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The principal results obtained from research conducted in the area of CTS and plasma physics in the USSR during the period extending from July of 1990 through July of 1991 are presented in the work at hand. Materials provided by the I. V. Kurchatov Institute of Atomic Energy, the Troitsk Institute of Innovational and Thermonuclear Research, the Soviet Academy of Sciences' A. F. Ioffe Institute of Applied Physics, the Soviet Academy of Sciences' Institute of General Physics, the I. N. Vekua Institute of Applied Physics in Sukhumi, the Ukrainian Academy of Sciences' Institute of Applied Physics in Kharkov, the D. V. Yefremov Scientific Research Institute of Electrophysical Instrumentation, and the Institute of Nuclear Physics of the Siberian Branch of the Soviet Academy of Sciences were used during the compilation of this review.

TOKAMAK–TYPE FUSION TEST REACTORS

1. Experiments relating to the generation of a noninductive current through the use of electromagnetic waves in the electron–cyclotron—resonance (ECR) frequency band on a T–10 tokamak–type fusion test reactor (the I. V. Kurchatov Institute of Atomic Energy, General Atomics, Lawrence Livermore National Laboratory, and Princeton Plasma Physics Laboratory). Superhigh–frequency (SHF) power with values of $\lambda = 3.69$ millimeters (mm) and $P_{SHF} \leq 2.2$ megawatts (MW) was injected from outside a torus at an angle of $\alpha = 21^{\circ}$ relative to the direction of the major radius of the torus (the main group of gyrotrons). The

gyrotrons in the supplementary group injected power with values of $\lambda = 4.0$ mm and $P_{SHF} = 0.64$ MW perpendicular to the direction of the toroidal magnetic field and were only used for plasma heating. Experiments were conducted in modes with discharge current values on the order of I_d =75–100 kiloamperes (kA) and electron concentration values on the order of $\bar{n} = (0.5–1.4) \cdot 10^{19}$ m^{-3} in the presence of a maximum microwave pulse duration of $t = 0.5$ seconds (sec). In order to determine the magnitude of the current generated by the electron–cyclotron waves, I_{cd}, discharge voltage values were compared during the generation of a current in the direction and opposite the direction of the electric field with all other conditions being equal.

The processing of the experimental data obtained, together with numerical modeling, demonstrated that a current magnitude of $I_{cd} = 110$ kA was generated in a plasma with values of $I_d = 175$ kA and $\bar{n} = 1 \cdot 10^{19}$ m^{-3} during the injection of SHF power with a value of $P_{SHF} = 1.45$ MW ($\lambda = 3.69$ mm). Here, current density in the center of the plasma filament came to $j(0) = 400$ amperes (A) per square

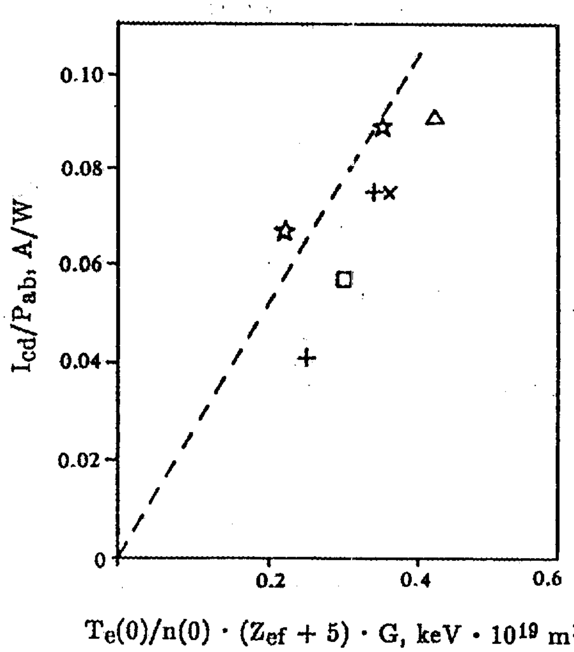

Fig. 1. The efficiency of entrainment current generation using electro–magnetic waves in the ECR frequency band on a T–10 tokamak–type fusion test reactor in the presence of microwave power with a value of $P = 1.2$ MW and a discharge current with a value of $I_d = 170$ kA (⋆), as well as in the presence of microwave power with a value of $P = 0.7$ MW and discharge currents with values of $I_d = 170$ kA (+), 140 kA (Δ), 100 kA (X), and 75 kA (□)

centimeter (cm^2). The efficiency of current generation was $\eta_{exp} = 0.09$ A per watt (W) at $T_e = 7$ kiloelectron–volts (keV). A comparison of η_{exp} parameter values and theoretical efficiency values calculated within the framework of a quasilinear approximation with allowance for the relativistic and toroidal effects demonstrated that $\eta_{exp} < \eta_{theor}$. This difference is largely due to the fact that energy lifetime comes to $\tau_E \sim \tau_{coll}$, where τ_{coll} denotes the Coulomb collision time for resonance electrons. Making allowance for the correction factor $G = 1 + \tau_{coll}/\tau_E$, which is linked to the finite value of the τ_E parameter, the values of the τ_{exp} parameter proved to be close to the predicted theoretical values. This is apparent in Fig. 1, where the broken line corresponds to the theoretical dependence of efficiency upon plasma parameters.

It should also be noted that modes in which the discharge current was completely replaced by a noninductive current consisting of a bootstrap current, I_b, and an electron–cyclotron current, I_{cd}, were forthcoming in the region of low discharge current values, $I_d < 100$ kA. Here, the share of the I_b component accounted for 30% of the total discharge current value.

2. Studies conducted on the T–15 tokamak–type fusion test reactor (the I. V. Kurchatov Institute of Atomic Energy). The comprehensive testing of this apparatus in modes with ohmic heating was necessarily completed during the first half of 1991. A mode involving the cryostatting of the superconducting winding of a toroidal magnetic field at a level of 4.5–5 coulombs (C) was sustained for a period of 280 hours (hr) in the presence of the simultaneous operation of an RG–2000 cooling unit and two OG–800 liquefiers. With working temperatures at a nominal level, the magnetic field at the torus axis reached a value of 3.5 teslas (T). Here, no resistive heat releases in excess of 100 W were recorded in the winding. Over the course of these tests, it became necessary to modify some of the subject cryogenic system's components due to the instable performance of this system.

The testing of poloidal–field power supply systems was carried out in the presence of current and voltage values which ensured the generation of a current on the order of 1–1.5 megaamperes (MA) within the plasma. Poloidal–field system control for the purpose of ensuring plasma filament equilibrium was undertaken in two variations: one involving the use of an analog system of automatic regulation and the other involving the use of a digital system. Both of these variations have shown themselves to be feasible.

Supplementary heating systems (the injection system and the gyrotron system) are being tested in autonomous modes. The performance of three cryomagnetic systems consisting of gyrotrons with individual helium filling was evaluated, as was the performance of an energy transfer line and gyrotron power supply systems. The first tests involving the injection of power into the T–15's chamber were carried out. Studies are ongoing in the area of primary injector adjustment.

3. Research conducted on the TSP tokamak–type fusion test reactor (the Troitsk Institute of Innovational and Thermonuclear Research). The perfection of power–engineering technology relative to the adiabatic compression of a plasma was continued and a technique for interrupting the primary current (40–70 kA) of an inductive storage device was refined, thereby making it possible to generate a magnetic field with a value of up to 7 T over the region of maximum filament compression [$R = 40$ centimeters (cm)].

Studies in the area of the generation of a pure plasma filament during the first discharge stage within a TSP tokamak–type fusion test reactor were carried out with great intensity. Together with the Soviet Academy of Sciences' Institute of Physical Chemistry and the "*Energiya*" Scientific Industrial Group, a method was proposed and adopted for boronizing the primary wall of a tokamak–type fusion test reactor by means of adding boron–containing gases based on carboboranes to a helium glow discharge.

During homologous experiments conducted on the T–11M (90 kA, the Troitsk Institute of Innovational and Thermonuclear Research) and T–3M (140 kA, the "*Energiya*" Scientific Industrial Group) secondary tokamak–type fusion test reactors, durable borocarbon coatings [with a thickness of 40–60 nanometers (nm)] were produced for the primary discharge–chamber wall. One result of the boronization carried out was a decrease in the value of the Z_{ef} parameter (from 2–3 to 1–1.2), together with an appreciable reduction in hydrogen recycling at the plasma–wall boundary. In the not–too–distant future, this method is slated for use in preparing the walls of the TSP tokamak–type fusion test reactor. An important feature of the proposed method is a high level of ecological cleanness, thereby making it possible to recommend this method for use during the *in situ* boronization of the walls and diverter plates of large tokamak–type fusion test reactors, particularly the ITER tokamak–type fusion test reactor.

The modeling of discharge–current damping (by 20–50%) was successfully carried out on the T–11M tokamak–type fusion test reactor for the purpose of narrowing the hot region of a filament. It has been proposed that this technique be employed during the first stage of operation of the TSP tokamak–type fusion test reactor instead of the previously planned preliminary compression along the minor radius.

4. Experiments relating to Bernstein plasma heating in the TO–2 tokamak–type fusion test reactor (the I. V. Kurchatov Institute of Atomic Energy). Experiments were conducted on the TO–2 apparatus for the purpose of studying the discharge modes of a tokamak–type fusion test reactor with supplementary heating via the direction excitation of an ionic Bernstein wave (IBW) at the frequency of the sesquiharmonic of ion–cyclotron resonance.

The excitation of an ionic Bernstein wave within a plasma was carried out using a high–frequency generator with an output of up to 500 kilowatts (kW), tuned to a frequency of 22.7 megahertz (MHz). A twin folded–dipole antenna was used to inject high–frequency power into the plasma. This antenna's current conductor was oriented along the "toroidal" magnetic field of the tokamak–type fusion test reactor so as to create the toroidal polarization of the electric field near the plasma filament boundary.

These experiments were conducted in a discharge mode with the following parameter values: a discharge current of $I_d = 40$ kA, a "toroidal" magnetic field of $B_T = 1$ T, and a mean concentration of $\bar{n} \cong 1.2 \cdot 10^{13}$ cm^{-3}. Hydrogen was used as the working gas. The magnitude of the "toroidal" magnetic field corresponded to the position of the zone of the sesquiharmonic of ion–cyclotron resonance for hydrogen ions in the center of the plasma filament. Switching on the high–frequency (HF) generator in this mode led to a change in the macroscopic parameters of the plasma filament, as well as in the magnetohydrodynamic (MHD) stability of the plasma at the level of power delivered by the HF generator in the presence of a load on the order of < 50 kW. Ion temperature measurements in the center of the plasma filament, which were performed through the use of a Fabry–Perot scanning interferometer via CV spectral line expansion, revealed efficient heating on the part of the plasma's ionic component. The temperature of the ions in the center of the plasma increased from the ohmic level of $T_{i_0}^{OH} = 220 \pm$

70 electron–volts (eV) to a value of $T_{i_0}^{\mathrm{IBM}} = 600 \pm 100$ eV during supplementary heating. Here, the electron temperature in the center of the plasma filament was not increased and came to $T_{e_0} = 350 \pm 50$ eV. The activation of the HF generator was accompanied by an increase in the concentration of electrons, as measured along the central chord of the SHF interferometer. The size of this increase was $\cong$ 20% of the ohmic level. The efficiency of ion heating, computed under the assumption that the total power delivered in the presence of a given load is absorbed in the plasma, reached a value of $\eta \cong 8$ eV/kW.

5. The investigation of the establishment of vertical stability and the regulation of the position of an elongated plasma on the TVD tokamak–type fusion test reactor (the I. V. Kurchatov Institute of Atomic Energy). In discharges with a quasistationary discharge current, a plasma filament with an elongation of $k \sim$ 1.4–1.5 is formed in front of the vertical separation. The maximum ellipticity of the magnetic boundary surface in discharges with a secondary current buildup comes to 1.6 and is reached in the presence of a small quadrupole–field magnitude value.

The efficiency of the stabilization of the vertical position of an elongated plasma using a combination of passive and active feedback systems was studied experimentally. The boundary separating the regions of "strong" and "weak" vertical instabilities was defined: $(-c/I_{\mathrm{d}} \partial B_z/\partial r)_{\mathrm{c}} = 0.85 \cdot 10^{-2}$ cm^{-2}. A dither–type relay system for actively controlling the position of a plasma suppresses vertical instability with a stability parameter value on the order of $m = 1/\tau_{\mathrm{S}}\gamma > 0.15$. When the number of azimuthal interruptions of the passive stabilization system was reduced from four to two, the stability boundary was shifted slightly into the region of the stronger quadrupole field. The magnitude of the critical quadrupole field rose by no more than 2.5%.

In the automatic relay system for horizontal control, the parameters of the proportional differentiating (PD) regulator in the dither–type modes were optimized. The appearance of creeping modes was detected during the development of a notching disturbance in the subject apparatus when using a PD regulator. The use of a proportional–integral–differential (PID) regulator resulted in an unstable process.

According to calculations, it is necessary to satisfy two conditions in order to produce a plasma with an ellipticity of $k > 2$: first, a sufficiently flat current profile (the current profile must be no thinner than parabolic for $k = 2.5$) and, secondly, a

monotonous dependence between plasma ellipticity and the external stretching field. Here, while a thin current profile does not permit one to produce a plasma with a high degree of ellipticity ($k > 2$), a flat profile hinders the development of a diverter configuration.

6. **Experiments conducted in the area of the initiation of an *H*–mode through the use of a radial electric field on the "Tuman–3" tokamak–type fusion test reactor (the Soviet Academy of Sciences' A. F. Ioffe Institute of Applied Physics).** A spontaneous transition to a mode with improved energy and particle retention — the "ohmic *H*–mode" — was detected over the course of previous

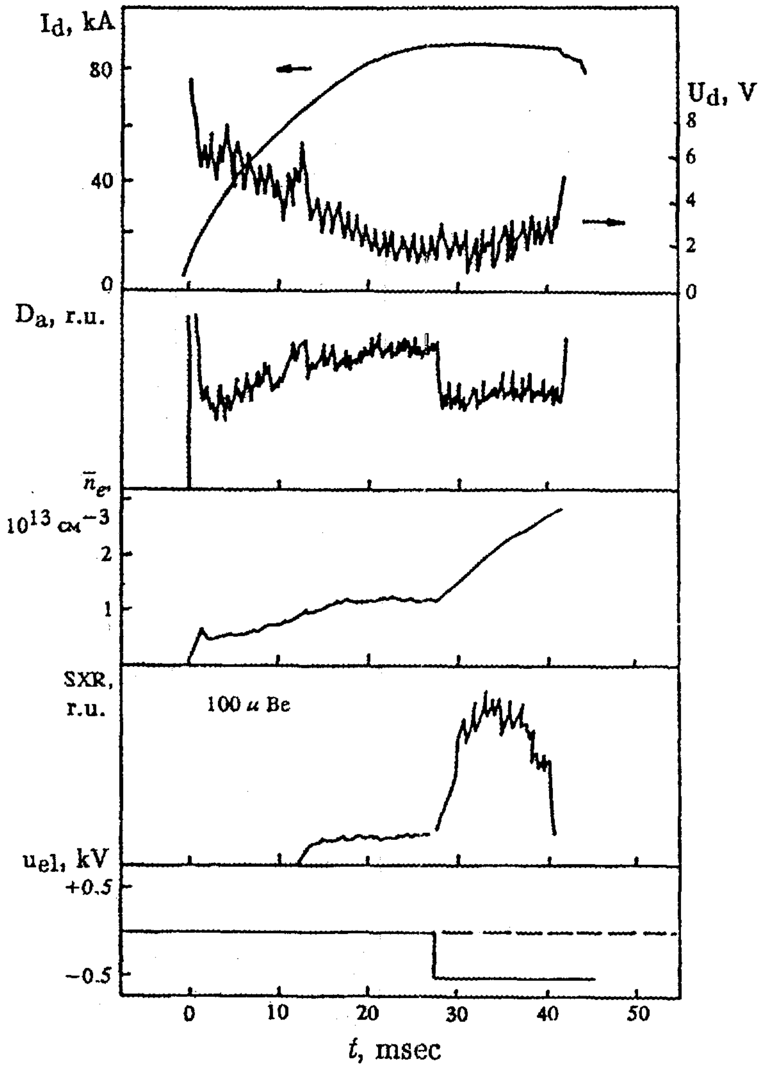

Fig. 2. The initiation of an *H*–mode via negative voltage

r.u. — relative units

experiments. According to extant theoretical concepts and experimental observations, a transition to the *H*–mode is accompanied by a radial electric–field increase in the peripheral region of a plasma. The purpose of the ensuing series of experiments conducted on the apparatus at hand was to verify the assumption that it is possible to initiate an *H*–mode by means of artificially generating an electric field at the aforementioned periphery. A radial field was generated through the use of an insulated electrode with a molybdenum tip, which was inserted a distance of 3–4 cm into an extreme closed magnetic surface. The tests carried out demonstrated that when a potential of any polarity with a value greater than 500 volts (V) is applied, a transition to the *H*–mode occurs. Here, an *H*–mode initiated via negative voltage is characterized by a more dramatic retention improvement effect than is associated with positive voltage (Fig. 2). The characteristics of a "negative" *H*–mode are in virtual agreement with the characteristics of the spontaneous ohmic *H*–mode. These experiments make it possible to reach the following conclusions: a negative electric field is formed near the plasma boundary during a spontaneous transition; potential applied by an external source leads to an *H*–mode transition, and; in the presence of negative polarity, the retention improvement effect proves to be more dramatic and plasma conductivity is higher.

7. Experiments conducted in connection with a rapid current drop on the "Tuman–3" tokamak–type fusion test reactor (the Soviet Academy of Sciences' A. F. Ioffe Institute of Applied Physics). The changes occurring in the principal parameters of a plasma ($R = 55$ cm, $a = 22$ cm, $B = 0.57$ T, and $\bar{n} = (1\text{–}1.5) \times 10^{13}$ cm^{-3}) due to a rapid current drop were studied on the "Tuman–3" tokamak–type fusion test reactor. Plasma current was cut in half (from 85 to 42 kA) over a time frame of 5–7.5 milliseconds (msec), which is roughly 4–6 times shorter than the time frame typically associated with magnetic–field diffusion. The characteristic behavior of the subject parameters is depicted in Fig. 3. Over the course of this current drop, slight changes in plasma energy, electron temperature, and ion temperature in the center of the filament were observed. The typical relaxation time for these parameters following the cessation of the I_d drop appreciably exceeded the value of the τ_E parameter and was comparable to the magnetic–field diffusion time frame.

Electron concentration and temperature profile measurements were performed. Langmuir sonde signal evolution, density values near the diaphragm,

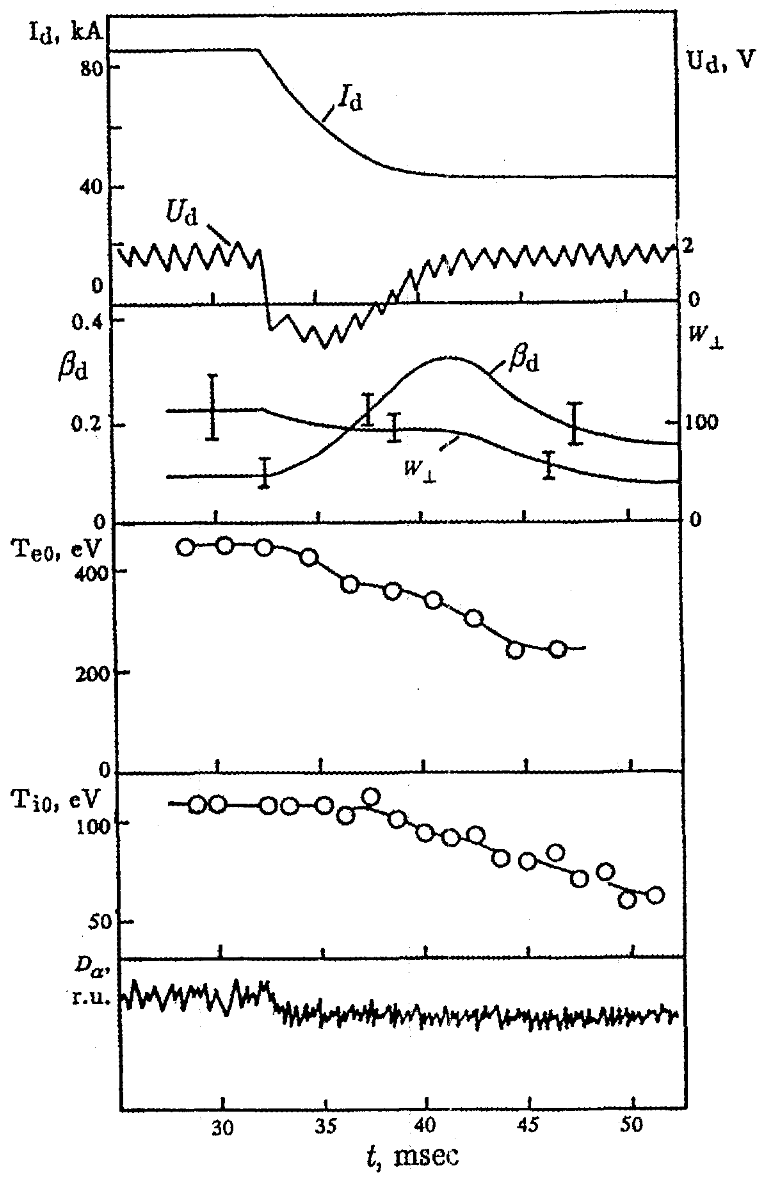

Fig. 3. The time–related evolution of parameters during an experiment involving a rapid current drop

and the mean square of density fluctuation amplitude, recorded through the use of a reflectometer, demonstrated that the rapid drop in current exerted only a slight influence on changes in the parameters of a plasma near the periphery.

8. The investigation of "runaway" electrons in helium discharges on the "Tuman–3" tokamak–type fusion test reactor (the Soviet Academy of Sciences'

A. F. Ioffe Institute of Applied Physics). The behavior of accelerated electrons was studied in connection with the ohmic heating of an He plasma in a discharge mode with a secondary current upsurge. An evacuated diaphragm was used to diminish recycling. Information on the aforementioned accelerated electrons was obtained by means of measuring the spectra of the synchrotron radiation and hard X–ray radiation emanating from this diaphragm. It was learned that accelerated electrons originate at the plasma periphery during a current upsurge and that hard radiation manifests itself following a synchrotron radiation outburst with a certain delay. It was shown that when one brings data concerning the relative delay of outbursts and peak hard radiation energy into play, the localization of the source of "runaway" electrons and the size of an effective vortex field can be determined.

9. The investigation of the mechanism of the generation of fast ions by lower–hybrid—band waves during an HF discharge on the FT–2 tokamak–type fusion test reactor (the Soviet Academy of Sciences' A. F. Ioffe Institute of Applied Physics). Previously, during experiments conducted in the area of preionization on the FT–1 tokamak–type fusion test reactor using the HF power normally reserved for lower hybrid (LH) heating, the generation of fast ions with an energy of 0.1–6 keV from the HF discharge formed in this instance was detected. During 1991, the localization and spectra of shortwave oscillations in the LH frequency band were investigated over the course of a series of experiments conducted on the FT–2 tokamak–type fusion test reactor [$R = 55$ cm, $a = 8$ cm, $B = 25$ kilogauss (kG), and a heating radiation frequency of $f_0 = 920$ MHz] via the intensified scattering of SHF waves at a frequency of $f = 60$ gigahertz (GHz). The plasma generated under the influence of a power on the order of ~ 50 kW at a frequency of 920 MHz was positioned near the outer wall of the tokamak–type fusion test reactor and had, at its peak, a density of $n_e \simeq 10^{13}$ cm^{-3}, $T_e \simeq 35$ eV, and $T_i \simeq 2$ eV. Spectral measurements were performed over a frequency band of 400–1,200 MHz. Decay–related parametric spectra with a complex structure were detected, which consisted of three parts. First, two lines, separated from the generator frequency by the ion–cyclotron frequency, f_i and $2f_i$, were isolated. Secondly, three lines, also separated from one another by the value of f_i, were isolated over the range of 680–760 MHz. And, finally, a line was isolated at a half–frequency of $\sim f_0/2$. Here, the latter line was observed both from the red and the blue sides of the transmitted wave, which suggests the excitation of two daughter waves, $\sim f_0/2$, that travel in

opposite directions. At all frequencies, the subject oscillations were localized within the body of the plasma formed, in the vicinity of the maximum concentration region. The generation of fast ions correlates to the appearance of an intensified scattering signal; i.e., to the development of a parametric instability. The spectra recorded over the course of this experiment are similar to the parametric spectra observed in various tokamak–type fusion test reactors during LH heating. This suggests a common parametric mechanism for the generation of fast ions under different experimental conditions and — in particular — confirms the possibility of the central heating of ions as the result of a parametric instability, which was previously established for the FT–2 tokamak–type fusion test reactor.

10. The excitation and propagation of Bernstein waves (the Soviet Academy of Sciences' A. F. Ioffe Institute of Applied Physics). Scenarios are presently being developed for the HF heating of a plasma on the "Tuman–3" tokamak–type fusion test reactor via the direct excitation of Bernstein waves at the plasma periphery near the ion–cyclotron harmonics. Based on a calculation performed through the use of a complete dispersion equation, the following heating scenarios have been selected: the excitation of Bernstein waves in a hydrogen plasma near the 2nd cyclotron harmonic and the absorption of these waves in the center of the plasma, either at the 1.5th cyclotron harmonic for a pure hydrogen plasma or at the 2nd harmonic of the cyclotron frequency by ^3He ions, and; the excitation of Bernstein waves near the 3rd harmonic of the cyclotron frequency of hydrogen ions and the absorption of these waves in the center of the plasma at the 2nd harmonic by the subject hydrogen ions. Working with a hydrogen plasma rather than a deuterium plasma makes it possible, when the size of the tokamak–type fusion test reactor's magnetic field is fixed, to increase the generator frequency and — thereby — to significantly reduce the absorption of the carbon, oxygen, and nitrogen impurities that exist in the "Tuman–3" tokamak–type fusion test reactor's plasma on partially ionized ions.

A program has been developed for calculating the radiation resistance of the antenna used to excite Bernstein waves. This program makes it possible to solve the attendant wave equation exclusive of a geometric–optics approximation with a nonlocal permittivity tensor over a frequency range no higher than the second cyclotron harmonics. Calculations of the coefficients of the transformation of fast magnetosonic (FMS) waves into Bernstein waves within the ionic hybrid resonance

region under the experimental conditions intrinsic to the "Tuman–3" tokamak–type fusion test reactor are presently being carried out as a means of testing the aforementioned program. In particular, it has been shown that when FMS waves are propagated from the direction of the strong magnetic field of a tokamak–type fusion test reactor, the coefficient of transformation is dependent upon how intensely a Bernstein wave is absorbed on electrons and impurity ions.

STELLARATORS

1. **A series of experimental investigations concerning the peripheral plasma and the diverter plasma in a torsatron with a "Uragan–3" diverter (the Ukrainian Academy of Sciences' Institute of Applied Physics in Kharkov).** Measurements have been made of radial plasma potential, electron density, and temperature profiles in the vicinity of a transition "from a region with closed surfaces to an ergodic layer". A poloidal asymmetry of profiles was detected: these profiles are flatter near the peaks of the separatrices than in their distant areas. Plasma potential in the transition layer is positive and reaches a value of 250 eV. The corresponding electric field reaches a value of 100 V/cm and is directed outward. The possible causes behind the appearance of a positive potential at the confinement region boundary are: increased electron escape along the magnetic lines of force and the detection of an HF field in the plasma layer near the antenna.

The characteristics of diverter plasma fluxes have been studied. It was learned that a diverter flux plasma consists of two parts: one that issues from the confinement region and another that is generated by the antenna's HF field. The flux resulting from fluctuations in plasma potential makes an appreciable contribution (tens of percentage points) to the flux of the plasma issuing from the confinement region.

2. **Theoretical research at the Soviet Academy of Sciences' Institute of Applied Physics in Kharkov.** Methods have been developed for optimizing the configuration of the magnetic field in stellarators from the standpoint of improving plasma stability and equilibrium, as well as reducing heat and particle transfer.

Techniques have also been proposed for the suppression of "islands" in the vacuum magnetic field of a torsatron by means of selecting a transverse magnetic–field structure. An effective procedure has been developed for the

regulation of helical magnetic–field inhomogeneities relative to the construction of the "Uragan–2M" torsatron — by means of the special fluting of this apparatus's toroidal magnetic field. This will make it possible to conduct research on the subject apparatus in the area of the influence exerted by the magnitude of helical inhomogeneities on the transfer of a collisionless plasma.

Using three–dimensional number codes, studies have been made of plasma equilibrium and stability in the "Uragan–2M" torsatron (in conjunction with the Oak Ridge National Laboratory in the USA). Conditions can be created in this apparatus which favor the transition to a second MHD stability region and the generation of a plasma with a β parameter value of up to 6% by altering the subject apparatus's magnetic configuration through the use of a toroidal magnetic field.

Calculations have been performed relative to the transfer coefficients of a collisionless plasma in the "Uragan–2M" torsatron (in conjunction with the Max Planck Institute of Plasma Physics in West Germany). It was shown that a plasma with an electron temperature of up to 2 keV can be generated in the "Uragan–2M" during scheduled power absorption (up to 1 MW) by electrons.

3. Theoretical research at the Soviet Academy of Sciences' Institute of General Physics. A procedure has been proposed which makes it possible to locate the magnetic fields arising due to the presence of a plasma with a finite pressure value in three–dimensional traps. A number code has been developed by means of which the destruction of external magnetic surfaces under the influence of the aforementioned fields are being studied relative to a plasma with a free boundary. It has been shown that the maximum permissible plasma pressure value for systems in which the topological stability of the vacuum magnetic structure is weak proves to be considerably lower than was previously assumed in more proximate estimates.

A model description has been prepared of stochastic α–particle losses in stellarators. The particle distribution function was found with allowance for energy losses and scattering along a pitch angle modeled by means of a Boltzmann–Gurevich–Kubelka (BGK) collision integral. It was learned that the through–going particle losses associated with conventional stellarator–type reactor parameters are low; i.e., the efficient transfer of plasma particle energy is achieved in this instance.

It has been shown that the use of the ambipolarity condition is sufficient for the determination of an ambipolar electric field. Equations for the determination of such a field have been derived and analyzed.

A possible explanation has been given for the hollow density and/or temperature profiles observed over the course of experiments conducted on stellarators.

OPEN–ENDED TRAPS

1. **The investigation of the interaction occurring between a powerful microsecond relativistic electron beam and a plasma (the Institute of Nuclear Physics of the Siberian Branch of the Soviet Academy of Sciences).** Experiments conducted on the GOL–3 apparatus for the purpose of investigating plasma heating by an electron beam with an energy content of 100 kilojoules (kJ) were continued. Primary attention was given to the study of the heating of this plasma's principal component through the use of two 90° Thomson scattering systems ($\lambda = 6{,}943$ Å). One of these systems was used to determine the density and temperature of the electron component at the plasma filament axis a distance of 250 cm from the point of beam injection into the plasma (the length of the plasma chamber was 700 cm). The measurement of the radial plasma density profile a distance of 360 cm from the inlet was undertaken using the second of the aforementioned systems.

The experiments carried out demonstrated that the heating of all the electrons in a plasma occurs in the intense beam relaxation mode. During the heating of a plasma with a density of $\sim 10^{15}$ cm^{-3}, the electron temperature varied from $T_{e0} = 1$–3 eV to $T_e = 0.6 \pm 0.2$ keV (at the point where $Z = 250$ cm). Here, the "laser" temperature value and the "diamagnetic" temperature value agreed with one another to an accuracy of 20%. The analysis of laser, diamagnetic, and other data *in toto* demonstrates that the plasma electron temperature reaches a value of $T_e = 1$ keV along the length of the subject apparatus (in the vicinity of the point of beam injection into the plasma) when beam energy release is at its peak.

Experiments have recently been begun on the apparatus under discussion relative to the "two–stage" heating of a dense plasma ($n_e = 10^{16}$–10^{17} cm^{-3}).

Within the framework of the GOL–3 program, studies are being carried out on the U–2 apparatus in the area of the generation of powerful ribbon beams. The

startup of a new system for generating, transporting, and converting ribbon–shaped relativistic electron beams (REBs) has been accomplished, with the subject system having an initial cross–section of 3 x 130 cm. A ribbon beam with a current of 25 kA in the presence of an electron energy on the order of 1 megaelectron–volt (MeV) and a beam duration of up to 8 microseconds (μsec) has been generated in a magnetically insulated diode. Experiments have been conducted relative to the transportation of a ribbon–shaped REB with the aforementioned parameters through a vacuum channel with a length of 2 meters (m) and a magnetic field with a value of 0.4 T. The losses incurred in this instance were negligible. During experiments aimed at transforming the 3 x 130 cm cross–section of a cold ribbon beam, it was possible to generate a beam with a lateral dimension of 6–7 cm in a magnetic field with a value of 4 T.

2. Experiments conducted for the purpose of studying Langmuir turbulence on the GOL–M apparatus (the Institute of Nuclear Physics of the Siberian Branch of the Soviet Academy of Sciences). Using a previously developed technique which makes it possible to observe the spectra of the collective scattering of a CO_2 laser emission [$\lambda = 10.29$ microns (μm)] at angles as low as 10^{-3} radians (rad), the spectrum of Langmuir turbulence excited in a plasma through the use of an REB was investigated.

It was shown that the spectral density of the power of resonance oscillations is localized in the region where $k_{||} = \omega_{re}/c$ and considerably exceeds the equilibrium level (up to 10^8 times). Here, the value of the $W_{k\perp}$ parameter diminishes with an increase in the transverse wave number of the subject oscillations:

$$W_{k\perp} \propto |k_{\perp}|^{-3} - |k_{\perp}|^{-4}.$$

As previously noted, the technique developed may prove to be useful in detecting the initial stages of electron escape through whistling in the presence of large separations on heavy–duty thermonuclear apparatuses of the ITER type. Calculations were recently performed which indicated that the collective scattering technique makes it possible to determine the parameters of the α–particles in the ITER with a reasonable degree of spatial resolution in the presence of moderate CO_2 laser parameters [an energy of 100 joules (J) and a pulse duration of 100 nanoseconds (nsec)].

3. Experiments conducted on the GDL apparatus (the Institute of Nuclear Physics of the Siberian Branch of the Soviet Academy of Sciences). The azimuthal spectrum of the flute–like oscillations that develop within a trap when the integral stability condition is violated was studied on the GDL apparatus. By varying the plasma's ion temperature via ion–cyclotron––resonance (ICR) heating and by altering the mean curvature of the lines of force of the trap's magnetic field, it was possible to trace the changes occurring in spectrum width as a result of the influence exerted by ionic finite Larmor radius (FLR) effects. The unstable mode increments measured are in good agreement with those calculated with allowance for FLR effects.

Following the redesign of the atomic injection system, which made it possible to increase the duration value from 0.25 to 1.5 msec, experiments were begun relative to heating at a full injection power of up to 4.5 MW. Here, the power entrained within the plasma was found to occupy the 1–MW level. The density of fast ions with a mean energy of 10 keV near the arrest points exceeded 10^{12} cm^{-3}. No noticeable manifestations of the development of an instability were detected amongst the fast–ion population within the trap.

4. Experiments conducted on the AMBAL–Yu apparatus (the Institute of Nuclear Physics of the Siberian Branch of the Soviet Academy of Sciences). Experimental research has been concluded relative to the behavior of a jet–type target plasma and its interaction with injected atomic beams.

It was learned that the relatively high ion temperature of 50 eV within the plasma jet is caused by ion heating on a Kelvin–Helmholtz instability. The radial nonlinear electric field resulting from a drop in the discharge within the plasma source leads to nonuniform azimuthal plasma drift in crossed fields. This nonuniform drift is also responsible for the development of a low–frequency Kelvin–Helmholtz instability, which is accompanied by corresponding radial electric–field frequency modulation. Instability saturation occurs during collisions of the wave–particle type. Stochastic ion heating takes place as a consequence of chaotic collision phase changes.

It was shown that the balloon mode which develops within the plasma jet due to the presence of an unfavorable magnetic field beyond the end face of the magnetic bottle near the plasma source effectively suppresses the internal radial currents along the conductors situated in the jet near the plasma source. Here, the

passage of the plasma jet through the magnetic bottle was considerably improved (by more than 3 times).

During atomic beam injection, a target plasma density decrease of up to 50% was detected. It was learned that this effect resulted from the jet's flow–wise velocity being increased to the ion sound level under the influence of the accumulated hot–ion population.

A subsequent increase occurred in the density of the hot ions accumulated in the magnetic bottle. In the presence of an aggregate injected atomic–beam flux of 160 equivalent amperes within the magnetic bottle, a hot–ion plasma with a mean energy of some 6 keV and with a mean density of 10^{13} cm^{-3} was generated in a volume of 3 liters (l).

Experiments relating to the ICR heating of a target plasma in a magnetic bottle were begun on the AMBAL–Yu apparatus in May of 1991.

BASIC RESEARCH IN THE AREA OF HIGH–TEMPERATURE PLASMA PHYSICS

1. **Theoretical research conducted at the I. V. Kurchatov Institute of Atomic Energy**. A mechanism has been proposed which explains the origination within a toroidal plasma of the small–scale island structure which results from plasma oscillation drift modes and which shares a self–consistent interaction with stochastic ion movements. Based on this concept, a mechanism has also been proposed for anomalous ionic heat transfer within a tokamak–type fusion test reactor.

The mechanism of anomalous ionic transfer, which is based on allowance for the mutual influence exerted by neoclassical and fluctuational effects, has been examined. The development and unification of number codes which describe different processes occurring within tokamak–type fusion test reactors and which make it possible to create a physical model of such an apparatus are ongoing. Theoretical studies have been made of electron–cyclotron (EC) current maintenance in a tokamak–type fusion test reactor. The calculated efficiency of current generation is in satisfactory agreement with experimental values. Work has been continued relative to the investigation of the global confinement of energy within tokamak–type fusion test reactors, on the basis of which the parameters of reactors

of this type that are still in the design stage — particularly the ITER tokamak–type fusion test reactor — are being selected.

Analyses have been made of passive and active systems for stabilizing vertical and horizontal plasma displacements in a tokamak–type fusion test reactor with an elongated plasma cross–section. The influence exerted by passive structures on the diagnosis of such displacements has been examined.

A new algorithm has been developed for controlling the temperature (neutral flux, thermonuclear output, etc.) of the plasma of a tokamak–type fusion test reactor. This algorithm requires a minimum of information on the object being controlled, makes it possible to eliminate position errors, and affords the opportunity of working with highly unsteady discharges. The numerical modeling of temperature control relative to the plasma of the ITER tokamak–type fusion test reactor has been undertaken through the use of the ASTRA sesquidimensional transport code.

The role of weak–colliding electrons relative to the transfer processes occurring in the near–wall plasma of a tokamak–type fusion test reactor has been investigated. It was shown that the influence exerted by epithermal electrons leads to an increase of roughly 1.5 times (as compared to its local value) in the near–wall potential difference that determines diverter plate atomization. The parameters of the near–wall plasma and the thermal loads on the receiving plates at the onset of a discharge in the ITER tokamak–type fusion test reactor have been studied.

For a tokamak–type fusion test reactor with an elongated cross–section, such as the ITER reactor, an appreciable correction has been made to the dependence of the critical poloidal β parameter upon the $q(0)$ parameter, which determines the boundary of the stability of the ideal internal helical mode $m = 1$.

A new approach has been developed to facilitate the search for magnetic plasma confinement systems which satisfy a sufficient condition of stability. This technique is based on finding a class of equilibrium values which satisfy the condition of a minimum Liapunov functional for a certain combination of MHD equation–of–plasma–motion integrals. An equilibrium with a value of $\beta \sim 15\%$ has been found which satisfies the reduction to zero of the first variation of the Liapunov functional. This equilibrium describes an axisymmetric plasma with a current and with a longitudinal magnetic field [$q(0) < 0.3$ and $q \approx 0$] that diminishes from the axis to the edge of the plasma.

Based on the equations derived for the interaction occurring between thin, oppositely aimed electron beams within a plasma and a magnetic field, a procedure has been proposed for the generation of a current within a tokamak–type fusion test reactor that is based on the accumulation of the electrons of a beam passing through this plasma's central region and the dissipation of a second beam at the plasma periphery.

A preliminary analysis has been made of systems with internal levitating conductors in order to facilitate the use of such systems as a foundation for a D–^{3}He reactor with a high β parameter value. A theoretical internal conductor arrangement has been examined which makes it possible to resolve the problem of neutron, radiation, and thermal loads on the internal conductor surface. A self–consistent analysis has been made of the fluxes at an internal conductor with allowance for the classical transfer mechanism and an anomalous transfer mechanism (based on a drift–cyclotron instability). A moderate thermal flux value (15–20 W/cm^2) was derived for reactor parameters. Based on the plotting of new drift–kinetic equation integrals, a closed system of equations of the magnetohydrodynamic type has been derived for a collisionless plasma which makes allowance for FLR effects and which is suitable for use in describing slow disturbances and stationary flows.

A method has been developed for solving equilibrium problems relative to a plasma with a free boundary within stellarators based on the two–dimensionalized principal of a virtual casing.

New atomic processes within a plasma have been identified: polarization–related recombination and polarization–related bound–bound transitions, which consists of the nonradiative relaxation of a plasma electron or a highly excited atomic electron, respectively, by means of the interaction of this electron with an atom (ion) shell. These processes can exert an appreciable influence on the kinetics of the level population of multiply charged ions, for example, in a nonequilibrium recombining plasma.

2. **Hall plasma dynamics as applied to the theory of plasma interrupters (the I. V. Kurchatov Institute of Atomic Energy).** During the 1980s, a new trend in theoretical plasma physics came into being at the Institute of Atomic Energy: electromagnetohydrodynamics (EMH). Depending upon the postulation of a problem, EMH can be defined either as a region of high current velocities,

$$V_{T_e}, V_{A_e} >> j/n_e >> c_s, V_A,$$

or as a region of sufficiently small spatial scales,

$$\rho_{B_i}, c/\omega_{pi} >> a >> \rho_{B_e}, c/\omega_{pe},$$

and/or brief characteristic time frames,

$$\omega_{B_e}, \omega_{pe} >> \tau^{-1} >> \omega_{B_i}, \omega_{pi}.$$

Within the framework of EMH, a number of new and — to some extent — unexpected effects have been isolated, including those isolated in problems with a sufficiently classical postulation. Instead of the skin effect, which is well–known in MHD, the nondiffussive penetration of a field into a conducting medium in the form of a "shock wave" with linear translation has been detected, together with the converse case of the occlusion of even a boundary–constant field within a plasma layer of finite thickness. As concerns the classical postulation of a problem with a periodic boundary condition, a "plasma detection" effect has been discovered, during which a field with a constant sign and with an amplitude of up to $B_0/2$ (where B_0 denotes the amplitude of the periodic field at the boundary) recedes deep inside a plasma.

In the work performed last year, the EMH approach was used to theoretically analyze the performance of plasma current interrupters (PCIs). At the present time, the PCI is a popular subject of research in the field of the physics of rapidly occurring processes within a plasma and represents a quite promising component in the field high–power pulse electrotechnology. In the work performed at the Institute of Atomic Energy (which was also simultaneously and independently performed at the NRL in the USA), it was learned that the high–intensity interruption process in a PCI occurs in several stages, among which the decisive stage is described perfectly well by electrohydrodynamics (quasineutrality, the Hall effect, and fixed ions). The EMH stage corresponds to the penetration of a field into a PCI plasma and the establishment of a current profile. Depending upon circuit parameters, technical interruption may also occur during the EMH stage. The influence exerted by field geometry at the PCI boundary has

been investigated, together with the role of anomalous plasma resistance, the rapid penetration of a field along the electrode, and — finally — the dynamics of the formation of a double layer, which characterizes physical interruption, based on a Bunemann instability. Consequently, an explanation has been forthcoming for a number of observed effects and quantitative predictions have been made which are essential to the design of plasma–type current interruption systems.

Thus, electromagnetohydrodynamics (or Hall magnetohydrodynamics), which was originally oriented toward specific effects and objects (as exemplified by the *Z*–pinch), lends itself to ever–expanding applied use by making a contribution to the study of objects such as high–intensity beams, the light liner, the plasma diode, the target corona, and — in the future — the components of a tokamak–type fusion test reactor.

3. Experiments conducted on the "Ogra–4" apparatus (the I. V. Kurchatov Institute of Atomic Energy). Under the aegis of the long–term International Thermonuclear Experimental Reactor (ITER) physics program, experiments were conducted on the "Ogra–4" apparatus for the purpose of studying those specific features of electron–cyclotron—resonance heating (ECRH) which exert an influence on the efficiency of the microwave generation of a toroidal current within the plasmas of tokamak–type fusion test reactors.

During plasma ECRH in magnetic traps, a hot–electron population with an energy on the order of 100 keV often originates. This phenomenon was studied on the "Ogra–4" apparatus (using an open–ended baseball–type trap) during the injection of SHF power (36 GHz and 200 kW) along a magnetic field. Basic EC resonance was used for heating.

It was found that hard X–ray radiation predominantly issues from that end face of the subject apparatus toward which the gyrotron is aimed. This suggests that hot electrons are primarily ejected from the trap in the direction of the microwave's propagation. The X–ray radiation was correlated to gyrotron performance and fell off instantly when the gyrotron was shut down.

A theoretical model was developed to explain this phenomenon. The subject model makes allowance for the autoresonance–related mechanism of electron acceleration and the attenuation of the microwave's amplitude at the resonance accesses. The ECR heating process is highly dependent upon the $N_{||}$ parameter (the

longitudinal index of electromagnetic–wave refraction). In particular, at $N_{\|} > 1$, electron acceleration is carried out to a maximum energy of

$$E_{max} = 2mc^2(B_{max}/B_r - 1). \qquad (1)$$

Electrons with an energy in excess of the E_{max} value vacate the magnetic well along the lines of force. The following designations were used in formula (1): B_{max} — the maximum magnetic–field value on a line of force; B_r — the resonance–related magnetic field, where the frequency of the electromagnetic wave is $\omega = \omega_e = eB_r/mc$, and m — electron rest mass. During the experiment we conducted, which involved the longitudinal injection of SHF power from the direction of large magnetic fields, a case with a value $N_{\|} > 1$ is realized. The experimental dependences of diamagnetic signal magnitude and maximum X–ray radiation energy

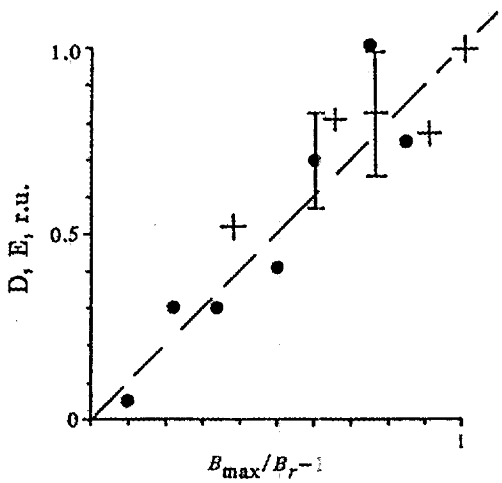

Fig. 4. The experimental dependences of diamagnetic signal magnitude, D (•), and maximum X–ray radiation energy from the end face, E (+), upon the value of the ratio B_{max}/B_r –1, where (— — —) denotes the calculation of the maximum energy of the X–ray quanta

from the the end face upon the value of the ratio B_{max}/B_r –1 are presented in Fig. 4. The maximum energy of the X–ray quanta is in agreement with formula (1).

The measured hot–electron (10–300 keV) distribution function is in good agreement with that predicted by theory.

The subject theoretical model also describes the egress of hot electrons from the magnetic well along the lines of force in the direction of wave propagation (when the plug ratios along the lines of force are identical). This is due to the fact that hot electrons are only accelerated when moving in the direction of wave propagation (with the converse being true for cold electrons). The asymmetry observed relative to the egress of the aforementioned hot electrons can lead to the appearance of a current along the trap axis. Such a current was recorded during the experiment at hand. The current observed was small (less than 1 A), since the electrons vacating the trap reached the apparatus's end face right away and transformed their energy into X–ray radiation at the end face. If these ejected (through–going) electrons were to be confined, as is the case, for example, in a tokamak–type fusion test reactor, the formation of megaamperage currents would then be possible.

4. Experiments conducted on the PR–8 apparatus relative to the modeling of the development of a drift instability in tokamak–type fusion test reactors (the I. V. Kurchatov Institute of Atomic Energy). The PR–8 apparatus was used to model the processes surrounding the development of a drift instability in a tokamak–type fusion test reactor. The role of a low–frequency drift instability (LFDI) in a plasma within a magnetic field without shear in the presence of a gently sloping radial drop in density was investigated. The results obtained suggest that an LFDI does not exhibit properties of aggressiveness. Despite its theoretically mandatory nature, LFDIs actually only appear in rare instances and do not last long. The losses caused by an LFDI (if there are any) do not exceed the Coulomb losses. There are apparently certain factors that the theory does not take into account which strongly suppress LFDIs. During the last series of tests run, it was learned that factors such as a the presence of a radial electric field or the type of the end electrodes on which a plasma rests have nothing to do with this. It seems likely that one suppression factor may be the partial absorption of LFDI waves upon reflection from the end regions of a plasma. It has been proposed that this hypothesis be verified by observing the reflection of artificially excited waves that are similar to drift waves.

An extraordinary result concerning the behavior of a plasma in a cusp trap was also obtained over the course of the experiments conducted on the PR–8 apparatus. It was found that plasma decay occurs quite slowly in the PR–8's cusp

cells, which contradicts the generally accepted notion that good confinement within a cusp is not possible due to the presence of an MHD instability that is turned inward toward the diabatic region. Special observations did not reveal any signs of this process, which holds out hope for the successful use of a cusp as an MHD "armature".

5. **A photoelectronic X–ray spectrometer for plasma diagnostics (the I. V. Kurchatov Institute of Atomic Energy).** Using this technique, the X–ray spectrum is recreated by means of the energy–related analysis of the photoelectrons knocked out of a shell target. Some advantages of the subject technique are its low energy threshold (starting at roughly 30 eV), it high degree of sensitivity, thereby making it possible to achieve good space and time resolution, its technical simplicity, and its insensitivity to neutron and γ backgrounds. The diagnostic technique under discussion has been successfully tested on several plasma apparatuses and is being made ready for use on the T–10 tokamak–type fusion test reactor. It was acknowledged to be the most adequate of a number of possible tools proposed for the performance of X–ray diagnostics on the ITER tokamak–type fusion test reactor.

6. **The development of laser techniques for the performance of plasma diagnostics on the ITER tokamak–type fusion test reactor (the Soviet Academy of Sciences' A. F. Ioffe Institute of Applied Physics).** The parameters and makeup of a diagnostic system intended for use in measuring the spatial distributions of electron temperature and concentration values, as well as neutral deuterium and helium atom concentration values, in the diverter chamber of the ITER tokamak–type fusion test reactor have been determined. The impending measurements are based on the time–of–flight principle of recording the radiation scattered within a plasma during laser sounding with subnanosecond–band pulses (the LIDAR system). It has been proposed that the LIDAR system be used in addition to the traditional Thomson scattering technique for the purpose of diagnosing a plasma by means of the near–resonance Rayleigh scattering of light on excited deuterium and helium atoms. Bench experiments have been conducted which were aimed at approving the time–of–flight principle for the detection of scattered subnanosecond–band light signals in the presence of powerful luminous interference from parasitic radiation that exceeds the useful signal by 7 orders. During these experiments, the conceptual feasibility of the time selection of the weakest possible scattering signals was proven (in conjunction with the time–related tuning out of powerful luminous interference

for a period of not less than 1 nsec) through the use of multistage chronographic image converter tubes. The fluctuational limitations of the sensitivity of such systems were determined experimentally, as was the advisability of the use of these systems for laser diagnostic purposes.

7. **The development of fast α–particle gamma–ray diagnostic techniques (the Soviet Academy of Sciences' A. F. Ioffe Institute of Applied Physics).** A diagnostic technique for use on α–particles with an energy of more than 1.7 MeV has been developed and proposed. This technique is based on the $^9Be(\alpha, n, \gamma)^{12}C$ nuclear reaction. It was shown that information on the α–particle distribution function can be obtained by means of measuring the intensity and analyzing the Doppler shape of the spectrum of γ–rays with an energy of 4.44 MeV. A detailed study was made of the spectra of neutrons and γ–rays during experiments conducted on the beam of the cyclotron at the Soviet Academy of Sciences' A. F. Ioffe Institute of Applied Physics over an α–particle energy range of 1.9–4.1 MeV. Information essential to the modeling of radiation spectra was obtained during an actual experiment on a tokamak–type fusion test reactor. Estimates demonstrate that diagnostics of this type can be used both in the case of a D–T plasma and during the performance of a D–^{3}He experiment in the presence of powerful neutral and ICR plasma heating. An experiment of this type is scheduled for the JET tokamak–type fusion test reactor.

8. **The development of instrumentation for γ–ray plasma diagnostics (the Soviet Academy of Sciences' A. F. Ioffe Institute of Applied Physics).** A spectrometric system has been developed and fabricated for use in T–15 tokamak–type fusion test reactor plasma diagnostics. This system is capable of recording γ–quanta with an energy of as much as 20 MeV in the presence of a resolution of 4% or 0.4%, depending upon the type of detector used. The subject apparatus makes it possible to obtain 128 energy spectra during a single discharge and to undertake the preliminary processing of the resultant data. This spectrometer was tested during experiments conducted on the T–10 tokamak–type fusion test reactor. An investigation was made of the hard X–ray radiation originating as a result of the yield of electrons at the diaphragm during discharges with electron–cyclotron injection. This radiation was seen to exhibit a high level of sensitivity to the parameters of a discharge.

A multicrystal γ–spectrometer has been development which is intended for use in performing plasma diagnostics during a D–T experiment; i.e., under conditions involving a high radiation background. This spectrometer has an active background suppression system and an active–passive low–energy radiation filter. The subject spectrometer possesses a high level of recording efficiency. At the present time, a spectrometer of this type is being developed for the TSP tokamak–type fusion test reactor.

9. **An analytical approach to the problem of the radial trajectories of lower hybrid waves in a toroidal plasma (the Soviet Academy of Sciences' A. F. Ioffe Institute of Applied Physics).** The general properties of the radial trajectories of lower hybrid waves in a toroidal plasma with an elliptical cross–section have been examined. A method has been developed which makes it possible to derive an analytical formula that describes the trajectory of a wave and any changes in its longitudinal moderation. The recurrent use of this formula affords the opportunity of studying the principal characteristics of the dynamic system under discussion that are essential during multipass wave moderation by means of simple mapping.

The use of mapping makes it possible to ascertain whether or not both regular and stochastic regions are present within a phase space. Here, regular motion corresponds to a high level of longitudinal moderation, which suggests the impossibility of an $N_{\|}$ diffusion set. The structure of the chaotic region is chiefly determined by the parameter $\eta \sim n/\omega^2$, where n denotes plasma concentration and ω represents wave frequency. Value ranges exist for this parameter in the presence of which a portion of the stochastic region has an island structure, which leads to dramatic variations in the $N_{\|}$ parameter that are sufficient for wave moderation.

10. **The propagation of lower hybrid (LH) waves in a turbulent plasma (the Soviet Academy of Sciences' A. F. Ioffe Institute of Applied Physics).** Bringing the calculation of radial trajectories and the construction of a mapping into the play, an analysis has been made of the broadening of the spectrum of longitudinal moderations for the $N_{\|}$ parameter of lower hybrid waves in a tokamak–type fusion test reactor with an annular cross–section. It was shown that this spectrum is appreciably broadened in the vicinity of the null and the first resonances during the weak attenuation of waves with a small degree of initial moderation, $N_{\|0}$. Broadening occurs following numerous reflections at the plasma periphery and can ensure the filling of the spectral gap. Null resonance enters the region of parameters

which correspond to the current generation mode. However, the range of density variations over which null resonance appears is narrow. In the absence of resonance conditions, propagation with allowance for multiple reflections does not lead to significant spectrum changes. Upper and lower limits always exist which restrict the value of the $N_{\|}$ parameter (for sufficiently small $N_{\|_0}$ parameter values) and which are dependent upon the value of the $N_{\|_0}$ parameter.

The mechanism governing supplementary broadening as a result of the scattering of lower hybrid waves on low–frequency plasma density fluctuations has been examined. It was shown that even at a relatively low fluctuation level ($\langle(\tilde{n}/n^2)\rangle \lesssim 0.01$), scattering slowly alters the nature of the changes occurring in the $N_{\|}$ parameter, making it diffusional. Scattering can ensure the filling of the spectral gap over a wide range of density values.

11. **Theoretical research (the I. N. Vekua Institute of Applied Physics in Sukhumi)**. The theoretical and numerical analysis of the transverse components of the permittivity tensor of a toroidal plasma has been completed. Simple expressions have been derived for this tensor with allowance for the cyclotron absorption of long waves. These expressions are suitable for use in 2D codes. The width of the cyclotron absorption zone is determined by the radius of the attendant magnetic surface. When the resonance zone is located to the side of a weak magnetic field, the principal contribution is determined by blocked ions.

A series of numerical calculations of the antenna impedance values associated with the excitation of fast waves in the TMR and ITER tokamak–type fusion test reactors by 1D and 2D codes has been performed. The strong relationship that exists between toroidal modes and different poloidal wave numbers was demonstrated. Such a relationship leads to the appearance of a continuous fast–wave absorption spectrum. This mode can be used for the generation of nonohmic currents in a tokamak–type fusion test reactor by fast waves with allowance for the injection of spiraling.

Theoretical research was continued relative to the preparatory planning of experiments on the GDL–KP2M gas–dynamic trap. The efficiency of the injection of a plasma from a θ–pinch into a gas–dynamic trap (GDT) through a plasma guide with a cusp configuration has been investigated. The parameters of the global resonances of fast magnetosonic waves (FMSWs) with $TE_{1,1,2}$ and $TE_{1,-1,2}$ modes in a deuterium plasma with a small hydrogen addition have been calculated. The

influence exerted by the thermal velocity value of addition ions on the global resonances of FMSWs of the $TE_{1,0,2}$ and $TE_{1,-1,2}$ types has been studied. The possibility of the acceleration of small addition ions through the use of FMSWs in a GDT for the purpose of creating a steady–state neutron source has been investigated.

12. The study of compact tori (the Troitsk Institute of Innovational and Thermonuclear Research). While studying the internal structure of compact tori (CTs), as well as the interrelationship that this structure shares with losses and MHD stability, it was learned that the magnetic–current starting losses (of up to 50% or more) that are inherent in a θ–pinch shaping circuit can be significantly diminished via the controlled generation of powerful viscous plasma flows along a neutral layer (through the use of a programmed gate system at the end faces of a cylindrical plasma chamber). The explanation here is that the B_z reversal procedure, which utilizes plasma retention by a wall, inevitably leads to abnormally rapid flux dissipation in the neutral layer, while the arrival of a longitudinal shock wave, which expands the neutral layer, disrupts the anomalous annihilation process. The profound consequences of longitudinal shock–wave interaction with respect to prolonged post–relaxation confinement have also been explained.

It was learned that by controlling CTs through the use of a technique based on a magnetically insulated shaping procedure (a magnetic barrier), the spontaneous development of anomalous plasma resistance can be prevented over the course of the B_z reversal process, which results from an increase in local flux lifetime during this phase ($\geq$ 100 μsec).

13. The development of diagnostic techniques at the Troitsk Institute of Innovational and Thermonuclear Research. A powerful laser–plasma source of radiation in the soft X–ray region has been developed and studied in detail relative to the roentgenoscopy of accelerated plasma clusters with density values as high as 10^{22} cm^{-3}.

A technique has been adopted which involves the use échelette gratings that operate on the principle of the transmission of the radiation under investigation for the soft X–ray region with quantum energies of ~ 1 keV in conjunction with high–speed X–ray—sensitive image converter tubes (ICTs) that operate in the slit scanning mode.

Studies are also being conducted in the area of providing a LIDAR system for the measurement of temperature and electron density distributions in the plasma of the JET tokamak–type fusion test reactor through the use of picosecond–band neodymium laser and special time–analyzing ICTs with light amplifiers. A complete LIDAR system for the performance of plasma–sounding light beam measurements via Thomsom scattering is being developed in conjunction with the research associates of the Culham Lab (England).

14. Systems with a high β value (the D. V. Yefremov Scientific Research Institute of Electrophysical Instrumentation). During 1990, optimization and parametric research was conducted for a version of a low–neutron thermonuclear reactor based on a pulsed toroid. The physical conditions have been determined under which calculations can be made relative to the creation of a reactor with minimized weight and size characteristics [an electric output of $P_e \simeq 300$ MV, $\rho \approx 5$ kilograms (kg) per kilowatt–electric (kWe) (for basic systems), and a toroid radius of $R_p \lesssim 1$ m].

The preliminary stage of the study of the shaping of plasma toroids through the use of a plasma accelerator on the SAPFIR apparatus has been completed. A toroidal configuration with a diameter of 0.6 m and a length of 1.2 m has been produced in a magnetic–field conservator.

CTS ENGINEERING PROBLEMS

1. Neutral beams for the ITER tokamak–type fusion test reactor (the I. V. Kurchatov Institute of Atomic Energy and the D. V. Yefremov Scientific Research Institute of Electrophysical Instrumentation). Neutral beams have been approved as the principal means of current maintenance in the center of the plasma filament of a tokamak–type fusion test reactor. The injection system used will consist of nine modules which are assembled in three vertical groups of three modules each. A vertical assembly made up of three modules will be aimed into an inlet nozzle, the axis of which is tangentially oriented with respect to the magnetic axis of the tokamak–type fusion test reactor. Each module will deliver 8.3 MW in a deuterium and hydrogen beam in the presence of a particle energy on the order of 1.3 MeV. Should one of these modules fail, the remaining modules will be able to operate in the 10–MW output mode, thereby enhancing the reliability of the delivery of the 75

MW that must be injected into the apparatus. A module may contain one or more neutral–beam sources that consist of series–arranged components: negative–ion sources with preaccelerators, accelerators, current profile control systems, neutralizers, and ion receptors. The subject injection module will have dimensions of 15 m in length and 4 m in diameter. Module connection to the tokamak–type fusion test reactor's chamber will ensure a tube with a length of 25 m. A version with 15 beam lines in a single injection module has been developed and proposed by the Soviet side.

2. **An H^- volumetric plasma source with a cesium cathode (the I. V. Kurchatov Institute of Atomic Energy).** This source presently constitutes the basic component for the development of a Soviet version of an ITER injection system. The subject source has been tested under steady–state operating conditions in the presence of an extracted hydrogen negative–ion current on the order of 1 A. The source at hand was operated seven hours a day for a period of one week.

3. **The acquisition of negative ions from a reflex discharge (the Ukrainian Academy of Sciences' Institute of Physics and the I. V. Kurchatov Institute of Atomic Energy).** Theoretical and experimental research has been conducted with respect to a reflex discharge from the standpoint of the use of such a discharge as a hydrogen negative–ion source. H^- current density values on the order of 80–100 milliamperes (mA) per cm^2 have been obtained in a pure hydrogen discharge using an extraction slit 1 x 40 mm in size. When cesium vapors are added to this discharge, the source used makes the transition to the surface plasma operating mode.

4. **The investigation of a "two–chamber" (tandem) version of the volumetric plasma technique for producing H^- (the I. V. Kurchatov Institute of Atomic Energy).** Research conducted for the purpose of ascertaining the possibility of constructing a negative–ion source based on the use of technique at hand yielded the following results.

1. Via the optimization of gas–discharge system parameters (magnetic–field magnitude at the walls, as well as in the filter separating the "two chambers", discharge voltage, etc.), it is possible to achieve a hydrogen negative–ion flux density on the emission surface of up to 40 ma/cm^2.

2. By introducing a transverse magnetic field and an electric field that runs in the same direction as this magnetic field directly in front of the emission slit, it is

possible to bring the current of the accompanying electrons down to a level of 0.5–0.8 of the negative–ion current value. It is possible to do this in the extraction system's slit geometry with clearances of < 4 mm between the magnet poles (when using existing magnets based on SmCo).

3. The shaping of a negative–ion beam in the slit geometry with a divergence on the order of 10–15 milliradians (mrad) is entirely feasible in the presence of an energy value of some 30–50 keV. During the preacceleration of beams of this type to a value of 1 MeV, angles of divergence on the order of 3–5 mrad can be expected.

The experiments conducted made it possible to undertake the preliminary design of a 3–5–ampere H^- ion source for use on the MIN–2 acceleration stand.

5. The MIN–2 acceleration stand (the I. V. Kurchatov Institute of Atomic Energy). One crucial facet of the program for the refinement of the injection of atomic beams into the ITER apparatus is the need for demonstrating the feasibility of a physical system for the electrostatic acceleration of powerful negative–ion beams to an energy on the order of 1.3 MeV.

According to the five–year program of research formulated by the international working group on neutral injection, this problem must be resolved over the course of experiments conducted on the MIN–2 acceleration stand, which will be constructed in the Department of Plasma Physics of the I. V. Kurchatov Institute of Atomic Energy.

The design of this stand and the fabrication of the unconventional equipment needed has already been begun. The first experiments must be conducted during 1993. The design parameters of the subject acceleration stand are:

Maximum accelerated–beam energy	1.3 MeV
H^- ion–beam current	3–5 A
Pulse duration	0.1 sec

6. Experiments conducted relative to the acceleration of H^- ions (the Moscow Institute of Reactor Technology, the Institute of Nuclear Physics of the Siberian Branch of the Soviet Academy of Sciences, and the I. V. Kurchatov Institute of Atomic Energy). Experiments have been set up relative to the acceleration of an H^- beam with a current of 1 A to an energy of 500 keV and a

pulse duration of 1–5 msec. An ion source of the surface plasma type has been installed on the stand used. This source's beam is being channeled through an electrostatic acceleration system.

Modes which will ensure the generation of an H^- beam with a current of 0.5–0.8 A in the presence of an energy value on the order of 20 keV and $\tau_{pul} \sim 1$ msec are presently being refined for the subject ion source. Voltage pulses of up to 600 kilovolts (kV) with a duration of 1 msec in the presence of a current with a value of > 100 A have been produced by a pulse generator at an equivalent load. The preliminary testing of an accelerator tube insulation has been performed while working with a proton beam ($U \sim 300$ keV, $I_p \sim 5$ A, and $\tau_{pul} \sim 0.1$ msec).

7. An injection heating system for the T–15 tokamak–type fusion test reactor (the I. V. Kurchatov Institute of Atomic Energy). The bulk of the installation work relating to the T–15 apparatus's injection heating system has been performed. This system consists of three injectors, the first of which has been readied for operation. The ion source for the subject injector have been tested on an IREK stand.

8. A proposal for the construction of a STIN international injector stand (the I. V. Kurchatov Institute of Atomic Energy). A physicotechnical proposal has been formulated for the construction of an injector stand which would serve as an ITER injector model. The parameters of the subject stand are:

Accelerated–ion type	D^-
D^- accelerated–beam energy	1.3 MeV
Beam current	Up to 5 A
Operating mode	Steady–state

A preliminary conceptual design workup is being carried out in conjunction with the Scientific Research Institute of Electrophysical Instrumentation and the State All–Union Design Institute. This design workup will be submitted to an international working group of experts for review.

9. Studies relating to the AMBAL–M ambipolar trap (the Institute of Nuclear Physics of the Siberian Branch of the Soviet Academy of Sciences). The assembly and component–by–component testing of the first stage of the AMBAL–M apparatus is ongoing. The fabrication of end tanks with chambers for

the half–cusps has been concluded, thereby making it possible to complete the assembly of this apparatus's first stage during 1991. The fabrication and component–by–component testing of a gyrotron system with an overall output of 1 MW for the first stage of the AMBAL–M apparatus has been concluded at the Soviet Academy of Sciences' Institute of Applied Physics.

10. The construction of the new–generation "Uragan–2M" stellarator complex (the Ukrainian Academy of Sciences' Institute of Applied Physics in Kharkov). The construction of the "Uragan–2M" torsatron, which has a supplementary longitudinal magnetic field, is being brought to a close. This apparatus will become one of the four largest stellarators in the world (together with the AFT stellarator in the USA, the "Wandelstein–7AS" stellarator in West Germany, and the "Heliotron–E" stellarator in Japan). One distinctive feature of the subject apparatus — a minimum of spiral field nonuniformity — adds to the range of problems which have been resolved under the aegis of the international coordination of work in the area of stellarators.

The "Uragan–2M" apparatus is equipped with a powerful plasma generating and heating system that utilizes HF output (up to 10 MW) and neutral–atom injection (up to 2 MW), as well as with a state–of–the–art instrumentation package for plasma diagnostics and experiment automation through the use of an electronic computer. This apparatus is scheduled for startup in December of 1991.

11. The design of the L–2/4 stellarator (the Soviet Academy of Sciences' Institute of General Physics and the D. V. Yefremov Scientific Research Institute of Electrophysical Instrumentation). The development of a compromise concept for a stellarator with reduced neoclassical losses and with the simultaneous retention of adequate MHD confinement properties has been concluded. Based on this concept, a design has been proposed for the L–2/4 stellarator. The detail design of this apparatus was concluded during 1990. The apparatus at hand is intended for use in continuing experiments at the Soviet Academy of Sciences' Institute of General Physics in the area of plasma confinement within toroidal systems over a parameter range of $T_{e,i} \sim 3$–5 keV, $n \sim 10^{14}$ cm^{-3}, and $n\tau_E \sim 10^{13}$ cm$^{-3} \cdot$ sec. The parameters which characterize the scale of the subject apparatus are as follows: a major radius of 3 m, an averaged minor plasma radius of $a_p = 0.25$–0.27 m, a sharply reduced helical spiraling of 0.03–0.05, a more rigidly fixed rotational transformation interval of $0.54 \leq \iota \leq 0.9$–0.92, a "bare" magnetic well of 1%, and a major magnetic shear

near the separatrix of $\theta(a_p) \sim 0.5$. The equilibrium β limit comes to 5%. The proposed power supply system consists of a flywheel–type storage device based on a hydrogenerator with a stored energy of 1.6–1.7 gigajoules (GJ), an output of more than 200 MW, and a magnetic pulse duration of 2 sec (in the presence of a maximum field on the order of 3 T). Heating system capacity comes to: 3–4 MW for ECR heating, 1–2 MW for ICR heating, and 2 MW for negative–ion (NI) heating.

Over the course of contractor design, fundamental solutions were found to all the attendant technological problems. The staggered spiral pole arrangement selected makes it possible to produce a magnetic system with good, convenient access to the plasma along the main axes of symmetry of the transverse cross–section for the diagnostic devices and the heating systems. The original thin–wall chamber design used, which has a suspension that is independent of the magnetic system, said suspension being fashioned in the form of a toroidal screw with a rotational elliptical cross–section, sharply enhances the manner in which the magnetic system's useful space is utilized and makes it possible to have a special chamber warmup system for the improvement of vacuum conditions.

12. The design of the "Globus" tokamak–type fusion test reactor with a small aspect ratio (the Soviet Academy of Sciences' A. F. Ioffe Institute of Applied Physics). Work has been continued in the area of the design of the subject apparatus. The numerical plasma–discharge modeling conducted in the ohmic heating modes and in the presence of supplementary heating via neutral injection demonstrated that a plasma with a current of $I_p \lesssim 1$ MA and with an elongation of $k \lesssim 2.5$ can be generated in a configuration with the lowest possible aspect ratio, $R/a \approx 1.5$, $R = 0.5$ m, and $a = 0.33$ m, and with a magnetic field that has a value of $B = 0.65$ T. The following questions were examined over the course of the modeling process: plasma energy retention, the determination of the supplementary heating capacity needed in order to achieve the maximum β value, the influence exerted by the bootstrap current, I_{BS}, and the beam current, I_{CD}, on the parameters of a discharge, and the calculation of an equilibrium magnetic configuration.

The use of a state–of–the–art data base demonstrated that energy retention time values on the order of $\tau_E \simeq 0.03$–0.04 sec can be expected in the limiting ohmic heating mode,

$$I_p = 1 \text{ MA and } \bar{n}_e = 8 \cdot 10^{19} \text{ m}^{-3},$$

while a value of $\tau_E \simeq 0.02$–0.025 sec should be anticipated in the nominal mode,

$$I_p = 0.5 \text{ MA and } \bar{n}_e \; 4 \times 10^{19} \text{ m}^{-3}.$$

In the limiting mode, a maximum possible value of $\beta_{max} = 9\%$ can be achieved in the presence of a supplementary heating capacity on the order of 4 MW. In the nominal mode, $\beta_{max} = 6\%$ is achieved in the presence of a supplementary capacity on the order of 2–5 MW. In the presence of limiting parameter values, one can count on the replacement of 50% of the ohmic current ($I_{CD} \simeq 0.3$ MA and $I_{BS} \simeq 0.2$ MA).

Plasma equilibrium modeling made it possible to select a winding arrangement for the poloidal system of the subject tokamak–type fusion test reactor (Fig. 5) in the presence of which the achievement of an elongation of up to 2.5 and the generation of diverter discharge modes are possible.

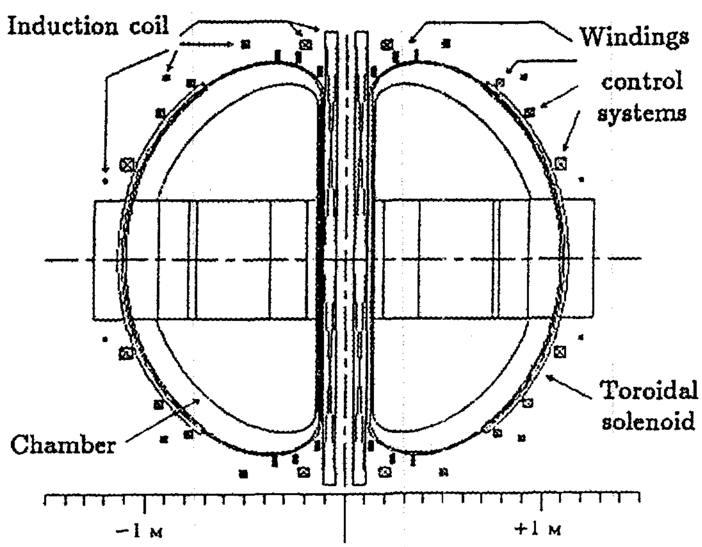

Fig. 5. The winding arrangement of the poloidal system of the "Globus" apparatus

The smallest possible aspect ratio and the highest possible degree of elongation necessitated the resolution of a number of complex engineering problems.

Preliminary design analysis with allowance for the specific features of the physical processes occurring in the subject apparatus made it possible to distribute engineering tasks relative to the design of this tokamak–type fusion test reactors main systems. A design workup is presently being carried out relative to the "Globus" apparatus's central air induction coil (an external coil diameter of 212 mm and a height of 2,200 mm), which makes it possible to generate a plasma current of up to 1 MA using the power sources on hand at the Institute of Applied Physics. The loads on the toroidal solenoid for versions 12 and 24 of the single–conductor coils and on the vacuum chamber are being calculated. The configuration of the subject vacuum chamber is depicted in Fig. 6. The upper and lower chamber

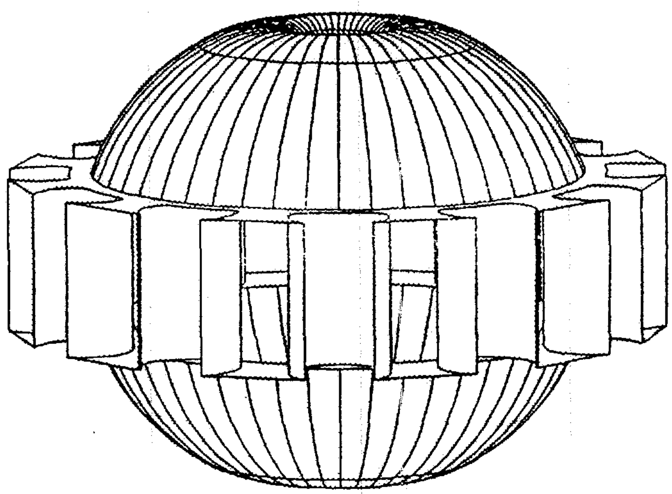

Fig. 6. The configuration of the vacuum chamber of the "Globus" apparatus

cupolas have a shape that is as close as possible to momentless as concerns atmospheric and electrodynamic loads. The design of the equatorial nozzles affords vast opportunities with respect to plasma diagnostics and supplementary heating via neutral injection.

A system for the general assembly of the subject apparatus is being developed. The adjustment and testing of power sources is ongoing.

13. A grill for the excitation of an *H*–wave in a plasma (the Soviet Academy of Sciences' A. F. Ioffe Institute of Applied Physics). Numerical research has been conducted relative to the injection of power into a plasma and the spectrum formed

for fast waves (H–waves) through the use of a "grill"–type moderating system. Calculations were performed in 3D geometry; i.e., the nonuniformity and the finite dimensions of the moderating system in both directions parallel to the plasma surface were taken into account. In order to ensure H–wave contact, the long sides of the waveguides used were oriented along the static magnetic field. It was assumed that plasma properties only varied in the direction perpendicular to the plasma surface. The fields within the waveguides were represented in the form of the sum of the incident and reflected modes, while the vacuum gap between the waveguide opening and the plasma was represented in the form of a Fourier integral for N_y and N_z. Fourier component reflection from the plasma was determined via surface impedance, $\rho = -E_y/H_z$. The condition of field joining within the waveguides and the vacuum gap leads to the derivation of the power reflection coefficient for the grill as a whole and the spectrum of the waves excited in the plasma.

A comparison was made of the results obtained from this research and those obtained from previous 2D calculations. It turned out that a reflection coefficient that ranges from 25–30% to 5–10% percent can be estimated during optimum grill design selection. A moderating system design has been proposed in the presence of which (as opposed to the 2D model) the filling of a waveguide with a dielectric that has a value of $\epsilon > 1$ is not required. Here, both plasma heating spectra which are symmetrical with respect to the N_z parameter and asymmetrical spectra can be formed with the sufficiently good directivity needed for current generation.

14. Studies in the area of the construction of the TMR tokamak–type current generator (the I. N. Vekua Institute of Applied Physics in Sukhumi). The installation of the TMR tokamak–type fusion test reactor ($R = 55$ cm, $a = 12$ cm, $B_0 = 2.5$ T, $I_p \simeq 100$ kA, $n_e \simeq 10^{14}$ cm^{-3}, and $P_{HF} \lesssim 4$ MW) is drawing to a close. The subject reactor is intended for use in conducting research in the area of noninductive current maintenance and the HF heating of a plasma by Alfvén waves (f=1–8 MHz). A system consisting of eight poloidal antennas which ensure the excitation of Alfvén modes with values of $m = +1$ and $n = 2.4$ is used for the injection of HF power. An antenna is mounted on a nozzle that is attached to the vertical flange of a port. The components of the slit–type electrostatic shield that prevents the radiating elements from making contact with the plasma are attached to the antenna's frame. The principal characteristics of the subject antenna are: a

voltage at the leads of 20 kV, a current in the antenna of 5 kA, a frequency of 1–5 MHz, a pulse duration of 0.1 sec, and an internal diameter of 260 mm.

The development and testing of a prototype of an HF generator frequency control system (HFFCS) for the Alfvén heating of a plasma in a tokamak–type fusion test reactor have been carried out. The makeup of this prototype includes: a frequency and phase control unit, a wideband buffer amplifier, and matching circuits. This control unit is a real–time digital system. The subject HFFCS ensures the synthesis of 12 phase oscillations of HF voltage with a frequency and with phase shifts that are discretely measurable in real time over a frequency range of 1–7 MHz. The output voltage of each of these 12 phases is controlled within limits of 10–15 V in the presence of a load on the order of 50 ohms. This voltage subsequently moves through a transformer with a volumetric turn to the buffer stages on the power amplifiers.

15. Studies conducted in the area of a gas–dynamic trap (the I. N. Vekua Institute of Applied Physics in Sukhumi). The construction of a gas–dynamic trap with a θ–pinch plasma injector and a powerful HF heating system (the GDL–KP2M gas–dynamic trap) was continued. Test stand and power supply system installation has been concluded. Startup and adjustment work has been begun.

16. The development of a gyrotron for the ITER tokamak–type fusion test reactor (the I. V. Kurchatov Institute of Atomic Energy, the Soviet Academy of Sciences' Institute of Applied Physics, the "*Toriy*" Scientific Industrial Group, and the "*Salyut*" Scientific Industrial Group). Sources of SHF radiation with a frequency of 140 GHz, with an output power of ~ 1 MW, and with the ability to operate in the quasicontinuous mode are needed for plasma heating in the ITER tokamak–type fusion test reactor and other thermonuclear apparatuses.

With allowance for the results emanating from the testing of laboratory mockups at the Institute of Applied Physics, a prototype of a gyrotron intended for use in attaining the entire complement of the aforementioned parameter values has been designed and fabricated by the "*Toriy*" Scientific Industrial Group. This lamp underwent preliminary testing at the Institute of Atomic Energy during the second half of 1990. The specific features of the operation of the subject gyrotron in the long–pulse (up to 0.5 sec) modes were investigated and the serviceability of the attendant resonator cooling system and collector were checked, as was that of the electron–beam and radiation interruption system selected.

A prototype of an industrial gyrotron has been designed and fabricated. A procedure for designing and fabricating a resonator with a cooling system that makes it possible to draw thermal fluxes of 5–7 kW/cm^2 from the resonator surface was used in this lamp. The subject gyrotron has a modular construction which permits one to make changes in a given subassembly and which lends itself to independent module fabrication.

Output power levels of 0.5 and 0.72 MW in the presence of pulse duration values of 0.5 and 0.21 sec and a pulse repetition frequency of 0.1 sec have been achieved as a result of preliminary testing. Here, the gyrotron efficiency factor (EF) came to 26–28%.

Output channel components have been developed for this gyrotron and studies have been made of gyrotron outlet port materials for use at different working temperatures.

When industrial gyrotrons developed in cooperation with the "*Salyut*" Scientific Industrial Group and the Institute of Applied Physics were tested at the Institute of Atomic Energy, the following parameter values were observed: (1) $f =$ 140 GHz, EF = 36%, $P = 0.5$ MW ($\tau = 0.5$ sec), and $P = 0.9$ MW ($\tau = 0.3$ sec), and; (2) $f = 167$ GHz, EF = 30%, and $P = 0.5$ MW ($\tau = 0.5$ sec).

17. A device for the selective isolation of hydrogen isotopes from a gas mixture (the I. V. Kurchatov Institute of Atomic Energy and the Bonch–Bruyevich Electrotechnical Institute of Communications in Leningrad). An experimental apparatus has been constructed and placed into operation on which a hydrogen isotope mixture that has been purged of impurities is being produced through the use of a superpermeable membrane and an atomizer. Experiments are being carried out at the Leningrad Electrotechnical Institute. A hydrogen isotope mixture compression of 100–fold or more can be achieved. The impurities detected over the course of the subject experiments were helium, oxygen, nitrogen, argon, etc. Calculations are being performed through the use of the Monte Carlo technique for the purpose of more accurately defining the parameters of this apparatus.

The technique described can be used to create:

(a) A vacuum pump for removing helium and other impurities from a thermonuclear reactor. Gas flux enrichment by helium and impurities occurs when employing a system that consists of superpermeable membranes and an atomizer, as a result of which there is no need to bring cryogenic evacuation into play, since

helium evacuation can be ensured through the use of turbomolecular pumps. The experiments and calculations performed made it possible to determine the principal constants of selective hydrogen isotope evacuation: the permeability of a niobium membrane with respect to hydrogen atoms and molecules, the coefficient of molecule atomization, the coefficients of hydrogen atom and molecule reflection from metal surfaces, etc. Based on the data obtained, three–dimensional Monte Carlo analyses have been made of ITER nozzle geometry using a superpermeable niobium membrane that was positioned along the walls of the ITER's evacuating nozzles and an atomizer that was located in that nozzle region where molecular hydrogen is primarily dominant.

(b) A system for isolating tritium from the gas mixture formed in the blanket of a thermonuclear reactor.

(c) A system for recirculating a D–T gas through a thermonuclear reactor and through other systems that are in need of the reuse of a D–T gas.

18. Studying a beam–plasma discharge in crossed electric and magnetic fields (the I. V. Kurchatov Institute of Atomic Energy). The manner in which a discharge of this type differs from a conventional beam–plasma discharge consists of the presence of a radial electric field that makes it possible to achieve discharge combustion in the steady–state mode in the presence of appreciably higher (by roughly two orders) working substance density values. Such a discharge has a volumetric nature (its transverse dimension considerably exceeds that of an electron beam), a degree of ionization that is close to 100%, and an electron temperature on the order of tens of electron–volts.

The aforementioned radial electric field makes it possible not only to achieve a discharge in the presence of elevated density values, but also to inject supplementary energy into a plasma from the radial electric field's source, thereby increasing both the density of the plasma formed and the temperature of this plasma's electron component.

A system of this type can be used:

(a) To study the interaction occurring between the materials from which a reactor's primary wall and diverter plates are made and a plasma under conditions which simulate ITER operating modes, as well as to investigate the structural materials of the ITER's primary wall and diverter plates. Experimental research

has been conducted relative to the atomization of different materials: copper, stainless steel, and tungsten.

(b) To investigate the possibility of the separation of isotopes and chemical elements in a beam–plasma discharge within crossed E and H fields. Experiments have shown that the spatial separation of isotopes and elements is feasible in such a system. The separation coefficients, α, for mixtures of inert gases have the following values: He and Ar — 6.6, Ar and Kr — 2.6, Kr and Xe — 2.2, and ^{20}Ne and ^{22}Ne — 1.28. The most detailed possible investigations of the separation of lithium isotopes have been conducted. The following data were obtained: $\alpha \sim$ 1.6–1.8 and a consumption of 10–14 grams (g) per hr. Preliminary experiments have been conducted relative to the separation of calcium isotopes. In a nonoptimized system, a separation coefficient of $\alpha = 1.4$ has been achieved for ^{48}Ca and ^{40} Ca in the presence of a consumption on the order of 3 g/hr. It has been proposed that a system of this type be used to separate isotopes with low content values instead of an electromagnetic separator with a two–stage arrangement.

(c) For the plasma treatment of different materials. Since a plasma with a sufficiently high density value ($> 10^{13}$ cm^{-3}) is formed in a beam–plasma discharge within crossed fields, the opportunity is afforded of efficiently performing different technological processes: plasma surface finishing, ionic atomization, alloying, and the application of coatings. Preliminary results have recently been obtained in these areas.

(d) As an ionizer during the creation of an ion source. In this case, it is possible to achieve higher degrees of working substance ionization than can be attained in a conventional arc–type source. Increasing the ionization of a working substance and concomitantly reducing the number of neutrals in the elongating and accelerating gaps improves ion–optical working conditions and enhances ion beam monochromaticity. In addition, cathode deterioration as a result of ion bombardment is sharply reduced, which leads to an appreciable increase in service life.

19. The testing of primary wall materials and the study of the physics of the interaction occurring between these materials and a plasma in the MKT and 2MK–200 apparatuses (the Troitsk Institute of Innovational and Thermonuclear Research). The physics of the subject interaction were studied under conditions similar to those which originate in the presence of plasma surges at the diverter

plates over the course of the interruption process. Conditions of this type are created during the efflux of a plasma through an annular slit to the expander of a trap with opposing fields. During the experiments conducted, a plasma exited through a slit with a width of some 1 cm, energy density in the slit reached a value of 300 J/cm^2, and specific output came to $P \lesssim 15$ MW/cm^2. Here, the relative pressure value, β, of the subject plasma occupied a level of 0.25. Interferometric measurements demonstrated that a plasma "cushion" is formed in front of a target made from graphite. Using calorimeters, it was learned that the total energy of a flux is assimilated by the target. The share of this energy, η, is dependent upon specific output, P. In this vein, at $P = 10$, 3.3, and 1.3 MW/cm^2, the η parameter has values of 0.2, 0.39, and 0.53, respectively.

20. **Studies conducted on the "Puma" pulse accelerator (the Troitsk Institute of Innovational and Thermonuclear Research).** The possibility of stabilizing plasma flows in curvilinear channels and intensifying a current for the purpose of load matching was studied. Along the way, it was shown that the discharge associated with the latter case constitutes a source of slow radiation with a yield of up to $5 \cdot 10^{11}$ neutrons (D–D) per pulse. This means that the system at hand can be changed over to the powerful X–ray pulse generation mode for the purpose of testing materials.

21. **Studies conducted under the aegis of the OTR/ITER experimental thermonuclear reactor program at the D. V. Yefremov Scientific Research Institute of Electrophysical Instrumentation.** One of the most crucial programs at this time is the magnetic system research and development (R & D) program that is oriented toward the development of niobium–tin conductors with increased current density, the development and testing of cryogenic steels, the selection and testing of insulation systems, and the creation of equipment for the testing of coil models.

Over the course of the work performed under the auspices of this program during 1990–1991 in cooperation with other facilities, a superconductor fabrication process was developed. A current–carrying capacity of up to 600 A per square millimeter (mm^2) was achieved in a magnetic field with a value of 12 T on specimens obtained via the bronze technique, while this figure for specimens obtained via a technique involving an internal tin source was up to 1,000 A/mm^2. Less–than–scale specimens of leads for a toroidal–field winding (TFW) have been fabricated (under laboratory conditions) and tested in a field with a value of 11.2 T.

The startup of equipment for testing short specimens of a superconducting lead in a field with a value of up to 11.2 T has been concluded. A design has been completed and the fabrication has been begun of a line for the manufacture of superconducting leads in cusps with a length of up to 500 m.

A design has been developed for a 12-tesla solenoid for use in testing TFW model sections in the presence of mechanical loads that approximate actual loads and during exposure to magnetic fields which correspond to the poloidal fields of the ITER, including those generated over the course of plasma current interruption.

TFW conductors for a field with a value of up to 14.2 T have been preliminarily examined and proposed for use.

Studies have been completed relative to the selection of a type of interturn and housing insulation for an electromagnetic system (EMS). Insulation specimens based on fiberglass have been fabricated and tested for mechanical strength under radiative irradiation conditions with values of up to $5 \cdot 10^9$ rad, exposure to heat shocks, and over a temperature range of 20° K to 273° K.

A technique has been worked out for producing steel of the 03Kh20N16AG6 type in thicknesses of up to 450 mm. The electroslag welding of steel with thickness values of this order of magnitude has been adopted. Tests have been conducted in the area of the low-cycle fatigue strength (in the presence of a number of cycles on the order of $1 \cdot 10^5$), the static crack resistance, and the cyclic crack resistance of both the subject base material and its weld joints.

Under the aegis of the program for the performance of materiological research, work has been continued in the area of the development and study of copper alloys for diverter heat-removing systems. Simulation research has been conducted relative to the swelling and high-temperature embrittlement of copper and copper alloys. It was shown that dispersion-strengthened alloys of the MAGT type (an analog of the Glidcop alloy in the USA) possess the highest possible degree of radiation resistance. Data have been obtained relative to changes in the physical and mechanical properties of copper alloys following their irradiation in the BOR-60 and SM-2 reactors.

Studies (including those involving the participation of U.S. specialists) have been conducted in the area of the simulation of the thermal phase of current interruption through the use of electron and plasma accelerators. Data have been obtained which confirm the hypothesis concerning the formation of a vapor cushion

during plasma irradiation which effects the shielding of a target from an incident thermal flux. Incident–power absorption coefficients have been measured as a function of power magnitude and the target material used. The thermal erosion of ROSO and MPG–8 graphites has been determined.

A series of studies has been carried out in the area of the testing of small cooled diverter prototypes under thermal loading conditions which simulate a normal cyclic reactor operating mode. Tungsten–copper and graphite–molybdenum (solder) prototypes have been investigated. It was shown that the selection of material–joining techniques is possible which will ensure prototype serviceability in the presence of a thermal load of up to 10 MW per square meter (m^2). Critical thermal load values have been derived as a function of heat carrier parameters and heat removal intensification techniques in the presence of unilateral thermal loading. The advantages of a porous intensifier have been demonstrated for a number of cooling modes. A technique has been worked out for producing the porous coatings needed.

Studies were conducted in the area of the creation of cryosorptive evacuation agents. A solid sorbent has been selected, together with a procedure for its attachment. The principal characteristics of the sorption process have been derived. Documentation has been issued and fabrication has been begun for a large–scale (D_y = 630 mm) prototype of a cryosorptive pump. The development of a design for cryopumps with gaseous sorbents is ongoing.

Model MHD experiments relating to the study of the flow–wise movement of a metal through slit channels, the flow–wise movement of free films, and the behavior of a drip–type screen have been conducted within the framework of the program for liquid–metal diverter devices and blankets in fields with a value of up to 4 T. An experimental model of a lithium blanket has been fabricated for the performance of joint (USSR–U.S.) thermohydraulic tests on the ALEX stand (the ANL in the USA).

Studies have also been continued in the area of electric power supply, cryosupport, and vacuum systems.

Experimental and design–related studies have been continued relative to the creation of a fuel pellet injection system.

Operational documentation has been issued and the fabrication has been begun of a light–gas injector and a stand for the testing of injectors, their systems,

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Operational documentation has been issued and the fabrication has been begun of a light–gas injector and a stand for the testing of injectors, their systems,

and their subassemblies. The parameters of the subject injector and stand are: a pellet velocity of 1–1.5 kilometers (km) per sec, dimensions of $d = h = 4$–8 mm, structural materials of hydrogen and deuterium, and a frequency–type operating mode.

A series of experimental studies has been conducted in the area of the investigation of the centrifugal pellet acceleration technique on a centrifuge with a rotor diameter of 300 mm. A system for the automatic production of a predetermined number (20–30 items) of pellets ($d = h = 2$ mm) was used. The fabrication of an electromagnetic pellet accelerator has been begun. A redesigned solid–hydrogen rod extruder has undergone testing.

22. The TSP–2 apparatus (the D. V. Yefremov Scientific Research Institute of Electrophysical Instrumentation). During 1990, an analysis was made of the possibility of creating a compact tokamak–type fusion test reactor with a gain factor of $Q \sim 5$–20 for investigating the behavior of α–particles under conditions similar to those in place in a thermonuclear reactor using the energy resources of the TSP complex.

Bringing a mathematical optimization model into play, the synthesis of the principal parameters of the subject apparatus has been undertaken. The designs of the basic components of this apparatus — its electromagnetic system and vacuum chamber — have undergone critical analysis. Modified versions of an electric power supply system have been examined.

The principal engineering characteristics of the apparatus under discussion are: a major radius of 1.9 m, a minor radius of 0.6 m, an elongation of 2, a plasma current of 9.9 MA, a toroidal field at the axis of 8.4 T, a current pulse duration of 8–10 sec, an α–particle output of 6 MW, and a maximum neutral injector output of 10 MW. The electric power supply system makes the best possible use of the capabilities of the TSP complex's equipment [four TKD–200 generators and thyristorized transformers with an aggregate output of $\sim$ 1 gigawatt (GW)]. The delivery of electric power to the TFW is accomplished by means of a power grid with an output of 300 MW. All the EMS's windings must be cooled to nitrogen temperatures.

PULSE SYSTEMS

1. Quasistationary plasma accelerators (the I. V. Kurchatov Institute of Atomic Energy, the Ukrainian Academy of Sciences' Institute of Applied Physics in Kharkov, and the Belorussian Academy of Sciences' Institute of Physics). Over the course of the reporting period, radical progress was achieved with respect to the investigation and optimization of quasistationary plasma accelerators (QSPAs). Modes with calculated magnetic and electric field distributions within a flux were attained on simplified QSPA models of the P–50 type, first at the Belorussian Academy of Sciences' Institute of Physics and then at the Institute of Applied Physics in Kharkov. This local mode "calculability" was retained over the entire course of a discharge (~ 300 μsec). In addition to this, the successful optimization of "full–block" QSPA models of the K–50 type was continued. In particular, record parameters for plasma fluxes leaving a QSPA at a calculated flow velocity of

$$V_M \sim \sqrt{2}\, c_{A_m}$$

were obtained on these accelerators at the Institute of Applied Physics in Kharkov, where c_{A_m} denotes the Alfvén velocity in place at the inlet into the main accelerator channel. More precisely, long hydrogen plasma "clusters" with a total energy content of ~ 200 kJ and with a particle energy of 0.5–0.8 keV were obtained with an efficiency of ~ 0.5.

Energy flux density, measured a distance of 1.5 m from the accelerator shear, exceeded $\rho > 100$ J/cm² ($\rho > 0.5$ kJ/cm² when scaled to a distance of 0.5 m).

The plasma fluxes produced at this time, which had a power density of $\gtrsim 0.5$ MW/cm² (in the presence of a flux diameter value on the order of 20–40 cm) in a pulse with a duration of ~ 0.1 msec, may, with certain allowances, simulate the conditions arising at the primary wall of a tokamak–type fusion test reactor during current interruption.

Research has been successfully conducted relative to the operation of QSPAs using nitrogen, argon, and other gases in connection with applied problems.

2. The investigation of a plasma focus (the I. N. Vekua Institute of Applied Physics in Sukhumi). Investigations of the parameters of the hard X–ray radiation (HXR) originating during the interaction of an electron beam (EB) shaped by a

plasma–focusing (PF) apparatus with thin metal foils located a distance of 40 cm from the point of EB generation have been continued by way of experiments conducted on the KPF–3 PF apparatus. A "revolver"–type system has been developed which makes it possible to effect target replacement without system vacuum release. An investigation has been conducted of the influence exerted by the parameters of the drift channel in the anode and the inlet diaphragm on the conditions surrounding EB transport from the point of generation to the target.

The spatial characteristics of the X–ray radiation field have been determined, which suggest that the source is extended both in the lateral direction (an explosive foil diameter of 26 mm) and in the longitudinal direction (by virtue of the interaction occurring between a portion of the EB and the walls of the drift channel).

The reestablishment of EB parameters has been carried out based on the data obtained from HXR time measurements performed through the use of silicon detectors shielded by different absorptive filters. The presence of a characteristic electron current drop which correlates to an increase in electron energy was demonstrated. This property may be linked to the "shutting off" of electron current transfer and the generation of high–energy ion beams.

Studies have been continued in the area of the creation of the KPF–4 large–scale plasma–focusing apparatus with a power–supply source energy of $W =$ 1.8 megajoules (MJ). The installation of the first capacitor bank stage ($W = 0.9$ MJ), the collector, the ignition generators, and the charge–blocking system has been completed.

The apparatus at hand is intended for use in performing research relative to the physics of a PF discharge under conditions involving a large energy contribution, as well as in studying scaling regularities for the purpose of creating a powerful source of ionizing radiation.

3. Experiments conducted on the "Mishen" laser apparatus (the Troitsk Institute of Innovational and Thermonuclear Research). Over the course of the performance of physics experiments on the "Mishen" apparatus, new data have been obtained concerning the specific features of the development of an instability of the Rayleigh–Taylor type during the thin–shell ablative acceleration stage under conditions involving the heating of these shells by plasma corona X–ray radiation.

The possibility of the low–entropy acceleration of a matter to high velocities (> 10^7 cm/sec) and the achievement of multimegabarn pressure values during the irradiation of cascade targets consisting of separate foils positioned one behind the other has been demonstrated.

4. The investigation of the compression of a dense plasma on the "Angara–5–1" apparatus (the Troitsk Institute of Innovational and Thermonuclear Research). Studies are being continued on the "Angara–5–1" complex relative to the compression of hollow gas jets (a cascade arrangement) and in the area of superfast Z–pinches. The principal goals of this research are the development of power intensification techniques, the application of these techniques to the study of inertial confinement, and the production of intense sources of soft X–ray and neutron radiation.

Liner cascade arrangement investigations were carried out in two basic directions: the calculative and theoretical analysis of surface heating in a cavity under the influence of powerful X–ray radiation, together with the analysis of reradiation efficiency for the purpose of developing a procedure for the experimental measurement of fluxes, and the experimental measurement of the temporal and spectral characteristics of radiation in the cavity of an inner liner.

During experiments conducted in the area of superfast Z–pinches, the anisotropy of the total yield of neutron radiation has been measured and the measurement of the spatial distribution of plasma density has been carried out through the use of laser sounding.

The anisotropy of the total yield of neutrons (in the presence of an absolute value on the order of $\geq 2 \cdot 10^{12}$), which equals 1.5–3, confirms that the mechanism governing neutron generation is accelerative in nature. The magnitude of this anisotropy suggests a deuteron beam energy value of $E_d \geq 0.3$ MeV. Data obtained by means of laser diagnostics permit one to reach the conclusion that the plasma present in the cathode–anode clearance is unevenly distributed, as was previously proposed. Plasma density at the cathode is no less than 3–5 times higher than at the anode. Several sausage–type instabilities are generally formed in a pinch. Here, these sausage–type instabilities develop quite a bit more rapidly near the cathode. The results obtained are in agreement with hypotheses concerning neutron generation by a flux of fast ions propagated through an axially nonuniform plasma.

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