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# *COOPERATION WITH SMALL COUNTRIES IN PLASMA SCIENCE AND ATTEMPTS TO APPLY TO INDUSTRIAL NEEDS*

***Part II***

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# Co-operation with small countries in the field of plasma science and attempts to apply it to the local industrial needs

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## 1. Introduction

Dense Plasma Focus (DPF) device is a remarkable source of copious X-rays (soft and hard), neutrons, fast electrons and ions and plasma streams as well. Because it has the same energy density (contrary to e.g. tokamak devices) at any feeding energy level (at least in the range 0.10 through 1,000.00 kJ) it has a predictable yield of these types of radiation. And due to its very short pulsed character and small sizes of the sources of the radiation it has an extremely high brightness making it very well fitted to different applications. It is so in spite of the fact that a quite complicated picture of physical processes ruling a generation of radiation of the above mentioned types still does not completed. Possibility to work with DPF on a low energy level and relatively low cost of the related equipment (even modern one) produce a unique opportunity to organize various types of activity - scientific, educational, and applications - even in small countries as well as in countries with restricted funds for scientific researches.

In any of the above mentioned types of activity, but in particular for applications, these devices should be reliable with high rep rate and long lifetime, and they should produce about the same dose in each step of its operation. These issues can be resolved now on a base of new technologies and by using a special type of its operation.

Our researches was step up:

- in the framework of AAAPT,

- in the United Nations University,
- in the International Centre for Theoretical Physics, Trieste, and
- within the collaboration between the National Institute of Education, Nanyang Technological University, Singapore, from one side, and Lebedev Physical Institute, Russian Academy of Sciences, and the Moscow Physical Society, from the other side.

## 2. Apparatus

During the last decade we have elaborated and use for different purposes three types of the DPF devices: UNI/ICTP PFF (Fig. 1 and 2), NX1 (Fig. 3a and 4a, b, c) and NX2 (Fig. 3b and 5). The first one appeared to be the best for education, yet some investigations in the field of basic plasma physics have been carried out with it.

Last several years have been devoted to an elaboration of a new DPF module for the feeding energy level of 2-3 kJ. Because of its application orientation main demands were high rep rate, long lifetime, and high efficiency. But these features also gave us a unique opportunity - previously unattainable - to investigate some fundamental plasma physics phenomena, which demanded a long continuous operation of a device without chamber opening. As a result of these efforts two devices – NX1 and NX2 – have been successfully implemented in many fields. Its design is based on principles as it follows [1].

1. We use capacitors counted for much higher voltage and current thus increasing their lifetime by several orders of magnitude - both because of a lower swing of current (what is important for polar type of dielectrics) and a large reserve of insulation.
2. As switches the pseudo-sparks of a special design are implemented. Its construction and materials used enhances its parameters up to several hundred kA of switching current and more than $10^6$ operations per its lifetime. Their switching time and jitter are less than 4 ns - so less than a communication time between main elements of the device.
3. We use DPF chambers of special geometry (one close to Mather type but with rounded electrodes) where we have paid special attention to the initial stage (surface breakdown). Special technology has been elaborated to manufacture these chambers by laser and e-beam welding thus they have no any rubber o-rings at all. Because of its design these chambers can operate in a very wide range of the working gas pressures and with a very

broad list of these gases and their mixtures. To withstand the extreme high load implied by very powerful flashes of hard radiation of various types a special insert in the central part of the anode has been used.

4. To make possible the device to work with a high rep rate (several tens of kW of average electric power inside several cm dimensions) water cooling system has been fitted to the chamber (to both DPF electrodes).
5. Modern charger system of a high rep rate has been protected by special means from overshooting taking place during the plasma collapse phase.

For different applications and sometimes even for the same application the chamber design and the electrode geometry should be properly modified in accordance with the specific demands. The same rule operates for a type of a working gas, its pressure (total or partial) as well as for an applied voltage.

To put a device into operation in a certain regime after any change of an electrode material or its geometry a set of conditioning "shots" is needed. During this period electrodes are saturated with a working gas, and an insulator surface is modified in a special manner. During this run a search for a proper charging voltage and an initial gas pressure is executed. After about 100 shots the device is ready to work. Thus the conditioning and optimization procedures appear to be a very important part of the work.

## 3. Diagnostics

For this optimizing procedure as well as for the subsequent activity of various kinds the following cost-effective diagnostics appeared to be sufficient (for specific tasks we use only parts of them).

1) Rogowski coil
2) Voltage divider
3) Multi-channel soft X-ray spectrometer, based on PIN diodes

Usually five BPX65 PIN detectors were used for our X-ray output spectral and absolute measurements. The glass window is removed and diodes are folded in different foils. The overall sensitivity curves of the filter diode combinations as a function of wavelength is shown in Fig. 6. Sensitivity is given in C/J, wavelength - in Å.

4) Pin-hole chamber with a CCD matrix
5) Soft X-ray crystal spectrometer
6) Neutron activation counters
7) Multi-channel nitrogen laser with 1 ns pulse duration for frame shadow plasma visualization
8) Fast ion spectrometer

## 4. Analytical equipment

At a study of a possibility to apply DPF to a certain problem (regardless whether it is fundamental or a practical one) a co-operation of plasma physicists with specialists of this particular field is a crucial factor of success. Usually appropriate materials and necessary technique become available at this mutual works from a co-operative side. But one point, which is common and new for both, should be mentioned separately.

As a rule in all applications, during the optimization of the device for a certain practical result, it is not enough to obtain data on the beams and plasma interaction *processes* with a target *during* the experiment. It is extremely important to have an access to modern analytical equipment. This equipment is used *after* the experiment, and usually there is a need in new, not used before by a counterpart, measuring instruments. It is so because principally new tools (DPF in our case) produce a very different impact on the samples (e.g. much stronger in our case). Namely these results, obtained *a posteriori*, been compared with the previous ones, may result in the conclusion in favor or against the new method under investigation.

E.g. for material science applications [4] it is absolutely necessary to have an admission to the following technique:

- SEM and to molecular force microscope for surface morphology investigation,
- X-ray microanalysis, X-ray photoelectron spectroscopy and secondary ion emission microscopy for sample composition researches,
- various mechanical testing methods (tribological, e.g. microhardness, scratch adhesion, film thickness, etc.),

- stresses and constituent phases measurements by X-ray diffraction and microstructure analysis by SEM, and others.

In applications of DPF in semiconductor industry (e.g. in microlithography) side by side with common equipment (spinner, precision heater, etc.) a success will be depended in a great extent from new materials (e.g. on modern resists with chemical amplification). For biological applications it is fruitful to have an access, e.g., to a thermo-luminescent spectrophotometer and various modern chemical equipment, but again in this case also namely possibilities to use clean, contemporary *materials* are of a prime importance. For applications using nuclear methods (e.g. Neutron Activation Technique) updated nuclear detectors are very crucial, etc.

And with these issues one have to take into account that real success, i.e. a creation of a commercial *product*, may be obtained because of the following points (necessary, but not enough):

- proper funding of the project,
- present day equipment and materials, and
- very tight collaboration (as one team) with specialists in the particular field.

## 6. General discussion

Let us discuss some issues, which can be relevant to the implementation of the above technique for scientific and industrial needs. We shall analyze here some of our works, both already explored experimentally as well as discussed hypothetically, which might be of interest for scientists and engineers working in this field.

### 1. Education

### 2. Fundamental researches of Dense Magnetized Plasma

We shall present in this chapter just as an example our last result on the dynamics of Dense Magnetized Plasma.

Recently because of demands implied by nanostructure manufacturing applications, namely to reach good X-ray yield in the spectral region of X-rays near 4 Å, we have studied different plasma mechanisms of attaining these goals.

We use a Dense Plasma Focus (DPF) device NX2, with improved insulator, electrode, and switching configuration, and with Argon filling to concentrate the main part of its radiation near 4 Å. In this case it can be used as a source for different aims in microlithography. One evident goal here is to increase spatial resolution of the method with the help of a source having a shorter wavelength in comparison with previously used Ne gas filling of the DPF (8-12 Å). In those case neon plasma temperature in NX2 was about 400 eV [1].

But besides of the resolution increase aim the 4 Å radiation can be implemented in particular in micromachining if DPF will emit enough harder X-rays with Argon as a working gas to provide deeper penetration of the radiation into a resist. In this case it will be easier to produce a 3D structure within the resist. It is attainable if plasma can reach $T_{pl} \geq 1$ keV at the pinching or another phases where it has a high enough density.

There are at least three possible ways to get the above temperature and high X-ray yield around wavelength of 4 Å. One is to use a mixture of light gas (ultimately deuterium) with argon to produce hot spots by plasma necking. In this case a process of plasma compression is ruled by flute instability.

Another one is to increase a current sheath (CS) velocity in pure argon. In this case final plasma temperature will be determined by a randomization process, taking place at the CS collapse near the axis of a chamber. Velocity increase will result in a corresponding temperature rise.

The third one is to use a mixture of heavy gas (e.g. krypton) with argon to produce separation of gases at the shock wave front of a DPF current sheath and subsequently to compress argon by a "heavy shell". In the last two cases longer electrodes and lower initial pressure are needed for DPF-bank matching.

Using a pinhole with a CCD matrix and a pair of folded by different foils pin diodes in all three methods we have successfully reached a reasonable yield in the above-mentioned

spectral range. Within all three modes of the DPF operation it was possible clearly to find a distinction between three characteristic regimes: a pinch regime (Fig. 8a), a hotspot regime (Fig. 8b, 9), and a runaway regime.

The important issues in the first mode of DPF operation are to understand how the number of hot spots depends on the percentage of argon admixture to deuterium and what is correlation between the number of hot spots produced and an overall X-ray yield. Fig. 7 shows that there is a clear minimum of the above number at about 20% of Ar contents. At the same time it was found that namely with this percentage our device gives the highest X-ray output.

It is the third way (compression by a heavy shell) which demonstrated a remarkable difference with the previous two. In this case we have received a pulse shape of X-ray with a very sharp rise-time (just equal to the temporal resolution of our oscilloscope – less than 1 ns) and relatively smooth tail (in contrast to Fig. 9). And the absolute yield was about an order of magnitude higher than in cases of the DPF operation with pure argon or a $D_2$+Ar mixture.

**Applications**

**a) X-ray microlithography (Ne)**

See Fig. 10

**b) X-ray micromachining (Ar)**

The photo-resist patterning process usually executed with a help of lasers with a wavelength of the close ultra violet range can be substituted by a relatively harder X-ray (below 1 nm) proximity scheme. It will be implemented here because of the deeper penetration depth of its radiation inside the resist thus providing a possibility to form within the resist's volume a three dimensional structure. Within the candidates for the appropriate X-ray source a Dense Plasma Focus device looks very promising because of its low cost and now available high rep rate and high efficiency of it. In contrast to synchrotron source its construction gives a possibility to operate with an X-ray beam directed at any angle to the resist layer (even adjustable during the operation). In our researches with Ar filling of the NX2 chamber (see above) we have received in various modes of its operation an X-ray output in the range of 1-10 J.

So we may state now that by this set of experiments we have shown in principle a possibility to reach with NX2 the efficiency in the region 3...4 Å of the same order of magnitude, which we had with this device for a neon gas filling (8...12 Å X-rays). But with those regime of this facility we made several successful exposures of resists with a 100-nm structure for several hundred shots (Fig. 10). Such a large number of shots are necessary because of a relatively big difference in the X-ray output of the device. But it is not dangerous. From one side it means that to preserve a reproducibility of the total dose from chip to chip not lager than 1% we have to make namely not less than 100 shots. But at the same time with a rep rat of 15 Hz and with a possibility to interrupt the exposure of a resist at any moment just following to the dosimeter readings it is possible to satisfy the demands of a microlithography or micromachining processing.

**c) Electron beam lithography**

**d) Application for material sciences**

- **Ion implantation, surface modification, plasma-wall interaction simulation for the goals of thermonuclear fusion (destruction tests)**

Interaction of high temperature (~ 1 keV) deuterium plasma jets (velocities up to $5 \cdot 10^7$ cm/s) and fast ion beams (50-150 keV) generated in Dense Plasma Focus (DPF) device (60 kJ, Filippov geometry) with low-activated austenitic steel 25Cr12Mn20W and ferrite steel 10Cr9W specimens positioned in cathode part of DPF camera has been investigated by us recently. These types of steel are counted to be perspective for the most loaded parts of hot plasma devices and thermonuclear fusion facilities. DPF can fulfill (during a short period of time) the demands implied on the first wall material testing.

The recoil nuclei method (Elastic Recoil Detection Analysis - ERDA [7]) was used in order to trace the deuterium atoms scattering profile within the irradiated specimens. The $He^+$ ion beam of the energy 1.9 MeV irradiated test sample at an angle of 15° to its surface. The recoil deuterons were registered at an angle of 30° to the incident beam direction. Mylar film 10 μm thick placed in front of the detector was used to separate the recoil ions from the

scattered $He^+$ ones. Resulted energy spectrum was converted into the scattering profile by means of RUMP (Rutherford Universal Manipulation Program) [8]. In order to indicate an absolute value of deuteron concentration the calibration specimen (the standard) - Tungsten-Deuterium sample - was used.

It was found that when the power flux density of both types of irradiation is about $q = 10^6 - 10^8$ W/cm$^2$, the ion implantation to the irradiating material surface layer is observed. When the power flux density increases up to $q = 10^9$ W/cm$^2$ and above, the so-called "broken-implantation" takes place. An ion diffusion velocity of the implanted deuterium through both interfaces - "layer-bulk material" and "layer-gas phase" - for Fe-based alloys has been estimated theoretically.

- **Neutron activation analysis for oil, gold, coal and other industries**

*Oil industry*

In this industry neutron activation analysis is already implemented for more than 10 years. Vacuum and gas-filled neutron generators are used to find in an oil-fields (wells) a border "oil-water" (due to high cross section for neutron capture by potassium, usually presented in the underground water), and for estimation of certain characteristics of oil. Yet DPF can find a niche, and namely in those problems where a very short and powerful pulse of neutrons is needed. In this case such a method of investigation as "Time-of-Flight" can be used. Between problems to decide there is determination of a leakage rate of oil along the well tube, estimation of an oil percentage within a pulp pumping from the wells, etc.

In *a coal industry* an important problem is to determine a degree of water, as well as the ash contents within the coal. As for *gold* it is a remarkable fact that a nuclear activation analysis (NAA) is probably the only possibility to check the gold in ingots. And namely DPF can be good because of two special advantages: short pulse duration (so sort time-of-flight base) and high cross-section for 2.45 MeV neutrons, which are almost monochromatic at the DPF operation with deuterium as a working gas.

**e) Safeguard service at airports**

This application is evident because of the following features of DPF:

- It is heap
- It is compact
- It is ecologically clean in comparison with Californium neutron emitting isotope
- In is fitted for a short time-of-flight base (about 1 m for 4 ns pulses)
- It is a quiet bright source of neutrons and X-rays thus producing a possibility to let X-ray beam through and to make AAA *at the same time.*

**f) Pulsed radiation biology and medicine**

The following problems, arising because of interest of scientists and physicians in nonstationary processes, low dose apparatus and in exploration of different parts of X-ray spectrum, are currently under the issue in these applications.

1. DIAGNOSTICS:

- X-RAY (TO LET BEAM THROUGH):
  a) Portable apparatus (emergency cars and military surgery)
  b) Soft X-rays (angiography, mammography, dentistry and pediatrics)
  c) High Resolution Computer Tomography (HRCT)
  d) X-ray Microscopy (high resolution imaging, elemental and chemical mapping, and X-ray excited fluorescent technique) (XRM)
  e) Miniature sources (laparoscopy)
  f) High sensitivity high resolution detectors (CCD)
- ONE- AND TWO-PHOTON EMISSION TOMO-GRAPHY (Positron Emission Tomography - PET)
  a) X-ray and γ-ray no-isotope sources *inside* the body of a patient
  b) Production of short-lived γ- and $\beta^+$-radioactive isotopes; *in vitro* directly in clinics; *in vivo?*

*General aims:*

Availability of hard radiation flashes with different

pulse duration and rep rate:

atto-, femto-, pico-, nano-... seconds, minutes, hours... years...

➢ 25 orders of magnitude!

*Parameters of sources*:

Pulse duration; coherence (spectrum); source's size or beam's divergence; dose or power flux density

2. THERAPY:
   - X-RAY AND γ-RAY:
     a) Low-dose high power (?)
     b) Multi-beam
     c) Miniature ecologically clean *powerful* sources inside the body
   - FAST ELECTRON THERAPY (10%):
     a) Same as above
     b) Outpatient service
     c) Adjustable electron energy spectrum
   - NEUTRON THERAPY (TUMORS AND ARTHRITIS):
     a) Same as above
     b) Monochromatic neutron spectrum?
   - PROTON AND FAST ION THERAPY:
     a) Same as above
     b) "Coulomb explosion"?
3. TESTS, SIMULATIONS (RADIOBIOLOGY):
   - CELL SURVIVAL
     a) Low-dose high power pulses (?)
     b) High rep rate
     c) Resonance frequencies (?)
     d) Combined illumination of tumors by different types of radiation as well as investigation of the consequences of mutual implementation of radiation therapy + chemotherapy
   - BIOCHEMICAL ACTIVITY
     a) Same as above (*a* through *d)*
     b) Resonance frequencies for pulse rep rate
     c) Resonance doses
     d) Spectrally selective absorption

Because of specific and very favorable features of DPF a question arise:

*DOES IT POSSIBLE TO IMPLEMENT A PORTABLE DPF FOR X-RAY DIAGNOSTICS IN MEDICINE?*

These features are as follows:

- 10 kg by weight,
- a single pulse exposure,
- 4 ns of pulse duration,
- feeding simply from the apartment's mains or from a battery,
- and having a low dose exposure (the last one has been proved by our experiments with an X-ray examination of a chicken leg).

In principle it looks very tempting, yet further investigations are needed. Our experiments with enzymes have shown as follows.

We illuminated of three types of enzymes (horseradish peroxidase, APF and angiotensine) by X-ray from isotopes and from our DPF. The radiation was concentrated mainly (by filter technique) near 9 keV. It appears that the DPF (Fig. 11 c) produces the same effects (both activation and inactivation of the enzymes by a factor of 2) as usual isotope source (Fig. 11 a and b). The difference is in scales: if isotope do it at the doses of about 1...10 Gy, in a case of the DPF source we need doses 4 orders (!) of magnitude lower. At present time we examine as possible reasons for this effect – side by side with a factor of power flux density (which is 8 orders of magnitude higher than it is for isotope) – two other possibilities. One is a selective (by spectrum) excitation of Zn atom positioned in the nuclei of the enzymes. Another is a problem of so called "resonance doses", i.e. meso-doses, having a value between a comic level and the one medically allowed.

**g) Underground cavity investigation**

It can be done because of short pulse duration, high brightness, good scattering and low absorption of neutrons in the cavities.

**h) Neutron calibration technique**

Because of the same features it is possible to use a portable DPF inside the modern huge chambers of thermonuclear devices (ultimately tokamaks and ITC) for mapping and investigation of their scattering and absorption characteristics under various angles and in different places. And it can be done with an ns time resolution.

**i) Radiation-stimulated chemical reactivity**

It is a well-known fact that there are only a few methods of increasing chemical reactivity [9] – increase temperature, concentration, external pressure (in all three cases to increase collision rate), and use catalyst and ultrasound (to provide an alternative, lower energy, pathway).

But using different types of hard radiation – separately or in combination – we may increase reactivity in a greater extent. In comparison with ultrasound this type of reaction stimulation differs by its volumetric action.

Indeed, for a sound and even for shock, burning and detonation waves there is a need in time to penetrate the volume occupied by the reactants. And this time usually is mush longer than the rate of reaction. Thus the stimulation occurs *sequentially, step by step* through the system. Just opposite to this because many reactions have a relatively long period of development in comparison with the speed of, e.g., light, we may illuminate the volume practically *instantly* in all its parts. 3 ns pulse of X-rays has a length of about 1 meter, and 14.0 MeV neutrons will penetrate for the same time a distance of about 15 cm. So it will be interesting in particular for those situations where one works within a relatively thin layers of reactants or with reactions at a solid/liquid and a liquid/liquid interfaces. It also can be important for various heterogeneous processes, e.g. taking place on the surfaces or within porous partitions. And we may use hard radiation for all above-mentioned situations: to increase temperature suddenly in many local points by specially introduced absorbers, to raise concentration and pressure by evaporating tiny inserts, and to release or just locally heat previously encapsulated or cooled catalysts.

We already have proved this general statement in our experiments on microlithography, where we used resists with chemical amplification. Another possible example of such a process is lasers with nuclear pumping which have a flat working volume.

**j) Positron Emission Tomography (PET)**

Positron emission Tomography (PET) is one of several methods currently exploring nuclear physics principles for health - so-called "nuclear medicine" (NM). It consists of detection, visualization and quantification of distributions of radioactive – positron-emitting – molecules administered beforehand to a living body and performing there its biological roles. In this method a positron emitted in a radioactive decay within the human body meet electron after traveling for a certain distance and annihilate with him. Two antiparallel quanta of energy 0.511 MeV can be detected in coincidence. Belonging to diagnostics, this method mainly yields functional and physiological data on human organs and systems under study, whereas information on anatomical structures is sometimes difficult to evaluate.

Generally PET consists of 3 elements: production of positron-emitting isotopes, synthesis of biological molecules labeled with the above positron emitters and scanning of a human body. The most commonly used at present time as PET tracers are the isotopes $^{11}C$, $^{13}N$, 15 O and 18 F, because they can be introduced into biological molecules without altering their composition. They are the short-life elements ($T½$ =20.03 min, 9.97 min, 2.03 min and 109 min correspondingly). These elements are also used, as they are "clean". It means that they do not produce any X-ray emission additional to the annihilation one.

At this time the only source for manufacturing of positron-emitting isotopes is a medium energy proton and deuteron accelerators of a cyclotron type. In fact they accelerate negative ions (later on stripped) of hydrogen-1 up to energy of about 10-20 MeV and hydrogen-2 for about a half of the proton energy. Beam currents are about 50 μA, which is able to produce during several minutes the radioactivity amounts up to 100 GBq. At the moment for a specialized cyclotron the PET medical centers are ready to pay US$2,000,000 (same as for a scanner).

In principle, Dense Plasma Focus (DPF) can generate fast electrons, X-rays and neutrons, but also fast ions. It should be noted that the high electric field (and corresponding hard radiation) is produced *inside* the chamber by *plasma mechanisms* and only for a several tens of nanoseconds. And the field is much higher than the initial bank charging voltage (usually

~20 kV). All of this makes the device ecologically much more acceptable in comparison with accelerators of classical types.

Demands imposed on the parameters of the ion beam generated by DPF depend on cross-sections of corresponding reactions of fast ions with those elements, which can transmute to the positron-emitting isotopes. In a view of known from the literature the above mentioned range of energy for the DPF generated ion streams (0.2...2.0 MeV) the most fitted to our conditions are the following reactions: 11 B (p,n) 11 C (2.5 mb at 0.2 MeV with 45.0 mb at 2.0 MeV); 10 B(d.n) 11 C (threshold at 0.5 MeV with 300 mb at 2 MeV); 12 C(d,n) 13 N (threshold at 0.6 MeV with about 250 mb at 1 MeV) and 14 N(d,n) 15 O (3 mb at 0.6 MeV and about 250 mb at 2 MeV). In this connection it should be noted 2 circumstances: 1) on many reactions related to the problem there are no any data in a literature; 2) the great majority of the data are related to the range of ion energies around 10 MeV and above. Both facts are a consequence that the measurements are produced usually with a help of cyclotrons. What kind of figures we can foreseen for the DPF device of a medium size (say about the same as in a reference [1] - 4 capacitors, E=3 kJ, total current I=320 kA)?

Because we have within the DPF a virtual plasma diode with a sweeping voltage across the gap, the spectrum of our ions accelerated has a power-like low decreasing to the side of the increased energy. Many authors have measured the index of the law. It is close to (-2.5). In accordance with this law it is possible to estimate a percentage of the total ion current fitted to the goal on our problem. It should be around 1% (correspondingly the current of very fast ions should be about 0.03...1.0 kA correspondingly). The ion pulse duration also has been measured many times. For the device of this size it is about 100 ns. Now it is easy to estimate that the necessary radioactivity of about 10 MBq can be elaborated with the DPF of the above size having the rep rate around 10 Hz.

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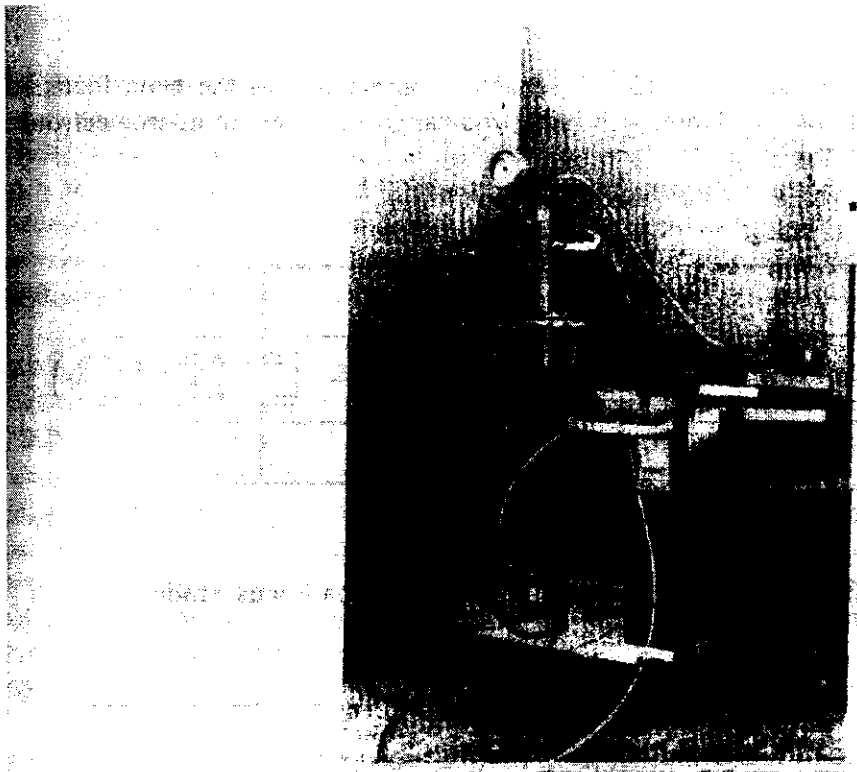
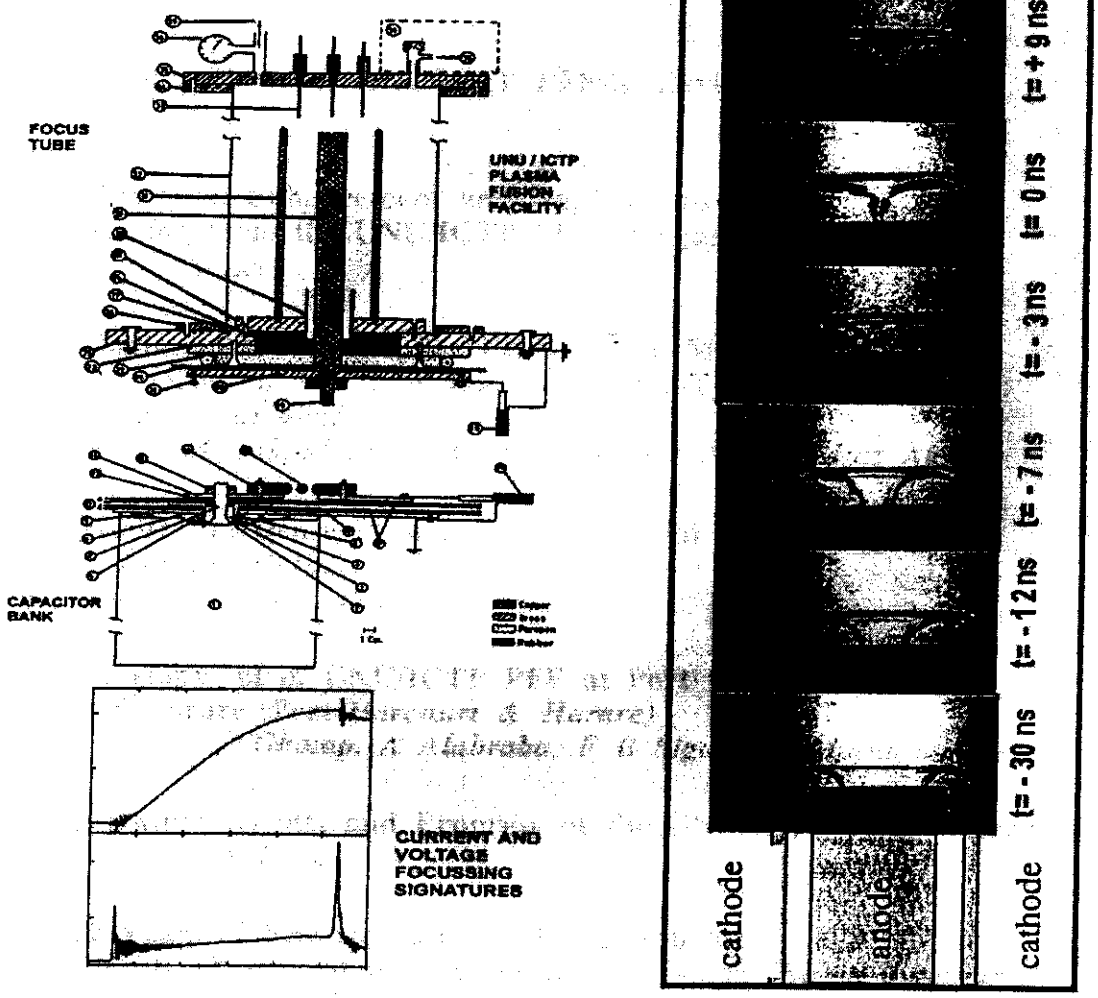


**The UNU/ICTP PFF placed at the ICTP in Trieste.**
It just fitted into the narrow elevator and was wheeled into Room A, Terrace Level for experiments during the Spring College on Plasma Physics in 1991 and 1993 when some 35 scientists carried out training/research experiments on this device in Trieste

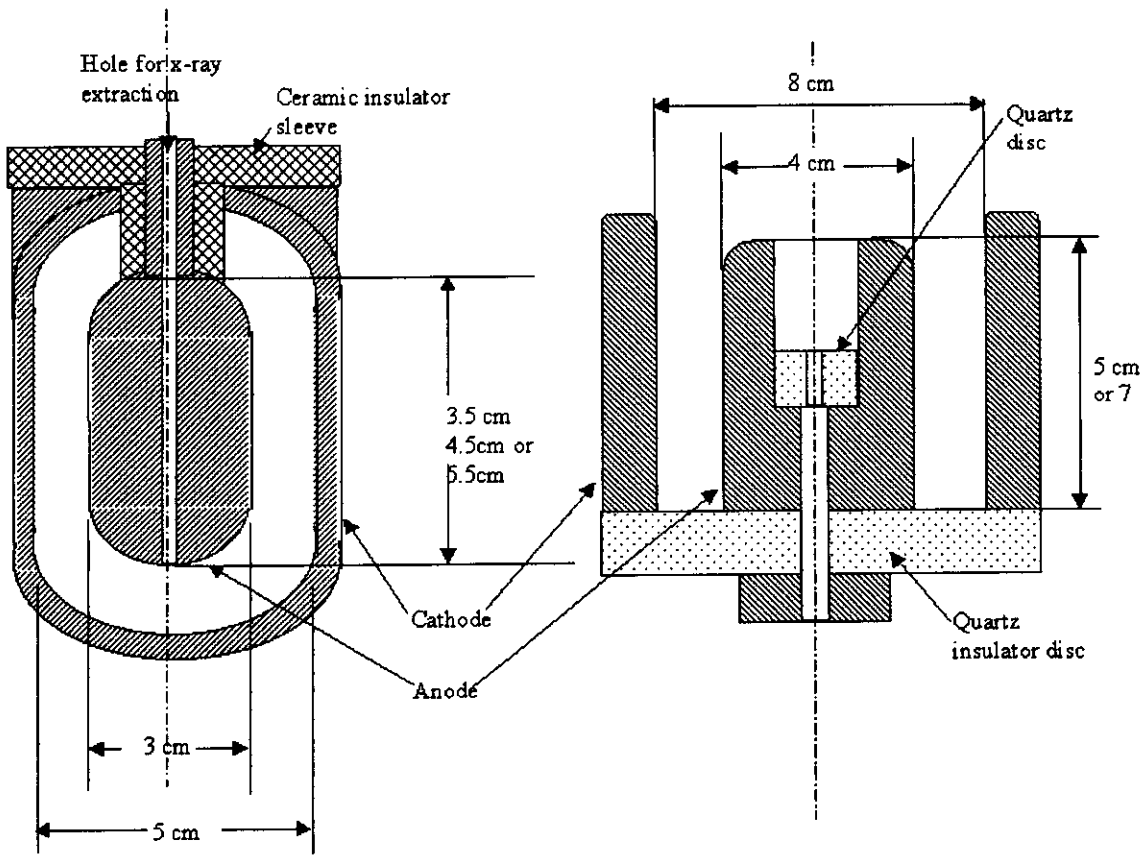
**Fig. 1**




**Sequence of compression in UNU/ICTP PFF at 4.0 mbar deuterium**

**UNU/ICTP PFF - Design, Signature and Dynamics**

**Fig. 2**

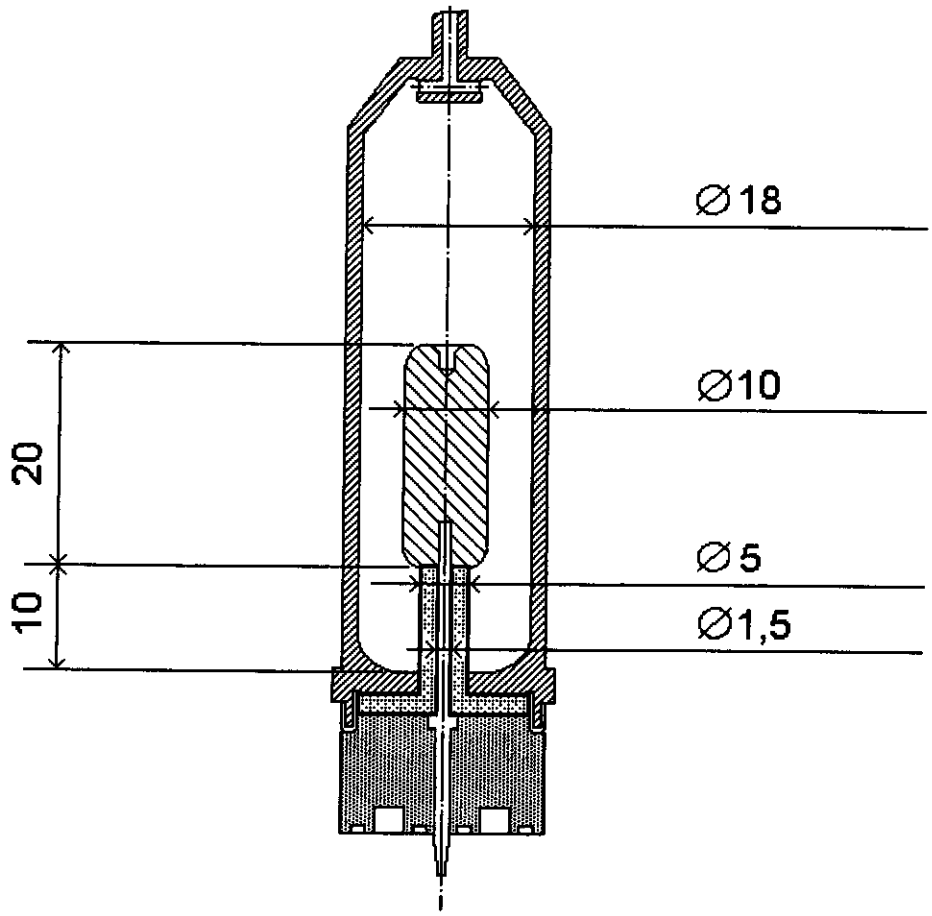

Hole for x-ray extraction
Ceramic insulator sleeve
3.5 cm
4.5cm or
5.5cm
Cathode
Anode
3 cm
5 cm
8 cm
4 cm
Quartz disc
5 cm or 7
Quartz insulator disc

NX1

NX2

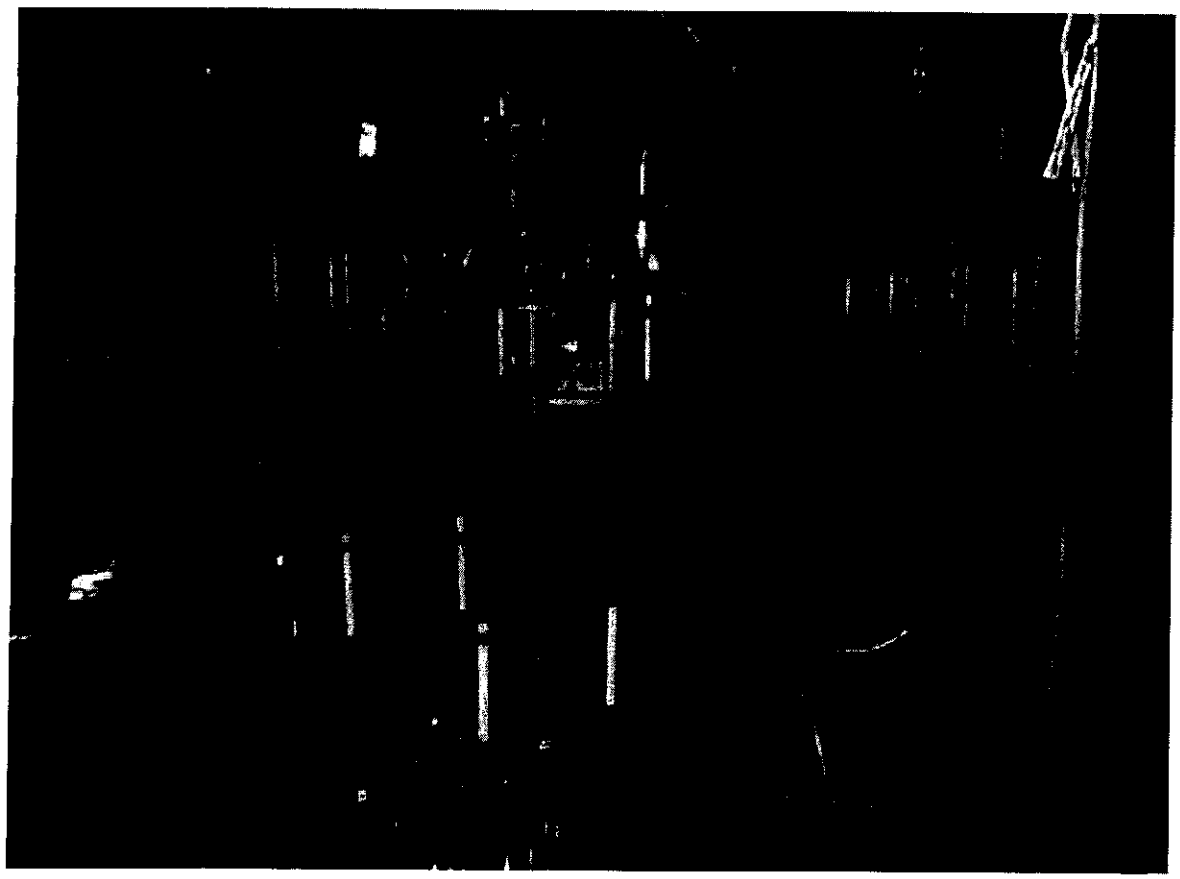
a)

b)

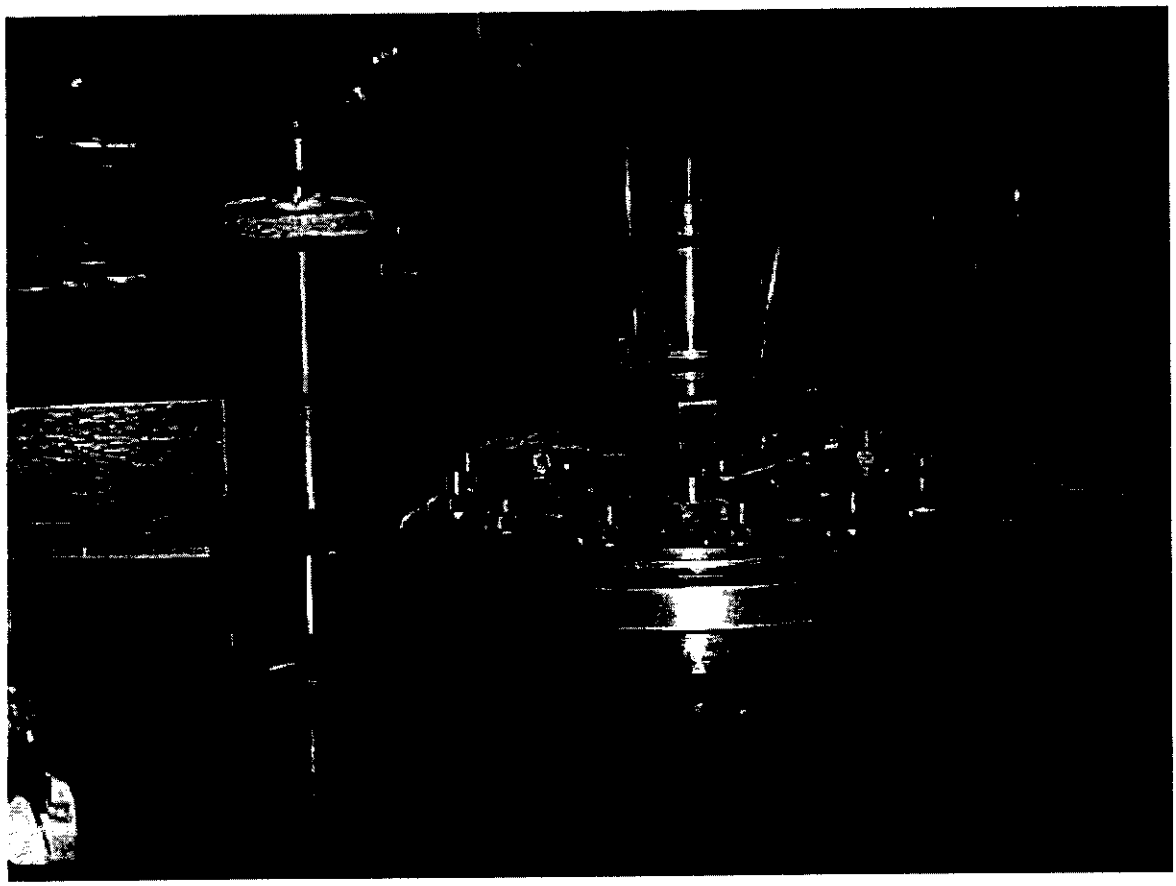



c)

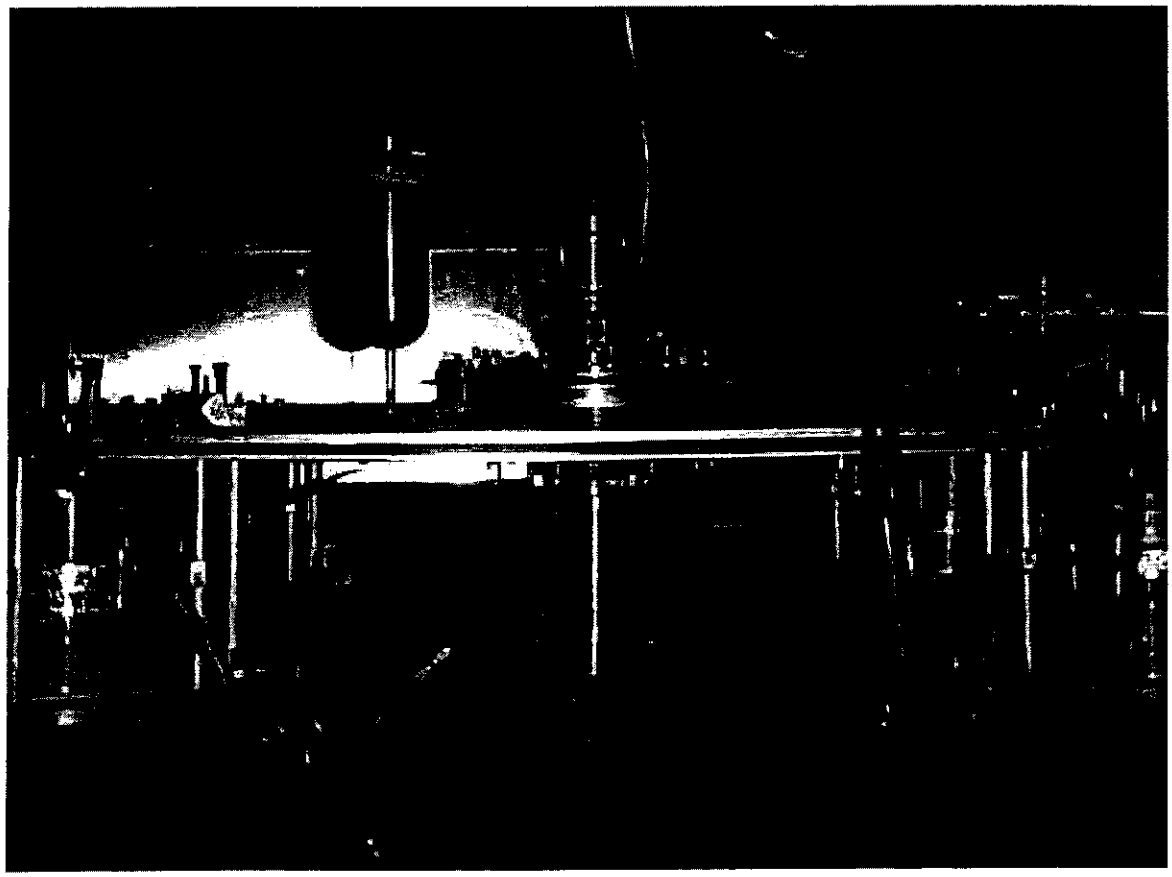
**Fig. 3**



a)



b)



c)

**Fig. 4**

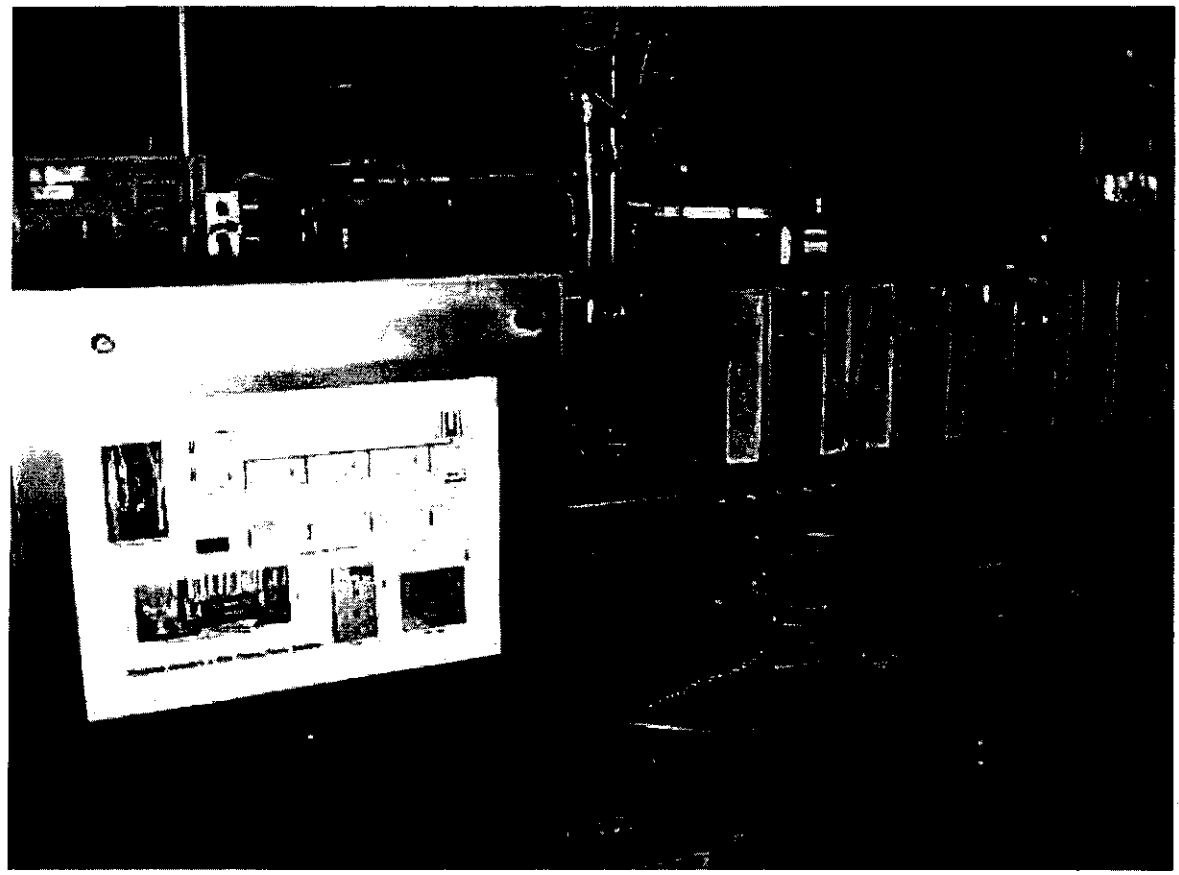


Fig. 5

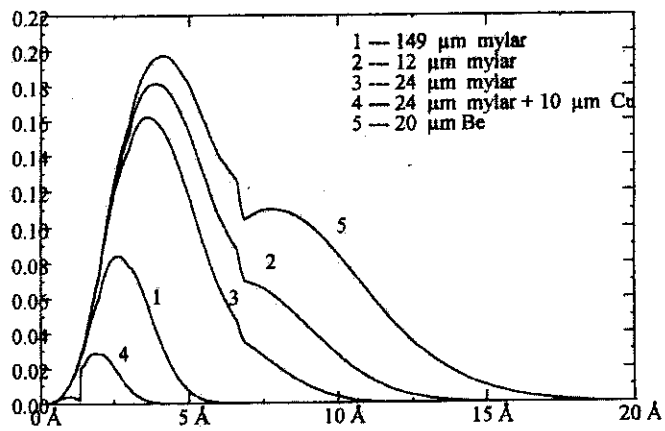

1 — 149 μm mylar
2 — 12 μm mylar
3 — 24 μm mylar
4 — 24 μm mylar + 10 μm Cu
5 — 20 μm Be
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0 Å
5 Å
10 Å
15 Å
20 Å
1
2
3
4
5

**Fig. 6**

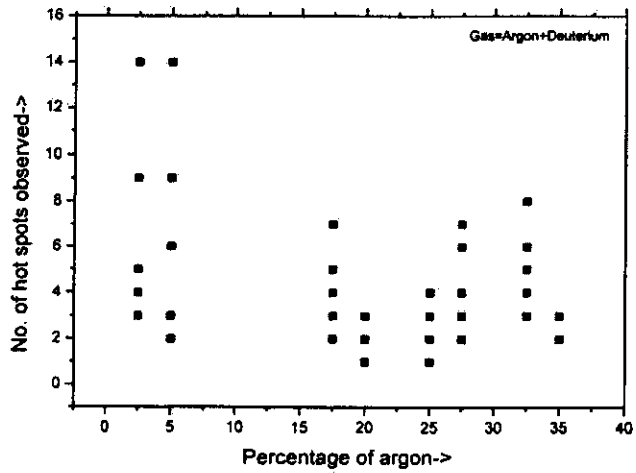
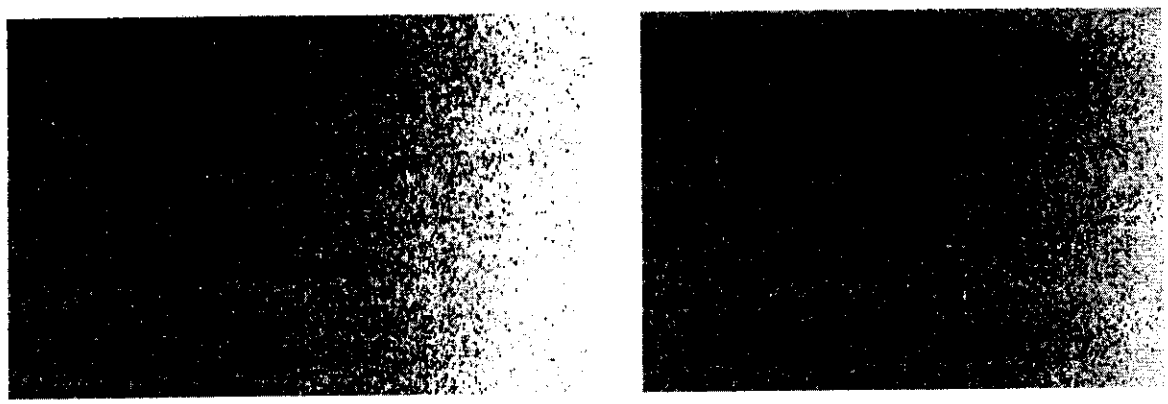

Gas=Argon+Deuterium
No. of hot spots observed->
Percentage of argon->
0
2
4
6
8
10
12
14
16
0
5
10
15
20
25
30
35
40

**Fig. 7**



a) b)

Fig. 8

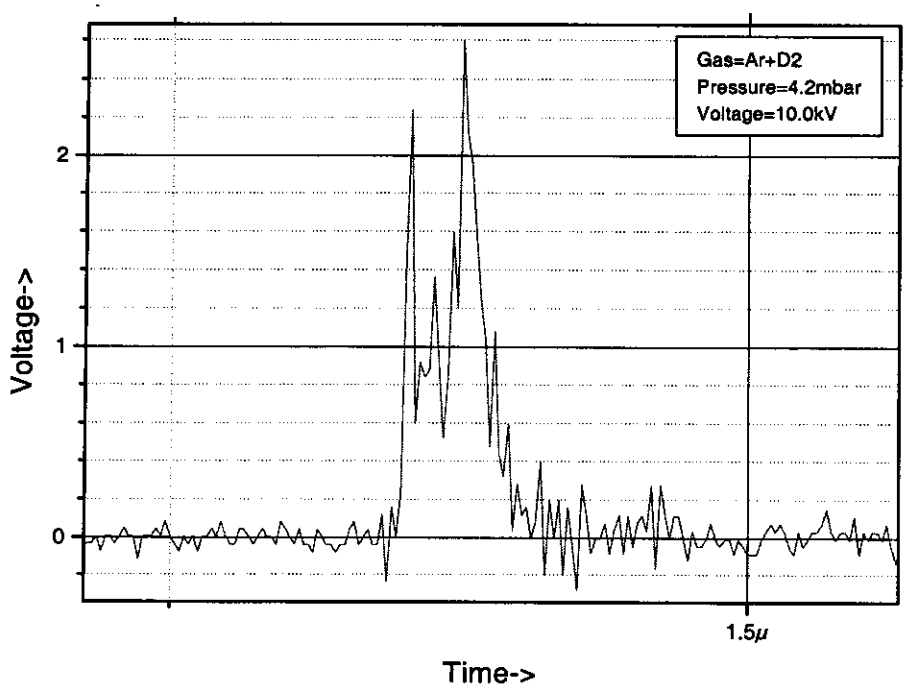

Gas=Ar+D2
Pressure=4.2mbar
Voltage=10.0kV
Voltage->
2
1
0
1.5μ
Time->

Fig. 9

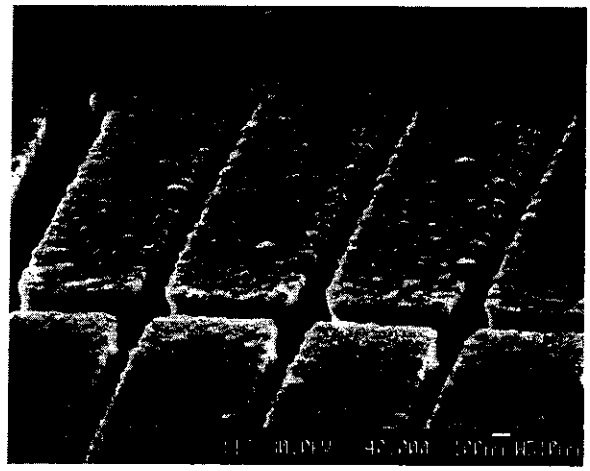
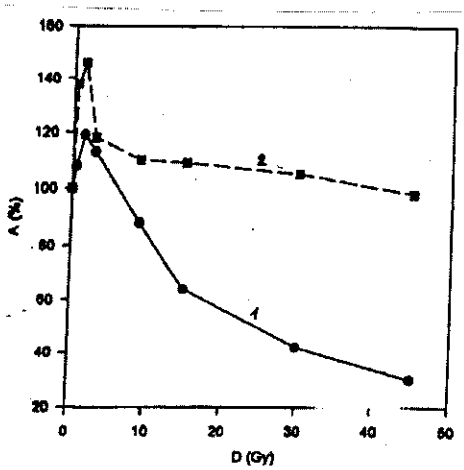
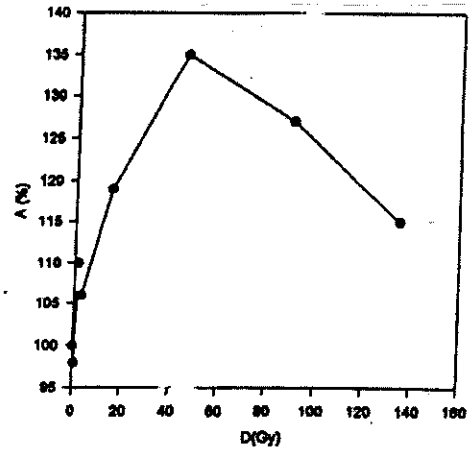


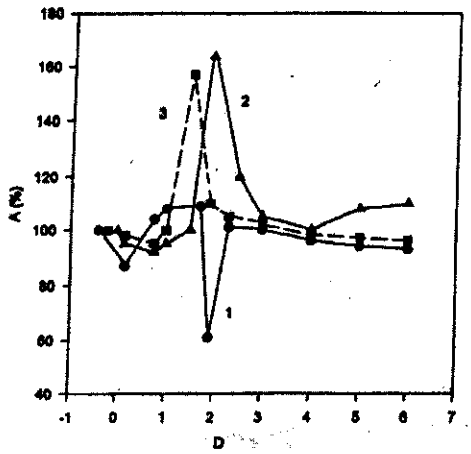
Fig. 10




γ-Irradiation induced changes in horseradish peroxidase catalytic activity. 1, native HRP; 2, recombinant HRP pretreated with $10^{-4}$ *M* $H_2O_2$. $10^{-7}$ *M* enzyme solution in acetate buffer, pH 6.0, substrate quaiacol.




γ-Irradiation induced changes in tobacco peroxidase activity. $10^{-7}$ *M* enzyme solution in acetate buffer, pH 6.0, in the presence of $5 \times 10^{-3}$ *M* $CaCl_2$, substrate- quaiacol.




DPP X-irradiation induced changes in enzymatic activity (Cu-filter, single pulse): 1, native HRP, $10^{-7}$ *M*, phosphate buffer, pH 6.0, substrate ABTS; 2, ACE, $10^{-6}$ *M*, phosphate-borate buffer, pH 6.5, substrate Cbz-Phe-His-Leu; 3, ACE, $10^{-8}$ *M*, phosphate-borate buffer, pH 7.5, substrate Cbz-Phe-His-Leu.

Fig. 11 a, b, c from the top to the bottom