Research gaps for reactor startup sequencing in the ITER era

D. A. Gates

Historically, the dynamic trajectory of the startup startup phase of fusion plasma research devices has been determined primarily by the needs of the experiment being conducted and the capabilities of the relevant actuators. For example, the current profile evolution and plasma shape evolution would follow a trajectory the might lead to the optimum probability of attaining a certain confinement regime. In many cases, the mode of startup is considered to be crucial to the development of these regimes. However, as fusion research progresses towards the burning plasma era this freedom will be starkly limited by device protection considerations, and in particular by the need for thermal stability of the device itself.

The need for modifying startup procedures due to thermal limitations is already apparent for ITER. This is because the thermal loads on the plasma facing components from the startup plasma are sufficiently high to raise the concern of surface melting and/or ablation. The limits placed on startup due to plasma facing components in DEMO will be substantially more severe than those encountered by ITER, but many of the PFC issues will be similar in nature.

However, the limitations imposed on ITER are much simpler than those that will be in place for a device that produces high steady-state neutron flux on the order of 1-2MW/m^2, particularly one that runs at elevated temperatures. At high temperature, metals become brittle and it is important to avoid thermal stress as the device is brought up to operating temperatures. Typical time scales for bringing up conventional power stations are several days to several weeks of operation at partial power output. This requirement has numerous important implications for any fusion reactor, but is particularly important for tokamak-like reactors where the magnetic helicity comes from driven current.

The requirement of long periods of operation at reduced power implies the need to have multiple steady state operating points. Each of these operating points will require a self-consistent steady-state solution. In particular, plasma wall interactions, current drive solution, and burn control solutions should be found for each operating point, as well as the need to stably transition from one point to the next.

For a steady-state tokamak where a large fraction of the plasma current is due to the bootstrap current the intermediate points in the startup may imply the need to have large amounts of current drive available. This transient extra current drive may deleteriously affect the electrical power flows - perhaps even requiring net flow of electrical power into the reactor during startup if the current drive requirements are sufficiently high. Of particular concern is the possibility that secondary current drive methods are required at the intermediate operating points, as this will use greater surface area in the reactor, reducing blanket coverage and therefore the effective tritium breeding efficiency.

In addition, multiple solutions will be required for ramp-down, since the problems of thermal expansion are the same with either transient scenario. The ramp-down solutions may well be different than the ramp-up solutions due to well known hysteresis issues. Examples include the H-mode power threshold hysteresis, and the tendency for current profiles to broaden during current ramp-up while current profiles tend to peak during current ramp down. The risk of loss of control, with resulting large transient electromagnetic forces and conversion of plasma current to large nonthermal electron populations, therefore becomes particularly high during the rampdown process.

The aforementioned thermal stress issues are the primary reason that a pulsed conventional tokamak reactor would be unattractive as an eventual power source. In order to avoid thermal stress in a device that was run in a pulsed mode, where the pulse length was on the order of a few days or less, it would be necessary to compensate for the loss of thermal load during the periods when the reactor was off. This would imply large thermal storage capacity (sufficient to maintain the temperature of the reactor) as well as the ability to switch the direction of thermal flows. The mechanisms to control and reverse these flows would add enormously to the cost of such a device compared with a device that can operate in a true steady state.

It should also be pointed out that a stellarator reactor would have a natural solution to many of the above stated issues, since the magnetic helicity is created largely by external coils. It is relatively straightforward to guarantee that a stellarator has a series of equilibrium solutions with differing fusion powers. Some of the hysteresis issues are also avoided. However, the need to provide divertor solutions consistent with each point in the ramp is common to both stellarators and tokamaks. In addition, the inherent three dimensional nature of the stellarator divertor surface may make monitoring and controlling the plasma-surface interactions more difficult, depending on the details of the actual divertor solution.

In summary, the limitations associated with start up and shut down of a fusion reactor are largely a result of thermal stress associated with the heating/cooing of the device to/from operating temperatures. This in turn places requirements on the robustness and controllability of the transient plasma. The long time scales of the ramp-up, set by the thermal equilibration times of the device itself, mean that these transient states are in fact additional steady-state plasma solutions. This means that the design of a fusion reactor will entail providing for the capability of numerous robust steady-state plasma solutions, which may add substantial complexity to the device.

Thrust

The thrust for this issue will consist of establishing the existence of the required intermediate equilibria required for startup and determining a self-consistent solution for the current drive requirement.