SOME OBSERVATIONS ABOUT THE CURRENT STATE OF EDGE PHYSICS

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1. INTRODUCTION

The following set of personal remarks is not in the nature of a research paper. There are no references, etc. My remarks are intended for internal, informal discussion within the edge physics community where all the matters referred to will be familiar ones. This informal approach will, I hope, encourage a reflective and candid response from my colleagues.

2. A MATTER OF CONCERN

Progress in edge/divertor research over the past two decades has been solid and encouraging. We have scoped out the problem. We have identified the critical questions. We have made a good start at answering these questions. We have identified, in the detached divertor state, the makings of a solution to the divertor problem, at high density.

I am, however, concerned about the widespread view that *tokamak edge physics is largely in hand*. This is substantially at odds with my understanding of the situation. I believe that our understanding of the following edge matters – although far from negligible – is sufficiently incomplete that, at some point, and unless rectified, these deficiencies could impede or stop progress to fusion power:

1. We do not know the controlling source of impurities in the confined plasma: chemical sputtering vs physical sputtering vesus evaporation/sublimation from hot tile edges, divertor targets versus walls, and if walls, whether it is due to neutral (charge exchange) or ion impact (plasma-wall contact).

2. Our understanding of how the impurities are transported through the edge plasma to the confined plasma, including the “puff-and-pump” process for impurity control, is poor.
3. The database on the natural flows along **B** in the edge is extremely limited, but very substantial flows have been measured. The magnitude of these flows does not appear to be consistent with our understanding of either ionization-driven flows, or of flows associated with classical or neoclassical drifts; their cause is unclear. Such flows must influence particle, momentum, and energy balances in the edge, affecting both the fuel species and impurities. Understanding of edge impuity transport is directly compromised by our lack of information and understanding of edge flows.
4. With regard to identifying the major routes by which power *leaves* a tokamak plasma, we do not understand the role of heat (or particle) convection to the main chamber walls, as reported on C-MOD, nor the narrow, high power peak at the outer strike point, reported by JET. These are specific examples of the more general problem that we do not understand cross-field transport in the SOL, nor are we even able to adequately characterize it to do reliable scaling, e.g. for SOL widths. The power width is a particularly critical issue; unfortunately, we are not even sure if the power dependence of this width is positive or negative.
5. We also know little about how the power *enters* the SOL across the separatrix: how important are drifts and turbulence in this region? how do changes in transport inside the separatrix influence the SOL? how does transport vary poloidally? Power handling is the most important practical matter at the edge. deficient understanding about edge power transport is potentially unsafe.
6. ELMs are recognized as having the potential to destroy the targets. While we have learned much about the fundamentals of the ELM instability, and while the EDA and QH–modes constitute potential solutions, a realized solution to this problem remains outstanding.

7. Long pulse operation – which will be essential in future – raises unresolved problems. On Tore Supra the situation appears steady over ~15 s but then a density runaway occurs. The long-time evolution of the particle content of the wall is poorly understood.
8. We do not understand how the main plasma is fueled. Is it due to recycling from the divertor targets? If so, is it the result of plasma-fueling (ionization outside the separatrix, followed by plasma transport across the separatrix) or is it due to neutral transport across the separatrix, and ionization in the confined plasma? If the latter, is it due to more-or-less direct, line-of-sight, neutral transport from the targets, perhaps through the private region? Or is it due to leakage around the outer-periphery of the plasma ('leaky divertor') with the neutrals then 'attacking' the plasma more-or-less uniformly around the entire outside? Or is plasma-contact with the walls and the resulting recycling there – the new C-Mod story – the principal fueling mechanism of the confined plasma? A number of important consequences attend our ignorance of this matter, including such critical questions as the relationship between the SOL and the pedestal, the effect of neutrals on high confinement modes, etc.
9. We do not understand the controlling processes in the private flux zone, a region that can be important for pumping and probably for recycle refueling, impurity behavior, and co-deposition.
10. The neutral behavior in the regions just outside the plasma is characterized by long-standing, unresolved questions. In some cases, for example the lower plenum pressure in DIII–D for attached plasmas, the situation is well understood. Often, however, as in C-Mod, the pressure is significantly higher than is computed using even the most modern, sophisticated neutral codes such as EIRENE and DEGAS, including neutral-neutral collisions, and even giving ourselves the advantage of taking the "plasma background" as being specified from experiment. Confidence in our ability to *predict* pumping, including helium removal, is therefore not on the sound basis that is needed.

11. We do not understand the carbon re-deposition behavior and therefore the tritium co-deposition behavior, in tokamaks. On JET operated with tritium, the tritium inventory built up without saturation limit. This problem may be so serious as to rule out the use of carbon in fusion devices. That, however, would eliminate the leading candidate material, and the one that, by a considerable margin, we know the most about. It would be a setback to be driven to the extreme of not being able to keep the carbon option open.

It is appropriate to expand on this last mentioned problem since it is potentially such a serious one. It is also a practical problem which requires, for its resolution, much improved understanding of a wide range of basic edge effects. There are several sub-components of carbon-tritium co-deposition behavior:

(a) Apparently large-scale convection in the SOL starts near the outer target and extends to near the inner target.

(b) A source of carbon, apparently some process at the wall, feeds into this convective flow.

(c) The carbon may or may not actually reach the inner target, but in any case it does not remain there on JET. It moves by some neutral transport mechanism to adjacent surfaces, which are not plasma-wetted, or even within sight of the plasma, and carbon re-deposition and the associated tritium co-deposition occurs there.

We have little understanding of each of these sub-component processes. (Fortunately, they can be studied in any tokamak that employs carbon, since the carbon re-deposition is the issue – the presence of tritium is not required.)

Such a list could be extended. We can have difficulty with such basic matters as the ratio of particle to heat fluxes onto solid surfaces, e.g. the surprisingly low sheath heat transmission coefficient, ~1, measured on DIII–D at the strikepoint. The power threshold for L→H transition decreased by a factor ~3 on DIII–D over the 1990s; the only obvious correlation is with wall conditioning, the result of accumulative boronizations; the causal link, however, is unknown, etc.

3. THE EDGE RESEARCH EFFORT HAS DECREASED

It therefore is a matter of concern that research in edge physics has decreased in recent years. In the U.S. Program, for example, the manpower commitment to edge work on the two major tokamaks, C-Mod and DIII–D, is now about half what it was a few years ago.

4. AT THIS TIME IT IS NOT TO BE EXPECTED THAT EDGE PHYSICS WOULD BE LARGELY IN HAND

The edge is intrinsically more complicated than the main, confined plasma:

1. More states of matter are involved. The three states – solid, gas, plasma – are always involved, and sometimes the liquid state also. Atomic physics effects are always important.
2. The shape of the edge region - long, narrow and twisted – is more problematical than that of the confined plasma. The large, round shape of the confined plasma makes diagnostic access straightforward. By contrast, diagnostic access of the edge can be obscured and difficult.
3. Just establishing the location of the SOL can be a problem since the SOL thickness can be comparable to the uncertainties in the location of the separatrix as calculated, for example, using the EFIT code.
4. The confined plasma can often be taken to be 1-D, while the edge region is usually 2-D, at least. This makes modeling more challenging. It also makes diagnosis a much greater problem than for the core. For the 1-D confined plasma any convenient diagnostic line through the plasma is adequate and many diagnostic lines are available because of the convenient shape. Because the edge is 2-D, an equivalent complete mapping would require prohibitive effort and expense – and is generally impossible physically because of

access limitations. It is likely that the edge plasma will never be completely measured and that interpretation of the edge will always be based on partial data.

5. For the 1-D confined plasma it can be possible to extract physics conclusions more or less directly from measurements. Because of the 2-D nature of the edge and because edge data sets are always partial it can be difficult to make very much out a single set of edge data – or even from a number of different types of edge measurements. One is generally obliged to use edge data within the framework of an interpretive code. Edge codes contain a number of adjustable parameters and unless a large and diverse set of edge measurements are available to be confronted simultaneously by the code, it can be under-constrained. It is not clear what has been learnt when matches are achieved between under-constrained codes and limited data sets. It is often not possible, however, to acquire sufficiently extensive sets of edge data to fully constrain interpretive codes. Much less effort and money has been invested in edge diagnosis than in diagnosis of the confined plasma.

5. IT IS TIME TO RE-INVIGORATE THE EDGE SCIENCE QUEST

In general, the research effort invested in the edge is far smaller – perhaps a few orders of magnitude smaller – than has been invested in the confined plasma. Our research colleagues working on the confined plasma have not as yet answered all its important questions. It would be surprising if, confronted with a substantially more complex problem, we in edge research had managed to get on top of all the critical edge questions. It would be surprising if tokamak edge physics *were* largely in hand.

Despite the magnitude of the edge task, there has been great progress:

1. We have – it may reasonably be hoped – identified most of the edge *questions*. That is usually the hardest part of a research job, and therefore we have made an excellent start. In fact, we have made an excellent start on *answering* many of the questions.

2. Today we have the makings of a divertor solution for a next step device like ITER, for high density operation – something we lacked a decade ago.
3. Diagnosis of the edge and divertor has been advanced greatly over the past decade or so. Today we have much better tools with which to address edge questions than we possessed a decade ago.
4. All major tokamaks are now well clear of the unproductive stage of struggling with prosaic problems, such as vacuum quality – and are now in a position to "make hay" in sorting out edge questions.

That so much progress has been made in edge research represents an impressive achievement. The world fusion effort has received good value for its investment in this area. There is every reason to expect further good return on future investment. A solid base has been established. Now we need to build on this strength and exploit it to sort out the critical matters that we have identified.

While the list of unresolved edge questions is sobering, defeatism is quite unwarranted and *it is time to re-invigorate the edge science quest* with justified optimism:

- Edge research efforts on existing devices need to be restored – and if possible, increased.
- ITER is needed as soon as possible.

ITER design has been a major driver of edge research over the past decade. Regardless of how fully we exploit existing tokamaks to address the unresolved edge questions, ITER is needed: presently identified effects will be sufficiently different and our understanding is too incomplete to be sure that new and critical edge questions will not arise. It is recognized that ITER is needed to advance the science of burning plasmas. It is needed equally to advance edge science.

6. SUMMARY AND CONCLUSIONS

The widespread view that tokamak edge physics is largely in hand is cause for concern. Understanding of a number of critical edge matters – although far from negligible – is sufficiently incomplete that, at some point, and unless rectified, these deficiencies could impede or stop progress to fusion power. While the list of unresolved edge questions is sobering, defeatism is unwarranted and it is time to re-invigorate the edge science quest with justified optimism: edge research efforts on existing devices need to be restored – and if possible, increased; ITER is needed as soon as possible.

Achievement of this goal might be helped if the edge science community were to express a consensus view on these matters.

ACKNOWLEDGMENT

Work supported by U.S. Department of Energy under Contract DE-AC03-99ER54463.

Some Observations about the Current State of Edge Physics

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IAEA Technical Committee Meeting on Divertor Concepts
Aix-en-Provence
11-14 September 2001

cause for celebration……

- **A decade ago we lacked a credible solution to the divertor problem.**
- **With the discovery of the cold, detached, radiating divertor in the 1990s, we now have (the makings of) a divertor solution for high power magnetic confinement devices.**
- **Congratulations are in order, *however…….***

…our understanding of tokamak edge physics is deficient.

- **The - perhaps growing - view that tokamak edge physics is adequately, or even largely, in hand is cause for concern.**

- **The manpower commitment to edge work on the two major US tokamaks, C-MOD and DIII-D, is now about half what it was a few years ago.**

- **It will be argued that, while the edge literature highlights a number of effects which can be explained, nevertheless our understanding of the following matters - although far from negligible - is sufficiently incomplete that, at some point, and unless rectified, *these deficiencies could impede or stop progress to fusion power*:**

1. We do not know the controlling source of impurities in the confined plasma:

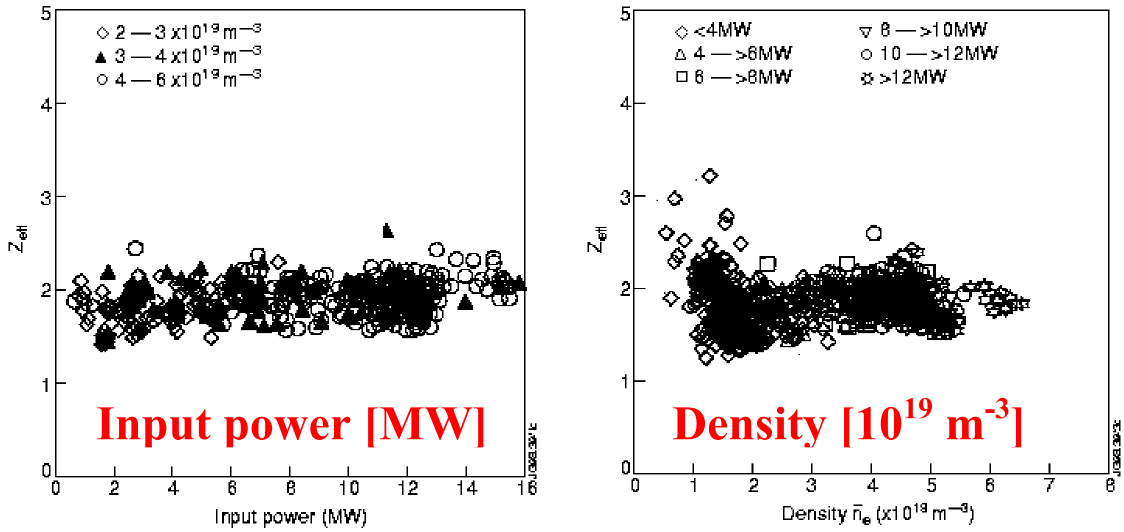
- **chemical sputtering vs physical sputtering vs evaporation/sublimation from hot tile edges,**
- **divertor targets vs walls,**
- **and if walls, whether it is due to neutral (charge exchange) or ion impact (plasma-wall contact).**

2. Our understanding is weak of how the impurities are transported -

- **through the edge plasma to the confined plasma,**

- **including the 'puff-and-pump' process for impurity control.**

JET Z_{eff}



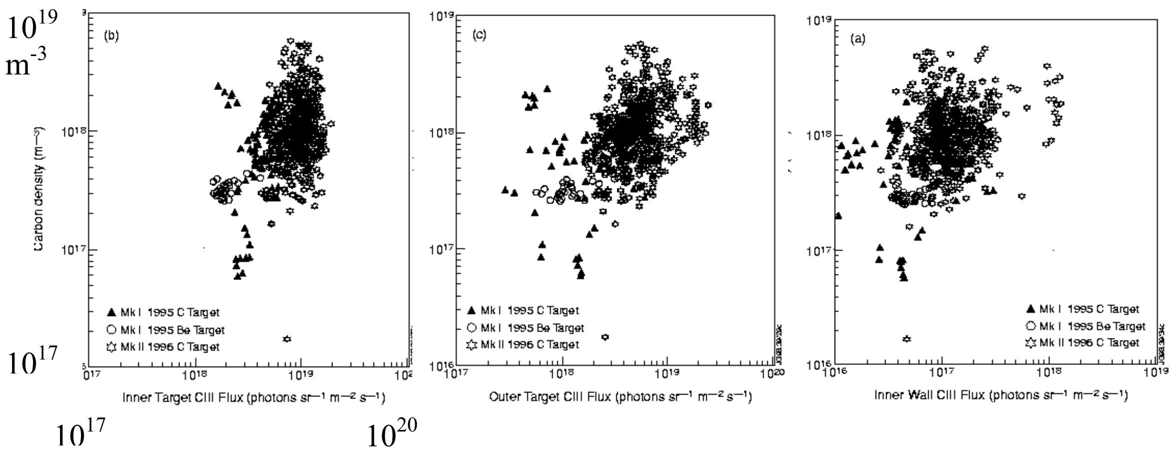
"Studies in JET divertors of varied geometry. III: Intrinsic Impurity Behaviour"

G.M. McCracken, et al, Nuclear Fusion 39 (1999) 41.

JET MkII diverted discharges, ELMy H-modes. 2.4 < I_p < 2.7 MA, ohmic and beam heated.

"The Z_{eff} and core carbon concentration are curiously independent of either input power or plasma density."

JET Core Carbon Density



CIII fluxes [photons sr^{-1} m^{-2} s^{-1}]

inner target **outer target** **inner wall**

"Studies in JET divertors of varied geometry. III: Intrinsic Impurity Behaviour"

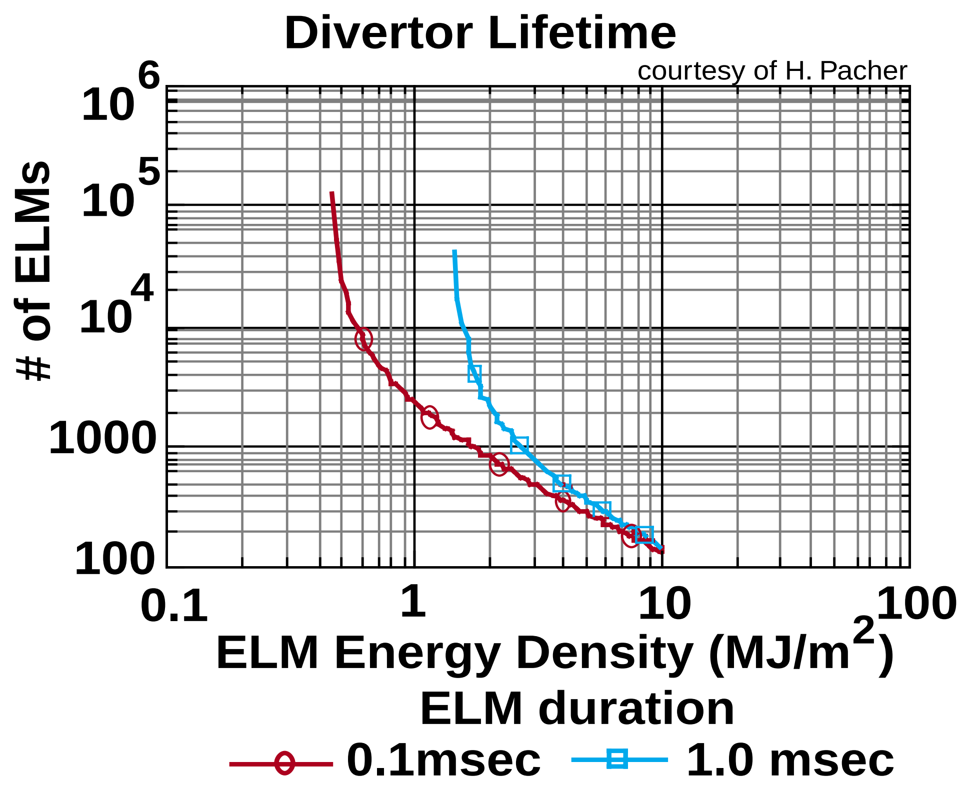
G.M. McCracken, et al, Nuclear Fusion 39 (1999) 41.

JET Mk I (C), Mk I (Be) and Mk II (C). ELMy H-modes. 10 < P < 14 MW. 2.4 < I_p < 2.7 MA. Ohmic and beam heated.

Any trends between carbon production rate and core impurity density are also difficult to discern.

3. ELMs are recognized as having the potential to destroy the targets.

- While we have learned much about the fundamentals of the ELM instability-
- and while the EDA and QH modes constitute potential solutions –
- a realized solution to this problem remains outstanding.



Courtesy of H. Pacher

For C divertor ablation starts at T ~ 2500 C.

For ELM energy density exceeding a threshold, divertor lifetime falls sharply.

Ablation Threshold: $Q\Delta t^{-1/2} \leq 23\ MJm^{-2}s^{-1/2}$.

4. We do not understand the controlling processes in the private flux zone, a region that can be important for pumping and probably for recycle refueling, impurity behavior, and co-deposition.

- **Often Monte Carlo codes, such as EIRENE, don't replicate the D_α emission from the PFZ.**

- **Is there fast cross-field transport directly onto the PFZ wall? 'Blobby' transport, hypothesized by Krasheninnikov?**

5. The neutral behavior in the regions just outside the plasma is characterized by long-standing, unresolved questions

- **Examples such as the lower plenum pressure in DIII-D for attached plasmas are welcome exceptions.**

- **Often, as in C-MOD, the pressure is significantly higher than is computed using even the most modern, sophisticated neutral codes such as EIRENE and DEGAS, including neutral-neutral collisions, and even giving ourselves the advantage of taking the 'plasma background' as being specified from experiment.**

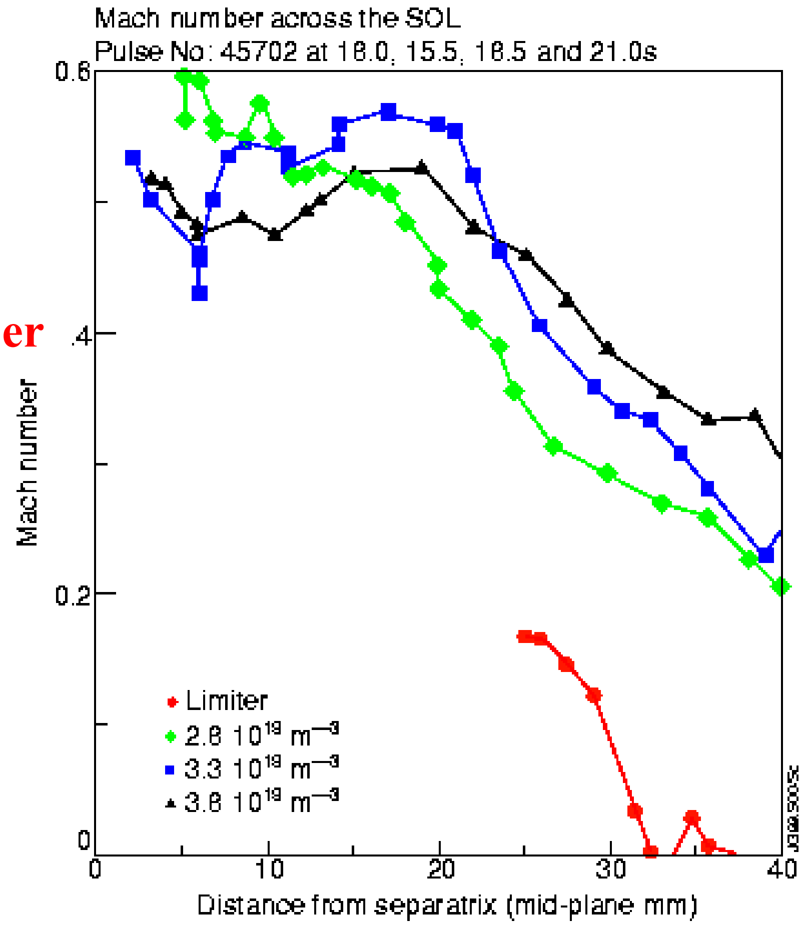
- **Confidence in our ability to *predict* pumping, including helium removal, is therefore not on the sound basis that is needed.**

6. Our understanding of edge flows is inadequate.

- The data base on edge flows is extremely limited –
- however, very high Mach numbers have been measured far from the targets.
- The magnitude of these flows does not appear to be consistent with our understanding of ionization-driven flows or of flows associated with classical or neo-classical drifts; their cause is unclear.
- Such flows must influence particle, momentum, and energy balances in the edge, affecting both the fuel species and impurities.
- Understanding of edge impurity transport is directly compromised by our lack of information and understanding of edge flows.

JET: High parallel Mach numbers measured in the SOL near top of torus

Mach Probe Mach Number

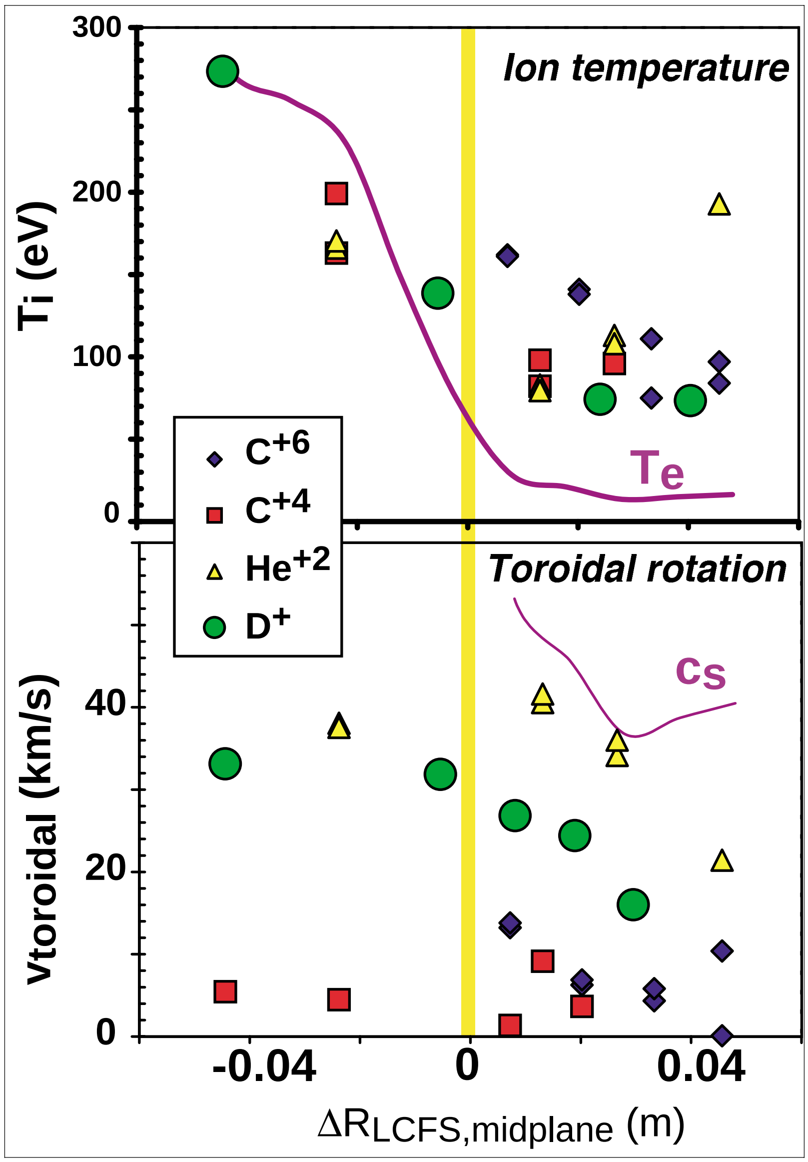


"Parallel flow in the JET scrape-off layer"

S.K. Erents, et al, PPCF 42 (2000) 905.

The radial profile of the Mach number across the SOL for a high-power L-mode discharge at different times.

DIII-D: High toroidal velocities measured by CER in the SOL at outer side of torus



Low density. L-mode.

DG Whyte, this meeting.

7. We do not understand the *carbon re-deposition* behavior and therefore the *tritium co-deposition* behavior in tokamaks.

- **On JET operated with tritium, the tritium inventory built up *without saturation limit*.**
- **This problem may be so serious as to rule out the use of carbon in fusion devices.**
- **That, however, would eliminate the leading candidate material, and the one that, by a considerable margin, we know the most about.**
- **It would be a setback to be driven to the extreme of not being able to keep the carbon option open.**

There are several sub-components of this behavior:

- **Apparently large-scale convection in the SOL starts near the outer target and extends to near the inner (generally detached) target.**

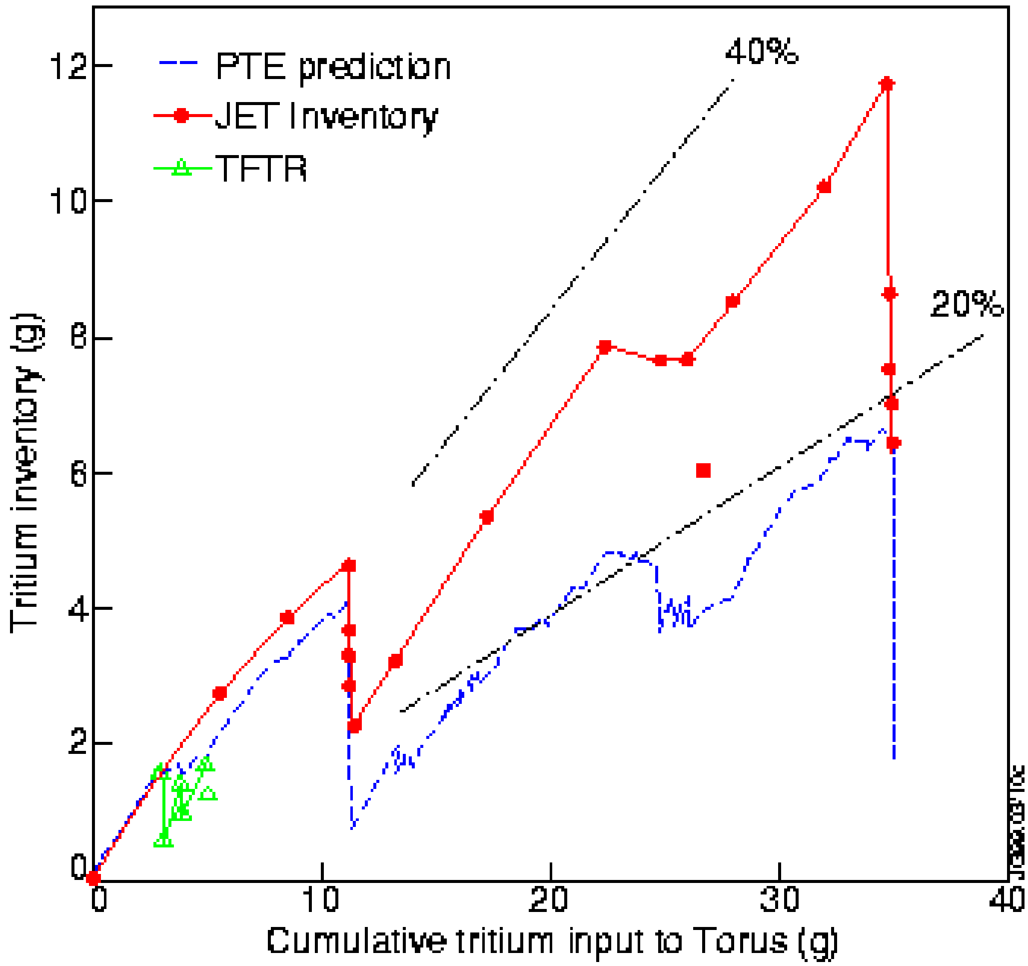
- **A source of carbon, apparently some process at the wall, feeds into this convective flow.**

- **The carbon may or may not actually reach the inner target, but in any case it does not remain there in JET. It moves by some neutral transport mechanism to adjacent surfaces, which are not plasma-wetted – or even in line-of-sight of the plasma – and the carbon re-deposition and tritium co-deposition occur there.**

For each of this contributing processes we have promising ideas and have made good starts at sorting each of them out – nevertheless, it is true to say that we still have very weak understanding for each of these contributing processes.

(Fortunately, however, they can be studied in any tokamak that employs carbon, since the carbon re-deposition is the issue - the presence of tritium is not required.)

JET: Retained Tritium

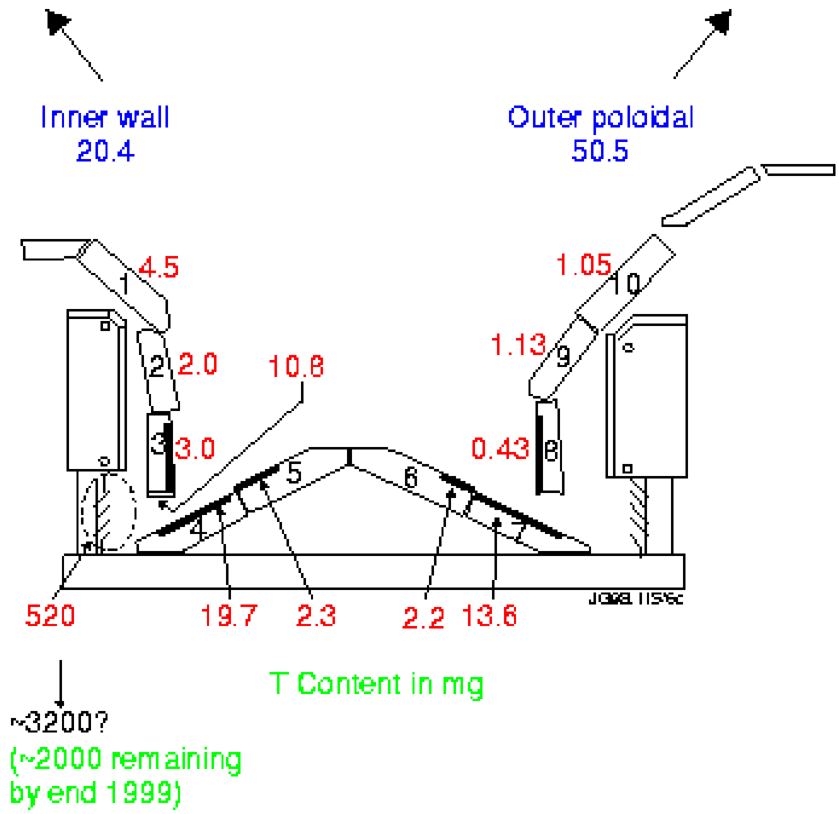


The rate of T retention in JET during DTE1 was 40% of input, reducible to 17% after cleanup in D, without sign of saturation.

P. Andrew, et al, FED 47 (1999) 233.

Extrapolation to Iter: the permitted in-vessel T-inventory, 0.5 kg, could be reached in 100 shots.

Location of tritium in JET vessel during the post-DTE1 shutdown



The location of the deposition is surprising: only a few mgs were found on typical tiles, but 520 mg were vacuumed up from the cooled, out-of-sight louvers, suggesting up to 3200 mg also that have fallen through to the vessel floor.

J.P. Coad, et al, J Nucl Mater 290-293 (2001) 224.

8. We do not know how the main plasma is fueled.

- Is it due to recycling from the divertor targets?

- If so, is it the result of plasma-fueling (ionization outside the separatrix, with plasma then transported across the separatrix),

- or is it due to neutral-fueling, i.e. neutrals cross the separatrix and ionize in the confined plasma?

- If the latter, is it due to more-or-less direct, line-of-sight, neutral transport from the targets, perhaps through the private region?

..fueling..

- **Or is it due to leakage around the outer-periphery of the plasma ('leaky divertor') with the neutrals then 'attacking' the plasma more-or-less uniformly around the entire outside?**

- **Or is plasma-contact with the walls and the resulting recycling there (as C-MOD reports) the principal fueling mechanism of the confined plasma?**

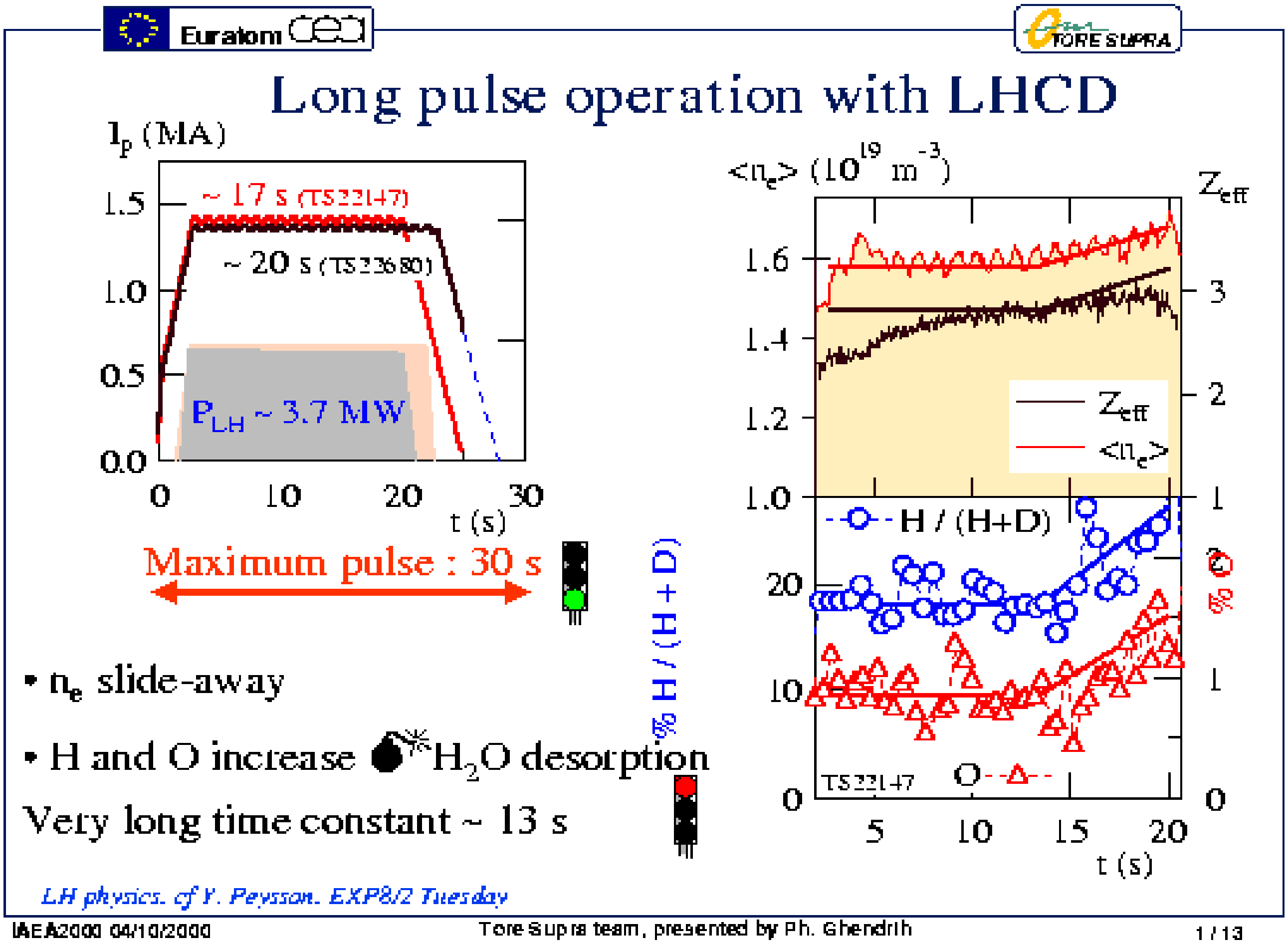
A number of important consequences attend our poor understanding of this matter, including such critical questions as:

- **the relationship between the *SOL and the pedestal*,**
- **the effect of neutrals on *high confinement* modes, etc.**

9. Long pulse operation – which will be essential in future - raises unresolved problems.

- On Tore Supra the situation appears steady over ~15 s but then a density runaway occurs.
- The long-time evolution of the particle content of the wall is poorly understood.

Tore Supra



Tore Supra Team, presented by Ph. Ghendrih. IAEA 2000.

Steady conditions until ~ 15 s, when n_e 'slide-away' occurs due to H_20 desorption.

10. We know little about how the power *enters* the SOL across the separatrix:

- How important are drifts and turbulence in this region?
- How do changes in transport inside the separatrix influence the SOL?
- What are the deviations from poloidal and toroidal symmetry?
- Power handling is the most important practical matter at the edge. Deficient understanding about edge power transport is potentially unsafe.

11. With regard to identifying the major routes by which power *leaves* a tokamak plasma:

- We do not understand the role of heat convection to the main chamber walls, as reported on C-MOD,

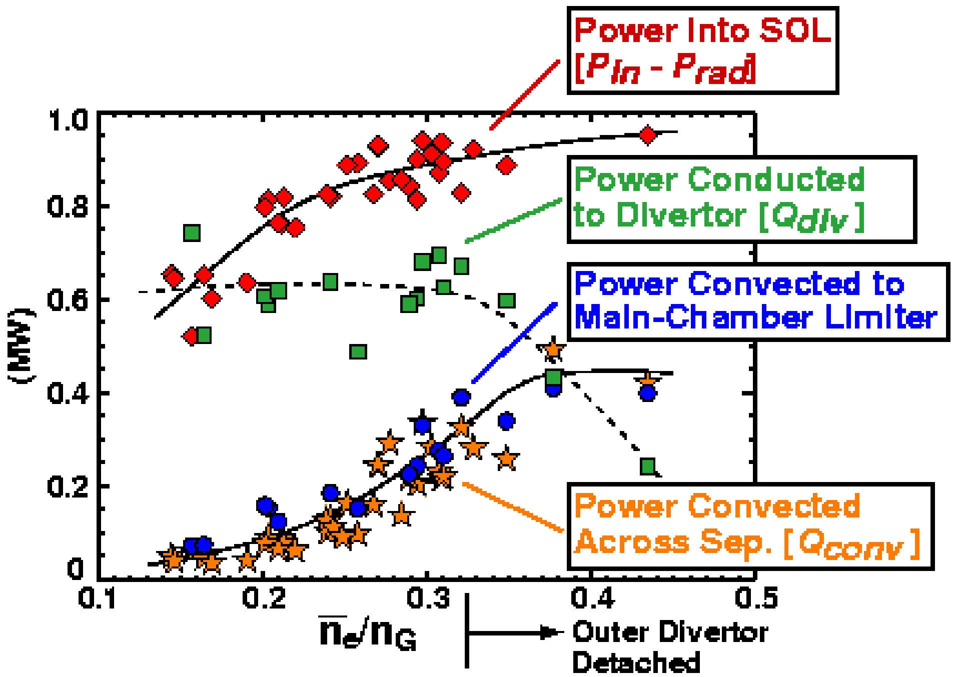
- nor the narrow power peak at the outer strike point, as reported by JET.

- These are specific examples of the more general problem that we do not understand cross-field transport in the SOL, nor are we even able to adequately characterize it to do reliable scaling, e.g. for SOL widths.

- The power width is a particularly critical issue; unfortunately, we are not even sure if the power dependence of this width is positive or negative.

C-MOD

Cross-Field Convection Increases with $\bar{n}_e/n_G$, Affecting SOL Power Balance



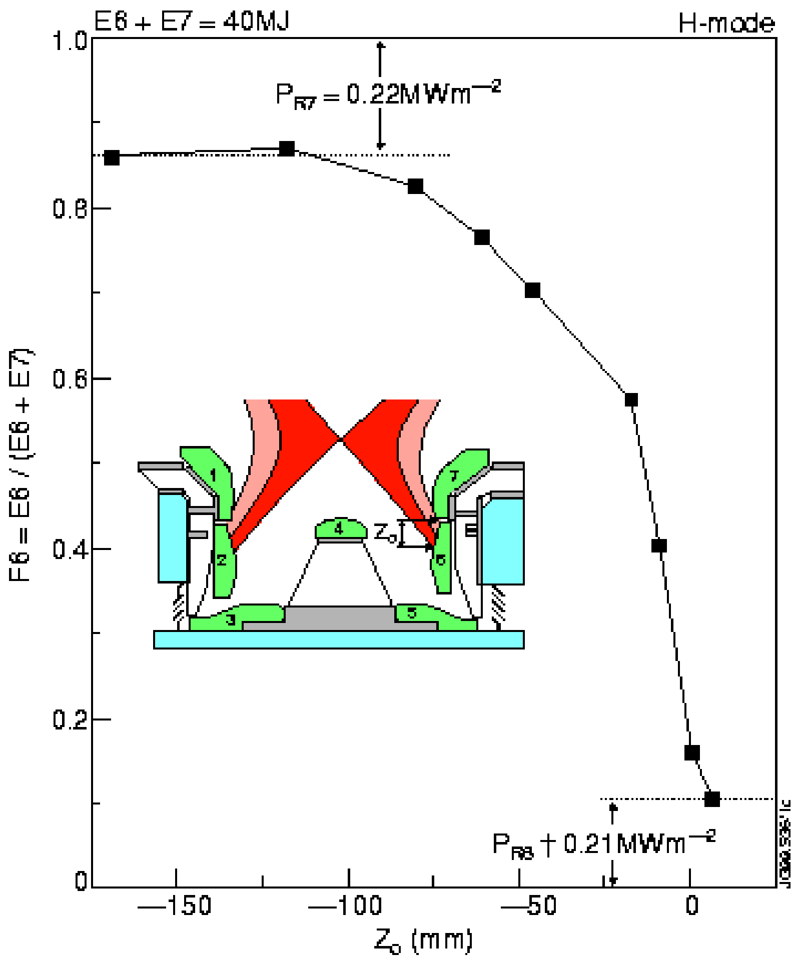
- At low density, parallel conduction to Divertor dominates SOL power balance
- At moderate density, cross-field heat convection to Limiter/Wall becomes important

=> Cross-field convection losses to main-chamber wall may precipitate divertor detachment

B. LaBombard, this Meeting.

"Divertor energy distribution in JET H-modes"

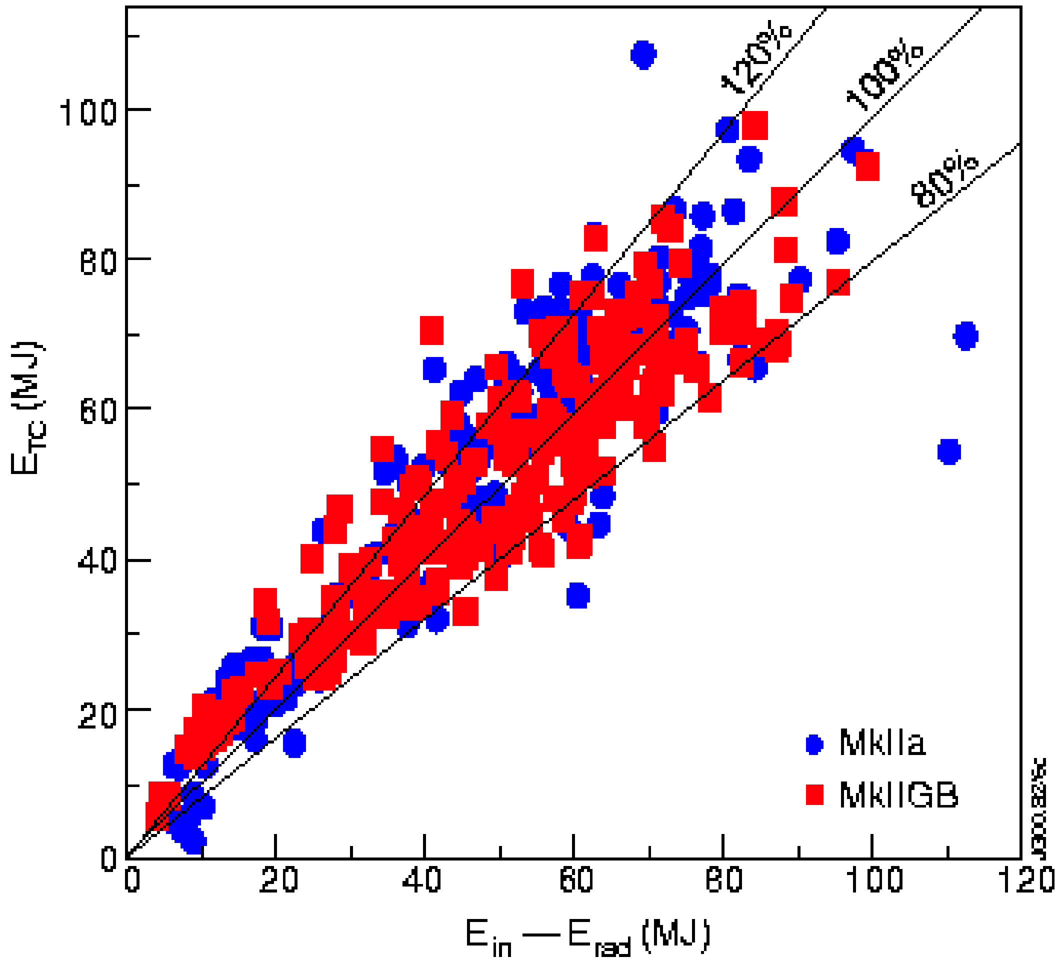
G.F. Matthews, et al, JNM 290-293 (2001) 668.



Fractional energy deposited on outer tile 6 vs vertical displacement of the strike point.

This thermocouple-based method gives excellent (a) energy accounting, (b) spatial resolution.

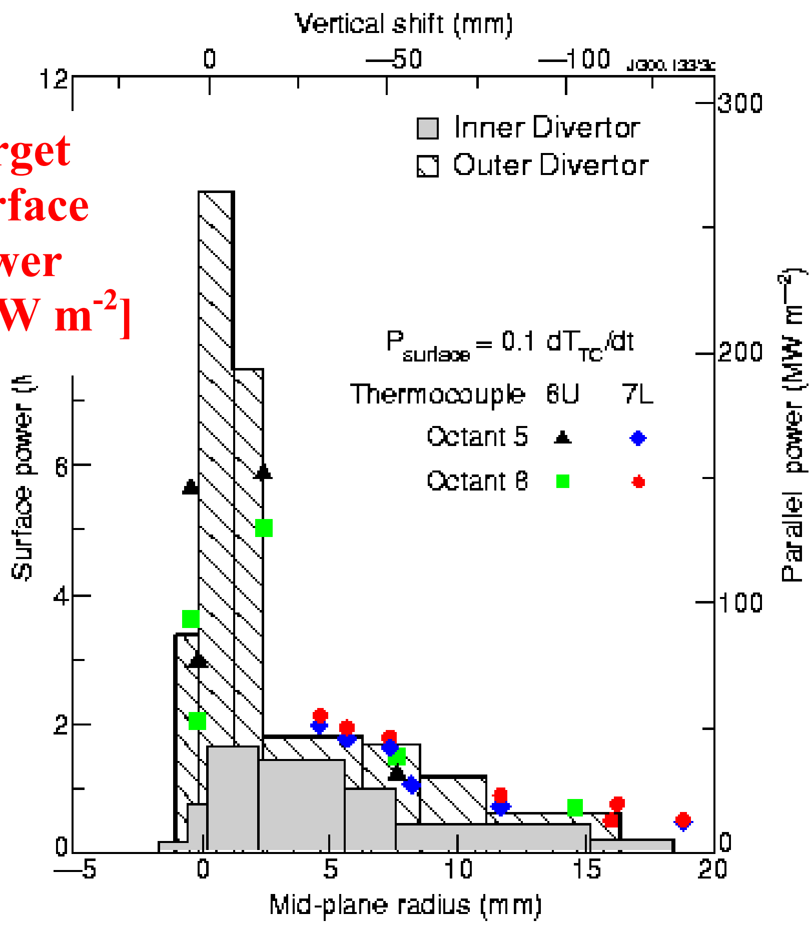
Excellent energy accounting now on JET



Measured E_{TC}, (thermocouple energy) vs E_{in} –E_{rad} for all JET steady-state shots in Mk IIa and MkIIGB.

But the JET power profile is *highly peaked*

Target Surface Power [MW m^{-2}]



- **12 MW unfueled H-mode shots.**
- **Narrow high power peak at outer target only ~2 mm midplane in width.**
- **Carries half the total divertor power in a typical type I ELMy H-mode.**
- **Dominant factor determining the in/out divertor energy asymmetry.**

At this time it is not to be expected that edge physics would be largely in hand

- **The research effort invested in the edge is far smaller than has been invested in the confined plasma.**

- **Many important questions about the confined plasma are still not answered.**

- **The edge is intrinsically more complicated than the confined plasma:**
  - **more states of matter involved**
  - **shape more problematical: long, narrow, twisted, inaccessible**
  - **SOL so narrow that we aren't even sure exactly where it is (EFIT uncertainties can be $\sim \lambda_{SOL}$)**
  - **main plasma can usually be modeled as 1D; edge requires 2D**
  - **diagnostic coverage never enough, since 2D**

It would be surprising if tokamak edge physics were largely in hand.

..despite all these problems..

No Grounds for Pessimism!

- **Today we have the makings of a divertor solution, for high density operation.**
- **We have – it may reasonably be hoped – largely identified the edge *questions,* the hardest part of any task.**
- **Divertor/edge diagnosis has progressed enormously.**
- **All major tokamaks are out of the unproductive stage of vacuum problems, etc. – and can now *'make hay'*.**

Therefore, while the list of unresolved edge problems is sobering, defeatism is unwarranted and it is time to re-invigorate the edge science quest with justified optimism.

The Edge Science Quest

- **We simply do not know enough about the science of the edge.**

- **We need to identify the controlling processes in the edge.**

- **This requires more extensive edge diagnosis.**

- **The biggest 'holes' are T_i and $v_{||}$. More edge CER would be particularly valuable.**

- **We will never have complete experimental mapping of the 2D edge fields of n_e, T_e, T_i, $v_{||}$ and will have to rely on interpretive codes to piece things out. We need measurements of n_e, T_e, T_i, $v_{||}$ at more locations to constrain the codes.**

- **More edge researchers – not fewer than the number before the recent reductions - are needed to identify the controlling processes, i.e. *to do edge physics.***

a specific research focus might be useful…

Possible Candidate: Tritium-Retention

- **Powerful motivation: it is apparent that this is a very serious problem.**

- **Requires improved understanding across a wide front of edge issues:**

  - **neutral-wall contact**
  - **plasma-wall contact**
  - **cross-field transport in the SOL**
  - **C-production**
  - **SOL flows**
  - **divertor detachment**
  - **C:H films**

- **This will require much more extensive edge diagnosis.**

- **By itself, the T-retention problem drives most aspects of edge research.**

Fusion Program Objective: Science or Burning Plasma?

- **An edge *science* quest fits naturally into a fusion program whose objective is the advancement of fusion *science*.**

- **On the other hand, if the fusion program objective is the early construction of a burning plasma device, the edge science quest takes on urgency due to the potential show-stopping edge problems. e.g. T-retention, ELMs, etc.**

The fusion effort has received good value for its (modest) investment in edge science. There is every reason to expect further good return on future investment. A solid base has been established. Now we need to build on this strength and exploit it to sort out the critical matters that we have identified – regardless of whether the program objective is science or burning plasma.

Progress in Edge Research has Lead to Misunderstanding

- **An incorrect view that edge physics is adequately in hand has developed in recent years.**
- **This appears to be the result of misunderstanding.**
- **Solid progress has occurred in edge research and the edge community has communicated that to the program leadership, quite appropriately.**
- **Our leaders, however, have misunderstood this to mean that edge physics is adequately in hand.**
- **Such misunderstanding is always a risk for edge research: program leaders are understandably (overly) receptive to any message that resources can be saved in an area which does not involve hot, fusion-producing plasma.**

Rectification of this situation probably depends on the edge research community clearly expressing a consensus view that edge physics is not adequately in hand.

Iter

- **Iter design has been a major driver of edge research.**

- **Regardless of how fully we exploit existing tokamaks to address unresolved edge problems, *Iter is needed asap*: presently identified effects will be different (enough) and new effects will (probably) be found.**

- **An implication of our weak understanding of edge science: the design of the Iter edge/divertor should include as much flexibility as possible, i.e. ability to change direction if required.**

Summary

- **A decade ago we lacked a credible solution to the divertor problem.**

- **With the discovery of the cold, detached, radiating divertor, we now have (the makings of) a divertor solution.**

- **Congratulations are in order.**

- **However, our understanding of tokamak edge physics is deficient. The - perhaps growing - view that tokamak edge physics is adequately, or even largely, in hand is cause for concern.**

- **While the edge literature highlights a number of effects which can be explained, nevertheless our understanding of many edge effects is sufficiently incomplete that, at some point, and unless rectified, these deficiencies could impede or stop progress to fusion power.**

- **Although the list of unresolved edge problems is sobering, defeatism is unwarranted *and it is time to re-invigorate the edge science quest* with justified optimism:**
  - **Edge research efforts on existing devices need to be restored – and if possible, increased. More diagnostics.**
  - **Iter is needed as soon as possible. Edge/divertor design should be as flexible as possible.**

- ***Achievement of this goal will be helped if the edge science community expressed a consensus view on these matters.***