Not for Publication   CLM - M51

VISIT OF U.K. NUCLEAR FUSION RESEARCH TEAM TO U.S.S.R., APRIL, 1965

Team Members

Dr. J.B. Adams
Dr. R.J. Bickerton
Dr. A. Gibson
Mr. J.D. Jukes
Dr. D.R. Sweetman

U.K.A.E.A. Research Group,
Culham Laboratory,
Nr. Abingdon,
Berks.

July, 1965.

CONTENTS

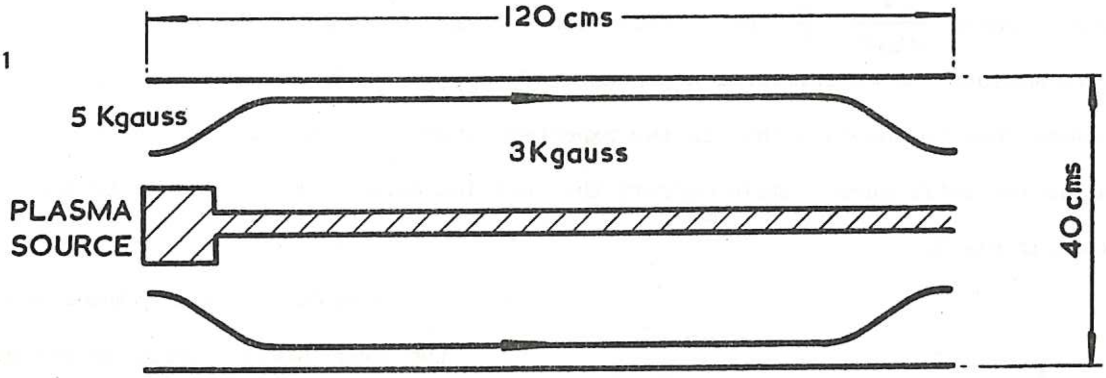
KURCHATOV INSTITUTE

ACADEMICIAN ARTSIMOVICH'S DIVISION

Dr. Ioffe's Experiment

This is the PR.5 mirror machine with the parameters given in Fig.1. There is an $\ell = 3$ Ioffe bar system making it a magnetic well.

Fig.1



The central plasma column has a density ~ 10^{12}/cc. In earlier experiments using either the ion magnetron method or the electron-beam induced unstable arc to fill the machine, stable plasmas with densities in the range $10^9 - 10^{10}$/cc and ion energies ~ 5 keV were obtained. All the recent work was therefore concentrated on trying to obtain a higher β plasma in the well. In the new injection method developed for this purpose a pulsed radio-frequency electric field at just below the ion-cyclotron frequency is applied between the central plasma column and the walls of the chamber. The resultant time dependence of the plasma density as deduced from the fast neutral particle emission is shown in Fig.2.

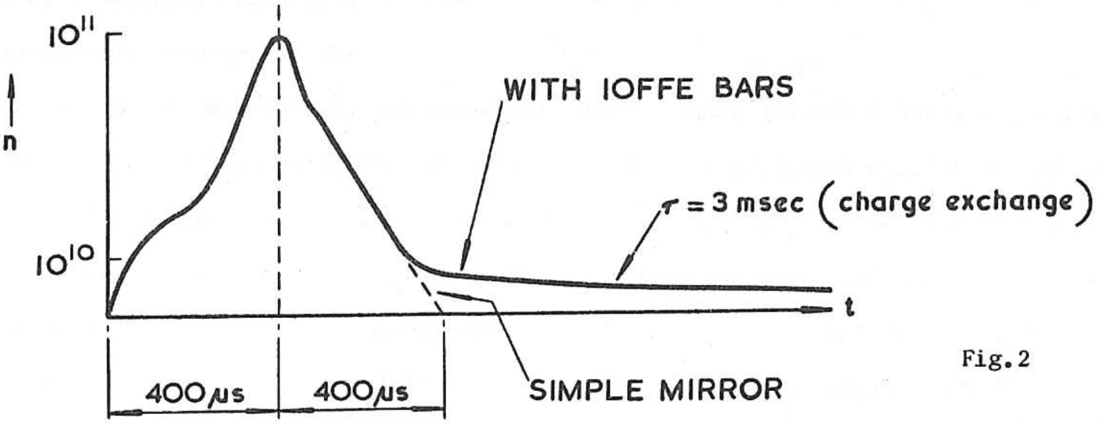


Fig.2

The density rises during the injection period to greater than 10^{11}. The mean ion energy is ~ 1 keV. After the injection is switched off there is a fast decay to ~ $3 \cdot 10^{10}$ and thereafter it decays slowly and stably as before with a time constant consistent with charge exchange. The peak density obtained at the end of the injection period depends on the r.f. power used, but it always falls rapidly to the same critical value ~ $3 \cdot 10^{10}$ after the power is switched off.

This behaviour is interpreted by Ioffe as due to the ion-cyclotron drift instability derived by Mikhailovskii and Timofeev (J.E.T.P., 17, 626, (1963)). According to this theory instability occurs when:

$$\left(\frac{\rho_i}{a}\right)^2 > 4\left(\frac{B^2}{4\pi n M_c^2} + \frac{m}{M}\right)$$

where ρ_i is the ion Larmor radius and $\frac{1}{a} = \frac{1}{n}\frac{dn}{dr}$. With the conditions in PR.5, B ~ 3 kG T_i ~ 1 keV and a ~ 5 cms, the critical density for instability is $\sim 3 \cdot 10^{10}$. Note that in this regime where $\frac{B^2}{4\pi n M_c^2} \gg \frac{m}{M}$ the critical density is proportional to B^4. Ioffe was preparing to measure the experimental dependence of n_{crit} on B and also to look directly for the plasma loss to the wall that is the expected consequence of this instability. With no current in the Ioffe bars (simple mirror) the fast ion density drops rapidly to zero as shown dotted in Fig.2.

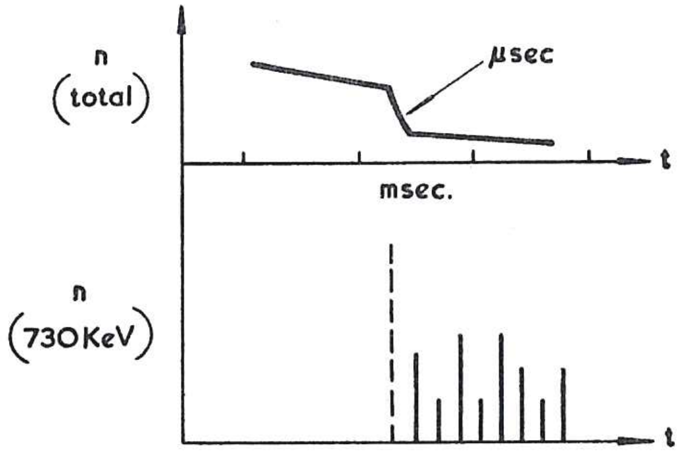


Fig.3

A more detailed examination of the long 'stable' decay in the magnetic well case shows the presence of occasional and sudden downward jumps in the fast ion density (Fig.3).

Potassium beam measurements show corresponding discontinuities in the electron density. Measurements with foils of the fast neutral flux with energies > 30 keV show the presence of such particles immediately after a density jump. These phenomena are interpreted by Ioffe in terms of the Post-Rosenbluth instability. This feeds on the non-Maxwellian nature of the particle energy distribution - instability occurs if there is a region of positive slope in the distribution function $f(\varepsilon_\perp)$. Such a region is an essential feature of any adiabatic mirror with a loss cone in velocity space. Presumably the density jumps occur when, through charge exchange and loss cone processes, the distribution function has evolved into a sufficiently unstable form.

Dr. Romanovski's Experiment

This is a mirror machine ~ 2.8 metres long, 40 cms diameter, mirror ratio 1.2, field strength ~ 2 kilogauss. The trap is filled by a 1 mA, 10 keV ion beam in conjunction with a gated mirror at one end. The trapped ions encircle the axis and the purpose of the experiment is to investigate the instabilities in plasma created by an ion beam. The transit time of the beam to the far mirror and back is 20 µsec. The charge exchange time is typically 2 milliseconds. A trapped density of $\sim 10^8$ is achieved. Oscillations at the ion cyclotron frequency and its harmonics are seen on both magnetic and electric antennae whether the gate coil is used or not. However the amplitude increases when the mirror is used. This presumably indicates the damping of instabilities due to the continuous flow of ions out of the system that occurs without the gate mirror energised. Using the mirror a plot of the reciprocal of the containment time versus gas pressure is linear and extrapolates back through the origin indicating that charge exchange is the only significant loss mechanism. Thus the main conclusion of the experiment so far is that the electrostatic (Harris) instabilities do not cause any particle loss. It is assumed that the low density and finite Larmor radius are the reasons why flute instability is not seen. The ion cyclotron emission is modulated at 100 - 200 kc/s - this is not understood. In future they intend to lower the mirror ratio and so to increase the sensitivity of the system to any velocity space diffusion that may result from the instabilities.

Tokomak Experiments

T.3

B_0	40 kG (max) typically 25 kG.
I	40 - 50 kA.
Minor diameter	40 cms.
Major diameter	200 cms.
Outer copper chamber	3 cms thick, with vertical and horizontal gaps.
Inner stainless steel liner	0.3 mm. thick.
Operating pressures	0.2 - 2.0 microns Hg.

The outer copper chamber is pumped by an oil rotary pump, the inner liner by Hg diffusion pumps with a water backing pump. The current pulse lasts 10 - 20 milliseconds. The energy distribution of fast neutrals arriving at the wall has been determined in the range 100 eV - 1 keV using a method developed by Fedorenko. (Gas stripping cell followed by energy analysis.) This indicates that the ion temperature in the discharge is ~100 eV. The electron temperature determined from the plasma conductivity is also of this order. The energy containment time is defined as $\tau = \frac{NkT}{I^2R}$ where N is the line density and R the discharge resistance (measured at peak current). τ is found to be ~ 3 milliseconds. A bolometer at the wall measures ~ 30% of the total energy input which is of the order 500 eV per particle. Thermocouple measurements at the limiter show that the loss there accounts for the remainder. Streak pictures of the discharge showed m = 3 instabilities - it was said that there was evidence of two helices rotating in opposite directions. Copious X-ray emission is observed from the limiter with energies from keV → MeV. No absolute intensity measurements had been made. The neutral gas pressure in the shadow of the limiter drops to $\sim \frac{1}{20} \cdot p_0$ when the discharge is fired.

TM.4

This is a new machine just being brought into operation. The parameters are,

B_{MAX}	~ 70 kG.
Minor diameter	20 cms
Major diameter	80 cms
Limiter diameter	16 cms
Energy source	8 MJ of condensers.

The copper outer is 2.5 cms thick with gaskets. The inside chamber is pumped by a silica gel absorption pump backed by a water pump. The limiting Kruskal-Shafranov current is ~ 150 kA. It is intended to use currents of order 20 kA for 60 - 80 milliseconds. The precision of the main magnetic field is such that $\frac{\Delta B}{B} = 0.1\%$ on the circular axis of the system. There are four conductors between the stainless steel liner and the copper shell so that time dependent transverse fields can be applied to control the motion of the plasma along the major radius. Temperatures of the order 100 eV are expected and the main objective is to measure the effect of magnetic field strength on containment time over a wider range than hitherto.

Dr. Osovet's Experiments

(i) R.F. Containment Experiment

A toroidal system is used, minor diameter ~ 10 cms major diameter ~ 80 cms with two travelling magnetic waves moving round the torus with equal and opposite phase velocities. To avoid a standing wave the two frequencies are different, 1.8 and 3.0 Mc/s. By this technique the d.c. Hall current which is set up when only one wave is used is reduced to zero. This reduces the tendency of the plasma ring to expand to the outer wall. The R.F. magnetic field is ~ 500 gauss at the wall. Two 60 MW power supplies giving 450 μsec pulse are used. Each power supply unit contains four hard valves with anode voltages up to 15 kV and carrying currents ~ 1 kA. The plasma loading reduces the Q of the system from 150 to ~ 10. Electron temperatures of the order 12 eV are achieved with only one travelling wave excited. No other plasma parameters were given.

(ii) Dynamic Stabilisation

In these experiments additional r.f. magnetic fields are applied to simple linear pinches in order to effect dynamic stabilisation. The r.f. power is obtained either from hard-valve oscillators as above or from the discharge of high Q condenser banks. For this purpose special condensers have been developed with a self-resonant frequency of 4 Mc/s, capacity 0.1 μF, voltage 50 kV and a Q ~ 80. A linear pinch ~ 50 cms long and 10 cms diameter has been used, the current rises to 100 kA in 3 μsec. Four bars outside the tube carry the r.f. currents which alternate in direction round the periphery (see Fig.4.)

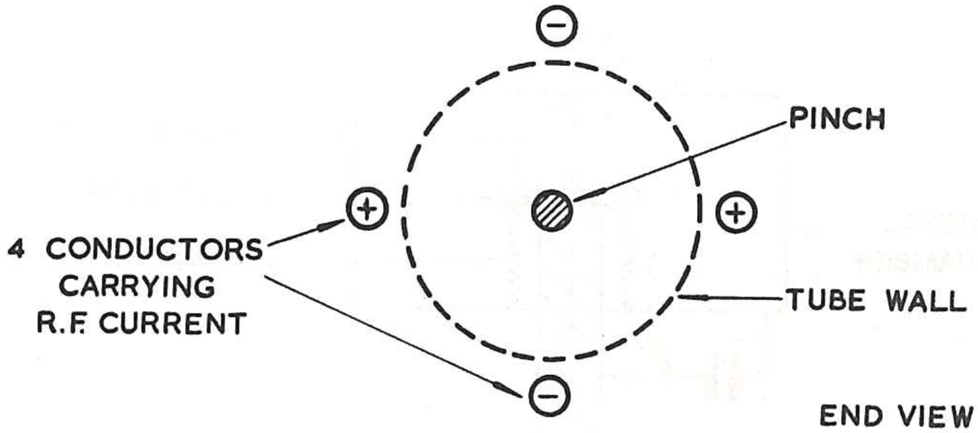


Fig.4

These currents exert stabilising or destabilising forces on the pinch depending on whether they are in the same or opposite direction to the pinch current. As in the inverted pendulum problem the net effect is stabilising, and stability will be achieved if two conditions are satisfied, (a) the frequency must be greater than the instability growth frequency, and (b) the amplitude must exceed some critical value. In practice with currents in the external bars of ~ 12 kA and frequencies > 700 kc/s very good stabilisation is observed in framing-camera pictures. Below this frequency the effect disappears. A toroidal pinch experiment using dynamic stabilisation was nearly complete. This used a four conductor stabilising winding as in the linear experiment. The torus was approximately 10 cms minor diameter and 80 cms major diameter. A more powerful linear system was also ready to go;it used 24 of the high Q condensers in Marx circuits to give 100 kV across six stabilising bars. A single vacuum spark gap is used for switching.

Dr. Komelkov's Group - Plasma Guns

The aim of the first experiment, which was just coming into operation, was to produce cleaner plasma blobs from a Marshall gun. To this end great care had been taken to eliminate oil contamination of the vacuum system. An absorption pump was used with silica gel at liquid nitrogen temperature, the pumping speed was 5,000 litres/sec, and a base pressure of 10^{-8} mm Hg had been achieved. The plasma gun itself was fairly standard with copper electrodes and a 30 μF, 25 kV condenser bank connected to it.

In a second installation a Marshall gun injected plasma with a velocity $\sim 2 \cdot 10^7$ cms/sec and density $2 - 5 \cdot 10^{14}$/cc into a 1 kG guide field. The aim of the experiment was to study the effect of a gating coil (rise time 8 μsec) on the transmission of impurities down the field. It is assumed that impurity ions are going more slowly than the deuterium so that the gate can be closed in between the two groups. No results had been obtained at the time.

Fillipov Pinch

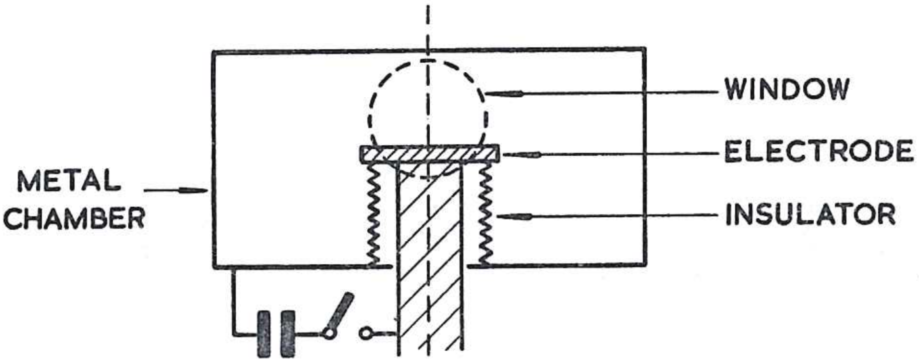


Fig.5

In this pinch a fast discharge is struck between an electrode mounted on a porcelain insulator and the walls of a short cylindrical metal chamber. The current sheet forms near the insulator and then moves under the action of magnetic force until a thin filamentory discharge is produced between the electrode and the top of the chamber. The formation of a 'focus' of hot (~ 1 keV) plasma, roughly spherical, ~ 1 mm across and lasting for 10^{-7} seconds was described at Salzburg. The shadowgraph technique has now been applied to this system using a Q-spoiled ruby laser as light source and looking through windows just above the electrode as shown in Fig.5. Pictures taken at different times with respect to the initiation of the discharge enable the current sheath motion to be reconstructed. The 'focus' itself was not clearly evident on the pictures - possibly because they are essentially line-of-sight averages.

In future they intend to look at collective scattering of the ruby light from the plasma. They hope to use the Zeeman splitting of the two satellite lines to measure the magnetic field strength.

ACADEMICIAN ZAVOISKI'S DIVISION

We were first given the following summary of their work. They are interested in the possibility of using current instabilities to heat plasma. There are three approaches:

Fig.6

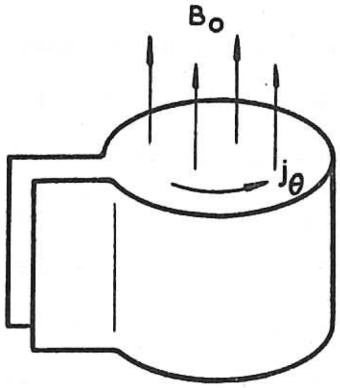
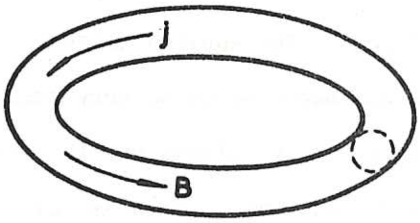


Fig.7



(i) $\bar{j} \perp \bar{B}$ - a single turn thetatron coil is used to excite large azimuthal current densities in the plasma. (see Fig.6). Experimental results from this approach were reported at Salzburg (i.e. $n \sim 10^{13}$/cc, $T_e \sim 1$ keV).

(ii) $\bar{j} \parallel \bar{B}$, toroidal experiment - in this method a large current is passed round the periphery of a torus parallel to the applied magnetic field. (Fig.7).

(iii) $\bar{j} \parallel \bar{B}$ mirror machine - here a current is passed along the lines of force through plasma injected into the system from two plasma guns. (Fig.8).

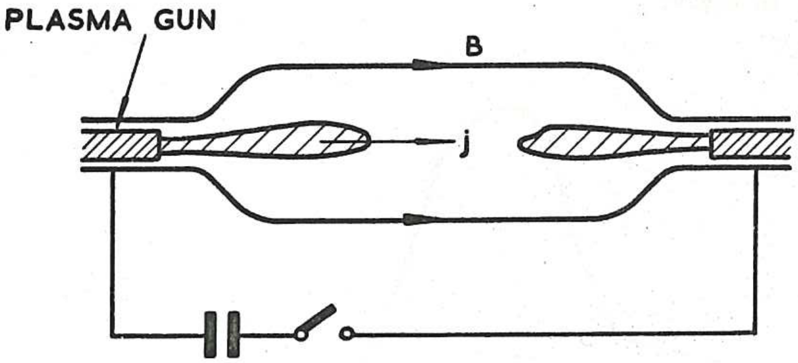


Fig.8

In all cases the current densities involved are in the range 1 - 10 kA/cm². When the electron drift speed

$$\bar{v} > c_s \left(= \sqrt{\frac{kT_e}{M}} \right)$$

then instabilities occur with growth rates

$$\gamma \sim \omega_{pi} \sqrt{\frac{m}{M}} - \omega_{pe} \sqrt{\frac{m}{M}} \ .$$

Strong fine scale turbulence results and the effective conductivity is reduced due to particle wave interactions. Thus

$$\sigma_{\text{effective}} = \frac{n\ e^2}{m\ \nu_{\text{turb}}} \sim 10^{12} - 10^{13} \text{ cgs.}$$

With $n = 10^{13}$, ν_{turb} (the effective collision frequency due to turbulence) $\sim 10^9 - 10^{10}$. This low conductivity means that rapid plasma heating can take place, the power density being

$$\left(\frac{j^2}{\sigma_{\text{eff}}} \right)$$

Using the first approach (i.e. a thetatron shock coil) followed by adiabatic compression the following parameters were achieved in a mirror machine, $T_e \sim 100$ keV (from X-rays),

$n \sim 10^{13}$ (from microwaves) and $T_i \sim 5$ keV (from neutron emission).

The toroidal experiment was 3 cms minor diameter, 30 cms major diameter, axial field ~ 2 kG. Four titanium washer guns were used to inject the initial plasma, density $10^{11} - 10^{12}$/cc. The applied electric field was 100 - 200 volts/cm at a frequency of 2½ Mc/s. The plasma was observed to be very resistive, 10 - 30 ohms. Approximately 10 keV/particle was dissipated in the plasma but the estimated electron temperature (from X-ray observations) was only ~ 1 keV. The system is, of course, not a containment geometry and so the large energy loss is attributed to contact between the plasma and the outer rim of the torus. Microwave radiation at frequencies $2\,\omega_{pe}$, $\frac{\omega_{pe}}{\sqrt{2}}$ and $\sqrt{2}\,\omega_{pe}$ had been observed, the energy in these oscillations $\approx nm\bar{v}^2$ (the drift energy of the electrons). This is as predicted by the theories of Drummond and Pines, and Rudakov and Velikov.

A similar apparatus, but about three times larger, was just coming into operation. Again there was no provision for a plasma equilibrium except that the axial field system could be excited to give a 'bumpy torus' configuration.

The $\bar{j}\,||\,\bar{B}$ mirror experiment is about 1 metre long. Plasma is injected from two Post type sources at either end with a voltage of 30 kV applied between them to drive the current. The current waveform is shown in Fig.9.

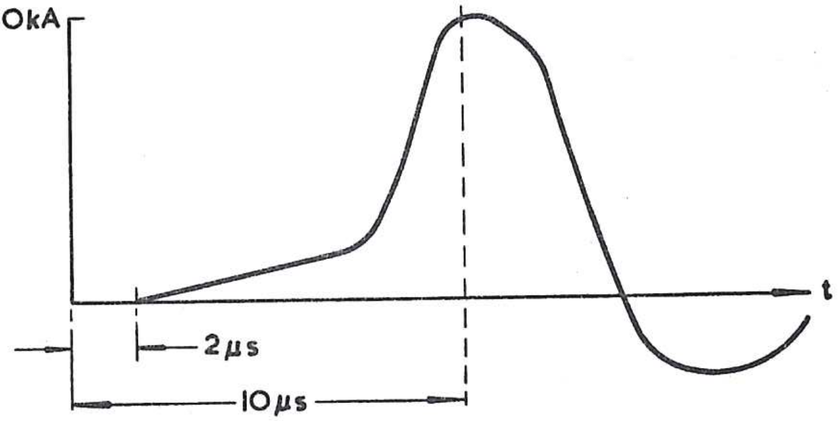


Fig.9

The system is full of plasma about 2 μsec after firing the guns and the current then begins to rise. The initial resistance is about 100 Ω dropping at about 10 μsec to ~ 1 Ω. The initial high resistivity is attributed to the turbulent phenomena discussed earlier. Magnetic probe measurements show the current to be uniformly distributed across the discharge section, i.e. there is no skin effect. This is so despite the fact that the line density N is such that

$$\frac{M}{m} > \frac{Ne^2}{mc^2} \gg 1 \,.$$

The final electron temperature deduced from X-rays and checked with a diamagnetic loop is ~ 5 keV.

Apart from these heating experiments there was a separate installation to investigate the structure of a collisionless shock wave propagating perpendicular to the magnetic field. A single turn coil was used with a diameter of 6 cms and length ~ 50 cms. This was fed by an artificial line to give a square pulse of field inside the coil, typical figures being amplitude 600 gauss, rise time 30 nsec, duration 250 nsec. Initial conditions $p_o \sim 6$ microns Hg, $n_e \sim 4 \cdot 10^{12}$/cc, $B_o \sim 300$ gauss. With a 2 mm. diameter magnetic probe a compression wave is seen moving through the gas with an Alfven Mach number slightly greater than one; the rise time of the field in the wave is consistent with the theoretical (Adlam-Allen) shock thickness of $\left(\frac{c}{\omega_{pe}}\right)$. Observations of helium spectral lines are used to deduce electron temperatures behind the shock of several hundred electron volts.

Another group in Academician Zavoiski's division works on the heating of plasma by magnetosonic resonance. The VEGA installation is ~ 5 metres long; plasma produced at one end by pulsed r.f. power diffuses along the system into a region of increased magnetic field. In the working section a plasma column 4.5 cms in diameter is obtained. The density is ~ 10^{13}/cc, the neutral gas pressure ~ 10^{-7} mm Hg. and $B_o \sim 1.5$ kG. Magnetosonic resonance has been demonstrated at low power using frequencies in the range 10 - 100 Mc/s. At the (higher) 1 MW level some electron and ion heating has been observed ($T_e \sim 50$ eV). Preparations are in hand to couple a 2 MW, 20 Mc/s generator to a magnetic mirror configuration - central field 6 kG, mirror ratio 1.25.

DR. GOLOVIN'S DIVISION

OGRA - I

A summary was given of the past program on OGRA - I.

Up to the winter of 1962/3 work had been without the Li arc and with a poor vacuum of ~ 10^{-7} Torr. During the summer of 1963 a vacuum reconstruction took place and a base pressure of a few × 10^{-9} Torr is now available. With plasma, the pressure was typically 10^{-8} Torr. Since that time most of the work has been with a Li arc as a trapping plasma. The properties of this arc are:

Mostly Li^+, Li^{++} ∴ green appearance

dia = 6 cms, current = 20 - 200 Amps

$n_e = 10^{12}$/cc.

After an initial burst of gas the base pressure is a factor of 2-3 lower with the arc running.

The hot component of the plasma is about 10^9/cc with the arc running. The arc suppresses the emission at ω_{ci} (i.e. down in intensity by 1 - 2 orders of magnitude). They remarked that this may be due to good conductivity along the field lines damping the oscillation. There was some evidence for this in that higher harmonics damped first.

Measurements had been made of the energy spectra of the charge exchange neutrals. With the Li arc the spectrum was degraded as in Fig.10.

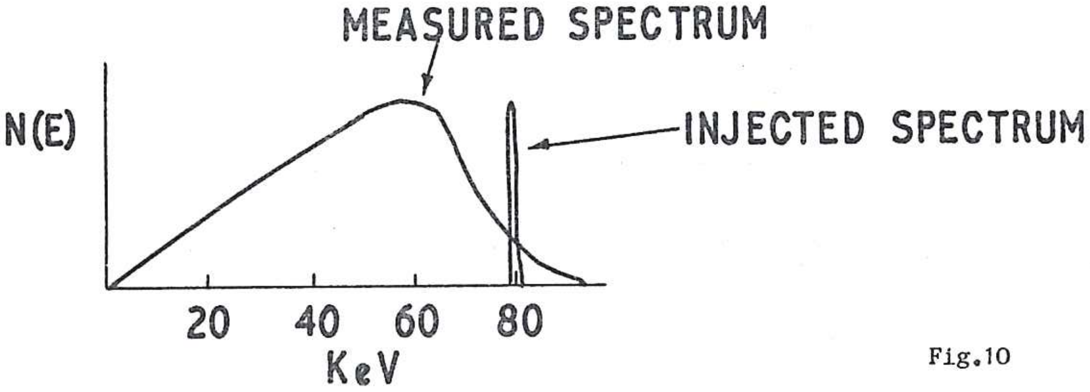


Fig.10

Because of the energy degradation and charge exchange loss the mean ion life time in the presence of the arc was only a few milliseconds and they were therefore unhappy about the use of arcs.

Measurements had been made of the energy spectra of the ions in the absence of the Li arc. This was confused by the presence of both H^+ and H_2^+. Measurements had been made from 0 to 24° to the normal to the field lines (the angle of injection was 18°).

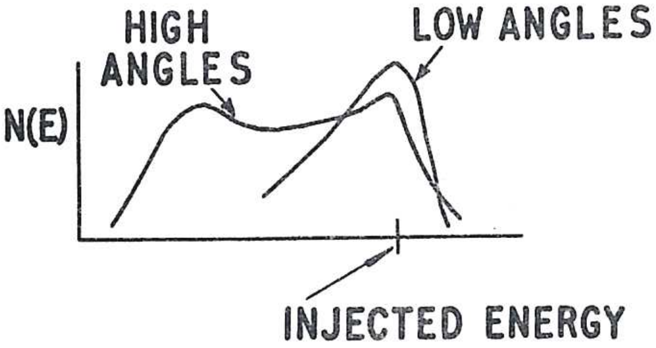


Fig.11

The energy distribution peaked at lower energies for high angles (Fig.11). This they suggested was due to particles being accelerated and deccelerated in $\upsilon_\perp$. The deccelerated particles appear at higher angles and the accelerated particles are lost to the walls and injector snout.

At present OGRA - I is limited in density without the Li arc, and in life time and energy with the arc.

They have for some time been thinking of putting the ion source directly inside the vacuum system - this move was precipitated by the accidental destruction of the injector snout in December 1964. Preliminary tests in a separate system suggest that 1300 mA should

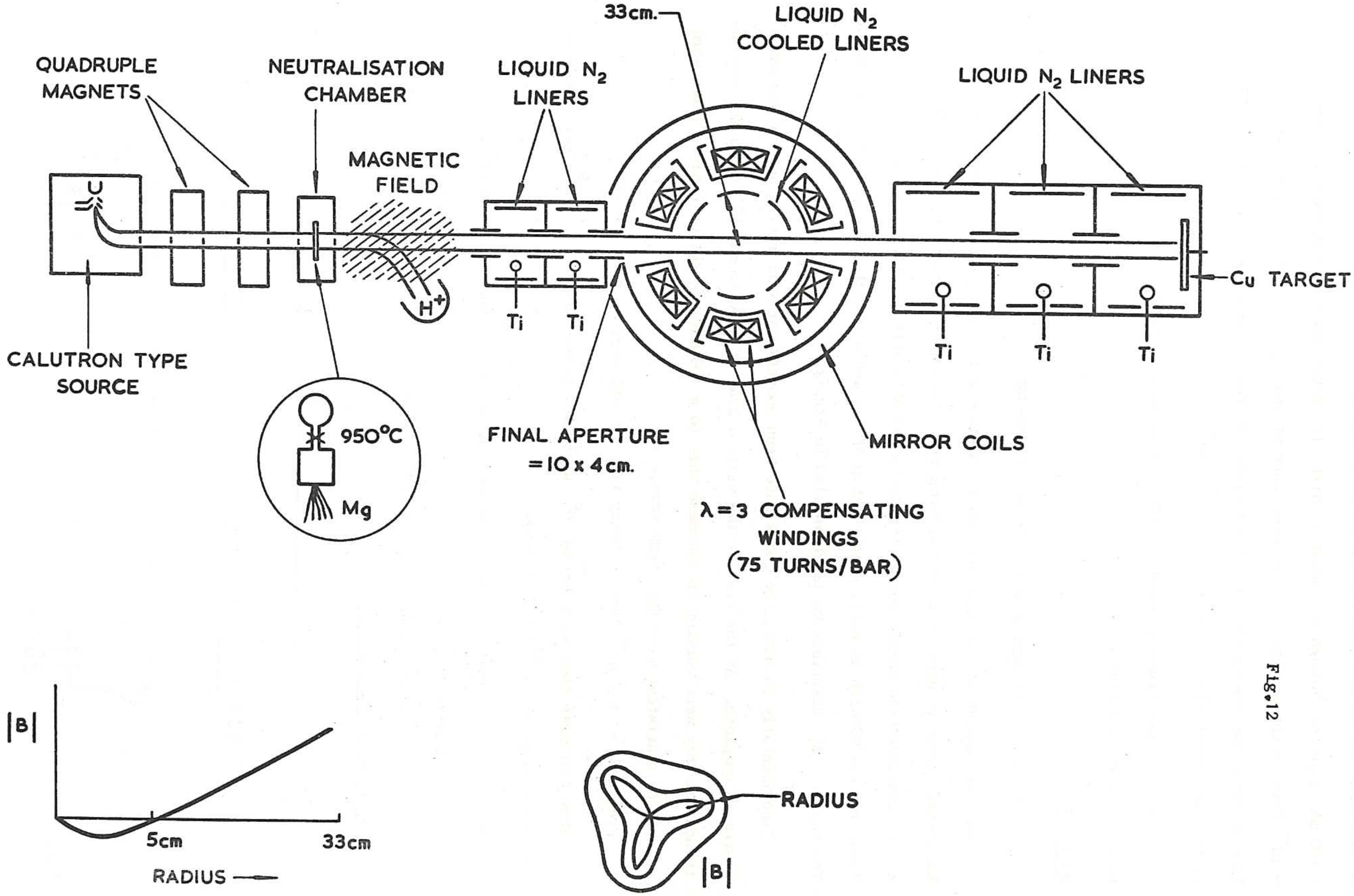

QUADRUPLE MAGNETS
CALUTRON TYPE SOURCE
NEUTRALISATION CHAMBER
MAGNETIC FIELD
H+
950°C
Mg
LIQUID N2 LINERS
Ti
FINAL APERTURE =10 x 4 cm.
33cm.
LIQUID N2 COOLED LINERS
λ=3 COMPENSATING WINDINGS (75 TURNS/BAR)
MIRROR COILS
LIQUID N2 LINERS
Cu TARGET
|B|
5cm
33cm
RADIUS
RADIUS
|B|

Fig.12

be available for an acceleration potential of 160 kV (which compares favourably with ~ 100 mA injected through the snout). With Ti gettering they estimate a pressure of ~ 10^{-8} Torr in the presence of the above current and $n_+ = 10^{11}$ may be possible. Also the lack of snout may remove the $v_\perp$ limitation. So far breakdown is limiting them to 50 kV extraction potential and a density of $10^7 - 10^8$/cc.

In general the future program of OGRA - I is to investigate the E_r field stabilisation at higher densities.

OGRA - II

We were shown the apparatus and detailed drawings.

The arrangement of the injector centre chamber and burial line is shown in Fig.12. Magnesium vapour is used as a neutralising gas. The compensating coils are arranged in an $\ell = 3$ configuration inside the mirror coils and all coils are water cooled. The central field is 16.7 kG with an axial mirror ratio of 1.5 and a radial ratio of 1.3 at the walls. The radial $|B|$ distribution is shown also in Fig.12.

Experimentally to date, the coils have been operated at full rating and the vacuum system is complete. At the time of the visit a beam of only 12 mA H^0 at 75 keV was obtained but they were working to increase this to a 100 mA. A set of figures which were said to be consistent with this beam were:-

Pressure ≃ 4×10^{-9} Torr; Decay time ≃ 400 msec; $n_+ = 10^7$/cc

They calculate that with 300 mA H^0 at 80 keV a pressure of 1×10^{-9} Torr should give exponentiation to ~ 10^{11} in 3 seconds.

The density in OGRA - II is at present low because of the large volume and low Lorentz trapping efficiency (due to low field gradient). There was, therefore, considerable interest in other means of trapping both in OGRA - I and OGRA - II.

Arc Experiments (Pistunovich)

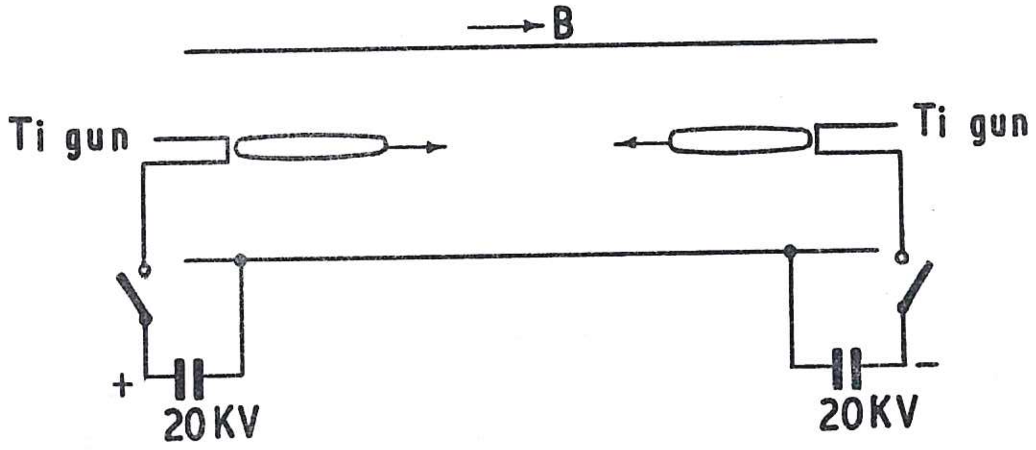


Fig.13

This is primarily of interest as an arc for dissociation in the OGRA experiments and the experiment was carried out in OGRA - I during the shut down period.

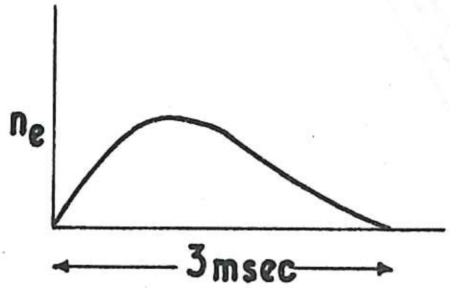


Fig.14

Two Ti washer guns are fired from opposite ends of OGRA and the 20 keV condenser banks are fired simultaneously (Fig.13). The discharge current is 1-5 kA and lasts for 100 μsec. They have measured with microwaves $n_e \sim 10^{12}$ in the 10 metre long discharge. The plasma lasts for about 3 msec (Fig.14). They would like to raise this time to > 100 msec for trapping use and so the arc is disappointing in this respect.

Optical Excitation and Ionization - PAMIR Experiment (Sokolov).

(1) Optical excitation

They consider the increase of the population of say the $n = 11$ state in a neutral beam by optical excitation from say the $n = 2$ state. 2s - 11p excitation (say)competes with 11p - continuum to give in equilibrium a fraction as high as 0.5 in the $n = 11$ state. In practice experiments would be in the non-equilibrium condition. They are talking of using a gas laser to give ~ 50 mW/cm^2 continuous or alternatively a thallium lamp which they say will give 1 watt at 3775 Å. These intensities are adequate to give good results in the PAMIR experiment but when scaled up to OGRA, kilowatts would be required for hundreds of milliseconds.

(2) Optical ionization

They consider direct ionization of high states with infra-red. The photoionization cross section for an individual state is maximum near the cut-off but because of the overlapping states almost any infra-red frequency is suitable and there is no advantage in using the narrow frequency spread of a laser.

The most powerful lamps (Xe or Kr) might give ~ 100 kJ in 5 msec which would only just compete in trapping efficiency with Lorentz trapping.

Both of these techniques are regarded as long-term and rely on improved light sources to become really competetive.

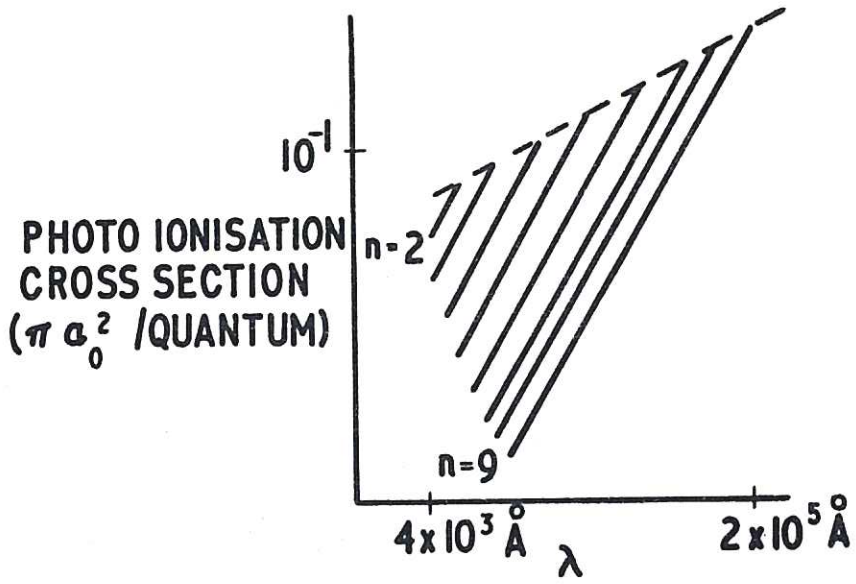

10⁻¹
PHOTO IONISATION CROSS SECTION (πa_0^2 /QUANTUM)
n=2
n=9
4x10³ Å
λ
2x10⁵ Å

Fig.15

NOVOSIBIRSK

Academician Budker gave an introductory talk on the plasma work at Novosibirsk. They were able to start work only about three years ago and they decided to try and work on different lines to those being followed in other Laboratories, i.e. to explore virgin lands. Their programme falls into four parts:

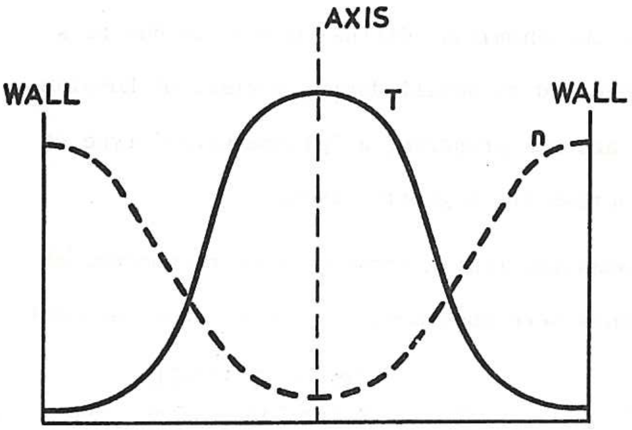
(i) Super hot plasma - relativistic electrons in mirror geometry.

(ii) Super cold plasma - thermal potassium plasma.

(iii) Super fast plasma - shock wave and turbulent heating.

(iv) Super dense plasma - constant pressure containment.

In case (i) the Debye length is greater than the size of the system initially but as the electrons lose energy by radiation a transition to the plasma state is made. The work under (iii) is carried out by Nesterikin and Sagdeev and is a continuation of similar work that they did in Moscow. In (iv) the idea is to have a plasma whose pressure is taken up on the walls of the vessel, i.e. abandon magnetic confinement. Then the pressure gradient must be zero so that to get thermonuclear reactions the central region is hot with relatively low density, while the region near the wall is cool and dense. (Fig.16).



$$\nabla(n \cdot T) = 0$$

Fig.16

A uniform magnetic field may be used to reduce the thermal conductivity of the plasma. No calculations have been made of the conditions required in such a system to give a net power gain. They would like to have a plasma with a density $\sim 10^8$ and a temperature $\sim$ 80 eV and then compress it so that T rises to $\sim$ 10 keV.

The relativistic electron mirror machine is 3 metres long between the mirrors and 50 cms diameter. The central field is 20 kG and the mirror ratio 2.5. The system is pumped with oil pumps and a base pressure of 10^{-10} mm Hg. is claimed after baking to 400^oC;

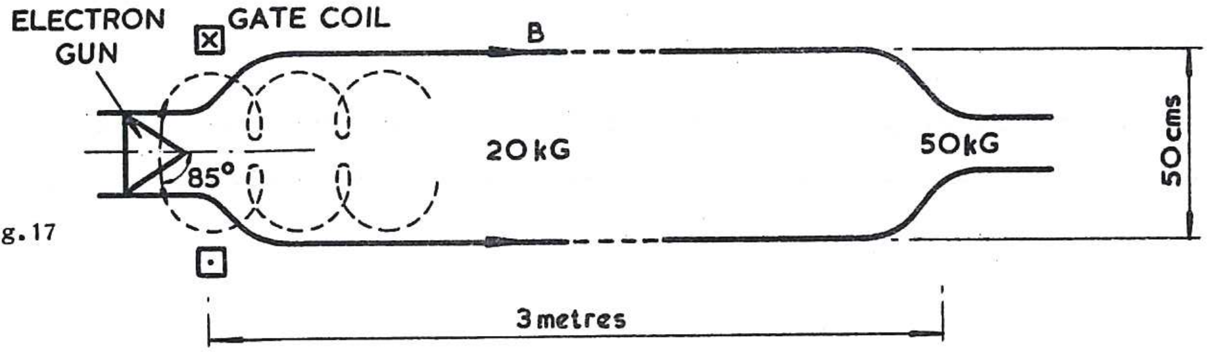


Fig.17

the volume is ~ 500 litres. At present an electron beam of 10 A at 200 keV is injected. This beam is annular and at an angle of 75° to the axis of the sytem (see Fig.17). A gate coil near the gun is used to trap the injected electrons - their transit time down the machine and back is 10^{-8} seconds. A trapped density of $3 \cdot 10^7$/cc is obtained. This does not rise as the injected current is increased so that already there is evidence for some particle loss, presumably due to instability. Ultimately a 4 MeV electron beam will be used and it is anticipated that ions created in the trap will be heated to ~ 50 keV in the space charge electric field of the electrons.

The potassium plasma experiment is fairly standard, surface ionization being produced with a hot tungsten plate. It is claimed that the anomalous diffusion seen is due to a universal instability. These results were reported in detail during a visit of Russian scientists to Culham in November, 1964. They are now preparing a 'plasma eater' type of probe to measure directly the flux of plasma across the magnetic field.

Discussing the fast plasma work it was emphasized that a great deal of technological development had to be done before the experiments were possible. A 100 kV paper and oil

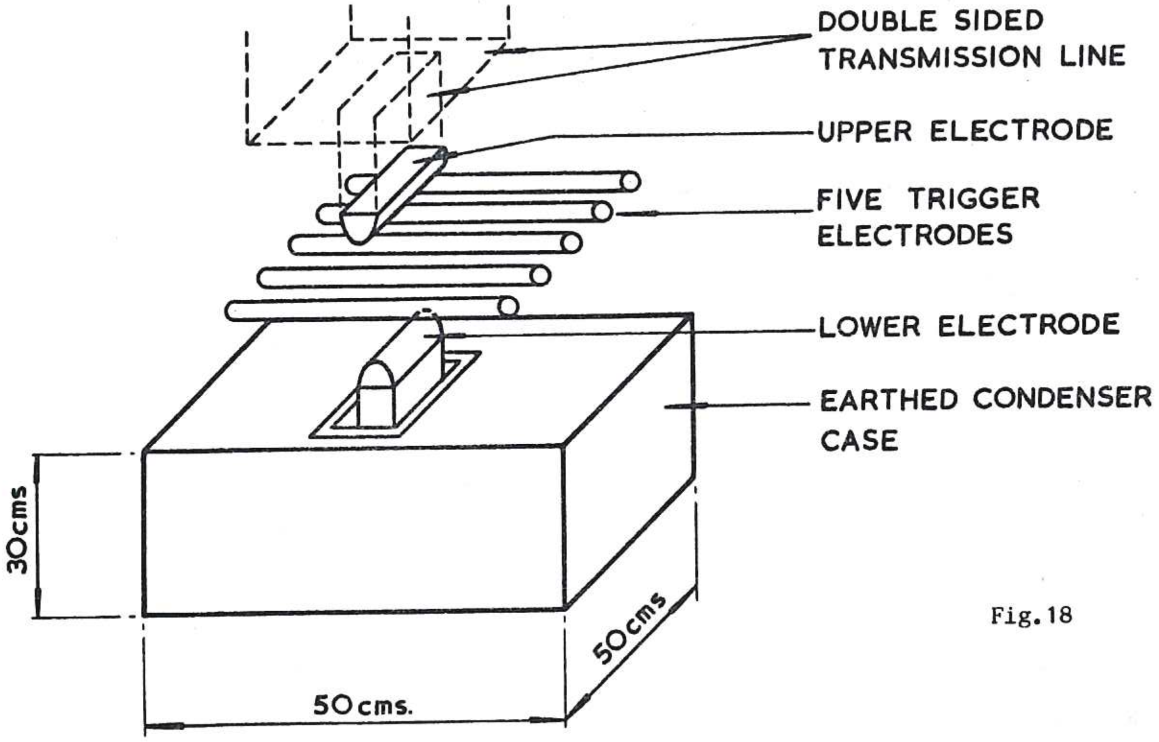


Fig.18

condenser had been developed with a capacity of 1.2 μF and a characteristic impedance of 0.1Ω. The output of this condenser is in the form of a double sided transmission line. (Fig.18). A special low inductance spark gap (5 nH) bolts on to the condenser. The electrodes are two half-round bars - one being the terminal of the condenser itself. There are five trigger electrodes mounted across the transmission line. The gap is pressurised to 3 atm and filled with nitrogen. It breaks down in five places corresponding to the trigger positions with a formative time of 2 nsec and a jitter time < 1 nsec. In studying the performance of this gap a framing camera with a shutter opening of 10^{-9} secs and an oscilloscope resolving 10^{-11} secs were used.

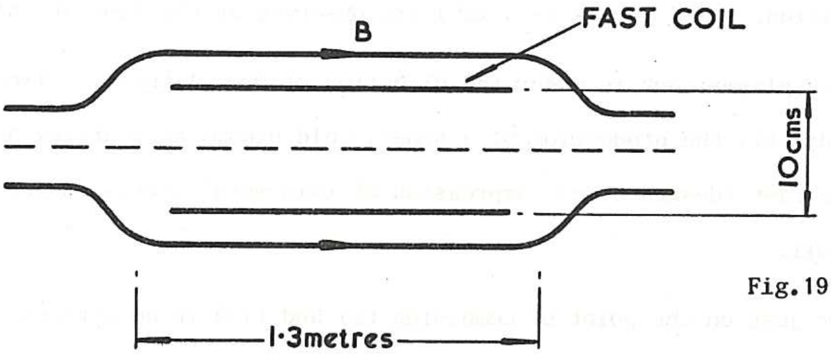


Fig.19

The first shock wave apparatus, SH4, was built specifically to study shock structure. It is shown in Fig.19. Two of the 100 kV condensers are used back to back. Initial conditions are $n_e \sim 10^{13}$, $B_o \sim 300$ gauss, the plasma being produced either by washer guns or R.F. Shock structure is studied using small, ~ 1 mm, open loop magnetic probes. The frequency response of these was said to be an order greater than with loops inside insulating tubes. For $M_A < 2$ the shock width is in agreement with theory $\left(\delta \sim \frac{c}{\omega_{pe}}\right)$. For $M_A = 3$ it is about 10 times wider. Radiation at 150 Mc/s (approximately ω_{pi}) is observed by a capacitative probe in the plasma as the shock wave passes the probe tip. Noise at ω_{pe} is detected at the time of shock convergence on the axis. Hard X-rays, > 30 keV, are also emitted at this time.

SH 5

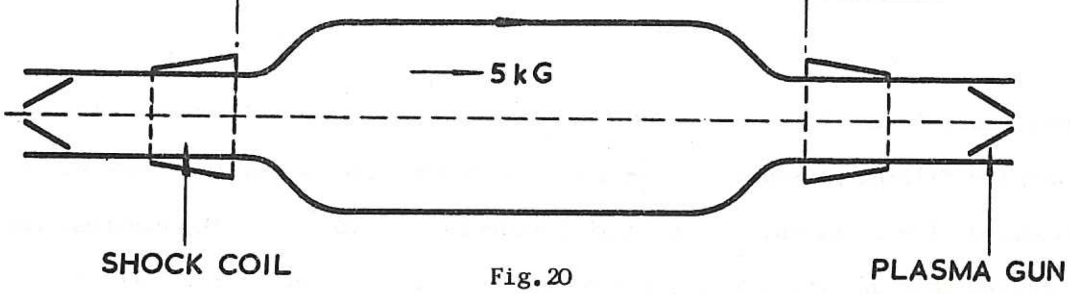


Fig.20

In this installation two conical thetatron guns produce plasma blobs with velocities $2-3 \cdot 10^7$ cms/sec (~ 1 keV). These plasmoids then pass through shock coils which produce fields ~ 10 kG oscillating at ~ 1 Mc/s. The effect is to turbulently heat the electrons in the plasma and to break it up into bunches which are accelerated into the centre of the machine. Thus these bunches are said to have a directed energy ~ 7 keV, $n \sim 10^{14}$/cc and $T_e \approx 10$ keV. The blobs collide in the middle through the excitation of ion sound instabilities to give a plasma with $T_e \sim 10$ keV, $T_i \sim 2$ keV, and $n \sim 10^{13}$/cc. This plasma decays in a stable manner with a time constant of 100 μsec. The trapped magnetic field in the colliding plasma is 50 - 100 gauss, but it is denied that this plays any role in the collision. Hard X-rays (~ 3 keV) are observed at the time of collision.

The dense plasma work is under the direction of Dr. Alikhanov. Two main lines have been pursued; (i) the production of a dense, cold plasma as starting point for compression and (ii) the fast (destructive) compression of thin metal liners inside a shot, strong, thetatron coil.

They are just on the point of combining (i) and (ii) in an attempt to create a dense hot plasma. To do (i) they were passing 200 kA with a rise time of 100 μsec through a ceramic pinch tube 15 cms long and 5 cms diameter, filled with hydrogen at a few mm Hg pressure. The measured pressure on the axis rises to ~ 100 atm and to somewhat lower at the wall. The conductivity corresponds to a temperature ~ 10 eV. The plasma is very impure but radiation trapping is said to keep the energy loss rate down so that the containment time is ~ 100 μsec. In another technique for (i) an arc is struck between the metal vessel and a rod which is then rapidly withdrawn. (see Fig.21).

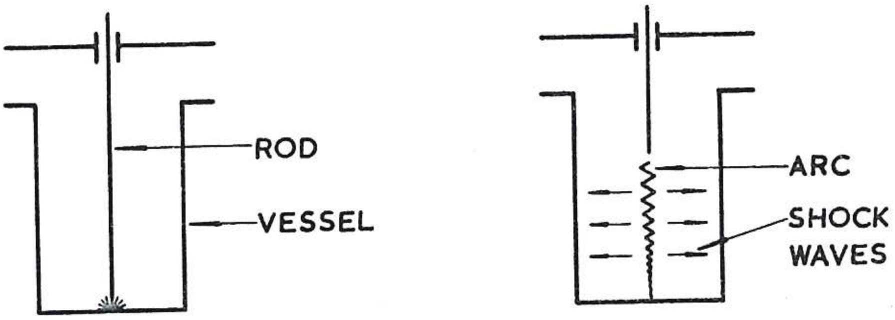


Fig.21

It takes about 7 msec to move the rod the length of the vessel (15 cms). The arc current ~ 1A and the filling pressure is ~ $\frac{1}{10}$ atm. From the velocity of the shock waves which are produced $T \sim 2$ eV, while from Stark broadening $n \sim 10^{18}$/cc. The eventual intention is to follow this up with a 50 kA current pulse to heat the gas still further.

For the magnetic compression (phase (ii)) a strong thetatron coil has been made and with an 800 kJ condenser bank a field of 400 kG is achieved with a rise time of 30 μsec. (See Fig.22). When a thin metal liner is put inside, up to 100 kJ of the stored energy can be converted into the kinetic energy of the liner itself.

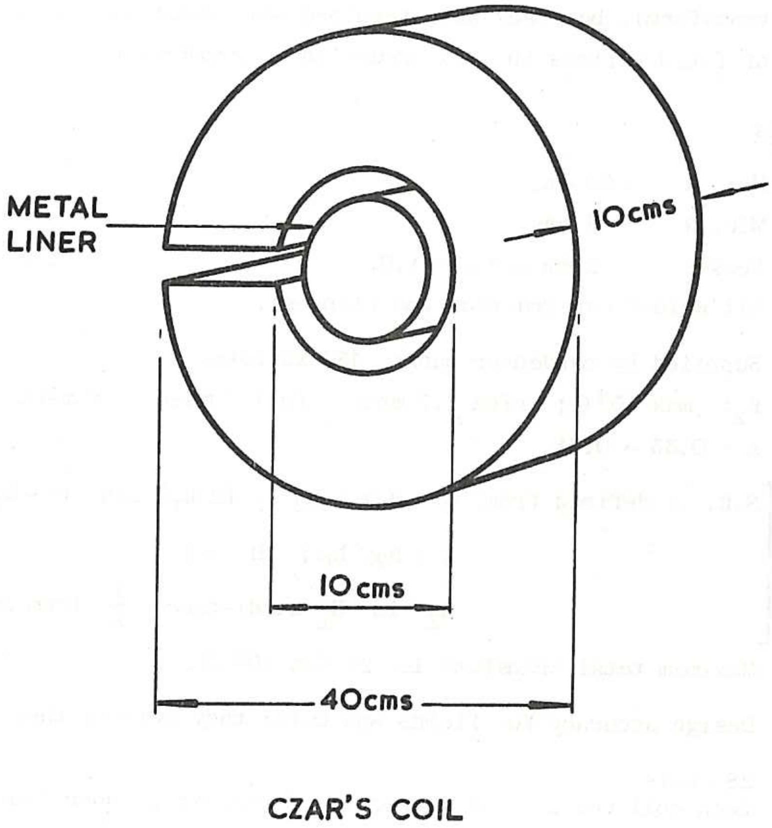


Fig. 22

LEBEDEV INSTITUTE, MOSCOW

THE LEBEDEV STELLARATOR (Dokl. Akad. Nauk, SSSR, 160, p.1293, 1965)

Object: To investigate adiabatic compression heating of plasma in a stellarator. The work to date (for one year) has mainly been electron beam measurements.

Construction: They have attempted to make a system with as little metal as possible (to permit penetration of pulsed fields). This has guided them to choose an $\ell = 2$ system (which is efficient in producing rotational transform), but they have retained some shear by having a large number of field periods ($n = 7$) around the circumference.

Dimensions and Fields

Mechanical:

Maj. R	60 cms
Min. R	5 cms
Vessel	2 mm S/S $\mu \sim 1.01$

All welded construction (no flanges).

Fields: Supplied by condenser banks 450 kJ total

B_z: max 10^4 G; rise 2.7 msec; fall 7 msec → 18 msec.

$\varepsilon = 0.33 \rightarrow 0.71$.

[N.B. ε defined from $\psi = H_0 z + h_2 I_2 (2 k_r) \sin 2(\varphi - k_z)$

$\varepsilon = h_2 / h_0$; $H = \nabla\psi$

h_2 is $H_\perp$ at distance $\frac{1}{k}$ from axis.]

Maximum total transform is 2π (at 10^4 G).

Design accuracy for fields was 0.1%; they believe they have achieved < 1%.

B_z coil design: 28 coils
Each coil consists of two pairs of pancakes, inner links between pancakes are helical with opposite pitch in each pair. Coil to coil connections are made at large radius. The coil systems are fed by parallel plate transmission line. Initial adjustment is to a scribed circle on a base plate and no further adjustment proved necessary.

Helical Winding: Wound directly on toroidal vessel in 8 mm dia. Cu wire by means of an indexing head on a rotating arm pivoting at torus centre. Complete winding potted in epoxy. No adjustment available.

Electron Beam Measurements

Based on small pulsed gun and a cylindrical, capacitive pick up electrode or a small target (3 mm × 3 mm). Electron energy ~ 100 eV, $r_L \sim 0.1$ mm. The results are compared with calculations based on toroidal perturbation of a cylinder Bessel function field plus corrugation perturbation due to B_Z coil system. They also had toroidal calculations for actual helical conductors, but we did not see them.

(1) The cylindrical pick up electrodes indicates 100 → 120 transits in the case of no 'resonance' and for the gun inside the separatrix this limit is set by the gun area (as an obstacle). It was said that the number of transits observed dropped to 5 or 6 when the gun was outside separatrix and when the transform was rational (a so-called resonance) - we presume this occurred when the gun was near to the wall.

(2) A small target was used to locate the beam after 20 → 30 transits (1 μsec pulse or gun and measure arrival time). With no low order rational transform anywhere in the bore they obtained elliptical surfaces somewhat displaced from the centre of the winding in agreement with calculation.

When the transform was $\frac{1}{3}$ or $\frac{1}{2} \times 2\pi$ at some radius in the bore, they got 'clustering of the lines' at this radius in agreement with the idea of closed lines rather than surfaces.

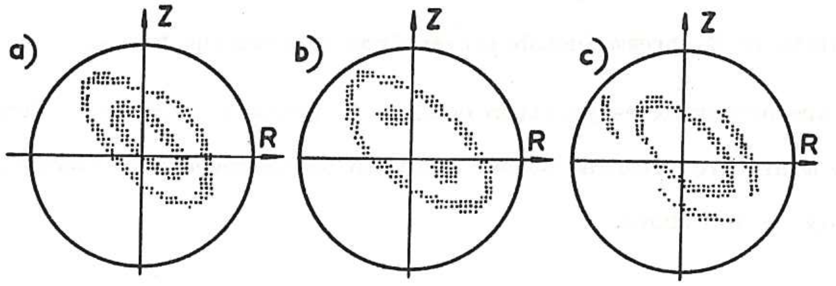


Fig. 23

Cross sections of magnetic surfaces for different ε

(a) $\varepsilon = 0.40$; (b) $\varepsilon = 0.37$; (c) $\varepsilon = 0.39$

(a) No resonance; (b) Resonance at $\ell = \frac{1}{2}*2\pi$; (c) Resonance at $\ell = \frac{1}{3}*2\pi$.

(3) They claim for $\ell = 2\pi$ (n = 1 resonance) the whole system of surfaces at all radii broke down after 20 → 30 transits leading to loss of lines (no pictures).

It was also stated that having a resonance anywhere in the bore led to rapid loss of field lines due to the action of perturbations. It seemed to us that a loss of field lines should only occur in a shear free field and that in fact the pictures (see (b) above) did not show a loss. The group said that this was because only 20 → 30 transits were observed, if more transits could be observed a loss would be apparent. The results with the cylindrical electrode were quoted in support of this assertion.

(4) They had measured horizontal shift by adding B_V. The shifts were in agreement with calculation, e.g. 40 G gave shift of the outer surface of ~ 1 cm.

Plasma Injection

(1) Plasma was injected by 4 Bostick button guns in one cross-section, across the B_z; the blobs collide in the centre and then move along the field lines. They measure $n = 10^9$/cc using an 8 mm microwave cavity method*. Langmuir double probe gives $T_e \sim 15$ eV.

Injecting on field rise does show some compression.

They measure the containment time by observing n_e (microwave cavity).

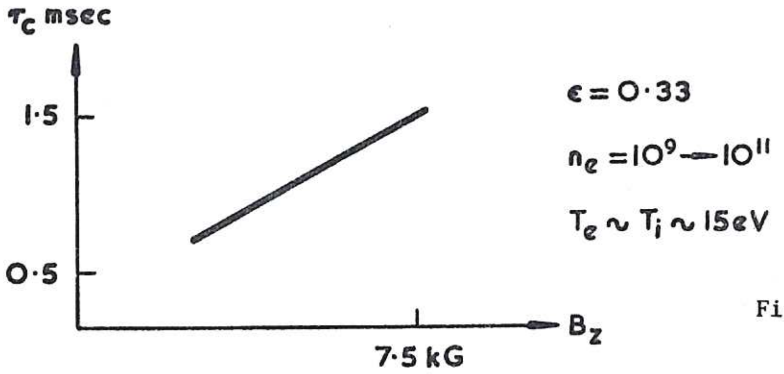


Fig. 24

(2) They do not have any explanation as yet for the short containment times, but speculate on 2 stream instabilities from interacting blobs.

(3) They are preparing e-cyclotron equipment, power 20 → 30 kW. They have developed a new miniature Titanium washer gun with an improved performance, but with a life of only ~ 200 shots.

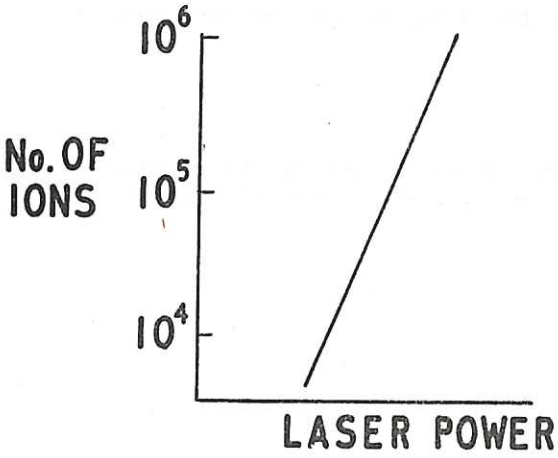
LASER PRODUCED PLASMA

A giant pulse from a ruby laser produced 0.5 to 1.0 Joule in a 15-40 nsec pulse giving a peak power of ~ 30 MW. This was focussed to a spot of 10λ to 100λ diameter. The large diameter is due to the "spottiness" of the light source. By using a long distance (~ 8 metres) between the light source and the focussing system they were able to use one "spot" and have achieved an image 10 μ diameter. They could then calculate the electric field E.

---

* AKULINA. Lebedev Report A - 27

For ionization of Xe gas:-



$$\text{Number of ions} \approx \text{Power}^{(7 \pm 1)} \approx \underline{E}^{14}$$

Fig.25

Using Keldishs' theory they therefore conclude that about 7 photons are required for ionization and this is in agreement with the ratio of ionization potential to photon energy.

When asked about future program they said they had no plans for solid H_2 work at the moment but were interested in using the laser to project solid particles at 10^{5-6} cm/sec at a solid H_2 target.

IOFFE PHYSICO-TECHNICAL INSTITUTE, LENINGRAD

We were given an introductory talk in which the following groups were mentioned:-

Under Prof. Dukelskii

Ankudinov V.A. Andreev E.P. Bobaschev S.V.	(1)	"Looch" (Ray) Experiment on Excitation by atomic collisions. Also optical emission m = 7-2 state and life time for radiative decay.
Bydin Yu.F.	(2)	Negative ions

Under Prof. Federenko and Prof. Afrosimov

Gordeev Yu.S. Pamov M.N.	(1)	Coincidence Experiments
Gladkowski I.P. and others	(2)	Corpuscular Diagnostics
Il'm R.N. Solov'ev E.S. Oparin V.A.	(3)	Lorentz Ionization
Flaks J.P. and 3 others	(4)	Charge exchange and ionization in gases

In a separate section

Skornyakov G.V. Peregood B.P. and others	(1)	Magnetic bottles, exploding wires
Kagansky M.G.	(2)	Toroidal installation with adiabatic compression
Vinogradov N.Y. Podushukova K.A.	(3)	Electron cyclotron heating
Lanonov M.M. Galaktionov B.V.	(4)	μ-wave diagnostics and probes used on alpha
Bulyginsky D.G.	(5)	Magnetic Bottles

Under Zaidel A.V. A small optical group

Malyshev G.M.	(1)	Laser diagnostics	
		(i)	Thompson scattering
		(ii)	Showgraph
		(iii)	Polarisation
Schreider E.Ya.	(2)	Vacuum u/v	
		(i)	Absolute calib. of u/v spectrometer
		(ii)	Transition probabilities in inert gases

CORPUSCULAR DIAGNOSTICS

Neutral emission from plasma was examined with a mass/energy analyser. In "active" experiments a probing neutral beam was passed through and the attenuation measured, in "passive" experiments the charge exchange emission was measured.

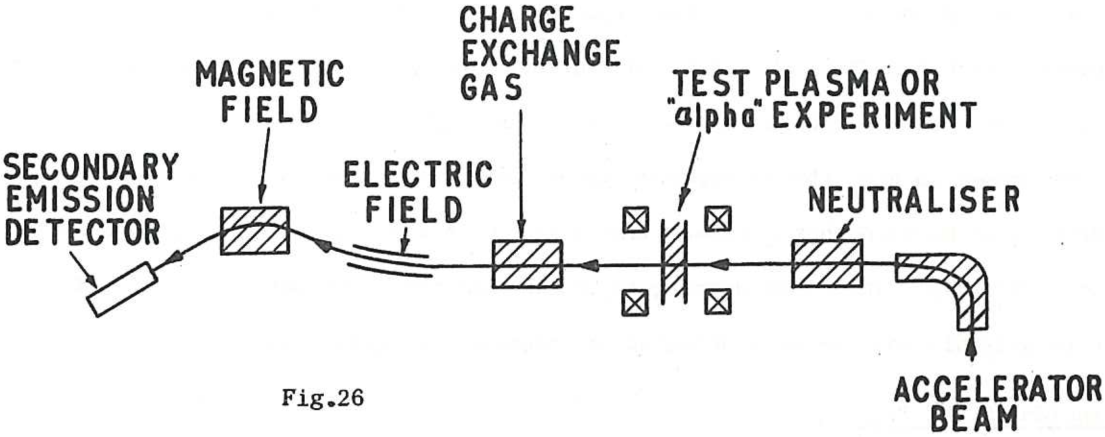


Fig.26

The device can select both momentum and energy and in this way the large background from the ALPHA experiments was eliminated. The beam is chosen to match the plasma, e.g. H with H^+ plasma, so that resonant charge exchange ensures this is the dominant loss process. The method is effective for energies of 100 eV and higher. The upper density limit was said to be $10^{16}/cm^2$ and the lower limit ~ $10^{12}/cm^2$. They have compared results with μ-wave results in the range $10^{13-14}/cm^2$ and obtained good agreement. A time-of-flight method was mentioned also which appeared to have no advantages over the spectrographic one.

MEASUREMENT OF EXCITED STATE POPULATIONS

Recent work had been concentrated on the excited state population of 10 - 100 keV H^+ beam after neutralisation by a thin target of alkali metal vapour. The technique is almost identical with that used at Culham and the results are indicated in the figure. These will be presented at Quebec.

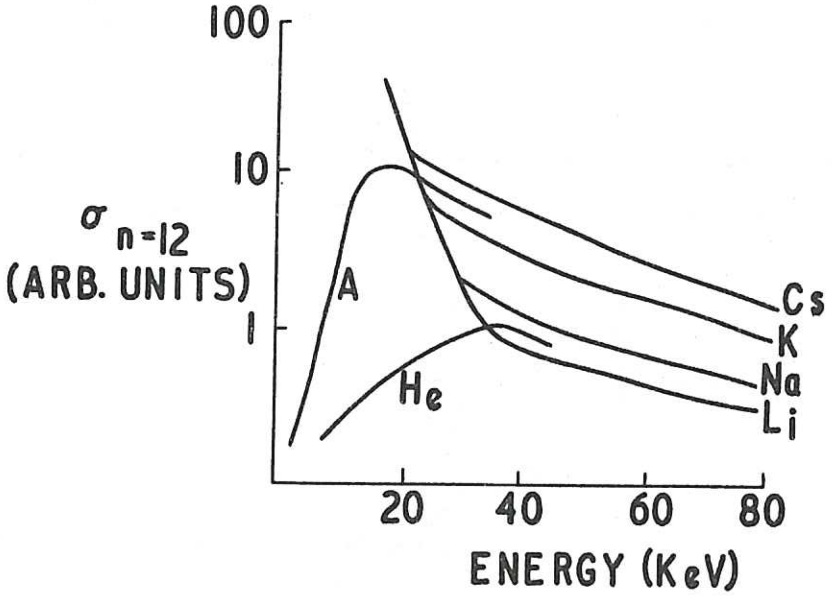


Fig. 27

THE G.V. SKORNYAKOV TRAP

Object: To find a closed system for stable confinement with no leviated conductors.

Preliminary Discussion on Lines and Surfaces

In a closed geometry there are two types of line, (a) rotational transform and (b) irrational transform. Type (b) trace out surfaces as they pass round and round the trap. Type (a) trace out only closed curves. Skornyakov emphasised the difference between these types and seemed to give the differences great importance even in a sheared system. After some discussion he said that a closed line (type (a)) would not be parallel to an adjacent surface (type (b)). This seemed wrong to us, but we could not obtain any clarification, and it is possible that we were defeated by language difficulties.

Description of the Trap

The central idea of the trap is to create a sheared magnetic field with magnetic surfaces, and having a region in which the field increases outwards everywhere. One of the outer irrational surfaces is then, ideally, replaced by a super conductor thus ensuring that all field lines stay within a finite volume. Field lines will leave the min $\underline{B}$ region and return to it through regions of adverse curvature.

Stability depends on connecting and averaging along the field lines. Calculations have been made only for $\beta = 0$ and for infinite conductivity, i.e. only the stability of the magnetic field has been considered.

To combat the possibility of loss in the adverse curvature regions, the field here is very strong and these regions are made a small part of the trap.

The idea is very similar to Tuck's caulked picket fence, but the fields are established without the use of levitated conductors.

Practical Realisation

Consider 'spherical' helix inside a thick copper sphere. Let the helix be fed by a current pulse so that the magnetic field is confined inside the sphere (Fig.28). The field

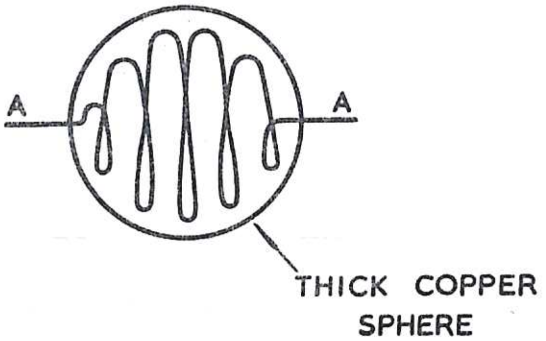


Fig.28

is weak in the centre and increases towards the helix. The field lines return to the centre via the strong field region between the helix and the wall. In this geometry the image currents can be calculated; they form a helix with opposite current, or alternatively a helix with same current direction and opposite pitch.

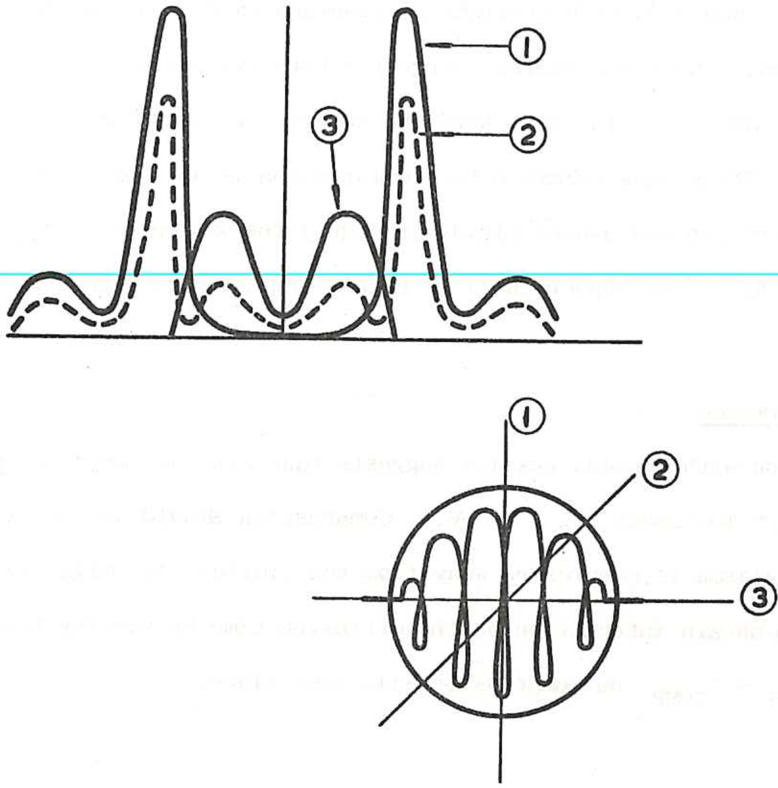


Fig.29

Traps of the copper shell and the double helix type have been constructed and the windings energised by condenser banks (37 kJ at 5 kV) the magnetic fields produced are measured with magnetic probes. Examples are shown in Fig.29. It will be seen that a double walled well is formed. The outer wall protects the poles and disappears at the equator, the inner wall has the opposite behaviour.

A major difficulty is to find a way to introduce plasma into such a device, which is surrounded by either a copper sphere or a double helix. The experimental group has constructed the helix from ferromagnetic material and intends to introduce a varying magnetic flux by means of an external iron yoke. Preliminary experiments using a rectangular yoke and a 30 kJ, 50 kV condenser bank have induced electric fields of 0.3 V/cm in air. A further difficulty is that the helix can only be supported at its poles and consequently collapses under the magnetic pressure; turn-to-turn shorts appear after about 8 msec.

No experiments have been performed with plasma as yet.

TOLMAN (GOLANT)

Object: To investigate adiabatic compression in a torus.

Apparatus

The apparatus is shown schematically in Fig.30. The quasi-d.c. fields indicated are produced by a lumped coil system. Additionally an open-coiled, two turn, helical compression coil is wound on each straight section and carries a current of 300 → 400 kA at peak compression. The total stored energy for both systems is 300 kJ. The time sequence is shown in Fig.30. In the future the compression coil current will be clamped at peak current. The plasma volume before compression is 15 → 20 ℓ and after compression, when straight section and u-bend fields are equal the volume is ~ 1 ℓ. Plasma equilibrium is established by a 5 mm copper shell on each u-bend, and by eddy currents in the compression coil.

Expected Performance

Comparison with Tokomak results suggests that with no compression it should be possible to get $\tau_C \sim 100$ μsecs, $T_e \sim 20$ eV. Compression should now increase T_e to 200 eV and since the plasma is compressed away from the limiter τ_C might be improved. It should be possible to obtain information on the diffusion time by varying the compression time since if $\tau_{DIFF} < \tau_{COMP}$ no compression will take place.

Results

(i) 8 mm microwaves are cut off before compression is applied. 4 mm diagnostics are being installed.

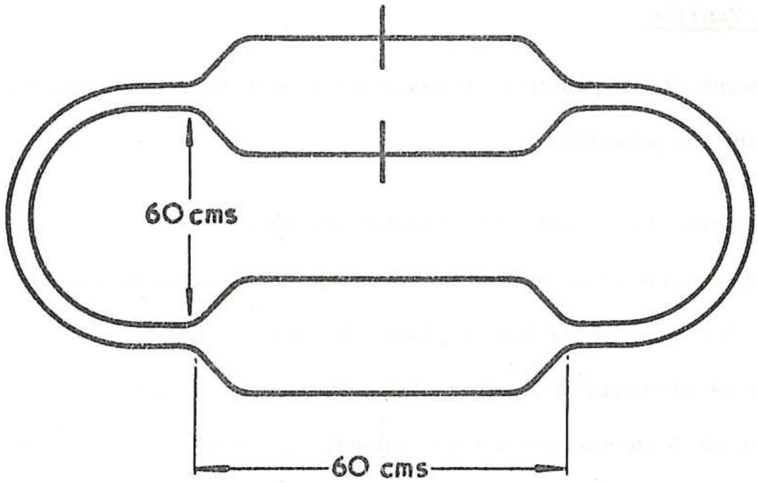
(ii) Streak cameras show gross instabilities for operating pressures below 2 mT and the usual operating pressure is 10 mT.

(iii) Streak cameras show that the plasma diameter in the u-bend is the magnetic image of the limiter, and that there is some compression in the straight sections.

(iv) On the basis of the conductivity temperature of 2 → 8 eV diamagnetic loop measurements, with no compression, show that n_e increases with B_z in the straight section (see figure) up to 1000 G. This behaviour is consistent with partial ionization at lower B_z, as is indicated by H_β light.

Future Work

The group is considering a suggestion by Constantinov for a non-equilibrium fusion experiment. The idea is to use a mixture of $D_2 + 1\% \ T_2$. Ion cyclotron heating at the tritium frequency is applied before compression when collisions are rare. In this way a population of energetic tritons is produced and these produce an enhanced reaction rate on compression.


60 cms
60 cms

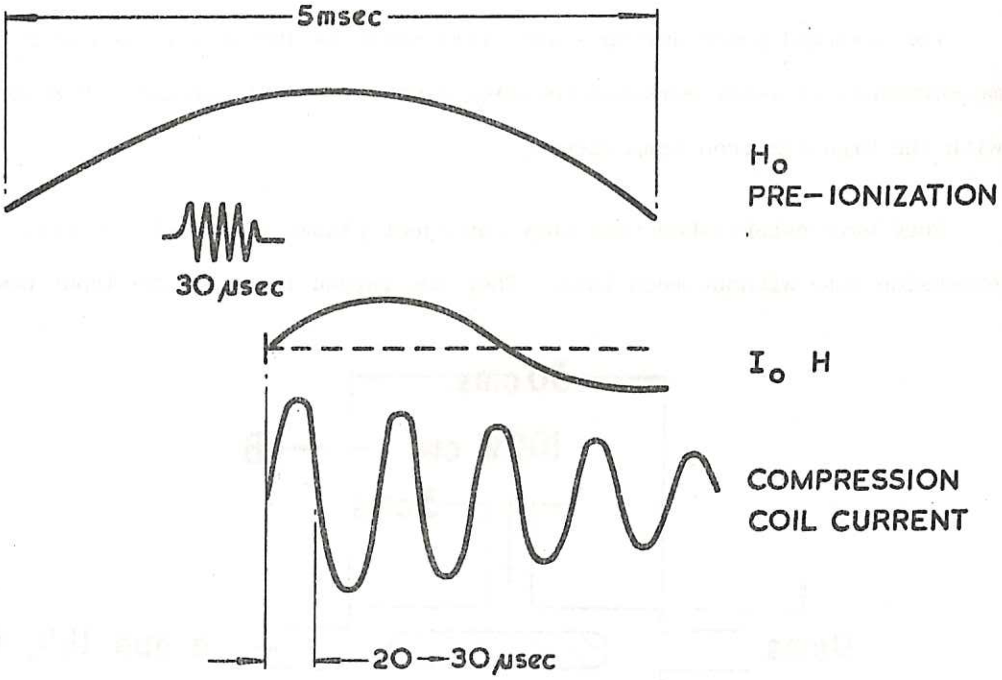
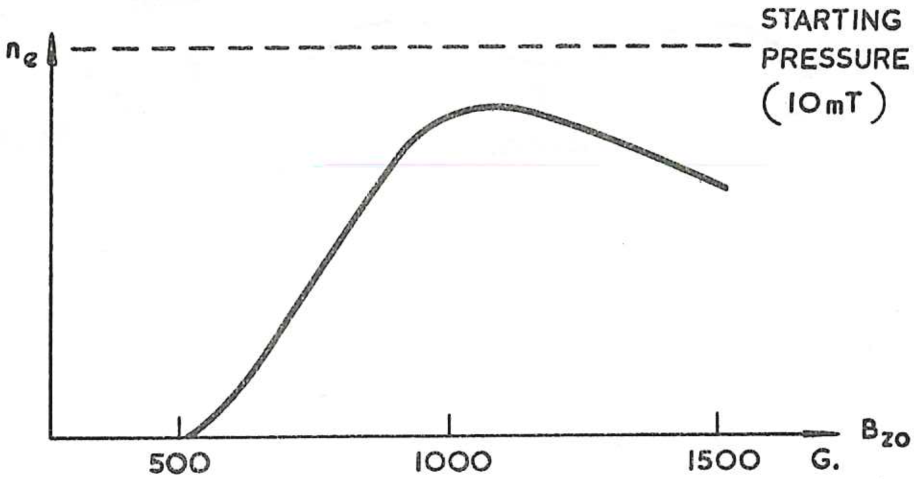

5 msec
H_o
PRE-IONIZATION
30 µsec
I_o H
COMPRESSION
COIL CURRENT
20—30 µsec

Fig.30


n_e
STARTING
PRESSURE
(10 mT)
500
1000
1500
G.
B_{zo}

ELECTRON CYCLOTRON HEATING

In this experiment it is planned ultimately to heat both ions and electrons at their respective cyclotron frequencies.

At present only electron cyclotron heating has been tried. A mirror magnetic field is used and heating occurs in a cylindrical cavity of dimensions shown. The pressure is 10^{-6} - 10^{-3} Torr. The experiment takes place in three stages:

(i) The gas is preionized with a 1 keV, 10 μA electron beam

(ii) 100 watt CW 3 cm microwaves are added. n_e reaches ~ 10^{10}/cc.

(iii) At peak field and ionization a 100 kW 10 μsec long burst of 3 cm microwave power is added. n_e reaches ~ 10^{12} in 5 μsec.

The absorbed power during stage (iii) suggests 100 kV/electron at $n_e = 10^{12}$, and measurements of x-ray emission energies give cut-off at 200-250 keV which is in agreement with the high electron temperature.

They have established that they can eject plasma from such a cavity into a glass extension tube without much loss. They now intend to raise the input power.

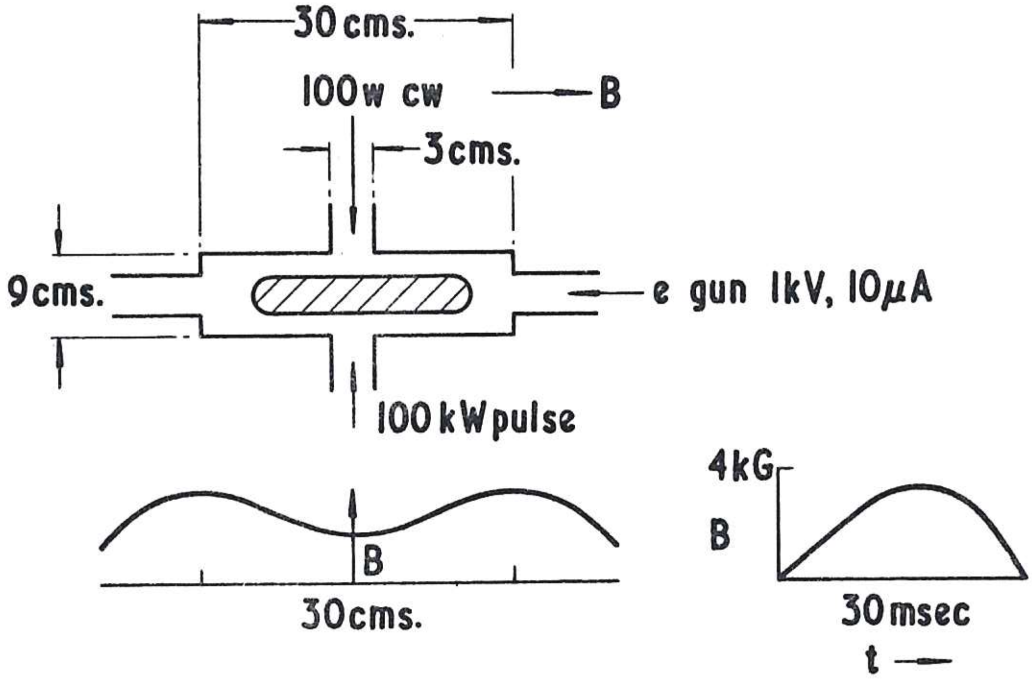
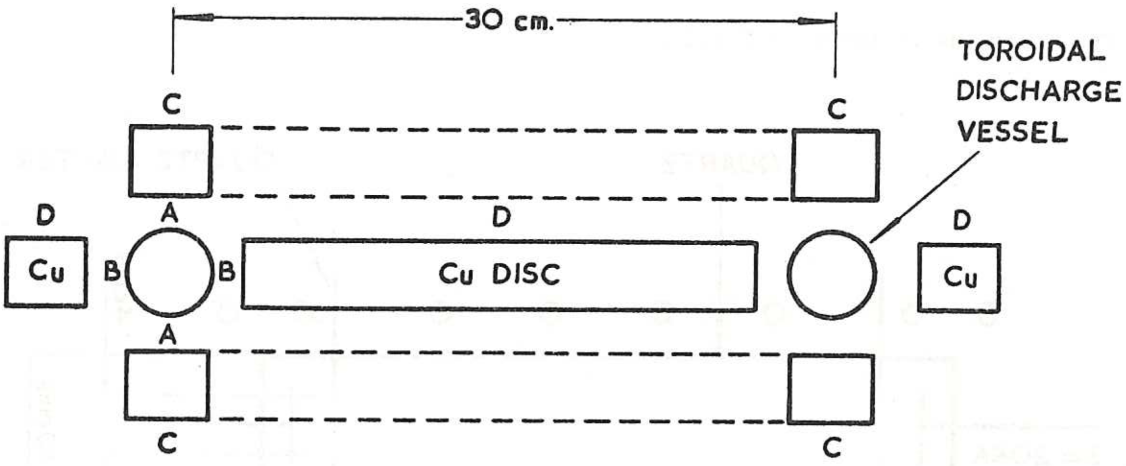


Fig.31

TOROIDAL CUSP EXPERIMENT (see Sov. Phys. Tech. Phys., 9, (4), 464, (1964))

The apparatus is shown in Fig.32. A toroidal cusp field is produced by pulsing the coils C C, which carry parallel currents, in the presence of copper discs D,D. In order to remove the field zero on the torus axis a weak axial field ($\sim \frac{1}{10}$ cusp field) can be applied. Axial electric fields are produced by the pulsed cusp fields; these are maximum at A A, and zero at B B. The $\underline{E} \wedge \underline{B}$ drift should cause plasma to concentrate at B B. It is intended to use a P.I.G. discharge to produce the plasma and all work to date has been concentrated on this aspect, so that when we saw the apparatus the discs D D were not fitted.



TOROIDAL CUSP EXPERIMENT

Fig.32

EFREMOV SCIENTIFIC RESEARCH INSTITUTE OF ELECTRO-PHYSICAL APPARATUS (KOMMAR)

ALPHA

The most interesting development is the measurement of plasma density by particle beams. The work is described elsewhere in this report.

RADIO-FREQUENCY STABILIZATION

We were told by Professor Kommar that this work is based on theoretical work by Kadomtsev, to be published at the Belgrade conference and we were later told in Moscow that Osevets and his group take an interest in the work. There are two experiments OMEGA, a straight Z-pinch device and TOLOSCOPE a toroidal pinch which at the time of our visit was just brought into operation.

OMEGA

The apparatus is shown in Fig.33.

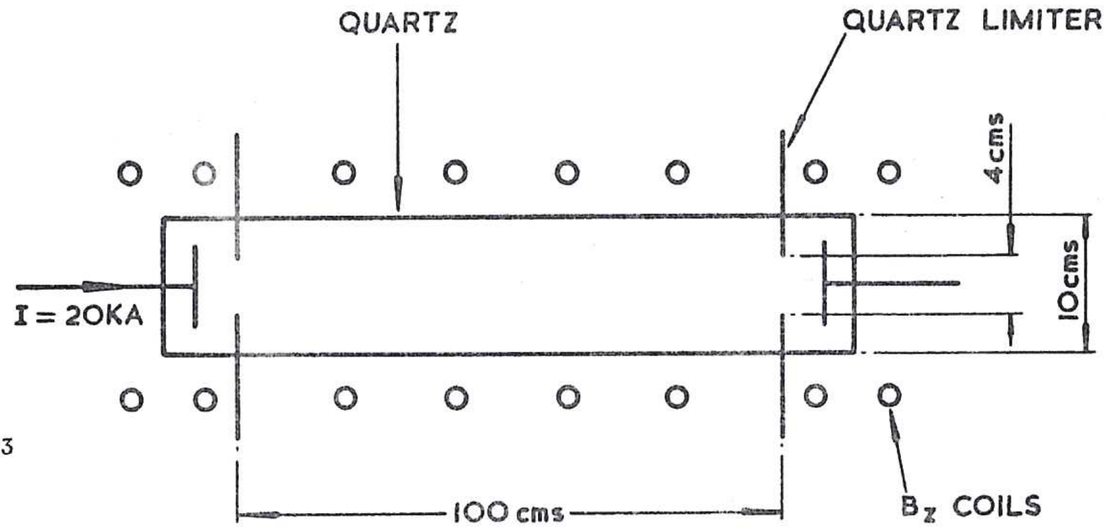


Fig.33

The return current flows in a coaxial cage outside the quartz vacuum vessel. The operating pressure is in the range 0.1 → 100 mT and the conductivity temperature is 10 → 13 eV. An r.f. pre-ionizing pulse is provided. The r.f. stabilizing current is applied through the main electrodes and may equal the ohmic heating current; it is supplied from a 20 MW pulse 1 Mc/s set. The sequence of operation is shown in Fig.34.

Results

When the B_z is set approximately equal to the quasi-d.c. B and $I_z \approx I_{r.f.}$ the r.f. current produces a marked reduction (5 → 10 times) in the fluctuations observed on magnetic probe traces and total light output, this reduction persists for the duration of the r.f. current.

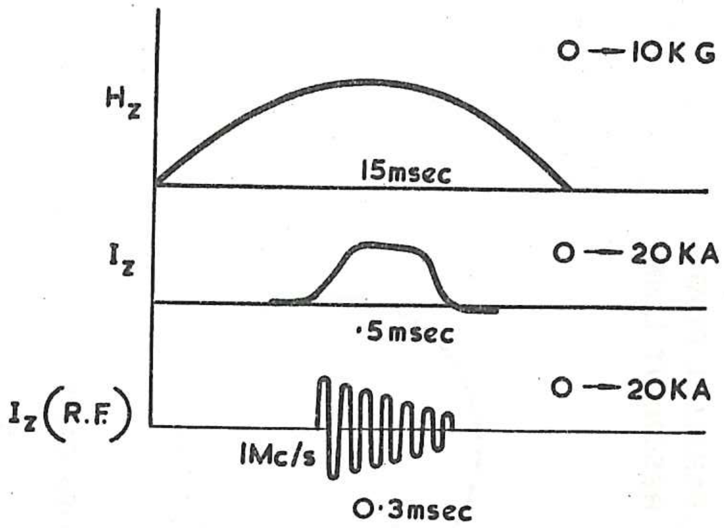


Fig.34

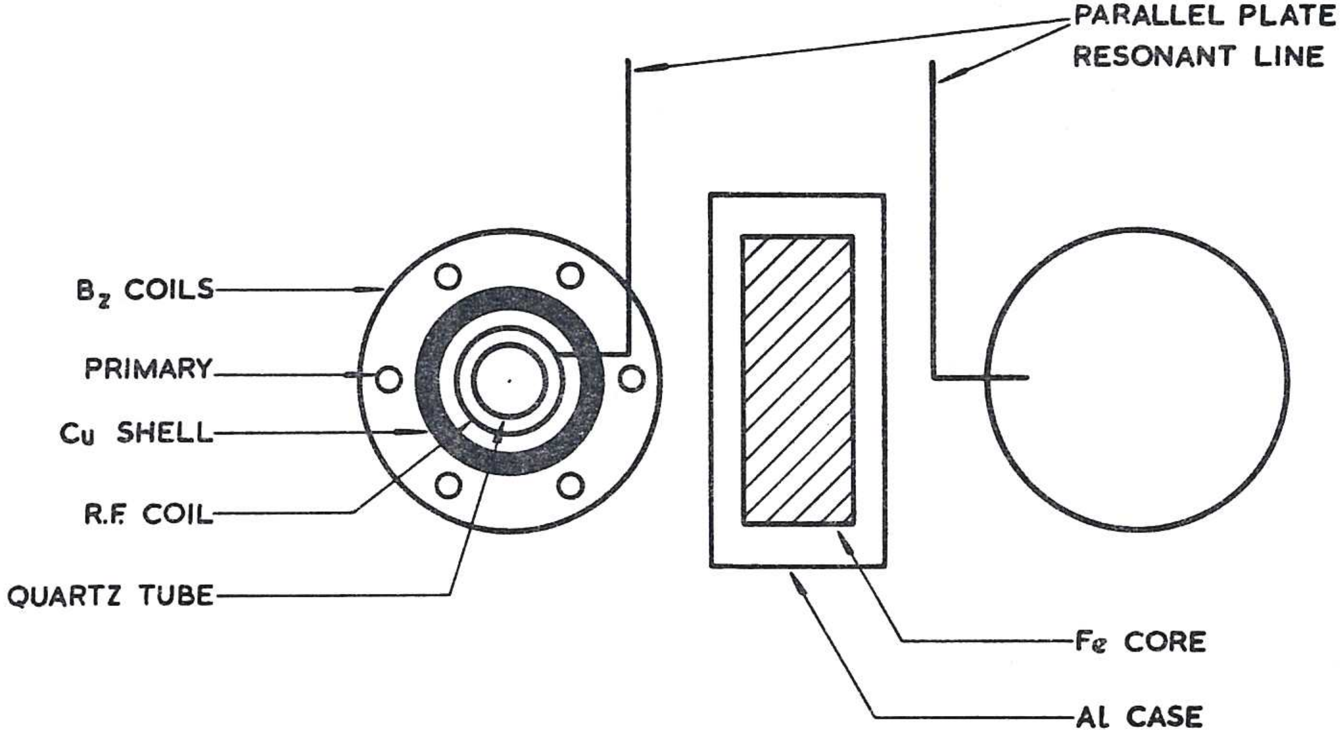
OMEGA

TOLOSCOPE

The toroidal apparatus is shown in Fig.35. The i.d. is 6.5 cms, major diameter 70 cms and base pressure 10^{-6} mm. The quasi-direct current is provided by an iron core and a primary winding on the torus. In addition to the features of OMEGA a 2 mm eddy current wall having 15 vertical slots and a horizontal slit, is provided for equilibrium, and there is provision for using the r.f. to modulate the B_z instead of the I_z. The r.f. generator is 50 MW pulse at 1 Mc/s and is mounted on top of the apparatus; other supplies are outside the building.

Results

Work has started using magnetic probes and photo-multipliers, but as yet data has been taken only with no r.f. applied. In argon and hydrogen and an axial field of 5000 G instabilities are observed when $I_{OH} > 2$ kA.



TOLOSCOPE

Fig.35

REPORT ON SOVIET PLASMA THEORY

One of the most important developments in Soviet plasma theory has been the extension of the quasi-linear theory of plasma turbulence, sometimes called the theory of weak turbulence, to the point where it can be applied to specific situations such as the universal drift instability$^{(1)}$ and the velocity space, mirror instability of Post and Rosenbluth$^{(2)}$. Naturally this is of direct importance in present and planned experiments. So far, the few applications have been evaluated only in a semi-quantitative way, but the preliminary results indicate the serious consequences of these well known instabilities for plasma containment.

Linearized theory tells us whether an instability will occur, but says nothing about the amplitude to which the instability may grow, or about its ultimate fate. Quasi-linear theory enables us to estimate the energy spectrum of the waves which have developed from the instabilities and to write down a diffusion type equation for particles in velocity and real space, from which may be calculated the anomalous diffusion of plasma, either in real space, or in velocity space as for a mirror machine. A rigorous mathematical description of the turbulent transfer processes involved is possible only for a weak instability when the turbulent state of the plasma can be visualised as a set of weakly interacting oscillations. This picture of plasma turbulence in the form of a set of oscillations, or waves, is reasonable if the growth rate of the instability γ is small compared with its frequency ω and the amplitude of the oscillation changes only slightly during the period of a single oscillation.

The formalism has been developed by R.Z. Sagdeev's group at Novosibirsk and they have solved several specific examples. Full details are available in many papers and reviews$^{(3,4,5)}$ and in the independent work of Drummond and Pines$^{(6)}$. To summarize very briefly, they begin with Vlasov's equations

$$\frac{\partial f}{\partial t} + v \cdot \nabla f = \frac{e}{m} \nabla \varphi \cdot \frac{\partial f}{\partial v} \qquad \ldots (1)$$

$$- \nabla^2 \varphi = 4\pi e \int f \, dv \qquad \ldots (2)$$

The wave potential φ is expanded in its Fourier components

$$\varphi = \sum_{k,\omega} \varphi_{k\omega} \, e^{i(kr - \omega t)} + \text{comp. conj.}$$

and then f is expanded in powers of $\varphi_{k\omega}$ thus

$$f(r,v,t) = f^{(o)}(r,v,t) + \sum_{k,\omega} \eta_{k\omega}^{(1)}(v,t) \, \varphi_{k\omega}(r,t) + \ldots \qquad \ldots (3)$$

The first term on the RHS is a slowly varying function, the remaining terms in the expansion contain the oscillatory parts. The coefficients $\eta^{(p)}_{k\omega}$ are obtained by iteration from equation (1) substituting $\eta^{(p-1)}$ in the RHS of equation (1) and then integrating along the unperturbed particle trajectory. Substituting f into equation (2) then gives the time variation of the oscillatory energy spectrum $|\varphi_k|^2$. Thus, if $\eta \propto |\varphi_k|^2$, this equation is, as far as On_k^2

$$\frac{d}{dt} n_k = 2\gamma_k n_k + \sum_{k'} R(k,k')\, n_k n_{k'}$$

$$+ \sum_{k'+k''=k} |V_{k\,k'k''}|\, \delta\,(\omega - \omega' - \omega'')(n_{k'} n_{k''} + \ldots)$$

$$+ \ldots \qquad \ldots (4)$$

The three terms on the RHS have a simple physical interpretation : the first is a linear (Landau) growth or decay, the second is the simultaneous adsorption of two waves by a particle (non-linear Landau effect) and the third term denotes the dispersion of waves throughout the spectrum by processes of creation and annihilation. The calculation of the matrix elements $R_{kk'}$ and $V_{kk',k''}$ follows from the iteration procedure, taken as far as $\eta^{(3)}$. The solution of the equilibrium $dn_k/dt = 0$ can only be obtained in order of magnitude from equation (4) giving

$$\frac{k^2 e^2 |\varphi_k|^2}{T^2} \sim \frac{\gamma_k}{\omega_k} .$$

By averaging equation (1) over the periods of the fast oscillations one obtains the quasi-linear equation for the averaged distribution function. Thus

$$\frac{\partial}{\partial t} f^{(o)}(r,v,t) = -\frac{e}{m} \sum_k i\, \underline{k}\, \varphi \cdot \frac{\partial f}{\partial \underline{v}}$$

$$= \frac{e^2}{m^2} \sum_k \frac{\partial}{\partial v} \left(\frac{|\varphi_k|^2\, \gamma_k}{(\omega - k \cdot v)^2 + \gamma_k^2} \right) \frac{\partial f^{(o)}}{\partial v}$$

$$\equiv \frac{\partial}{\partial v} D \frac{\partial f^{(o)}}{\partial v} \qquad \ldots (5)$$

where D , so defined, plays the role of a diffusion coefficient in velocity space. This theory has had two major applications which are now reviewed briefly.

(a) Anomalous diffusion resulting from the universal drift instability$^{(7)}$.

In this case D has been calculated and found to be in order of magnitude

$$D \sim 10^{-2} \left(\frac{m_e}{\beta m_i}\right)^{\frac{1}{2}} e a_i\, D_\beta \text{, where } D_\beta \equiv a_i v_i \qquad \ldots (6)$$

and $\frac{m_e}{\beta m_i} < 1$. Here a_i is the ion Larmor radius $\varepsilon = \nabla\eta_0/\eta_0$ and other symbols have their usual meaning. In this example D is the diffusion coefficient in real $\underline{r}$-space along the density gradient. However this anomalous diffusion rapidly distorts the original distribution function in velocity space and this is a self stabilizing mechanism. Thus the distribution function $f^{(o)}$ would tend to a stable shape and the instability would cease were it not for collisions which try to re-establish a near Maxwellian $f^{(o)}$. The balance between these two processes eventually determines the value of D so that the above value in fact is only valid if the electron collision frequency ν exceeds a critical value

$$\nu > \varepsilon v_i \frac{(\varepsilon a_i)^2}{10} \; . \qquad \ldots (7)$$

(b) Anomalous diffusion into the velocity cone of a mirror machine

This is the loss which arises from the growth of the Post-Rosenbluth instability, or presumably any Harris-type instability. In this case the diffusion coefficient D(v) is in velocity space only. It turns out that a necessary condition for the instability to grow into the non-linear phase in the first place is that the length of the mirror machine L exceed a minimum value L_{c1} where L_{c1} is density dependent and $L_{c1} \approx 4 \cdot 10^3 \frac{v_i}{\Omega_{pi}}$. For $L < L_{c1}$ the containment time $\tau \to \infty$, but for $L > L_{c1}$, τ decreases with L and Galeev gives

$$\tau \approx 3 \cdot 10^5 \, a_i^2 / L \, v_i \; . \qquad \ldots (8)$$

Under these conditions the ions empty into the loss cone which remains practically empty so long as $\tau > L/v_i$ = transit time τ_*. The upper critical length at which $\tau = \tau_*$ is given by $L = L_* = 500 \, a_i$.

If the machine length $L > L_*$ the loss cone no longer has time to empty and begins to fill. In these conditions, however, $\tau \approx {}^{L}/v_i$ and the machine is not behaving as a mirror trap but rather as a theta pinch with open ends. In practice, with $n > 10^{12}$ ions/cc, $L_{c1} \ll L_* \sim$ metres and therefore the loss of ions is determined essentially only by the transit time.

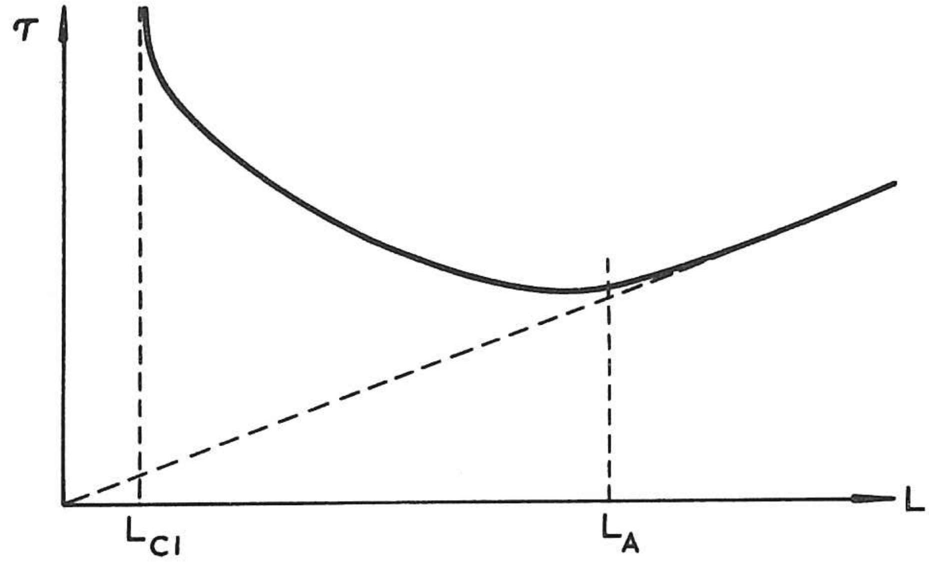


Fig.36

REFERENCES

1. KADOMTSEV, B.B. and TIMOFEEV, A.V., Soviet Phys. - Dokl., vol.7, no 9, March 1963, p.826.

2. POST, R.F. and ROSENBLUTH, M.N., Phys. Fluids, vol.8, no.3, March 1965, p.547.

3. VEDENOV, A.A., VELIKHOV, E.P. and SAGDEEV, R.Z., Nucl. Fusion, vol.1, no.2, 1961, p.82.

4. VEDENOV, A.A. J. Nucl. Energy Pt. C, vol.5, no.3, May/June 1963, p.169.

5. GALEEV, A.A., KARPMAN, V.I. and SAGDEEV, R.Z. Soviet Phys. - Dokl., vol.9, no.8, February 1965, p.681.

6. DRUMMOND, W.E. and PINES, D. Nucl. Fusion Supplement (Salzburg Conf. Proceedings) Pt. 3, 1962, p.1049.

7. GALEEV, A.A. and RUDAKOV, L.I. Soviet Phys.- JETP, vol.18, no.2, February 1964, p.446.

8. GALEEV, A.A. Novosibirsk Preprint. Culham Translation CTO/196.