A quest for record high beta in tokamaks

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The original fusion reactor patent of Thompson & Blackman in 1946 featured a toroidal pinch and with a classical estimate of energy confinement of many seconds, D-D fusion appeared straightforward! Alas confinement proved far from classical, and worse, disruptions occurred on microsecond timescales. Some improvement was indeed obtained experimentally, but it was not until the development of the ‘tokamak’ with its strong toroidal field, that real progress was made towards the ultimate goal of economic fusion energy.

However this strong toroidal field imposes a price in terms of increased design and build costs, increased running costs, and risks associated with the large stored energy in the magnet systems. Compared to the pinch, the tokamak has much reduced ‘efficiency’ measured by beta, where beta is the ratio of plasma pressure contained to the magnetic field pressure required to contain it.

Experiments were performed on various tokamaks world-wide to derive empirical scalings for the maximum attainable beta, and theoreticians struggled to derive analytic expressions. A major step forward occurred in two independent presentations at the Aachen EPS Conference in 1983: Sykes, Turner & Patel derived a universal expression from modelling based mainly on ballooning limits; and Troyon presented a scaling based on modelling using the ERATO stability code. The scalings were expressed in different units, the Culham work being in terms of volume average beta and safety factor q, both of which were difficult to measure experimentally before the advent of accurate equilibrium reconstruction, whereas the Lausanne expression was in ‘experimentalists’ beta and plasma current. Troyon pointed out that the expressions were almost identical except for a scaling factor.

As a consequence of this improved understanding the Culham team advocated use of low aspect ratio, then being promoted by Peng, and Derek Robinson, Director of Culham, proposed to build a low-aspect-ratio tokamak, and put Sykes in charge of it. Designed largely by Tom Todd, START was a huge success and fully demonstrated the potential of the Spherical Tokamak (ST) by obtaining an impressive beta value of 40%, over 3 times the previous record held by DIII-D.

Early ST experiments (START, MAST, NSTX) exploited their improved stability by obtaining high plasma current (and headline record beta values) by stable operation at low toroidal field. Recently, high resolution diagnostics on MAST have provided new insight into plasma behaviour (including instabilities such as neo-classical tearing modes) at high normalised beta.

However for practical applications of fusion as an energy source or a neutron source, attention is now concentrated on maximising fusion yield at high toroidal field. The high-beta capability of the Spherical Tokamak makes it the preferred choice for neutron sources such as a Component Test Facility. The key role played by beta limits in future applications of fusion will be discussed.

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