Hybrid Regime as an Alternative Scenario for High-Beta, Steady-State Plasmas

C. Craig Petty, General Atomics

Physics Issue

The physics basis of high-beta, steady-state hybrids needs to be completed so that it becomes a reliably, robust baseline scenario for future burning plasma devices.

Background

Definition of AT regime. A "conventional" tokamak that operates at high plasma current with an H-mode edge is an excellent candidate for a burning plasma experiment in the near future. However, an inherent drawback of the tokamak as a fusion power plant is the need to sustain this high plasma current in steady state. "Advanced" tokamak (AT) scenarios seek to match the fusion performance of the conventional scenario but at reduced plasma current, which would enhance the commercial attractiveness of the tokamak as an energy producing system [1]. The features of a AT fusion reactor include: high fusion power density which requires high β, high fusion gain which demands high $\beta\tau$, and steady-state operation at low recirculating power which entails a high bootstrap current fraction. The bootstrap current fraction increases with safety factor like $f_{BS} \propto q^2\beta$; thus, high β and q_{95}~5 are needed. However, increasing q without decreasing β also requires an improvement in the stability limit because $\beta_N \propto q\beta$. Finally, since the energy confinement time is observed to have a nearly linear dependence on the plasma current, the confinement factor will need to increase like $H \propto q$ in the AT scenario to achieve a similar fusion gain ($\beta\tau$) as in the conventional scenario.

Conventional thinking about the AT scenario is that a high value of the safety factor minimum is needed to maximize the bootstrap current. Typically AT scenarios with $q_{min}>2$ are envisioned, leading to f_{BS} values around 80%. While such high q_{min} values are likely detrimental to the confinement time, it is generally thought that such scenarios will have higher stability limits ($\beta_N \geq 4$) and of course larger f_{BS}, which would more than offset the confinement disadvantage. However, operation of high β AT scenarios with $q_{min}>2$ is challenging for several reasons. First, very good alignment of the bootstrap current profile and the desired plasma current profile is required. As the bootstrap current is driven by the pressure gradient, this situation results in a complex coupling between the q profile, turbulence-driven transport, plasma pressure profile, and bootstrap current profile. Second, about 20% of the plasma current needs to be externally driven near the plasma periphery (ρ~0.8) to achieve steady-state operation. This appears difficult to achieve with either NBI or RF waves, partially because the current drive must have a specific profile and partially because the current drive efficiency is modest in this location. The current drive efficiency is important because if a large amount of power is needed to drive 20% of the plasma current, then the recirculating power will not be low.

New developments. Recent experiments have demonstrated the potential for a different AT regime with $q_{min} \approx 1$ based on the "hybrid" scenario. The hybrid scenario was first developed as an operating mode for ITER to allow high fusion power to be achieved at reduced plasma current [2]. However, hybrid plasmas have several favorable attributes that propel it into the AT regime discussed above. These favorable properties are largely due to the presence of a benign m/n=3/2 tearing mode that suppresses the sawtooth instability by raising q_{min} to ≈1.05 owing to magnetic flux pumping [3]. This removes a trigger mechanism for the deleterious m/n=2/1 mode and allows very high β_N to be obtained; there is also evidence that the m/n=3/2 tearing mode directly inhibits the destabilization of the 2/1 mode by robbing it of a source of free energy. Values of β_N around 3.5, well above the ideal no-wall stability limit, have been obtained for several seconds in hybrid plasmas, limited only by the available heating power. The energy confinement time in high β hybrids is also excellent, with confinement factors often reaching H_{98y2}=1.6. Even in the case of strong electron heating, experiments on DIII-D obtained H_{98y2}=1.4 with $T_e \approx T_i$ for $\rho \geq 0.2$.

Having $q_{min}\approx 1$ in hybrids does result in a lower bootstrap current fraction compared to the $q_{min}>2$ AT regime, but this is offset by a higher current drive efficiency in hybrids since the required external current can be driven in the plasma center. For otherwise similar plasmas, f_{BS} drops from ~80% for $q_{min}>2$ to ~50-60% for $q_{min}\approx 1$, requiring at least twice as much current drive for steady-state hybrid operation. However, the current drive figure-of-merit measured in A/W can be more than a factor of two higher for deposition at ρ≈0 compared to ρ≈0.8. Thus, the current drive power needed for a high-beta, steady-state hybrid plasma is no more, and may be lower, than for the $q_{min}>2$ AT regime. Remarkably, experiments have shown that such strong current drive in the center of hybrids does not result in significant sawtooth activity, as magnetic flux pumping continues to maintain $q_{min}\approx 1.05$ even for ~100% noninductive current fractions. The robust current profile, insensitive to the driven current, is a great advantage of hybrids over the $q_{min}>2$ AT regime as fine control of the current density is not needed.

Applications. The physics basis for high β hybrids is closer to being established than for the $q_{min}>2$ AT regime; thus, hybrids are an excellent candidate for near term burning plasma experiments such as ITER and FDF. An example is given in Table 1, where the parameters for a Q=5 hybrid scenario in FDF are listed. Note that the required current drive efficiency is consistent with the established physics basis [4]. Additionally, if a lower confinement factor is assumed, then a lower current drive efficiency can be tolerated (because more auxiliary power is available). Longer term, hybrids may compete with the $q_{min}>2$ AT regime for DEMO, especially if new current drive methods with higher efficiency can be achieved.

Table 1. Parameters for steady-state hybrid D-T plasma in FDF with Q=5.

R (m)	R/a	B (T)	I (MA)	β_N	n_{GW}	f_{BS}	H_{98y2}	P_{CD} (MW)	γ_{CD} (A/Wm^2)
2.6	3.5	5.5	7.8	3.7	0.44	0.53	1.6	59	3×10^{19}

<u>Research Requirements</u>

- Determine the stability limits (essentially the onset point of the m/n=2/1 mode) of hybrids in "reactor relevant" regimes, especially as a function of input torque (Mach no.) and plasma shape.
- Develop the basis of a confinement extrapolation from present day experiments in the "reactor relevant" regime to future burning plasma devices, including
  - The dependence of transport & confinement on T_e/T_i, input torque (Mach no.), and plasma shape.
  - The dependence of transport & confinement on "size scaling" dimensionless parameters such as ρ^* and ν^*.
  - The validation of turbulence simulation codes using measurements of the turbulence characteristics and heat/particle/momentum transport.
- Combine the hybrid core plasma with an H-mode edge plasma that is compatible with the first-wall of a burning plasma device. This includes a study of
  - ELM suppression (through RMPs or edge rotation control).
  - Radiative divertors.
- Demonstrate that the above features of hybrids are maintained under steady-state conditions where central current drive is applied to reduce the surface loop voltage to zero.
- Develop new current drive methods with higher efficiency.

<u>Research Thrusts</u>

Achievement of these research requirements does not require a new facility (rather the aim of this hybrid thrust is to aid the operation of new facilities). The research thrust advocated here is a combination of upgrades to existing US tokamaks, as well as a national experimental campaign to complete the physics basis of high-beta, steady-state hybrids. The hardware upgrades include

- Additional core current drive power and methods to allow for steady-state experiments under a variety of conditions. RF sources are especially desired.
- Facility upgrades to access "reactor relevant" conditions such as $T_e \approx T_i$, low torque injection, and low collisionality. RF sources are especially desired, and edge particle control (i.e. pumping) is needed.
- Facility upgrades to allow the study of the core/edge integration, especially in regard to survival issues of the first wall in future burning plasma devices. Methods for ELM control and a radiative divertor are needed, and a variety of plasma-facing components need to be tested.

A national experimental campaign requires sufficient run time on the existing US tokamaks, and an increase in scientific staff devoted to studying the experimental and theoretical aspects of high-beta, steady-state hybrids. Joint international experiments on this topic should be welcomed.

[1] T. S. Taylor *et al.*, Plasma Phys. Control. Fusion **36**, B229 (1994).
[2] T. C. Luce *et al.*, Nucl. Fusion **43**, 321 (2003).
[3] C. C. Petty *et al.*, Phys. Rev. Lett. **102**, 045005 (2009).
[4] ITER Physics Basis, Nucl. Fusion **39**, 2137 (1999).