A Frictionless Steering Mechanism for the Front Steering ECCD ITER Upper Port Launcher

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Abstract. A FS launcher is being designed for the ITER upper port, which offers enhanced physics performance over the RS launcher. A two mirror system is used to decouple the focusing and steering aspects of the launcher and provide a relatively small beam waist (<20mm) projected far into the plasma (>1.6m from the steering mirror). The resulting NTM stabilization efficiency (maximum CD density divided by the local bootstrap current > 1.6) is above marginal for the q=2 and 3/2 rational flux surfaces of the relevant ITER equilibria (scenarios 2, 3a and 5) and a factor of ~3 relative to an equivalent RS launcher. The performance of the FS launcher strongly depends on the reliability of the steering mechanism, which is used to rotate the plasma facing steering mirror. CRPP has designed a frictionless steering mechanism assembled in a compact cartridge capable of up to ±10° rotation (corresponding to a poloidal steering range of up to ±20° for the microwave beam around a fixed axis of rotation) that offers a high operation reliability despite the close proximity to the thermal and neutron flux coming from the ITER plasma.

1. Introduction
The purpose of the ITER electron cyclotron resonance heating (ECRH) upper port launcher will be to drive current locally inside a q=3/2 or 2 island in order to stabilize the neoclassical tearing mode (NTM). Unfortunately, the uncertainties due to our limited experience using ECCD for NTM stabilization magnified by extrapolation to ITER, results in a relatively large range of current drive densities and injection angles that may be needed on ITER. Although the remote steering (RS) launcher design [1] offers the advantage of not requiring moving parts within the vessel vacuum boundary (far from the thermal and nuclear radiation of the plasma), it has a angular range of ±12° limited by the beam transmission properties of the square corrugated waveguide and a relatively broad beam spot size at the resonance surface. The angular range is decreased (~ ±10°) due to additional focusing affects of the plasma facing mirror after the waveguide aperture. Whereas, the front steering (FS) launcher offers an extended angular range (~ ±20°) and a narrower spot size at the resonance. A FS launcher [2] is already being planned for the equatorial port where thermal and neutron radiation fluxes are, in fact, higher than at the upper port. In light of this, an alternative FS launcher for application on the ITER upper port is proposed [3, 4]. Although the standard ITER design value is currently 1 MW per beam, the launcher is capable of injecting over 16MW per port, assuming eight beams of 2MW and in anticipation of the the 2MW gyrotron under development within the European Community [10]. A two mirror system (1 focusing-fixed and 1 flat-steering) for focusing and redirecting the beam towards the q=3/2 or 2 flux surfaces for all envisioned plasma equilibria is used.

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This paper provides a brief description of the envisioned optical front mirror steering mechanism followed by a conclusion.

A simplified poloidal section view of the current FS launcher design is shown in figure 1. Eight circular waveguides enter at the port entrance on the right, with the waveguides arranged in two rows of four. A miter bend ‘dog-leg’ assembly is used to angle the 8 beams (both in toroidal and poloidal directions) to one single focusing mirror, the incident beams partially overlap in both toroidal and poloidal directions. The reflected beams are then directed downward to two separate flat steering mirrors, which redirect the beams into the plasma with a toroidal injection angle. Since the beams are allowed to expand from the waveguide aperture, they can be refocused to a narrow waist far into the plasma (>1.6m after steering mirror). The angular rotation of the steering mirror (±6.5˚) provides access along the resonance layer from \( Z_{res} = 1.8 \) to 3.6m.

2. Steering Mechanism requirements

The steering requirement imposed by NTM physics, taking into account the rather unfavourable location with high z elevation of the upper ports, is for a beam rotation of ±13˚, equivalent to mirror rotation of ±6.5˚. ITER relevant requirements include the sustaining of continuous thermal and nuclear radiation, to withstand electromagnetically induced forces during disruptions, to provide accurate angular positioning with an error of less than 0.2˚, the compatibility with water circuit interfaces (cooling, baking) and the compatibility with remote handling tools and procedures. The steering system has to work reliably and guarantee fail-safe operation avoiding major interference with the tokamak activity.

Additional requirements have been formulated by CRPP, they include a preferably frictionless and backlash-free mechanical transmission and actuation system (to avoid bearings, bushings, push rods). In order to fulfill extended physics requirements to include ELM control and CD [4-6], the beam steering range should be increased to ± 20˚ (± 10˚ at steering mirror). Optimal beam focusing at deposition location allows to increase the overall performance and reliability margin of the ECCD through higher \( j_{el}/j_{th} \) values, since failure of a number of beam lines can be tolerated while still...
achieving full NTM stabilization. The $j_{co}$ deposition will be measured relative to the rational flux surface ($q=2$ or 3/2) in the plasma using diagnostics systems such as ECE for real time feedback control of the mirror launcher angles, thus bypassing the need for an angular measuring and feedback system on the steering mirror. However, the angular position of the mirror may be optionally monitored using, for example, rotational variable capacitor or an opto-encoder.

3. Description of steering mechanism

In order to demonstrate the feasibility of a front steering EC antenna system which accommodates the limited space constraints within the upper port plug of the present ITER reference design and yet offer full beam steering capability over an angular range of +/- 20°, a robust steering mechanism with a reduced number of components is described. The FS launchers on existing tokamaks have been hindered when the steering mechanism grips. Experience with mechanical assemblies involving ball bearings, bushings, push/pull rods and various types of linkages and cams operating in UHV conditions have shown to be insufficiently reliable and frequently subject to excessive wear or gripping. Tribological failures are the main cause for premature break down of systems where friction, wear and the absence of lubrication of interacting surfaces in relative motion are dominant. Movements of small amplitude and high frequency are exacerbating tribological problems, as does the potential presence of metallic and ceramic dust particles and sputtered surface contaminants. These are the justifications for the use of elastically compliant concepts, which eliminate friction, backlash, clearance. The proposed design offers sufficient stiffness and is intrinsically play-free and thus avoids backlash and stick-slip phenomena.

As shown in figure 2, a set of elastically compliant flexure pivots replace the traditional ball bearings in centering and guiding the rotation of the steering mirror. Made of just five machined parts in its current implementation, it utilizes a orthogonal set of three flat spring blades in a typically cylindrical cartridge housing. The main advantage of the flexure pivot lies in frictionless and backlash free operation. There is no need for static preloading to remove clearance. By choosing the appropriate material combining good elastic properties under cyclic loading conditions and simultaneous neutron

**FIGURE 2.** Exploded view of the main elements of the front mirror and the steering mechanism (below) and assembly view (top).
irradiation, as those expected in the region behind the first wall shielding, the flexure pivot provides precise and repeatable rotation with a very small excentricity over a large number of cycles.

FIGURE 3. A sketch on the pneumatic principle of the actuator.

The mirror movement is achieved by a helium gas actuator assembly replacing the generally used push-pull rods. The mirror rotation is controlled by the helium pressure in the bellows counteracted by a set of compressive springs, as shown schematically in figure 3. The pressure in the seamless bellows is controlled via a single small bore gas feed line by a piezoelectric servo valve located outside the vessel vacuum behind the closure plate. A magnetically driven servo valve could be used with appropriate electromagnetic shielding or at a location where the magnetic field would be acceptably low. Two arms extend past the edge of the mirror, and are positioned symmetric about the mirror axis. Each arm passes between a set of tangentially arranged bellows and preloaded compressive springs. The mirror is rotated when the arms are moved by either increasing or decreasing the pressure in the bellows, counteracting the recalling torque imposed by the compressed springs. The complete system is integrated into a cartridge type construction, with all static forces and torques being fully balanced within and thus requiring no structural link to the embedding neutron shielding and plug structure other than the centering housings interfacing with the flexure pivots. The mirror can be controlled on a sufficiently rapid time scale with a calculated time constant of typically 20 ms, into which the time delay caused by the long helium feeding pipe is included. This simple servovalve system with pressure feedback control, as shown in figure 4, works on the linear relationship between bellow pressure and spring compression proportional to the steering angle. Although rotation angle measurement is not necessarily required as the actual orientation of the beams can be detected by indirect means via the invessel diagnostic systems with pulsed beam modulation or small angular range scanning, systems using a variable capacitor integrated into the rotor [7] or a optical encoder with optical fiber [8] are under consideration.
FIGURE 4. Linear relationship between bellow pressure and spring compression proportional to the steering angle allows for servovalve control with pressure feedback.

FIGURE 5. Possible reduction of EM induced forces by further reducing the steering mirror size.

The cooling water removes the surface heat generated through ohmic losses of the reflected beam at the mirror surface and the volume heat from neutron absorption in all massive components. The water circulates through the static and the rotating parts of the front steering cartridge. The fluid paths are optimized for keeping the lowest possible temperature at the reflecting mirror surface while minimizing thermal gradients and consequent distortions of the mirror rotor, which would degrade the beam quality. The use of water feeding and fatigue sensitive and thus less reliable bellows or corrugated tubes to circulate the water in the rotor is avoided by winding a pair of spiral pipes around the section of the mirror housing the actuators and springs, welded between the mirror/rotor and the stator parts.

4. Critical elements
The steering mechanism is the critical component of the FS design and a failure of one steering mechanism would render four mm-wave beams unavailable for NTM stabilization applications. It is important to note that a failed steering mechanism can only be replaced during a normal tokamak opening. However, half of the total number of FS steering mechanisms could fail and still provide sufficient NTM stabilization performance (8 beam/3 port configuration).

The EM forces related to the induced currents during a disruption were estimated for the steering mirror in the worst configuration and assuming no shielding effect from the port wall, dB/dt=25T/s (plasma current 17.85MA and linear current decay time 0.04s [11]) and B_T=5.0T. The latest values given for disruptions of type III [12] will be accounted for in the final design of the mirror and flexure pivot assembly. The mirror dimensions are 305mm (toroidal), 210mm (poloidal) and >0.5mm (copper thickness), with the mirror made from steel, while electrical insulation breaks are introduced on the back side limiting the effective thickness. The resulting net torque on the mirror is 590Nm, resulting in a force of <2 kN per flexure pivot (a flexure pivot is positioned on each side of steering mirror). The flexure pivots are capable of supporting up to 3.5kN at full steering angle for the present configuration. The induced EM forces will actually be less than 45% of the flexure pivot force limit once the shielding effect of the port wall is taken into consideration, as shown in Fig. 5.

The flexure pivots are made of a titantium alloy (Ti6Al4V or Ti5Al2.5Sn) capable of withstanding the neutron fluxes and induced stresses during plasma disruption and offering the appropriate tensile
and fatigue behavior under irradiation. The stress versus strain curves and fatigue life have been determined for irradiated samples at 350 °C in vacuum [9], with yield strength reaching 800 MPa, as shown in Fig. 6. The desired design values for the flexure pivot and similar elastically deformed components are stress below 200 MPa and strain below 0.5%, while strain of typically 1% results in fatigue life of at least 10'000 cycles. The proposed stress/strain values are comparable to those found in the flexible mechanical attachments used to hold the first wall blanket shield modules, made of Ti6Al4V [8].

![FIGURE 6. Stress / strain curve for irradiated titanium alloy samples [9].](image)

Fatigue cycling, thermomechanical and hydrostatic loads under simultaneous neutron flux exposure are equally critical in structural elements such as the pneumatic bellow actuator, the compressive spring and the cooling water feed coil. Concepts aimed at reducing mechanical stress in the spiral coolant feeds, such as tubes with rectangular rather than circular cross section, are under investigation. Particular attention is given to the welded connections of the pipework. A coiled cooling tube with either a single or double wall is envisioned to provide method of water leak testing.

The spot sizes on both the focusing and steering mirrors are relatively large (65.0mm and ~50.0mm respectively) and, as a result, the peak power density is reduced significantly despite the partially overlap of multiple 2.0MW beams. The maximum power density reaches ~3.4MW/m², which occurs on the lower steering mirror. Absorbed power is calculated assuming circular polarization and an absorption coefficient of 0.005 to account for increased temperature, surface roughness and surface impurity effects. The relatively low power density on the FS steering mirror offers the possibility of using non-copper reflective material such as beryllium or tungsten to avoid copper sputtering into the plasma or reduce surface erosion.

5. Mechanical and hydraulic fail safe operation
The FS system is designed to provide mechanical and hydraulic fail safe operation. For example, the steering mirrors use dedicated cooling circuits, which can be isolated and evacuated if a water leak is detected. The quantity of water released into the torus vacuum is minimized. Furthermore a passive cooling scheme to remove heat generated by absorbed neutrons in case of failure of the water cooling is necessary and foreseen, where radiative and conductive heat fluxes are sufficient to maintain the
steering mirror components at a reasonably low temperature for the remaining time of tokamak operation, until replacement of the FS assembly is possible.

6. Conclusion
Despite the stringent geometrical, thermo-mechanical, nuclear and RF requirements, a FS launcher system based on an invessel steering mechanism appears feasible. To achieve the sufficient reliability and fail-safe operation of the FS steering mechanism, frictionless elements with determined properties of elastic compliance systematically replace traditional components where friction and rolling contacts between surfaces limit the functional lifetime inside the torus vacuum. The backlash and clearance free flexure pivot replacing the ball bearing is typically made of an ITER compliant titanium alloy. Integrating the pneumatic actuator principle based on pressure controlled helium into a self contained cartridge type assembly replaces external push-pull rods. The addition of spiral cooling pipes to avoid bellow coolant feeds makes the launcher hydraulically and mechanically fail safe, where tokamak operation is maintained even after the failure of a front mirror assembly. The steering mechanism is designed to support at least two times the electromagnetically induced loads expected during a VDE in ITER. The realized design features include a beam scanning range of ±20°.

The complete engineering study is ongoing and will be finalized with the production of manufacturing drawings, the construction and finally the test of a prototype under simulated ITER conditions, including low power RF beam tests of the optical system.

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