ICRF Traveling Wave launcher for fusion devices

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Abstract. Ion Cyclotron Resonance Heating and Current Drive is a method that has the ability to heat directly the ions in the Deuterium-Tritium fuel to the high temperature needed for the fusion reaction to works. The capability of efficiently couple the Radio Frequency power to the plasma plays a big role in the overall performance of a fusion device. A Traveling Wave Antenna in a resonant ring configuration is a good candidate for an Ion Cyclotron Resonance Heating and Current Drive system. It has the capability to increase the coupled power with respect to present designs and to have a highly selective power spectrum that can be peaked around the maximally absorbed wave. It is also insensitive to the loading variations due to fluctuation of the plasma edge increasing the reliability and the efficiency of the system. It works as a low power density launcher due to the possible large number of current carrying elements.

1. Introduction

One of the most deeply investigated methods to confine the plasma is the use of magnetic field. In particular, in the last decades, one configuration among others has received more attention: the tokamak. This donut shaped machine uses a combination of toroidal and poloidal magnetic fields to confine the plasma. The poloidal component of the confinement field is produced by inducing a current in the plasma itself, by means of a transformer action, via a central solenoid. This is a peculiar feature of the tokamak configuration. Inducing a current has incidentally the advantage of heating up the plasma due to its resistivity $\eta$. This method is called ohmic heating. Unfortunately the power $P_{\text{ohmic}}$ is related to the temperature by $P_{\text{ohmic}} \propto \eta J^2 \propto T^{-3/2}$, being $J$ the induced current density and $\eta \propto T^{-3/2}$ [1]. The maximum level of achievable temperature with this method in a tokamak reactor is on the order of 2 – 3 keV. To reach the higher values of temperature needed for the D-T reaction to minimise the requirements on pressure and confinement time, auxiliary heating systems are required.

There are two main typologies: injection of neutral particle beams and injection of Radio Frequency (RF) waves [2]. Neutral particles are unaffected by the magnetic field, they can be injected inside the plasma where they can be ionised by collisions with the background plasma. Being now confined, they can transfer their energy to the plasma via Coulomb collisions. In this case the major problem is to have neutral particles with energy high enough to reach the core of the plasma. For fusion reactors, beams energy in the order of 1 MeV are required to have good penetration and this gives rise to serious technological challenges that are now faced up by the research community [3]. As far as the second option is concerned, the injection of RF waves has a simple idea behind: high-frequency waves are launched from an external source into the plasma where they can be absorbed, via a collision-less damping mechanism, when the source
frequency matches one of the natural resonant frequency of the plasma. There are many natural resonant frequencies in a plasma like the cyclotron frequency (and harmonics) of electrons and ions. Depending on the chosen frequency, it is possible to have Electron Cyclotron Resonant Heating (ECRH) or Ion Cyclotron Resonant Heating (ICRH). The latter is the one of interest for this paper.

2. ICRF Heating

Particles gyrate around the magnetic field lines with a gyro (Larmor) radius \( r_L = v_\perp /\omega_c \), where \( v_\perp \) is the component of the velocity perpendicular to the field line and \( \omega_c = qB_0/m \) is the cyclotron angular frequency of a particle of charge \( q \) and mass \( m \), being \( B_0 \) the background magnetic field. For electrons and negative ions the angular frequency has a negative value. The idea behind heating a plasma with RF waves exploits the resonant wave-particle interactions when the injected angular frequency is \( \omega = N\omega_\| + k_\| v_\perp \) (with \( N = 0, 1, 2, \ldots \) the cyclotron harmonic number), where \( v_\perp \) is the thermal velocity of the particles and \( k_\| \) is the component of the wave vector \( k \) parallel to \( B_0 \). In a tokamak configuration, the magnetic field is inhomogeneous with \( B(R) \propto 1/R \) with \( R \) the major radius of the torus. This has an effect on the cyclotron frequencies giving the possibility to control the location of a cyclotron resonance by varying the value of the magnetic field.

To study how waves propagate inside a inhomogeneous magnetised plasma and how power is absorbed by resonant species one has to derive the dispersion relation \( D(\omega, k) = 0 \) or \( \omega = \omega(k) \) taking into account the plasma properties [4]. A simplified version of the dispersion relation can be obtained with the so called "cold plasma approximation" where all thermal effects are removed. Taking a reference system in which the \( z \)-axis is aligned with the background magnetic field and the \( x \)-axis is aligned with the direction of the inhomogeneity of the plasma and considering, for simplicity, a slab geometry as an unfolded torus geometry then \( k_\perp \equiv k_\perp, k_\| \equiv k_\parallel \), where for simplicity but without loss of generality \( k_\perp = 0 \). In this case, the parallel and perpendicular direction referred to the magnetic field lines (see the following section for a schematic view). A wave is launched from the outside of the plasma with a \( \omega \) fixed by the RF source and a \( k_\parallel \) imposed by the launcher configuration (\( k_\parallel \) is a real number). The dispersion relation is used to compute the value of \( k_\perp = k_\perp(\omega, k_\parallel, x) \). As long as \( k_\perp \) remains real, the waves propagates inside the plasma. Two interesting phenomena occurs when \( k_\perp \) changes sign crossing zero (cutoff) or passing through infinity (resonance). In the first case, at the cutoff point \( k_\perp^2 = 0 \) and after that the wave become evanescent with no further propagation but instead with an exponential decay of the amplitude. The resonance occurs when \( k_\perp^2 = \infty \) with a slowing down of the energy flow opening, in principle, the possibility of energy absorption when some dissipation is introduced. A full kinetic description of the plasma reveals a different picture in which the wave resonance is modified in a mode conversion mechanism [5] where an incoming plasma wave is transformed into another different plasma wave. With carefully chosen plasma parameters there can be a strong wave-particle interaction with strong absorption, being the wave-particle resonance and not the wave resonance the mechanism responsible for the absorption of power.

The discussion will be focused only on one of the two roots of the dispersion relation, namely the one called Fast Magnetosonic Wave (FMW) [6] due to its lower value of \( k \), thus higher phase velocity, and due to fact that the direction of propagation of wave is across magnetic field lines thus perpendicular to the background magnetic field \( B_0 \). This is the one of main interest in the Ion Cyclotron Range of Frequencies (ICRF). An important aspect to describe wave-particle interactions is the wave polarisation, defined as the \( E_+/E_- \) where \( E_+ \) is the component rotating in the direction of the gyro motion of the ions while \( E_- \) with the electrons. The absorption will then takes place where the polarisation of the wave field is favourable to interact with the resonant particles. In that location, the particles see, in their reference frame, an accelerating electric field. Unfortunately it is not possible to impose the polarisation of the field from the
outside; the Electric field polarisation depends mainly on the plasma composition. In case of more than one ion species, with a different concentration, the polarisation will have the form $|E_+/E_-| \simeq \left| \frac{\omega_{\text{cm}} - \omega_{\text{cM}}}{\omega_{\text{cm}} + \omega_{\text{cM}}} \right|$. As example with minority (few %) of Hydrogen in D, $|E_+/E_-| \simeq 1/3$ recalling that $\omega_{\text{cH}} = 2 \omega_{\text{cD}}$. The point here is that only part of the power carried by the wave is actually used to transfer energy to the particles. The ideal condition to heat ions is then to have the E-field made all of $E_+$ at the foreseen absorption location [7,8,9].

A systematic study of the wave propagation and absorption will lead to power deposition profiles. Solving the wave equation in realistic geometry taking into account kinetic effects requires a substantial computational effort and several codes are available [10,11,12]. The power deposition profiles are used to find the more promising heating scheme for a given scenario. This means finding, among other variables, the angular frequency $\omega$ and $k_\parallel$ that are then used in the ICRF system [7,8,9,13].

3. ICRF system

The most general schematic of an ICRH&CD system is shown in Fig. 1. The system is composed by a power generation unit connected to the antenna (launcher) with a transmission line. The matching unit has the role of provide impedance matching between the RF generator output impedance and the antenna input impedance to ensure maximum power transfer. The launcher is responsible of coupling the power from the generator to the plasma. A simple sketch of a ICRF launcher is represented in Fig. 2, on the right. It is made usually by a short array of metal straps aligned in the poloidal direction and facing the plasma edge. One end of the strap is connected to the metallic backplate and the other end is connected to input transmission lines. When an oscillating electric current density is driven on the straps, an oscillating electromagnetic field is generated. In Fig. 2 the two components $E_y$ and $B_z$ are represented at an arbitrary distance in front of the antenna. This electromagnetic (EM) field is the excitation source for the plasma FMW. The wave behaviour in the region of the antenna is very different from the one described above for the core plasma. Fig. 2, on the left, illustrates the problem. The strap inside the antenna box faces the inhomogeneous plasma with a given density profile that influences the dispersion relation. The region around the scrape-off layer is very important for the antenna coupling. On one side there is vacuum or very low density residual plasma, on the other side a bulk plasma where the FMW can propagate. The EM fields that excite the FMW are evanescent from the strap in the vacuum region up to a cutoff density where $k_\perp^2$ become positive and the wave starts to propagate. In Fig. 2 the amplitude of $E_y$ and $B_z$ component are depicted, with the density profile, showing an exponentially decaying behaviour followed by the characteristic

![Figure 1. General schematic of an ICRH&CD system with the components highlighted.](image1)

![Figure 2. Schematic view (left) of the coupling mechanism and sketch (right) of a launcher.](image2)
oscillating propagative mode. The farther away the cutoff point is, towards the core, the higher are the fields at the antenna in order to couple the same amount of power. The limit is the maximum possible electric field on the antenna before breakdowns that is around 45 kV. An issue specific of this kind of antennae is the mutual coupling between radiating straps. As shown in Fig. 2 right, the magnetic field generated by the current on one strap will link the adjacent straps inducing a current on them. This gives rise to the problem of mutual coupling when the straps are operated at arbitrary current phasing. A way to compensate this problem is to use septa in between straps to isolate one from the others. The drawback is that the septa increase the inductance of the straps reducing the amount of coupled power. Sometimes also external decouplers are added to balance the power flow. The arbitrary phasing of the current is needed to obtain a radiation spectrum as close as possible to the optimal one that comes from the absorption analysis. A change in the position of the cutoff density always implies a modification in the amount of power coupled and continuously happens in reactor plasmas due to the fluctuation of the edge in front of the antenna. The effect is that the generator will see a rapidly changing loading. This is taken into account while designing a ICRF system and the capability of being not sensitive to those changes is called load resilience.

The power coupled to the plasma can be computed via the Poynting theorem as

$$P_{\text{rad}} = \frac{1}{4\pi^2\omega\mu_0} \Re \iint |E_y|^2 \frac{1}{\xi_0} dk_z dk_y$$

where $1/\xi_0$ is the surface conductance at the aperture of the box and $\Re$ is the real part of the expression. An example of surface conductance computed for a typical reactor like plasma at a certain frequency is given in Fig. 3. It is a function of $k_y$ and $k_z$ rapidly decreasing for large $|k_z|$ and asymmetric in $k_y$ due to the plasma anisotropy. The coupling spectrum of an array of eight straps is shown in Fig. 4, red solid line. The dashed orange line is the cut of the surface conductance of picture 3 that shows the shaping action of the surface conductance on the power spectrum of the array represented by the dashed blue line. The position of the maxima are given by the ratio of the current phase difference $\Delta \phi$ and the strap inter distance $d$ plus an integer multiple of $2\pi/d$, $k_{z\text{max}} = (\Delta \phi + p2\pi)/d$ where $p = 0$ is the main maximum and $p = \pm1,\pm2,\ldots$ are the secondary maxima (side lobes) [14]. Due to the effect of the surface conductance, a smaller $d$ will push the side lobes outside reducing the power in those component of the spectrum. Increasing the number of the strap will increase the directivity of the antenna

![Figure 3. Surface conductance for a typical reactor like plasma. The dashed line is the cut $k_y = 0$ used in figure 4.](image1)

![Figure 4. Example of coupling spectrum for eight straps. The dashed orange line is the cut for $k_y = 0$ of the surface conductance of figure 3.](image2)
decreasing the width of the peaks. A change of phase will move the position of the main maximum and consequently the secondary ones. A combination of \(d\), \(\Delta\phi\) and number of straps will give the optimum spectrum and a Traveling Wave Antenna is a convenient way to achieve that [14,15].

4. Traveling Wave Antenna
A Traveling Wave Antenna is a structure where the current that generates the radiation fields is in the form of a traveling wave. A sketch of a TWA is shown in Fig. 5. This particular configuration is called combline and it is vastly used in the RF and microwaves filter domain. An array of straps is tuned by capacitors to resonate at a certain frequency. If a signal is injected at the input port it travels along the structure up to the output port. The arrows on the straps depict the amplitude and phase difference, for a given time step, of the current density on each strap. The mutual coupling between elements is essential for this type of antennae differently from what for the conventional ones. The absence of septa between straps leads to an increased coupling capability [15]. The electrical response of the structure for two cases with different loading is shown in Fig. 6. The \(S_{11}\) (reflection) and \(S_{21}\) (transmission) coefficient of the structure are shown in red and blue respectively. The band-pass behaviour is similar to the one of a filter and is clearly visible around 50 MHz. Those results were obtained by full-wave simulations and confirmed by measurements on dedicated mock-ups. What is interesting is that the structure is not sensitive to changes of loading resistance [14]. This can be seen on the figure noting that, in the band-pass, the reflection coefficient does not change appreciably for the two different cases of loading resistance represented by the solid and dashed lines. The transmission coefficient presents instead a considerable effect. It can be shown that only the phase between the input and the output is changing. The behaviour of a TWA is then similar to a lossy transmission line. This fact is exploited in the resonant ring configuration where a power coupler is connected to a TWA, a generator and a dummy load in such a way to form a ring in which the power is recirculated while the generator is always seeing a matched load [14,15]. A sketch of this configuration is shown in Fig. 7 together with the contour plot of the \(B_z\) field component in the plane \(xz\). The field is computed in TWA box and in the plasma in front of it (see also Fig. 2 for the boundary conditions). A coupling code was modified to self consistently compute the fields from the current distribution on the TWA structure. The resonant condition is ensured by a proper tuning of the line stretcher. The power flow in the resonant ring is shown by means of orange arrows. The system is load resilient, characteristic that is required for the use in a fusion reactor.

![Figure 5. TWA schematic with connections and tuning capacitors.](image)

![Figure 6. Electrical response of the TWA section.](image)
Figure 7. Resonant ring configuration and contour plot of the $B_z$ in the TWA and the plasma in front of it.

5. Conclusions
A general overview of the ICRF wave propagation and system configurations was used to highlight the difficulties in the design of a launcher capable of providing a suitable coupling spectrum. The required current distribution is the key point to obtain the desired performance. The Travelling Wave Antenna is a good candidate for a launcher because it is capable of providing a current distribution without the necessity of feeding all the straps. If operated inside a resonant ring, the system shows load resilience and perfect matching of the generator. With this type of launcher, the absence of septa leads to higher coupling with respect to the conventional one. There are still open questions like how to properly design the tuning capacitor and what is the mutual effect of multiple neighbouring sections. The high value of auxiliary heating power likely to be injected in a fusion reactor requires ICRF systems capable of dealing with that power level without exceeding voltage standoffs and ensuring an high efficiency. The TWA in a resonant ring seems a good candidate showing a higher power coupling capability, an intrinsic load resilience and, due to the higher number of straps, more selective spectra. The limit for the number of straps depends on the coupling itself and on the feeding scheme. Further studies are ongoing to understand which configuration is the best in order to meet the requirement for a fusion reactor.

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