Study of non-inductive plasma current ramp-up in spherical tokamaks

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Introduction. In spherical tokamaks practically there is no space for central solenoid. That is because the substantial part in the central area of tokamak is necessary to place the toroidal magnetic field coils. Hence in general case the possibility of inductive ramp up of the plasma current in spherical tokamak is very limited, the plasma current ramp up problem in such devices becomes a very important problem. One of the methods for the plasma current ramp up in spherical tokamaks could be the combined one, which includes the high frequency current drive (HFCD) and neutral beam current drive (NBCD) generations.

The proposed HFCD generation scheme assumes that low-density plasma is produced by radio frequency pre-ionisation around the fundamental electron cyclotron resonance (ECR) layer. Then a double mode conversion scheme is considered for electron Bernstein wave (EBW) excitation in plasmas with densities lower than the ordinary (O) mode cut-off density ($n_{e0}<3{\cdot}10^{19}$m^{-3} for 49 GHz). The scheme consists of the conversion of the O-mode, incident from the low field side of the tokamak, into the X-mode with the help of a grooved mirror-polarizer incorporated in a graphite tile on the central rod. The X-mode reflected from the polarizer propagates back to the plasma and experiences a subsequent X-EBW mode conversion near the upper hybrid resonance (UHR) as shown in Fig. 1 [1]. Once the EBWs are excited, they are efficiently absorbed close to the electron cyclotron harmonics and their current drive efficiency is predicted [2] and experimentally confirmed [3]. Experiments with such system have been carried in tokamak MAST at 28 GHz [4]. Presented paper demonstrates the results of study with use of DINA code [5] of the non inductive plasma current ramp up scenarios in the spherical tokamak, which is considered in the project of neutron source VNS [6], which has the next plasma parameters: plasma current 1 MA, major radius 0.9 m, minor radius 0.4 m, plasma elongation ~2 and toroidal magnetic field 1 T.

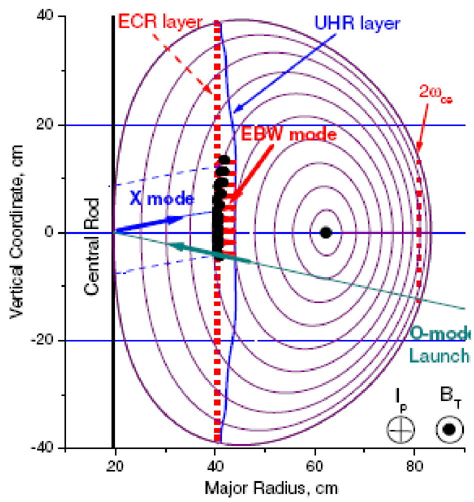

Fig. 1. Schematic of the EBW assisted plasma current start-up [1]

Physical models of HFCD and NBCD in DINA code. The value of HFCD due to EBWs absorption is modeled in DINA code with use of scaling, which corresponds to the data presented in Fig. 2 [7], which gives the expression $0.25T_e(keV)/n_e(19), A/W$. The absorption area is defined from the mode-coupling requirement $\Omega_{CE} < \varpi_{RF} < \varpi_{UH}$, where $\Omega_{CE} = eB/m_e$ is the electron cyclotron (EC) frequency, $\varpi_{UH} = \sqrt{\varpi_{pe}^2 + \Omega_{CE}^2}$ is the UHR frequency and $\varpi_{pe} = \left(e^2 n_e /(\varepsilon_0 m_e)\right)^{1/2}$ is the electron plasma frequency. The main issue is to have the UHR frequency inside the plasma as shown in Fig. 1 during the plasma current rump-up. Model of NBCD in DINA code corresponds to [8]. DINA code includes the free boundary plasma equilibrium evolution in external magnetic fields together with poloidal magnetic flux diffusion equation. Physical model of DINA code includes the 0-dimentional balance of the electron/ion energy as well as the neutral/ion density together with 0-dimentional impurity radiation model.

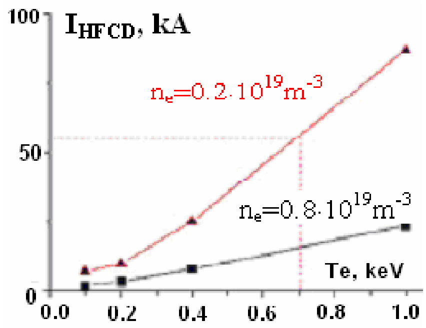

Fig. 2. Calculated $I_{HFCD}(T_e,n_e)$ data for P_{HFCD}=75 kW [7]

Modeling results. We present the DINA modeling results of non-inductive current ramp-up in VNS plasma without using of the central solenoid. In Fig. 3 the distributions of magnetic

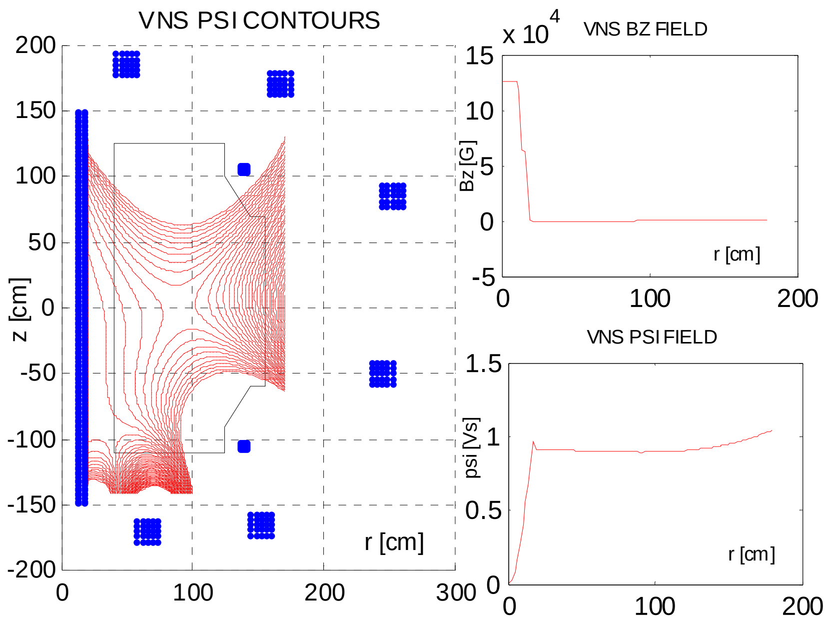

Fig. 3. Distributions of magnetic poloidal flux, horizontal magnetic field and poloidal magnetic flux in the meridian plane of VNS tokamak before breakdown

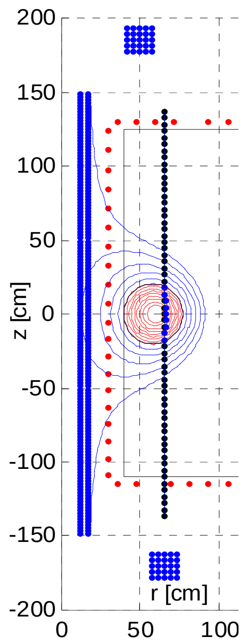

Fig. 4. Equilibrium of VNS plasma just after breakdown

poloidal flux before breakdown, horizontal magnetic field and poloidal magnetic flux in the meridian plane of VNS tokamak are shown. It is seen that the magnetic flux reserved in central solenoid corresponding to the moment of plasma breakdown is of the order of 1 Wb, which is used to provide a plasma breakdown and to obtain an initial current in VNS plasma. Equilibrium of plasma just after breakdown is presented in Fig. 4. In such plasma the green line corresponds to the place of the ECR absorption for Ω_{CE} = 49 GHz EC frequency in 1st harmonic of ordinary mode, which corresponds to the magnetic field equal 1.75 T. For such selected Ω_{CE} frequency the value of cut-off density is about n_{e0}≅$3\cdot10^{19}$m^{-3}. As stated above the HFCD generation can take place if the area between the ECR and UHR layers (see Fig. 1) is located inside the plasma. In Figs. 5 the EBW absorption area evolution in VNS plasma is presented ("a"– at time moment 1 s, "b"- at time moment of end of ramp-up). Starting low-density (n_e≅$0.4\cdot10^{19}$m^{-3}) plasma is produced by radio-frequency pre-ionization around the fundamental ECR. At the end of plasma current ramp-up the electron density is n_e≅$2\cdot10^{19}$m^{-3}< n_{e0}. One can see from Figs.5 that during the plasma current ramp-up the UHR layer is located within 70 cm < r < 100 cm. Further increase of electron density will cause the UHR layer could be outside of plasma. Fig.6 demonstrates the time traces of the main parameters during presented non-inductive VNS plasma current ramp-up. HFCD generation is carried out till 5 s time moment. At this time the electron density is increased up to n_e≅$1\cdot10^{19}$m^{-3}, the ECH power reaches the value of P_{ECH}=2 MW and the high frequency current drive runs up to maximum value I_{HFCD} ≅ 0.9 MA. At that time moment the value of current drive exceeds the plasma current value more than twice. After time moment of 5 s the value of plasma density is high enough to provide a shine-through operating limit for neutral beam injection with energy 80 keV. During the

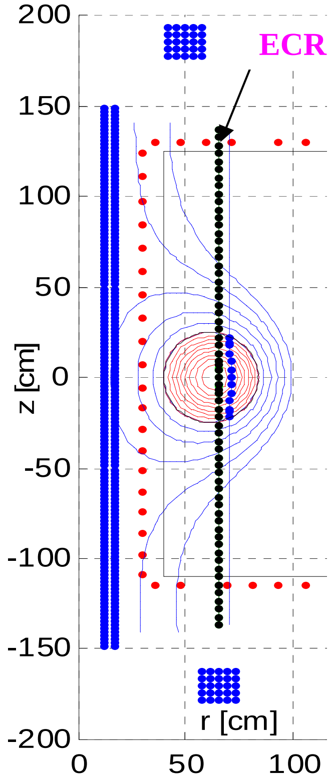

Fig. 5a. EBW absorption area at t=1 s (I_p=100 kA)

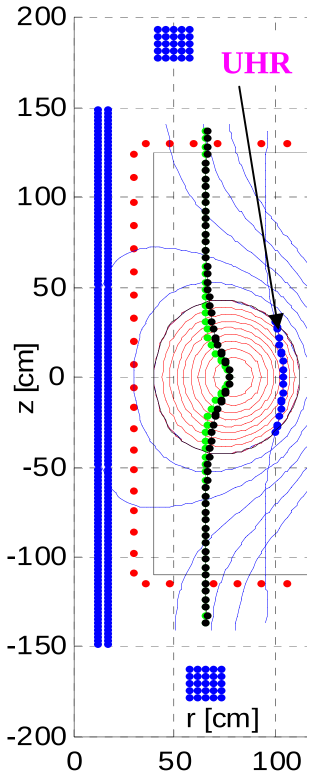

Fig. 5b. EBW absorption area at t=15s (I_p=800 kA)

subsequent 10 s time period the neutral beam power is increasing up to 4 MW providing the current drive generation on the level of ~350 kA. Bootstrap current is small, less than 50 kA.

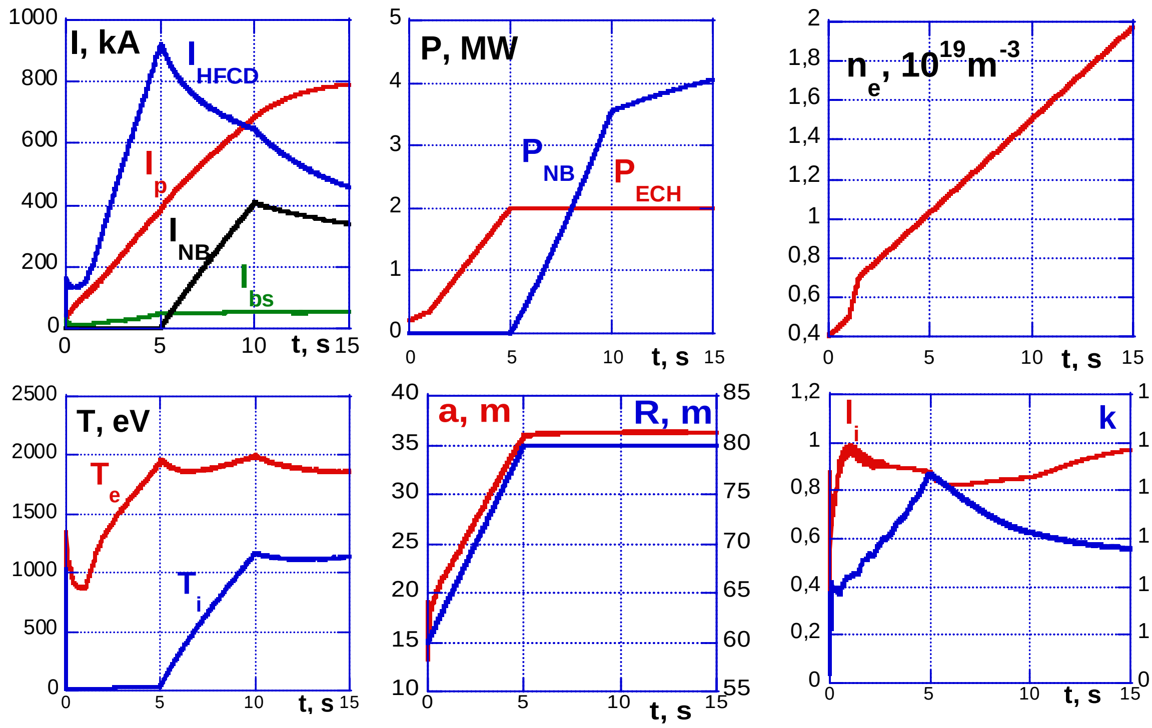

Fig. 6. Time traces of the main parameters during non-inductive VNS plasma current ramp-up

Conclusion. Results of the non-inductive plasma current ramp-up to 0.9 MA in spherical tokamak VNS are presented. Proposed scheme consists of the double conversion of the 2 MW O-mode, incident from the low field side of the tokamak, into the electron Bernstein wave combined with the 4 MW neutral beam current drive generation. During HFCD stage one needs to provide the more than twice overdrive.

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