Advances in the Ion Source Research and Development Program at ISIS

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ABSTRACT

This paper covers the advances in the ion source research and development Program at ISIS over the last 2 years. The work is a combination of theoretical finite element analysis calculations and experiments conducted on a purpose built development rig. The broad development goals are higher beam current with longer pulse length.

A Finite Element Analysis (FEA) model is used here to understand the steady state and dynamic thermal behavior of the source, and to investigate the design changes necessary to offset the extra heating.

Electromagnetic FEA modeling of the extraction region of the ISIS H^- ion source has suggested that the present set up of extraction electrode and 90º sector magnet is sub-optimal, with the result that the beam profile is asymmetric, the beam is strongly divergent in the horizontal plane and there is severe aberration in the focusing in the vertical plane. The FEA model of the beam optics has demonstrated that relatively simple changes to the system should produce a dramatic improvement in performance. The theoretical and experimental results are compared here.

INTRODUCTION

The ion source research and development program at Rutherford can be broadly split into 3 sections: Infrastructure, Thermal and Electromagnetic. Each of these sections involves the model, design and experiment cycle.

The practical work is carried on the Ion Source Development Rig (ISDR)**[1]** to allow testing without affecting ISIS itself.

Infrastructure changes to the ISDR include the up-rating of power supplies and flange and support redesign. Thermal work covers thermal finite element modeling of the source, allowing many different load and cooling scenarios to be tested. Electromagnetic modeling allows different extraction and beam transport electrode geometries to be studied and optimized.

INFRASTRUCTURE

The configuration of the ion source and magnet flange for the ISDR has now been changed so that the ion source assembly can be loaded from the top, rather than the back of the magnet flange, as shown in Figure 1. A schematic of the top loading ion source and extended magnet flange is shown in Figure 2.

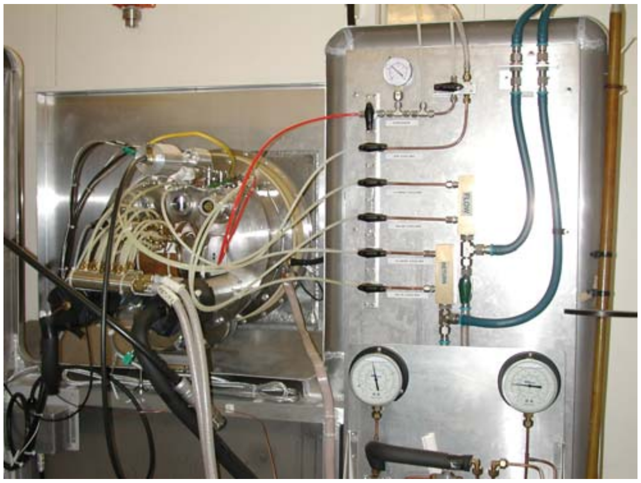


Figure 1: The top loading ion source mounting flange.

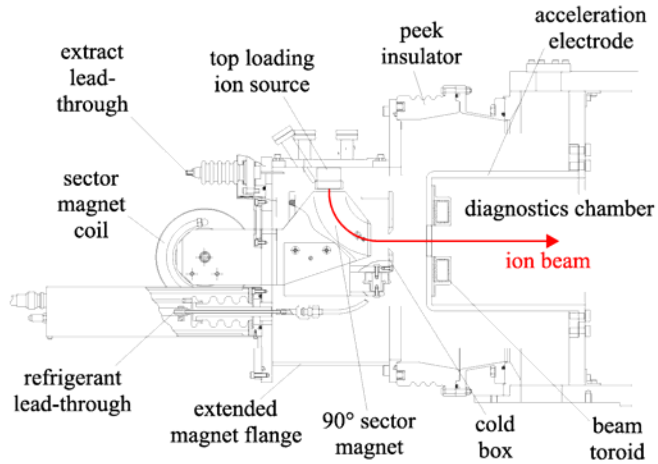


Figure 2: Schematic of the top loading ion source.

This allows greater flexibility for future source developments, where additional space for scaling of source components or more aggressive cooling strategies can be provided by inserting a spacer ring between the ion source flange and the magnet flange. The penalty for this innovation, however, is that the source has had to be moved back by about 200 mm from its original position. The emittance scanners on the ISDR were designed for use with the ISIS RFQ test stand**[2]**, and were only required to scan over ~30 mm to cover the maximum extent of the Low Energy Beam Transport beampipe. This means that, with the distance from the cold box front plate to the emittance scanners now increased to 685 mm (56 mm of acceleration gap and 629 mm of drift), the extent of the divergent ion beam would be larger than the range of the scanners. This problem has been addressed by modifying the scanners so that two or more separate scans can be taken and then merged to create a single scan over a range of ~78 mm.

The high voltage platform has been extended provide space to fit a new extract voltage power supply. The new power supply will allow an increase of the extract voltage from 17 to 25kV and an increase in pulse length up to 2.5ms. An additional 3-phase isolating transformer has also been installed to power the new extract voltage power supply.

Work is currently underway to provide a separately excitable penning field to allow the effect of penning field to be studied.

THERMAL

A thorough understanding of the thermal characteristics of the ISIS ion source is essential if operation is to be extended to the higher duty factors, whilst maintaining an optimal regime for H^- ion production and source lifetime.

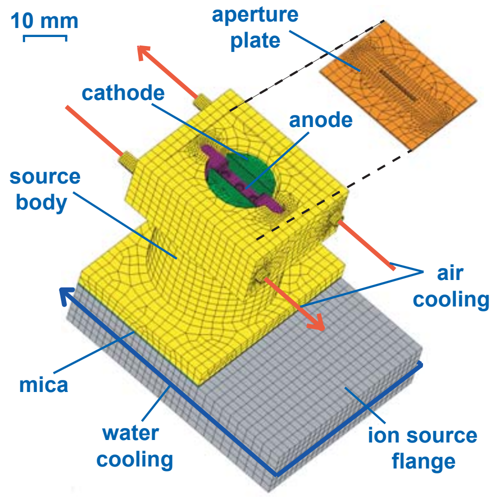


Figure 3: ALGOR thermal model of the ISIS ion source.

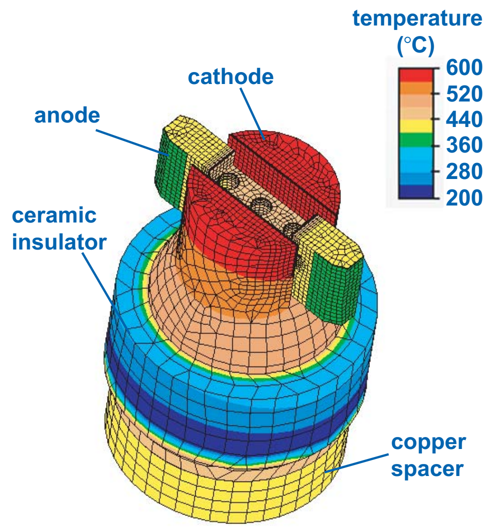


Figure 4: Component temperatures from the steady state model.

Figure 3 shows the model of the ion source. The source is of the Penning type, comprising a molybdenum anode and cathode between which a low pressure hydrogen arc is struck. Hydrogen and caesium are fed into the arc via holes in the anode; these can be more clearly seen in Figure 4. The anode and cathode are housed in the stainless steel source body. The anode is thermally and electrically connected to the body, whereas the cathode is isolated from the body by means of a ceramic spacer. The whole assembly is bolted to a flange, separated by a thin layer of mica to provide electrical isolation for the cathode.

Source cooling is provided by two systems illustrated in Figure 3: air cooling via two pipes in the source body nearest the electrodes and water cooling via a channel cut into the ion source flange. Air flows along one pipe and is then returned down the other as shown in Figure 3. Air is used because of the safety hazards involved with having water close to the caesiated ion source.

The ions are extracted through the slit in the aperture plate.

ALGOR**[3]** FEA software has been used for thermal modeling. The details of the model and its validation have been discussed previously**[4].**

The typical ISIS ion source operating conditions are a 4 kW, 0.5 ms, 50 Hz arc. An assumption is made that all the electrical power as measured in the external circuit goes into heating the electrode surfaces exposed to the discharge. The arc is bounded on all sides by sections of the cathode, anode and aperture plate.

When all the parameters that correspond to normal operation of the ISIS source are applied to the model the temperatures obtained are very close to the temperatures measured in the actual source (Table 1). This provides validation that the model is realistic.

To obtain a steady state solution the average power densities over the 50 Hz cycle are applied to the electrode surfaces.

Location	From Model			Actual ISIS
	Thermocouple	Surface	Difference	
Anode	456°C	496°C	40°C	400-600°C
Cathode	501°C	585°C	84°C	440-530°C
Source Body	416°C	441°C	25°C	390-460°C

Table 1: Theoretical thermocouple, electrode surface and actual thermocouple temperatures.

In normal operation the source temperatures are monitored using three thermocouples: Cathode, Anode and Source Body. All these thermocouples are positioned some distance from the electrode surfaces exposed to the arc plasma so they do not give actual surface temperatures. The realistic model of the source allows this difference between measured and surface temperature to be calculated, Table 1. The difference between these values depends on the distance between the measurement point and the electrode surface. It is greatest for the cathode because the measurement point is at the very base of the cathode.

The electrode surface temperatures are an important factor when considering the performance of the ion source as these surfaces play an important role in the plasma physics of the arc; the caesiation of the surface is temperature dependent for example.
The aim of the modelling work is to find out what is required to maintain the electrode surfaces at the temperatures in the current source whilst increasing the duty cycle.
The duty cycle is doubled to 1 ms and the cooling represented by a Heat Transfer Coefficient (HTC) in the head and flange increased. Figure 5 shows the results.

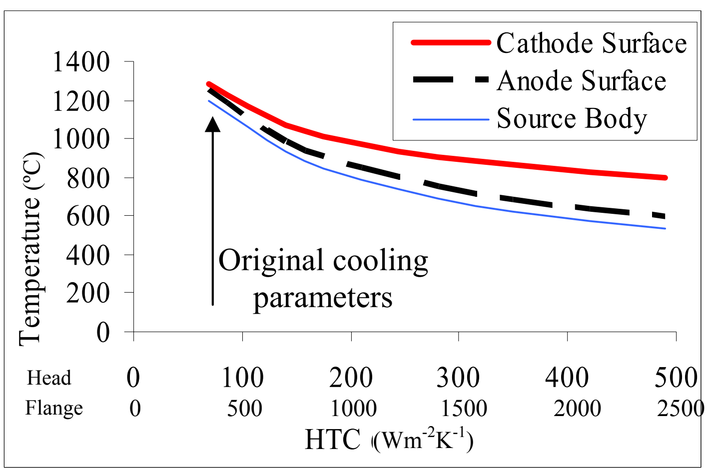


Figure 5: 1 ms duty source steady state temperatures for increased cooling.

Without increasing the cooling, the source temperatures approximately double. As the water and air flow rates are increased the anode and source body temperatures come down together, however the cathode surface temperature decreases more slowly. This is because the cathode is thermally isolated from the cooling systems by the layer of mica and the ceramic insulator. For a

1 ms duty cycle there is no combination of coolant flow rates that will produce the original surface operating temperatures.

Mica is a very poor thermal conductor. To improve the cooling to the cathode the layer of mica is removed from the model. With the mica removed the steady state surface temperatures shown in Table 1 can be reached easily for a 1 ms duty cycle.
The mica is present to provide electrical isolation of the cathode from the flange, so in practice a thin layer of material with good electrical insulation properties and high thermal conductivity (such as aluminium nitride) will have to be used.
Removal of the mica will cause problems with source start up. It will be difficult to heat the source up to reach operating temperature. Modifications being considered include a heating element to pre-heat the cathode.

The steady state calculations only calculate the average electrode surface temperature. Using the steady state solution as a starting point it is possible to run a transient study. This allows the peak surface temperatures reached at the end of the arc on period to be calculated. To ensure accurate results the elements of the FEA model near the electrode surfaces are made very thin (10^{-5} m) in the direction of heat flux.

Figure 6 shows how the peak temperatures vary though the cycle for the 0.5 ms and 1 ms duties. During the on period there is a rapid increase in the surface temperature of the materials directly exposed to the plasma; this temperature then decays away as the arc energy dissipates into the thermal mass of the material. The peak source body temperature does not vary because it is not directly in contact with the plasma. In a similar way there is no detectable change in temperature at the thermocouple measurement points.

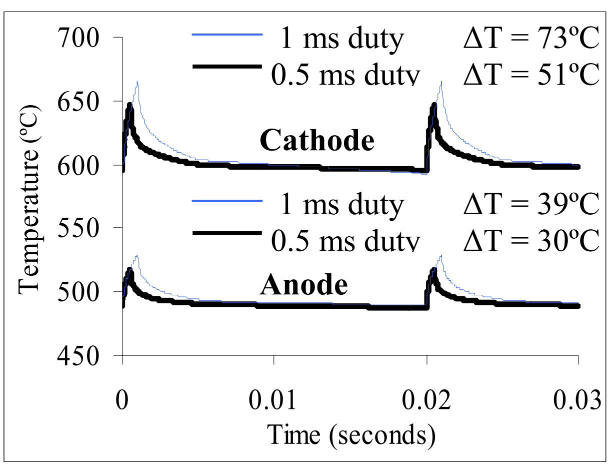


Figure 6: Anode and cathode surface temperatures for 0.5 ms and 1 ms duty cycles for the normal sized ion source calculated from the transient model.

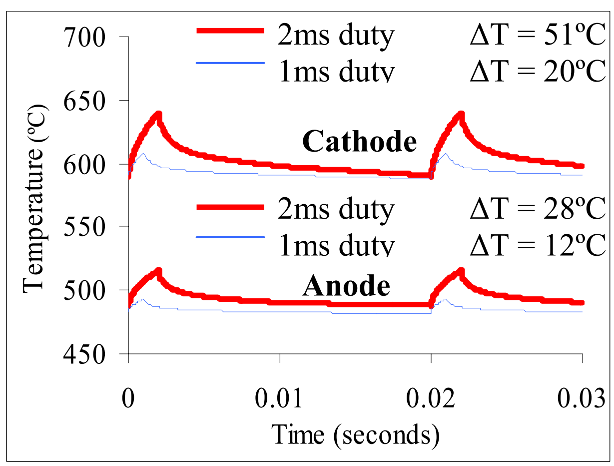


Figure 7: Anode and cathode surface temperatures for 1 ms and 2 ms duty cycles for the double sized ion source calculated from the transient model.

The exact implications of this electrode surface temperature rise during the on period are poorly understood for a surface Penning ion source. The temperature rise is clearly larger for the 1 ms duty cycle, but it is not known how this will affect the ion source operation. All that is known is that the existing source operates very well. Work is currently underway to test the ion source with a 1 ms duty cycle on the ISDR at RAL.

The electrode surface temperature rise during the on pulse cannot be mitigated with additional cooling because the energy does not have time to conduct away from the surface. The surface temperature rise is therefore mainly dependent on the power density applied by the plasma to the electrode surfaces and the length of time it is applied. The total arc power and length of time cannot be changed, therefore the electrode surface area must be increased to decrease the power density.
All linear dimensions in the model are doubled and the simulation repeated, keeping the instantaneous power at 4 kW as before. Scaling the ion source dimensions has been successfully implemented by previous researchers**[5]** at Los Alamos National Laboratory. Figure 7 shows the transient results. For a 1 ms duty cycle the surface temperature rises are significantly reduced.

In the double sized source, the duty cycle can be further increased to 2 ms and the surface temperature rises are very similar to the normal ion source for a 500 µs duty. This confirms that the surface temperature rise is largely dependant on surface power density and time. (4X duty balanced with 4X increase in surface area).

ELECTROMAGNETIC

A recent paper**[6]** has described MAFIA**[7]** modeling of the extraction region of the ISIS H^- ion source**[8,9]**. This demonstrated that optimization of the beam optics should result in a significant improvement in the measured emittance of the source. The design incorporates new pole pieces for the 90° sector magnet, and a 'maximag' magnet steel tube (internal diameter 30 mm, wall thickness 5 mm) extending from 3 mm in front of the 90° plane to flush with the cold box exit. Together these should deal with fringe fields of the 90° sector magnet more effectively. In addition two new extraction geometries were specified: one a terminated version of the standard ISIS extraction geometry and the other a Pierce geometry**[10]**. Figure 8. All of these new components have now been manufactured and tested on the ISDR.

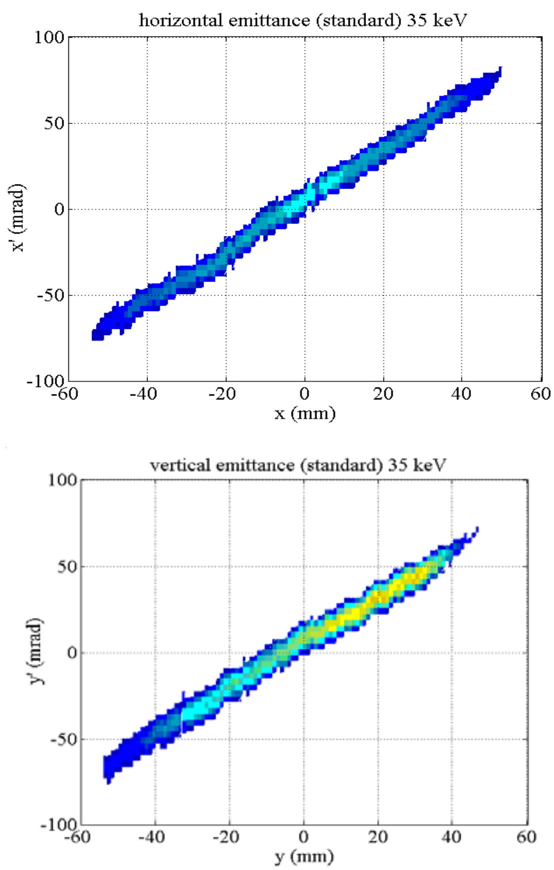
Figure 8: Extraction electrodes and aperture plates for the ISIS standard geometry (centre), terminated standard geometry (left) and Pierce geometry (right).

Emittance scans were taken for four combinations of extract electrode geometry and pole pieces: ISIS standard geometry with old pole pieces, ISIS standard geometry with new pole pieces, terminated standard geometry with new pole pieces and Pierce geometry with new pole pieces. In each case the source parameters were kept as constant as possible, with an extract voltage of 17 kV, a beam energy of 35 keV, a pulse width of 250 μs and a beam current of between 45 and 55 mA. Previous experiments on the ISDR**[1]** have shown that there is very little space charge compensation in the diagnostics chamber when the pressure (of 1.7×10^{-5} mbar) is determined solely by the transmission of H_2 from the ion source chamber. The introduction of Kr as a buffer gas has been shown to provide space charge compensation and improve the emittance measurements. To investigate this effect further in the present measurements Kr was introduced into the diagnostics chamber to raise the combined pressure of H_2 and Kr to levels of 2.2×10^{-5} mbar, 4.0×10^{-5} mbar and 1.0×10^{-4} mbar. The results are shown in Table 2, where all values are for the normalized rms emittance in πmm mrad.

	H2 (1.7×10-5 mbar)	H2+Kr (2.2×10-5 mbar)	H2+Kr (4.0×10-5 mbar)	H2+Kr (1.0×10-4 mbar)
Standard Geometry Old Pole Pieces	εH = 0.97 εV = 0.94	εH = 0.99 εV = 0.84	εH no measurement εV = 0.91	no measurements
Standard Geometry New Pole Pieces	εH = 0.97 εV = 0.90	εH = 0.91 εV = 0.92	εH = 0.92 εV = 0.90	εH = 0.83 εV = 0.72
Terminated Standard New Pole Pieces	εH = 0.91 εV = 0.98	εH = 0.85 εV = 0.97	εH = 0.82 εV = 1.06	εH = 0.77 εV = 0.97
Pierce Geometry New Pole Pieces	εH = 0.73 εV = 0.80	εH = 0.72 εV = 0.83	εH = 0.71 εV = 0.79	εH = 0.62 εV = 0.73

Table 2: Emittance values for the four combinations of extract electrode and pole pieces with varying pressures of Kr in the diagnostics chamber. All values are for normalized rms emittance in πmm mrad during a 10 μs interval 150 μs into the 250 μs pulse, with an extract voltage of 17 kV, beam energy of 35 keV and a beam current of between 45 and 55 mA.

The emittances in both planes display the general trend that the values get smaller with each successive geometry refinement and the introduction of more Kr, but this is not always the case. For instance replacing the ISIS standard geometry extraction electrode with the terminated standard leads to an increase in the vertical emittance values. However, it can be seen that overall the worst values are those for the ISIS standard geometry and old pole pieces with no introduction of Kr (worst case, shaded orange in Table 2) and the best values are those for the Pierce geometry and new pole pieces with Kr introduced to 1.0×10^{-4} mbar (best case, shaded green in Table 2). Figure 9 shows the worst case. It is immediately obvious that the spatial extents of ≈±50 mm in both the horizontal and vertical planes justify the modification of the emittance scanners to scan over a wider range. Indeed there is evidence that previous emittance measurements quoted for the ISDR**[1]** may have been too small because the edges of the beam were being missed. Figure 10 shows the best case. The spatial extent of the beam in the horizontal plane has been reduced to ≈±30 mm, and in this plane the beam displays three distinct peaks. This structure is evident in all of the scans taken with the Pierce geometry, irrespective of the amount of Kr, and is taken to be indicative of a slight overfocusing in the horizontal plane of the extract electrode. This will be investigated at a later date by reducing the angle of the recess in the Pierce geometry aperture plate (see Figure 8). In the vertical plane the beam is asymmetric, and has been positioned to maximize the charge on axis, but again covers a range of $\approx\pm 60$ mm. The asymmetry of the vertical profiles in both the best and worst cases may be evidence that there is not an even distribution of charge across the slit in the aperture plate when the ions are extracted. Examination of many used ion source cathodes has shown erosion concentrated towards the area where Cs is fed through the anode into the source. If this is a consequence of the plasma being localized near the Cs feed this could well result in an asymmetry in the vertical plane. A new Cs delivery system, which should give a more even plasma distribution has been designed and manufactured, and awaits testing on the ISDR. Although the changes in normalized rms emittance values (from $\varepsilon H = 0.97$, $\varepsilon V = 0.94$ πmm mrad in the worst case to $\varepsilon H = 0.62$, $\varepsilon V = 0.73$ πmm mrad in the best case) are not as dramatic as those predicted by MAFIA modeling**[6]**, there is still a marked improvement in both the horizontal and vertical planes as a result of the Pierce geometry, new pole pieces and the introduction of Kr. It is hoped that future refinements of the extraction geometry and Cs delivery system will improve the situation still further.



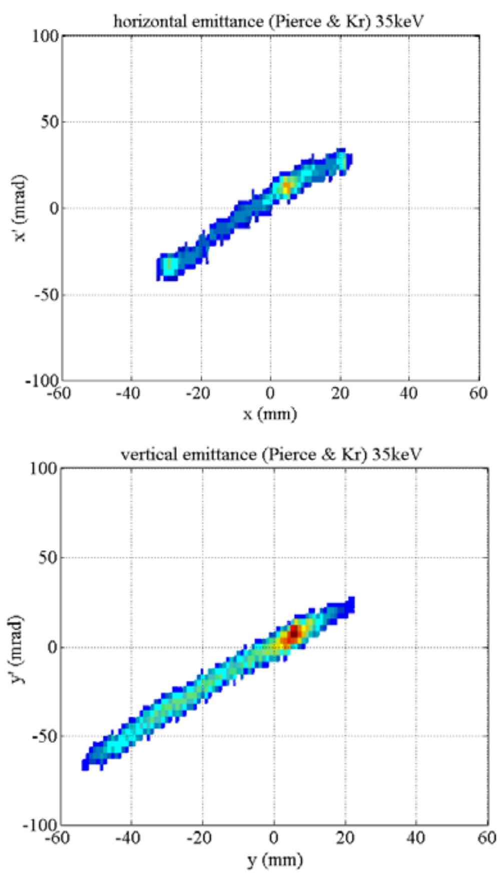


Figure 9: ISDR horizontal and vertical emittance plots for the ISIS standard geometry and old pole pieces with no introduction of Kr.

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Figure 10: ISDR horizontal and vertical emittance plots for the Pierce geometry and new pole pieces with Kr introduced to raise the diagnostics chamber pressure to 1×10^{-5}mbar.

CONCLUSIONS

To increase the duty on the ISIS ion source the cathode must be cooled more directly by replacing the mica sheet with a better thermal conductor

If the electrode surface temperature rise is critical it will be necessary to move to larger electrodes.

Improved extraction electrodes and beam transport have improved beam quality.

ACKNOWLEDGMENTS

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