$\chi^{(3)}(w; w, -w, w)$ of around 1 esu — some 8 orders of magnitude higher than usual! This corresponds to a change in refractive index of ~ 0.1% for 1 W/cm². Theoretically the subject has attracted much attention with early work by Rudolpho Bonifacio and Luigi Lugiato in Italy being continued and joined by Pierre Meystre in Garching, to mention only two of the theoretical papers from Europe presented at the First International Conference on Bistability recently completed in Asheville, North Carolina. Theory does not always relate closely to experiment, however, but ideas abound and the subject will certainly expand excitingly in the next few years.

An intriguing question that can now be posed is: will an all-optical computer compete in practice with microelectronic VLSI and Josephson junction devices? It is too early to give an answer as yet but there already exist positive features of both a qualitative and quantitative nature. First, qualitatively, the optical devices are based, at their simplest, on the non-linear Fabry-Perot etalon already discussed. This is two-dimensional in character so that image processing is possible in principle. Additionally, multistability with more than two stable states has already been demonstrated. Thus, optical processors can conceptually go beyond 1-dimensional sequential binary logic for their modus operandi.

The next considerations concern power, size and switching times which are to some extent related to each other. Normal electronic devices are intrinsically limited by electron transfer times across junctions to times around 1 nanosecond, whereas the latest field effect transistors can reach 50 ps and Josephson junctions (limited by electromagnetic propagation) can go down to ~ 20 ps. Optical devices made from Fabry-Perot resonators of micrometric dimension are limited by two factors — macroscopically, the internal resonator field build-up time, which is of the order of a picosecond for a device of ~ 10 µm in length, and, microscopically, the response of the non-linearity which is needed to obtain bistability. In practice this is also likely to be of the order of picoseconds for "switch up", depending on how much power is applied but may be longer for switch down. Even in high refractive index semi-conductors, light can travel ~ 1 mm in 10 ps so propagation delays should be comparable with or better than those to be obtained from Josephson devices.

Keeping the bistable switch near operating point requires a holding power for which, at present, the best value is 8 mW, i.e. of the order of µW/µm. Switching energy limits of femto-Joules (10^{-15} J) are predicted for devices of the limiting cross-section λ^2, where λ is the wavelength of the light (~ 0.25 - 1 µm inside the material).

At the very least, optical bistability offers the possibility of having all-optical switching elements for integrated optics with a performance comparable to normal electronic switching; at best it may give a new option for high speed data processing in the longer term.

ASDEX

A Step Towards Impurity Control in Fusion Experiments

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One of the most severe problems in controlled nuclear fusion based on magnetic confinement of a hot plasma, is the contamination of the hydrogen plasma by heavy atoms, such as iron, from the walls of the vacuum vessel. These impurities can strongly enhance the radiation losses (by line radiation, recombination and bremsstrahlung radiation) thereby affecting the power balance of the plasma. A simple energy balance consideration shows that for ignition of a deuterium-tritium plasma, the maximum tolerable iron concentration is 10^{-3}, while for the heavier tungsten the limit is 10^{-4}. A second unfavourable effect of the impurities is that they increase the gas-kinetic pressure of the plasma thus reducing the reacting fuel density when the total plasma pressure is limited. This also applies to the helium ash that results from the fusion process itself and which therefore has to be pumped preferentially.

The Divertor Concept

One of the most promising methods for impurity control is the magnetic divertor, a scheme that was proposed almost 30 years ago by L. Spitzer at Princeton[1]. External currents divert the confining magnetic field outside the plasma surface and conduct it to a separate chamber (divertor chamber). Charged particles that are lost from the bulk plasma follow these diverted field lines into the divertor chamber where they are neutralized (on neutralizer plates) and pumped off (e.g. by strong getter pumps). At the same time, the divertor boundary layer can shield the plasma core against wall-originated impurities by ionizing them and sweeping them into the divertor along with the outflowing plasma.

ASDEX Device

In Europe, DITE at Culham, UK and ASDEX at Garching, FRG are the only experiments in which the divertor concept of impurity control is being tested. While DITE is equipped with a bundle divertor (only a small bundle of magnetic field lines is diverted), ASDEX (**A**xially **S**ymmetric **D**ivertor **EX**periment) employs a poloidal divertor in which the total poloidal flux outside the plasma is diverted, i.e. charged particles reach the divertor along field lines after a few revolutions around the major circumference. This scheme thus guarantees a short path for particle transport into the divertor and also preserves the axisymmetry of the tokamak configuration.

ASDEX is a large toroidal device of the tokamak-type[2] which was constructed during the past six years at a cost of about 40 Million DM (with strong financial support from Euratom) and started operation early this year. The plasma ring has a major diameter of 3.3 m and a minor diameter of 0.8 m. A plasma current up to 500 kA heats the plasma to about 10 M degrees. (In 1981 the injection of high energy neutral hydrogen atoms will allow a further increase in this temperature by a factor of up to five.)

First Experimental Results

In order to be able to assess the improvements in plasma purity by the divertor, the magnetic field configuration of ASDEX is designed in such a way that diverted and undiverted plasmas of equal size and cross-section can be compared. A pair of circular half-limiters, that can be retracted without breaking the vacuum, allows the passage from mechanically (limiter) to magnetically (divertor) defined plasmas between shots. In all, four types of tokamak discharges have been compared keeping the plasma parameters as similar as possible: Limiter, i.e. the standard tokamak mode (in the following denoted by L); Limiter with titanium gettering in the divertor chamber (LP); Divertor — limiter retracted — without getter pumping (D); and Divertor with getter pumping in the divertor chamber (DP). In the following, only the most important results can be summarized (a detailed description is given in reference 3).

Figure 1 shows the time behaviour of plasma current I_p, mean electron density $\bar{n}$ and intensities of Fe XVI (336 Å) and O VI (1032 Å) lines for typical L, LP, D and DP discharges. Comparing the limiter (L) and divertor (D) discharges, the main effect of switching on the divertor field is a reduction of iron (material of the limiter) by more than an order of magnitude. This result is further supported by soft X-ray and surface probe measurements which, in addition, show that iron is not replaced by titanium, the material of the neutralizer plates. The intensity of the O VI line on the other hand, is about a factor of two larger in the divertor than in the limiter case. This is most likely due to the fact that wall conditioning by discharge cleaning is difficult in the divertor chamber, so that the oxygen coverage of the walls is relatively high. Nevertheless, the lack of oxygen reduction indicates that the shielding efficiency of the divertor boundary layer is rather small. This is explained by spectroscopic measurements which show an anomalous fast radial diffusion of the oxygen ions (with a diffusion coefficient of about 0.8 m^2s^{-1} which is of the order of the Bohm diffusion) resulting in a large fraction of the ions diffusing across the boundary layer before they reach the divertor along field lines.

The situation is quite different if titanium is gettered in the divertor chambers. In this case, both in limiter (LP) and divertor (DP) discharges, the oxygen content is reduced by almost an order of magnitude (c.f. the O VI line intesities in Fig. 1) and the radiated power is down by about 50%. In the divertor case (DP), this leads to $Z_{eff} \cong 1$, i.e. the resistivity approaches that of a pure hydrogen plasma. While in limiter discharges light (oxygen) and heavy (iron) impurities radiate as much as 80% of the ohmic power input, radiation from the bulk plasma accounts for only 20 to 40% of the power input in gettered divertor discharges. Since only part of the remaining power is found on the neutralizer plates, it is conjectured that a sizeable fraction of the input power is lost inside the divertor chamber by ionization, radiation and/or charge-exchange. This possibility, which would be most desirable from the engineering point of view for future large tokamaks and a possible reactor (as it lowers the heat load on the neutralizer plates by spreading the exhaust energy over a large divertor wall area) has to be further investigated in forthcoming experiments.

In conclusion, first experiments on ASDEX have shown that light impurities are minimized by titanium gettering, while heavy impurities are reduced by a divertor field configuration that moves the region of plasma-wall contact to a place remote from the bulk plasma. Only the combination of both techniques leads to a strong reduction of light *and* heavy impurities with Z_{eff} values of about 1. In addition, diverted plasmas are much less dependent on base pressure and the condition of the vessel walls which results in a high reproducibility of the discharges and an increased operational range.

A most encouraging result of applying the divertor techniques described, is the extension of the duration of discharges up to 3 s which is a factor of three longer than has hitherto been obtained in other tokamak experiments.

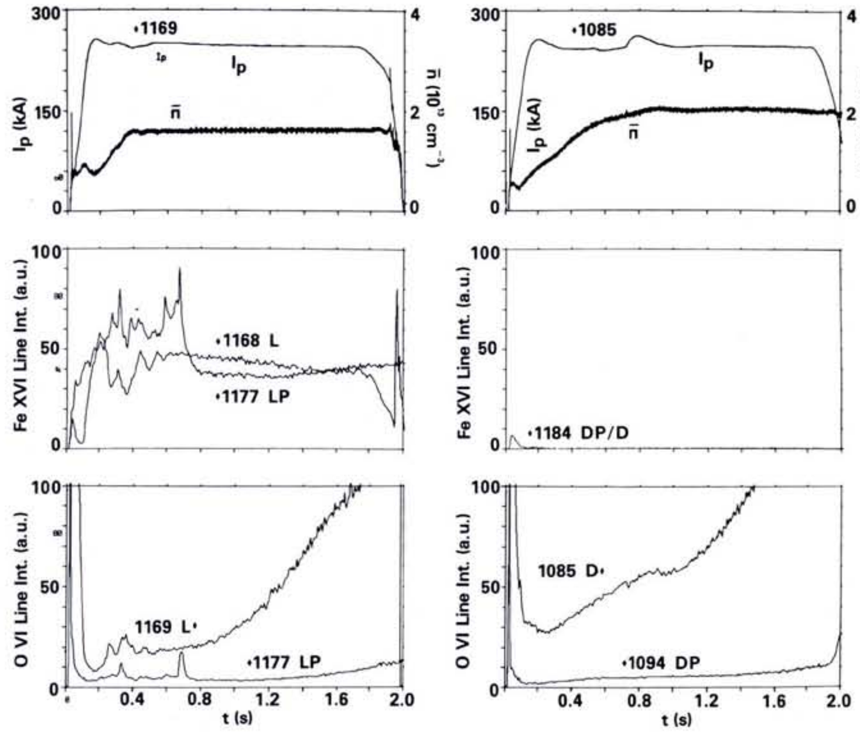

Fig. 1 — Plasma current I_p, mean electron density $\bar{n}$ and intensities of Fe XVI and O VI lines for typical limiter (L) and divertor (D) discharges with (P) and without getter pumping.

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