Important Gaps in the ST and AT Programs

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Executive summary of proposed strategic element: Spherical Tokamak (ST) and Advanced Tokamak (AT) concepts have made considerable progress, but important gaps need to be resolved for these concepts to translate to an economical fusion power plant.

First, present high performance discharges rely on neutral beam injection (NBI) for core fueling and toroidal momentum injection to provide rotation and rotation shear control to reduce transport and improve plasma stability limits. However NBI is projected to be much less effective for core fueling and toroidal momentum injection for a reactor regime. In addition, due to neutron streaming through the large port ducts, NBI may not be a reactor relevant technology for steady-state operation of a fusion power plant.

Second, advanced ST and AT scenarios also rely on optimized density and pressure profiles to maximize the bootstrap current drive, so that most of the needed current drive could be generated by the plasma itself, and thus increase the overall power plant efficiency. However, to maintain these optimized profiles, the fueling system must be able to deposit required amounts of fuel at specified locations without strongly perturbing the optimized profiles needed for maximizing the bootstrap current drive. Because frozen fuel pellets must be large in size for deep penetration in reactor grade plasmas, pellet injection technology is inconsistent with non-perturbative maintenance of the required density and pressure profiles. This is reflected in the fact that, today, steady-state high-bootstrap fraction discharges on JET and DIII-D do not use pellet fueling but rather rely on NBI for core fueling.

Finally, the solenoid, which has been an essential element in all tokamak and ST devices for generating the plasma current, is an expensive and complex component. But it is really only needed for plasma start-up. Because a solenoid is an inductive system (analogous to an electrical transformer in which the solenoid windings are the primary windings of a transformer, and the plasma forms the secondary winding), it cannot be used to sustain the discharge during steady-state operation. However, reliance on a large complex transformer increases the risk for a power plant as a fault in the solenoid winding would be both extensive and very time consuming to repair. Building a tokamak / ST power plant without reliance on a solenoid for plasma current initiation would simplify, reduce the cost, and most important - improve the reliability of these power plants.

Steady-state ST and AT based reactors could be significantly simplified and their prospects for an economical power plant substantially improved if the above-mentioned issues could be addressed with innovative reactor-relevant systems. Increased emphasis on the following systems would help achieve these important tokamak reactor optimizations: Solenoid-free plasma start-up using Transient Coaxial Helicity injection (CHI),[1] advanced fueling and momentum injection based on Compact Toroid injection (CT),[2] and off-axis current drive using Electron Bernstein Waves (EBW).[3]

These three concepts are briefly described.

Transient Coaxial Helicity Injection non-solenoidal startup:

Transient CHI has generated 200 kA of closed flux current on NSTX. Scaling of this method to larger machines is well understood. The scaling is simple. The amount of current that can be produced is proportional to the amount of poloidal flux that can be injected into the vessel.[1] It was the plan on NSTX-U to generate 400 kA of closed flux current and then to ramp that current non-inductively to 1 MA. The plan was to do this demonstration over a 5 to 8 year time period. The CHI system has now been removed from NSTX-U, so that at this time there is no near-term plan to solve this issue, as only small experiments are being conducted at this time. The physics and scaling of other solenoid-free plasma start-up methods in not well understood at this time to extrapolate to larger machines.

CT injection:

A Compact Toroid (CT) is small magnetized plasma that can be accelerated to the velocities needed for core fueling reactor grade plasmas. In addition to providing the needed fuel, it turns out that CTs also inject sufficient momentum to provide rotation and rotation shear control in reactor grade plasmas. A 5 MW CT system injecting 2 mg D_2 CTs at 20 Hz will impart the same momentum as a 69 MW, 500 keV NB injector, while supplying 14 times more core fueling.[2] The development of this concept is immature, and about ten to fifteen years would be needed to turn this concept into a viable system. Without such a system, it is difficult to see how Tokamak / ST based reactors could be adequately fueled, and the rotation control needed to maintain plasma stability limits be provided. A CT-like system would not only solve these important problems but in so doing it would also reduce the reactor recirculating power and make the AT / ST system more attractive.

(3) EBW Current drive:

In optimized configurations, in addition to maintaining the optimized density profiles, and a small amount of core current drive, the only other need is for a small amount of off-axis current drive. The efficiency of conventional Electron Cyclotron Heating (ECH) current drive rapidly decreases at large radius due to trapping of electrons in banana orbits. As a result the Fisch-Boozer current drive that relies on current drive provided by passing particle is no longer effective at large radius. However, the same particle trapping mechanism now allows another form of current drive, the Ohkawa current drive to increase its current drive efficiency. Electron Bernstein Wave Current Drive (EBW CD)[3] relies on this Ohkawa CD mechanism, and has the potential to meet these needs for these high-performance ST/AT type discharges.

1. R. Raman, T.R. Jarboe, B.A. Nelson, F. Ebrahimi, D. Mueller, M. Ono, S.C. Jardin. Development of a Transient Coaxial Helicity Injection for Solenoid-free Plasma Start-up and Subsequent Non-inductive Sustainment, FESAC TEC Panel White Paper (2017): www.burningplasma.org/activities/?article=FESAC%20TEC%20Panel%20Public%20Info%20Home%20Page

2. R. Raman, Momentum Injection and Precise Core Fueling for Reactor Grade Plasmas, FESAC TEC Panel White Paper (2017): www.burningplasma.org/activities/?article=FESAC%20TEC%20Panel%20Public%20Info%20Home%20Page

3. J. Decker, PSFC/JA-03-17 Report, MIT, Cambridge, MA 02139 USA and J. Decker, et al., 31st EPS Conf. on Plasma Physics, 28 June – 2 July 2004 ECA Vol. 28G, P-2.166 (2004)