Issue: Tearing Mode Avoidance and Stabilization
(Rob La Haye, General Atomics, March 2, 2009, with thanks to Richard Buttery and Dave Humphreys for comments)

While the destabilization of the ideal kink is the ultimate limit to beta in an advanced tokamak, the inevitable (so far) evolution of the profiles usually leads to destabilizing a tearing mode. This is the practical limit to beta and is encountered in almost all circumstances. This "penultimate" limit to plasma pressure is due to resistive modes that tear magnetic surfaces. With finite plasma resistivity, ideal MHD breaks down at rational surfaces with safety factor q=m/n. Advanced tokamaks with elevated q_{min} (well above 1) and flat or slightly reversed q-profiles in the core ($q_m > q_{min}$) and with large bootstrap fraction (f_{boot}) for steady state are susceptible in two ways for the destabilization of tearing modes.

When q_{min} equals a low order rational q value (lowest m and n possible are the easiest to destabilize), the absence of magnetic shear can classically destabilize the tearing mode. Examples of this in DIII-D are shown in Fig. 1 in which q_{min} is *not* sustained and drops through m/n=8/3, 5/2 and 2/1 in sequence, destabilizing the modes.

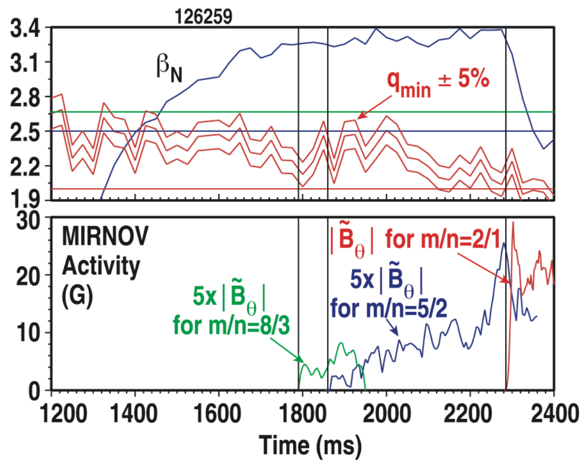

Figure 1. An AT discharge in DIII-D that is *not* sustained. (a) q_{min} drops below 2.67, then 2.5, and then below 2 as $\beta_N \approx 3.3$ is held constant by NBI feedback (not shown). (b) Mirnov activity showing 8/3, 5/2 and 2/1 modes.

If destabilized, a classical tearing mode can convert to and be sustained at large amplitude as a neoclassical tearing mode (NTM). The NTM is maintained by the helical perturbation to the pressure-gradient driven bootstrap current and is therefore a particular problem in the AT. Of additional concerns for an AT are: (1) the operation at beta above the no wall n=1 (and 2 and 3?) ideal kink limit which can destably couple to n=1 (and 2 and 3?) tearing [1], and (2) operation at low plasma rotation which can make tearing less classically stable [2].

The evolution of the q-profile plays a key role in the destabilization of tearing modes: thus an active system is needed for both q-profile control and for mitigation if the q-profile becomes tearing unstable. The issues for a DEMO are the "soft landing" of the q-profile during the startup as q_{min} comes down and beta is built up and the maintenance of the steady state profile between the "rails" of the desirable q values (q_m at ρ=0 and q_{min} at ρ_{min}) so that tearing modes of any significance are avoided or quickly suppressed. Local narrow electron cyclotron current drive (ECCD) at rational surfaces can stabilize or even preempt the existence of an NTM by both replacing the missing bootstrap current and increasing the classical tearing stability [3]. A combination of both broad ECCD capability to adjust and maintain the current profile for complete non-inductively driven current density *and* local ECCD at key rational surfaces for NTM stabilization must be in the mix. A "broad brush" electron cyclotron current drive added to the mix of bootstrap and neutral beam injection (NBI) current drive can indeed sustain the q-profile in DIII-D stably "between the rails" of unstable q values [4] as presently demonstrated only for q_{min}~1.6 with available ECCD as shown in Fig. 2. This discharge had neither feedback on the location nor on the magnitude of the ECCD; a trial and error feed forward application of the ECCD was made. The plasma was both tearing stable (mostly) and non-inductively driven (in total) as the surface loop voltage was zero as long as the ECCD and the beams were run. About 12% of I_p was by ECCD. This is shown in Fig 3.

The key issue is the feedback control of a predominantly noninductive (f_{boot}~1) current density profile (including the alpha heating from the burn) by real-time measure of the q-profile and the maintenance of the desired stable profile by a real-time variable location and amplitude ECCD. This would include active intervention of local ECCD for stabilization of specific modes.

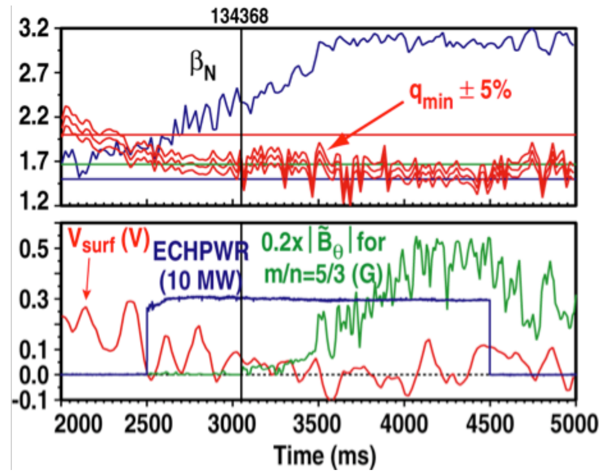

Figure 2. An AT discharge in DIII-D that *is* sustained. (a) q_{min} is maintained above 1.5 as β_N≈3.0 is held constant by NBI feedback (not shown). (b) Surface voltage from EFIT, calibrated injected EC power, and the unique Mirnov mode amplitude (m/n=5/3).

Requirements for Resolving the Issue

An AT plasma with a large fraction of non-inductively driven current is needed as a basis. Clearly a predominantly bootstrap current driven AT would be next in complexity and a device with f_{boot} ~100% that includes the pressure contribution from the burning plasma is ultimately needed for study.

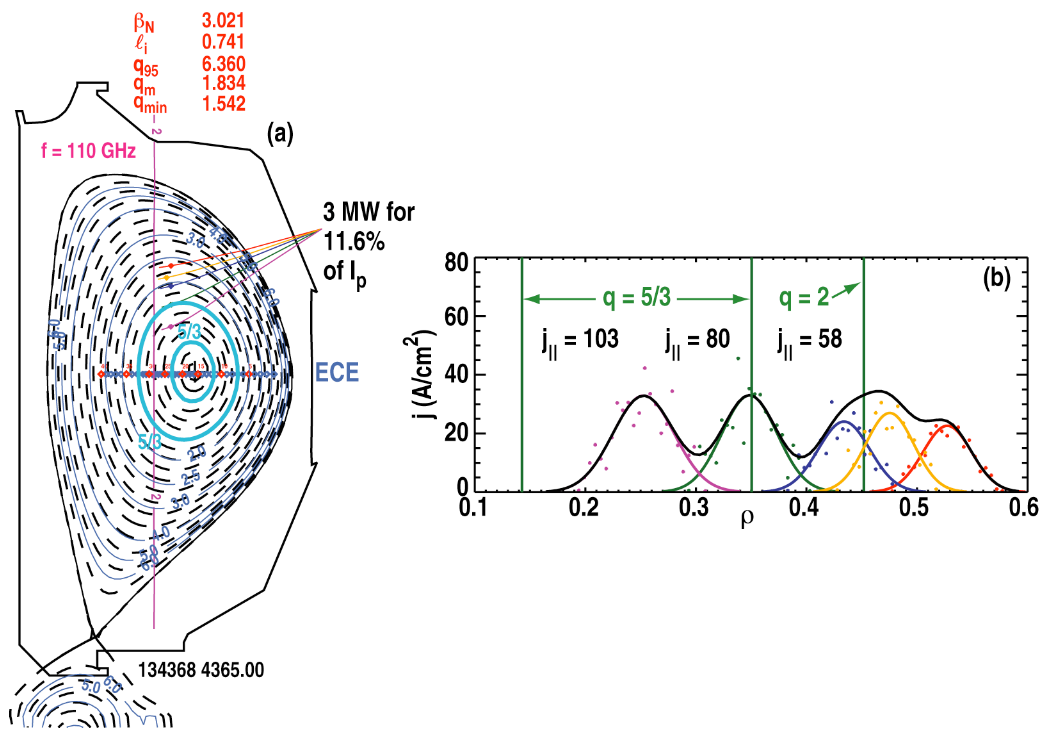

Figure 3. Same discharge as in Fig. 2. (a) Cross-section and selected parameters. (b) ECCD from five launchers (five gyrotrons used) along with the total envelope.

Real-time accurate measurement of the q-profile is needed. Given a fixed q_{95}, determination of q_m at ρ=0 and q_{min} at ρ_{min} would allow a q-profile to be well-constrained. Estimated uncertainty in measuring q in real-time with the MSE-EFIT is ±5%. Thus control (taking this uncertainty as an example) needs to keep q on axis to no more than 0.95*q_m(target) and q_{min} to no lower than 1.05*q_{min}(target); these would be the stable "rails". The location of ρ_{min} is uncertain because of the zero shear although it is assumed that the "shear in the shear" is non-zero. Given an uncertainty in q of ±dq, $d\rho_{min}=\pm\mathrm{sqrt}(dq/d^2q/d\rho^2)$ at ρ_{min}.

An ECCD system capable of driving ~10% of the total plasma current, at multiple simultaneous locations from near-axis out to the q=3 surface, with real-time adjustment of the launch angles is needed. It might be necessary for some ECCD capability in the counter to I_p direction and/or the ability to swing from co to counter during a discharge. It is assumed that the ECCD "tweaks" the total non-inductively driven current density profile to push it into the narrowly prescribed desired stable state. This is the equivalent of a tugboat docking a super tanker. Any tearing mode that started to grow would need to be identified in real-time by the PCS and gyrotron power aimed to drive localized co-ECCD at the rational surface for prompt suppression as in Ref. 5.

The specification of a desirable q-profile for a burning AT plasma is needed. This could be the ARIES-AT configuration for example with some experimental guidance for tearing stability, i.e. q_{min}>2.5 instead of 2.4 as has been specified might be better and would avoid even the possibility of a 5/2 mode.

Modeling is needed (as in Ref. 6) of the effect of localized ECCD pulses to nudge the current and q-profiles. This would be input to the ECCD requirements and a starting point for implementation of an element of the real-time plasma control system (PCS) that controls the multi-location ECCD to maintain the profiles between the desired target and limits. Tearing mode stability would need to be modeled with PESTIII, NIMROD etc.

Elements of a Research Thrust to Resolve the Issue

A research thrust could proceed from DIII-D, to the new Asian tokamaks, to an FDF, to ITER AT Scenario 4, to DEMO in an overlapping timeline. This would be to study the maintenance of a tearing stable profile with large fraction of non-inductively driven current (DIII-D), to a largely bootstrap driven current without the burn (Asian tokamaks), to an FDF with large bootstrap fraction and some burn, and finally to ITER AT with significant bootstrap fraction and full burn.

Plans for DIII-D envision increasing injected gyrotron power to 9 MW (from 4 MW at present). This will allow the study of sustained AT discharges with q_{min}~2.5 as proposed in Fig 4. A state-of-the-art plasma control system (PCS) and real-time profile diagnostics will allow investigation of the optimal use of ECCD for stable sustained discharges. Similar resources will be available in the later years of ITER for the ITER AT Scenario 4. However this ITER concept is only for β_N=3 at q_{min}=2.4 with f_{boot}~50% so below the fully bootstrap current β_N of 5 envisioned for a DEMO. How much ITER can contribute to an AT demonstration will depend in part on sufficient off-axis current drive and the ITER schedule of experimental development.

Sustaining tearing stable AT discharges with β_N>4 and f_{boot}~90% is expected to be carried out on the three new superconducting Asian tokamaks, EAST, KSTAR and JT60-SA. However, these experiments will not integrate steady state in a burning plasma where the issues of plasma control may be quite different.

FDF should have all the features of a DEMO to study in having an AT plasma with β_N~5, at q_{min}~2.5, f_{boot}~90% and a Q of 2–5 with a significant fusion burn. It should be designed to have both significant total broad ECCD of ~10% as well as multiple localized ECCD of j_{eccd}/j_{boot}~1 at several key rational surfaces for NTM preemption. An FDF that comes online before the ITER AT Scenario 4, can add to the DIII-D and new Asian tokamaks demonstration of q-profile and tearing mode control for leap-frogging to DEMO after ITER. FDF must also produce and demonstrate a sustained duration solution for DEMO; gyrotrons of high reliability cw operation are needed to test feasibility of the mission.

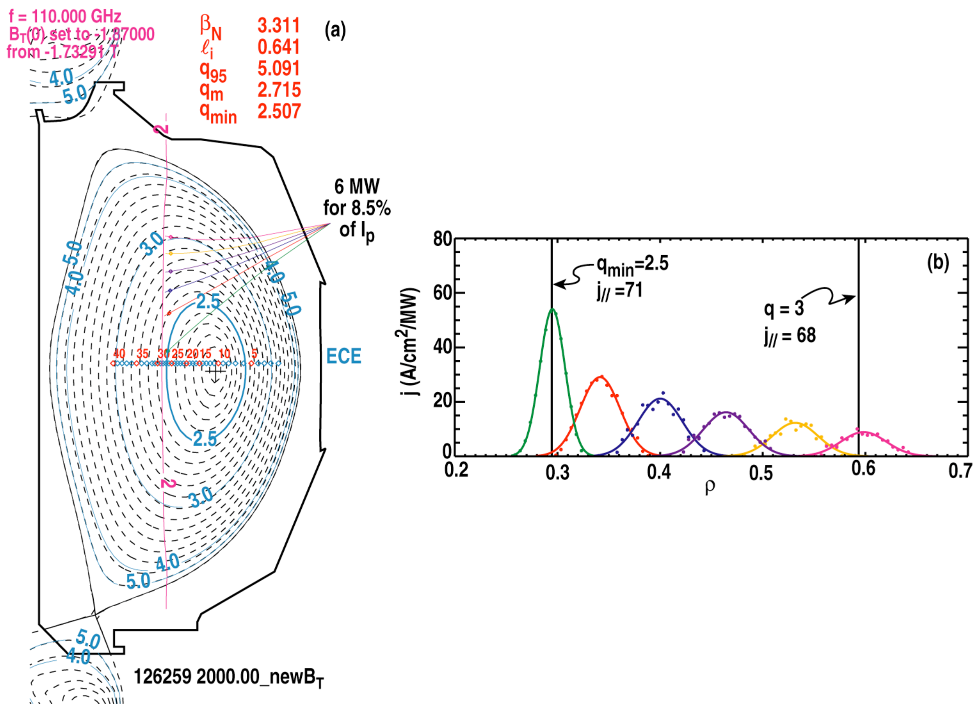

Figure 4. Combination of broad brush ECCD injected into high q_{min} AT to be sustained *and* with local ECCD at q=5/2 and 3/1 for specific mode control. (a) Cross-section and selected parameters. (b) ECCD per MW.

References

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