

ABSTRACT

The article describes the results of numerical simulation of the time evolution of plasma currents and runaway electrons (RE) during discharge failure in an ITER scale tokamak. A zero-dimensional approach similar to that of Martin-Solis et al. (2015) was used to solve a system of two differential equations for plasma and RE currents. The use of tungsten collector injection can significantly reduce the amount of RE in plasma after disruption. The requirements for the selection of collector parameters and injection characteristics are formulated in such a way as to ensure safer operation of the tokamak. The simulation results show that the most promising scenario for eliminating the consequences of discharge disruption is the simultaneous injection of several 80-gram tungsten collectors into the plasma at a speed of 250 m/s immediately after thermal failure (TQ).

INTRODUCTION

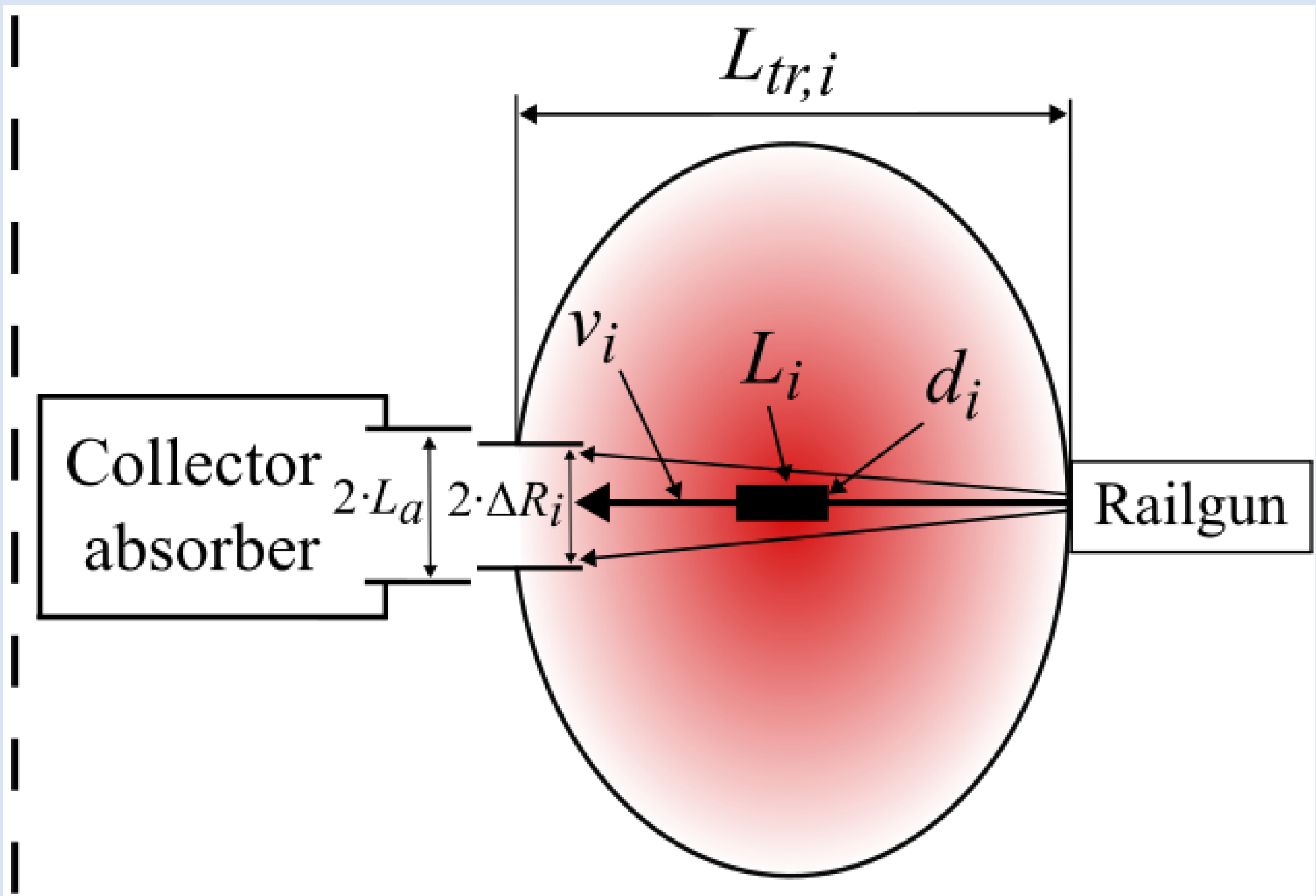
- Currently, one of the central problems of plasma magnetic energy output is the generation of an avalanche current of runaway electrons commensurate with the plasma current values after thermal quench. Disruption Mitigation Systems (DMS) are being developed to address these issues.
- To prevent an avalanche of RE, various ways of influencing plasma are being considered. A massive working gas injection is proposed, which can make it possible to suppress the avalanche current using a collision mechanism [1] with an increase in the initial density of the working gas up to 100 times. However, such an increase in the number of particles in the plasma can create a significant loads on technological systems such as pumping systems, isotope separation systems, etc.

COLLECTORS INJECTION SCHEMECXEMA /MODELING TASKS

When modeling the suppression of the avalanche current of ruaway electrons, three geometries of collector injection [2] were considered. The radial injection in the poloidal section is shown in the figure. The length of the collector trajectory is $L_{tr,i} = 4$ m. When selecting the parameters of collector injection, the requirements are formulated: 1) The IRE current should not exceed $I_{max} = 0.15$ MA; 2) Deviation from the rectilinear trajectory is less than $R_{max} = 1$ cm. 3) Collector temperature is less than $T_{max} \approx 2900$ K. The plasma current output at the CQ stage was modeled using a system of 0–dimensional equations [3] for the total plasma current $I_p(1)$ and the runaway electron current IRE (2)

$$\frac{dI_p}{dt} = -\frac{I_p - I_{RE}}{\tau_{CQ}}, \quad (1)$$

$$\frac{dI_{RE}}{dt} = \left(\frac{4\pi\epsilon_0^2 m_e^2 c^3 \sqrt{\frac{3(5+Z_{eff}CQ)}{\pi}}}{e^4 n_{eCQ}} \right)^{-1} \cdot I_{RA} \cdot \left(\frac{E}{E_R} - 1 \right) - I_{RE} \cdot \sum_{i=1}^{N_c} \frac{1}{\tau_i} \cdot H[t - t_i] \cdot H \left[\frac{L_{tr,i}}{v_i} + t_i - t \right]. \quad (2)$$



Radial injection schematic

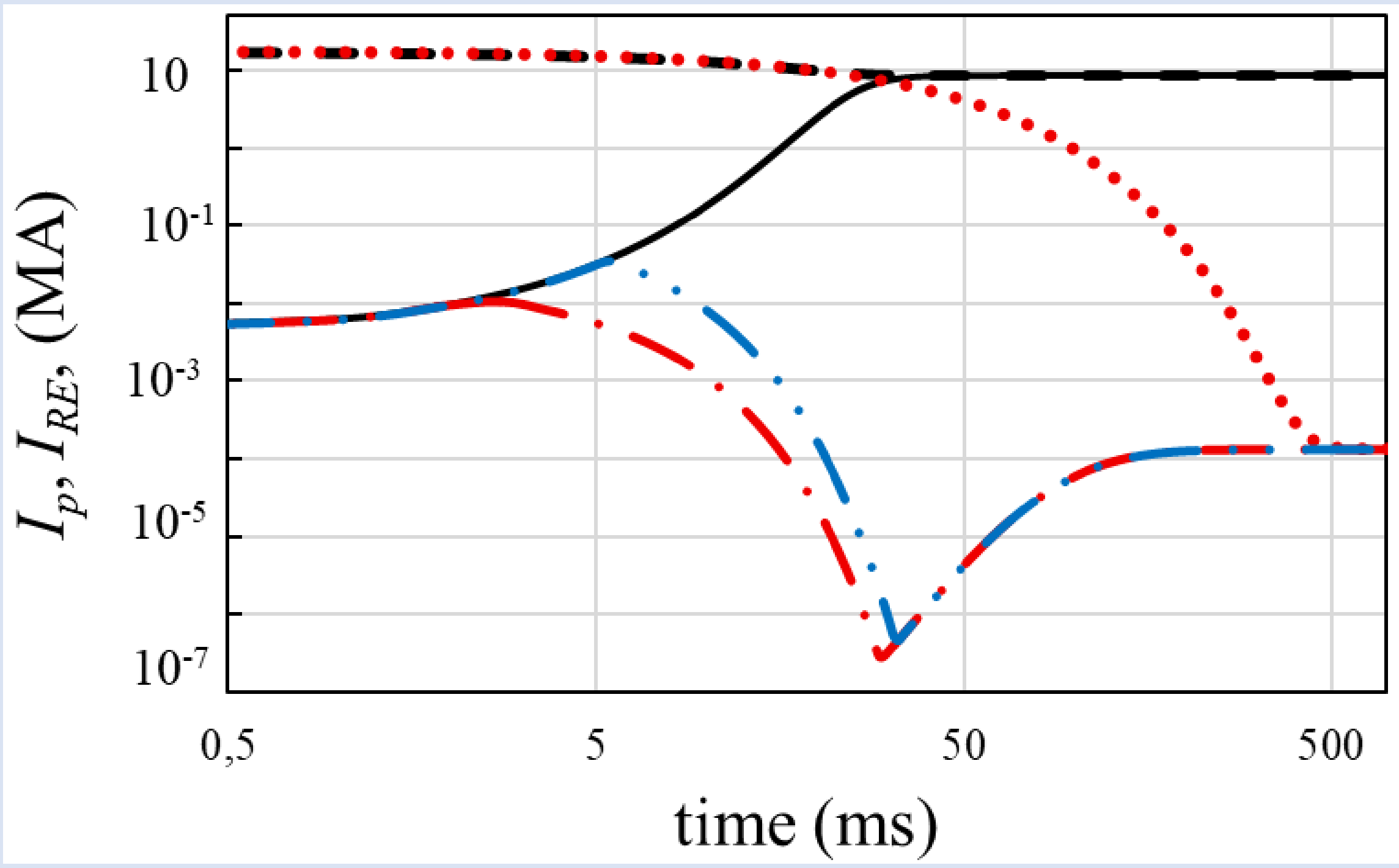
MODELING RESULTS

The collector parameters were selected during modeling in accordance with the three requirements formulated above. The simulation was performed for vertical, radial, and tangential collector trajectories. The interaction time of the collectors with the CQ plasma, $t = 27$ ms, was selected from the calculation of the characteristic current decay time CQ $t = 34$ ms. This allows you to find a range of collector speeds and masses in accordance with the three requirements and from a technical point of view of their acceleration. The figure shows that without collector injection, an unacceptably large avalanche current RE $I_{RE} = 56 \times I_{max} = 8.4$ MA is generated in scenario 1. In order to reduce the RE current and meet the formulated requirements, various injection scenarios were considered. As can be seen from scenario 2, the problem can also be solved by injecting a single collector with a sufficiently large mass. Acceleration difficulties increase as the mass of the collector increases. Therefore, scenario 3 with the injection of two collectors of the same mass and scenario 4 with the injection of three collectors with a reduced mass of almost two times was considered. Such injections satisfy all the formulated requirements.

Parameters of collectors for radial injection

№	N_c	v_i , M/c	d_i , MM	L_i , MM	m_i , KГ	T_i / T_{max}	$\Delta R_i / \Delta R_{max}$	I_{RE} / I_{max}
1	-	-	-	-	-	-	-	56
2	1	150	11	110	0.2	0.75	0.2	0.86
3	2	150	11	110	0.2	0.2	0.04	$1.1 \cdot 10^{-5}$
4	3	150	8	80	0.08	0.33	0.08	$1.3 \cdot 10^{-3}$

Evolution of total current and avalanche current during injection of 3 collectors with a delay of 2 ms and 5 ms



CONCLUSIONS

- To ensure the safe operation of an ITER scale tokamak in conditions of large discharge disruption, requirements for collector injection parameters were formulated. Based on these requirements, injection scenarios for collectors were modeled. In addition, various geometries of collector injection trajectories were considered. The most promising scenario involves simultaneous injection after TQ of three collectors weighing 80 grams each.
- Even in the event of an emergency, if one of the three collectors has not been injected, all the requirements for safe discharge termination are still met.
- The allowable delay in collector injection time is from 2 to 5 ms, depending on the injection trajectory.

REFERENCES

1. S. Putvinski et al., Journal of nuclear materials. 241 (1997) 316-321.
2. V. Y. Sergeev, B. V. Kuteev, Nuclear Fusion. 61 (2021) 086021.
3. J. R. Martín-Solís, A. Loarte, M. Lehnen, Physics of plasmas. 22 (2015) 082503.