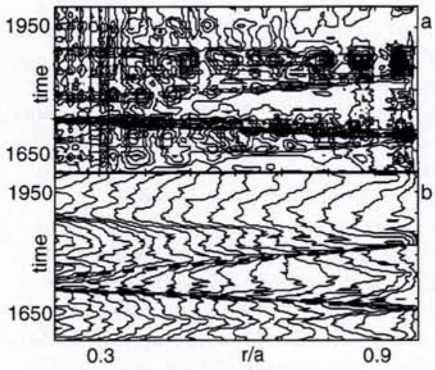

Fig 2 Isoflux ***a*** and isobars ***b*** as a function of radius and time for a 2D fluid simulation. Dashed lines indicate fast transport events, similar to avalanches in sandpile automatons

and have to be understood. Again, mode coupling and self-organization are candidates since they may affect the turbulence correlation lengths.

- The understanding of improved confinement is crucial to design optimized configurations. Most of the simulations show that high shears of magnetic field and plasma flow improve the confinement, in agreement with experiments (see *chapter* 3.1 for details). The stabilising effect of shear flow is observed both in linear and nonlinear regimes, as shown in *figure* 3. Interestingly, a drift turbulence usually self-regulates by generating a shear flow. Also the magnetic topology can be optimized to stabilize a large class of drift waves. This property has also been evidenced numerically, in agreement with recent experiments in tokamaks where the magnetic shear has been reversed. Thus several mechanisms have been identified to explain transitions of the confinement which are observed in fusion devices (*eg* the transition from Low to High confinement regime). However, a full simulation of the LH transition has still to be done.

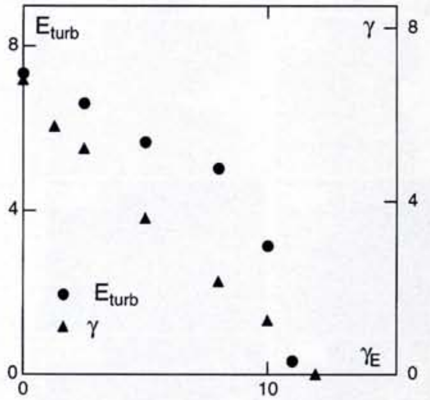

Fig 3 Turbulence level E_{turb} and growth rate γ versus flow shear rate. The growth rates are multiplied by 100 and the time unit is a minor radius divided by the acoustic speed

These encouraging results open the way towards the computation of optimized magnetic configurations with a low level of turbulence.

The Fast Ignitor

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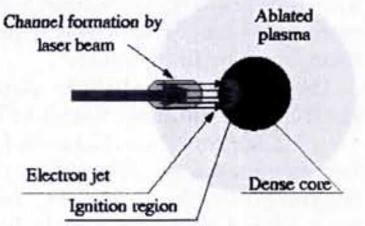

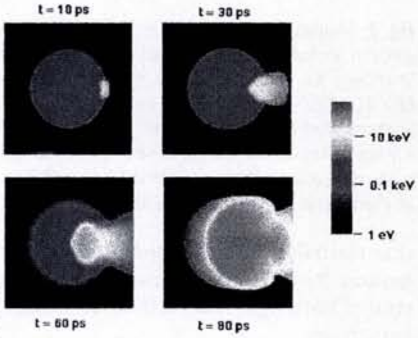

Fig 1a Fast ignition by an external laser beam; **1b** two-dimensional hydrodynamic simulation of fast ignition and burn of a precompressed (300 g/cm^3) deuterium-tritium core; the ignition spot of only 1 mg mass is heated by an energy pulse of 20 kJ deposited in 20 ps. In this simulation transport through surrounding ablation plasma was not considered. (*S. Atzeni et al Nucl. Fusion 37 1665 1997*)

The fast ignitor is a new concept in inertial confinement fusion—to ignite precompressed fuel by an additional external laser pulse of high power. It was proposed by M. Tabak *et al* (*Phys. Plasmas* 1 1626, 1994). The advantage of this method is that fuel ignition is separated from fuel compression and does not depend any more on Rayleigh-Taylor unstable hot spot formation in the centre of the imploding capsule. It is actually this hot spot formation which sets the stringent symmetry conditions in the standard ICF implosion scheme. Aiming only for high compression without central ignition relaxes both symmetry and peak power conditions. On the other hand, one has to deal with new problems concerning the ignitor beam, and these are not yet sufficiently understood.

The idea of the fast ignitor is sketched in *figure* 1a. The energy of the external laser pulse has to be transported to the imploded high-density core through over-dense plasma surrounding the core. This transport occurs partially through a propagation channel which the laser beam bores into the ablated plasma, and then via relativistic electrons which the laser drives in the form of an electron jet and which heat the ignition spot. Here, we report on two-dimensional hydrodynamic simulation of fuel ignition and burn (*figure* 1b) and on three-dimensional particle-in-cell (3D-PIC) simulations of laser channelling and electron jet formation (*figure* 2).

The goal is to create the hot ignition spot very rapidly during the 100 ps of fuel stagnation after implosion, hence the name 'fast ignitor'. Though the general idea has been discussed since the 1960s, it is only now that the new laser technique of chirped-pulse amplification provides a tool to generate the required petawatt pulses (10^{15} W). Again, the energy to be invested in the ignition spot scales roughly like $1/\rho^2$, and one needs highly compressed fuel to keep this energy at an acceptable level. An actual simulation of fast ignition and burn is shown in *figure* 1b in terms of the temperature evolution. A remarkable result of these simulations is that one can also ignite pure deuterium using a DT ignition spot.

The fast ignitor concept involves the interaction of laser light with plasma at intensities of 10^{20} W/cm^2, at which laser-driven plasma electrons become relativistic. This modifies the index of refraction and leads to self-focussing of the light beam. Light can propagate in a plasma up to a critical density. A light pulse incident on the plasma can self-focus into a narrow propagation channel having a diameter of 1-2 wavelengths. Another relativistic effect is: the laser pulse drives electrons by means of the $(v/c) \times B$ force in the direction of light propagation. This creates huge currents (of the order of 10^{12} A/cm^2) comoving with the light. Self-generated magnetic fields of the order of 100 MG pinch the current, and this fur-

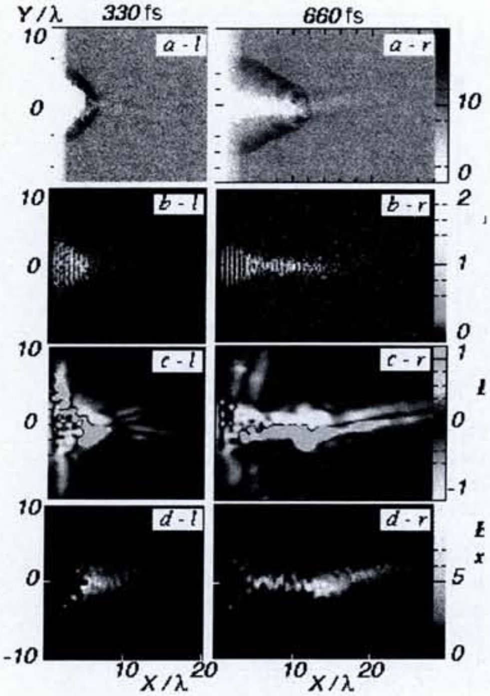

Fig 2 Simulation (2D-PIC) of laser hole boring and electron jet formation in a tenfold overcritical plasma. Snapshots are shown after 330 fs (left column) and 660 fs (right column) of ***a*** ion density n_i/n_c, ***b*** instantaneous light intensity I (10^{20} W/cm^2), ***c*** cycle-averaged magnetic field B (10^8 G), ***d*** electron power flux to the right as a percentage of the incident laser flux. (*A. Pukhov et al Phys. Rev. Lett. 79 2686, 1997*)

ther contributes to the super-channel formation. Recent experiments have demonstrated both light channelling and magnetic fields.

The process of laser hole boring and electron jet formation is demonstrated in *figure* 2. It displays a model case, based on a 2D-PIC simulation of a 10^{20} W/cm^2 laser pulse incident on a tenfold overcritical plasma layer. Snapshots of *a* ion density, *b* light intensity, and *c* magnetic field evolution are shown after time intervals of 330 fs and 660 fs. One observes the formation of a depleted density channel bored by the light pressure which amounts to 10-100 Gbar at these light intensities. Inside the density channel the light can propagate and drives relativistic electron currents to the right. They penetrate into the ambient plasma where they split up into filaments due to the Weibel instability and are seen in the middle of *figure* 2*c-l* as a stratified magnetic field pattern. At a later time, the filaments combine in a single, strongly magnetized electron jet, seen in the right half of *figure* 2*c-r* as a slightly tilted magnetic structure. Trapped relativistic electrons with an almost thermal energy spectrum ($T \approx 2$ MeV) are transported in the jet. The conversion of laser energy into energy carried by electrons from left to right is shown in *figure* 2*d* by plotting the right-bound electron power flow as a percentage of the incident laser power. It is seen to peak at 40% in the region of the laser channel head. These PIC simulations confirm both hole boring and efficient energy conversion to electrons which are indispensable requirements for laser fast ignition.

The coupling of the light to relativistic electrons and collective plasma fields is of truly kinetic nature and has to be followed on the microscopic scale of time (inverse plasma frequency $1/\omega_p$) and space (skin depth c/ω_p) in three dimensions. Responding to this demand, the first fully relativistic electromagnetic 3D-PIC code VLPL (Virtual Laser Plasma Laboratory) has been developed at the Max-Planck-Institute for Quantum Optics (MPQ) and is presently run on the 788 processor Cray T3E-600 at the Rechenzentrum Garching. The new object-oriented C++ version of VLPL performs at 100 Mflop/s per processor. A typical run comprises 10^9 particles in 10^8 cells. Despite this enormous computing power a complete 3D-PIC simulation of the fast ignition process is still out of range because of the huge plasma densities involved. Combination of kinetic and magnetohydrodynamic simulation including plasma resistivity will have to be used in future investigations. Important questions still open concern the directional stability of the channel, sufficient current neutralization in the electron jets, the power limit they can transport, collective stopping of the relativistic electrons in the hot spot, and the overall coupling efficiency.

Let us emphasize that the importance of these studies reaches far beyond fusion applications. The front of short-pulse laser development moves to ever higher powers and focused intensities and is just now at the border of particle physics. According to our simulations, laser pulses now available can accelerate bunches of electrons up to GeV energies in plasma channels just 30 μm long and allow for ultra-bright sources of bremsstrahlung photons and different kinds of nuclear radiation. First positrons were observed in recent experiments at Livermore using 10^{21} W/cm^2 pulses and also abundant neutron production. Deuterium fusion neutrons were observed even with a 1J, 10^{18} W/cm^2 table-top laser at MPQ. On the theory side, the essence is relativistic plasma physics on the scale of micrometers and femtoseconds. It involves electric and magnetic fields of the order of 10^{10} V/cm and 10^8 Gauss, respectively. Of particular interest are the plasma dynamics of the relativistic electron currents which far exceed the Alfven limit as well as the corresponding return currents. This new field already enriches plasma research and opens fascinating new possibilities for the future.

First results of fast ignitor interaction experiment with imploded core at ILE/Osaka

Experimental results on the fast ignitor scheme demonstrate for the first time the interaction of external laser beams with an imploded precompressed core. The experiment was performed in 1998 at the Institute of Laser Engineering at Osaka University, Japan, using the GEKKO XII laser facility. The images below show time-integrated X-ray pinhole pictures of a spherical target implosion and the interaction with two additional pulses. The shell target made of deuterated plastic (0.47 mm diameter) was imploded by 10 beams of GEKKO XII; the outer circle of x-ray emission marks the region of the laser ablation driving the implosion and the central spot stems from x-rays emitted during central plasma stagnation. Two colinear interaction pulses, each 100 ps long and separated by 400 ps, were shot on the stagnating target, 750 ps after the implosion pulse. The first interaction beam was injected when the shell had imploded to 1/3 of the initial radius. The two interaction beams may be looked at as the channel formation pulse and the ignitor pulse, proposed in the fast ignition scheme. Their focus was at 70 μm outside the original shell surface. The beams self-focus when penetrating the ablation cloud and are clearly seen as X-rays originating from a small spot at the channel head. The channel itself is not visible. In the two frames, this spot is seen from different perspectives, according to different viewing angles as indicated in the third drawn image. *by Kazuo A. Tanaka, Institute of Laser Engineering, Osaka University.*