Modelling of Ion-Tail Acceleration and Neutron Generation in ST40

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Abstract. Codes NFREYA and NFIFPC are used to calculate the fast ion distribution and the neuron yield due to NBI (Neutral Beam Injection) and ICRH (Ion Cyclotron Resonance Heating) in the ST40 Spherical Tokamak. It is shown that the maximum pitch angle of 55 degrees is achieved with a beam injection tangency radius of R_b = 30 cm. The ICRH produces a sharp peak at E_{perp} = 1MeV. After a relaxation time of ~1 sec a stationary distribution is achieved, and the neutron yield due to beam deuterons reacting with a deuterium plasma is $Y_{DD} \sim 1.5\ 10^{16}$/sec. For tritium ions reacting with a deuterium plasma the analogous rate is $Y_{TD} \sim 4\ 10^{17}$/sec.

Introduction

Acceleration of fast ions produced by NBI (Neutral Beam Injection) by ICRH (Ion Cyclotron Resonance Heating) is considered to be tested in ST40 [1] (design parameters: R/a = 0.4/0.25m, B_t = 3T, I_{pl} = 2-3MA pulse duration 1-2 sec, NBI–power 3MW, NBI-energy E_b = 25-55 keV, ECRH/EBW power 2 MW) to produce neutrons by DD – and TD reactions. The ICRH antenna is not installed on ST40 and one of the purposes of this paper is to evaluate options for the use of ICRH for the acceleration of the beam tail. Depending on the beam geometry, the generated fast ions have a pitch angle such that v_{perp} (speed perpendicular to the magnetic field) is a considerable fraction of the total velocity. The ICR wave absorbed at the resonant cylinder increases the ion temperature which results in an increase in the Larmor-radius, thus reduces the pitch and allows for a considerable increase in the neutron yield.

The modelling has the following aims:

1. To determine by means of the Fast Ion Fokker-Planck Code (FIFPC) the distribution function of the fast ions due NBI.

2. To investigate the relaxation of the ICRH-heated tail ions due to Coulomb - collision until a stationary state is reached and to compute the corresponding neutron yield due to beam-target reactions.

3. To compute banana orbits of the very low pitch particles generated by the ICRH.

Modelling of the tail heating

To compute the deposition profile distribution due to NBI and to determine the evolution of the distribution function of the fast ions due to additional ICRH the Monte – Carlo code NFREYA [3] and the finite-difference code NFIFPC are used.

NFREYA - Beam deposition by Monte Carlo Methods

NFREYA uses the beam and plasma geometry to compute the deposition profile H(r) in an arbitrarily shaped (axisymmetric) plasma by a Monte - Carlo method using the pseudo collision technique. H(r) is proportional to the source terms in the Fokker-Planck equation to be solved at a flux surfaces with effective radius r.

NFIFPC - Fast Ion Fokker-Planck Code [3]

The Fokker - Planck equation is obtained from the Boltzmann equation under the assumption that only small scattering processes are important. We get for the distribution function of the fast particles an equation accounting for the particle and power input, charge exchange, energy diffusion, pitch angle scattering and the drag by electrons and ions.

Results

Starting the NBI (tritium beam) without ICRH we get the distribution shown in Fig 1 (right) as 3d plot and as contour plot (right). The background is a deuterium plasma (Ti_{max}/Te_{max} = 5400/4300eV, n_e^{max}=1.5 $10^{14}/cm^3$) The beam tangency radius is 30 cm and the time is 20 ms after the injection begins. The distribution has 3 peaks belonging to the 3 beam components with the energies E_b, $E_b/2$ and $E_b/3$. The peak belonging to E_b is located at v_{perp}~ 0.8v_{max} and v_{para}=0.5 v_{max}, corresponding to a pitch angle of ~55 degrees. During ICRH the peak is moved to v_{perp}~v_{max}(1 MeV). Here it is assumed that the ICRH power is completely absorbed by the tail ions. The influx of tail ions suited for amplification by the ICRH is around 5% of the total influx of I_{beam}=1 MW/50keV = 20 Amp. The fraction f_{acc}=5% corresponds roughly to the volume of the peak in Fig. 1 in velocity space divided by the volume occupied by the total beam in Fig.1. The ICRH heats the fraction f_{acc} to the energy E_{perp}=1MW/1Amp=1MeV of the Larmor rotation if collisions are neglected. Since NFIFPC takes collision into account we get after 100 ms the distribution in Fig. 2 (left) and after 200 ms the distribution in Fig.2 (middle). The strong peak at v_{perp}~0.9v_{max} at 100 ms is due to the ICRH. The broadening at 200 ms is due to collisions. The stationary state in Fig. 2 (right) is reached after 0.7 sec. The neutron yield increases from 3 10^{15}/sec at 100 ms to 1.5 10^{17}/sec. If a deuterium beam is shot into a deuterium plasma, the neutron yield increases, due to the ICRH, from 2.0 10^{13}sec at 100 ms to 6.1 10^{15}/sec at 0.7 sec.

Orbits

The stationary distribution in Fig.2 is broad in v_{perp} and narrow in v_{para}. Because of the ICRH, the kinetic energy E_{kin} is mainly determined by v_{perp}. Therefore, the density of the particles with v_{perp}/v_{para}>0.9 is much larger than in the case of a Maxwellian. Thus, banana orbits appear during slowing of the tail ions. The poloidal projection in Fig 3 (left) gives an example for a banana orbit (E_{kin} =1MeV, I_p=6 MA, pitch p=0.57) with the banana tips almost pinched together (‘pinch ‘orbit, ‘world’s fattest banana’). This orbit is the limit between the banana - and circulating orbits. A parallel projection of the same orbit (Fig. 3, middle) also shows the toroidal movement of the particle in addition to the radial and poloidal movement. In analogy to the globe the outermost flux surface is indicated by 8 meridional lines and 14 circles of constant latitude. It can be seen that the particle moves mainly in the vicinity of the axis of symmetry. Fig.3 (right) shows an orbit with E_{kin}=300 I_p=2 MA and a very low pitch p=0.1. The parallel projection (Fig.4, left) shows movement more outside of the radius of the banana tips. Fig 4 (middle and right) shows a D – shaped orbit. Here the particle encircles the axis of symmetry 5 times before going to the outside.

Conclusions

The modelling shows that the neutron yield increases by a factor ~300 to 6.1 10^{15}/sec if a D-beam is shot into a D plasma and by a factor ~50 to 1.5 10^{17}/sec if a tritium beam is shot into a deuterium plasma if ICRH is applied. Increased first orbit losses due to the ICRH can hardly be expected because the ICRH changes the co – running particles due to NBI to well confined banana or D-orbit particles.

1. M. Gryaznevich O. Asunta and Tokamak Energy Ltd. Team. FED 123 (2017) 177-180

2.K. K. Kirov et al.,AIP Conference Proceedings 2254, 030011 (2020)

3. A Nicolai, M Gryaznevich, Plasma Phys. Control. Fusion **54** (2012) 085006

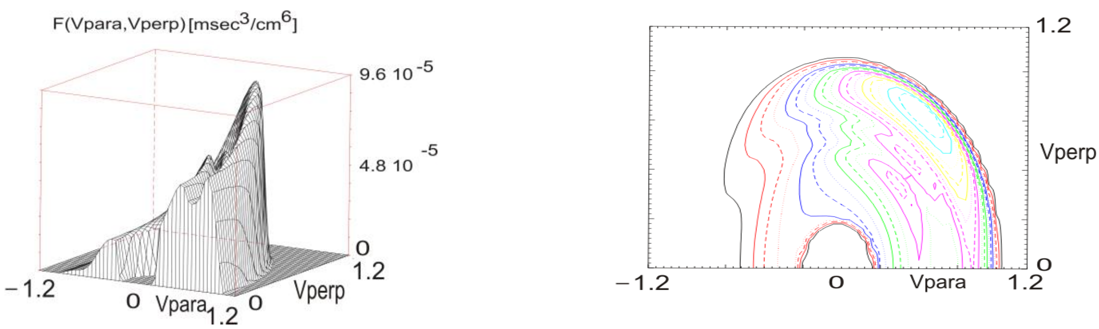

Fig.1. Fast ion distribution of the W_b=2 MW E_b=50 keV, R_b=30 cm beam as 3d-plot (left) and contour plot (right)

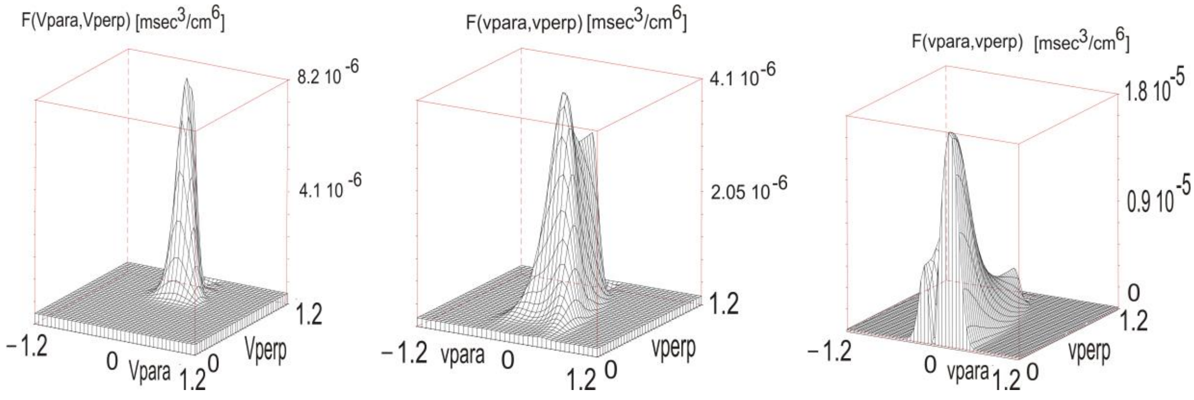

Fig.2. Distribution of the tail ions at 100 ms (left),at 200 ms (middle) and the relaxed distribution at 800 ms.

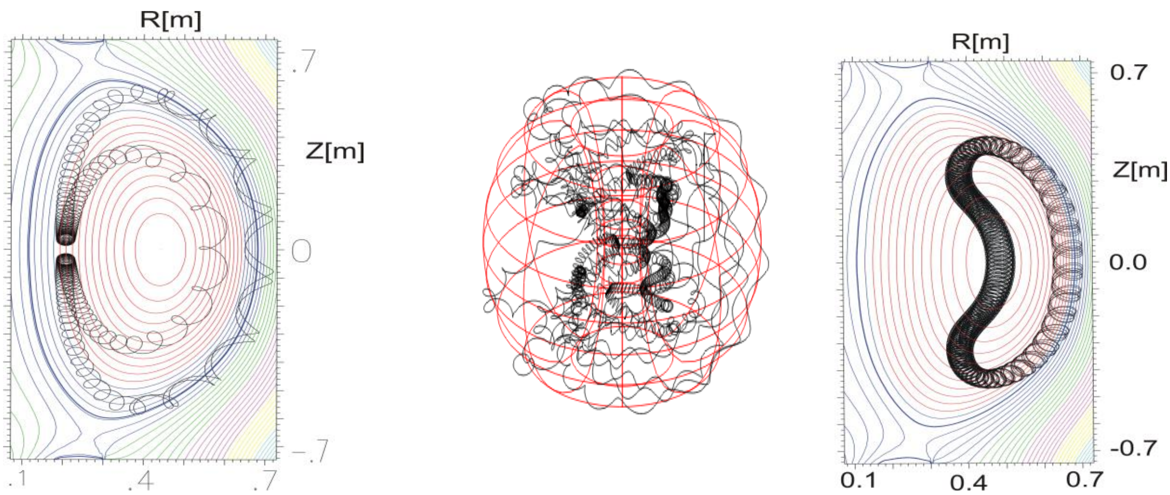

Fig.3. Pinch orbit ('the world's fattest banana') with the initial pitch p= 0.58 (left) and I_p=6MA, 3d view of the same orbit (middle) showing that the particle mainly moves at the inboard side. Banana orbit (right) with the energy E_b=500 MeV and a very low pitch of p=0.1 and I_p=3MA.

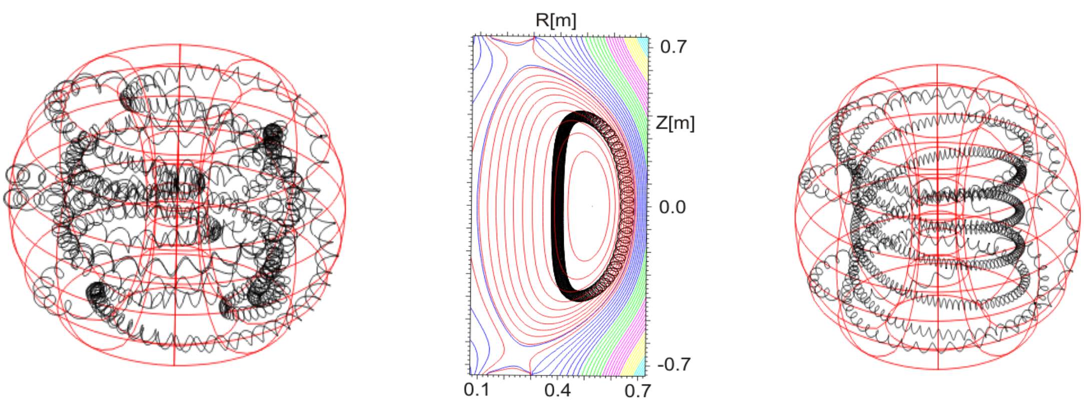

Fig.4. 3d view (left) of the orbit before showing that the particle moves to the centre post at the banana tips. D shaped orbit with the pitch p=0.2 and I_p=2MA (middle). The 3d view (right) of the same orbit shows that the particle encircles the axis of symmetry 5 times before going to the outside.