Key Physics Issues of a Compact Tokamak Fusion Neutron Source

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Abstract. The paper describes a concept of a compact tokamak fusion neutron source based on a small spherical tokamak (FNS-ST) with MW-range of the DT-fusion power and considers key physics issues of this device. The major and minor radii are ~0.5 and ~0.3 m at magnetic field ~1.5 T, heating power less than 15 MW and plasma current 2 MA. The production rate of DT-neutrons of (3-10) × 10^{17} n/s and the neutron wall load of 0.2 MW/m^2 provide the device to be sufficient for fusion-fission demonstration experiments. The problems of major concerns are discharge initiation, current drive, plasma-fast ion beam stability and high first wall and divertor loads. The conceptual design of enabling systems suggests feasibility of FNS-ST.

1. Introduction

The fast track to fusion applications associates with the development of an intense fusion neutron sources (FNSs) [1]. Such FNSs are of interest for many branches of technology and basic research, including transmutation of elements, nuclear fuel production, material science and neutron scattering. Compact spherical tokamak is considered as an efficient device for these applications. If modern confinement scalings are valid in low collisionality plasma, a MW range level of D-T fusion reaction (3.6×10^{17} n/s) could be realized on the basis of contemporary fusion technologies in a tokamak with major radius as small as 0.5 m [2]. Meanwhile, the problem of steady state operation (SSO) remains critical for the device, and very thorough optimization of physics and technology is needed to get the desirable performance.

In this report we discuss key physics issues of SSO in the compact tokamak FNS-ST. The basic motivation for conceptual analysis of this device is reduction of the neutron load on the first wall and the capital cost and operation expenses substantially below those of Component Test Facility (CTF) designs [3,4]. At the same time, the device should keep capability to produce neutron fluence comparable to that of a contemporary accelerator neutron source, or even higher.

2. FNS-ST concept

The mission of the FNS-ST is to be a prototype of a fusion-fission hybrid system with the fusion power below 10 MW and fission power below 100 MW, being capable to produce neutrons with fast/thermal spectra with the system life time of several decades.
The design constraints defining the basic system parameters are as follows. Minimization of the device size is desirable to reach highest neutron flux density. Reducing the total electric power consumption below 50 MW follows from the desire to keep the capital cost <200 M$ and operation cost <30 M$ with the duty factor of 0.3. The power consumption of the

magnetic system is to be below 30 MW and the heating and the current drive power below 15 MW. Tritium consumption is to be less than 50 gram per one operation year.

Main parameters of the device are set by physics and engineering constraints. The major radius R=0.5 m, reasonably low aspect ratio A=1.66 and high elongation k = 2.75 provide the desirable plasma parameters. The device has the plasma volume of 2 m^3 and the first wall surface of 10 m^2. The toroidal magnetic field was considered 1.5 T, which is the lowest limit for MW range devices. The basic operation current is 1.5 MA, however the increase up to 3 MA may be possible with normalized current *I[MA]/a[m]B[T]* = 6.66 and reaching normalized beta β_N = 6 in case of effective RWM stabilization.

The toroidal magnetic system consists of 12 single turn coils welded at the bottom and water cooled. The central pole part of the coil is twisted (see Fig.1) that makes possible connecting the coils without joints. The poloidal magnetic system is positioned outside the toroidal coils (see Fig. 2); it is water-cooled and consists of 6 multi-loop coils. It provides double null divertor configuration and plasma equilibrium control. Passive conducting elements in the X-point vicinity increase the VDE development time longer than 10 ms making the vertical position control possible. A removable central solenoid with the magnetic flux of 0.4 Wb assisted by EC-radiation of gyrotrons provides discharge breakdown and current ramp-up to 1 MA.

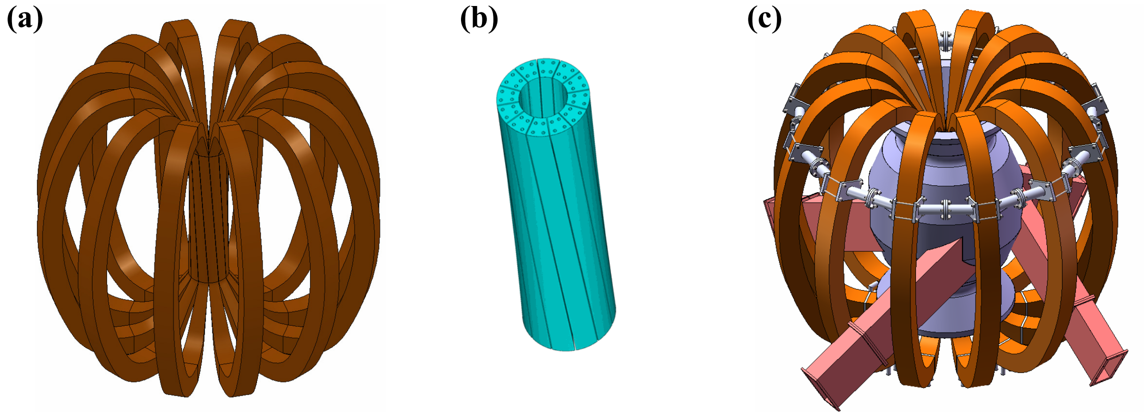

Fig. 1. The toroidal magnetic system: Cu alloy, 20 tons, 80 m length, 250 kA current, 46.8 V, 11.7 MW, 1.35 T at R = 0.47 m, T_{max} = 132° C (a) with twisted central pole (b). Assemblage of the vacuum chamber is fulfilled inside the TF magnet (c).

The vacuum vessel is manufactured of sections with 1 cm thickness formed by a tungsten cover tiles (3 mm) and 1 cm CuCrZr-tubes for water cooler. The construction provides operation at the heat flux up to 1.5 MW/m^2.

Double null divertor with strongly asymmetric legs (the inner leg length is 10 cm and the outer is 40 cm) is equipped by targets with W-tiles protected by lithium films. It operates in steady state at heat loads up to 10 MW/m^2.

The blanket placed between the first wall and toroidal magnetic coils consists of multiple layers. The layer closest to the first wall is made of lead or beryllium. It provides neutrons' multiplication and accumulation in the vessel volume. The blanket design provides its connecting with active cores and moderators for thermal and ultra cold spectra production. The blanket operates in magnetic fields up to 1 T, which affects the design. Pure neutron production, U or Th fuel cycles and transmutations may be provided by different types of blankets. The blanket zone in FNS-ST including shielding has the thickness of 1 m.

Structural materials considered in the design are commercially available steels, copper and vanadium alloys, hastelloy. Tungsten is used as the plasma facing material. Water, F-based molten salts and lead are used as coolers. Lead, heavy water, molten salts and graphite are used as reflector and moderators. Spinel ($MgAl_2O_4$) based insulators are used in neutron environment. Aluminum based barriers are used for tritium permeation control. A thin protecting layer of lithium on the plasma facing components is produced by Li dust injection.

The device operates using deuterium and tritium mixture with ratio 1:1. This mixture is used in the neutral beam injectors as well. Enriching the fuel mixture is assumed to compensate the tritium burning and capture in the fuel cycle.

Vacuum pumping system uses turbo-molecular pumps with the total pumping rate 20 m^3/s.

The additional heating and current drive system utilizes neutral beams with the energy of 130 keV and power up to 15 MW (positive ion source) and gyrotrons with frequency of 140 GHz and the power of 5 MW. Steady state operation and fully non-inductive current drive are provided.

Remote handling system is used for full exchange of the toroidal magnetic system and vacuum vessel with inner elements after reaching 2 MW×year/m^2 neutron fluence or in a case of heavy accidents. The remote handling system provides maintenance of the H&CD system in the radiation environment.

Magnetic, neutron, microwave, spectroscopy and fast particle diagnostics support tokamak control in standard regimes. Power supplies of magnetic and heating system, gas puff and pump system, cooler controllers are used as actuators. Due to small energy storage in the plasma below 600 kJ no special tools for disruption and ELM mitigation are needed.

Safety of the system will be affected by using less than 50 g of tritium per year. The storage of up to 100 g at the machine site and less than 10 g in the vacuum chamber is foreseen. The nuclear blanket safety is evaluated as for a sub-critical system with the effective multiplication factor k_{eff} less than 0.95.

Design and construction period for FNS-ST is evaluated as 5 years. The operation period is 30 years at duty factor 0.3. It may be prolonged up to 60 years after changing the magnetic system and vacuum chamber necessary due to central pole resistance growth.

3. Physics issues

A cut view of the compact spherical tokamak FNS-ST is shown in Fig. 2 and its basic parameters are given in Table I. Although the size of the device is between START and MAST/NSTX sizes, extrapolation to much higher heating power density and higher toroidal field requires justification of applicability of the available modeling tools. Problems of the major concern are the plasma start-up, long pulse sustainment and exhaust. Additional issues are connected with stability, plasma facing components, fuel cycle and the device maintenance. Reduction in the Q-value down to 0.1 compared to the proposed CTF concepts

(~1) still leaves questions about possibility of reaching the required fusion power. In such small and high density device, the contribution of neutrons produced by the beam-plasma interaction is dominating, which leads to the need of a special analysis of fast ion losses including orbits losses, turbulence and losses in magnetic ripples.

Table 1. Basic parameters of FNS-ST.

R, m	**0.5**
R/a	**1.66**
k	**2.75**
δ	**0.5**
I_p, MA	**1.5**
B_t, T	**1.5**
n, 10^{20}m-3	**1 - 4**
P_{wall}, MW/m2	**0.2**
E_b, keV	**130**
P_b, MW	**10**
Angle NBI, deg	**30**
P_{EC}, MW	**5**
H-factor	**1-2**
β_N	**5**
$f_{non\text{-}ind}$	**1.0**
P_{diss}, TF, MW	**14**
P_{diss}, PF, MW	**3.5**
S_{wall}, m2	**13**
V_{pl}, m3	**2.5**

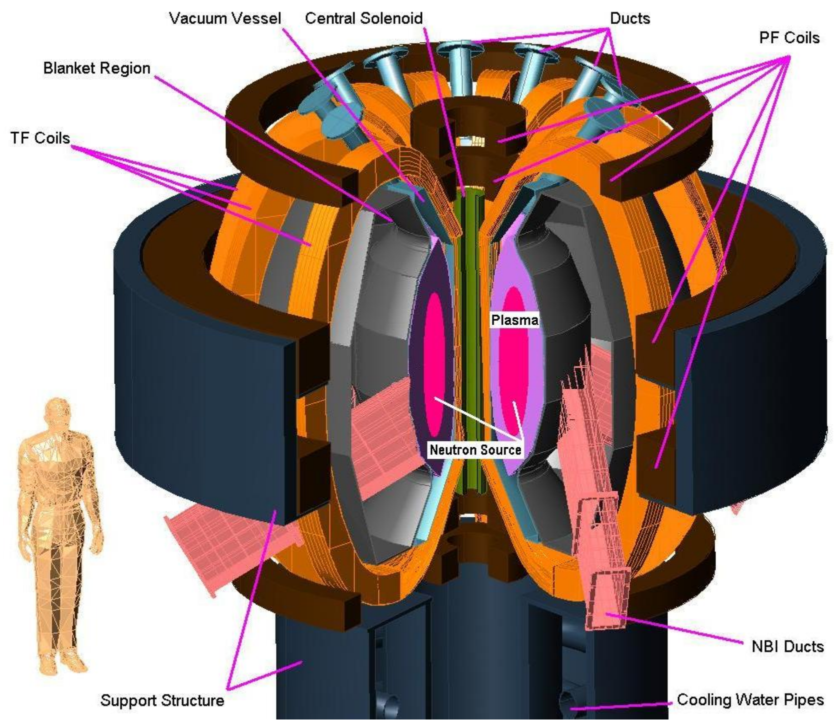

Fig. 2. Cut view of FNS-ST.

Evaluations using ASTRA, DINA codes and semi-analytic models [5,6] have shown that the performance is very sensitive to the confinement enhancement factor (H-factor) and the energy of the neutral beam injection. The performance significantly increases when *H*-factor grows from 1 to 2 and the beam energy E_b increases from 100 to 300 keV. Variations of the plasma current in the range of 1-3 MA as well as the heating power up to 15 MW have shown that the central electron temperature T_{e0} is 4-5 keV and the fusion power remains substantial between 0.5 MW and 1.5 MW. ASTRA simulations of the size effect on the plasma performance are presented in Table 2 for basic FNS-ST regime and MAST-U-size tokamak with the increased magnetic field up to 1.5 T. A small variation of neutron source rate for these two devices indicates that in the MAST-U-size case, the increase of fusion output due to higher confinement is compensated by the reduction of that due to lower power density and lower fast particle fraction. The latter is essential as the beam-plasma neutron production dominates in FNS-ST over the thermal D-T reaction.

MHD stability has been analyzed using SPIDER, DINA and KINX codes. Equilibrium magnetic configurations have been found for most extreme regimes of FNS-ST with currents up to 3 MA. Meanwhile, robust operation is expected at normalized currents $I_N = I/aB$ below 5 that corresponds to plasma currents less than 2.25 MA. A typical magnetic configuration is shown in Fig.3 for maximal current 3 MA. This configuration was used in our analysis of a vertical displacement event in the device. It was shown that passive copper elements in the vicinity of X-points (especially those placed at the inner part) reduce the values of instability growth rates below 100 s^{-1}. This allows operation using contemporary control systems.

Table 2. Comparison of FNS-ST and MAST-U-size device (ASTRA code data).

	R/a	<n> $10^{20} m^{-3}$	I MA	B T	Ebeam keV	Pbeam MW	Rbeam, m	k	δ
FNS-ST	0.5/0.3	1	1.5	1.5	130	6	0.6	2.75	0.5
MAST-U	0.8/0.5	1	1.5	1.5	130	8	0.9	2.75	0.5

	T_{e0}/T_{i0} keV	P_{input}/P_{tot} MW	I_{cd} MA	I_{bs} MA	H-factor	τ_E, ms	$l_i(3)$	W_{th}/W_{tot}	β_N	Source rate 10^{17} n/s
FNS-ST	4.7/7.9	3+3+1/6.5	1.1	0.5	1.3	43	0.42	0.58	4.9	5.2
MAST-U	4.4/5.5	4+4+1/6.8	0.4	1.1	1.9	151	0.44	0.86	4.3	4.5

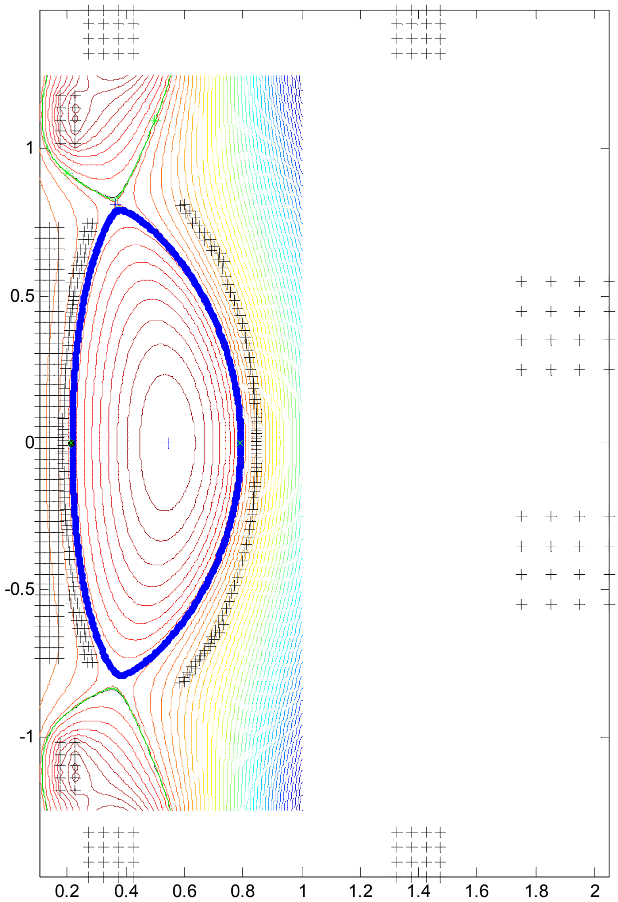

Fig. 3. *Equilibrium magnetic configuration at I=3 MA used for evaluations of the maximal values of magnetic coils power consumption and VDE growth rates.*

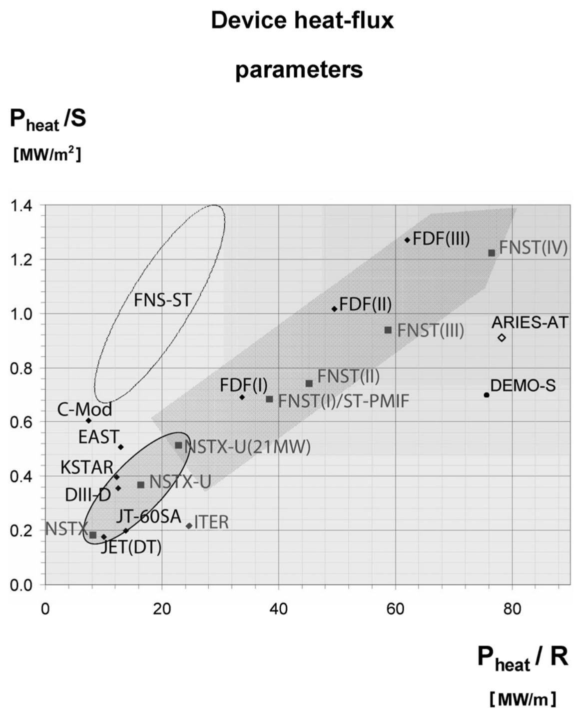

Fig. 4. Wall and divertor power loads of FNS-ST. Operation limits of FNS-ST are placed at the plot illustrating US fusion development program [7] and Russian DEMO-S.

Start-up is a challenge for any spherical tokamak. Inductive breakdown using small central solenoid (0.4 Wb) accompanied by ECR heating and CD has been simulated by DINA code. It was shown that it is a possible solution for reaching 1 MA plasma current. The further current ramp-up to 2-3 MA level is possible using NBI injection (CD and bootstrap overdrive).

The modeling shows that an off-axis NBI current drive together with the bootstrap current may be sufficient for steady state operations. The efficiency of the CD depends on the NBI injection angle. Simulations by DINA, ASTRA and NUBEAM codes have shown that injection at an optimal angle of 30-40 degrees increases the efficiency by a factor of 2 compared with the conventional equatorial injection. Since the CD-efficiency is very sensitive to the plasma density and temperature $\sim T_e/n_e$, low-density regimes with dominant CD and high-density regimes with dominant bootstrap fraction are both possible.

Parameters P_{heat}/S and P_{heat}/R determine the wall and divertor plate loads in a tokamak correspondingly. Here, P_{heat} is plasma heating power and S is first wall area. The FNS-ST operation limits are shown in Fig. 4 together with the data from Ref. [7] and the point illustrating Russian project DEMO-S. The level of the power load to the FNS-ST divertor is of the order of ITER values. Therefore, existing ITER technologies for divertor operation may be utilized. One of the important issues of the FNS-ST device is very high thermal wall load, exceeding that for ITER by factor of 6. This requires using the divertor target technology for the first wall as well. It should be noted that in the basic FNS-ST regime (Table 2) $P_{heat}/S \sim 0.6$ is close to Alcator C-Mod and DEMO-S values. Due to relatively low energy content, loads connected with ELMs or disruptions are not critical as they are comparable to the present levels at MAST and NSTX.

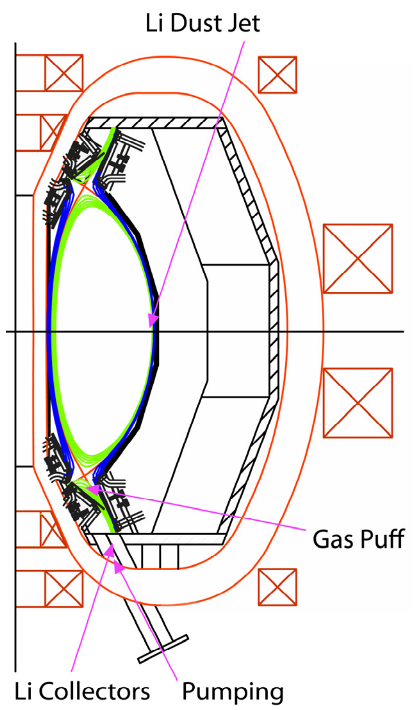

Fig. 5. Schematic of the FNS-ST divertor.

In the basic regime (Table 2) the evaluated upstream flux density of FNS-ST is 130-140 MW/m^2. It converts to the power density below 10 MW/m^2 at the strike point of the FNS-ST DN divertor target tilted at the angle less than 5 degree relatively to the poloidal magnetic field (Fig. 5). This was evaluated by the semi analytical hybrid model [6] verified on the

NSTX data [8, 9] closest to the considered FNS-ST regime. Power losses due to mantle, SOL radiations, fast particles were estimated to be less than 30% of P_{heat} and 5 mm SOL width in middle plane was used according to scaling proposed in [10,11].

A schematic of the FNS-ST divertor is shown in Fig.5. To control plasma-wall interaction the adjusted Li dust jet injection in the region of outer separatrix is foreseen together with a possibility to collect Li liquid wall coats [12]. Injection of gases (working and impurities) at the X point region is considered to approach partial detached conditions of the divertor operation as have been recently obtained in NSTX [8].

The analysis of the device neutronics has been performed using MCNP and IAEA fusion evaluated nuclear data library FENDL2.1. A schematic diagram of the used model is given in Fig.6. A specific feature of the spherical tokamak as a neutron source is that the copper central pole cannot be protected by a reflector or moderator because their thickness increases the tokamak aspect ratio. The modeling has shown that in the fast neutron spectrum with heavy moderators the fast neutron flux in the first wall region increases the effective neutron damage by a factor of 3. For a thermal neutron source combining Be multiplier and carbon reflector-moderator is perspective.

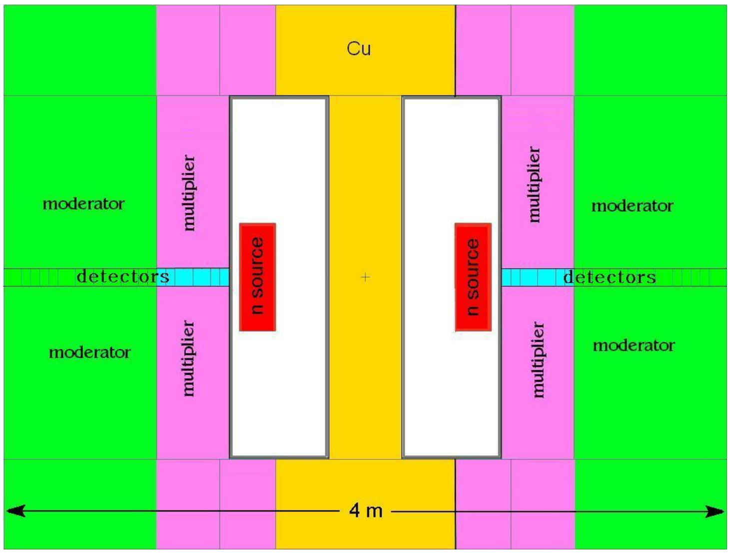

Fig. 6. Model configuration used in the FNS-ST neutronics analysis.

4. Conclusions

The presented pre-conceptual analysis indicates that the Compact Tokamak Fusion Neutron Source based on a small spherical tokamak may be possible. The MW range fusion reaction is feasible if contemporary transport scalings do not change greatly in regimes with low collisionality and no significant instabilities occur at high fast ion fraction. Improved confinement compared with the ITER scaling makes high density regimes with dominating bootstrap current possible. Those are preferable for divertor operation and have a reduced fast ion fraction. Solutions for the discharge initiation and current rump-up are possible using inductive, neutral beam and microwave techniques. The steady state operation at higher currents is easier reachable for a confinement scaling with a positive density dependence (like ITER one). The average heat loads on the first wall in FNS-ST are comparable with those of DEMO and divertor target loads are close to the ITER values, so it is possible to use the ITER divertor technology for the first wall and divertor targets of the FNS-ST. Neutronics of the FNS-ST is greatly affected by tokamak magnets, vacuum vessel and blanket. Thus further efforts are needed to optimise used materials and auxiliary heating sources.

Acknowledgments

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