U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Advances in boronization in NSTX-U

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NSTX-U Results Review
PPPL
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ILLINOIS

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Chemical and Biological Engineering

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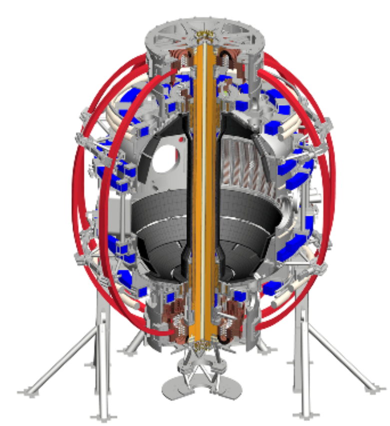
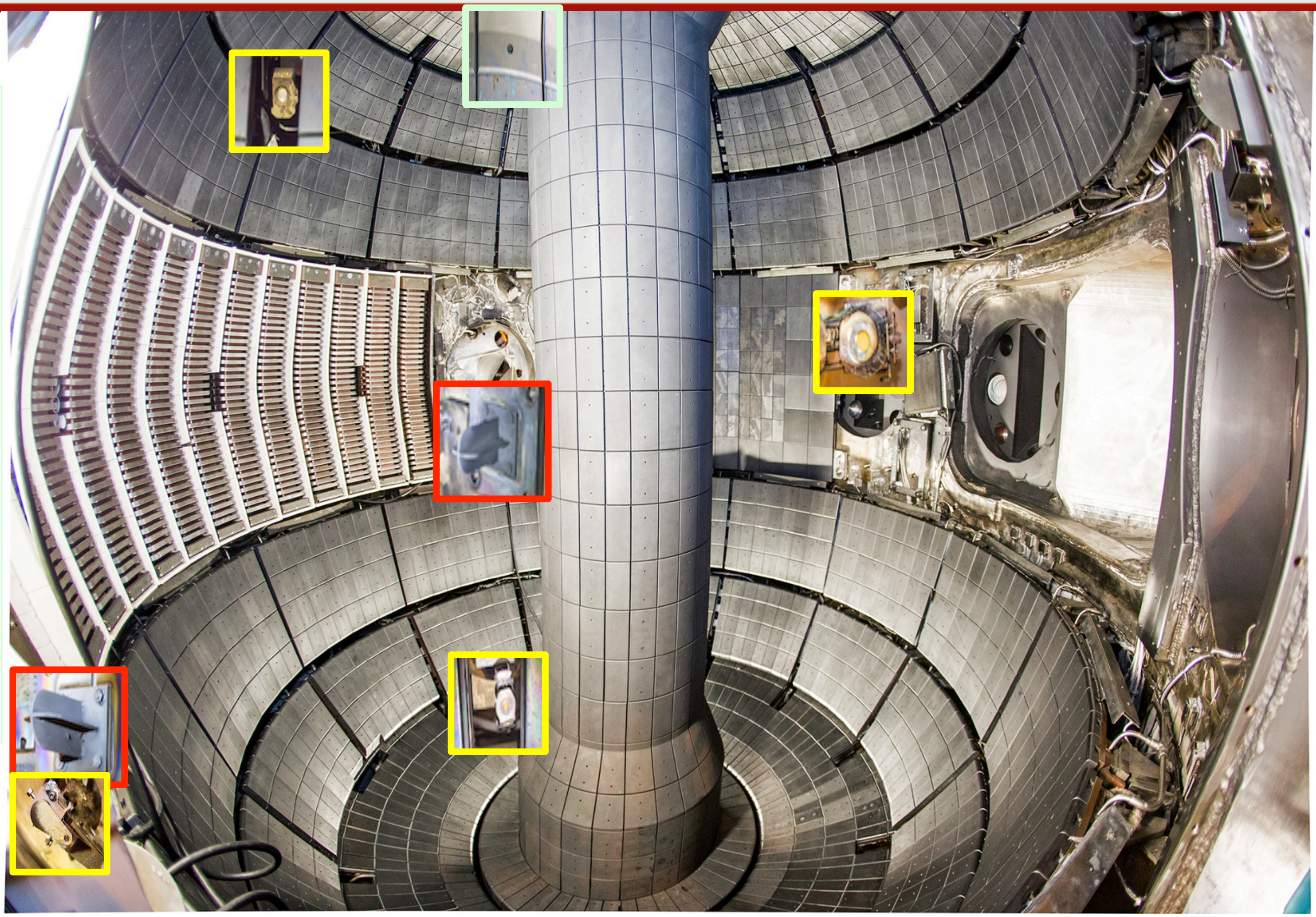


NSTX vessel

Electrodes:
Bay B
Bay G

Gas inlets:
Bay C lower
Bay D upper
Bay F mid

Quartz Xtal Microbalances
Bay B mid
Bay E top
Bay F lower
Bay I mid



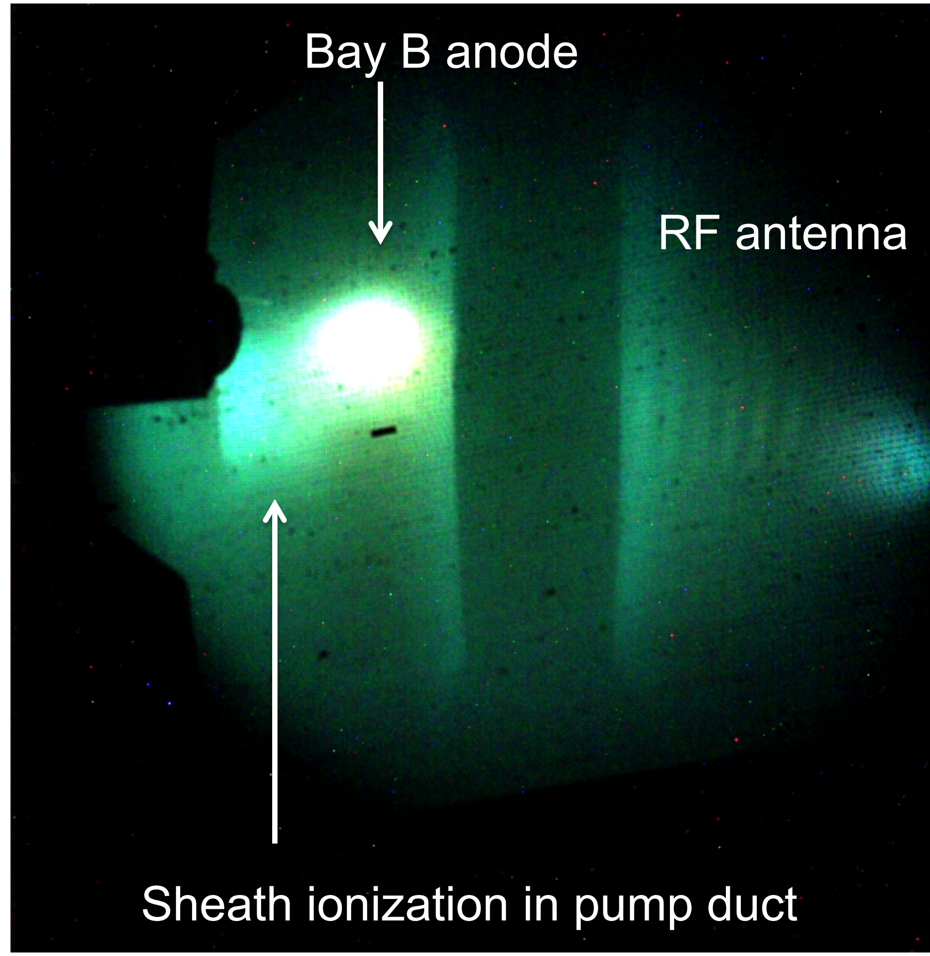
D Cai et al., submitted to TOFE proceedings (2016)

- Boron/carbon coatings applied onto PFCs through plasma-enhanced chemical vapor deposition
- Trimethylboron is dissociated in a helium glow discharge and ionized boron containing radicals then impinge onto the PFC cathode to form a hard, reactive and corrosion resistant coating.

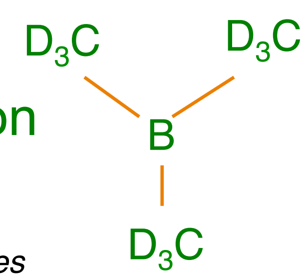
NSTX-U Glow Discharge

Glow Discharge Physics:

- Basically a hollow-cathode discharge,
- sustained mainly by ionization by secondary electrons emitted from the 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 in the vicinity of the anode.



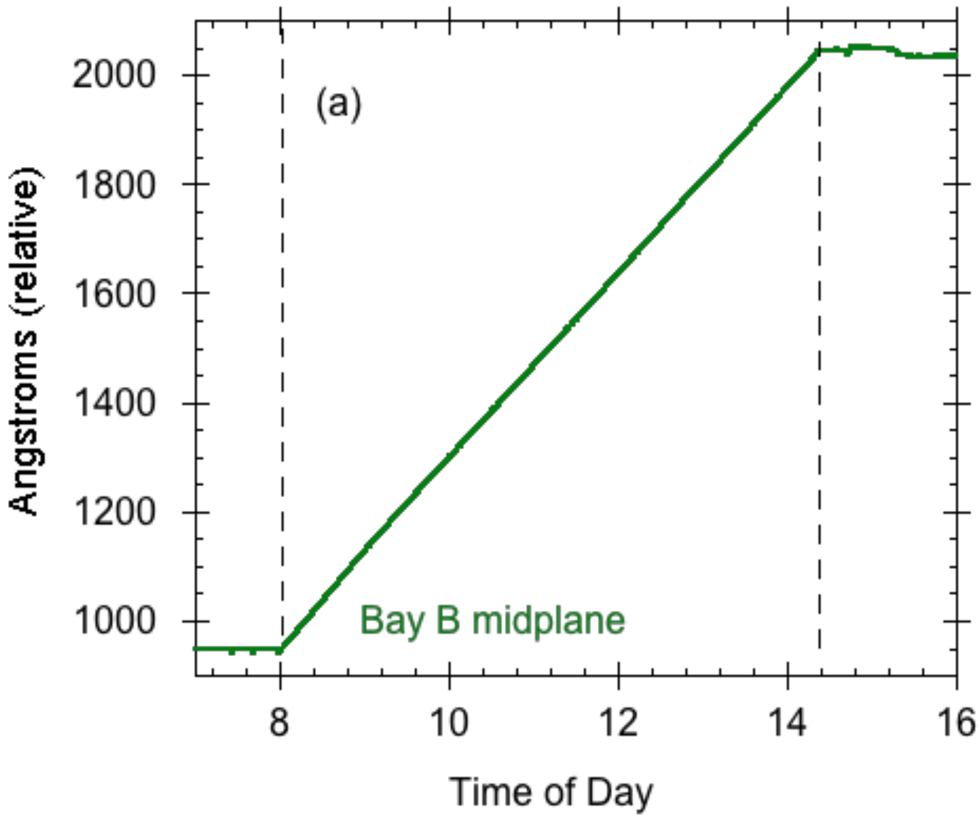
Tri-methyl boron



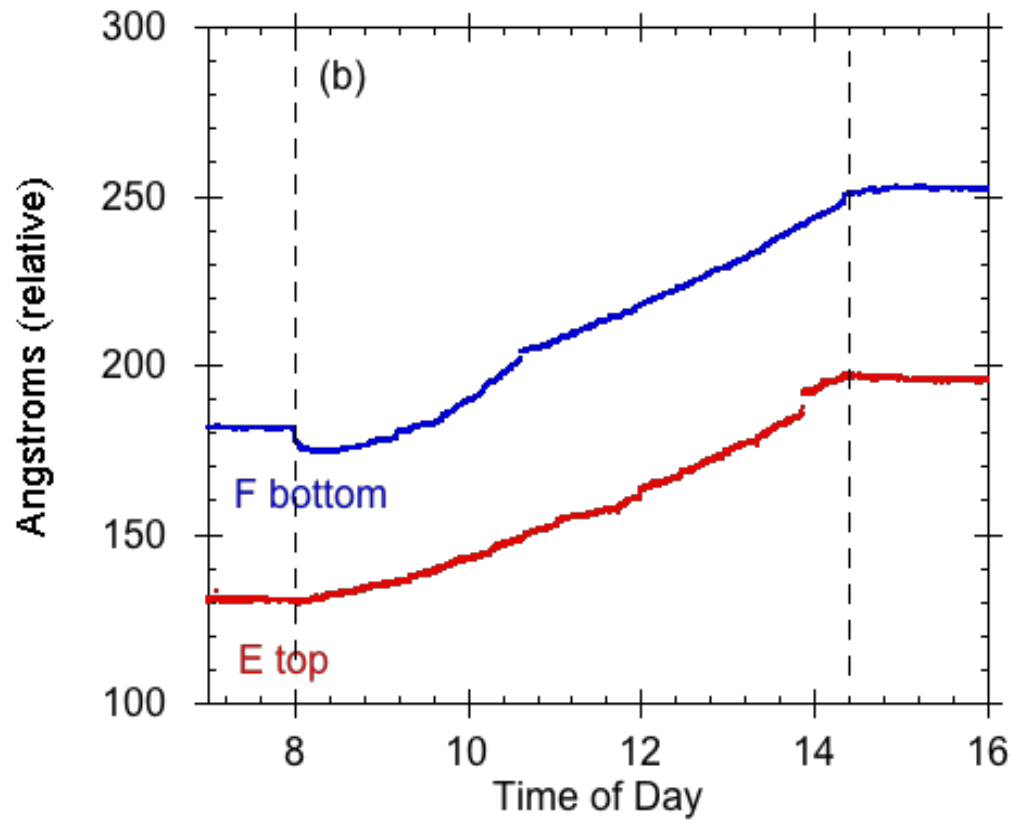
Hagelaar Plasma Phys Contr F **57** (2015) 025008 *Modelling of tokamak glow discharge cleaning I physical principles*

Deposition during boronization

Deposition at Bay B midplane

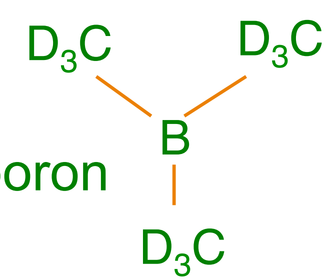


Deposition at F bottom and E top



'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.
'mini boronizations also used w/ 1.5 g-TMB
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})

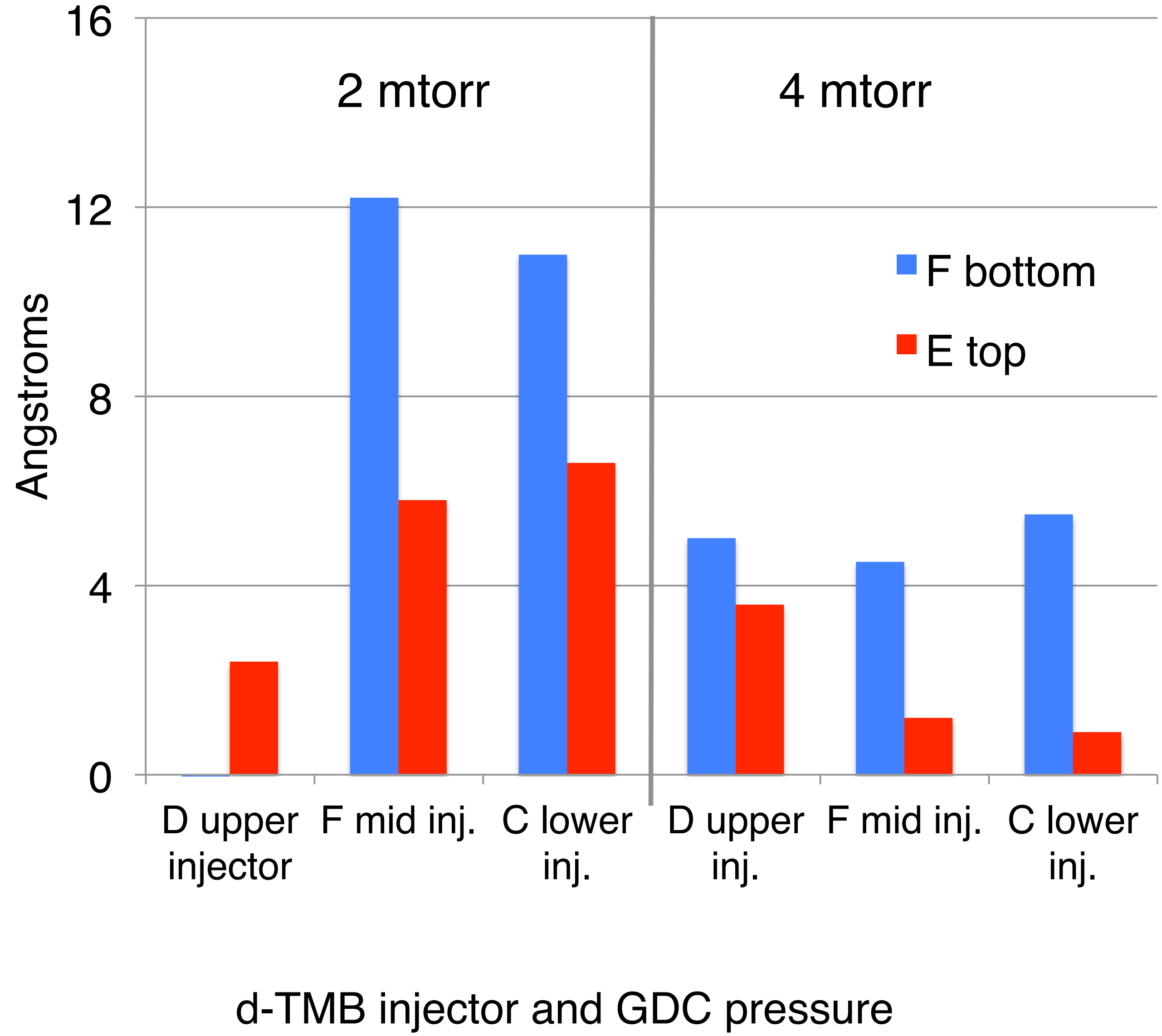
Tri-methyl boron



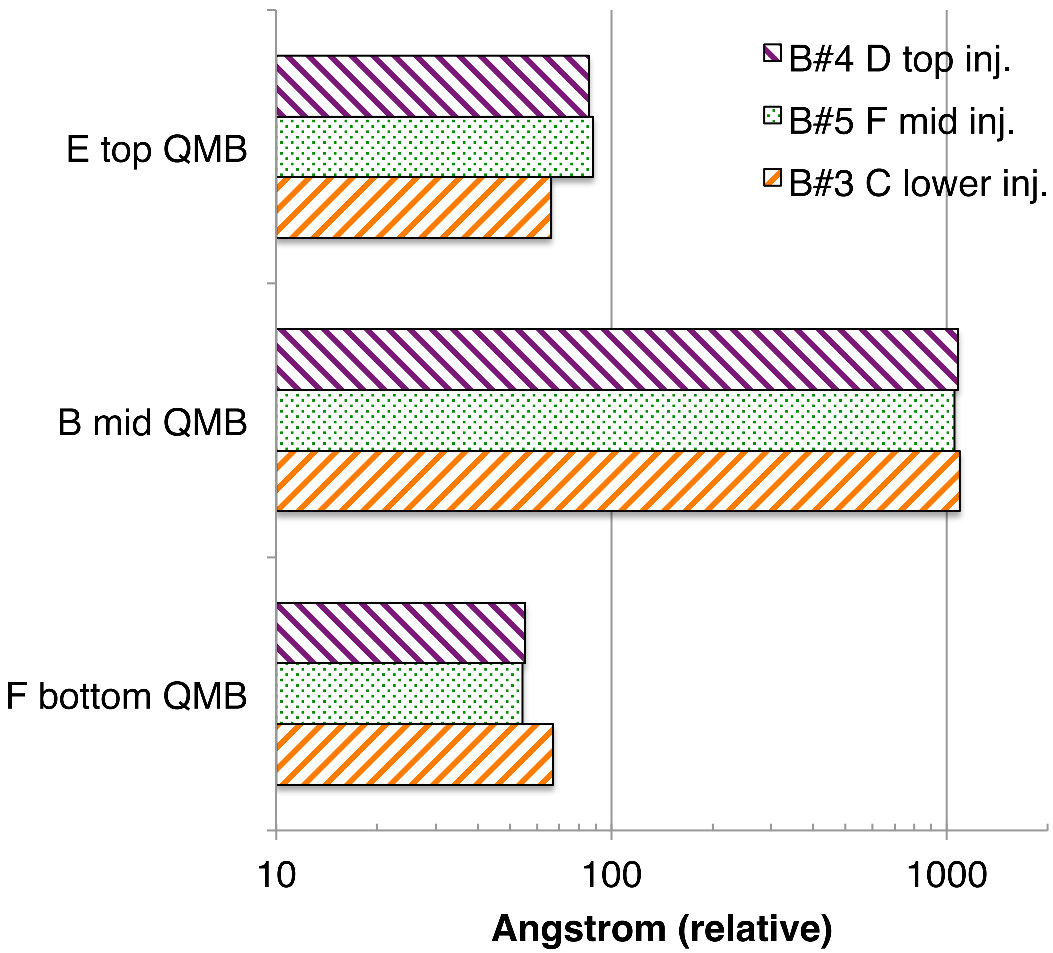
More divertor deposition @ 2 mtorr

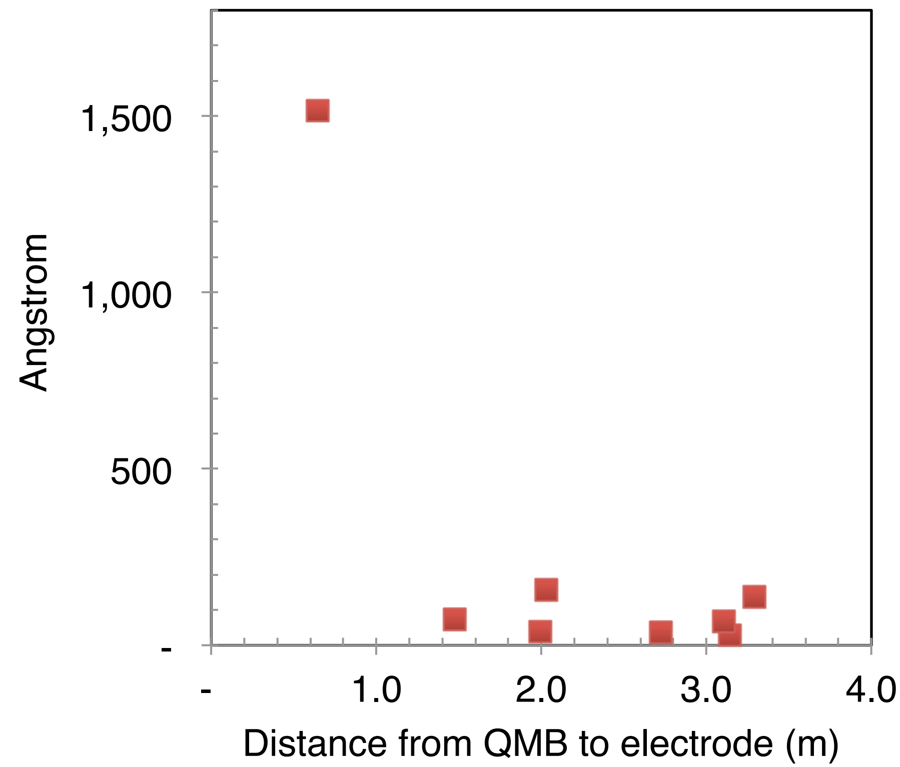
Deposition at top and bottom of vessel increased at lower pressure (longer mfp).

Subsequent boronizations used 1.7 mtorr.



More deposition near gas injector, Most deposition near electrode

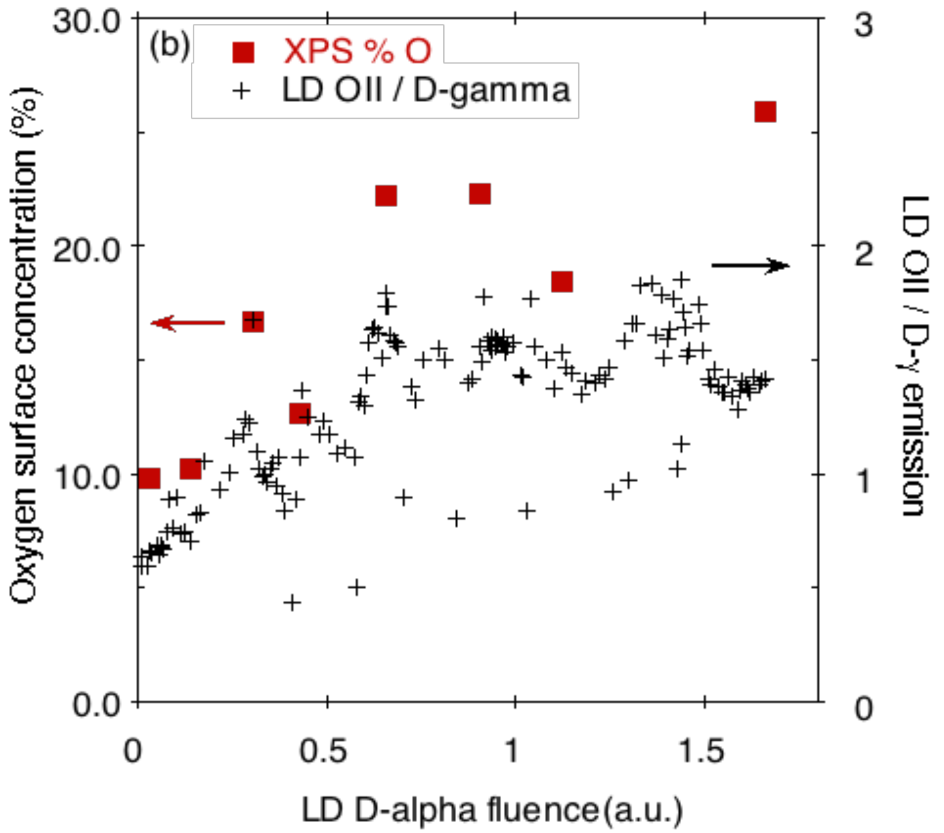


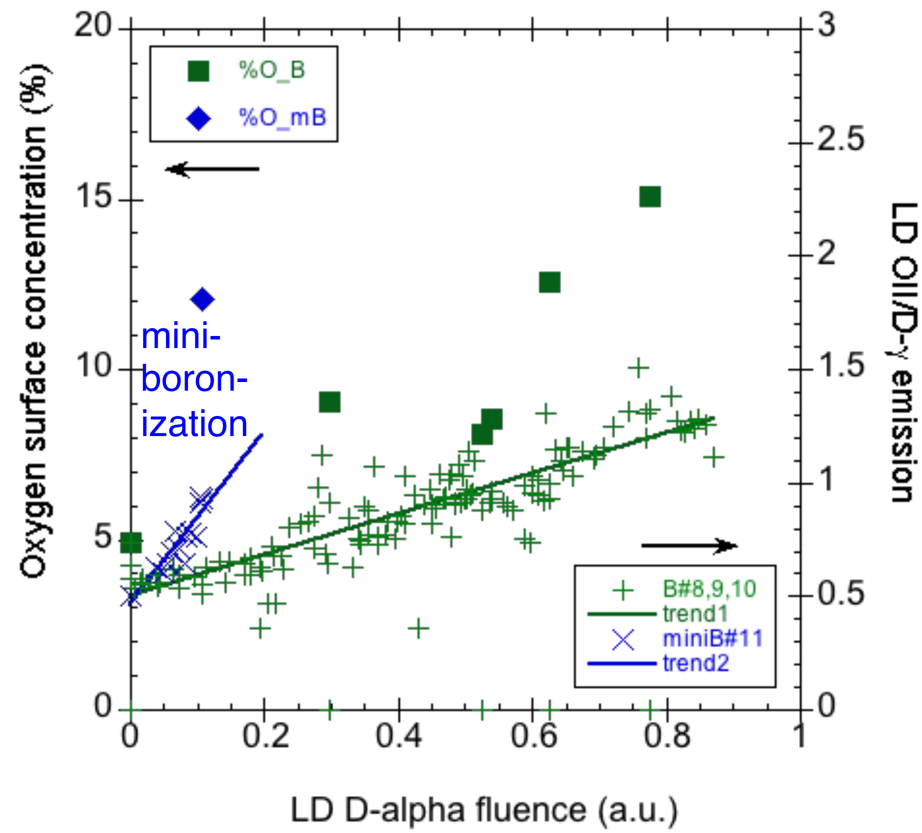


Using the D top injector enhances E top deposition by 30% and the C lower injector enhances the F bottom deposition by 21 %

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

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





- Surface oxygen concentration was reduced to 4% - 9% by boronization
- …then increased by 0.14%/sec plasma exposure from 7.6% up to 26%
- Increase in surface O was correlated with rise in OII plasma emission. (B#5)
- Both surface %O and OII emission rise faster after 'mini-boronization' (1.8g cf 9g) as expected from shorter erosion lifetime of thinner boronized layer

Conclusions:

- After boronization, both surface oxygen, measured by MAPP, and OII 441 nm emission from plasma increased with plasma exposure.
  - nice correlation of surface composition and plasma behavior !

- 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.

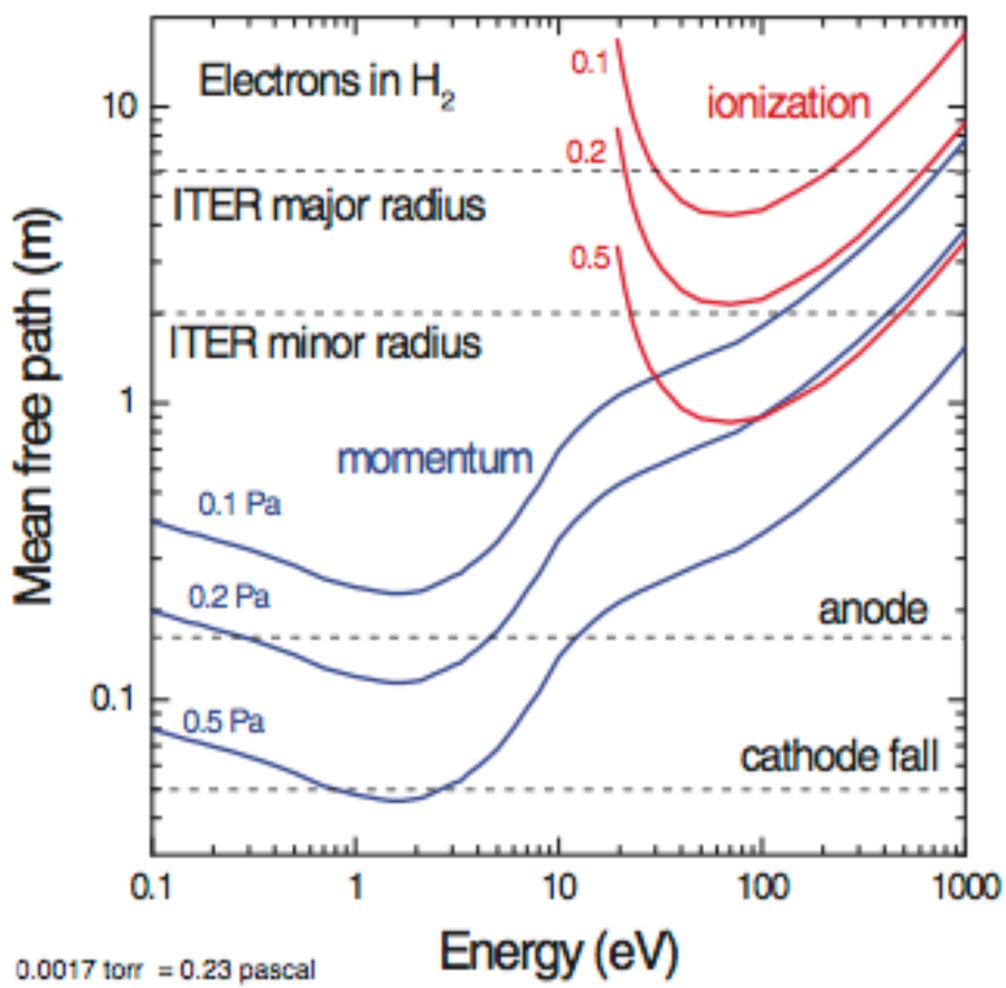
- But boron deposition in divertors rather skimpy (10s of monolayers) compared to other machines.

- **Options to increase boron on divertors:**
  - **Increase fraction of d-TMB/He from 5% to 10%**
  - **Use multiple bottles of d-TMB**
  - GDC electrodes in divertor region ?
    - need toroidal coverage - convert select divertor tiles to anodes ?
  - More boron rich gas e.g. B_2D_6 - but toxic & explosive.

Backups:

Modeling and RFX, JET benchmarks

G J M Hagelaar et al



0.0017 torr = 0.23 pascal

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

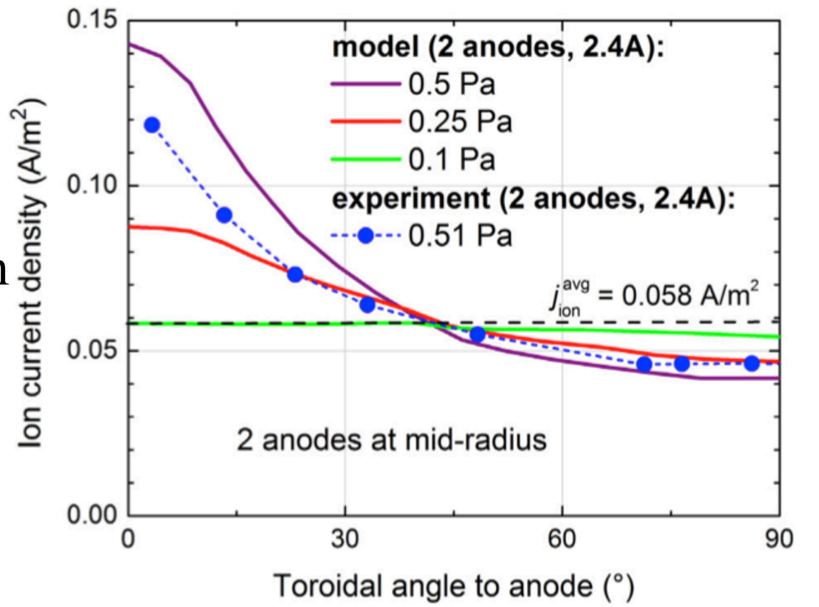
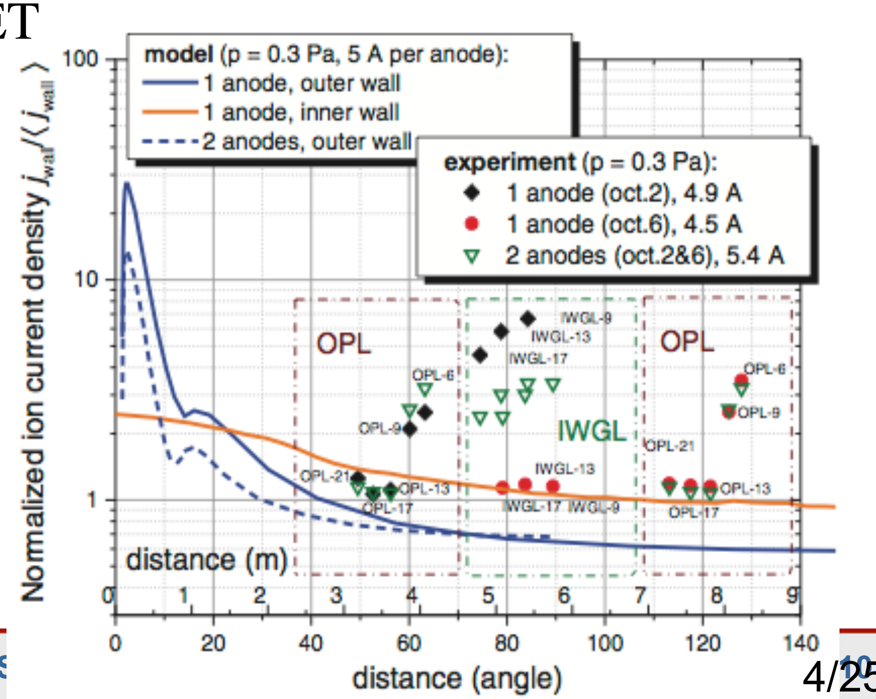


Fig. 3. Measured and simulated ion current density distribution over the outer walls of RFX.

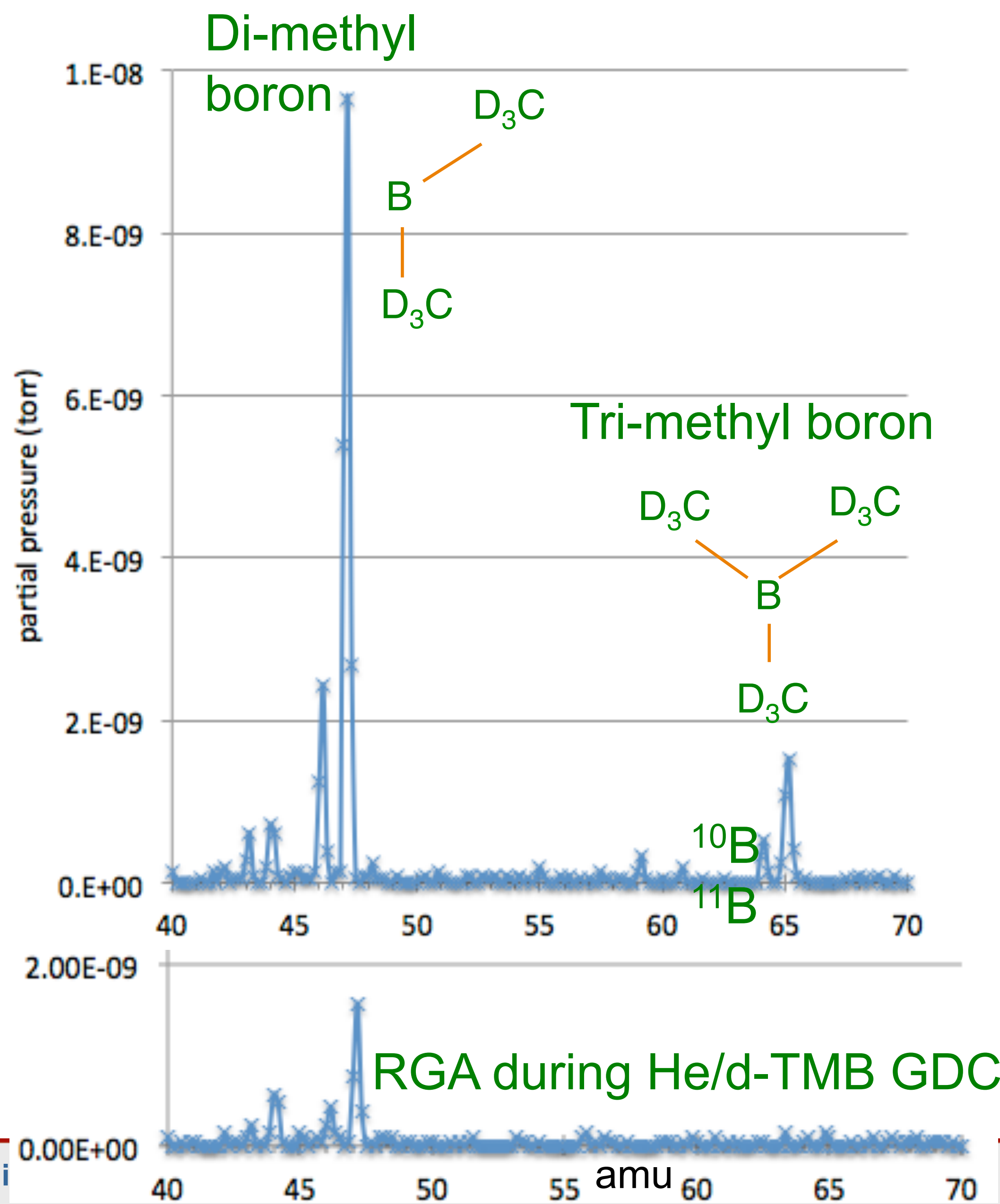
JET



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



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 $10m^2$'
- 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 ?