A frictionless steering mechanism for the Front Steering ECCD ITER Upper Port Launcher

F. Sanchez , R. Bertizzolo, R. Chavan, M.A. Henderson, J.D. Landis,

Ecole Polytechnique Fédérale de Lausanne (EPFL)
Centre de Recherche des Physique des Plasmas
CH-1015 Lausanne, Switzerland

francisco.sanchez@epfl.ch

***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 relevent 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 ±7° rotation (corresponding to a poloidal steering range of up to ±14° 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.**

Keywordst;ITER ECRH, front steering, flexure pivot, FS launcher

I. 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 (~ ±14°) 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. 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.

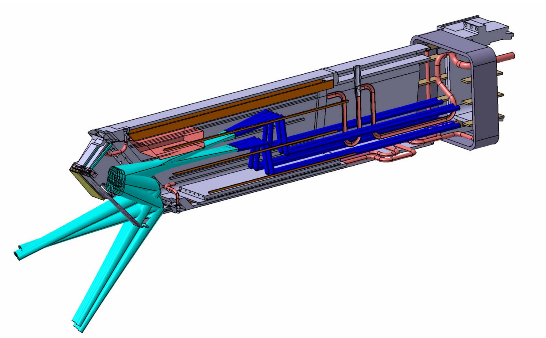


Figure 1. Mid-plane section of upper port plug, showing the position of beam transmission elements.

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 (±7°) provides access along the resonance layer from Z_{res} = 1.8 to 3.6m

This work was supported in part by the Swiss National Science Foundation and the European Fusion Development Agreement under the EFDA Technology Programme (contracts TW4-TPHE-ECHULB1 and TW5-TPHE-ECHULB1).

II. THE STEERING MECHANISM

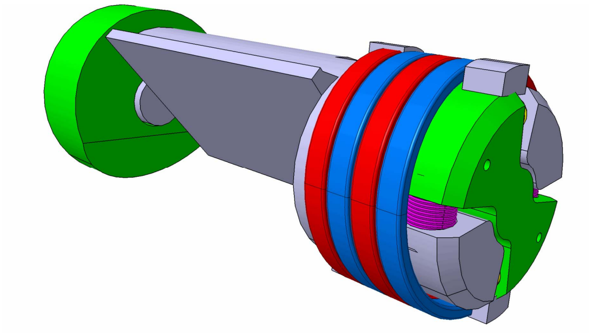


Figure 2. View of the steering mechanism

A. *Steering mechanism requirements*

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 steering requirement imposed by NTM physics, taking into account the rather unfavourable upper port location with high z elevation, is for a beam rotation of ±13˚, equivalent to mirror rotation of ±6.5˚. ITER relevant requirements include the sustaining of continous 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.

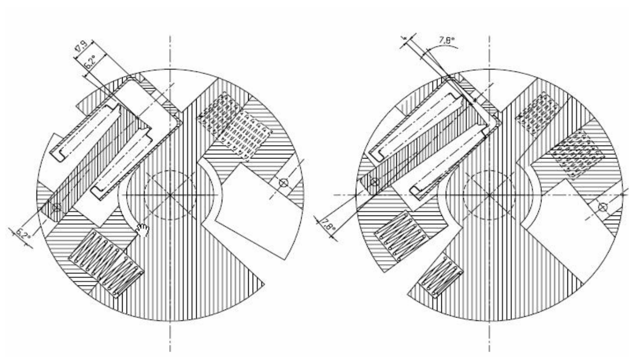
Additional requirements have been formulated by CRPP, they include a preferably frictionless and backlash-free mechanical transmission and actuation system (to avoid bearings, bushings, push rods). In order to fulfill extended physics requirements to include ELM control and CD [4-6], the beam steering range should be increased to ± 20˚ (± 10˚ at steering mirror). Optimal beam focusing at deposition location allows to increase the overall peformance and reliability margin of the ECCD through higher j_{CD}/j_{BS} values, since failure of a number of beam lines can be tolerated while still achieving full NTM stabilization. The j_{CD} 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.

B. *Elements & description of the steering mechanism*

Figure 3 show the assembly of the mechanism: It is composed by two main bodys: The stator is fixed to the launcher, while the mirror is fixed to the rotor of the main body. The system rotates on two flexure pivots, which movement is produced by a set of counteracted bellows and springs, and is cooled by a flexible spiral pipe.

The proposed design offers sufficient stiffness and is intrinsically play-free and thus avoids backlash and stick-slip phenomena. The rotation is controlled by the helium external pressure in the bellows, counteracted by a as set of compressive springs.

The next cross sectional views (Figures 3 and 4) show the extreme positions of the mechanism. The X-shaped central part of the cylinder is the stator, and is attached to an externally pressurized bellows which housess an internal piston attached



at the end to the rotor. Due to the effect of the external pressure, the bellows compresss or expand, producing the required rotation of the system.

Figure 3. Rotations under maximum and minimum bellows pressure.

Figure 3 right shows the system under maximum external pressure (210 bar), which produces an axial compression of 7 mm and an angular deviation of 6.2 degrees in the bellows at the same time, while **Figure 3 left** shows the system at its maximum extension, which corresponds to an axial extension of 7 mm and an angular deviation of 8 degrees in the bellows at the same time.

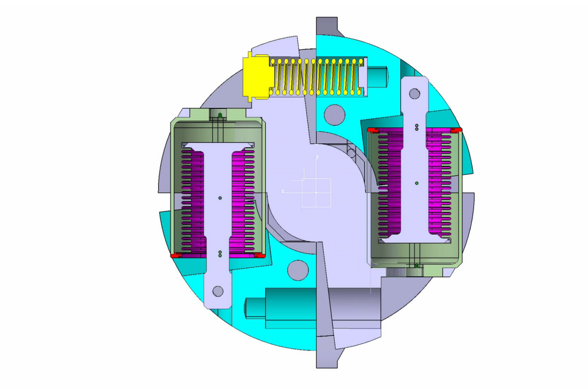


Figure 4. Perpendicular cut through the steering mechanism.

III. 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).

A. *Mirror*

The mirror dimensions are 305mm (toroidal) x 210mm (poloidal). It is made in three layers: a reflective surface made from copper or beryllium, a thermal conducting layer made in Inconel 600, and a high resistive layer made in Inconel 718 to provide structural rigidity to the mirror. Electrical insulation breaks are introduced on the back side limiting the effective thickness.

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/m^2, 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.

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_P/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 II and III were accounted for the final design of the mirror. The resulting induced torque on the mirror is >500Nm, resulting in a force of <2 kN per flexure pivot (a flexure pivot is positioned on each side of steering mirror).

B. *Flexure Pivots*

The flexure pivots are made of a titanium 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 flexure pivots are capable of supporting up to 3.5kN at full steering angle for the present configuration. Taking into account the shielding effect of the port wall, the induced EM forces will actually be less than 45% of the flexure pivot force limit. The EM induced forces also risk the buckling of the flexure pivot, (a detailed calculation is ongoing).

A FE analysis considering the flexure pivot cooled by thermal conduction at its external perimeter, show that for a volumetric heating of 1.5 MW/m^3, the internal temperature is around 160 C.

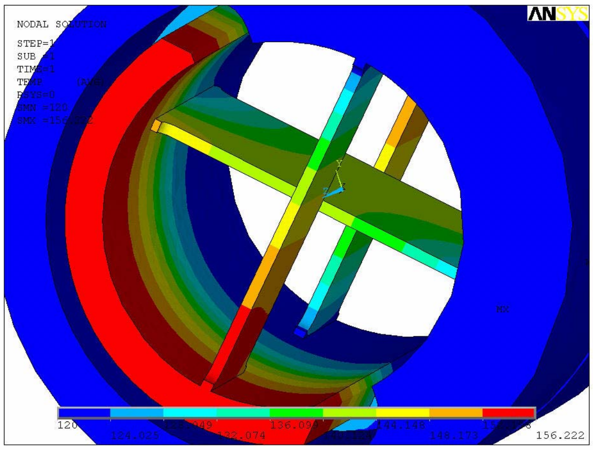


Figure 5. Temperature distribution in the flexure pivot due to neutron heating (1.5 MW/m^3)

The stress versus strain curves and fatigue life have been determined for irradiated samples at 350 C in vacuum , with yield strength reaching 800 MPa, as shown in Fig. 6. The desired design values for the flexure pivot and similar elastically deformed componenets 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 [7].

of a rectangular shaped helicoidal coil

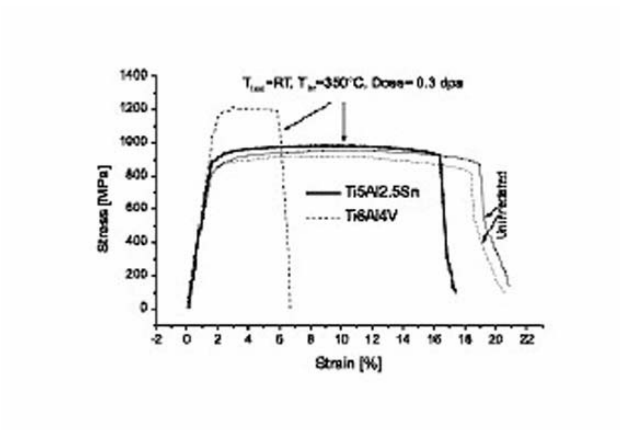


Figure 6. Stress / strain curve for irradiated titanium alloy samples [7].

C. Bellows

The bellows must be strong enough circumferentially to withstand the pressure and flexible enough longitudinally to accept the deflections for which it was designed, and as repetitively as necessary with a minimum resistance. The limited space and high deflection & pressure requirements conflict from the design side: withstanding a high internal pressure having enough buckling safety margin needs a a thick wall, with the cost of a higher spring rate and the reduction in the bellows flexibility (max deflection allowed).

According to the EJMA standards for our boundary conditions, a compromise between hoop, circumferential, bending, membrane stresses, fatigue life and column stability could not be reached, resulting likely in a reduced fatigue-life rate or in the squirm due to the required internal pressure.

This issue is solved with the current design in which bellows are externally pressurized. The two extreme working pressures result in a full expansion and contraction, guiving thus the required rotation (figure 3)

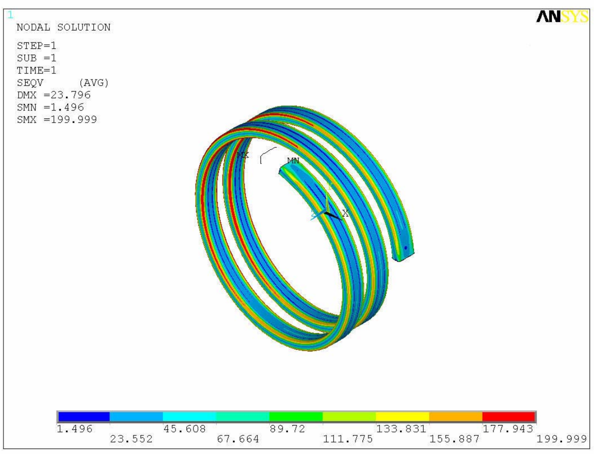


Figure 7. Von Mises stress for a 3MPa internal pressure and 15 deg rotation

D. Cooling pipes

Fatigue cycling, thermomechanical and hydrostatic loads under simultaneous neutron flux exposure are equally critical in structural elements such as 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 pipe. A coiled cooling tube with either a single or double wall is envisioned to provide method of water leak testing.

IV. CONCLUSION

Despite the stringent geometrical, thermo-mechanical, nuclear and RF requirements, a FS launcher system based on an in-vessel 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 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 externally pressurized controlled bellows 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 ±14˚.

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.

REFERENCES

[1] Verhoeven A G A 2004 *Design of the mm-wave system of the ITER upper port launcher* Proc. 13th ECE & ECH, Nizhny Novograd, http://www.ec13.iapras.ru/on-line-papers.htm

[2] Takahashi K, Imai T, Kobayashi N, Sakamoto K, Kasugai A, Hayakawa A, Mori S and Mohri K 2005 Fusion Science and Technology **47** 1.

[3] Chavan R, Henderson M A and Sanchez F *An alternative ECRH Front Steering Launcher for the ITER Upper Port*, accepted for publication in Fusion Engineering and Design.

[4] Henderson M A *et al*., *The Front Steering Launcher Ddesign for the ITER ECRH Upper Port*, accepted for publication in JCPS IAEA-TM on ITER/ECRH.

[5] H. Zohm, "The ITER ECRH upper launcher - physics goals and design requirements", Proc. 13th ECE & ECH, Nizhny Novograd (2004), http://www.ec13.iapras.ru/on-line-papers.htm

[6] Zohm H, Heidinger R, Henderson M, Poli E, Ramponi G, Saibene G, Verhoeven A G A 2005 *Comparison of the performance of different options for the ITER ECRH Upper Launcher,* submitted JCPS IAEA-TM on ITER/ECRH.

[7] Marmy P. et al., 2001 Impact of irradiation on the tensile and fatigue properties of two titanium alloys Journal of Nuclear Materials **296** 155-164