Synergy Study of the Equatorial and Upper Port ITER ECH Launchers for an Enhanced Physics Performance

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Abstract. The ITER ECH heating and current drive system consists of 24MW at 170GHz, which can be directed to either the equatorial or upper port launching antennas (launchers) depending on the desired physics application. The equatorial launcher[1] (EL) sweeps the beam in the toroidal plane providing co-ECCD over the range of 0.q$\leq\rho_\psi\leq$0.65, while the upper launcher[2] sweeps the beam in a poloidal plane providing co-ECCD over the range of $0.64\leq\rho_\psi\leq0.93$[3]. The present requirements for physics applications are very imbalanced between the two launcher systems, with the UL devoted to stabilising the neoclassical tearing modes while the EL has to satisfy all other physics applications inside of $\rho_\psi \leq 0.65$, including control of the sawteeth, assisting in current profile control, on and off-axis current drive and heating. None of the beams launched from the EL can access the entire desired range due to geometrical and refraction effects[4]. In the region of $\rho_\psi>0.45$, the current deposition profile width (w_{CD}) is rapidly increasing, such that the EL may not be able to control the sawteeth in this region. Modifying the scanning range of both launchers, seeking a synergy between the two systems, can enhance the physics capabilities of both launcher systems, also allowing to exploit further the specific characteristics of the two launchers: very localised CD for the UL vs. higher CD efficiency for the EL. Possible modifications to the two launchers are suggested along with a global analysis of EC H&CD capability in ITER are provided with the ultimate aim of providing an enhanced ECH physics programme for ITER.

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INTRODUCTION

The Electron Cyclotron Heating and Current Drive (ECH&CD) system[5] for ITER is planned to consist of 24MW (CW) installed power at 170GHz and an additional 3MW at ~120GHZ for assisting in plasma breakdown. The layout of the ECH&CD system is shown in figure 1. There will be up to 24 170GHz gyrotrons ($\geq$1MW) provided by the three ITER partners: European Union (EU), Russian Federation (RF) and Japan (JA), with the 3 120GHz gyrotrons provided by India (IN). The ECH power is transmitted to the torus via an evacuated 63.5mm HE_{11} waveguide (~100m in length) provided by the United States (US). Included in the transmission line is a remote control switching system that directs the ECH power to either the Equatorial Launcher (EL, provided by JA) or four Upper Launchers (UL provided by EU).

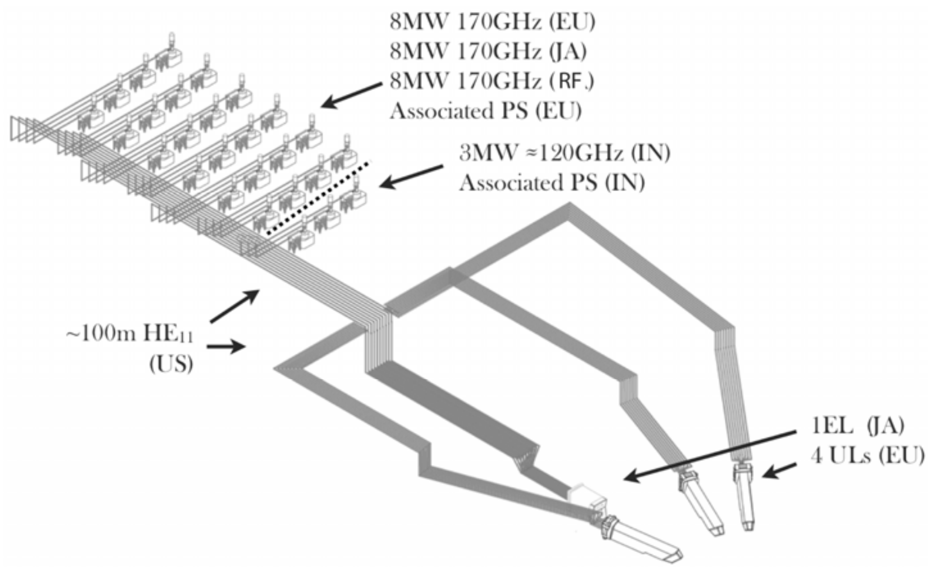

FIGURE 1. Layout of the 24MW ECH system for ITER based on the procurement agreement of 2005.

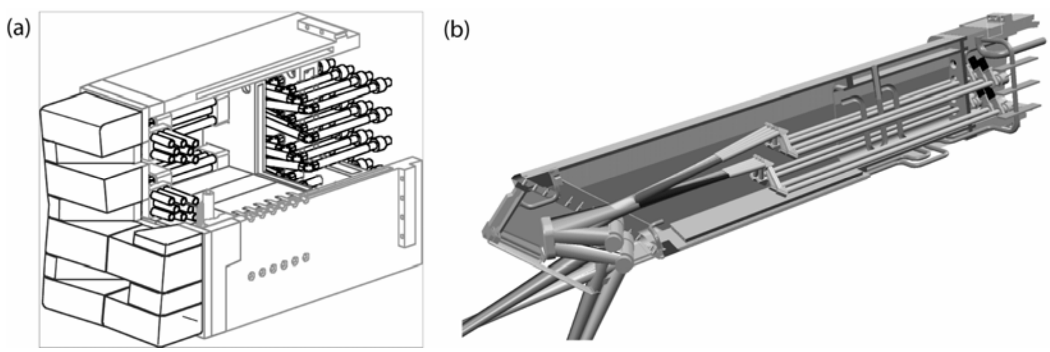

FIGURE 2. (a) The equatorial launcher[1] has all 24 beams in one port with all beams scanned in a toroidal plane over the range of $20º \leq \beta \leq 45º$. (b) The upper launcher[2] has 8 beams per port (4 ports in total). All beams have a fixed toroidal injection angle (b~20º) and are scanned in a poloidal plane with $\Delta\alpha \sim \pm 11º$.

The ECH power can be directed to either launcher during a discharge with the choice depending on the physics application. For example, when desiring more central deposition ($0.0 \leq \rho_\psi \leq 0.65$) the EL is used, while for off axis deposition ($0.64 \leq \rho_\psi \leq 0.93$) the UL is used so that ECH&CD can be deposited across nearly the entire plasma cross section. The reference design of both launchers uses a front steering (FS) mirror placed close to the plasma offering the largest steering range and optimized beam focusing. The EL (see figure 2a) has three sets of steering mirrors with 8 beams incident on each mirror and steered in a horizontal plane over the range of $20º \leq \beta \leq 45º$, where β is the beam's toroidal angle measured from a poloidal plane to the beam centre line. The UL (see figure 2b) has two steering mirrors per port plug with 4 beams incident on each steering mirror. The beams are steered in a vertical plane over a range of $\Delta\alpha$~22º (values of α are different for the two steering mirrors), where α corresponds to the angle from a horizontal plane down to the projected beam centre on to a poloidal plane. The vertical steering plane has β~20º relative to a poloidal plane, this toroidal injection angle is chosen the maximum j_{CD}, optimum for stabilizing the neoclassical tearing mode (NTM)[6].

The requirements of the ECH&CD system based on ITER Project Integration Document (PID)[5] are outlined in Table 1 and graphically illustrated in Figure 3. The UL is used only for NTM stabilization and the EL is used for all other physics applications.

TABLE 1. The requirements of the ECH&CD system based on the ITER PID[1].

Application	Launcher	Requirement
Heating for Q>10	EL	Central deposition (ρ_ψ<0.5) with co-ECCD
L to H –Mode transition	EL	Central deposition (ρ_ψ<0.5) with co-ECCD
SS operation	EL	Central deposition (ρ_ψ<0.5) with co-ECCD; large I_{CD} desired
Current profile tailoring	EL	Central deposition (ρ_ψ<0.5) with co-ECCD; large $\|I_{CD}\|$ desired
Sawteeth control	EL	Deposition over range of q=1 surface (~0.3≤ ρ_ψ ≤~0.7); narrow deposition profile with large $\|I_{CD}\|$ desired (Note sawteeth control is a desired not required physics objective in the PID)
NTM stabilisation	UL	Deposition in range of q=2 and 3/2 surfaces (0.64≤ ρ_ψ ≤0.93); large j_{CD} desired with $\max(j_{CD})/j_{BS}$>1.2

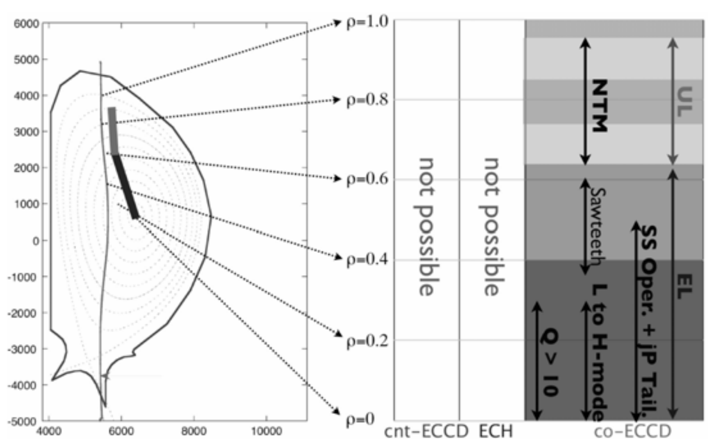

FIGURE 3. The deposition location required for the envisioned physics applications based on the Project Integration Document.

The present requirements limits the physics potential of the ECH system, in particular, there is no possibility for counter (cnt)-ECCD or pure ECH. The cnt-ECCD is useful for current profile tailoring in providing an additional tool for creating a hollow current profile for Internal Transport Barrier (ITB) formation, or can be used in combination with co-ECCD to provide pure ECH (heating with no current drive)[7]. Disassociating the heating and current drive is useful for heating applications (such as central heating for maintaining Q>10), where controlling q_0 >1 (or q_0<1) may be required to avoid (or introduce) sawteeth. An additional limitation in the present configuration is that the EL is required to perform nearly all of the physics applications, which include applications requiring a narrow deposition profile (sawtooth control) and a large amount of bulk current drive (SS operation and current profile tailoring). It is impractical to dedicate the same launcher to both sets of applications, since the large current drive requires a significant toroidal injection angle resulting in a broad deposition profile that is incompatible with the sawtooth application. In addition, the EL is required to scan a range twice that of the UL even though the EL occupies a single port plug and the UL four port plugs. Note that flexibility in focusing and steering the beams is strongly dependent on the available space within a port plug.

There is a potential for improved performance of the ECH system by optimizing the partitioning of the physics applications between the two launchers. The present partitioning was based on creating two zones in the plasma: everything inside of $\rho_\psi \leq 0.65$ is attributed to the EL, outside of this zone is attributed to the UL[4]. An alternative approach is to partition the applications according to the strengths of each launcher. For example, the EL drives more total current (I_{CD}) than the UL, as shown in figure 4a, physics applications needing large I_{CD} requires deposition in the range of $\rho_\psi \leq 0.5$. The toroidal injection angle of the UL is optimized for a peak j_{CD} profile (or narrow deposition width), which is important for applications such as sawtooth control and NTM stabilization in the range of $\rho_\psi \geq 0.35$. The scanning range of the UL can be increased to access further inward[8,9] to $\rho_\psi \sim 0.4$, with a narrower deposition profile than the EL, as shown in figure 4b. With this approach both launcher would have equivalent scanning ranges ($\Delta\rho_\psi \sim 0.5$) and provide an improved ECH physics performance for ITER.

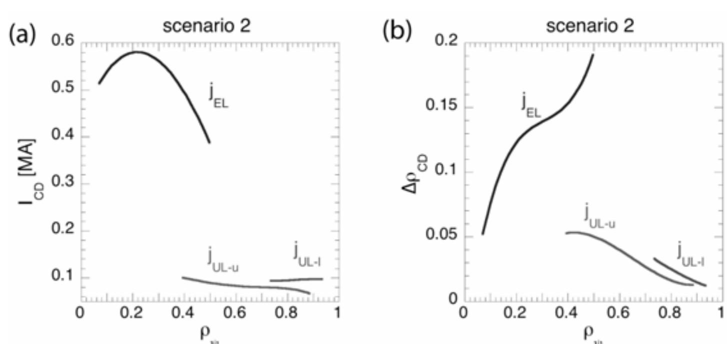

FIGURE 4. Comparison of the EL and UL capabilities in (a) driving total current and (b) providing a narrow deposition profile. A simplified model of a single beam representing the 8 (4) beam assembly per EL (UL) steering mirror is used.

The capabilities of the present ECH system is evaluated in the first section followed by a similar comparison of the synergy design of the two launchers described above. A conclusion is provided at the end of this report.

PRESENT CAPABILITIES OF THE ECH SYSTEM

Three applications are chosen as an evaluation of the present ECH system: NTM stabilization, sawtooth control and bulk current drive.

NTM Stabilisation

The NTM stabilization is accomplished using the upper port launcher, which is being designed and procured by the European Union under the direction of the Close Support Unit (CSU) of the European Fusion Development Agreement (EFDA). EFDA-CSU has supported the development of two launcher designs: remote (RS) and front (FS) steering, with the aim of providing the optimum system based on the physics, engineering, costs, reliability, etc[8]. The development of the two systems was closely monitored by ITER-IT, which performed an evaluation of the two systems at the end of 2005 and chose the FS launcher as the reference design. The two systems offered equivalent operating reliability, but the FS launcher demonstrated a significant improvement in NTM stabilization efficiency[3] (η_{NTM}=max(j_{CD})/j_{BS}) at a significantly reduced cost (<60%) compared to that of the RS launcher. A target value of η_{NTM}=1.2 was set for the UL, which should provide adequate modulated driven current inside of the island to stabilize the NTM based on a multi-machine database[3]. The FS launcher surpassed this target by a factor of 1.5 to nearly 3 depending on the q surface and scenario under consideration (see Table 2), which provides adequate safety margin in case not all ECH power is available or to accommodate for errors in extrapolating to ITER.

TABLE 2. Comparison of the RS and FS launchers capabilities in stabilizing the NTMs, η_{NTM} values are given for the three ITER scenarios based on the calcuted j_{CD}[1] values using GRAY[10].

	Scenario 2		Scenario 3a		Scenario 5	
	q=3/2	q=2	q=3/2	q=2	q=3/2	q=2
RS Launcher[11]	0.56	1.27	0.36	0.69	0.53	0.91
FS Launcher[2]	2.52	3.54	1.82	2.69	1.93	2.07
Relative difference	4.5	2.8	5.1	3.9	3.6	2.3

Sawtooth Control

The control of the sawteeth oscillation can be achieved by depositing co-ECCD either inside (de-stabilising or shortening the sawtooth period) or outside (stabilizing or lengthening the sawtooth period) the q=1 flux surface[12], where the sawtooth crash is assumed to be triggered when the shear threshold is obtained at the q=1 surface. Depending on the physics application, the option of de-stabilising or stabilizing the sawteeth may be desired depending on the physics application, for example experiments on JET have demonstrated that sawtooth de-stabilisation can avoid the sawtooth crash from triggering an NTM[13]. The efficiency in modifying the local shear depends on plasma and ECCD parameters, typically the changes in sawtooth period are proportional to I_{CD}/w_{CD}^2 assuming only current drive effects[14,15], where w_{CD} is the e^{-1} radius of the j_{CD} profile (taken as a Gaussian profile). The maximum change in the shear is obtained when the CD deposition is either inside or outside of the q=1 by a distance of w_{CD}. The EL may be inadequate for sawtooth control as the I_{CD}/w_{CD}^2 decreases rapidly as shown in figure 5a due to the Doppler broadening of the deposition profile as was shown in figure 4b. In addition, the broad profile limits sawtooth stabilization when the q=1 is inside of ρ_ψ~0.4 and de-stabilisation inside of ρ_ψ~0.6, note that for scenario 2 the q=2 surface is expected to be in the region of $0.45 \le \rho_{q=2} \le 0.55$.

Bulk Current Drive

The ECH system is also envisioned to drive bulk current to minimize the amount of ohmic driven current or to save transformer ‘volt-seconds’ for a prolonged discharge. The maximum driven current is obtained using the EL with ρ_ψ~0.2, see figure 4a, however ECCD is not an efficient source for driving bulk current. The ECH system can only contribute a significant fraction of the total current (>10%) if the total plasma current (I_{TOT}) is ≤6MA, as shown in figure 5b. For the steady state scenarios with a I_{TOT} = 9MA, the I_{CD} contribution decreases to ~8% and <4% for the Q>10 scenarios with I_{TOT} > 15MA. Note that there will be an increase in the bootstrap current associated with the additional heating that is not included in this estimateion. The deficiency in driving large amounts of bulk current is not because of the EL design, but because ECCD is not an efficient source of driving bulk current. The usefulness and uniqueness of the ECH system is to provide a localised heating and/or current drive source steerable from external actuators, useful for applications such as current profile control. For example, with only 1/3 of the total injected power, the j_{CD} amplitude from the middle steering row exceeds that of the total current density ($1.4MA/m^2$ for scenario 2) as shown in figure 5c.

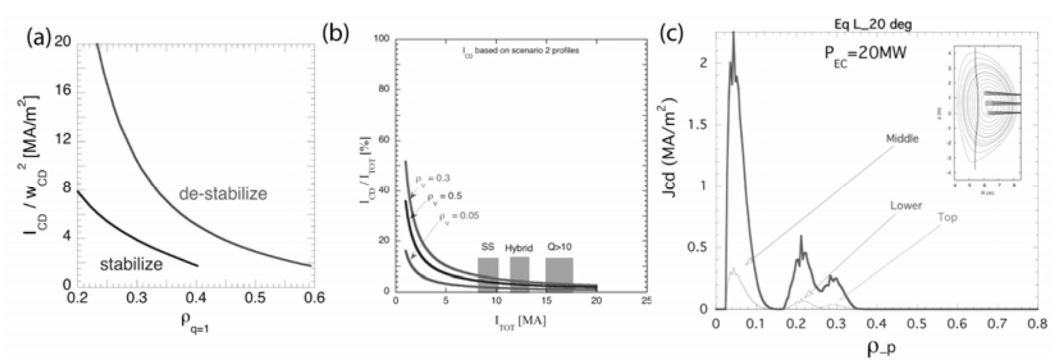

FIGURE 5. (a) The control of the sawteeth is dependent on I_{CD}/w_{CD}^2, which rapidly drops of outside of ρ_ψ>0.4 for the EL. (b) The percentage of CD current as a function of the plasma total current for three deposition locations using the EL. (c) The inner most deposition location for the three EL steering rows.

The Figure 5c highlights a potential weakness in the EL configuration of the top and bottom steering mirrors. The beams from these mirrors can't access the plasma center since the mirrors scan in a horizontal plane. The bottom row access up to $\rho_\psi>0.2$ and the top row up to $\rho_\psi>0.3$. This limitation can be avoided by tilting the steering plane[9] such that access inside of $\rho_\psi\sim0.1$ can be achieved providing adequate flexibility to distribute the full power over the range of $0.1\leq\rho_\psi\leq0.5$. Note that full power deposited on access would result in a strong central current profile peaking, which is normally not desirable.

The EL steering mirrors rotate through the toroidal angle range of $20\leq\beta\leq45^o$. When $\beta>38^o$ the deposition is in the region of $\rho_\psi>0.5$ and the beams start to become strongly refracted such that not all of the power is absorbed. Maintaining a steering range beyond $\beta=38^o$ will result in some of the power being directed to a neighboring equatorial port risking damage to either a diagnostic or another heating system. In addition, the deposition becomes extremely broad and the driven current drops off rapidly, rendering the ECCD in the range of $\rho_\psi>0.5$ from the EL relatively useless.

Score Card of Present ECH System

A summary of the present ECH physics capabilities is provided in Table 3. As discussed above, the present system provides adequate safety margin for full NTM stabilization with ≤13MW required. However, system is limited in controlling the sawteeth and not properly applicable for efficient bulk current drive (as compared to other ITER heating and current drive systems).

TABLE 3. The requirements of the ECH&CD system based on the ITER PID[1].

Application	Score	Evaluation
Heating for Q>10	Limited	Can't decouple heating and co-ECCD, may desire central heating without CD to avoid modifying the q profile.
L to H –Mode transition	Good	Main criteria is central deposition ($\rho_\psi<\sim0.5$) with either ECH or ECCD, which is achieved with EL.
SS operation	limited	ECCD is not an efficient bulk current drive source, 20MW will provide only 4 to 8% of the total current (depending on the scenario). However, heating effect will provide increased bootstrap current.
Current profile tailoring	Limited	Tailoring of profile can only be achieved with adding current inside of $\rho_\psi<0.5$, cnt-ECCD could provide greater flexibility for control of central current hole in ITB scenarios.
Sawteeth control	Limited	EL has a very broad profile in range of $\rho_{q=1}$, which is non-optimal for sawteeth control. Sawtooth stabilization only feasible with $\rho_{q=1}\leq0.4$.
NTM stabilisation	Good	Access to all q=2 and 3/2 surfaces ($0.64\leq\rho_\psi\leq0.93$) in NTM relevant scenarios with $\max(j_{CD})/j_{BS}>1.8$

There are also limitations in the ECH system to provide an optimal heating and current drive source for current profile tailoring and Q>10 applications. These limitations arise from the fact that there is only co-ECCD capabilities and no cnt-ECCD or pure ECH. For example when heating centrally for Q>10, the present system can't disassociate heating from current drive and the central current profile will increase. In some scenarios it may be desirable to have central heating but keep a broad current profile so that q>1 (avoid sawteeth). This can be achieved if the present system could also inject cnt-ECCD, offering the flexibility of pure heating (balancing co and cnt-ECCD)[7] or independent control of heating and current drive (changing ratio of co and cnt-ECCD). The cnt-ECCD would also provide a useful tool in current profile tailoring, for example the depth of a hollow current profile (in reverse shear applications) can be controlled with the amount of cnt (or co)-ECCD applied.

IDEAL ITER ECH SYSTEM

A potential 'ideal' ECH system for ITER is represented in Figure 6 based on the graphic representation introduced in Figure 3. This 'ideal' system would have the possibility of central (ρ_ψ<0.3) cnt-ECCD for current profile tailoring or to provide pure ECH by balancing the co and cnt-ECCD contribution as discussed above. Partitioning the roles of the two launchers based on their strengths (EL for applications requiring large I_{CD}, UL for applications requiring narrow w_{CD}), would then imply using the UL for sawteeth control. This would provide a better balance of applications between the two launchers, alleviating some of the responsibility place on the EL, which could then possibly be modified to provide some cnt-ECCD. In addition, applications such as control of the Frequently Interrupted Regime (FIR)[16] or the Edge Localised Modes (ELMs) could be accomplished with the UL.

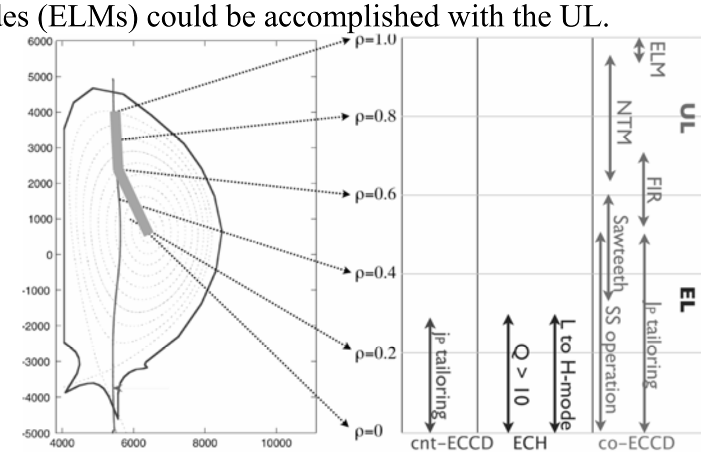

FIGURE 6. The 'ideal' ECH system for ITER would have all of the applications mentioned in the PID with the addition of cnt-ECCD and ECH capabilities and potential control of ELMs and FIR. The partitioning of the applications would be based on the strengths of each launcher EL for applications requiring large I_{CD} and EL for applications requiring narrow w_{CD}.

First, modification of the UL is proposed for accessing either further inward (sawteeth control) and/or further outward (ELM control). Depending on the success of the UL modifications, the corresponding implications on the EL is discussed.

Extended Physics Upper Launcher

There are four ports available for the upper launcher, which implies a total of 32 entries for the 24 ECH beam lines. The optimum use of the additional 8 lines would be to reduce the engineering constraints on the steering mechanism (the critical component of the FS launcher) and (if possible) provide an enhanced physics programme. Both of these are feasible by spreading out the scanning region of the two steering mirrors (as described in reference [8]) and provide a switching system to deviate the ECH power to either of the two steering mirrors. For example, the upper steering mirror can aim further inward (to provide access for sawteeth control), which would increase the overall UL access to $0.4 \leq \rho_\psi \leq 0.93$ (from $0.64 \leq \rho_\psi \leq 0.93$), see Figure 7a. A total of 20MW can be applied in the overlap region but only 13MW (16 beams) in the region accessible to only the upper (USM) or lower (LSM) steering mirrors. The overlap region is kept relatively broad to insure a majority of the flux surfaces susceptible to NTMs are accessible with the full 20MW. Note that the mirror is rotated over a smaller range ±5.5º rather than ±6.5º and the opening in the front panel is decreased, reducing the radiation to the steering mechanism. Despite the relatively poor position of the upper port for central deposition, the UL is more effective in controlling the sawteeth due to the relatively narrow deposition width (as shown in Figure 7b) even though only 13MW is applied from the UL compared to the full 20MW from the EL.

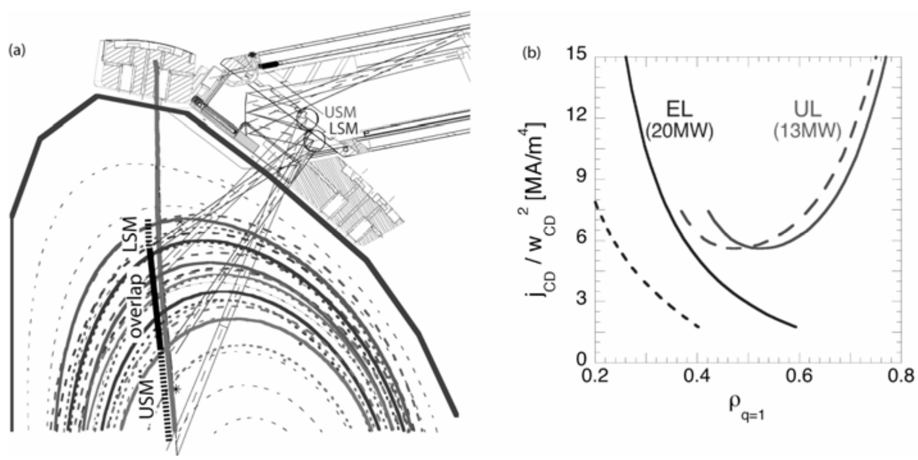

FIGURE 7. (a) The UL can access a larger range in the plasma by spreading out the steering range of the upper (USM) and lower (LSM) steering mirrors. (b) Despite the relatively poor port location, the UL (13MW) is more efficient for sawtooth control than the EL (20MW).

FIR control can also be accomplished with the UL by triggering an NTM on the q=4/3 surface, note that the 4/3^{rds} surface falls between the q=1 and 3/2 surface and it is assumed that the UL is capable of triggering the FIR if it is adequate for sawtooth control and q=3/2 NTM stabilization. ELM control using ECCD has not been demonstrated on present day tokamaks, however, the UL could be used to access the plasma edge by shifting the LSM scanning range further outward. This would decrease the overlap region, which has been kept large to insure that all 20MW can be applied to the greatest number of NTM relevant flux surfaces. Such a modification can easily be integrated into the present design, but should occur only if there has been adequate experimental demonstration of ELM control by ECCD.

Note the increased steering range is feasible for the FS launcher design that achieves NTM stabilization on all relevant flux surfaces with only a fraction of the total power. All RS launcher designs investigated to date[17] due not provide adequate NTM stabilization efficiencies required for the above physics enhancements.

Implications On The Equatorial Launcher

Using the extended physics launcher as described above would alleviate the large steering requirements ($0.0\leq \rho_\psi \leq 0.65$) such that the EL would only have to access $0.0\leq \rho_\psi \leq 0.5$ thus reducing the steering range to $20^o\leq\beta\leq 37^o$. This impacts the opening required in the blanket shield module (BSM), which could be decreased (see figure 8a) to reduce the radiation impact on the EL steering mechanism. Note that the steering mechanism in the EL is more susceptible to nuclear damage than in the UL due to the proximity and direct line of sight to the plasma core.

The EL launcher[1,18] can be modified to provide cnt-ECCD by including a fixed mirror in the BSM region as illustrated in Figure 8a. To change from co to cnt-ECCD the ECH beam would be turned off, the steering mirror rotated to aim at the additional mirror and then the ECH beam turned back on again with the beam reflected in the counter direction. The mirror curvature, tilt angle and size is somewhat variable to optimize the deposition region and profile in the cnt-ECCD direction. This modification can be made to all three steering rows providing the flexibility from 20MW in co-ECCD to 20MW in cnt-ECCD with a switching time of <1sec. Note that the steering range would increase slightly from $\Delta\beta=25^o$ to $\sim 32^o$ (depending on desired flexibility, design optimisation and engineering limitations of the steering mechanism).

In addition to the possibility of providing independent control of the heating and current drive contribution, cnt-ECCD can also be used to control the degree of negative shear in the internal transport barrier (ITB). For example, in Figure 8b, 14MW of co or cnt-ECCD is applied centrally to either fill-in or deepen the hollow current profile of scenario 4, which results in either a flattening or more reversed q-profile (as shown in Figure 8c). This provides a mechanism for optimizing the ITB performance, controlling both q_0 and q_{min} and avoiding the onset of ideal MHD modes that can occur near rational values of q_{min} or too steep of pressure profiles.

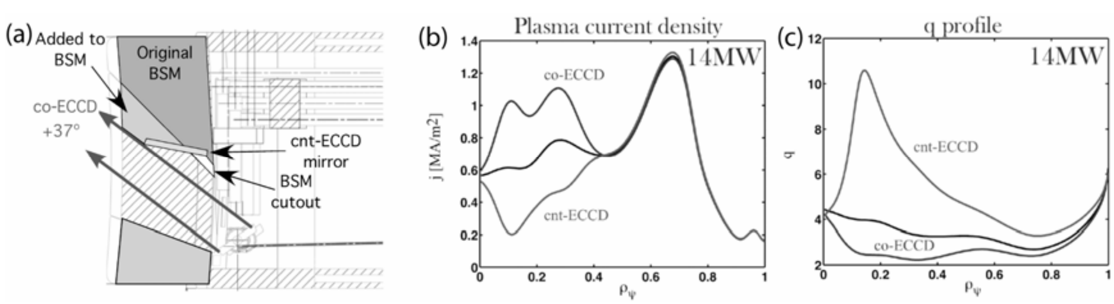

FIGURE 8. (a) counter ECCD possible with mirror in BSM. (b) modifications of current profile using co or cnt-ECCD in scenario 4 and (c) corresponding changes to the q profile.

CONCLUSIONS AND ACKNOWLEDGMENTS

The present ITER ECH system uses two launchers (equatorial and upper) with the physics applications partitioned between the two systems. There is a strong imbalance in the partitioning with the UL responsible for only NTM stabilization and the EL for all other applications requiring twice the access range as compared to the UL. The EL is also required to perform applications that require a large driven current (current profile control, bulk current drive, etc.) and narrow deposition profile (sawtooth control), which are difficult to accomplish with in the physical limitations of the launcher (scanning range, port size, BSM opening, etc.). As a result the ECH system has limited performance in applications such as sawtooth control, current profile tailoring and Q>10.

An alternative partitioning of the physics applications has been proposed that separates the applications requiring large driven current (access provided by the EL) from those requiring a narrow deposition profile (access provided by the UL). For example the UL is capable of deposition inside $\rho_\psi \leq 0.4$ and is shown to be more effective for sawtooth control than the EL. This relaxes the requirements placed on the EL offering a reduction in the steering range, a decrease in the BSM opening (decrease nuclear irradiation) and injection of cnt-ECCD and ECH for a more enhanced ITER ECH system. Most of these modifications that enhance the physics programme also reduce the engineering constraints of the two launchers.

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