Steady State Operation of Tokamak Reactors: Current Drive Requirements

Miklos Porkolab and Paul Bonoli, MIT Plasma Science and Fusion Center

Steady state tokamak reactor operation poses considerable challenges, well beyond those of ITER, and will require significant R&D not only in technology (materials, magnets), but also in plasma physics. While MIT has already submitted white papers on magnets (Joe Minervini) and materials issues (Lipschultz and Whyte), this white paper concentrates on the plasma physics issues associated with steady state operation at reactor relevant parameters. In our view, many of these physics issues can and should be resolved in currently operating facilities, which offer extraordinary flexibility in operations and diagnostic capability, and low cost as compared to resolving such issues on ITER. In addition, resolving some of these issues on ITER will come much too late, making it impossible to move ahead with DEMO design and construction on the time scale needed to provide fusion energy by mid-Century. It will also be necessary to find solutions to some of these issues for an effective FNSF machine design, which should be operational in parallel with the ITER nuclear phase (mid to late -2020s) and before the final design of DEMO, so as to provide data on nuclear materials issues. We will use the ARIES AT and ARIES RS reactor design studies to identify the key plasma physics parameters which are essential for designing DEMO and which will not be resolved in a timely fashion on ITER. These issues must be resolved in order to bring the tokamak to true steady state, one of the key challenges on the path to reactors.
The steady state issues in tokamak plasmas have been explored in the 1990s, and documented by the ARIES reactor studies, and may be summarized with the help of the current profiles shown in the figure:

Table 1.
Plasma parameters in ARIES-AT
(after S.C. Jardin et al, FED 80, 25 (2006).)

B_0=5.8 T, I_P = 12.8 MA, R = 5.2 m, R/a = 4.0,
ß = 9.1%, $ß_N$ = 5.4, q_0 = 3.5, q_{min} = 2.4, κ = 2.2,
$n_e(o) = 2.7\times10^{20} m^{-3}$, $n_e(r/a = 0.9) = 2.0\times10^{20} m^{-3}$,
$T_{e0} \cong T_{i0}$ = 30 keV, I_{BS} /I_P= 0.91, I_{LHCD}/I_P = 0.91,
P_{LH} = 40 MW, P_{FW} = 10 MW (or P_{EC}).

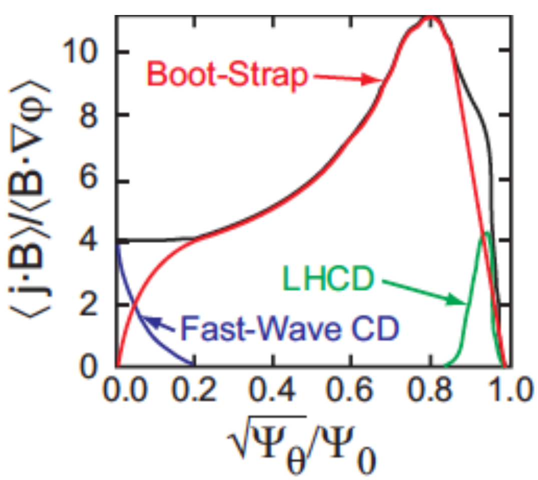

Fig. 1 Radial profiles of currents needed in ARIES AT due to different sources (BS=bootstrap current, LH = lower hybrid microwave driven edge currents ; FW = RF wave driven core currents, could be ECCD); these currents are needed to maintain a steady state equilibrium.

These parameters, and the current profiles, show the critical requirements for a steady state reactor plasma: it must operate with up to 90 % bootstrap current; a few percent of central current must be driven by fast ICRF waves (FW) or electron cyclotron waves (ECCD) and a critical component is the edge current drive, with about 10 %, driven by lower hybrid waves, to anchor q_{min} above 2.0 near r/a= 0.8. ARIES RS has similar requirements, with about 88 % bootstrap current and 8.0 Tesla central magnetic field, as opposed to about 5.8 Tesla in ARIES AT. The most critical issue is that to achieve these high bootstrap current fractions, the plasma must operate with $\beta_N \geq 5$, has to have q > 2 in the plasma core (hence q_{min} is at r/a = 0.85-0.9) to avoid MHD and sawteeth, and establish a reversed shear q profile for r/a < 0.9. This will stabilize fine scale turbulence (ITG, TEM, etc) and thus improve confinement. At this high β the machine will rely on wall stabilization of MHD kink modes and also, includes RMP coils and rotation to stabilize additional MHD modes. Detailed MHD studies have established that the free boundary MHD limit for such plasmas is at β_N ~3, with a maximum bootstrap current of 70% (see, for example, the ATBX design, Porkolab et al, Yokohama IAEA meeting, 1998). We note that in ITER the target bootstrap current is only 60% with $\beta_N < 3$. The necessary density to achieve the ARIES reactor parameters ($\beta_N \geq 5$) at the appropriate peak electron and ion temperatures of 25 to 30 keV is about 2.7×10^{20} m^{-3}. At such high densities, accessibility of the lower hybrid waves becomes an issue even to r/a = 0.9 as in Fig. 1. While in ARIES RS this was solved by using 8 Tesla central field, (or 16 Tesla on the coils), in ARIES AT, at about 5.8 T central field, Fast Lower Hybrid (FLH) waves (or High Harmonic Fast waves) were introduced into the design to penetrate the plasma periphery. Unfortunately to couple to such waves requires a dielectric loaded waveguide array (to rotate the wave polarization by 90 degrees) and those launchers at the plasma edge will not survive in a reactor (nuclear radiation) environment. Hence, it is desirable to operate the reactor at least at 8 Tesla so as to ensure penetration ("accessibility") of the conventional "slow" lower hybrid waves through the edge pedestal density (namely the perpendicular dielectric constant, $\omega_{pe}^2/\Omega_{ce}^2$ should be less than unity near the plasma edge in front of the launcher so that the slow wave, with a typical index of refraction, $N_{//} \approx 1.8$- 2, can penetrate). Furthermore, in a reactor type plasma with high edge electron temperatures (8 – 10 keV at r/a ≈ 0.9) such slow waves will be absorbed efficiently by electron Landau damping, hence establishing the requisite q_{min} and current profile. While in earlier experiments in the 1980s we have demonstrated LHCD at such high reactor relevant densities in Alcator–C (circular machine with limiters), the density limit being due to parametric decay instabilities (PDI)), in C-Mod's diverted geometry a lower density limit was observed, by factors of up to two. The reason for the reduced density limit in C-Mod is under investigation at the present time. In the earlier LHCD experiments and in related theoretical studies it was shown that the density limit due to PDI could be avoided by raising the frequency of the launched RF waves to twice (or higher) above the local lower hybrid frequency, thus setting the density limit at a given magnetic field. This also meant that a relatively high frequency for the launched waves is necessary, limited only by engineering considerations of launcher fabrication and cooling. These considerations led to LHCD frequencies of the order of ~5 GHz at central magnetic fields of 5-8 Tesla, for reactor relevant central densities of $2.7 \times 10^{20} m^{-3}$, and edge (pedestal) densities of $2.0 \times 10^{20} m^{-3}$ (ARIES AT value). This is also the relevant frequency even at the lower densities envisaged in the ITER steady state scenario (0.7×10^{20} m^{-3}) where absorption of the lower hybrid waves by alpha particles must be avoided. These parameters are easily matched by the Alcator C-Mod (f = 4.6 GHz) which also utilizes reactor-relevant metallic PFCs. Recent experiments on C-Mod have started to elucidate the complicated role of PDI in a diverted tokamak where it was observed that poloidal density variations must be taken into account in regard to PDI excitation. To avoid this problem, it may be necessary to move the launcher poloidally toward the top of the plasma column, to increase single pass LH wave penetration and absorption, a concept that could be tested in future C-Mod experiments. Higher edge temperatures in DEMO would also help to alleviate this problem by ensuring efficient single pass absorption of LH waves. An alternate operating scenario may be the recently discovered I- mode in C-Mod, where the edge densities tend to be lower while the edge electron temperature pedestals are high. This is just one example where C-Mod can play a critical role in demonstrating reactor relevant current drive techniques. In addition, C-Mod's goal in the future is to demonstrate reversed shear profiles at a β_N up to 3 (the free boundary β limit) by utilizing the existing 6 MW of ICRF heating power combined with an upgraded LH power capability of 3 MW. This will put C-Mod clearly in the electron transport dominated regime, allowing us to study transport with reduced (or even eliminated) micro-turbulence as we switch from monotonic q to reversed-shear profiles. This base scenario, in combination with an aggressive plasma-wall interaction program in steady state (L/R time of about 3 seconds, equal to the achievable pulse length), with metallic walls, would be unique in the world and an essential step toward establishing the viability of current drive requirements in an FNSF and ultimately in DEMO/reactor.