Deposition and dust results from NSTX

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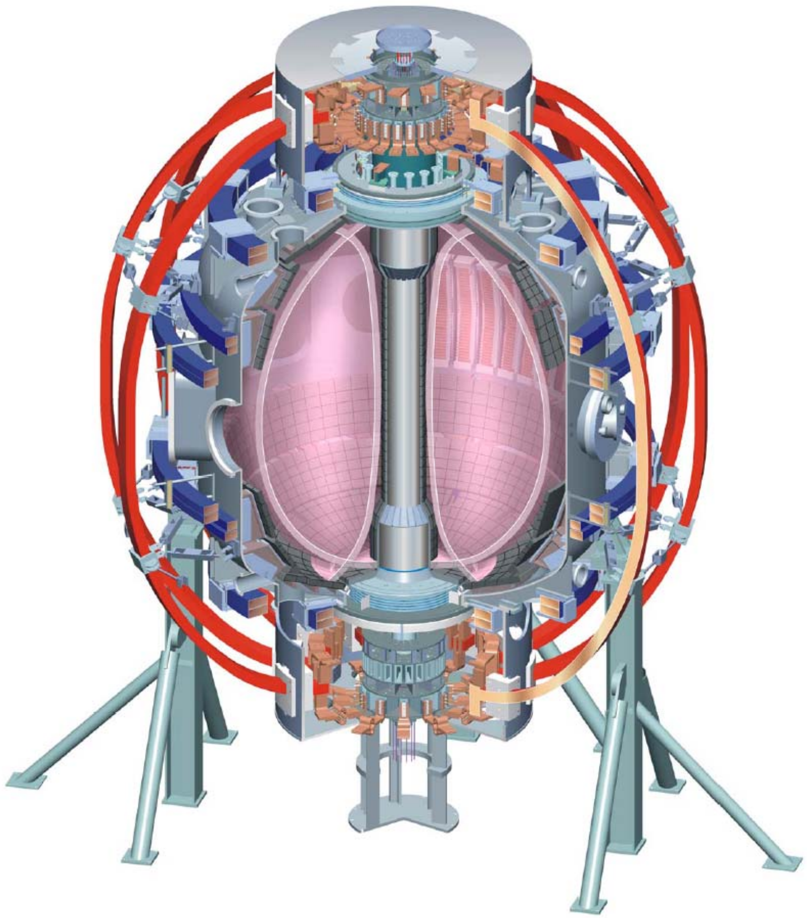
William Wampler, SNL, John Hogan, ORNL
with National Undergraduate Fellows:
Aaron Bader, Cooper Union, New York
Chris. Voinier, College of New Jersey



- DEPOSITION IN NSTX:
  - Motivation
  - Hardware
  - Deposition Results
    - Plasmas
    - Boronization
- ADVANCES IN DUST DETECTION
  - Motivation
  - Dust in NSTX
  - Results from new dust detector
- Concluding remarks

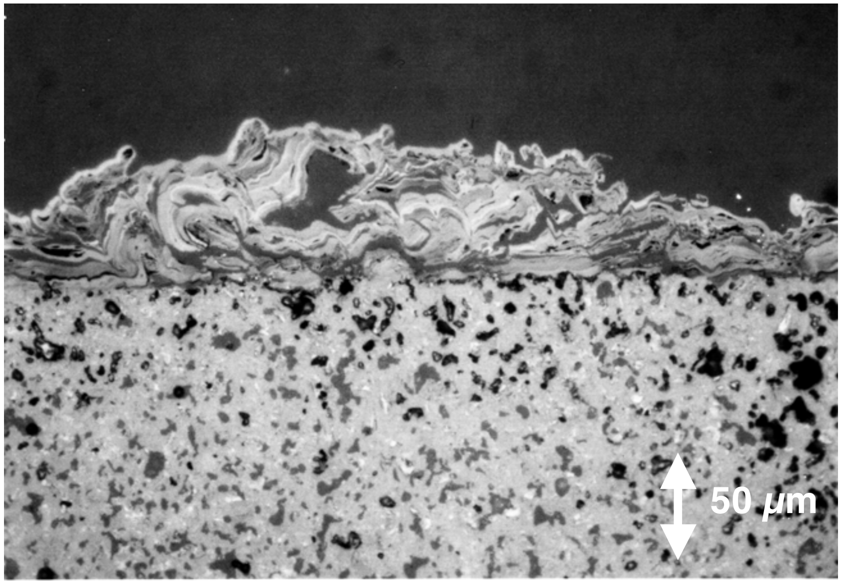
IAEA RCM Vienna Oct.18–19th, 2004

Supported by US DoE DE-AC02–76CH03073

Motivation:

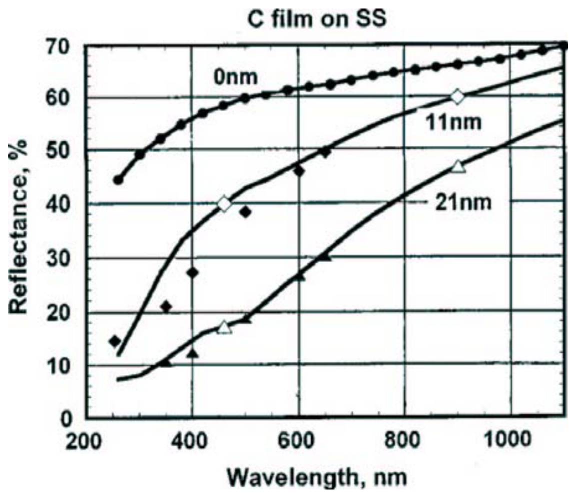
- Condition of plasma facing surfaces is key factor in plasma performance, but generally remains hidden and undiagnosed.
- Deposition:
  - affects recycling,
  - covers up boronized layer
  - coats diagnostic windows & mirrors
  - is major cause of tritium retention

- For 2005 NSTX will reconfigure boronization probe and has embarked on lithium wall conditioning by pellets / evaporation / and possibly flowing Li wall module.
- Real-time direct measurements of deposition are crucial to obtain understanding and control of deposition.



Deposition on TFTR graphite tile

S Willms and W Reisiwig LANL



Deposition on mirrors

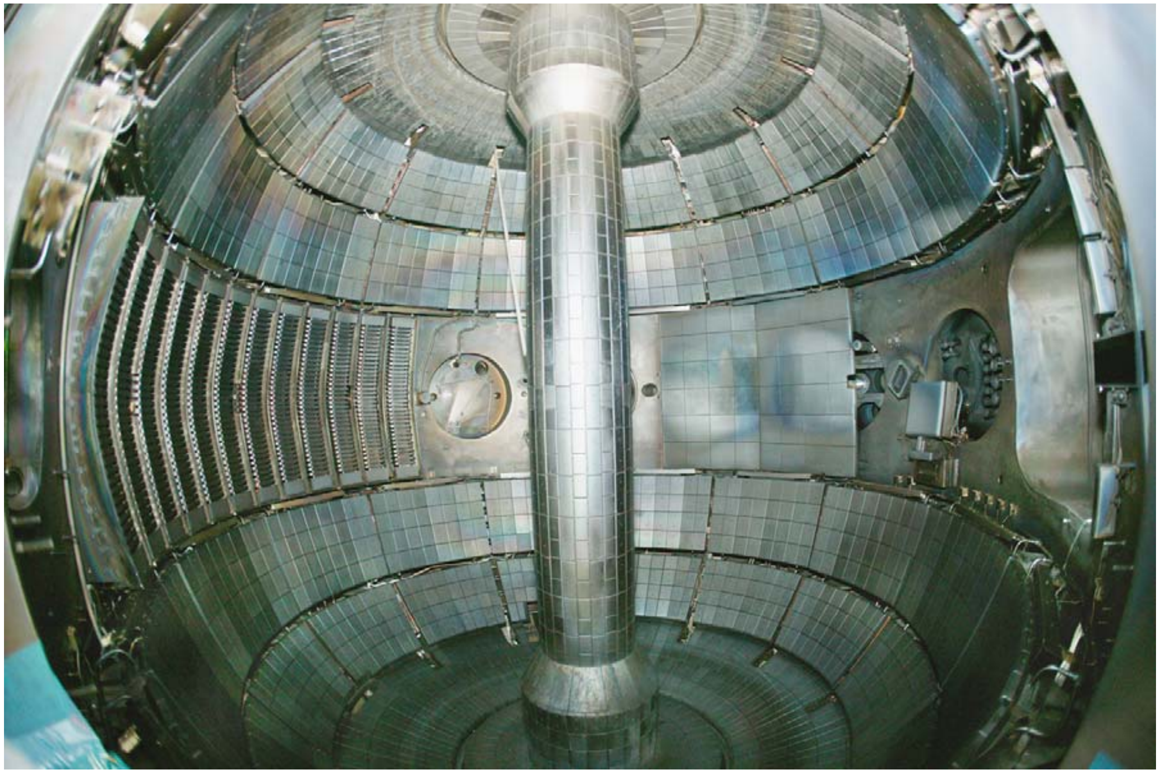
Experimentally measured solid points and calculated lines with corresponding open markers spectral dependencies of effective reflectance for clean SS and for SS with carbon coating of thickness shown on each curve.
Voitsenya et al., Rev. Sci. Instrum. 72 (2001) 480.

NSTX

The National Spherical Torus Experiment (NSTX) research program is aimed at:

- exploring the physics of high beta and high confinement in a low aspect ratio device
- demonstrate non-inductive current generation and sustainment.

- plasma major radius: 0.85 m,
- minor radius: 0.68 m,
- toroidal field of up to 0.45 T,
- plasma current up to 1.5 MA
- pulse duration up to 1 s.
- 5 MW neutral beam injection
- 6 MW of high harmonic fast wave RF at 30 MHz.

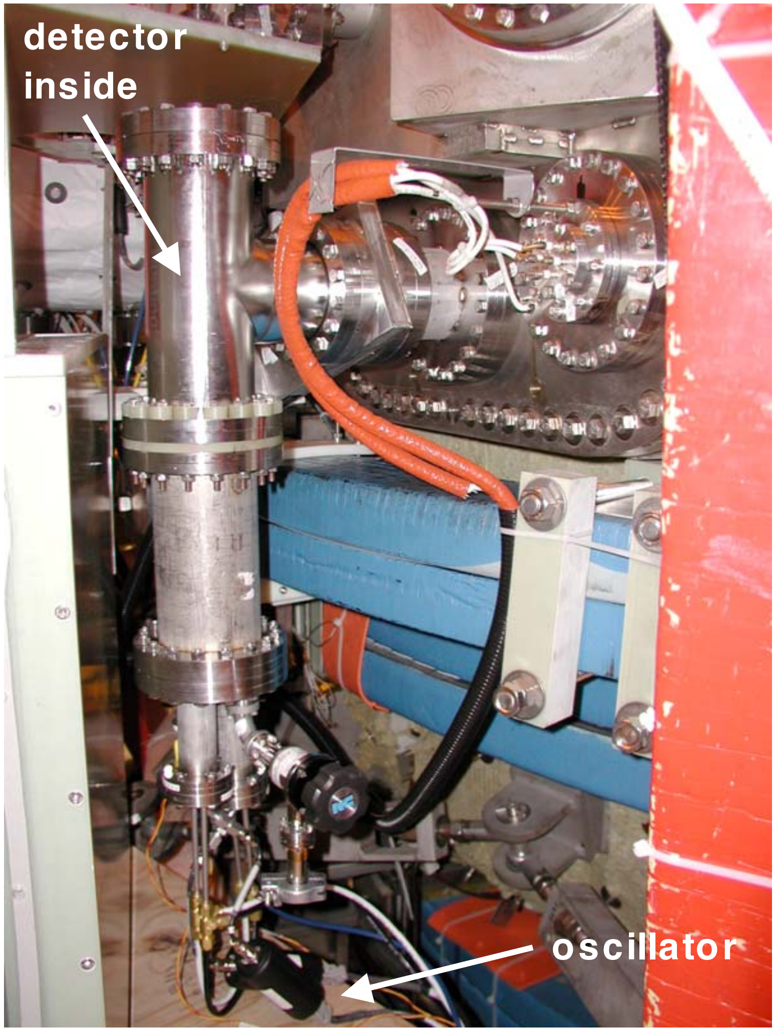


Plasma facing components that are in contact with the plasma are protected by a combination of graphite and CFC tiles.

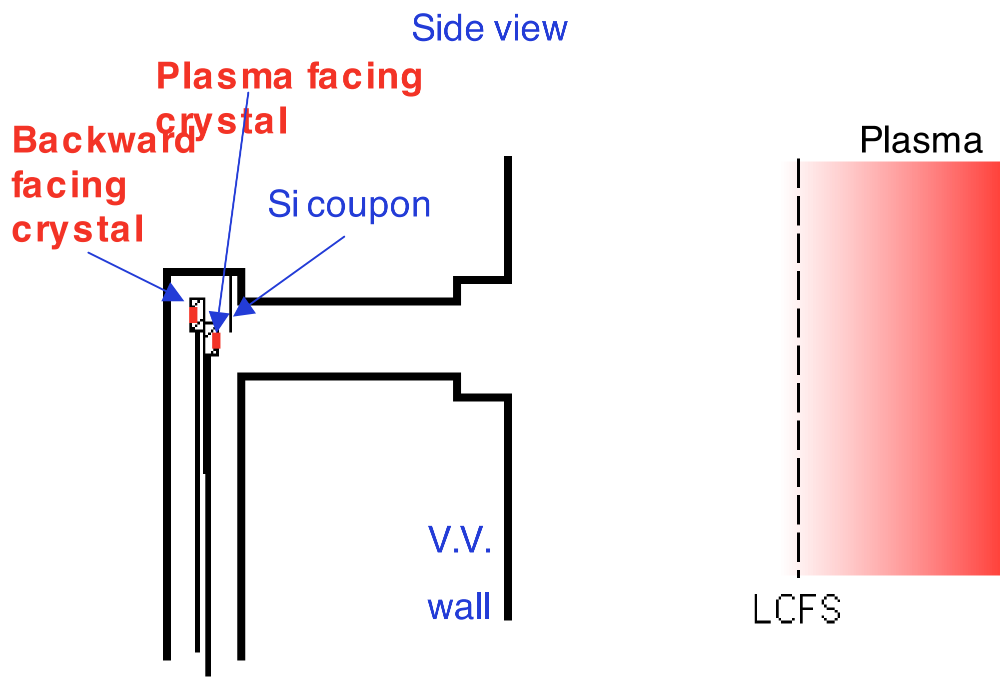
E.J. Synakowski, et al., Nucl. Fus. 43 1653–1664 (2003).

Two deposition monitors are installed on NSTX

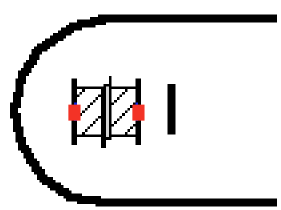
NSTX Bay K



crystal @ R= 231 cm, ~ 80 cm from last closed flux surface, 33 cm below midplane mimics typical diagnostic windows and mirrors,
- samples neutrals deposited on NSTX wall



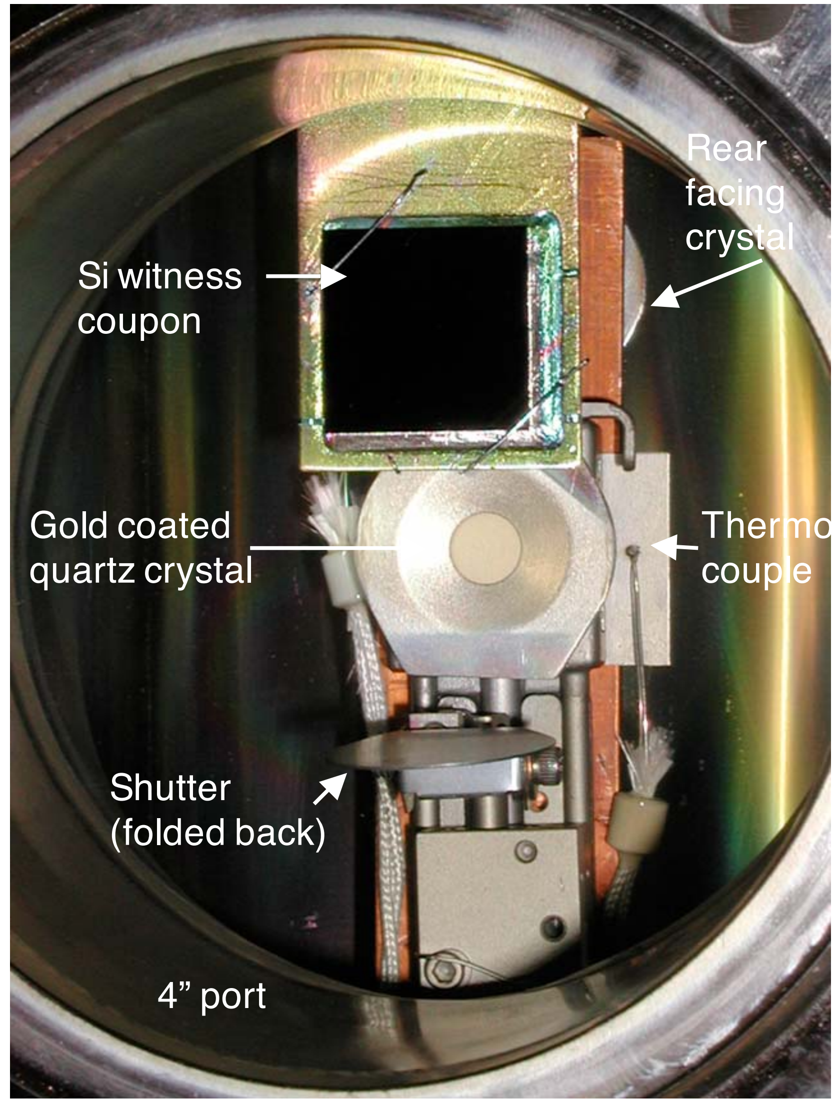
NSTX Bay K Top view



Quartz Crystal Oscillator

- Quartz crystal oscillates at ~5.9 MHz, the exact frequency depends on mass and on temperature.
- Deposition inferred from change in frequency (measured to ~0.1 Å, ~0.05 Hz)
- Location relatively far from plasma enables continuous recording of deposition before and after discharge.
- 1/4 s response time
- Thermocouples on both detectors record temperature
- Bakeable to 450°C.
- Built in shutter on plasma facing detector.
- Data acquisition via analog port and RS232 link

View from plasma side:



Quartz Crystal Microbalance:

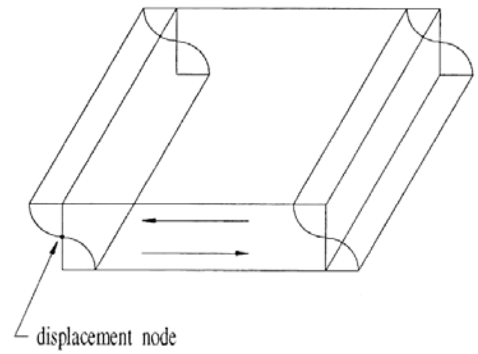
- Deposition changes crystal oscillating frequency.
- Widely used for process control during vacuum deposition.
- Used in TdeV, ASDEX, JET TEXTOR and NSTX tokamaks.
- Frequency measured by pulse accumulator controlled by 20 MHz reference oscillator.
- Commercially available system is relatively fast (1/4 s), precise, able to measure heavily loaded crystals and has immunity from mode hopping.

$$\frac{\text{film mass}}{\text{crystal mass}} = \frac{\text{frequency change}}{\text{bare crystal frequency}}$$

more complex relation available that takes account of acoustic properties of film and is valid up for to 40% frequency shifts.

Calculated sensitivity: -81 Hz / μg /cm^2
or -13 Hz /n.m
(for film density of 1.6 g/cm^3)

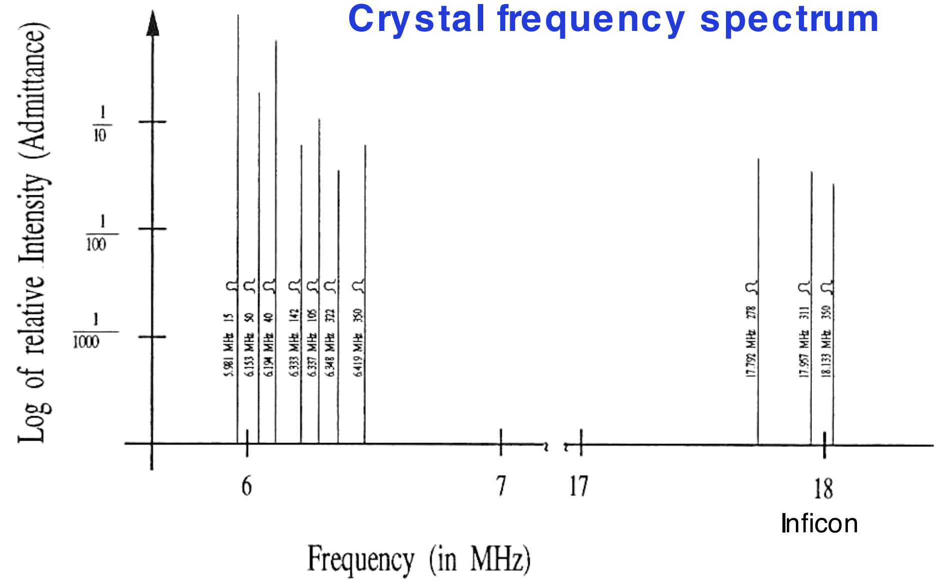
Caveat: frequency also sensitive to temperature, electronics may not be suitable for ITER environment.



Inficon

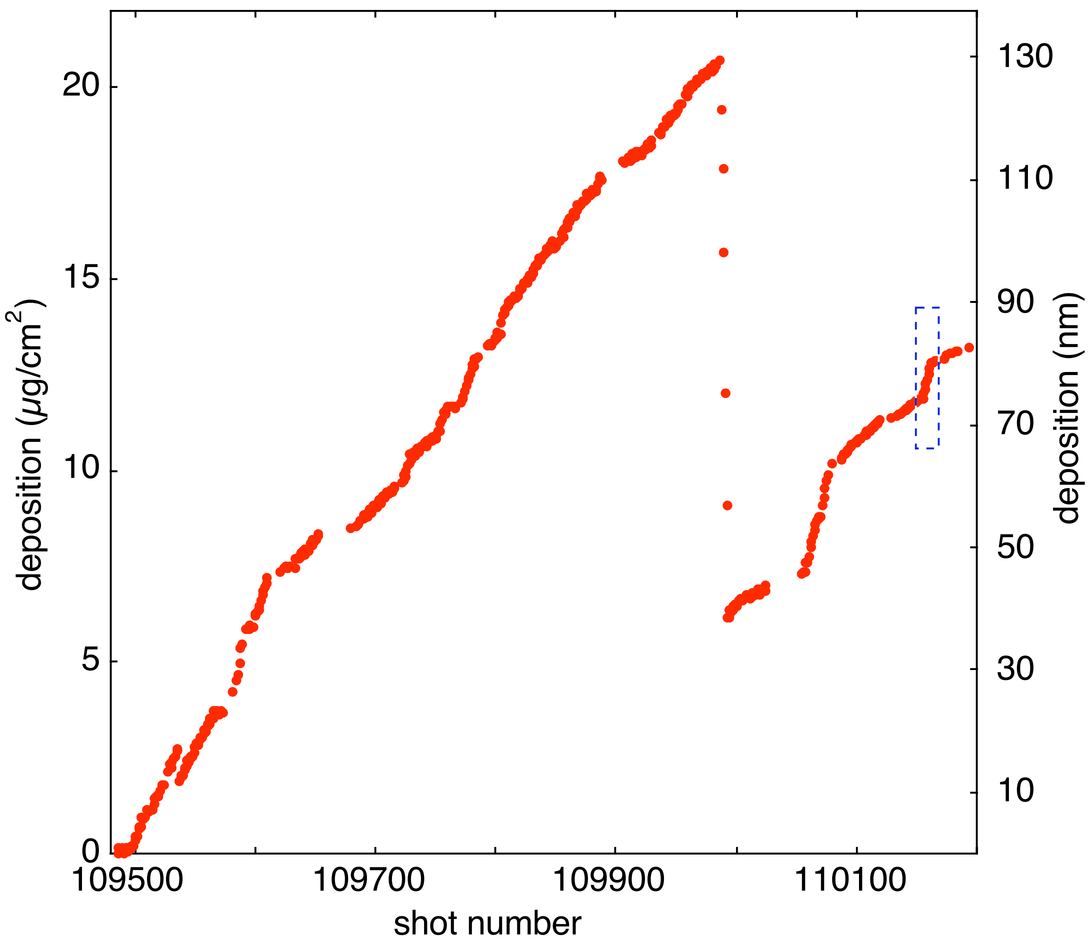
Crystal 'wobbles' in thickness shear mode

Crystal frequency spectrum



5.9 MHz fundamental resonance constantly identified by zero phase difference between applied signal voltage and current passing through crystal.

Deposition Results 2003:



Deposition over period
January 10th – February 14th 2003
Continuous rise punctuated by sharp material loss.

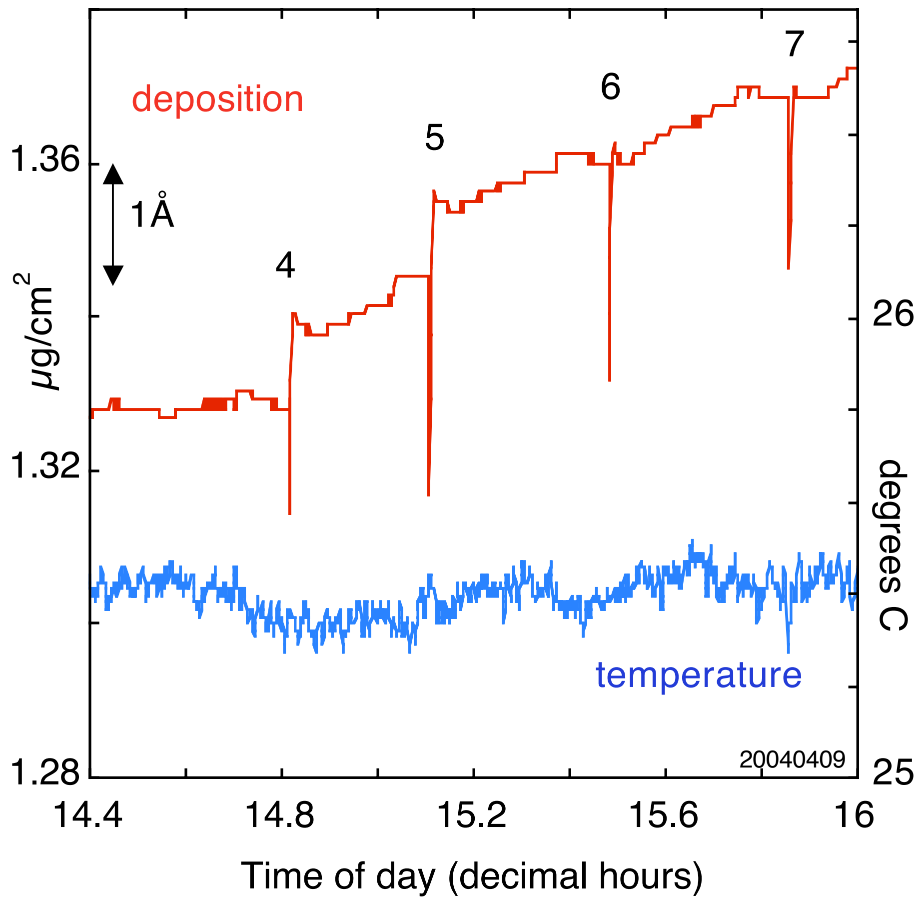
Excellent agreement between mass measured by nuclear reaction analysis and by quartz microbalance

deuterium (IBA)	0.20	μg/cm^2
carbon (IBA)	11.4	μg/cm^2
oxygen (from XPS)	1.96	μg/cm^2
D+C+O mass	**13.5**	μg/cm^2
Microbalance	**13.3**	μg/cm^2

- Deposition on back facing crystal 1.30 μg/cm^2, – about 10% of front facing crystal
- Data reflects sticking probability of hydrocarbon radicals.

2004 data acquired continuously at higher resolution via RS232:

Deposition over 4 shots 112014–017.



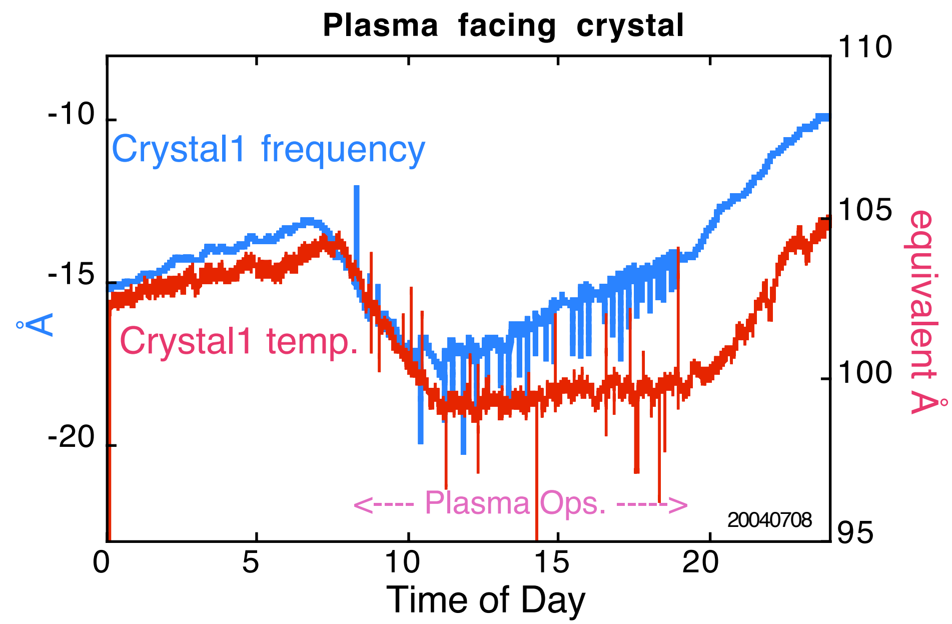
- Deposition often occured at first discharges in day.
- Slow deposition continues after discharge[1].
- Important implications for migration of codeposited tritium
- NSTX diagnostic shutters now closed imeadiately at end of discharge to minimise exposure.

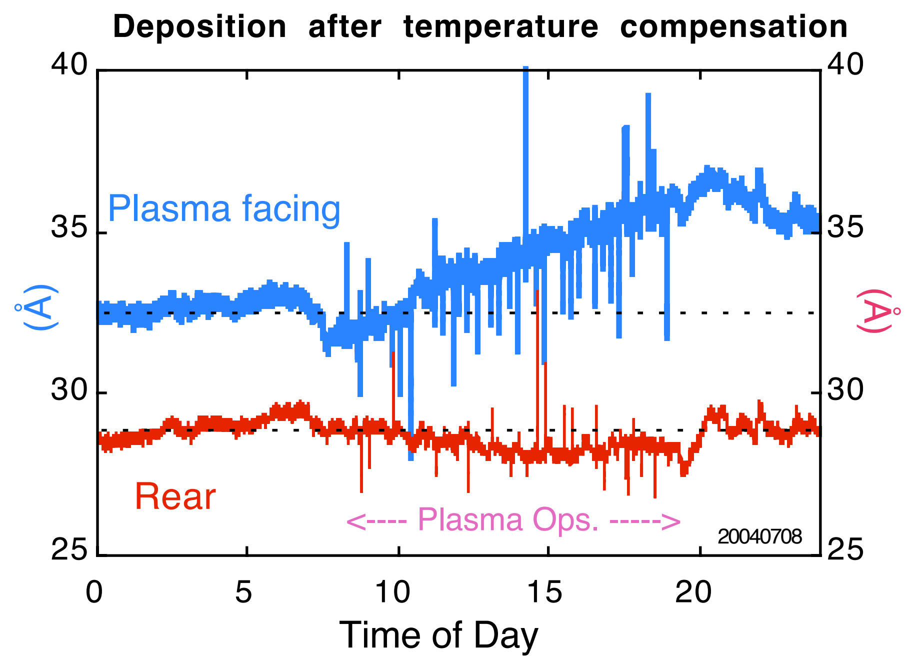
Average net deposition
in 2003 0.027 μg / discharge
in 2004 0.005 μg / discharge

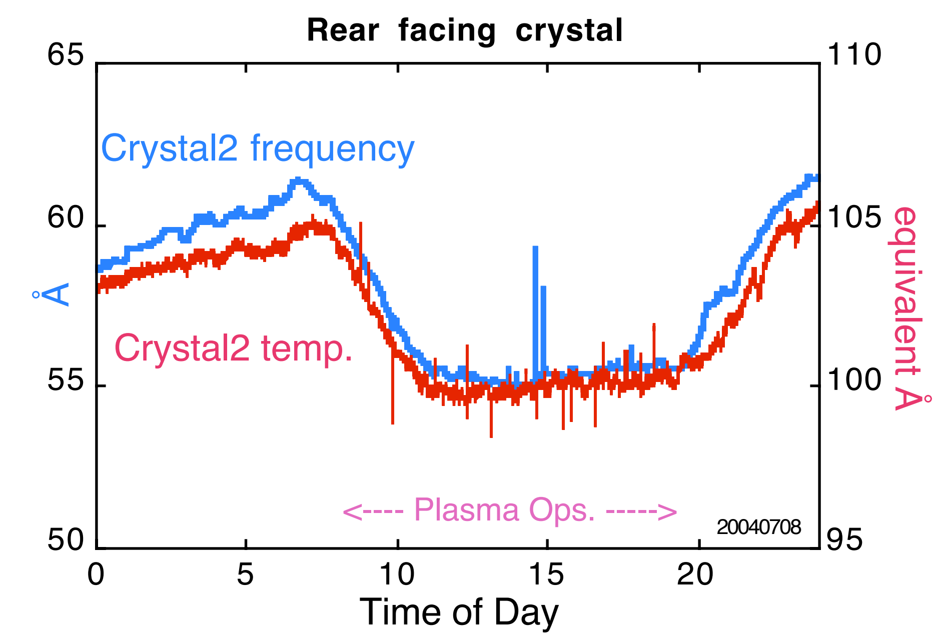
Typically the first shots in the day showed deposition.
The temperature (blue curve) shows that the slow continuous rise in deposition is not a temperature effect

[1] A. von Keudell, C. Hopf, T. Schwarz-Selinger, W. Jacob, Nucl. Fus, 39 (1999) 1451. "It is also conceivable that, due to the relatively high surface temperature in JET (>500K), polymer-like films produced during plasma interaction evaporate after each discharge and are deposited on the cold louvers in pulse pauses as well."

Deposition shows slow but persistent rise during plasma ops.







- Calibrate temperature response of crystal frequency with heated water.
- Convert temperature and crystal frequency to equivalent Å.
- Rear crystal frequency tracks temperature
- Front crystal frequency shows excess due to continuous slow deposition.

Modelling:

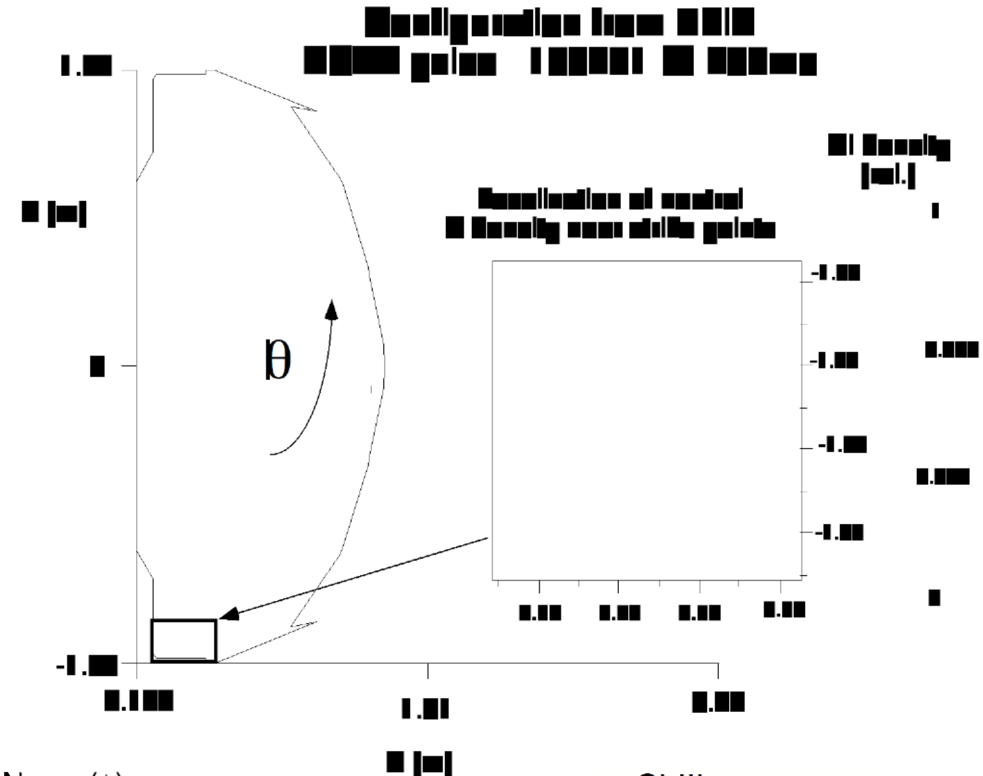
John Hogan ORNL

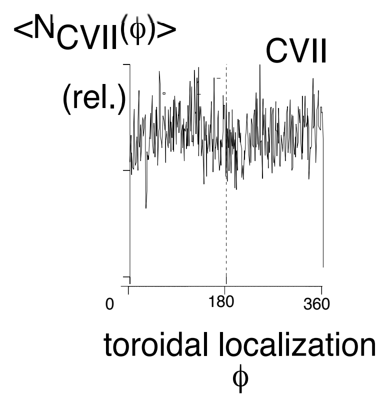
- BBQ calculations of <u>quiescent</u> cross-field transport of impurities generated at the divertor strike points find little mid-plane deposition, using conventional models.
- 'Bursty' low-field side, far-SOL transport and/or ELMs should give higher deposition rates

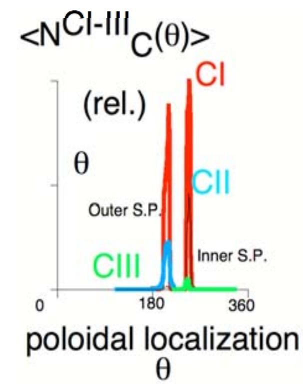
BBQ details:
Collision model Similar to LIM, WBC, ERO codes, detailed magnetic geometry (EFIT)

Background parameters assumed (n_e, ,l_n, T_e, l_T)
[local D^+ flux amplification, sheath electrostatic (es) field, E_{SOL}]
$M_Z\, dV_Z/dt = -F_{friction} - F_{es}$ + random // and ^ diffusion
$F_Z = -M_Z (V_{SOL}-V_Z) / t_s$; $F_{es} = Z_e E_{SOL}$
$F_{//}$ = Random // diffusion, $D// = (8E_Z/3pM_i)\, t_{//}$
$F_{\wedge}$ = Random ^ anomalous diffusion ($D_{\wedge}$)
Particle energy (W_Z)
$dW_Z/dt = (kT_i - W_Z)/t_T + R_{friction} + R_{es}$

Molecular processes: Erhardt-Langer, Janev-Reiter hydrocarbon break-up rates
Atomic processes (ionization, recombination, D0 charge exchange) for carbon
Birth gyro-collisions with surface







Toroidal localization ~uniform

Poloidal localization around strike points

Boronization measured directly

Note sensitive tracking of few monolayers only of boron deposition processes and apparent subsequent removal of deuterium on plasma facing crystal (well correlated with logbook entries).

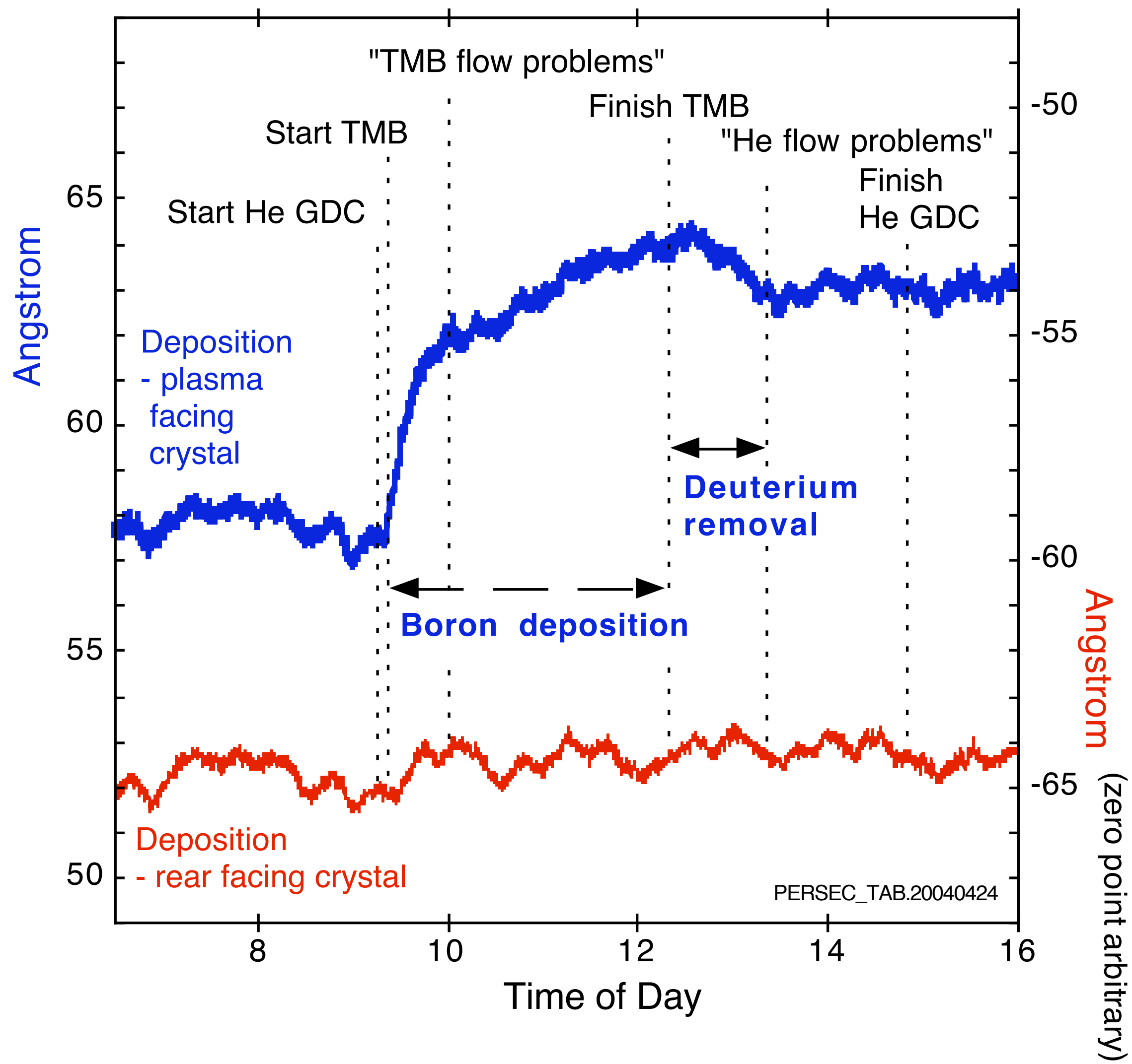
Total thickness ~5Å very low due to poor penetration of glow discharge to detector.

Future: Plan to use four detectors on VV wall to monitor B and Li deposition directly.

Note:

- Crystal frequency also changes due to temperature change.
- Plot shows thickness after averaged temperature compensation
- Crystal measures deposited mass.
- Thickness derived from assumed density of 1.6 g/cm3

Deposition on plasma facing and rear facing crystals during Saturday boronization 24 April 2004.
- comments from operators logbook.



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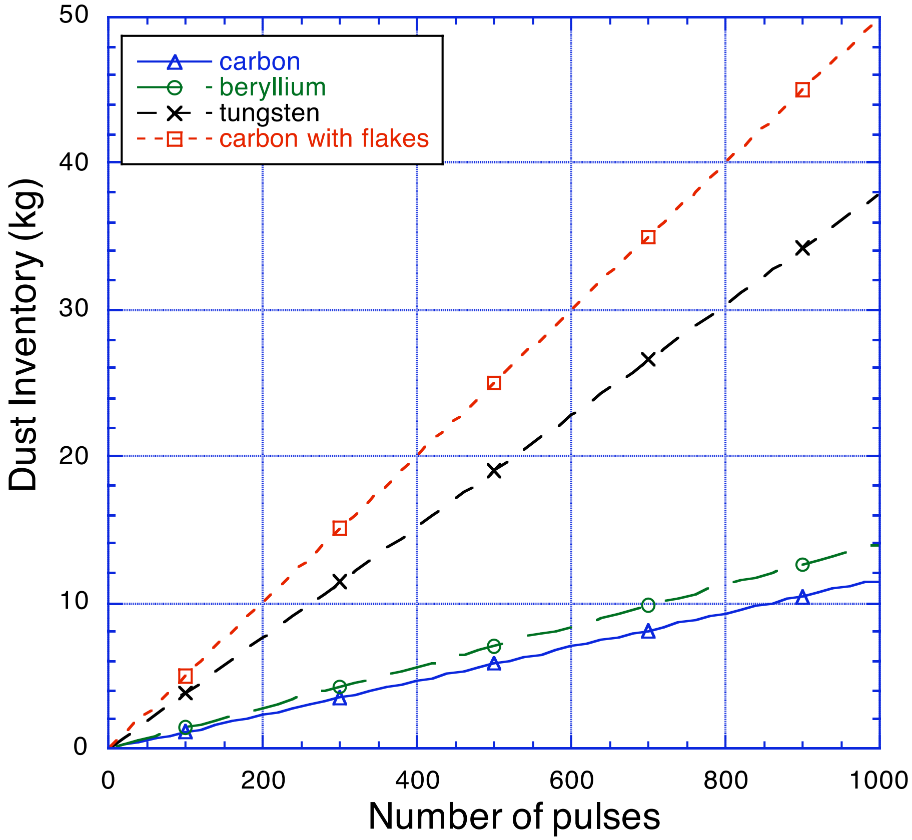
ITER safety depends on limiting dust inventory

Estimated Dust Production Rate



ITER schedule calls for 2,000 pulses / year

ITER dust production crudely estimated at 10% of sputtered, 50% of evaporated material assumed + flakes for CFC [G Federici, ITER JCT]
(first experimental data becoming available)

Dust Hazards:

Dust	**Safety Issue**	**Limits (kg)**
Beryllium	Reactivity with steam and H_2 Toxic	10-20 on hot surfaces
Carbon	Tritium retention Explosion with air	~100
Tungsten	Activation	100-400

•Limits for C-and Be-dust are related to an explosion (e.g., H produced by Be reactivity with steam).

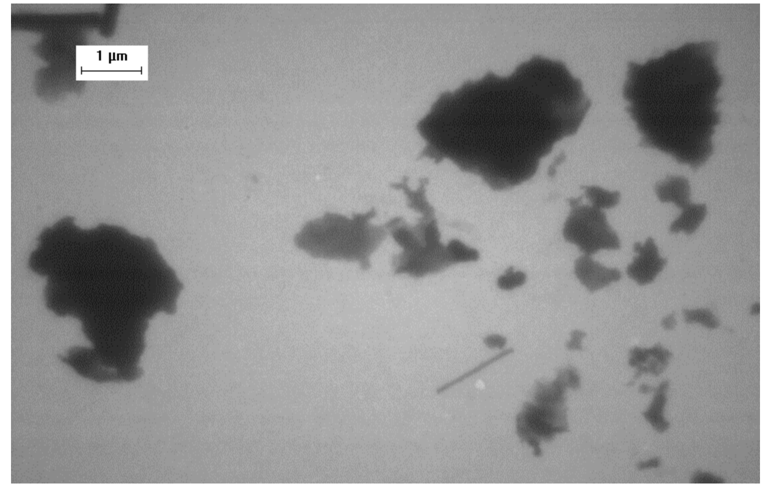
•The limit for W-dust is related to the containment function of the ITER building (is more flexible).

Dust diagnostics needed to assure ITER safe operation

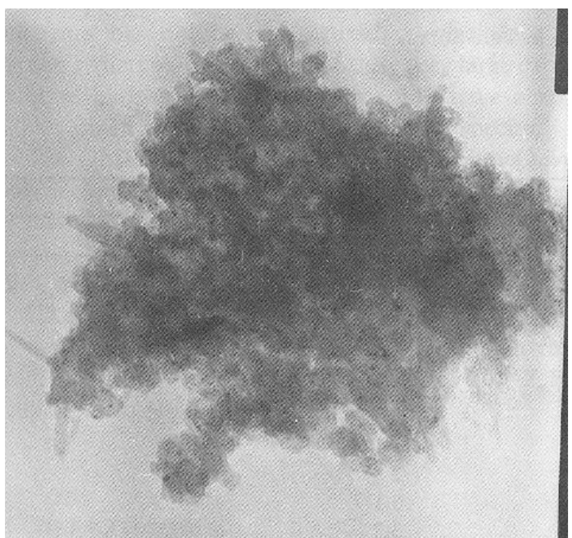
Independent of safety considerations: dust particles can move with high speed and could contaminate core plasmas.
[S. I. Krasheninnikov et al., Phys. of Plasmas 11 (2004) 3141]

Dust in contemporary tokamaks

Debris and dust on TFTR vessel floor 1 cm

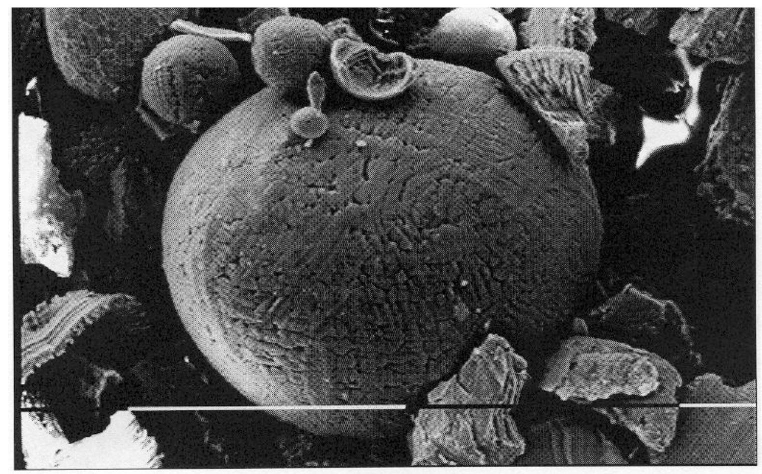


Dust retrieved from TFTR.



100 nm

TEM image of flakes from Tore Supra: globular and elongated structures.
Ph. Chappuis et al., J. Nucl. Mater 290–293 (2001) 245



0.1 mm

Iron spheres from TEXTOR-94 with the large sphere showing a regular surface texture
J Winter, Plasma Phys. Control. Fusion, 40 (1998) 1201

Dust in NSTX plasmas

- Dust particles can move with high speed and could contaminate core plasmas in NSTX *[S. I. Krasheninnikov et al., Phys. of Plasmas 11 (2004) 3141]*
- Dust diagnostics are *necessary* to assure safe operation of next-step devices (avoid steam explosion!)
- – but necessary technology does not exist.

Slow motion movie of discharge 112117 in NSTX, (100 μs exposure, at 4 ms intervals)

T. Biewer

Dust in NSTX

Microscope image of Bay B lower viewport
exposed 11 March – 5 August 2004

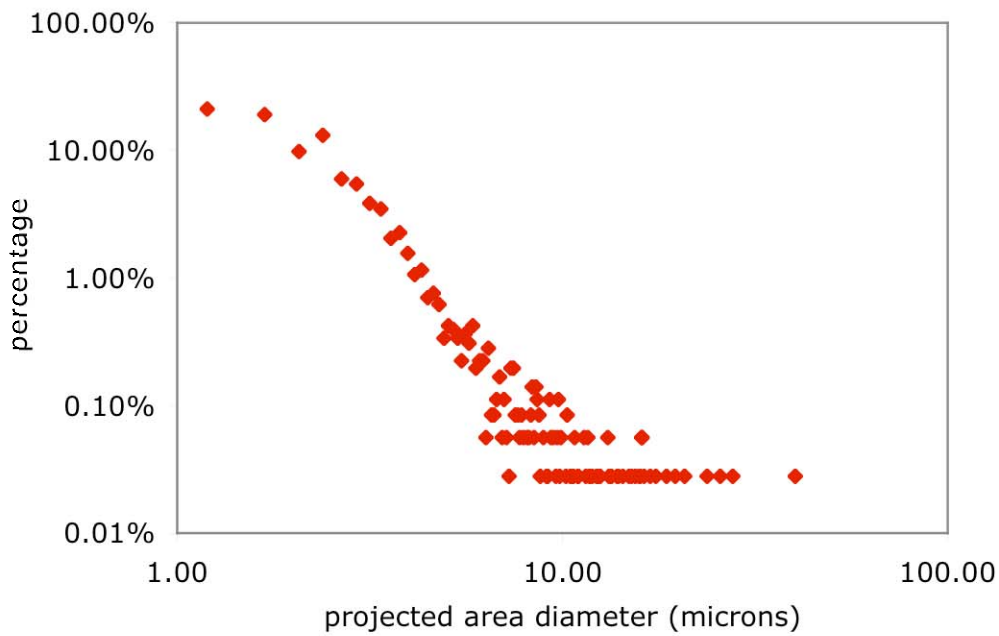
1,659 plasmas
793 s total duration
10,372 particles / mm^2
(excl. those < 1 micron)

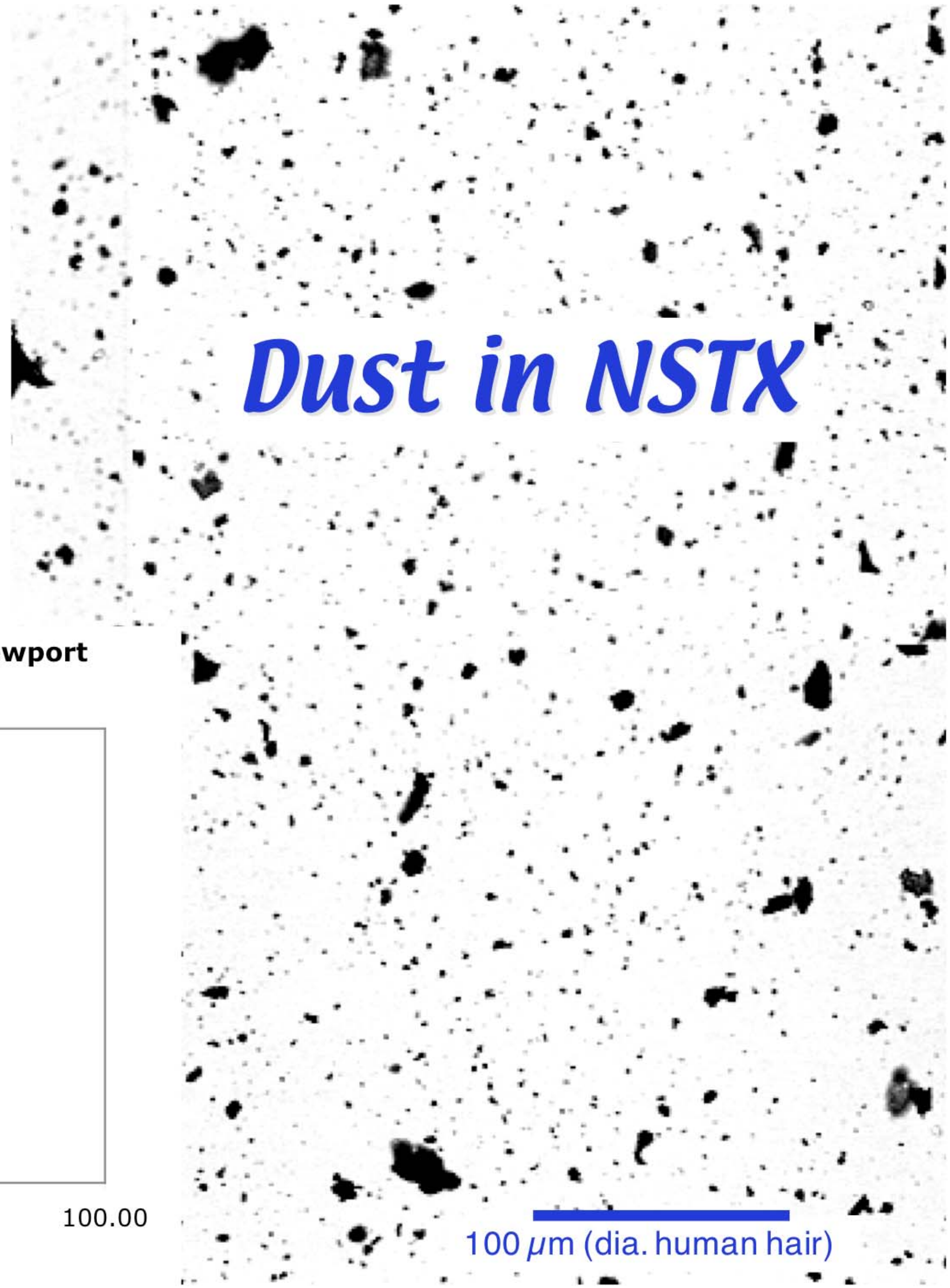
Dust est. surface area 1.2 mm^2 / mm^2

-exceeds area of viewport

Count Median Diameter = 2.07 μm
Geometric Standard deviation = 1.83 μm
Diameter of average mass = 3.56 μm

Size distribution of dust on Bay B lower viewport

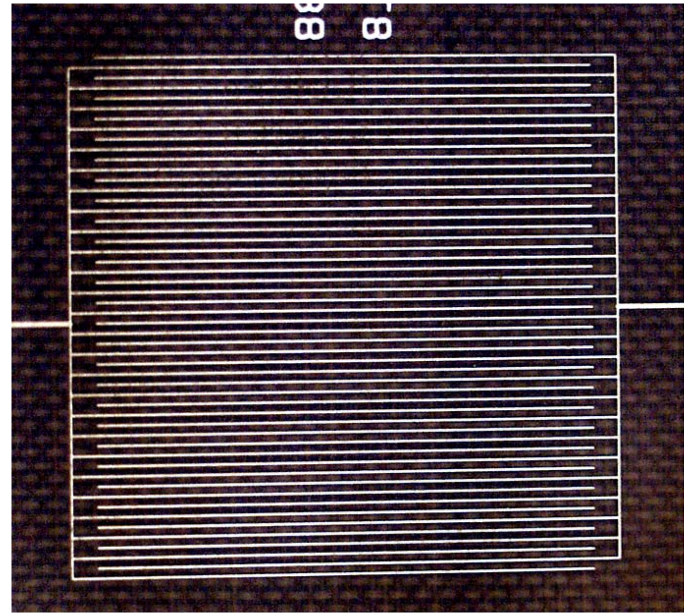


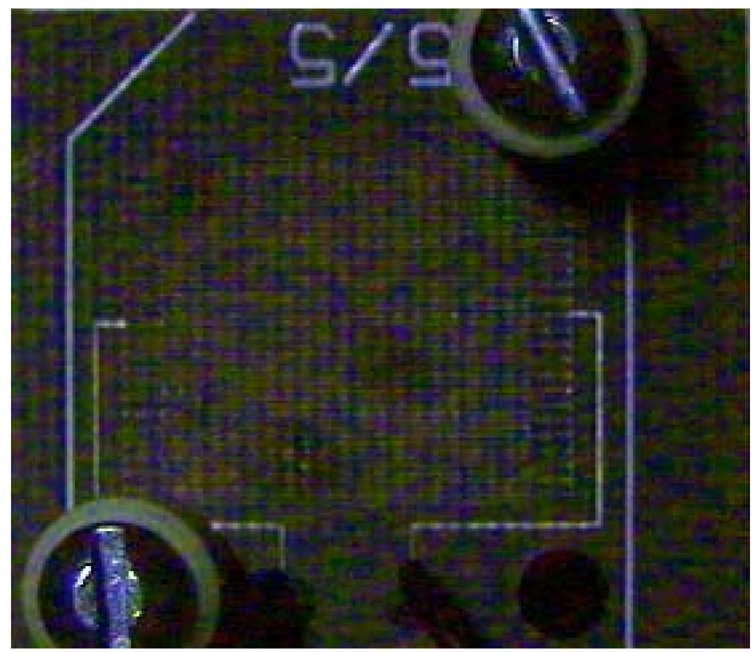


Novel electrostatic surface particulate detector for tokamaks

Principle:

- A fine grid of interlocking traces is biased with 30–50 v DC.
- Grid spacing range 25 μm – 762 μm (vacuum standoff > 200 v)
- Impinging dust produces a short circuit and current pulse that vaporises the dust.
- A signal is generated by the return current and recorded with standard nuclear counting electronics
- Laboratory tests confirmed sensitivity in air and vacuum to particles mechanically scraped from CFC tile (DPP APS poster 2004)





In collaboration with National Undergraduate Fellows:
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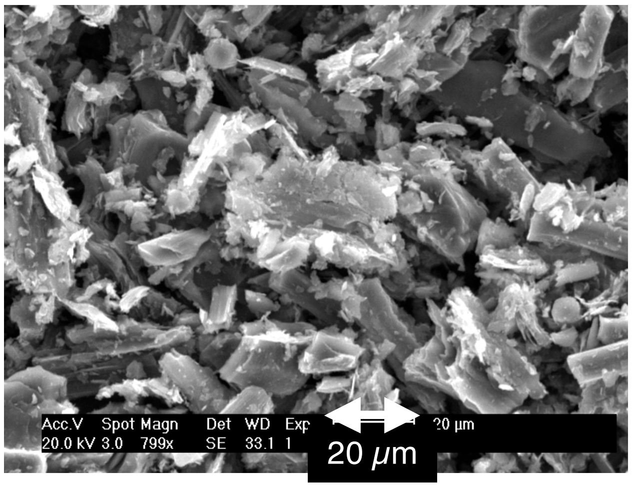
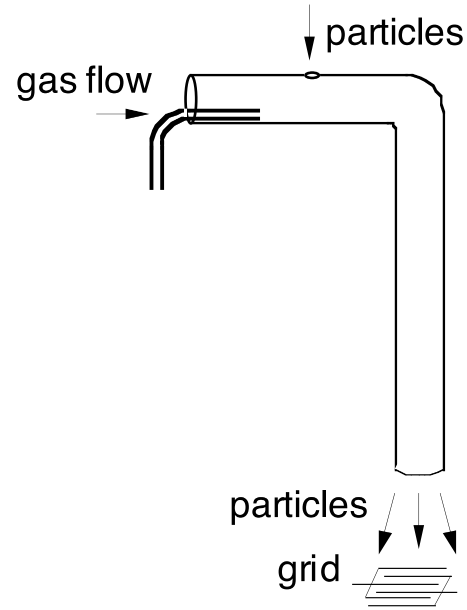
Chris Voinier, College of New Jersey

Laboratory tests in air:

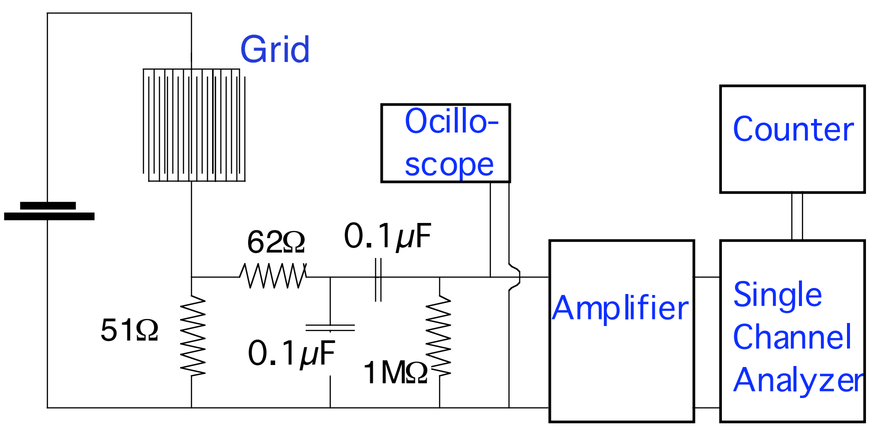
Particles scraped from CFC tile





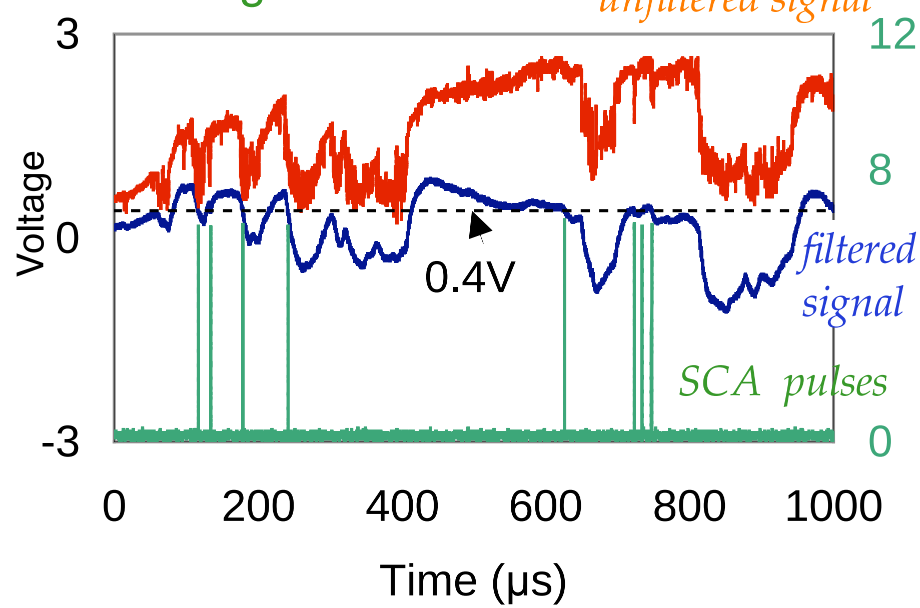
Electronics

30v DC bias



1.6 Hz – 25 kHz bandpass RC filter

Signals



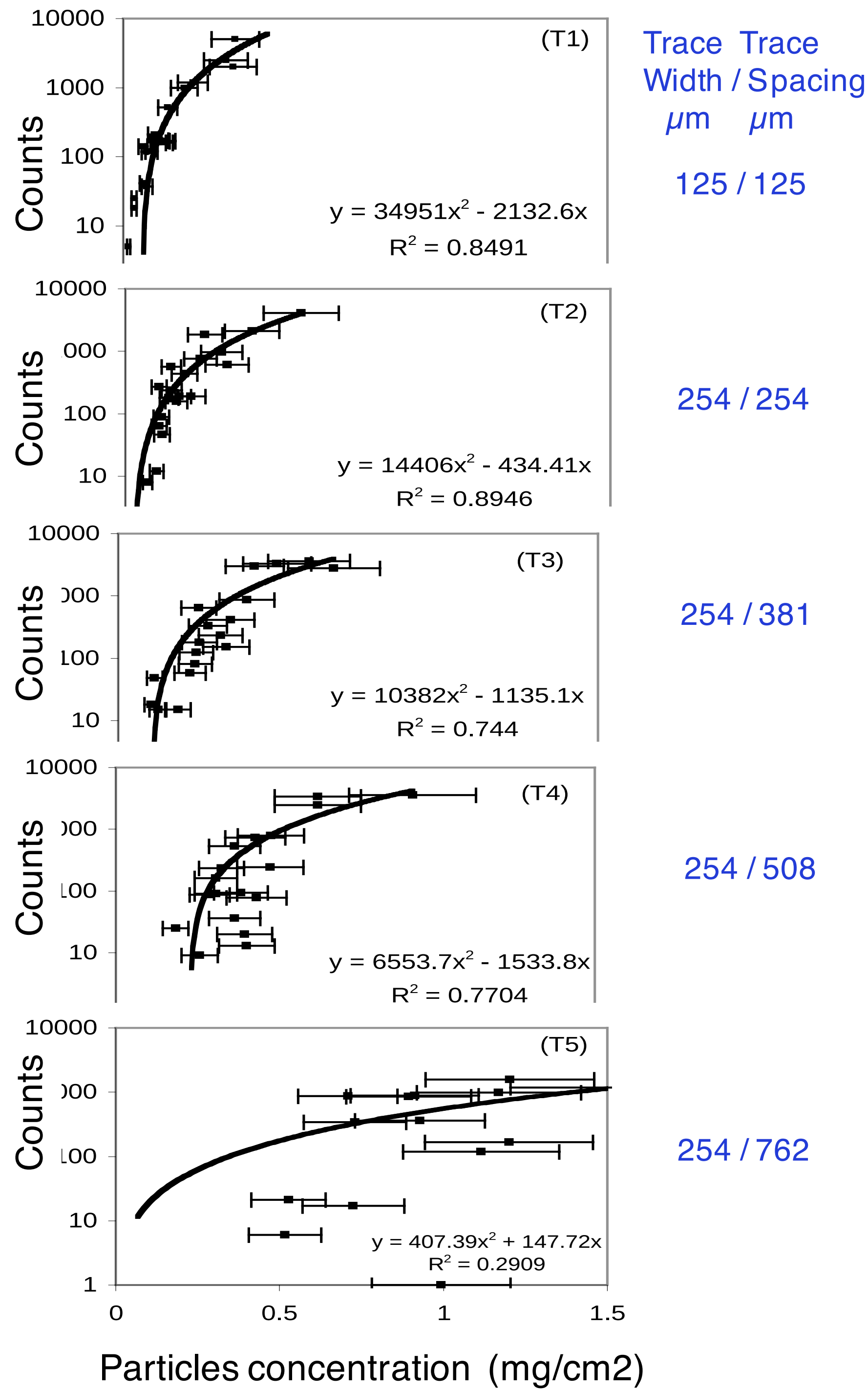
Recorded counts related to amount of particles:

Counts vs. areal density of particles on
5 grids with spacing 125 μm – 762 μm
30 v bias, counts accumulated for 10 s.

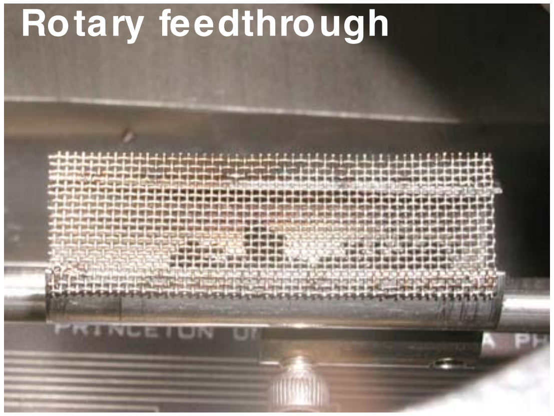
Horizontal bars represent variability in particle deposition.

Data fit to 2nd order polynomial

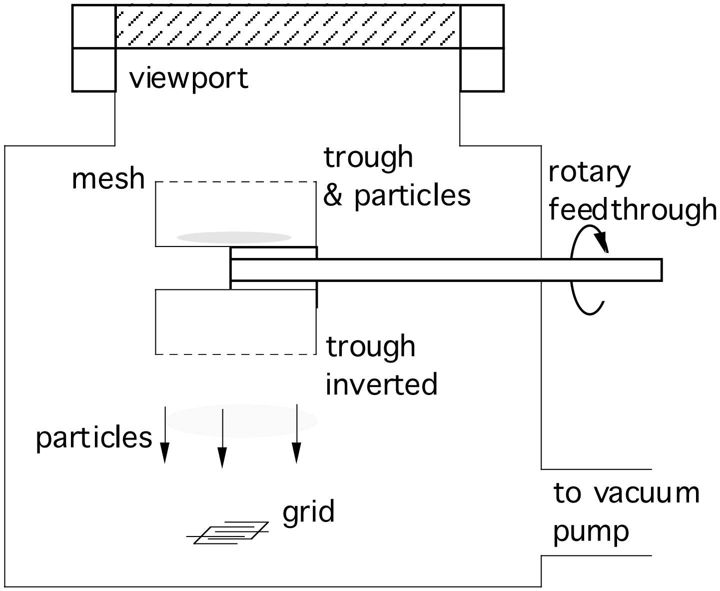
Operating principle is electrostatic not gravimetric.
However some correlation between recorded counts and particle concentration, especially at fine grid spacings.



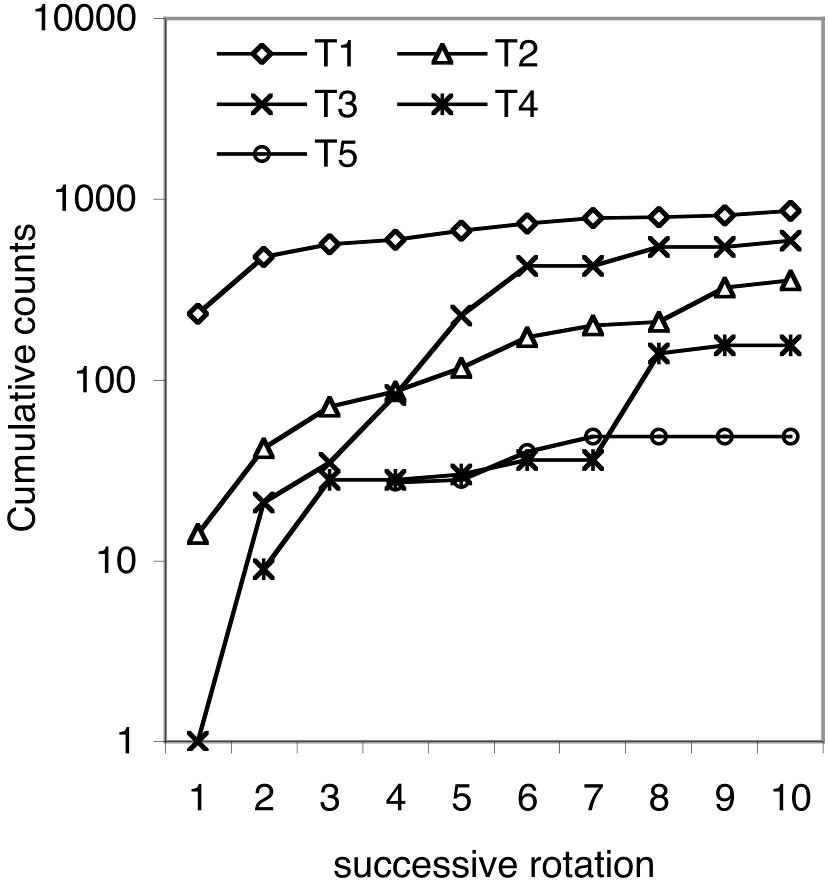
Tests in vacuum:



10 rotations deposited 0.7 mg on grid area
50 v bias needed to vaporize particles in vacuum

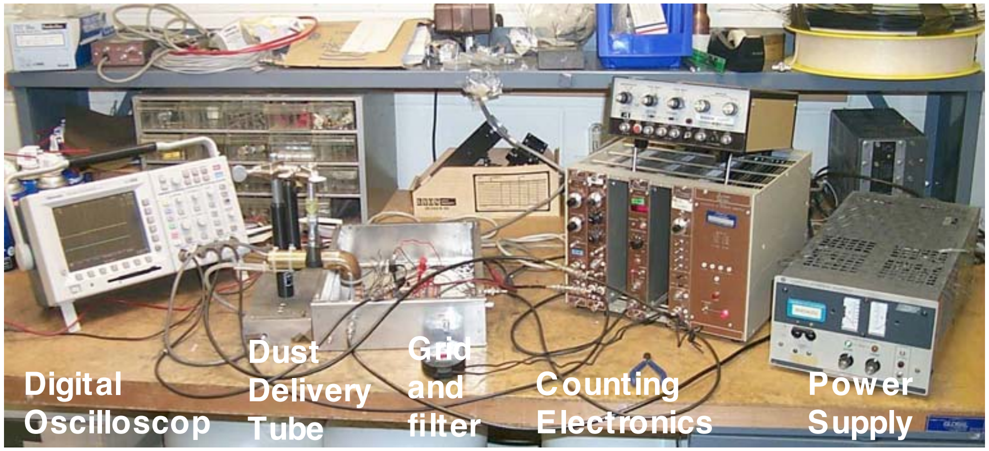


Cumulative counts per successive rotation
est. 0.07 mg dust/ rotation
Data shown for 5 grids with spacing 125 – 762 μm

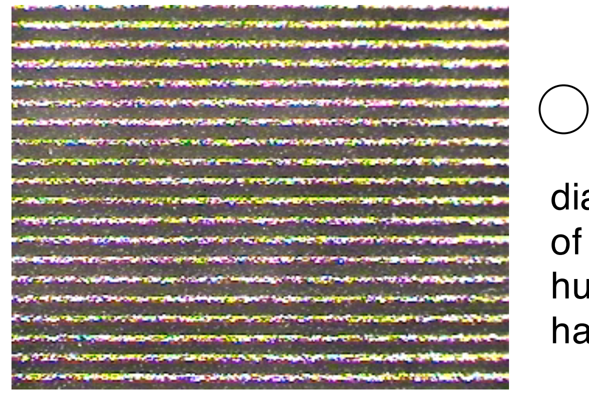


More info. in Rev. Sci. Instrum. ***75,*** *370 (2004).*

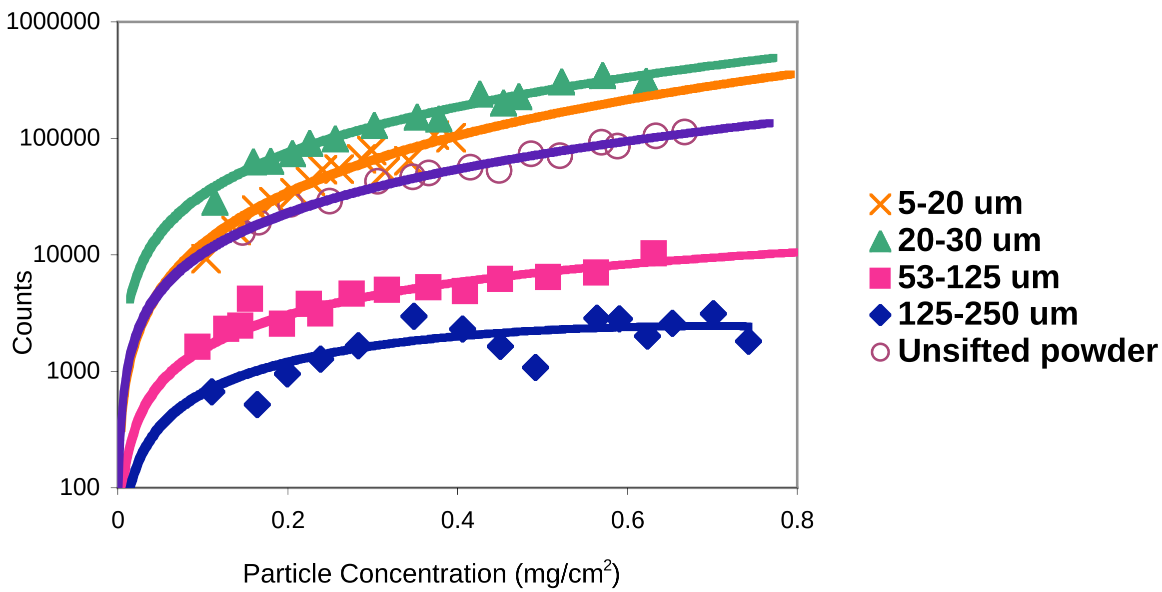
Sensitivity increased ~ x 30 with finer grids



Close up of grid with 25 μm traces



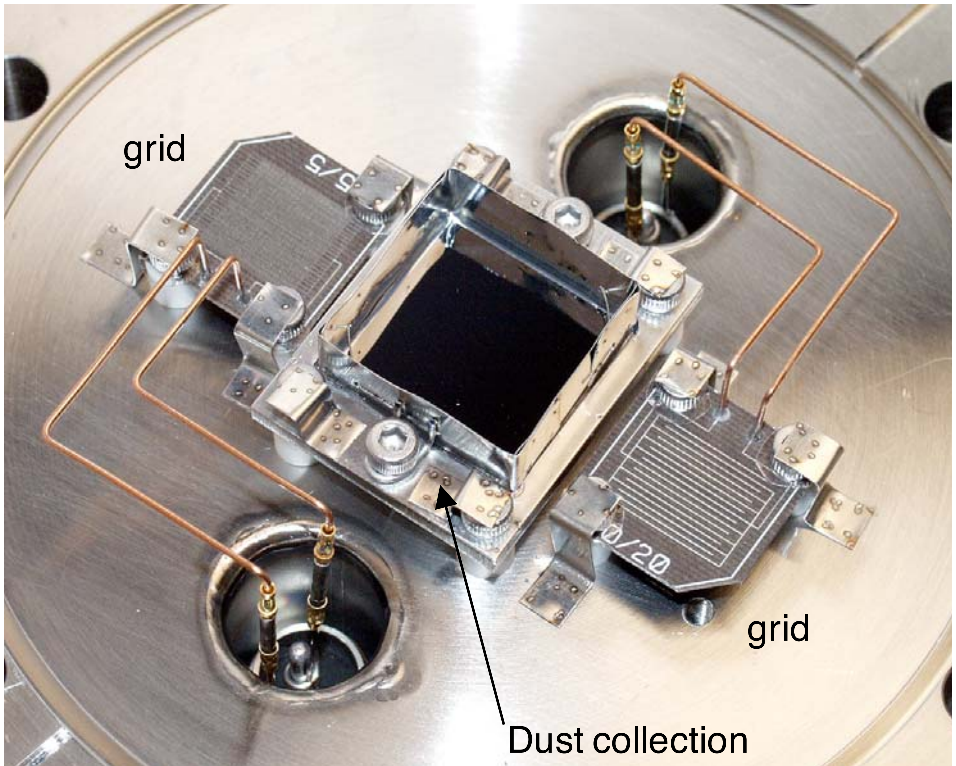
Counts recorded with 25μm grid as function of particle size.

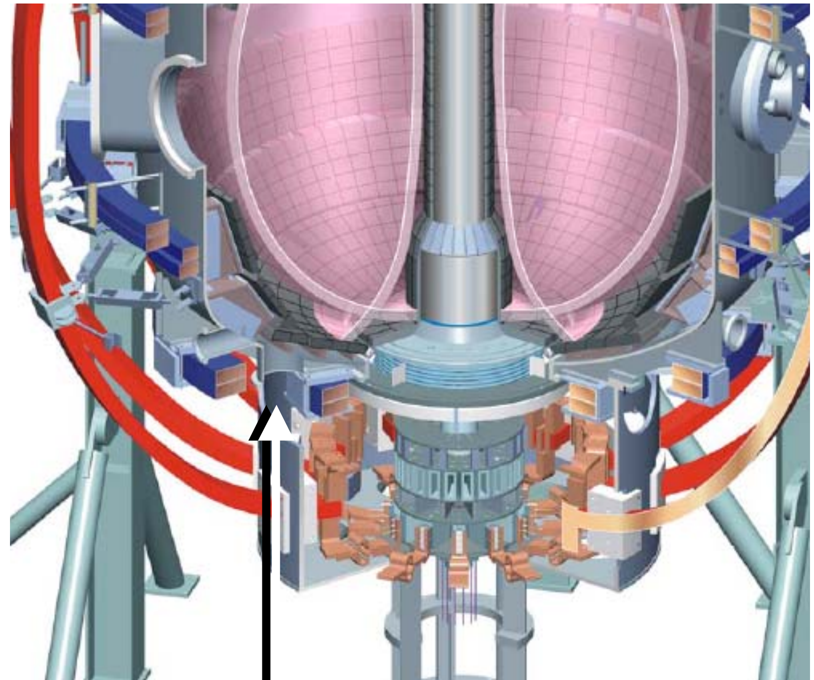


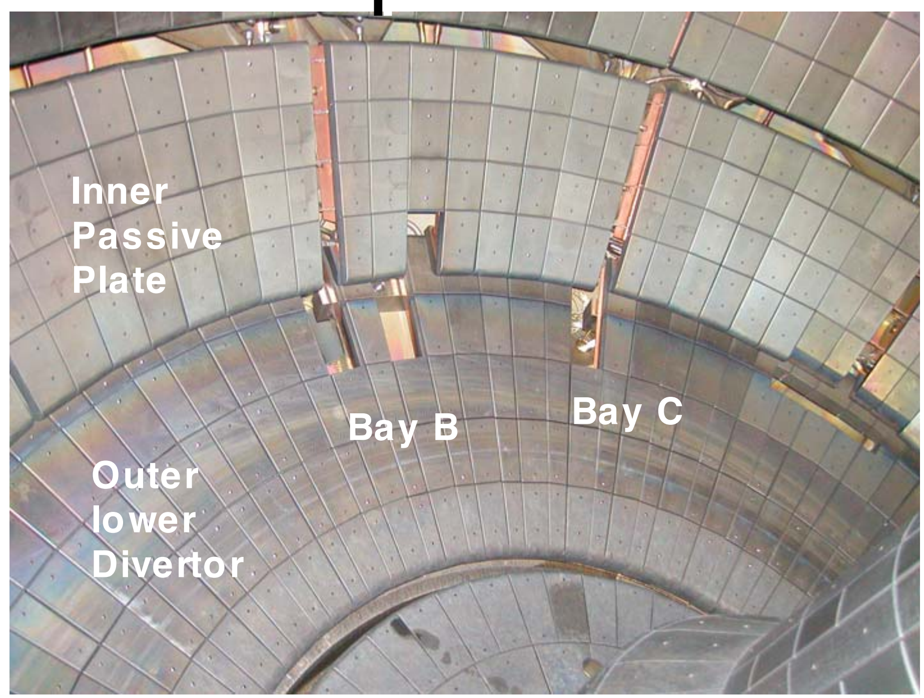
Ultimate sensitivity ?

Detector installed in NSTX:

Dual grid configuration installed at Bay E bottom on NSTX 25 March '04







Status:
Signals detected on NSTX with 125 μm spacing grids but uncertainty over effects of UV.
25 μm grids > 10 x more sensitive grid
ready for deployment next run

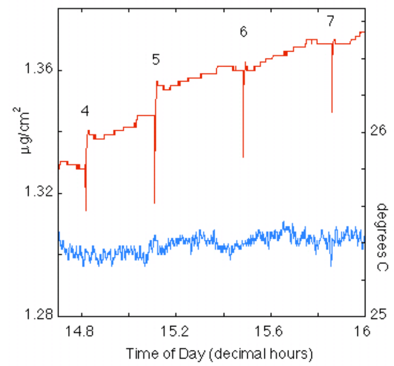
Summary:

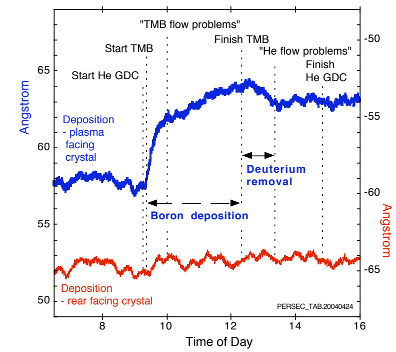
DEPOSITION:

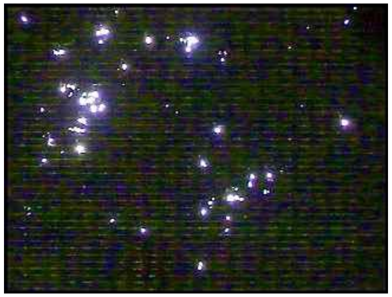
- Deposition typically measured on first discharges of day.
- Deposition slowly accumulates between discharges – tritium migration ?
- Deposition measured during boronization

DUST:

- Most NSTX dust is few microns scale; surface area significant.
- Electrostatic dust detector developed
  - in 2004 sensitivity increased ~ x30 with ultrafine (25 μm) traces.
  - *Enhanced sensitivity detector will be deployed on NSTX next run.*







Appendix:

5 viewgraphs:

Report from 2002 work with Nd laser:

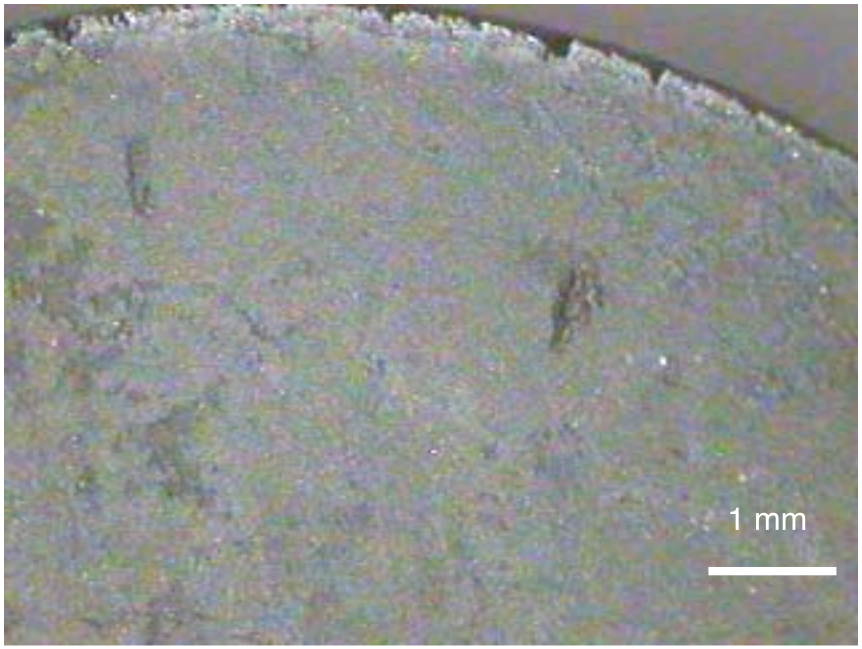
- Be/C layer appears to form 'beads' in response to heat flux.
- Thermal response of Be/C material:
- Thermal response of ion damaged tungsten

- **Plasma Facing Materials for ITER DT**

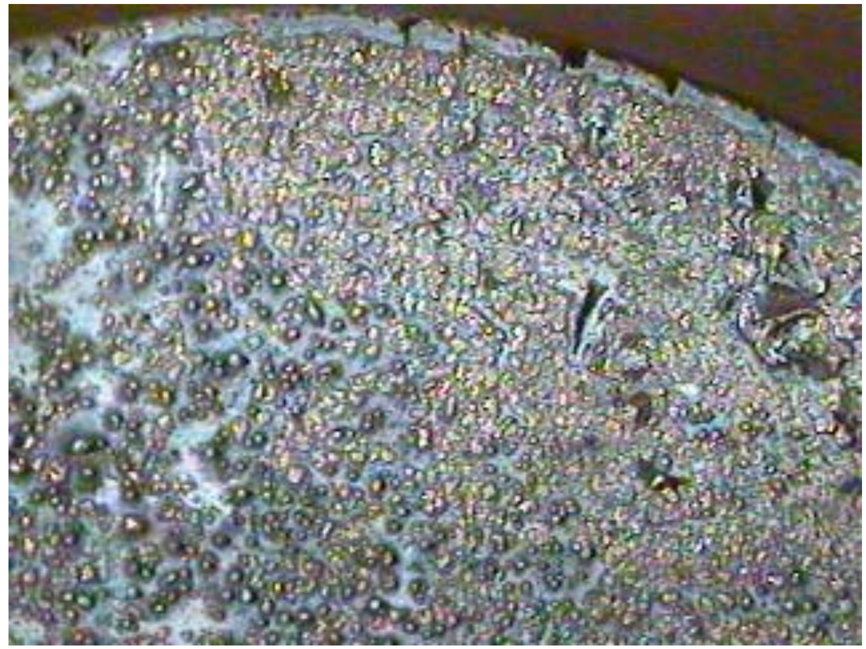
  a personal view :

Be/C layer appears to form 'beads' in response to heat flux.

JET tile IN3–16 (vertical tile, inner divertor) before Nd laser scan

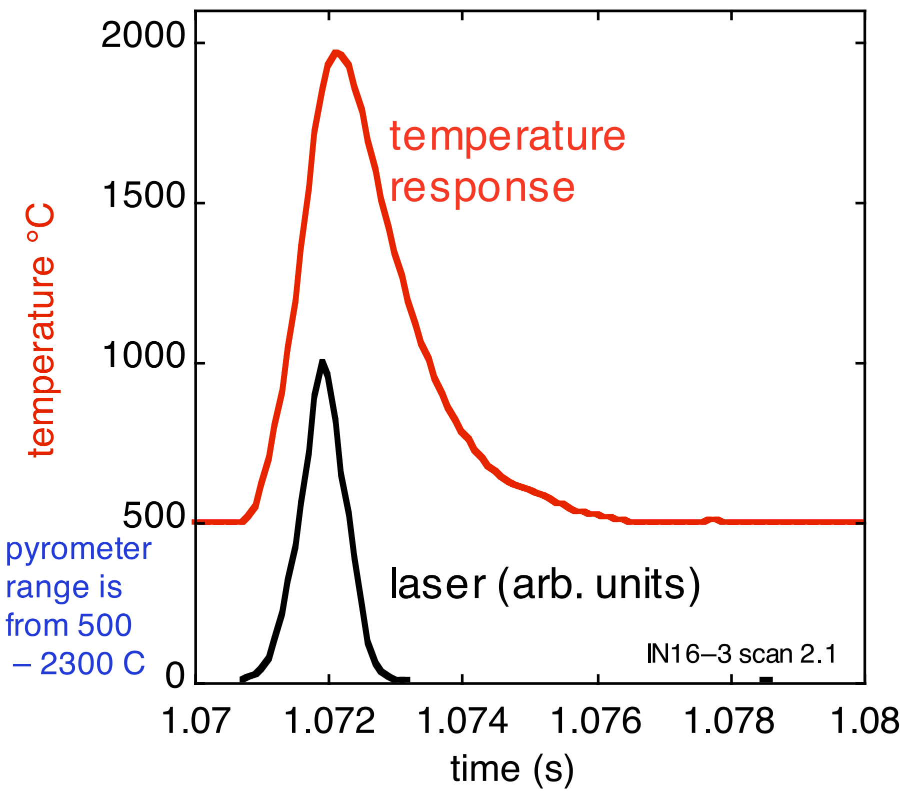


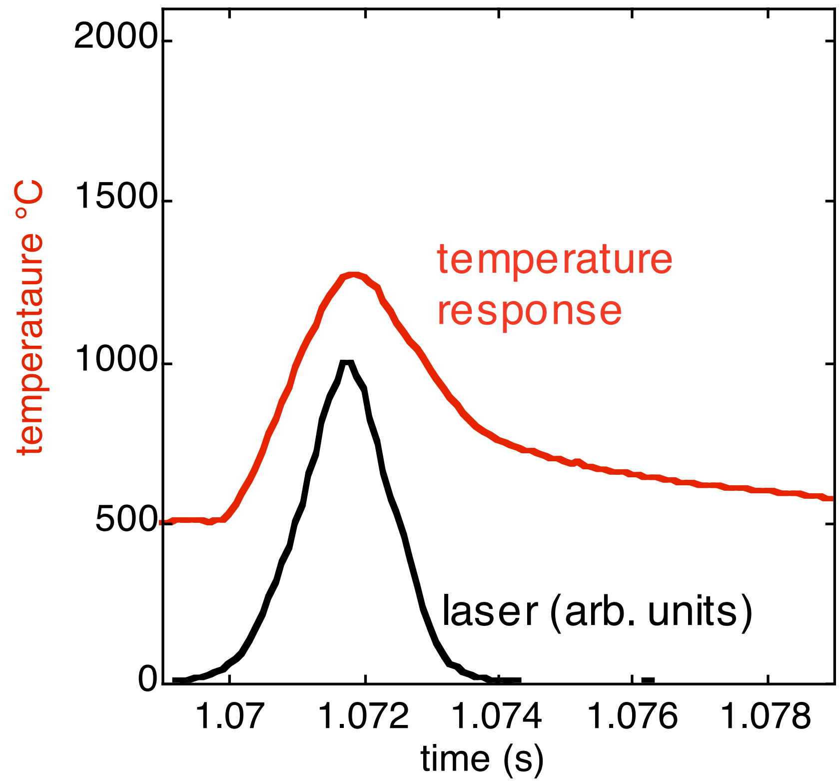
After laser scans



'Globules' of Be formed after laser heating.
21 temperature excursions above 1000 C, peak temperature 2,100 C.
Subsequent scans at same laser power and speed resulted in lower temperatures (1,601 C then 1,314 C) as layer became more thermally conducting similar to the manufactured material.
Other codeposits (without Be) did not show this major temperature decrease.

Thermal response of Be/C material:





1st laser scan.
Duration over point 0.8 ms FWHM
temperature rises to 1963 C.

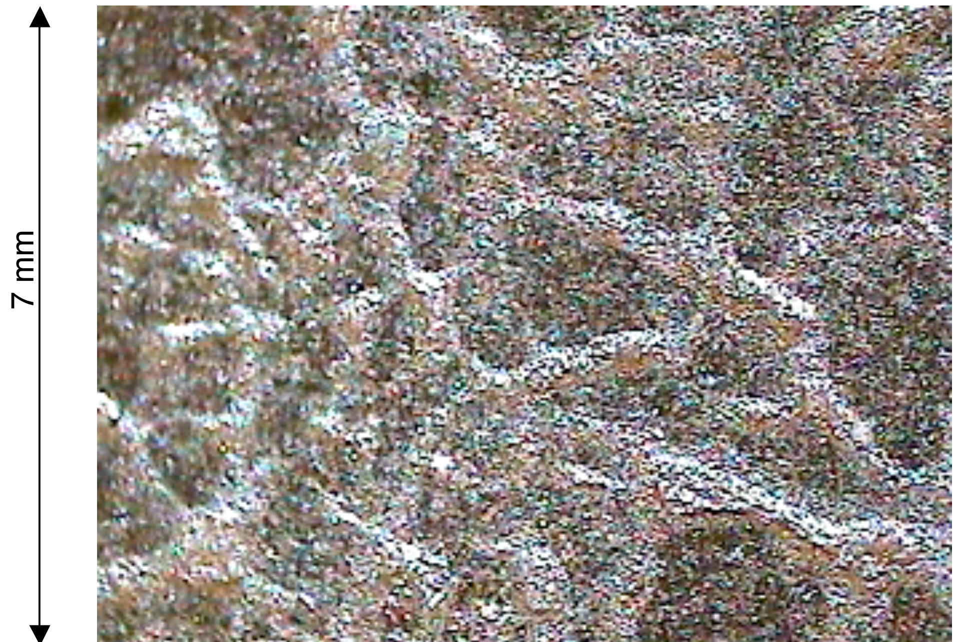
20th heat pulse over same area.
scan speed reduced x2; pulse 1.6 ms.
temperature rise only 1270 °C

– surface has changed....

Illustrates potential for ‘surprises’
with mixed materials – and underlines
case for operating current tokamak with ITER materials

Thermal response of ion damaged tungsten

W sample implanted with 1e21 D @ 200 eV (courtesy of J. Roth).



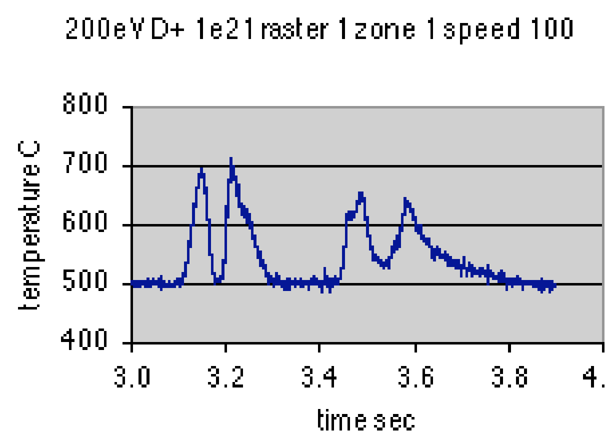
200evD+1e21x1x4_e.BMP

low power x4
optical microscope

Use scanning Nd laser to transiently heat (laser has smooth focal spot)

During laser scan

W_03still.jpeg



Ion implantation features change thermal response.
- PFC surfaces manufactured by tokamak and may not have same properties as factory-manufactured material.

Plasma Facing Materials for ITER DT

a personal view – Charles Skinner:

Present ITER PFC strategy:

- Use CFC in divertor for H/D operation,
- Assess H-isotope retention and PMI issues
- Decide on W or C divertor for DT operations

BUT:

- Retention in H-phase will be obscured by H_2O in tiles.
- No plans exist for deposition diagnostics to measure codeposits in ITER.
- No substantial effort exists to develop and test suitable tritium removal technology in tokamaks (and this is 16 years after discovery of codeposition in TFTR and JET !).

CONCLUSION:

- Full W divertor for ITER-DT appears inevitable.
- Carbon specific parts of ITER physics base will <u>not</u> be relevant to ITER-DT.

Scale-up in required T removal rate ($\times 10^4$) is higher than any other ITER parameter.

	TFTR	ITER projections
Tritium site inventory	2g	350 g
T removal efficiency	50%	~ 100%
T removal rate	1 g / month	100 g **overnight**

See:

C. H. Skinner, J. P. Coad and G. Federici 'Tritium removal from carbon plasma facing components' Physica Scripta T111, 92-97, 2004.
G Federici 11th European Fusion Physics Workshop (Heraklion Crete Dec. 2003) ed. D. Campell to be published in PPCF

Biggest technical risk in ITER could be choice of plasma facing materials:

To make carbon a credible choice for ITER DT needs a crash program in tritium removal:

- Selection of existing H-isotope removal techniques for intensive development.
- Testing of H-isotope removal in existing tokamaks.
- Demonstration of H-isotope removal from hard to access areas (e.g. gaps between tiles)
- Demonstrate tokamak removal rates that extrapolate to ITER requirements i.e. ~ 100 g overnight (10,000 x higher than achieved in TFTR or JET).
- Demonstration of close to 100% removal efficiency (cf ~50% achieved in TFTR and JET).
- Real time deposition diagnostics in present machines (exists in NSTX, planned for C-mod and DIII-D).
- Modeling codeposition and T migration - validation of modeling against expt.
- Expect close scrutiny by nuclear regulators

For an all-tungsten divertor:

- Present ITER physics base is derived mostly from carbon machines.
  - How much will carry over to an all-tungsten divertor?

Need more emphasis on tungsten, e.g.:

- Transport of tungsten melt layer loss after ELM/disruption melting ?
- Benchmark disruption simulation codes (e.g. HEIGHTS) against experimental disruption simulators.
- Expand use of tungsten in present tokamaks - develop high performance plasma scenarios without carbon. (W planned for C-mod, what about DIII-D & NSTX ?).
- Adapt diagnostics (e.g. CHERS) to carbon-free situation.
- Expand atomic physics base (emission lines, collision cross sections…) of highly ionized tungsten.
- Solid state properties of tungsten ?
- Mixed material issues
- Less emphasis on studying carbon specific phenomena