Key issues relating to Erosion, Dust production and Tritium Retention in ITER

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Content

- Background

	Source	Measurement	Management
Erosion	• Plasma heat and particle source • Wall component lifetime	• LASER ranging techniques • Impurity flux measurement	• Scheduled replacement • Observation during operation
Dust Accumulation	• Inventory limits • Hot and cold dust	• Local microbalance • Other methods	• Dust Removal
Tritium Retention	• Inventory limits	• Global measurement • Local measurement	• Tritium removal

- Summary

Background

- Erosion
  - Facing a plasma wears out material surfaces
  - Need to know when end of component life is approaching

- Deposition
  - very little eroded material is exhaust from the tokamak
  - it tends to redeposit on walls, often travelling some distance from its origin

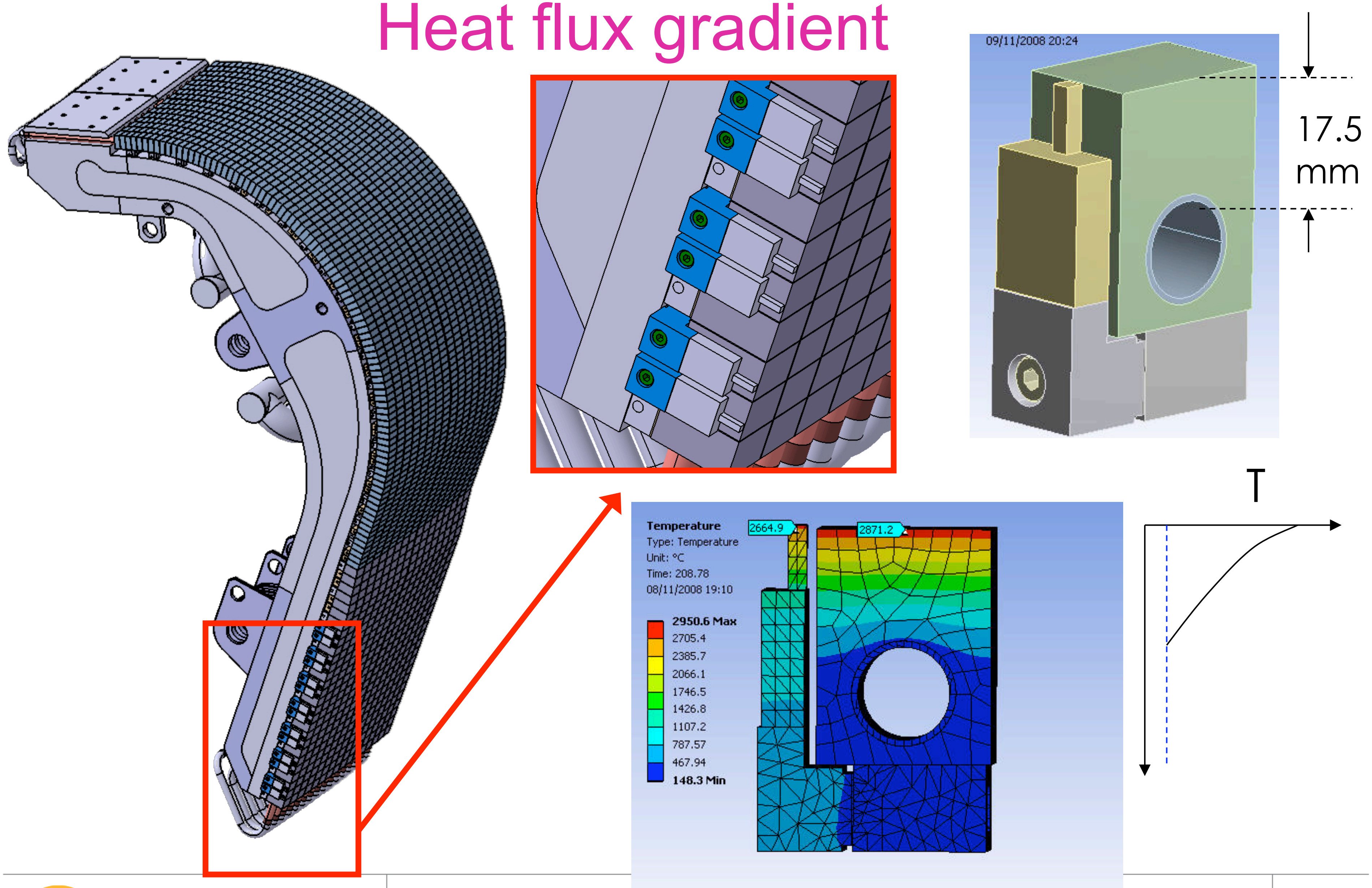
- Dust Accumulation
  - Some of the eroded material ends up as dust in the tokamak
  - The dust in the machine presents several safety issues

- Tritium retention
  - eroded material and fuel bombard surfaces simultaneously
  - fuel gets buried in the growing redeposited layer
  - In ITER safety regulations limit the amount of tritium permitted in the torus.

Source of Erosion

- Even though plasma is confined by magnetic field
  - Particles must flow out of the plasma
  - Heat must flow out of the plasma
- Contact with the plasma eventually “wears out” the surfaces
- Surface wear
  - is concentrated over a well defined surface
  - occurs both in a steady and transients events
  - ITER divertor must last for ~ 5 years
  - rest of ITER wall must last ~ 20 years
- Plasma/coolant distance
  - For steady heat removal: thinner -> cooler surface
  - For transient heat load: thicker
  - In ITER distance to coolant typically 1-2cm

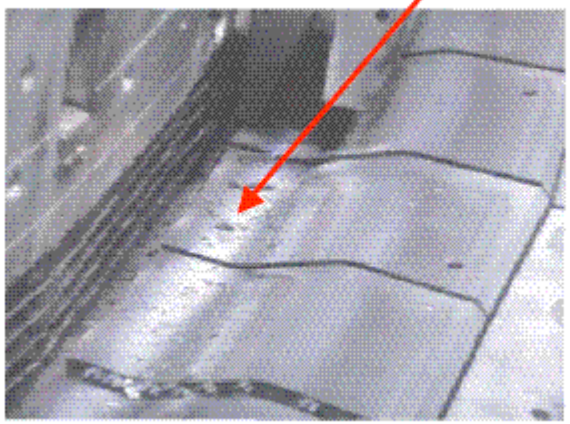
Heat flux gradient

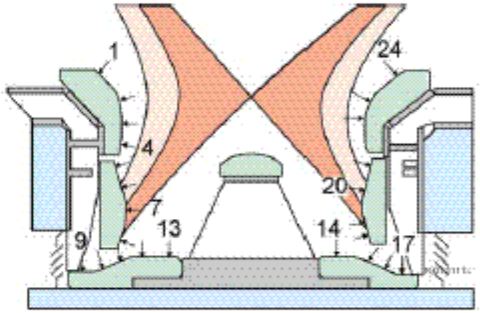


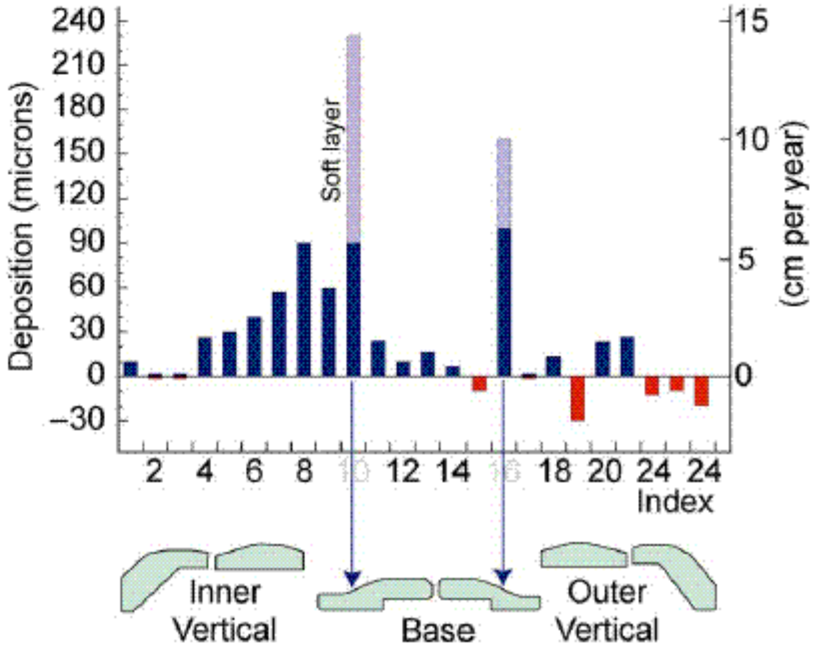
Erosion profile

- Net deposition ➔ wall source
- In/out asymmetry ($\mathbf{B}\times\nabla\mathbf{B}\downarrow$)
- C migration to remote areas

Macroscopic debris (flakes)







Erosion Measurements

- Divertor erosion measurement
  - Measurement parameters established

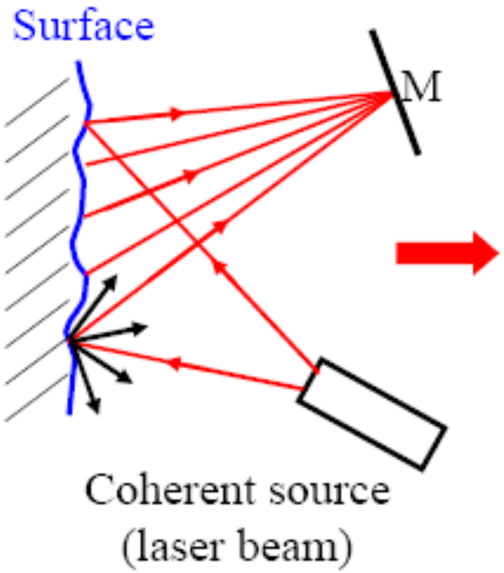
MEASUREMENT	PARAMETER	CONDITION	RANGE or COVERAGE	RESOLUTION		ACCURACY
				Time or Freq.	Spatial or Wave No.	
16. Divertor Operational Parameters	Erosion rate		$1 - 10 \times 10^{-6}$ m/s	2 s	10 mm	30 %
	Net erosion		0 – 3 mm	Per pulse	10 mm	12×10^{-6} m

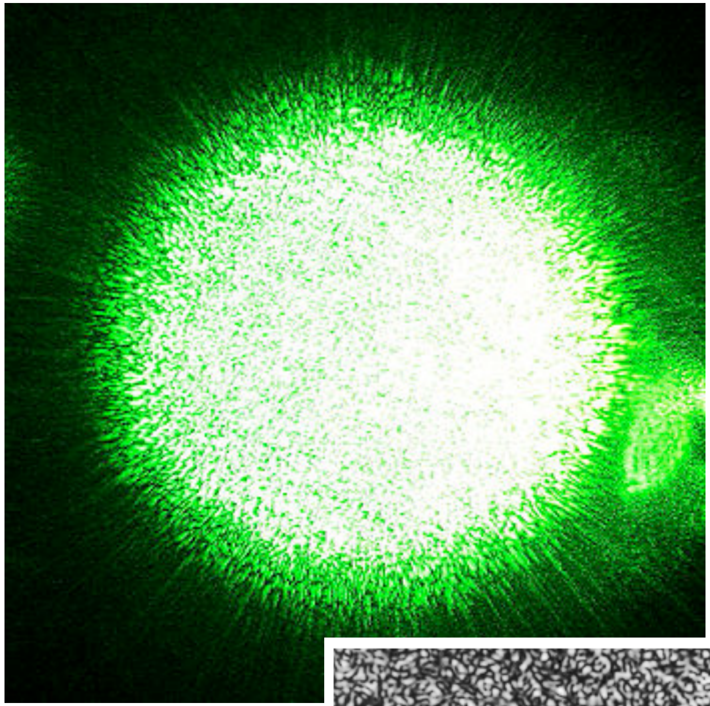
  - 2 Laser based methods under consideration
    - Speckle interferometry
    - Laser Radar
- Wall erosion measurement
  - Measure impurity influx into plasma

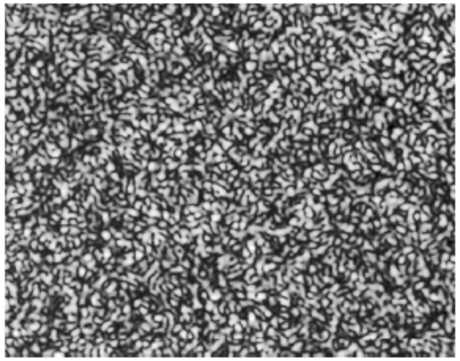
Speckle patterns

– Coherent light reflecting off a rough surface results in a pattern of constructive and destructive interference

– This pattern contains surface profile information

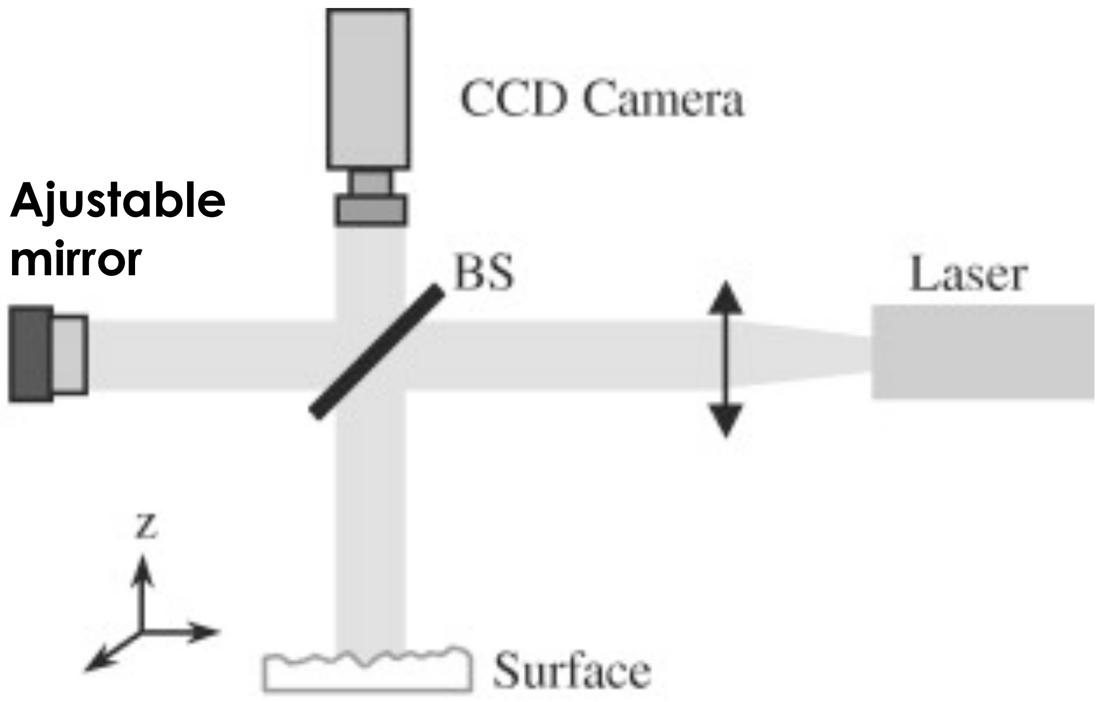






Speckle interferometry

– Use Michelson Interferometer geometry to combine
  - Reference coherent light with different phase shifts
  - Light reflected off surface



3 variables

Need minimum 3 equations

$I_1=I_0+I_m\cos(\varphi)$

$I_2=I_0+I_m\cos(\varphi+\pi/2)=I_0-I_m\sin(\varphi)$

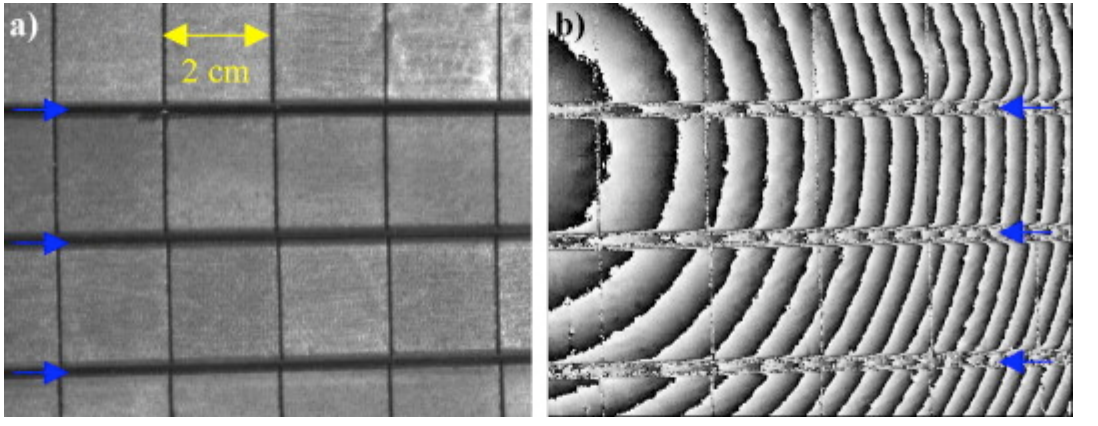
$I_3=I_0+I_m\cos(\varphi+\pi)=I_0-I_m\cos(\varphi)$

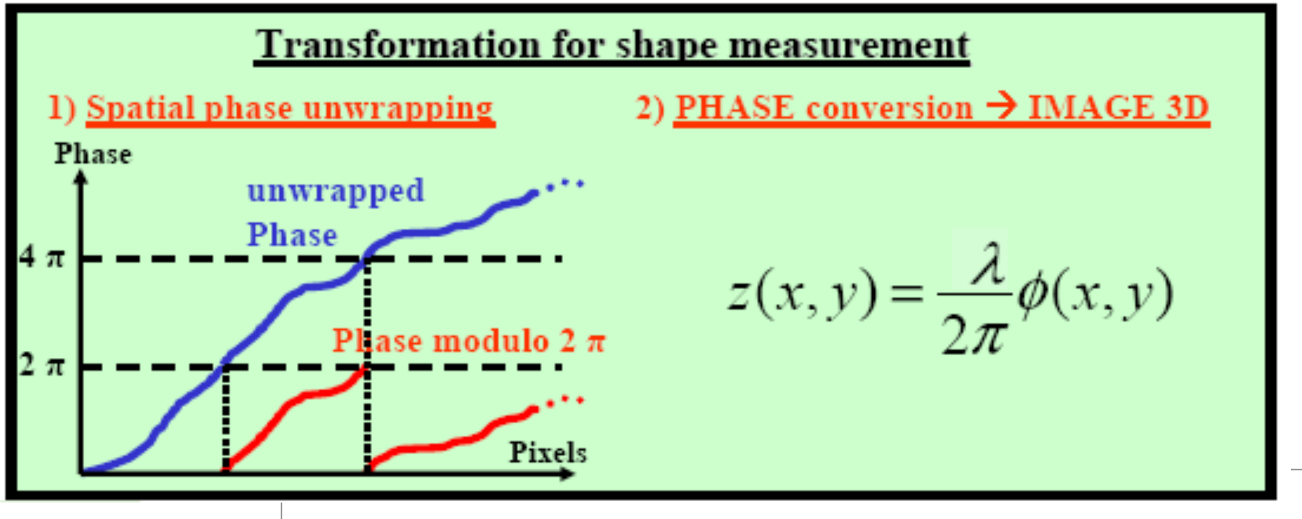
$I_4=I_0+I_m\cos(\varphi+3\pi/2)=I_0+I_m\sin(\varphi)$

$\varphi(x,y)=\arctan(I_4-I_3)/(I_1-I_2)$

Speckle interferometry

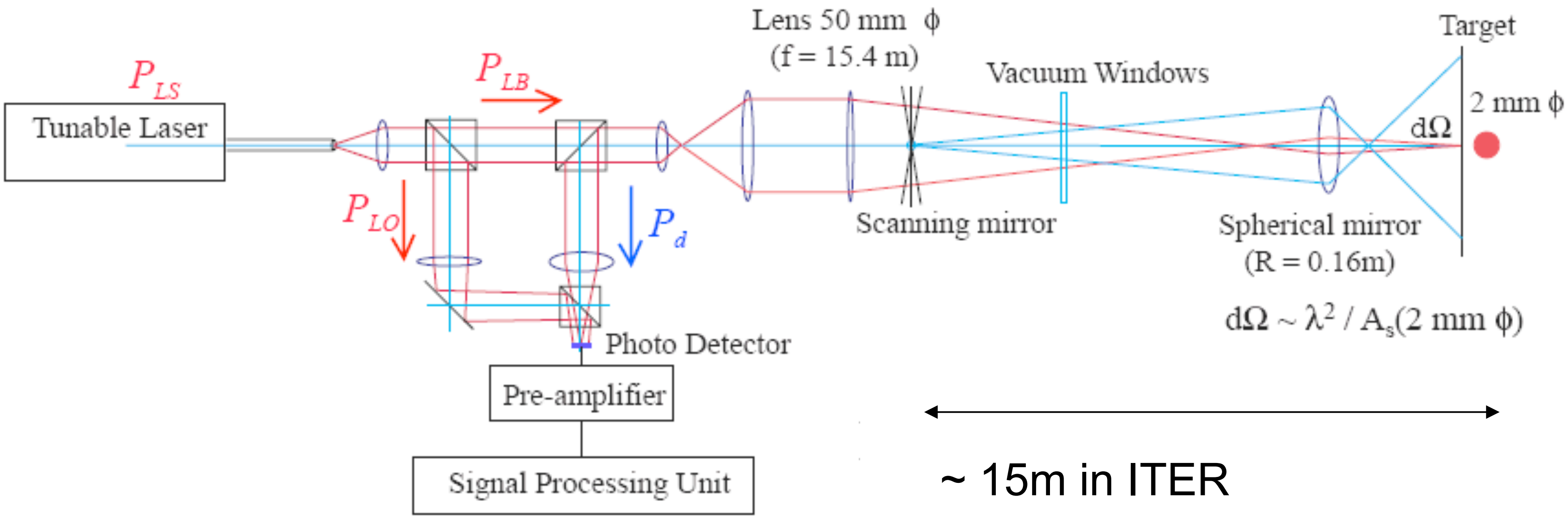
- This results in an interference image giving φ(x,y)
- Unwrapping phase gives the surface surface height
- Combining 2 different wavelenghts increases dynamic range





LASER radar

– Distance of probed surface determined from time of flight of laser light



~ 15m in ITER

– Eg. Thomson scattering (LIDAR) laser pulse $\Delta L = c \times 3\text{ns} \sim 1$ m

LASER radar

– LASER beam is frequency modulated so that a “leading edge” feature is distinguishible

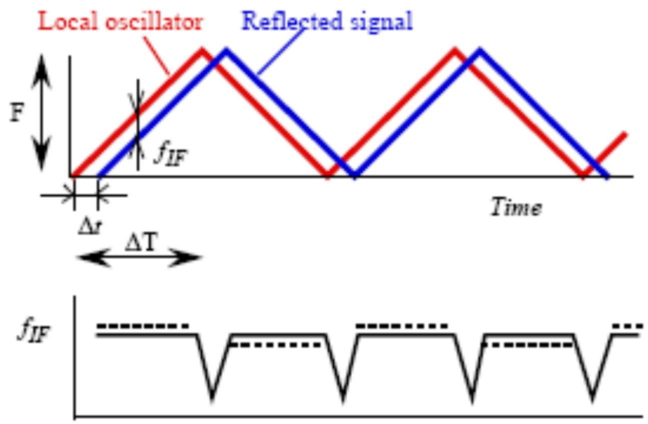


Fig. 1 FM laser radar measurement

$$R = c\,\tau/2 = c\,F_{beat} / (2\,\Delta F/\Delta t)$$

- Specifications of the tunable laser

  $\Delta F \leq 100$ GHz

  $1/(2\Delta t) \leq 1$ kHz

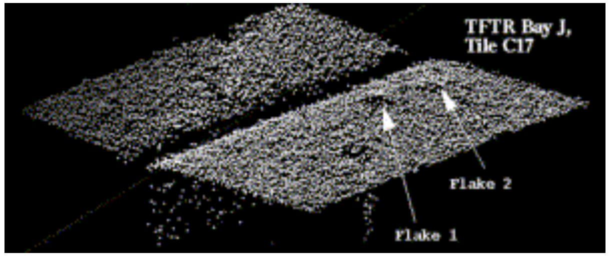
  Linearity of $\Delta F/\Delta t$ is crucially important

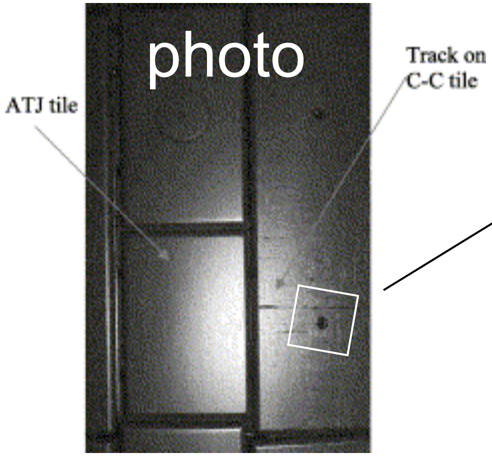
- When $\Delta F = 100$ GHz and 0.5 kHz sweep is applied, $F_{beat} = 10$ MHz will be detected by the optical heterodyne measurement for R = 15 m.

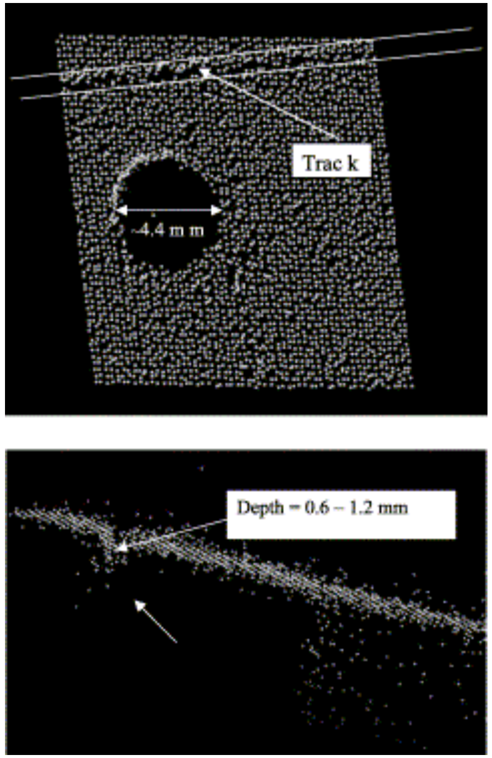
LASER radar

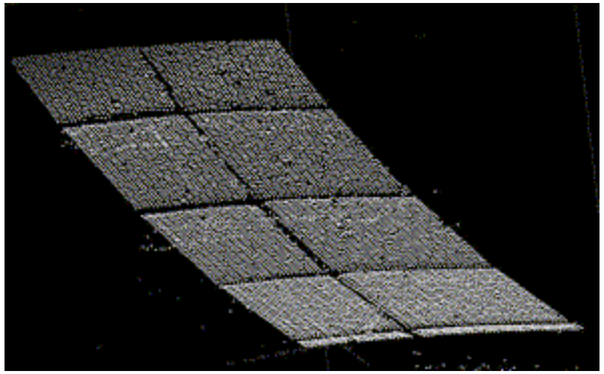
– Images taken in TFTR & NSTX tokamaks

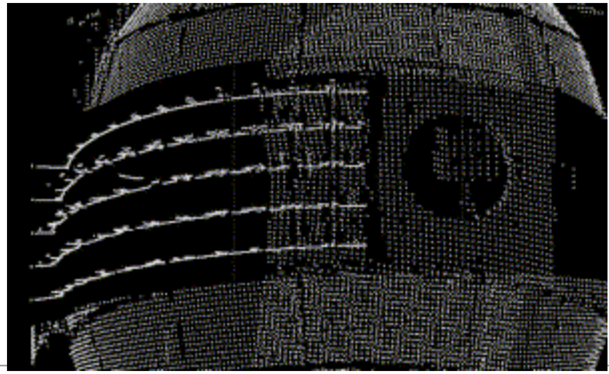
– Features < 1mm distinguishable











M.M. Menon et al. Fusion Engineering and Design

Volumes 58-59, November 2001, Pages 495-498

Comparison of 2 methods

– There are 2 LASER based depth probing techniques (LASER radar[1] & Speckle interferometry[2]) which meet ITER requirements

– Measure both erosion and deposition

– No Tokamak tested prototype, however, LASER radar used off-line

– Speckle uses laser to illuminate surface, but needs an imaging system to collect light

– FM Laser collects light back through laser path, but needs steerable mirrors to scan target

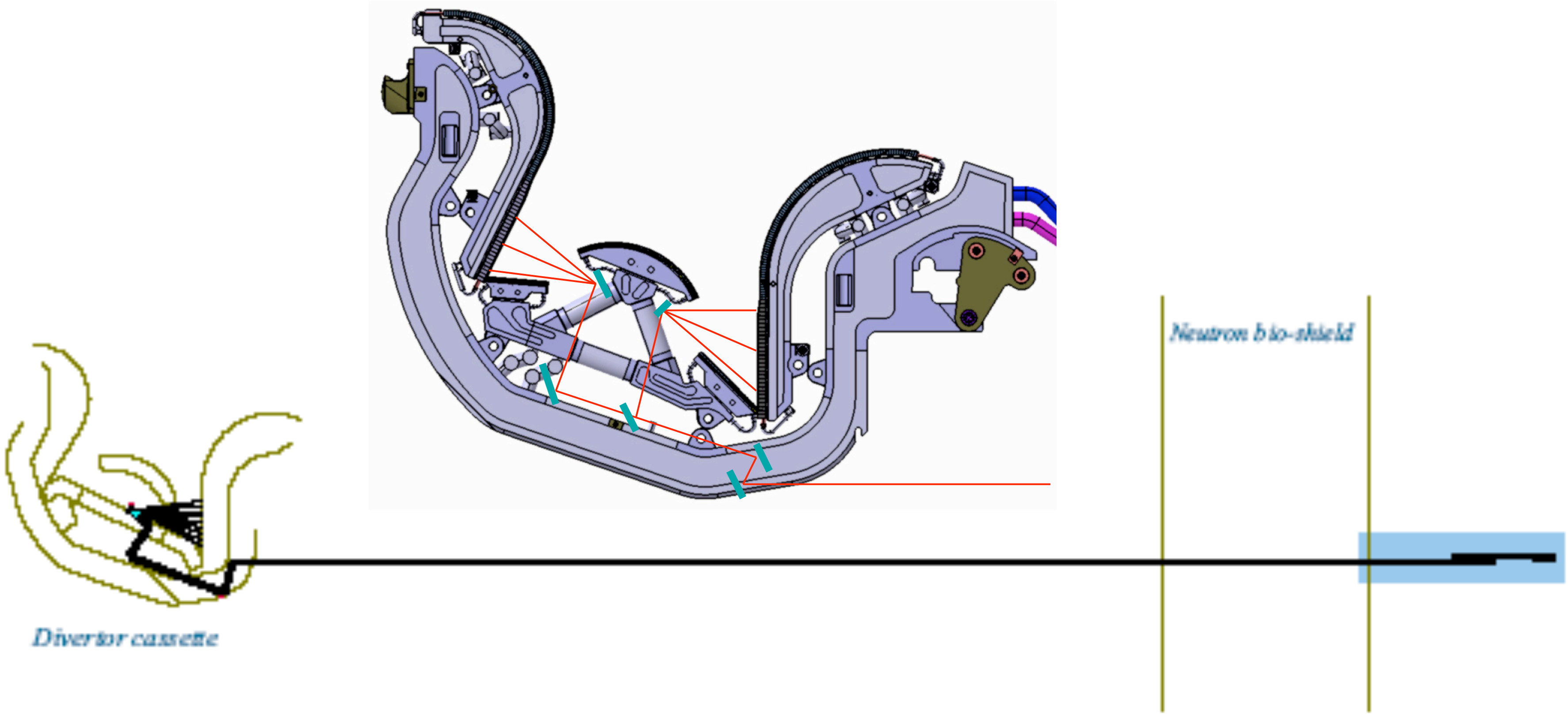
[1] K Itami et al

[2] P. Dore et al

Comparison of 2 methods

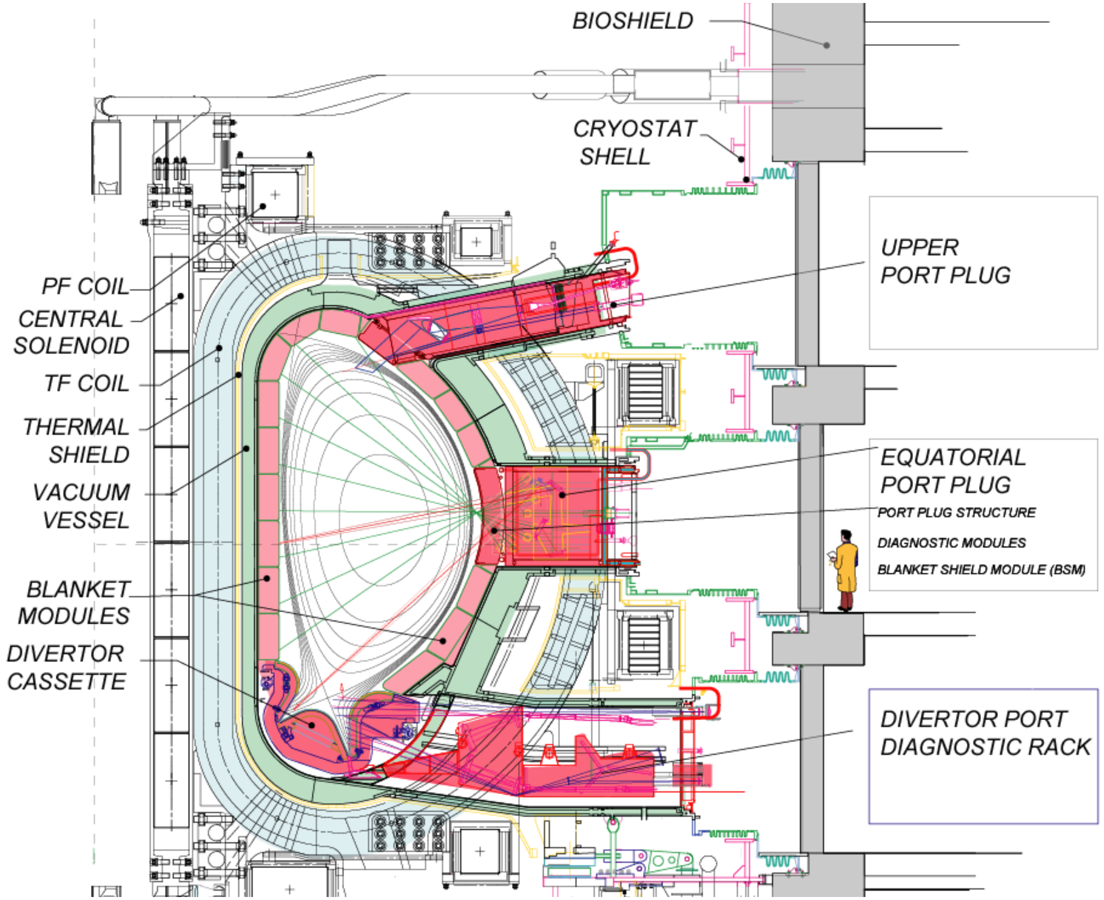
– Both techniques need reference point to distinguish erosion from vessel/divertor displacement

– from dome, target strike zones are visible (change in divertor profile)



Spectroscopic measurement of wall erosion

- ITER impurity spectrometers can give estimates of impurity influxes to plasma (WI, BeI, CI,II, etc)
- Assume total wall erosion = integrated influx to plasma
- Global measurement
- Transient events difficult
- Might be useful for estimate of mass of redeposited material



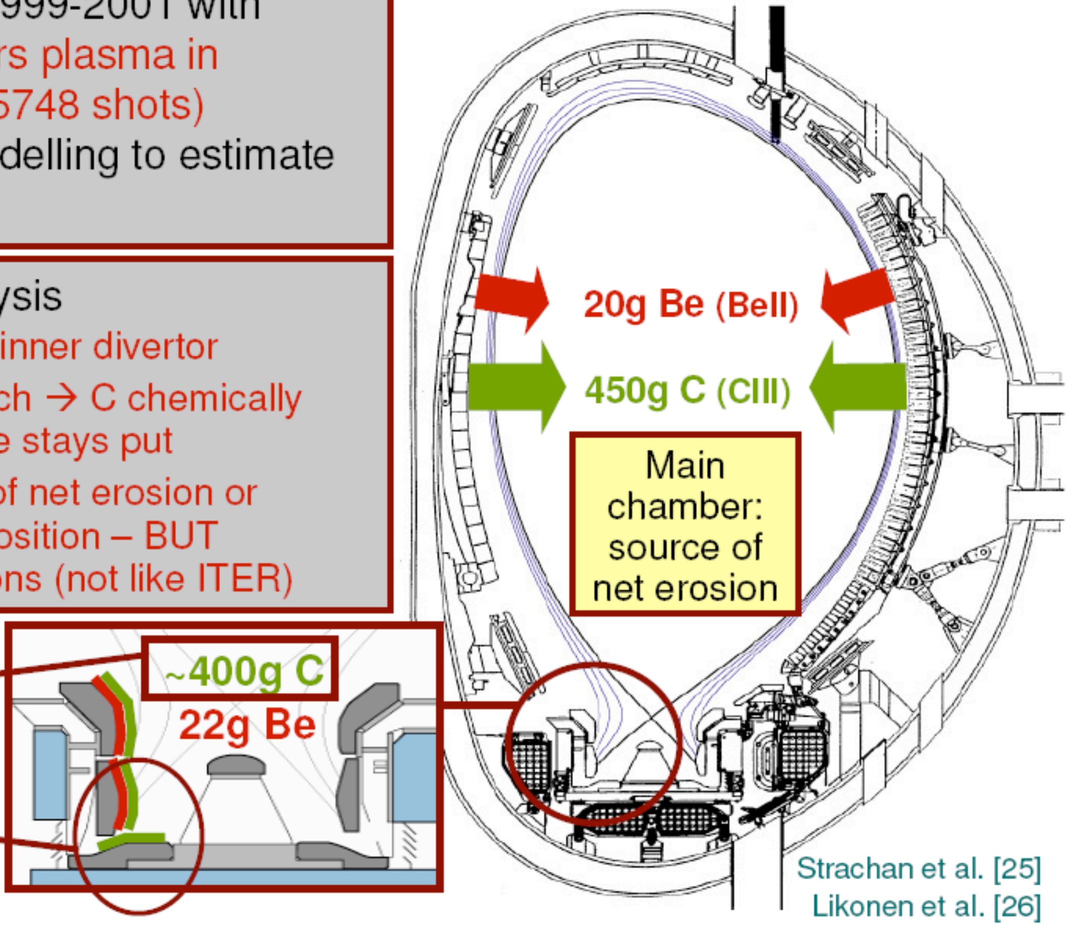
Example of quantitative measurement

Migration balance – example from JET

- Make balance for period 1999-2001 with MarkIIGB divertor: 14 hours plasma in diverted phase (50400 s, 5748 shots)
- Use spectroscopy and modelling to estimate main chamber sources

- Post mortem surface analysis
  - Deposition almost all at inner divertor
  - Surface layers are Be rich → C chemically eroded and migrates, Be stays put
  - Outer divertor – region of net erosion or balanced erosion/redeposition – BUT mostly attached conditions (not like ITER)

~250 kg/year if JET operated full time! Carbon migrates to remote locations forming D-rich soft layers (high T-retention)



Strachan et al. [25]
Likonen et al. [26]
Coad et al. [27]

Management of Erosion

- Monitoring
  - Divertor Erosion monitor tracks divertor target erosion
  - Impurity influx monitoring tracks wall erosion, rough quantitative estimate of the amount of deposited material
  - IR TV watches for hot spots during operation
  - An in-vessel viewing system inspects walls during short breaks in operation

- Replacement
  - Divertor is scheduled to be replaced 3 times in the 20 year ITER operating life
  - Main Chamber wall segments are designed to be replaceable, but are meant to last the whole ITER lifetime

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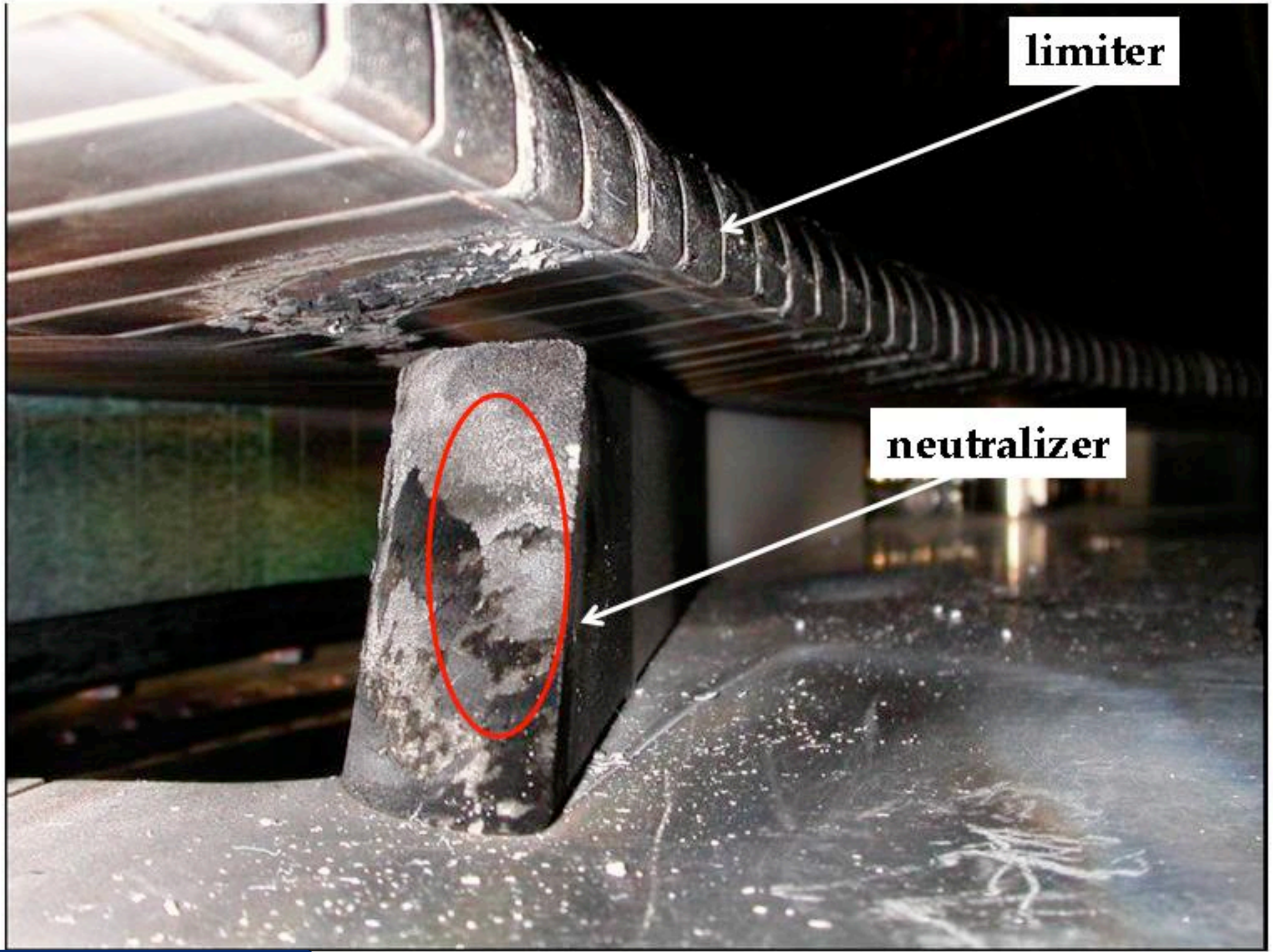
Dust Accumulation	• **Inventory limits** • **Hot and cold dust**	• **Local microbalance** • **Other methods**	• **Dust Removal**
Tritium Retention	• Inventory limits	• Global measurement • Local measurement	• Tritium removal

- Summary

Deposits and dust on the floor of the Tore Supra

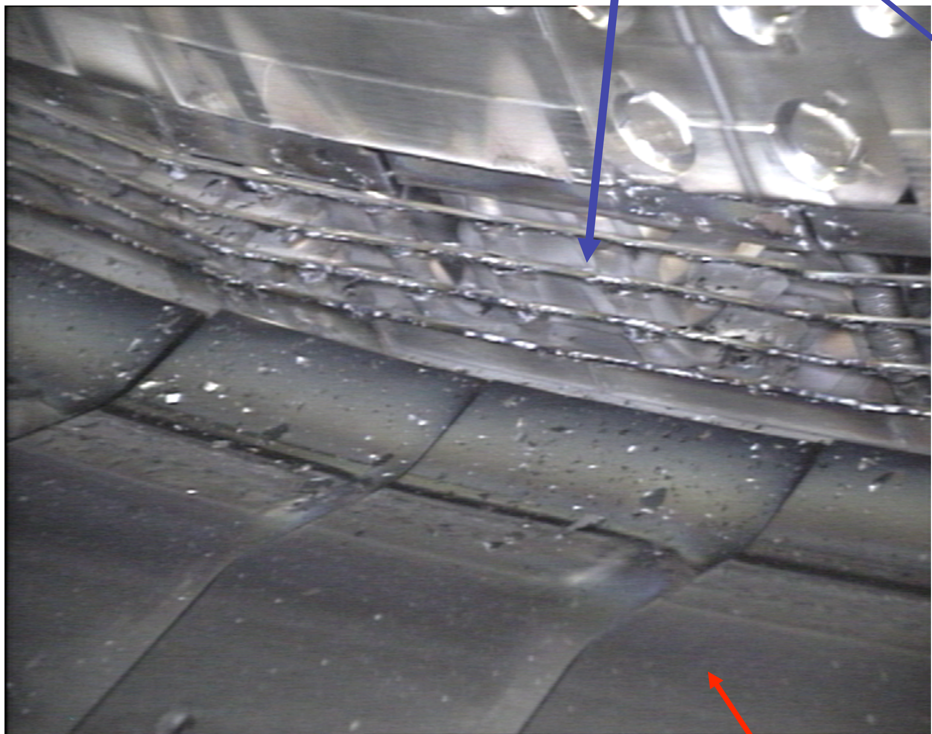


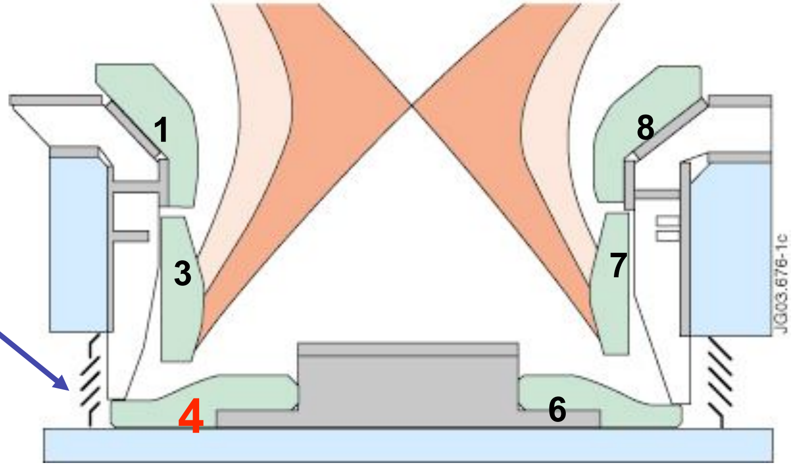
Euratom cea

P. Roubin, PSI 18th, Toledo, May, 26 - 30, 2008

Flaked-off deposited films and dust: JET Divertor

Pumping slots





Tile 4

J.P. Coad, 1998

Flaked-off deposited films and dust: under divertor

J.P. Coad, 2001

Before vacuuming **After vacuuming**

Source of Dust Limit

- Dust presents several safety issues:
  - Dust only hazardous if there is loss of vacuum

  1) Dust suspended in air can explode
     - Coal dust explosions
     - Grain dust explosions
  2) If the vacuum vessel has leaked air in, radioactive material could leak out (suspended tungsten dust)
  3) Hot Be dust can react with steam to produce H_2. H_2 + air gives explosive mixture

- Analysis of various accident scenarios ➔ inventory limits
  - Accident analysis quantifies risk
  - Inventory limit set so that risk is acceptably small

Dust Inventory limit

- Total amount of dust in vessel
  - Limit set by release of activated dust (primarily W) to the environment via loss of vacuum vessel integrity (only 10's of grams released)
  - Inventory limit: 1000 kg (assumes all W, no carbon, Be hazard is less)
    - Based on specific Cadarache site (2007)
  - Consider total amount of divertor erosion
    - ~10cm poloidal x 1cm deep x 40m toroidal x 2 strikepoints
    - ~ 0.08 m^3, or 160kg of C, or 1 Tonne of W

Dust Inventory limit

- Total amount of dust on hot (> 400°C) in vessel surfaces
  - Reflects a pressure vessel limit (2 bar) from an H_2 + O_2 explosion, requiring:
    1. **hot dust (W, Be, C, < 0.1 mm) – on or near divertor plates (400°C)**
    2. **water leak (H_2 production from reaction with dust)**
    3. **an air leak (O_2 ingress)**
  - This is really an H_2 limit (4 kg):
    - 4 kg of H_2 reacts with O_2 to produce a 2 bar pressure rise in the vacuum vessel
    - This translates to 6 kg each of W, Be and C

  - Why 400°C?
  - Note in the case of Be, reaction with water is exothermic

Cold vs. Hot dust

- A fraction of the dust in ITER will reside on hot surfaces ? $(8m^2/200m^2) \sim 4\%$?
- The limit on hot dust is rather smaller: ~6 kg hot dust compared to 1000 kg cold dust
- The ITER strategy for hot dust is not yet established, and the monitoring techniques considered so far address mainly cold dust

ITER approach for dust

- The frequency of scheduled in-vessel component replacement is expected to be adequate for dust
- Never-the-less, monitoring of the dust during operation and during maintenance periods is an integral part of the ITER dust and tritium control strategy

Dust monitor: status and needed effort

- Established
  - Measurement requirements
  - Concept for technique and integration in divertor cassettes

MEASUREMENT	PARAMETER	CONDITION	RANGE or COVERAGE	RESOLUTION		ACCURACY
				Time or Freq.	Spatial or Wave No.	
46. Dust Monitoring	Dust accumulation rate		10^{-4}-10^{-2} kg/m^2/pulse	Per pulse	Several positions	50% abs 20% repr
	Dust concentration		10^{-2}–10 kg/ m^2	Daily	Several positions	50% abs 20% repr

- Next steps
  - Design, fabrication and testing of laboratory mock-up
  - Test a prototype system on an existing machine

Local Dust Measurement system

– Several different concepts have been proposed: a capacitance diaphragm microbalance appears most promising

093501-4 Counsell *et al.*

Schematic and sample data for a CDM (G. Counsell et al)

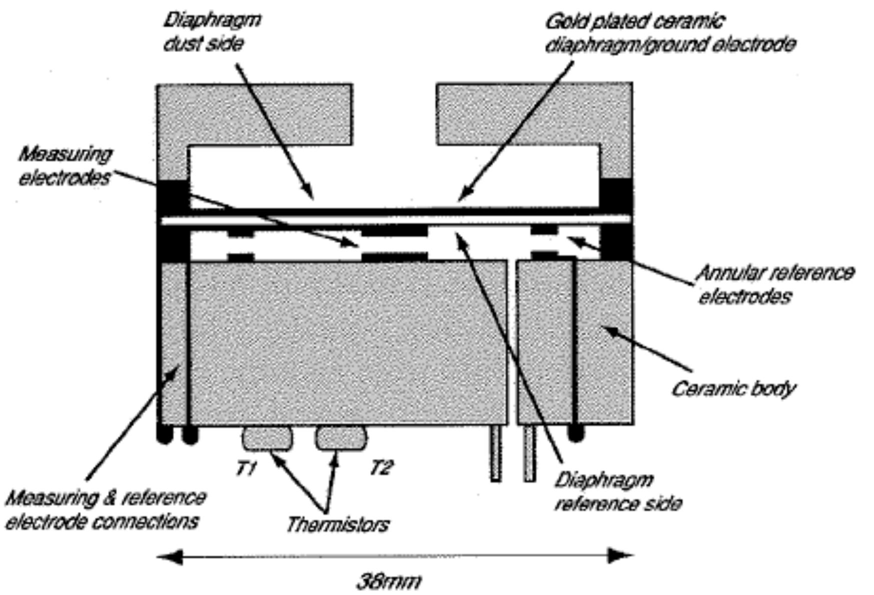


FIG. 5. Hybrid design of dust sensor showing the measuring and reference electrodes together with the ground Faraday shielding.

093501-3 CDG for dust detection in fusion devices

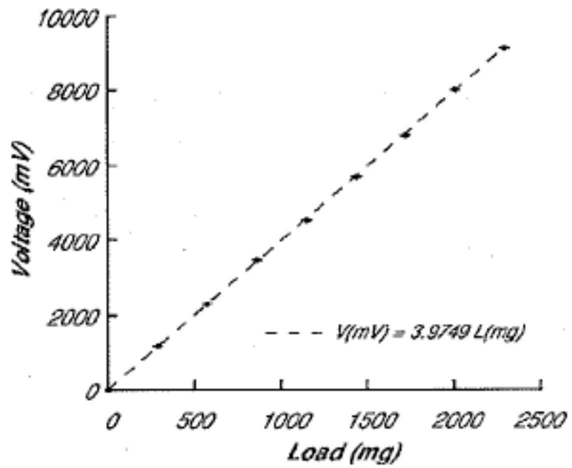
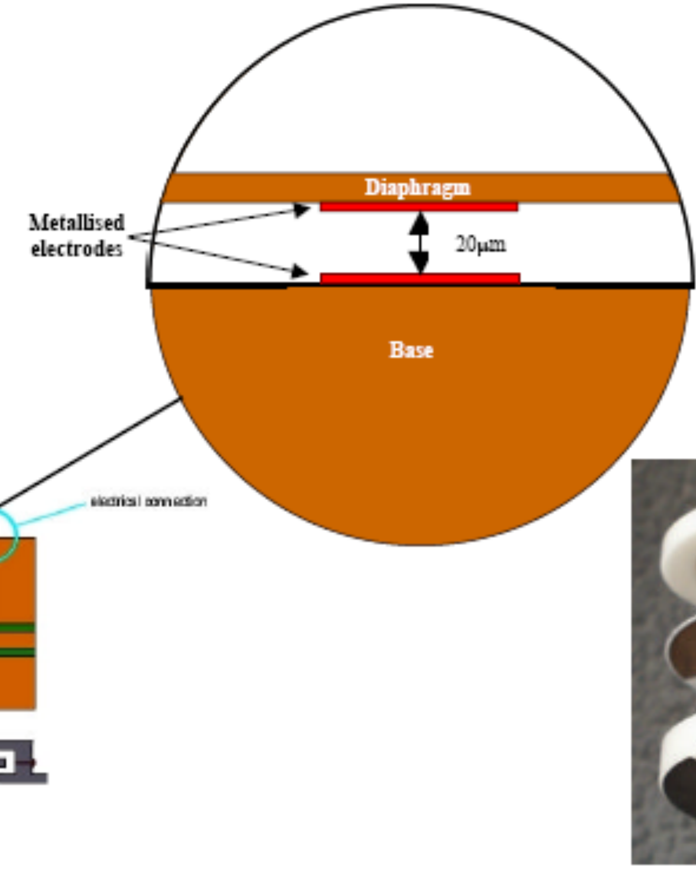


FIG. 2. Calibration of the modified Inficon CR090 manometer using copper wire weights applied close to the center of the diaphragm. Data are solid symbols, dotted line is a linear least squares fit.

CDM - Capacitive Diaphragm Microbalance



EFDA Carbon Workshop, 18-19 September 2000 UKAEA Fusion Working with Europe

Infer dust weight from erosion measurement

- use the following simplifying (and conservative) assumption:

  - **The material that has disappeared from plasma-facing components resides as dust in the vessel.**

    - Dust = f_{dust} x Net Erosion

Something that is simpler to measure

- Where we assume (for now) that $f_{dust} = 1.0$

- f_{dust} depends on specifics, i.e. plasma conditions, detailed geometry

- Later, as we gain experience from other devices and from initial H-operation in ITER, we <u>may</u> reduce f_{dust}

Other Dust measurements

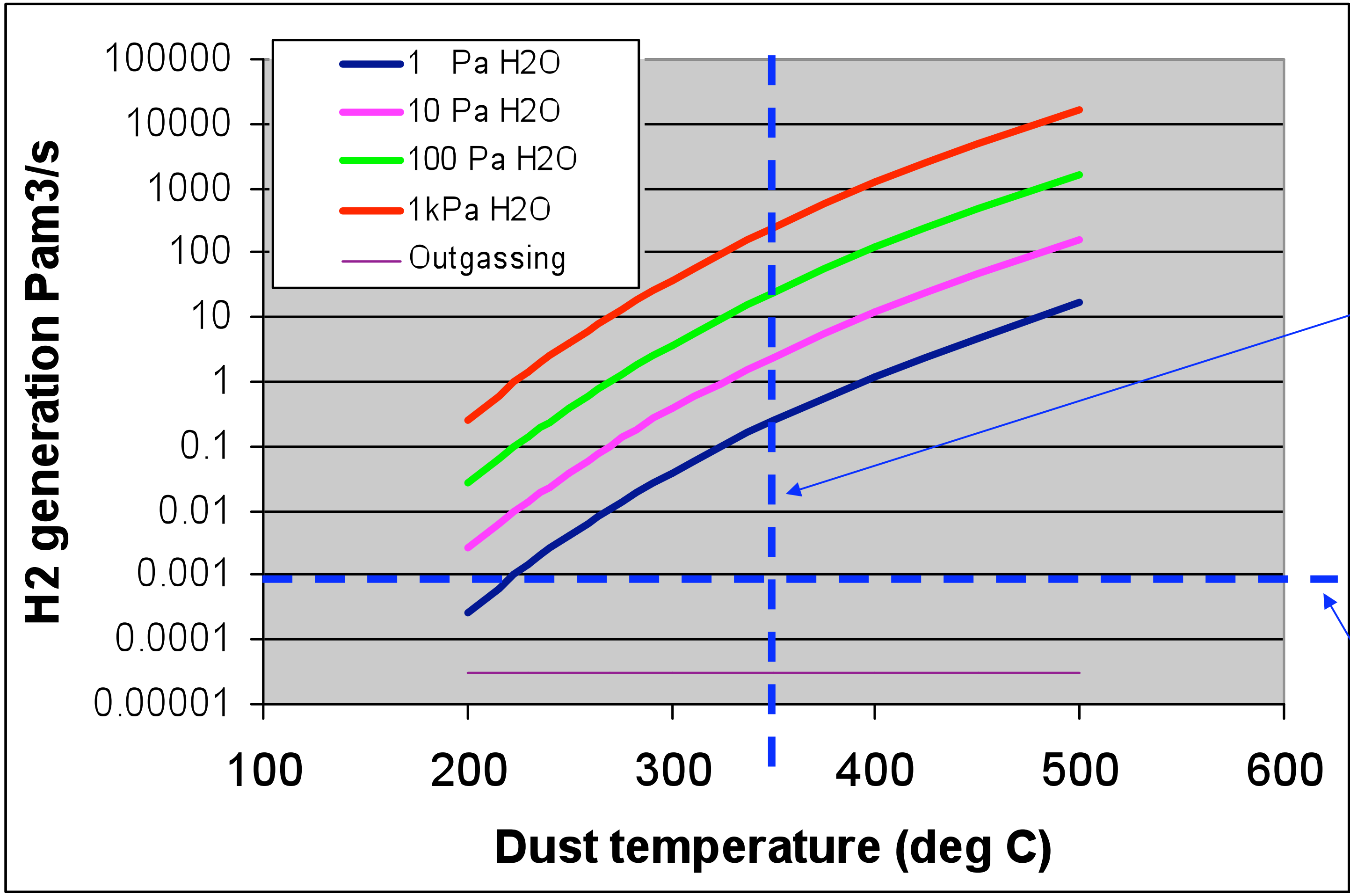
Removable samples

- Standard surface analysis of removed components
  - More a remote handling exercise than a diagnostic

Hot dust measurement

- under consideration, but not yet part of ITER baseline design
- Hot dust chemical reactivity measurement
  - Bake divertor to 350°C, introduce water vapour, look for hydrogen production

Global dust measurement, baked divertor



Assumes 4m2/g dust

Max divertor bakeout temperature

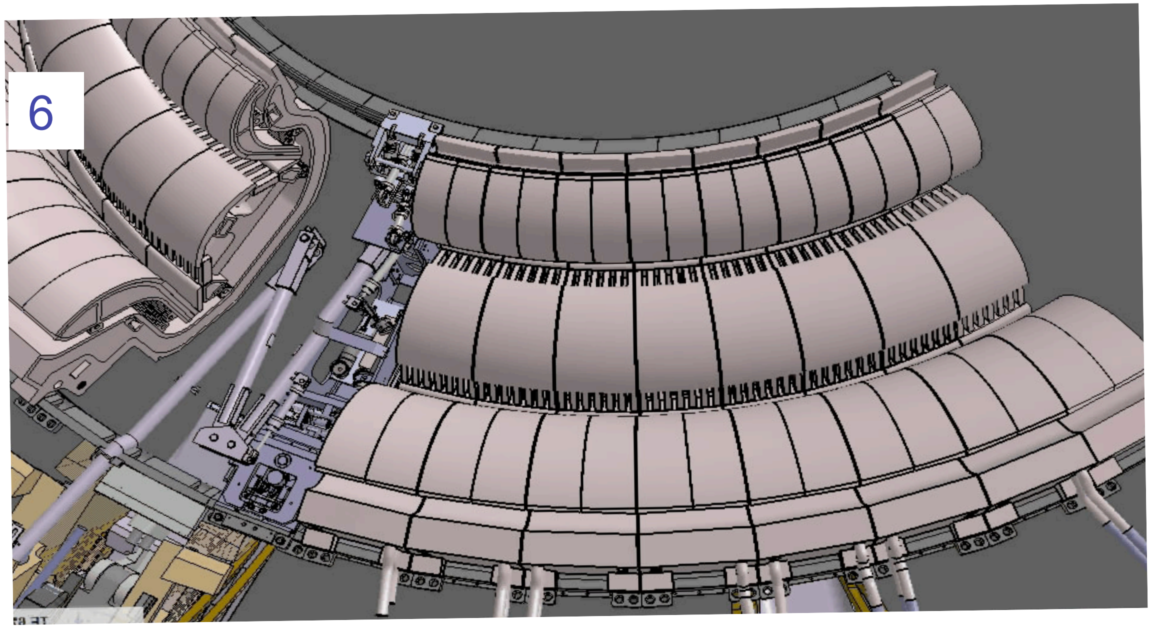
Less optimistic base level

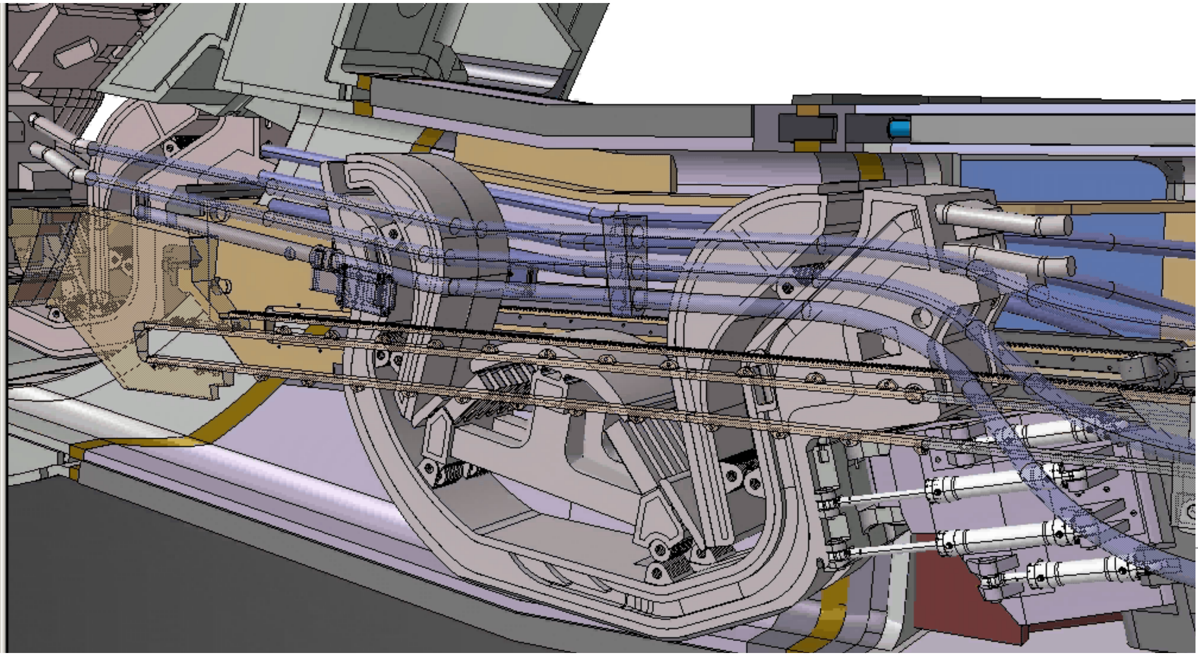
Dust Strategy

- Measurements
  - Erosion measurement (wall and divertor)
  - Learn to correlate erosion with dust generation
    - Eg. initially assume dust = 100% of erosion
    - refine with experience
  - sample Local dust concentrations
  - Global dust measurement resulting from removal

- Removal
  - vacuum cleaning vacuum vessel floor during scheduled divertor replacement (with remote handling tools)

Divertor remote handling tools





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- Summary

Source of Tritium limits

1) Case studies of accident scenarios result in limits on the amount of tritium which would be available for release

   – 4 kg site limit

   – 1 kg torus limit,

   – 120g cryopump limit

   – 1 kg Hot cell limit

   – Processing of divertor cassettes (eg. Baking & storage, recycling)

2) Tritium economy

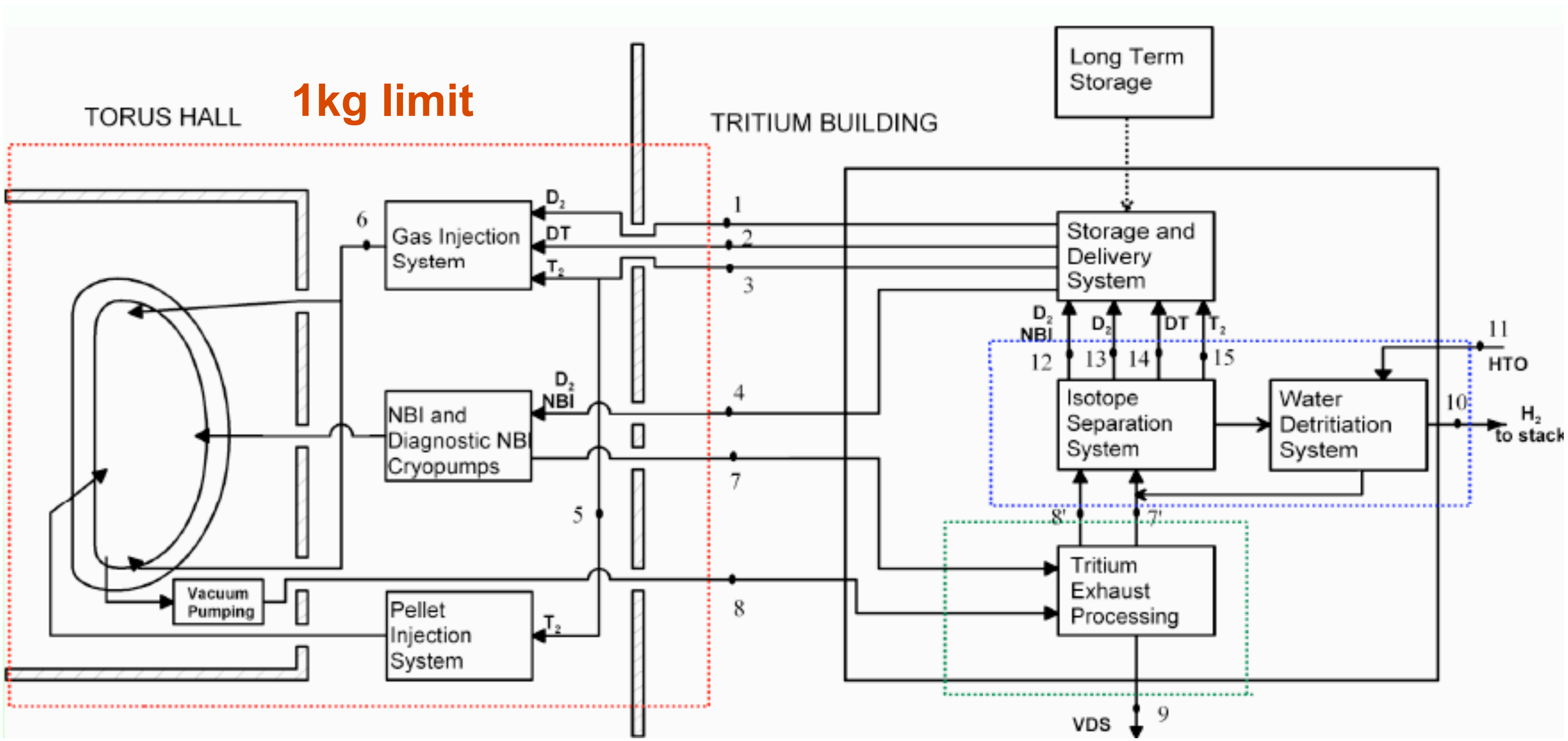
   – Even if safety were not an issue, ultimately the economy of a fusion reactor depends on the tritium consumed by retention < tritium consumed by fusion

Amounts of Tritium in ITER

- For comparison an ITER plasma will have
  - $10^{20}m^{-3}$ x $500m^3$ = $5x10^{22}$ electrons = 2.5E22 T ~ 0.1g of T in plasma
  - 50g of tritium flowing through plasma during a pulse (the flow is needed to flush out impurities, especially He ash, from the plasma)
  - 0.35g of tritium burned (fusion) in a full power pulse
  - ~0.15g of tritium retention per pulse
- Note: expected retention is for the case of no graphite in ITER

Tritium retention in ITER

4kg limit

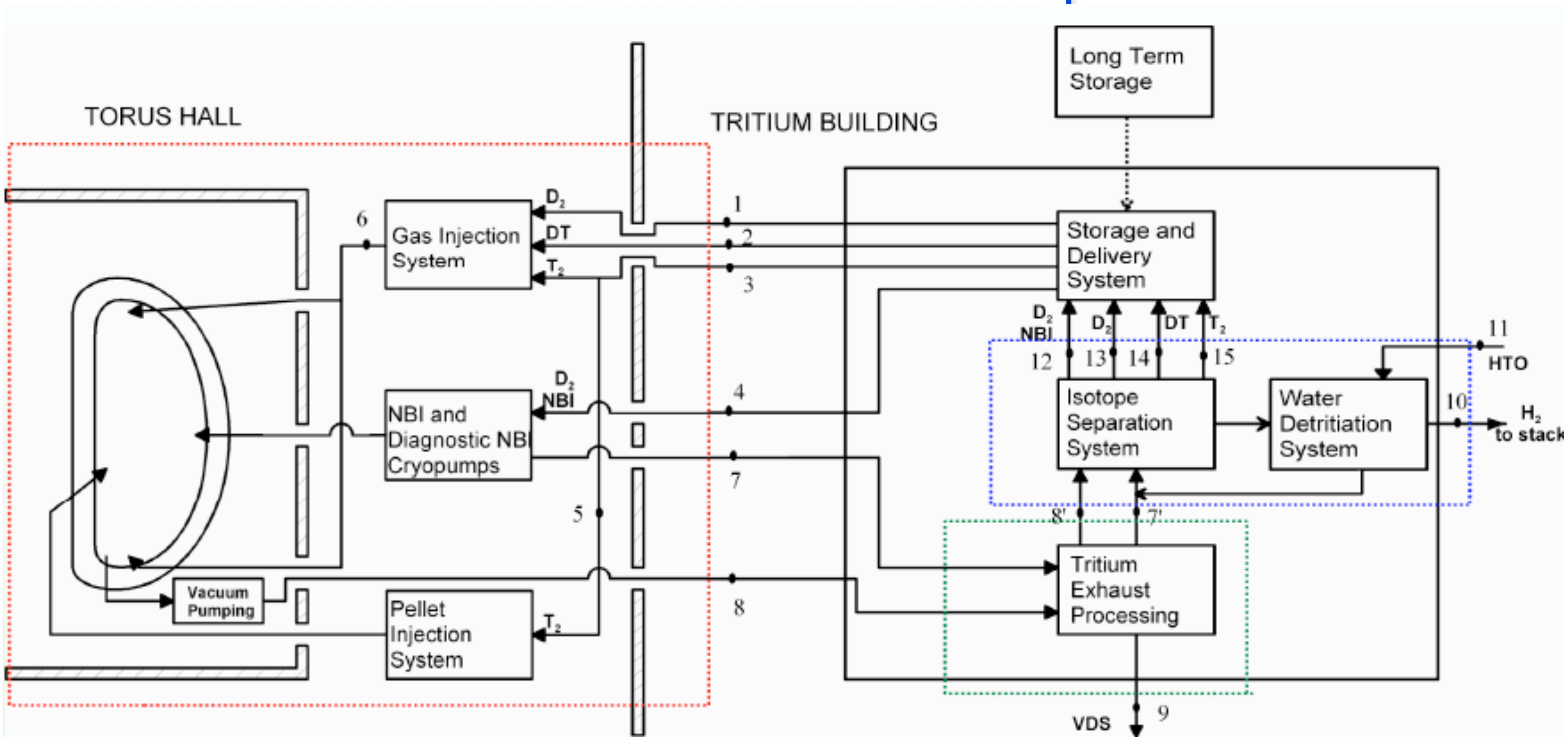


Tritium Inventory Measurement

- Fuel accounting
  - Main measurement of torus inventory: gas balance
    - Difference in flows in an out of Torus
      - 50g input vs. 0.15g retention
    - Deficit in tritium plant inventory
      - 4kg site limit vs. 1kg torus limit
    - Error in T burn-up measurement (i.e. integrated neutron rate) becomes significant late in ITER life
  - Global measurement
  - Not direct: needs support of direct measurement

Fuel Accounting

- Tritium Handling system can measure **available** tritium inventory to 0.5-1% (measure of T decay heat)
- Measurement done outside operation (eg. overnight)
- Tritium deficit = T retention + T burn up



Amount of T

- 10% error in neutron fluence (T burn up) measurement over 10 years results in 0.5kg error in T measurement

- DT ITER pulse
  - 0.35g T burned
  - 0.035g T error in burn
  - Retention: > 0.14g T
- Each operating period of 3000 pulses results in
  - 1kg T burned
  - 100g T error in burn
  - Retention: > 420g T
- With each shutdown
  - Divertor is replaced, floor is cleaned, torus retention significanty reset
  - However, error in the T burn is not reset, and accumulates.

Local measurements

- Need a direct measurement of inventory
  - deal with accumulated error in T burned
- Traditional method: remove wall tiles
  - remotely detachable wall/divertor samples
  - probably still need to vent
  - Not suitable for water cooled components
- In-situ methods
  - Laser ablation of wall target with spectroscopic measurement of ablation cloud

Tritium Inventory Measurement

- Measurements
  - Long term global: Tritium plant gas accounting
    - Error in T burn-up measurement (i.e. integrated neutron rate) becomes significant late in ITER life
  - Erosion measurement (as for dust)
  - Sample local T concentrations during shutdowns

- Removal
  - Baking divertor to 350°C (~ 1-2 times per year).
  - Removal of divertor cassettes and tritiated dust during divertor replacement shutdowns

Local surface tritium analyser

- System deployed by in-vessel remote manipulator during shutdown
- Laser pulse excites atoms on the surface
- Surface composition determined from spectroscopic analysis
- Sensitive to H, D & T

Schematic of surface analysis diagnostic (E.E. Mukhin et al.)

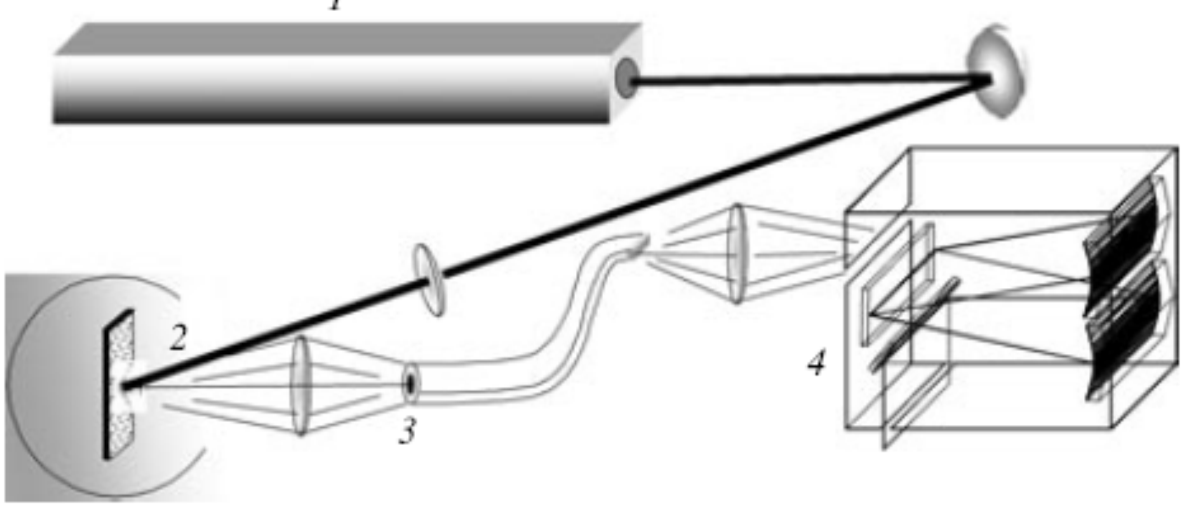
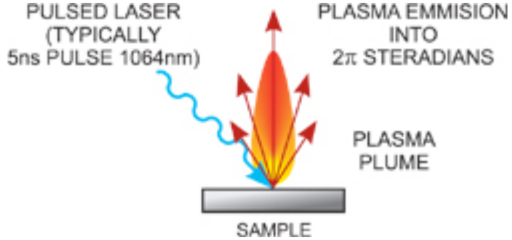
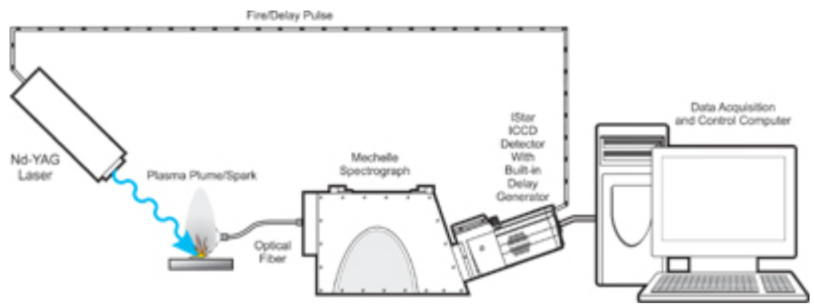


Fig. 1. Schematic diagram of the experimental test bench: (*1*) laser, (*2*) sample in the vacuum chamber, (*3*) fiber-optic line, and (*4*) monochromator with the detection system.

Local surface tritium analyser

- Laser pulse focussed onto surface being probed
- Laser energy
  - Vaporizes material near the surface
  - Creates a plasma plume in front of the surface
- Emission from plume analyzed with spectrometer
  - Indicates chemical composition of suface material
  - With calibration references, can be quantitative





Tritium monitor: status and needed effort

Proposed system only measures during shutdowns. Still useful although does not meet target resolution requirement

- Established
  - Measurement requirements
  - Concept for introducing monitor into vacuum vessel

MEASUREMENT	PARAMETER	CONDITION	RANGE or COVERAGE	RESOLUTION		ACCURACY
				Time or Freq.	Spatial or Wave No.	
47. Tritium Monitoring	H,D,T accumulation rate		$2\bullet10^{19}$- $2\bullet10^{21}$ H,D,T/m^2/pulse	Per pulse	Several positions	50% abs 20% repr
	H,D,T concentration		10^{20}- $2\bullet10^{24}$ H,D,T/m^2	Daily	Several positions	50% abs 20% repr

- Remaining steps
  - Preliminary design to establish monitor size and weight as input to remote manipulator design
  - Remote manipulator development
  - Build prototype & test on wall samples from an existing tokamak

Tritium Strategy

- Measurements
  - Long term global: Tritium plant gas accounting
    - Error in T burn-up measurement (i.e. integrated neutron rate) becomes significant late in ITER life
  - Erosion measurement (as for dust)
  - Sample local T concentrations during shutdowns

- Removal
  - Baking divertor to 350°C (~ 1-2 times per year).
  - Removal of divertor cassettes and tritiated dust during divertor replacement shutdowns

Summary

- In July 2008, ITER incorporated a dust and tritium control strategy into the baseline design

- 3 new diagnostic systems added, not yet assigned to parties
  - Divertor erosion monitor (during operation, divertor targets)
  - local dust concentration monitor (between pulses, below divertor)
  - local surface tritium analyser (in-vessel, during shutdown)

- Implementation of these diagnostics ~ 1-3 M€ each

- The diagnostics would also require an R & D program of order 1-2 M€ total to develop the measurement concepts

Summary

- To stay in a safe operating state, ITER will limit the amount of:
  - tritium retained in the vessel to 1kg
  - dust retained in the vessel to 1000 kg
  - dust which sits on surfaces which achieve >400°C to 18kg
- ITER includes in its diagnostics capability erosion measurements
  - this address target lifetime monitoring
  - The erosion rate will help get a handle on the rate of dust production and tritium codeposition
- Local measurement of T and dust concentrations will alos be implemented
- The need to mechanically remove dust & T from the vessel is expected to coincide the need for divertor target replacement

Abstract

- The plasma facing material surfaces in ITER will gradually be eroded by contact with the plasma. To cope with the rate of material erosion, the area of most intense plasma-surface interaction, the divertor, is designed to be a routinely replaced component. It is foreseen to replace the divertor, on average, once every 5 years of operation. The level of erosion will be monitored by a LASER ranging diagnostic which will measure the change in the position of the divertor target surface relative to some reference points.
- A byproduct of material erosion by the plasma is the generation of dust. Dust has been observed in minute quantities in existing tokamaks, but could amount to 100's of kg in ITER. Such large amounts of dust present several safety issues: an easily mobilized inventory of radioactive and toxic material, and a large chemically active surface area for reaction with air or steam in the case of a vacuum vessel leak. To manage the dust inventory, limits are set on the total amount of dust permitted in the vacuum vessel, dust microbalances are implemented in the divertor, and dust will be removed from the floor of the vacuum vessel during divertor replacements.
- Finally, normal operation of the tokamak leads to retention of a small fraction of the tritium fuel. This also results in an inventory of radioactive material which must be limited and monitored. The main method of determining the in-vessel tritium inventory in ITER will be assessment of the deficit in the ITER tritium fuel supply. This will have to be complemented by direct measurements of the inventory: local surface analysis performed without removal of the in-vessel components. As most of the retained tritium is expected to reside in the divertor, ITER is designed to allow the divertor to be heated to 350°C to thermally desorb tritium, a procedure which is estimated to be required annually.

Time scale

- Dust monitor
  - Needs to be delivered for divertor cassette assembly: **2015**

- Erosion monitor
  - Some mirrors need to be ready for divertor cassette assembly
  - Bulk of system needs to be ready for end-to-end test prior to divertor installation: **2016**

- Tritium monitor
  - Bulk of effort cannot start until status of remote manipulator confirmed (2009)
  - Should be used in pre-tritium phases
  - Although not required until 1st shutdown, should aim to test before 1st plasma: **2017**

Particle debris generated during ELM's