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Summary

A stabilized pinch configuration is described, consisting of a D-shaped plasma cross section wrapped tightly around a guiding axis. The “helical–D” geometry produces a very large *axial* (toroidal) transform of magnetic line direction that reverses the pitch of the magnetic lines without the need of azimuthal (poloidal) plasma current. Thus, there is no need of a “dynamo” process and its associated fluctuations. The resulting configuration has the high magnetic shear and pitch reversal of the reversed field pinch (RFP). (Pitch = $P = qR$, where R = major radius.) A helical–D pinch might demonstrate good confinement at $q \ll 1$.

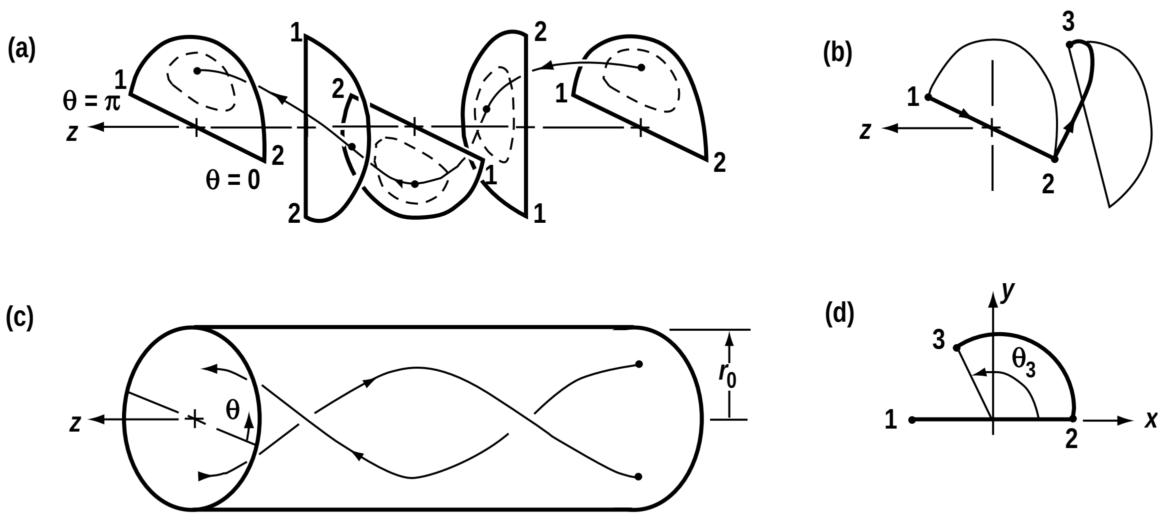
Background

The conventional RFP requires large azimuthal currents, which are sustained by dynamo activity, in order to reverse the axial magnetic field near the edge from that of the magnetic axis [1]. Observations from many RFP experiments and 3-dimensional resistive MHD numerical calculations show the dynamo to be closely associated with stochastic magnetic lines [1]. The relatively short open magnetic lines limit confinement. Conversely, longer magnetic lines would yield higher confinement. Indeed, when the MST RFP was operated so as to transiently induce an azimuthal electric field that partially drove the azimuthal current, the fluctuation level decreased and confinement increased [2]. As a consequence, serious consideration is now being given to driving azimuthal current by rf waves or other means in order to reduce RFP fluctuations. Direct pitch reversal by axial magnetic transform produced by external multipole helical windings was proposed by Ohkawa [3] and embodied in the OHTE experiment. The hypothesis is that a large externally imposed magnetic shear will stabilize the now superfluous “dynamo modes,” reduce fluctuations and improve confinement. The new helical–D geometry [4] produces a much larger axial transform than helical windings, whose transform is very small, and might be a better test of Ohkawa’s idea.

The Helical–D Pinch

We illustrate helical–D translational transform by an example consisting of a helical wire carrying current inside of a superconducting helical tube of “D”–shaped cross section,

Fig. 1(a). The magnetic field **B** of the wire is fully contained within the tube. For simplicity, let the curved surface of the D be circular with radius r_0 centered on axis z of a cylindrical coordinate system. Since the wire path has an azimuthal component, its magnetic field has an axial component. Such a magnetic line at the circular surface is shown as segment 2–3 in Fig. 1(b). Magnetic lines at the straight surface of the D are straight lines, like segment 1–2 in Fig. 1(b). To prove this, consider the related system of Fig. 1(c), consisting of a twisted pair of helical wires carrying equal and opposite currents inside a concentric superconducting circular cylinder. Since the same magnetic flux distribution is produced around the wires in Figs. 1(a) and 1(c), **B** is the same, too. By symmetry, the magnetic field along any diameter located symmetrically between the wires in Fig. 1(c) has no z or θ components and is purely radial in the cylindrical coordinate system, like segment 1–2. Therefore, magnetic line 1-2-3 at the helical–D wall



[Figs. 1(b, d)] has a transform in the negative-z direction. Pitch P, defined as the average advance in z divided by the number of radians of encirclement of the helical magnetic axis, is $P/r_0 = -\alpha r_0/[2 + (\alpha r_0)^2]$ at the wall [4]. Here α is the inverse of the pitch of the helix. The maximum normalized pitch $|P/r_0|$ is $1/(2\sqrt{2}) \approx 0.35$ when $\alpha r_0 = \sqrt{2}$. The helical–D transform is produced *geometrically* by the helical symmetry and the flattened side (D cross section) and is much larger than that of conventional multipole helical coils. Numerical tracing of magnetic lines for a distributed "plasma" consisting of current only in the helically invariant (axial) direction shows that P varies approximately parabolically with average minor radius of the magnetic surface. Therefore, the transform is not only large, but it is also distributed throughout the plasma cross section to produce an RFP–like pitch profile.

RFPs achieve MHD stability by a combination of a strong magnetic shear, a monotonically varying (with minor radius) q or pitch profile, a nearby conducting wall and closeness to the Woltjer–Taylor relaxed or minimum energy state [5]. Monotonic pitch avoids the double tearing instability, and the relaxed state in a closely fitting conducting shell is stable against ideal and resistive tearing modes. The relaxed current distribution, $\mu_0 \mathbf{J} = \mu \mathbf{B}$ with μ a constant across the cross section, requires a large current near the edge, because $\mathbf{B} \approx \mathbf{B}_\theta$ is large there. Constant μ is not fully attained in practice. In experimental RFPs the edge current decays naturally until mild instabilities grow and drive a dynamo that sustains a current distribution not too far from the relaxed one.

The helical–D pinch obtains large shear and pitch reversal by geometry rather than dynamo. However, the Ohmically determined **J** profile will be centrally peaked rather than relaxed. It should be determined, for example by 3–dimensional resistive MHD computations, whether there exist shear–stabilized, unrelaxed, peaked–J configurations that might be quieter than conventional RFPs. The search for favorable regimes should also include the unreversed regime ($0 < q < 1$), where unstable modes tearing at the low–rational q surfaces limit operation. Here the axial transform might be used to keep $q(r)$ entirely between two rational fractional values, for example between 1/2 and 1/3.

Conclusions

The helical–D geometry produces large magnetic line transforms that might enable quieter, low–q pinches, both reversed and unreversed, with improved confinement. The major physics question is whether a peaked, unrelaxed, Ohmic current profile will be stabilized by the applied transform, so that the listed benefits might be obtained.

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