A simpler approach to a fusion neutron source.

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Abstract

Recent progress in toroidal physics suggests that a simpler approach to a fusion neutron source (FNS) could be attractive. Namely, an L-mode tokamak operating at $q_\ell \lesssim 2$ with $q_0 \gtrsim 2/3$ To achieve the required duty cycle this device would operate in an "AC" mode. The primary purpose of this paper is to lay out the research required to justify an FNS based on a non-diverted, L-mode plasma that is operated in this regime.

1 Physics Basis

In a recent study of the internal kink [Lazarus, IAEA (2012) Paper TH/P3-02] it was seen that a saturated internal kink could be created with a small m/n=1/1 edge perturbation; $\delta R/R_0$ in the range of $10^{-4} - 10^{-3}$. That work was done as an extension of the cylindrical tokamak problem [Rosenbluth, *et. al.,* (1973) Phys. Fluids 16]. While toroidicity stabilizes the mode, a relatively small boundary perturbation was seen to restore the saturated internal kink. It was proposed that this effect (via field errors) could explain the TEXTOR results of $q_0 \approx 0.7$ with a sawtooth collapse producing a $\delta q_0 \approx 0.03$ [Soltwich,*et. al.,* (1987) Plasma Physics and Controlled Nuclear Fusion Research] Similarly it could explain JET results were $q_0 \approx 0.7$ [O'Rourke (1991) Plasma Phys.&Control.Fusion] was also observed. Furthermore, JET observed "snakes" and saw the snake persist through several sawtooth cycles. Taken together these strongly support the likelihood that the observed "sawtooth" was the m/n=2/3 instability. It was likely quite a mild sawtooth as δq is small and it apparently did not disturb a surrounding m/n=1/1 instability. Note that a proper identification would have required anticipation of a small n=3 signature within a much larger n=1 signal.

As to the safety factor at the limiter, work on RFX [Martin, *et. al.,* IAEA (2012) Paper OV/5-2Rb], operating as a tokamak, demonstrated control of the external kink and operation at $q_\ell \approx 1.8$. The experiment conclusively demonstrated that the kink growth rate could be maintained at a negative (stable) value. It was done using rather simple saddle coils outside the conducting shell and a fastidious approach to the preparation of the feedback signal. In other work on RFX, operating as an RFP, a single helicity core is created and the confinement is improved over that of normal RFP operation; particularly in the core. We also note that in oval-shaped plasmas on DIII-D the sawtooth experiments [Lazarus, *et. al.,* (2007) Phys. Plasmas] showed that as a helical core developed within a sawtooth cycle the core electron confinement, χ_e, was dramatically improved. (χ_i was excellent throughout the sawtooth cycle.)

2 A new L-mode configuration

While a basis has been tentatively established for operation at $q_\ell \lesssim 2$ with $q_0 \gtrsim 2/3$. It is true that further work is needed. In particular, demonstration that active control of the external kink can be maintained at higher β than that available in an Ohmic tokamak and that the conditions needed for sustaining a saturated internal kink (m/n=1/1) do not interfere with those required for active control of the external kink (m/n=2/1).

The next issue would be demonstration of immunity to disruptions; it is possible that, once the m/n=2/1 mode is removed from the plasma, n=2 might become more problematic than is seen in normal tokamak operation. A first question is whether the density limit is disruptive [Gates, *et. al.,* (2012) PRL **108**, 165004] as is normal in tokamaks or becomes a matter of radiative power balance [Sudo, *et. al.,* (1990) Nucl. Fusion **30**, 11] as is typical in stellarators. Immunity from instability as discussed here, excludes the case of an electrical failure of the feedback circuit, and mean stable in the sense of modern jet fighter aircraft that are unstable without active feedback.

Such a low-q, high β^* device will be unsuited for steady state operation and it is proposed that development focus on AC operation [Huart, *et. al.,* (1991) Fusion Engineering, 1991. Proceedings., 14th IEEE/NPSS Symposium]. It has been estimated that, in reactor-scale devices, a duty cycle in excess of 90% could be achieved.

In order to avoid inadvertent limiter H-mode, the shaping would need to be relatively weak ($\kappa \lesssim 1.8$, $\delta < 0.2$, $A \lesssim 3$, up/down symmetric). Pumped limiter operation is anticipated. Using a confinement based on JET/DIII-D scaling, Q_{DT} can be estimated [Lazarus (2001) 2^{nd} Burning Plasma Workshop, San Diego] as

$$Q_{DT} \approx \frac{B^2 R^2}{\pi^2} \cdot \left[\frac{\hat{S}}{q_\psi}\right]^2 .$$

This expression allows the operational limits to be defined in terms of axisymmetric ($\hat{S}$) and external kink (q_ℓ) stability limits and is phenomenologically consistent with the best operation points on DIII-D, TFTR, JT-60U, and JET where it is seen that $H \cdot \beta^*/\beta$ is approximately constant; although, H and β^*/β vary considerably. The geometry assumed here results in $\hat{S} \approx 1$; operation at $q_\ell = 1.8$ would require $B \cdot R \lesssim 6$ [T-m]. A somewhat different evaluation [Paccagnella (2012) http://arxiv.org/abs/1206.3083] concludes that reactor-level operation would require $B \cdot R \approx 33$ [T-m], In such a device, I estimate $\ell_i \approx 1.2$ and expect the limit $\beta_N = 4 \cdot \ell_i$ is not a problem; the β-limit will be well above the operating point. The elongation should not be an issue;

both DIII-D and TCV have demonstrated successful operated up to the ideal n=0 stability limit.

Note that many of the problems of the "advanced tokamak" are now removed from the problem. It is anticipated that the plasma pressure will be peaked, the poloidal flux in the core will be large, as will the density, and the problems of toroidal Alfvén eigenmodes creating α-particle loss will become inconsequential [Van Zeeland (Jan. 28, 2013) Winter Workshop on Energetic Particles, UCI]. This is largely a result of the monotonic q-profile; though high density operation ($\beta_\alpha << \beta$) also helps reduce this activity. The issues resulting from diverter heat loads will be greatly reduced, as there will be no diverter. The sensitivity of Q to the H-mode pedestal height is no longer an issue. As to the viability of pumped limiters, new "additive manufacturing" (3D printing) techniques offer the opportunity for heat removal that were not conceivable a decade ago. [http://www.ted.com/talks/lisa_harouni_a_primer_on_3d_printing.html & http://www.youtube.com/watch?v=A10XEZvkgbY]. These manufacturing techniques offer the possibilities of better contouring of leading edges, better control of the pumping duct geometry, and an amazing control of both the density and shapes of cooling channels.

3 Required research

The design basis could be done in a DIII-D sized device. The program would be:

- Establish control of the external kink at finite β ($\beta_p \approx 1$).
- Investigate disruptivity with $q_\ell < 2$, *e.g.,* is the density limit disruptive or stellarator-like, is the β limit disruptive and the ideal limit or is it a control instability?
- Establish control of the internal kink, producing the helical core.
- Investigate any interference between the control of the internal and external kink
- Examine confinement, in particular β^*/β to optimize the plasma shape.
- Investigation of pumped limiter operation: heat loads and particle removal capacity.

Such an investigation that would justify this next step could likely be done in 2 years or so in the DIII-D device, allowing time for the necessary upgrades and modifications.

4 Summary

The possibility of an attractive toroidal fusion neutron sources (namely, $q_\ell < 2$, $q_0 \gtrsim 2/3$, L-mode operation) is presented. Much of the simplicity is achieved by deliberately limiting the scope of the work to just that; a neutron source. This makes an actual realization more likely. Dispensing with current drive allows a more "tokamak-like" mode of operation (monotonic q and moderately high density). In turn, this makes the research precursors practical and rather straightforward. The elimination of the diverter will simplify design and make for a more rugged device than the diverted tokamak. Immunity to disruption at $q_\ell < 2$ is yet to be demonstrated, but is quite plausible. Advances in additive manufacturing are anticipated to allow a successful construction of top & bottom, toroidally continuous, pumped limiters that were not previously possible.