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CURRENT INITIATION AND SUSTAINMENT IN SPHERICAL TOKAMAKS

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Abstract

Current ramp-up using bootstrap overdrive for Spherical Tokamaks appears promising. Large $\varepsilon\beta_P$ is achievable and stability to ideal and resistive MHD is favorable. Several rf methods using ECH and FW mode conversion are available to effectively increase the electron beta.

Current initiation, ramp-up, and sustainment are key issues for low aspect ratio Spherical Tokamaks (ST). A reliable, totally non inductive plasma current initiation and ramp-up would enable an ST option devoid of inductive transformer coils in the inboard side. All the available center post volume can then be dedicated to toroidal field generation and neutron shielding, which would increase the ultimate performance of the ST either as an energy producing power plant or a volumetric neutron source. In this study, we assume, based on experimental experience, that producing the initial plasma current of a few hundred kiloAmperes can be achieved using variations of standard start-up methods such as utilizing the flux available from poloidal field coils. The study will focus on how to increase a small plasma current, sufficient to form closed magnetic surfaces, to the megaAmpere level necessary for steady-state operation of STs.

Consider the following 0-D equation governing current ramp-up,

$$dI_P / dt = (I_{BS} + I_{CD} - I_P) / \tau_{L/R} \ . \tag{1}$$

To save valuable TF coil volt-seconds, a high ramp-up rate is desired which requires simultaneously maximizing $(I_{BS} + I_{CD} - I_P)$ and minimizing the current diffusion time, $\tau_{L/R}$. For rf or neutral beam driven non-inductive current, maximizing I_{CD} requires high current drive efficiency, which in turn requires high electron temperature T. However, $\tau_{L/R} \propto T^{3/2}$ also increases with increasing temperature. The combined effect significantly limits the current ramp-up rate. Alternatively, if the non-inductive current is provided by the bootstrap current which scales favorably at low I_P, it may be possible to achieve a higher ramp rate provided the collisionality can be kept low through density control.

One can obtain an estimate of the bootstrap ramp rate by expressing the bootstrap current qualitatively as $I_{BS} = C_{BS}\varepsilon^{1/2}\beta_P I_P$ with $\beta_P \propto nT / I_P^2$. In terms of the Greenwald density limit: $n = f_G\, n_G$; $n_G(10^{20}\ m^{-3}) = I_P(MA) / \pi[a(m)]^2$,

$$I_{BS} = C_1 C_{BS} f_G \varepsilon^{1/2}\, T = k_{BS}\, T \ . \qquad (2)$$

At constant f_G, the maximum ramp rate is given by $\dot{I}_P = 2 I_P / \tau_{L/R}$ at $I_{BS} = 3I_P$, which gives $\dot{I}_P \sim 6$ MA/s for $I_P(0) = 0.3$ MA, $T = 0.1$ keV and $\tau_{L/R} = 1.0$ s. To stay at the optimum ramp rate, the density has to increase linearly with the plasma current, and the electron temperature also has to increase linearly with I_P by adjusting the power (constant β_P). Alternatively, one can keep the power constant and I_P will eventually reach a saturation. In this case, T remains constant and is proportional to $P^{1/2}$. Figure 1 shows both solutions of Eq. (1), at constant power (solid) and at constant β_P (dashed), using more accurate expressions for I_{BS} and $\tau_{L/R}$, and taking the energy confinement factor $H = 2$ in $\tau_E \sim H I_P / P^{1/2}$ to calculate the temperature increase. The current ramp rate behaves as expected, and in the case of constant power, the saturated current can also be shown to scale as $P^{1/2}$. Moreover, the results verify the need for high $\varepsilon\beta_P$, exceeding a minimum of 2.5, for bootstrap overdrive to take off. Since a simple equilibrium limit (valid for $\varepsilon \to 0$) suggests that even at $\kappa = 3$, the equilibrium is bounded above at $\varepsilon\beta_P = 2.5$, the existence of equilibrium suitable for bootstrap overdrive is called into question. Computation of actual equilibria contradicts this prediction, however. Using a fixed boundary equilibrium code TOQ [1], equilibria with $\varepsilon\beta_P$ values significantly exceeding large aspect ratio limits ($> 60\%$) have been produced for $A(= R / a)$ of 1.4. It is found that a large q_{edge} / q_{axis} ratio, typical of low aspect ratio equilibria, favors larger $\varepsilon\beta_P$. In addition, these equilibria are characterized by a large Shafranov shift and high elongation near the magnetic axis.

The stability of the ST equilibria during bootstrap overdrive is considered next. One of the attractive features of the ST is a very high theoretical beta limit with 100% bootstrap current [1]. That however, is achieved with optimized pressure profile and shape, which cannot be counted on during ramp-up. ST equilibria feature large edge pressure gradients hence high edge bootstrap current densities leading to low internal inductance, ℓ_i. DIII–D discharges with high edge current density have been observed to destabilize moderate n edge kink modes which tend to limit the edge pressure gradient and degrade plasma

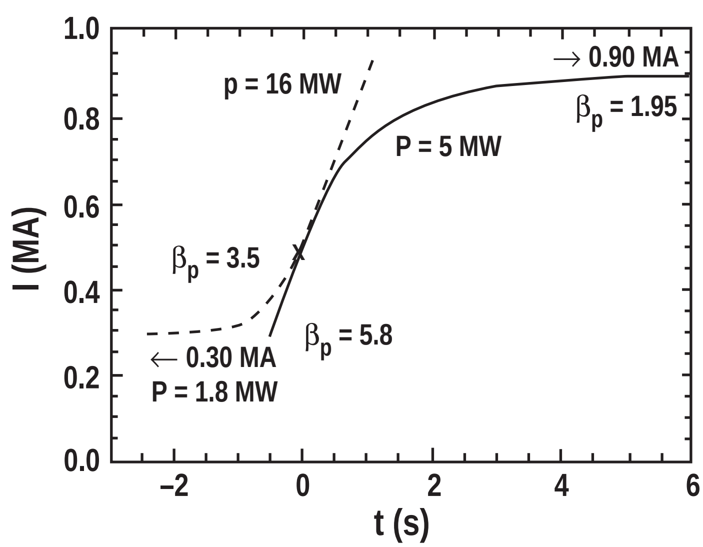

FIGURE 1. Current evolution in bootstrap overdrive for constant power (solid) and constant β_P (dashed).

beta [2]. DIII–D data have also shown that for low ℓ_i discharges, the stability boundary agrees very well with the scaling β_N $(\equiv \beta aB / I_P) \leqq 4\ell_i$. Based on this criterion, we have computed the values of β_N and ℓ_i for a sequence of equilibria at different currents during the ramp-up corresponding to the constant power case of Fig. 1. The results are shown in Table I. For fixed power and Greenwald fraction, β_N is proportional to T which stays approximately constant, while li increases gradually from a very low value. If T stays at a moderate value, β_N can be kept small. For this case, $T = 1.0$ keV with $P = 5$ MW and β_N is significantly less than $4\ell_i$ throughout the ramp-up. We thus conclude that the plasma should be stable to ideal MHD modes during ramp-up.

Resistive MHD instabilities represent another challenge for ramp-up. On DIII–D, tearing modes are observed to limit operational space and ramp-up using neutral beams by degrading fast ion confinement [3]. They may also impact thermal confinement and beta limits. If the instability is associated with neoclassical tearing modes driven by the absence of bootstrap current inside a magnetic island, the high β_P tends to worsen the situation as can be seen in the third term on the RHS of the following equation describing the evolution of the magnetic island.

$$\frac{\mu_0}{1.22\eta}\frac{dw}{dt} = \Delta' + \frac{5.4\varepsilon^2(Lq/Lp)(1-q^{-2})\beta_\theta w}{s(w^2+w_d^2)} - \frac{a_1\varepsilon^{1/2}(Lq/Lp)\beta_\theta w}{w^2+w_d^2} + \text{other effects} \quad . \quad (3)$$

A stabilizing effect given by the second term on the RHS, known as the Glasser effect, is usually neglected in conventional tokamaks since it is of order ε^2 and the ratio of Glasser effect/neoclassical bootstrap drive $\propto \varepsilon^{3/2}(1-q^{-2})/s$ is small. This effect can be significant in STs. Both low aspect ratio and high q are favorable. The impact of the shear parameter $s(= r/q\ dq/dr)$ warrants some discussion. At first glance, weak shear (small s) appears to be very favorable, especially a weak negative shear, since the neoclassical bootstrap term would also be stabilizing. A closer examination of the Glasser term shows that it is closely related to the resistive interchange stability criterion [4] and the stability window for weak negative shear in $q' - p'$ space is quite small. It turns out that STs are advantageous over conventional tokamaks in this regard. Even though they naturally possess hollow current profiles, the q-profile remains monotonic, with weakly positive shear in the core and strong positive shear near the edge as depicted in Fig. 2. This is highly compatible with a pressure profile which is flat in the center and steep in the edge, typical in high performance H–mode plasmas, for resistive interchange stability. We have evaluated the resistive interchange criterion for the same sequence of equilibria during ramp-up and verified that they are indeed stable.

A closer examination of the bootstrap current physics [5] shows that it is more effective to drive bootstrap currents by heating electrons. Electron cyclotron heating can readily be used to increase the electron beta subject to density limits. For a 110 GHz

TABLE I. β_N and ℓ_i for ST equilibria during ramp-up

I_P (kA)	β_N	$4\ell_i$
300	0.88	1.40
500	0.88	2.80
700	0.88	3.20
900	0.88	3.35

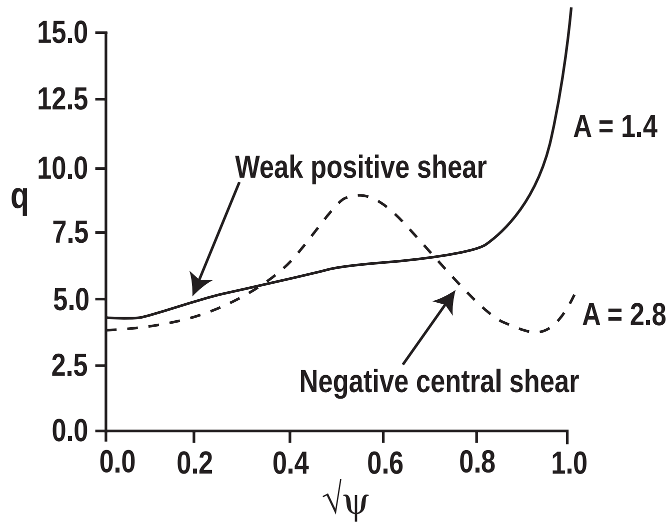

FIGURE 2. Safety factor profile for ST (A = 1.4) and conventional tokamak (A = 2.8).

gyrotron source, the density limit for second harmonic X–mode heating is 7.5×10^{19} m^{-3}. Absorption is strong up to the density limit for T exceeding a few hundred electron volts. For the O–mode, the density limit is higher at 14×10^{19} m^{-3}, but the absorption weakens as the limit is approached. Current drive by electron cyclotron current drive would be an additional benefit. However, at $T = 1.0$ keV, its contribution is insignificant.

Fast wave at the ion cyclotron frequency range can also be used to heat electrons via several mechanisms: minority heating which has the disadvantage of poorly confined energetic ions at the edge due to large q; electron Landau and TTMP damping which is temperature sensitive and requires moderately high T to be effective; and mode-converted ion Bernstein waves which appear most promising. We have computed the power partition from mode converted ion Bernstein waves in a H–D plasma with 40% hydrogen using the SEMAL code [6] and found that almost all the power is effectively absorbed by the electrons under ramp-up conditions.

In conclusion, current ramp-up using bootstrap overdrive for STs appears promising. Large $\varepsilon\beta_P$ is achievable and stability to MHD is favorable. Furthermore, several rf methods are available to effectively increase the electron beta.

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