Objectives, physics requirements and conceptual design of an ECRH system for JET

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Abstract. A study has been conducted to evaluate the feasibility of installing an ECRH system on the JET tokamak. This paper presents an overview of the studies performed in this framework by an EU-Russia project team. The motivations for this major upgrade of the JET heating systems and the required functions are discussed. The main results of the study are summarised. The usefulness of a 10MW level EC system for JET is definitely confirmed by the physics studies. Neither feasibility issues nor strong limitations for any of the functions envisaged have been found. This has led to a preliminary conceptual design of the system.

1. Introduction

The future JET programme [1], after the installation of the ITER-like wall [2], will be mainly focused on the consolidation of the physics basis of the three main ITER scenarios, i.e., the ELMy H-mode, the hybrid scenario and the advanced steady-state scenario [3]. In ITER, these scenarios will make substantial use of Electron Cyclotron (EC) waves, for heating as well as for control of both the MHD activity and the current density profile [4,5]. Therefore, a programme for preparation, validation and optimization of the ITER scenarios in present tokamaks would strongly benefit from, and even require, an ECRH/ECCD system. This gives a strong motivation for examining the feasibility of the construction and implementation of such a system in JET by 2014-2015, for an intensive exploitation before the start of ITER. The possibility of implementing an ECRH system on JET has already been considered in the

* See the Appendix of F. Romanelli et al., paper OV/1-3, this conference

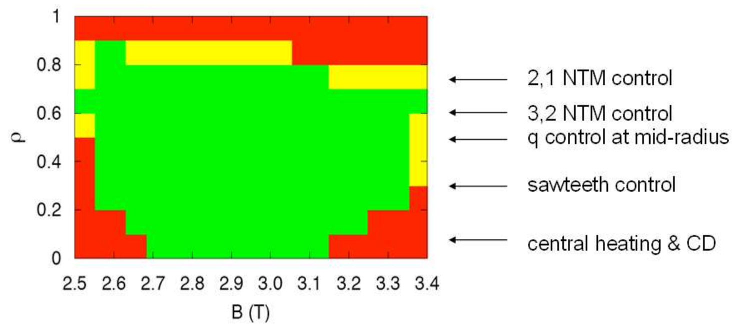
past [6]. The 2000-2002 project is of course a good basis for the new feasibility study, however, changes in the general context and evolutions of motivations, physics and technology in this area had to be taken into account. Involvement of the Russian Federation in the construction and the operation of the system is considered a key element for the success of the project, and Russian scientists have actively participated in the feasibility study. Synergies with the development of the ITER ECRH system [7], and especially with the elements corresponding to European procurements, have been systematically pursued, in particular through the involvement of scientists from ITER IO and F4E (the European ITER Domestic Agency).

This paper reports on the results of these feasibility studies for a JET ECRH system, carried out under bilateral agreement between the European Union and the Russian Federation. Both physics studies, aiming at a definition of the basic parameters of the system (wave frequency, launching geometry, power required), and exploration of the main technical options (wave generation and transmission, antenna design, power supply, auxiliaries, layout and port allocation, control systems, diagnostics) have been performed in parallel. A preliminary assessment of cost, time schedule, manpower and risks has been made.

2. Physics requirements studies

The main functions of an ECRH system on JET can be summarized as follows: i) Central electron heating – to equilibrate electron and ion temperature, to scan the electron/ion power share up to ITER relevant values and to control impurities. ii) Current profile control – to improve the performance and stationarity of advanced and hybrid scenarios. iii) Sawtooth control – to shorten sawteeth through local current drive near the q=1 surface and hence avoid triggering Neoclassical Tearing Modes (NTM). iv) NTM suppression through local current drive at the relevant rational q surface. These objectives were translated into the requirement to heat the plasma or drive currents at various plasma minor radii. In order to fulfil all the objectives, the system should be able to deposit the ECRH power over almost the full range of plasma minor radii. For MHD control, the width of the deposition profile is also an important parameter. As the ECRH power is absorbed at or near the Electron Cyclotron Resonance, the physics objectives can only be fulfilled for a selected range of toroidal magnetic fields.
Several state-of-the-art codes have been used to perform these studies, in particular the beam-tracing code GRAY [8] and the integrated modelling suite CRONOS [9]. Two recent JET discharges, both with parameters compatible with the ITER-like wall, have been identified and chosen as reference discharges for the simulations: discharge 73344 (for H-mode and hybrid scenarios) and 77895 (for advanced scenarios).

Wave propagation and absorption. The first aim of the study was to determine the best choice of operating frequency [10]. Two gyrotron options were considered: either 1) dual frequency gyrotrons (113GHz, 150GHz) as used on ASDEX Upgrade with minor modification to increase the frequency; or 2) the 170GHz gyrotrons developed for ITER. The study produced a comprehensive evaluation of the minor radii accessible as a function of toroidal field for the two options. The results showed that the 113GHz, 150GHz option allowed good performance for toroidal fields below 2.7 T (2^{nd} harmonic extraordinary mode at 150GHz) and for fields above 3.3 T (fundamental ordinary mode at 113GHz) while operation around 3 T would be difficult with this frequency choice. Choosing 170GHz (2^{nd} harmonic, extraordinary mode) would on the other hand allow excellent performance in the interval 2.7-3.1 T with off axis current drive available in a significantly wider range (see Fig. 1). Given that the largest fraction of JET operation is foreseen to use toroidal fields around 3 T it was decided to focus the further studies on the use of 170GHz gyrotrons. Furthermore, this frequency choice allows JET to take full advantage of the significant efforts which have been and are being made in designing components for the ITER ECRH system. With this choice of gyrotron frequency the injection angles required to fulfil the objectives were found to be: toroidal: -25° - +25° , poloidal range: 30° around an appropriate mean value.



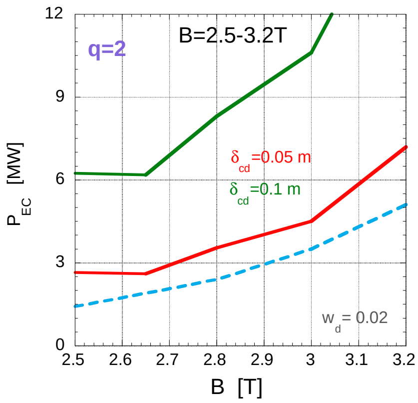


FIG. 1: Operation diagram for a JET ECRH system at 170 GHz, computed for a reference H-mode scenario. Green means that the envisaged funtions (listed on the right) are possible, red not possible, yellow marginally possible

FIG. 2: EC power needed for suppression of the (2,1) mode. Dashed line corresponds to the driven current widths δ_{cd} computed by beam-tracing; solid lines to the fixed values δ_{cd} = 0.05 and 0.1 m.

NTM stabilisation. Use of localised ECCD has been considered for stabilisation of (3,2) and (2,1) modes in H-mode scenarios [11]. The beam-tracing results have been used in connection with the generalised Rutherford's equation [12] to study the evolution of the magnetic island width in the presence of ECCD. It is found that EC power < 5-10 MW is sufficient for full island suppression in most cases of interest, without power modulation, provided the driven current is localised in a radial range < 10 cm. Note that beam-tracing calculations predict typical CD radial width of 5 cm for a single beam, however the superposition of multiple beams will make this requirement challenging. The EC power necessary for full suppression of the (2,1) island is shown vs magnetic field in Fig. 2.

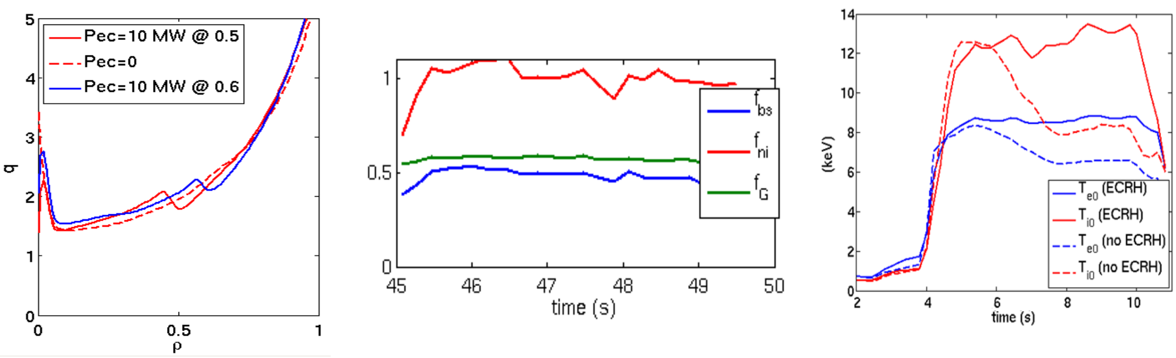


FIG. 3: Predictive simulations of a JET advanced scenario by the CRONOS code. Left: safety factor without and with ECCD at two different locations (ρ ~ 0.5 and 0.6). Middle: bootstrap, non-inductive and Greenwald fractions vs time, with ECCD at ρ ~ 0.6. Right: time evolution of electron and ion temperatures with and without ECCD at ρ ~ 0.6. (B_0 = 2.7 T, I_p = 1.8 MA, P_{NBI} = 22.5 MW, P_{ICRH} = 6.5 MW, P_{LH} = 2 MW)

Sawtooth control. Beam-tracing calculations combined with ASTRA transport simulations [13] and the Porcelli model [14] have been used to estimate the power required in order to have a significant impact on the sawtooth period for the H-mode scenario. It is found that

ECCD localised close to the q = 1 surface can be used, counter-CD being more effective than co-CD. A power of the order of 2.5 MW is sufficient to double the sawtooth frequency.

Integrated modelling of JET scenarios with EC waves. The CRONOS code has been used for integrated modelling of full JET scenarios. Both interpretative and predictive simulations (using the Bohm/gyro-Bohm transport model [15]) of the reference discharges have been performed, in order to test the predictive capability of the code with respect to the current and temperature profiles. Benchmarks with the JETTO code have been done for the H-mode reference discharge. Scenarios at higher heating power and with ECRH/ECCD have then been simulated. It is found that a wave power of the order of 10 MW, absorbed in the central plasma region, is adequate in order to equilibrate electron and ion temperatures in the H-mode scenario. For advanced scenarios, 10 MW of off-axis ECCD is marginally adequate to significantly modify the q profile (see Figure 2). These calculations also indicate that fully non-inductive discharges at high power and density can be achieved. Nevertheless, a full inversion of the q profile inside the radius of ECCD absorption does not seem possible, owing to the dominant contribution of the current driven by the NBI power [16]. Note that with the use of LHCD in the current ramp-up phase an ITB can be triggered, however it is lost after a few seconds (Fig. 3 right, dashed lines). The use of off-axis ECCD allows to sustain this ITB for much longer times (solid lines).

3. System components and conceptual design

Gyrotrons. Availability of adequate power sources (1 MW / 20 s) produced by the Russian partners has been investigated. IAP/GYCOM can provide gyrotrons satisfying the requirements for both frequency options [17]. A 170 GHz gyrotron of this type already exists: it is the tube developed for ITER, which has already attained performances exceeding 1 MW, 200 s pulse duration, 50 % efficiency [18]. A double-frequency 113-150 GHz gyrotron would require a modest development with respect to the existing 105-140 GHz tubes developed for Asdex-U. The present industrial production capability of GYCOM is of 5 tubes per year. The delivery of 12 gyrotrons for JET would be favourably phased with respect to that of 8 gyrotrons for ITER. Therefore, the production of 12 gyrotrons in 4 years appears a reasonably achievable target, with minimum risk.

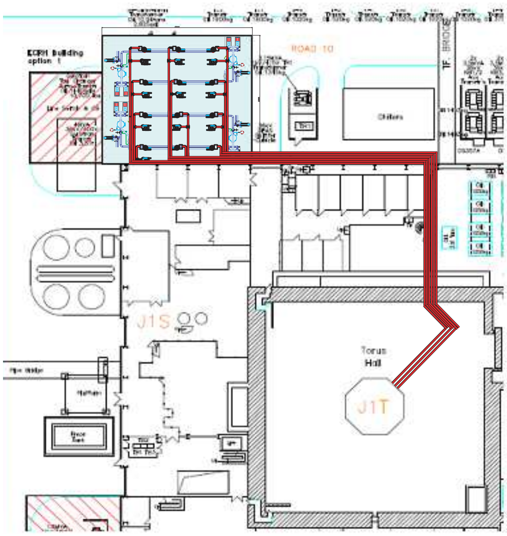


***FIG. 4**: sketch of the plant layout and waveguide routing from the gyrotron building to the tokamak*

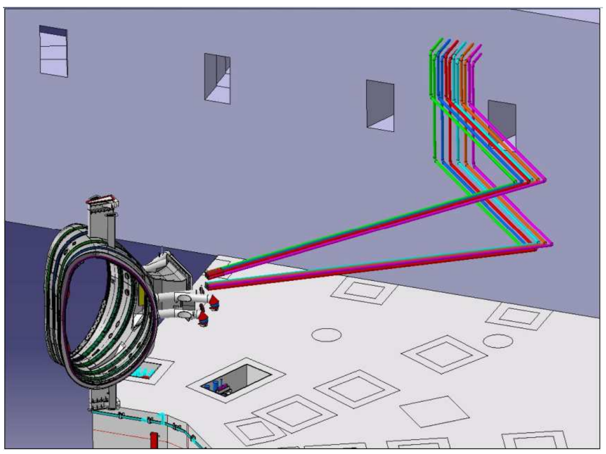


***FIG. 5**: preliminary design of the waveguide system in the JET Torus Hall, from the North wall to Octant 2.*

Layout and port allocation. Finding an adequate port and location for the EC system in the present JET environment is not easy. Four port options have been identified: Octants 1, 2, 5, or 6. Octant 2 could be a simple solution in the case of removal of the ITER-like ICRH antenna. Octant 6 would require relocation of several diagnostics, a problem that would be minimised in the case of Octants 1 or 5. Four different locations for the EC system (gyrotrons with auxiliaries and power supplies) have been identified, most of them requiring the construction of new buildings. A floor area requirement of at least 400 m^2 has been estimated, in 2 storeys. All of the possible locations require removal of existing equipment. Octant 2 has been chosen as the reference port allocation for the ECRH antenna ; consequently, a gyrotron building located north of J1 is the best solution [19]. A sketch of the plant location and waveguide routing from the ECRH building to Octant 2 is shown in Fig. 4.

Transmission lines. The basic question of choice between quasi-optical and waveguide transmission has been addressed. Although in the considered frequency range the two options could be equivalent for a system and a machine environment to be designed from scratch, the quasi-optical approach seems difficult to implement in the very busy environment of JET and complying with the safety requirements connected with tritium operation. The ITER-relevant evacuated waveguide solution is now considered preferable from the technical, safety and cost points of view and has been used as a reference solution for the JET ECRH system. A study of the waveguide routing has been performed [20], and a sketch is shown in Fig. 4. The best solution is a transmission line of length ~75m, with only 6 bends and expected attenuation of 4.1 %. A preliminary design of the transmission lines in the Torus Hall is shown in Fig. 5.

Windows. Diamond windows are the only viable solutions, owing to the power / pulse length combination. Since 170 GHz is chosen, the same windows used for the ITER ECRH system could be employed, with substantial synergy with ITER. The use of two windows per line (for tritium segregation) has been considered [20]: in this case, two separate windows (one at the entrance of the Torus Hall and the other at the vacuum vessel) are preferable to a double window, from the safety point of view. The time to produce such a large number of windows (24) is presently difficult to determine and could be a source of delay. The single window solution has also been investigated and a thorough assessment has concluded that installing a single diamond window in each waveguide near the torus is sufficient for tritium containment. To reduce the risk of contaminating the line with tritium in the case of window damage, a valve, permitting the window to be removed without breaking the JET vacuum, is required. Another valve situated near the torus hall wall will isolate the torus hall from the rest of the world when the line in the torus hall is disconnected as will be required for certain JET shutdown activities. The behaviour and lifetime of these windows is a significant element of risk, but also a contribution of risk reduction for the ITER ECRH system.

Launcher. Possible options for a launcher design have been analysed, with the following requirements: plug-in launcher fitting in an equatorial port, 12 waveguides, toroidally and poloidally steerable actively cooled mirrors, use of the ITER steering mechanism [21] for at least one of the two movements. Available space in the port and the port shape suggest considering a two-module system, i.e., one set of mirrors in the upper part of the port and one in the lower part, each launching 6 beams, with the 12 waveguides grouped in the middle of the port. On this basis, three main options have been considered [22], all of them using the ITER steering mechanism for the poloidal movement (which should be controlled in real time) and a simpler solution for the toroidal movement, on a shot-to-shot basis. Fig. 6 shows the option selected for conceptual antenna design with the ITER steering mechanism located at the back of the port where more space is available. Only the upper module of the antenna is shown, the lower module being the mirror image of the upper one. The antenna relies on the propagation of Gaussian beams emitted by waveguides terminated at the port back plate. From the waveguides the beams diverge until they encounter fixed focusing mirrors which direct the beams, in groups of 6, onto a plane poloidal steering mirror mounted on the ITER steering mechanism. Rotating this mirror around a horizontal axis allows control of the poloidal injection angle. After the poloidal steering mirror, the beams encounter the toroidal steering mirror; a large vertical mirror that can be rotated around a vertical axis for toroidal injection angle control. For co-current drive the beams are injected directly from the toroidal steering mirror. By rotating the toroidal steering mirror beyond the point corresponding to the maximum positive toroidal injection angle the beams will be reflected by the final vertical mirror allowing counter-current injection. A possible arrangement of the poloidal and toroidal steering mirrors is shown in Fig. 7. The waveguides will be terminated in tapers to improve the purity of the emitted Gaussian beams [23]. Tapers and focusing mirrors are designed to minimise the beam size in the plasma. The design of a mechanical port plug structure to support the antenna mirrors, a preliminary version of which is shown in Fig. 8, has started. Finite element computations assessing the structural integrity of this design are proceeding, with the same codes and methods that are being used for the ITER Upper Launcher design [24]. An example of the deformations of the plug structure due to electromagnetic forces associated with disruptions is shown in Fig. 9.

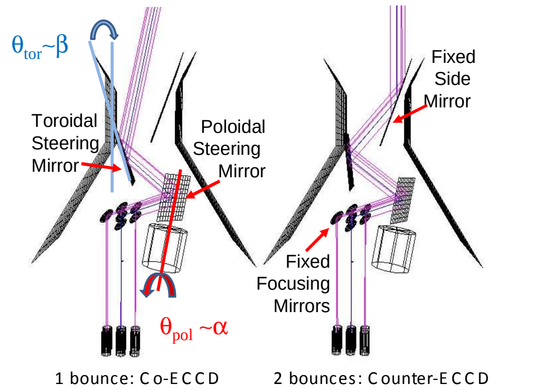


***FIG. 6**: sketch of one module (6 wave beams) the JET EC launcher (top view)*

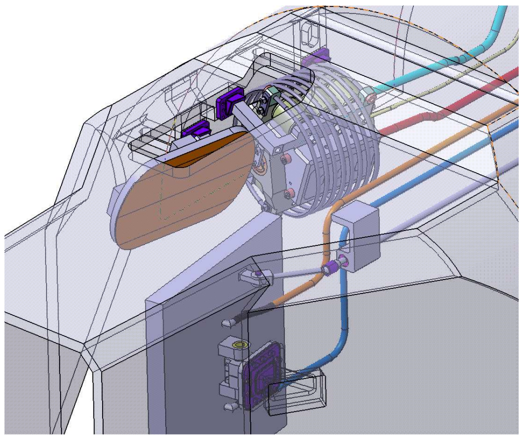


***FIG. 7**: preliminary design of the JET launcher: mirrors for poloidal and toroidal steering.*

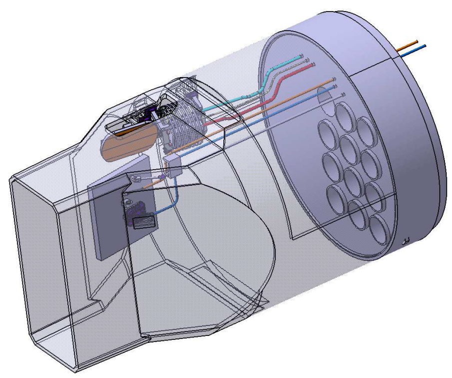


***FIG. 8**: preliminary design of the JET launcher: outer structure of the plug-in unit*

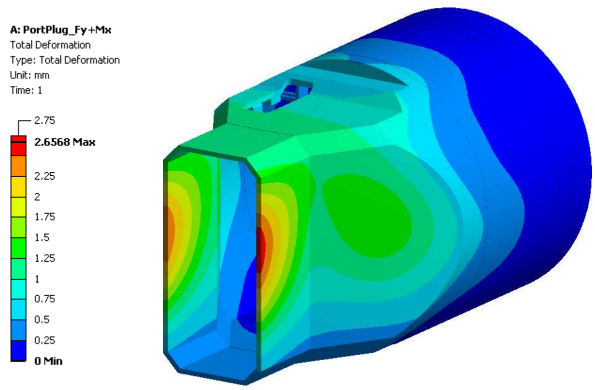


***FIG. 9**: Total deformation of the plug (in mm) due to e.m. forces: 1MN force in toroidal direction and a 1MNm moment in radial direction (Finite Element simulation)*

Power supplies. The 170 GHz GYCOM gyrotrons require a main power supply rated at -65 kV, 50 A and a body power supply rated at 30 kV, 50 mA. The possibility of using an existing NBI power supply, manufactured by Siemens 27 years ago and no longer in use at JET, has been analysed. It has been found that only half of this system can be used with minor modificatons while the other half requires major refurbishement. The modification of both halves nevertheless seems both technically and economically attractive. An approach based on the use of the refurbished NBI powers supplies (type 1) to supply 8 gyrotrons and 4 new solid state power supplies (type 2) for the remaining 4 gyrotrons has been developed [25]. The Type 1 Power Supply consists of a rectifier transformer and a tetrode tube connected in series to the transformer DC - output: the old transformers are re-used here. Type 2 consists of new solid-state technology power supply, either PSM (Pulse Step Modulation) or primary clocked switch mode. A new building would be necessary for this type of power supply, although a solution using containers is also possible and cheaper. Corresponding requirements for the body voltage power supplies have also been determined. The old power supplies have the significant advantage of allowing fast power modulation (15-20 kHz), useful for NTM control.

Auxiliaries. A significant amount of auxiliary equipment and services are required to make the ECRH plant operational: cooling water, superconducting magnets for the gyrotrons, auxiliary power supplies (for the superconducting magnets, filaments, collector sweeping magnets, ion pumps), vacuum pumps and gauges, compressed air, motors for moving polarisers, mirrors and switches, arc detection systems, microwave measurement systems, etc.). The requirements for all these auxiliary systems have been analysed [26], using the GYCOM gyrotron specifications. No major feasibility issue has been encountered.

Control systems and diagnostics. This project would yield a good opportunity to design a control system that adopts and tests a number of ITER-CODAC standards, possibly in close connection with the ITER-CODAC group. A number of diagnostics, in particular microwave based ones, will require adequate protection from stray radiation produced by the gyrotrons [27]. Stray radiation caused by ECRH power is assumed to be a few mW in normal operation, and may rise by a factor of 100 to 1000 under fault conditions. For the latter case, if components can handle 10 dBm (10 mW) a 40 dB rejection at 170 GHz is needed. A very narrow frequency width (~1GHz) is assumed for the 170 GHz source, to take into account any frequency jitter - particularly during switching. An upgrade of the ECE radiometre real-time network will also be necessary, for MHD control applications.

4. Conclusions

The usefulness of an EC system for JET is definitely confirmed by the physics studies and strong limitations for any of the functions envisaged have been found. However, the power of 10 MW should be considered as a minimum, and some limitations in the magnetic field values at which the system can be used appear unavoidable, in particular for a single frequency system. The chosen frequency 170 GHz would maximise the synergies with the ITER system. This choice takes into account physics requirements and properties, together with the availability of existing GYCOM gyrotrons, the much simpler window concept (with respect to a double-frequency system) and the possibility of components and solutions being developed jointly with the ITER and F4E teams.

In conclusion, an ECRH system for JET seems feasible, but it will be a complex project, with significant associated costs. From a technical point of view, the most critical issues concern the launcher design and the behaviour of new components such as the gyrotrons, the diamond windows and the mirror steering mechanism. However, these components are the same as for the ITER ECRH system, therefore their full scale test within the JET ECRH system would constitute a valuable risk reduction contribution to the ITER system. The total cost of the system is estimated ~ 55 M€. The manpower necessary for design, construction, tests, system commissioning on plasma and project management is estimated to 114 ppy. A preliminary planning is compatible with the delivery of 10 MW ECRH power in the plasma in approximately 5 years, provided adequate funding and highly qualified manpower are available.

Acknowledgements

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