# Thermo-mechanical Assessment of the JT-60SA Fast-Ion Loss Detector

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A fast-ion loss detector (FILD) is being designed for the JT-60SA tokamak. In this work, the preliminary mechanical design of this diagnostic is described. The expected motion needed to move the probe head between the parking and the measuring positions has been estimated by numerical simulations. A finite element thermal assessment of the detector is presented, to characterize its thermal response during the operation of the machine. Finally, the results of a preliminary electromagnetic analysis are reported to evaluate the impact of major disruptions on the structural components the system.

Keywords: fast ion loss detector, FILD, JT-60SA, plasma diagnostics, mechanical assessment, thermal assessment.

## 1. Introduction

Fast ion loss detectors (FILD) are scintillator-based diagnostics used in most of all major fusion devices to study fast ion losses [1-3]. They provide velocity-space measurements of the escaping ions with very high temporal resolution. This information is essential to identify the plasma fluctuations provoking the losses and can be used to validate the performance of different strategies that can be developed to mitigate these fluctuations.

To collect the charged particles, the FILD head needs to face the plasma, therefore, being exposed to high thermal loads [4,5]. In JT-60SA, plasma pulses will last up to 100 s and, due to constructive and operational reasons, the probe head will be retracted to a parking position for cooling down. Consequently, a thermal assessment is essential to define the time the probe head is held in measuring position and to assure the structural integrity and the proper performance of the detector.

The JT-60SA FILD will be installed inside a port plug within an equatorial diagnostics port, therefore, being affected by electromagnetic events, such as plasma disruptions. This can lead to high EM force in conducting components of FILD that need to be assessed from a structural standpoint [6].

In section 2, the mechanical design of the JT-60SA FILD is described, along with its expected motion according to numerical simulations. In section 3, the thermal behaviour of the detector is characterized by means of thermal finite element simulations. Finally, in section 4, the mechanical response of the system during plasma major disruptions is presented.

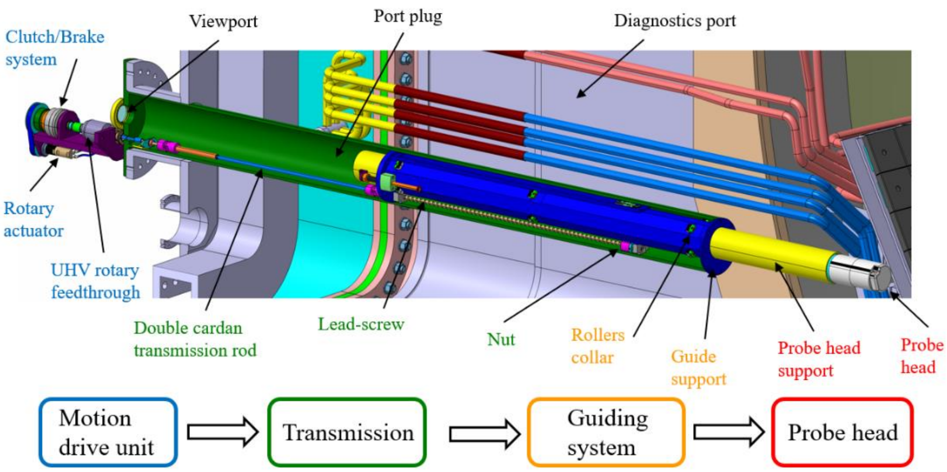


Fig. 1. JT-60SA FILD mechanical design: the motion of the probe head is provided, ex-vessel, by the drive unit, transferred to the head support by a lead-screw and guided by roller collars attached to the fixed guide support.

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## 2. FILD mechanical design and motion

The JT-60SA FILD will be located in the equatorial diagnostic port in sector 15, slightly below the midplane of the tokamak. Its design, shown in figure 1, allows the system to be installed within a port plug attached to the main diagnostics flange. The scintillator (not shown in the figure) will be positioned inside the probe head and will emit light when hit by the fast ions escaping from the plasma. This light will be collected, through the viewport, by a light acquisition system (fast visible camera and photomultipliers) that will be attached outside the vacuum vessel to the port plug flange. The light acquisition system has been omitted in figure 1 to improve the visualization of the FILD mechanical components.

During FILD operation, the probe head will move between the parking position, inside the port plug, and the measuring position, right behind the stabilizing plate of the tokamak. For that, the FILD head needs to travel 1 m. This stroke will be realized by the drive unit consisting of different elements:

- a reversible pneumatic rotary actuator will provide the torque, that will be transferred in-vessel by means of a pulley-transmission belt system and a bellow-based rotary feedthrough compatible with UHV conditions. During the design process, the use of a linear actuator has been considered. However, given the long stroke needed for the detector operation, this option was discarded due to space limitations.
- due to constructive reasons, the feedthrough can only transfer 10 N·m torque and, because of that, a pneumatic clutch system will be installed. This system can be calibrated to limit the torque provided by the actuator, thus protecting the feedthrough against overload.
- a rotary encoder and a pneumatic brake system will also be installed to monitor and control the FILD head position real-time.

As can be seen in figure 1, an in-vessel transmission system will transfer the rotation of the feedthrough shaft to the probe head. This transmission consists on a rod connecting the feedthrough to a lead screw system by a double universal joint. This joint allows accommodating axial misalignments between the connected parts that could, otherwise, induce forces in the rods and lead to damage and bad performance of the motion system. This approach has been used in other FILD systems such as FILD5, installed in the ASDEX Upgrade Tokamak [7].

The lead screw will convert the rotation provided by the actuator into a linear displacement of the probe head. This displacement will be guided by roller collars attached to a fixed support. The roller collars are expected to provide a smooth guidance with low friction to the linear motion of the probe head support as observed in FILD4, a magnetically driven FILD installed in the ASDEX Upgrade Tokamak [8,9].

A numerical model, represented schematically in figure 2, has been developed to study the FILD motion dynamics. This motion is described by the 1 degree of freedom second order differential equation (1).

$$I\ddot{\theta} + c\dot{\theta} + k\theta = T_{motor} - T_{friction} \quad (1)$$

$$x = x(\theta(t)) \rightarrow Head\ position$$

where $\theta$ is the angle rotated by the actuator, $I$, $c$, and $k$, represent, respectively, the inertia, the damping and the stiffness of the system, $T_{motor}$ is the torque provided by the pneumatic actuator and $T_{friction}$ is global parameter representing the frictional torque of all the elements of the system. The rotation of the actuator ($\theta$) can be related to the displacement of the probe head ($x$) by knowing the pulley system transmission ratio and the pitch of the lead screw.

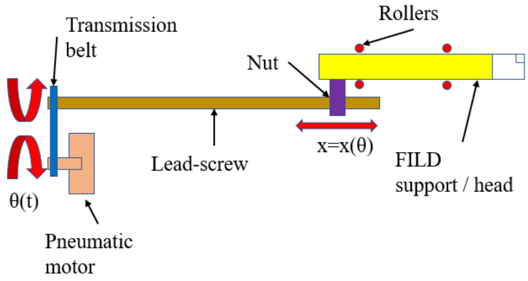


Fig. 2. Schematic representation of the model developed for studying the FILD motion dynamics. The rotation originated in the actuator ($\theta$) is converted into a linear displacement of the probe head ($x$) by the lead-screw.

To simulate the dynamic behaviour of the FILD motion, when moving from the parking to the measuring position, the equation of motion (1) has been integrated using the MATLAB® built-in numerical integrator ode45. The results obtained are represented in figure 3, where the time-evolution of the displacement, speed and acceleration of the probe head are represented. Also, the torque provided by the rotary actuator is represented in this figure as a function of time.

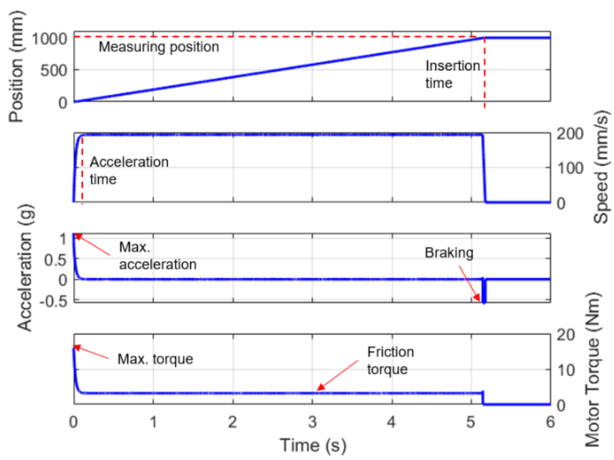


Fig. 3. Time-evolution of the position, velocity and acceleration of the FILD probe head. The torque provided by the rotary actuator is also represented.

As can be seen in figure 3, the FILD probe head reaches the measuring position by displacing 1 m stroke in approximately 5 s. For that, the head accelerates from 0 to constant speed (200 mm/s) in less than 0.2 s. This means that the maximum acceleration expected in the system is lower than 1.5 g and, therefore, low force and stress are foreseen in the system due to its motion.

It is important to highlight that the motion of FILD is governed by the power provided by the pneumatic rotary actuator, which mainly depends on the input air pressure and flow. This power is used to provide a torque at a certain rotation speed and is characterized by the power curve, an intrinsic characteristic of the actuator determined by the manufacturer. For the actuator selected for FILD, this curve can be approximated as linear for fixed input air pressure (6 bar) and ranges from 15 N·m at 0 rpm to 0 N·m at 280 rpm. Considering this, it can be noticed that the maximum torque provided by the actuator is larger than the one allowed by the feedthrough justifying, therefore, the use of a clutch as a protection element.

The power provided by the actuator will be used to displace the movable parts and to overcome the friction of the system, as can be deduced from the equation of motion (1). The friction has been estimated, preliminary, to be 4 N·m and this value needs to be confirmed by in-vacuum motion tests, to be performed once the system is built.

The numerical model of the FILD motion is being used to select the drive unit, the transmission elements and to design the position control system, including the encoder, the brake/clutch system, the position switches and the mechanical hard stops.

## 3. Thermal behaviour

The thermal behaviour of the JT-60SA FILD has been studied by means of finite element (FE) analysis, using the ANSYS Workbench Mechanical suit. To that end, a FE model of the FILD system has been developed and transient thermal simulations of full plasma shots have been performed.

The reference plasma scenario considered during the FILD thermal simulations consists on a 100 s plasma pulse, followed by a dwell period of 1800 s (inter-pulse). It is expected that JT-60SA will perform 30 plasma pulses (with the corresponding inter-pulses) during a standard operation working day. During the inter-pulses, the machine will cool down and all the operation and diagnostic systems (among others) will be conveniently set, in order to perform the next plasma pulse.

During the plasma pulses, the perpendicular heat flux ($q_{perp}$) due to plasma radiation is given, as a function of the radial coordinate, by the curve represented in figure 4. During the simulations, this heat flux has been applied, according to their position, to all the surfaces of the FILD components exposed to the plasma. As can be seen in this figure, $q_{perp}$ has a value of 0.3 MW/m$^2$ at the stabilizing plate radial position.

When FILD is operated, during a plasma pulse, it has been considered that the probe head is held in measuring position for 20 s. This is also shown in figure 4, where the duration of the plasma pulse and of the inter-pulse period are represented too.

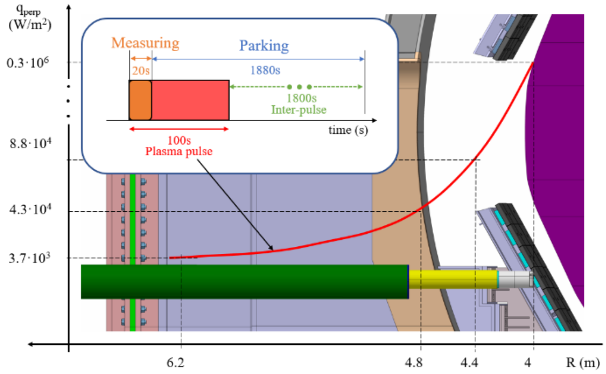


Fig. 4. Perpendicular heat flux ($q_{perp}$) during plasma pulses as a function of the radial position. The duration of the plasma pulse and inter-pulse periods, as well as the FILD measuring and parking times considered for the thermal simulations are also indicated in the figure.

It is important to clarify that 20 s is an extremely long measuring time selected, in this work, to explore the thermo-mechanical limits of the system. However, during the real operation of FILD, the detector is not expected to be kept in measuring position for such a long time, given that it can obtain proper measurements in a significantly shorter period. Indeed, the performance of this diagnostic is based on a scintillating sensor with a measuring frequency in the MHz order. Therefore, measuring periods in the range of milliseconds would provide information enough to properly characterize the fast ion losses.

During the actual operation of the detector, the probe head will be inserted several times during a complete plasma pulse and the duration of each insertion will be conditioned by the thermal response of its components. The model described in this section is being used to optimize the design of the system in order to maximize the amount of data obtained when operating it.

The components of FILD included in the FE model and their corresponding materials are shown in figure 5, where the system is represented in parking position. As can be observed in this figure, the scintillating sensor is located within the probe head, thermally protected by a graphite shield. The system includes a copper (CFC) heatsink to transfer heat from the scintillator to a cooler zone of the probe head support. The design of this heatsink has been optimized to maximize the heat extraction from the scintillator.

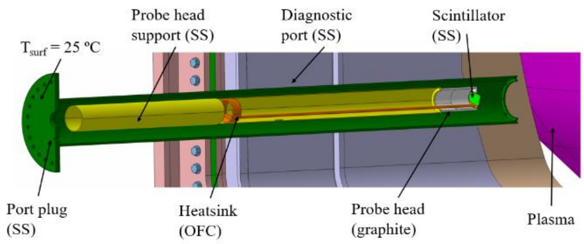


Fig. 5. FILD model setup for FE thermal simulations including the materials of the components.

During the simulations, conductive (when applicable) and radiative heat exchange between all the elements and the environment have been considered. As can be observed in figure 5, the temperature of the port plug flange has been fixed to 25ºC. To consider the radiative exchange of the system with the environment, the temperature of the diagnostic port has been set to linearly decrease from 100ºC, at the edge closer to the plasma, down to 25 ºC at the further edge. The temperature dependence of the thermal properties of all the elements in the model (thermal conductance and specific heat) have been considered.

The thermal behaviour of FILD has been simulated, in parking and measuring positions, during the standard operation of JT-60SA within a full working day (30 plasma pulses plus the corresponding inter-pulses, as mentioned in previous paragraphs). The results of these simulations are described next.

In figure 6, the time-evolution of the maximum temperature in different components of FILD is represented, when the system is held in parking position for a complete JT-60SA working day. This represents the thermal response of the detector when it is not operated but the machine is. These graphs show that the maximum temperature expected in the FILD elements is far away from their material and operational limits. For example:

- the recrystallization temperature of the stainless steel is above 1000ºC while the maximum temperature expected at the port plug is below 400ºC.
- the graphite sublimates at a temperature above 2000ºC but, in parking position, the probe head is not expected to exceed 250ºC.
- the scintillator material (TG-Green) degrades at a temperature above 500ºC but, according to the simulations, its temperature will not exceed 150ºC, when the probe head is parked inside the port plug. It is important to remark here that the efficiency of this sensor decreases significantly when its temperature is above 200ºC [10], but its performance is recovered when the temperature decreases below this level.

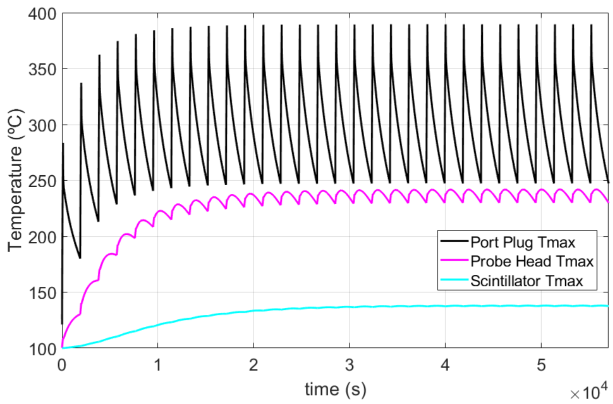


Fig. 6. FILD in parking position: Maximum temperature of FILD components as a function of time found during FE thermal simulations.

The results obtained when simulating the FILD operation during a complete working day are represented in figure 7. In this figure, the evolution of the maximum temperature of different FILD components is represented, as a function of time.

As mentioned previously in this section, due to the high temporal resolution of the scintillator and in order to obtain physics-relevant measures, the FILD probe head needs to be in measuring position only for a very short period of time (much less than one second). However, to explore the thermo-mechanical limits of the system, during the simulations, an extremely long-lasting measuring time has been selected.

Specifically, it has been considered that FILD will measure every 5 plasma shots, for a period of 20 s, starting at the beginning of the pulse. This can be observed in figure 7, which shows that:

- the maximum temperature of the probe head, when inserted for measuring, reaches around 600 ºC. This is a relatively low temperature when compared to the sublimation temperature of the graphite (above 2000ºC).
- the maximum temperature of the port plug stays below 400 ºC, a behaviour like the one observed when FILD is held in parking position, represented in figure 6.
- the maximum temperature of the scintillator is always below 200 ºC, showing that, as discussed previously in this section, the performance of the detector will not be affected during its operation.

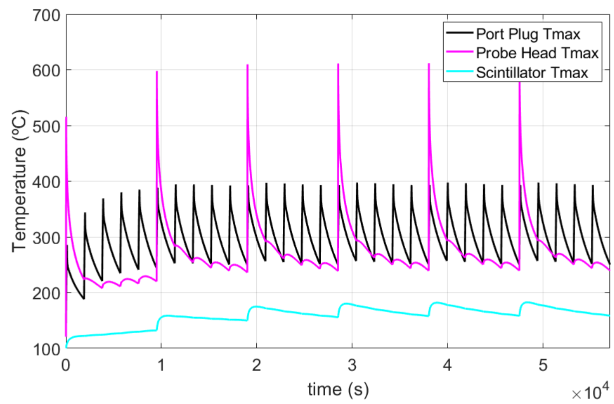


Fig. 7. FILD measuring for 20 s every 5 plasma pulses: Maximum temperature of FILD components as a function of time calculated during FE thermal simulations.

Using the thermal model presented in this section, the FILD operation will be optimized, depending on the plasma scenario and the expected temperature in its components. For this, the number of insertions of the probe head and their duration during plasma pulses will be maximized. The performance of this thermal model will be checked and fine-tuned by real-time measures provided by thermocouple sensors, to be installed in the FILD probe head and in the scintillator plate.

## 4. EM response during plasma disruptions

A preliminary electromagnetic (EM) analysis has been performed to study the mechanical response of FILD during plasma major disruptions. To that end, transient FE simulations have been performed using the ANSYS Maxwell suit.

In JT-60SA, during plasma major disruptions, the plasma current is assumed to linearly drop (current quench) from 6 to 0 MA in approximately 4 ms [6]. This current time-variation will induce eddy currents in conducting components of FILD that, in combination with the magnetic field existing in the machine, lead to force acting on them. The EM force on FILD will mainly depend on:

- the magnitude of the plasma current time-derivative, that will have a constant value equal to $1.5 \cdot 10^9$ A/s, given that the current quench is linear.
- the magnitude and direction of magnetic field in the zone where FILD will be installed.
- the area of the loop followed by the induced eddy currents in the conducting elements.

The EM simulations have been performed for FILD in measuring position to consider the worst-case scenario since, in this position, the detector is closer to the plasma. Only the structural elements have been considered during the EM analysis as represented in figure 8, where the EM model setup is shown. As can be observed in this figure, only the toroidal field coils (TFC) have been considered in this preliminary study, generating a 2.3 T toroidal magnetic field at the plasma magnetic axis. The plasma has been modelled as a torus with circular cross-section where the plasma current is uniformly distributed.

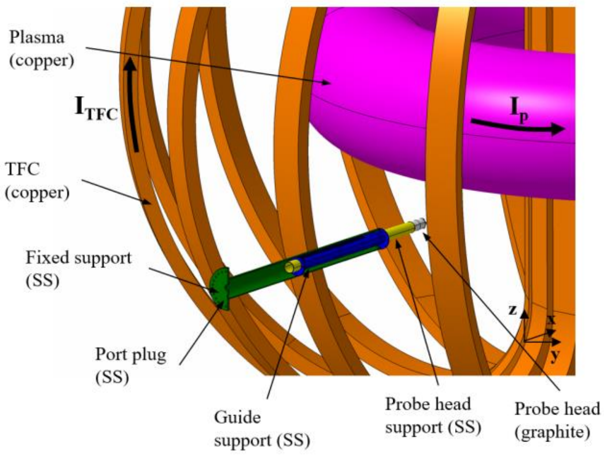


Fig. 8. FILD model setup for FE EM simulations including the TFC and the plasma.

The results of the EM simulations are described next. Table 1 summarizes the force acting on the FILD elements considered in the model. As can be observed in this table, the force is relatively low in all the elements, with a maximum value of approximately 250 N induced in the port plug. Attending to the induced torque, presented in table 2, it can be noticed that this torque represents the most important action on the system. For example, the port plug will be subject to high torsional and bending moments, with a combined value slightly below 1.5 kN·m.

Table. 1. Force acting on FILD components determined by EM simulations.

| Element | $F_x$ (N) | $F_y$ (N) | $F_z$ (N) | $F_{tot}$ (N) |
|---|---|---|---|---|
| **Port plug** | 0.23 | 207.17 | -130.64 | 244.92 |
| **Guide support** | -83.79 | 11.10 | 124.51 | 150.49 |
| **Head support** | -2.56 | 24.98 | 3.14 | 25.31 |
| **Head** | -2.89 | 1.37 | 2.27 | 3.92 |

Table. 2. Torque acting on FILD components determined by EM simulations.

| Element | $M_x$ (Nm) | $M_y$ (Nm) | $M_z$ (Nm) | $M_{tot}$ (Nm) |
|---|---|---|---|---|
| **Port plug** | 1032.70 | -140.90 | 949.80 | 1410.20 |
| **Guide support** | 114.32 | -256.05 | 89.23 | 294.27 |
| **Head support** | 178.02 | -46.28 | 130.65 | 225.62 |
| **Head** | 6.33 | -0.36 | 4.85 | 7.98 |

Considering the actions presented in the previous tables, a preliminary FE structural analysis of FILD has been performed. To that end, these actions have been transferred to the ANSYS Mechanical module where, after the definition of proper boundary conditions, the distribution of the von-Mises stress on the detector components has been obtained. This is represented in figure 9 and allows concluding that, during major disruptions:

- the maximum von-Mises stress in the port plug is shown to be lower than 40 MPa. This is a relatively low value compared to the yielding stress of the Stainless Steel (around 200 MPa) for a temperature of 50ºC. This is the temperature expected in the port plug, close to the flange, according to the thermal simulations.
- the torsion induced in the probe head support will be transferred to the guide support by an anti-rotation system, leading to a stress lower than 75 MPa in both elements. This value is half of the yielding stress (150 MPa approximately) for the Stainless Steel at 200ºC, the temperature expected in the probe head support at the zone where the stress is maximum.

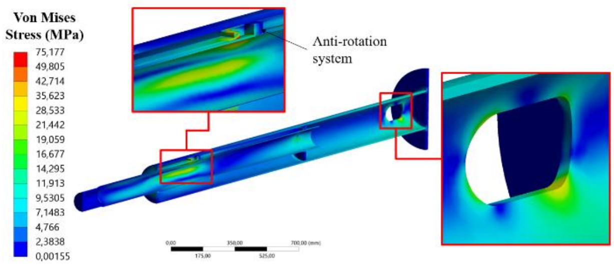


Fig. 9. Von-Mises stress estimated in FILD structural components during FE structural assessment.

It is important to highlight that only the effect of the current quench, during a plasma major disruption, has been considered in this preliminary analysis. To complete this structural assessment, the effect of the Halo current and plasma vertical displacement events (VDE), as well as functional vessel structures, will be considered in further studies. Also, it is worth mentioning that, given that the design is preliminary, the results presented here correspond to a global structural assessment and that detailed local analysis of the FILD components will be carried out during the final design phase.

## 5. Summary

The preliminary mechanical design of the JT-60SA fast-ion loss detector (FILD) has been described in this work. The numerical characterization of the motion, needed to move the probe head between the parking and the measuring positions, has been presented. Results show that the system is able to perform the required movement (1 m stroke) in approximately 5 s with an acceleration value lower than 1.5 g.

FILD shows good performance in preliminary thermo-mechanical analysis considering the plasma thermal effect during the tokamak operation. Also, the mechanical response of the detector, during plasma major disruptions, has been assessed showing that the stress induced in FILD elements is well below the materials limit. The effect of the plasma vertical displacement and Halo current, as well as other non-EM events such as earthquakes, will be considered in further studies.

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