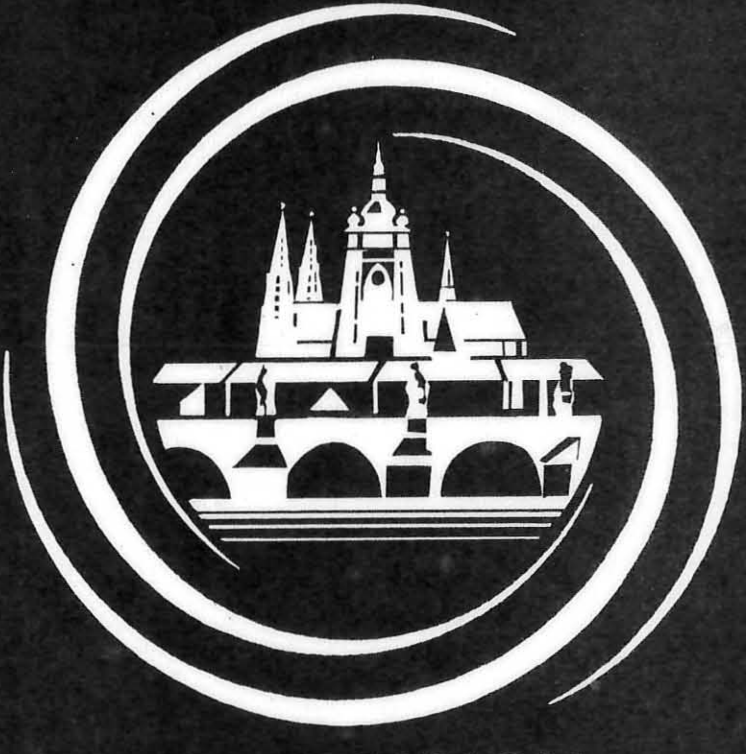
EIGHTH EUROPEAN CONFERENCE ON CONTROLLED FUSION AND PLASMA PHYSICS

Stellarator Workshop



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PRAGUE 1977

WORKSHOP ON STELLARATORS

Zdíkov

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M.S. Rabinovich, USSR
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CONTENTS

PREFACE

M.S. Rabinovich

We now have important changes in the aim and significance of stellarator investigations. These changes are not only due to new results on stellarators but are also due to developments in the CTR program, and to increased understanding of the processes going on inside toroidal plasmas. The Tokamak is losing its primerdial simplicity. New Tokamaks need auxiliary windings for divertors, for stabilization, for profiling (doublet), and for increasing maximum beta. Till now we have not fully understood or utilized the possibility of stellarators as steady state devices. This would be important when considering the use of superconducting windings and supplementary RF heating methods. Investigations of Tokamaks and stellarators are now beginning to approach each other. Till now these changes in stellarator art were not reflected in the contents or size of the stellarator program. One of the important aims of our workshop is the formulation of priorities in stellarater investigations. It is my point of view, that it is of fundamental importance for the future stellarator research, that one finds adequate methods of heating.

For the last 2 years we have tried to compare stellarators with Tokamaks. This was necessary for the survival of the stellarator program, and also the survival of the whole CTR program. But now we must change to more important physical investigations. The most pressing seem to be:

1. Comparison of stellarators with and without current, and with and without supplementary heating.
2. Following the first point, solve some of the mysteries of the behaviour of plasma in toroidal systems:,
    a) Enhanced electron thermal heat conductivity coupled with non-anomalous ion thermal conductivity.
    b) Nature of the disruptive instability.
    c) Impurity transport, including the role of the magnetic limiter, especially α particle transport including.
    d) The initial part of the discharge.
    e) Effects of supplementary heating on confinement + equilibrium.
    f) Steady state, refuelling and ash removal.
3. It seems that helical windings may be very helpful in solving the following problems:
    a) Increasing the maximum OH current with the help of high frequency helical windings, importance of resonance part of the helical field.
    b) Stabilization of the disruptive instability.
    c) Divertors with helical windings or locallized divertors.
    d) Hybrid systems, stellarator/Tokamak, with high current so that the total q is less than unity.
    e) New type of stellarators (elliptical, two star, high β etc.).

  - f) Fuel feeding systems for steady state operation.
  - g) Building stellarators in modular form.

4. Important stellarator problems for theoreticians:
  - a) Maximum attainable beta in stellarators.
  - b) Minimum $\underline{q}$ in hybrid stellarator/Tokamak systems.
  - c) Explain internal and major disruptions in stellarators.
  - d) Behaviour of thermonuclear plasma in stellarators, including α particles, etc.
  - e) Equilibrium configurations in stellarators.
  - f) Nature of transport processes in stellarator.

Now we are at the point where it is necessary to begin studying conceptual stellarator reactors. Moving ahead in the stellarator program, it would be helpful to have a coordinated worldwide program. We should meet again in two years time.

OHMIC HEATING

Chairman: I.S. Shpigel

1) In the second generation stellarators L-2, Cleo, W VII A and Uragan 2 in the ohmic-heating regime we obtain plasmas with electron temperature 200-900 eV, $T_i \simeq 100 - 320$ eV and density $5.10^{12} - 6.10^{13} cm^{-3}$. These values are obtained at the moderate levels of toroidal magnetic field $B_t = 12 - 35$ kG and ohmic heating currents 6 - 35 kA. The energy replacement time is about 1 - 10 msec and particle confinement time 5 - 30 msec.

2) As the ohmic heating current increases to a value which is characteristic of the particular apparatus, the ohmic heating power increases (L-2), the profiles flatten (W VII A, Cleo) and energy lifetime τ_E falls.

3) The main reason for the flattened profiles and the fall of τ_E is possibly the occurence of an island structure and MHD instability $m = 1$ accompanied by sawtooth oscillations (W VII A) in the central region (W VII A) or at the edge (L-2). These effects limit any further increase of plasma temperature for a fixed density.

4) The experiments made in the stellarator Uragan-2 has shown the possibility of increasing the total transform in the regime of ohmic heating up to valuer

$\iota_\varphi \leq 1.6(\iota_\Sigma = \iota_{st} + \iota_I)$.

They assume: for a racetrack stellarator, in which the length of the straight section is not very large, that there exists a further stable regime which allows values of total transform $\iota_{\Sigma} > 1$. There are stable discharges in Heliotron D for $\iota_{I} > 1$ when the vacuum transform $\iota_{st} \simeq 2 - 3$. MHD instabilities which arise at rational values of ι_{Σ}, are stabilized and localized by the high shear and possibly play a relatively unimportant role.

5. All that which is written above shows that the experimental results of an installation confirm those of other machines and allow the following conclusions to be drawn:

a) Ohmic heating in stellarators is an effective method of creating hot and dense plasmas.

b) The efficiency of ohmic heating in stellarators is largely due to the comparatively small thermal conductivity of electrons originating from the vacuum poloidal field of the stellarator. For example in the stellarators L-2 and Cleo the equivalent current is 4 - 5 times larger than the ohmic current and the associated poloidal vacuum field rises to 1 - 2 kG at the plasma boundary.

c) The plasma current is limited by an MHD instability associated with $\underline{q}$ values of 1 and 2.

6. At the same time there remain unexplained differences between the three experiments:

a) In L-2 and W VII A the energy lifetime τ_E rises with current up to the value of 15 - 18 kA; at larger values of current τ_E falls. In the Cleo stellarator the maximum value of τ_E occurs at the minimum measured value (5 kA) and falls with rising current.

b) It is not understood why the ion temperature is only half the value given by the Artsimovich formula. A possible explanation is the losses due to the charge exchange flux but up to now there is no experimental evidence to support this.

7. It seems necessary to continue experiments with gas puffing to obtain regimes of high density above $6.10^{13}cm^{-3}$. This allows for the opportunity of checking the scaling laws, in particular the increase of energy lifetime with density, the dependence of the electron temperature and of investigating the confinement of plasmas with equal ion and electron temperatures.

EXPERIMENTAL RESULTS FROM CURRENT-FREE STELLARATOR PLASMAS

Chairman: V.T. Tolok

Non ohmic method of plasma heating such as RF heating, neutral injection, laser pellet injection can be used to create a hot plasma in magnetic traps. These methods can be used both in Tokamaks and Stellarators. For Tokamaks, these methods are considered auxiliary, while for Stellarators they may be the main ones. The importance of these methods can be considerably increased if steady state operation of Stellarators, i.e. the main advantage of Stellarators will be achieved. For Stellarators RF methods of heating have been investigated most widely. Effectiveness of RF heating was demonstrated in special heating experiment. A plasma with an ion temperature $T_i = 0.5 - 3$ keV, electron temperature $T_e = 50 - 250$ eV and a density of $n = 10^{12} - 10^{13} cm^{-3}$ has been obtained with Ion cyclotron (IC) and Fast (F) waves (Sneg, Omega, B-64 and others). The homogeneous heating in a toroidal device of a two species plasma, consisting of hydrogen and deuterium (H + D), has been accomplished with Ion-Ion hybrid resonance (IIHR). Temperatures of up to 250 eV was reached with densities of $10^{14} cm^{-3}$ (Omega). However the very important problem of the influence upon plasma confinement of the heating method used has not been studied.

For the Stellarators (B-65, Model "C", Sirius, Saturn, Proto-Cleo, RO-2, Uragan 1, Uragan 2) RF heating was investigated over a wide frequency band (LHR, ICR, FW, TTMP, IIMR, Acoustic waves). In Uragan 1 a plasma with $T_i = 600$ eV and $n = 2 \div 4.10^{12} cm^{-3}$ has been obtained. Ohmic heating was not used in this experiment. The plasma was preionized with a nonresonant RF gas discharge. The main heating was performed by Ion cyclotron waves. The transport phenomena investigation showed that scaling laws for diffusion and ion thermal conductivity were similar to the neoclassical ones within a factor of 2.

The LHR has been widely studied in many toroidal devices. Recent results from "Wega" and "FT-1" devices demonstrated an efficiency of 15 ÷ 30% for ion heating. Thus this heating method appears promising.

Recently T.T.M.P. heating has been used with success on the Tokamak Petula. The ion temperature of a plasma of density $2.10^{13} cm^{-3}$ and a temperature 200 eV was increased by 30% according to the theoretical predications. No density increase or loop voltage change was observed. Finally no pump out was noticed which was significantly different than the previous T.T.M.P. experiment on the Proto-Cleo and Wendelstein Stellarators.

Alfven wave heating has been attempted on several Stellarators (Uragan, Proto-Cleo, Heliotron and RO-2) with good heating and should be investigated to determine its effects on confinement.

For heating of electrons ECRH appears to be a very promising method, but it will require further technological development of sources.

All the forementionned methods have a common property: In contrast to neutral injection, RF sources can be placed very far from a fusion reactor and thus not be subject to neutron damage.

The most important tasks for the development of methods for high frequency heating of plasmas now are:

1) The effect on plasma confinement and equilibrium of HF heating, including excitation of instabilities, production of fast ions, and/or enhanced transport.

2) Improving of the efficiency of heating for each method.

3) Concerning the sources of RF power and important effort comparable to that made of neutral injector has to be made for their development.

4) Greater understanding of the physics of HF heating methods.

5) Fully non-axisymmetric theory of heating as applied to Stellarators.

6) Extension of theory to large devices, including reactors.

One additional attractive fueling method for Stellarators, laser pellet injection, has been studied in the TOR-1, Proto-Cleo and W II B Stellarators. Plasma parameters were 10^{11} to $5.10^{12} cm^{-3}$ at electron temperature of up to 5 eV and ion temperature up to 100 eV . The lasers used were up to 100 joules in energy with maximum efficiency of

10%.

In the case of W II B isolated D_2-pellets have been used, but the temperatures have not yet been measured.

The most developed plasmas heating method used in Tokamaks - neutral injection - has not yet been used for Stellarators. Neutral beam experiments are being planned for Cleo, W VII and Uragan 3 Stellarators. Neutral injection seems to be most useful for bigger stellarator devices.

Generally the construction of large Stellarators devices is extremely important both in order to obtain longer life time and to facilitate plasma heating.

MAGNETIC ISLANDS, CONVECTION, MHD-ACTIVITY, DISRUPTION

Chairman: H. Wobig

1) Magnetic Islands

Magnetic islands have been investigated in nearly all stellarators (C-Stellarator, Heliotron D, Cleo, W VII a, L-2). Theoretical arguments show that islands can arise because of different field perturbations: field errors, toroidal currature, plasma currents. In the Stellarators Cleo, L-2, Model C measurements with an electron beam have shown the existence of islands, in W VII a the islands seem to be small.

The experimental results in L-2 and Cleo show that magnetic islands do not affect the plasma behaviour appreciably. Also in W VII a there is no indication, that magnetic islands, created by field perturbation have an effect on the plasma confinement. A question has been raised, whether the magnetic islands are enhanced or reduced by the selfconsistent plasma currents.

2) Convective losses

Convective losses in a plasma can arise from different reasons: an instability leads to a stationary or rotating convective state, local inhomogeneities like heat sources and mass sources can give rise to convection. On ergodic surfaces inhomogeneities are smeared out easily but on rational surface this occurs only along the closed field line. Therefore convective cells especially arise on rational magnetic surfaces.

The experiments in JIPP-I-stellarator show that rotating convective cells enhance the plasma loss in the $l = 2$ case at $\iota = 1/2, 1/3, 1/4 \ldots$. Probe measurements show the $m = 2$ structure in the case of $\iota = 1/2$. By introducing shear ($l = 3$-winding) the losses could be reduced and the confinement time improved. This effect of shear was also found in the Saturn stellarator. The convective losses found in W VII a $\iota(a) = 0.5$ are stationary, here mainly are particle losses occur.

Asymetries in the plasma profiles were not found, but in the emission of oxygen light asymmetries were found which seem to be correlated to the $\iota = 0.5$ - surface. The origin of the convection is not known, but the increase of these losses with decreasing helical field shows, that the helical field determines the size of these convective cells. A furhter investigation of the mechanism of these losses is necessary since it might be correlated to the mechanism of disruptive instability, which occurs at low values of the rotational transform.

MHD - Modes and Sawtooth Oscilations

Measurements in W VII a show a rather low level of MHD-modes at $\iota_0 = 0.23$, dominating mode is the $m = 3$, $n = 2$ - mode. It is surprising that also in the case

$\iota(a) < 0.5$ the $m = 2$ mode does not dominate.

At lower values of ι_o ($\iota_o \lesssim 0.11$) the amplitude of the $m = 2$ mode can reach values which are a factor of 10 higher than at $\iota_o = 0.23$.

This demonstrates the stabilizing effect of the stellarator field on MHD-instability. An open question in this context is the influence of the MHD-modes on plasma confinement.

Sawtooth oscillations with large amplitude are seen only in the W VII a -stellarator (Weller, Rau). The reason is that $q = 1$ is reached in the plasma centre. In L-2 and Cleo this effect does not occur, since $q = 1$ is first reached at the edge of the plasma. Weller showed that at low values of external transform mode-coupling between $m = 1$ and $m = 2$ modes occur. An increase of density leads to predisruptions and soft current disruptions. A scaling for the maximum energy density in several devices (Tokamaks and Stellarators) was proposed by Girard. According to ergodisation of field lines in the central part of the plasma the maximum energy density scales with $\frac{a}{R}\sqrt[4]{q(a)}\,B_\varphi^2$. W VII a and most of the tokamaks seem to fit into this scaling.

Current limitation at $q = 1$ has been reported from Cleo, L-2 and Heliotron D (Lees, Shpigel, Motojima). In Cleo and L-2 these effects occur if q is nearly 1 all over the plasma, the current decays fast but not in form of a disruptive instability.

In Heliotron D also additional gas puffing could lead to that effect.

At $q(a) = 2$ no current disruption was reported from the stellarators Cleo, L-2 or Heliotron D. $q = 2$ only occurs in the current rise phase in these machines. In W VII a major current disruptions were only found at low external transform ($\iota_o \leq 0.055$). The phenomena are similar to those observed in Tokamaks, but it is believed that the position of the plasma column and the equilibrium plays a role in the origin of the disruption.

Conclusions:

1. Magnetic islands induced by outside perturbation could experimentally not be identified. They seem not to be a serious threat to plasma confinement. If they occur in the boundary region, the effective plasma radius could be reduced by the islands.

2. Convective motion can reduce the confinement of the plasma appreciably. Methods to avoid this motion are shear, homogeneity of boundary conditions, and irrational magnetic surfaces close to the boundary.

3. Sawtooth oscillations, which introduce anomalous plasma transport can be avoided in systems with increasing $\iota(r)$ over the radius. These systems are also favourable with respect to MHD-activity, since stationary discharge with $0.5 < \iota(r) < 1$ do not exhibit the $m = 2$ and $m = 1$ - MHD-modes.

For systems with $\iota(a) < 0.5$ (W VII a) the stabilizing effect of the helical fields needs to be explained.

4. The disruptive instability, which in Tokamaks is correlated to MHD-activity around the $q = 2$ - surface, can be avoided by helical fields which are large enough (W VII a, $\iota_o \geqq 0.11$) or by preventing the $q = 2$ surface at all (Cleo, L-2, Heliotron D). The current inhibition at $q = 2$ as found in Cleo, can be overcome, but it seems to be impossible to surpass the $q = 1$ limit without reducing the plasma confinement. In Heliotron D, where the termination of the current occurs similar to the disruptive instability, the mechanism seems to be different from those in Cleo and L-2. Because of the variety of events found, the stellarator seems to be a good means to suppress or investigate the disruptive instability.

THEORETICAL CONCLUSIONS

Chairman: V.D. Shafranov

I. Stellarators without OH current

A main advantage of OH currentless plasma is that it should not suffer from mayor disruption.

Disadvantages

According to present theories of plasma stability, average magnetic well is necessary to stabilize resistive interchange modes. Tokamak systems are favorable from this point of view. Stellarators with circular magnetic axes usually have rather low well, or none at all. Existing calculations show a β limit of ~ 1% in stellarators with a well. (The presence of the well implies a small number of periods and small aspect ratio.)

There are not at present calculations analogous to those given recently for Tokamaks that would show the possibility of stable confinement in stellarators at $\beta \sim 10\%$. Development of corresponding numerical codes would be useful.

There is a very close analogy in MHD description between stellarators and Tokamaks. This allows extrapolation from Tokamaks to stellarators of calculations concerning ballooning modes. Thus ballooning modes of the same type will occur in stellarators.

It was shown by analytic calculation [1] that a critical β, of the order 6% - 12%, exists above which bifurcation phenomena apparently occurs, and $m = 1$ axisymmetric instability sets in.

II. Stellarators with OH current

Theoretical considerations show that OH current does not destroy the general structure of the magnetic configuration. Small scale island formation, that may be responsible for enhanced transport, must be investigated for a sufficiently large current, $(B_\theta^J)^2 \gg (B_\theta^{stell})^2$

A numerical study of the stability criterion for kink and tearing modes, based on the Princeton model, shows the possibility of stable operation at $\iota < 1$, when ι_J is less than ι_{stell}. In order to determine the possibility of hybrid Tokamak/stellarator systems, extention of this work to $\iota > 1$ with ι_J and ι_{stell} comparable, would be useful. It would also be useful to extend this calculation to the case of large helical destortion, where the Princeton model is inapplicable.

Small helical fields seem to be useful as an influence on resonant effects and disruptions in Tokamaks.

III. New approaches

Recently interest has been excited into looking for new possibilities of currentless plasma confinement. Calculations of magnetic systems based on multipole stellarators with a noncircular contour for the helical winding coils have been performed. They showed the possibility of creating systems of nested toroidal magnetic surfaces surrounding a region of island structure. These systems are of the doublet type [2] , or have many axes [3]. The real utility of such systems are not yet clear, but they can have large shear and deep magnetic wells.

Systems with nonplanar axes continue to deserve attention because

a) they can have a rather deep well,

b) the structure may be smooth, so that they need not be as limited by trapped particle effects.

A future meeting to discuss the features of these devices will be useful.

References:

[1] J.L. Johnson, J.M. Greene, K.E. Weimer, Plasma Phys. 8, 145 (1966)

[2] T. Ohkawa Kakuyogo-Kenkyo, 22, No. 6, 395 (1969)

[3] Danilkin, I + L. Kovrizhnykh, JETP Lett., 19, 119, 1974
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STELLARATOR TOKAMAK COMPARISON

Chairman: S.M. Hamberger

The discussion was essentially limited to ohmically heated stellarators, and therefore the main topics relate to the effect of the ohmic current on the confinement, the resistive anomaly, control of runaways etc.

The current in a stellarator can have several different effects on the confinement including e.g.

(1) Gross effects
   (a) shift of equilibrium position
   (b) change of shape of magnetic surfaces.

(2) Transform effects
   (a) change of radial variation of ι , shear, sign of transform gradient
   (b) modify structure of magnetic surfaces, e.g. by causing island formation.

(3) Drive (or possibly amplify) instabilities, such as drift waves, which can lead to turbulent diffusion.

(4) Stray field effects, caused by imperfections in the ohmic heating transformer arrangement, which can adversely influence the magnetic surfaces and/or shift the equilibrium position.

In the presentation and discussion which followed it was clear that (1), and to a large extent (4), could properly be taken into account and were not regarded as serious problems, when making comparisons, the main effect of the current for our purpose being due to (2). There was no discussion of (3).

An attempt was made to find a proper basis for comparison. Several scaling laws were suggested for the equivalent Tokamaks including the Hugill-Sheffield empirical forms derived for Tokamaks. WOBIG showed that on this basis all the stellarators discussed (CLEO, L-2, Wendelstein VII a) had energy confinement times which exceeded by a factor 3 - 10 those expected for Tokamaks of the same size, field, and density. However, in the case of W VII a the best confinement times at very low (0.055) and normal (0.23) values of vacuum transform were the same, although they occurred at different ohmic current. In the case of CLEO (LEES), where direct comparison (at reduced toroidal field) had been possible, the confinement time was approximately twice in the stellarator configuration than as a pure Tokamak (due to the wider profile in the former case) at the same, rather large, current (17 kA at 12 kG), while the factor increased significantly at lower currents. SHPIGEL suggested a simple scaling law:

$$\tau_E \propto a^2 B_p$$

where the poloidal field B_p included the average vacuum field for the stellarator case. Another illustrated by

LEES which showed stellarator confinement times rather larger than the equivalent Tokamaks, suggested

$$\tau_E \propto a^2 B_p^2$$

The problem of runaways was discussed, since it is clear that stellarator fields offer good prospects for their confinement. However, it was reported that they could be completely avoided either by sufficient pre-ionization ($\sim 10^{11} cm^{-3}$ in L-2, and W VII a) or by using the fact that stellarator breakdown can occur with quite low loop voltages and allowing the current to build up more slowly (CLEO). This contrasts with Tokamaks where some initial runaway is needed to produce the first closed surfaces during the start-up phase.

One problem which appears to be outstanding is the unexplained anomalous resistance reported in CLEO and L-2. These were typically larger than classical by a factor $R_A \sim 2 - 4$, but in CLEO could be as high as 10 at low currents and high T_e, while soft X-ray emission spectra in both CLEO and L-2 showed only a small anomaly and $Z_{eff} \sim 1.1$.

In general stellarators and Tokamaks exhibited much the same overall behaviour in respect of surface phenomena, such as recycling and impurity input, although there have been no reports so far of metal-dominated hollow profiles, as seen e.g. in PLT or DITE.

A more meaningful comparison of transport properties can only be made when precise measurements of temperature, density and impurity profiles are available in stellarators.

STELLARATOR ENGINEERING

Chairman: B. Streibl

The session was divided into three parts

- Stellarator-Torsatron, basic properties
- Possibility of modular construction
- Some reactor aspects

1. Stellarator-Torsatron, basic properties

1.1. Magnetic field properties (Dr. Maschke)

The Torsatron showes slightly better properties with respect to shear and magnetic well.
The stellarator on the other hand should exhibit smaller magnetic mirrors.

1.2. Magnetic forces (Dr. Maschke)

It is possible to reach an average force compensation with the Torsatron.
This is not possible for the stellarator.
With respect to local forces, which give rise to bending moments, for both configurations roughly the same behaviour is expected under comparable conditions. Bending moments are the main problem.

A real force free winding can not exist as proved by Prof. Schlüter. It is only possible to look for a favourable force distribution as proofed by Prof. Pfirsch.

Efforts should be made therefore to find bendingfree distributions, i.e. to balance the external forces only by tensile stresses (example: dropshape of toroidal field coils).

1.3. Mechanical stresses (Prof. Miyamoto)

Stress calculations for a cylindrical tube were used to find a scaling law for the mechanical stresses. For constant rotational transform, and constant magnetic field the stresses in the tube remain constant, if one conserves the geometric relations. So there are no additional difficulties to expect for the reactor.

Changing the magnetic field, the stresses vary quadratically, which calls for lowest possible magnetic field from this point of view.

2. Possibility of Modular Construction

For the Torsatron as well as for the Stellarator two modular systems have been discussed. The systems proposed for the Torsatron are less investigated than those for the Stellarator.

- Torsatron

Dr. Lidsky proposed to disconnect the windings at the module edges by normal conducting joints. A large number of joints will be needed ($\sim$ 40 000). Ohmic losses however seem to be tolerable. The impact of mechanical stresses on the joints is not yet investigated.

Dr. Motojima proposed to split up the Torsatron winding into modular coil systems (Fig. 1). In order to avoid the return currents the windings are fed from the small major radius side.

- Stellarator

The Modular Helix system of Fig. 2 was presented. It is specially designed for variable rotational transform. Hence two different coil systems are needed: the modular magnets to create the helical field, and the toroidal field coils. This system is thus interesting only for the experiments of the next step, not for a reactor. It provides for a reliable support sutructure and for good access.

For a stellarator reactor, the twisted coil system which creates both helical and toroidal field with one system of modular coils is favourable. The principle of those coils is shown in Fig. 3. Like the Torsatron, this stellarator concept can use the full toroidal field coil current for producing the helical field components.

Further investigations are need to decide whether a modular Torsatron or Stellarator is the better reactor concept.

3. Some Reactor Aspects

Physical features are only mentioned here as far as they concern the technical concept of the reactor immediately.

Prof. Suprunenko pointed out that ion losses will be dominant in a reactor plasma. In order to avoid trapped ion losses a stellarator reactor should work in the plateau regime. For a $l = 3$ ultimate Torsatron, a plasma aspect ratio of about 20 has then to be accepted.

Pfirsch-Schlüter currents in a stellarator reactor may play an important role. They have to be investigated in more detail. Rough estimates indicate that the Pfirsch--Schlüter currents of a stellarator reactor might well reach 10 MA. In this case a vertical field of the order of the poloidal field is needed for the stellarator to control those currents.

Critical beta values of about 2 - 3% were reached in Heliotron D. It is hoped that 10% might be reached in the reactor.

Prof. Pfirsch pointed out in an earlier session, that the helical current in one winding package of a stellarator is larger than the plasma current in a Tokamak, for equal rotational transform.

He also mentioned the ripple problem in the stellarator. Special care has to be taken with respect to the superbanana losses of high energy ions and α-particles. This problem is also associated with the main magnetic field ripple of Tokamaks.

Maintenance and blanket removal requirements call for a simple modular reactor system. There is hope to reach this target both with the stellarator and the Torsatron. Both should try to operate without ohmic heating in order to simplify the design.

Conceptual reactor design studies allowing also for technical aspects should highlight the advantages and disadvantages of Stellarator and Torsatron-reactors in the near future.

MODULAR l = 2 TORSATRON

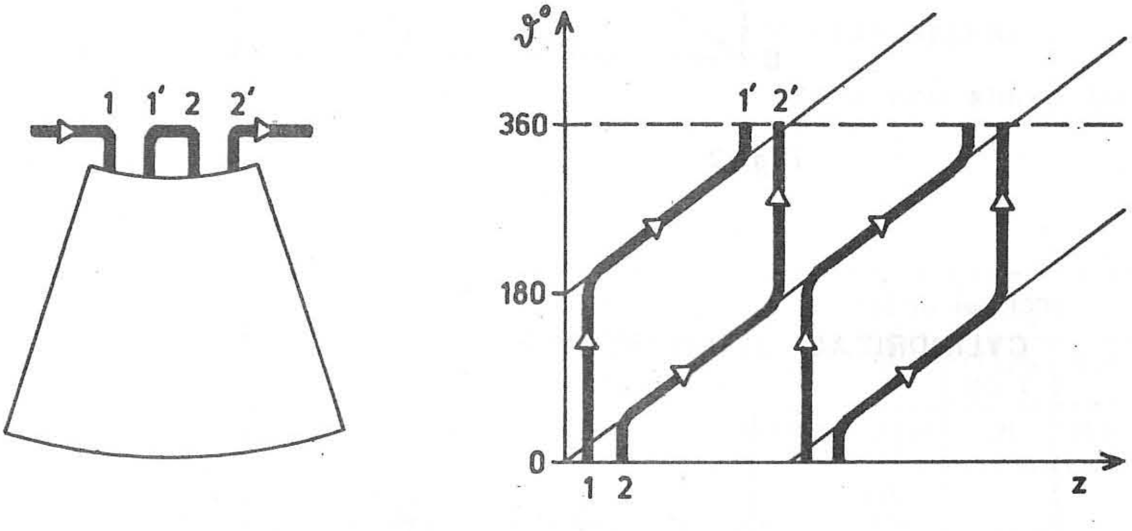

Fig. 1

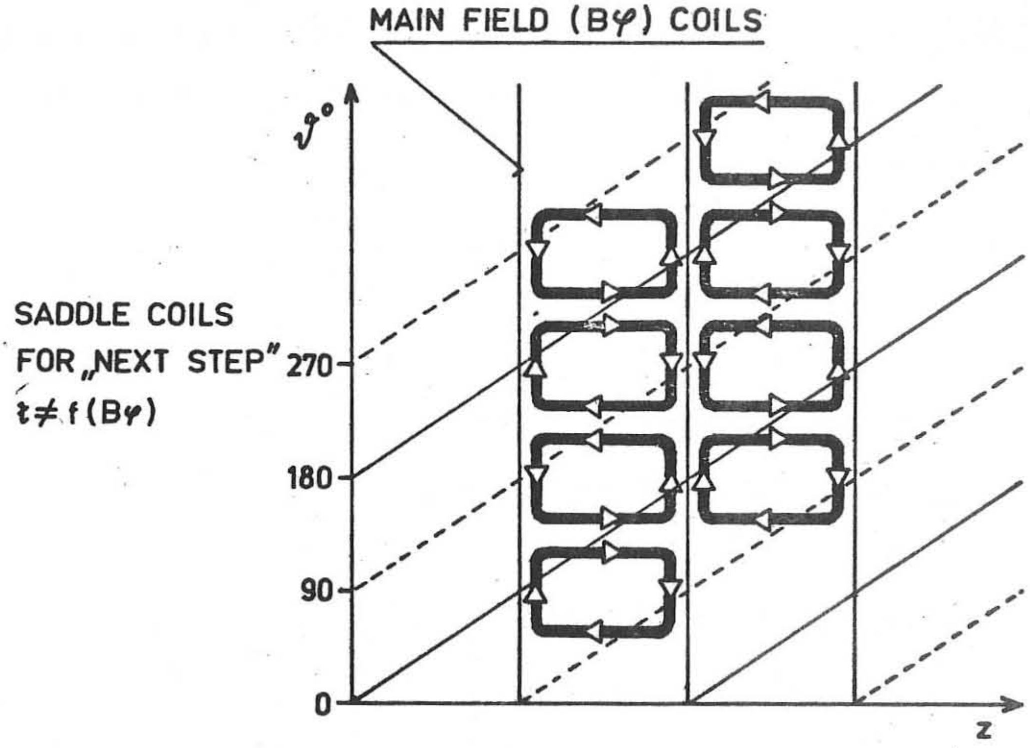
MAIN FIELD (Bφ) COILS
ϑ°
SADDLE COILS
FOR „NEXT STEP"
ι≠f(Bφ)
270
180
90
0
z

Fig. 2

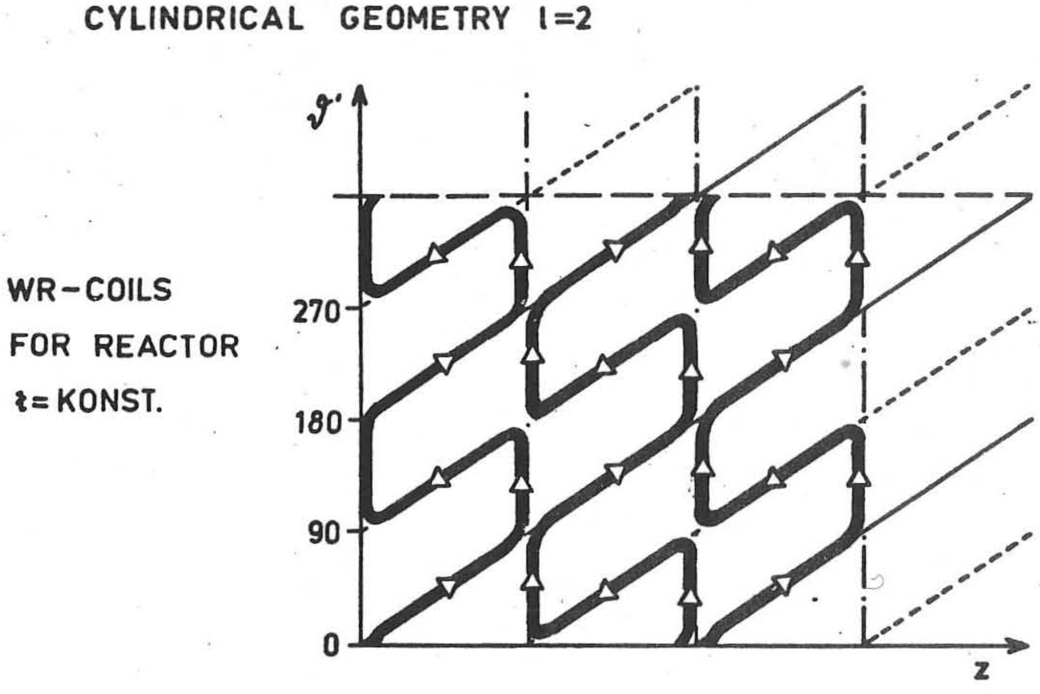
CYLINDRICAL GEOMETRY l=2
ϑ'
WR-COILS
FOR REACTOR
ι=KONST.
270
180
90
0
z

Fig. 3

FUTURE EXPERIMENTS

Chairman: K. Miyamoto

Cleo, W VII a, L-2 and Uragan 2 are relatively large stellarators which are operating now. JIPPT-II will start stellarator experiment at the end of 1977. Wega may be converted to stellarator in 1978.

Uragan 3, 1 = 3 Torsatron with divertor, will complete the construction in 1979. Heliotron E will appear in 1979-1980. List of the parameters of devices are shown in Table I.

TABLE I.

FACILITY	R	A_p	A_v	A_h	B	l	m	ι	HEATING METHODS			
		cm			kG							
CLEO	90	10	13		20	3	7	0,5	OH	NB	LASER 1000 J	ECH
PROTO CLEO	40	7			3	3	7	0,5	OH	ALFVEN	LH	ECH
W VIIa	200	13,5	17		35	2	5	0,3	OH	NBI. 1MW		
WEGA	72	16	19	23,5	14 (25)	2	5	0,25	OH	LH 400kW		
L 2	100	11,5	17,5		20	2	14	0,7	OH	LASER 300 J	ICH	
URAGAN 2	110	6,5	10	12,7	20	3	18	1	OH	ICH 1,5MW		
URAGAN 3(T) 1979	100	15	30		30	3	9	0,7	OH	ICH	NB	
JIPPT-II.	91	17	20	31	30	2	4	0,3	OH	NB 200kW	LH 160kW	ECH 150kW
HELIOTRON E(T) 1980	220		21 x41		20	2	19	2,5	OH	ICH LH	ALFVEN	NB

(A_p, A_v and A_h are plasma radius, inner radius of vacuum vessel and the radius of helical coil respectively)

Now we will cover all kinds of stellarator and torsatron devices. Studies of MHD behaviour of ohmically heated plasma will be continued intensively in most of stellarators.

There are many plans of neutral beam injections and RF heating.

Neutral beam injections are being prepared in W VII a, Cleo and JIPPT-II. They will be applied in near future.

Ion cyclotron heating, which are being studied intensively in Uragan 2, will be succeeded by Uragan 3. Ion cyclotron heating is also planned in L-2 stellarator.

Lower hybrid resonant heating experiment, which is being carried out in Wega tokamak, will be applied to stellarator configuration of Wega. Lower hybrid resonant heating experiment are prepared also by JIPPT-II, Proto-Cleo and Heliotron E.

Electron cyclotron heating, which is other interesting heating method, are under the preparation in Cleo, Proto-Cleo and JIPPT-II.

Laser pellet experiment filling the plasma into stellarator was tested in W II b and are being prepared in L-2, Cleo. Plans of additional heating are listed in Table II.

TABLE II.

OH	$l=2$(L)	W VIIa	JIPPT-II.	WEGA
	$l=2$(S)	L 2	HELIOTRON D,E(T)	
	$l=3$	CLEO	URAGAN 2	URAGAN 3(T)
ALFVEN	PROTO CLEO	HELIOTRON D		
ICH	URAGAN 2, 3	L 2	HELIOTRON D	
LH	WEGA	JIPPT-II.	PROTO CLEO	
	HELIOTRON E			
ECH	CLEO	JIPPT-II.	PROTO CLEO	
NB I.	W VIIa	CLEO	JIPPT-II.	
	URAGAN 3	HELIOTRON E		
LASER PELLET	L 2	CLEO	W IIb	

If these plans will proceed successively, we can get more information on the additional heating as well as on the possibility of steady state operation of stellarators.

Sehr geehrte Herr Professor Pfirsch:

At this for you so remarkable day
we all remember the role you play
in generous and large proportion
in thermonuklearer Forschung.

Wir Wünschen you to be all right
und viel Erfolg in Your Arbeit
including great success in fusion
but don't enhance, please, more diffusion.

And stellarators when you touch
do not be, please, against so much
at our workshop that now ends
nochmals viel Glück and health!

Your Friends

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