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A LOW-ASPECT-RATIO TORSATRON FOR
HIGH-BETA TOROIDAL CONFINEMENT

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A Low-Aspect-Ratio Torsatron for
High-Beta Toroidal Confinement

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ABSTRACT

A new type of torsatron configuration is characterized by: (1) flux-surface symmetry compatible with high-beta optimization of a tokamak-torsatron hybrid, and (2) unentangled coil topology.

The tokamak has become the favored candidate as a near-term fusion reactor,¹ because of its relative simplicity, symmetry, modest size, modestly sufficient beta value, and extensive experimental data base.² Addition of certain stellarator-torsatron³ features would, however, be desirable in order to improve MHD stability and to facilitate steady-state operation. Unfortunately, there is an inherent contradiction between the condition for optimum-beta tokamak design² (i.e., low aspect ratio R/a with substantial vertical elongation b/a) and the conventional condition for stellarator/torsatron flux-surface symmetry³ (i.e., high aspect ratio without vertical elongation).

This contradiction can be resolved by a torsatron winding (Figs. 1 and 2) with screw symmetry pointing along the z-axis [i.e., all quantities obey $f = f(R, \phi - kz)$], rather than conventional screw symmetry, pointing along the toroidal minor axis [i.e., $f = f(r, \theta - k\phi)$, where r is the minor radius and θ is

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the associated poloidal angle]. Windings that obey the present condition are topologically unentangled (Fig. 1): they can always be removed individually, for example, by displacement along the helical symmetry coordinate.

In the torsatron configuration of Fig. 2, the coils that generate the basic toroidal field $B_{\phi 0}$ are deformed so as to lie in screw planes $\phi = \phi_0 + kz$ (Fig. 1). The large-R sides of these coils are well-separated from each other, and act like a conventional helical winding,³ generating an average vertical field $\langle B_{zh} \rangle$ that becomes strong near the winding. In addition, the tiltedness of the coils gives rise to a global vertical field B_{zoh} . To produce closed magnetic surfaces, an externally generated field B_{zoe} , opposing B_{zoh} is superimposed; the exact magnitude and radial variation of B_{zoe} can be used to control the location and shape of the resultant closed surfaces.

The combination of a helical winding localized on the large-R side of the torus with an axisymmetric vacuum poloidal field, for flux-surface closure, was first proposed in Ref. 4 as a stellarator configuration having a strongly favorable magnetic well. Some other innovative stellarator designs combining similar ingredients are described in Refs. 5 and 6. The application of the "semi-stellarator" concept of Ref. 4 to the improvement of tokamak positional stability was suggested by S. Yoshikawa to the authors of Ref. 7; this technique has proved to be highly beneficial in tokamak plasma-shaping experiments of modest size and temperature.^{7,8}

The present torsatron concept simplifies the coil system of Ref. 4 and introduces the features of easy disassembly and improved symmetry. As in Ref. 7, a major goal is the enhancement of tokamak stability, but the present emphasis is on the pursuit of beta-maximization. The present torsatron can be used for vacuum field confinement; the limiting beta value appears to be competitive with that of the conventional tokamak.⁹ We expect, however, that the greatest potential of this configuration consists in its geometric compatibility with tokamak-torsatron hybridization; we therefore refer to it as the "tokatron" configuration.

While ideal symmetry is approached in conventional stellarator/torsatrons as $R/a \rightarrow \infty$, tokatron symmetry is independent of R/a and becomes ideal as $b/a \rightarrow \infty$. A section of tokatron vacuum field that approaches ideal symmetry is illustrated in Fig. 3. (We note, incidentally, that this type of highly elongated tubular plasma-confinement scheme closely resembles the E-layer of the Astron concept.¹⁰ Since field-reversal can be achieved already in the vacuum state, we refer to the present configuration as a V-layer.) Superposition of a toroidally directed plasma current or energetic-particle current is compatible with the maintenance of highly elongated equilibrium configurations; accordingly, there is a prospect of creating a physical embodiment for the mathematical concept of the "one-dimensional" tokamak current layer, which is shown in Ref. 11 to have favorable high-beta stability properties.

In practical application, the degree of desirable vertical elongation of the tokatron will be constrained by various engineering considerations. The basic tokatron symmetry then suffers from the introduction of a substantial extraneous z -dependence $f = f(R, \phi - kz, z)$. As in the case of the finite- R/a conventional stellarator/torsatron,³ the degree of unfavorable impact of asymmetry on magnetic flux surfaces and particle orbits depends on the degree of optimization of detailed coil design.

The realization of nearly perfect magnetic surfaces and orbits can best be approached by means of a tokatron configuration that has three distinct symmetry regions.

1. $f = f(R, \phi - kz), \quad 0 < |z| < b_h$
2. $f = f(R) \quad , \quad b_h < |z| < b_e$
3. $f = f(R, z) \quad , \quad b_e < |z| < b$

Regions 1 and 2 and Regions 2 and 3 are compatible in the sense of preserving at least one ignorable coordinate. Regions 1 and 3 are incompatible; their interconnection must be approached in a special manner that has been addressed previously in the stellarator literature as "circularizer" design.¹²

Within Region 1, flux surfaces on the large- R side have the typical form $R = R_0 + \epsilon \cos(\phi - kz)$. When such a surface is mapped by field lines passing out through $z > 0$ around the minor periphery and back to the $z < 0$ side of Region 1, there can be a destructive interference, leading to island formation and eventually to outward spiraling of the field lines. The objective is

therefore to map the scalloped surface of Region 1 into a surface of nearly circular cross-section before Region 3 is entered. Circularizer design concerns itself with the detailed shaping of the helical windings in the transition region.

A rudimentary tokatron vacuum-field configuration with modest vertical elongation and without a circularizer is illustrated in Fig. 4. This case uses a set of simple filamentary coils of the form shown in Fig. 1, but succeeds, nonetheless, in providing well-formed magnetic surfaces. The average vertical field on the large-R side is substantial ($\langle B_z \rangle \sim 0.25B_\phi$), while the central rotational transform remains small [$\iota(0) \sim 0.17$]. From the point of view of tokamak-toratron hybridization, these are both favorable features, since a large $\langle B_z \rangle$ is needed to improve ballooning-mode stability at high beta, while a low vacuum-field contribution ι_h leaves room within the Kruskal-Shafranov limit ($\iota_h + \iota_c < 1$) for a substantial tokamak-current contribution ι_c .

There are two promising lines of further investigation:

(1) Toroidal plasma current can be added explicitly to a moderately elongated "practical" tokatron configuration, such as that in Fig. 4, in order to raise the total transform towards the Kruskal-Shafranov limit. Appropriate field-line integrations using a simplified toroidal-current model have been found to produce the desired enhancement of transform with only moderate destruction of outer flux surfaces. MHD equilibrium codes for self-consistent modeling of three-dimensional tokatron plasmas are now in preparation.

(2) The degree of approximation to ideal tokatron symmetry can be improved by studying more highly elongated configurations and following the three-region approach outlined above, with helical modulations restricted to Region 1. The vacuum-field tokatron case then encounters an inherent geometric dilemma: the decrease of $\langle B_{zh} \rangle$ away from Region 1 tends to inhibit the desired field-line transition to Regions 2 and 3. This difficulty is most easily resolved by the introduction of the additional vertical-field contribution B_{zoc} , generated by a tokamak plasma-current layer. In this sense, tokamak hybridization may be an essential feature of the high-symmetry tokatron, rather than an optional feature, as in the case of the conventional stellarator/torsatron.

A number of other analyses are being carried out on plasma-physics topics relevant to tokatron confinement. Because of the novel symmetry condition, the neoclassical transport coefficients in the tokatron are expected to differ somewhat from the conventional stellarator and tokamak cases. Stability against resistive MHD modes is improved relative to the conventional tokamak; ballooning mode stability should also be improved, but a new class of local ballooning modes can be introduced by the discreteness of the helical windings.

There are two main options for driving a toroidal plasma current: (1) conventional long-pulse transformer induction; and (2) steady-state current driving by rf-waves¹³ or injected particle beams.¹⁴ In either case, a tokatron hybrid can introduce geometric benefits and has the basic advantage of providing an initially closed vacuum-field configuration.

The preceding discussion has neglected the contribution of the small-R side of the tokatron coil to $\langle B_{zh} \rangle$. For coils of the type shown in Fig. 1, there is actually a small region of reverse transform in the immediate vicinity of the inner helical windings, which gives rise to a second set of closed magnetic surfaces (not shown in Fig. 4) centered at smaller R. This phenomenon is easily suppressed by smoothing out the current distribution on the small-R side. Alternatively, one can create an "inverse tokatron" configuration by smoothing out the current distribution of the helical windings on the large-R side. The "inverse tokatron" has some attractive features in respect to particle orbits and MHD properties, but implies a less convenient type of coil structure than that of the normal tokatron.

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Figure Captions

Figure 1

Idealized filamentary tokatron coil, defined by the intersection of a toroidal surface and a screw surface.

Figure 2

Schematic of the tokatron vacuum field. "Helical windings" refer to the outer and inner sides of the tokatron coils.

Figure 3

Illustrative V-Layer with ten helical windings ($R_2 = 4$ m, pitch = 0.25 radian/meter) and return current of 50 MA on the z-axis ($R_1 = 0$), so that $B_{zoh} = -2.5$ Tesla. (a) Flux surfaces for $B_{zoe} = 0$. (b) Flux surfaces for $B_{zoe} = 2.44$, containing equal fluxes of $\pm \langle B_z \rangle$. (c) $\langle B_z \rangle$ vs. R for $B_{zoe} = 2.44$.

Figure 4

Illustrative tokatron field, using six coils of the form defined in Fig. 1. (a) Flux surfaces "under" a coil; (b) "between" coils; (c) normalized rotational transform ι and $\langle B_z \rangle / B_\phi$ on the large- R side, vs flux-surface number.

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Fig. 1

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Fig. 2

Fig. 3

Fig. 4