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STELLARATOR HYBRIDS

By

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Stellarator Hybrids*

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The late Academician M.S. Rabinovich had a clear vision of the promise of the stellarator concept -- both as a successful approach to fusion plasma confinement, and as a means of improving other confinement concepts. The latter possibility was explored by the Lebedev experimental program specifically in connection with the enhancement of tokamak stability and confinement.¹ The present paper briefly reviews the subject of tokamak-stellarator and pinch-stellarator hybrids, and points to two interesting new possibilities: compact-torus-stellarators and mirror-stellarators.

Helical windings can be used to generate a poloidal field component from the basically toroidal vacuum field of a tokamak. The resultant stellarator-based rotational transform ι_s is additive with the plasma-current-based transform ι_c , and generally serves to enhance MHD stability.² In the case of the tokamak configuration, the nonlinear resistive-MHD phenomena that give rise to major disruptions³ are sufficiently sensitive to details of the profile $\iota(r)$ so that a quite small contribution $\iota_s(r)$ can intervene successfully to suppress the disruption process.⁴

Another potentially useful application of helical windings is to the vertical stabilization of tokamak plasmas (i.e., stabilization of the $m = 1, n = 0$ mode). In Ref. 5, the standard

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stellarator concept of generating rotational transform -- i.e., a curved secondary field -- from a basically straight primary magnetic field was inverted: the straight (vertical) secondary field component was generated from a curved (toroidal) primary field. This inverse technique has come to be called the generation of a "translational transform." Some related ideas were discussed in Ref. 6. The application of the translational transform technique to the shaping and vertical stabilization of highly elongated tokamak discharges, as proposed in Ref. 7, was given a convincing experimental demonstration on the RECTOR device.⁸

The use of translational transform to produce a weak external toroidal field for the spheromak has been suggested,⁹ but the effect on MHD stability was not analyzed. The major new initiative in this area is the OHTE¹⁰ -- a reversed-field-pinch-stellarator hybrid -- where translational transform is used to reverse the external toroidal field, instead of leaving that task to the spontaneous dynamo processes¹¹ of the RFP. The experimental success of the OHTE^{1,2} has confirmed the realism of hybridizing stellarator windings with plasma-confinement configurations that depart strongly from the vacuum field, and has served to stimulate the search for other hybrid options.

2. Compact-Torus Hybrids

From the point of view of achieving high-beta value and simple geometry, one of the most attractive fusion reactor options is the field-reversed θ -pinch configuration or FRC.¹³⁻¹⁵ The surprisingly long observed lifetime of the FRC plasma is typically terminated by the onset of rapid rotation, accompanied

by a growing $m = 2$, $n = 0$ mode. The superposition of a straight longitudinal multipole field -- as in a minimum-B mirror machine¹⁶ -- was found to suppress this rotational instability.^{15,17} Recently, the stabilization experiment was repeated with quadrupole windings of variable helical pitch.¹⁸ The magnitude of winding current required to suppress the rotational instability was found to decrease substantially as the winding slope $rd\theta/dz$ increased from zero (straight quadrupole) to about $1/3$ (i.e., a typical stellarator winding). Associated spectroscopic observations show that the instability is not suppressed by arresting the plasma rotation, but rather by "squeezing down" the $m = 2$ mode.

The use of stellarator windings, instead of straight multipoles, in conjunction with the FRC has the further advantage that the resultant geometry is much better suited to the retention of good magnetic surfaces. In the case of the straight multipole, all magnetic surfaces are destroyed as soon as skin relaxation permits interpenetration of magnetic fields. (For example, a field line in a plane midway between two windings simply spirals outward, while remaining in the same plane.) The stellarator-FRC case is illustrated in Fig. 1. Superposition of a helical field $\bar{B}(R, \theta - kz)$ on the midsection of an FRC gives rise to a helical ignorable coordinate and therefore becomes compatible with perfect magnetic surfaces in the limit of an infinitely long FRC configuration. In an FRC of finite axial extent, the end regions have the incompatible symmetry $\bar{B}(R, z)$. One can see, however, that the effective symmetry can be made arbitrarily good by means of the "circularizer" approach.¹⁹ The

idea is to attenuate the helical shaping gradually over several field periods, so that the regions of incompatible symmetry, $\overline{B}(R, \phi - kz)$ and $\overline{B}(R, z)$, do not overlap. The resultant configuration ranks with the conventional small- a/R stellarator as having the potential for arbitrarily close approach to true symmetry, and therefore to arbitrarily good magnetic surfaces. (In the FRC case, the conventional stellarator expansion parameter a/R is replaced by R/L , where L is the axial extent of the circularizer region.) These general concepts were first developed in the context of stabilizing the vertically elongated tokamak.²⁰

As a first step towards the analysis of self-consistent FRC-stellarator MHD equilibria, a study of magnetic surfaces has been carried out by means of a simple vacuum-field configuration (Fig. 2): a thin solenoid of uniform current density (plus an external B_z -field) to generate the poloidal field, surrounded by a helical winding to produce the toroidal transform. A pathological case of this type is shown in Fig. 3. The illustrative magnetic field line is trapped between two helical windings and quickly spirals out into the FRC separatrix -- approximately the same behavior that would have been expected in the straight multipole case. By increasing the number of helical winding periods per axial transit of the magnetic field line, a somewhat better result is obtained (Fig. 4). It is convenient in the present context to define a toroidal rotational transform $\iota_t = (2\pi)^2/\iota_p$, where ι_p is the conventional poloidal stellarator transform. Good magnetic surfaces are favored by keeping ι_t rather small. In the case of Fig. 4, ι_t is only about 3° , but

the nonaxisymmetry of the magnetic surface is already very pronounced, and field lines slightly further out are on rapid escape trajectories. The strong shaping of the magnetic surface in the example of Fig. 4 is not found to conform with the slope of the helical windings -- i.e., it does not rotate as a function of z . It represents a chain of $m = 0$, $n = 8$ islands, caused by the finite length and abrupt axial termination of the $\ell = 8$ helical winding. The size of the $m = 0$ islands is sensitive to the toroidal angle ϕ_h between the top edge and the bottom edge of the helical windings: the end effects would be expected to reinforce when ϕ_h is an integral multiple of $2\pi/\ell = 22.5^\circ$. The case of Fig. 4, which corresponds to maximal island size, has $\phi_h = 112.5^\circ$. When the slope of the windings is adjusted so that ϕ_h is reduced to 101.3° , one obtains minimal island size, as in Fig. 5. After three transits around the torus, the magnetic surface in Fig. 5a appears to have good integrity, with a transform ι_t of $\sim 7.5^\circ$. Slightly further out, however, the field lines begin to escape to the axisymmetric separatrix.

Further increases of ι_t , consistent with good magnetic surfaces, can be achieved by applying the circularizer approach described in Fig. 1. A rudimentary case of this kind is illustrated in Fig. 6, where the ends of the helical winding are made to curve away from the confinement region. The radial "thickness" of the projected flux surface, as shown in Fig. 6a, is now seen to be quite limited on the small- R side (where the stellarator field is weak), relative to Figs. 4a and 5a, while the radial thickness on the large- R side remains substantial -- due to the local modulation of the magnetic surface by the

helical windings. That the $n = 8$ shaping of the magnetic surface in Fig. 6b corresponds to local stellarator modulation, can also be verified by noting that the $n = 8$ shape rotates as a function of z , so as to match the shape of the helical windings. The non-axisymmetry seen in Fig. 6b thus corresponds to the desired helically symmetric $n = 8$ shaping, rather than to the formation of $m = 0$, $n = 8$ islands, as in the case of Fig. 4. The transform angle ι_t is $\sim 12^\circ$.

Further gains can be made by increasing the vertical elongation of the FRC, as in Fig. 7 (where ι_t is $\sim 25^\circ$). In view of the very large demands that the study of such configurations places on computer running time, however, a systematic optimization has not been carried out, and the exact dependence of attainable transform on FRC length and number of stellarator field periods remains to be established.

The introduction of a supplementary axisymmetric toroidal field component is also helpful in preserving the integrity of the magnetic surfaces at higher transform angles ι_t . Configurations of this kind resemble the prolate spheromak: the critical issue is, whether the addition of helical windings is effective in suppressing the tilting and vertical-displacement instabilities that would characterize a purely axisymmetric spheromak of this shape.⁹ The experience with the stabilization of vertically elongated tokamaks^{7,8} is perhaps encouraging in this regard.

3. Mirror Hybrids

The successful suppression of the rotational $m = 2$ mode in the FRC studies of Ref. 18 reminds one of the famous "Ioffe bar" experiment reported in Ref. 16. In the earliest phase of mirror

research, axisymmetric mirror machines had suffered from an even grosser disturbance than the FRC -- namely a rotating $m = 1$ mode. The superposition of Ioffe bars suppressed this mode. In addition, it had the singular theoretical merit of creating a minimum-B configuration,²¹ in which all other low-frequency modes could be suppressed. If the Ioffe bars had been turned into stellarator windings, the theoretical advantages of the minimum-B configuration would have been lost, but one wonders whether the experimental results might not have been equally good -- at least for hot-ion plasmas where the higher- m MHD modes tend to be suppressed. (One may indeed speculate that, if Ioffe's work had been carried out at the Lebedev Institute, the history of mirror research might have taken a different turn!)

Supposing that stellarator windings are equally effective in producing MHD stability, they would have definite advantages relative to Ioffe bars in regard to the confinement of particle orbits. Essentially the same remarks concerning symmetry apply as in Sec. 2: An infinitely long "central section" with helical windings would have particle orbits as good as those of an axisymmetric mirror machine. If a long central stellarator winding is properly circularized in its end regions, the classical superbanana transport should become small -- just as in the related case of a high-aspect-ratio stellarator.²² If a mirror-stellarator hybrid of this sort were to be used as the central section of a tandem mirror machine, most of the advantages envisaged for an axisymmetric tandem²³ could perhaps be realized.

4. Conclusion

The rudimentary illustrations offered in this paper are meant to stimulate interest in innovative stellarator hybrids. Evidently, there is need for extensive theoretical analyses in such areas as MHD stability, break-up of magnetic surfaces, and classical particle transport. Further experimental work is needed, particularly with stellarator hybrids of the FRC, prolate spheromak, and mirror machine types.

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Figure Captions

- Fig. 1 The toroidal plasma current of an FRC produces an axisymmetric poloidal field. A superimposed helical winding serves to generate a weak toroidal-field component.
- Fig. 2 Simplified computational model, using a solenoidal plasma current I_p and finite helical winding (length L).
- Fig. 3 For $LB_z/I_p = 6$ and a helical winding with $N = 4$, $I_h/I_p = 0.0625$ and $\phi_h = 52^\circ$, the magnetic field line escapes without forming a surface. (a) Field-line projections into R - z plane. (b) Field-line intersections with x - y plane at $z = 0$. Arrow marks starting point.
- Fig. 4 For a helical winding with $N = 8$, $I_h/I_p = 0.15$, $\phi_h = 112.5^\circ$, $\iota_t \sim 3^\circ$, a magnetic surface with $m = 0$, $n = 8$ islands is formed.
- Fig. 5 With the same parameters as in Fig. 4, but $\phi_h = 101.3^\circ$, $\iota_t \sim 7.5^\circ$, a smoother magnetic surface is formed. Field line is shown passing 3 times around z -axis.
- Fig. 6 A curved helical winding with $N = 8$, $I_h/I_p = 0.20$, $\phi_h = 101.3^\circ$, $\iota_t \sim 12^\circ$, produces an island-free magnetic surface.
- Fig. 7 When L and I_p are tripled, with $N = 8$, $I_h/I_p = 0.67$, $\phi_h = 280^\circ$, island-free surfaces are obtained with $\iota_t \sim 25^\circ$. In addition to the midplane cross section (b), the x - y plane at $z \approx 90$ cm is shown (c).

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Fig. 1 The toroidal plasma current of an FRC produces an axisymmetric poloidal field. A superimposed helical winding serves to generate a weak toroidal-field component.

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Fig. 2 Simplified computational model, using a solenoidal plasma current I_p and finite helical winding (length L).

Fig. 3 For $LB_z/I_p = 6$ and a helical winding with $N = 4$, $I_h/I_p = 0.0625$ and $\phi_h = 52^\circ$, the magnetic field line escapes without forming a surface. (a) Field-line projection into R - z plane. (b) Field-line intersections with x - y plane at $z = 0$. Arrow marks starting point.

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Fig. 5 With the same parameters as in Fig. 4, but $\phi_h = 101.3^\circ$, $\psi_t \sim 7.5^\circ$, a smoother magnetic surface is formed. Field line is shown passing 3 times around z -axis.

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Fig. 6 A curved helical winding with $N = 8$, $I_h/I_p = 0.20$, $\phi_h = 101.3^\circ$, $\ell_t \sim 12^\circ$, produces an island-free magnetic surface.

Fig. 7 When L and I_p are tripled, with $N=8$, $I_h/I_p=0.67$, $\phi_h=280^\circ$, island-free surfaces are obtained with $\ell_t \sim 25^\circ$. In addition to the midplane cross section (b), the x-y plane at $z=90$ cm is shown (c).

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