Design of the ITER Electron Cyclotron Wave Launcher for NTM Control

G Saibene[1], P Barabaschi[1], A Bruschi[2], DJ Campbell[1], R Chavan[3], S Chiocchio[4], E Ciattaglia[1], S Cirant[2], I Danilov[5], B Elzendoorn[6], D Farina[2], MF Graswinckel[6], R Heidinger[5], M Henderson[3], W Kasparek[7], K Kleefeldt[5], E Poli[8], G Ramponi[2], D Ronden[6], O Sauter[3], A Serikov[5], P Spaeh[5], AGA Verhoeven[6] and H Zohm[8]
e-mail:gabriella.saibene@efda.org

1. EFDA Close Support Unit - Garching, 85748 Garching, Germany. **2**. Istituto di Fisica del Plasma, EURATOM-ENEA-CNR Association, 20125 Milano, Italy **3.** CRPP, EURATOM – Confédération Suisse, EPFL, CH-1015 Lausanne Switzerland **4**. ITER IT, 85748 Garching, Germany **5**. Forschungszentrum Karlsruhe, EURATOM-FZK, D-76021 Karlsruhe, Germany **6**. FOM-Rijnhuizen, Association Euratom-FOM, TEC, PO Box 1207, Nieuwegein, The Netherlands. **7**. Institut für Plasmaforschung, Stuttgart University, D-70569 Stuttgart, Germany **8.** MPI für Plasmaphysik EURATOM Association, 85748 Garching, Germany,

Abstract. Neoclassical Tearing modes (NTM) are potentially unstable in plasmas with a positive shear, above a certain marginal beta, and ECCD is the method of choice in ITER for NTM control. A parameter for evaluation of NTM stabilisation efficiency is the ratio η of the peak driven current density, j_{cd}, to the bootstrap current density j_{bs}, at the mode location. A fit to experimental data provides a quantitative criterion that was used for the launcher design evaluation, where sufficient stabilisation is achieved for $\eta >1.2$. Physics analysis for ITER NTM stabilisation was based on 3 selected H-mode scenarios having considerably different q profiles and j_{bs}. Only 3/2 and 2/1 modes were included in the analysis, that was carried out with beam tracing codes used for calculating j_{cd} and injected power P_{EC} to achieve $\eta >1.2$. An EC launcher for ITER has to satisfy the functional requirements for NTM stabilisation as well as ensuring reliability and availability over the whole lifetime of the ITER device. Concerns about the attainable reliability of a "standard" front-steering (FS) launcher in ITER (steerable mirror in the primary vacuum) led to the initial choice of a Remote Steering (RS, all moving parts outside the primary vacuum) launcher concept. Although the design work showed that an RS launcher could be integrated into the ITER environment, the analysis also identified intrinsic limitation in the achievable beam focussing in the plasma for the required steering range, resulting in j_{cd} being insufficient to stabilize NTMs over the designated range of ITER plasma scenarios. On the basis of these results, the design of a FS launcher was resumed, achieving very narrow driven current profiles in the plasma and high figures of merit for all scenarios, in excess of requirements for NTM stabilisation. Experience gained in the port plug integration of the RS launcher was transferable to the FS design. Detailed analysis has been performed on the steering mechanism design to demonstrate resilience to EM forces, nuclear heating, radiation damage and cycling fatigue. On this basis, the FS has been adopted as the reference concept for the ITER upper launcher. The high performance margin achievable with the FS design opens the way to further exploitation of EC waves for ITER, especially sawtooth control.

1. EC H&CD for MHD control in ITER.

Control of MHD modes, especially of Neoclassical Tearing Modes (NTMs) is a major requirement for the Electron Cyclotron (EC) system of ITER. In fact, NTMs are potentially unstable in all plasmas with a positive shear, above a certain β_N ($\beta_{N,marg}$ = marginal β_N above which NTMs are unstable). Experimental studies indicate a ρ^* (normalised Larmor radius) scaling of $\beta_{N,marg}$, that for ITER predicts $\beta_{N,marg} <1$ [1,2]. In addition, NTMs are metastable, requiring a perturbation (seed island) to become unstable. In sawtoothing plasmas (such as those foreseen for the H-mode ITER scenarios 1, 2, and 5 [3]), sawtooth crashes provide by far the most common NTM seed, although other MHD events, such as large Edge Localised Modes (ELMs) or fishbones, can also destabilize NTMs. The low value of $\beta_{N,marg}$ predicted for ITER, together with the metastable nature of these modes, implies that in ITER all H-mode plasmas with positive shear will potentially be prone to NTMs, probably from right after the L-H transition and that the NTM-β limit (or β_{onset}) will be determined by the physics of the seeding process. The impact of NTMs on plasma confinement in present day tokamaks demonstrates the need to control NTMs. Commonly observed modes are (*m*/*n*) 5/4, 4/3, 3/2 and 2/1, with varying impact on confinement, ranging from 15% (3/2 mode) to 25% or more (2/1), especially for plasma with q_{95} ~3 or lower [4]. In the case of (2/1) NTMs, mode locking is also often observed, leading to an even more severe loss of confinement and, in some cases, to plasma disruption. Predictions for ITER [5] indicate that fusion power, and thus Q, could be approximately halved by 2/1 NTMs, while the predicted Q for a 3/2 mode in a standard H-mode would be reduced from 10 to ~7. These simple considerations show that NTMs are not acceptable for ITER, and that avoidance and control schemes need to be developed to ensure the performance goals of the device.

ECCD is the method of choice in ITER for NTM control. The ITER EC H&CD [3] system consists at present of up to 24, 170 GHz gyrotrons, each of 1 to 2MW power, for a nominal injected power (P_{EC}) of 20MW. This power is shared between the Upper Launcher (UL, using up to 4 Upper ports) system and the Equatorial Launcher [6] (EL, 1 equatorial port). The EC launchers are designed to inject mm-waves in the plasma at various locations, and their main function is to steer (and focus) the mm-wave beams. The ITER EC system has several main tasks, among which there is electron heating for the EL and NTM stabilisation for the UL. This paper describes recent progress in the design of the EC Upper Launcher system, starting from the design concepts and functionalities as stated in the ITER Technical documents in 2001 [7]. We shall briefly describe the methodology used for incorporating new experimental evidence into the ITER functional requirements, and how these changes have impacted on the design choices for an Upper Launcher for ITER. As described in more details below, the paper summarizes how the launcher design options were judged against a set of “objective comparison criteria” that included launcher performance against physics indicators, engineering criteria and safety constraints, and the resulting changes in the ITER reference functionality requirements and design.

2. Physics-based performance indicators & physics design criteria. The first step for the launcher performance assessment and optimisation is to establish a simple criterion to measure the NTM stabilisation efficiency of a launcher concept. The main mechanism for stabilisation of NTMs by localised ECCD is the replacement of the “missing” bootstrap current in the island by externally driven current. Theoretical considerations show that an appropriate parameter for evaluation of the stabilisation efficiency by ECCD is the ratio of the peak driven current density, j_{cd}, to the local bootstrap current density, j_{bs}, at the mode location. Therefore, we define the NTM stabilisation efficiency $\eta_{NTM} = j_{cd}/j_{bs}$. Based on this, and supplemented by a fit to experimental data [8], the following quantitative criteria applicable to both 3/2 and 2/1 modes were used for the launcher design evaluation:

Sufficient→$\eta_{NTM} > 1.2$; Marginal→$1 < \eta_{NTM} < 1.2$; Insufficient→$\eta_{NTM} < 1$.

Note that the above criteria imply that ECCD is used to achieve full stabilisation of the mode, i.e. the island width w is reduced to w_{marg}, (w_{marg} is the width of the island where the unstable parameter space is removed and the growth rate of the island becomes negative [1]). Implicit in this evaluation is also the use of modulation of the EC power, in phase with the island rotation, if the driven current deposition width d>w.

To fulfil its function of NTM stabilisation, the ITER UL should be capable of steering mm-wave beams over the possible location of NTMs. Therefore, the second main step for the design of the launcher was a re-appraisal of main ITER scenarios, for the identification of the steering and current drive requirements for the UL. The analysis of NTMs in present-day Tokamaks and extrapolation of onset conditions to ITER (briefly summarised in section 1) led to the conclusion that the ITER launcher should in principle be able to reach the q=3/2 and q=2 surfaces of all foreseen H-mode plasma scenarios with positive shear. Given the very low $\beta_{N,marg}$ foreseen in ITER, it was also recognized that stabilisation may be required not only during the flat-top phase of such an ITER

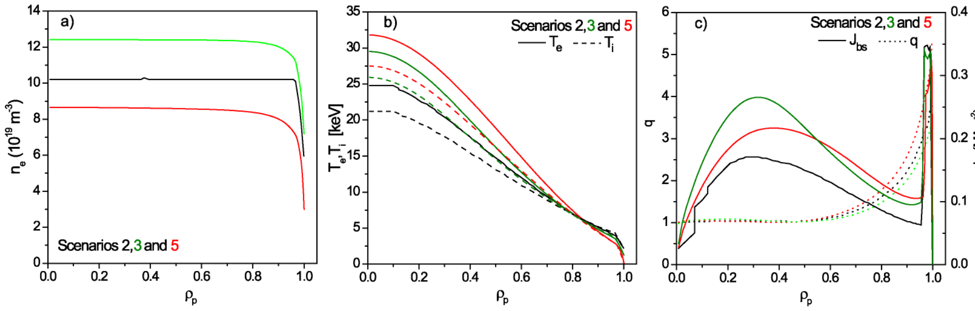


***Figure 1**: plasma profiles of the 3 ITER scenarios (ASTRA simulations) vs. ρ_{po} , used for the performance analysis of UL designs. a): electron density; b) electron (full lines) and ion (dashed lines) temperature, and c) bootstrap current (full line) and q (dashed line). The scenarios are identified by colour.*

discharge, but including (for any given scenario) the variation in time of the position of the relevant q surfaces from the L-to-H transition until some time into the plasma ramp down after end of burn (EOB). Moreover, the optics of the launcher has to be designed to provide sufficient focusing (i.e. sufficiently high local current density) over the whole steering range.

In practice, the physics analysis of all launcher design options was based on 3 selected full field H-mode scenarios (scenarios 2, 3 and 5 [3], respectively at 15, 12 and 17 MA) having considerably different q, T, n and bootstrap current profiles at the EOB time slice (see figures 1 a to c), rather than studying each scenario in detail at several time slices. To account for the obvious uncertainties in the detail predictions of ITER plasma profiles, the database for equilibria calculations and analysis was extended to include variations of β_p and l_i (normalized plasma pressure and internal inductance), compatible with the poloidal field coil system of ITER and representative of typical variations observed in JET and ASDEX Upgrade H-modes with q_{95} between 3 and 4. Specifically, a variation of β_p of ~ 15% to 25% was allowed for, and for each β_p in each scenario, l_i was varied in 3 steps (from 0.7 to 1.0), resulting in a total of 21 equilibria. Finally, only the two modes having the most severe effect on plasma confinement, 3/2 and 2/1, were included in the stabilisation analysis. This set of conditions was considered sufficient for the determination of the access requirements for the UL, and provide the basis for the definition of the steering range. The range of interest is from ρ_p~0.65 to ρ_p~0.93, which is representative of typical likely locations of the 3/2 and 2/1 q surfaces in most NTM-prone ITER plasmas.

The performance of each launcher design variant was evaluated for the set of plasma conditions described above, using the beam tracing codes GRAY [9] and TORBEAM [10]. Those provide an accurate estimate of j_{cd} (and therefore of $\eta_{NTM} = j_{cd}/j_{bs}$, with j_{bs} from ASTRA simulations), allowing a simple quantification of the NTM stabilisation as well as the calculation of the power needed for achieving the required η_{NTM}. Note that, in principle, the required η_{NTM} can always be achieved, provided that enough power is available. However, the additional input power required for NTM stabilisation is not very effective for plasma heating (off-axis deposition) and could have an adverse effect on the Q of the plasma. This was analysed as part of the launcher performance optimisation work, although Q maximisation was not a primary design optimisation parameter. 0-D analysis of the impact of the power used for NTM stabilisation on Q was carried out for the Q=10 ITER Scenario 2 [5]. The impact of P_{EC} on Q turns out to be more complicated than a simple linear dependence, due to effects related to the island saturated, marginal and actual size, as well as on the achievable η_{NTM}. In any case, the analysis indicates that the P_{EC} should be ~10MW or less, to limit the impact on Q to less than 15% (at H_{98}=1, assuming full stabilisation).

3. Comparative analysis of Remote and Front Steering concepts. The design of an EC launcher for ITER has to satisfy the functional requirements for the system as well as the strict environmental constraints of ITER. These include resilience of the launcher components to neutron fluxes, provision of sufficient shielding to the launcher components themselves and surrounding critical components (such as vessel welds, toroidal field coils, etc.), active cooling of most components, remote handling requirements, etc. Most importantly, the launcher design must be reliable and ensure maximum availability of the system over the whole lifetime of the ITER device.

Concerns about the attainable reliability of a standard front-steering (FS) launcher design (steerable mirror placed in a blanket shield module of ITER, i.e. inside the primary vacuum and close to the plasma) led to the initial choice in 2001 of a Remote Steering (RS) launcher as the reference ITER design for the Upper Port system. This concept is attractive for ITER because it allows placing all moving parts (i.e. the steering mechanism) outside the primary vacuum of the tokamak. At the time of the selection of the RS concept, the functional specification of the launcher included only NTM stabilisation for the Q=10 Scenario 2. This of course means that the steering requirements were limited (~10^o at the plasma side), since the beam had to reach only the q=2 and q=3/2 positions for one scenario. As the EU team started the development of the launcher design from a pre-conceptual level towards detailed design, it also carried out a revision of the physics requirements for NTM control in ITER, resulting in the criteria described in section 2, that is in a substantial increase in the steering range requirements.

Performance analysis of successive RS launcher variants identified drawbacks of an RS-based launcher design, namely the limitation in the achievable beam focussing in the plasma for the required steering range (~25^o to ~28^o), associated to the concept and mainly due to spatial restrictions of the ITER port. This limitation results in low j_{cd} at the resonant surfaces, insufficient to provide the required NTM stabilisation efficiency over the range of ITER plasma scenarios used as the design basis. Given the difficulties of the RS-based launcher design in meeting the functionality requirements, the design of a FS ITER UL was resumed in parallel to the continuing optimisation of the RS launcher. From the early pre-conceptual design, a FS-based ITER UL seemed to provide excellent NTM stabilisation performance. This is due to the decoupling of the steering and focussing in the launcher optics, resulting in very narrow beams in the plasma for all scenarios, and high figures of merit, in excess of requirements for NTM stabilisation.

Both design concepts were pursued in parallel until end of 2005, to develop both of them to a level where a thorough technical comparison was possible, and arrive at the selection of one reference concept for ITER. For achieving this, the team developed a list of so-called “Objective Comparison Criteria” or OCC. The OCC aim was to identify minimum requirements for the launcher design and to “grade” the two designs against these requirements. The grading was done with a simple pass-no pass mark, although, for some criteria, a “conditional pass” was granted (no showstopper, but more R&D required). The physics and engineering analysis required to answer the OCCs was organised in “Critical Design Issues” or CDIs. The CDIs were divided in 3 groups: mm-wave issues for the FS launcher, RS launcher and common structural issues (port plug & window design).

28 OCC were identified, and grouped in 8 categories, as summarised in table 1, and analysed for both designs. One of the major engineering concerns was cycling fatigue failure of the front steering mechanism (moving parts) or of the fixed front mirrors of the RS launcher (due to the high power density, >5MWm^{-2}). Since one of the ITER requirements is that all components of the launcher have to be designed for the full ITER lifetime, an analysis of the operational mode of the launcher became necessary to estimate the number and amplitude of the cycles. For doing this, two types of movement were identified: *full cycles* (when the beams are moved from q=2 to q=3/2 and back) and *modulation cycles* (small movements of the beams to track an island in the plasma).

n	OCC	Description
3	Human safety	Definition of 1st and 2nd T barrier & radioactive waste
1	Impact of faults	Identification of faults with impact on ITER operation & fail-safe/mitigation strategies
3	Reliability of mm-wave components	Neutron fluence at CVD diamond window, stray radiation & arc detection
6	Physics performance	Access range, η_{NTM} and P_{EC} for all scenarios (q=2 & 3/2), steering speed
10	Component Engineering	Operational reliability of the steering mechanism, incl. EM forces and fatigue (SM & mirrors), window stresses, stresses under baking & over-pressure.
1	Nuclear	Radiation damage, shielding and dose for hands-on access
3	mm-wave parms	Transmission efficiency, power density on mirrors, electric fields
1	Cost	Structural & mm-wave components.

Table1*: list of OCC categories. The first column indicates the number of criteria identifies for each category*

Furthermore, it was assumed that 70% of the 30.000 ITER pulses might have NTMs, the launcher is on for 400s for each of those pulses, and each sawtooth crash can trigger an NTM, and that a modulation cycle has a characteristic time of the order of twice the energy confinement time (~ 3s [3]). With these assumptions, it was found that the steering mechanism and all other components subject to cyclic fatigue should survive 2.1 10^4 full cycles and 8.4 10^5 modulation cycles. The lifetime requirements defined above plus the magnitude and type of the cyclic load (elastic deformation of bellows, thermal cycling of mirrors, etc.) were used as common input for all fatigue analysis.

4. Results of OCC analysis. The launcher designs analysed for the OCC were a 4-launcher system (6 waveguides each) RS dogleg [11] design (figure 2), with 6 steering mechanisms (one per beam) and a 3-launchers (8 waveguides each) FS design [12] (called NTM launcher, figure 3), with 2 steering mechanisms per launcher (4 beams each). Steering mechanisms and optics were designed, according to ITER specifications, with poloidal steering only, and with sufficient steering capability to cover the NTM zone, as defined in section 2. In general, the analysis demonstrated that both the RS and the FS launchers overall satisfied engineering sufficiency criteria as laid down in the OCC.

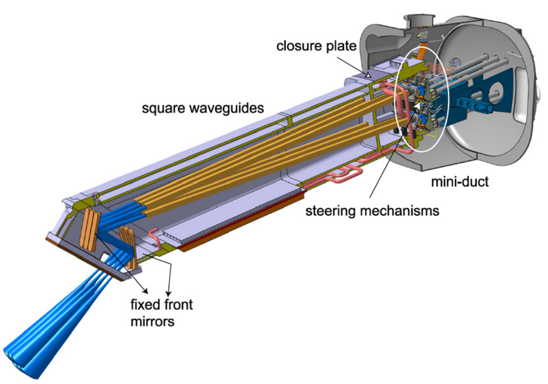


***Figure 2**: the RS dogleg launcher. Only part of the port plug structure is shown, and all internal shield elements are removed to show the mm-wave components. Each launcher houses 6 waveguides. The steering mechanisms (1 per beam) are located in the mini-duct, providing secondary vacuum.*

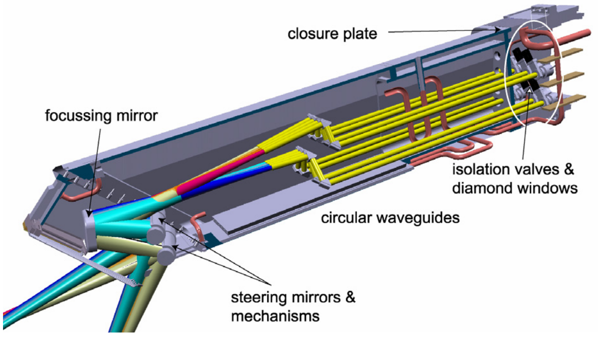
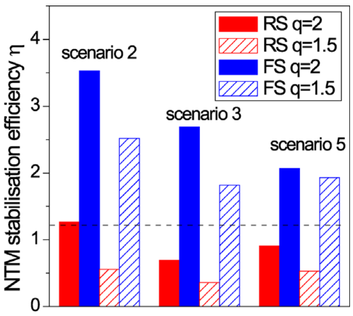
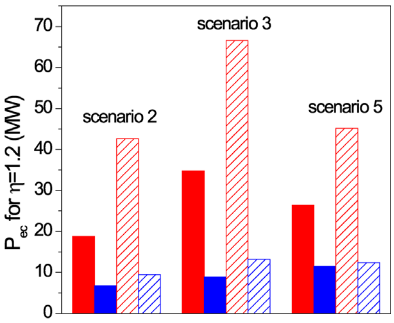


***Figure 3**: the FS NTM launcher (8 waveguides). As for the RS launcher, the model is highly simplified to show the mm-wave components. The closure plate seals the plug to the port. Diamond windows & valves are in air. Note that from ~2/3 of the launcher length, the beam is not guided, to allow for expansion.*

Specifically, both designs were fully compatible with safety and nuclear constraints [13], while the other major engineering criteria (integration, access, thermo-mechanical, components reliability, etc) were either satisfied by the design or conditionally satisfied. Particular attention was devoted to the FS steering mechanism, to demonstrate resilience to EM forces, nuclear heating and radiation damage, and to cycling fatigue. Among the issues requiring further R&D, but not constituting a showstopper for the design were: fail-safe design for the cooling of front mirrors, mirrors stress and fatigue for the RS concept, while for both the documentation of compliance of the SM mechanism bellows (FS) and moving parts (RS) under cycling fatigue was judged not yet complete. The cost analysis was done in an approximate way, and the result was that the structural costs would be similar for the two options. The mm-wave components and the CVD diamond window would be more expensive for the RS launcher than for the FS, mainly due to the cost of the square waveguides and to the larger diameter required for the RS window compared to the FS (106 vs. 75mm diamond disks).

The major and decisive difference between the two concepts emerged from the physics performance analysis. This was carried out for both designs on the 3 reference ITER scenarios plus their variants, and the results were expressed in terms of η_{NTM}, as well as of the power required to achieve $\eta_{NTM} = 1.2$, for both (2/1) and (3/2) NTMs. Power modulation was assumed in all cases, and this is particularly relevant for the cases where the driven current width $d>>w$. A summary of results of this analysis (data only for the 3 reference scenarios) is shown in figures 4, 5 and 6. The NTM stabilisation efficiency achieved by the FS NTM launcher is > 1.2 for all scenarios, while the RS launcher fails to exceed the performance target in all cases, apart for the q=2 of Scenario 2. For the FS, the power required for complete NTM stabilisation is less or of the order of 10MW, with favourable implications for Q. This excellent performance, in excess of requirements is simply due to





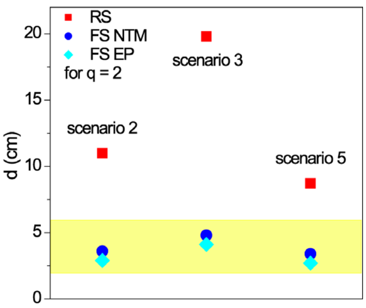


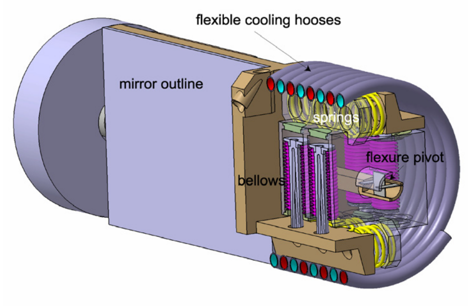
***Figure 4** (left): η_{NTM} for the 3 reference scenarios, q=2 and q=3/2, for the RS dogleg launcher (red) and the FS NTM launcher (blue). The dashed line is drawn at $\eta_{NTM} = 1.2$. **Figure 5** (centre): EC power requirement to reach $\eta_{NTM} = 1.2$, same colour coding as figure 5. **Figure 6** (right): driven current full width at 1/e for the q=2 surface of scenarios 2, 3 and 5 obtained with the RS dogleg, FS NTM and FS EP launchers. The yellow area shows the predicted marginal island width w_{marg} for ITER, between 2 and 6 cm [1].*

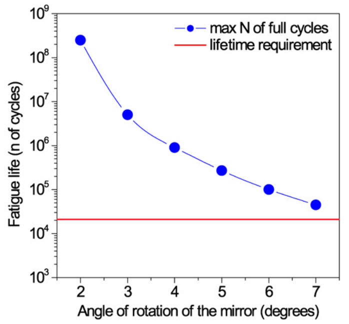
the fact that the decoupling of steering and focussing in the FS launcher optics produces very narrow beams at the deposition location in the plasma across the whole steering range, while the localisation achievable with the RS launcher is largely insufficient, although the total driven current is similar for the two designs.

The consequences of theses results have been quite far-reaching for the UL design, with the main one being that the FS concept was adopted at the end of 2005 by ITER as the reference for the UL design. The performance margin achievable with the FS NTM launcher has also opened up the possibility of extending the UL applications from NTM stabilisation to including sawtooth control. As mentioned in section 2, sawtooth crashes are the most common seeding events for NTMs in present-day tokamaks, and likewise ITER, because ITER will operate at relatively low q_{95} in H-mode and will have long sawtooth periods (i.e. large crashes) especially in the high Q regimes. Finally, the adoption of the FS design as reference ITER concept has focussed the effort of the EU design team to the detailed engineering of the concept, particularly in the Steering Mechanism (SM) design, analysis and qualification, in the design of all structural components, as well as in integration (both of mm-wave in the port plug and of the launcher in the ITER environment).

5. Ongoing work and outlook. The FS NTM launcher was a 3-launcher system designed exclusively for NTM control. The FS design that has emerged from the ITER design review exploits both the availability of a fourth port and the high NTM stabilisation efficiency to include sawtooth control in its functions. To distinguish it from the NTM launcher it has been named Extended Performance FS launcher or EPL [14]. All the basic concepts developed for the NTM launcher are found in the EPL as well, including the waveguide arrangement, the free propagation of the beams from shortly after the mitre-bends to the focussing mirror and, crucially, the design of the steering mechanism. Moreover, the design solutions found for the RS launcher in the port plug integration work (port plug structure, cooling schemes, shielding, etc) were generic enough to be adaptable in most cases to the FS launcher [15].

The steering mechanism designed for the ITER FS launcher [16] is based on a frictionless/backlash free mechanism that avoids the risk of seizing, commonly encountered in present day EC launchers. The SM relies on frictionless elastic deformation of guiding and actuating components to produce the required mirror rotation (figure 7). A flexure pivot allows the rotation of the mirror on its axis, while pneumatically driven bellows (externally pressurised to avoid buckling) acting against preloaded springs provide the actuation. The whole system is dimensioned to be in zero momentum balance for any angle of rotation. As mentioned already, the main issue with such a design is the cyclic fatigue on its components, and especially for the bellows. The maximisation of the cyclic lifetime is ongoing work, but solutions have been identified that provide the required number of cycles. The study has involved the analysis of several different geometrical configurations for the SM components, as well a survey of commercially available bellows. Alloy 718 is the material of choice at the moment, but alternative materials could also be used. The final choice will also depend on the availability of reliable material properties after irradiation (typically 0.2 dpa for this component) as well as on specific manufacturing constraints. The bellows have been analysed





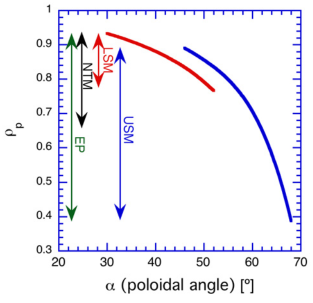
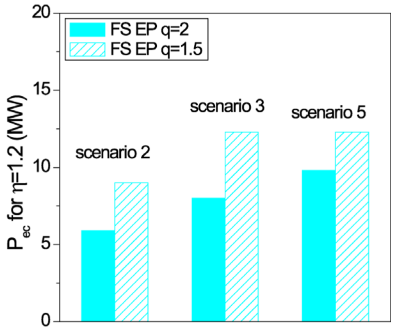


__Figure__ 7 (left): split view of the SM, showing the flexure pivot, bellows and springs as well as an outline of the cooling and pneumatic circuits. ***Figure 8** (middle): fatigue life of an Inconel Alloy 718 bellow (in n of full cycles) as function of the maximum angle of rotation of the mirror. The red line is at 2.1 10^4, that is the lifetime requirement.* ***Figure 9** (right): region covered by different EC launchers; in black: NTM launcher coverage area; the EPL coverage (green) is the envelope of those achieved using separate dedicated steering mechanisms(red: LSM, blue: USM* according to the protocol specified in the EJMA [17] code, and it is found that the number of full cycle is the dominant factor in determining the lifetime of these bellows, and that this lifetime rapidly decreases for increasing angular range (figure 8).

The EPL aims at adding to the NTM stabilisation capability, sawtooth control by localised current drive in the region of the q=1 surface. Although with some (large) uncertainties, the location of the q = 1 surface in ITER, for the 3 reference scenarios, is estimated in the range from ρ_p~0.35 to ρ_p~0.65. This represents a considerable extension of the total steering range requirements (figure 9). To cover the NTM range of ρ_p~0.65 to ρ_p~0.93, ±6° rotation of the mirror was required (corresponding to ~22° of angular span in the plasma), translating in an engineering requirement of ±7° to include zero adjustments (centering) and mechanical tolerances. As shown in figure 8, a rotation angle of ±7° is viable, but near to the maximum achievable with this design. To achieve the large total coverage required for sawtooth control and NTM stabilisation without putting unrealistic demands on the SM, the EPL exploits the concept of "dedicated" steering mechanisms. The EPL system consists of 4 launchers, each housing 8 beams and 2 steering mechanism, positioned at different heights in the port plug. The two SMs are identified as the Upper and the Lower steering mechanisms (or USM and LSM). Since each SM carries 4 beams, each set of 4 SM controls up to 16 beams or ~13.3MW total. The extension of the total beam coverage of the plasma is achieved by having the two sets of SM to cover different regions of the plasma, as illustrated in figure 9. Specifically, the USM coverage extends towards the plasma centre, while the LSM covers the outer region of the plasma, with some overlap of the two, for a total coverage from ρ_p~0.4 to ρ_p~0.93. This means that the extended steering range is achieved at the price that, in some regions of the plasma only 13.3MW maximum EC power can be used for NTM control instead of ~20MW, and that only 13.3MW maximum are available for sawtooth control. The overlap region is dimensioned and chosen to include the location of q=3/2 and q=2 surfaces for the 3 reference scenarios (albeit marginally for q=2 of scenario 5), while some of the variants fall in regions where only one or the other SM set can reach. The EPL optics is still being optimised, but performance is already satisfactory. Figure 10 shows the power required (using the LSM) to achieve η_{NTM} =1.2 for the 3 reference scenarios: the requirements are very similar to those found with the NTM launcher, and the current localisation is also similar, of the order of w_{marg}, as it was for the NTM launcher (figure 6, cyan points).

It is interesting to note that the rotation requirements on each SM in the EPL is reduced by ~1° compared to the NTM launcher, considerably increasing the fatigue lifetime margin (figure 8). Finally, since the EC plant provides 24 beam lines (to be shared via high power, fast on-line switches between the UL and EL systems), an additional set of switches is used to direct some of the beams to the required set of SMs. The sharing (between EL and UL systems, and for the different applications of the UL) will have to be handled by real-time control systems, at the moment still in a very initial state of design.

As already mentioned, the central role of sawteeth in providing the seed island for NTMs has been clearly demonstrated (see, for example [19] and reference therein), providing a very strong motivation for a system where control of the sawtooth period could offer a possibility for NTM



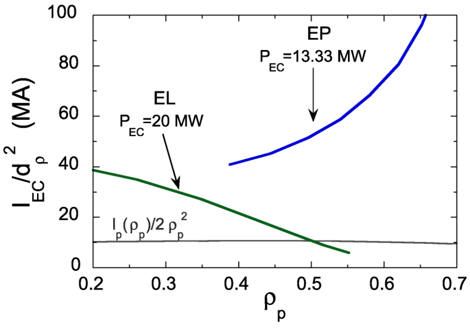


Figure 10 *(left): power required to achieve* η_{NTM} *=1.2 with the EPL, using the LSM.* ***Figure 11*** *(right): Comparison of sawtooth de-stabilisation efficiency of the EPL (USM) and EL, compared to a criterion proposed by Merkulov [18], indicated by the black line at* I_{EC}/d_ρ^2 *=10 (local driven current density required for changing the local shear by a factor of 2)*

avoidance, on the top of the classic NTM stabilisation schemes. While NTMs have been thoroughly studied both theoretically and in many experiments, the theory of sawtooth control by localised current drive is less developed despite extensive experimental studies, and it is more difficult to find quantitative criteria to measure the efficiency of any specific design to achieve a degree of destabilisation (i.e. small enough sawtooth period) sufficient to avoid the formation of a seed island. Nonetheless, both Merkulov [18] and Graves [20] have proposed criteria to quantify the effect of localised ECCD on sawtooth period. These criteria have been applied to the ITER Scenario 2, and the potential for de-stabilisation of sawteeth calculated for the EPL and compared to that of the equatorial launcher. According to both criteria, the EPL should be more efficient for sawtooth destabilisation than the EL, in the range of ρ_p~0.4 to ρ_p~0.6. An example is shown in figure 11 [21], for the Merkulov formulation indicating that, in that range, the local shear variation due to ECCD with the EPL would be well above the minimum requirement for affecting the sawtooth period.

The comparison of the EPL and EL also suggests that the original division of roles in ITER between the UL and EL systems (UL for NTM control, EL for all other EC applications with co-current drive) can be improved [14]. In fact, not only the EPL is more efficient in providing localised current drive in the ρ_p~0.4 to ρ_p~0.6 range than the EL, but for the EL at large toroidal injection angles, trajectories and high $n_{//}$ effects lead to poor localization and incomplete power absorption [21]. Calculations carried out for the ITER scenario 2 indicate that for ρ_p~0.55, up to ~20% of the EC power is not absorbed, strongly suggesting that the injection angles of the EL should be limited to ρ_p~0.50, and its role taken up by the EPL outside that radius. The reduction in the steering range requirements for the EL can potentially open up options for modifications of the design, including some capability for core counter-current drive, additional to the existing co-current.

The high performance margins achievable with the FS Upper Launcher design have opened the way to further exploitation and optimisation of the unique features of EC waves for ITER. The design of the EPL launcher is now being brought to the level of detail required for the preparation of blue prints for ITER procurement, foreseen to start by the end of 2008. The combination of physics based analysis of requirements and performance with engineering has produced a design for the ITER upper launcher that exceeds the initial specifications and opens up the possibility of simultaneous optimisation of both Upper and Equatorial launcher systems. The extended functionalities of the UL system established by this work are now integral part of the ITER technical requirements [3].

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