Draft-2

Cost-Effective Spherical Torus Steps Toward Fusion Power*

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I. Introduction

The Spherical Torus (ST) was identified in 1996 by FESAC as one of the leading innovative confinement concepts to be pursued vigorously within the U.S. Fusion Energy Sciences Program. A national project (by PPPL, Columbia University, ORNL, and U. Wash.) began in 1996 to design and build the relatively compact Proof of Principle, National Spherical Torus Experiment (NSTX). The NSTX Project has since been successful in approaching completion in April 1999. A nationally based research team, composing of researchers from 14 fusion institutions, has recently been established by DOE to carry out the NSTX Research Program, for the first time in the U.S. at the MA level in plasma current.

A concise summary (see, attached) of the nature, the status, and the merits of the ST fusion research program in the U.S. has been prepared as input to the current FESAC review. Here we will focus on a discussion of the possible medium-term ST steps (up to 20 years) envisioned to develop the scientific and technological database needed before entering the stage of Engineering Test Reactor (ETR) and possibly the Pilot Plant. This time scale before the ETR has been commonly assumed in recent broad community discussions of the U.S. Fusion Energy Sciences Program.

Here we will describe in Section II the characteristics of the ST magnetic configuration and identify the attractive opportunities so introduced by the ST for scientific discovery and innovation in a widened parameter domain. Exploration and confirmation of these scientific opportunities in NSTX is expected to lead to highly cost-effective ST steps for Performance Extension (toward Proof of Performance) and subsequently for Fusion Energy Technology Development. In Section III we will provide a summary of the parameters and requirements of these devices and their merits. In Section IV we will identify the critical scientific issues to be resolved by the Proof of Principle and Performance Extension ST experiments to establish the database needed by the Fusion Energy Development device. The uncertainties and opportunities intrinsic to the ST innovation and how we may take advantage of them will be discussed in Section V.

II. New Scientific Opportunities

New scientific opportunities are introduced by the unique magnetic configurations of the ST plasma. As shown in Figure 1, the aspect ratio ($A=R_0/a$) of the ST plasma approaches unity (1.1–1.6 typically) compared to A=2.5–5.0 so far for the Tokamak and the Advanced Tokamak (AT). As a result the ST plasma resembles a sphere with a modest hole through its center.

The ST uses modest applied toroidal field and has large I_p/aB and I_p/I_{tfc} values, indicating a much-increased efficiency for utilization of the externally applied toroidal field. Its magnetic surfaces combine short field line of bad curvature and high pitch angle (relative to the horizontal plane) toward the outboard plasma edge with long field line of good curvature and low pitch angle toward the inboard plasma edge. The ST outboard field lines resemble the outboard field lines of the Compact Toroids (CT), while the inboard field lines resemble the inboard field lines of a high edge-q Tokamak. New opportunities are therefore introduced for the ST to benefit from the scientific strengths of the Tokamak as well as the CT.

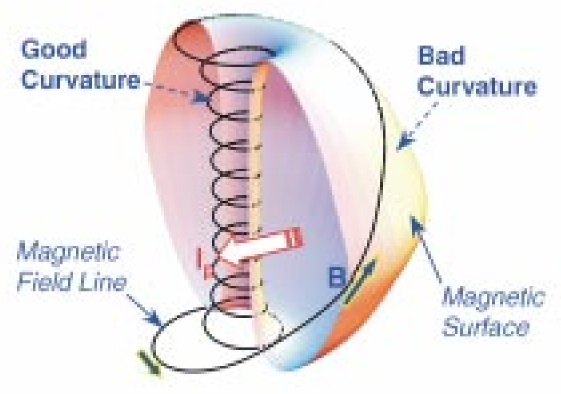

Figure 1. ST plasma magnetic configuration with A ~1.25, elongation k ~2, and edge safety factor q = 12.

A consequence of the dominating good field line curvature is MHD stability at high plasma pressure, leading to the potential for order-unity average toroidal and central plasma betas ($\beta=2\mu_0 p/B^2$). High β and the special magnetic configuration combine to widen the plasma parameter domain beyond the present state of art in MFE. The characteristics of this widened parameter domain projected for the Proof of Principle experiments (at ~1 MA in plasma current, such as the NSTX in U.S. and the MAST in U.K.) and a possible Performance Extension experiment (at ~10 MA in plasma current) are summarized in the table below. Much of these projections have utilized Tokamak analysis tools modified for the ST.

Table 1. Characteristics of the Widened Scientific Domain Anticipated for ST plasmas at 1-MA and 10-MA levels

Physics	**Potentially Attractive Parameters**	**1-MA ST**	**10-MA ST**
Confinement	- High particle trapping fraction	≤0.87	≤0.85
	- High edge safety factor	~10	~10
	- Strong magnetic well	~0.3	~0.4
	- Large normalized ion gyroradius (ρ_i*)	~0.03	~0.015
	- Large diamagnetic flow shear rate (ω_D*, s^{-1})	~10^6	~10^6
Stability	- High stable average toroidal beta (β_t)	~0.4	~0.6
	- Strong ideal wall stabilization ($\beta_{N\text{-with wall}}/\beta_{N\text{-without wall}}$)	~2	~2
	- Low flow speed for stabilizing wall mode (~0.1 v_A)	« c_s	< c_s
	- Large Pfirsch-Schlüter/plasma current density	~1	~1
H-Mode	- Edge T_i pedestal (high heat flux, ρ_i, magnetic shear)	large	large
	- Low L-H transition power threshold (∝ nB at edge)	~2 MW	~10 MW
	- H-mode for inner-wall limited operation	likely	likely
Divertor (Outboard SOL for inboard limited "natural divertor" plasma)			
	- Large SOL magnetic mirror ratio	~4	~3.5
	- Large SOL flux tube expansion	≥10	≥10
Noninductive	- Small plasma helicity per I_p (~1.6 $\ell_i \kappa a^2 I_{TF}$, H-Wb)	~0.5	~9
Ramp up	- Small plasma poloidal flux per I_p (~$\mu_0 \ell_i$ R, H)	~0.3×10^{-6}	~0.4×10^{-6}
	- Stable bootstrap current overdrive at very high q	yes	yes
Current	- Good NBI ion and α orbit containment	≤80 kV D^+	≤400 kV D^+
Maintenance	- Different energetic particle driven instabilities	$v_{NB} > v_A$	$v_\alpha \gg v_{NB} \geq v_A$
	- Large RF plasma dielectric constant, ~$(\omega_{pe}/\omega_{ce})^2$	~40	~10
	- Stable aligned bootstrap current fraction	~80%	~100 %

It is seen that the widened scientific domain defined by these projections encompasses all topics of interest to making large and desirable progress in magnetic fusion plasma science. For example, the strong magnetic well, large ρ_i^*, large flow shearing rate, and high edge pedestal ion temperature all contribute to large improvements in plasma confinement. Relatively modest Alfvén speed compared to the plasma sound speed in the outboard plasma region introduces the possibility of wall mode stabilization at relatively small Mach numbers. The large Pfirsch-Schlüter current density increases the stability of the neoclassical tearing modes (NTM) even at significant island width and potentially removes the ability for the NTM to severely reduce the beta limit. The very large mirror ratios and flux tube expansion introduces the possibility of dispersing the intense plasma exhaust fluxes over large areas of plasma facing components, without having to introduce significant impurities for radiative edge cooling. The theoretical possibility of nearly complete alignment of bootstrap current with stable current profiles at high beta minimizes the need for external current drive of current maintenance. This should mitigate against uncertainties associated with RF current drive in the presence of very large plasma dielectric constant, which has been theorized to permit efficient heating and current drive by High Harmonic Fast Wave (HHFW). Finally and also of high importance, the very low values for the "specific" helicity and flux content of the ST plasma should encourage efficient current ramp-up via noninductive means, which would also allow slow current ramp via an overdriven stable bootstrap current.

These and other theoretical projections indicate that the ST plasma could introduce broad opportunities for making large progress and significant discoveries in magnetic fusion energy science. If successful, the ST research would therefore strengthen the scientific basis for attractive MFE and other fusion applications, as well as introduce cost-effective steps in MFE development.

The ST concept could be improved further by its closer connections to the CT plasmas. Recently in TS-3 (U. Tokyo), strongly diamagnetic, ST-like, Field Reversed Configuration (FRC) plasmas of near unity-beta were formed in the presence of a small external toroidal field. This suggests the possibility of further increases in ST magnetic well and beta limits by suppressing MHD modes, possibly via an energetic ion population. Recently in MST (a Reversed Field Pinch, RFP, at U. Wisc.), improved stability and confinement were obtained by edge current drive to approach the paramagnetic "Taylor" minimum energy condition. This suggests the possibility of using edge current drive in ST to reduce the edge safety factor and increase the edge paramagnetism while maintaining an attractive diamagnetic ST plasma core. Success in this direction would reduce the external toroidal field needed by the ST plasma and the resistive dissipation of the center toroidal field coil leg in future power plants. Indeed, new theoretical analysis has recently begun by a research group in India to estimate the theoretical viability of this approach.

III. Cost-Effective ST Steps for Science and Technology R&D

A national research team has been formed to begin in FY 1999 experimental tests on NSTX of these attractive properties. The MAST device having size similar to NSTX, as well as smaller innovative ST devices such as Globus-M (Ioffe Institute), Pegasus (U. Wisc.), HIT-II (U. Wash.), CDX-U (PPPL), TS-4 (U. Tokyo), ETE (Brazil), etc., have begun or are soon to begin experimentation. The key parameters, testing capabilities, and the anticipated performance of NSTX are summarized in the Table 2 below.

Assuming successful Proof of Principle tests in NSTX/MAST, projections can be made of the two ensuing stages of scientific and technology R&D. These are the Performance Extension ST experiment with possible limited deuterium-tritium testing capability (a DT-capable ST), and the steady state Energy Technology Development ST commonly called the Volume Neutron Source (VNS). These estimates are also provided in the table. It is seen that these ST devices have modest sizes and requirements, relative to their potential performances and contributions to the development of fusion energy.

Table 2. The key parameters, performance, and requirements projected for Proof of Principle, Proof of Performance, and Energy Technology ST Experiments

Near-Term ST Devices	**NSTX**		**DT-Capable ST**		**VNS**	
Mission: To prove or extend	*Physics Principle*		*Physics Performance*		*Energy Technology*	
Mode of operation	*First Regime*	*Adv. Regime*	*Sustained Current*	*Transient Hi-Current*	*First Regime*	*Adv. Regime*
Major radius (m)	0.86		~1.2		~1.1	
Aspect ratio	≥1.25		1.4		1.4	
Toroidal field (T) at major radius	0.3–0.6		1.7		2.1	
Plasma current (MA)	1		10	18	~10	
Edge safety factor	10		10	5	9	
Plasma cross section elongation	2		3		3	
Normal beta (%Tm/MA)	5	8	7	3.3	4	7.6
Average toroidal beta (%)	25	45	50	40	25	45
Average plasma pressure (%T^2)	~10		~100		~100	
Bootstrap current fraction (%)	50	80	90	25	50	95
Auxiliary (RF+NBI) power (MW)	11		40	10	40	70
NBI energy (keV)	80		110		110	400
H (ITERH-PB98y,1) [9]	1–2		2.5	1.2	1	2
Plasma flattop (or burn) time (s)	~1–5		~20	~10	~1000	
Fusion power (MW)	–		60	200	66	260
Neutron wall load (MW/m^2)	–		1.1	2.6	1.0	4.0
Neutron fluence/year (MW/m^2)	–		~0.003		~0.3	~1.2
Site power demand (MW)	~30		~100		~200–300	
Planned (or anticipated) TPC ($M)	23.8		~300		~1000	

It is useful to note that two important regimes of scientific development are anticipated for the ST plasma: the First-Stability and the Advanced-Physics Regimes.

The First-Stability Regime is characterized by stable ST plasmas with moderate normalized poloidal beta (~0.5) and high normalized beta (~5 %Tm/MA), and permitting lowered edge safety factor (~5) without requiring a near-by stabilizing wall. A moderate bootstrap current fraction (~0.5) is expected for this regime, which does not require detailed external control of the plasma profiles. This type of ST plasmas have been produced for brief durations in the modest-scale START ST device (U.K.), achieving average toroidal betas as high as 40%. This regime would be tested early in NSTX for significant pulse lengths and plasma parameters. The data will be of high relevance to the pulsed higher-current and high-Q operations in DTST, as well as the more nearly sustained lower current and moderate-Q (~1–2) driven conditions called for in VNS. The anticipated parameters for these conditions are summarized in Table 2 under the column of "transient high current" for DTST and "first regime" for VNS.

Success of the First-Stability Regime test in DTST would therefore establish the burning plasma physics basis for the ST VNS to focus in the energy technology R&D. Success of the ST VNS could also enable viable nearer-term non-electric applications, such as source for neutron science, transmutation of nuclear waste, and production of tritium and isotopes for fusion, industrial, and medical uses. The fusion plasma physics and technology requirements for such applications are significantly less than those required for fusion power.

The Advanced-Physics Regime for the ST plasma, however, would be required for economic fusion power. This regime is presently anticipated to be analogous to the AT Regime being pursued in Tokamaks in recent years. This ST regime is characterized by high edge safety factor (≥10), high normalized poloidal beta (≥1), and very high normalized beta (~8–9 %Tm/MA), and requires a near-by stabilizing wall. A nearly fully aligned bootstrap current fraction (~0.9–1.0) would also be theoretically possible for such plasmas, requiring detailed external control of all plasma profiles, such as density, temperature, diffusivities, including the values at edge.

The Advanced-Physics Regime also promises strong suppression of turbulence and approach to neoclassical confinement conditions in the ST plasma. Achieving such conditions would enable near ignition conditions in the DTST and VNS-level plasmas. Successful testing of these highly desirable confinement conditions in NSTX and DTST would further enable the VNS to take on the mission of an ETR: the integrated testing of ignited fusion burn and energy technologies. Such an outcome would pave the way to a highly cost effective Pilot Plant, which utilizes the science and technology database provided by the DTST and VNS to enable a test of net electricity production. A cost-effective Pilot Plant should address the interests of the Utility Industry.

By utilizing existing equipment and facility at PPPL and ORNL, and benefiting from the expertise already available within the broad MFE community, the TPC for NSTX has been moderate ($23.8M). The relatively simple ST configuration enables a reduced time for construction (~2 years). If the extensive MFE expertise, equipment, and facility in the U.S. can be fully utilized, including the auxiliary heating systems, power control systems, and neutron dose capabilities, the scale of TPC for a DTST is anticipated to be in the range of ~$300M. If an existing nuclear site in the U.S. can be utilized, capable of handling up to a couple hundred MW of fusion neutron power under steady state conditions, the TPC for a ST VNS would hopefully be close to ~$1B, based on scaling comparisons with the ITER-EDA design.

A roadmap of these cost-effective ST steps toward attractive fusion energy is shown in Figure 2. There it is shown that concept innovation such as the ST could enable cost-effective advances in fusion plasma science by several orders of magnitude in energy amplification Q via NSTX and DTST. This would establish the scientific foundation for embarking on cost-effective R&D via the VNS to advance fusion energy technology by several orders magnitude in neutron fluence. This roadmap holds the promise of enabling in ~20 years an ETR based on VNS-size plasmas.

IV. Critical Scientific Issues

The critical scientific issues to be tested by NSTX for the DTST are identified. These include

1) Noninductive current formation and ramp-up to eliminate the solenoid, via CHI and RF-only techniques, taking advantage of anomalous plasma resistively.
2) Plasma heating and current drive via HHFW and NBI for near steady-state operation.
3) High plasma beta to permit high fusion power density, with well-aligned bootstrap current to ease current drive.
4) Confinement in the presence of transport barriers via turbulence suppression and improved neoclassical ion transport.
5) Limited power and particle flux densities at the plasma facing components via large mirror ratio and flux tube expansion of the Scrape-Off Layer (SOL), and radiation via impurities in the edge regions.

The capabilities of NSTX are designed and built for the investigation and resolution of these issues.

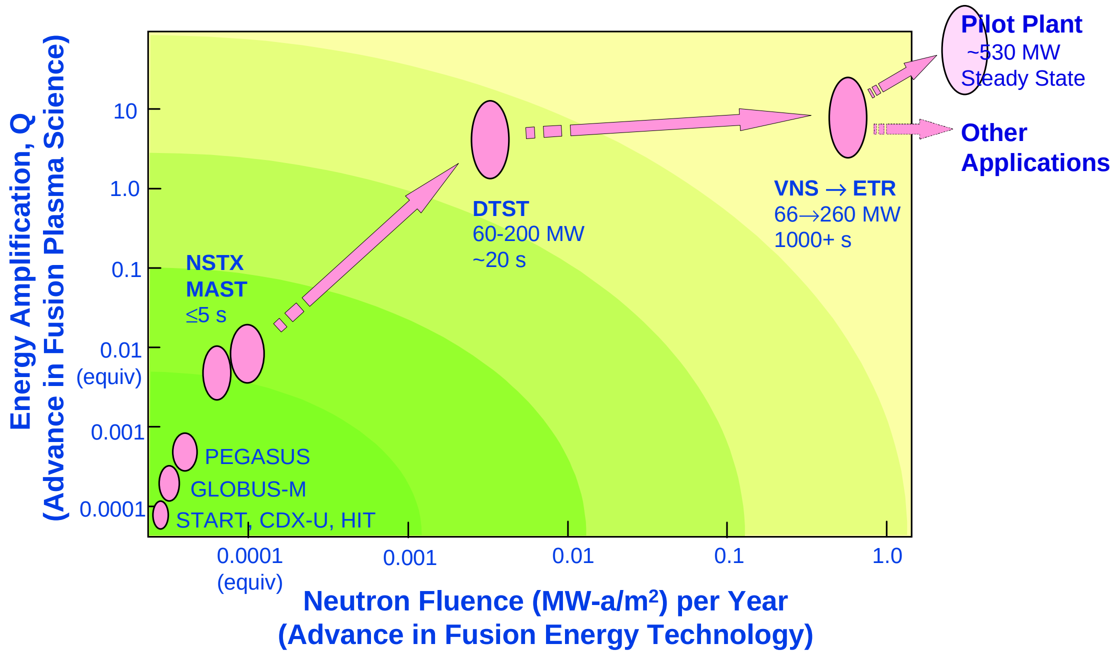

Figure 2. NSTX and DTST advance the fusion plasma science (energy amplification Q), VNS advances the fusion energy technology (neutron fluence), each by more than two orders of magnitude.

Key issues of fusion plasma performance to be tested in the DTST for the ST-based VNS should stem primarily from significant heating by the fusion alpha particles and high power density for operations at very high beta and significant Q values in a compact ST device.

1) In these ST plasmas the Alfvén speed is expected to be significantly below the energetic alpha and NBI ion speeds in the outboard region, leading to a new regime for differing Alfvén mode instabilities.
2) 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 and sheared flow may reduce such orbit losses.
3) The interaction of the energetic alpha particles with the HHFW heating and current drive is expected to be of interest.
4) The effects of dominating alpha heating would become important if Q~10 or higher could be reached, including the sustainment of transport barrier in the Advanced-Physics Regime.
5) Noninductive schemes for initiation and ramp up to full plasma current is of great importance to the VNS to ensure the elimination of the solenoid and hence modest size for the VNS device.
6) Techniques for dispersing large particle and energy fluxes on the plasma-facing component.

The DTST should be designed with capabilities to investigate and resolve these other issues of interest to VNS operation.

V. Discussion

Recent theoretical projections of the ST plasma properties suggest that NSTX will provide broad opportunities for making important new progress in MFE in the upcoming years. However, these projections are nevertheless based on the extensive knowledge and tools verified for the Tokamak plasmas and being used to guide the AT investigations. Because of the rather large extension from the present state of art in MFE (see Table 1), there should be anticipated considerable challenge as well as opportunities in the outcome of investigation into the ST fusion plasma domain. The Proof of Principle and the Performance Extension experiments should take advantage of these, to verify the projections and discover new physics for the benefit of attractive fusion energy.

Further, these projections for DTST and VNS have so far been highly attractive in potential low cost and high performance. It is therefore wise to begin early modest assessments of the feasibility and requirements of the DTST and VNS devices and facilities, on a nationally or worldwide basis. Such an effort would provide timely and valuable guidance on the important scientific and technical issues to be addressed by the emerging ST research programs in U.S. and worldwide.

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