# Confinement in some detail- Explosion in Fusion Enterprise

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# Recollecting / Building the Magnetic-Fusion Logic

- Dramatis Personae: Confinement time $\tau_c$ plus

  1)$|B|$, the gyro frequency $\Omega$,

  2)the machine size $a$, a pressure scale length $L$

  3) the thermal speed $v_{th}$, gyroradius $\rho = v_{th}/\Omega$, and the dimensionless measure $\rho^* = \rho/a$

  4)some effective "collision" frequency, in fact, a correlation frequency$\gamma$-generally the growth rate of the "dominant" mocroinstability, $[\gamma \approx v_{th}/a$,k$\rho \approx 1]$

- The projected turbulence dominated transport:

$$D_t = \gamma(\Delta x)^2 \approx \gamma/|k|^2 \approx \rho^2 v_{th}/a = \rho{*}^2 a v_{th} \tag{1}$$

  implying a confinement time

$$\tau_c = a^2/D_t = \frac{1}{\rho{*}^2}\frac{a}{v_{th}} \tag{2}$$

  Gyro-Bohm scaling on which ITER like machines were planned. To get the best confinement time, go to lower $\rho^*$- totally consistent with the naive ideas of magnetic confinement -**Increase the magnetic field- increase the minor radius.**

# Fusion- Breakeven - Ignition

- Energy produced in a Fusion Reactor

$$E = \frac{1}{4} n^2 < \sigma V > \mathcal{E}, \tag{3}$$

where $\mathcal{E}$= energy released per unit reaction, $< \sigma V >$ will be the reaction rates for D-T reactions.

- For net energy gain, we must demand

$$E > E_{loss} + E_{expended}, \quad define \quad Q = \frac{E}{E_{loss} + E_{expended}} \tag{4}$$

- The more moderate scientific First Ambition is to define $Q_{sc}$

$$Q_{sc} = 1, \quad when \quad E = E_{loss}, \qquad Q < (<<) Q_{sc} \tag{5}$$

- We are still struggling to get $Q_{sc} = 1$ in any semi steady setting
- Fusion will be an economic reality when Q approaches infinity=Ignition=burning plasma

# Is the Fusion Enterprise well grounded- not a chimera

Two Fusion Systems - The stellar (that works) and terrestrial (our pursuit)

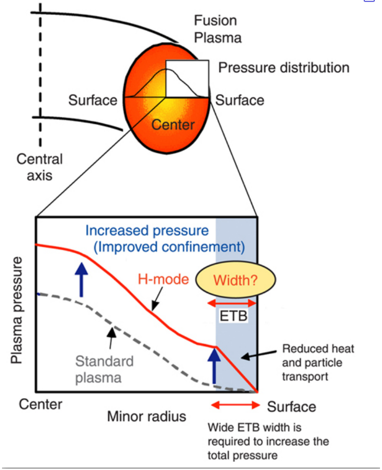
# A little Twist- the bad side of small $\rho^*$!

- We will soon see why small $\rho^*$ may not always be a blessing!

# A little digression into history of Fusion

- Fusion enterprise was stuck at low confinement - scaling with power were bad etc.
- Then a miracle was wrought by experimentalists at Garching- they created a plasma configuration which had considerable more confinement
- Self-Organization- Large Plasmas develop steeper gradients with formation of an edge barrier .
- This high confinement H-mode, in fact pulled fusion research from a very depressing era ( the l-mode era) in which the progress towards fusion seemed so stagnant.
- H-modes ( and their cousins, Internal transport barrier modes ) are routinely Produced in the lab. We have made tremendous strides in exposing the H-Mode dynamics.
- IFS/ExoFusion group (our group) is an original and major player in this research- unlocking the secrets behind this spectacular phenomenon

# High Confinement Mode- H-Mode the saviour



# What is needed for a burning plasma

- A. Good H-mode confinement

  1) “Sufficient ” MHD Stability The pedestal must have good MHD stability to reach high pressure

  2) “Enough” velocity shear A good H-mode must also have enough velocity shear at the pedestal top

- The latter is fundamental to suppress turbulence so that the pedestal transport is low

- B. Acceptable Power Exhaust

  1) Time Average heat must be $<$ the engineering limit: 10 MW/m2

  2) Transient ELM heat load must be below the melting limit - The restrictions could be far severer

# Deep Connectivity between A and B

- Experience on present devices does establish some aspects of connectivity
- For instance : Degradation of H-mode for higher degrees of detachment- often induced by higher degrees of gas-puffing
- Nonetheless, the magnitude of the difficulty posed by this connectivity is underestimated for burning plasma parameters
- The primary reason lies in a lack of appreciation of what may constitute adequate velocity shearing rate
- **In fact, most times, the adequacy of velocity shear at burning plasma parameters is taken for granted**

one of our projects was to subject this belief to a critical scrutiny

# The H-Mode Pedestal

- The edge transport barrier- or pedestal- is the key to good H-mode confinement
- Energy transport in the core is “stiff” , the pedestal top- the “boundary condition” for the core- is the key to core performance
- After $L \rightarrow H$ transition, the pedestal becomes“well developed”- roughly steady state
- This pedestal phase, primarily, sets the core confinement
- The higher the pedestal-top temperature, the higher the central temperature, the high the $D - T$ cross-section, the higher the Fusion Energy Production
- But what , if at all, does it to have do with velocity shear?

# The H-Mode Pedestal- The velocity shear

- The transition to H-mode is accompanied ( experimentally) by the spontaneous generation of a sheared flow
- The shear flow is associated with the appearance of a radial electric field $E_r$
- For well developed pedestals, the radial electric field Er is well approximated by the neoclassical estimates
- Neoclassical estimates are abundantly verified in experiments on multiple tokamaks (ASDEX, DIII-D, C-mod, etc.)
- The shearing rate associated with this $\mathbf{E} \times \mathbf{B}$ flow

$$\gamma_E = c\partial r(\frac{E_r}{B}) \tag{6}$$

is a fundamental construct for understanding the pedestal turbulence

# The Shearing Rate and Turbulence suppression

- it is, perhaps, somewhat intuitive that if the shearing rates are “high” the core turbulence could be quenched ( nonlinearly).
- The “usual” core turbulence: primarily “electrostatic modes”- ITG, trapped e-modes, etc.
- The electrostatic turbulent transport is expected to be suppressed when the velocity eddies are “sheared apart” faster than they are formed
- That is if $\gamma_E > \gamma_L$, the linear growth rate; the latter is a measure of the eddy formation rate
- Years of simulations, theory, and experimental benchmarking, find that transport -quenching requirements are a little stronger :$\gamma_E$ must be several times larger than $\gamma_L$-, may be by a factor 2.5-3.
- Till now the fusion community, at large, has assumed that this requirement will be true for burning plasma H-modes.

This we will soon see has been a critical oversight

# The Shearing Rate/ linear growth rate - why small $\rho^*$ is not always a blessing

- For standard modes , one can simply estimate

$$\Gamma = \frac{\gamma_E}{\gamma_L} \approx \rho^* \tag{7}$$

$\rho^*$ being the ratio of the thermal gyro radius to an equilibrium length.

- It is eminently true that Present devices in ELMy H-mode operations have more velocity shear than is needed to suppress the electrostatic transport-the suppression parameter $\Gamma$ is considerably greater than 1
- it makes sense, then, to examine if the the projected $\Gamma$ for ITER that has a much lower $\rho^*$, will be large enough to allow such a happy state- a robust H-mode pedestal.
- Experimental examination, unfortunately, cannot be done

ITER- relevant $\rho^*$ is unattainable in present devices -especially at relevant collisionality → DIIID pedestal may not accurately reflect the ITER pedestal- they are in different physics regimes!

# How do we examine the projected ITER pedestal

- Fortunately, in the last many years , our simulation/ computational abilities have increased tremendously
- In particular , the gyro kinetic simulation codes have attained a high level of maturity and reach
- Combined with very high quality equilibrium codes (that can accurately generate the magnetic geometry, temperature density, current and flow profiles etc), the gyro kinetic codes can simulate the pedestal turbulence and its consequences.
- We have, recently, put together a program using the equilibrium codes VMec, Corsica, EFIT ,and the highly used and benchmarked gyro kinetic code GENE to investigate pedestal physics- For ITER ( and other possible future machines) and also current machines like JET
- Ot must be noticed that such powerful investigating tools ( to probe Nonlinear fully electromagnetic turbulence, for instance) have just come of age- They were certainly not available for ITER design- And really not for all these interim years

# Gyrokinetic Simulations- Initial Results JET, ITER

- We cut our teeth on simulating the JET experimental pedestal (Prof Hatch will give detailed picture)

  JET: the level of turbulent transport agrees with experiment There is sufficient $\Gamma$ to suppress the electrostatic transport. Electromagnetic modes, which are more resistant to velocity shear, predominate
- ITER: At relevant low $\gamma_E$, the e.s turbulence produces huge transport

  Almost an order of magnitude more turbulent transport losses (many hundreds of MW) than the ITER heating power ≈100MW

  → It appears that the transitional $\Gamma$ ($\rho^*$) below which the e.s turbulence may become too high lies somewhere between JET and ITER.
  → with this ITER heating power, the pedestal top will be considerably lower than needed for good core confinement and high enough central temperature.
- The problem is made even worse by strategies that are generally proposed to control divertor heat flux and eliminate ELMs

# ITER-Severe Exhaust problems-Inter ELM, ELM phases

- Radiation enhancement in the divertor, to lower the burden on the plate, may require a high SOL density
- This boundary condition for the pedestal density affects turbulence through two different channels: 1) It decreases $\Gamma_E$ ( ExB shear), and 2)

  by decreasing the density gradient (resulting in increasing $\eta$ =ratio of temp to density gradients), it bolsters the growth rates of electrostatic modes
- Thus already low $\Gamma$ becomes even lower
- Strategies to eliminate ELMs come with unfortunate side effects:

  Standard Resonant Magnetic perturbations appear to reduce $\Gamma_E$

  “Quiescent H-modes” requires edge counter rotation → reduces $\Gamma_E$
- These considerations are rather sobering

# A Critical Look at Gyrokinetic Results

- Early results of GK simulations of the pedestal are very interesting, but also very disturbing
- Several questions can be immediately raised
- Are these results a bolt from the blue? Could one “predict the difficulties with burning plasma pedestals in general, and ITER in particular? and if one could, why did we not undertake a systematic examination of the ITER pedestal all this time?
- I will try to attempt answering these questions but surely, even at best, it will be a very inadequate answer

But grapple with these questions, we must

# Pedestal and Gyrokinetics- A short history

- That inadequacy of velocity shear can lead to excessive turbulent (electrostatic) transport is well established by a variety of gyro kinetic modelers- In fact, the result that $\Gamma = \Gamma_E/\Gamma_L > 2.5$ is needed to keep e.s turbulence in check was established (for the core) by a huge number of nonlinear runs, and extensively "verified" by existing experiments
- the crucial relationship that $\Gamma$ is determined by $\rho^*$ is surely obvious
- However, though clearly pointed out, it was not "appreciated" or taken seriously

  That the ITER pedestal, because of its considerably smaller $\rho^*$, may not have adequate $\Gamma$ to suppress electrostatic turbulence → the ITER H-mode may not be robust enough for high gain.
- I will now speculate now on some of the possible reasons why?

# ELMY H-modes-the width W

- The importance of $\rho^*$ was a matter of serious contention/controversy in the early era of ITER
- If the character of the H-mode pedestal was to be determined by the transport threshold, then one expects that the pedestal width $W$ will scale as $\rho_p$
- Very detailed and intensive/impressive multi- machine experimental effort, however, was undertaken to check this- The results were shown not to obey this scaling
- Instead it was claimed that the width scales more like $\sqrt{\beta_p}$ - which, of course, differs from $\rho_p$ via a density dependence-
- the natural conclusion, then, would be that the width is not transport controlled- therefore all the fuss about $\rho^*$ was, simply, all fuss.
- And $\rho^*$ was almost edited out of memory for pedestal studies
- For quite a many years the dominant effort was the experiment- DIID, ASDEX, CMOD even JET. as it ought to have been

# The EPED Era

- This empirical picture of the Pedestal got a resounding boost from what “could’ be termed as an underlying theory, The EPED model, developed at GA, basically claimed that the pedestal characteristics (crudely, height and width) were set by MHD alone - micro-turbulence played little role
- The EPED model was applied to all working tokamaks and it was supposed to be working well - a few notable exceptions were seen as a bit of an irritant but there was/is a broad “consensus” written, inspired, and shepherded by P.Snyder, the originator.
- The new theoretical-speculative content of EPED : The stability boundaries of two MHD instabilities- the so called peeling-ballooning mode and the Kinetic ballooning (KBM)-are the principal determinants of the pedestal- micro turbulence is not a major player- And really most good H-mode pedestals do show suppressed turbulence
- Through a joint modeling-experimental synergy, based on a rigorous study of rather good H-modes on current machines, it was projected that the ITER pedestal would be broad and high enough for high Q.

# Outliers- Experimental

- Although EPED has been an overwhelming and dominant force, there were some dark clouds on the horizon-

- 1) there is the so called IMode which does not ELM but does have an enhanced level of micro-turbulence
- 2) In magnetic field scans, there is considerable departure from EPED predictions in the higher field regime
- 3)The JET pedestal is expected to be in the second MHD stability regime- it would seem the fundamental assumptions of EPED should not pertain
- 4) several simulations of the JET and some other pedestal see little evidence of KBM control- casting doubts on the KBM engineered pedestal
- Question- Are we beginning to see something different as we travel towards ITER via JET- largest of the current machines with the lowest $\rho^*$

# Dilemma- Change in thinking!

- Our insistence on the best possible understanding of pedestal on current machine (and the underlying mechanisms that set the primary characteristic of the pedestals) was to know enough about ITER
- EPED was very welcome as an attempt to “unifying” pedestal physics -a trustworthy extrapolation from current machines to ITER could be possible
- After a considerable era of EPED success, one was beginning to see chinks in the armor especially when applied to JET - This change from a great match for (DIIID , ASDEX-U —) to not so great a match for JET experiments created a serious dilemma?
- Do we believe EPED projections for ITER ( quite optimistic) or do we not?
- And if if not what are the determinants of the ITER pedestal and how are they different from the determinants marshaled by EPED.
- Could ITER be in a different physics domain that is essentially inaccessible to the best diagnosed machines of today?

# Rho* as an ordering parameter- Transport as a determinant?

- There are physics considerations which might help to create some order
- That is reviving the possibility of micro-turbulent transport as a possible player for larger machines like ITER and high field runs(on current machines).
- It is quite clear that $\rho^*$ for ITER will be considerably smaller than for the current machines (compounded by a lack of external rotation in ITER)- This is not the first time that $\rho^*$ enters the battle-field.
- Big question: Is it conceivable that $\rho^*$ for ITER is low enough that micro-turbulence, which is strongly suppressed, say, in DIIID, may end up determining the properties of the ITER pedestal
- More explicitly: The DIID is an over-sheared machine (relatively large $\rho^*$)- micro turbulence is highly suppressed, and only MHD (EPED) stability boundaries set pedestal parameters while for ITER-relevant $\rho^*$, the electrostatic turbulence is strong enough that micro-transport together with MHD ( and not MHD alone) will control the pedestal.
- A fundamental question for ITER/Fusion: Is $\rho^*_{ITER} < \rho^*_{crit}$ or $\rho^*_{ITER} > \rho^*_{crit}$? A vigorous investigation of ITER pedestal must follow- EPED projections may not be reliable

# What are the tools of investigation

- Since none of the current experiments can be readily run in the required range of $\rho^*$, the only dependable alternative left is simulation using a combination of the best equilibrium and gyro kinetic codes
- One should also look for niche experiments on current machines which can best mimic ITER - the standard, highly investigated H-mode may not lead us to correct predictions- there will, likely, be qualitative differences
- At UT, we have struggled with these questions ( Mike Kotschenreuther and I and then David Hatch joined us a good ten years ago) for long years- Purely theoretical thinking was put on a firmer footing through a a somewhat ambitious program ITER (like) pedestal investigation by employing the state of the art code GENE (nonlinear fully electromagnetic simulations) fed by highly resolved full-geometry equilibria from VMec and CORSICA- To the best of our knowledge, this was the very first attempt at this problem at such an encompassing level.
- The results are highly interesting and highly sobering!

# Where do we find large enough Gamma for burning plasmas- A digression from the ITER line

- An alternative burning plasma parameter regime may be sought in the Lower aspect ratio (LA) machines
- The LA tokamaks can have larger (much) $\rho^*$ → larger $\Gamma_E$
- The toroidal field is much lower for the same plasma pressure or fusion power
- Other geometrical and plasma effects reduce $\Gamma_E$ , the linear growth rate for electrostatic modes
- The combined effect will be a strongly enhanced $\Gamma$- hopefully large enough for suppressing e.s turbulence.
- The UT group is vigorously exploring the LA as well as (what we call) the intermediate aspect ratio (IA) regimes; the latter regime is being investigated so as to allow a superconducting option.
- Preliminary results are encouraging

# Foundational Changes in Understanding

- My idea of advancing your understanding of Fusion sciences is not to advocate one approach or the other but to introduce you to the most powerful ideas that may help you analyze and figure out how to do it yourself.
- these ideas , stemming from advanced understanding of physics ( plasmas, thermodynamics—) have been and are tested by advanced simulations (experiments)
- it is also my considered opinion that these ideas must be in the tool kit of every fusion physicist , perhaps every fusion scientist
- Directly or indirectly all these idea concern confinement

# The H-mode- The transport barrier

- In the world of Fusion (via Magnetic Confinement), plasma configurations with Transport Barriers (TBs), whether internal (ITB) or edge (H-Modes) are clearly the uniquely favored (if not the only) vehicles to commercially viable fusion power.
- For the time being, think of a TB as a region with rather sharp pressure gradients.
- In fact a TB represents precisely the culmination of the magnetic fusion quest - to have a high pressure /high temperature confinement region surrounded by relatively cold low pressure surroundings
- surely there have to be large gradients at some boundary!
- Just as surely sharp gradients mean lots of free energy- it is a state far from thermodynamic equilibrium.

# Transport Barriers, TBs

- Repeat -Creating and sustaining sharp pressure gradients- (Transport Barriers) is the very essence of the controlled thermonuclear enterprise
- Long life of a TB, however, **is a simple contradiction in terms- How do the turbulent losses decreases with sharp gradients?**
- Standard behavior - increase a gradient and faster flows the physical quantity- **heat should flow more rapidly for sharper temperature gradients**
- **What exceptional process operates in magnetically confined plasmas ?**
- What prevents the enormous free energy from driving the system towards an equilibrium- implies dis-association of free energy from instability!
- What dynamical Constraints, if any, forbid the conversion of free energy into turbulence? what prevents the normal play of thermodynamics so that such highly self-organized states may exist!
- Magnetic fusion transport barriers are simple a subset of high gradient states that frequently occur in nature

# A glimpse of the twenty first century fusion physics-1

- there, indeed, is a dynamic constraint : the instability induced current (charged flux ) must be zero otherwise such an instability cannot exist no matter how much is the free energy!
- This constraint opens up new knobs ( in addition to, or instead of velocity shear) that allow barrier formation – sharper density gradients could do the job that velocity shear did, for instance.
- Plus: several more ways to create current imbalance -Impurity current can stabilize if the electron and ion currents balance
- This is an immediate reprieve for machines of future that will definitely have a paucity of velocity shear
- A comprehensive reference on the constrained dynamics : M. Kotschenreuther, X. Liu, S.M. Mahajan, D.R. Hatch, and G. Merlo, Nucl. Fusion 64 (2024) 076033 (41pp)

# A glimpse of the twenty first century fusion physics-2- Non equilibrium thermodynamics

- fundamental macroscopic theory of a transport barrier- it is constructed within the framework of non equilibrium thermodynamics. *it does not solve equations of plasma electrodynamics- nor does it construct an empirical model based on experiments!* -
- transport barrier is a heat engine that operates by maximizing entropy production in a plasma layer whose one end is kept at fixed temperature $(T_0)$ and a quantity of heat enters through the inner layer; the game is to maximize the temperature difference $T_1 - T_0 > T_D - T_0, T_D = temp.$ if diffusion prevailed
- The trick is to convert the incoming power to creating macro scale flows and other ordered motions instead of diffusion

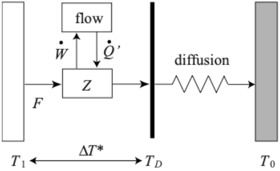


FIG. 1. Equivalent diagram of a heat engine in a boundary layer. If $\Delta T^* > 0$, the heat engine can work to drive flow ($P$ is the power driving the flow; $\dot{Q}'$ is the dissipated power; in steady state, $P = \dot{Q}'$). The flow produces an additional "nonlinear impedance" $Z = \eta_1(P)$ that sustains the temperature contrast $\Delta T^*$ yielding a free energy to drive the flow itself.

# A glimpse of the twenty first century fusion physics-2- Non equilibrium thermodynamics

- The heat engine can create a state of enhanced gradients (there is a bifurcation) if the incoming heat flux is above a threshold. In a simple model calculation, this translates to

$$\frac{T_1}{T_D} = \frac{F^2}{F_c^2} > 1, \quad F_c = \frac{T_D}{(aT_0)^{1/2}} \equiv \frac{T_0}{\sqrt{T_0 a} - \eta_0} \tag{8}$$

  where $a$ (efficiency of thermal conversion to do work) and $\eta_0$ is some baseline diffusive impedance.

- This equation makes sense only if

$$T_0 > \frac{\eta_0}{a^2} \tag{9}$$

  **The edge temperature cannot be too low for an L-H transition to occur**. In fact $F_c$ is a minimum at $4\eta_0/a^2$- This amazing result was systematically derived form the macroscopic theory for the very first time- Experiments did know that, though( Prof hatch will elaborate)

- I will now share with you some thoughts why and how the processes that create maximum disorder (maximum entropy) can simultaneously create order ( the transport barrier).

# Macro Non equilibrium thermodynamics plus Micro plasma simulations

Yields the most satisfactory theory of transport barriers till to date. Professor Hatch will show how well the marriage works

A Unified theory of transport barriers (TBs) in magnetically confined systems, Swadesh.M. Mahajan, David Hatch, Zensho Yoshida, and Mike Kotschenreuther- sent to Nuclear Fusion (2026),

Z. Yoshida, and S. M. Mahajan, Physics of Plasmas 15, 032307 2008)