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OPTIMIZATION OF A STELLARATOR DESIGN INCLUDING MODULATION OF THE HELICAL WINDING GEOMETRY

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The optimization of the helical winding geometry of the next generation of high performance stellarators is of critical importance as the current in the helical conductors must be kept to a minimum to reduce the very large electromechanical forces on the conductors.

General Optimization

Using a modified version of the Culham computer code MAGBAT[1] we have calculated the separatrix r_s as a fraction of the helical winding radius a and the parameter, $\iota_s(a/R)$ calculated at the separatrix, as functions of the helical winding pitch angle $\psi = \tan^{-1}(m\ a/R)$, for $\ell = 3$ stellarators with aspect ratios $4 < a/R \leq 16$. The results are plotted in Figs. 1 and 2 respectively for different values of the ratio I/Ba, where I is the helical conductor current and B is the toroidal magnetic field. The width of the helical conductors has been approximated by 3 current filaments each carrying I/3 and spaced poloidally 10° apart. The graphs show an optimum ψ for a given value of I/Ba which increases with increasing I/Ba. Examination of the poloidal rotation of field lines (e.g. see Fig. 3) shows that surfaces will

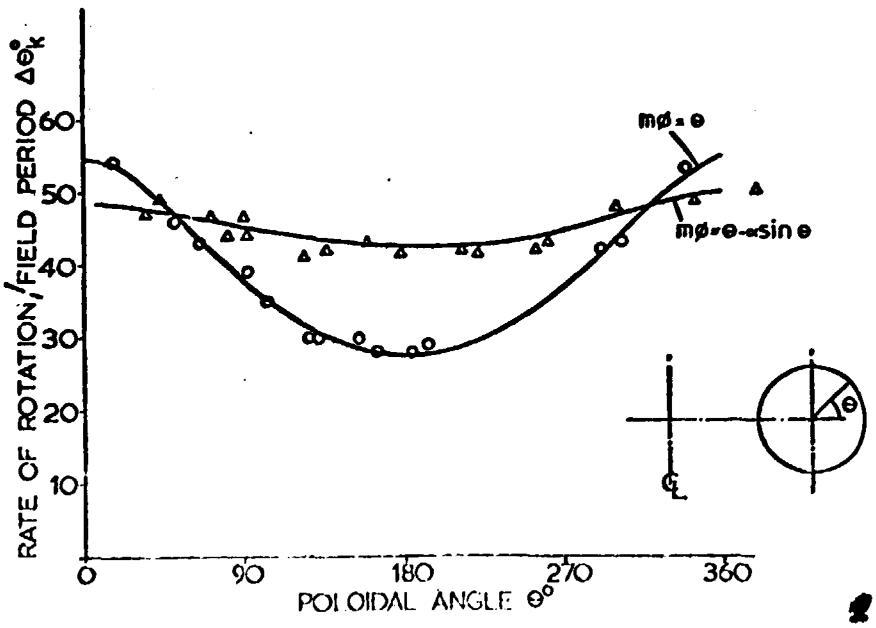

Fig. 3. The rate of rotation of a magnetic field line starting at $\theta = 0$, $r = 26$ cm for modulated stellarator with $\alpha = 0.05$ and unmodulated stellarator $\ell = 3$, $m = 7/3$, $R = 2.15$ m, $a = .34$, $B = 40$ kG, $I = 330$ kA.

open when the *local* pitch of the field line (corresponding to 2 to 3 times the *average* value) approaches ϕ. Thus as the winding pitch is decreased below the optimum value the separatrix shrinks and as a consequence $\bar{\iota}_s a/R$ falls. Nevertheless, as the electromechanical forces on the helical conductor increase with ψ it is advisable to choose the lowest acceptable winding pitch angle.

Taking the set of curves for which $I/Ba = 0.25$ as an example, the effect of toroidicity can be seen to be important for small aspect ratios $R/a \geq 4$ and to become negligible when $R/a \sim 12$. It is thus important when comparing the curves of Figs. 1 and 2 to use the actual value of R/a if ≤ 12.

The influence of toroidicity can be reduced if the helical winding pitch is modulated according to the equation

$$m\phi = \theta - \alpha\sin\theta$$

where α is a constant found by computer iteration. The effect of α on the helical winding geometry is to make the winding on the outer circumference steeper, and shallower on the inner circumference, thus causing the field line to rotate more uniformly with poloidal angle. This is illustrated in Fig. 3, where the case of constant pitch winding is shown for comparison with the parameters $\ell = 3$, $m = 7/3$, $R = 2.15$ m, $a = 0.34$, $B = 40$ kG, $I = 330$ kA. For these calculations the conductors were approximated by single filaments. The effect of modulation is to increase the rotational transform by ~ 20%.

It should be noted from Fig. 2, that little improvement can be expected using modulation when $R/a > 12$. By using different values of α for the forward and return helical conductors, a local vertical field which is modulated in phase with the winding is introduced. This produces both a finite rotational transform on the magnetic axis (Fig. 4) and its displacement in major radius without causing break-up of the outer surfaces. This is in contrast to the distortion of the surfaces and serration near the separatrix found by Gibson [2] when a uniform vertical field was added to a constant pitch stellarator.

Modular Configuration

Fig. 5 compares magnetic surfaces of a continuously wound stellarator with that in which a number of azimuthal gaps (4 diagnostic gaps of 4.5° and 12 gaps of 1° for finite conductors and insulation) have been introduced, and shows little effect on the gross features of the magnetic surfaces. The helical winding modules are oriented so that the end points of the conductors are rotated in azimuth with the same poloidal coordinates across the gap.

The case chosen is that of the Canberra Modular Stellarator [3]. Fig. 6

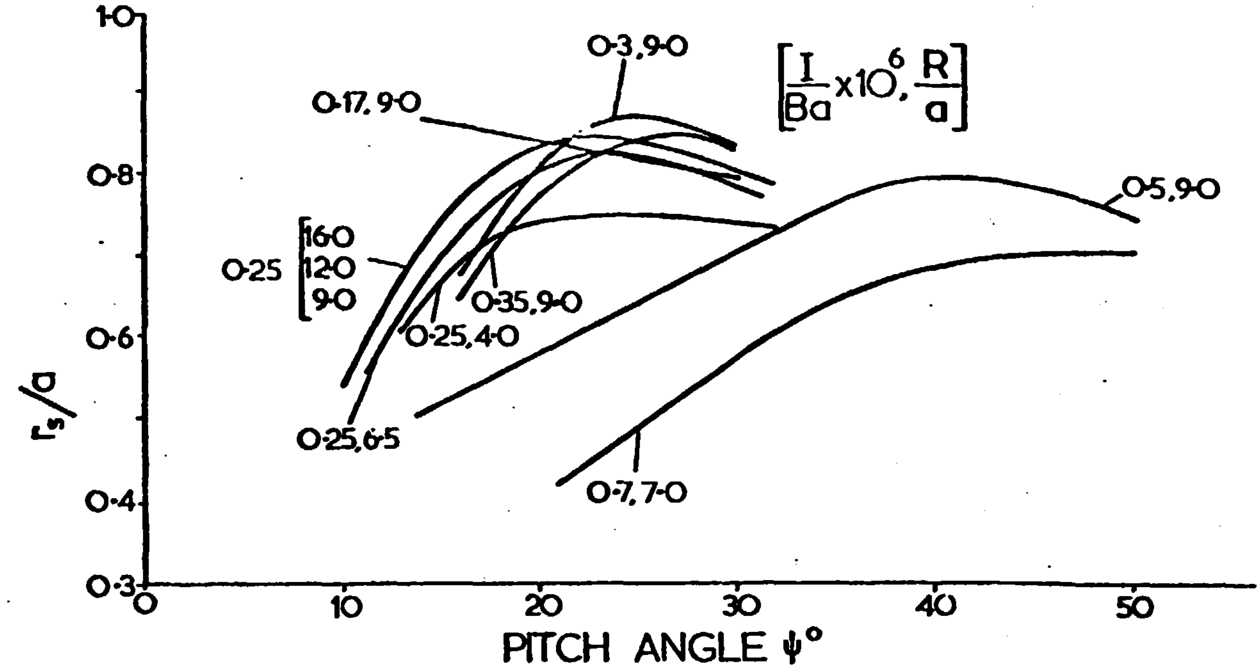

Fig.1. r_s/a as a function of winding pitch angle ψ for various I/Ba and aspect ratios.

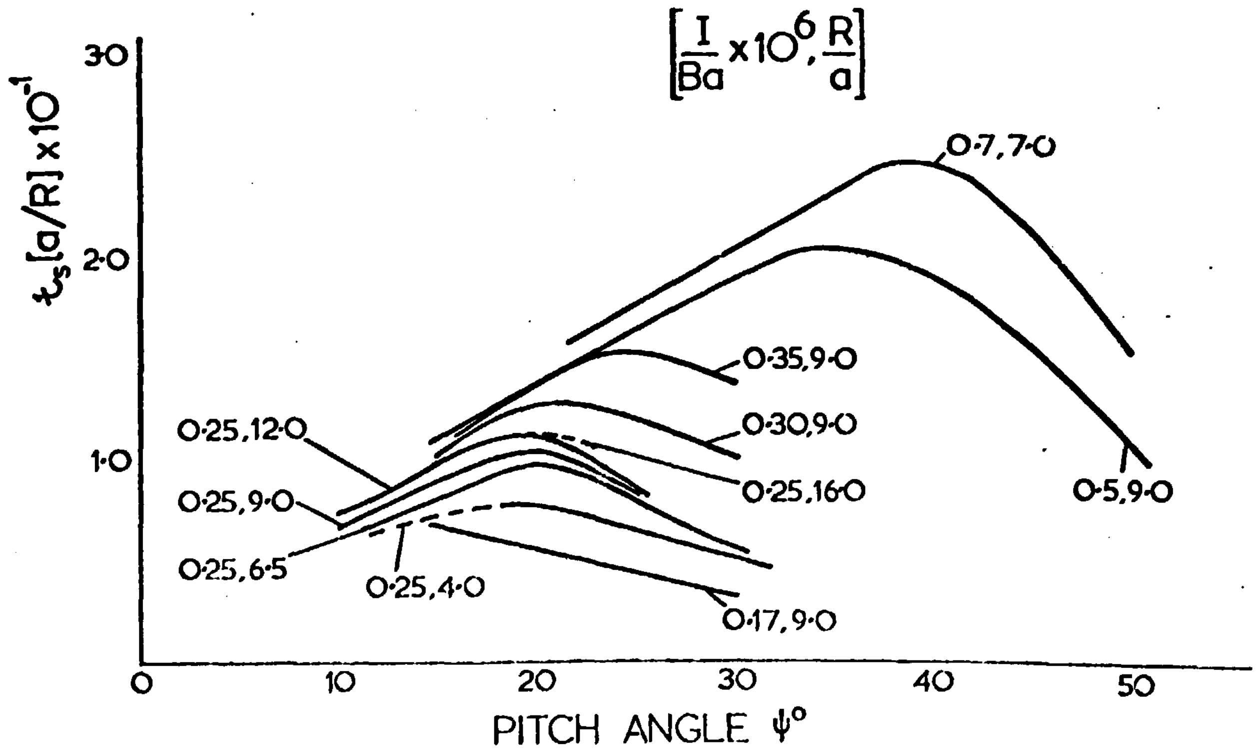

Fig.2. $\tau_s a/R$ as a function of ψ, for various I/Ba and aspect ratios.

shows the effect of varying the total gap width up to 45° varying the ratio of the above two types of gaps. The main effect is a decrease in the rotational transform with the outer surfaces themselves remaining intact. This appears to hold provided the individual gap width is not large compared with the winding-separatrix distance.

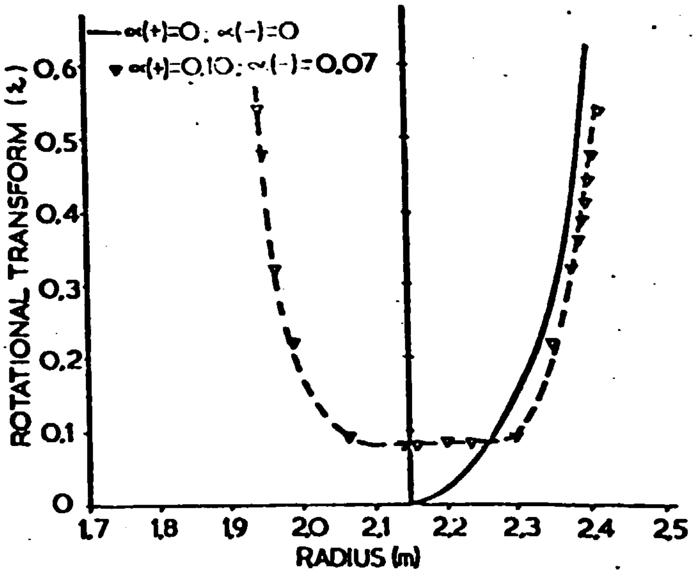

Fig.4. ι as a function of the initial radius of a field line for constant pitch (solid) and modulated stellarator (dashed) with $\alpha(+) = 0.10$ and $\alpha(-) = 0.07$ showing finite ι on the magnetic axis.

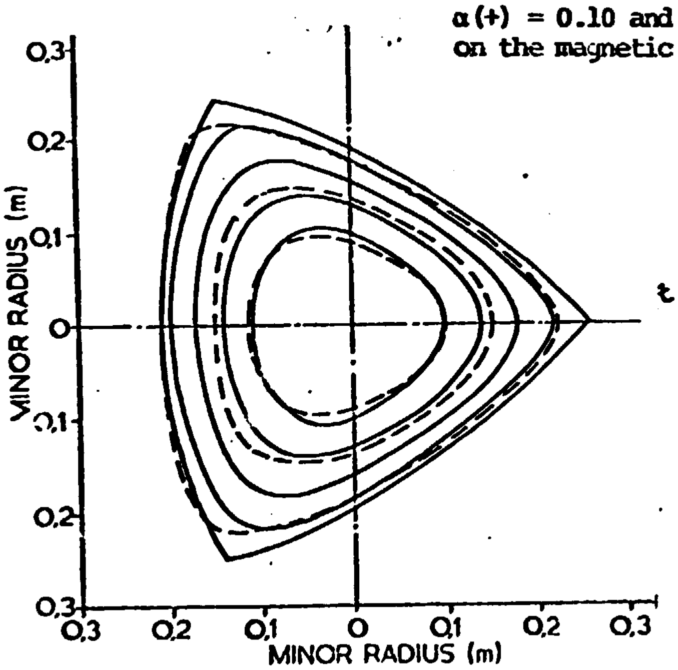

Fig.5. Magnetic surfaces (i) – – – for modular stellarator with $4\times4^{\circ}$ and $12\times1^{\circ}$ gaps. (ii) —— continuous helical winding. $\ell = 3$, $m = 8/3$, $R = 2.0$ m, $a = 0.34$ m, $B = 40$ kG and $I = 370$ kA.

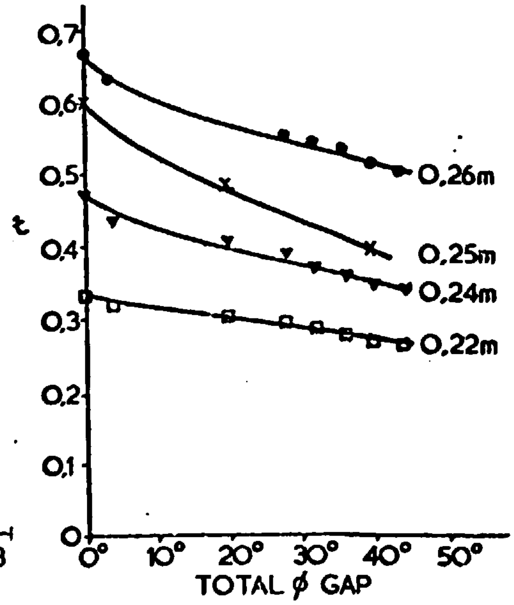

Fig.6. ι as a function of total azimuth gap angle with 4 large and 12 small gaps, helical windings approximated by single filaments $\ell = 3$, $m=7/3$, $\alpha=0$, $R=2.2$m, $a=0.34$, $B=40$ kG, $I=330$ kA.

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(2) GIBSON, A., Phys. Fluids, 10 (1967) 1553.
(3) HAMBERGER, S.M., SHARP, L.E., PETERSON, L.F., "A large stellarator based on modular coils", these Proceedings.