Discussion point #1: radiated power (1)

- **Quoted best chordal resolution of 5 cm (along the legs) in the divertor is adequate but will be insufficient for zones just above the divertor target:**
    - ◆ **B2-Eirene simulations of ITER "partically detached" scenario show flat "convective" region extending poloidally ~ 10 cm with low (< 5eV) T_e at the outer divertor strike zones ("detached" zone)[1]. This convective region is likely to extend further poloidally at the inner target which will be "more" detached.**
    - ◆ **Further along the target, the power flux peaks (start of "attached" zone) and poloidal gradients of T_e and n_e much steeper - the resulting variations in total radiation could not be resolved with the proposed bolometer resolution.**
- **The partially detached state leads to an extremely wide variation in the 2-D distribution of T_e and n_e throughout the divertor volume. Apparent best possible resolution in the inverted signals of 10-20 cm is insufficient in the target vicinity, but should be adequate in the bulk of the divertor volume where T_e and n_e change over longer spatial scales.**
- **Conclusion: chordal resolution of 10 cm along the divertor legs inadequate, 5 cm adequate, less would be better in the zones near the targets if possible. This measurement is potentially the most valuable of the divertor diagnostic set and every effort should be made to provide the best resolution possible.**

[1] **Simulations supplied by A. Kukushkin**

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Discussion point #1: radiated power (2)

- **If possible ITER should consider the use of zero dead layer AXUV* (Absolute Extreme Ultraviolet) diodes as a *complementary* diagnostic during the low activation phase:**
  - **Diodes are insensitive to low energy < 500 eV neutrals - can compare with total radiation from foil bolometers (containing neutral contribution). Especially important in the divertor where the two systems (foils and AXUV) would be valuable for code validation during the physics phase.**
  - **Diodes are very fast - useful for measurement of divertor instabilities (if seen on ITER), for ELM induced effects on radiation profiles and for studying profile changes during disruptions.**
  - **Diodes are small and compact - improved spatial resolution. They require little or no calibration. Cabling and signal amplication can be delicate, but no more so than a foil bolometer system.**
  - **Long term stability of these detectors is improving - new SXUV series has greatly (orders of magnitude) improved resistance to XUV photon impact - lifetime compatible with hundreds of ITER discharges without serious degradation of detector responsivity**
  - **Neutron-induced damage will, however, be fatal to these detectors at the present level of technological development.**

***see http://www.ird-inc.com**

Discussion point #2: target power deposition (1)

- **Quoted target spatial resolution (~3 mm) perfectly acceptable (wavelength multiplexing system)**
- **Issue of time resolution and sensitivity is much more complex and depends on what is really required from the system:**
  - **FDR specification is 2 ms for default operation (10% accuracy) and 0.1 ms for disruption (also presumably Type I ELMs?) at 20%. Sensitivity very strongly dependent on magnitude of temperature being measured (FDR WBS 5.5.G.06).**
  - **Type I ELM at targets depends on: fraction of ΔW_{ELM} reaching target, surface area over which ELM energy at target is deposited ($A_{ELM} = (1\text{-}2)A_{SS}$ with SS = strike zone surface) and characteristic time for the energy deposition, τ_{ELM} which is determined by the ion flow times from outer midplane (where the mhd event occurs) to the targets (modified to account for pedestal collisionality).**
  - **For ITER operating point, predicted ΔW_{ELM} ~ 12 MJ, 50% arrives at 2 targets with duration ~ 200 μs[1]. If this is spread over A_{SS} only (6 m^2 for 2 targets) ⤳ 0.4 MJm^{-2}.**
  - **Surface temperature rise to max. value occurs in ~ 100 μs for C and W (RACLETTE code[2]). Starting temperature depends on asssumed heat flux in between ELMs ⤳ 1000ºC for assumed worst case 10 MWm^{-2} (B2-Eirene). Max. temp. excursion at peak of power deposition close to or exceeding values for sublimation (C) or melting (W). W melts at ~ 3650 K, C suffers enhanced erosion due to RES above 2000 K.**

[1] **A. Loarte, IAEA 2000**

[2] **G. Federici, Divertor Physics EG, Naka, July, 2001**

Discussion point #2: target power deposition (2)

- ◆ **Assumptions fraught with uncertainty, but if ELM induced surface temperature excursion is roughly linear with time at ~ 2500 K in ~ 100 µs, resolving the event with target IR, will need time resolution ~ 20 µs. Current target value of 0.1-0.2 ms is insufficient.**
- ◆ **According to RACLETTE, temperature will drop to approx. the inital value (in betwen ELMs) in around 100 ms. Code also indicates that surface temp. ratcheting not an issue for ELMs of frequencies ~ few Hz.**
- ◆ **SNR for 1 kHz system in FDR WBS 5.5.G.06 ~ 110 for 1st and 2nd order at 1000ºC, rising to to 8000 (1st order) @3000K.**
- ◆ **Depending on choice of detector, the current choice of relay optics system might suffice as is to resolve ELMs of magnitude assumed here. Steady state (in between ELMs) probably compromised if ELM measurement required at the same time (SNR too low).**
- ◆ **One major problem in the presence of large ELMs and disruptions will be the formation of melt layers and subsequent emissivity changes which are likely to result in large uncertainties in the derived temperature, however fast it is resolved. Radiation from the target plate due to the ELM also likely to be a problem.**

- **Conclusion: resolution of 0.2 ms insufficient for studying target power deposition due to Type I ELMs. Better 0.02 ms for fast rise phase. Given the high initial target temperature, currently proposed system might suffice for resolution of ELMs if a fast enough detector is available.**

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Discussion point #3: target plate erosion (1)*

- Current expected erosion and redeposition rates 3-10 nm/s on the currently planned graphite plates for "standard" ITER divertor target plasma without ELMs or disruptions.
  - ◆ For ITER pulse length of ~500 s → 1.5 - 5.0 µm changes in target "height".
  - ◆ Type I ELMs and disruptions will completely change this number
- Proposed "likely" achievable resolution of 100 µm will only allow measurements on the scale of several 10's of discharges:
  - ◆ Tritium co-deposition rate estimated at ~ 2.5 g/500 s pulse for carbon[1]
  - ◆ So, if 1.5µm/pulse only, after 200 discharges → 300 µm "change" in target height but 500 g T codeposited and layers would have to be "removed" to release T and continue operations.
  - ◆ 100 µm may suffice for studies during the physics phase (no T), but we should try to do better. If we want useful measurement for the D-T phase, 100 µm is insufficient.
- Techniques available:
  - ◆ Ellipsometry - "real time", but max. range ~ 1 µm and so "too sensitive".
  - ◆ Colourimetry: good below ~ 1µm → "too sensitive" - requires extensive in-vessel divertor plate inspection systems.
  - ◆ Visible spectroscopy combined with depth markers: can be real-time, but can only measure net erosion and requires placement of the marker elements in tile material.

*thanks to D. Whyte, UCSD for comments

[1] G. Federici et al., JNM 290-293 (2001), 260

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Discussion point #3: target plate erosion (2)

  - Speckle interferometry: could provide micron level resolution and wide area coverage of the target plate area but probably not real time - too much interference from plasma light (helium). Nevertheless, inter-discharge measurements could be extremely valuable. Technique, though difficult to implement has advantage of measuring both erosion and redeposition.
  - Quartz microbalances - very sensitive to mass changes but measurement of net erosion requires deposition of a finite layer on the balance first. Since this layer cannot be more than a few micron, use for net erosion is probably questionable in the divertor. Also, balance has a finite range for net deposition (to be checked) - ~ few 10's of μm. Application on ITER might be very tricky and noise during plasma will probably limit the technique to inter-discharge measurements (JET soon to test one of these devices!).

- To adequately measure erosion and redeposition "chamber-wide" and to account for ELMs and disruptions would need multiple methods in combination
- Conclusion: real time measurements, appear impossible, so individual ELM effects on erosion and redeposition could not be diagnosed. Resolution of 100 μm is too coarse for a serious study and is not useful for D-T phase. Suggest an attempt to provide "global" measurement at target areas such that the effects of a single or at most a handful of discharges can be quantified. Specialised measurements could occasionally provide higher resolution. But this is a critical issue and ITER should drive research in this area now.

Discussion point #4: target probe measurements (1)

- **Planned target Langmuir probe coverage (3 sets of 80 probes with pitch 1 cm at inner and outer targets at 1 toroidal location) is perfectly adequate - should provide excellent coverage.**
- **On the question of validity of T_e measurements by probes:**
  - **Situation is currently extremely confused and no definitive answer can be given yet.**
  - **C-Mod divertor target probes measure extremely low T_e's, compatible with spectroscopic values. Note that C-Mod has extremely high density divertor and high magnetic field.**
  - **Everywhere else (at least no evidence to the contrary in the (relatively sparse) literature on the subject), target probe T_e's under high recycling and partially detached conditions too high to be compatible with local spectroscopic measurements or the presence of significant volume recombination.**
  - **Serious ongoing theoretical work on this issue is being undertaken in a collaborative effort between Stangeby (Toronto), Pitts, Horacek (CRPP) and Batishchev (MIT) - idea is to try and find out why. Some good progress being made but likelihood is that the probes do read the wrong T_e under conditions of interest to ITER and that we are unlikely to be able to resolve the issue experimentally, even if we understand it theoretically. It may be, however, that the higher B_T and higher density of the ITER divertor plasma (cf. JET for ex.) might yield "more reliable" T_e's as in C-Mod.**

Discussion point #4: target probe measurements (2)

- **Planned use of triple probes on ITER will pose even more serious problems for T_e measurement in high recycling/detached conditions due to the observed decrease in the electron to ion saturation ratio which renders the triple probe T_e and I_{sat} measurement physically meaningless[1].**
- **Single probe measurements, even if giving the wrong absolute T_e in operating conditions of interest, could nevertheless be used in the sense that T_e will be sensitive to changes in local conditions. Fast "neural network" algorithms could be used to extract T_e from single probe characteristics in real time (proof of principle analysis planned at CRPP in early 2002 (J. B. Lister/R. A. Pitts)).**
- **Use of triple probes would be necessary for ELM and disruption physics (higher time resolution) but note that the anticipated Type I ELM "burn-through" may yield target T_e's too high to be within planned measurement range.**
- **Note the incompatibility of the ITER probe T_e measurement specification range (1 eV - 1keV in DDD 5.5.G) with the proposed power supply capability (max. 250V @5A).**

- **Provided probes can survive long enough (cannot easily be answered without buillding ITER!), independently of confidence in T_e absolute value, particle flux measurements will be a very sensitive indicator of detachment (along with target IR).**
- **Conclusion: spatial resolution more than adequate, problem with T_e interpretation may not be a serious handicap. More work required to assess probe longevity (modelling plus work with JET probes).**

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[1] R. D. Monk, Phd thesis, 1996

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Discussion points #5,6: T_e measurements in the divertor (1)*

- Combine these two discusison points since they are strongly related.
- Points listed for bolometry (Discussion pt. #1) are common to the T_e, n_e, issue.
- A slight, but important inconsistency (opinion of the present author!)
  - In ITER-FEAT DDD 5.5.C, resolution of divertor imaging TS system given as ~5 cm along outer leg and 3 - 10 mm across the leg (pg. 75). A. Costley[1] quotes 10 cm along leg. This is also the value given in Table 2 on pg. 4. Which is correct?
- Divertor Impurity Influx Monitor and T_e:
  - Difficult to judge from the DDD's exactly how the Divertor Impurity Monitor sightlines overlap and how many there are. But 1 cm spatial resolution along divertor legs quoted.
  - If tomographic inversion possibilities are limited and only a few perpendicular sightlines are possible, then there is not a lot to be gained from making substantial (and expensive) efforts to go beyond the planned divertor TS system.
  - But, there is no reason to sacrifice the 1 cm longitudinal resolution in impurity influx since having a few n_e and T_e anchor points from the TS along the leg will permit serious constraints on code simulation and therefore allow the high resolution experimental data to be compared with simulation. Codes will evolve enormously in the years up to ITER and their usefulness during the physics phase should not be overlooked.

[1] A. Costley, Divertor Physics EG, Naka, July, 2001

* thanks to D. Whyte, UCSD for comments

Discussion points #5,6: T_e measurements in the divertor (2)

- ◆ **The proposed longitudinal TS resolution will be inadequate in the target vicinity where poloidal gradients change rapidly but this is also true for bolometry. With relatively limited target sweeping (or tilting the input beam), sufficient 2-D information could be provided for a reasonable interpretation of real fluxes from the spectroscopic data.**
- ◆ **Given the strong poloidal variation of T_e and n_e in the divertor volume, the resolution of ~ 5 cm is barely adequate and 10 cm is inadequate. Note, for example, that the CII photon efficiency varies by an order of magnitude in the range 1-5 eV. This is precisely the range of temperatures that will be found in the target vicinity.**
- ◆ **The absence of TS at the inner leg is unfortunate (given that inner and outer divertor volumes will behave somewhat differently, especially near the targets), but X-pt LIDAR TS together with target IR, Langmuirs and spectroscopy will help to fill this gap. If there is any possibility at all to remedy this (by other diagnostic methods?), it should be vigourously pursued, especially for the physics phase.**

- **Ionisation front position:**
  - ◆ **Concern is location of the ionisation front along the leg(s) in an operations sense.**
  - ◆ **In this case, and if graphite is to be used at least somewhere in the machine (at the targets for the physics phase?), then the divertor impurity monitor can be used to identify the positions of the CII and CIII visible line emission. The relative positions of their radiation along the leg identifies the 5 eV and 8 eV contours and so any strong decrease in the ratio I_{CII}/I_{CIII} locates the approximate position of the ionisation front.**

Discussion points #5,6: T_e measurements in the divertor (3)

  - Technique could be very robust and might be an attractive route towards feedback control of "degree of detachment" if spatial resolution adequate (1 cm along legs is sufficient, but a reasonable idea the poloidal distribution would also be required).
- The need (or not) for UV spectroscopy:
  - If there is to be no carbon in the machine (Tungsten targets?), then some degree of UV spectroscopy will almost certainly be required if some knowledge is required for divertor transport of eroded material. WI and WII can be seen in the visible, but these low charge states would not live long enough for serious transport studies.
  - In the presence of significant carbon, much of the power radiated will be in CIV (UV) but the bolometer systems will also be a sensitive measurement of this contribution. Likely scenario (see DIII-D studies[1]) is intense hydrogen isotope radiation at the plates and strong C radiation further up the leg. Note also the severe problems of opacity for H/D/T line radiation in the high n_e plasma near the strike zones.
- Conclusion: if C will be present in ITER and good bolometric resolution can be assured, UV spectroscopy not a pre-requisite in the divertor. Proposed visible spectroscopy resolution acceptable and could be used as an ionisation front position controller if C present. But every effort should be made to provide the best possible 2-D resolution (2D imaging??). Sparsity of T_e, n_e measurements (divertor TS) regrettable, but combination of modelling, bolometry, spectroscopy and target measurements can compensate to some extent. The divertor TS measurements are, however, indispensable to allow any degree of quantification of the spectroscopic data.

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[1] M. E. Fenstermacher, Phys. Plasmas 4 (1997) 1761