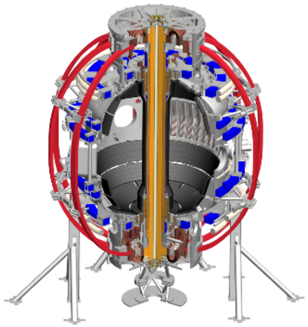
Advances in boronization in NSTX-U

C.H. Skinner, F. Bedoya, F. Scotti, J.P. Allain,
W. Blanchard, D. Cai, M. Jaworski, B.E. Koel

58th Annual Meeting of the APS Division of Plasma Physics
San Jose California
Oct 31 – Nov 4, 2016,



U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

ILLINOIS

PRINCETON
Chemical and Biological Engineering

PPPL

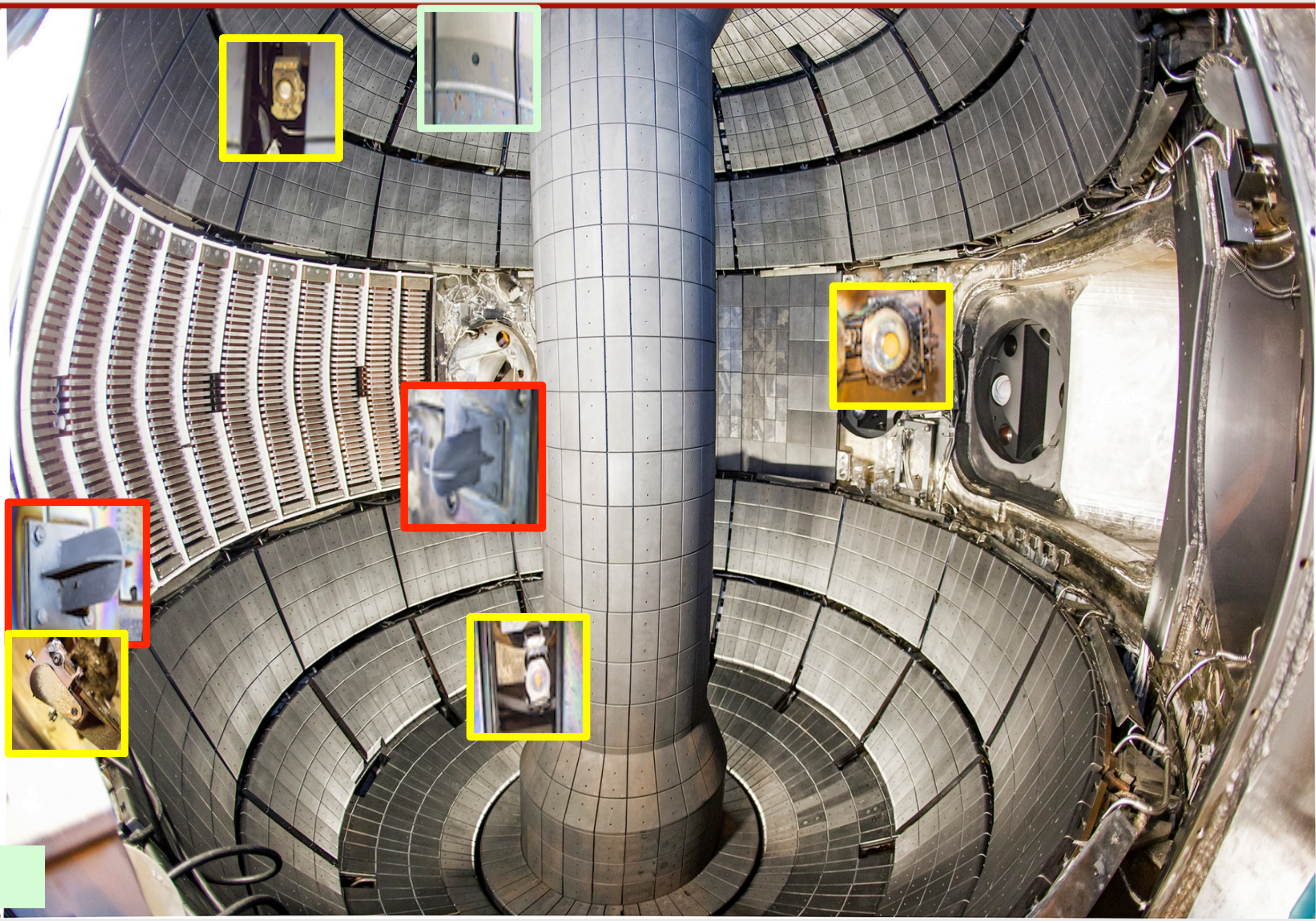
NSTX-U Boronization

- Boronization was main wall conditioning technique in 2016
- Trimethylboron ws dissociated in a helium glow discharge. Forms a hard sputter resistant coating on PFCs.

2 Electrodes: 30°, 180° toroidally

3 Gas inlets:
60° lower, 90° upper, 150° midplane

4 Quartz Microbalances:
30° mid, 120° top, 150° lower 240° mid



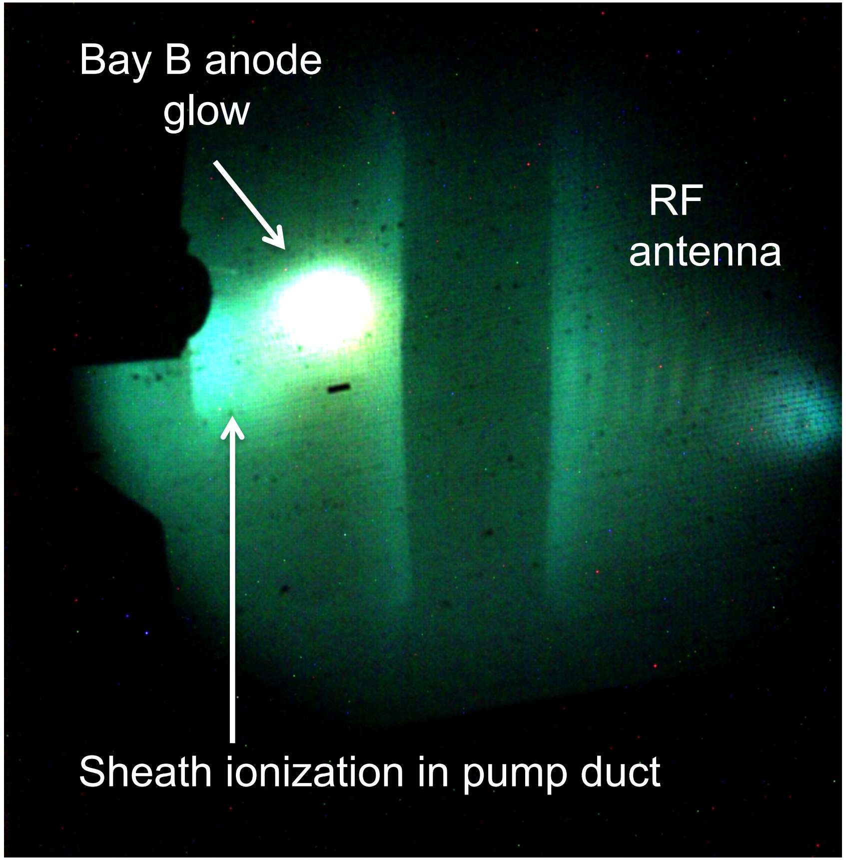
D Cai et al., TOFE proceedings (2016)

NSTX-U Glow Discharge

Glow Discharge Physics:

- A hollow-cathode discharge,
- sustained mainly by ionization by secondary electrons emitted from the vessel wall (cathode),
- accelerated ballistically through a thin cathode sheath, penetrating the plasma as a fast electron beam,
- trapped by the cathode fall surrounding the plasma on all sides.
- The electric field distribution inside the plasma is controlled by low-energy plasma bulk electrons.

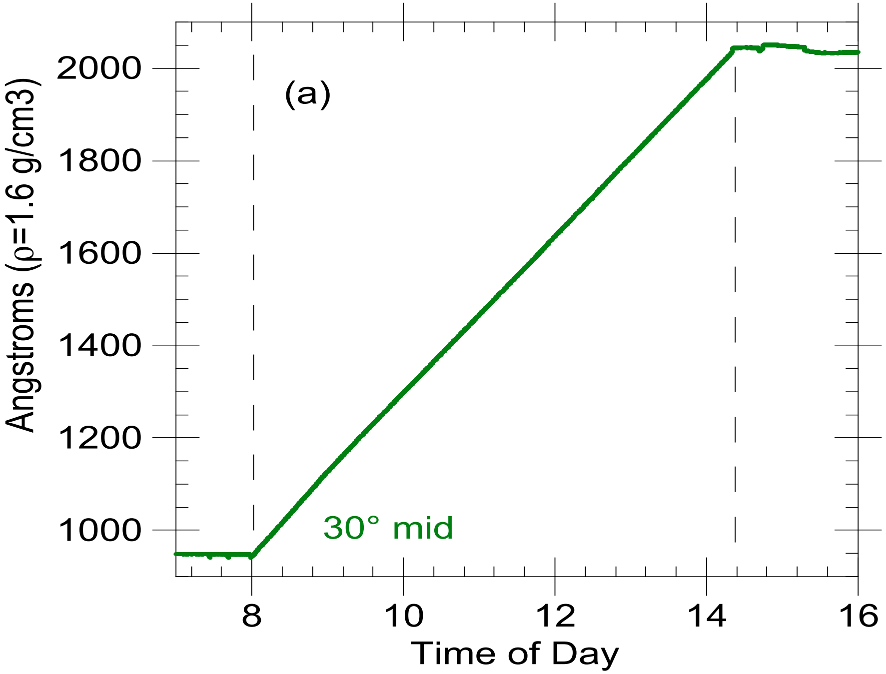
- *The anode has a much lower surface area compared to the cathode (vessel wall)*
  - leads to the formation of an anode glow and an order-of-magnitude higher ion flux near the anode.



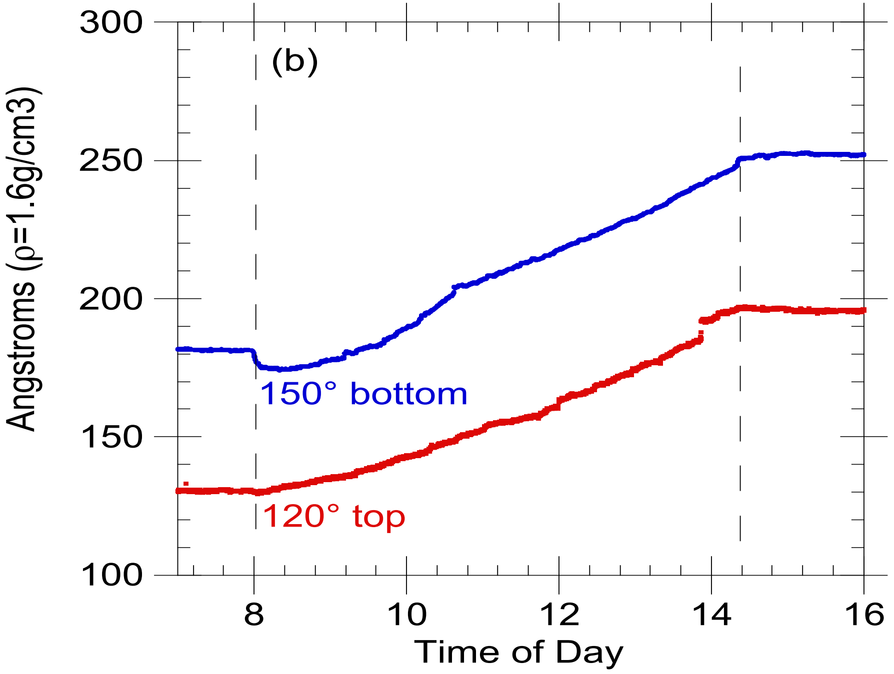
Hagelaar Plasma Phys Contr F **57** (2015) 025008

Most deposition at midplane

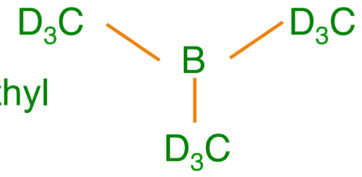
Deposition at midplane during boronization



Deposition at top and bottom



'Full-bottle' procedure: 30 s of He-GDC followed by 6 h of 5% (9 g) dTMB, 95% He GDC
Followed by 2h He-GDC to deplete co-deposited D from tiles.
Bay C lower gas injector used for above data.
Note the difference in Y-axis scales (Å based on ρ=1.6 g cm^{-3})

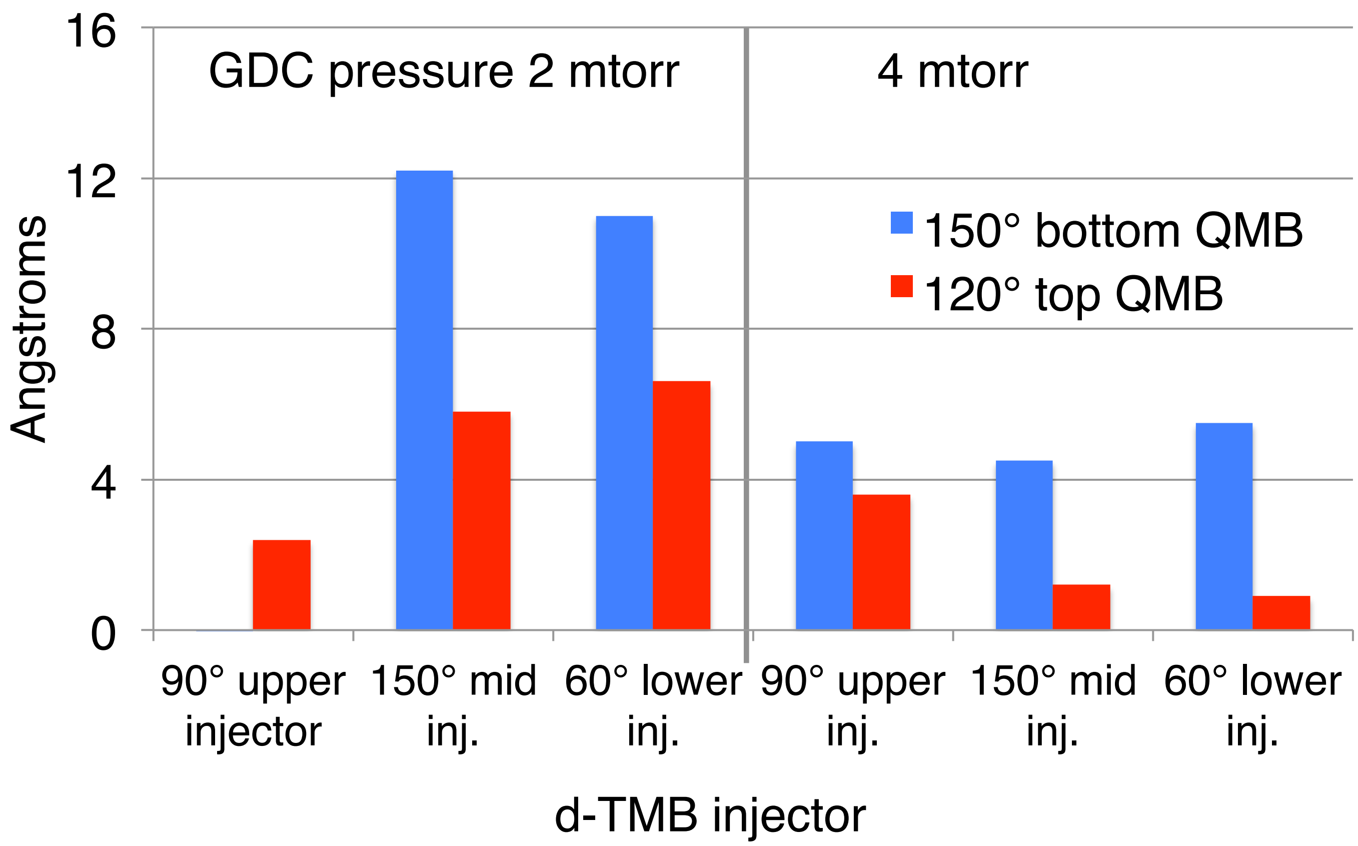


Tri-methyl boron

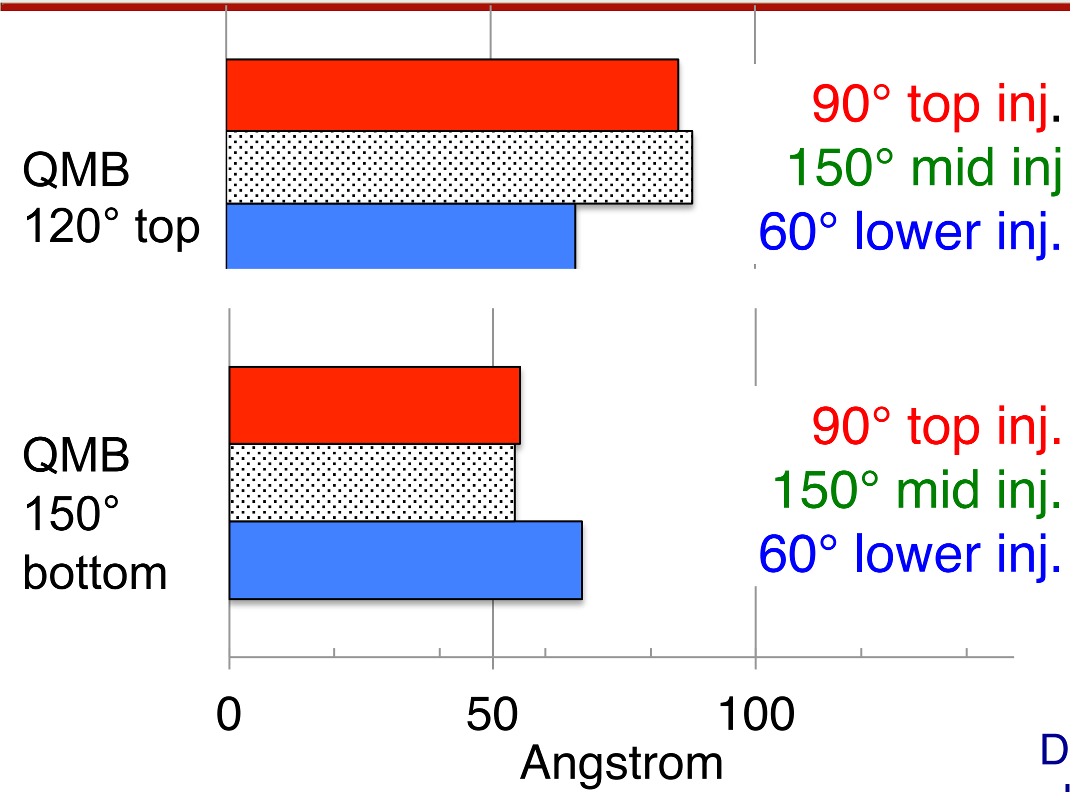
More divertor deposition @ lower pressure

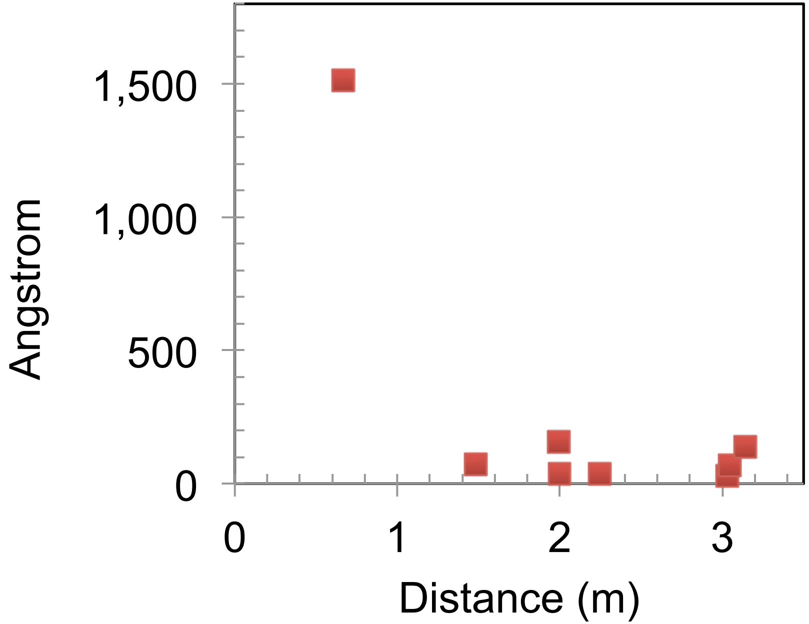
Deposition at top and bottom of vessel increased at lower pressure (longer mfp).

Subsequent boronizations used 1.7 mtorr.



More deposition near gas injector, most deposition near electrode





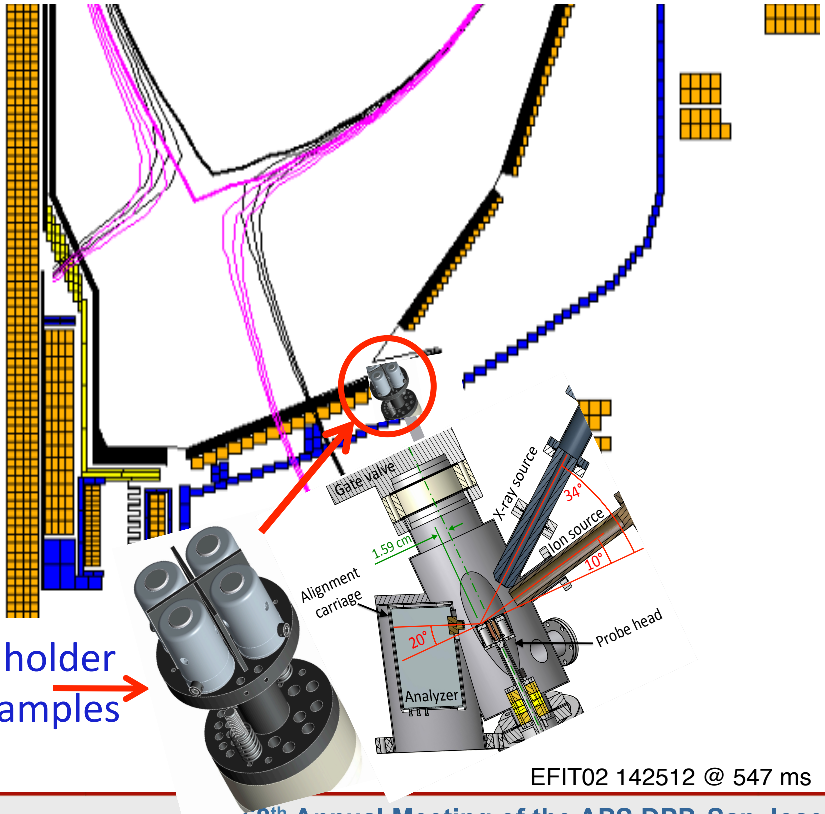
Top injector enhances top deposition by 30%.
Lower injector enhances bottom deposition by 21%

Deposition on the QMBs using only one GD electrode, plotted as a function of distance to the electrode in use. The high point at 1,515Å is deposition on the 30° QMB when the nearby 30° GD electrode is in use.

Surface chemistry monitored with MAPP

Materials Analysis Particle Probe (MAPP)

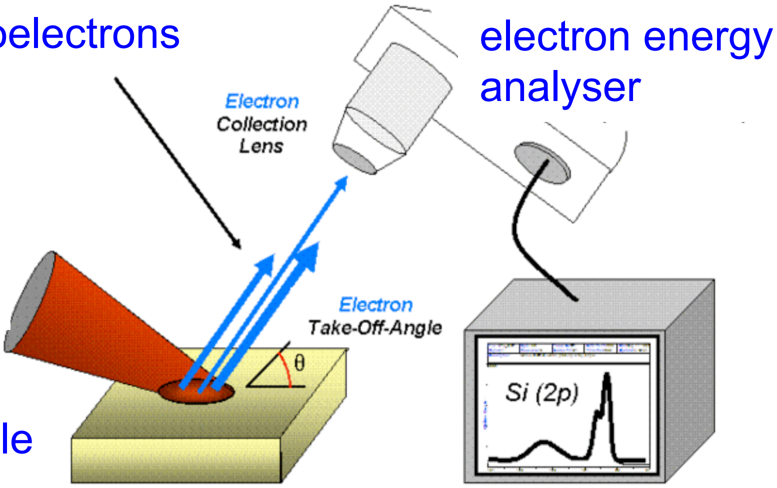
JP Allain, B Heim, F Bedoya, R Kaita et al…



Sample holder with 4 samples

EFIT02 142512 @ 547 ms

X-ray Photoelectron Spectroscopy



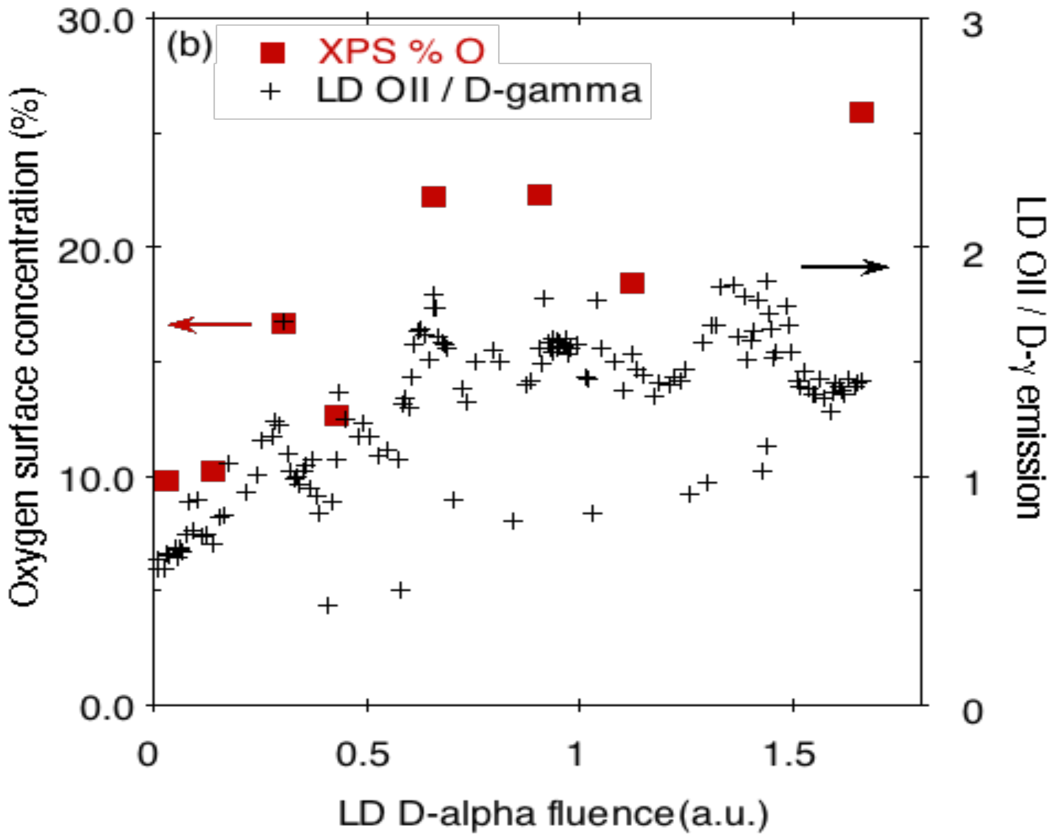
XPS spectrum shows elemental composition and chemical shifts.

https://commons.wikimedia.org/wiki/File:System2.gif

See next talk: GO6.00009: C Bedoya et al.,

MAPP probe revealed OII emission correlated with surface O rise after boronization

- Boronization reduced surface oxygen concentration to 4% - 9%
- Surface oxygen then increased with plasma exposure by 0.14%/sec from 7.6% up to 26%.
- This increase in surface oxygen concentration was correlated with a rise in lower divertor OII plasma emission.

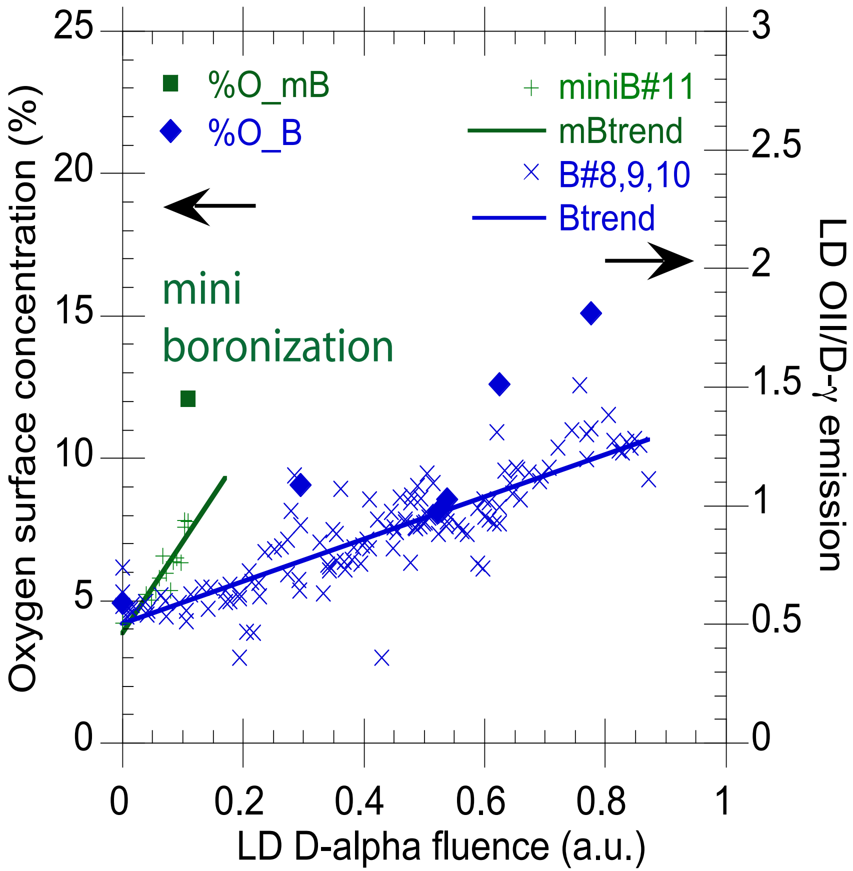


(plasma exposure)

boronization #5

Surface %O and OII emission rose faster after ‘mini-boronization’

- ‘Mini-boronizations’ used 1.8 g dTMB compared to full-bottle 9 g.
- Both surface %O and OII emission rose faster after ‘mini-boronization’, as expected from shorter erosion lifetime of thinner boronized layer



(plasma exposure)

Conclusions:

- After boronization, surface oxygen, as measured by XPS, and OII 441 nm emission from plasma both increased with plasma exposure. H-mode achieved after full bottle boronization. - nice correlation of surface composition and plasma performance !

- Deposition uniformity was improved by operating the glow discharge at low pressure.

- The deposition was enhanced by 20 – 30% in the region local to the gas injection port.

- But boron deposition in divertors relatively low (10s of monolayers).

- Considering to increase fraction of d-TMB/He from 5% to 10% - 20% next year.

- Extensive program of surface analysis of samples retrieved from NSTX-U is underway

Backups

GDC Modeling; RFX, JET benchmarks

G J M Hagelaar *et al*

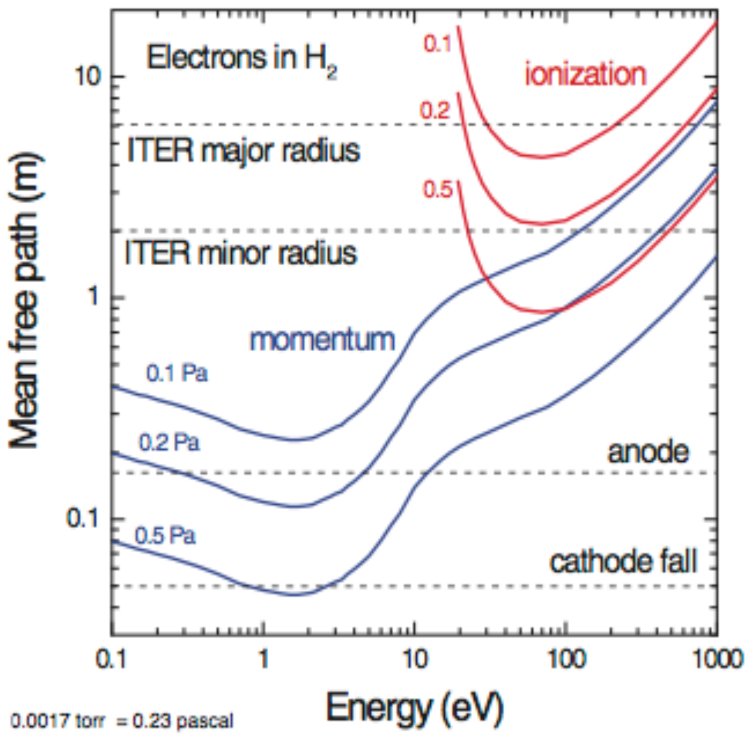


Figure 1. Electron mfps in molecular hydrogen compared with various system dimensions, as a function of electron energy and for different gas pressures (these are standard pressures corresponding to 300 K).

RFX: R=2m, a=0.43m

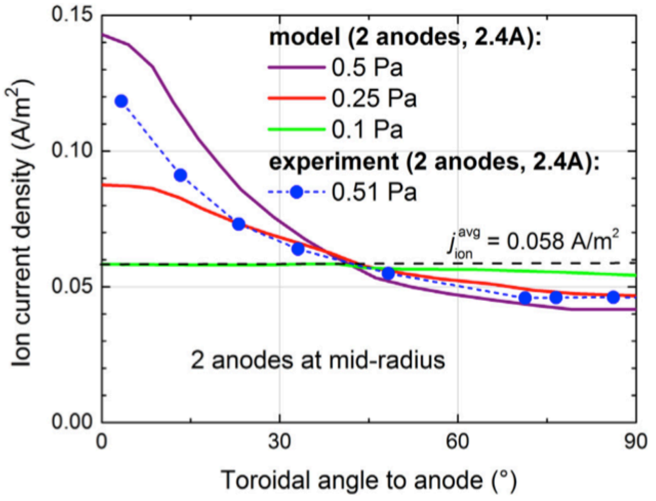
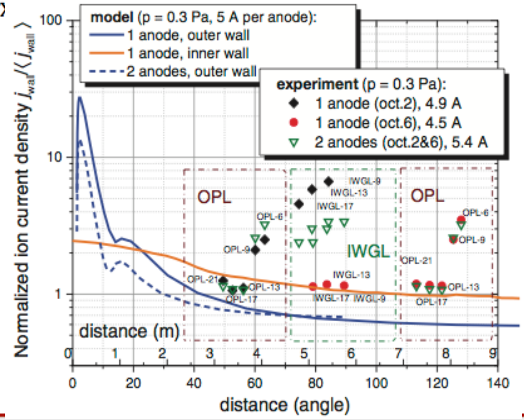


Fig. 3. Measured and simulated ion current density distribution over the outer walls of RF

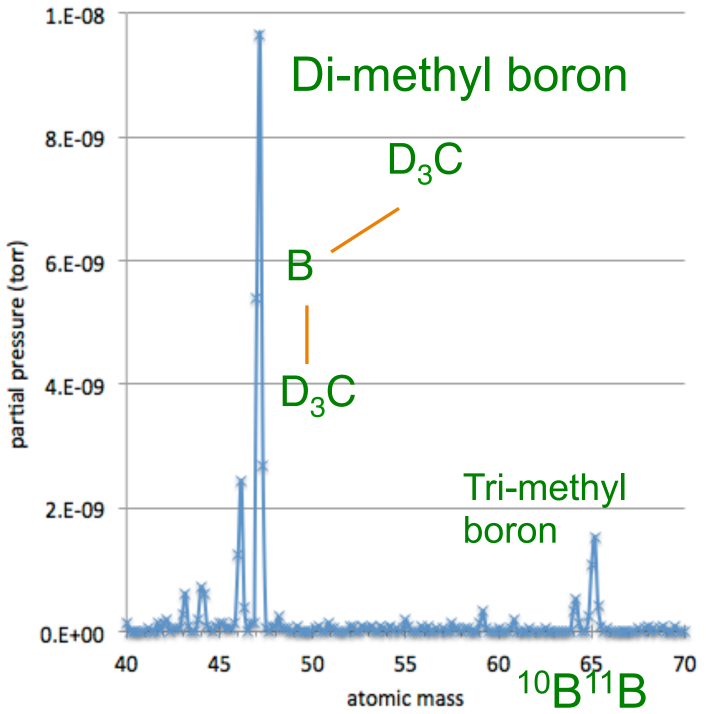
JET



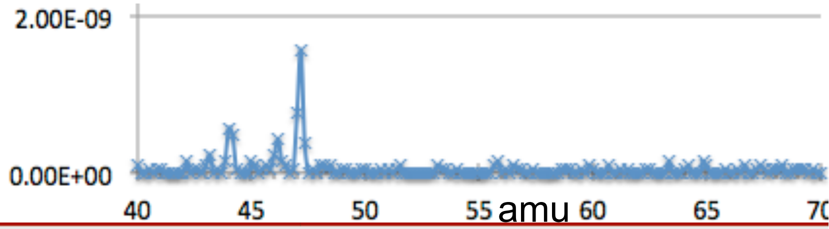
Boronization conditions:

- Typically Bay B electrode 540 V, 2.3 A
  Bay G electrode 530 V, 1.8 A
- One 9-g bottle d-TMB / per full boronization
- Gas mix: 5% d-TMB 95% He
- 75% carbonization 25% boronization
- Ion fluence = current x time, is close to total d-TMB + He atoms/mol used
- Vessel pressure set at 1.7 mtorr
- Nominal vessel area: 40 m^2
- Average coverage would be ~ 1400Å but is not uniform
- Expected erosion rate: 1 – 10+ Å/s

RGA during He/d-TMB pumpout



RGA during He/d-TMB GDC



Other machines, Options for more boron coverage:

- C-mod uses ECDC sweep in He/diborane (B_2H_6) (Lipschultz)
  Thickness: *'1500-2000 Å assuming uniform deposition over 10m²'*
- DIII-D uses GD 90% He/ 10% diborane (B_2H_6) (Jackson)
  'average 1000 Å thickness 90% B, 10% C film (AES)'
- JT60 GDC He/decaborane - 70-g $B_{10}D_{14}$ lasted 50 shots (Nakano)
- Carborane: $C_2B_{10}H_{12}$ @ 180 C (solid at room temp) EAST, KSTAR; (Wu, Hong)

Conclude more boron needed in NSTX-U divertor:

- Increase fraction of d-TMB from 5% to 10% ?
- Relocate GDC electrodes to divertor ?
  - need toroidal coverage - convert select divertor tiles to anodes ?
- More boron rich gas e.g. B_2D_6 - but toxic & explosive;
- Mega boronization ! - just use more d-TMB ?