Development of EC Launcher components for ITER

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Abstract. EC launcher components for the ITER have been designed and developed. Thermo-mechanical analysis of a front shield module and a steering mirror for the ITER equatorial launcher were carried out. Maximum temperature and induced stress of the front shield module are estimated to be 232 ºC and 351 MPa, respectively. Maximum temperature of 302 ºC is expected at the steering mirror surface under the 1 MW-CW operation. Maximum induced stress at the mirror surface and the inner surface of the cooling tube are 150 MPa and 248 MPa, respectively. These values are less than allowable level. A cyclic loading test of the spiral cooling tube to supply cooling water to the steering mirror revealed the durability over one million rotational cycles. A diamond window with copper coated edge was developed as a reliable torus window in terms of safety. The result of the 1MW relevant experiment of the window shows no degradation of the high power transmission performance. It is thermo-mechanically and experimentally verified that most of the EC launcher components that has been developed for the ITER are acceptable.

1. Introduction
An electron cyclotron heating and current drive (EC H&CD) is an attractive tools for plasma heating, non-inductive current drive and suppression of magneto-hydro-dynamic (MHD) instabilities such as neoclassical tearing modes (NTMs), sawtooth and so on. In fact, the experiments of EC H&CD and suppression of those instabilities by ECCD have been done in the various present machines and the validity has been confirmed [1-5]. An EC H&CD system is, therefore, required in a fusion reactor such as the International Thermonuclear Experimental Reactor (ITER) as well. The ITER EC system consists of twenty-four 170GHz, 1MW gyrotrons and three 121.4GHz, 1MW gyrotrons as millimeter (mm) wave sources, twenty-four transmission lines to guide the mm-wave power to the vessel and launchers to steer rf beam injection into plasma.

There are two types of EC launchers; a front steering (FS) and a remote steering (RS). The FS launcher consists of a corrugated circular waveguide and a steering mirror located at the waveguide outlet. This concept has the possibility for a wide steering of incident rf beam and is suitable for the various EC H&CD experiment in the present plasma devices such as JT-60, TCV and etc…[6, 7]. The RS launcher consists of a rectangular or square corrugate waveguide and a steering mirror installed at the waveguide inlet. Although the RS concept has the limitation to the steering range of beams, it has a technological advantage that a steering mirror is installed far from plasma [8, 9].

In the ITER, the EC launchers are required to install in an equatorial port and three or four upper ports. The design specifications of the equatorial EC launcher are listed in Table1. Since the wide steering capability is required for the equatorial launcher to meet the physics demands, the FS concept has been selected for it. A conceptual drawing of the ITER equatorial EC launcher designed with the
FS concept is shown in Fig. 1. The launcher components installed in front will be exposed to high energy neutrons, a high heat and a particle flux from plasma, which have not been considered in the present machine. They must tolerate under these severe conditions. Once the launchers are operated under deuterium-tritium (D-T) plasma discharge, a remote maintenance has to be applied for them. Therefore, the systematic design of the launchers, which takes into account the maintenance, is remarkably necessary. This subject is also completely different from the present devices.

In this paper, the design and the development of the ITER equatorial EC launcher is described. In section 2, the design of the equatorial launcher is briefly indicated. The development of its components, such as front shields, steering mirrors and so on, based on the design, are described. Thermo-mechanical analysis of those components and high power rf experiments of the bend mirror and cyclic loading tests of the spiral tube are also reported. In section 3, the development of a torus diamond window as a vacuum and tritium barrier for the launcher is described.

### Table 1 Design specification of an equatorial EC launcher

| Items                  | Specifications                                      |
|------------------------|-----------------------------------------------------|
| Function               | Heating (access to H-mode)                          |
|                        | On/Off axis current drive                           |
|                        | Start-up (121.4 GHz), Discharge cleaning            |
| Frequency              | 170 GHz                                             |
| Injection Power        | 20 MW/port                                          |
| Beam Steering          | Toroidal 20–45 deg.                                 |
| Ave. Neutron flux      | 0.57 MW/m²                                          |
| Ave. Heat Flux         | 0.20 MW/m²                                          |
| Shield Capability      | Dose rate behind the closure plate at $10^6$ sec after shutdown : $< 100 \mu$Sv |
|                        | Neutron fluence limit for window : $10^{16}$ n/cm² |

2. Equatorial EC launcher and its components

In the design requirement of the ITER EC launchers, the equatorial launcher should have the steering capability of rf beam injection with the range from 20° to 45° and the injection power of 20 MW. As shown in Fig. 1, the launcher consists of a front shield to protect the launcher components in a port plug. The front shield is segmented by fourteen modules so as to create three slots for rf beam injection toward plasma. In the port plug, three optic steering mirrors, the waveguide transmission lines, internal shields and so on are installed. The port plug has a closure plate at the end in order to shut out tritium and activated dusts. Three drivers for the mirrors and the torus windows are attached the closure plate.

![Figure 1 ITER equatorial EC launcher.](image)
2.1. Front shield. The front shield is installed in front of the launcher to protect the components in the port plug from a direct neutron irradiation and a high heat flux exposure. There are three narrow slots for a RF beam injection toward plasma. The minimum slot size is determined as \(240 \times 640 \text{ mm}^2\) for the inside and \(240 \times 1000 \text{ mm}^2\) for the outside facing to plasma. The tapered slots inhibit the degradation of the neutron shield capability. There are three kinds of shape for the shield module and the design concept of all module is based on the shield blanket reported in the ITER FDR(1997) [10, 11]. An example of the structure is shown in Fig. 2. It consists of a first wall and a SS316 body. The first wall has a 10 mm-thick beryllium armour in front and a 20 mm-thick heat sink layer made of a copper alloy (DSCu : Dispersion strengthened copper or CuCrZr) in behind. Each module has the support key on the back and it is inserted into a hole of the support plate and welded. The cross section and the length of the key are \(140 \times 200 \text{ mm}^2\) and 140 mm, respectively. The heat sink layer and the SS316 body have several cooling channels to eliminate heat loads from plasma and nuclear heating. The inner diameter of the tubes in the heat sink layer and the shield body are 10 mm and 24~40 mm, respectively. The application of hot isostatic pressing (HIP) technique for the fabrication of the shield modules is expected.

Thermo-mechanical analysis of the module shown in Fig. 2 was carried out. The analysis model and the calculation conditions are shown in Fig. 3(a). Temperature of the inlet cooling water is assumed to be 121 °C in the first wall and 125 °C in the SS316 body. The expected flow speed of cooling water in the first wall and the SS316 body are 5.1 m/sec and 0.9 m/sec, respectively. Heat load from plasma and nuclear heating estimated by the analyses are indicated in the model. The fixed boundary is the support key. Distribution of temperature and induced stress (von Mises stress) at the steady state condition are shown in Fig. 3(b) and 3(c), respectively. The calculated maximum temperature is 232 °C at the surface of the SS316 body exposed to heat flux from plasma and lower than allowable level. Maximum stress of 351 MPa is expected at the inlet of the cooling channel for the first wall. However, it can be acceptable if “3Sm” (\(3S_m = 400\text{MPa}\) for SS316), where \(S_m\) is 1/3 yield strength so-called the design stress intensity value, is considered as the allowable stress. It was concluded that the design of the front shield module was thermo-mechanically acceptable.

![Figure 2](image1.png)

**Figure 2** Example of a shield module structure. It consists of a first wall and a SS316 body.

![Figure 3](image2.png)

**Figure 3** Thermo-mechanical analysis of a shield module. (a) Analysis model and distribution of (b) temperature and (c) von Mises stress.
2.2. Steering mirror. In the previous design of the steering mirror [12], it consisted of a thin reflection surface (250×360 mm², 5 mm-thick) made of copper alloy (DSCu or CuCrZr), a SS316 body (45mm-thick) having several cooling holes milled inside and a SS316 rotational shaft. The rotational shaft also should have a cooling channel. Thermo-mechanical analysis of the mirror showed that the induced stress at the reflection surface was about 200 MPa, which was comparable to the allowable stress of DSCu (210MPa). Then, the mirror design has been modified so as to reduce the stress. The drawing of the modified mirror design is shown in Fig. 4. It consists of a 30 mm-thick DSCu or CuCrZr body and ten SS316 cooling tubes inside. The area of the reflection surface and the thickness are 250×360 mm², which is the same as before, and 30 mm, respectively. The inner/outer diameter of the tube is 12/14 mm, respectively. The application of HIP technique for the fabrication of the mirror is supposed as well as the front shield described in the previous subsection.

Thermo-mechanical analysis of the mirror was carried out. The 2D analysis model based on the design and the calculation conditions are shown in Fig. 5(a). Heat load is mainly yielded from ohmic loss when the rf beams are reflected at the surface. The distribution of the beams is assumed to be Gaussian. The expected peak power density, where the beam power and electrical resistivity are 1 MW and 8×10⁻⁸ Ωm respectively, is 3.2 MW/m². Heat load from plasma and nuclear heating are also considered. Temperature of inlet cooling water is assumed to be 100 ºC. The expected flow speed of cooling water in the mirror is 4.0 m/sec that corresponds to heat transfer coefficient of 31 kW/m²/K. The fixed boundary is the support on the back of the mirror. Distribution of temperature and induced stress (von Mises stress) at the steady state condition are shown in Fig. 5(b) and 5(c), respectively. The power of each beam is 1 MW. The calculated maximum temperature is 302 ºC at the reflection surface.

![Figure 4 Design of a steering mirror. It consists of a 30 mm-thick DSCu or CuCrZr body and ten SS316 cooling tubes inside.](image)

![Figure 5 Thermo-mechanical analysis of a steering mirror. (a) Analysis model and distribution of (b) temperature and (c) von Mises stress.](image)
surface. Maximum stress at the inner surface of the cooling tubes and the region of copper alloy are 248 MPa and 150 MPa, respectively and can be acceptable if “3Sm” (3Sm = 400 MPa for SS316, 210 MPa for DSCu and 230 MPa for CuCrZr) is considered as the allowable stress.

2.3. Miter bend. The equatorial launcher has the dog-legged waveguide transmission line to reduce the direct neutron streaming to the port end so that the torus window, the drive system for the steering mirror and other components are protected. In order to form the dog-leg, a miter bend is introduced. The drawing of the miter bend design for the launcher is shown in Fig. 6. It consists of a short inlet/outlet waveguide and a reflection mirror. The mirror consists of a 3 mm-thick reflection surface made of copper alloy and a 14 mm-thick mirror body with several milled holes for cooling water, which is made of SS316. A 1 mm SS316 plate is inserted between the copper region and the mirror body to close the cooling holes. The inlet/outlet waveguide and the bend body made of SS316 also have the cooling channels to eliminate ohmic loss and nuclear heating.

The mock-up of the bend mirror based on the design was fabricated and the high power transmission experiment was carried out. The photograph of the mock-up is shown in Fig. 7. Several thermocouples were installed inside the mirror, at 5mm from the reflection surface. Time evolution of incremental temperature in the bend mirror is shown in Fig. 8. The rf power and pulse length are 420kW and 4.7sec, respectively. The rf frequency is 170GHz. The circles and the triangles are the calculated temperature increase at the center (r=0) and the 22 mm-peripheral location (r=22) from the center. The solid lines are the experimental results. It is verified that the experiment agrees with the calculation. Thermo-mechanical analysis under the CW transmission was also carried out. The peak power density, where rf power 1 MW and electrical resistivity $4 \times 10^{-8}$ Ωm are assumed, is 2.4 MW/m$^2$ and the assumed temperature of inlet cooling is 100 ºC. Heat transfer coefficient is 13 kW/m ²/K, which is the equivalent to the experimental condition. Maximum temperature and induced stress are
250 °C at the reflection surface and 290 MPa at the inner surface of the cooling channel, respectively. Considering these results and the allowable stress of copper alloy and stainless steel described in the previous subsection, it is concluded that the bend mirror structure withstand the ITER operation.

The expected transmission efficiency of the bend is 1-1.2%. The ohmic loss about 0.2% was measured at the experiment and we, therefore, have considered that the amount of wrong modes is 0.8-1.0%. In addition, we speculate that the power of wrong modes would be mostly deposited in the inlet and outlet waveguide wall of the bends and consider that the waveguide design needs a cooling structure in the wall. The further investigation of the deposited power in the bend waveguides is necessary to design the optimized cooling structure of the bend and the waveguide of the dog-leg.

2.4. Spiral tube, drive mechanism for steering mirrors and other components. The spiral cooling tubes to supply cooling water to the rotating mirror has been designed as shown in Fig. 4. Two or three turns of spiral are considered. The inner/outer diameter of the tube and the diameter of spiral are 12/14 mm and 180 mm, respectively. The mock-up of the SS316 spiral tube was fabricated and the cyclic loading test was done to investigate the fatigue property. The rotation angle of the tube is ± 6.5°. The corresponding range of incident beam angle is ± 12.5° (θ_T = 20–45°). The strain on the outer surface of the tube was directly measured by several strain gauges attached on the surface. Using the measured data, the stress was then estimated to be about 180MPa, which was comparable to the calculation result (194MPa). The durable test of the tube at the rotation of ± 6.5° was also carried out and the rotation cycle more than 1.3 ×10^6 was successful. It is recognized that the spiral tube is acceptable to the steering mirror.

A specially developed ball bearing is introduced for the steering mirror and designed to install at the top and bottom, relatively far from the mirror to reduce the neutron irradiation on them as shown in Fig. 4. No lubricant and retainer are applied to the bearings to eliminate the unexpected event on them due to neutron irradiation effects. Tungsten carbide (WC), stainless steel with high content of manganese (SS_Mn) and silicon nitride (Si3N4) are considered as the candidate materials for the bearings. Neutron irradiation of WC and SS_Mn bearings were made in JMTR (Japan Material Testing fission Reactor). The irradiation fluence and temperature were 10^{24} n/m^2 (En > 0.1MeV) and 220-270 °C. The fluence is equivalent to the expected value for the bearings during the ITER life time. In order to investigate the irradiation effects on the performance of the bearings, the rotation tests were carried out before and after the irradiation. It was, then, verified that the smooth rotation was obtained although torque of both bearings doubled after the irradiation. The ball bearings are possibly recognized to use for the steering mirror.

A drive system for the steering mirrors has also being developed. In the equatorial launcher, a push-pull mechanism consisted of a drive shaft and a driver is introduced. The conceptual drawing of the driver is shown in Fig. 9. An ultrasonic motor and a linear guide to convert the rotation to the linear motion are applied for the driver. The ultrasonic motor is attractive since it can be driven by electricity even in magnetic field. The motor and the linear guide are supposed made of all non-magnetic materials and they should be neutron and γ-ray irradiation proof. Some materials used in the

![Figure 9 Design of a drive system for a steering mirror. It consists of an ultrasonic motor, a linear guide to convert the rotation to the linear motion and a drive shaft.](image)
ultrasonic motor are the future issue to be solved since there is the uncertainty of the irradiation proof. The air motor, which can be made of non-magnetic and neutron and \( \gamma \)-ray irradiation proof materials, is considered as an alternative drive source.

3. Torus window

As shown in Fig. 2, a torus window is installed at the closure plate and should take a role of a tritium barrier for the launcher. In terms of the safety, the window must have the highly reliable structure. A diamond is nowadays the standard material for the torus window in the EC H&CD system since it has the outstanding properties such as low loss tangent and high thermal conductivity so that the 1 MW-CW, HE\(_1\) mode transmission is promising. The schematic structure of the conventional diamond window is shown in Fig. 10(a). Both sides of a diamond disk edge is bonded to an inconel cylinder by aluminum braze and a stainless steel housing is welded to the other side of the cylinder so as to make the cooling channel at the disk edge. When rf power pass through the window, heat deposition in the center region of the window mainly occurs and the heat is dissipated to the disk edge and eliminated there by cooling water. Although the structure is simple, a cooling water leakage would possibly happen if a crack was produced by, for instance, arcing on the window surface and grown toward the edge. The leakage event makes the degradation of vacuum in a vessel, which leads to collapse of plasma. The high reliability of the window is therefore required.

In order to prevent the presumed water leakage event described above, a new diamond structure with a copper (Cu) coated edge has been proposed [13]. A 0.5mm-thick Cu layer is coated on the window disk edge as shown in Fig. 10(b). The coating also avoids the aluminum corrosion and no corrosion inhibitor is necessary in cooling water. Based on the unique concept, the diamond window assembly with the Cu-coated edge was fabricated and the high power transmission experiment was carried out. Infrared image of the window and time evolution of temperature at the window center are shown in Fig. 11. It is recognized that a Gaussian-like beam transmits through the window. The beam width is about 26mm in radius, as expected. The circles are the experiment that agrees with the calculation indicated by the solid line. Thermal conductivity of 1.9 kW/m/K and heat transfer coefficient at the cooling region estimated to be 5 kW/m\(^2\)/K based on the size of the cooling channel and the flow rate of 18 l/min were applied for the calculation. Transmission power and frequency were 55 kW and 170 GHz, respectively. The transmitted power is indicative to 1.2MW since loss
tangent of the diamond used in the experiment is $8.5 \times 10^{-4}$, much higher than the standard ($\tan \delta = \sim 2 \times 10^{-5}$). The pulse length was 3.5 sec and temperature of the window was almost saturated. Thermo-mechanical analysis of the Cu-coated window was also done. In this analysis model, Cu-coating ($t=0.5\text{mm}$) not only on the disk edge, but on the entire outer surface of the inconel cylinder are introduced since solubility of copper for tritium was lower than that of inconel [14, 15]. Temperature and von Mises stress of the window under the condition of 1 MW-CW HE$_{11}$ mode transmission are shown in Fig. 12. Maximum temperature and stress are 104 $^\circ$C and 73 MPa at the window center and the diamond disk edge. Temperature of the window is similar with that of the conventional window. Maximum principal stress of the diamond window was also calculated to be 62 MPa at the edge. The stresses are less than the median fracture strength of diamond (300-400 MPa) [16]. It was confirmed that the Cu-coating did not degrade the transmission performance and the cooling capability and increased the reliability of the torus diamond window.

4. Summary and Conclusion

Recent status on the design and the development of the equatorial EC launcher components for the ITER were reported. The front shield has three tapered narrow slots for a RF beam injection, which inhibit the degradation of neutron shield capability. Thermo-mechanical analysis of the module shows that maximum temperature and stress are 232 $^\circ$C and 351 MPa at the SS316 surface exposed to plasma and at the inlet of the cooling channel for the first wall, respectively. As the induced stress is less than the allowable stress (400MPa for SS316), the design of the front shield module is thermo-mechanically acceptable.

Regarding to the steering mirror, the design and thermal analysis of the mirror and the cyclic test of a spiral tube to supply cooling water into the mirror have been done. The preliminary result of the analysis shows that maximum temperature increase of 202 $^\circ$C at the reflecting surface and the maximum stress of 248 MPa at the inner surface of the cooling tube are expected. Stress on the reflection surface is 150MPa. It was confirmed that the mirror design was thermo-mechanically acceptable. In the cyclic test of the spiral tube mock-up, the cyclic number of $1.3 \times 10^6$ was succeeded without failure and it was recognized that the spiral tube was the possible structure of the water feed line for the steering mirror.

In the window development, the Cu-coated edge diamond window was proposed so as to increase the reliability. The temperature measurement of the window at the high power experiment, which is indicative to the 1.2 MW-level transmission, agrees with the calculation. Thermo-mechanical analysis of the window at the 1 MW-CW HE$_{11}$ mode transmission indicated that temperature increase was similar to the conventional window and no serious stress in the diamond disk was obtained. It was concluded that the Cu-coated window was capable of MW-level transmission and the Cu-coating improved the reliability of the diamond window.

Some technological points on the development of the equatorial launcher components need to be improved. One is the support structure of the launcher plug against electromagnetic force caused by
plasma disruption. The design of the steering mirror is considered available and the fabrication and assembly technologies, however, have to be demonstrated. The further investigation of the wrong mode generation in the miter bends has to be done for the optimization of the waveguide design with the cooling structure. As for the torus diamond window, the demonstration of 1MW-CW transmission with the mock-up and the design to meet the ITER safety baseline that will be determined are remained as the further development issues. Finally, the assembly procedure of the launcher considering the remote maintenance may need to improve further since the remote handling in an ITER hot cell is still under discussion.

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