28th IAEA Fusion Energy Conference (FEC 2020)

Contribution ID: **646** Type: **Regular Poster**

Stellarators as a Fast Path to Fusion

Thursday 13 May 2021 12:10 (20 minutes)

The sometimes-apocalyptic statements on the steady increase in carbon dioxide are unleashing powerful political forces but have aroused little interest in scientific solutions—neither carbon-dioxide removal nor carbon-free energy sources. Science can move quickly in periods of societal crisis. The splitting of the nucleus to nuclear weapons required less than seven years, and a fission powered submarine required only nine additional years.

Developing options to the point of deployment costs little compared to the cost of deployment. Fusion could be demonstrated with a gigawatt power plant, but deployment would require replacing a large fraction of the world capacity for electricity production, ~7000 GW. Direct removal is necessary for a timely return to the levels of atmospheric carbon dioxide of an earlier era. Humans place approximately forty gigatons of carbon dioxide in the atmosphere each year. The societal cost of removal would be four trillion dollars per year using the common estimate of a hundred dollars per ton.

The societal cost of each year's delay in the development of carbon-free energy sources is enormous compared to the development costs themselves. Any informed person should ask how quickly could fusion be developed, https://arxiv.org/pdf/1912.06289.pdf.

The stellarator, among all fusion concepts, has properties that best open a fast and low-risk path to reactors. These properties can be illustrated by comparing stellarators with tokamaks. Many more details about fusion plasmas are required for the design of a tokamak than of a stellarator reactor. The step to a power plant from ITER appears more difficult than going directly using our present understanding of stellarators.

1. No proof-of-principle issue, such as disruption avoidance in tokamaks, blocks rapid development of stellarators. Disruptions are an existential threat to reactor-scale tokamaks, particularly the threat of strong currents of relativistic electrons. Without a reliable method of avoidance, planning for a tokamak power plant is problematic.

a) The danger from relativistic or runaway electrons (RE) has been prominent in the literature for more than twenty years. But, Breizman, Aleynikov, Hollmann, and Lehnen noted in their review Nuclear Fusion <59>, 083001 (2019): "With ITER construction in progress, reliable means of RE mitigation are yet to be developed."

b) In tokamaks, a loss of position control accompanies disruptions and each megaampere of decay in the plasma current can increase the current in relativistic electrons by a factor of ten. The severity of the damage that can be produced by even a single incident of a few megamperes of relativistic electron striking the wall implies: (i) The achievement of the ITER mission will be difficult when more than one such incident occurs in a year. (ii) The strategy for avoidance must be fundamentally based on theory and computation.

c) Tokamak disruptions are often said to result from exceeding operating boundaries. But, methods of steering tokamak plasmas during a fusion burn are extremely limited and slow. In addition, a disruption can be initiated if a part of a wall tile or even a tiny flake from the tungsten diverter targets were to enter the plasma.

d) The externally-produced rotational transform is used in standard stellarator designs to avoid tokamak-like disruptions and relativistic electrons: (i) The plasma remains centered in its chamber regardless of the plasma behavior. (ii) The poloidal flux is largely independent of the plasma. The loop voltage, which accelerates electrons, is the rate of slippage of the poloidal relative to the toroidal magnetic flux. The robustness of stellarators against disruptions eliminates the Greenwald density limit. Ignited stellarator plasmas require no external power source, which is an economic burden on tokamaks.

2. The stellarator is unique among fusion concepts, magnetic and inertial, in not using the plasma itself to provide an essential part of its confinement concept. This allows stellarators to be designed computationally with far more reliability than any other fusion concept. The alternative to computational design is extrapolation from one generation of experiments to another, as is traditional in tokamaks, which has four disadvantages:

a) Experiments are built and operated over long periods of time—often many decades. Multiple experiments carried out at the same time do not delay development. Extrapolation using consecutive generations of experiments does, which imposes enormous societal costs.

b) The cost of computational design is many orders of magnitude smaller than building a major experiment, as well as having a much faster time scale.

c) Experiments build in conservatism—even apparently minor changes in design are not possible and there-

fore remain unstudied.
d) Extrapolations are dangerous when changing physics regimes. Examples are (i) plasma control in ignited versus non-ignited plasmas and (ii) the formation of a current of relativistic electrons during a disruption. ⌧In existing tokamaks, external heating provides plasma control that is not present when the heating is dominated by fusion power. ⌧
3. Stellarator reactor designs are only weakly dependent on the plasma pressure profile.
a) The sensitivity of tokamaks to the profile of the current density makes them highly sensitive to the pressure profile.
b) Microturbulent transport is an issue for all magnetic-fusion systems. The insensitivity of stellarators to the pressure profile implies that only the overall level of the transport is of central importance. For tokamaks, not only is the overall level important, but also the radial dependence of the transport.
c) Tokamak and stellarator scaling laws imply the transport can be normalized to gyro-Bohm ⌧transport by a coefficient D. Too large a D implies that either the power output of a single reactor or the magnetic field strength become excessively large. Too small a D implies the plasma radius is small compared to the thickness of the blankets and shields, which means the power production is too small compared to the reactor cost. D of order but somewhat smaller than unity is optimal.
d) The higher electron temperature required in tokamaks for current maintenance has negative implications: (i) Confinement is degraded. The degradation with power seen in empirical scaling laws implies a degradation with temperature. For a given quality of confinement, wall loading, and aspect ratio, the total power output P_T∝a^2 can be made smaller by using a larger magnetic field and a lower plasma temperature—as long as T>10keV. The higher central temperature in tokamak reactors offsets the advantage of a smaller aspect ratio for allowing fusion power plants to have a smaller total power output P_T. (ii) The higher the electron temperature the greater the number of energetic alpha particles, which increases the sensitivity to energetic particle instabilities.
4. Stellarators offer far more freedom of control than do tokamaks. Approximately fifty externally-produced distributions of magnetic field are available for plasma control in stellarators. Approximately five are available in axisymmetric tokamaks, which require careful time dependent control unlike in stellarators. The plasma profiles in tokamaks require far more control than in stellarators, but the available degrees of freedom to provide that control are far fewer.
5. The coil systems in stellarators, unlike those in tokamaks, can be designed for open access to the plasma chamber. A helical coil plus saddle coils can have this feature. If fusion is to be developed rapidly, a power plant must be designed to allow first wall components to be changed quickly—too many uncertainties remain in first wall materials, in concepts such as walls being covered by liquids, and in blankets for breeding tritium for it to be otherwise. Open access also shortens maintenance times in operating reactors.

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Session Classification: P5 Posters 5

Track Classification: Fusion Energy Technology