Physical Design and Performance Prediction of the STOR-U Spherical Tokamak

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Abstract

STOR-U (R_0 = 55 cm, A = 1.7, I_p = 2 MA) is a spherical tokamak recently proposed to study high beta plasma physics and engineering. In this paper, physical design and performance prediction of the STOR-U are presented. Various equilibria have been obtained to meet different discharge requirements. Eigenvalue expansion technique was employed to optimize the poloidal field system for current start-up with careful consideration given to eddy current effects in the vacuum chamber. Performance prediction is made using ASTRA code. Simulation results reveal that ion temperature increases significantly in NBI heated discharge. Different NBI configurations are also studied.

1. Introduction

It is widely recognized that fusion energy, as a leading candidate of energy source for the future, might be an ultimate solution to the energy crisis the mankind is facing today. The goal of the ITER (International Thermonuclear Experimental Reactor) project is to demonstrate a cleaner way to produce electricity in a large scale via fusion energy [1]. ITER has a conventional tokamak configuration (R_0/a = 6.2/2.0 m, I_p =15 MA and B_t = 5.3 T). Paralleling to the ITER, research on innovative confinement concepts and new device configurations are undertaking for a more cost effective way to harness fusion energy. For a future fusion reactor, a crucial parameter is plasma β $(= 2\mu_0\langle P\rangle/B_t^2)$, where $\langle P\rangle$ is the volume-averaged pressure and B_t is the toroidal filed at the geometric axis. Higher β value indicates better confinement and higher fusion power density. When the tokamak aspect ratio $A \leq 2$, a conventional tokamak transforms to a spherical tokamak, the ST, characterized by a smaller space existing in between the central solenoid and toroidal vacuum chamber. Such a change in geometry will induce profound changes in plasma behavior, including (1) higher β, up to several tens of percent, (2) high stability against MHD instability, (3) large bootstrap current fraction, which is crucial for steady-state operation, (4) compact size and lower toroidal magnetic field required, leading to reduced capital cost. The concept of ST as an attractive pathway for fusion energy development was proposed in 1990 [2] and tested in the START device [3]. In the past two decades, experimental efforts worldwide on several STs, e.g. MAST and NSTX have experimentally demonstrated higher β value in ST configurations, e.g. 35% of β in NSTX, than the conventional tokamaks ($A \geq 2.5$) [4]. In addition, similar plasma confinement and transport characteristics with conventional tokamak are found in recent experiments in MAST and NSTX [5, 6].

In the Plasma Physics Laboratory at the University of Saskatchewan, a small tokamak, STOR-M, has been in operation for more than 22 years. It is a conventional tokamak with R_0/a = 46/12 cm and the aspect ratio A = 3.8. Many important issues on fusion plasma research have been explored on the STOR-M [7]. In order to study high β plasmas we propose a new fusion experimental facility - the Saskatchewan TORus Upgrade (**STOR-U**) tokamak. The STOR-U will be a mid-sized spherical tokamak and its design parameters are shown in Table 1 in comparison with the STOR-M and the current leading ST experimental device - NSTX [8]. The main goals of STOR-U are to study (1) high β plasma confinement and transport, (2) ST plasma shaping and position control, (3) advanced tokamak fuelling by compact torus injection (CTI), (4) innovative ST plasma start-up technique using helicity injection (HI) and (5) development of state-of-art plasma diagnostics for comprehensive plasma parameter measurements with high spacial and temporal resolution.

		STOR-U	NSTX	STOR-M
Plasma	Major radius (R_0)	55 cm	85.4 cm	46 cm
	Aspect ratio (R_0/a)	1.7	1.25	3.8
	Elongation (k)	≤ 3.0	1.3 - 2.1	1
	Trianguliarity (Δ)	≤ 0.5	0.2 - 0.6	
	Current (I_p)	2.0 MA	1.0 MA	50 kA
	Ramp time	0.5 – 1 s	0.2 - 0.4 s	5-10 ms
	Flat top (inductive)	0.5 s	0.5 s	30 ms
	Flat top (non-inductive)	0.5 s	5 s	N/A
Toroidal filed	Field at major radius	1.5 T	0.3/0.6 T	0.7 T
Ohmic heating	Flux (double swing)	2 × 1.2 V·s	2 × 0.3 V·s	0.1 V·s
	Initiation loop voltage	10 V	5 V/ turn	15 V
NBI Heating	Neutral beam injection	2×1.5 MW, 30 keV,0.5 s	5.0 MW, 80 keV, 5 s	N/A
Bakeout	Temperature	150°C VV	150°C VV 350°C PFCs	N/A

Table 1 Summary of STOR-U engineering requirements compared with the NSTX and the STOR-M.

STOR-U will be equipped with a NBI heating system to heat the plasma and provide a routine way to access high confinement mode (H-mode) discharges. Prediction of STOR-U plasma behaviour with NBI and Ohmic heating will be of great importance to make the design work more robust and successful. In this paper we report the results of STOR-U design and performance prediction including plasma equilibrium calculation, current start-up analysis and transport simulation.

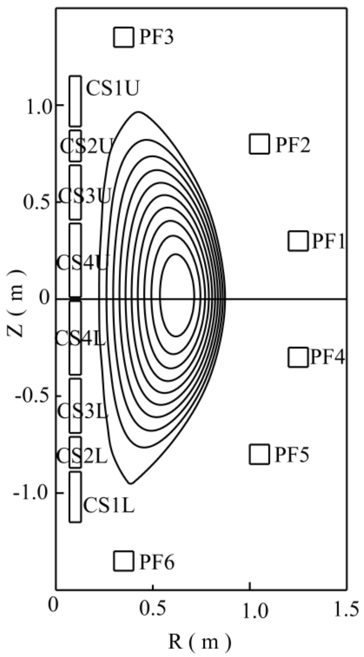
The paper is organized as follows. A brief STOR-U design overview is given in Section 2 including design requirements, machine and plasma discharge parameters and description of toroidal filed (TF), poloidal field (PF) systems and vacuum vessel. In Section 3 results of plasma equilibrium calculation are presented using a 2-D free boundary toroidal plasma equilibrium code, TEQ [9]. For plasma initiation and current ramp-up the poloidal field (PF) system is optimized to meet the requirements of sufficient loop voltage and null field region. The STOR-U plasma performance prediction has been carried out using a 1.5-D tokamak transport code – ASTRA [10]. Effects of NBI heating are addressed and different injection configurations are examined. The simulation results are presented in Section 5, followed by a brief summary in Section 6.

2. STOR-U design overview

The proposed STOR-U is a spherical tokamak aiming at exploring high β plasma physics and engineering to advance fusion science and technology in Canada. The criteria of determination of STOR-U machine and plasma discharge parameters are based on (1) the present theoretical and experimental research progress on ST plasma, (2) reasonable capital cost, (3) some important research topics requiring further development and experiment originated from the STOR-M, e.g. advanced tokamak fuelling technique by repetitive compact torus injection.

The STOR-U machine consists of toroidal field (TF), poloidal system (PF) system and vacuum vessel (VV). The toroidal system generates the main confinement magnetic field of 1.5 Tesla. It consists of 16 coils with 4 turns in each coil. Total stored energy in the TF system is 11.7 MJ. TF field ripple, defined as $\delta B/\langle B\rangle = (B_{max} - B_{min})/(B_{max} + B_{min})$, is about 0.5% at the plasma edge region (a = 32 cm), which is acceptable for the TF design.

PF system drives plasma current and provides plasma equilibrium. The system consists of 7 pairs of coils with up-down geometrical symmetry as indicated in Table 2. The inner 4 pairs of coils form the central solenoid – ohmic heating (OH) coil, which initiates plasma current and provides ohmic heating. The outer 3 pairs of coils (marked with PF1-6) are external equilibrium coils. The STOR-U PF system is capable of shaping the plasma to achieve maximum elongation k = 3.0 and trianguliarity Δ = 0.5.



Coil#	R(m)	Z(m)	Width(m)	Height(m)	Nz × Nr
PF1	1.250	0.300	0.100	0.100	5 × 5
PF2	1.050	0.800	0.100	0.100	5 × 5
PF3	0.250	1.250	0.100	0.100	5 × 5
CS1U	0.100	1.020	0.060	0.260	13 × 3
CS2U	0.100	0.790	0.060	0.160	8 × 3
CS3U	0.100	0.550	0.060	0.280	14 × 3
CS4U	0.100	0.200	0.060	0.380	19 × 3
PF4	1.250	-0.300	0.100	0.100	5 × 5
PF5	1.050	-0.800	0.100	0.100	5 × 5
PF6	0.250	-1.250	0.100	0.100	5 × 5
CS1L	0.100	-1.020	0.060	0.260	13 × 3
CS2L	0.100	-0.790	0.060	0.160	8 × 3
CS3L	0.100	-0.550	0.060	0.280	14 × 3
CS4L	0.100	-0.200	0.060	0.380	19 × 3

Table 2 STOR-U PF coil parameters.

The vacuum vessel is made of stainless steel of a thickness of 10 mm. Ports of various sizes are designed for pumping, NBI heating, CT injection, helicity injection and diagnostics access purposes. Figure 1 illustrates the STOR-U TF/PF system and vacuum vessel.

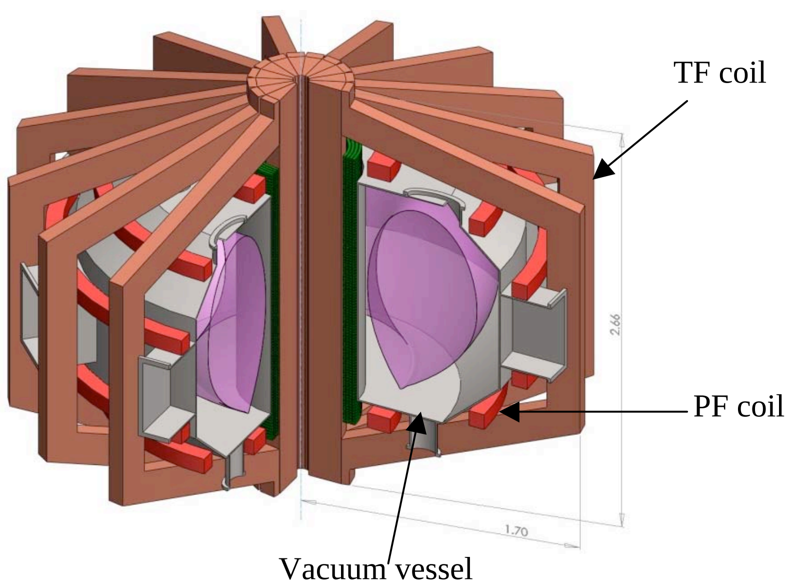


Figure 1 3D cut-away view show ' systems anc essel.

3. STOR-U plasma equilibrium

A 2-D, free boundary tokamak equilibrium code, TEQ was used in the equilibrium calculation. The code solves the Grad-Shafranov equation for the poloidal flux function in cylindrical coordinates on a rectangular mesh, (*R*, *Z*). Equilibrium magnetic flux surfaces are calculated through iterations by solving the PF coil currents to meet prescribed constrains by a least square fitting method. In order to minimize the total number of power supplies for the entire PF system, the inner four pairs of central solenoid coils (CS1L/U, CS2L/U, CS3L/U and CS4L/U) are designed to be connected in series and share the same power supply for each pair. Therefore, the total number of PS is reduced to ten. Such an arrangement is capable of producing various plasma equilibria to fulfil different plasma shaping requirements.

Both the single null diverted (SND) and double null diverted (DND) plasma equilibrium configurations have been obtained in STOR-U. Figure 2 shows equilibrium magnetic flux surfaces in both SND and DND configurations with the maximum plasma shaping parameters $k = 3.0$ and $\Delta = 0.5$. The input constrains for the equilibrium in SND, see Figure 2(a), are: $l_i = 0.5$ and poloidal beta $\beta_p = 0.9$. In Figure 2(b), $\beta_p = 1.0$. The corresponding plasma safety factor $q(r)$ and toroidal current density profile $j_\phi(r)$ for the DND configuration are presented in Figure 3. It can be seen that the *q* at edge $q(a)$ is about 10 and j_ϕ peaks at the centre.

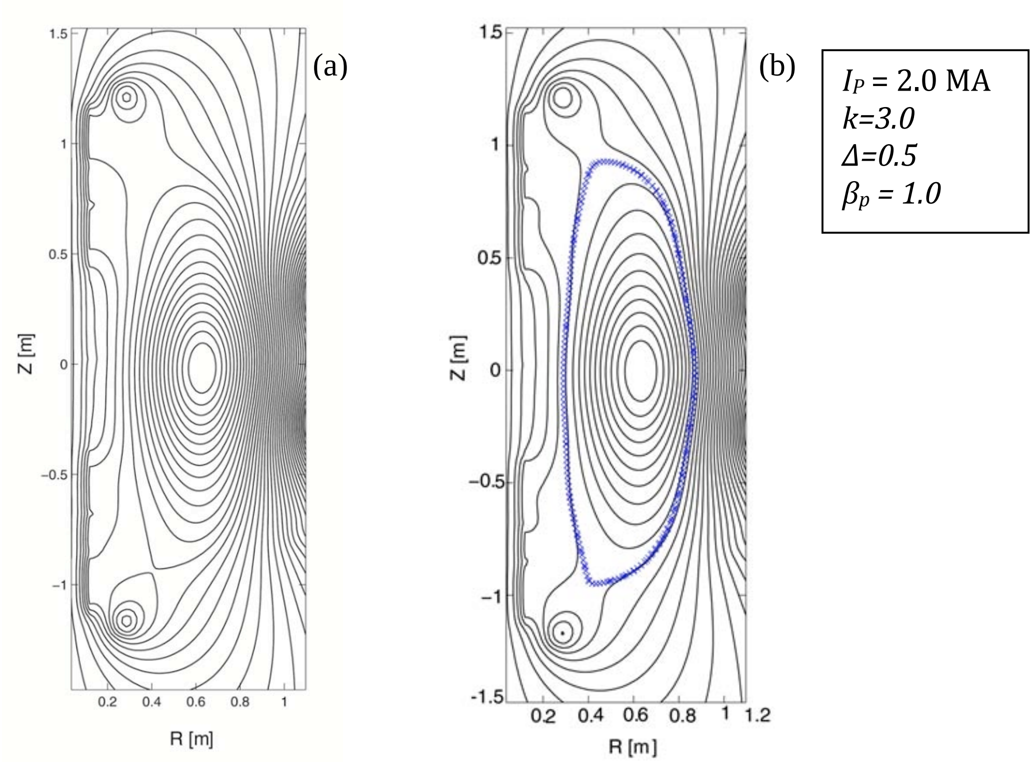


Figure 2 (a) SND configuration: $I_p = 2.0$ MA, $k = 3.0$, $\Delta = 0.5$ and $\beta_p = 0.9$, (b) DND configuration: $I_p = 2.0$ MA, $k = 3.0$, $\Delta = 0.5$ and $\beta_p = 1.0$. Line with markers shows the last closed flux surface (LCFS) in the DND configuration.

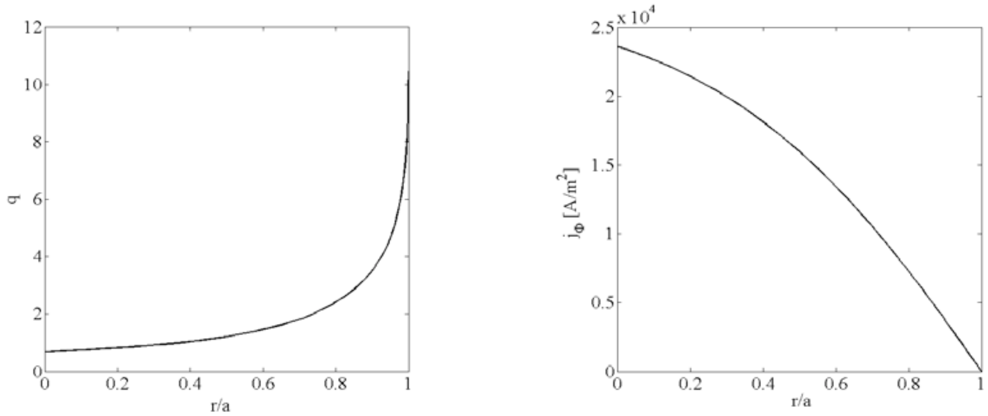


Figure 3 Radial profiles of safety factor q and toroidal current density j_Φ for the DND configuration.

4. Plasma initiation and current start-up

In STOR-U conventional inductive scheme is utilized for plasma initiation and current ramp-up due to its technologically simple and cost effective nature. The plasma breakdown is caused by the toroidal electric field induced by the central Ohmic solenoid. The applied toroidal electric field initiates a classical Townsend avalanche. The primary loss mechanism is direct loss along magnetic field lines at the beginning of the avalanche. An important parameter for plasma breakdown is the toroidal connection length L, expressed approximately as $L \approx aB_t/B_\perp$, where a is the length scale of the breakdown region and $B_\perp$ is the stray field. In the inductive scheme, the undesirable transverse stray field $B_\perp$ should be kept at a low level inside the plasma breakdown region because the magnetic flux loss due to the stray field is crucial in the initial start-up phase during which closed magnetic flux surfaces are not formed yet. For a specific working gas, the L determines the minimum electric filed required for a reliable plasma breakdown. In general, the initial magnetic configuration should be adjusted to contain the null point where the poloidal magnetic field is set to be zero to obtain a large connection length.

Due to the toroidally continuous nature of the STOR-U vacuum chamber eddy currents will be inevitably induced in the chamber wall and thus enhance the stray filed and hinder reliable plasma breakdown. Even worse, the time-dependent vertical field produced by pre-programmed PF coil currents required for the current ramp-up will be interfered and the predicted current ramp-up rate would not be achieved. To eliminate the adverse effects of eddy currents the STOR-U PF system has been optimized to achieve sufficient null field region and loop voltage for reliable plasma breakdown and current start-up. Eddy current effects have been considered in the optimization process using eigenvalue expansion technique [11]. Eddy current filaments were solved and the currents in outer 3 pairs of PF coils are optimized using least square fitting technique under constrains of (1) a loop voltage of 10 volts, (2) null field at the breakdown point and 32 prescribed points, which represent the breakdown region, and (3) $dB_Z/dR = 0$ at the breakdown point. In this study the breakdown point was assigned at chamber center (R = 55, Z = 0 cm) and the prescribed breakdown region is a circle with a radius of 16 cm. Total 32 points, as fitting points, are evenly spaced along the circumstance. For the plasma breakdown $B_z = 0$ at all the 33 points and B_z is set to be the required vertical field in the later current ramp-up phase. In this study, 20 ms prior to plasma breakdown and 30 ms of current ramp-up are calculated with a time step of 1ms. In the breakdown phase, there is no plasma current; in the ramp-up phase, the current is set as increasing with a linear ramp-up rate of 2 MA/s.

The results for stray field contour in breakdown phase are shown in Figure 4. Three time sequences at *t* = -20, -10 and 0 ms, respectively, are chosen for representing the temporal evolution. At t = 0 ms the breakdown occurs. It is shown that a sufficient region (0.4 m × 0.5 m) with stray field strength of less than 5 Gauss exists in the central region of the vacuum chamber in the 20 ms duration. The induced loop voltage is more than 10 volts. The connection length, $L \approx 600$ m at the assigned breakdown point (*R* = 55, *Z* = 0 cm) and about 150 m in the nearby area of 0.8 m × 0.7 m. If the working gas is hydrogen and the prefilled gas pressure is 1.5 $\times 10^{-4}$ torr, the evaluated loop voltage for reliable breakdown is about 1.7 V in STOR-U. It is much less than the designed value = 10 V. All of this indicates that the conditions for good plasma breakdown have been created. In Figure 5, the time traces of loop voltage, vertical field and its gradient are compared in the cases of with (in solid line) and without (in dashed line) eddy current effects. It shows that eddy currents cause a delay in breakdown. The increase in the wall thickness will increase the amplitude of the eddy currents, as shown in Figure 5(b).

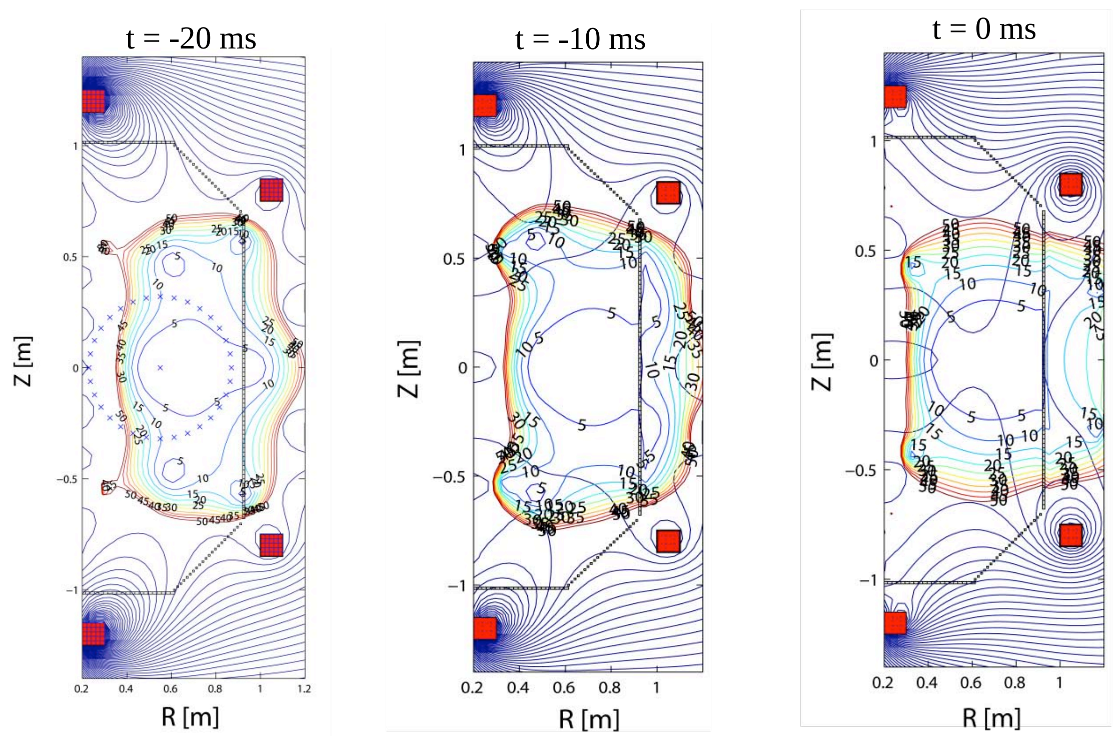


Figure 4 Temporal evolution of stray field in the plasma initiation phase, from left, -20, -10 and 0 ms (breakdown occurs), respectively. The cross markers represent the objective points in the least square fitting to solve the outer PF coil currents.

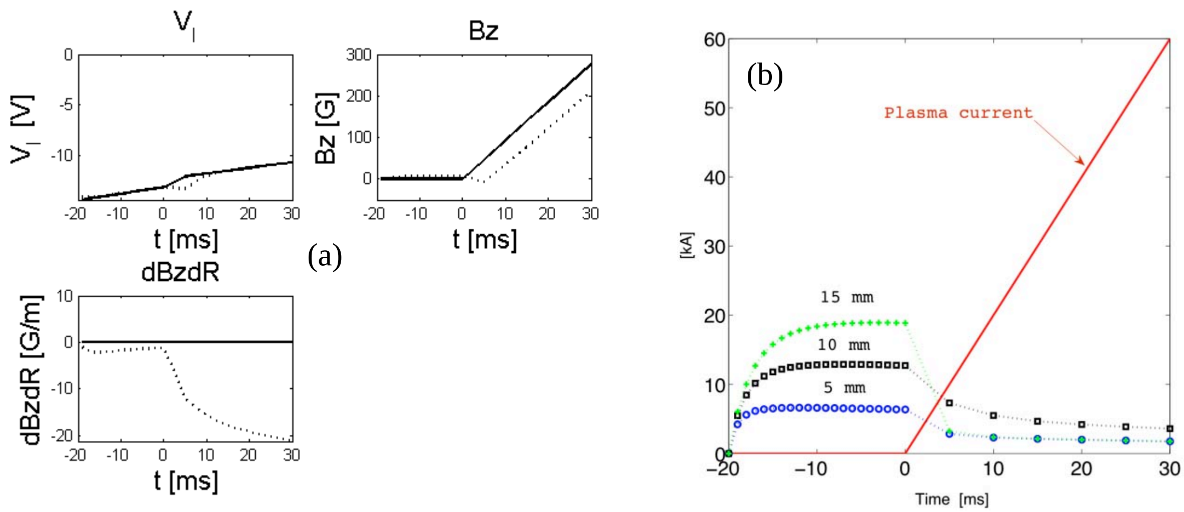


Figure 5 (a) Time traces of the parameters in STOR-U current start-up. (b) Wall thickness dependence of the eddy currents in the current start-up phase.

5. Performance prediction

In STOR-U, a 3MW NBI heating system is envisaged to be the main plasma heating scheme and offers the capability to study H-mode ST plasma and momentum transport. Performance prediction for NBI heating will provide valuable information on STOR-U discharge characteristics. Transport simulations on STOR-U have been performed using a 1.5D tokamak transport code, ASTRA. ASTRA solves coupled, time-dependent, 1D transport equations for particles, heat and current as well as 2D MHD fixed boundary equilibrium self-consistently with realistic tokamak geometry. An embedded NBI package is used for the calculation of NBI heating and current drive.

Simulations on thermal energy transport and current evolution in the core region $(\rho/a \leq 0.9)$ were performed; particle transport was not considered and instead the electron density profile was prescribed as: $n_e = (n_0 - n_b)\left[1-\left(\frac{\rho}{a}\right)^2\right]^{0.5} + n_b$, n_0 is the central electron density prescribed in simulations and $n_b = 0.5 \times 10^{-19}\ \mathrm{m}^{-3}$ is the electron density at edge, fixed in all simulations. In terms of transport model the ITER H mode empirical scaling approach was used. The ITER reference H mode scaling, ITER-98P(y,2), for thermal energy confinement is described as [12]:

$$\tau_{E,\_H98P(y,2)} = 0.0562 I^{0.93} B^{0.15} \bar{n}_{19}^{0.41} P^{-0.69} R^{1.97} k_a^{0.78} \epsilon^{0.58} M^{0.19}, \qquad (1)$$

in units of s, MA, T, $10^{19}\mathrm{m}^{-3}$, MW, m and atomic mass unit. The value P in (1) is the total heating power P_{tot} corrected for the radiation inside the separatrix: $P = P_{tot} - P_{rad,eff} = P_{oh} + P_{nbi} - (P_{brem} + P_{cycl} + \frac{P_{line}}{3})$. Radial profiles of the thermal diffusivities χ_e is chosen in the form: $\chi_e = Cf(\rho)$, $f(\rho) = 2 + 5\rho^2$, fitted by the experimental data in MAST [4] and C is a constant. Ion thermal diffusivities is assigned to be the neoclassical value, $\chi_i = \chi_i^{neo}$. In the simulations, the scaling (1) is used to normalize the transport coefficients in such a way that the energy confinement time computed by the code coincides with that given by (1). The confinement enhancement factor $HH(=\tau_E/\tau_{E,H98P(y,2)})$ is unity in this work. The Hirshman model is used for plasma resistivity [13]; the Sauter model is used for bootstrap current and the neoclassical ion and electron transport coefficients are from [14, 15].

Figure 6(a) shows the radial ion and electron temperature profiles in discharges with and without NBI heating. It can be seen that significant increase in ion temperature when NBI heating is employed. The central ion temperature $T_i(0)$ achieves 2.4 keV, compared with 1.6 keV in the Ohmic discharge. The ion temperature increase 46% and electron temperature 15%. The energy flows to ion channel preferably. The χ_e and χ_i profiles are shown in Figure 6(b). In the simulation the beam energy was 30 keV. The central temperature, $T_i(0)$ and $T_e(0)$, increase significantly when the beam energy increases. More than 5 keV of ion temperature can be achieved when beam energy is larger than 60 keV. The results are shown in Figure 7.

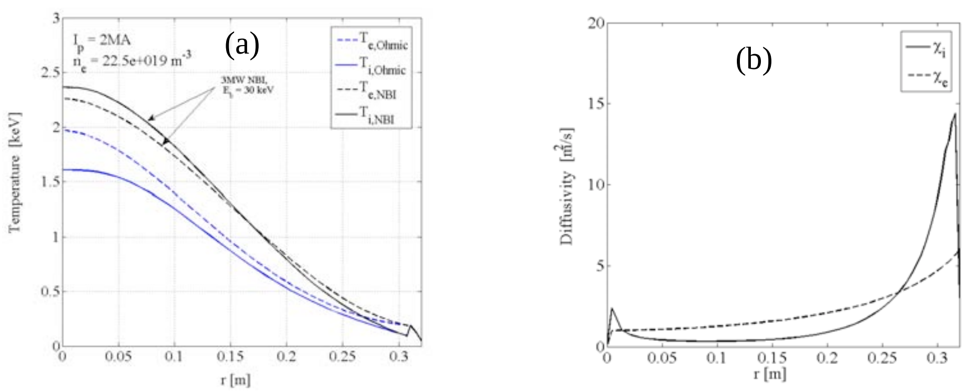


Figure 6 (a) T_i and T_e profiles for discharges with Ohmic heating and 3 MW NBI heating using ASTRA. (b) χ_i and χ_e profiles used in the simulation, χ_i is neoclassical and χ_e is parabolic, fitted using MAST data.

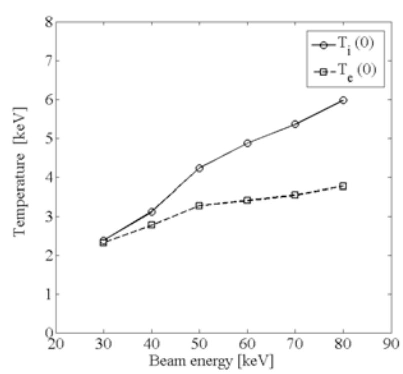


Figure 7 Predicted central ion and electron temperatures dependence on beam energy in on-axis NBI, plasma conditions: I_p = 2 MA, n_e = 20e+019 m^{-3}.

Various NBI schemes have been examined. Figure 8(a) shows the temperature variations with NBI power in on-axis injection with two injectors in co-co configuration. The central ion temperature increases monotonically with NBI power; the increase in central electron temperature saturates at P_{NBI} = 5 MW. In the case of co-counter injection, as indicated in Figure 8(b), the same trends are found for both ion and electron temperatures. However, the increases are smaller compared with co-co injection case.

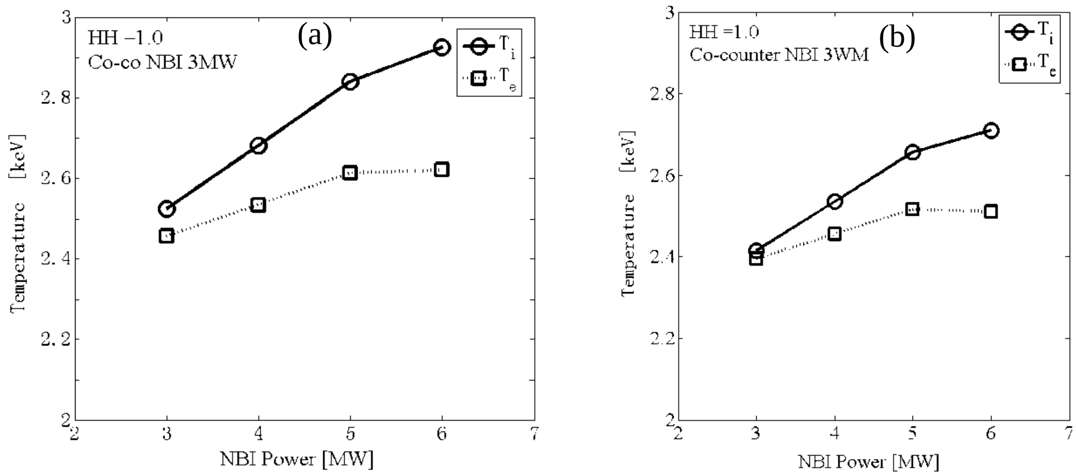


Figure 8 Central ion and electron temperature variations in co-co configuration (a) and co-counter configuration (b), plasma conditions: I_p = 2 MA n_e = 20e+019 m^{-3}.

6. Summary

To explore high beta ST plasmas, the STOR-U, a tokamak with low aspect ratio = 1.7, was proposed. The machine parameters are: R_0 = 55 cm, a = 32 cm, I_p = 2 MA and toroidal field B_t = 1.5 Tesla. Physical design of TF and PF systems have been accomplished and results show that it has the capability to obtain various plasma equilibria to meet the plasma shaping requirements, $k = 3.0$ and $\Delta = 0.5$. Plasma initiation and current start-up were studied numerically with careful consideration given to the wall eddy current effects. Sufficient toroidal electric filed and null field region for plasma breakdown have been obtained. Predictive transport simulation reveals significant increase in both electron and ion temperature in NBI heated discharges and ion heating is dominant. The effects of different NBI configuration on the central ion and electron temperature are investigated. The results suggest 3MW, 70 keV NBI heating is able to heat the plasma to 5 keV.

7. Acknowledgements

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