CONFERENCE PRE-PRINT

NTST, A NEGATIVE TRIANGULARITY SPHERICAL TOKAMAK

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Abstract

NTST (Negative Triangularity Spherical Tokamak) is the world's first spherical tokamak with intrinsic negative triangularity under construction by Startorus Fusion. It is designed to explore the performance and application prospects of negative triangularity plasmas in fusion reactors. The device features a specially shaped central column, which resembles an hourglass, conforming to the shape of the NT plasma and freeing up space on the high-field side. Two pairs of PF (poloidal field) coils are positioned on the high-field-side, an unconventional arrangement for an ST (Spherical Tokamak) that enhances plasma control and mitigates engineering challenges associated with the central column. Based on these considerations, the magnetic design of NTST is implemented. The coil positions, the magnetic field null configuration, along with the discharge scenario, including breakdown and plasma phase for both NT (negative triangularity) and PT (positive triangularity) plasmas have been devised. By incorporating small additional in-vessel passive conductors, the VDE (Vertical Displacement Event) of NT plasma can be stabilized, and the high-field-side PF coils are proven to be the optimal choice for VDE control. Overall, the NTST device demonstrates its suitability for NT operations.

1. MOTIVATION

In recent experiments on TCV and DIII-D, it is found that plasmas with negative triangularity (NT, $\delta<0$) have better confinement properties compared with conventional positive triangularity (PT, $\delta>0$) plasmas, it is stated that NT L-mode is comparable to PT H-mode, meanwhile avoiding the problems of H-mode, e.g. ELM [Austin 2019]. This discovery arouses massive interest among fusion research community in recent years. At the same time, spherical tokamak (ST) has been believed to be a promising way toward fusion energy, for its compactness, higher beta and lower cost compared with conventional tokamaks. TCV and DIII-D are conventional tokamaks, they have access to H-mode while most STs don't for lack of heating power. Apart from physical consideration, ST with NT divertor configuration also shows attractive engineering advantage, especially for divertor heating load. In NT configuration, the strike points are shifted outward, this would significantly relieve the divertor load and make maintenance easier. One may naturally think: what if we combine NT and ST, will such device exhibit higher performance than any former devices of both kinds? Would it be a competitive candidate for future commercial fusion powerplant?

Such an attempt was not carried out till now for the following reasons. Firstly, early theoretical and experimental research have shown that NT plasma has poorer MHD and VDE stability properties, for NT plasma has shallower magnetic well and lower average magnetic field compared with PT. NT plasma magnetic lines have longer bad curvature portion, the strong ballooning mode located there places a serious restrictions on NT beta limit; NT plasma is more strongly shaped by PF's field, resulting in a lower decay index and thus higher Z displacement growth rate, i.e. bad VDE controllability. So, NT was not a mainstream configuration in tokamak researches. Fortunately, these problems have been relieved by recent progresses in profile tuning [Medvedev2015] and feedback control techniques, making NT a feasible option. Secondly, ST both benefits and suffers from its compactness, the narrow space of central column is packed with solenoid and TF coils, defying the installation of high-field-side PF coils, which are essential for good NT shaping and VDE control. Specific designs may be needed for a ST oriented for NT operation.

2. PHYSICAL AND ENGINEERING DESIGNS

The main objective of NTST device is to explore the combination of ideas of negative triangularity configuration and spherical tokamak, to test whether the advantages of both ideas would sum up, resulting in a compact device with high confinement performance, low cost and easy maintenance. The main parameters of NTST are: major radius (R_0), 0.87 m; minor radius (a), 0.56 m; maximum on-axis toroidal field (B_{T0}), 1.0 T; nominal plasma current

(I_P), 1300 kA; maximum elongation (κ), 2.0; triangularities (δ), -0.8 – 0.6. The wall of the vacuum vessel is made of Inconel 625 stainless steel, thickness = 2 mm on high-field-side, 6 mm on low-field-side. The magnetic field penetration time is 0.5 ms from high-field-side, 5.5ms from low-field side. This means plasma would respond faster to high-field-side coils. Additional reinforcing ribs are attached to the wall. The configuration of poloidal coils is shown in *FIG. 1* left. The engineering design of NTST is shown in *FIG. 1* right. There is a larger cryostat containing the whole vessel and coils, not drawn in the picture.

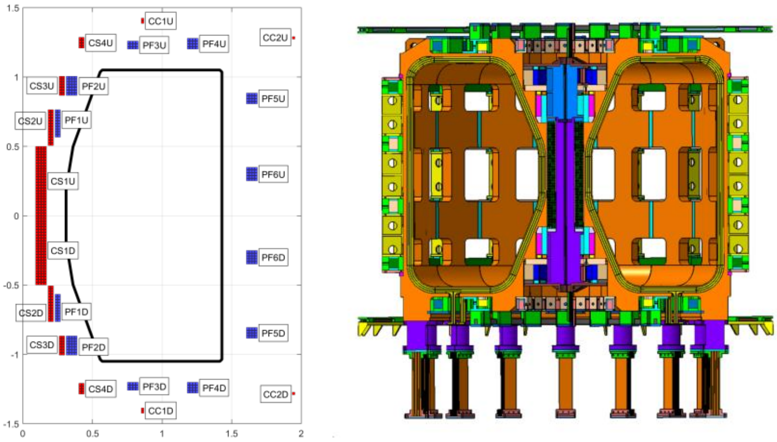

FIG. 1 The poloidal cross-section of NTST (left), the engineering design of NTST (right)

Two example diverted configurations with 1000 kA plasma current are shown in *FIG. 2*, one is NT (δ = -0.8), another is PT (δ = +0.6). Overall properties are kept same: $R_0 = 0.77$ m, a = 0.4 m, A = 1.9, κ = 2.1, $\beta_p = 0.4$, $l_i = 1.3$, $q_0 = 1.05$, while q_{95} differs: NT is $q_{95} = 3.3$, PT is $q_{95} = 4.4$. This comes from the obvious fact that NT bulk plasma locates further outside than PT, resulting in weaker mean B_T. We can see that the PT one has a less average coil current, because this is a more natural shape for ST since ST plasma tends to be elongated and PT-shaped. We will have to spend more effort to shape the plasma into NT, and such deviation from natural shape shall cause stronger instabilities, as is well known.

We can clearly see the difference in divertor strike points' radius and area, the idea of enlarging strike area by NT is verified. Owing to the proper locations of PF3,4,5 coils, a snowflake divertor readily forms in NT configuration, making the strike area even larger.

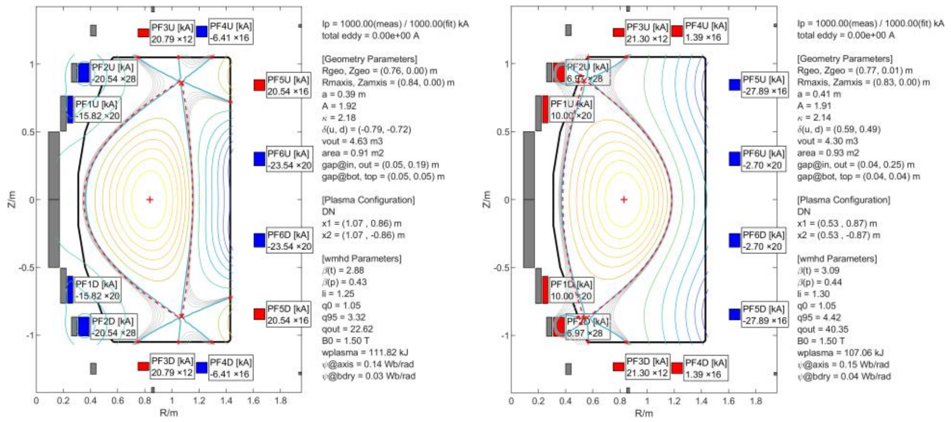

FIG. 2 The NT (left) and PT (right) configurations of NTST

3. SOME BENEFITS FROM NT CONFIGURATION

Compared to conventional tokamaks, spherical tokamaks achieve significantly improved plasma confinement by compressing the central column of the toroidal plasma, thereby maximizing the fraction of plasma residing in the high-confinement region. However, this compression results in an extremely compact central region characterized by intense magnetic fields, high current densities, and a high concentration of electrical feedthroughs, busbars, and joints. These conditions pose severe engineering challenges, and indeed, many operational failures in existing STs have occurred in this critical area.

In contrast, negative-triangularity ST configurations allow the central column to expand from a slender cylindrical shape into a more spacious hourglass geometry. This expansion substantially increases the available volume, markedly reduces current density, and greatly simplifies the routing and installation of electrical connections and support structures. Consequently, the primary engineering limitation of conventional (positive-triangularity) STs is nearly eliminated.

FIG. 3 compares the central regions of a positive-triangularity ST and a negative-triangularity ST. In the positive-triangularity case, conductors, cooling lines, and mechanical supports are densely packed, resulting in an extremely congested and harsh operational environment that is difficult to access and maintain. By contrast, the negative-triangularity configuration offers significantly greater design flexibility and engineering accessibility, alleviating many of the constraints that have historically hindered ST development.

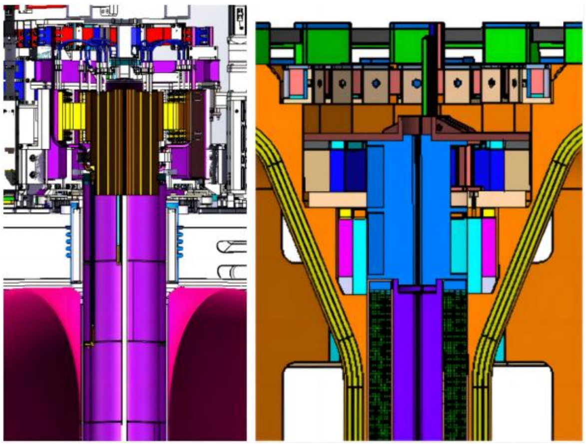

FIG. 3 The central region of a positive triangularity ST (left) and a negative triangularity ST (right)

An additional, previously unanticipated advantage of negative triangularity in spherical tokamaks lies in the substantial reduction of the electromagnetic energy burden on the central solenoid power supply. In conventional positive-triangularity configurations, the plasma cross-section is vertically elongated with a convex outward shape, requiring the magnetic flux from a straight, cylindrical central solenoid to be strongly "pinched" or bent into a near-vertical orientation to effectively link the entire plasma volume. This geometric mismatch between the solenoid's intrinsic field topology and the required flux linkage path results in significant magnetic energy storage—much of which does not contribute efficiently to plasma current drive but instead represents parasitic inductance that must be supplied and managed by the power system.

In contrast, the hourglass-shaped plasma cross-section characteristic of negative-triangularity configurations aligns more naturally with the magnetic field geometry produced by a correspondingly shaped (i.e., tapered or hourglass-like) central solenoid. This improved topological compatibility allows the magnetic flux to link the plasma with minimal distortion, eliminating the need for excessive field bending. As a result, the total magnetic energy stored in the solenoid for a given amount of coupled flux is dramatically reduced, thereby alleviating the demands on the power supply in terms of both peak current and total volt-second budget.

As illustrated in *FIG. 4*, when coupling nearly identical poloidal flux to the plasma, the conventional cylindrical solenoid required for a positive-triangularity discharge stores approximately 818 kJ of magnetic energy. By comparison, the optimized hourglass-shaped solenoid used for the negative-triangularity configuration stores only 263 kJ—a reduction of over 67%. This substantial decrease not only lowers the capital cost and complexity of the power supply system but also enhances operational flexibility and reliability, particularly in long-pulse or repetitive-pulse scenarios where solenoid volt-second consumption is a critical constraint. Thus, negative triangularity offers not only improved engineering accessibility in the central column but also a fundamental energetic advantage in solenoid design and operation.

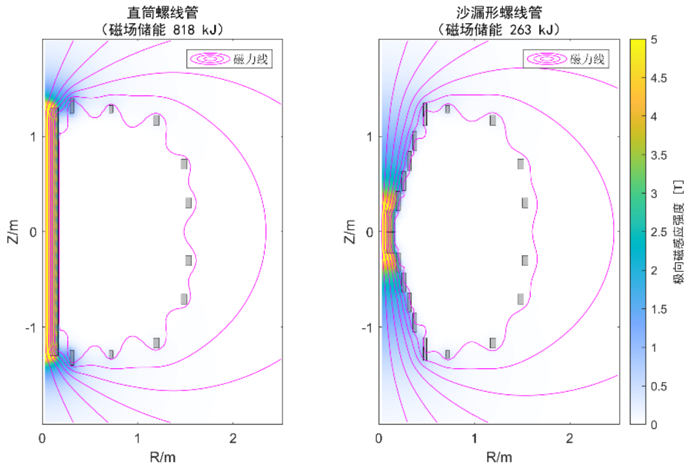

FIG. 4 The poloidal magnetic field of a positive triangularity ST (left) and a negative triangularity ST (right)

4. SUMMARY

NTST (Negative Triangularity Spherical Tokamak), under development by Startorus Fusion, is the first spherical tokamak designed specifically for intrinsic negative triangularity ($\delta \approx -0.8$). It may integrates the high-beta, compact advantages of spherical tokamaks with the ELM-free, high-confinement potential of negative-triangularity plasmas. Its hourglass-shaped central column alleviates the severe engineering constraints of conventional STs by expanding central space, lowering current density, and simplifying coil and service routing. High-field-side poloidal field coils enable robust plasma shaping and vertical stability control. Notably, the compatible solenoid geometry reduces magnetic energy storage by 67% (263 kJ vs. 818 kJ) for equivalent flux coupling, easing power supply requirements. The NT divertor naturally spreads heat load, with a snowflake configuration readily accessible. With $R_0 = 0.87$ m, $I_p = 1.3$ MA, and $B_t = 1.0$ T, NTST offers a compelling path toward a compact, maintainable, and high-performance fusion reactor.

ACKNOWLEDGEMENTS

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