Modelling of Merging-Compression Formation of High Temperature Tokamak Plasmas

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Abstract. Codes TSC, NFREYA and TORUS II are used to calculate time evolution of the plasma parameters during and after the merging-compression plasma formation in the ST40 Spherical Tokamak. It is shown that keV-range ion temperatures can be obtained during formation and the following heating by Neutral Beam Injection (NBI) may increase the ion temperature to the 10 keV range.

Introduction

The new generation high field spherical tokamak ST40 (design parameters: R_0=0.4m, A=1.6-1.8, I_{pl}=2 MA, B_t=3 T, k=2.5 /1/) is currently operational. As in START and MAST /2/, the merging-compression method is used for the plasma formation. Plasma rings are formed around two in-vessel poloidal field coils (MC-coils, Fig.1) and merged via magnetic reconnection into one plasma ring at the midplane. The plasma is then radially compressed to form the ST configuration. Experimental and theoretical studies /2, 3/ allow to expect that this formation method may produce high-temperature ST plasma, (over 10 keV for the ST40 parameters), even without using any additional heating, possibly providing a direct path to a burning plasma relevant regime.

The performed modelling had the following aims:

(1) To determine the deposition profile of the power released by fast ions formed during magnetic reconnection using the fast particle full-orbit code NFREYA /4/. The slowing down and the deposition profile D(r) are computed by solving the Fokker-Planck equation.

(2) To obtain the ion temperature profile and its evolution after the reconnection heating and adiabatic compression along the major radius using the TSC code /6/.

(3) To estimate the ohmic electron heating power, Ampere's law is applied to the current sheet /2, 3/ which is formed between the reconnecting plasma rings.

(4) To model the plasma heating by NBI applied after the merging-compression formation.

Modelling of the reconnection heating

To estimate the power deposition of the fast ions produced during reconnection /2/ and model the evolution of the ST40 plasma during and after the compression phase supported by the additional heating, numerical codes NFREYA /4/, TSC /6/ and Torus II /7/ are used.

NFREYA – Monte Carlo simulation

The modelling is mainly based on the assumption that the ions formed during the reconnection reach the energy f_E E_{alf} /2, 3/ and are mainly running in co-direction (E_{alf} is the poloidal Alfven energy, f_E is a correction factor accounting for effects (e.g. viscosity) not included in /3/). Since the inflowing ions have Maxwellian energy distribution, a small spread in the energy and in the pitch angle (~10 degrees) is assumed. The deposition and slowing down of accelerated ions are modelled by the fast particle part of NFREYA /4/. The reconnection and therefore the acceleration of the ions takes place on the sub-millisecond time scale. The subsequent slowing down, taking place on the ms - time scale, is described by the Fokker-Planck equation accounting for pitch angle scattering and the energy and momentum transfer to the background particles. Since the speed of the reconnected ions is much lower than the critical speed below which the ions are preferentially heated /5/, only the power deposition profile of the ions D(r) is important. To estimate the current of the accelerated ions, the experimental results are used, which indicate that by reconnection heating in ST40 and MAST, the values of $T_i \approx 1$ keV are achieved. TSC simulations (see below) show that a power of $P \approx 20$ MW is needed (which is in the same range as estimated on MAST and TS-3 /3/) to reproduce this heating within the slowing down time of $\tau_{sd} \approx 4$ ms. Assuming near monoenergetic ions of energy ≈10 keV, an outflowing current of $I_{out} \approx 2$ kA is needed for this.

TSC simulation of ion heating and compression

The two-dimensional, time dependent, free boundary code TSC resolves the MHD and transport equations describing the evolution of an axisymmetric plasma on the micro - second time scale, thus suited to simulate fast processes as the reconnection heating and the following compression. The Coppi-Tang model /8/ for the transport, neoclassical resistivity and additional heating taking the radial deposition profile from reconnection or NBI is used.

Central electron heating

To estimate the central ohmic electron heating power, Ampere's law is applied to the current sheet that is formed at X-point between the reconnecting rings /3/. The current density in the sheet with the half width δ is given by $j = \frac{1}{\mu_0}\nabla\times\vec{B} = \frac{1}{\mu_0}\frac{B_{in}}{\delta} = \frac{10^7 B_{in}[T]}{4\pi\delta[m]}\frac{A}{m^2}$, where B_{in} is the field on the inflowing side (reconnecting poloidal field). With the speed of the outflowing ions (E_{alf} = 10 keV), $v_{out} = \sqrt{f_E}\ 1.6\ 10^8$cm/sec, and the density $n = f_d\ 2\ 10^{13}\text{cm}^{-3}$, we get the current density $n v_{out} e_0 = 512 f_d \sqrt{f_E}$ A/cm^2. Here a global electron movement is neglected but in f_η (see below) it can be accounted for. The area between the rings where electron heating and ion acceleration takes place becomes after reconnection the central area around the magnetic axis. We assume that radial and poloidal extension differ by factor f_p and get as area $F_{rec} = f_p\ \pi\delta^2$. From nv_{out} and I_{out} we get the estimate of $\delta = 1.08 f_E^{-3/4} f_d^{-1/2} f_p^{-1/2}$ cm. We note the scaling with density $\sim f_d^{-1/2}$. With this estimate, the current density is $j \approx 0.8\text{x}10^{-2} f_E^{3/4} f_d^{1/2} f_p^{1/2}$

MA/cm^2. With the anomalous resistivity $\eta = f_\eta \eta_{\rm Spitzer}$ (T_e=100 eV) we get the power density $Ej=\eta\, j^2=1.20\, f_\eta f_E^{3/2} f_d f_p$ kW/cm^3 with the central cylindrical volume $V_{cent}= \pi f_p \delta^2 2\pi R_0 f_R$ cm^3 (f_R =R[cm]/75), the total power is P_e= E j V_{cent}=$1.1\, f_\eta f_E^{-3/2} f_d^{-1} f_p^{2} (\delta\,[\mathrm{cm}])^2 f_R$=$1.3 f_R f_\eta$ f_p MW.

Results

Assuming in the TSC simulations flux conservation, current in P3 coil I_{p3}~400 kA produces, after ramp down, plasma current of ~0.8 MA, thus producing an effective poloidal reconnecting field of ~ 0.8 T. Fig. 1 shows an example of an equilibrium configuration after the compression with vertical field coils P5 (BVL), pusher coils P4, merging-compression coils P3 (MC) and divertor coils P2. Fig. 2 shows the time evolution of the plasma current which increases almost linearly in time during compression. In ST40, a plasma current of 400 kA has been obtained with I_{p3} ~ 430kA, which is less than expected because of resistive losses in the plasma rings and coupling to the passive conductors. Adding passive conductors in TSC simulations results in reduction of the final plasma current by ~50%, which makes better agreement with experimental results.

Since the reconnected ions are released in the vicinity of the X - point and run in co-direction with a small spread (~10 degrees) in pitch angle, the deposition profile is hollow, peaked close to the plasma periphery with a width of ~ 5 cm. Fig. 3 shows a typical slowing down orbit and banana orbit for 1keV and 10keV ions and Fig. 4 shows the deposition profile D(r).

Assuming the reconnection heating power of 20 MW with the deposition D(r) and a heating time of 3 ms, temperature of T_i ~1 keV is obtained in rough agreement with the ST40 results. If the reconnecting magnetic field will be (as expected) increased by a factor of 2 – 3, further increase in the ion temperature to the 10 keV-level may be expected /3/. The deposited energy of 6 kJ is lost mainly by heat conduction, due to the steep T_i-gradient, and only a part produces the increase of the ion temperature. Fig. 5 shows the time evolution of the ion temperature profile T_i(R). However, in TSC simulations, the fast reconnection process on the sub-millisecond timescale is replaced by the magnetic field diffusion from the plasma rings around P3 coils into the central region. Here the plasma current is built up according to the Faraday's law and then the plasma is heated with the profile D(r) due to slowing down of fast ions and by ohmic heating in the formed current sheet. Fig. 6 shows the evolution of T_i after the reconnection, when a NBI (2 MW, 70 keV) is used, starting at 5 ms. The repetitive pellet injection is used to increase the plasma density. The recycling rate was reduced to 0.96 in these simulations, relying on the proposed use of the Li conditioning /1/. After the heating phase at 200 ms, T_i is increased from 1 to 10 keV. If, after the planned ST40 upgrade, MC current and so reconnection field and T_i will be increased, to reach 10 keV and achieve burning plasma relevant regime lower NBI power or none may be needed.

Summary and Conclusions:

The ion power deposition and ion heating due to reconnection is calculated and depends mainly on the energy, current and the orbits of the reconnected ions. Simulation of the reconnection heating by TSC, reproducing experimental ion temperature, allows to estimate the current of the reconnected electrons and thus the electron heating power. Simulations show that with 2MW of the NBI and pellet injection for fueling, $T_i \sim 10$ keV can be reached.

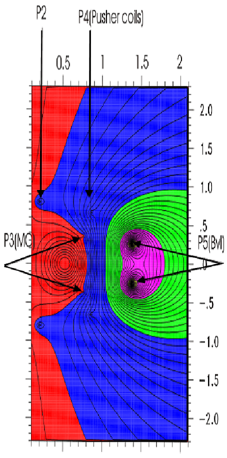

Fig.1 Equilibrium after compression. Position of poloidal field coils is shown.

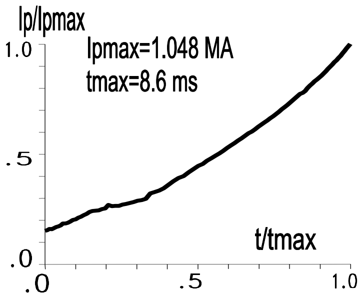

Fig 2 Time evolution of the plasma current during compression.

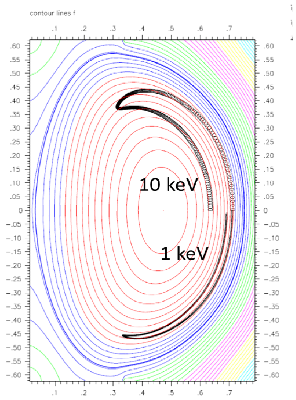

Fig.3 Orbits of the ions produced by reconnection, 10 keV top, 1 keV bottom.

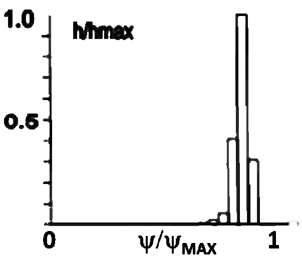

Fig. 4 Deposition profile of the reconnected ions D(r).

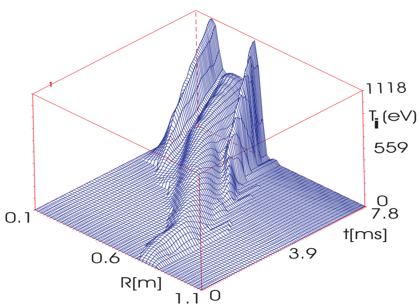

Fig.5 Time evolution of the ion temperature due to the reconnection heating.

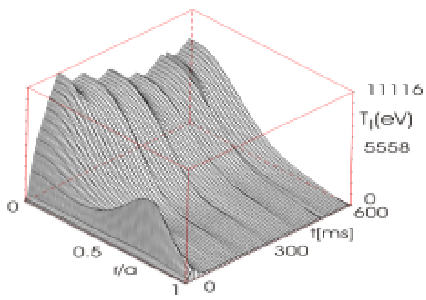

Fig.6 Ti- evolution due to reconnection, beam heating and repetitive pellet injection.

/1/ M Gryaznevich et al 45th Conf. on Plasma Physics (EPS-2018, Prague, 2–6 July 2018) P2.1077;
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