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Role of radiation loss in transport processes in self-organized plasmas in toroidal devices

At many tokamaks in regimes with additional heating, improved plasma confinement after injection of impurities (helium, neon, argon) has been observed [1–3]. Despite an obvious increase in radiation loss, both plasma energy, and energy lifetime increase. This phenomenon of increasing plasma energy lifetime after the injection of impurities and the corresponding increase in radiation loss is being actively studied both experimentally and theoretically [4]. It has been described as the transition to the radiative improved (RI) mode [5].

These experiments inspired us to find out whether improving plasma confinement with increasing radiation loss could be observed at the L-2M stellarator.

The L-2M stellarator is a classical two-turn stellarator (number of helical windings $l = 2$, number of field periods around the torus $N = 7$) with major radius $R =$ 1 m, plasma radius $a = 0.115$ m, and magnetic field $B_0 =$ 1.34 T near the axis of the plasma column [6]. In experiments on electron cyclotron resonance heating (ECRH) , pulsed microwave radiation was used to create and heat plasma. Ohmic heating was not used. ECRH was performed at the second harmonic of the plasma electron gyrofrequency (microwave radiation frequency 75 GHz). At L-2M, the ECRH power can vary in the range of $P_{ECRH} =$ 100–1000 kW, and the chord-averaged plasma density can be $n_e = (1–3) \times 10^{19}$ m^{-3}.

The L-2M experiments described here were conducted without special injection of impurities. All impurities

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At many tokamaks, plasma energy confinement improves after impurities are injected and increased radiation loss is observed. We have experimentally studied whether this effect is observed at the L-2M stellarator. We ascertained that at L-2M, over a range of operating parameters, the energy lifetime does not depend on the radiation loss power. We analyzed plasma confinement in L-2M in the ECRH regimes at different powers of radiation loss. Analysis of the data obtained at L-2M made it possible to advance a hypothesis concerning the mechanism for improving plasma confinement in tokamaks when there is increasing radiation loss. 1

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penetrate into the plasma from the vacuum chamber wall. In this study, the L-2M database was used, which includes experiments conducted both with and without boronization of the vacuum chamber walls. The working gas in these experiments was hydrogen. During experiments with boronization of the vacuum chamber, mainly boron penetrates into the plasma from the wall, and to a lesser extent, carbon. In experiments with boronization, the level of radiation loss is 10–20% of the input microwave power. Without boronization, the main impurities coming from the wall are carbon and oxygen. In such experiments, the level of radiation loss increases to 50% of the input power. In the experiments under consideration, the limiter was not used, and the plasma size was determined by the separatrix. No high-*Z* impurities were observed in these experiments. The impurity composition was monitored by spectroscopic diagnostics. No measurements of the radiation loss profile were performed. However, it is obvious that at central electron temperatures in the range of 700–1000 eV in L-2M, the observed boron, carbon, and oxygen impurities radiate mainly at the plasma edge.

We also investigate how radiation loss affects plasma confinement in the L-2M stellarator in the quasi-stationary phase. We used the databases on chord-averaged plasma density and ECRH power (Fig. 1a) and radiation loss and ECRH power (Fig. 1b) for quasi-stationary stages of L-2M shots in the on-axis ECRH regime, in which the average plasma density, radiation loss, and ECRH power vary in wide ranges: $0.5 \bullet 10^{19} \leq \bar{n}_e \leq 3 \bullet 10^{19}$ m^{-3}, $10 \leq P_{rad} \leq 270$ kW, and $100 \leq P_{ECRH} \leq 600$ kW, respectively.

Figure 2 shows the experimental dependence of the normalized energy lifetime on the radiation loss power in the quasi-stationary stage of L-2M shots. Here, radiation loss power is normalized to ECRH power. The figure demonstrates that plasma confinement time in the L-2M stellarator (energy lifetime) does not depend on the radiation loss power in a wide range of the radiation loss power variation.

This result does not agree with the data for the T-10 [3] and TEXTOR [5] tokamaks. At T-10, with increasing radiation loss power, a linear increase and further saturation of the τ_E^{exp} (P_{rad}/P_{ECRH}) dependence was observed. At TEXTOR, the energy lifetime increased after injection of impurities.

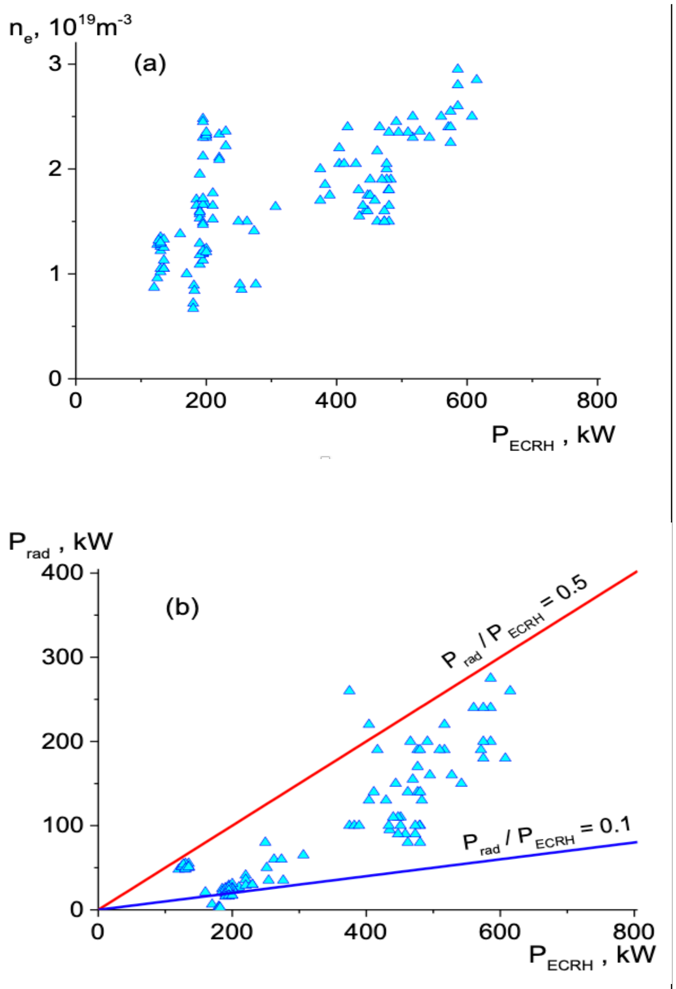

Fig. 1. Data on (a) chord-averaged plasma density and ECRH power and (b) radiation loss and ECRH powers in quasi-stationary stages of L-2M shots.

Analysis of the data obtained at the L-2M stellarator made it possible to advance a hypothesis concerning the mechanism for improving plasma confinement in tokamaks with increasing radiation loss. It explains the experimental data obtained at all three facilities: TEXTOR, T-10, and L-2M.

In both tokamaks and stellarators, a self-organization mechanism maintains the plasma in a state with minimal energy flows directed outward across the plasma boundary. This state corresponds to the so-called canonical plasma pressure profiles [7]. When impurities

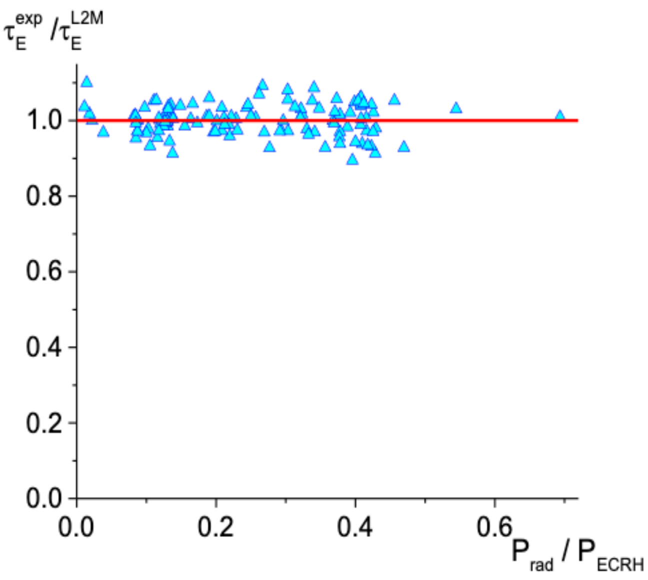

Fig. 2. Normalized plasma energy lifetime as a function of relative radiation loss power P_{rad}/P_{ECRH} in the quasi-stationary stage.

are injected, radiation loss at the plasma edge increases, but the total energy loss out of the plasma remains constant, because it is determined by the processes of plasma self-organization. This was experimentally demonstrated at the L-2M stellarator [8]. In this case, energy flow is redistributed between loss channels, and an increase in radiation loss does not lead to an increase in the total energy loss and deterioration of plasma energy confinement. This is exactly what was observed in experiments at the L-2M experiments under consideration.

This mechanism works much the same way at tokamaks, without causing deterioration in plasma confinement after impurities are injected. In tokamaks, another mechanism, not associated with self-organization, results in improvement of plasma confinement after injection of impurities. In tokamak plasmas, an increase in radiation loss caused by the injection of impurities leads to changes in the current profile at the plasma edge due to the following mechanism. In the edge plasma, an increase in radiation loss results in a decrease in both the electron temperature and its conductivity, which causes a local decrease in the plasma current at the plasma edge and a corresponding increase in the ratio of safety factors q_b/q_0. Thus, in experiments with injection of impurities at the T-10 and TEXTOR tokamaks, the plasma current profile changed, as did the gradient of the safety factor at the plasma edge. Turbulence at the plasma edge was reduced. This resulted in an increase in the plasma energy lifetime after the injection of impurities. Similar improvement of plasma confinement occurred in experiments at the Tuman-3 tokamak, with a sharp decrease in the plasma current at the plasma edge without impurity injection [9].

We consider the mechanism that causes an improvement in plasma energy confinement after a local decrease in the plasma current at the edge by one means or another. We believe that an increase in the safety factor at the edge results in a suppression of plasma density fluctuations in this region and a decrease in the particle and energy flows transferred due to fluctuations, and, consequently, in an increase in the energy lifetime. The mechanism for suppressing this type of turbulence is associated with the presence of a shear of poloidal velocity of plasma rotation in crossed fields: inhomogeneous radial electric field and toroidal magnetic field. It is known [10] that the turbulence suppression criterion has the form $\gamma < \omega_{E\times B}$, where

$$\omega_{E\times B} = \left|\frac{RB_\theta}{B_T}\frac{\partial}{\partial r}\left(\frac{E_r}{RB_\theta}\right)\right|$$

is the shear of poloidal rotation velocity, γ is the turbulence growth rate, B_T and B_θ are the toroidal and poloidal components of the magnetic field, E_r is the radial component of the electric field, and R and r are the major and minor plasma radii. Based on the known definition of the safety factor, $q(r) = B_T r/B_\theta R$, the expression for the shear of the poloidal rotation velocity is often presented in the following form [11]:

$$\omega_{E\times B} = \left|\frac{B_T}{q(r)/_r}\frac{\partial}{\partial r}\left(\frac{E_r}{B_T}\frac{q(r)}{r}\right)\right|.$$

From this expression, it follows that with increasing gradients of both the radial electric field and the safety factor, the shear of the poloidal rotation velocity increases and, as a consequence, turbulence is suppressed. Thus, an increase in the ratio of safety factors q_b/q_0 (due to an increase in q_b) should result in suppression of turbulence and corresponding improvement in plasma energy confinement. We note that in experiments on impurity seeding in tokamaks, the radial electric field can also change. We are not aware of experimental data on changes in the radial electric field after impurity seeding. Since the magnetic configuration of the L-2M stellarator is created by external conductors, the profile of the rotational transformation angle ($\iota = 1/q$) does not depend on processes occurring in the plasma, such as an increase in radiation loss or a change in temperature at the plasma edge. Therefore, the mechanism for suppressing turbulent loss discussed above does not work in the stellarator, and no improvement in energy confinement involving this mechanism is observed. However, due to the mechanism of plasma self-organization, no deterioration in plasma confinement occurs with increasing radiation loss, since energy is redistributed between loss channels while the total heat flow out of the plasma remains constant.

We note that this explanation of the improvement in plasma confinement in experiments with impurity injection is suggested for tokamaks with limiters. Its applicability to tokamaks with divertors can be ascertained only based on further studies.

In summary, we experimentally showed that, at the L-2M stellarator, energy lifetime does not depend on radiation loss power in the quasi-stationary stage of discharges. The increase in radiation loss that occurs at the plasma edge due to impurities does not lead to deterioration in plasma confinement, since self-organization mechanisms redistribute energy between loss channels while maintaining the total heat flow outward.

It would seem that in tokamaks, in which self-organization processes operate in exactly the same way as in stellarators, with increasing radiation loss, the energy lifetime should also remain unchanged. However, this does not agree with experimental data from tokamaks, for which an improvement in energy confinement is observed after impurities are injected. We have proposed a mechanism for the increase in energy lifetime after the injection of impurities into tokamaks. This mechanism is associated with the suppression of turbulence by the shear of the poloidal rotation velocity of the plasma. The proposed mechanism eliminates the seeming contradiction between experimental data from tokamaks and stellarators on the dependence of energy lifetime on radiation loss power.

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Type One Energy prepares to build testbed

Type One Energy is preparing to begin construction on Infinity One, its first prototype stellarator, which is set to be the world's most advanced device of its kind. Once completed, Infinity One will verify crucial design features for the company's future high-field stellarator Fusion Pilot Plant (FPP), including operating efficiency, reliability, and affordability.

The project is being developed at the site of the recently decommissioned TVA Bull Run Fossil Plant (Fig. 1), symbolizing a shift from fossil fuels to cleaner, sustainable energy solutions. The repurposing of this site aligns with Tennessee's broader goals of decarbonization and innovation in energy technologies.

The company expects Infinity One to play a critical role in demonstrating that fusion energy can be both reliable and scalable. Specifically, Infinity One's core missions are to:

- prove the efficacy of modular high-temperature superconducting (HTS) magnet systems for stellarators,
- evaluate stellarator performance in the presence of a reactor-relevant metallic first wall,
- verify and quantify plasma turbulence reduction, and
- confirm improved divertor exhaust efficiency.

The device design builds on recent breakthroughs in theoretical and numerical methods for stellarator optimization, which have enabled the stellarator community to identify configurations with record-low neoclassical transport, as well as reduced turbulent transport.

Type One Energy is currently considering a baseline scenario for Infinity One, selected to accomplish FPP-relevant objectives in a cost-efficient way and within tight schedule constraints. Key physical parameters for this baseline scenario are given in the second column of Table 1. The scenario involves plasma heating by electron cyclotron resonance heating, the use of auxiliary coils for scenario development and to maximize operational flexibility, and mostly hydrogen-fueled discharges, with only a limited number of deuterium-fueled discharges in order to minimize activation.

As shown in the third column of Table 1, the company is also evaluating the merits of an expanded size and magnetic field strength for Infinity One, to access higher absolute performance and enhanced core-edge integration tests.

In addition, Type One has also established its new headquarters in Knoxville, TN, under Project Infinity, a collaboration between Type One Energy, the Tennessee Valley Authority (TVA), and the U. S. Department of Energy's Oak Ridge National Laboratory (ORNL) to explore opportunities to further advance commercial deployment of fusion energy in the East Tennessee region. Type One is also the first recipient of funding through the $50 million Nuclear Energy Fund, which was proposed by Gov. Bill Lee and approved by the Tennessee General Assembly in the 2023–2024 budget.

Parameter	Notional Baseline	Expanded scope options
R (m)	2	3
a (m)	0.3	0.45
B (T)	3	5
P (MW)	4	> 10
t_{pulse}	10 s	24 hrs

Table 1. Design parameters for Infinity One baseline and expanded scope scenarios,

The decision to base the company's headquarters in Knoxville is part of a broader strategy to support long-term growth and collaboration with local research institutions, including ORNL and the University of Tennessee. This positioning provides access to a wealth of scientific resources, which will aid in further advancing the technical capabilities of Infinity One.

In late July, Type One Energy closed an oversubscribed $82 million financing round, one of the largest ever in the energy sector. Among the largest investors of this round are Bill Gates' Breakthrough Energy Ventures (BEV), GD1 from New Zealand, and Centaurus Capital.

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Fig. 1. Bull Run Coal plant. The tall smokestack was replaced by the smaller one that supposedly only emitted steam. Note the huge mountain of coal in the background. In case fusion does not work, there is an alternative source of fuel.

W7-X starts new experimental campaign (press release)

After a one-year maintenance phase, the world's largest and most powerful stellarator resumed experimental operation with significant improvements. One of the goals: The plasma temperature is to be increased step by step.

After Wendelstein 7-X generated a record plasma in February 2023 (lasting 8 minutes with a power output of 1.3 gigajoules), the stellarator at the Max Planck Institute for Plasma Physics (IPP) in Greifswald was shut down as planned. Since then, the Wendelstein 7-X team has extensively maintained the machine and added new modules.

W7-X will now start the new experiment phase OP2.2 on 10 September 2024, having been significantly optimized. Numerous extensions, improvements and repairs were made to Wendelstein 7-X itself, the control and data acquisition systems, the heating systems and the almost 50 different plasma diagnostics. An important goal was to significantly improve the availability and reliability of the systems, for which a systematic failure mode analysis was carried out. In addition, the scientific capabilities of all systems were significantly expanded and important new observation instruments were added.

Two of the most important enhancements:

- A heating element (gyrotron) is now available, which can generate significantly more than 1 MW of power into the plasma via microwaves. This electron cyclotron resonance heating (ECRH) method emits microwaves into the plasma at the exact frequency at which the electrons in the plasma circulate on helical paths around the magnetic field lines. Previously, Wendelstein 7-X had ten such modules, whose output over several minutes of operation was less than 1 MW each. A total of 7.5 MW was possible over several minutes. The new module can feed up to 1.5 MW into the plasma at peak times. Twelve such elements are to be available for future operating phases. This will significantly increase the maximum ECRH output. ECRH is the most efficient and most important type of heating in long-pulse operation. The new ECRH module was developed by the Karlsruhe Institute of Technology (KIT) and the Munich-based company Thales. It is the most powerful gyrotron in the world. The W7-X team also has the ion cyclotron heating and the neutral particle beam heating at its disposal.

- The new steady-state pellet injector will also be used for the first time. It was built at the Oak Ridge National Laboratory, a research centre of the U. S. Department of Energy (DOE), especially for W 7-X and is a world leader in its category. It is used to ensure the supply of hydrogen particles into the plasma—an important step on the way to a nuclear fusion power plant. The pellet injector produces long rods of frozen hydrogen, from which small pellets are regularly cut off at intervals of fractions of a second in order to shoot them into the plasma at high pressure, as in a blowpipe.

Aims of the new experimental campaign

The extensive scientific program of the new measurement phases OP2.2 and OP2.3 is primarily concerned with gradually increasing the performance parameters for the generated plasmas. In the last measurement phase OP2.1, it was possible to briefly heat the ions in the plasma to around 35 million degrees Celsius (plasma physicists express this as 3 kiloelectronvolts) and exhaust the heat energy in a controlled manner via the divertor (the most heat-resistant component). In future, this should be possible over periods of several minutes at higher plasma temperatures. “We are gradually approaching higher heating powers,” says IPP Director Prof. Thomas Klinger. “On the one hand, the aim is to carefully test the heat load limits on the carbon walls of W7-X. On the other hand, we want to understand turbulence-controlled transport processes in the plasma and the exhaust of heat and particles.”

Unlike in the last phase of the experiment, the W7-X team is not aiming for new records for the plasma duration, but aims to increase the energy throughput. “It would be possible, but of little scientific value, to generate long plasma pulses at low power values now,” explains Prof. Klinger. “The aim is to achieve long pulses at high plasma temperatures. And that’s what we’re working on right now.”

The current schedule for the next experimental phases of Wendelstein 7-X:

OP2.2: September 2024 – December 2024
OP2.3: February 2025 – May 2025
Maintenance: June 2025 – August 2026
OP2.4: August 2026 – December 2026
OP2.5: February 2027 – May 2027

Posts of interest

Internet posts that the Editor deems of interest:

- Fusion’s public-relations drive is obscuring the challenges that lie ahead.
- Peter Gwynne, “US plasma physicists propose construction of a ‘flexible’ stellarator facility,” Physics World, 26 July 2024, https://physicsworld.com/a/us-plasma-physicists-propose-construction-of-a-flexible-stellarator-facility/ (report on the white paper by Parra et al.)
- -F. I. Parra et al., “Flexible Stellarator Physics Facility,” https://arxiv.org/abs/2407.04039.
- National Stellarator Coordinating Committee, “The Compelling Need for a Mid-Scale Stellarator Facility,” https://www.osti.gov/servlets/purl/2370175.
- Prototype fusion reactor planned for TVA site.