NOBEL SYMPOSIA

Report from the lecture presented by Robert Aymar

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At the time of the meeting, we were once again at the threshold of an international agreement to go ahead with the construction of the ITER (International Thermonuclear Experimental Reactor) project, uniting the research efforts of Europe, Japan, China, Korea, Russia and the USA. At the time of reading, preparations at the construction site in Europe are well underway. The project is ambitious and carries a significant construction cost, roughly 450 million euros per year over 10 years of construction. Although this is of course a very large sum for a scientific research project, it still only represents the sum of 2 euros for a European taxpayer (the price of a small beer in Europe for each taxpayer every year), a much lower cost than many marketing projects. It is symbolic that the honour to present the project was given to Dr. Robert Aymar, the first founder of the Cadarache fusion laboratory and the former Director of ITER project.

Why spend so much? What will we learn from ITER? were addressed eloquently and in some detail. These questions have been raised in some academic circles at the meeting, contesting the size of such an investment in a scientific experiment. The reply was given by Dr. Aymar, addressing the general research community and explaining what will be achieved and especially what lessons will be learned. Is ITER a project in the basic sciences lineage, searching ultimate truths about the nature of the world, or about the origins of our universe? The answer is "No". Such questions have an essential purity about them, a purity that has always appealed, both to the initiated and to the uninitiated, as representing a noble cause, a scientific golden fleece. The world's largest accelerators have always received relatively constant support in Europe to satisfy these needs. ITER is nonetheless a noble cause, even though its main motivation stems from our increasingly urgent quest for sustainable energy. The nobility resides equally in the physical understanding to be acquired of the complexity of plasmas and in the technical challenges to be met. The requirements for controlled nuclear fusion are potent drivers for advances in physics and technology. This quest has also brought a harvest of fundamental knowledge in physics, in such complex areas as turbulence, magnetohydro-dynamics and even material sciences, with implications for apparently unrelated areas such as astrophysics, space physics and industrial plasmas, spawning applications ranging from plasma processing to space propulsion systems, the development of novel materials and superconductors. The ITER project is set to take this endeavour a major step further into uncharted territory.

Addressing the logical question “why ITER?” the status today has been simply stated, that we believe that our long-term vision can become a reality, but we need to make a leap forwards to demonstrate this. ITER is the long-awaited step needed to take fusion out from the present large laboratory experiment in the direction of a full power station. In simple words, the question “why ITER?” was replied by a simple answer “to establish whether our vision can become real”.

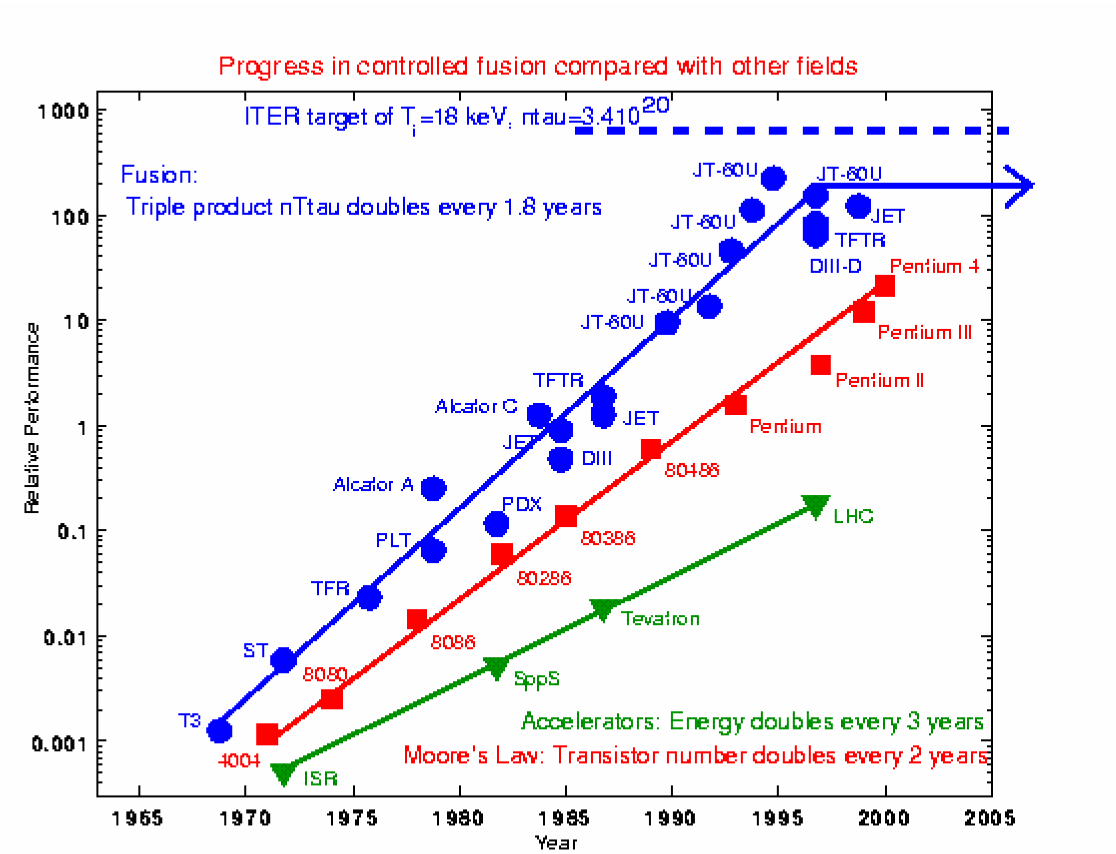

Fig. 1: The progress of fusion performance figure of merit, nTt, compared with advances in silicon wafer technology and high energy physics accelerators. The somewhat arbitrary timescale is the date when an experiment was planned for accelerators and performed for tokamaks.

The extrapolation of the experimentally measured energy confinement time in existing tokamaks towards ITER is considered to be robust because the scaling laws have been validated for range of values larger than two orders of magnitude (Fig. 1) and ITER does not differ any more in size from JET and JT-60 than these devices themselves differ from several currently operating medium size devices. Yet, ITER will enter unexplored territory. The relevant physics variables are not the engineering parameters of the device, but dimensionless parameters such as the pitch of the field lines, the ratio of plasma pressure to the magnetic pressure ($B^2/2\mu 0$), the ratio of the Larmor radius to the machine radius and the ratio of the Coulomb collision frequency to the frequency of the periodic drift motion in the inhomogeneous field. The combination of the values for the two latter parameters (key parameters for anomalous transport), as required for a reactor, cannot be achieved in current devices and must be assessed by experiments in a reactor sized device. Extrapolation of other key plasma parameters and present tokamak operating procedures to ITER also has uncertainties, because the reactor plasma conditions cannot be fully emulated in present day devices. The mission of ITER will be to demonstrate that all the physics issues, and most of the technology issues, that fusion reactors will be facing can be dealt with in an integrated way. These issues include the effects of the alpha particle population produced by the fusion reactions on the plasma. After birth at 3.5 MeV, the alphas slow down, transferring their energy and momentum to the thermal particles, mostly to the electrons. In ITER they are expected to provide more than 2/3 of the heating power necessary to sustain the plasma, corresponding to the target fusion gain, $Q \sim 10$, where Q is the ratio of the fusion power to the auxiliary heating power. Energetic particles are known to stabilise certain usually benign instabilities in the plasma core, as well as to produce new kinds of plasma instabilities, which may enhance transport, especially that of the alpha particles, and thereby reduce the fusion power. The transport of fuel to the hot core, where most of the fusion power is released, and the transport of the resulting helium ash away from it, is also an issue. If particle transport is too slow compared with heat transport, fusion output is reduced as the fuel slowly poisons itself with helium, increasing the radiated power loss and diluting the fuel. Other issues are linked to the 400-1000 second duration of the discharges in ITER and the necessity of actively cooling the plasma facing vessel components. The very nature, magnitude and distribution of the heat load is particularly difficult to extrapolate because of the wide variety of behaviour observed in existing devices. The last closed flux surface (LCFS), defining the confined plasma, is not in direct contact with a material wall. Beyond the LCFS a set of open field lines channel the heat and particles from the plasma towards a target area called a divertor. On the way, the majority of the heat is lost as radiation, cooling the edge plasma. However part of the power flowing to the divertor arrives as millisecond bursts of energy, caused by MHD instabilities at the plasma edge, which can cause accelerated erosion of the plasma facing components, as well as contaminating the plasma with impurities and diluting the fuel. These bursts vary from insignificant to excessive in current devices, which are developing countermeasures. The general control of plasma-wall interactions needs to be demonstrated in ITER before the road is cleared towards a reactor. The avoidance and handling of potentially damaging sudden terminations of the plasma current and confinement termed plasma disruptions which can lead to large twisting forces on the in-vessel components will be addressed on ITER.

Finally, why then is this such a complicated field of physics? The fundamental difficulty is not simply the large number of particles. The difficulty is when electrons and ions drift apart, they create electrical fields. The particles are therefore moving in magnetic and electrical fields generated partly from the outside using magnetic coils (imposed fields) and partly as a result of the movement of all the other particles (self-consistent fields). As a result, it is difficult to predict (and presently not achievable through ab – initio theoretical analysis) the collective behaviour of plasma particles and most importantly of particle and heat transport through the plasma. A "neoclassical" description of transport resulting only from Coulomb collisions and particle orbits in inhomogeneous fields, essentially the imposed fields, was developed more than 30 years ago, but underestimated most of the observed transport processes by 1-2 orders of magnitude. The reason is that low amplitude small scale collective instabilities, with typical wavelengths of a few ion Larmor radii, develop in confined magnetised plasmas, creating turbulence which is responsible for the lion's share of the heat and particle transport out from the hot core of the confined plasma.

This turbulence is sustained by the free energy available in the gradients of temperature and number density and causes these gradients to be eroded leading to a worse global confinement. Despite being the rule, rather than the exception, this form of transport is still referred to as anomalous. Nevertheless, in some important cases a steep gradient of temperature can be established which itself stabilises the turbulence and allows achieving better confinement. Advances in theory and computing power are still leading to substantial progress in the modelling of anomalous transport, but it is fair to say that a first principles prediction of transport in fusion plasmas is still some way ahead. The major difficulty is associated with the disparity of scales. For example, the ion Larmor radius is typically millimetres, but the distance covered before a fuel ion undergoes a fusion reaction is about in meters $10^{7.}$

Dr. Aymar concluded expressing the confidence in ITER achieving its objectives.
It was asserted that there is a consensus of the Fusion community worldwide resulting in readiness to embark on ITER construction. Its siting is now decided and will be in Europé/ Cadarache.

Literature: J. Lister, H. Weisen Europhysics News 2. 47- 50, 20005