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Evolutionary development of an ignited toroidal fusion reactor

M. Zarnstorff, J. H. Harris[a], D. T. Anderson, S. Knowlton[c], J. F. Lyon[a]

Princeton Plasma Physics Laboratory, USA
Oak Ridge National Laboratory[a], USA
University of Wisconsin[b], USA
Auburn University[c]

e-mail: zarnstor@pppl.gov

The tokamak, with its axisymmetric field configuration and induced plasma current, has been the primary vehicle for studying the physics of toroidal plasma confinement, and can be used effectively to explore burning fusion plasmas. The stellarator has traditionally been seen as a contrasting alternative to the tokamak, substituting external non-symmetric helical fields for the plasma current to form nested magnetic surfaces.

However, as we move forward towards a reactor in which a high-pressure plasma must be stably sustained for weeks or more, the tokamak configuration is evolving. The axially symmetric tokamak develops unstable, non-symmetric helical perturbations whose suppression requires the imposition of multiple helical control fields and/or carefully programmed local heating. Continuous, toroidally asymmetric sources of current drive and momentum input are required to maintain the plasma in an enhanced confinement regime: the steady-state power required for these can exceed that used initially to raise the plasma to fusion temperatures. All these maintenance schemes require active feedback control.

Recent advances in toroidal physics understanding and computation techniques allow these essential sustainment functions to be carried out using a carefully shaped 3-D stellarator field in place of the numerous active schemes. The rotational transform required to make magnetic surfaces together with the shaping required to maintain plasma stability come directly from the structure of the DC magnetic field itself. Additional rotational transform required for high-beta confinement comes from the self-consistent bootstrap current. The sheared flows required for improved confinement come from the ambipolar electric field, which arises naturally in suitably tailored 3-D configurations. The losses of heat and fusion alphas arising from particle orbits in the 3-D field can be reduced to low values by optimization that minimizes the departure from symmetry in a chosen direction. The ARIES collaboration has developed a 1 GWe compact stellarator fusion reactor embodiment based on these concepts (ARIES-CS). The design fits within the size envelope of typical tokamak reactor designs, with $R/a = 4.5$, and yields a comparable cost-of-electricity.

Key questions about the physics features and engineering challenges of these compact stellarators require experimental assessment. Therefore, the US stellarator program has embarked on a series of experiments involving university-scale and national laboratory devices. These include three quasi-symmetric configurations, the Helically Symmetric Experiment (HSX, Univ. Wisconsin, operating), the National Compact Stellarator Experiment (NCSX , PPPL, under construction) and the Quasi-Poloidal System (ORNL, under design). These experiments explore the physics properties of quasi-symmetric configurations. An additional university device, the Compact Toroidal Hybrid (Auburn Univ., operating) is being used for studies of the diagnosis, stability, and control of current carrying stellarator plasmas.