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Ultra-simple Stellarators

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ABSTRACT

An ultra-simple approach to achieving a high rotational transform, low aspect ratio toroidal magnetic confinement system is presented, featuring just two planar coils, optionally interlinked. The effect of the principal free parameters on the vacuum magnetic topology of the configuration is explored, suggesting a compromise between minimising magnetic field ripple and plasma aspect ratio. It appears that an attractively simple, magnetically robust design can be achieved, with the possibility of further improvements by more sophisticated optimisation of the coil shapes.

Magnetic confinement fusion is presently undergoing a revival of interest in stellarators, with a number of new devices recently commissioned and others in advanced stages of planning. The majority of these devices feature a daunting level of technology, whether of the classical helical winding types such as ATF, U2-M and LHS or the more recent modular and heliac [1] types exemplified by W7AS, H-1 and TJ-II. As such they are beyond the resource capability of all but the relatively well-endowed plasma physics institutions, unless built more on the scale of Shatlet-M, IMS or Sheila. Some other institutions e.g. universities in developing countries, would pursue the physics of plasmas in stellarator configurations if they were as easy to build as the small tokamaks or plasma focus experiments commonly favoured, thus broadening the stellarator community to the benefit of all concerned.

So what is the simplest possible geometry for a stellarator? Since helical or severely non-planar coils are inevitably prone to engineering difficulties, it would seem reasonable that a heliac constructed from planar coils might be preferred. Such devices typically feature several field periods, each consisting of several toroidal field coils, but there is no reason in principle why the number of field periods and coils per period should not be reduced to one. This is equivalent to constructing a global $q = 1$ surface and then resonantly perturbing it with the stray field from the return limb of the single toroidal field coil employed. Besides reducing the number of field periods, the choice of $q = 1$ for the global structure has the advantage of producing the minimum density of neighbouring low-mode-number rational surfaces, enhancing the immunity to satellite perturbations from harmonics of the vacuum fields, constructional errors or pressure-driven plasma currents. The basic structure of the proposed configuration is accordingly a single large rectangular TF coil with a hardcore ring arranged axisymmetrically around one long limb, as shown in Fig 1.

When the TF coil is extremely large (200R x 200R, R being the ring radius) the structure of the magnetic surfaces is broadly consistent with simple linear theory for the structure of an island in the gradient of global rotational transform, $\nabla\bar{\iota}$, i.e.

$$(r - r_o) = \pm(w/2\sqrt{2})\sqrt{cos(m\theta_1) + f}$$

and

$$\frac{1}{\bar{\iota}_{private}} \equiv q_{private} = \frac{4\sqrt{2}}{m\pi w \nabla\bar{\iota}} \int_o^{cos^{-1}(-f)} \frac{d(m\theta_1)}{\sqrt{f + cos(m\theta_1)}}$$

Here r_o is the radius of the resonant surface, m is the resonant poloidal mode number, w is the full island width, given by

$$\frac{w}{2} = \sqrt{\frac{-4Rb_{ro}}{mB_\phi \nabla\bar{\iota}}}$$

(where R is the major radius of the resonant surface, b_{ro} is the amplitude of the perturbing field and B_ϕ is the toroidal field), θ_1 is the poloidal angle subtended between the o-point and a point in the island, and f is the nesting parameter, varying between -1 (representing the o-point) and +1 (corresponding to the separatrix). The value of the integral is $\pi/\sqrt{2} \approx 2.22$ at $f = -1$, rising slowly to ≈ 4.1 at $f = 0.9$ and diverging to ∞ at $f = +1$.

Clearly as the size of the TF coil is reduced towards more manageable proportions, the field from the return limb rises, eventually becoming too large for clean island generation and creating stochasticity. However the field from the return limb can be compensated by tilting and/or outwardly shifting the hardcore, until some optimum is reached where the magnitude of the satellite perturbation spectrum (and hence the degree of magnetic surface destruction) arising from the various non-axisymmetries is just tolerable. A wide range of such configurations has been found by simple field line tracing, featuring various ratios of ring current to TF coil current and TF dimensions.

A natural property of simple heliacs is that the magnetic field strength explored by the field lines includes the global variation with major radius, so that the field ripple rises with the inverse aspect ratio of the original resonant surfaces, i.e. the ratio of ring to TF current. The achievement of good surfaces when this ratio was low, however, was possible only with a moderately large toroidal field coil, so that for a given plasma volume a compromise between machine size and trapped particle losses due to field ripple seems to be necessary. Figure 2 shows a sequence of surface cross-sections at the outboard midplane for various ratios of I_{ring}/I_{TF} with TF dimensions $10R \times 16R$, the longer dimension being directed along the axis of (global) symmetry. All of these cases feature a monotonic rotational transform profile falling from $\leq 2/3$ at the centre to $\geq 1/2$ at the surface. Sliding the ring too far away from the return limb causes private m=2 ($\bar{\iota} = 1/2$) islands to appear at the edge, while sliding it the other way creates an m=3 ($\bar{\iota} = 2/3$) island chain near the magnetic axis. These effects are due to the whole rotational transform profile shifting downwards as the compensation of the return limb field is increased, consistent with the linear theory above. Another class of configurations with $\bar{\iota}(r) \leq 1/2$ (as found in the 200 m square TFC case) could only be preserved for modest reductions in the size of the TFC, down to $\approx$ 20Rx40R, without becoming ergodic.

Very tight aspect ratio configurations are possible with this approach, as shown at various toroidal angles in Fig 3 for a case with $I_{ring}/I_{TF} = 0.15$ (hence very large field ripple) and TF dimensions of 7Rx14R. This achieves a ratio of mean major radius to mean minor radius (volumetrically averaged) of 2.74, while the equivalent current of the outermost surface ($I_{eq} = I_{TF}\bar{\iota}(\bar{a}/\bar{R})^2$) is 49% of the ring current. Fig 4 shows the profiles of rotational transform, magnetic field ripple and specific volume $V' = \frac{1}{\phi}\int_o^\phi \frac{d\ell}{|B|}$ for this case and another at $I_{ring} = 0.05$, TF size 10Rx16R. Evidently although the achievable aspect ratios and rotational transform profiles of this configuration class are (serendipitously) very favourable, the ripple and well depth (or rather, hill height) leave much to be desired.

The presence of a magnetic hill is theoretically expected to destabilise modes such as the resistive interchange [2] but the non-linear effects of such activity on energy transport etc are not easily predicted and could perhaps be acceptable, as suggested in ref [3] for modest hills. Devices such as asperators [4], bumpy tori [5,6,7] and levitrons [8,9] have been operated successfully at low β with magnetic hills, so that plasma initiation is not in question. The equilibrium currents associated with finite plasma pressure will, particularly at tight aspect ratio, cause an outward shift of the inner magnetic surfaces, reducing the vacuum hill, while the strong shear of the configuration will exert a stabilising influence, but the necessary equilibrium and stability analyses to quantify these effects are beyond the scope of this study.

Adding a uniform vertical field or single extra circular coil alters the shape of the surfaces considerably but has no significant effect on the profile of specific volume. Various shapes and/or winding elongations for either or both of the coils have been tried, preserving their planarity, but the principal effect was to introduce strong splitting of the magnetic surfaces. It may be that the addition of $\ell = 2$ fields (i.e. another ring coil, paralleling the plasma) would reduce the hill, but this or any more sophisticated optimisation, e.g. via an implementation of the Cary-Hanson technique [10], may well result in non-planar coil deformations as well as additional coils, complicating the structure.

A potential advantage with a penalty of increased geometrical complexity arises if the coils are formed without interlinking, as favoured for any wound-wire construction. As a demonstration of the robustness of the configuration, two such cases corresponding to case 4 of Fig 2 but with the ring substituted by a "Pacman" shaped coil (modelled by $\approx$70 straight filaments specified only to an accuracy of 10^{-2} of the ring radius) were evaluated with and without a compensation loop. Despite the broad spectrum of perturbations these distortions created, the surface splitting was found to be quite modest even in the uncompensated case, Fig 5, and could presumably be nulled by a more subtle optimisation.

The lowest order resonance in this family of configurations ($0.5 < \iota\!\!- < 0.667$) is at $\iota\!\!- = 0.60$ with $m = 5, n = 3$, and small islands were observed here in some of the cases studied, as shown in Fig 6. However the effective $n = 3$ spectrum can be modified by forming the toroidal field coil conductor stack into a triangular or trifoliate cross-section where it passes through the ring, readily producing a null or inverse island phase in the cases examined, and simultaneously improving the outermost surfaces, where the $m = 6, n = 3$ is marginally resonant. Fig 7 shows the result of optimising the case of Fig 6 in this way, with an inset showing the toroidal field coil configuration used.

In conclusion this limited study has shown that there exist classes of tight aspect ratio, high rotational transform heliac stellarators which feature extreme engineering simplicity and very robust magnetic surfaces, capable of providing a suitable basis for the investigation of generic stellarator issues such as magnetic hill and ripple effects. It seems likely that related configurations should exist which would preserve the fundamental simplicity of these examples but improve upon their magnetic properties.

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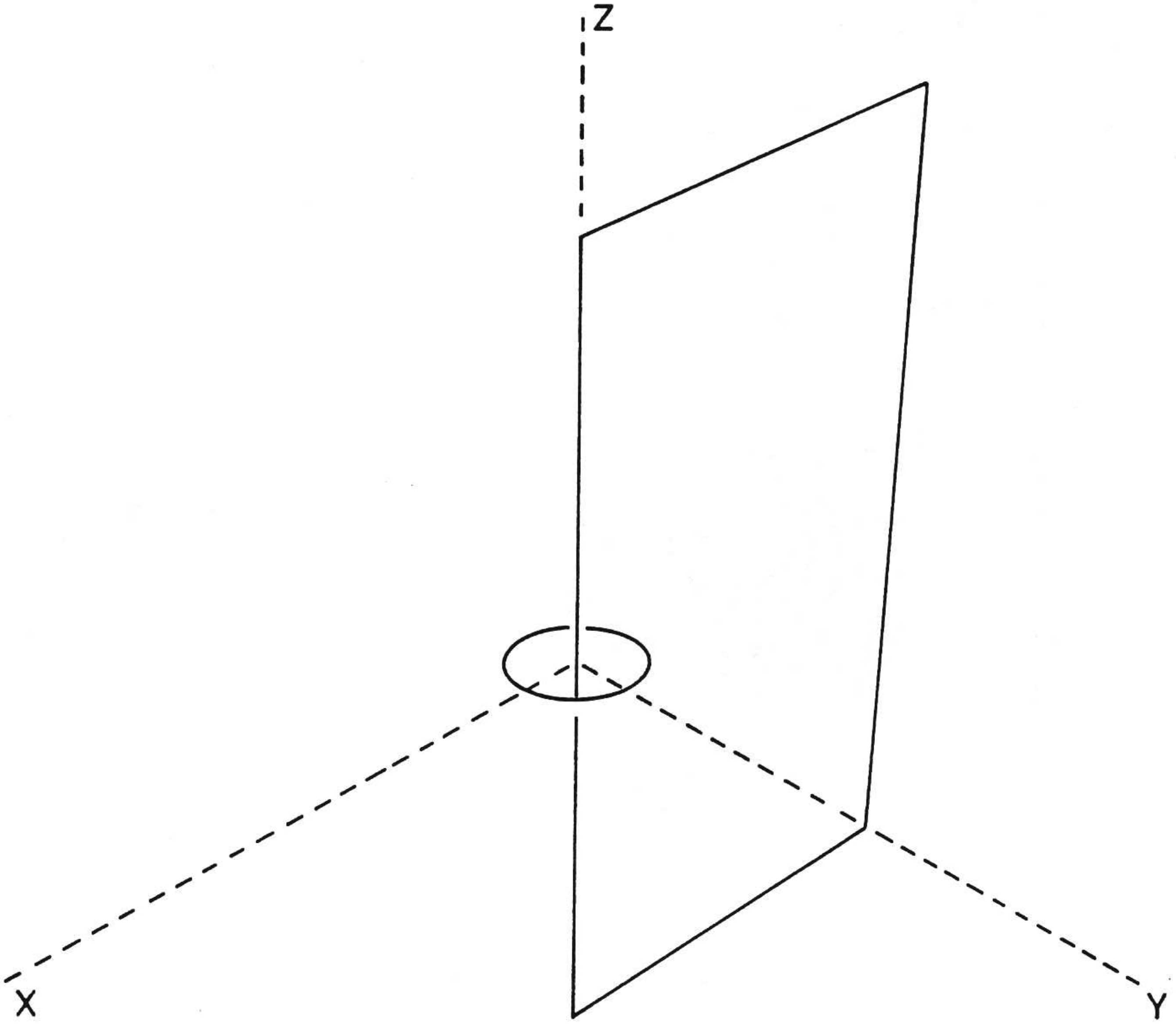


Figure 1.
Complete coil layout of ultrasimple, single field period heliac.

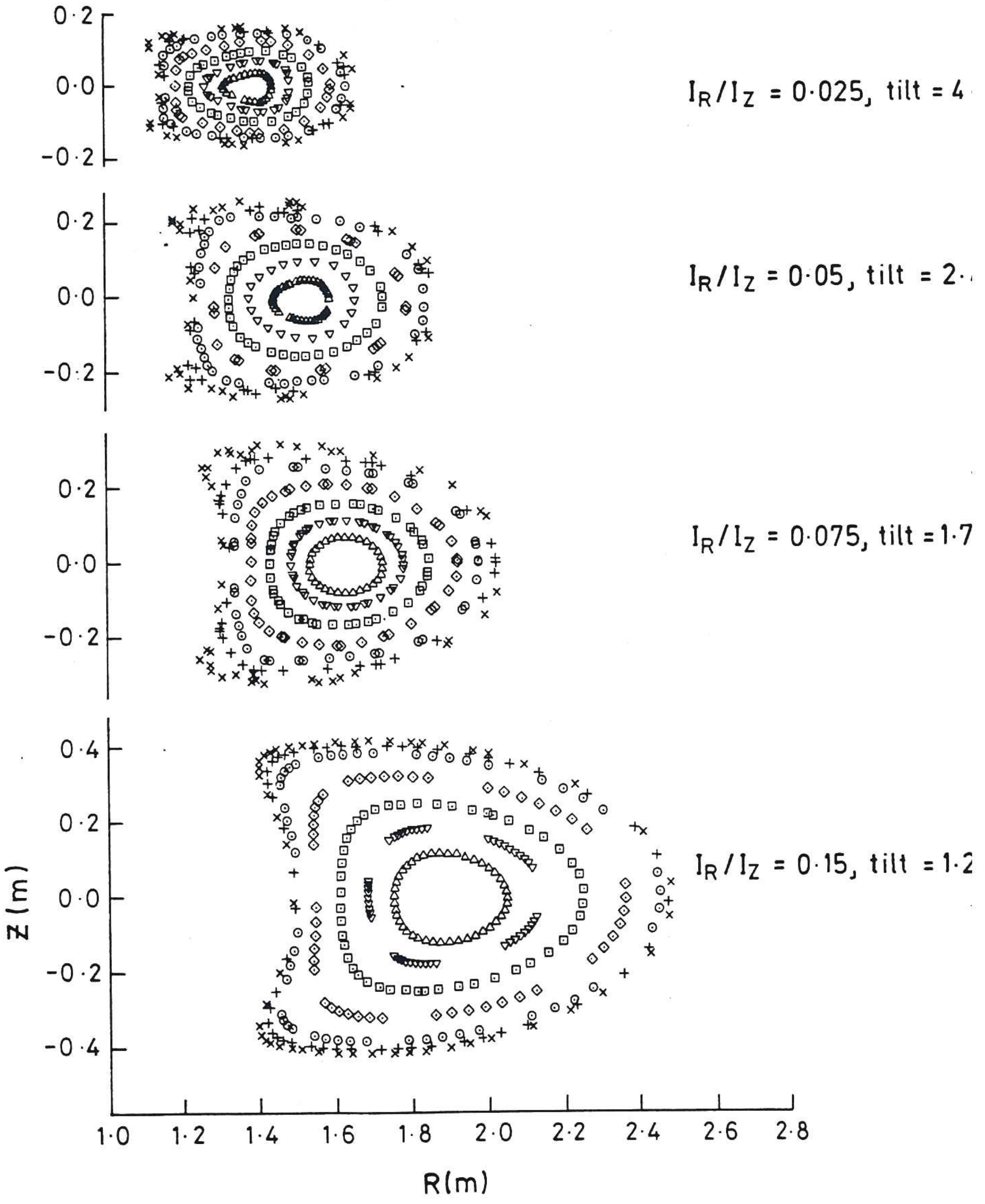
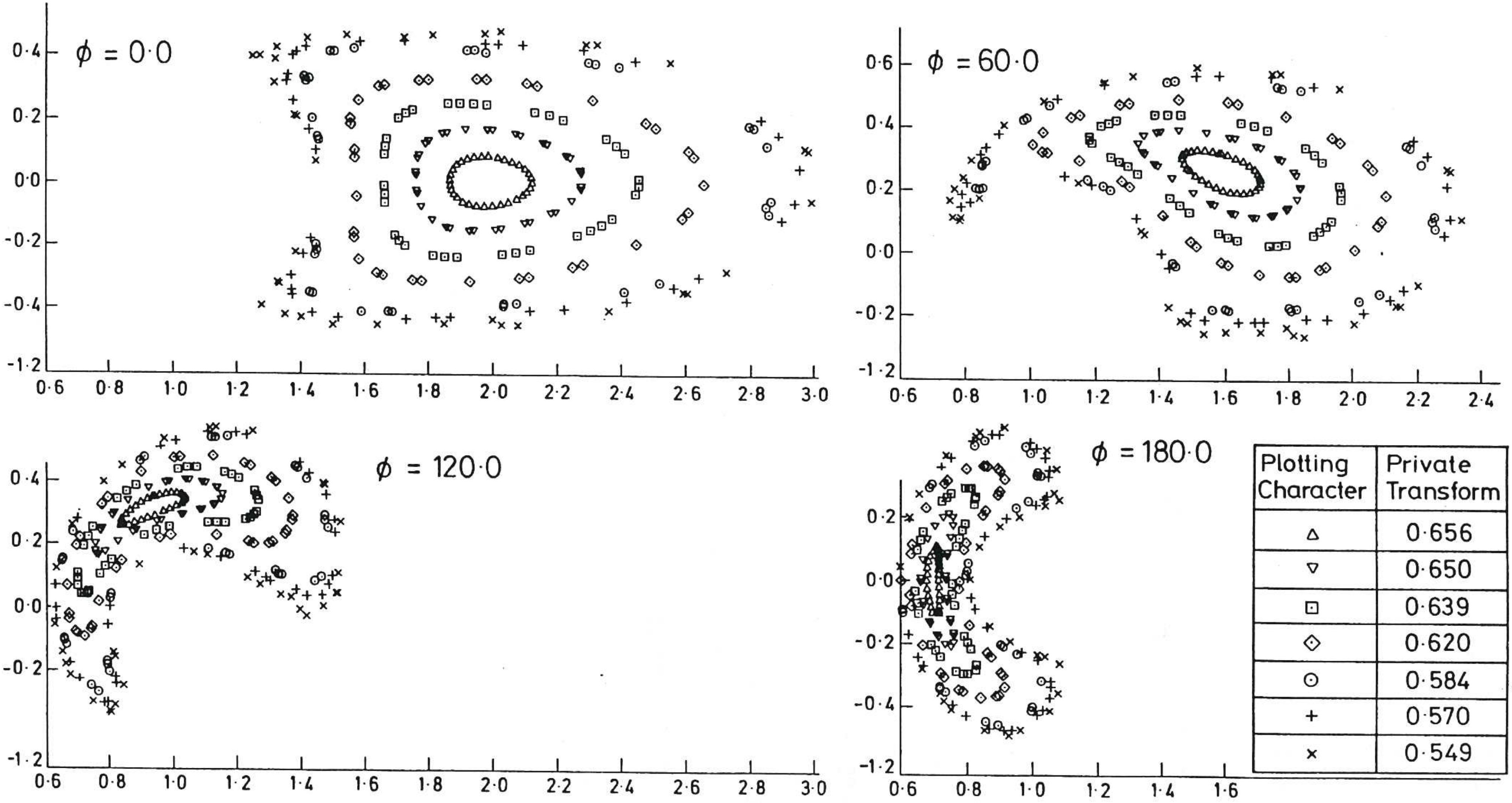


Figure 2.
Effect of varying I_{ring}/I_{TF} (shown as I_R/I_Z) with optimum ring tilt, for TF size = 10R x 16R



Plotting Character	Private Transform
△	0·656
▽	0·650
⊡	0·639
◇	0·620
⊙	0·584
+	0·570
×	0·549

Figure 3
Low aspect ratio, high transform example ($I_R/I_Z = 0.15$, tilt = 0^o, TFC size = 7R x 14R) shown for four toroidal angles ϕ. $\phi = 180^o$ corresponds to the angle of the TFC return limb.

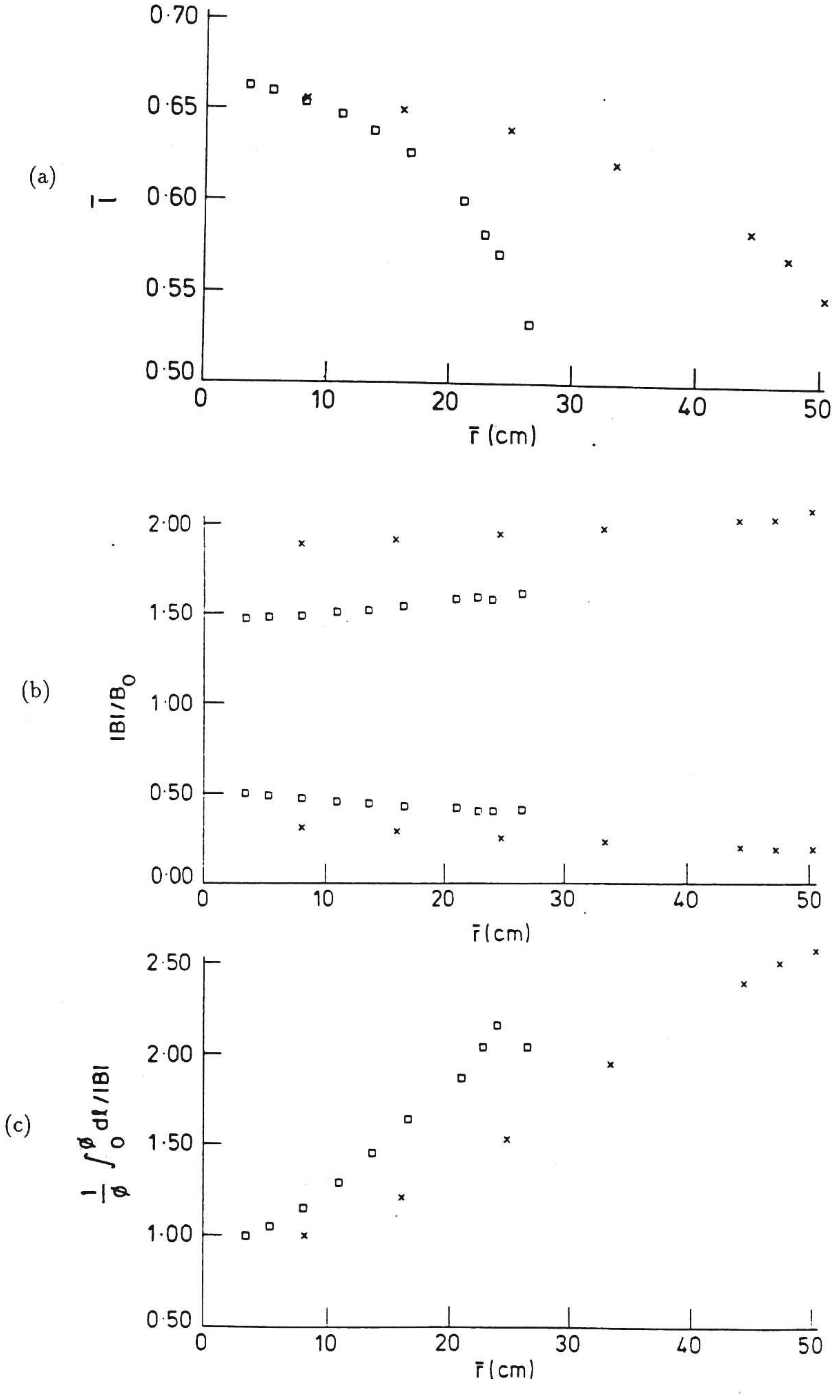


Figure 4
Profiles of (4a) rotational transform ($\bar{\iota}$) (4b) magnetic field ripple (max and min $|B|$) and (4c) specific volume ($\frac{1}{\phi}\int_o^\phi \frac{d\ell}{|B|}$) for the cases of Figure 2, $I_R/I_Z = 0.05$, and Figure 3.

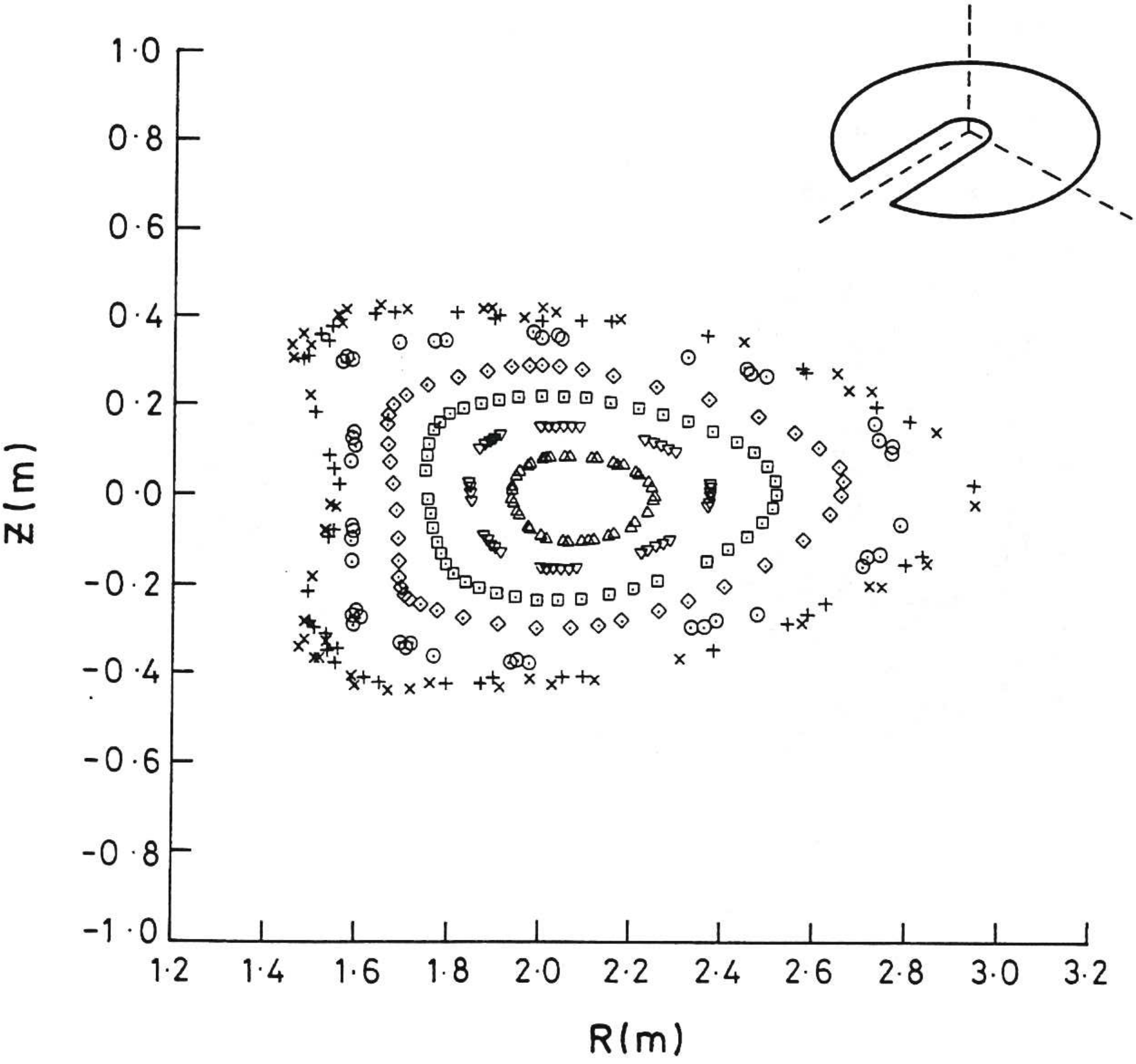


Figure 5
Magnetic surfaces with uncompensated "Pacman" ring coil (shown in the inset).

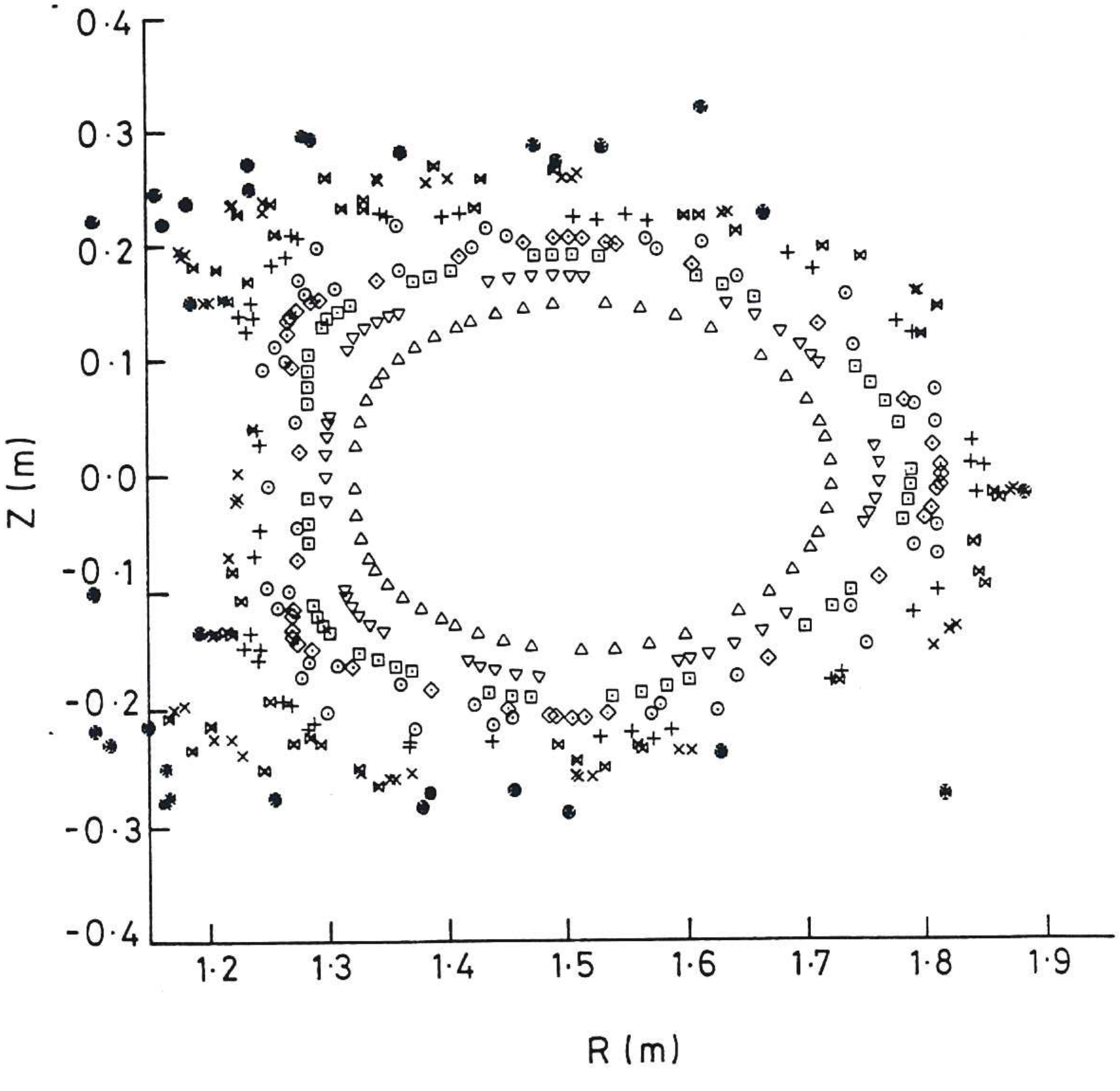


Figure 6
The $I_R/I_Z = 0.05$ case of Fig 2 in detail, showing the clear m=5, n=3 island chain and peripheral stochasticity.

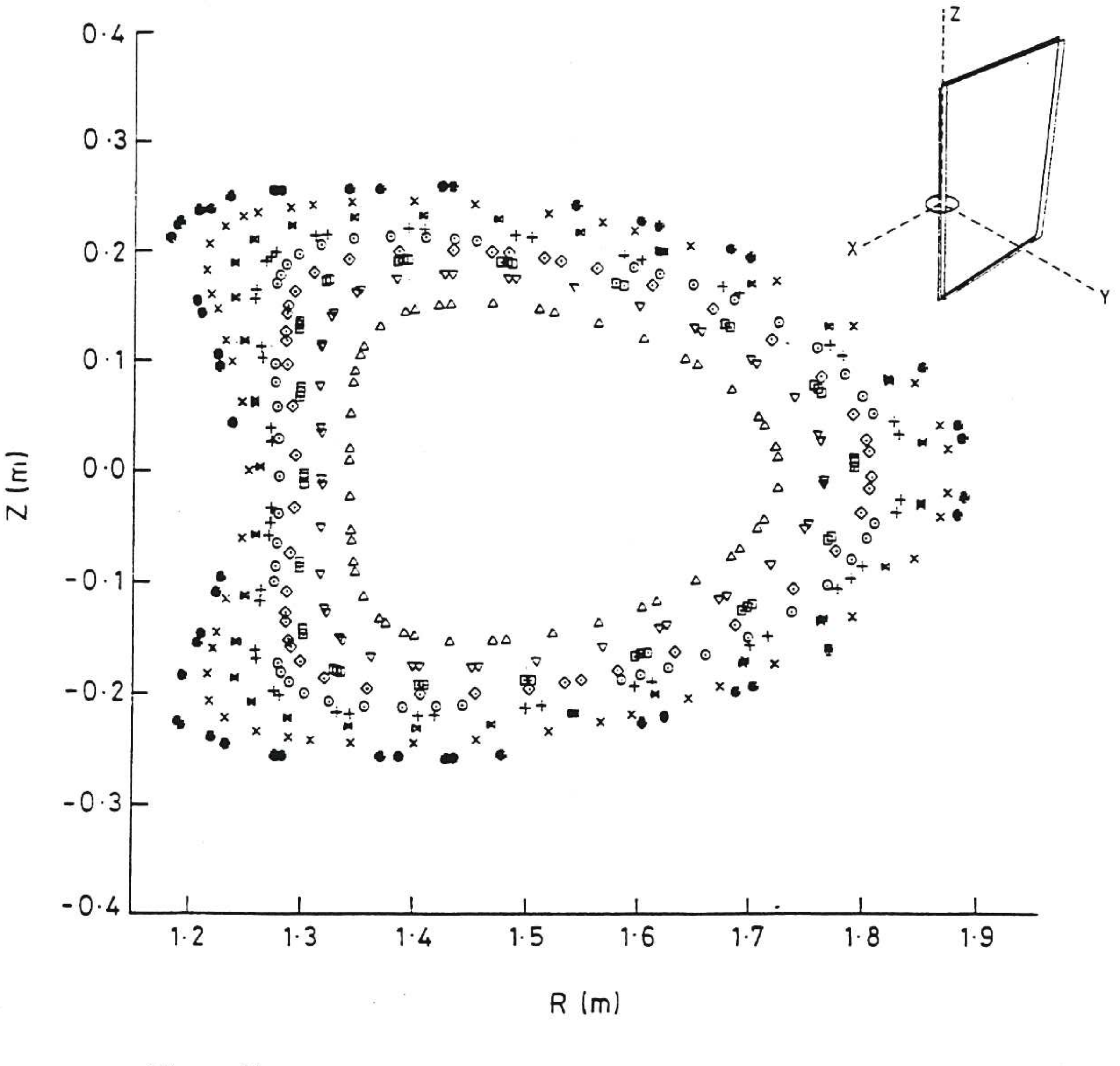


Figure 7
The same configuration as in Fig 6 but with a trifoliate toroidal field coil conductor (modelled as three filaments each displaced 23cm from the original single filament, as shown in the inset).