

ENERGETIC PARTICLE RIPPLE LOSS IN ITER

S.V. Konovalov^{a)}, E. Lamzin^{b)}, K. Tobita^{c)}, Yu. Gribov^{d)}

^{a)} *RRC “Kurchatov Institute”, Moscow Russia*

^{b)} *Efremov Institute, St. Peterburg, Russia*

^{c)} *JAERI, Naka, Japan*

^{d)} *ITER JCT, Naka, Japan*

Potentially significant loss of the fusion alpha particles and high-energy ions produced by the neutral beam (NB) injection or ICRF heating can occur in ITER-like machines due to the toroidal field (TF) ripple, i.e. perturbations of the toroidal magnetic field due to discreteness of the TF coils [1].

Toroidal solenoid of the ITER, consisting of 18 TF sections, provides a relatively small ripple magnitude (at the plasma separatrix maximum ripple value is of 1.14%). Besides, ripple magnitude decreases rapidly towards the plasma center. Owing to these facts, in most operation regimes the ripple wells occupy narrow regions near the outer plasma boundary and in the vicinity of the midplane ($B_R = 0$ surface). Besides, a vertical asymmetry of the single null equilibrium configuration hardens transition to the stochasticity. In such conditions drift islands slightly broaden the ripple loss cone created by the outer part of the ripple well region. Therefore, most typical mechanism of the fast ion loss in ITER is the collisional scattering in the ripple loss cone, which becomes most effective for the particles slowed down to the energies of several hundred keV when scattering on the bulk plasma ions becomes comparable with slowing down by electrons. Such a behaviour of fast ions is dominant with exception of the strong reversed shear (SRS) operating regime, when due to high q value the ripple well region covers essential part of the plasma column.

The most dangerous effect of the fast ion ripple loss manifest itself in production of significant heat loads on the first wall (FW) and plasma facing elements. Even at the relatively low for the energy balance loss fraction, fast particles, due to their high energy, could create significant heat loads. Besides, ripples assist to additional peaking of them.

For the downward ion $[\mathbf{B} \times \nabla \mathbf{B}]$ drift direction (specified for reference scenarios of ITER-FEAT) which is opposite to the gradient of ripple amplitude, most of the fast ions leave the plasma in the toroidally trapped (banana) state. In such conditions, the spatial distribution of the FW heat load depends crucially on a mutual geometry of the ripple loss cone and plasma surface relative to FW shape, and shape of fast ion source profile. Additional toroidal peaking of the heat loads is associated with magnetic field line oscillations caused by poloidal

components of the perturbed magnetic field. Reliable predictions of the FW heat load amplitudes allowing for accurate account of detailed plasma and FW geometry and Coulomb collisions can be done with the orbit-following Monte Carlo (OFMC) codes. Efficient OFMC codes [2,3] have been developed and validated by comparison with experimental results.

Alpha particle loss rates have been calculated for the nominal $Q=10$ inductive and two RS operating scenarios using the HYBRID Monte-Carlo numerical code [2]. Results are shown in Table 1. It can be seen that the particle and power losses in the inductive regime as well as in the steady state regime with weak RS ($q_{\min} \approx 2$) are tolerable. In the scenario with a strong RS ($q_{\min} \approx 3.75$), α -particle losses are rather large. The peak power load on the first wall produced by the escaping α -particles in this scenario exceeds permissible level of 0.5MWm^{-2} .

An essential reduction of ripple amplitude can be achieved using the ferromagnetic inserts (FI) [4]. At the nominal value of toroidal field, the proposed configuration of the FI set (not optimized) [5] provides a reduction of the ripple amplitude by a factor of 2 at the plasma separatrix and is even more effective in the inner regions. It effectively suppresses (almost to zero level) alpha particle ripple loss.

Table 1 Ripple loss of fusion alpha particles in various ITER scenarios with and without Ferromagnetic Inserts.

	Inductive		Weak RS (#4)		Strong RS	
	TFC	TFC+FI	TFC	TFC+FI	TFC	TFC+FI
particle loss (%)	2.15	~0	6.6	0.08	21	0.75
power loss (%)	0.65	~0	2.3	0.04	9.3	0.13
FW load (MW/m^2)	<0.1	~0	<0.2	0.005	0.8	0.025

Loss fractions and associated heat loads shown in the above Table 1 were calculated for rather peaked α -source corresponding to the parabolic (versus normalized poloidal flux) ion temperature and flat density profiles. Calculations [6] performed for a broad fusion source profile (like after ST crash) and equilibrium similar to that in the weak RS (#4) scenario without FI gave much higher α -power loss fraction (of 12.2%) and peak heat load (of $\sim 0.8\text{MW/m}^2$). In recent calculations of the same scenario with FI (done with use of the code [3] upgraded to account multiple harmonic structure of the ripple perturbation [5] and validated against experimental observations [4]) power loss fraction was found to be of order 7% (c.f., 0.04% in Table 1, calculated for the peaked source profile). It is noteworthy that spatial redistribution (broadening) of fast ions due to Alfvén and other MHD instabilities

could essentially increase ripple losses. Therefore, the question to what extent such a broadening would be permissible should be answered in a near future.

The NBI ion (injection energy is 1MeV) ripple loss was estimated for the worst case of a strong RS equilibrium without FI (Table 2).

Table 2 NB ripple loss in ITER RS configuration at the DT and H operation phases.

	⁰ D on-axis	⁰ D off-axis	⁰ H off-axis
Particle loss fraction (%)	17.1	15.5	24
Power loss Fraction (%)	4.0	3.2	5.1
Maximum heat load (MW/m ²)	0.24	0.23	0.33

Heat loads in Table 2 correspond to 50MW of the NB injection power. For the hydrogen operation phase the same equilibrium was taken with reduced, by 2 times, toroidal magnetic field and plasma current and, therefore, reduced plasma density to keep it below the Greenwald limit. The latter results in an increase of H-beam shine-through loss up to 12.3%. Similarly to the case of α -particles, NBI ion ripple losses reduce to the almost zero level when FI effect is taken into account.

For ITER reversing of the ion [$\mathbf{B} \times \nabla \mathbf{B}$] direction weakly affects α -particle and NB ion ripple loss. Counter (to the plasma current) NB injection will be accompanied by an appearance of prompt (first orbit) losses. These losses could be substantial due to high density of the plasma periphery where a significant fraction of the beam atoms is ionized.

Including of FIs in ITER design poses two potential dangers: the first is overcompensation of ripples at lower toroidal field amplitude due to saturated magnetization of ferromagnetic, and the second is penetration of the higher ripple harmonics into the plasma due to closeness of FIs.

In the design accepted the inserts are made of steel SS430 and located under TF coils in the outboard area between the vacuum vessel shells (Fig.1). There are no ferromagnetics in the place assigned for equatorial ports. The density of ferromagnetic material (filling factor, C_{ff}) can vary along the FI body. For uniform C_{ff} taken close to its maximum possible value (~ 0.7 in the upper part of FI) [5] TFC ripple was overcompensated by FIs in the vicinity of outer plasma boundary even at the nominal toroidal field. At 2 times lower toroidal field, suggested for the hydrogen phase of operation, total ripple amplitude at the plasma separatrix was found to be at least twice as higher than produced by TFC alone.

The possibility to vary C_{ff} then was used to optimize FIs in ITER [8]. For this FI body was split for eight regions with uniform $C_{ff}^{i=1,8}$. Optimum set of C_{ff}^i , $0.23 < C_{ff}^i < 0.64$, was selected to satisfy simultaneously 2 requirements: all values of total ripple amplitudes at the specified point array along the plasma boundary should be positive at the nominal toroidal field (to avoid overcompensation), and these amplitudes should be minimal. In result, optimised FIs effectively suppress ripples at nominal as well as two times lowered toroidal field. Similar way of optimisation, by varying FI thickness, with similar effect was done in [7].

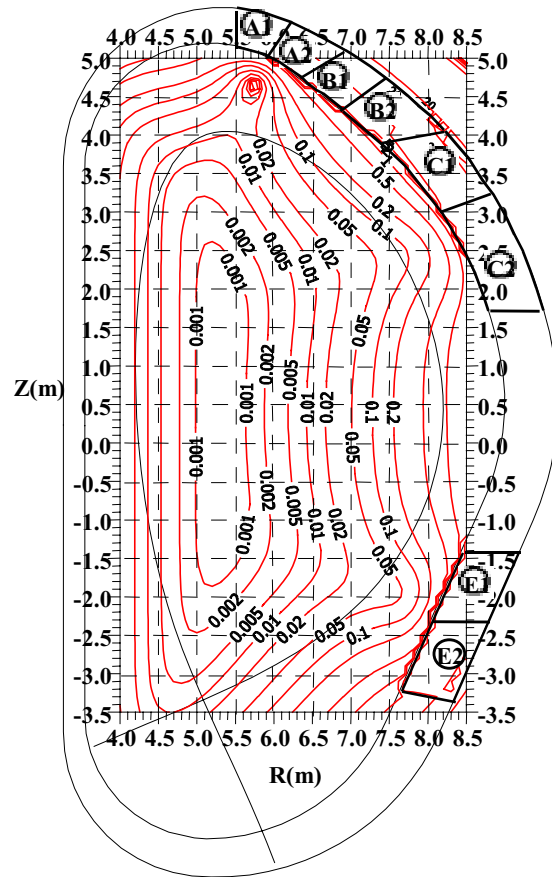


Fig.1 Total $\delta\%$ for optimised C_{ff}^i set at nominal toroidal field

Following calculations [7] revealed dramatic decrease of α loss (0.65% in WRS, broad S_α).

Amplitudes of the higher ripple harmonics at the plasma separatrix was found to be of order of 17% and 0.6% of fundamental one for the second and third harmonics, respectively [8]. Higher ripple harmonics steeply drop within the plasma. The effect of the higher ripple harmonics on the α -particle loss in the WNS scenario was studied in [7]. Calculations of [7] performed for the broad fusion profile have shown that total α -power loss was not changed within statistical errors when one, two or three ripple harmonics were accounted.

[1] ITER Physics Basis, Chapter 5 Section 3, Nucl.Fusion **39** (1999) 2475-2478.

[2] S. Konovalov et al., JAERI-Research 94-033, 1994.

[3] K. Tani, M. Azumi, R.S. Devoto, J. Comp. Phys. **98** (1992) 332.

[4] H.Kawashima et al., IAEA-CN-77/EX9/3, 18th IAEA Fusion Energy Conference, Sorrento, Italy, 2000.

[5] Alekseev et al., Efremov Design Office report, July 2000.

[6] Tobita K., report at the 8th ITER Expert Group Workshop on Energetic Particles, Heating and Steady State Operation, Frascati, Italy, Oct. 2000.

[7] Tobita K., report at the 9th ITER Expert Group Workshop on Energetic Particles, Heating and Steady State Operation, Garching, Germany, April 2001.

[8] A. Alekseev, et al, Efremov Design Office report, June 2001.