PF zone

Erosion on heated sample must be due to the elevated temperature

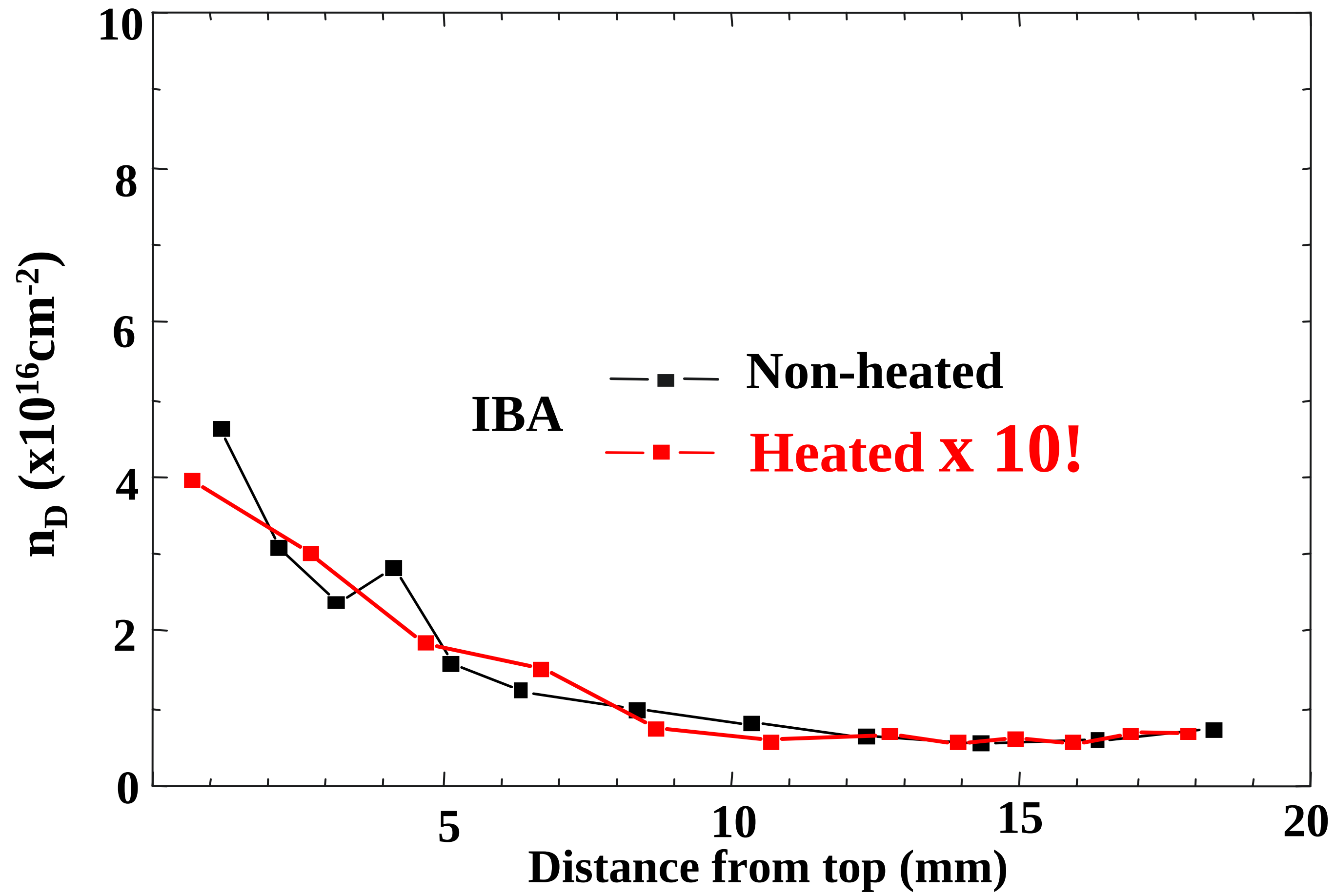
Whyte et al., Nucl. Fusion 41 (2001) 1243

Carbon deposition inside the gap was a factor of 2 - 4 lower in the heated exposure



- C deposition inside the gap was ~ 2 - 4 times lower in the heated exposure
- The deposit thickness profiles from ellipsometry are in good agreement with the carbon areal density from IBA
- Ellipsometry failed to resolve the deposit thickness in the heated exposure
- Some C may have been absorbed into the wafers to form silicon carbide

D co-deposition inside the gap was an order of magnitude lower in the heated exposure



- **Potentially good news for ITER: by controlling the PFC temperature it may be possible to control WHERE the T co-deposition would occur**
- However, increased carbon impurity production at high temperature may offset the advantage of higher re-erosion rates in the gaps

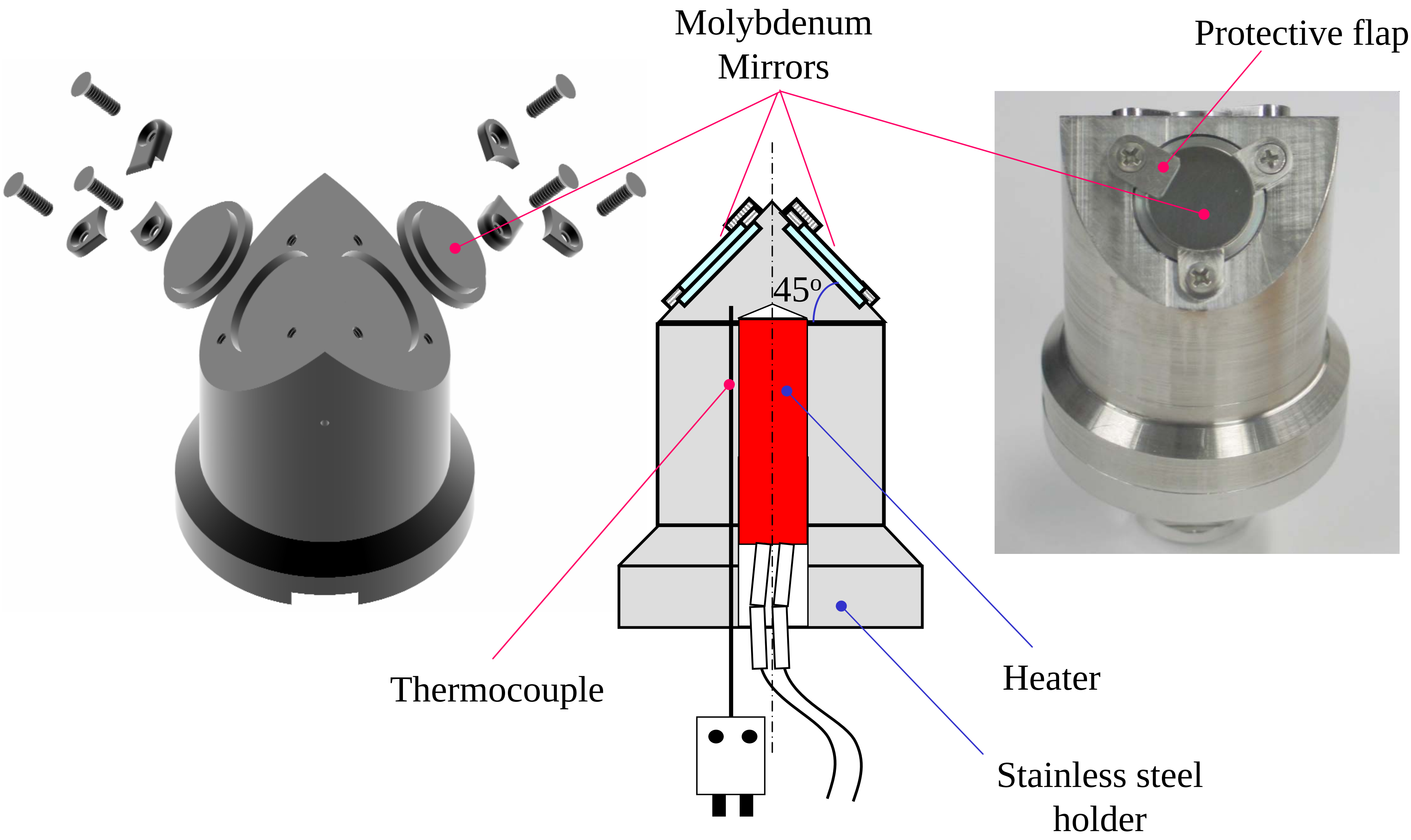
Tests of ITER-relevant diagnostic mirrors in a tokamak divertor - Mirror DiMES

Originally proposed by Andrey Litnovsky
Forschungszentrum Jülich, Germany

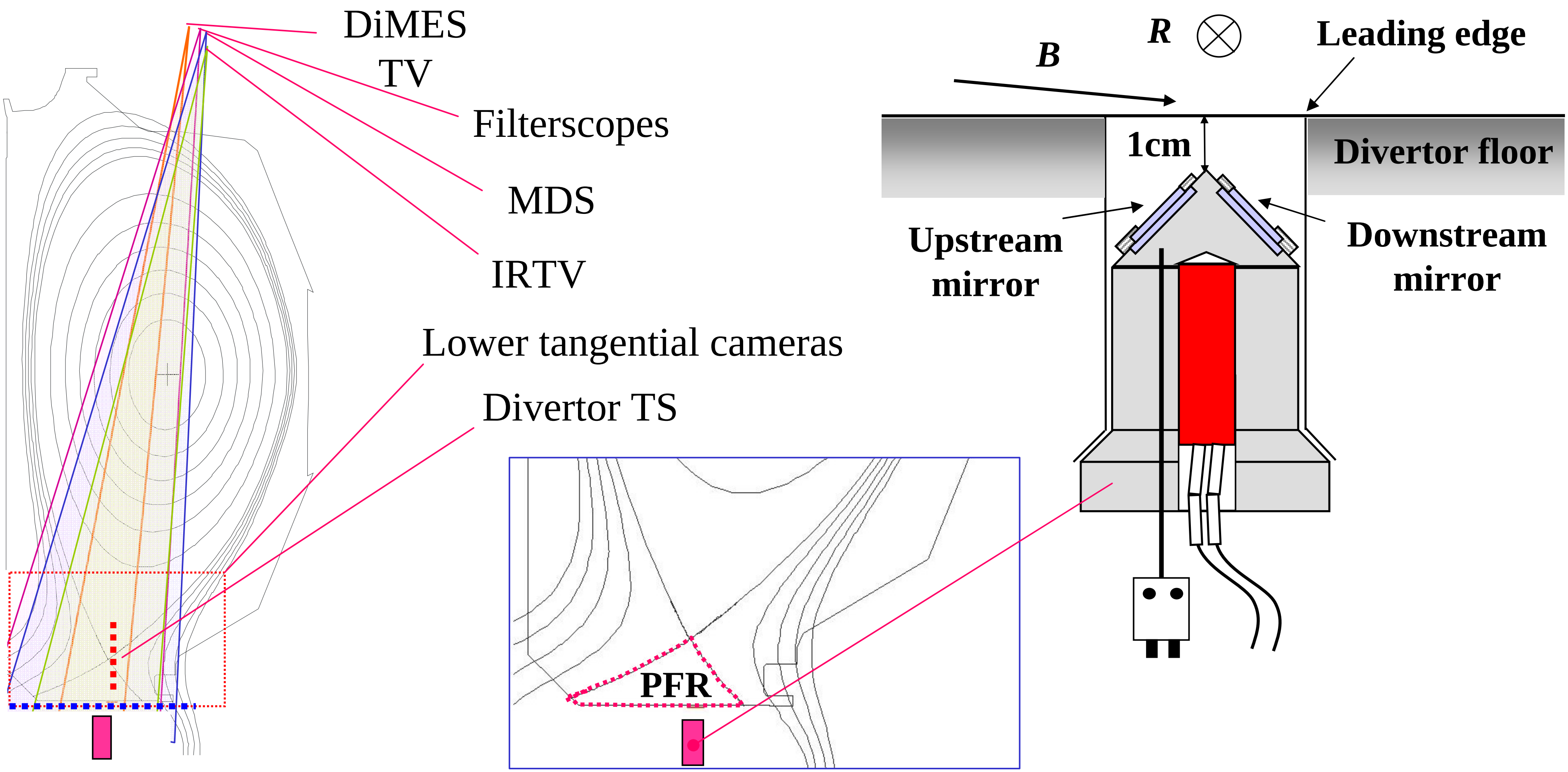
Motivation

- Optical mirrors are foreseen in ITER for many diagnostics, and will be used in infrared, visible and ultraviolet wavelength ranges
- High-priority ITPA topic
- Mirrors in the ITER divertor will likely suffer from deposition, and dedicated experiments in tokamak divertors are urgently needed
- Using DiMES, we had a chance to perform first ever tests of ITER-relevant mirrors in a tokamak divertor under well-diagnosed plasma conditions

Mirror DiMES experimental concept and design



Mirror DiMES exposure geometry



DiMES TV

Filterscopes

MDS

IRTV

Lower tangential cameras

Divertor TS

PFR

B

R ⊗

Leading edge

1cm

Divertor floor

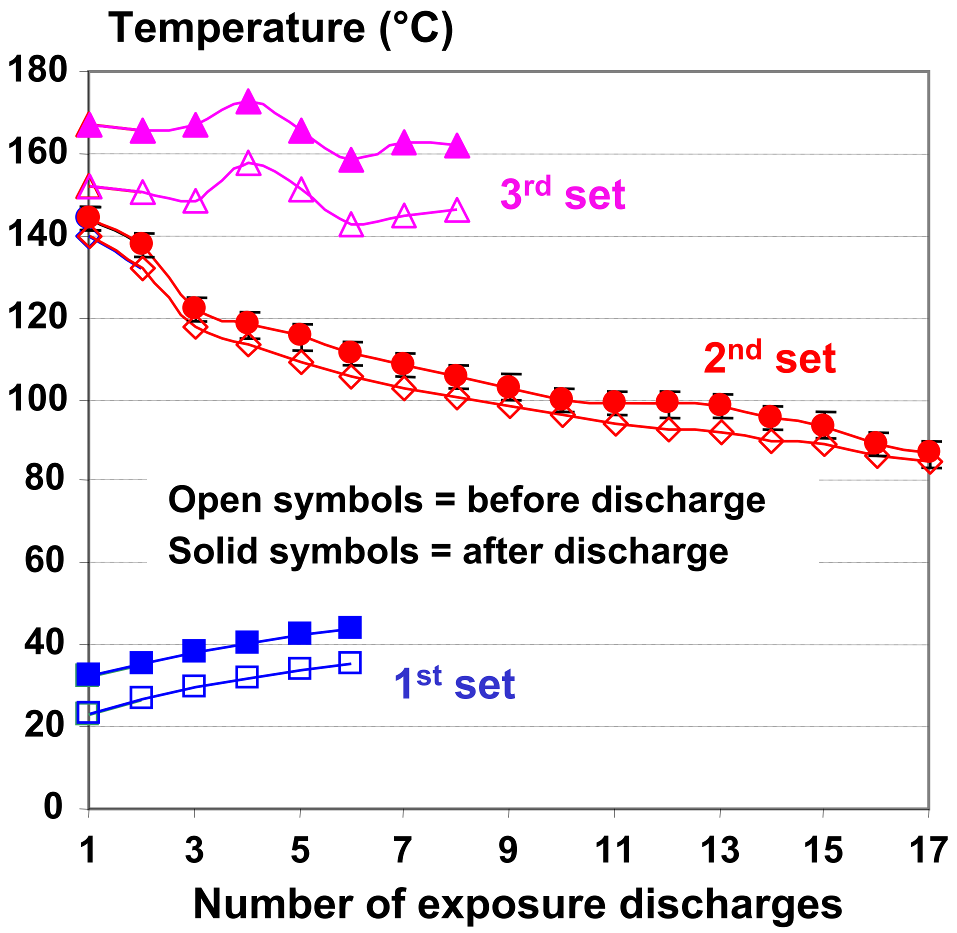
Upstream mirror

Downstream mirror

- Lower Single Null SAPP-like shape
- DiMES located at the Private Flux Region
- Highly reproducible ELMing H-mode discharges with detached outer strike point

Three exposures at different temperatures

- 1st set of mirrors was exposed at ambient temperature for a total of ~ 25 s
- Visible deposits were found on both mirrors and holder upon removal
- 2nd mirror set was exposed for a total of ~70 sec at elevated temperature changing from 140° C to 90° C (planned exposure at 400° C but heater failed)
- Upon removal, practically no deposits were visible on the mirrors
- Recently 3rd mirror set was exposed at ~150 ° C for a total of ~36 sec.
- No visible deposits were found on the mirrors



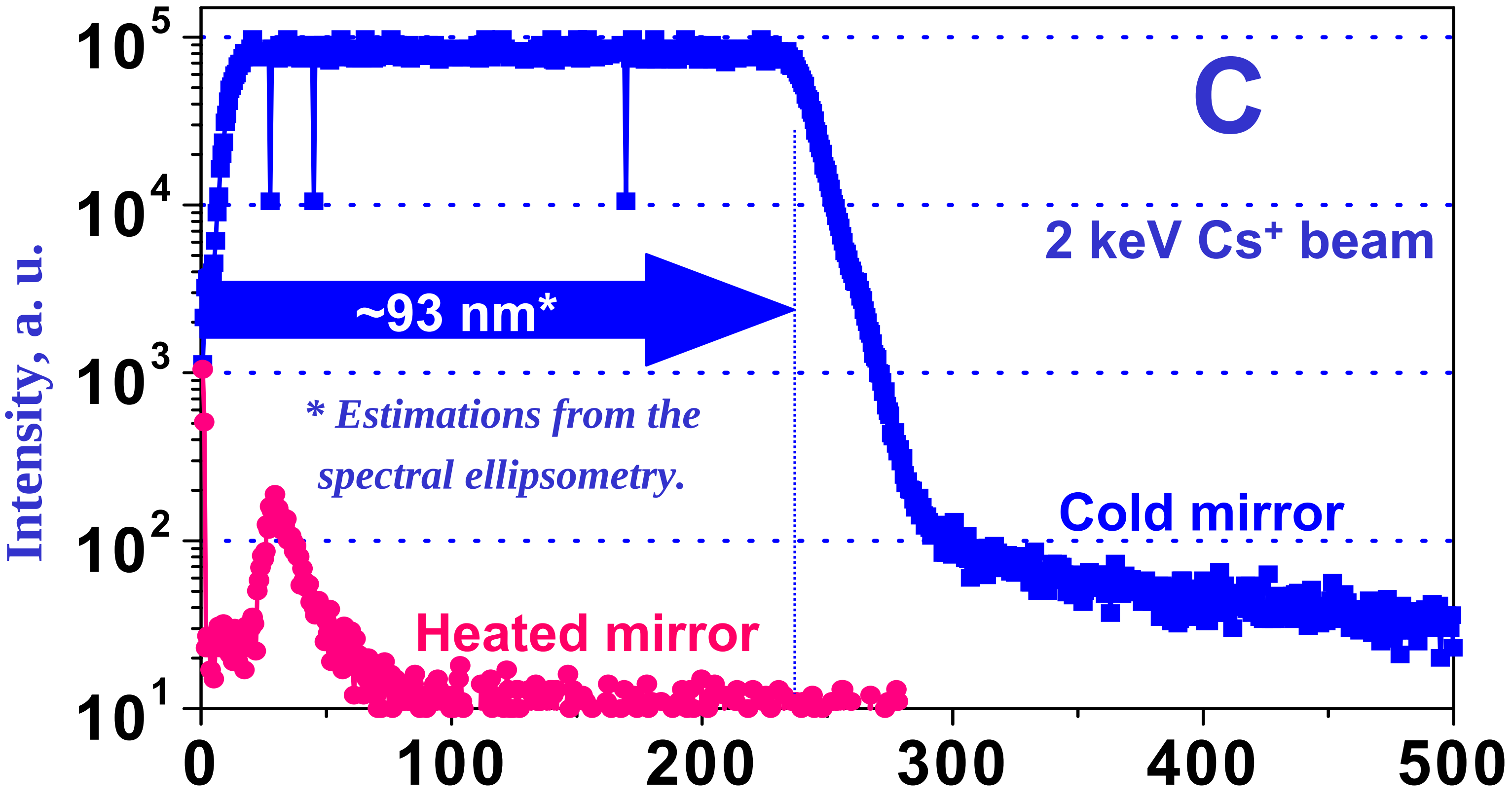
Note: in 1st and 2nd exposures the thermocouple measured the bulk temperature of the holder.

In the 3rd exposure thermocouple measured temperature at the back of a mirror

Deposition is suppressed at elevated temperature

● Secondary Ion Mass Spectrometry
● (SIMS) measurements locations

SIMS shows significant C deposition on the cold mirror and virtually no deposits on the heated mirror



Sputter time, s (measure of film thickness)

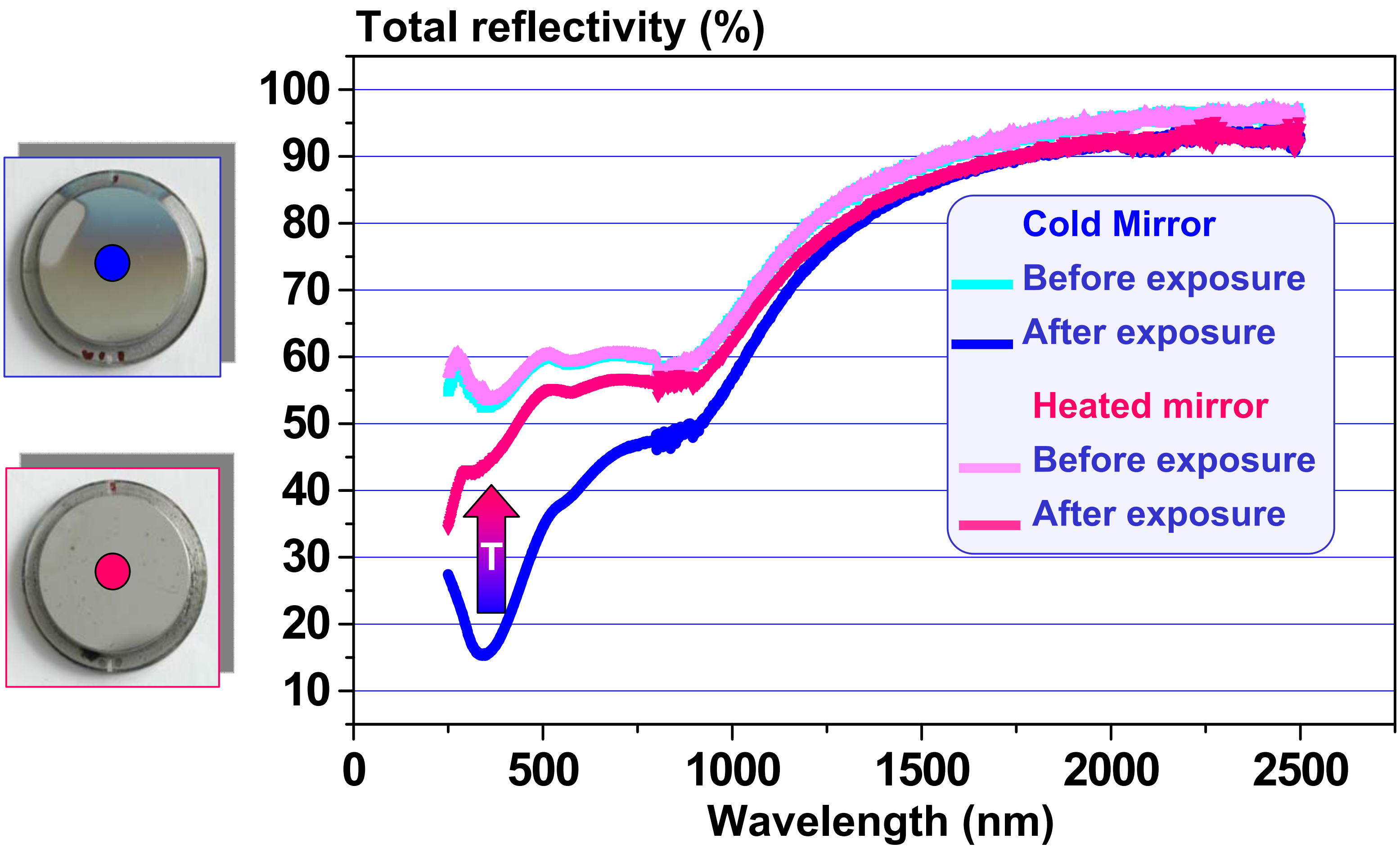
Deposition rate of ~ 4 nm/sec at room temperature

Negligible deposition at elevated temperature

Potentially very good news for ITER:

it may be possible to mitigate carbon deposition by moderate heating of diagnostic mirrors

Elevated temperature mitigates the reflectivity drop



Measurements made on **downstream** mirrors are shown

Note that heated exposure was almost 3 times longer

- Elevated temperature mitigates the reflectivity drop
- The reflectivity of the heated mirrors was essentially preserved in the wavelength range above 500 nm
- Between 250-500 nm the reflectivity of the heated mirror was slightly degraded due to a thin (<15 nm) oxide film formed on the mirrors, presumably from long term storage in air

Part I Summary

- At 200º C we observed net carbon erosion at a rate of ~ 3 nm/sec from a plasma-facing surface under detached conditions, where normally net deposition is observed

- At 200º C carbon deposition down a simulated tile gap was reduced by about a factor of 2 - 4 and D co-deposition by an order of magnitude compared to those at room temperature

- Carbon deposition was observed on molybdenum mirrors recessed below the divertor floor at room temperature and was suppressed at elevated temperature between 90 - 175º C

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Part II

Migration of artificially introduced carbon dust in the DIII-D divertor

Motivation

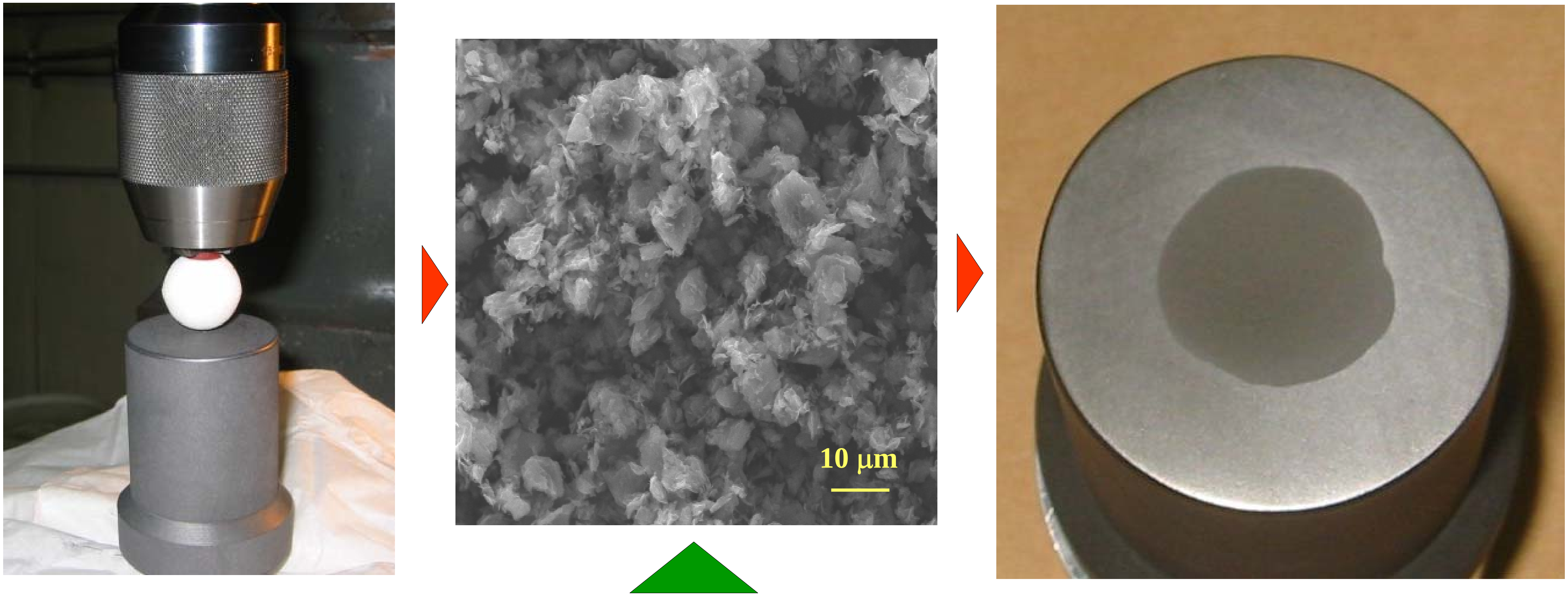
- Micron size dust is commonly found in tokamaks
- Dust can be a serious problem for ITER for a number of reasons:
  - Tritium retention and co-deposition with Carbon dust
  - Accumulation of toxic and radioactive materials
  - Be dust in the divertor may cause hydrogen explosion hazard
  - Dust can cause core contamination and degrade performance
- In DIII-D dust is commonly found during vents in ports, between tiles etc. Possible sources include:
  - ✓ Flakes from deposited a-C:D films
  - ✓ Blistering
  - ✓ Leading edges
  - ✓ Monopolar arcs
  - ✓ Thermal Stress Induced Fracture
  - ✓ Particles left over from entry vent
  - ✓ Degradation of grafoil under tiles
  - ✓ Volume condensation

Dust can be a source of core impurities

- Recent analytic work [S. Krasheninnikov et al, Phys. Plasmas **11** (2004) 3141, Plasma Phys. Control. Fusion **47** (2005) A339] and modeling [A. Yu. Pigarov et al., Phys. Plasmas **12** (2005) 122508] show that in a tokamak edge plasma dust particles can move with high speed and traverse distances comparable to tokamak radii
- Due to acceleration by plasma flows (ion drag) and reflections prom PFC surfaces micron size dust particles can acquire velocities of 10-100 m/s
- Transport of dust particles can be an important mechanism of core plasma contamination by impurities
- Estimates from Thomson scattering (TS) data show that in DIII-D under normal operation dust is not a significant contributor to core contamination [W.P. West et al., presented at PSI-17 (2006), submitted to J. Nucl. Matter.]
- Naturally occurring dusts in DIII-D are hard to diagnose – typically 1-2 or less events per shot both from TS and TV cameras
- Size is not resolved by TS for particles larger than 0.25 microns in diameter
- We decided to artificially introduce pre-characterized micron-size carbon dust in DIII-D divertort to see whether any of the dust would make it into the core plasma

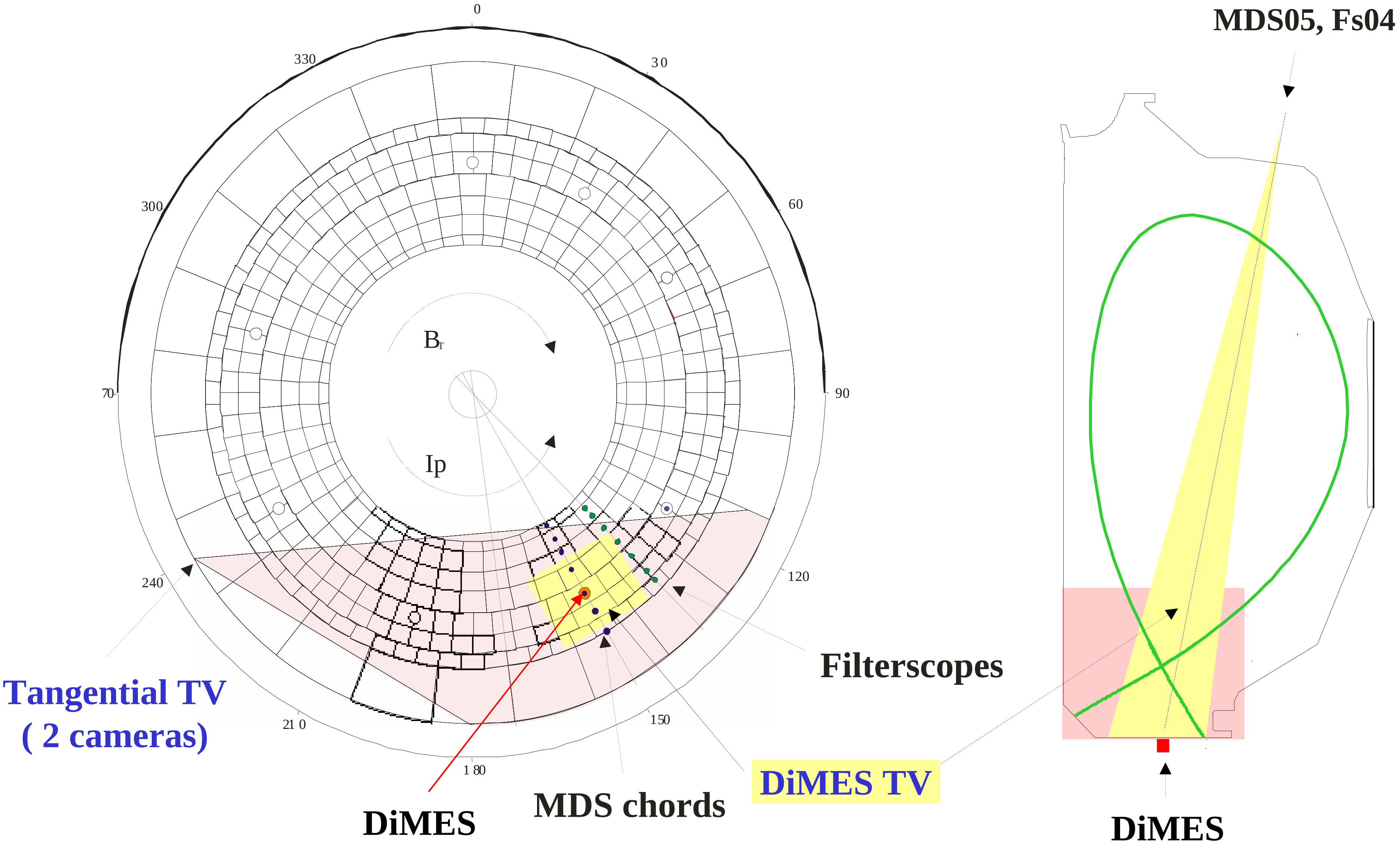
Dust DiMES experiments

- Three individual experiments were performed
- About 1 mg of dust was used in the first experiment, not enough to cause any effect
- 25-30 mg of dust was used in second and third experiments
- A suspension of dust in alcohol was prepared and applied to a shallow dip in the holder
- Upon drying the dust formed a rather uniform layer clinging to the holder



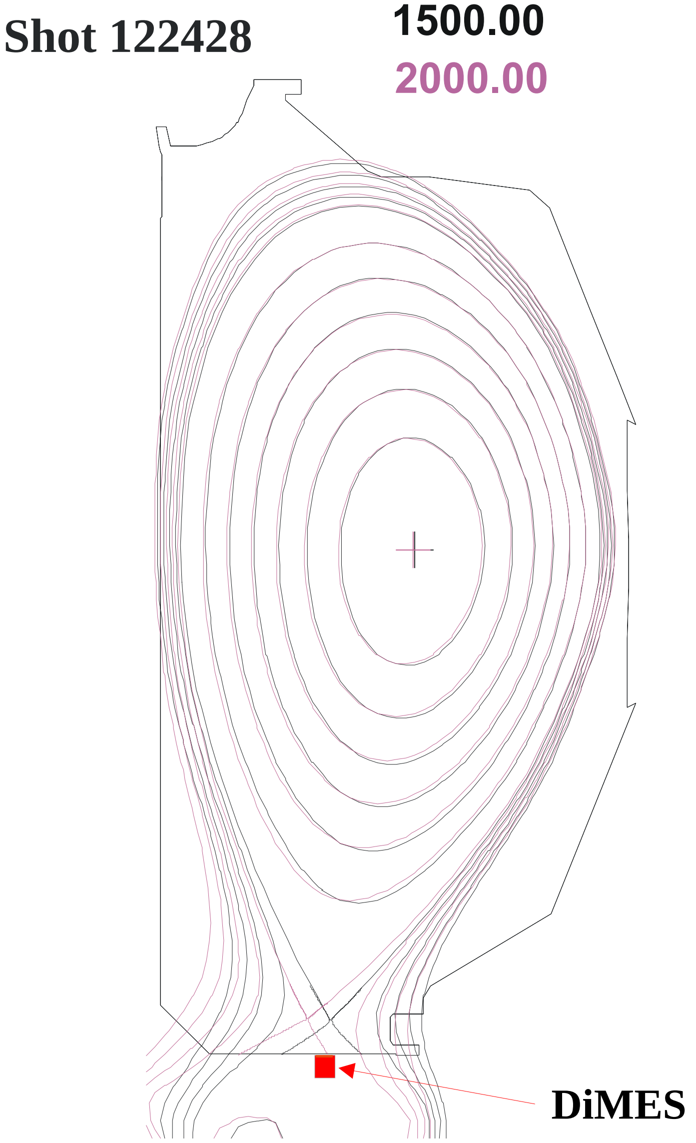
- Carbon dust supplied by Toyo Tanso Company, Ltd., Japan
- 0.5–10 μm diameter flakes, ~6 μm median diameter from volume count
- ~10^{13} C atoms per median size dust particle

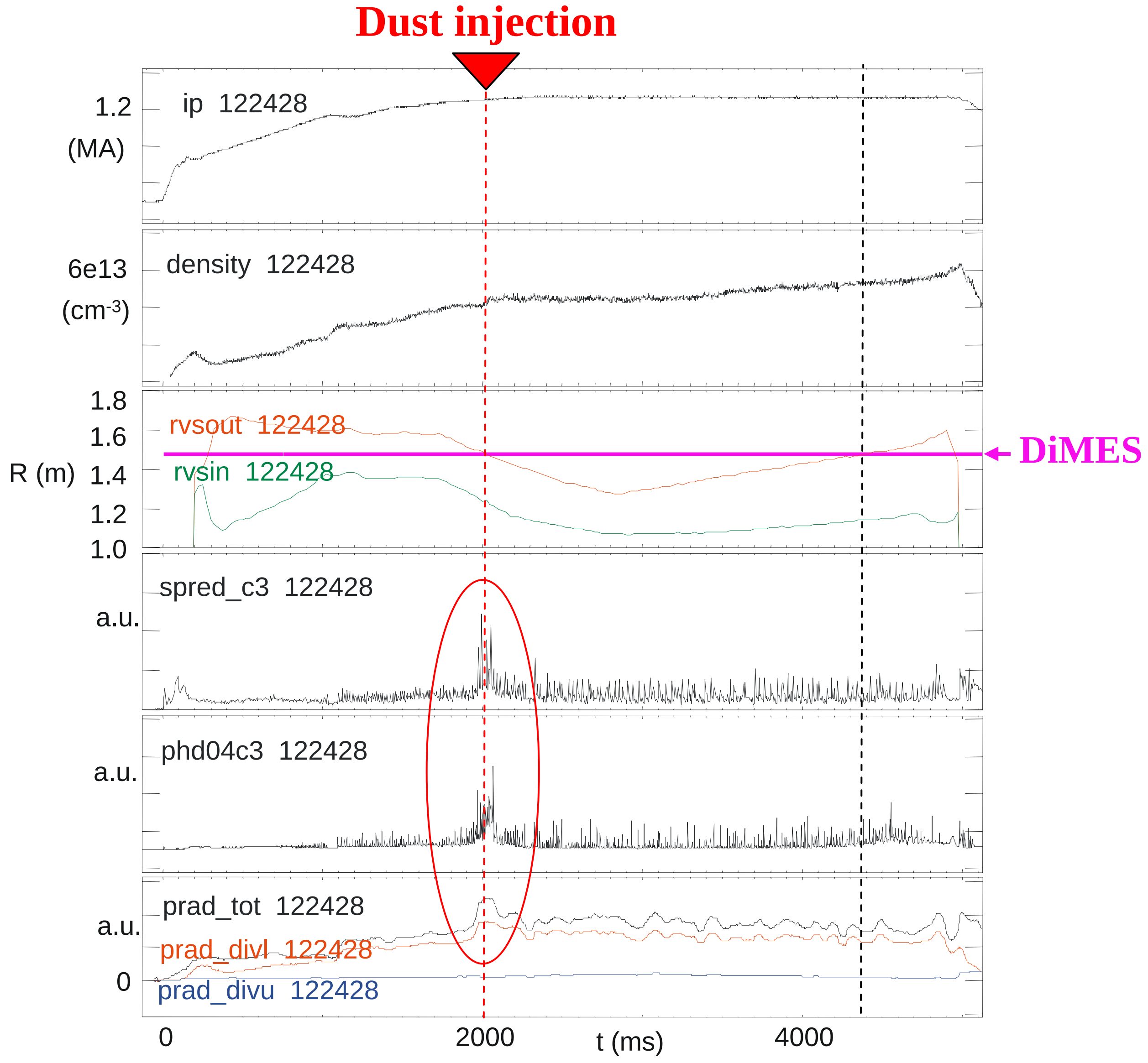
Diagnostic setup for the dust DiMES experiments



- DiMES TV and one of tangential TVs equipped with Kodak Wratten 89B IR filters with less than 1% transmission below 680 nm
- The second tangential TV equipped with CIII filter

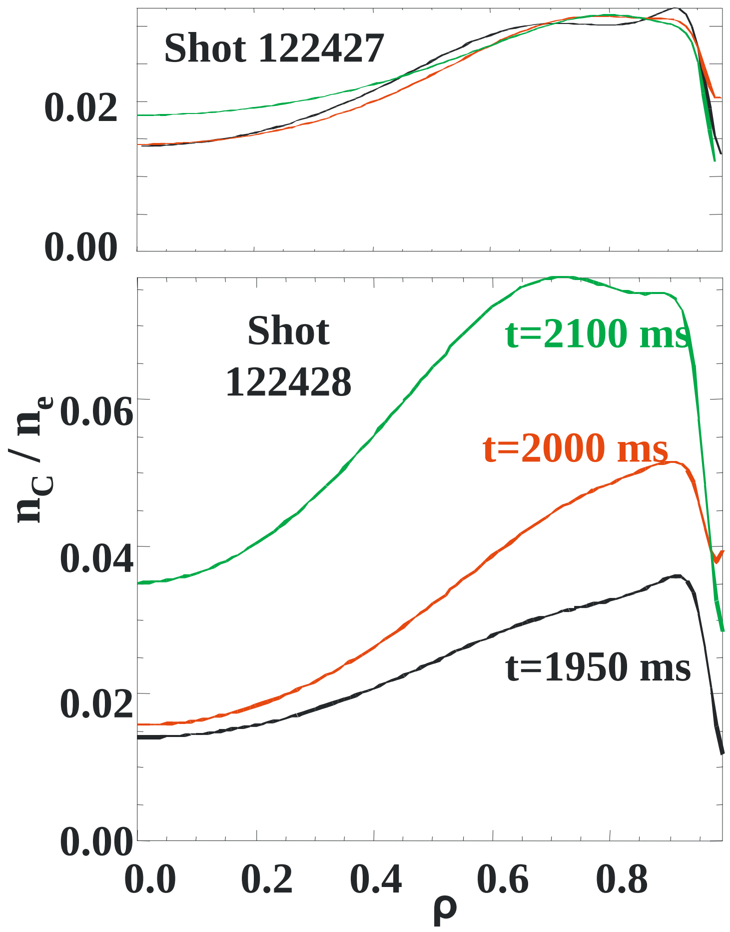
Dust DiMES experiment No.2

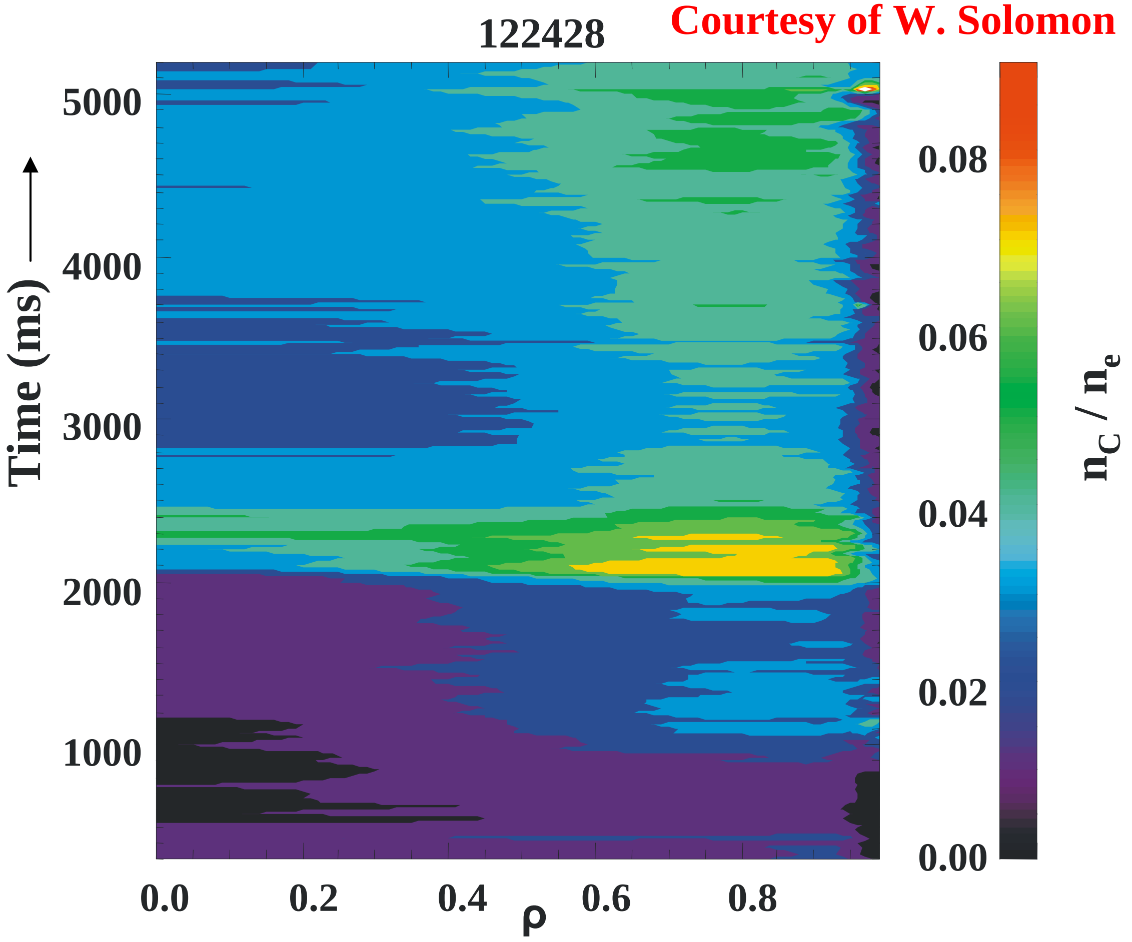




- High-power ELMy H-mode discharge with OSP swept inward and back
- Significant increase in C radiation during the first pass of OSP over DiMES!
- **Cameras observed dust tracks**

CER data show strong increase of core carbon content after OSP passes over DiMES around 2 sec





Courtesy of W. Solomon

Rough estimate of the amount of C that got into the core:

$5\times10^{19}\text{m}^{-3} \times 0.02 \times 20\text{m}^{3} = 2\times10^{19}\text{atoms} = 4\times10^{-4}\text{g} \sim 10^{6}$ dust particles

About 1.5% of the dust carbon made it into the core!

Dust velocities are 10 – 100 m/s

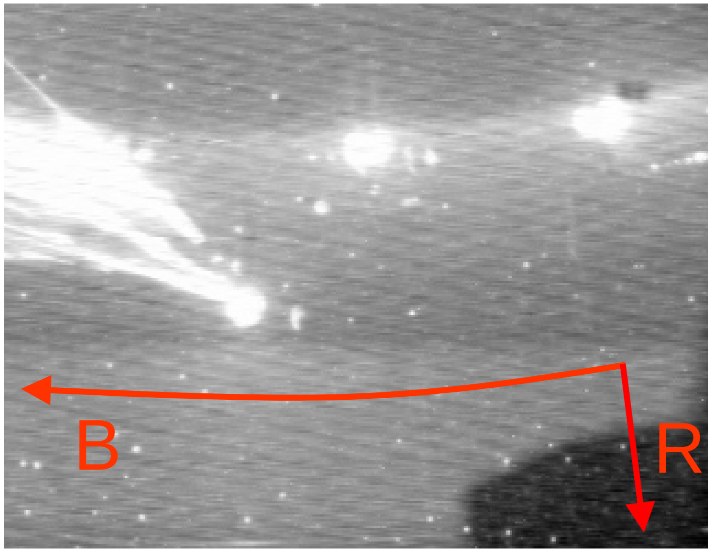
- From DiMES TV we can only make a low-bound estimate since most tracks go off screen

Track length: $l_{track} \sim 20 – 40$ cm

Exposure time: $t_{exp} = 16.7$ ms

$v \sim l_{track} / t_{exp} \sim 10 – 20$ m/s

Frame #146, 2430 ms



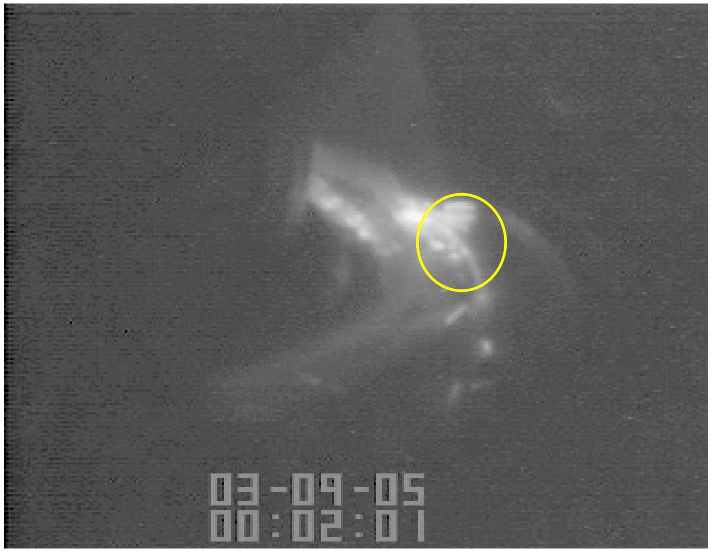
- Tangential camera view is inclined, but we can still make an estimate

Track length: $l_{track} \sim 10$ cm

Exposure time: $t_{exp} = 1$ ms

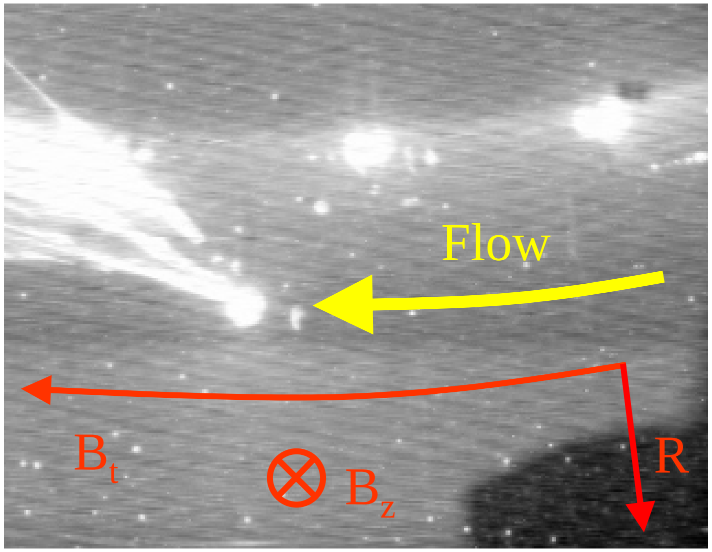
$v \sim l_{track} / t_{exp} \sim 100$ m/s

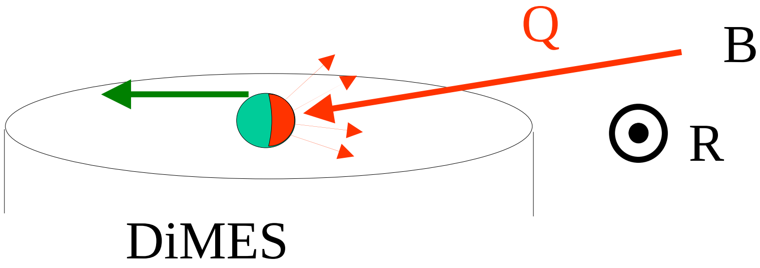
2010 ms



Dust trajectories are consistent with ion drag force

- Toroidal direction is what one would expect – same as that of the plasma flow into the divertor
- Dust particles are accelerated by the plasma flow (ion drag)
- Apparent high field side inclination of trajectories may be either a projection effect or a drift effect
- Another mechanism that may accelerate the dust particles is the “rocket force” from asymmetric ablation due to the plasma heat flux coming preferentially from upstream side



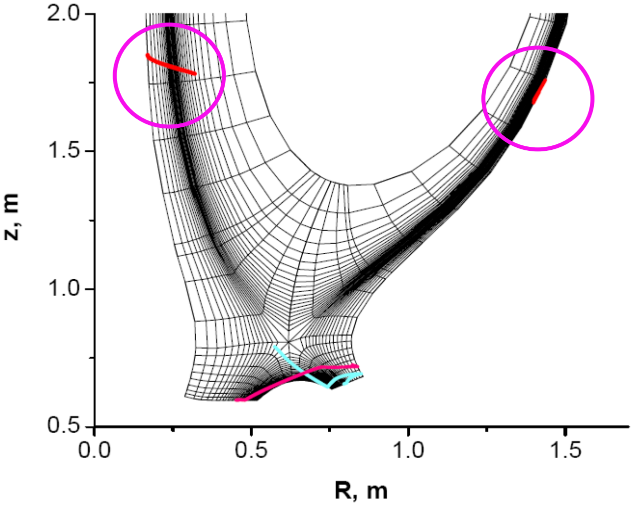


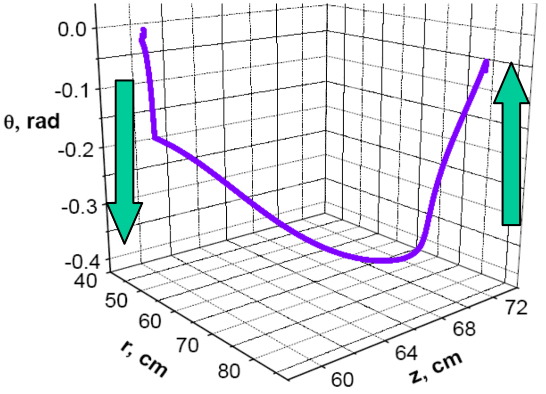
Note: according to DustT modeling rocket force does not play a big role

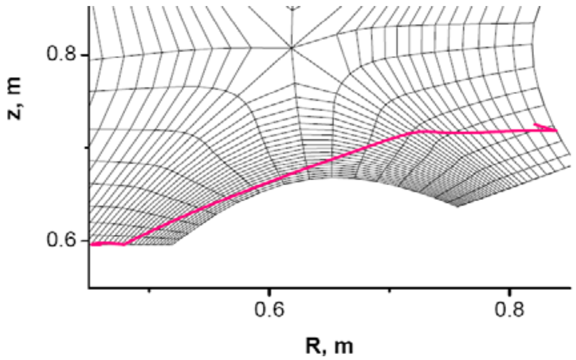
- Both the flow and the rocket force should push dust particles towards the plate
- Particles can bounce from surface corrugations and fly towards the core

S. Krasheninnikov and T. Soboleva, PPCF 47 (2005)

Comparison to modeling: Dust Transport *DustT* code







- *DustT* code solves equations of motion for dust particle in 3D self-consistently with ablation model given by equations for dust temperature and radius
- The code uses magnetic equilibrium mesh and plasma background from UEDGE code
- Based on UEDGE data, the forces acting on dust particle from plasma are calculated
- *DustT* employs Monte Carlo method for incorporating the dust collisions with walls and micro-turbulence
- *DustT* is capable of reproducing important features of tokamak experiments:
    - ✓ Dust particles preferentially move in the direction of plasma flow
    - ✓ Dust trajectories are “elongated” in toroidal direction
    - ✓ The “cruise” velocity of dust in plasma is 10-100 m/s

[A. Yu. Pigarov et al., Phys. Plasmas 12 (2005) 122508]

Part II Summary

- Micron size carbon dust introduced in the lower divertor of DIII-D penetrated core plasma raising the core carbon density by a factor of 2-3
- The amount of C that penetrated the core plasma following the dust injection was equal to 1.5-2 % of the total dust carbon content (equivalent to a few million of dust particles)
- Experimentally observed dust trajectories can be explained by combination of ion drag force, E×B drifts, and reflections from PFC surface corrugations
- 3D modeling of dust dynamics using *DustT* code is capable of reproducing experimentally observed dust velocities and trajectory shapes