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Science and Technology of the 10-MA Spherical Tori*

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The Spherical Torus (ST) configuration has recently emerged as an example of confinement concept innovation that enables attractive steps[1] in the development of fusion energy. The scientific potential for the ST has been indicated by recent encouraging results from START,[2] CDX-U, and HIT. The scientific principles for the D-fueled ST will soon be tested by NSTX (National Spherical Torus Experiment[3]) in the U.S. and MAST (Mega-Amp Spherical Tokamak[4]) in the U.K. at the level of 1–2 MA in plasma current. More recently, interest has grown in the U.S. in the possibility of near-term ST fusion burn devices at the level of 10 MA in plasma current. The missions for these devices would be to test burning plasma performance in a small, pulsed D-T-fueled ST (i.e., DTST) and to develop fusion energy technologies in a small steady state ST-based Volume Neutron Source (VNS[5]). This paper reports the results of analysis of the key science and technology issues for these devices.

The parameters for the 10-MA ST devices have been estimated using a ST version of the SUPERCODE[6]. The results are given below, in comparison with NSTX and MAST.

Near-Term ST Devices	**NSTX/MAST**		**DTST**		**VNS**	
Mission: to test or develop	Phys. Principle		Phys. Performance		Energy technology	
Major radius (m)	~0.80		~1.1		~1.1	
Aspect ratio	≥1.25		1.4		1.4	
Toroidal field (T) at major radius	0.3–0.6		1.9		2.1	
Plasma current (MA)	1–2		~10		~10	
Plasma cross section elongation	2–3		3		3	
Toroidal beta (%)	25	45	24	40	24	46
Bootstrap current fraction (%)	50	80	50	80	50	90
Plasma drive power (MW)	6–11		18	33	21	50
NBI energy (keV)	~80		120		400	
Fusion power (MW)	–		33	66	66	263
Plasma flat-top pulse (s)	5–1		~20		~1000	
Neutron wall load (MW/m^2)	–		0.5	1.0	1.0	4.0
Neutron fluence/year (MW/m^2)	–		~0.003		~0.3	~1.6

We find that the D-T-fueled ST plasmas at the 10-MA level would be characterized by modest major radii (~1.1 m) and toroidal fields (~2 T). The DTST would entail an NBI energy of 120 kV, a burn pulse length ~20 s, and a minimal neutron fluence per year (~0.003 MW-yr/m^2) to prove fusion plasma performance at the level of Q~2 and fusion power ~33 MW. Only a relatively conservative toroidal beta (~24%) would be required for this purpose. For the technology-intensive, steady state VNS, the initial operation could rely on the burning plasma data from the DTST and provide ~1.0 MW/m^2 in neutron wall loading and ~0.3 MW-yr/m^2 in neutron fluence per year. NBI energies of ~400 kV could be used to access the "advanced physics regimes" given in the right-hand column of the above table characterized by high beta (~46%), improved confinement, fusion power (~200 MW), neutron wall load (~3 MW/m^2), and neutron fluence per year (~ 1.2 MW-yr/m^2). A relatively conservative confinement, H~2 for ITER 93H already measured in START, is assumed for the estimates in the left-hand column.

Key scientific principles to be tested by NSTX/MAST for the DTST are identified and estimated. These include 1) noninductive current formation and ramp-up to eliminate the solenoid to permit a small DTST, including CHI, RF-only techniques[7] possibly taking advantage of bootstrap current overdrive[8]; 2) plasma heating and current drive via HHFW[9] and NBI[10] for efficient steady-state operation; 3) high plasma beta[11] with well-aligned bootstrap current to permit high fusion power density and ease current drive; 4) confinement in the presence of transport barriers[12] and improved neoclassical ion transport[13]; and 5) reduced power and particle flux densities at the limiters and divertors in SOL with large mirror ratio and flux expansion.[14]

Key issues of fusion plasma performance to be tested in the DTST for the ST-based VNS should stem primarily from the presence of significant heating by the fusion alpha-particles for operations at Q~2. In these ST plasmas the Alfven speed is expected to be below the energetic alpha and NBI ion speeds in the outboard region, leading to a new regime for possible Alfven mode instabilities. For high safety factors q~10 at edge and ≥2 at the axis, an increased vulnerability to orbit losses enhanced by magnetic ripples is expected. Orbit compression due to strong magnetic well[11] and sheared flow[12] may reduce such orbit losses. The interaction of the energetic alpha particles with the HHFW heating and current drive is expected to be an important new issue of interest. Issues relating to dominating alpha heating would become important if Q~10 could be reached, assuming strong transport barrier[15] and the "advanced physics" regime.

Our analysis also indicates that the enabling technologies in plasma heating, current drive, fueling, plasma-surface interaction, and power and particle removal required by DTST and VNS could be developed based on the present state of art in fusion research. Energy technology issues unique to the compact VNS stem primarily from the copper, water-cooled, single-turn center leg[16] of the toroidal field coil. This center leg is expected to endure intense neutron bombardment, radiation hardening, significant activation,[17] and entail special safety issues of copper disposal and related to LM coolant of the test blankets. At ~1 MW/m^2 in neutron wall loading, essentially all fusion core components for the ITER EDA could be adopted for the VNS.

The database for the "advanced regime" physics could be tested in NSTX/MAST and DTST; that for the energy technologies at high neutron wall loads (~4 MW/m^2) could be developed in VNS (in the right-hand-columns of the table). These could eventually justify the economic viability for small Pilot Plants[18] and attractive Power Plants[19] in the future.

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