Perspective of Negative Triangularity Tokamak as Fusion Energy System

M. Kikuchi[1], S. Medvedev[5], T. Takizuka[6], A. Fasoli[2], Y.Wu[3], P. Diamond[4], X. Duan[7], Y. Kishimoto[8], K. Hanada[9], L. Villard[2], O. Sauter[2], S. Coda[2], B. Duval[2], H. Reimerdes[2], S. Brunner[2], G. Merlo[2], J. Jiang[3], M. Wang[3], M. Ni[3], D. Chen[3], H. Du[3], W. Duan[3], Y Hou[3], A. Ivanov[5], A. Martynov[5], Y. Poshekhonov[5], Y. Ueda[6], L. Yan[7], X. Song[7], G. Zheng[7], J. Liu[7], K. Nagasaki[8], K. Imadera[8], K. Mishra[9], A. Fujisawa[9], K. Nakamura[9], H. Zushi[9], M.J. Pueschel[10], X. Xu[11], P. Zhu[12], D. Told[13], G.Q. Li[14], M. Furukawa[15], T. Ozeki[1], K. Shimizu[1], K. Kawashima[1], H. Urano[1], M. Honda[1], T. Ando[16], M. Kuriyama[16]

[1]*JAEA, Japan*, [2]*CRPP−EPFL, Swiss*, [3]*INEST, China*, [4]*UCSD, US*, [5]*KIAM, Russia*, [6]*Osaka U., Japan*, [7]*SWIP, China*, [8]*Kyoto U., Japan*, [9]*Kyushu U., Japan*, [10]*U.Wisconsin, USA*, [11]*LLNL, US*, [12]*USTC, China*, [13]*UCLA, US*, [14]*ASIPP, China*, [15]*Tottori U., Japan*, [16]*JAEA Retired*

Introduction

Power and particle control in fusion reactor is quite a challenge and we have studied the negative triangularity tokamak (NTT) as an innovative concept to reduce the transient ELM heat load and the quasi steady-state heat load[1], [2], [3]. A double-null NTT is stable to ideal MHD modes for a reactor relevant $\beta_N > 3$ while it is a magnetic hill configuration[4]. In this paper, we report the configuration study of single-null NTT and its ideal MHD stability.

Lessons from Fusion Reactor Studies and Experiments

High performance magnetic confinement experiments are limited to short pulse. Fig. 1 a) shows the database of fusion triple product $nT\tau$ v.s duration for existing experiments and the objective regime of ITER and DEMO; the $nT\tau$ is within an order of magnitude while the sustainment time is seven order far from our achievements. The expected steady state heat load is also quite higher compared with existing power sources such as fossil power plants and fission power stations as shown in Figure 1 b). The transient heat load becomes as large as $\sim 1 GW/m^2$.

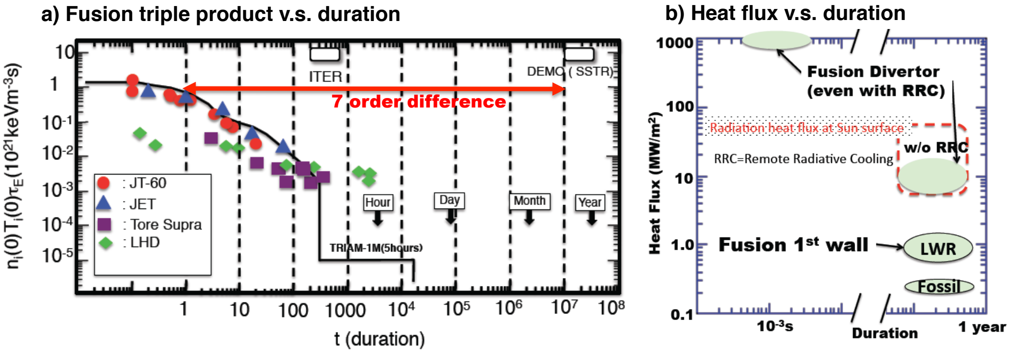


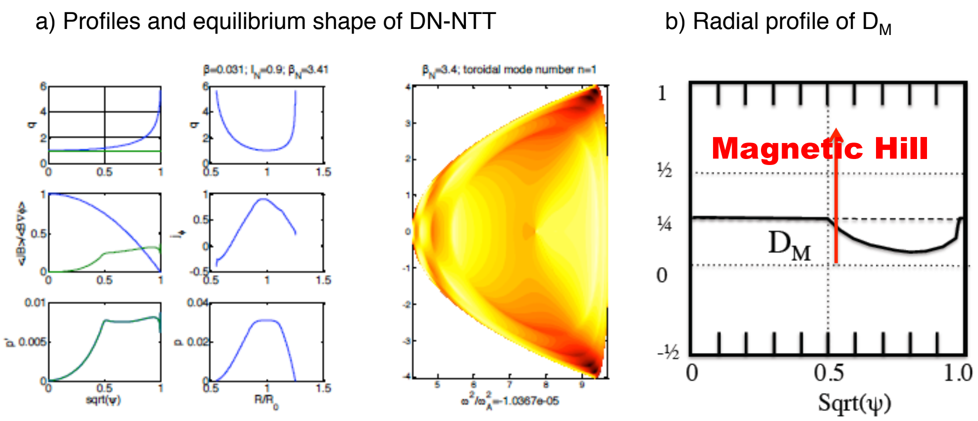
Figure 1: a) Fusion triple product v.s. duration [5]. b) Heat flux v.s. duration for fusion, fossil and fission (LWR) [3]. Fusion has huge transient heat loads by ELM and disruption besides steady heat load.

Power Handling the First for Fusion Reactor Design

Present-day standard tokamak operation mode is a H-mode operation with strongly D shaped tokamak to improve core confinement, i.e. "Core the First"- design. ELM strength is enhanced with high edge pedestal in strongly D-shaped plasma associated with high edge bootstrap current and 2nd stability access [6]. Power e-folding length becomes very narrow due to the reduced perpendicular transport in the H-mode edge leading to significantly higher peak heat load at the divertor plate [7]. These issues are associated with this standard tokamak operation mode. If we think the power handling is so critical for the realization of fusion power plant, it may be reasonable to take the design philosophy "Power Handling the First".

Negative Triangularity Tokamak

NTT is attractive for the power handling because of its divertor location at the outboard side, which can decrease the heat load without increasing the tokamak major radius, and relevant for the "Power Handling the First" design philosophy. As for the confinement performance, suppression of trapped electron modes (TEM) in the NTT configuration has been observed in TCV[8], which gives a possibility to apply NTT to the future reactor. On the other hand, NTT looses magnetic well property to stabilize interchange instabilities ($D_M - \frac{1}{4} < 0$ is the stability condition and $D_M > 0$ is magnetic hill). Therefore shear stabilization is expected in NTT. We started our assessment on NTT with the double-null (DN) configuration where the strong shear is realized at the edge region. The result shown in Fig.2 was given by Medvedev et al. in FEC 2014 and published in Ref. [4]. Key optimization is to reduce pressure gradient near the core region ($\sqrt{\psi/\psi_s} < 0.5$) to be marginally stable against Mercier mode ($D_M = \frac{1}{4}$) expecting kinetic stabilization[9], while the limiting pressure gradient is determined by ballooning modes and is further lower than marginal stability against Mercier stability at outer half region ($\sqrt{\psi/\psi_s} >$ 0.5). The stability calculations with the KINX code [10] imply the NTT can be stable at the reactor relevant normalized beta $\beta_N > 3$.



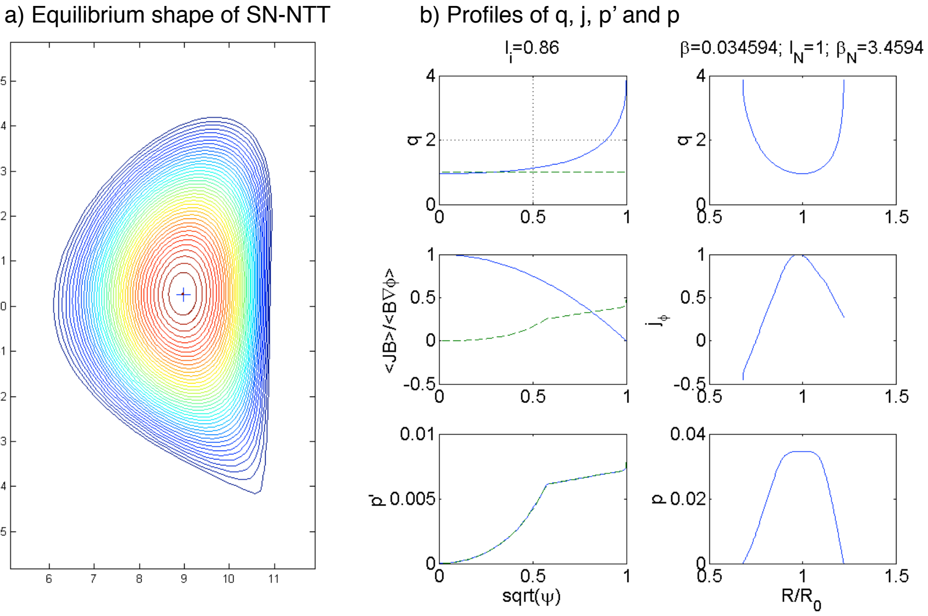
a) Profiles and equilibrium shape of DN-NTT

b) Radial profile of D_M

Figure 2: a) $q, j, p' and p$ profiles of DN-NTT [4]. b) Radial profile of D_M [4].

Single Null Negative Triangularity Tokamak

While ideal stability of DN-NTT is reasonably good, DN is subject to very careful control of vertical position to equalize heat flux sharing between upper and lower divertors [11]. We have evaluated the stability of single-null (SN) NTT. Figure 3 shows plasma shape for stability calculation and optimized profiles for interchange and kink/ballooning modes. The machine parameters are major radius $R_p = 8.6m$, aspect ratio $A = (R_p/a_p) = 3.5, \kappa = 1.75$, $\delta_u/\delta_x = -0.5/-0.9$, $I_p = 15MA$, $I_N = 1.0(\beta_N = 3.46)$. Stability calculation shows this configuration is stable to $\beta_N = 2.70(n=1), 3.05(n=2), 3.18(n=3), 3.24(n=4), 3.26(n=5)$ and $3.45(n=\infty)$ without wall stabilization. If we place wall at $a_w/a = 1.3$ similar to ITER, we have improved stability $\beta_N(n=1) = 3.11$. The axisymmetric (vertical instability) growth rate is several times larger than for ITER, $\gamma = 24s^{-1}$ but still within the limit $\gamma < 50s^{-1}$ of the active vertical stability control system.


a) Equilibrium shape of SN-NTT

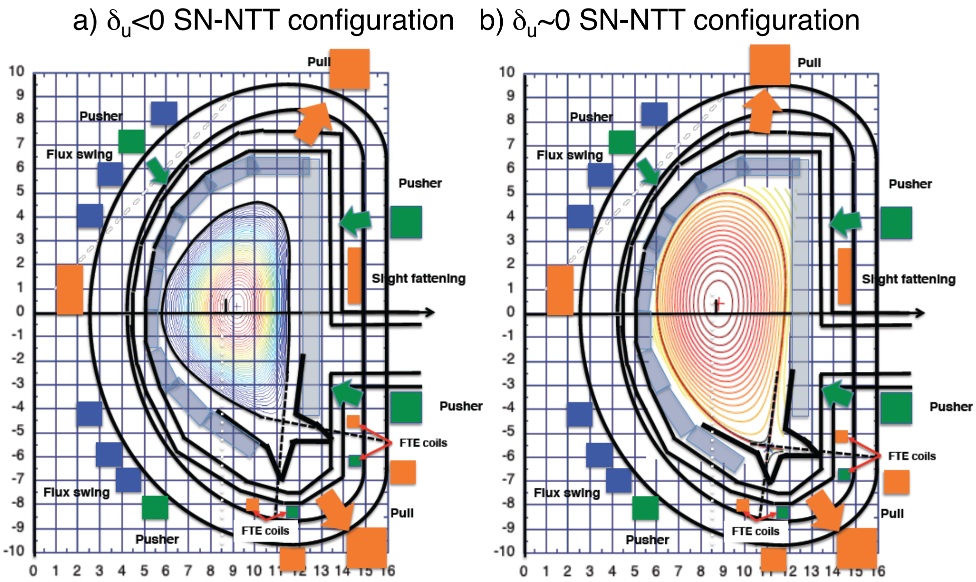
b) Profiles of q, j, p' and p

Figure 3: a) Equilibrium shape of SN-NTT. b) q, j, p' and p profiles of SN-NTT.

Divertor Configuration of SN-NTT

For the "Power Handling the First" philosophy, $\delta_x = -0.9$ may enable the use of advanced divertor concepts. The Snowflake [12] is one of candidates. Recently Takizuka [13] proposed a new and robust method to reduce heat load to the divertor target called the **Flux-Tube-Expansion** (FTE) by combining long leg and flux tube expansion. The key advantage of FTE divertor is that the divertor leg position can be robust against various plasma perturbations with three sets of divertor control coils. Another more important advantage is that internal coils for flux tube expansion (shown in FTE coils in Fig.4) can be small (each coil carries $\sim 4MAT$) to achieve flux tube expansion of $B_p^0/B_p^{FTE} \sim 3$ which may be realized by using the sector coils.

We may need non-pure tension shape TF coils if we want to eliminate the interlinked PF coils to produce strongly negative upper triangularity δ_u as shown in Fig. 4 a). Since we expect the stabilization of TEM via Shafranov shift [14], the optimization of upper triangularity depends on improved confinement with Shafranov shift for TEM by operating high β_p regime relevant for efficient steady state operation. This is for the future study.


a) δ_u<0 SN-NTT configuration

b) δ_u~0 SN-NTT configuration

Figure 4: a) $\delta_u = -0.5$, $\delta_x = -0.9$ SN-NTT configuration with flux tube expansion divertor. b) $\delta_u \sim 0$, $\delta_x = -0.9$ SN-NTT configuration with flux tube expansion divertor.

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