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Thermal Design of GA ECH Launcher Mirror for Long Pulse Operation

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Abstract— Each GA ECH Launcher mirrors is used to transmit 800 kW of power to the plasma. Until 2000, the pulse length for use of these mirrors was limited to 2 s due to temperatures of the mirrors resulting from 1) a high ratcheted bulk temperature and 2) a large increase in temperature of the mirror during the pulse.

A new design was proposed and implemented which has extended the capability of the mirror to 10 s with passive cooling. The important features of the new design are 1) increase in the passive heat transfer rate during cooling and 2) a modified shape of the mirror. The analysis shows that, the new mirrors can be used for 10 s pulses.

The new mirrors have been installed in DIII–D, they have been used for up to 2 s pulses.

I. Introduction

The DIII–D tokamak is designed for 10 s plasma operation followed by a 10 min cool-down time. ECH is one of the many methods used to heat the plasma. Launcher mirrors are used to transmit 800 kW ECH power to the plasma.

Fixed focusing mirrors are mounted at the end of open ended wave guides. These mirrors focus the beam to provide optimum beam width. Below these mirrors is a tilted steering mirror to provide desirable toroidal and poloidal launch angles.

A small percentage of the transmitted power is lost on the surface of the mirror. Due to location of the mirror inside the vacuum chamber, it is desirable to passively cool the mirrors in between shots. Mirror operation in DIII–D prior to 2000 was limited to 2 s. By some simple design modifications, the capability of these mirrors has been extended to 10 s while still retaining the feature of passive cooling.

II. Heat Loads on the Mirror

There are two types of heat loads on the mirror. The first is radiation from the plasma. The second is losses during transmission. The plasma radiant heat load on the mirrors was determined by measuring the temperature rise of the existing mirrors during plasma operation without ECH input. This experiment indicated that the energy input to the mirror surface was 0.36 J/cm^2 per MJ of energy input to the plasma. This agrees with calculations based of view factors within 10% [1]. The maximum energy input to the DIII–D plasma in a single pulse is:

Neutral Beams = Each beam 2.5 MW, 8 beams, for 5 s = 100 MJ

ECH = 8 MW, at 80% efficiency, for 10 s = 64 MJ

Total = 164 MJ

Thus the maximum radiant energy load is estimated as 59 J/cm^2 for 10 s pulse and 47.5 J/cm^2 for 5 s pulses.

The ECH losses during transmission are distributed over an elliptical area on the surface of the mirror.

$$q(x,y) \sim J_o(2.405x/R1) \times J_o(2.405y/R2)\sqrt{\sigma(T)/\sigma(T_o)} \quad (1)$$

where

J_O = Bessel function of order 0
T = local surface temperature, °C
To = 20 °C
σ =electrical resistivity of mirror surface = 1.86×10^{-06} [1.0 + 0.003(T–20)] ohm–cm
R1 = 2.55 cm
R2 = R1/cos(φ)
φ = angle of the mirror rotation

In order to minimize the losses the mirrors are made from Glidcop Al-15. The ECH losses are about 0.15% of the transmitted power at room temperature for this material. The maximum heat flux, including the effect of temperature on the losses can be as high as 150 W/cm^2. The peak heat flux can be about six times the average heat flux.

III. Performance of the Old Mirror

The old mirror was made from Glidcop Al-15 and was 0.30 cm thick flat plate cooled by radiation to the vessel walls.

Figure 1 shows the maximum calculated temperature of the mirror for several 2 s pulses with 10 min cool down time. During the first few seconds of the cool down the mirror temperature, which is very non uniform at the end of the pulse, becomes uniform, reducing the peak temperature. All thermal calculations were performed by the finite element (FE) code COSMOS [2]. After many pulses, the maximum temperature at the end of the pulse is 505°C. The ratcheted temperature at the beginning of the pulse is 295°C.

It is obvious that the old flat mirror could not be used for pulse lengths longer than 2 s.

IV. Design Improvements

In order to increase the pulse length we decided to evaluate two design changes and one operational change. The first design change was to increase the effective emissivity of the back side of the mirror. This will reduce the ratcheted temperature. The second change was to increase the thickness of the mirror at the center of the mirror where heat flux is maximum. An operational option is to increase the cool down time to reduce the ratcheted temperature.

A. Emissivity

The emissivity of copper is between 0.02 to 0.6 depending on the surface condition. In order increase the cooling rate, we wanted to increase the emissivity

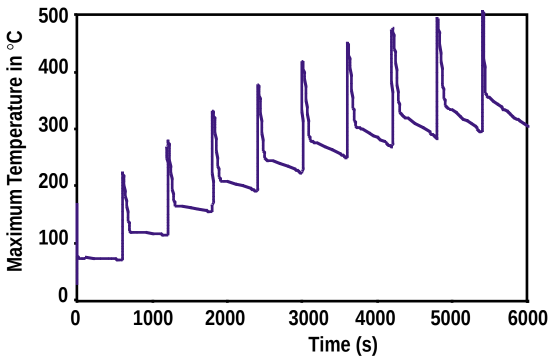

Fig. 1. Thermal Performance of Flat Mirror for 2 s Pulse and 10 min. Cool-down time.

as close to 1.0 as possible. This can be achieved by oxidizing *and* roughening the back of the mirror surface [1]. An experiment was conducted to determine emissivity of grooved oxidized copper surfaces. The experiment consisted of looking at the heated surface with an IR camera. The camera has a setting for the emissivity and temperature. Thus, if the temperature of the surface is known, camera readings show the emissivity.

We used a graphite tile to determine the emissivities by comparison. The assumptions were: 1) the heat flux on all surfaces, at steady-state is equal and 2) emissivity of CFC is 0.8. The geometry of the grooves was "V groove cavity" with 2 ϕ angle of 60°(Fig. 2).

The emissivities of surfaces determined from the experiment were :

TABLE I
SURFACES TESTED

Surface	Emissivity
Large grooves (1.5 mm height)	0.99
Small grooves (0.75 mm height)	0.90
Flat oxidized cooper	0.60
Shiny cooper	0.018

Thus we are sure that we can achieve an emissivity of more than 0.8 on the back side of the mirror. If the design grooves of 0.75 mm height were used.

If the emissivity is increased to 0.8 at the back (we will ignore cooling from the front surface), for a 5 s pulse, the ratcheted temperature is reduced from 380°C to 160°C. In fact, the reduction in peak temperature is even more because ECH losses are a function of the temperature.

B. Shape of the mirror

The largest heat flux is at the center of the mirror. If the mirror stayed isothermal, the peak heat flux due to ECH losses is 3.8 times the average loss as described by Eq. (1). However, since the ECH losses are function of the square root of the resistivity of copper, the ECH losses at the center can be as high as six times the average. Hence the temperature rise at the center of mirror during pulse is several times higher than

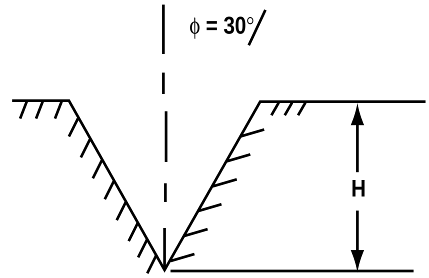

Fig. 2. Shape of the grooves machined on the back side of the mirror to increase the emissivity.

the average temperature rise. In order to make temperature rise more uniform, shape of the mirror was modified to have larger thickness at the center as shown in Fig. 3. This does not increase the electromagnetic eddy current forces significantly because the added mass is at the center of gravity of the mirror.

The addition of the mass at the center of the mirror increases the eddy current by 13% compared to the flat mirror. The maximum stress due to eddy current loads is 10.3 ksi at the supports. The allowable bending stress for the material is 18.4 ksi.

C. Cool Down Time

The third option is to increase the cool down time of the mirror. As seen from Fig. 1, the mirror does not cool down to initial temperature in 10 min. Since 10 s pulses are not likely to be used often, increasing the cool down time to 15 min for 10 s pulses is a viable option. This will reduce the ratcheted temperature.

V. EXPECTED THERMAL PERFORMANCE

The comparison of new and old mirrors for 2 s pulse for 800 kW transmitted power and 10 min cool-down is shown in Fig. 4. The peak temperature is significantly reduced because reduction in temperature also reduces losses.

The peak temperature of the mirror for the new design as a function of pulse lengths is shown in Fig. 5.

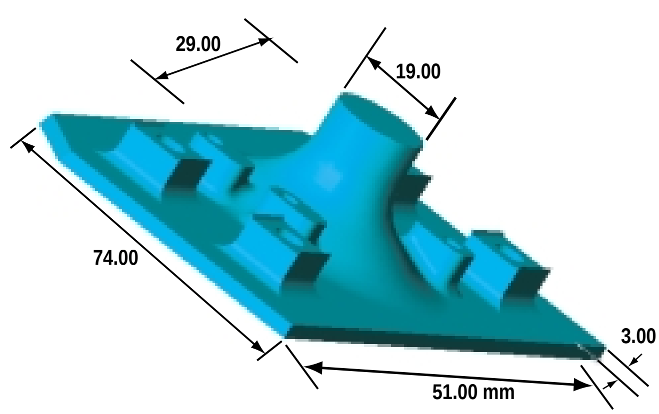

Fig. 3. Shape of the new mirror.

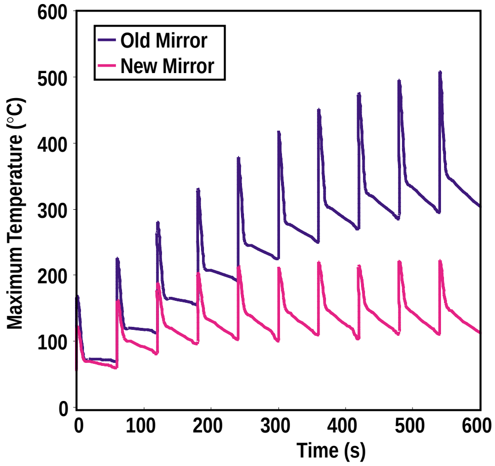

Fig. 4. Comparison of old and new design for 2 s pulses.

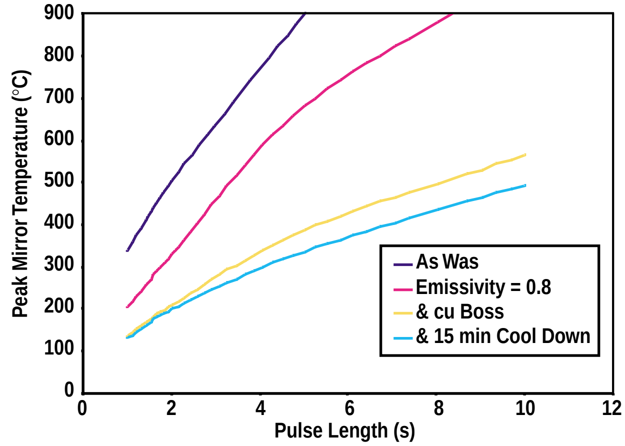

Fig. 5. Peak temperature of ECH mirrors for 800 kW of transmitted power. The temperatures plotted include ratcheting and temperature rise during the pulse.

VI. CONCLUSION

It is possible to design ECH mirrors, without any brazed components, for 10 s operation, with passive cooling to transmit about 800 kW power.

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