Nuclear fusion – energy for future

Marek J. Sadowski

Abstract This invited paper has been written on the 50th anniversary of the Institute of Nuclear Research (IBJ). The introduction describes basic nuclear fusion reactions and the appearance of high-temperature plasma, as well as different methods of the plasma generation and containment. The first part of the paper contains a concise description of the present status of research on controlled fusion and the construction of a thermonuclear reactor. The most important results of experiments oriented on magnetic confinement fusion (MCF) or inertial confinement fusion (ICF) are characterized. The second part of the paper presents a story of high-temperature plasma research carried out at IBJ (and now continued at IPJ) at Świerk. The main experimental facilities and scientific results, as obtained with those, are described. The most important achievements of IBJ (IPJ) researchers in the field of plasma physics and technology are indicated, and in particular: invention and development of the so-called RPI facilities producing intense plasma-ion streams, discovery and experimental study of a new configuration of a magnetic trap called the spherical multipole (SM) configuration, development of various plasma diagnostic techniques, and the optimization of different plasma-focus (PF) facilities.

Key words fusion reaction • magnetic confinement • inertial confinement • RPI facility • SM magnetic trap

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Introduction

Nuclear energy can be released not only by the fission of heavy nuclei (i.e. of uranium or plutonium), but also by the fusion of light nuclei into heavier ones [5, 20, 38]. An example of the fusion reaction might be joining four protons into a helium nucleus, but probability of such a process is very small. This process can be realized through a series of intermediate reactions (in the p-p cycle), e.g. inside the Sun and other stars with internal temperatures below 15 millions K. The whole p-p cycle releases energy of 26 MeV. Hence, 1 g of hydrogen can deliver 6×10^5 MJ. The described fusion reactions run inside the Sun very slowly, but (due to gigantic dimensions of our daily star) they deliver enough energy to keep very high temperature and to make it possible life upon the Earth. Other nuclear fusion reactions can occur inside very hot stars, e.g. reactions $^{13}C + {}^{4}He \rightarrow {}^{16}O + n$ occur at temperatures above 100 millions K. The free neutrons can then be absorbed by heavy nuclei and produce still heavier elements. Since the described nuclear fusion reactions occur at very high temperatures usually in the thermodynamic equilibrium state, they are called the thermonuclear reactions.

Aiming at the mastering of nuclear fusion, physicists have been looking for reactions possible in the laboratory conditions [5, 20, 38, 40]. It has been found that one can relatively easily realize the fusion of deuterons and tritons through several reactions:

(1) $^{2}D + ^{2}D \rightarrow ^{3}T + p + 4.0$ MeV
(2) $^{2}D + ^{2}D \rightarrow ^{3}He + n + 3.2$ MeV
(3) $^{2}D + ^{3}T \rightarrow ^{4}He + n + 17.6$ MeV
(4) $^{2}D + ^{3}He \rightarrow ^{4}He + p + 18.4$ MeV

These fusion reactions are possible if the interacting nuclei have energy high enough to overcome the repulsion of their positive charges (so-called the Coulomb barrier). In analogy to the chemical burning process one can say that it is necessary to achieve the nuclear "ignition temperature". At very high temperatures the matter is in the plasma state, which constitutes a mixture of free electrons and positive ions or atomic nuclei. Hot plasma can lose energy by an intense electromagnetic emission. Weakly ionized plasma emits different spectral lines of ions, but at higher temperatures fully-ionized plasma can emit the continuous spectrum from recombination (of ions and electrons) and electron bremsstrahlung. With an increase in the temperature the efficiency of nuclear fusion increases faster, and the "ignition temperature" is achieved when energy released from fusion reactions is higher than radiation losses. It amounts to about 350 millions K for pure deuterium plasma, and about 45 millions K for a deuterium-tritium mixture. The fusion reactions can also be realized by acceleration of deuterons or tritons and the bombardment of targets containing deuterium or tritium, but such processes occur without thermodynamic equilibrium and they cannot be called thermonuclear reactions. In high-temperature plasma the energy distribution of electrons is often different from that of ions, but (in spite of a lack of the equilibrium) the use is made of such parameters as electron temperature (T_e) and ion temperature (T_i). These parameters are usually expressed in electron-volts (eV), keeping in mind that 1 eV corresponds to about 11,400 K.

Aiming to the mastering of new energy sources, physicists undertook tests to perform thermonuclear reaction on the Earth. In the early 50s of the last century there were performed tests with the so-called enriched atomic bombs, which contained ^{235}U and some amounts of deuterium and tritium [20]. The first fully thermonuclear explosion, which was equivalent to 10 megatons of TNT, was performed by the US army in 1952. About 10 months later the Soviet Union army realized the first thermonuclear explosion with the use of lithium reactions:

(5) $^{6}Li + n \rightarrow ^{4}He + ^{3}T + 4.8$ MeV
(6) $^{6}Li + p \rightarrow ^{4}He + ^{3}He + 3.9$ MeV
(7) $^{6}Li + ^{2}D \rightarrow 2\,^{4}He + 22.3$ MeV

In the modern 3F-type (fission-fusion-fission) bombs the fission of ^{235}U or ^{239}Pu triggers the thermonuclear fusion reactions of the material containing lithium and deuterium, while the emitted neutrons induce the fission of an outer shield made of ^{238}U. It should be reminded that the fission of 1 kg of uranium releases energy equivalent to 20 kilotons of TNT, while the fusion of 1 kg of ^{6}LiD releases energy of 68 kilotons of TNT, and 1 kg of D-T mixture can deliver energy of 80 kilotons of TNT.

In the early 50s of the XX century, simultaneously with military oriented tests, a research was undertaken to realize controlled fusion and to construct a thermonuclear reactor. Taking into account that the fossil fuels can be exhausted, and the conventional nuclear (fission-based) reactors produce radioactive wastes, the fusion research was strongly motivated by search for new energy sources. It was estimated that the deuterium resources in water upon the Earth are about 10^{17} kg, equivalent to about 10^{24} kWh, while the present power consumption amounts to about 5×10^{9} kW.

In order to achieve the positive energy balance in the thermonuclear reactor, high-temperature plasma must have an appropriate concentration and lifetime, i.e. at the lower density (n), the confinement time (τ) must be longer [38]. This condition is determined by the so-called Lawson criterion: for the D-D, fusion one must obtain $n\tau > 10^{16}$ s/cm^3, and for D-T fusion, this product should be $> 3 \times 10^{14}$ s/cm^3. Considering the dependence on the plasma temperature (T), it is more reasonable to use the so-called triple product $Tn_e\tau_E$, where τ_E is the energy confinement time (taking into account losses due to electromagnetic and corpuscular radiation, particle diffusion, thermal conductivity, convection, etc.).

Progress in nuclear fusion research

From the very beginning of fusion studies, it was known that the most simple method to produce hot plasma is the application of high-current electrical discharges. Taking into account that fully ionized plasma consists of charged particles (ions and electrons), physicists tried to contain it by means of magnetic fields. Different types of such magnetic traps are presented in Fig. 1.

Unfortunately, field lines in the magnetic traps of Mirror- or Cusp-type are not closed inside the plasma volume, and charged particles can partially escape through the so-called loss cones. Using various methods of the plasma generation and heating, e.g. by means of current pulses and injection of high-energy ions, in such systems it was possible to obtain the plasma concentration of 10^{13}–10^{14} cm^{-3} and confinement times of the order of 10^{-3}–10^{-1} s only. Therefore, the next step was the use of quasi-toroidal traps with closed magnetic field lines: Stellarators (developed in the USA) and Tokamaks (developed in the Soviet Union). In Stellarators, additionally to coils generating a toroidal field (B_z) there were used special windings producing the so-called poloidal field (B_Θ), which caused some twisting of the magnetic field lines and improved plasma stability. To heat plasma in Stellarators, the use was usually made of electromagnetic waves of frequencies ensuring the cyclotron resonance of electrons or ions.

In the late 60s of the XX century, particular attention was paid to Tokamaks, in which the poloidal magnetic field was produced by a strong current flowing induced in plasma ring by mean of a large transformer [38]. Very good results obtained within the T-10 facility (at the Kurchatov Institute in Moscow) changed directions of

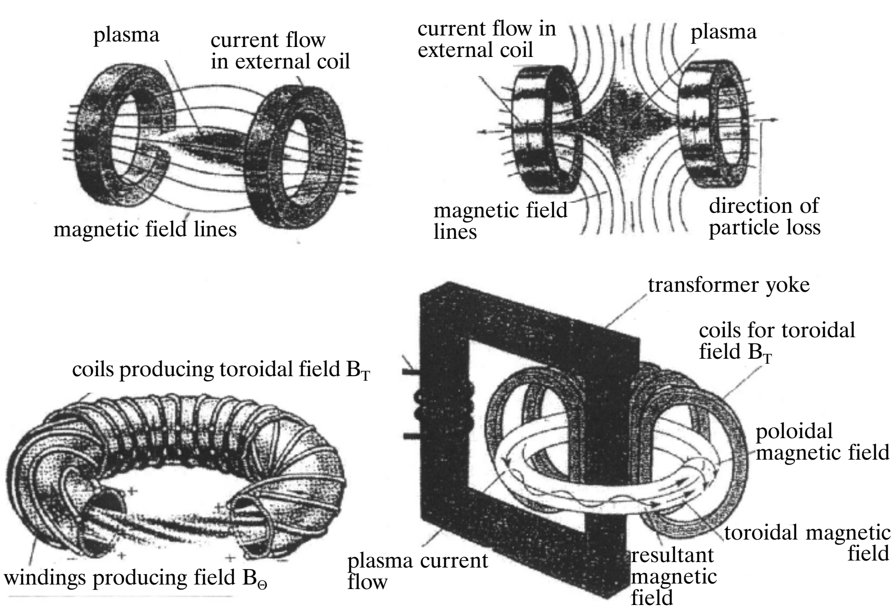


Fig. 1. Various types of plasma magnetic traps. In the upper row – open-ended magnetic traps of the Mirror-type (on the left) and Spindle Cusp-type (on the right). In the lower row – the Stellarator and Tokamak traps.

fusion research considerably. Numerous different tokamaks were built and investigated all over the world. The most famous is the large JET (Joint European Torus) facility constructed by the European Community in Culham, UK. It still remains the largest tokamak in the world. The vacuum chamber of JET is shown in Fig. 2.

The large toroidal chamber of JET consists of many segments and it has complicated structure, because walls must be protected against high-temperature plasma and it is necessary to arrange an appropriate number of heating antennas and diagnostic ports. There is also an internal limiter (of the plasma surface) and the so-called divertor region, where a special configuration of magnetic field lines enables some impurity ions to be collected.

Other examples of the large tokamaks were the TFTR (Tokamak Fusion Test Reactor) facility operated at PPPL in the USA (but shut down a few years ago) and the JT-60 facility in Japan (still in use). A comparison of the main parameters of these devices is given in Table 1.

Extensive studies of different tokamaks, which were run in many laboratories, ensured a considerable improvement in plasma parameters, as shown in Fig. 3.

In 1991, using a D-T mixture, the JET team obtained from fusion 1.8 MW during about 1 second. In 1994, the TFTR facility delivered about 10 MW in 0.7-s pulses.

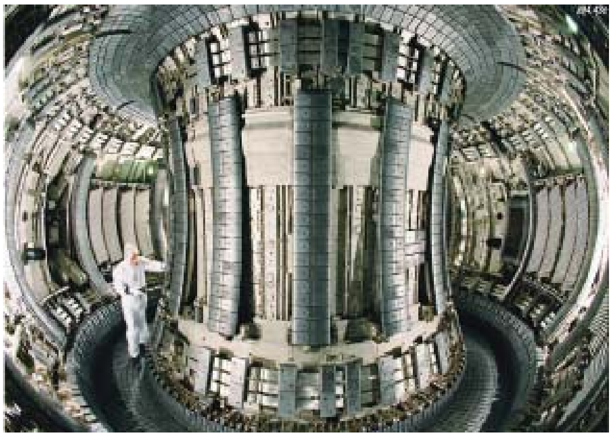


Fig. 2. Large experimental chamber of the JET (Joint European Tokamak) facility. There are shown the central column (containing a yoke of the large transformer used for inducing the main discharge current), some equipment (microwave antennas) for additional plasma heating, diagnostic ports upon the external wall and the divertor region (at the bottom).

Three years later the JET was able to produce pulses lasting about 6 s and releasing about 4 MW. In 1997, there was also achieved a record power of 16 MW in pulses lasting about 2 s [15]. It should, however, be noted

Table 1. Parameters of the large Tokamak facilities

	JET (Europe)	JT-60 (Japan)	TFTR (USA)
Minor radius, m	2.10/1.25	0.95	0.85
Larger radius, m	2.96	3.0	2.48
Toroidal magnetic field, T	3.45	4.5	5.0
Plasma current, MA	7.0	2.7	3.0
Pulse length, s	30	5–10	2
Additional heating, MW	44	54	27
Working gas	D-D	H	D-D or D-T

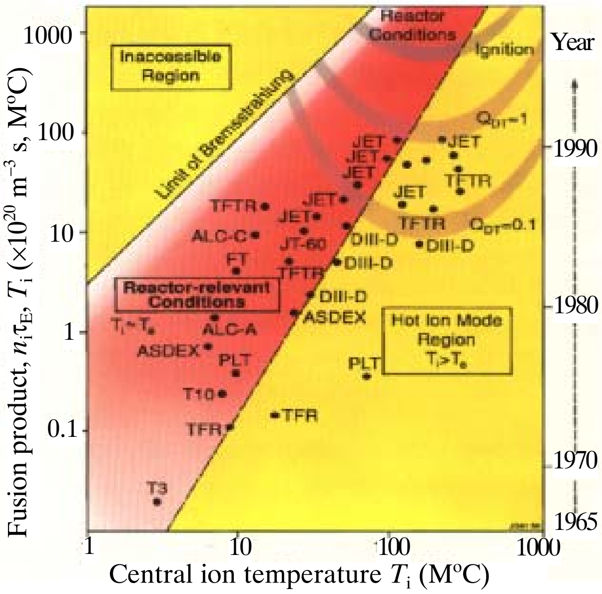


Fig. 3. Results of the largest tokamak-type experiments, which show the progress in fusion research. Values of the so-called fusion product ($n_i T_i \tau_E$) include the highest values of the ion concentration (n_i), ion temperature (T_i) and energy confinement time (τ_E).

that the plasma heating in those experiments consumed 22 MW in energetic neutral particles (NBI) and about 3 MW in microwaves (ICRH). Nevertheless, these good results accelerated the design of a large ITER (International Tokamak Experimental Reactor) facility. Four large teams of scientists (from EC, Japan, USA and Russia) were engaged in various tokamak studies and the detailed project of ITER. Some crisis appeared in 1996, when two theoreticians (W. Dorland and M. Kotschenreuther) from Texas University presented a theoretical model describing the development of strong turbulences inside high-temperature plasma under conditions assumed for ITER. The US government shut down the financing of several laboratories and decided to withdraw from the ITER project. Design studies have, however, been continued by EC and Japanese teams, as shown in Fig. 4.

Some stoppage of tokamak research (in the mid 1990s) accelerated studies of other options. Germany and Japan continued intense research on advanced Stellarator systems. After a series of successful experiments with several Wendelstein facilities, which showed good agreement with theoretical predictions, the German government undertook decision to finance the construction of a large Stellerator Wendelstein 7-X in a new research centre in Greifswald [39]. A considerable progress has also been achieved with helical facilities investigated in Japan. New Japanese experiments and the Wendelstein 7-X machine (probably available in several years) should enable to verify the scaling laws and to make next step towards the construction of a fusion reactor based on these complicated magnetic configurations.

Simultaneously with studies of different magnetic confinement fusion (MCF) concepts, in some military research centres, there was carried out intense research

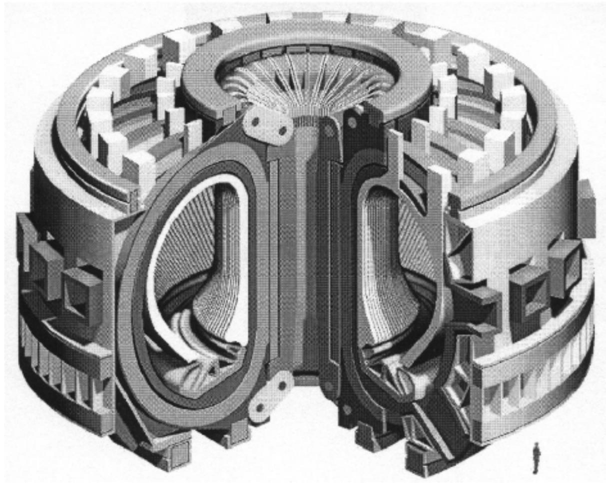


Fig. 4. Artistic view of the future ITER facility, which shows the size of the main experimental chamber and magnetic coils. The large radius of the chamber should be 6 meters, and the overall ITER dimensions should be about 30 m × 30 m. The facility should produce 500 MW in repetitive pulses lasting 100 s each.

on the inertial confinement (ICF). In that case the main aim was to produce very dense and hot plasma, in which (in spite of its very short lifetime) one could achieve a large number of fusion reactions. The simplest method was based on the use of ultrahigh-current linear discharges (so-called Z-pinch experiments) which produce their own magnetic fields for the plasma confinement. Many Z-pinch experiments have demonstrated that such facilities might be sources of very intense X-ray pulses [40], as shown in Fig. 5.

Another method of the generation of very dense magnetized plasma was based on the use of two coaxial electrodes [4, 25]. A high-current pulse discharge between such electrodes can form a dense plasma layer (current sheath), which (after its acceleration along the electrode) can collapse at the z-axis and form a dense plasma region (plasma focus).

Due to the described processes, it is possible to produce dense and high-temperature plasma of a concentration of 10^{17}–10^{19} cm^{-3}, temperatures ranging from several hundred eV to several keV and lifetimes of the order of 100–200 ns. It should be noted that studies of such plasma discharges have been carried out in Poland for many years. Several PF-type facilities have been constructed and investigated at IBJ (and continued by IPJ) at Świerk, and later on at the Military Academy of Technology (WAT) and IPPLM in Warsaw. On the basis of those studies a new mega-joule PF-1000 facility [26, 35], which is the largest Mather-type machine in the world, has been designed and constructed, as shown in Fig. 6.

Progress in the pulse power technique made it also possible a revival of Z-pinch experiments [40]. A new technology enables the generation of current pulses of intensities ranging many MA. Experiments with the generation of intense electron- or proton-beams (in PBFA and ANGARA machines) have been shut down, mainly because of the difficulties with the focusing of such beams upon nuclear micro-targets. Fusion-

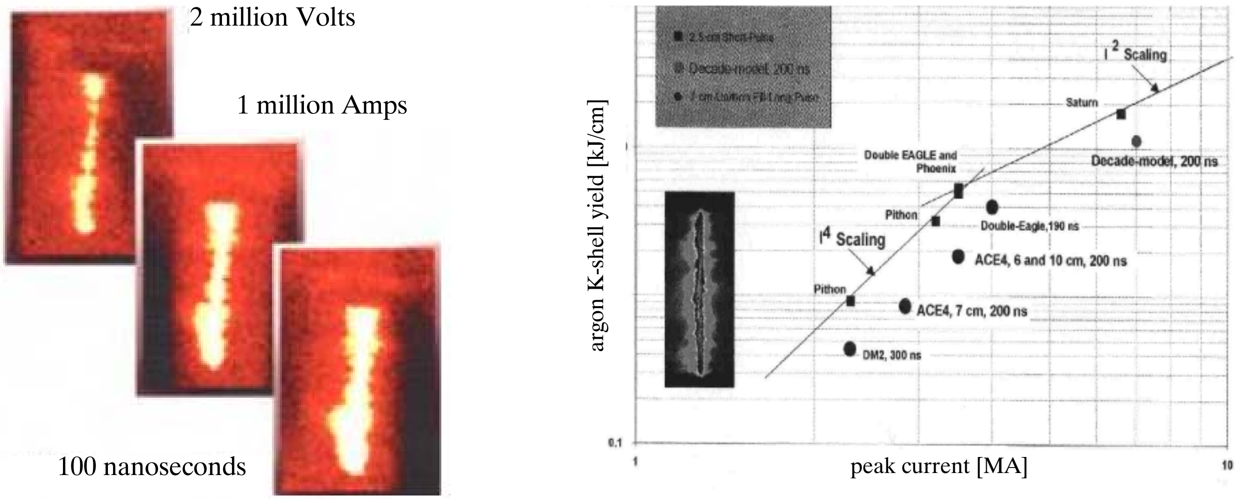


Fig. 5. High-speed camera pictures of Z-pinch type discharges (on the left) and the X-ray emission yield *vs*. the discharge current, as measured in several Z-pinch experiments carried out in the USA.

oriented research based on the use of high-energy heavy ions has never been started on a reasonable scale. Nevertheless, the rising interest in extremely high-current discharges induced the design and construction of many Z-pinch facilities, particularly in the USA and Russia. The modular construction of those facilities enabled record discharge power of 10^{14}–10^{16} W to be achieved, but fusion neutron yields appeared to be moderate. A simplified scheme of a powerful SATURN facility is presented in Fig. 7.

This system was used for numerous Z-pinch type experiments with the implosion of thin cylindrical targets composed of many (from several dozens to several hundreds) very thin metal (usually W) wires. The experiments with the implosion of 12.5-mm-i.d. cylinders (consisted of 70 tungsten wires of 7.5 μm in diameter) generated X-ray pulses of energy equal to 450–800 kJ. After some modernization, the SATURN machine was converted into the Z-Machine in which one can generate current pulses of intensity reaching 27 MA. In the experiments with cylindrical targets consisting of 480 very thin tungsten wires there were produced record X-ray yields of the total power of 290 TW. Such X-ray pulses could be used for ICF purposes, but recent computer simulations have shown that one needs X-ray pulses of power ranging 1000 TW and energy of about 16 MJ. For these purposes, the Sandia Laboratories has started to build a new X-1 Machine. Due to rapid development of laser technology, the ICF research has been oriented on the use of different powerful lasers. Initially the use was made of Nd-glass lasers (λ = 1.05 μm), and micro-targets in the form of miniature glass spheres filled up with a D-T mixture. In the USA, in the 1970s, there were built several powerful laser systems, e.g. JANUS (0.2–0.4 TW), ARGUS (2–4 TW) and SHIVA (25–30 TW). In the 1980s, there were put into operation new systems: SHIVA-II (100–200 TW) and SHIVA-NOVA (200–300 TW). Large laser facilities were also built in France (PHEBUS and LULI), in Japan (from GEKKO-II to GEKKO-XII), in GB (VULCAN and HELEN) and in the Soviet Union (DELFIN and other).

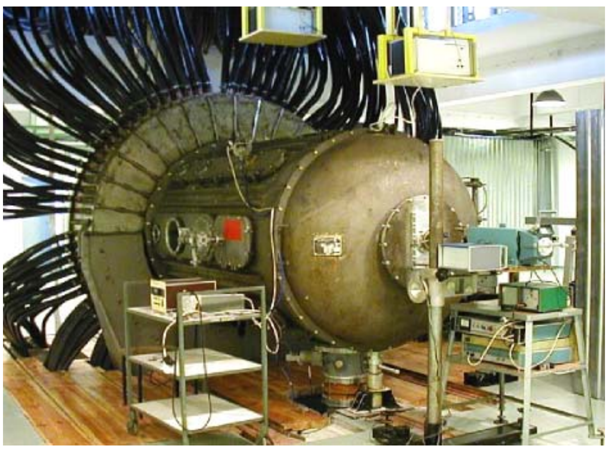


Fig. 6. Experimental chamber of the mega-joule PF-1000 facility, which was designed at IPJ at Świerk, Poland, and assembled at the IPPLM in Warsaw. It is now used by the International Centre for Dense Magnetized Plasma operated under UNESCO auspices.

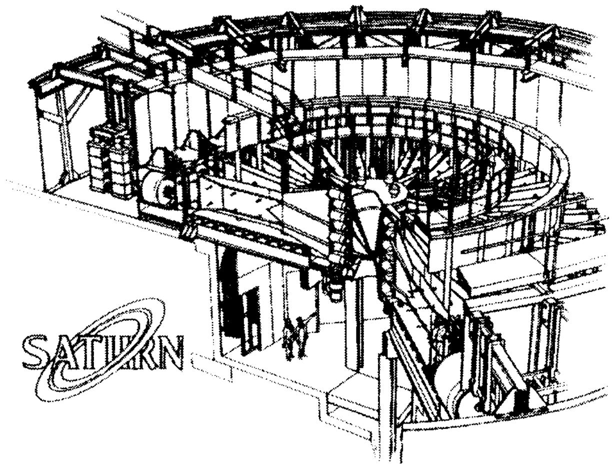


Fig. 7. Scheme of the large Z-pinch experiment SATURN, which was designed and constructed at the Sandia Laboratories, USA. The size of the facility can be estimated by a comparison with people figures (shown inside).

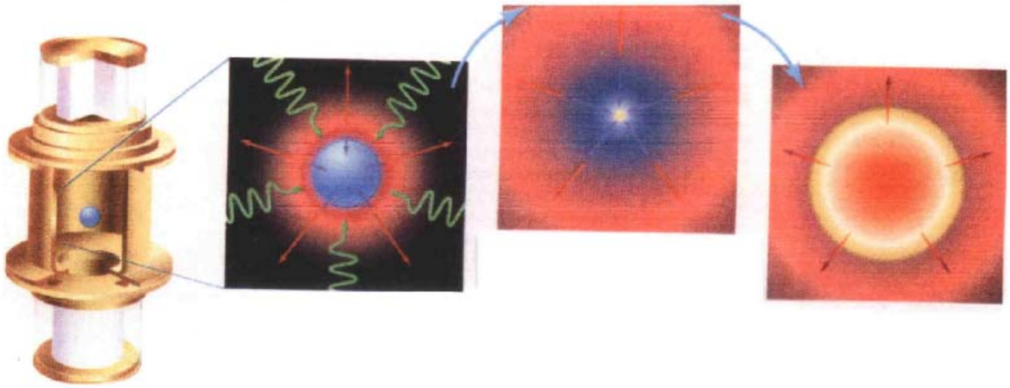


Fig. 8. Scheme of the fusion experiment with a triple Hohlraum-type target and a micro-target placed in the centre. Intense X-ray pulses, which are to be generated by high-current Z-pinch discharges through thin wire sets (placed at the both ends), have to ionize the micro-target and to induce the nuclear fusion ignition.

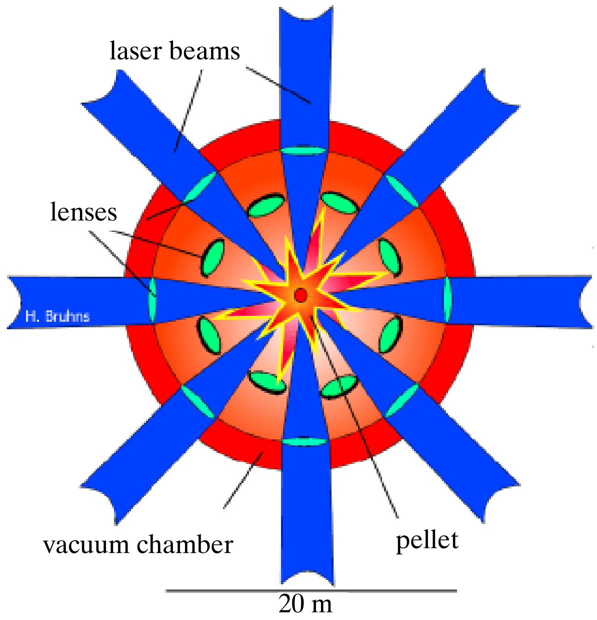
When it was proved that the short-wavelength radiation is better absorbed by micro-targets some studies have been oriented on the use of the 3rd harmonics. Considerable improvements have also been made in the construction of the micro-targets and in uniformity of their irradiation. Using the modified micro-targets, the GEKKO-XII experiment (with 12 laser beams of the total power of 50 TW) generated 10^{12} neutrons per shot.

In order to improve the plasma compression, there were developed new micro-targets with so-called indirect drive. In such systems, the laser beams are introduced into a metal mini-target (Hohlraum), where they are converted into intense X-rays which heat and compress a micro-target placed in the centre. A simplified scheme of such an experiment is shown in Fig. 8.

Experiments performed in the large NOVA facility with different micro-targets and computer simulations have demonstrated that for ICF one should generate laser pulses of power above 500 TW and the length of about 4 ns, i.e. about 2 MJ. Therefore, it was decided to build a very large laser facility called the NIF (National Ignition Facility). A scheme of a multi-beam laser fusion experiment and a picture of the NIF chamber are shown in Fig. 9.

It should be addend that the laser technology develops very quickly, and very high laser beams become available. A new concept of the so-called fast ignition has been proposed [37], in which the first powerful laser pulse ensures the preliminary formation and compression of hot plasma, and the second (even more powerful, e.g. 10^{15} W) laser pulse drills a small hole in such a plasma target, inducing the fast triggering of fusion reactions. There are constructed new powerful CO_2 and KrF gas lasers. In the recent years, a considerable progress in the construction of diode-pumped solid-state lasers (DPSSL) has been achieved. Such lasers are characterized by high efficiency and very high repetition. Several large laboratories (particularly ILE in Japan and LLNL in the USA) have started to design the DPSSL systems for controlled fusion purposes.

Coming back to estimates of prospects of fusion-based power stations, one should pay attention to political and financial decisions on support of tokamak-based research [7, 20]. The progress in this field is unquestionable. The recent increase in activities of



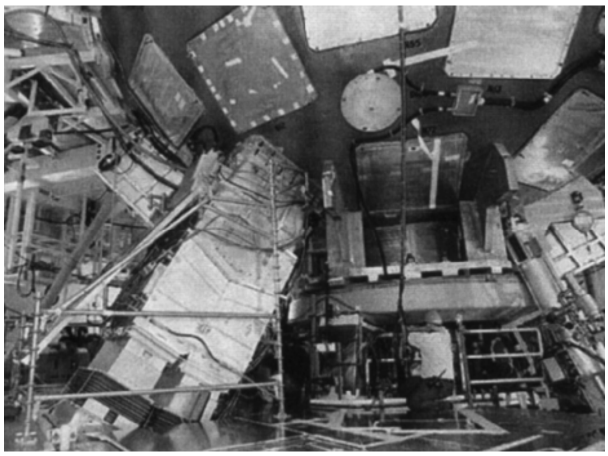


Fig. 9. Scheme of the multi-beam laser fusion experiment and a picture of the bottom part of the NIF (National Ignition Facility) designed for mega-joule laser experiments at the LLNL, USA. The picture was taken before the first light-shots with 32 laser beams in 2003.

many groups engaged in tokamak research has led to the revival of the ITER project. Six partners (EC, China, Japan, Russia, South Korea and the USA again) have agreed to consider different options and to support the construction of ITER. After many discussions the EC authorities have chosen the CEA centre in Cadarache, France, as the optimal site for ITER. Japan, South Korea and USA have preferred another location in Rookasho, Japan. The final decision about the location of ITER at Cadarache was undertaken in June 2005. A new step towards the construction of thermonuclear reactors will be made if the ITER facility is built in about ten or dozen years. Therefore, many experts are engaged in detailed technical projects of future fusion-power stations. A simplified scheme of such an energetic system is presented in Fig. 10.

The most important parts of such a system will be internal- and external-shields, which must ensure the energy transfer from fast fusion-produced neutrons (about 2.5 MeV from D-D reactions and 14 MeV from D-T fusion). The other fusion products as helium and tritium should be captured by appropriate physical and chemical processes in the shielding layers. The recovered tritium gas might then be used as the fusion fuel again. The whole system must of course be equipped with appropriate heat exchangers, gas turbines and electric current generators. During the designing and construction of future fusion power stations, particular attention must be paid to a proper choice of constructional materials and modular structures, in order to enable full robotics service inside the fusion chamber. Some technological solutions have already been tested in large tokamaks (like JET and TFTR), but extensive material studies must still be performed under radiation and thermal loads similar to those expected for future thermonuclear reactors.

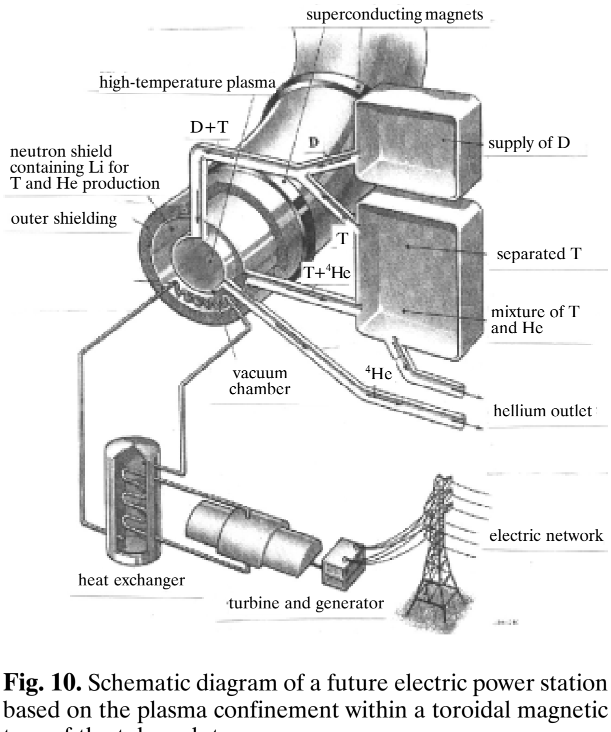
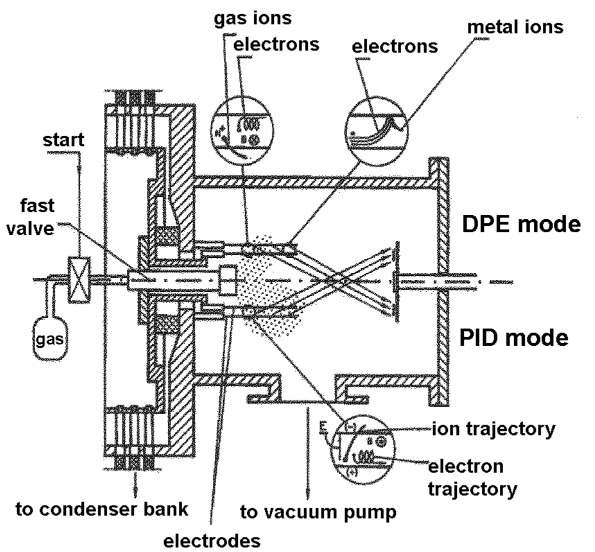


Fig. 10. Schematic diagram of a future electric power station based on the plasma confinement within a toroidal magnetic trap of the tokamak-type.

High-temperature plasma research at IPJ (previously IBJ) at Świerk

Experimental and theoretical studies of high-temperature plasmas were initiated at the IBJ (now IPJ) in the mid 1950s. The first studies concerned a theoretical analysis of fusion chain reactions, which are of particular importance for astrophysics [8]. The first experimental studies were devoted to observations of hot plasma generated by a special coaxial injector designed by M. Gryzinski *et al.* [10]. On the contrary to the conventional coaxial injectors, the system was equipped with two coaxial electrodes consisted of many (2–3 dozens) thin metal rods distributed symmetrically around the electrode periphery. It made the electrodes penetrable for charged particles produced by a high-current pulse discharge within the inter-electrode region. A scheme of a multi-rod plasma injector (RPI) system and a picture of one of the first experimental setups are shown in Fig. 11.

In the 1950s, experimental studies were carried out by a team headed initially by Prof. A. Sołtan, and



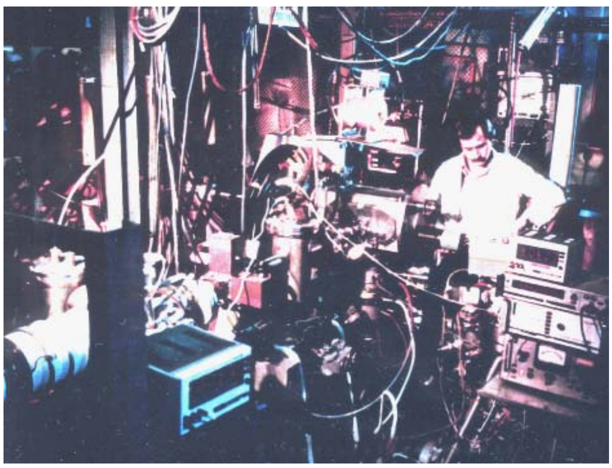


Fig. 11. Scheme of the RPI-type system, which presents the electrode configuration and ion trajectories for two different operational modes, and the RPI-15 device (of nominal energy equal to 15 kJ) used for studies of intense plasma-ion streams in the mid 1970s.

successively by Prof. Z. Wilhelmi and Dr M. Gryzinski. The studies included optical observations with high-speed cameras and detailed measurements of plasma by means of different probes and optical-spectroscopy tools, e.g. spectrometers and mono-chromators. The theoretical studies concerned motion of accelerated ions, mostly by means of a single-particle model. Results of those experimental and theoretical studies were summarized in a series of IBJ reports, which were later on published in "Nukleonika" [9, 10, 30]. The most important result was the determination of different operational modes of RPI systems and the main parameters of the produced plasma-ion streams, i.e. their dimensions and dynamics, concentration and temperature distributions etc. These results became the basis for the design and construction of new experimental facilities of the RPI-type. It was demonstrated that the RPI facilities can generate high-temperature plasmas of parameters interesting for basic research on controlled nuclear fusion. In the RPI discharges performed with the pure deuterium puffing, there were observed fusion-produced neutrons, although their yield was not very high. In order to optimize the RPI discharges, particular attention was paid to development of different diagnostic techniques. X-ray pinhole cameras and various analyzers of charged particles were designed and applied in experimental studies. Results of those investigations were presented at different conferences and published in a series of papers [1, 3, 31, 32].

It should be noted that almost simultaneously with the development of RPI research some efforts were undertaken to investigate the magnetic confinement of high-temperature plasmas. An original concept of the so-called spherical multipole (SM) magnetic trap was developed by M. Sadowski [22], and a new experimental system was designed [23]. The main idea of that experiment was to contain plasma within the minimum-B configuration formed by 32 magnetic dipoles (in practice – small coils), which were distributed around a spherical vacuum chamber and oriented in the radial direction (see Fig. 12). It was shown that such a SM-configuration ensures the magneto-hydrodynamic (MHD) stability and simultaneously it enables plasma losses to be reduced, due to the elimination of the so-called magnetic slits and the formation of narrow "loss-cones" only. In the first SM-type experimental facility (called the KAKTUS machine) high-temperature plasma was produced by 6 coaxial injectors distributed symmetrically around the trap, as shown in Fig. 12.

The most important result of the KAKTUS experiment was the demonstration that the charged particle losses have considerably been reduced and the confinement time has been increased [24]. In 1968, the author of this concept (M. Sadowski) received a fellowship from the Kosciuszko Foundation to study plasma confinement problems at the Princeton Plasma Physics Laboratory, USA. After his come back to Świerk in 1969, experimental investigations of the SM configuration were continued and a second KAKTUS-II device was constructed. The KAKTUS-II machine was designed especially to be filled up with clean plasma produced by an intense laser beam. Some preliminary experiments with laser-produced plasma were performed, but due to organizational and financial limitations that research was stopped in the 1970s. Nevertheless, the concept of the SM configuration has later been adopted by other researchers for the construction of multi-dipole Q-machines [17]. This idea is still exploited for the confinement of plasma in sources of intense ion beams [18].

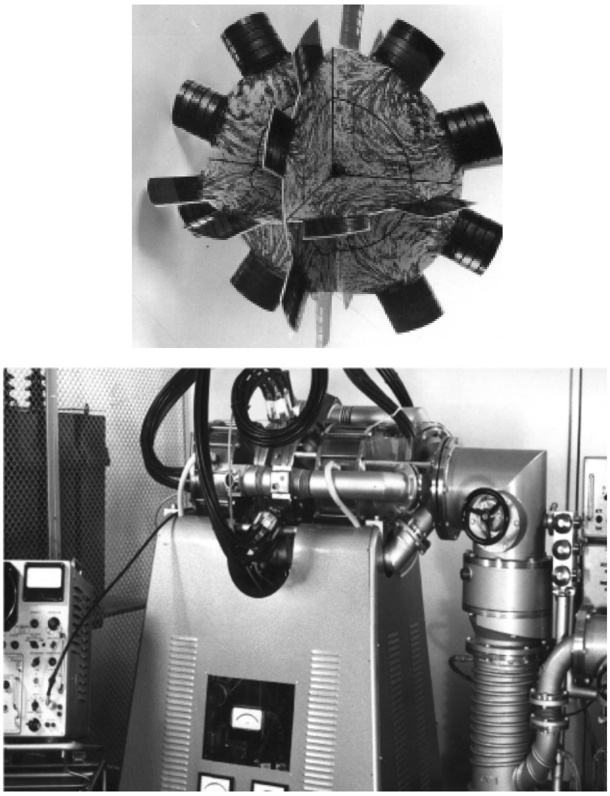


Fig. 12. Model of the SM magnetic configuration, which shows the magnetic field lines distribution (in 3 symmetry planes), and the KAKTUS facility filled up with plasma from 6 plasma injectors located symmetrically and powered simultaneously.

In the late 1960s, the IBJ team became involved in new plasma experiments organized by Prof. S. Kaliski at the Military Academy of Technology (WAT) in Warsaw. The IBJ team was responsible for the design and construction of the so-called plasma-focus (PF) facilities and the development appropriate diagnostic techniques, e.g. a laser interferometry for measurements of the dense plasma concentration. The first PF-20 and PF-150 devices (of energy ranging from 20 kJ to 150 kJ) were constructed at Świerk, and after tests they were transferred to WAT. When the plasma physics group was established at WAT, the main research activities became concentrated on studies of laser-produced plasmas and PF-type discharges. Experimental studies of PF discharges within the PF-20 and PF-150 facilities were carried out by joint teams from IBJ and WAT. The most important results of those studies were presented at different conferences [2, 6]. In particular the results of the PF-150 experiment, as performed with the additional plasma heating by means of a 100-J CO_2 laser beam, were presented at the international conference in Lausanne in 1975 [14]. That experiment, in which an increase in the fusion-neutron yield was achieved, became the basis for a large mega-

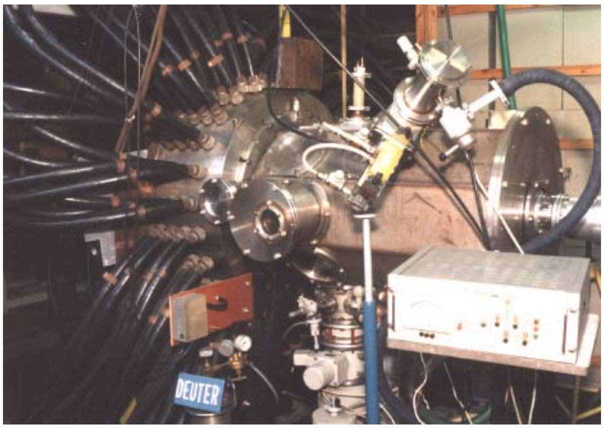


Fig. 13. General view of the PF-360 experimental chamber, as constructed at Świerk, and some diagnostic equipment used for studies of X-rays, fast ion beams and fusion-produced neutrons from D-D reactions.

joule project. The IPJ plasma team was asked to design and construct the mega-joule PF-facility and HV supply units for a more powerful laser. In the late 1970s a larger PF-360 device, which constituted a prototype module for the PF-1000 facility, was constructed and put into operation at Świerk, as shown in Fig. 13.

Experimental studies of plasma phenomena within the PF-360 facility were carried out by joint teams from IBJ (IPJ) and WAT (later on IPPLM). The most important results were reported at numerous international conferences and published in different journals, e.g. [11, 33]. Particular attention was paid to the studies of the plasma dynamics and neutron yields.

Simultaneously with research on PF phenomena, extensive studies of RPI discharges were continued at Świerk and a new larger RPI-type facility (so-called SOWA-400 machine) as well as two smaller devices. IBIS and MAJA facilities of about 150 kJ each were designed and constructed. The SOWA-400 facility is shown in Fig. 14.

The most important results of measurements, as performed within IBIS and MAJA facilities, were mass- and energy-spectra of ions delivered by the pulsed plasma streams produced in these devices. It was also

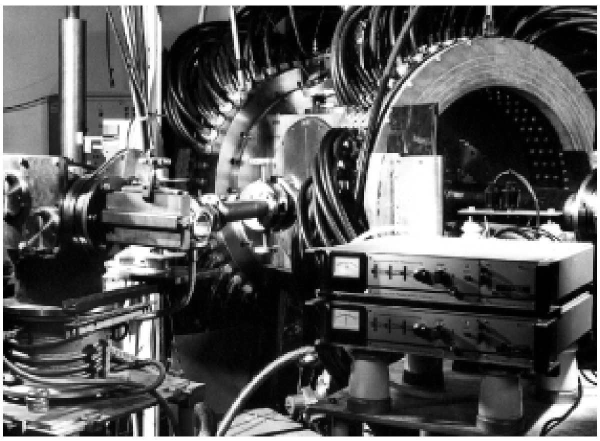


Fig. 14. General view of the SOWA-400 facility and some diagnostic equipment during tests carried out at IBJ in the early 1970s.

Fig. 15. General view of the IONOTRON-SW30 machine equipped with the RPI-type plasma accelerator of the vertical axis and a carousel holder of samples (below), capacitor banks (behind and on the right), and an electronic control unit (on the left).

shown that the plasma streams, containing special admixtures introduced by gas puffing, can be used for modifications of different materials, e.g. for the production of solar cells [19]. In order to deliver laboratory equipment to other research institutes, a special RPI-type facility (so-called IONOTRON-SW30) was designed and constructed, as shown in Fig. 15.

Results obtained with the different RPI facilities (mentioned above) were reported at international conferences and published in several journals [27, 36]. On the basis of an optimistic scaling, assuming an effective interaction of two counter-streaming discharges, a new project of a mega-joule SOWA-1000 facility was launched. Due to financial limitations it was realized very slowly, and it became completely stopped in the 1980s, but the large experimental hall and some parts of equipment have been used for other purposes. On the contrary to the SOWA-400 and SOWA-1000 facilities, which have not been completed, a smaller MAJA device (after its use for RPI studies) was converted into the modernized MAJA-PF facility, which has been exploited mainly for research on the formation of "hot-spots" and polarization of selected X-ray lines, as shown in Fig. 16.

Several series of experiments within the MAJA-PF delivered important information that X-ray spectral lines, particularly those emitted from "hot-spots", have evidently different polarization [12]. It appeared to be the experimental evidence that some electron beams (inside the pinch column) move also in the radial direction [13]. During recent ten years particular

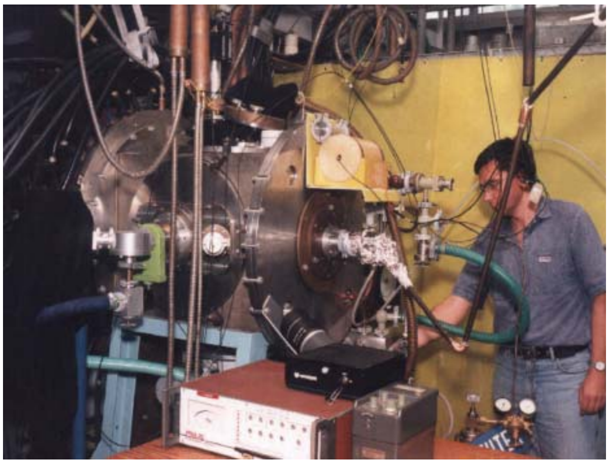


Fig. 16. General view of the MAJA-PF facility and some diagnostic equipment used for studies of the corpuscular emission and the polarization of X-rays.

Fig. 17. UHV stand equipped with the linear (cylindrical) arc plasma source and laser trigger system, built in the frame of the European Community-Research Infrastructure Activity under the FP6 "Structuring of the European Research Area" program (CARE, contract number RII3-CT-2003-506395).

attention was paid to the optimization of different PF facilities. As mentioned above, the PF-1000 device (designed at IPJ at Świerk) was assembled at IPPLM in Warsaw. It was put into the operation at a lower energy level in 1994. The experimental investigations were carried out in the frame of the bilateral scientific collaboration of IPJ and IPPLM [28, 29]. Some studies were also performed in the frame of the international collaboration with the Czech Technical University in Prague, the IPF in Stuttgart, the Physico-Technical Institute in Kharkov, as well as the Kurchatov Institute and Lebedev Institute (both in Moscow). Many joint papers have been presented at different international conferences and published in various journals [28, 29, 34].

Plasma studies at the IPJ at Świerk have been run mainly in the Department of Plasma Physics and Technology P-V (headed by Prof. M. J. Sadowski), divided into several experimental and theoretical groups, as described in the World Survey of Activities in Controlled Fusion Research. At the moment, this Department employs about 30 persons (including 17 scientists and engineers). Selected theoretical studies, in particular those on solitons and strong non-linear phenomena, have been performed by a plasma theory group (5 persons, headed by Prof. E. Infeld) in the Department of Nuclear Theory P-VIII. Some technological studies, and in particular those on material engineering with plasma discharges, have been carried out within the cooperation with an experimental team (5 persons) in the Department of Material Studies P-IX (headed by Prof. J. Piekoszewski and Prof. Z. Werner).

In recent years, activities of Dept. P-V in the field of plasma technology have been concentrated upon the application of ultrahigh-vacuum (UHV) arc-discharges for the deposition of thin superconducting (pure niobium) layers upon internal surfaces of RF cavities for particle accelerators [16]. A special UHV facility has been designed by the team headed by Dr J. Langner. That facility has been assembled and put into operation, as shown in Fig. 17.

Coming back to fusion-oriented plasma research, it should be noted that after the establishment of the Association EURATOM-IPPL on January 1, 2005, the Dept. P-V of IPJ became an active member of this association. Two experimental groups have undertaken responsibility for the realization of different tasks. The first task concerns the elaboration of special Cerenkov-type detectors applicable for measurements of fast electrons escaping from tokamak-type facilities, e.g. TORE-SUPRA in Cadarache, France. The second task concerns the application of solid-state nuclear track detectors (SSNTD) for measurements of fast protons and other fusion products emitted from tokamak-type facilities, e.g. TEXTOR in Juelich, Germany. It means that the IPJ plasma teams have been involved in an active participation in large-scale plasma experiments at foreign laboratories within the frame of the EURATOM fusion program.

Summary and conclusions

This invited paper can be summarized as follows:

- Resources of natural fuels undergo destruction and might be exhausted, and the conventional fission reactors have difficulties with radioactive wastes. Therefore, the mastering of fusion is of great importance for many nations all over the world.
- Future fusion power stations will eliminate many wastes and they will be safe in the operation as well as from the point of view of the proliferation of nuclear materials.
- Fusion power stations will not be larger than the large conventional energetic systems, and they will not undergo influences of weather or season. Safe thermonuclear reactors might be located near large industrial or human concentrations in order to reduce expensive and complicated systems of the power transfer.

The important achievements of IBJ (IPJ) in high-temperature plasma research are as follows:

- Invention and development of the so-called RPI-type facilities applicable for studies of intense plasma-ion streams and technology-oriented research.

– Discovery and experimental study of a new-type SM configuration of a plasma magnetic trap, which is still widely used in many ion sources.
– Development of plasma diagnostic techniques, e.g. charged-particle analyzers, laser interferometers, Cerenkov-type detectors, solid-state nuclear track detectors (SSNTD) and time-resolved optical spectroscopy.
– Optimization of different PF-type facilities, and, in particular, the determination of the emission characteristics of X-rays, fast electrons, accelerated ions, fusion-produced neutrons, and changes in optical spectra of the visible radiation.

It should be added that the active participation of the IPJ plasma groups in the EURATOM fusion programme opens new possibilities.

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