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DEPARTMENT OF THERMONUCLEAR RESEARCH
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ANNUAL REPORT 1988

Edited by
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Department of Thermonuclear Research Annual Report 1988 presents a short review of theoretical, experimental, and techological studies performed within a framework of two research programs: Diagnosics of High-Temperature Plasma (CPBP 01.10) and Nuclear Techology (CPBR-5.8). We describe theoretical investigations on the modelling of Tokamak edge plasmas, ion motions, atomic collisions, high-voltage electrode systems, and plasma-focus (PF) facilities. The experimental studies on plasma-ion streams, high-current discharges of the PF-type, and on the interaction of ion beams with gaseous targets, are shortly summarized. Also presented are techological studies on electronic and high-voltage systems, as well as applications of the IONOTRON type plasma devices.

Raport Roczny 1988 Zakładu Badań Termojądrowych przedstawia krótki przeglad badań teoretycznych, eksperymentalnych i technologicznych, wykonanych w ramach dwóch programów badawczych: Badania Diagnostyczne Plazmy Wysokotemperaturowej (CPBP 01.10) i Technika Jadrowa (CPBR-5.8). Opisano badania teoretyczne dotyczące modelowania plazmy przyściennej w Tokamakach, ruchów jonów, zderzeń atomowych, wysokonapięciowych układów elektrodowych i urządzeń typu plasma-focus (PF). Krótko podsumowano badania eksperymentalne strumieni plazmowo-jonowych, silno-prądowych wyładowań typu PF oraz oddziaływań wiazek jonowych z tarczami gazowymi. Przedstawiono również badania technologiczne dotyczące układów elektronicznych i wysokonapieciowych oraz zastosowań urządzeń plazmowych typu JONOTRON.

Рапорт за 1988 г. Отдела термоядерных Исследований представляет краткий обзор теоретических, экспериментальных и технологических исследований проведеных в рамках двух исследовательских программ: Диагностические Исследования Высокотемпературной Плазмы (CPBP 01.10) и Ядерная Техника (CPBR-5.8). Описаны теоретические исследования моделирования пристеночной плазмы в Токамаках, движения ионов, атомных соударений, высоко-вольтных электродных систем и установок типа плазменный фокус (ПФ). Представлены итоги экспериментальных исследований плазменно-ионных потоков, сильно-токовых разрядов типа ПФ и взаимодействия ионных пучков с газовыми мишенями. Предствлены технологические исследования электронических и бысоко-вольтных систем, а также применения плазменных установок типа IONOTRON.

CONTENTS

I. PREFACE

by M. Sadowski

In 1988, the main activity of the Department of Thermonuclear Research (P-V) of the Soltan Institute for Nuclear Studies (SINS) in Swierk, Poland, was concentrated upon the continuation of previous investigations [1]. Theoretical and experimental plasma studies were carried out within the framework of two programs: Diagnostics of High-Temperature Plasma (CPBP 01.10), and Nuclear Technology (CPBR 5.8).

The theoretical investigations concerned the modelling of Tokamak plasmas, ion motions among current filaments, and ion-proton collisions. Numerical calculations of high-voltage pulse systems, and those of electric field distributions, were also performed.

The experimental studies were concentrated on plasma-ion streams generated by various cylindrical devices (IBIS, MAJA, SOWA-400), and on high-current discharges of the plasma-focus (PF) type, as observed in different facilities (MAJA-PF, PF-360, PGN) with energy ranging from several kJ to above 200 kJ.

Technological activity concerned electronic measuring and control units, high-voltage supply systems, design of a large SOWA-1000 facility, as well as the use of IONOTRONs for the pulsed ion doping (PID) and modification of solids.

Some studies mentioned above have been performed within a framework of the scientific cooperation with other departments of SINS, with the Institute of Plasma Physics and Laser Microfusion in Warsaw, and with Warsaw University. The international scientific cooperation, in particular with the Kurchatov Institute of Atomic Energy in Moscow (SU) and with the Institut für Plasmaforchung in Stuttgart (FRG), has also been developed.

This annual report describes the most important results achieved in 1988, and includds necessary references.

2. THEORY AND COMPUTATIONAL PHYSICS

2.1. Numerical Modelling of Tokamak Edge Plasma (CPBP 01.10.01.2.2)

by M.Rabiński

The EDGE1D package of computational codes [1,2], which was developed for one-dimensional analysis of tokamak edge plasma and neutral gas, has been improved by the development of a more sophisticated model of plasma transport with nonlocal heat fluxes and viscosity stresses. Equations describing the problem have been derived [3,4] on the basis of the thirteen-moments Grad approximation method with some simplifications motivated by hydrodynamic conditions. The main aim of using this approach in the macroscopic fluid description was to take into account phenomena following from comparability of a particle distribution characteristic time-scale and a temperature relaxation time.

The partial differential equations describing the problem in question have been solved by a time and space centered finite difference scheme elaborated for the quasilinear parabolic equations. For nonlinear terms, the first order Taylor expansion has been used to accelerate the convergence. The numerical method applied has been linear according to the i-th approximation of the variable at a new time step, therefore the tridiagonal matrix equations obtained could be solved succesively by the highly efficient Gauss technique.

Other studies have been carried out in order to investigate the influence of nonlocal coefficients on the plasma parameter distributions along the field line. In particular, one could expect an explanation of discrepancy between the experimental data and computational results for the temperatures and concentration in the mid-plane of a tokamak scrape-off-layer. It has been found that this effect is probably caused by overestimating the thermal conductivities and viscosity values in a region where validity of the hydrodynamic approach is violated.

2.2. Analysis of Ion Motion in the Field of Current Filaments

(CPBP 01.10.03.1.1)

by W.Frejlak, M.Kowalski, and M.Sadowski

Taking into account the filamentary structure observed in high-current experiments*, a special MIFCF.V1 numerical code was developed [5], and ion motion in a regular system of parallel current filaments was analysed [6]. Numerical calculations carried out for different initial conditions (more than 350 cases) revealed many interesting effects, e.g. the magnetic trapping of deuterons (see Fig.1) and the focusing of high-energy ions.

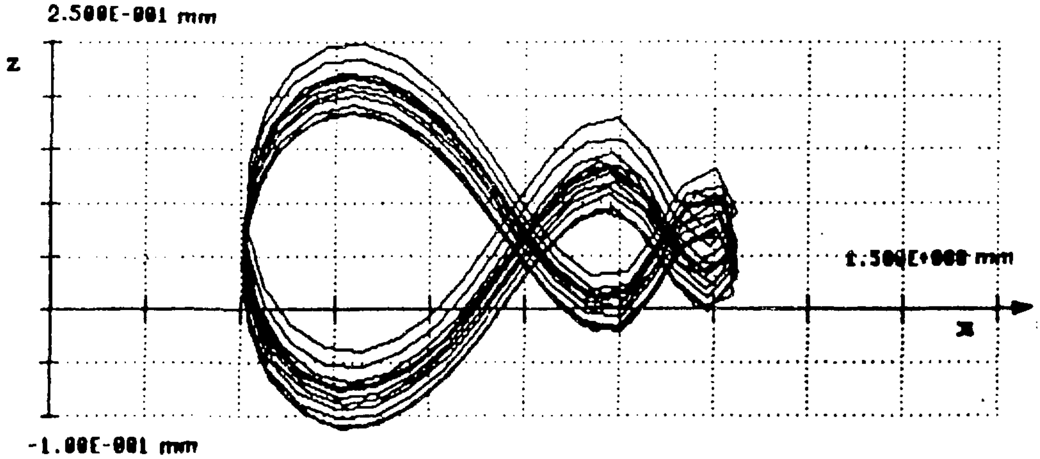

Fig.1. An example of magnetic trapping of 10-keV deuterons (z-axis along the current flow, x-axis in the radial direction).

On the basis of the calculations performed [6] it has been shown that an angular distribution of high-energy ions emitted from the PF pinch column is determined mostly by its filamentary structure [7]. Results of recent calculations, as carried out by means of a new MIFCF.V2 code, have demonstrated that taking into account axial and radial electrical fields inside the pinch column one obtains better agreement with experimental observations.

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* M.Sadowski, J.Żebrowski, E.Rydygier and L.Jakubowski: *Proc. 4th Intern. Workshop on PF&Z-Pinch Research* (Warsaw, 1985).

2.3. Software Package for Graphic-Patterns Digitalization, Acquisition, and Processing (CPBP 01.10.03.1.1)

by K.Przybylski

The TRANS_DIG program package was elaborated for a computer processing of photo-registered oscillograms [1]. This software package has recently been modified to the TRANS_DIG version 2.0 [8]. It consists of three modules:

1. a module for the remote control of the RVT52 digitizer,
2. a module for the graphic-pattern transmission and storage,
3. a module for the graphic-pattern processing.

The first module is responsible for the following functions:

- an analog or binary-patterm display on an auxiliary monitor,
- the determination of dimensions of a pattern to be transmitted,
- the selection of a discretization treshold.

The second module makes possible the buffered transmission from the digitizer to the computer throughout an RS-232 standard interface (with a maximum speed 9600 baud). The data base unit enables the patterns to be stored on a hard disk, and after that to be loaded back to RAM for future processing in a very convenient way [8,9].

The third module is designed for the statistical processing of graphic patterns, in order to transform the oscillogram pattern into a corresponding unique function. The statistical-analysis procedures employed have been developed to eliminate random pixels (or groups of pixels) as well as to proceed through oscillogram peculiarities. The obtained function enables required mathematical operations to be performed upon the oscillogram, e.g, scaling, integration, etc.

The TRANS_DIG package has been written in Pascal language (Turbo 4.0 compiler). It is user friendly due to a clear and readable pull-down menu structure, which enables the user to operate without a separate instruction [9].

2.4. Numerical Simulation of the Operation of HV-Pulse Supply Systems (CPBP 01.10.04.3.3)

by B.Bartolik (Warsaw Univ.), A.Jerzykiewicz, and L.Kociński

To study processes occuring during the operation of HV-pulse supply systems several numerical codes have been developed [10]. Simple one-sectional circuits can be analysed by means of the ISKRA code. Analysis of multi-sectional systems can be performed by means of the GENRAT and FEEDER codes. To simulate the operation of a Marx-type generator use can be made of the MARX code.

Following questions can be studied:

- influence of a triggering circuit, and in particular of a pulse shape and its amplitude, on the switching processes,
- effects of non-simultaneous switching of spark-gaps,
- the matching of a supply system to a receiver,
- influence of different subunits on energy dissipation,
- propagation of waves along the cables.

All the codes described have been adopted to a PC/AT computer. A new procedure has been added [10] to make possible analysis of switching influence on the pulse generation as shown in Fig.2

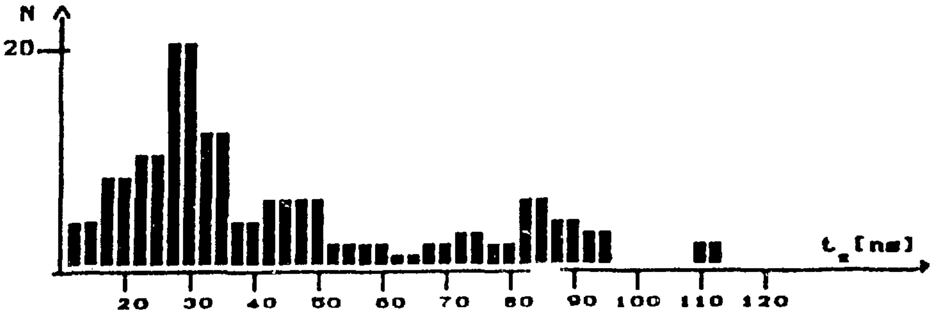

Fig.2. Switching time jitter, as calculated for a 21C3 spark-gap.

Based on the results of experimental studies, it has been assumed that the normal distribution of jitter for every spark-gap can be described by the distribution of Heilbronner coefficients for interelectrode gap. These coefficients can be generated by a random-numbers generator.

2.5. Calculations of Electric Field Distribution during Breakdown in Plasma-Focus Device (CPBP 01.10.04.06.4.2)

by W.Nawrot, and B.Bartolik (Warsaw University)

Computational and experimental studies of breakdown processes between plasma-focus electrodes have been undertaken within a framework of the optimization of the neutron emission from the PF-360 facility. Computations of the electric field distribution as a function of time, using a modified version of the computational program [1], have been carried out for different configurations of the insulator and electrodes, different polarizations of a central electrode, and with or without a magnetic field B_θ [11-12].

The computations performed have included the gas ionization by an electric field, screening the electric field by an emerging plasma, and influence of the magnetic field B_θ. The computational results have been compared with experimental ones obtained with the auxiliary stand [11-12]. It has been found that:

- The magnetic field B_θ moderates processes of the ionization as well as the electric field deformation, as shown in Fig.4.
- The electrode and insulator configuration has a great influence upon processes of generation and motion of charges at the beginning of breakdown, and therefore it determines dynamics features of the breakdown.

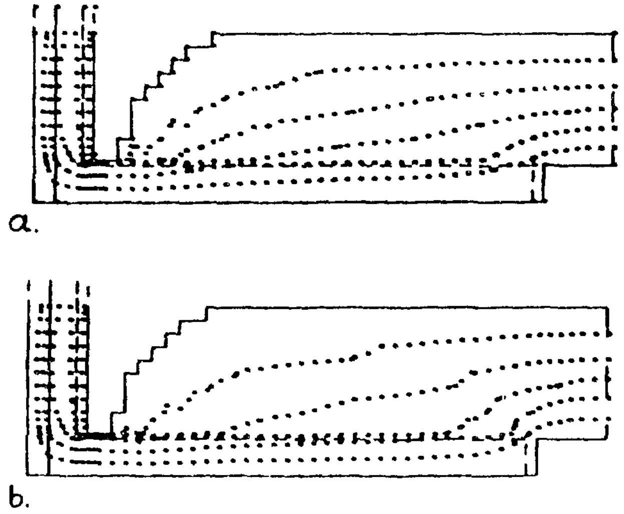

Fig. 4. Electric field distribution
a - with a magnetic field.
b - without any magnetic field.

2.6 Calculations of Charge Exchange in A^{+Z}+ H Collisions and Free-Fall Atomic Model (CPBP 01.10.10.01)

by M. Gryziński, M. Kowalski, and M. Wlazło

Capture of electrons in p + H collisions by protons scattered at the given angle ϑ, was investigated on the ground of classical physics using the free-fall (ff) atomic model* and solving numerically equations of motion for three particles [13-14]. The calculations performed have shown that the long-distance interaction, which results in the reorientation of the atom in the field of the incoming proton, must be taken into account to describe correctly collisions within a low energy range [15]. The formula describing the reorientation of the ff-atom in the precollision stage has been found to have following form

$$d\theta = 2\mathrm{arctg}\left\{\exp\left(-v_e/v_p\right)\ \mathrm{tg}\left(\theta_0/2\right)\right\} \qquad (1)$$

where v_e, v_p are velocities of electron and proton, respectively. It follows from the above that the ff-atom, being initially oriented at the θ_0 angle with respect to the beam, changes the orientation in the pre-collision stage to the θ angle. Consequently, all the collisions between low energy protons and the hydrogen atom, independently on the initial orientation of ff-atoms, are head-on (or almost head-on) collisions. Effective capture probabilities have also been calculated

$$\langle p_c\rangle^{\vartheta} = \frac{1}{2}\int_0^{\pi} p_c\left[\theta(\theta_0)\right]\sin\theta_0\, d\theta_0 . \qquad (2)$$

Good agreement with experiments has been obtained (see Fig. 4).

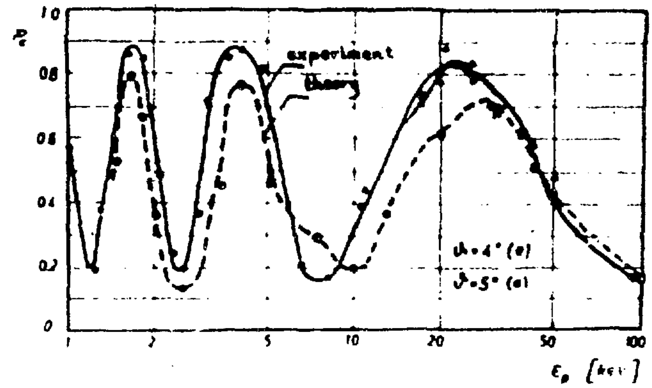

Fig. 4. Capture probability for p + H.

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[*] M. Gryziński, *Phys. Rev. Lett.* 14 (1965), 1959.

3. EXPERIMENTS

3.1. Investigation and Optimization of Plasma-Ion Streams in the IBIS Facility (CPBP 01.10.03.2.1)

by J. Baranowski, K. Czaus, and E. Składnik-Sadowska

In 1988, experimental studies with the IBIS facility [1] were concentraced on the optimization of plasma-ion streams emitted by this device equipped with coaxial multi-rod electrodes of the cylindrical type [16]. Measurements were carried out with a Thomson analyser [17], X-ray and ion pinhole cameras, as well as with auxiliary metalic targets [18]. It has been found that the IBIS facility generates plasma-ion streams of energy from 2-80 keV for different operational modes (see Fig. 5). Optimal propagation of the plasma-ion streams has been observed for τ = 190 μs. In that case, at a distance of 2 cm from the electrodes along the z-axis, is formed a dense plasma region of about 2 cm in diameter and 5 cm in length, which constitutes the main source of neutron pulses [18]. Radial dimensions of the plasma-ion streams have also been determined from X-ray pinhole pictures taken for various metallic targets. The optimization tests of the IBIS current-pulse generator have shown that connections of different condenser sections influence considerably on the period of the discharge current [18].

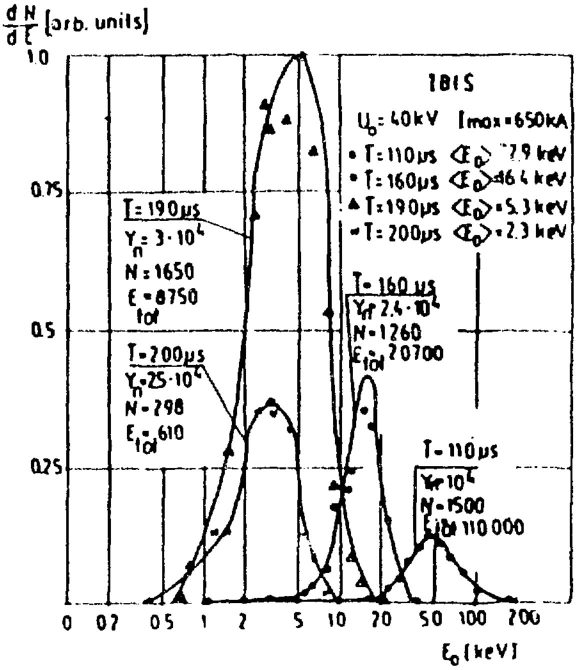

Fig. 5. Deuteron energy spectra, as measured under different operational conditions.

3.2 Studies of Ion Beams and Modernization of the MAJA Facility

(CPBP 01.10.03.2.2)

by E.Składnik-Sadowska, J.Baranowski, K.Czaus, and M.Sadowski

In 1988 our main efforts were concentrated upon a comparative analysis and summary of the results of previous studies on plasma-ion streams generated in the MAJA-60 kJ facility with cylindrical and quasi-conical electrodes of the multi-rod type [16-17,19-21].

It has been proved that the MAJA device can emit deuteron beams of energy ranging from several to several dozen keV, depending on the operational mode [21]:

- for the high-pressure mode (at τ = 200 μs) $\langle E_D \rangle$ = 20 keV,
- for the medium mode (at τ = 160 μs) $\langle E_D \rangle$ = 50 keV,
- for the low-pressure mode (at τ = 110 μs) $\langle E_D \rangle$ = 80 keV.

Space structure of the dense plasma region depends also on the initial gas conditions. For τ = 210 μs the ion source region at the electrodes outlet is about 4 cm in diameter and 8 cm in length, while the X-ray emitting region is only 1 cm in diameter and 6 cm in length. Sharp ion beams pictures, as obtained for that case, suggest a ballistic character of ion motions. For other operational modes the ion pinhole pictures are foggy and the ion focusing is less efficient. The highest neutron yield is observed for the high-pressure mode. It amounts to some 10^9 n/shot and can be explained by deuteron beams interaction with a gas target.

Another field of activity was connected with the modernization of the MAJA facility [21]. The main condenser bank has been enlarged by 4 new 12-μF sections. Old energetic cables have been exchanged. A new control desk has been installed, and some electronic units, e.g. activation counters, have been replaced by modernized ones.

In spite of valuable experimental results [16-17,19], it has been decided to shut down the operation of MAJA device in the ion-implosion mode. The modified MAJA facility has been odopted for other experiments (see Sec.3.3).

3.3. Investigation of Plasma-Focus Discharges with Gas Pulsed Injection (CPBP 01.10.03.2.3)

by M.Sadowski, J.Baranowski, L.Jakubowski, E.Rydygier, E.Składnik-Sadowska, A.Szydłowski, and J.Żebrowski

In order to study dependence of the PF formation on the initial gas conditions use was made of the modified MAJA-PF facility [1] equipped with a solid 7.2-cm-dia. inner electrode and a 12.4-cm-dia. outer electrode of the squirrel-cage type. The both electrodes were 30 cm long, and the tubular insulator was 7.2 cm in length. The facility was operated under static and dynamic initial gas conditions [22-23]. For the dynamic mode, the working gas was injected towards the insulator surface. The main discharge was powered by a 48-μF condenser bank charged up to 40 kV.

For shots performed under the static initial pressure all the characteristics were almost identical with those observed for the conventional PF discharges [24-25]. For gas-puffed shots the current- and voltage-waveforms were similar to those registered for the standard PF facilities. In that case there was observed a typical pinch column, as shown in Fig. 6. Optical measurements have also shown that a plasma-sheath velocity during the run-down phase was equal to $(0.8-2.5)\times10^{7}$ cm/s [26]. The neutron emission was proportional to that velocity, as for the static pressure mode. The highest neutron yield was obtained when the initial deuterium pressure inside the valve plenum was high enough (up to 40 atm). A correlation function $I_x(Y_n)$ - has also been investigated [26].

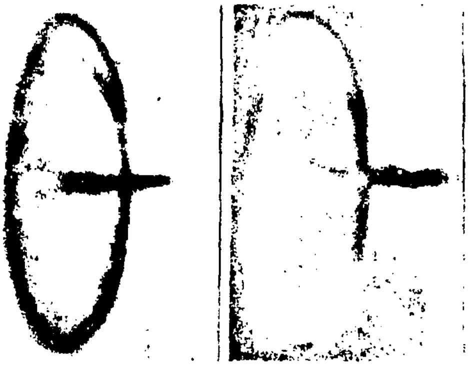

Fig. 6. X-ray pinhole pictures: A - for a shot under the static pressure, B - for the gas-puffed discharge.

3.4. Current Distribution Measurements along Electrodes of PF-360 Device

(CPBP 01.10.10.04.02.3.2)

by K. Kocięcka, and A. Jerzykiewicz

Within the framework of PF research program [23,27-30] an effort has been undertaken to measure currents flowing through the inner electrode of the PF-360 facility [1].

To measure the current in question use has been made of a Rogowski coil placed inside the inner electrode composed of several disks [1,31]. The measurements have been performed with coils placed at distances 2.5 cm and 13 cm from the front of the insulator, at the bank energy equal to 90 kJ. Current waveforms, as measured in the electrode, have been compared with the total current, as shown in Fig. 7.

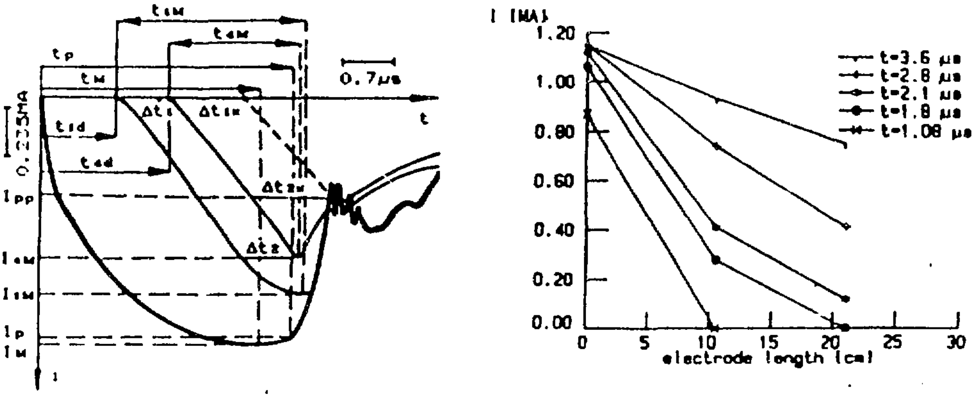

Fig. 7. Comparison of current waveforms (on the left) and the current distribution along the inner electrode.

The results of the measurements can be summarized as follows:

- velocity of a current-sheath front is higher than that of the tail,
- the current-sheath is broader than it was assumed before,
- a leakage current is observed only during the training,
- due to the large width of the current-sheath, only porton of energy stored can be used during the radial phase,
- a neutron yield at the optimal deuterium pressure is a function of the current-sheath velocity and current rise-time [31].

3.5. Modelling of PF-360 Experiment with Dynamic Introduction of Deuterium (CPBP 01.10.04.02.3.3)

by A. Jerzykiewicz, L. Kociński, W. Nawrot, W. Polak, and J. Stanisławski

In order to find optimal operation conditions for a future PF-360 experiment with a pulsed gas injection, extensive laboratory tests have been performed with the use of the PF-360 electrodes and the electromagnetic valve built in 1987 [1]. Using an auxiliary stand, which was equipped with a vacuum chamber identical with that of the PF-360 facility, breakdown voltage between the electrodes has been measured as a function of initial hydrogen or helium pressure within valve plenum and the time delay, which was counted from the beginning of a current passage through the valve coil [32-33]. In order to reduce the breakdown voltage and to localize the discharge a sharp thin disk has been located upon the inner surface of the outer electrode. The results of measurements have performed have been presented in Fig. 8.

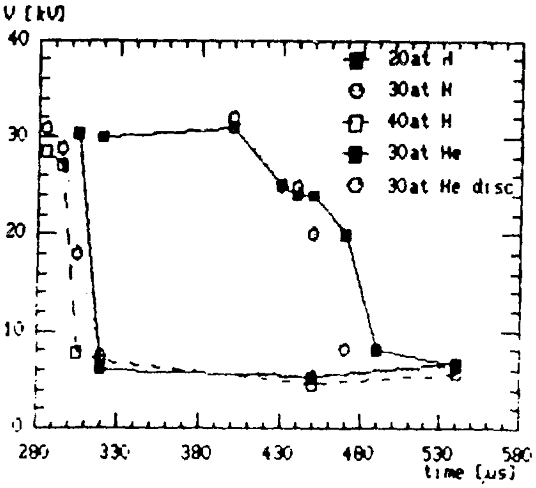

Fig. 8. Breakdown voltage vs time for different pressures and working gases.

3.6. Breakdown Voltage Measurements in PF-360 Device
(CPBP 01.10.04.02.3.4)

by A. Jerzykiewicz, and K. Kocięcka

Measurements of breakdown voltage in the plasma-focus PF-360 facility [1] have been continued [11]. A new type of the inner electrode has been used. A multilayer electromagnetic screen has been placed between the electrode and the insulator tube in order to decrease the initial value of the magnetic field at the insulator surface, and to preserve the electric field value. Using this electrode, dependence of the breakdown voltage on a storage bank capacitance has been investigated [34]. It has been found that in this case the time t_1 values are reduced. At the same time the ratio V_1/t_1 is increased considerably, as shown in Fig. 9. It has also been confirmed that there is only a weak dependence of the breakdown voltage on the initial pressure, and that the breakdown voltage is a rising function of the charging voltage and the storage bank capacitance.

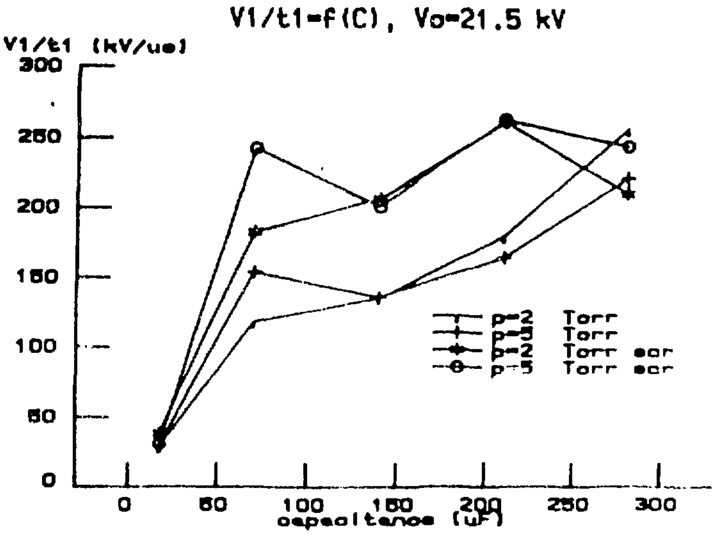

Fig. 9. Ratio of breakdown voltage to the time delay as a function of the bank capacitance, and operational pressure

3.7 Investigation of X-Ray Emission from the PGN-Device

(CPBP 01.10.04.06.4.1)

by Sz. Brandt

Taking into account an interest in plasma-focus devices as X-ray sources an effort has been made to increase the X-ray emission from the PGN device [35-36]. The integral X-radiation dose has been measured by means of an ionization chamber. It has been found that the application of a tungsten target placed inside the inner electrode increases the X-ray emission 3÷4 times [37]. A further increase in the X-ray emission has been obtained by the use of working gases heavier than deuterium. The measurements have shown that for He and Ne the highest X-ray emission is obtained at lower pressure (see Fig. 10).

For Ar and Xe no X-ray emission has been registered. An X-ray pulse shape has been measured with a scintillator-photomultiplier probe. The registered pulses have had the FWHM equal to about 30ns. The X-ray emission has also been investigated by means of a pinhole camera with a 10μm-thick Be-filter. The X-ray pictures as taken at the outlet of the inner electrode, have revealed that there appear irregular emission sources [37].

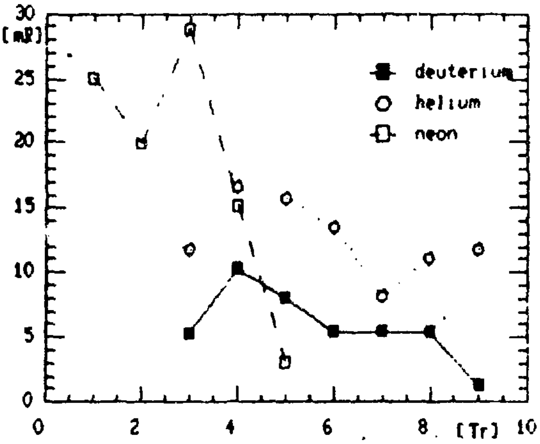

Fig. 10. X-ray dose vs. pressure for shots with initial energy 3.5 kJ.

To describe the correlation between the X-ray emission and the neutron yield use has been made of a linear dependence: $Y_x = \alpha \cdot Y_n$. The correlation coefficient has been found to be 0.85÷0.95. It has been observed that with an increase in the initial pressure the coefficient α decreases considerably.

3.8. Interaction of High Density Ion Beams with Gaseous Targets (CPBP 01.1010.01)

by M.Gryziński, J.Stanisławski, and W.Komar

The interaction of high-density D^+ beams with various gaseous targets has been investigated by means of high-speed photography and X-ray diagnostics. The maesurements have been carried out at the SOWA-400 facility [1]. Density of the D^+ beams has been about 1 kA/cm^2, the mean ion energy has been equal to 20-30 keV, and the ion beam pulse-length has been of the order of 0.5 μsec [20, 38]. Optical and X-ray measurements have been performed for gaseous targets of various densities and volumes (see Fig.11). The interaction of the D^+ beams induces a compression of the gas target [39], as shown in Fig. 11.

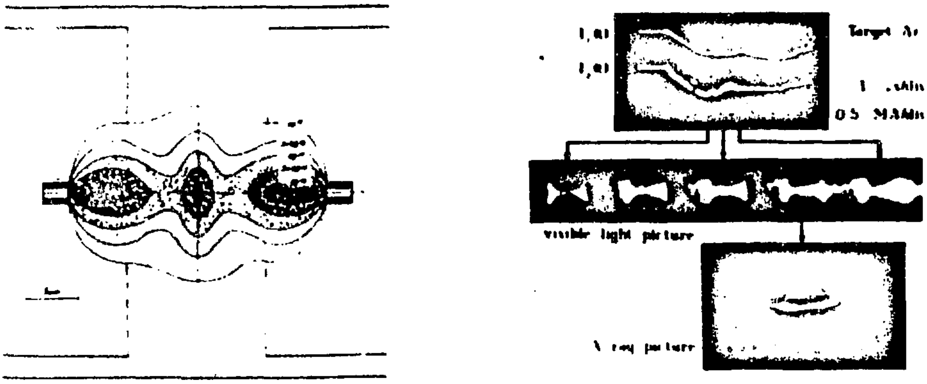

Fig. 11. Gas target density distribution (on the left) and compression of the Ar-target, as observed in VR and X-rays.

The gas target bombarded by the D^+ beam emited X-rays which have been detected by means of pinhole cameras equipped with Al-foil filters. Observing the attenuation of X-rays by different Al filters one could estimate an average energy of the X radiation. In the experiments performed with the SOWA-400 facility the mean X-ray energy has been about 1 keV [40].

4. TECHNOLOGY

4.1. Electronic Measurements and Control Systems

(CPBP 01.10.01.1.4 and 01.10.04.0.5)

by M.Bielik

In 1988, a new crate for 20 channels of optoelectronic receivers of the Analog Fiber-Optic Transmission System (AFOTS) was designed [42] and partially constructed [43-44]. There were also performed further tests on the application of the AFOTS model for current measurements in the TOKAMAK T-10 facility in Moscow. It was shown that the model tested is applicable for measurements at high potential and very low transmition frequency (down to f=0.1 Hz). Particular attention was paid to the construction a new insulated power supply for the crate with 20 modules of optoelectronic transmitters, provided that insulation between channels with stands more than 1 kV. A conceptual project of such a power supply has ben discussed with specialists connected with T-10 and T-15 experiments at the Kurchatov Institute in Moscow.

Another branch of activity was conected with the design and construction of a broadband (25 Hz - 20 MHz) AFOTS model. Results obtained during tests of the transmitter and opto-electronic detector units were promissive. The parameters required have been obtained with home-made fiber connections, equipped with the Burrus type CQYP42F emiter and a P-I-N photodiode of the BPYP42F type.

Separate efforts have been connected with an automatic control system, which was designed and costructed for a 2.4-MV surge generator. This system makes possible to control symetric charging voltage, generator switching, pulse chopping, spark-gap blowing-through, and triggering of HV oscilloscopes. It can also provide synchronization of the generator operation with a required repetition rate. Control signals can be transmitted through the opto-electronic system, provided that transmitters are built into delay units and receives are located near devices controlled.

4.2. HV Supply System with Magnetic Energy Storage

(CPBP 01.10.04.04.3.1)

by R.Mirowski

Inductive storage systems have an important advantage in comparison with capacitive ones, namely the high-density of energy which can be accumulated in a coil volume. The utilization of such systems in plasma research facilities might considerably reduce the volume of these devices and improve their quality. This was the main reason why technological studies on this subject was undertaken at SINS [45].

An energy storage unit of the supply system built at SINS (see Fig.12) was an air-core coil with inductance variable within the range of 0.1-1.3 mH. The current commutation was performed with a HV thyratron because of its good switching and breaking characteristics. A consequence of the current breaking was high overvoltage appearing on the load. Some tests were performed [46] for hydrogen thyratrons of two different types: TGI1-130/10 and TGI1-1000/25. Variable parameters of the system were capacitance C, inductance L, and supply voltage of the thyratron pulser. The system was able to store energy up to several hundred Joules, and the maximum current reached the value 3 kA.

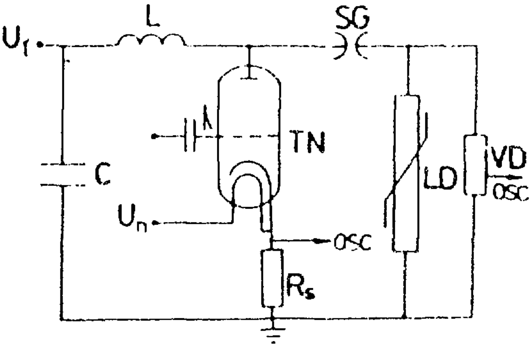

Fig.12. Schematic of the inductive storage system.

The experiments [46] have demonstrated that the system can generate microsecond pulses, with an amplitude many times higher than the charging voltage value. It was, however, observed that the two types of thyratrons have different points of work. Furthermore, the hydrogen thyratrons exploited for the current-breaking reveal great instability in the operation and low efficiency, which makes their use doubtful.

4.3 Experimental Determination of Constant in the Heilbronner Formula (CPBP 01.10 04.3.2)

by K.Kociecka

Within a framework of research on high-voltage switches were performed numerous laboratory studies of triggered spark-gaps [47-50]. In connection with those technological studies were also investigated time-resolved signals of inter-electrode voltages in a 2IPB spark-gap of the field-distorsion type [51]. Results of the measurements were presented in voltage diagrams, as shown in Fig.13. These voltage diagrams were used to deter- mine the constant τ for the modified Heilbronner formula*. Results of the studies performed can be summarized as follows:

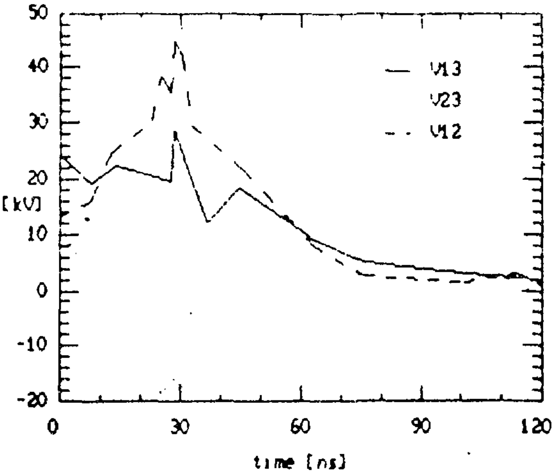

Fig. 13. Voltage changes at $d = (5+5)$ mm, $R = 4\ \Omega$, $k = 0.8$, $\tau_1 = 41.5$ ns, $\tau_2 = 1.4$ ns, $V_1 = 14$ kV.

- Circuit parameters and operational conditions of the spark-gap determine the value of constant τ.
- Values of constant τ, as measured for different inter-electrode gaps, are different and do not fit the value range given by Heilbronner. It has been found that for high-voltage electrode τ = 10.5-76 ns, and for earthed electrode τ = 0.4-40.5 ns.
- The value τ changes from shot to shot according to a statistical distribution. This can be taken into account in the simulation of a spark-gap jitter when numerical calculations of HV circuits are performed.

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*B.Bartolik, K.Kociecka: *Arch. Elektrot.* XXVIII(1979)613-622.

4.4 Design and Construction of SOWA-1000 Facility

(CPBP 01.10.10.02 and 01.10.10.03)

by M.Gryziński, K.Czaus, E.Górski, and M.Wójtowicz

Within the framework of a research program on ion implosion [1], which has been based upon the concept of the realization of nuclear fusion reactions with the use of the ordered motion of ions [40], there have been continued design and constructional efforts in order to elaborate different subsystems of a large SOWA-1000 facility.

Particular attention has been paid to laboratory tests of the model section of a condenser bank which has to supply high-current discharges in the main experimental chamber. Extensive exploitation tests have been the basis for some improvements in the construction of this section, and particulary in spark-gaps, non-linear resistors used for the current limiting, etc.

Another activity has concerned the design studies on a high-voltage three-phase supply system equipped with an inductive-capacitive converter [52].

Separate efforts have been connected with the design and construction of a gas pulsing system needed for the SOWA-1000 experiment [53]. Numerous laboratory tests of high-speed pumping units have also been performed in order to make ready the high-vacuum equipment.

A review of physical principles and a preliminary design of the SOWA-1000 experiment has been presented in a separate paper [54].

4.5. Use of Ionotrons for Pulse Ion Doping and Modification of Solids (CPBR 5.8-1.27)

J.Langner, J.Appelt, K.Czaus, E.Górski, A.Horodeński, W.Ziemski (Z. P-V), and J.Piekoszewski, C.Pochrybniak, J.Białoskórski, J.Zaremba (ZDAJ)

Studies on the application of pulse ion beams were started in 1981, when the first formation of the p-n junction was achieved by means of Pulse Ion Doping (PID) technique[*]. The technical basis for PID was provided by the IONOTRON device [1,20]. In 1986-87, several IONOTRON machines were constructed.

In 1988, investigations on the n-type silicon doping were continued in order to form p^+-n-n^+ structures for solar-cells. Tests on the treatment of a p-type silicon with PF_5 ion beams were also undertaken. The photovoltaic cells with 8.6-% conversion efficiency (without a rear contact p-p^+ structure) were obtained.

Some efforts were also undertaken to approach the shallow-junction formation. It has been shown that for the n-type silicon the junction depth < 0.5 μm can be obtained in 75-mm-diameter wafers with the use of BF_3 plasma, as shown in Fig 14.

IONOTRON devices have also been used for some pilot experiments on the surface modification of the N9-type steel with H^+ and N^+ plasma-ion pulses [55-56]. Laboratory tests have shown that for 1, 2, and 20 pulses, the surface microhardness was increased by a factor of 1.6, 2.3, and 3.7, respectively [57-59]. Some initial studies on a plasma deposition of a Cu-layer upon an Al-ceramic surface were also performed [59]. Preliminary results have revealed a good adhesion of the metal-film, but up to now an amount of the deposited metal has been too small.

Within the scope of an international cooperation there were performed some studies on a sputtering yield of Ti and TiC under O_2 exposure [60].

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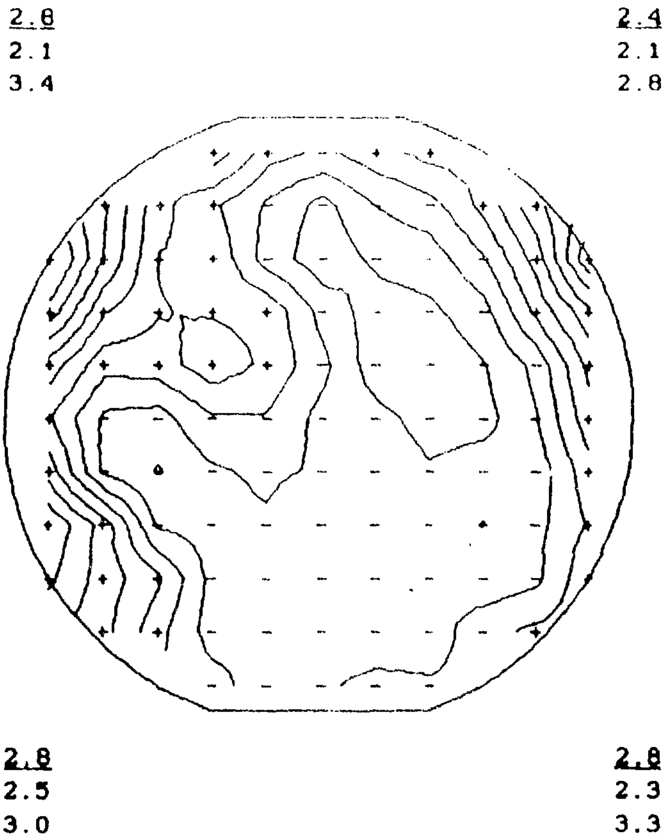
[*] J.Piekoszewski, M.Gryziński, J.Langner, and Z.Werner; J.Physique 43(1982)1352.



mean sheet resistance: 51.7 Ω/■

standard deviation: 20.9 %

isoline decrement: 10.0 % of m.s.r.

device: IONOTRON number of pulses: 2

main bank: 30 kV valve bank: 6.5 kV delay: 210 μs

distance: 35 cm gas: BF_3, 1.7 atm

Fig. 14. Distribution of surface resistivity of a 75-mm-diameter Si wafer implanted with B^+ ion

5. PUBLICATIONS, CONFERENCE PROCEEDINGS AND CONTRIBUTIONS.

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2. One-Dimensional Modelling of Plasma and Neutral Gas in a Scrape-Off Layer of Tokamak with Poloidal Divertor (in Russian), by M.Rabiński, *SINS Internal Report* No.0-19/P-V/88.
3. Preparation and Tests of 1D Numerical Code for Calculations of Dynamics of Tokamak Edge Plasma in Grad Approximation (in Russian), by M.Rabiński; *SINS Internal Report* No.0-23/P-V/88.
4. EDGE1D - Packet of One-Dimensional Models of Edge Plasma Dynamics in Tokamak (in Polish), by M.Rabiński; *Proc. 1988 Plasma Symposium (Jachranka 1988)* - in print.
5. Ion Motion in Magnetic Field of Regular System of Parallel Current Filaments, Part I. Description of Field, Equations of Motion, and Numerical Code (in Polish), by W.Frejlak, M.Kowalski, and M.Wlazło; *SINS Internal Report* No.0-04/P-V/88.
6. Ion Motion in Magnetic Field of Regular System of Parallel Current Filaments, Part II. Results of Numerical Calculations (in Polish), by W.Frejlak, and M.Kowalski; *SINS Internal Report* No.0-17/P-V/88.
7. Analysis of Ion Motion in a System of Parallel Current Filaments (in Polish), by W.Frejlak, M.Kowalski, and M.Sadowski; *SINS Internal Report* No.0-29/P-V/88; *Proc. 1988 Plasma Symposium (Jachranka 1988)* - in print.
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10. Numerical Simulation of the Operation of HV-Pulse Supply Systems, Taking into Account Time-Jitter of Switches (in Polish), by B.Bartolik (Warsaw University), A.Jerzykiewicz,

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11. Investigations of Breakdown Between Plasma-Focus Electrodes. by W.Nawrot, S.Brandt, A.Jerzykiewicz, and K.Kocięcka; *Proc. 15th European Conf. on Controlled Fusion and Plasma Heating (Dubrovnik-Cavtat 1988)* Vol.12B, Part II, pp.565-568.
12. **Simulation of Electrical Field Distribution during Breakdown in Plasma-Focus Device (in Polish), by W.Nawrot, and B.Bartolik (Warsaw University);** *Proc. 1988 Plasma Symposium (Jachranka 1988)* **– in print.**
13. **Deterministic Theory of the Atom – Real Possibility or Utopia, by M.Gryziński;** *Proc. Intern. Conf. on Classical Dynamics in Atomic and Molecular Physics (Brioni 1988)* **– in print.**
14. **Atomic Collisions – New Results of Theory and Their Consequences for Plasma Physics (in Polish), by M.Gryziński;** *Proc. 1988 Plasma Symposium (Jachranka 1988)* **Vol.II. Invited Papers – in print.**
15. **Charge Exchange in p+H Collisions and Free-Fall Atomic Model (in Polish), by M.Gryziński, M.Kowalski, and M.Wlazło;** *Proc. 1988 Plasma Symposium (Jachranka 1988)* **– in print.**
16. **Investigation of Convergent Deuteron Beams within a Penetrable Electrode System. by E.Składnik-Sadowska, J.Baranowski, and M.Sadowski;** *Proc. 15th European Conf. on Controlled Fusion and Plasma Heating (Dubrovnik - Cavtat 1988)* **Vol. 12B, Part II, p.633-636.**
17. **Mass and Energy Analysis of Pulse Plasma Streams Emitted by IONOTRON-type Devices**, by E.Składnik-Sadowska, **J.Baranowski, and M.Sadowski;** *Proc. Intern. [illegible] Ion Implantation in Semiconductors and other Materials [illegible]* p.147.
18. Studies and Optimization Tests of Plasma Streams in IBIS Facility (in Polish), by J.Baranowski, K.Czaus, and E.Składnik-Sadowska; *SIN Internal Report* No.0-31/V/88; *Proc. 1988 Plasma Symposium (Jachranka 1988)* – in print.
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24. Neutron Emission and Dynamics of POSEIDON Plasma-Focus with Alumina Insulator within Operational-Range from 280 to 500 kJ (in German), by H.Herold, H.J.Kaeppler, M.Sadowski, H.Schmidt; and M.Shakhatre; *Institut für Plasmaforschung Report* No. IPF-88/Stuttgart 1988/.
25. Comparative Analysis of Large Plasma-Focus Experiments Performed in IPF Stuttgart and IPJ Świerk, by H.Herold, A.Jerzykiewicz, M.Sadowski, and H.Schmidt; *Nuclear Fusion* - in print.
26. Preliminary Results of Studies on PF-Type Discharges with Gas Pulsed Injection (in Polish), by L.Jakubowski, J.Baranowski, E.Rydygier, M.Sadowski, E.Składnik-Sadowska, A.Szydłowski, and

J.Żebrowski; Proc. 1988 *Plasma Symposium (Jachranka 1988)* – in print.

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29. Progress in Theory and Experiment of Plasma-Focus (in Polish), by M.Sadowski; *Proc. 1988 Plasma Symposium (Jachranka 1988)* Vol. II. Invited Papers – in print.
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33. PF-360 Plasma-Focus Facility with Dynamic Introduction of Deuterium (in Polish), by A.Jerzykiewicz, L.Kuciński, W.Nawrot, W.Polak, and J.Stanisławski; *Proc. 1988 Plasma Symposium (Jachranka 1988)* – in print.
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41. Studies of Ion Implosion in SOWA-400 Pilot Facility (in Polish), by M.Gryziński, J.Stanisławski ,and W.Komar; *Proc 1988 Plasma Symposium (Jachranka 1988)* - in print.

42. Project of Optoelectronic Line for Transmission of Analog Signals up to 20 MHz (in Polish), by M.Bielik; *SINS Internal Report* No.0-08/P-V/88.

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44. Opto-electronic System of Analogue Signals Transmission. Designs and Results of Measurements (in Polish), by M.Bielik; *SINS Internal Report* - to be published.

45. Design Foundations for Magnetic Energy-Storage System (in Polish), by L.Kociński; *SINS Internal Report* No.0-07/P-V/88.

46. Supply System with Magnetic-Energy Storage (in Polish), by R.Mirowski; *Proc. 1988 Plasma Symposium (Jachranka 1988)* - in print.

47. Comutation Characteristics of 250-kV Spark-Gap with Higher Pressure and Field Distortion (in Russian), by L.Kociński; *Proc. IV All-Union Conf. on Engineering Problems of Thermonuclear Reactors (Leningrad 1988)* - in print.

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56. Evaluation of Pulse Shape of Ion Beams Produced by the IONOTRON-Type Ion Sources, by A.Horodeński; *Proc. Intern. Conf. on Ion Implantation in Semiconductors (Lublin 1988)*; *Phys. Status Solidi* – in print.
57. Studies of Materials in Technology of Thermonuclear Reactors (in Polish), by J.Langner; *Proc. 1988 Plasma Symposium (Jachranka 1988)* Vol. II. Invited Papers – in print.
58. Use of Pulse Ion Beams for Modification of Surface Properties of Semiconductors and Other Technological Materials (in Polish), by J.Langner; *Proc. 1988 Plasma Symposium (Jachranka 1988)* – in print.
59. Report on Realization of Studies Performed in 1988 within Framework of PK-3, Aim 1.27, CPBR-5.8 (in Polish), by J.Langner, J.Piekoszewski, J.Appelt, J.Baranowski, A.Horodeński, E.Górski, C.Pochrybniak, W.Ziemski, and J.Zaręba; *SINS Internal Report* – to be published.
60. Light-Ion Sputtering Yield Measurements of Ti and TiC under Exposure at High Temperature, by A.Santaniello, J.Appelt, J.Bohdański, and J.Roth; *J. Nuclear Mat.* (1988) 163-165.
61. Studies of Plasma Magnetic Traps, Other than Tokamaks (in Polish), by M.Sadowski; *Proc. 1988 Plasma Symposium (Jachranka 1988)* Vol. II. Invited Papers – in print.

6. LECTURES PRESENTED AT INTERNATIONAL SEMINARS AND SYMPOSIA (UNPUBLISHED)

1. M.Gryziński: IONOTRONS - Plasma Devices for Fusion and Technology; lecture presented at Plasma Seminar at IPF-Stuttgart Uni. (Jan. 1988).
2. M.Sadowski: Comparative Analysis of Large Plasma Focus Experiments Performed in IPF-Stuttgart and IPJ-Świerk; lecture presented at Plasma Seminar at IPF-Stuttgart Uni. (Apr. 1988).
3. M.Sadowski: X-Ray, Ion, and Neutron Emission from Nuclear Fusion Facilities; invited lecture presented at Nuclear Seminar at ISV-Uppsala Uni. (June 1988).
4. J.Langner: Ionotron-Plasma Device for Modification of Surface Properties of Technological Materials with Pulsed Ion Beams (in Polish); invited lecture presented at IV Conf. on Physics for Industry in Gliwice (Sept. 1988).
5. A.Jerzykiewicz: Industrial Applications of High-Voltage Pulse Technology Used in Thermonuclear Studies (in Polish); invited lecture presented at IV Conf. on Physics for Industry in Gliwice (Sept. 1988).
6. M.Bielik: Industrial Applications of Control Systems Used in Thermonuclear Studies (in Polish); invited lecture presented at IV Conf. on Physics for Industry in Gliwice (Sept. 1988).
7. J.Kuciński: Neutron Production at H-Injection in ASDEX; lecture presented at Neutron Diagnostics Seminar at IPP-Garching (Nov. 1988).
8. M.Sadowski: Progress in Controlled Fusion Research; invited opening lecture at the First National Symposium on Plasma Physics in Baghdad (Dec. 1988).
9. A.Jerzykiewicz: Optimization of Plasma Focus Facilities as Pulsed Neutron Generators; invited lecture presented at the First National Symposium on Plasma Physics in Baghdad (Dec. 1988).
10. M.Sadowski: Diagnostics of Physical Phenomena in Plasmas

Produced by High-Current PF Discharges; invited lecture presented at the First National Symposium on Plasma Physics in Baghdad (Dec. 1988).

11. A.Jerzykiewicz: High-Voltage Pulse Technology; invited lecture presented at the First National Symposium on Plasma Physics in Baghdad (Dec. 1988).

7. LIST OF VISITORS

1. Dr. Hellmut Schmidt
from the Institute für Plasmaforschung, Uni. Stuttgart, F.R.G.,
visited the Dept. P-V on 18 March, 1988.

2. Prof. Katsumi Hirano
from the Dept. of Electronic Engineering, Gumma Univ., Japan,
visited the Dept. P-V on 18-21 September, 1988.

3. Prof. Rudolf Wienecke
from The Institute für Plasmaforschung, Uni. Stuttgart, F.R.G.,
visited the Dept. P-V on 18-25 September, 1988.

4. Dr. Diethelm Düchs
5. Mrs. Mariagrazia Pacco
both from the JET Joint Undertaking, Abingdon, U.K.,
visited the Dept. P-V on 19-24 September, 1988.

6. Prof. Nils G. Sjöstrand
from the Dept. of Reactor Physics,
Chalmers University of Technology, Gothenburg, Sweden,
visited the Dept. P-V on 5 October, 1988.

7. Dr. O.P. Pyecherski
8. Dr. I.V. Bogdanov
both from the Yefremov Institute
of Electrophysical Equipment, Leningrad, S.U.,
visited the Dept. P-V on 17-23 October, 1988.

9. Dr. Hans J. Bluhm
10. Dr. John B. Greenly
both from the Institut für Neutronenphysik u. Reaktortechnik,
Kernforschungszentrum - Karlsruhe, F.R.G.,
visited the Dept. P-V on 2-6 November, 1988.

11. Prof. K. Hamza
12. Dr. S. Al-Jobari
13. Dr. A. Ibrahim
14. Mr. M. Ali

all from the Iraqi Atomic Energy Agency, Baghdad, Iraq
visited the Dept. P-V on 4-11 November, 1988.

15. Dr. Ibrahim Steif

from the Aleppo University, Aleppo, Syria,
visited the Dept. P-V on 15 November, 1988.

16. Dr. Vladimir Gulyayev

from the Kurchatov Institute of Atomic Energy, Moscow, S.U.,
visited the Dept. P-V on 28 Nov. - 10 Dec., 1988.

17. Prof. Eh.P. Kruglyakov
18. Dr. V.M. Federov
19. Dr. I.V. Vecheslavov

all from the Institute of Nuclear Physics, Novosibirsk, S.U.,
visited the Dept. P-V on 15 December, 1988.

8. LIST OF STAFF.

8.1. Scientific Staff

1. Appelt Jacek, Ph.D.
2. Baranowski Jarosław, M.Sc.
3. Bielik Mirosław, D.Sc.
4. Gębalski Stanisław, M.Sc.
5. Gryziński Michał, Ph.D. - Assoc. Prof. - Head of Division
6. Horodeński Andrzej, M.Sc.E.E.
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8. Jerzykiewicz Andrzej, D.Sc. - Assoc. Prof. - Head of Division
9. Kocięcka Krystyna, M.Sc.E.E.
10. Kociński Lech, M.Sc.E.E.
11. Komar Włodzimierz, M.Sc.
12. Kowalski Marian, M.Sc.
13. Kuciński Jacek, M.Sc. - on leave of absence since Feb.1988
14. Langner Jerzy, D.Sc.- Deputy Head of Department
15. Nawrot Witold, M.Sc.
16. Przybylski Krzysztof, M.Sc.
17. Rabiński Marek, D.Sc.
18. Sadowski Marek, Ph.D.- Professor - Head of Department
19. Składnik-Sadowska Elżbieta, Ph.D.
20. Szydłowski Adam, Ph.D.
21. Wlazło Mariusz, M.Sc.
22. Żebrowski Jarosław, M.Sc.E.E.

8.2. Engineers

1. Borowska Elżbieta, M.Sc.E.E.
2. Brandt Szymon, M.Sc.E.E.
3. Czaus Krzysztof, Eng.
4. Ćwiek Ewa, Eng.
5. Górski Eugeniusz, Eng.

6. Frejlak Wojciech, M.Sc.- partial employment
7. Mirowski Robert, M.Sc.ME - employed since May 1988
8. Polak Wawrzyniec, Eng.
9. Puchalski Zygmunt, M.Sc.E.E. - employed since Oct.1988
10. Rydygier Edward, M.Sc.
11. Stanisławski Jacek, M.Sc.E.E.
12. Witkowski Jan, Eng.
13. Wójtowicz Marek, M.Sc.M.E.
14. Wyszyński Władysław ,Eng.
15. Ziemski Waldemar, M.Sc.

8.3. Technicians

1. Cywiński Krzysztof
2. Gątarczyk Krzysztof
3. Gniadek Krzysztof
4. Grzeszczyk Zdzisław
5. Jankowski Marek
6. Jęda Andrzej
7. Karpiński Paweł
8. Kasperski Krzysztof
9. Kołakowski Bernard
10. Kołnierzak Ryszard
11. Królik Jerzy
12. Kuk Mirosław
13. Kwiatkowski Marek
14. Machalski Piotr
15. Michalik Krzysztof - employed since July 1988
16. Nawrocka Halina
17. Pijanowski Wojciech
18. Rybicki Ryszard
19. Skwara Sławomir
20. Staszkiewicz Bogdan
21. Winiarek Grzegorz - employed until June 1988

22. Wiraszka Andrzej
23. Zagórski Jerzy

8.4. Workshop

1. Całka Henryk
2. Jędrzejczyk Marek
3. Król Janusz - employed until April 1988
4. Niewiadomski Andrzej
5. Żaczek Jerzy

8.5. Administration Staff

1. Gawrońska Alicja
2. Osica Elżbieta, employed until June 1988
3. Pijanowska Jadwiga
4. Presner Franciszek
5. Salamońska Anna, employed since Sept. 1988

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