Two-Energy-Component Toroidal Fusion Devices

H. L. Berk, H. P. Furth, D. L. Jassby, R. M. Kulsrud,
C. S. Liu, M. N. Rosenbluth, and P. H. Rutherford

Plasma Physics Laboratory, Princeton University,
Princeton, New Jersey 08540, USA

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and

T. Johnson, J. Killeen, A. A. Mirin, and M. E. Rensik

Lawrence Livermore Laboratory, University of California,
Livermore, California 94550, USA

From the point of view of reactor energy multiplication, the ideal way of heating a D-T plasma is by injection of an energetic deuteron beam. As shown in Ref. 1, energetic break-even can be attained in tritium plasmas with $n\tau$-values as low as $10^{13}cm^{-3}sec$, if a bulk temperature of ~5 keV is maintained by injection of 150-keV deuterons. The required ratio Γ of fast-ion energy density to bulk plasma energy density can be about unity. Since the steady-state distribution function of the energetic ion component tends to be monotonic, and can be made roughly isotropic, there appear to be no substantial destabilizing effects in the parameter range of practical interest. Experiments with 15-keV deuterium beams and ~1-keV deuterium plasmas[2] support these theoretical indications.

The present paper includes a number of studies designed to lay the foundation for the practical implementation of the two-component reactor concept:

(1) Slowing-Down. One and two-dimensional multi-species Fokker-Planck computations are being used to obtain the ion distribution functions in energy (and pitch angle). The energy multiplication factors F of Ref. 1 are found to be enhanced by ~10% by taking into account the dispersion in energy of the injected ions. Particular attention is given to the effects of "clamping" the injected deuteron energy by adiabatic compression or by the tokamak electric field, thus extending the ion slowing-down time through the energy range of maximum reactivity. The energy multiplication factor F can be enhanced in this way by a factor of about 2, and can become as large as 7-8. The various effects of high-Z impurities (increased electron and ion drag and angular scattering) are calculated.

(2) Power Production. Power multiplication factors Q are calculated for the distribution functions obtained in (1), for various D-T mixtures. Break-even can be obtained in practical "clamped" regimes, for temperatures as low as 3 keV, at $n\tau \sim 5 \cdot 10^{12}cm^{-3}sec$, with 120 keV injected energy. For increasing bulk plasma temperatures and $n\tau$-values, there is a continuous range of regimes with increasing Q-values, increasing fractions of deuterium in the optimal bulk plasma mixture, and decreasing Γ-values. The improvement in Q obtained by heating the bulk plasma by injection of reacting beams remains substantial up to $Q \sim 3$ for steady-state operation. For pulsed operation, the use of reacting beams remains important even if ignition ($Q = \infty$) is reached during the pulse.

(3) Gross Equilibrium. The toroidal equilibrium of a two-component tokamak plasma is obtained from a spatially two-dimensional code. The fast ions are simulated by superparticles whose guiding-center motion is computed and which contribute to the toroidal current. Optimal fast-ion-injection profiles and limiting β-values are calculated.

(4) Stability. The velocity-space stability of various distribution functions is examined, employing analytical solutions for the steady-state distribution functions, as well as computational results of (1). An important parameter is the ratio of injected ion velocity v_o to the Alfvén velocity: $v_o/v_A = (3\beta W_o/4T)^{1/2}$. Since the ratio of injection energy W_o to bulk plasma temperature T is generally in the range 10-40, and since tokamak β-values tend to lie below 5%, we have $v_o \lesssim v_A$ as the range of interest. The beam density is generally a small fraction of the overall plasma density, so that the beam is only a perturbation on the response of the background plasma to infinite-medium waves and drift waves. For infinite-medium waves, the excitation of instability requires the inverse dissipation due to the beam-particle resonances to exceed the dissipation due to the background plasma. This condition is never met for isotropic steady-state injection, and is difficult to achieve, even for steady-state injection purely parallel to the magnetic field. In the latter case, we have found the following:

(a) Ion-acoustic waves are stable, as they are strongly damped by the background ions.

(b) Loss-cone modes and shear-Alfvén waves are stabilized by electron-Landau damping.

(c) A strong inverse dissipation source that can be tapped by the high-frequency compressional Alfvén wave, occurs for a minimum speed $v_o = 1.5(3)^{1/2}v_A$.

(d) A less potent instability mechanism than (c) involving the compressional Alfvén wave occurs for $v_o > v_A$ (i.e., at the edge of the practical operating range), when the distribution function increases with increasing parallel velocity. For steady-state injection, this inversion can be achieved at energies near the injection energy, before the distribution is significantly modified by pitch-angle scattering; with energy clamping, or with a transient pulse, the strength of this instability can be increased.

A survey of the effects of the energetic ion component on finite-medium effects, including MHD kink-like modes, drift waves, and trapped-particle modes, is under way. The phase velocity of these modes falls in the range $v_A > \omega/k_\parallel > v_i$, where v_i is the bulk ion thermal velocity, so that they can be resonant with the energetic ion component. The interaction appears to be generally stabilizing, but is too weak to be useful in actually suppressing the bulk-plasma modes by means of the energetic ions. The effects on energetic-ion transport and diffusion in velocity-space are calculated.

(5) Confinement. A time-dependent radial transport code is used to follow the evolution of specific models of beam-injected tokamak plasmas. The effects of impurities, neutral gas, and various instabilities are included. The attainment of break-even is calculated for illustrative tokamak devices in the 1-MA range.

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[1] DAWSON, J. M., FURTH, H. P., and TENNEY, F. H., Phys. Rev. Lett. 26 (1971) 1156.

[2] BOL, K., et al., Princeton University, Plasma Physics Laboratory Report MATT-1029 (February 1974), submitted to Phys. Rev. Letters.

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