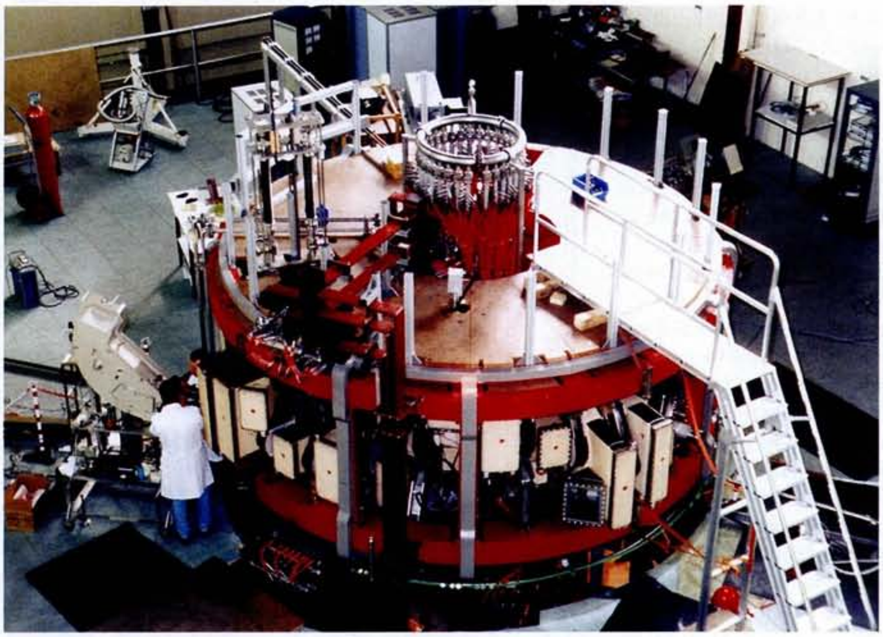

Fig 1 The photograph shows the TJ-II device before the diagnostics were installed in the machine. The position of the experimental windows (in white) hint at the strong helicity of the vacuum chamber

TJ-II The Flexible Heliac

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The fusion experiment TJ-II started recently in the middle of renewed world interest in the family of magnetic confinement systems called stellarators. In Europe TJ-II joins the medium-sized stellarator Wendelstein VII-AS, in operation since 1988 at the Max-Planck-Institut für Plasmaphysik in Garching. Furthermore, a large superconducting stellarator, Wendelstein 7-X (*see F. Wagner, Europhysics News* **26** 3 1995) is under construction in Greifswald, Germany, and in Japan, at the National Institute for Fusion Science near Nagoya, the Large Helical Device (LHD), also a superconducting device, has just started plasma operation. So it is legitimate to ask why the 'revival' of the concept, which originating at Princeton with the ideas of Lyman Spitzer in the late 50s and was practically abandoned with the emergence of the Tokamak concept, is happening at all.

Two fundamental issues have being essential in bringing this turn around: the advent of powerful supercomputers and the basic progress in technology. Powerful computers have enabled researchers to design sophisticated magnetic traps with the right physical properties for the confinement of plasmas and then continue to the engineering design of the needed coils to produce such properties. On the other hand, the advance in technology has allowed us to realize such designs with the tight tolerances and sophisticated techniques required by stellarators. TJ-II is a good example of these advances, which is shown, for instance, by the fact that it has been possible to design and construct its magnetic trap which required a helical copper coil with 100 MA/m² of current density, 3 meters in diameter and deviations from the ideal helix of less than 1 mm.

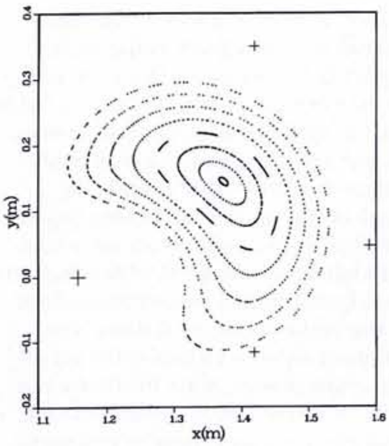
The TJ-II configuration consists of 32 toroidal field coils whose centres follow a toroidal helix of major radius 1.5 m, minor radius 0.28 m and pitch law $\theta = -4\phi$ where θ and ϕ are the usual poloidal and toroidal angles. The magnetic configuration is completed by a central conductor made up of two coils: a pure horizontal circular one of 3 m diameter and a helical winding wrapped around the circular coil following the same winding law as the TF coils. The nominal magnetic field produced by these coils at the centre of the plasma is 1 T. *Figure* 1 shows the completed device.

The main characteristics of TJ-II are: strong helical variation of its magnetic axis (centre of plasma); high plasma pressure (up to 5-6% of the magnetic pressure); flexibility in operation and also a bean-shaped plasma cross section.

Magnetohydrodynamic (MHD) theory shows that helical magnetic axis devices have a potential for high pressure confinement which makes TJ-II especially interesting for studying basic physical properties of plasmas at reactor relevant pressures. To explore this capability, the TJ-II experiment was designed with enough flexibility to cover a wide range of achievable key physical values like plasma size, rotational transform (a measure of the twisting of the magnetic field lines) or magnetic well (a measure of the average curvature of the magnetic field lines) which have a strong influence on the equilibrium, stability and transport properties of magnetic configurations.

Stellarators relying exclusively on external magnetic coils are very sensitive to errors in the manufacturing and positioning of the coils and therefore the first experiment conducted in TJ-II was to take a 'photograph' of the resulting confining field using the fluorescent rod technique: an electron beam is injected in a precisely determined fixed (but moveable from shot to shot) position inside the vacuum vessel. The beam then follows very closely the magnetic field lines of the configuration and its intersections with a moving fluorescent detector are recorded by means of an intensified CCD camera and then digitally integrated to obtain a contour of one magnetic surface. *Figure* 2 shows the remarkable agreement between the predicted and experimental surfaces for one of TJ-II configurations. The nicely nested magnetic surfaces shown in the figure are a guarantee of the successful construction of this sophisticated, and technically demanding stellarator and therefore of its experimental life.

Plasma breakdown and heating is produced by using two 0.5 MW gyrotrons working at 53.2 GHz. In the coming years more additional heating will be introduced. A system of 2 MW of 40 keV accelerated hydrogen atoms (NBI) is being installed that will allow us to explore the finite pressure effects on heliacs. If this experiment is successful two additional MW of power are foreseen to take the machine as close as



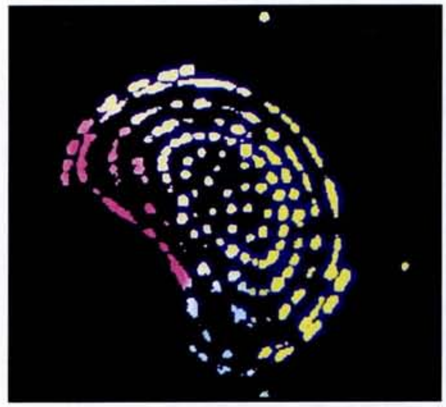


Fig 2 ***Left*** the calculated confining magnetic surfaces of TJ-II and ***right*** the experimental ones measured at 5% of the nominal field using the fluorescent rod method. The excellent agreement between both indicates that the positioning and geometry of all coils is within the specified construction tolerances (< 1 mm)

possible to its physical limits.

Main areas of research in TJ-II are: studies of plasmas in low collisionality regimes aimed at understanding the nature of transport mechanisms caused by the physical properties of magnetically confined plasmas; operational limits in high pressure regimes—in particular we plan to use the flexibility of TJ-II to experimentally validate existing theories of instability development; and studies of confinement optimization and its relationship to radial electric fields.

Encouraged as we should be by all the progress made in the last decade in magnetic confinement, one of the greatest scientific challenges confronting our community is still open: the development of models to fully explain the mechanisms underlying the transport of energy in fusion plasmas. Our hope is that the experimental flexibility of TJ-II could play an important role in finding the solution to this fundamental question. The facility is up and running and at the full disposal of our European scientific community.

MAST **The Spherical Tokamak**

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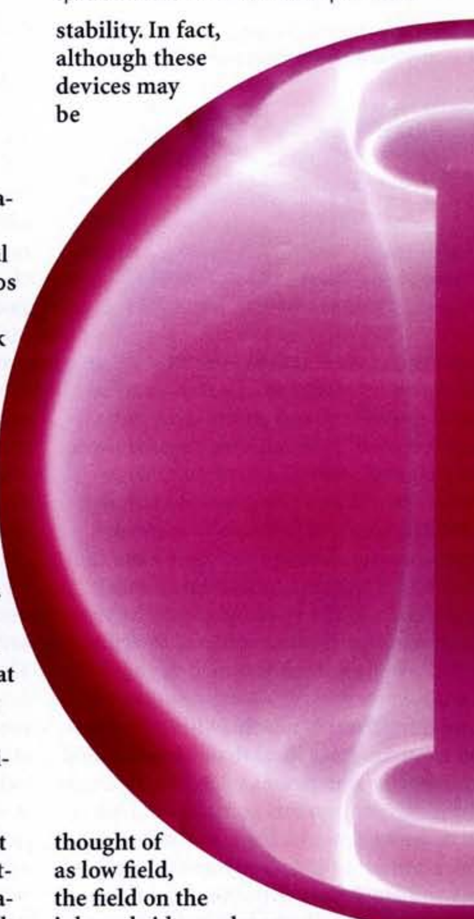
Fig 1 below Photograph of a plasma in START. A central column carries the current to make the main toroidal magnetic field, but it is so compact that the overall impression is of a spherical plasma. The diameter of the 'sphere' is about 1 m and it carries up to 300 kA



When magnetic fusion has reached such an advanced state, it is fair to ask why another variant on the tokamak is being discussed, as well as how it is possible for a torus to be spherical. *Figure* 1 addresses both questions: the simplicity and compactness of such a plasma have attractions as the core of a fusion device, and the plasma is spherical in appearance.

There is a firm database in support of a burning plasma device with a conventional aspect ratio (ratio of major to minor radius of the torus), as embodied in the ITER design for example. If, however, there are advantages in pursuing a somewhat different plasma geometry, for instance with a larger or smaller aspect ratio, then present confidence is limited by the restricted range of aspect ratio data in the experimental database. A major aim of MAST (Mega Amp Spherical Tokamak) is to broaden the tokamak database as well as to provide a novel environment in which to test many aspects of tokamak physics and operation, and transfer results to more conventional aspect ratio devices. Conversely, progress with the spherical tokamak (ST) concept has been extremely rapid as it is built on a wealth of experience from traditional tokamaks.

The ST is largely based on theoretical ideas initially developed in the late 1970s and 1980s. One of the major costs and engineering challenges for the tokamak is the production of an adequate magnetic field to confine the plasma, so it is important to make optimal use of it. This means that the plasma pressure should be as high as possible for a given field –the fusion performance can be written in terms of the product of the density, temperature and confinement (or energy replacement) time. Theoretical calculations using magnetohydrodynamic stability codes, tested against existing tokamak data, show that the highest ratio of plasma pressure to magnetic field pressure is achieved by reducing the aspect ratio as far as possible, and raising the plasma current (and/or reducing the magnetic field). Furthermore, good plasma confinement time is found experimentally to be related to high plasma current. A natural feature of ST geometry allows plasmas with very high plasma currents to be confined at low magnetic field while maintaining stability. In fact, although these devices may be thought of as low field, the field on the inboard side can be as high as on larger aspect ratio devices.

One of the traditional concerns about a