Some thoughts on the future direction of rotamak research

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[Author's credentials:

(a) Citation on The American Physical Society Fellowship Certificate:
"For advancing the understanding of the interaction of radio frequency power with plasma and pioneering the use of rotating magnetic fields to produce the Rotamak compact torus configuration."

(b) Acknowledgments in: A. L. Hoffman, Phys. Plasmas, 5, 979 (1998)
"The author wishes to thank Ieuan Jones for his persistence in developing the RMF approach to current drive and for many discussions explaining the physics and describing the recent encouraging results on larger rotamak experiments. RMF current drive will be a major part of the new TCS experiment, and the larger power supplies available to this facility should enable the next step in FRC/rotamak development to be taken."]

1. Introduction

An applied rotating magnetic field (RMF) can be used to drive plasma currents in a steady-state, noninductive fashion. By now it has been the subject of numerous publications and for a straightforward summary of the basic mechanism, see Section II of Ref [1].

[1] Ieuan R. Jones
"A review of rotating magnetic field current drive and the operation of the rotamak as a field-reversed configuration (rotamak-FRC) and a spherical tokamak (rotamak-ST)"
Phys. Plasmas, 6, 1950 (1999).

The investigation of plasma/field configurations of the compact torus variety is of current interest in the field of fusion research. Two configurations of this genre are the field reversed configuration (FRC) which does not have an externally applied toroidal magnetic field and the spherical tokamak (ST) which possesses such a field. In February 1979, a proposal was made (Ref [2]) to generate a compact torus configuration having the unique and distinctive feature that the steady toroidal plasma current is driven in a steady-state, noninductive fashion by means of the application of a rotating magnetic field. The toroidal current ring is kept in horizontal and vertical equilibrium by an externally applied magnetic field and, if the conditions are appropriate, it can reverse this equilibrium field thus generating a compact torus configuration of the FRC type (the rotamak-FRC configuration).

[2] I. R. Jones
"The rotamak concept"
Technical Report No. FUPH-R-151, Flinders University (1979)
Available as Report NTIS-PB85-133858 from the National Technical Information Service, Springfield, VA.

By means of a simple modification, a steady toroidal magnetic field can be added to the basic rotamak apparatus and the configuration then becomes that of an ST maintained in steady state by means of the application of the RMF.

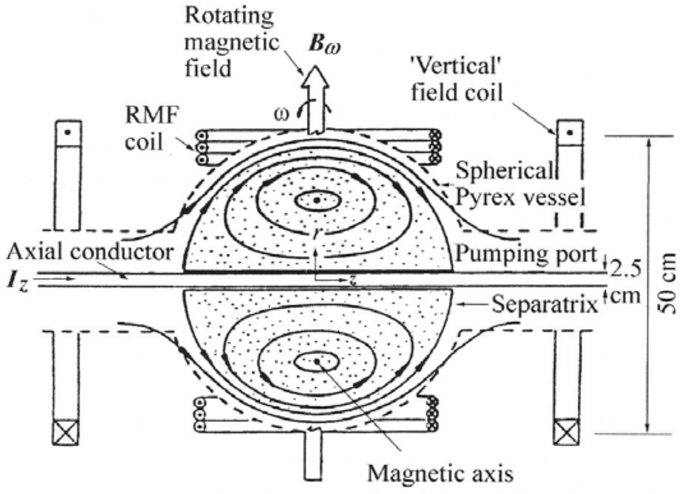

Fig. 1 The Flinders rotamak

Fig. 1 is a diagram of the last rotamak to be experimented upon at Flinders University, South Australia; the apparatus is now located at Prairie View A&M University, Texas. RF currents, dephased by 90^o, and passing through two orthogonal coils (only one phase is shown in Fig. 1) produce an RMF of amplitude, B_ω, and angular frequency, ω. Steady currents passing through the two vertical field coils generate the equilibrium field which is characterized by its value, B_v, at the centre of the spherical discharge vessel *in the absence of plasma*. When required for the generation of a rotamak-ST configuration, a steady toroidal magnetic field is produced by passing a current through a conductor which passes along the central axis of the discharge vessel. Various entry ports allow the introduction of electric and magnetic probes and the placement of a Rogowski coil around a poloidal cross-section of the discharge vessel yields a measurement of the driven toroidal plasma current, I_ϕ. The discharge vessel is furnished with a pumping port which connects it to a conventional vacuum system. In normal experimentation, hydrogen gas continuously flows through the vessel at an equilibrium pressure, p_f.

The name ‘rotamak’, coined in 1979, is given to a piece of apparatus in which the *sole* application of an RMF to a weakly preionized fill of gas raises and maintains the level of ionization and, at the same time, drives a steady toroidal current that reverses the equilibrium field, B_v, and generates a field-reversed configuration. Depending on whether or not a steady toroidal magnetic field is incorporated into the apparatus, the name ‘rotamak’ also refers to the type of field/plasma configuration produced within it, either rotamak-FRC or rotamak-ST. Contrary to assertions made in the published literature by some authors, it is not the name given to a particular series of experiments undertaken at Flinders University during the period 1977-2000.

Australian research into RMF current drive and rotamak physics was conducted at two locations, Flinders University (Adelaide, South Australia) and the Australian Nuclear Science and Technology Organization (ANSTO) (Lucas Heights, New South Wales), during the periods 1977-2000 and 1981-1987, respectively. The author was appointed Senior Consultant (Fusion) at ANSTO in 1981 and liaised between the two groups between 1981 and 1987. To the author's knowledge, in addition to the two Australian institutions, rotamak research has been/is being conducted at: Essen University; Tokyo Institute of Technology; UCLA; University of Washington; Princeton University; Prairie View A&M University; Osaka University and Kansai University.

2. Rotamak-FRC operation in the Flinders rotamak

[3] P. Euripides, I. R. Jones and Chuanbao Deng
"Rotamak discharges in a 0.5 m diameter, spherical device"
Nucl. Fusion **37**, 1505(1997)

For operation as a field-reversed configuration, the stainless steel tube which carried the axial current along the central axis of the discharge vessel was removed; no steady applied toroidal magnetic field was used in this mode of operation.

The characteristics of the rotamak-FRC configuration produced in this apparatus are determined by the following preset parameters: the hydrogen filling pressure, p_f ; the amplitude of B_v (measured at $r = z = 0$ in the absence of plasma); and the value of V_o. Here, the equatorial plane of the sphere is the $z = 0$ plane and r is measured from the z axis. V_o is the open-circuit voltage of the RF generators which are used to produce the RF current pulses (0.5 MHz, 40msec pulse duration). Its value determines the maximum RF power which the generators are capable of delivering.

Keeping the filling pressure (1mTorr H_2) and V_o (2750 V, which corresponded to a maximum available input power of ~ 90 MW) constant, a series of measurements of the driven toroidal plasma current, I_ϕ , was made corresponding to an ever-increasing set of B_v values. Below a critical value of B_v = 23 G, the termination of I_ϕ and the period of field reversal coincided with the end of the RMF pulse and Fig. 2 shows that the corresponding values of (B_v, I_ϕ) fall on a straight line. For B_v greater than 23 G, the value of I_ϕ is seen to decrease rapidly and it is observed in the experiments that the driven current terminates prematurely before the end of the RMF pulse.

Three cases, A, B and C, are identified in Fig. 2. The noteworthy reproducibility of rotamak discharges enabled us to make detailed measurements of the magnetic configuration for each of these cases; the measured flux contours are shown in Fig. 3. For cases A and B, the magnetic configuration is that of a field reversed compact torus with the separatrix sitting at the discharge vessel wall.

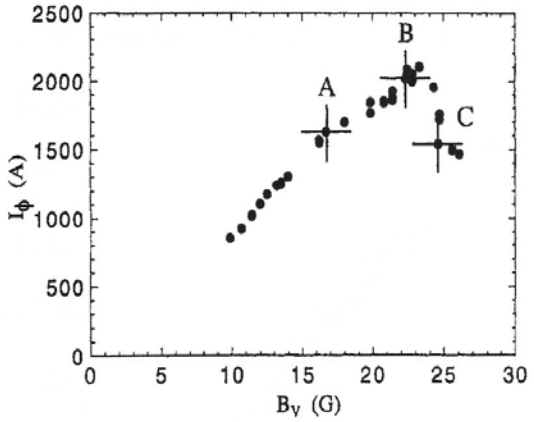

Fig. 2 Plot of I_ϕ against B_v (measured at t = 20 ms into the RMF pulse).

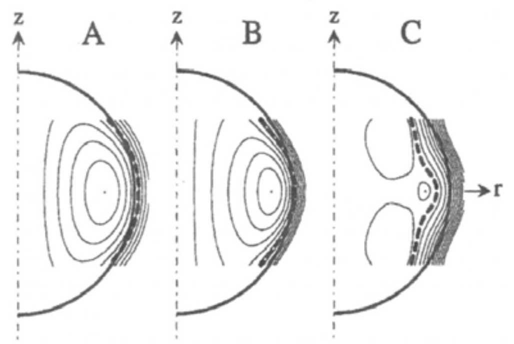

Fig. 3 Poloidal flux contours for experimental situations A, B and C (B_v = 17, 22 and 25 G, respectively).

The current termination phenomenon associated with a critical value of B_v had been a noteworthy and characteristic feature of all the rotamak-FRC experiments conducted at Flinders and ANSTO for some time, had been well documented, and had eluded explanation until Refs [4] and [5] were published. This work showed that the properties of the rotamak-FRC discharge are mainly determined by the behaviour of the circuit used to couple the RF generators to the plasma load. The circuit/plasma interaction is of paramount importance.

[4] N. Donaldson, R. Hahnheuser, I. R. Jones, G. Staines and S. Xu
"Parametric investigation of the rotamak discharge in a 10-litre spherical vessel"
Plasma Phys. Contr. Fusion **36**, 259 (1994)

[5] N. Donaldson, P. Euripides, I. R. Jones and S. Xu
"On current termination in rotamak discharges"
Plasma Phys. Contr. Fusion **37**, 209 (1995)

An ever increasing value of B_v requires a matching increase in I_ϕ for the same degree of reversal to occur, and for the present series of rotamak-FRC discharges where one has incomplete ionization and low electron temperatures, a larger I_ϕ requires a larger transfer of RF power to the plasma. If that is not forthcoming and, in fact, the coupling circuit behaviour is such that the transferred RF power actually starts to decrease with increasing B_v, then the value of I_ϕ will fall together with the degree of field reversal. This is what has happened in case C; the value of I_ϕ is such that it cannot reverse the field to the same extent as in cases A and B, and the configuration starts to change from that of a reversed field compact torus to, eventually, that of a magnetic mirror.

What happens if we repeat the case C experiment but with a larger value of V_o, that is, with the possibility of transferring more RF power to the plasma? Fig. 4 shows that with a higher value of V_o, more toroidal current is indeed driven and we recover the magnetic configuration having its separatrix at the vessel wall.

Fig. 5 shows (B_v, I_ϕ) data obtained using three values of V_o and it is important to note that, with more available RF power, one can obtain rotamak-FRC configurations having ever increasing values of I_ϕ (up to 3500 A in these experiments using these particular RF generators). The only barrier we faced in this research was the lack of available RF power. It is of interest to note that the slope of the (B_v, I_ϕ) line (92 A/G) is well described by the compact torus, Solov'ev solution ($P \sim \psi$) of the Grad-Shafranov equation, which predicts that:

$$I_\phi / B_v = 5R/\mu o = 99 \text{ A/G} \quad \text{(here } R \text{ is the radius of the separatrix)}$$

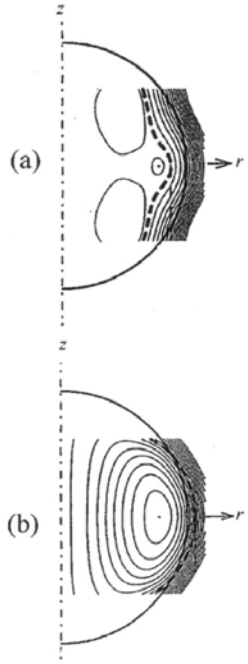

Fig. 4 Poloidal flux contours for discharges having:

p_f = 1 mTorr H_2; B_v = 25 G
(a) V_o = 2750V (b) V_o = 3160V

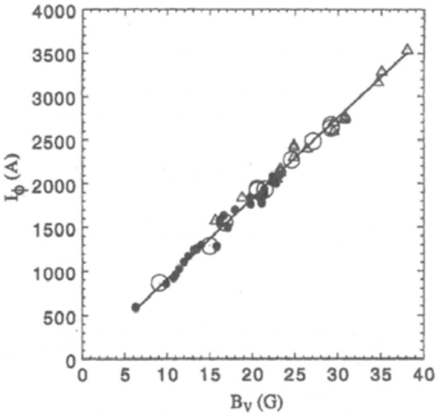

Fig. 5 Plot of I_ϕ against B_v for p_f = 1 mTorr H_2;

Black dots: V_o = 2750V
Open circles: V_o = 3160V
Open triangles: V_o = 3790V

The following additional measurements and observations were made on rotamak-FRC devices at Flinders University and ANSTO:

(a) The rotamak-FRC discharges are highly reproducible. Some experiments have involved the generation of many thousand identical discharges.

(b) The rotamak-FRC discharge is observed to be macroscopically stable over discharge durations of up to 40 ms. Conventional MHD stability theory predicts the FRC configuration to be unstable on the microsecond(s) timescale. The reason for the observed stability is not known at present and remains an open question.

(c) The shape of the separatrix can easily be controlled from slightly oblate to highly prolate. In rotamak-FRC discharges, the position of the separatrix on the equatorial plane is at, or very near, the vacuum vessel wall.

(d) As is the usual case for H-mode inductive RF discharges, the electron density is a linear function of the total RF power dissipated in the plasma. Volume averaged electron number densities and temperatures of 2.5 x 10^{18} m^{-3} and 17.5 eV, respectively, have been achieved in these rotamak-FRC experiments. The plasma generated in the Australian series of experiments had modest properties but it was not, as has been asserted in the open literature by a couple of authors, "in contact with the vessel wall" and it did not have "significant plasma pressure on the containment vessel wall”. This can be seen from Fig. 6 which shows *measured* electron pressure profiles and contours for a rotamak-FRC discharge. The electron pressure has a very small value at the separatrix (and, hence, the vacuum chamber wall).

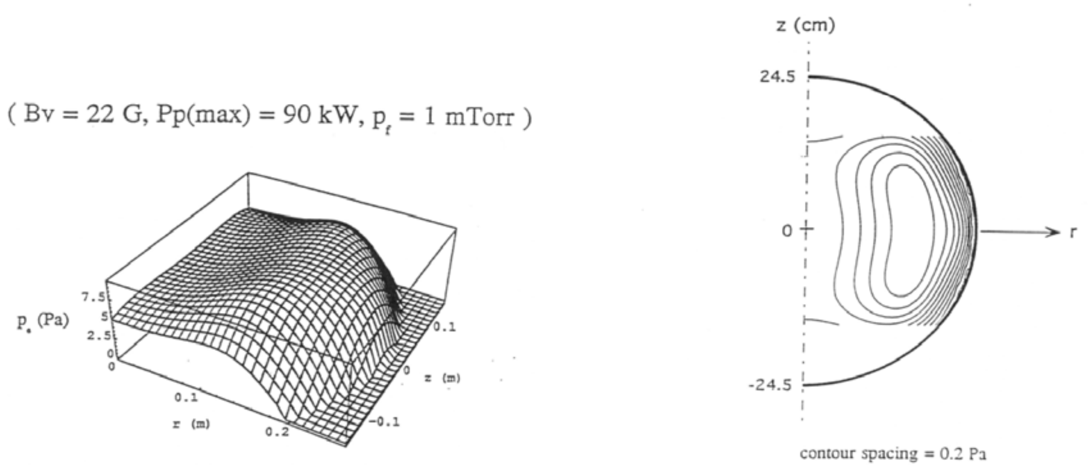

Fig. 6 Electron pressure profiles and contours

(e) The application of an applied transverse RMF to a closed field system produces open magnetic field lines which can cut vessel walls. Calculations (Ref [6]) have shown that electron and ion orbits are nevertheless confined within the magnetic configuration and particle confinement is possible under these circumstances.

[6] W. N. Hugrass and M. Turley
“The orbits of electrons and ions in the fields of the rotamak”
J. Plasma Physics **37**, 1 (1987)

However, electron thermal conduction along the open field lines can take place and can compromise energy confinement. The problem is alleviated somewhat the longer the length of field line before it intersects the chamber wall.

In the rotamak-FRC experiments which we have just described, the amplitudes of B_v and B_ω are comparable; this is not an ideal situation since it leads to open field lines of a short length. Fortunately, a solution to this problem has appeared in recent years. Cohen and Milroy (Ref [7]) have proposed an antisymmetric arrangement for the antennas which produce the RMF, an arrangement which leads to field-line closure. Experiments ([Ref 8]) have demonstrated improved energy confinement for rotamak-FRC configurations formed and sustained using these antisymmetric RMF antennas.

[7] S. A. Cohen and R. D. Milroy
“Maintaining the closed magnetic-field-line topology of a field-reversed configuration with the addition of static transverse magnetic fields”
Phys. Plasmas **7**, 2539 (2000)

[8] H. Y. Guo, A. L. Hoffman and L. C. Steinhauer
"Observations of improved confinement in field reversed configurations sustained by antisymmetric rotating magnetic fields"
Phys. Plasmas 12, 062507 (2005)

Before moving on to discuss rotamak-ST operation in the Flinders rotamak, we wish to draw attention to some remarkable results which have been achieved with 'modern' versions of the rotamak-FRC at the Redmond Plasma Physics Laboratory (RPPL), University of Washington and at Princeton Plasma Physics Laboratory (PPPL), Princeton University.

Two recent papers from RPPL:

[9] K. E. Miller *et al*.
"The TCS upgrade: design, construction, conditioning and enhanced RMF FRC performance"
Fusion Science and Technology **54**, 946 (2008)

and

[10] H. Y. Guo, A. L. Hoffman and R. D. Milroy
"Rotating magnetic field current drive of high temperature field reversed configurations with high ζ scaling"
Phys. Plasmas **14**, 112502 (2007)

have highlighted the noteworthy improvement in rotamak-FRC plasma properties which can achieved by subjecting the discharge vessel to modern cleaning methods. Rotamak-FRC plasma temperatures have been increased from tens of electron volts in previous experiments to more than 200 eV in the present ones. The authors directly attribute this improvement to reduced impurity levels within the vacuum chamber and to better particle confinement times.

The following paper from PPPL:

[11] S. A. Cohen, B. Berlinger, C. Brunkhorst, A. Brooks, N. Ferraro, D. P. Lundberg,
A. Roach and A. H. Glasser
"Formation of collisionless high-β plasmas by odd-parity rotating magnetic fields"
Phys. Rev. Lettrs. **98**, 145002 (2007)

reports on the formation of rotamak-FRC plasmas having average electron energies exceeding 200 eV. This has been achieved by a combination of much higher RF power density than has previously been used, a 14 MHz RMF, and the use of odd-parity antennas.

It appears that neither the RPPL nor PPPL group is interested in adding a toroidal field to their apparatus in a further effort to improve particle and energy confinement. The future of rotamak-FRC research is in their hands.

3. Rotamak-ST operation in the Flinders rotamak

By adding a current-carrying central rod to the basic rotamak apparatus, a magnetic configuration can be produced which is that of a spherical tokamak (ST) maintained in steady state by the application of a rotating magnetic field (Refs [12] – [15]).

[12] W. N. Hugrass, I. R. Jones, K. F. McKenna, M. G. R. Phillips, R. G. Storer and H. Tuczek
"Compact torus configuration generated by a rotating magnetic field: The Rotamak"
Phys. Rev. Lettrs., **44**, 1676 (1980)

[13] I. R. Jones, M. D. E. Turley, J. E. Wedding, G. Durance, G. R. Hogg and J. Tendys
"An experimental investigation of low power, long duration rotamak discharges"
Aust. J. Phys., **40**, 157 (1987)

[14] G. A. Collins, G. Durance, G. R. Hogg, J. Tendys and P. A. Watterson
"Small aspect ratio tokamak configurations generated by rotating magnetic field current drive"
Nucl. Fusion **28**, 255 (1988)

[15] I. R. Jones, Chuanbao Deng, I. M. El-Fayoumi and P. Euripides
"Operation of the rotamak as a spherical tokamak: The Flinders Rotamak-ST"
Phys. Rev. Lettrs., **81**, 2072 (1998)

Refs [12] – [14] report on the first experimental studies ever made of the spherical tokamak configuration. Here, we will concentrate on the results reported in Ref [15].

In addition to the filling pressure of working gas, p_f ; the equilibrium ('vertical') field, B_v ; and the generator voltage, V_o; the rod current, I_{rod} , becomes an extra free parameter. In a first series of measurements, the values of the driven toroidal current, I_ϕ, and P_p, the total RF power dissipated in the plasma were measured at a fixed time within discharges having pre-set values of p_f (0.4 – 2.8 mTorr $H_{2)}$, B_v (9 – 81 G), V_o (2750 – 4320 V) and I_{rod} (670 – 16130 A) lying within the indicated ranges.

Fig 7(a) shows I_ϕ plotted versus B_v for the whole data set. It is immediately clear that the introduction of a toroidal magnetic field has resulted in values of I_ϕ being generated which are three times greater than the maximum obtained in the rotamak-FRC device. It is also clear from Fig 7(b) that, at the present stage of rotamak research, the generation of more toroidal plasma current demands the transfer of an ever increasing amount of RF power from the generators to the plasma.

The electron number density, n_e, and the electron temperature, T_e, were measured in the vicinity of the magnetic axis for a subset of these discharges and the emission of H_α radiation was monitored. The H_α signal is a measure of the rate of recombination which, in equilibrium, must equal the rate of ionization. The quantity n_e/ H_α is, therefore, a measure of the electron particle confinement time. Fig 8(a) shows that this time increases rapidly for $I_{rod} > 10$ kA. The quantity $n_e T_e/P_p$ is a measure of the electron energy confinement time. Fig 8(b) shows that this also increases significantly once $I_{rod} > 10$ kA. For these 'cold' rotamak discharges, the first dominant energy loss channel which is encountered is particle recycling (Ref [16]) (continual influx of neutral particles and subsequent ionization).

[16] I. J. Donnelly, E. K. Rose and J. L. Cook
"Power balance models for rotamak plasmas"
Aust. J. Phys., **40**, 393 (1987)

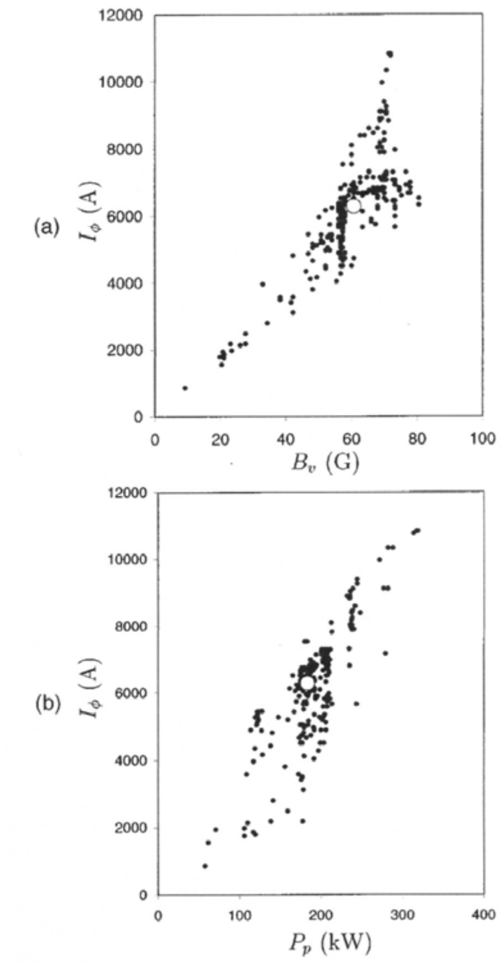

Fig 7(a) I_ϕ vs B_v and (b) I_ϕ vs P_p
for rotamak-ST discharges

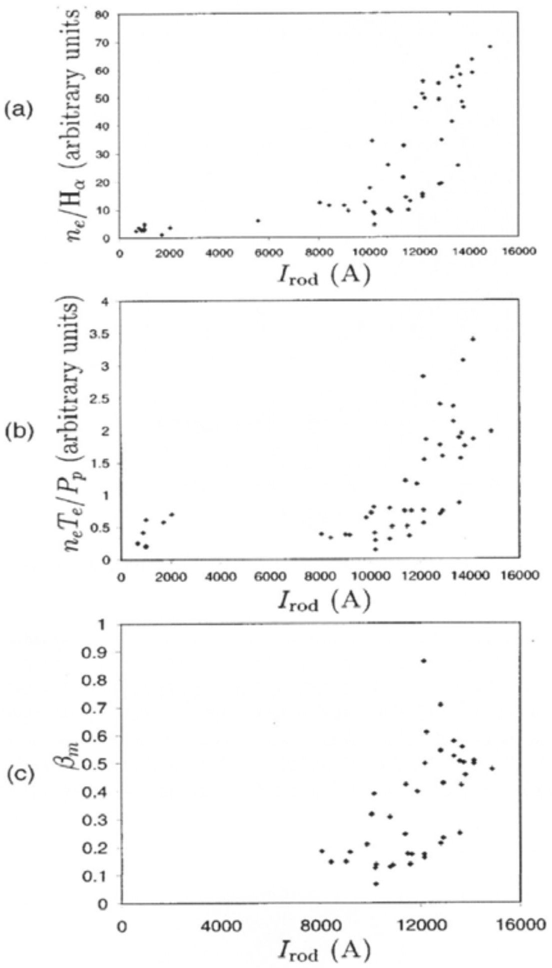

Fig 8 (a) n_e/H_α vs I_{rod}
(b) $n_e\,T_e/P_p$ vs I_{rod}
(c) β_m vs I_{rod}

It is thus gratifying to see that when the electron particle confinement improves, so does the electron energy confinement time. The improved electron energy confinement time also allows the value of β at the magnetic axis to exceed 50% for sufficiently high I_{rod} values (see Fig 8(c).

The particular discharge indicated in Fig 7 by an open circle was studied in detail. Measurements were made at a fixed time during the discharge. At this time, I_{rod} = 9650A, B_v = 60 G and the driven current I_ϕ = 6300 A; the filling pressure was 1mTorr H_2. The total RF power delivered by both RF generators was 240 kW, of which 42 kW was dissipated in the coils and matching circuits while 198 kW was dissipated in the plasma; that is, the overall efficiency of RF power transfer to the plasma was a remarkable 82%.

Electric probe measurements of $n_e(r,z)$ and $T_e(r,z)$ were made. Compared to similar measurements undertaken in the smaller rotamak-ST experiments of Collins et al. (Ref [14]), the values of T_e are significantly higher (typically 30 eV compared to 12 eV) at the magnetic axis. Since the electron number densities and the input RF power densities are comparable in the two experiments, this suggests that the electron energy confinement time improves with device size.

The quasisteady (dc) components of the magnetic field, B_r, B_ϕ and B_z, were each measured, on a shot-to-shot basis, on a matrix of 546 points (42 *r* positions, 13 *z* positions) lying in a poloidal plane. The satisfactory collation of this magnetic field data depended on the excellent shot-to-shot reproducibility of the rotamak-ST discharge.

Fig 9 shows the poloidal flux contours derived from this magnetic field data. While investigations of rotamak-FRC discharges in the same apparatus have consistently revealed compact torus configurations having their separatrices at the vessel wall (r = 25 cm) (see Figs 3 and 4 above), here we see that the separatrix in the rotamak-ST sits well inside the vessel wall at r = 22 cm. The magnetic axis is at r = 15.7 cm and the aspect ratio is 1.12.

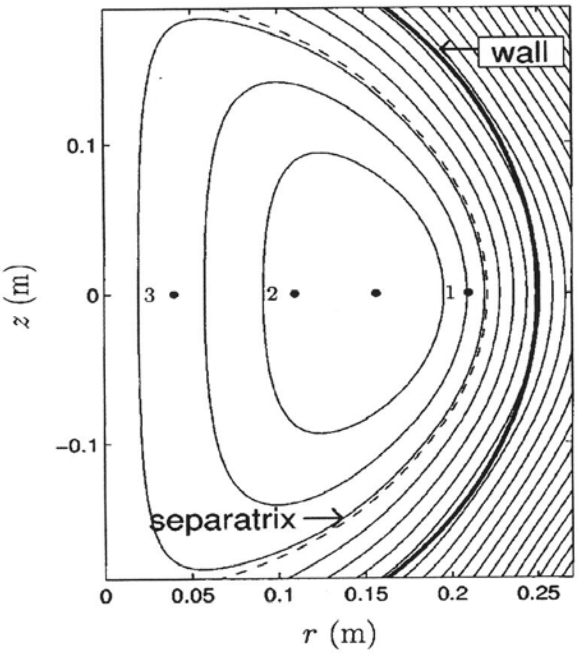

Fig 9 Poloidal flux contours
Contour spacing = 96 x 10^{-6} Wb

Fig 10 shows the derived two-dimensional surface for the toroidal current density, j_ϕ, together with two representative cuts through the surface. The use of the RMF current drive technique has led to a distribution of the 6300 A in the poloidal plane which is hollow and elongated, a combination which is favourable from the point of view of discharge stability.

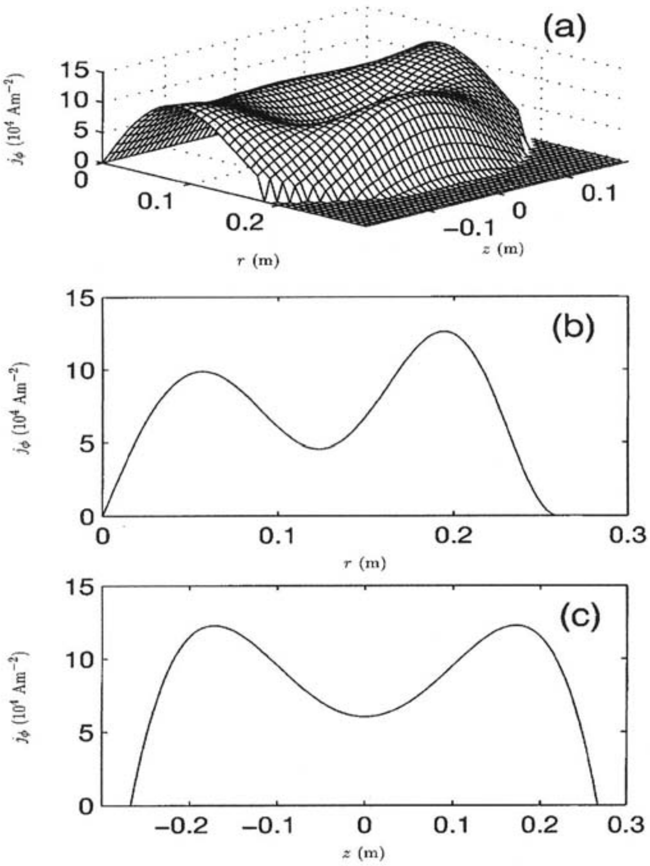

Fig 10 (a) The toroidal current density

Profiles at:
(b) $z = 0$
(c) $r = 0.1$ m

The distribution of the RF components of the magnetic field within the plasma was measured. A better penetration of the RF fields into the plasma is observed in the rotamak-ST discharges compared with the rotamak-FRC ones. This is not necessarily a good indication because there is good evidence to suggest that the improved penetration is associated with wave excitation brought about by unfavourable alignment of RF screening currents and steady magnetic fields.

Theoretical calculations predict that RMF current drive becomes more efficient the lower the electron collision frequency, that is, the hotter the plasma. On the other hand, they predict that this current drive technique is less efficient in situations where waves can be excited in the plasma, as is the case in rotamak-ST discharges. The fact that we observe much more driven toroidal current in rotamak-ST discharges than in rotamak-FRC ones strongly suggests that, in the former, the effect of better energy confinement (and, consequently, lower collision frequencies) more than compensates for unfavourable alignment of RF screening current and steady magnetic fields.

To date, the RF magnetic fields within the plasma has always been comparable in amplitude to that of the steady field in Rotamak-FRC discharges and this circumstance has engendered criticism of this approach based on the belief that open field lines and poor confinement will follow. On the contrary, the measurements made on the rotamak-ST discharges showed that the amplitude of the RF field within the plasma was only a small fraction (less than about 6%) of the steady confining field. This was the first time that such a situation had been reached in rotamak research. It is a positive indication for the rotamak-ST approach.

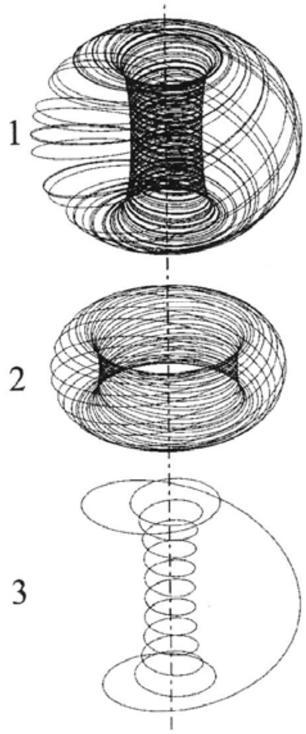

Fig 11 Reconstructed magnetic field lines for a rotamak-ST discharge

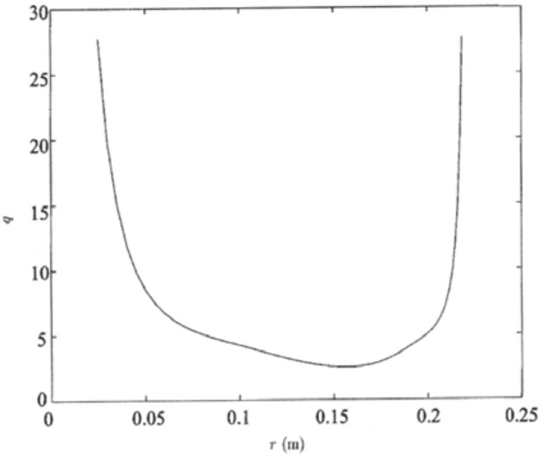

Fig 12 Radial profile of the safety factor in the *z* = 0 plane

Given the values of B_r, B_ϕ and B_z at each point in the poloidal plane, it was possible to reconstruct, by integration, the structure of the magnetic field lines within the rotamak-ST discharge. The magnetic field lines which pass through points 1, 2 and 3 indicated in Fig 9 are shown in Fig 11. Magnetic field lines 1 and 2 are irrational while line 3 is rational with q = 12. These field lines are representative of those which constitute a spherical tokamak configuration. Fig 12 illustrates the efficient manner in which the ST configuration makes use of the toroidal field. Whilst the q-value at the edge of the rotamak-ST plasma reaches as high as 35, the cylindrical equivalent is only 2.4.

The spherical Flinders rotamak is now located at Prairie View A&M University where T. S. Huang and his colleagues are continuing the investigation of the rotamak-FRC and rotamak-ST configurations. They have recently constructed a new rotamak device having a cylindrical vacuum chamber. They have performed a series of experiments in which they compare rotamak-FRC and rotamak-ST discharges produced in both the new cylindrical and the existing spherical device (Ref [17]). The conclusion is that the rotamak-ST discharge produced in the spherical chamber is the best option having regard to the amount of driven toroidal current and the properties of the plasma.

[17] X. Yang, Yu Petrov and T. S. Huang
"Comparison of rotamak plasma discharges in cylindrical and spherical devices"
Plasma Phys. Contr. Fusion **50**, 085020 (2008)

These authors also report on an interesting set of experiments in which the vertical field, B_v, was temporarily increased during the duration of both the rotamak-FRC and rotamak-ST discharges produced in the cylindrical device. Provided the increase in B_v was below a certain critical value, the result was an increase in the amount of driven toroidal plasma current by up to 150%. This increase in driven current was very reproducible from shot-to-shot. If B_v was increased beyond the critical value, then the RMF current drive was disrupted and dropped suddenly in value.

Similar work has been reported in Ref [13] where forced radial oscillation of the rotamak-FRC equilibrium was brought about by modulating B_v at a fixed frequency.

The rotamak configurations, especially the rotamak-ST variety, appear to be very robust and show no tendency to disrupt even when they are subjected to large amplitude disturbances. These results indicate that it should be feasible to use an active feedback system to control the equilibrium in the rotamak-FRC and rotamak-ST configurations.

4. The future direction of rotamak research

During the 30-year history of rotamak research no insurmountable barrier has appeared which threatens the viability of the rotamak concept. All results to date indicate that rotamak research would profit enormously from a significant increase in available RF power. For a fixed filling pressure of working gas, an injection of more RF power will result in a higher degree of ionization. More toroidal plasma current will be driven and this, together with a larger vertical field, will produce stronger poloidal magnetic fields. The applied toroidal magnetic field can be increased proportionally and, overall, the particle and energy confinement should be much improved. The electron collision frequency should drop and the RMF current drive will become more efficient. All the indications point towards the rewards to be gained from the use of much more RF power!

Based on experimental results and on other considerations, I am of the opinion that the next step in rotamak research should, ideally, continue along the following lines:

(a) the primary focus should be on the rotamak-ST configuration,

(b) the next stage in the development of the rotamak concept should recognize that in its eventual reactor embodiment, the rotamak configuration will need to be generated within a metal vacuum chamber. The next experiments should be conducted using a spherical metal vacuum vessel,

(c) of necessity, the RMF coil structure will have to be located within the metal vessel and due consideration will need to be paid to the influence of the RF screening currents which will be induced in the vessel wall,

(d) the most important requirement of the next generation of rotamak experiments is the provision of much more RF power than has been used in prior investigations, especially during the start-up phase of the rotamak discharge,

(e) the provision of a full suite of RF diagnostic tools,

(f) the provision of a full suite of tools to diagnose the magnetic and plasma properties of the rotamak discharge,

(g) the provision of an active feedback control system, such as is used in modern tokamaks, to influence the shape of the magnetic configuration and to control the amount of RMF-driven plasma current.

We now expand on these perceived needs.

(a) Primary focus on the rotamak-ST configuration

Experimental results show that the rotamak-ST discharge has superior properties with respect to the amount of RMF-driven current, the electron number density and the electron temperature when compared to the rotamak-FRC discharge. There is evidence that particle and energy confinement times are better in the rotamak-ST discharge. There is also evidence that the rotamak-ST is more robust when attempts are made to reshape its magnetic configuration by changing the equilibrium field during a discharge (Ref [17]). Ref [17] also describes a comparison which was made between rotamak-FRC and rotamak-ST discharges produced in both a cylindrical and a spherical rotamak device. The conclusion reached is that the rotamak-ST discharge produced in the spherical chamber is the best option.

I am persuaded that the next step in rotamak research should concentrate on the spherical ST configuration. If significant improvements in plasma properties are obtained by this approach, then the time would be ripe to re-visit the rotamak-FRC.

(b) Spherical stainless steel vacuum chamber and the steady toroidal magnetic field

It is self-evident that in its eventual reactor embodiment, the rotamak discharge will need to be generated within a metal vacuum chamber ... it is difficult to conceive of a fusion reactor having pyrex or quartz walls. A first attempt to produce a rotamak-FRC discharge within a metal chamber has been made and the results are reported in the following paper:

[18] H. A. Kirolous, D. Brotherton-Ratcliffe and I. R. Jones
"The magnetic structure of a rotamak discharge produced in a metal-walled vessel"
Plasma Phys. Contr. Fusion **31**, 79 (1989)

It was a modest experiment conducted in a cylindrical stainless steel vessel, 50 cm in length and 75 cm in diameter. The RF power transferred to the plasma was only 30 kW (cf with the 180 kW measured in the rotamak-FRC experiments described in Ref [3]) with a total RMF-driven current of 550 A. Nevertheless, magnetic probe measurements showed that an FRC configuration was produced within the RMF coil structure and the main goal of the experiment was achieved.

It is proposed that the spherical rotamak ST configuration be produced in a spherical, stainless steel discharge chamber. In the absence of any definite guidance, I believe that the dimensions of the ST configuration within the interior of the internal RMF coil structure should be at least the same as that of the latest spherical rotamak-ST studied at Flinders and Prairie View Universities which had a separatrix radius of ~ 25 cm. This choice, as will be explained later, dictates that the stainless steel chamber has a diameter of about 75 cm.

The steady toroidal magnetic field which is required in the rotamak-ST configuration will be produced by passing a current through a conductor which lies along the central axis of the vessel.

Following the successful path laid down by RPPL (Ref [9]), the spherical rotamak-ST vessel should be constructed with the aim of achieving an ultrahigh vacuum environment. It should be subjected to the same rigorous cleaning techniques as used at RPPL.

(c) The RMF antenna structure

Of necessity, the RMF antenna will have to be located within the spherical metal discharge chamber and my proposed coil structure is shown in Fig 13 (Note: the 'vertical' (equilibrium) field coils are not shown in this sketch). In deciding the exact location of the antenna rods, a balance has to be made between the deleterious effect of eddy currents in the shell on the amplitude of the RMF and the desired volume of the inner compact torus configuration. Calculations based on a two phase, two coils per phase, system located inside a cylindrical metal shell (Ref [18]) indicate that for the dimensions shown in Fig 13 (metal shell at 37.5 cm; antenna rods at 25 cm), the RMF at the centre of the vacuum chamber will be reduced to about 50% of its value in the absence of the shell.

Because of the influence of the eddy currents in the shell, the extent of the applied RMF in the z-direction will be localised to a region around the equatorial plane and this will drive a more ring-like toroidal plasma current. This may be advantageous.

The antenna rods will have to be encased with a low-Z, non-conducting material, possibly carbon. In addition to producing the RMF, the antenna rods will play a secondary role in acting as rail limiters which define the edge of the plasma.

Given the promise of better plasma properties arising from the closure of magnetic field lines, the possibility of installing odd-parity antenna (Ref [7]) should be kept in mind.

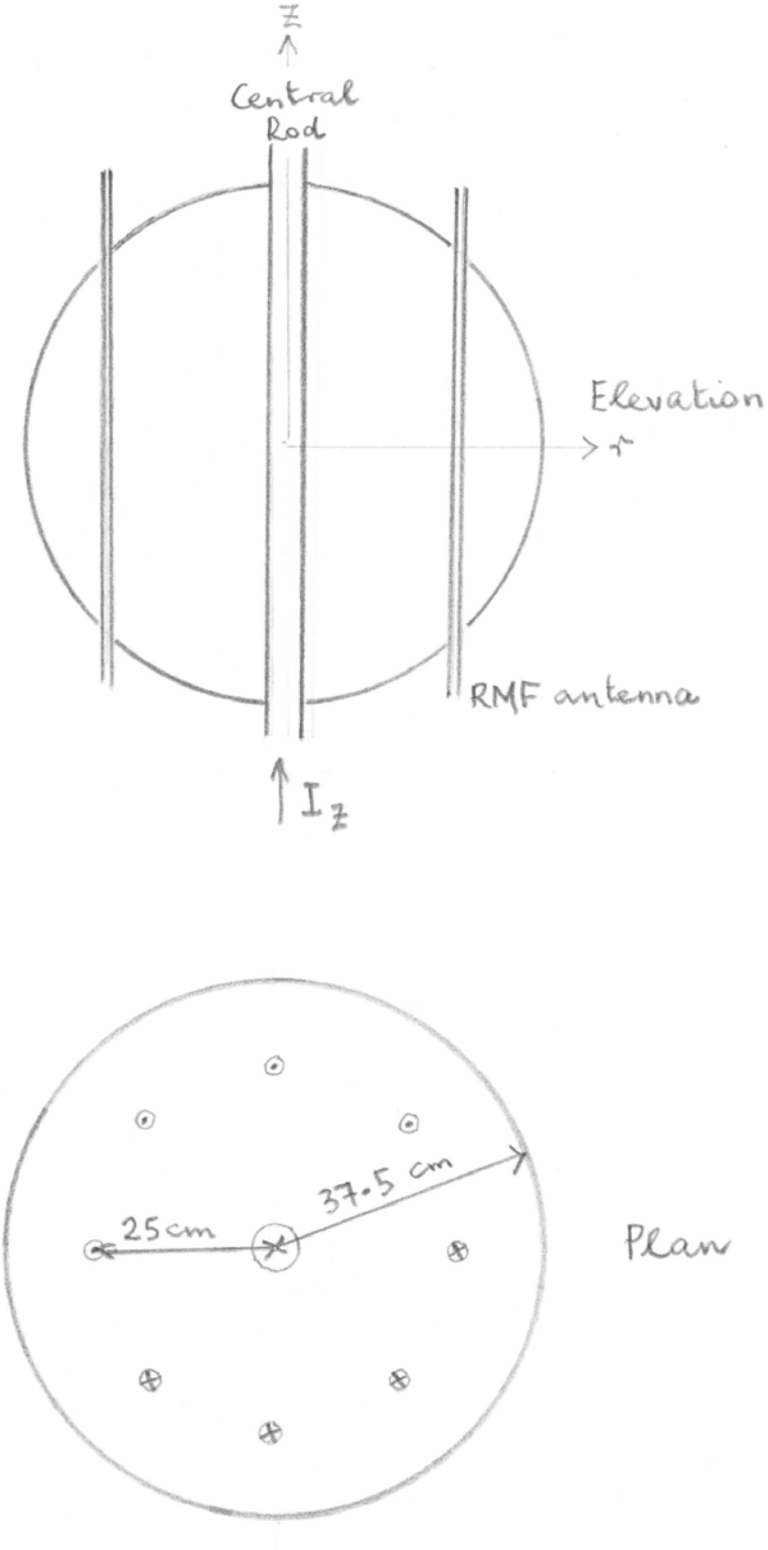

Fig 13 Spherical stainless steel vacuum vessel with two phase, two coils per phase, antenna system

(d) RF power

The success of this proposed experiment will depend on how much RF power is available to be dissipated in the rotamak-ST discharge.

The RF power transfer in the Flinders rotamak-ST experiments was typically 3 MW/m^3 with a remarkable overall efficiency of power transfer from RF source to plasma of over 80%. Roughly similar RF power inputs were observed in the ultra-clean TCSU experiments (Ref [10]) where total plasma temperatures of > 200 eV were achieved.

If we take a margin of safety and assume that we need 5 MW/m^3, we consider a spherical discharge vessel of 0.375 m radius and we assume an 80% transfer of RF power from the generators to the plasma, then a simple calculation tells us that we require two RF generators, each capable of delivering 0.7 MW. A description of the RF generators which were constructed at Flinders University can be found in:

[19] G. Besson and G. R. Cottrell
"400 kW RF pulse generators with programmable waveforms"
Meas. Sci. Technol. **2**, 581 (1991).

Each of the two generators which were built could produce a 40 ms duration pulse of 0.5 MHz oscillations and the oscillations in each pulse were dephased by 90^o with respect to each other. The pulse waveform which was used in the Flinders experiments is shown in Fig 9 of Ref [19]. It delivered large RF power at the beginning of the discharge when the rate of ionization was highest and was followed by a period of constant power at a lower level.

To the author's knowledge, no systematic investigation of the influence of the RMF frequency on the properties of rotamak-FRC and rotamak-ST discharges has been undertaken although individual rotamak experiments have been carried out at a number of RMF frequencies lying in the range 0.1 – 14 MHz. Minor modification to the design presented in Ref [19] would allow operation at frequencies in the range 0.3 – 1.0 MHz.

(e) RF diagnostic tools

Given the pre-eminent role of the coupling circuits in determining the behaviour of a rotamak discharge, considerable effort was expended at Flinders University in measuring accurately the RF currents and voltages, and the phases between them, which are generated when the RF sources are connected to the plasma load via the circuits.

When a plasma is present in the discharge vessel, it introduces an additional reflected resistance, R_p, into the coupling circuit and, because of its screening of the applied RMF field, it also decreases by an amount, ΔL, the value of the RMF coil inductance, L, from its vacuum value. A knowledge of R_p and ΔL yields information about the plasma (for example, a better penetration of the RMF into the plasma leads to a decrease in ΔL) and it is also needed in the process of matching the RF generators to the plasma load. A small mutual coupling inevitably exists between the RMF coil sets. Care must be taken to cancel this out otherwise significant errors can be made in the measurement of the RF power delivered to the plasma.

For these and other reasons, it is important to have a trusted and well calibrated set of RF diagnostic tools with which important measurements and matching operations can be done with confidence.

The complex interactions between the RF circuit and the plasma discharge in RMF current drive experiments are discussed in the following paper:

[20] W. N. Hugrass, T. Okada and M. Ohnishi
“Plasma-circuit interactions in rotating magnetic field current drive”
Plasma Phys. Control. Fusion **50**, 055008 (2008)

(f) General diagnostic tools

A full suite of plasma diagnostic tools should be available.

(g) Active feedback control

It has already been demonstrated (Ref [17]) that the rotamak-ST discharge is sufficiently robust for the equilibrium field to be used to reshape the separatix without disrupting the RMF-driven current. In fact, the driven current is seen to increase by up to 150% during the process. This result suggests that an active feedback system can be used to control the equilibrium of a rotamak-ST discharge and, ideally, this proposed experiment should incorporate such a system sometime in the future.

I have here proposed an experiment which, one way or another, should demonstrate whether or not the ‘rotamak concept’ has a future in fusion research. In 30 years so far, it has not come face-to-face with an impassable barrier and I believe the rotamak, especially in its ST embodiment, merits further investigation. This experiment would fall into the category of a small, tightly focussed programme costing a few $M per year.