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Drift-energy replacement effect in multi-ion magnetized plasma

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Fast rotation can improve the stability and confinement of fusion plasmas. However, to maintain a rapidly rotating fusion plasma in steady state, significant energy must be invested in spinning up each incoming fuel ion. We show [1, 2] that, under the right circumstances, collisional cross-field radial fueling can directly transfer drift energy between outgoing and incoming ions without the need for external power recirculation, thereby reducing the energy costs of maintaining the rotation.

Fast rotation can be desirable in plasma traps for nuclear fusion. Rotation often suppresses instabilities. In centrifugal mirror fusion, rotation provides axial confinement. For significant axial confinement, the rotation typically must be supersonic, often with a Mach number much greater than one.

However, high Mach numbers present a very serious problem for centrifugal fusion devices. In steady state operation, new fuel ions replenish the ions that are burned through fusion. For plasma spinning at a high Mach number, the energetic “spin-up cost” for each new ion can be large, possibly a large fraction of the energy derived from fusion. The ratio of spin-up cost to fusion energy production depends on plasma temperature, Mach number, and fusion energy output. Hence, it is sensitive to the choice of fuel in the fusing plasma. Aneutronic fuels such as p-B11, while being attractive for technological and regulatory reasons, require high temperature ($\gtrsim$ 100 keV) plasma to access sufficient fusion reactivity, exacerbating an already thin power balance margin. Therefore, understanding the properties of the rotation energy is crucial to determine the viability of sonic or supersonic rotation in a plasma fusion reactor if aneutronic fuel is used. However, the same considerations apply to any steady-state, supersonically rotating fusion plasma at sufficiently high Mach number.

Of course, fast plasma rotation also means that the fusion byproducts are then born with substantial rotation energy. When the fusion byproducts are extracted, their rotation energy might then be captured and converted into electricity, which could offset the energy cost of spinning up the fuel. However, converting and re-injecting energy in this way involves substantial inefficiencies.

Remarkably, we find that, under certain circumstances, fuel ions may be collisionally exchanged for the fusion ash (fusion byproducts), while the fuel ion rotation energy is retained in the plasma. This surprising result flows from the constraint that collisions in magnetized plasma do not move charge across field lines. In fusion reactions, were the ash to include neutrons, rotation energy must be lost. However, for aneutronic fusion reactions, where both reactants and byproducts are charged and magnetized, the reactants can pick up the byproduct rotation energy.

We identify [1, 2] the drift-energy replacement effect, a new and fundamental transport effect that can obviate the need to recover the drift energy of fusion ash. Surprisingly, when ions of different species move via collisions across magnetic field lines in opposite directions, incoming ions can automatically take all or part of the drift energy directly out of the outgoing ions. In cases where the transfer does not meet the drift energy needed, the difference between the drift energies of incoming and outgoing ions would be provided by the potential energy driving the drift (the electrostatic potential, in the case of the $E \times B$ drift). This difference can also be negative if more drift energy is removed than replaced; in that case, power can be drawn from the circuit providing for the rotation.

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References

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