

## Confinement in a Wave-Driven Rotating Plasma Torus

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*Introduction:* Charged particles immersed in only a toroidal magnetic field tend to drift upward or downward (the direction of the axis of symmetry), depending on the electric charge, thereby spoiling confinement. Rotational motion of these particles in the poloidal plane stabilizes these drifts. If the rotation is fast enough, then, for particles say drifting upward, half the time the drift will be upward away from the center of the poloidal cross section, and half the time the drift will be upward towards the center of the poloidal cross section, thus stabilizing the trajectory. In a tokamak, this rotational motion is achieved by a poloidal magnetic field. Charged particles, following the field lines, then rotate in the poloidal plane. For particles with a large enough parallel velocity, this rotation may be large enough to counter the tendency to drift out of the device. The poloidal magnetic field requires a toroidal current, which can be provided by a dc toroidal electric field or by noninductive means.

Alternatively, single particle confinement in a toroidal magnetic field can be achieved by adding instead a radial electric field over the minor cross section. This configuration produces poloidal rotation through an  $E \times B$  drift that serves to counteract the vertical drift of particles, much like the poloidal magnetic field produces poloidal rotation in a tokamak. The difference here is that the poloidal rotation is produced by radial electric field instead of a poloidal magnetic field. The radial electric field needs to be maintained by some mechanism to push charge across the toroidal magnetic field. That mechanism could be passive, such as a differential loss of charges due to differential charge confinement. It might also be imposed via electrodes, but then the field tends to be localized at the surface near the electrode and nowhere else.

However, the most promising way to provide with control this radial electric field over the entire minor cross section is to inject suitable waves into the plasma. The steady state plasma confinement device, comprising a toroidal magnetic field and a radial electric field maintained by waves, has been called the *Wave-Driven Rotating Torus* or *WDTR* for short [1]. In proposing the WDRT, Rax et al. [1] noted two significant features: one, that the energy content of the rotating plasma can be smaller than the energy content of the poloidal magnetic field; and, two, that the power dissipated in maintaining the radial electric might be smaller than the power dissipated in maintaining the toroidal current, at least in the limit of very large aspect ratio,

$R/a \rightarrow \infty$ , and in comparison to rf-based techniques for maintaining a steady state tokamak current by means of rf waves [2].

*Adding Rotation Effects:* It can be expected that the stabilizing poloidal rotation produced in the WDRT is proportional to the radial electric field, while any power dissipation would be proportional to the stored energy, which would be proportional to the square of the radial electric field. The analogous statement in tokamaks is that the poloidal rotation of particles is proportional to the poloidal magnetic field, while any power dissipation would be proportional to the stored energy, which would be proportional to the square of the poloidal magnetic field. This suggests that, to minimize the energy consumption while achieving the same particle rotation, it would be advantageous to employ both radial electric fields with poloidal magnetic fields to achieve the rotation. If the rotations simply added, then the total power dissipated would be halved. However, unfortunately, while there may be other advantages to employing both types of rotation, the rotations do not simply add.

In the case of a poloidal magnetic field, particles traveling in one toroidal direction rotate in one sense around the minor axis, while particles traveling in the opposite toroidal direction rotate in the opposite sense. However, for  $E \times B$  rotation, the sense of rotation is independent of the sign of particle toroidal velocity. Thus, if the rotations are additive for particles traveling in one direction, they must necessarily be subtractive for particles traveling in the opposite toroidal direction. This means that, while there may be other advantages in having both poloidal magnetic fields and radial electric fields, the two rotational effects cannot be simply added.

*Challenges and Uncertainties:* Clearly, there are many issues to address and even possible showstoppers that will make the WDRT unworkable as a possible confinement device for controlled nuclear fusion. First, the power dissipated needs to be small enough for reasonable aspect ratios. This has yet to be shown. Second, even if single particle confinement were to be achieved, the configuration needs to be in force balance in the major radius direction in order to counter the so-called *hoop force*. In a tokamak, a vertical magnetic field is applied, so that the toroidal current crossed with the vertical magnetic field balances the hoop force. In the WDRT, there is no toroidal current. One possibility might be to exploit instead the non-neutrality of the plasma through electrostatic forces, for example through a central electrode. However, as a preferred means to achieve force balance, an rf-driven, but small, toroidal current can be employed along with a larger vertical field, thereby achieving force balance much like in a tokamak, but with far less toroidal current [5]. Third, it remains to ascertain exactly how the configuration might be sustained in the first place. It is anticipated that the configuration will be maintained by pushing charge across field lines, like in alpha channeling [3], but in a rotating plasma [4];

however, it remains to identify the specific waves that might best accomplish this effect. Fourth, once force balance is achieved with specific waves, it remains to investigate what would be the stability properties of what amounts to a magneto-electric trap. It can be anticipated that various limits in tokamaks will have analogues in the WDRT configuration [1], or alternatively in the force-balanced WDRT configuration [5]. For example, in achieving force balance, there could be a tendency for a so-called *ballooning mode* instability, or a distortion of the plasma due to the forces, even if on average adequate, not being distributed where needed. Fifth, it remains to examine the transport properties both in the WDRT configuration [1] and in the force-balanced WDRT configuration [5]. In this respect, there are also trapped-particle analogues to tokamaks which can dominate transport.

*Upside Potential:* However, there appears to be significant upside potential to the WDRT configuration, motivating the addressing of these challenges and uncertainties. Some of the advantages accrue from the inherent features of the WDRT, but some of the advantages accrue from flexibilities in accomplishing other goals in making fusion more practical. First, and as an example of an inherent advantage, the sudden release of reactive energy storage in a plasma disruption is likely to be less damaging in a WDRT than in a disruption of the plasma in a tokamak for two reasons: one, the free energy available in the kinetic energy and the electric field energy can be much less than that in the poloidal magnetic field energy in tokamaks [1]; and, two, any sudden disruption of the plasma that might release this energy does not create very high energy particles. This is in contrast to the tokamak, where the sudden disruption of the plasma results in a sharp decrease in poloidal magnetic field, which in turn generates an electric field with curl, which then has the potential of accelerating runaway electrons to tens of MeV, which might then cause significant damage to structural components. In the WDRT, sudden changes in electric field energy, which generate magnetic fields with curl, do not have the property of accelerating particles to high energy. Second, the WDRT configuration stabilizes both electron and ion orbits regardless of the sign of the radial electric field. The key point for single particle confinement is only that the rotation occur fast compared to the vertical drift time; in this regard, the sense of rotation is insignificant. Consider then the possibility that the plasma is charged negative, perhaps to as much as an MeV or 1.5 MeV. Note that this means that alpha particles are born in a deep magnetic well of perhaps 2 to 3 MeV. In that case, if for some reason magnetic perturbations of any type were to deteriorate the confinement of the 3.5 MeV alpha particles born in a DT reaction, those alpha particles would leave the WDRT at the boundary having lost most of their energy. If the alpha particles are then captured and removed at the plasma boundary, this extraction of the alpha particles together with their potential

energy would be a form of direct energy conversion, and an example of flexibilities provided by the WDRT configuration in accomplishing other goals. Note that this would fall under the possibility of *passive* means of maintaining the radial electric field, although certainly waves might be advantageously employed to supplement this effect. Note also that, in this case, the negative potential is highest at the plasma center, thereby advantageously drawing fuel ions into the plasma. Of course, it is also the case that these advantages accrue only if the electrons are well confined, since the loss of electrons also means the loss of considerable electric potential energy. However, it can be imagined that, while magnetic perturbations on a scale of the alpha particle Larmor radius might significantly affect alpha particle confinement, the electrons would not be very sensitive to turbulence on such a large scale. Third, while the maintenance of the radial electric field does incur significant dissipation, particularly for finite aspect ratio, there is the speculative possibility that that energy also could serve to maintain a *hot ion mode* of operation, namely where the ion temperature exceeds the electron temperature. In the case of maintaining a radial electric current against dissipation through electron-ion collisions, much like maintaining a toroidal electric current against dissipation through electron-ion collisions, the tendency would be for the dissipated power to heat electrons rather than ions. However, to the extent that the dissipation in the WDRT is caused by ion viscosity, which is expected to dominate for small enough aspect ratio, it would be expected that the dissipation results in ion heating rather than electron heating. The possibility of a hot ion mode confers significant advantages to fusion reactivity [6].

*Roadmap:* Given the high upside potential, there is motivation both to quantify the upside potential as well to evaluate possible showstoppers. The key uncertainty is likely the perpendicular conductivity in the large aspect ratio limit. The aspect ratios contemplated might already be as large as 50 [5], which already suggests that the preferred embodiment of a WDRT-like confinement device is almost linear. Thus, the first experimental test of the perpendicular conductivity in the large aspect ratio limit might best take place in a linear device, with plasma rotation in crossed electric and magnetic fields. This configuration, essentially a plasma centrifuge, has its own separate advantages, particularly with respect to nuclear waste remediation [7].

## References

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