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Additive Manufacturing of Steady-State Mirrors for the KSTAR ECH Launchers

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Additive Manufacturing of Steady-State Mirrors for the KSTAR ECH Launchers

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***Abstract*— Electron Cyclotron Heating (ECH) launchers typically use a fixed and a steerable mirror to direct a microwave beam to a small volume of a plasma, for the purpose of heating or current drive. Superconducting tokamaks such as KSTAR are now operating their ECH systems at pulse lengths that require steady-state equilibrium between heat input and heat extraction. Princeton Plasma Physics Laboratory has designed, and fabricated, a set of fixed and steerable mirrors for use in the KSTAR system during the 2015 campaign. During the course of our design work, the emergence of additive manufacturing, or 3-D printing, of metal components prompted a decision to take advantage of this technology in our mirrors.**

This paper gives a brief overview of additive manufacturing. The design of the fixed and steerable mirrors is described. Some analytical results are presented, and the use of novel design features made possible through 3-D printing is described.

Possibilities for additional applications of 3-D printing are discussed.

Keywords—microwave, plasma, heating, launcher, metalworking

I. Introduction

Electron Cyclotron Heating (ECH) and Electron Cyclotron Current Drive (ECCD) are essential to the operation of advanced tokamaks[1,2,3]. Heat and current drive can be deposited at precise locations in the plasma, and ECCD can be used for suppression of Neoclassical Tearing Modes[4] (NTM), for current profile[5] and plasma rotation control, and other applications.

An ECH/ECCD system typically consists of a gyrotron, which supplies a millimeter-wave beam at about 1MW; a low-loss waveguide, which transmits the power from the gyrotron to the tokamak, and finally the launcher, located on the tokamak, which directs the beam to its desired location in the plasma. A combination of a fixed, focusing mirror and a flat, steerable mirror are used for beam shaping and steering. [figure 1]

ECH systems have evolved in recent years, with higher power, pulse length and frequency gyrotrons becoming available, and increased launcher capability. In 2001, PPPL delivered the P2001 ECH launcher to the DIII-D project[6]. This launcher, first in a series of four, provided steering in the toroidal direction from co- to counter-injection, and in the vertical direction from below the midplane to the top of the plasma, for two 1MW, 10 second, 6cm diameter beams. Steering was remotely controlled using motors, and encoders for position feedback. The fourth launcher was delivered in 2011. Its mirrors enabled the use of a 1.5MW, 10sec gyrotron, and it had fast poloidal steering to enable tracking and suppression of NTMs. The other three launchers were all upgraded to the same specification.

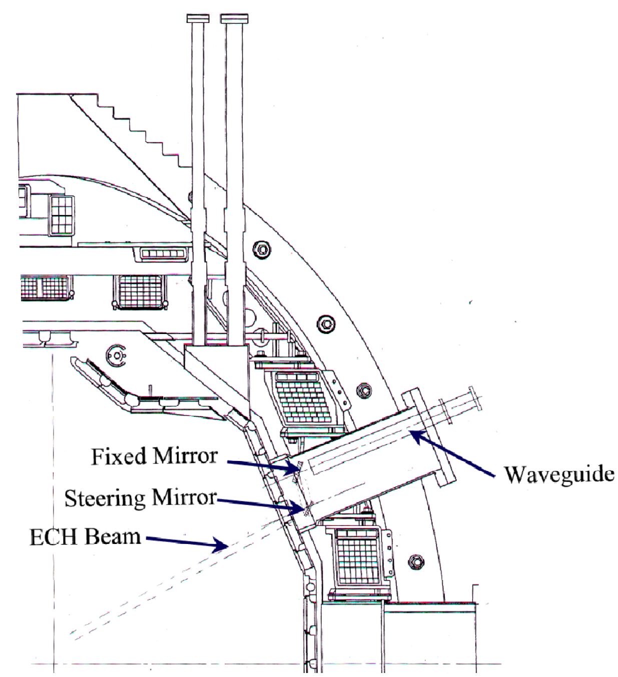

Fig. 1. Schematic view of an ECH launcher on DIII-D

II. Overview of the KSTAR ECH Launchers

In 2006, PPPL delivered the first KSTAR ECH launcher[7] [figure 2], with mirrors and steering gear identical to the DIII-D P200x launchers, and adapted to the KSTAR midplane port geometry. A second launcher of the same design, to be used with the new 170GHz system[8], was delivered in 2011. This launcher was upgraded in 2013 with the latest DIII-D style mirrors[9]. These mirrors are passively cooled, meaning that they cool during long intervals between pulses by radiating heat. The large temperature excursions inherent in this type of design result in significant thermal fatigue stresses, and these mirrors are thus "finite life." There are designed for one run year of 4000 shots at 1.5MW, 10s. This is roughly equivalent to 1MW, 15s, and the pulse length could be extended to 20 seconds at the cost of some fatigue life.

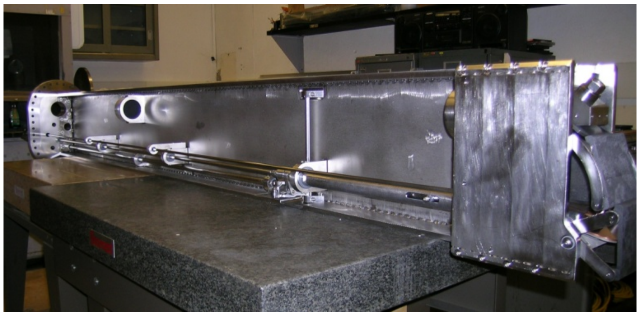

Fig. 2. KSTAR ECH Launcher

The 2014 campaign for KSTAR saw pulse lengths, up to 300 seconds, that require mirrors designed for steady-state operation. A set of actively cooled, steady-state mirrors, designed by KSTAR, was installed on the 170 GHz launcher, while PPPL designed steady-state mirrors intended for the 110 GHz launcher. The PPPL mirrors have employed additive manufacturing, or 3D printing, during their fabrication.

III. A Brief Overview of Additive Manufacturing

Additive manufacturing involves continuous addition of material to a part, typically starting from an empty surface, until the entire solid component has been generated. In recent years, the terms "additive manufacturing" and "3-D printing" have been used interchangeably, and we will do so in this paper, although we should acknowledge other well established forms of additive manufacturing such as electroforming.

3-D printing began in the 1980s. Charles Hull was awarded, in 1984, a patent for stereolithography: "a system of generating three-dimensional objects by creating a cross-sectional pattern of the objects to be formed." He also developed the "stl" file format that is so common in 3-D printing today.

3-D printers using extruded plastic emerged in the late 1980s, and were used for rapid prototyping applications. The first decade of the 20^{th} century saw a large increase in sales of 3-D printing equipment. Beginning in the next decade, 3-D printing techniques were established in the metalworking industry. Some of the common techniques are Selective Laser Melting [SLM], which is used for Titanium alloys, cobalt and chromium alloys, stainless steel and aluminum, and Electron-Beam Melting [EBM] which applies to a larger variety of metal alloys.

IV. Design Parameters of the Steady-State Fixed Mirror

The power flux of the beam emerging from the waveguide is expressed as

$$Q''(r) = Q''_{\max} J_0^{\,2}(r),$$

where r is the distance from the beam axis and J_0 is the Bessel function of the first kind, order zero. Typically r is normalized to the first zero of J_0, and we have $r' = rz_1/a$, where a is the half width of the mirror, and this definition implies that the beam is expanded to the width of the mirror. The normal to the mirror is tilted 50 degrees from the axis of the beam, and the circular beam is projected onto the mirror surface as an ellipse with long axis $b = a/\cos(50°)$. Absorbed power is calculated from the formula[10]

$$A = 1 - R = 4\sqrt{\pi f \rho \varepsilon_0}.$$

Operational experience, where the beam reflection can be degraded by material deposited on the mirror surface, suggests the use of 0.12 per cent in thermal analyses. The heat flux at the mirror surface is thus

$$q'' = q''_{\max} \left|J_0(xz_1/a)\right|\left|J_0(yz_1/b)\right|$$

The launcher design prevents heat radiated by the plasma from reaching the fixed mirror, so the heat load is due entirely to the microwave beam. For our power and beam parameters, peak heat flux is $84W/cm^2$.

The mirror is made from 316 stainless steel on a 3-D printer. It is water cooled with forced convection. A film coefficient of $1W/cm^2K$ was assumed for analysis, and that the coolant flow path has a diameter of 8mm [.31in]. A copper plate, 0.75mm thick [.03in] is brazed to the front surface in order to minimize absorption of the microwave beam.

Initial calculations indicate that, for an assumed water flow rate of $305cm/s$, the film coefficient for heat conduction will be $h = 1.23W/cmK$, verifying our assumption, and the pressure drop for the flow path through the mirror and including the path to the water feedthrough at the vacuum flange, will be

$$P = 7.35*10^5 dyne/cm^2 = 10.6psi.$$

The temperature rise[11], based on the mass flow rate and heat absorbed, is $\Delta T = 2.5K$.

V. Overview of the Fixed Mirror Design

The PPPL-designed steady-state fixed mirror for the KSTAR ECH launcher is a 3-D printed, 316 stainless steel block. The cooling channels are printed into the block [figure 3], resulting in a high level of structural integrity. A 0.75mm thick copper sheet is brazed to the front surface of the stainless steel block in order to minimize absorption of the incident microwave beam, and two tube stubs are welded on in order to facilitate connection to the water system [figure 4]. It is evident from this description that one advantage of 3-D printing is that the manufacturing steps after printing are minimized.

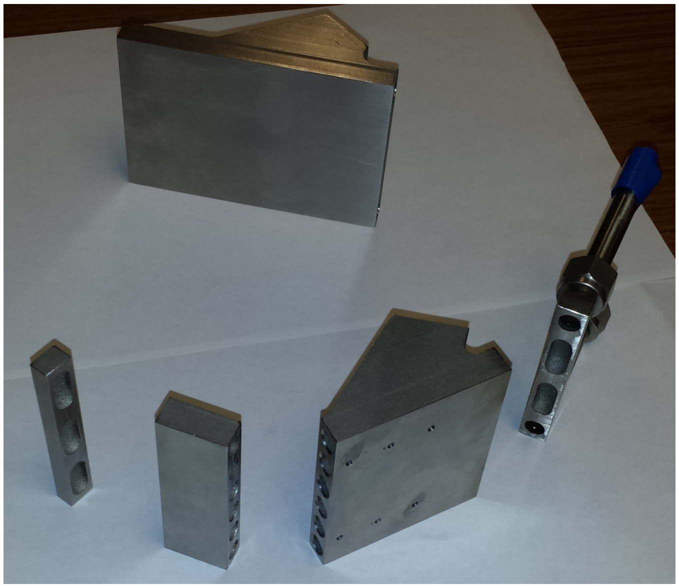

Fig. 3. Stainless steel 3-D printed mirror blocks. Top, whole. Bottom, segmented after testing

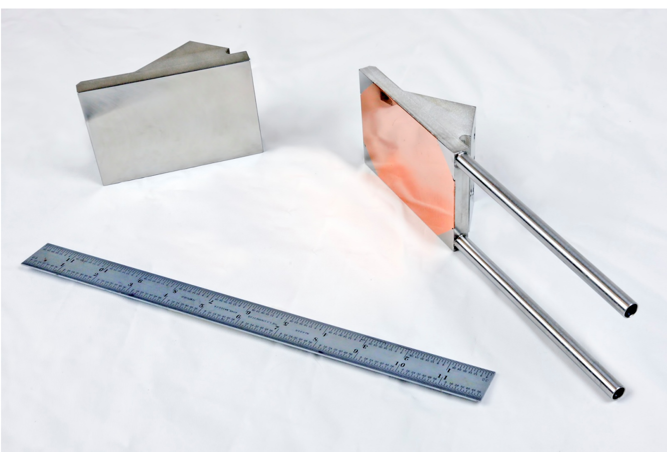

Fig. 4. Printed mirror block, left, and final weldment with copper reflecting surface, right

A finite element thermal analysis was performed on the mirror, indicating that, while the temperatures will be higher than those of a solid copper mirror, they will be acceptable [figure 5].

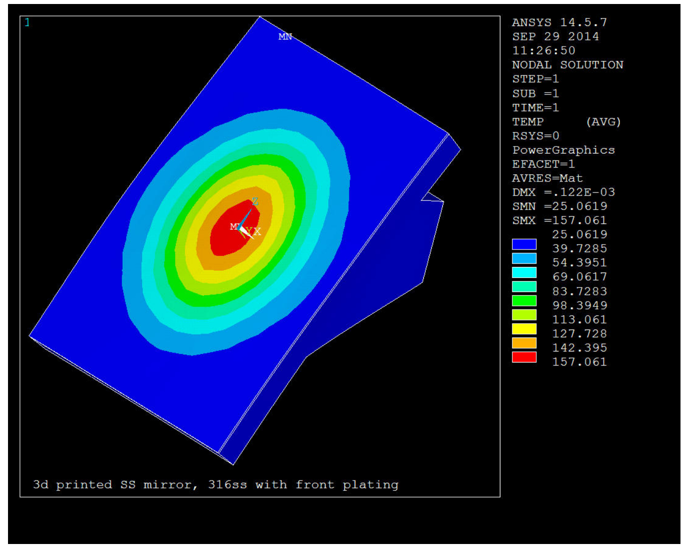

Fig. 5. Temperature contours for fixed mirror, steady-state operation

Thermal tests and water flow tests were performed on an early prototype, which was then sectioned in order to inspect the cooling channels.

During manufacture, an additional sample mirror block was produced and sectioned in order to evaluate the accuracy of the internal features. We achieved better than 0.2mm accuracy for the internal features, and the overall dimensions were held to an accuracy of 0.4mm as printed.

After printing, the front surface of the block was machined in order to prepare for brazing and to minimize the thickness of stainless steel. After brazing, the copper surface was machined to its final thickness, the mounting holes were drilled and tapped, and the tube stubs were welded on.

VI. Overview of Steerable Mirror Design

The steady-state steerable mirror is to replace the passively cooled version in the KSTAR ECH launcher. Again, PPPL chose to use 3-D printing for the design. In this instance, we took more advantage of this advanced manufacturing process by making the cooling channels in the mirror rectangular, rather than circular in cross section. This has several advantages: the maximum distance from the cooling channel boundary to the heated surface is reduced, and the overall volume of the mirror is also reduced, resulting in lower electromagnetic forces. As in the fixed mirror, a thin sheet of copper is brazed onto the front surface. Water is routed through cooling passages printed into the steering fork, and then into tubes contained inside the main steering tube. [figure 6]

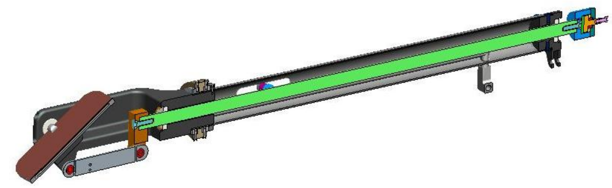

Fig. 6. 3D printing allows cooling features to be integrated into the steering assembly

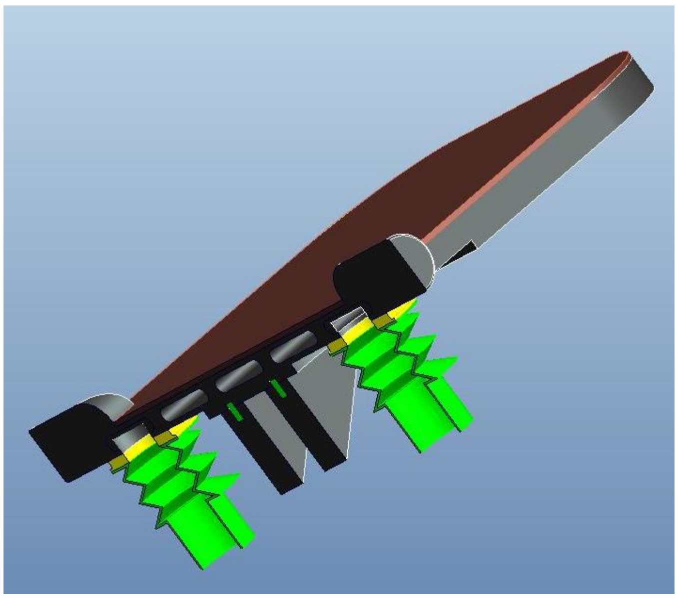

Fig. 7. Rectangular cooling passages are printed into the mirror. Bellows located at pivot axis transfer water into mirror.

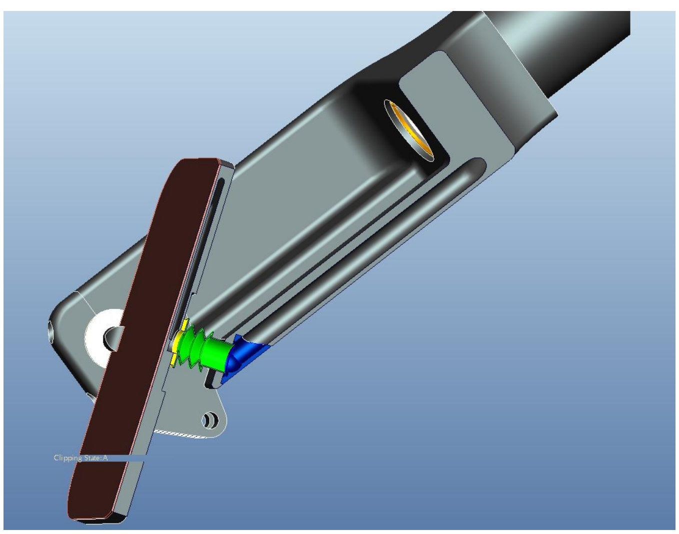

Fig. 8. Water channels are printed into the fork

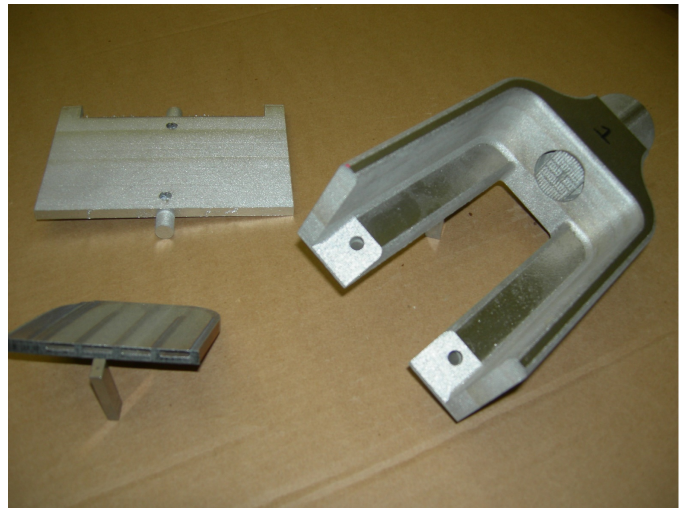

Fig. 9. Fork and mirror are printed to near-final dimensions

The ECH launcher will eventually be used with fast steering to stabilize neoclassical tearing modes. It is therefore important to minimize the resistance to mirror rotation[12]. Flexible connections near the pivot axis of the mirror connect the flow path in the mirror to water passages in the steering fork [figures 7 and 8]. The steering fork is also printed rather than machined, with integral water flow paths. Two stainless steel tubes are welded to the back end of the fork. When the steering tube is welded to the end of the fork, an integrated assembly, with maximum protection of the water flow paths, results.

The water channels in the mirror are asymmetric, but finite element analysis shows that the temperature distribution is acceptable [figure 9].

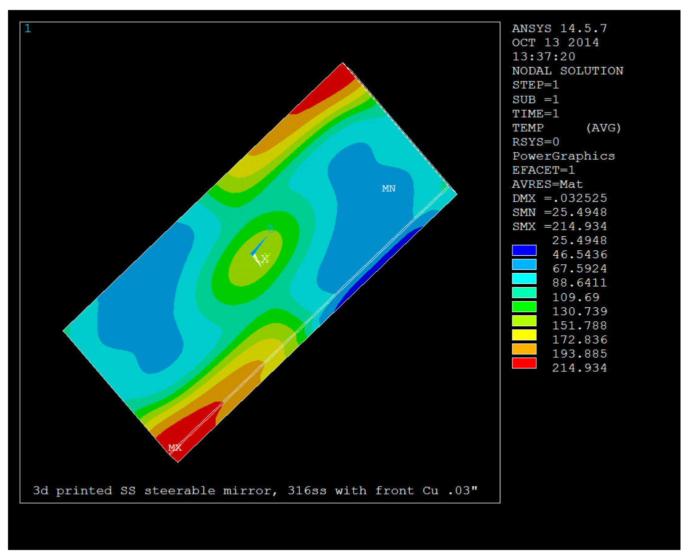

Fig. 10. Finite element analysis, heating from microwave beam only, shows that temperatures are acceptable despite asymmetric cooling passges

VII. PRESENT STATUS OF THE 3-D PRINTED MIRRORS

The fixed mirror was completed and shipped to NFRI in 2014. Fabrication and assembly of the steerable mirror assembly was completed in May of 2015.

VIII. FUTURE DIRECTIONS FOR 3-D PRINTING IN FUSION TECHNOLOGY

Additive manufacturing, or 3-D printing, is a rapidly developing technology that enables novel solutions to design challenges. Although the choice of materials is limited at present, advances in printing technology will enable a wider range of material choices. The advent of printers with dual, or multiple material capability, will enable the printing of thin shells by printing the necessary support structure out of a low melting temperature material, and melting it away after the printing is complete. Increases in the maximum print size will enable larger, more complex printing tasks.

Development of nondestructive techniques for evaluating internal features of printed components is also progressing rapidly. Testing of 3-D printed materials, to verify their mechanical, electrical and thermal properties, is required to fully qualify this process for demanding applications.

IX. SUMMARY AND CONCLUSIONS

Fixed and steerable mirrors, printed from stainless steel, have been produced for KSTAR. Their use in a tokamak environment will provide valuable operational experience. The rapidly evolving technology of additive manufacturing can enable novel solutions for challenging problems in fusion technology.

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