Review on Recent Progress in Ion Cyclotron Range of Frequency Systems, Experiments and Modelling for Magnetic Confinement Fusion

From modelling, technology and experiments

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# Abstract

This paper is a broad overview and a summary of the recent progress achieved in Ion Cyclotron Range of Frequency (ICRF) Systems, Experiments and Modeling during the last twenty years in magnetic confinement fusion experiments. It has been written mainly for students or newcomers in this exciting field and introduces the different applications and lists the main detrimental effects associated with the use of ICRF in magnetic fusion experiments. Modelling techniques and state-of-the-art ICRF systems are described. Recent results obtained with ICRF in fusion plasma experiments are summarised. Planned ICRF projects such as ITER or future fusion reactors and the remaining issues that remain to be solved are detailed.

# Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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# Introduction

With the goal to one day produces electricity from thermonuclear fusion power, magnetic confinement fusion uses magnetic fields to stabilise the high-temperature plasma over long time scales (Wagner 2018; Ongena et al. 2016; Kikuchi et al. 2012). Whatever the fusion mixture and the confinement scheme chosen, auxiliary heating techniques are mandatory to raise and eventually maintain the ion (and electron) temperature to achieve a sufficient amount of fusion reactions. For Deuterium-Tritium reactors, a temperature of 10 to 20 keV is required. Several auxiliary heating systems have been developed in the history of fusion experiments, and two broad types are used, namely neutral beam injection and radiofrequency methods (*Fundamentals of Magnetic Fusion Technology* 2021). The former involves the injection of high-energy beams of neutral atoms that can cross the machine's magnetic field and transfer their energy to the plasma via charge exchange reactions. The latter involves the coupling of electromagnetic waves excited by antennas located in the vicinity of the plasma to plasma waves that propagate and ultimately transfer their energy to the plasma's charged particles (Dumont 2021).

Among the radiofrequency methods, many concepts have been tested in the history of magnetic fusion research (Granatstein and Colestock 1985; Golant and Federov 1989; Cairns 1991). As the size and complexity of the fusion machines increased, a selection occurred on the kinds of selected RF systems, constrained by the obtained performance, cost considerations, the know-how of the time, and the people in charge experience. Nowadays, the main RF systems used in large fusion experiments are Ion and Electron Cyclotron Resonance Heating (ICRH and ECRH) and Lower Hybrid Current Drive (LHCD). As these RF systems are not used only for plasma heating or current drive respectively, they are commonly designed using the generic terms Ion and Electron Cyclotron Range of Frequency (ICRF and ECRF) and Lower Hybrid Range of Frequency (LHRF).

Nowadays, ICRF is the RF heating scheme whose highest powers have been transferred to a magnetised plasma, with, for example, up to 22 MW in JET in L-mode (Wade et al. 1992; Jean Jacquinot, Putvinski, and Bosia 1999). ICRF is used in almost all present-day tokamaks and stellarators at a multi-MW level and is likely to play an essential role in next-generation experiments and fusion reactors. Additional applications of ICRF than plasma heating are developed in the next section and deeply discussed in (Wilson and Bonoli 2015; Ongena et al. 2017; Jean-Marie Noterdaeme 2019).

This paper is a broad overview and a summary of the recent progress achieved on ICRF during the last twenty years in magnetic confinement fusion experiments. It has been written mainly for students or newcomers in this exciting field. The reader is encouraged to dive into the references used in this paper to learn more information and details. Section 4 introduces the different applications of ICRF in magnetic fusion experiments. No system is perfect, and Section 5 lists the main detrimental effects associated with the use of ICRF. Section 6 describes the various parts and the state-of-the-art of an ICRF system. Section 7 is dedicated to the modelling techniques, and Section 8 summarises the most recent results obtained with ICRF in fusion plasma experiments. Finally, Section 9 describes the future ICRF projects in the subsequent fusion machines such as ITER and future fusion reactors as well as some issues that remain to be solved.

# Applications of Ion Cyclotron Range of Frequency

## Plasma Heating

### Ion Cyclotron Heating Schemes

Plasma magnetic confinement experiments use magnetic fields for electrons and ions to follow and gyrate around magnetic field lines (Wesson and Campbell 2011; Freidberg 2007). Looking in the direction opposite the magnetic field, ions and electrons rotate in the clockwise and counter-clockwise directions, respectively. The cyclotron frequency (or, equivalently, the gyrofrequency ) corresponds to the number of cycles a particle of electric charge and mass completes around its circular trajectory every second in a magnetic field of magnitude . The magnitude of the magnetic field of past and present-day experiments leads to ion cyclotron frequencies between 10 to 100 MHz.

The resonances that could arise between the natural cyclotron motion of an ion in a static magnetic field with an electromagnetic wave having the same (gyro)frequency have been identified early in the magnetic fusion research as a bulk plasma heating method (Berger et al. 1958; Thomas H. Stix and Palladino 1958). These processes occur when the wave frequency f=ω/2π, defined by the RF power source, matches the condition :

( 1 )

where *p* is a positive integer (), is the parallel wavenumber of the RF wave and the ion parallel velocity along a field line. The term is the wave Doppler-shift gyrofrequency correction. The case *p=1* is known as *fundamental* cyclotron frequency damping, while cases *p>1* are known as *harmonic* damping. In magnetic confinement experiments, such as Tokamak or Stellarators, the confinement magnetic field has a spatial dependence so that these conditions only occur in localised spatial regions of the plasma.

Experimental confirmations rapidly confirmed the theoretical findings (T. H. Stix and Palladino 1958; Thomas H. Stix and Palladino 1960; Hooke et al. 1961; Rothman et al. 1969). Hot plasmas being weakly collisional, ICRF plasma waves, known as fast (magnetosonic) waves, are damped in the plasma core mainly by two non-collisional wave-particle resonant damping mechanisms on both ions and electrons (Becoulet 1996). The wave power is damped on one or several thermal species, resulting in an increase of their kinetic energies and the creation of energic particle populations. These populations then heat the plasma from collisional relaxations (Dumont 2021). Depending on operating conditions, the electrons can absorb a very substantial part of the power by Landau damping/Transit Time Magnetic Pumping or linear mode conversion to Ion Bernstein Waves (IBW) (Thomas H. Stix 1965; M. Brambilla and Ottaviani 1985; Mantsinen, Mayoral, et al. 2003).

### Minority Heating

The plasma heating physical mechanisms at play at the ion cyclotron resonance are not as evident as the naming seems to imply. They are reviewed in more detail in references (F. W. Perkins 1984; Becoulet 1996). In a single species plasma, the plasma wave carrying the RF power from the edge to the plasma centre has two possible circularly polarised components. The first one rotates in the direction of the cyclotron rotation of the ions, while the second one rotates in the opposite direction. Hence, for a particular couple of the magnetic field magnitude and the RF frequency, a rotating ion can see in its frame of reference a constant electric field that can accelerate (or decelerate) it, depending on the phase of its electric field (i.e. its direction) to the instantaneous speed of the ion.

However, at the location of this resonance, the amplitude of the former component, whose electrical field is rotating in the direction of the ions, vanishes, and then no absorption occurs (Porkolab 1994). The reason is that the polarization is mainly influenced by the dominant plasma species while the absorption is reigned by the resonant species (T. H. Stix 1975). Hence, the composition of the plasma can highly affect wave polarization. The problem is overcome if the dominant species is different from the resonant species. Hence, if a second ion species, called the *minority* species, is added into the plasma with a much lower concentration than the dominant one (typically a few per cent), then the component of the wave with the right polarisation at the resonance (of the resonant species) is different from zero and efficient heating of the minority species can take place. In addition, if the minority is small enough, the ion-ion hybrid resonance layer is also close to the fundamental resonance layer and locally enhances the magnitude of the right polarisation component, increasing further the heating efficiency (F. W. Perkins 1984). Once absorbed, the minority species transfers its energy to the bulk plasma by Coulomb collisions. This method is called *minority heating* and is still the most used in tokamaks (Jean Jacquinot, Putvinski, and Bosia 1999; F. W. Perkins 1984). In current experiments, it is widespread to heat hydrogen in deuterium plasmas, with a typical concentration of hydrogen of about 1 to 20%. Experiments made on JET with ITER-like plasma-facing components show that the plasma energy reached per MW of RF power at constant density is typically optimum for hydrogen concentration in the range of 5 to 15% and degrades for higher concentrations (Lerche, Eester, et al. 2014). Similar experiments on other machines showed optimal absorption conditions for Hydrogen concentrations between 4 to 8% on WEST (Urbanczyk et al. 2021) or below 10% on KSTAR (Lee et al. 2021).

The ICRF plasma heating efficiency can be increased when used in combination with neutral beam injection. This enhancement is attributed to both the lower collisionality of the preheated plasma using neutral beam injection and the Doppler-shifted ion-cyclotron resonance absorption of the fast beam ions (Lerche et al. 2009). In such a situation, RF power can be eventually absorbed away from the resonance layer due to enhanced Doppler shifts. It is also important to mention that a non-negligible fraction of the power, 20-25% for example on JET (Lerche, Eester, et al. 2014), is lost in the various plasma edge loss mechanisms. These processes are an important research topic and are reviewed in Section 5.

While successfully used in current experiments, the minority heating scheme at the fundamental harmonic of the cyclotron resonance of hydrogen (or helium-3) is not desirable in a D-T fusion reactor. Indeed, as Deuterium and Helium-4 (alpha particles) have the same charge over mass ratio, their cyclotron frequency is hence identical, and alpha-particles created from D-T fusion reactions will be heated by second harmonic heating (cf next section) with a strong absorption (Hellsten et al. 1985). Further accelerating alpha-particles is not desirable in a fusion reactor as the latter relies on alpha-particle slowing down as the main heating schema in ignited plasma (Dumont and Zarzoso 2012). To avoid this drawback, other minority species heating schemes are envisaged and have been tested, such as minority 3He on Deuterium or Hydrogen plasmas, relevant to ITER (Eester et al. 2009; 2012). More advanced heating schemes are also possible and are reviewed in the following sections.

### Higher harmonics and combined schemes

It is possible to use higher harmonics of the ion cyclotron frequency to heat the plasma ions, i.e. with *p>1*. This method is called *harmonic heating* and has been combined with minority heating since the beginning of ICRH experiments (J. Jacquinot, McVey, and Scharer 1977; Hosea et al. 1979). The theoretical analysis shows that good accessibility persists and that a reasonable portion of the wave has the proper in-phase polarisation for strong wave-particle resonance. However, the damping rate depends sensitively on temperature and density and thus is not as robust and reliable as one might like. Second-harmonic heating of 3He in a deuterium plasma can also be used to study fusion and α-particle confinement without creating a large neutron flux (Hellsten et al. 1985; Mantsinen, Eriksson, et al. 2003).

When multiple antennas are available, multiple-frequency ICRF heating schemes can be combined for ion bulk heating to benefit from synergetic effects from various fast ions populations, eventually also from neutral beam injected ions (Mantsinen et al. 2021; V. Bobkov et al. 2020). Dual H and 3He minority heating on Deuterium plasma experiments have been carried out on JET and ASDEX Upgrade as a scenario relevant for ITER (Mantsinen et al. 2021). Another possible combination involves 3He minority heating combined with the second harmonic heating of tritium in D-T plasmas, a scheme also relevant to ITER.

### 3-Ion Schemes

Fusion plasmas are intrinsically multi-ion species plasmas, intentionally or not, because of the impurities coming from the plasma-facing components or the neutral beam ions. This state of fact can be used as an asset by intentionally considering ICRF heating scenarios with three ions to integrate a minority heating with mode conversion scenarios. A mix of two majority ions leads to a mode conversion layer where the amplitude of the wave's electric field with the right polarization is increased. Locating this layer at the position of the resonance of a third minority species can lead to high absorption by this minority and highly accelerated ions (Kazakov et al. 2015). This heating scheme has been validated on Alcator C-Mod (Kazakov et al. 2017), ASDEX (V. Bobkov et al. 2020) and JET (Kazakov et al. 2021). Such scenarios can be used as a source of high-energy ions in stellarators and mimic alpha particles, such as in the non-activated phase of ITER (Kazakov et al. 2015), and are promising for ITER and fusion reactors to provide efficient bulk heating using their intrinsic operational impurity species, such as Beryllium (Ongena et al. 2017).

## Wall Conditioning

The operation of ITER and future fusion reactors is subject to compliance with a strict safety limit on the in-vessel Tritium inventory (T. Wauters et al. 2020). The ability to control and remove Tritium from the plasma-facing materials is thus essential. In addition, superconducting coils producing permanent high magnetic fields for days or weeks prevent glow discharge conditioning, which is presently one of the preferred methods for wall-conditioning (Mantsinen, Eriksson, et al. 2003). On the contrary, Wall Conditioning initiated with Ion Cyclotron waves (ICWC) or Electron Cyclotron waves (ECWC) is fully compatible with magnetic fields and helps recover from disruptions in a tokamak, radiative collapses in a stellarator or vacuum and water leaks.

Experimental comparisons showed that ICWC removes more particles faster than ECWC in the tokamaks TEXTOR, Tore Supra, ASDEX-Upgrade and JET (Lyssoivan et al. 2011; T. Wauters et al. 2011; Douai et al. 2015) and stellarator WEGA (T. Wauters et al. 2014). ICWC operations showed the highest Tritium release rate in LHD compared with glow discharges or ECWC (Tanaka et al. 2021). In JET, while baking alone removed a significant amount of fuel, the subsequent ICWC and glow discharges sessions removed slightly higher amounts than found previously in isotopic changeover experiments with the vacuum vessel at 200°C (Tom Wauters et al. 2022). An ICWC system is under development for W7-X (Schweer et al. 2017; Castaño Bardawil et al. 2021). ICWC is considered to mitigate the Tritium inventory build-up in ITER (Douai et al. 2015).

## Plasma Startup

Superconducting poloidal field coils in tokamaks require low loop voltage plasma startup to reduce the heating due to eddy currents in the central solenoid (Mueller 2013). In ITER, the inductive field is limited to 0.3 V/m for its startup phase. Thus, plasma startup at low inductive or completely non-inductive current is an important research topic for superconducting tokamaks such as JT-60SA or ITER.

To address this challenge RF systems can be used to inject RF waves, typically ECRF, into the vacuum chamber to initiate plasma discharges robustly and reliably in the presence of a toroidal magnetic field (Jackson et al. 2007). ITER will start its operation at 1.8 T to commission the plasma control system, achieve H-mode more efficiently and test ELM mitigation techniques (M. Schneider et al. 2019). At this low field, the breakdown may be more challenging to achieve as the connection lengths of the open magnetic field lines are shorter compared to half-field and full-field operations. Additionally, at 1.8 T, the efficiency of the ITER 170 GHz ECRF system used on the third harmonic resonance remains an open issue. Hence, following successful experience in TEXTOR (Koch et al. 2005) and more recently in LHD (Kamio et al. 2021), ICRF pre-ionisation is suggested as a possible solution.

## Current Drive

Steady-state tokamak operation relies upon the drive and sustainment of a significant fraction of the toroidal current by non-inductive methods (Fisch 1987). While LHRF and to a lesser extent ECRF are currently the main RF current drive actuators in current experiments, several schemes involving RF waves in the ICRF have also been proposed and evaluated. Among these methods, fast-wave current drive (FWCD), also known as Ion Cyclotron Current Drive (ICCD), is obtained by exciting the fast magnetosonic wave with a toroidally asymmetric antenna spectrum (Bilato et al. 2002; Mantsinen, Eriksson, et al. 2003; Bilato, Brambilla, and Fable 2014).

In current machines, the ICRF electron current drive efficiency is modest in the usual frequency range (20-75 MHz) and affected by significant parasitic damping by alpha-particles (Bilato et al. 2002; Bilato, Brambilla, and Fable 2014). However, the situation is different in reactor-grade plasmas such as ITER or fusion reactors, where the large electron temperature significantly enhances the current drive efficiency (Dumont and Zarzoso 2012; Kazakov, Van Eester, Wauters, et al. 2015). In addition, operating at a much higher frequency would also be beneficial, while the antenna's location becomes an important point to consider to avoid parasitic alpha-particles heating (Lerche, Van Eester, et al. 2014). Higher frequency fast waves, nowadays better known as "whistler" or "helicon" waves, allow a better penetration (higher accessibility) up to mid-radius in reactor-grade plasmas in comparison to LHRF (slow) waves (Pinsker 2015). For this reason, this topic is the object of a renewed interest in current experiments (Wi et al. 2018; J. Kim et al. 2021; X. Li et al. 2020; Jingchun Li et al. 2020; Ganji et al. 2022; Torreblanca et al. 2019).

# Detrimental Effects

## Impurity Production

Despite its relatively good performance (Steinmetz et al. 1987), ICRF is also known for long to have detrimental effects, including the generation of metallic impurities in the plasma (Adam 1987; J -M Noterdaeme and Oost 1993; F. W. Perkins 1989). Early ICRF experiments have reported non-linear interactions between high-power RF waves and edge plasma, leading to an influx of impurities that prevented efficient heating of the plasma (Rothman, Sinclair, and Yoshikawa 1966). As radiative losses go as the square of the electric charge of the ions, heavier metal impurities impair the fusion power budget more than light elements. This problem of impurities had been partly solved in previous experiments by using graphite limiters and carbon-coated metallic surfaces. However, due to gas retention issues, these materials cannot be used in a future fusion reactor, and plasma-facing components equipping the experimental devices have been progressively changed to metallic ones, highlighting the impurity problem again (Ongena et al. 2017). Since then, despite improvements in antenna design and plasma operation that substantially reduced these undesirable phenomena, it remains a critical operational limitation of ICRF (Jean-Marie Noterdaeme 2019). While the problem has been partially solved with the latest generation of antennas (see Section 8), it remains an important research topic.

Because of their mass difference, ion and electron motions behave differently along magnetic field lines: electrons accumulate faster than ions on Plasma Facing Components (PFC) and form a thin, negatively biased layer that repulses electrons and attracts ions. This attraction increases the parallel energy of ions attracted into the wall and thus enhances the ion bombardment of the PFC. Ions impacting the PFC can cause sputtering of impurities that can reach and contaminate the plasma. In addition, when released, light impurities can lead to enhanced wall sputtering, increasing further the core plasma contamination with high-Z impurities (Dux et al. 2009; V. Bobkov et al. 2009). In the presence of RF waves parallel to the magnetic field lines driven by the ICRF antenna (which can be induced by the Slow-Wave polarisation), sheaths are enhanced. Instead of being constant in time, the DC potential drop across the sheath is then the superposition of a DC component and RF oscillations, called *RF-induced sheath rectification* (F. W. Perkins 1989). This mechanism has been identified as a significant cause of the increased interaction with the wall and is still an intense research topic (Colas et al. 2019; V. Bobkov et al. 2019; Křivská et al. 2019). RF sheaths can form when a magnetic field line makes a connection between two points on the antenna surface or the nearby plasma-facing components. These are qualified as “near-field” RF sheaths. RF sheaths can also form by the RF waves propagating between the plasma and the vacuum chamber, for example, in case of weak damping In the plasma, and are known as “far-field” RF sheaths.

Furthermore, the rapid variation of the rectified potential across the equilibrium magnetic field can cause significant convective transport (E × B drifts) in the scrape-off layer region (Wei Zhang et al. 2021). A review of the experimental characterization of ICRF-induced edge plasma modifications over the past 20 years of various tokamaks worldwide and on the LArge Plasma Device (LAPD) has been recently published (Colas et al. 2021). An extensive overview of the RF sheath concepts has also been recently published (Myra 2021).

## Edge Plasma Modifications

ICRF wave fields drive plasma drifts and change the edge plasma density, perturbing antenna-plasma coupling and wave propagation, while edge plasma also rectifies the RF near-antenna electric field, contributing to these perturbations in a non-linear way (W. Zhang, Tierens, et al. 2017). These modifications might also perturb the operation of other actuators, such as LHRF wave coupling and generate hot spots (Colas et al. 2007; Ekedahl et al. 2007).

ICRF waves scatter at density inhomogeneities such as density filaments (blob) in high harmonic fast wave regimes (R. J. Perkins et al. 2012). This scattering can redirect part of the power from the perpendicular direction to the parallel direction and enhance the resistive losses on the antenna limiters and RF sheaths on the magnetically connected elements of the wall (W. Tierens, Zhang, et al. 2020; Wei Zhang, Tierens, and Usoltceva 2020; W Tierens et al. 2022).

## Coaxial Mode and Surface Waves

Transverse Electric and Transverse Electromagnetic modes can be excited by ICRF antennas in the scrape-of-layer region between the wall and the plasma edge for parallel wavenumber components |k//|<k0 where k0 is the vacuum wavenumber (A. Messiaen and Maquet 2020; A Messiaen, Maquet, and Ongena 2021; Maquet, Druart, and Messiaen 2021; Wouter Tierens and Colas 2021). For plasma with large edge density gradients, the plasma behaves for these modes as the central conductor of a coaxial line, hence the name of these modes. Coaxial modes propagate in the toroidal direction, between the vacuum vessel and the Lower Hybrid resonance layer. In addition, surface waves can propagate toroidally and poloidally in the edge region on the surface corresponding to the LH resonance. A large radial electric field characterizes both fields, which can excite RF sheath at locations far from the antenna, eventually even not magnetically connected, further contributing to impurity releases.

## Arcs

RF breakdowns and arcs are recurrent problems in high RF power applications such as magnetic nuclear fusion experiments. A vacuum arc is defined as an electric discharge occurring between two electrodes in vacuum (Timko 2011). In the context of RF heating and current drive for tokamaks, electrical breakdown almost always means a vacuum arc affecting RF systems and both terms are generally used with the same meaning.

Recent experimental and modelling works performed for accelerators argue that vacuum arcing can be explained by the properties of surface cracks and unipolar (or cathodic) arcs, striking between one solid electrode and plasma and explained from the following steps (Insepov and Norem 2013; Norem, Hassanein, and Insepov 2019): 1) An initial mechanical failure/cracks of the surface due to fatigue, producing detached fragments; 2) High external electric field is applied, locally enhanced at the failure/cracks location (known as emitters); 3) Electrons extracted from field emission or secondary emission[[1]](#footnote-1) further ionize these fragments; 4) A local plasma is initiated, controlled by the plasma sheath and material properties; 5) The plasma density increases exponentially up to some equilibrium state, during which local temperature increases due to ion bombardment/current hitting the wall, eventually melting it. Ion-induced sputtering is a source of additional ions for the plasma; 6) The arc produces additional surface damage due to heating, melting, and cooling, which can further initiate new arcs.

As noted in step 3, both field emission and secondary emission have been identified as the primary mechanism leading to an increase in the electron population, which further causes ionization and electron avalanche (Höhn et al. 1997). The leading cause depends on the geometry, the RF frequency at play and the material properties (roughness, work function, secondary emission) and history (contamination, dust, etc.), but also the background DC magnetic field (Caughman et al. 2007). It is generally admitted in the fusion community that field emission is the primary mechanism limiting ICRF power at high power, while it is primarily secondary emission triggered by the multipactor effect for LHRF (M. Goniche et al. 2014; Wukitch et al. 2004). However, multipactor can also affect ICRF systems at relatively low power (~1-10 kW), especially during RF conditioning phases. Multipactor can cause surface heating, gas desorption and physical damage (Kishek et al. 1998; Graves, LaBombard, et al. 2006). Multipactor can also provide electrons seeding glow discharges even far below the expected Paschen breakdown pressure and eventually breakdowns if not stopped (Graves, Wukitch, et al. 2006).

If the energy source that gave birth to the arc is not stopped, the arc can continuously burn. In general, the arc will tend to move towards the RF source, as the electrons in the arc are attracted to the source of the electric field. The arc movement will be also affected by the presence of a magnetic field, following a retrograde motion in the **J**x**B** direction (Wesson and Campbell 2011).

# ICRF Systems

ICRF, like any RF heating and current drive system, share the following requirements: 1) Some high-power RF generators that transform electrical power into electromagnetic power; 2) Transmission Line elements to transport the electromagnetic power from the generators to the antennas; 3) Antennas to couple the electromagnetic power to plasma waves; 4) Wave propagation and absorption on ions or electrons by wave-particle interactions. The following sections review the recent progress on each of these topics.

## RF Generators

The conversion from electric to electromagnetic power in the Ion Cyclotron Range of Frequencies is carried out using a series of amplifiers. For a given frequency, the RF signal generated by an oscillator (<20 mW) is amplified up to 1 to 3 MW through multiple power amplification stages, typically 3 or 4. Electronic tubes, known as *tetrodes* or *diacrodes*, are still used for the last stages of amplification, while nowadays, solid-state amplifiers are used for the intermediate ones (Cairns and Phelps 1996; Benford, Swegle, and Schamiloglu 2007). Table 1 lists the current existing or planned ICRF systems.

|  |  |  |  |
| --- | --- | --- | --- |
| **Device (Country)** | **Frequency range (MHz)** | **Max Plant Power (MW)** | **Reference** |
| LHD (Japan) | 25-100 | 8 (4 generators) | (Kenji Saito, Seki, et al. 2020) |
| ASDEX Upgrade (Germany) | 30-120 | 10 (5 generators) | (Faugel et al. 2005; 2020) |
| JET (UK) | 23-57 | 32 (16 generators) | (Graham et al. 2012) |
| EAST (China) | 25-70 | 12 (6 generators) | (Mao et al. 2013) |
| WEST (France) | 46-65 | 9 (6 generators) | (J. Hillairet et al. 2021) |
| SST1 (India) | 20-30,45.6,91.2 | 3 (3 generators) | (Bora et al. 1999) |
| NSTX (USA) | 30 | 6 (6 generators) | (LeBlanc et al. 2001) |
| ITER (planned) | 40-55 | 24 (8 generators) | (Mukherjee et al. 2015) |
| SPARC (USA, planned) | 120 | 25 | (Rodriguez-Fernandez et al. 2022) |
| DTT (Italia, planned) | 60-90 | 4 (1st phase) | (Ravera et al. 2021) |

Table 1. Current existing or planned ICRF Systems

Ongoing R&D addresses the development of the ITER ICRF sources. The specifications of these sources are a power capability of 2.5 MW/CW at VSWR 2:1 in the frequency range 35–65 MHz or 3.0 MW/CW at VSWR 1.5:1 in the 40–55 MHz band, along with additional requirements on transient VSWR, frequency deviations and harmonic levels (Mukherjee et al. 2015; 2016). As no unique amplifier meets these specifications, two chains of three-stage amplifiers will be combined using a 4-port wideband power combiner. Operating at these high power and VSWR levels in a steady-state regime brings new thermal management challenges and source stability (Chakraborty et al. 2019).

Ion cyclotron was often promoted as the "cheapest" RF scheme since it has the advantage of operating in a frequency range where high power sources were readily available for MF to VHF frequency bands. However, this assertion should be moderated nowadays. As bandwidth demand in radio and telecommunications led to an increase of the frequencies, which comes with higher propagation losses, leading to shorter ranges and the multiplication of lower (but more numerous) power sources, the demand for high power transmitters tubes has been progressively dropped. Low-power semiconductor amplifiers are now used to fill a part of the demand remaining from the plasma-surface industry. However, they can only produce moderate RF powers, typically a few tens of kW. Vacuum tubes are still necessary for hundreds of kW and MW ranges of RF power, and only a couple of high-power vacuum tube manufacturers now remain.

## Transmission Lines Elements and Vacuum Feedthrough

The transport of the RF power in the ICRF is assured with rigid coaxial transmission line elements. These components are commonly available with characteristic impedances of 30, 50 or 75-Ohm. 30-Ohm lines maximize the power handling while 75-Ohm lines minimize the attenuation (Pozar 2012). In between, 50-Ohm lines are a compromise between power handling and attenuation. The RF current density is larger on the inner conductors than on the outer conductors. The former are generally made in copper to minimise RF losses, while the latter are often made of aluminium. These coaxial lines are usually filled with dry air or nitrogen up to a few atmospheres to reduce the dielectric voltage breakdown threshold. Despite relatively low RF losses, handling high power during long pulse durations can be limited by the temperature and the thermal expansions of the conductors. Forcing dry air or nitrogen flow between inner and outer conductors is not always sufficient to cool them, and active water cooling is then necessary.

In ITER, four transmission line components carry the power from the RF sources to each antenna. Each line has to carry up to 6 MW at VSWR 1.5:1 in continuous conditions (Goulding et al. 2014). The inner conductors are cooled by nitrogen gas pressurized at 3 bar absolute and circulating at a velocity of 3-6 m/s. The RF power is then divided nearly equally by hybrid power splitters, which also serve for ELM resilience (see section 6.5), before entering the pre-matching stages and then the antenna.

Testing new transmission line components at the MW level in continuous operation and up to the expected voltages and currents before connecting them to the high-power RF sources requires specific test facilities. Dedicated programs have been set up by the domestic agencies in charge of providing these components (Jha et al. 2015; 2020; Goulding et al. 2014) or in the frame of specific R&D programs (Bernard et al. 2011). A Traveling-wave resonator has been realized by US-ITER DA to produce 6 MW circulating power for an input power of 340 kW and used to test gas barriers up to 3600 s (Goulding et al. 2014). RF contacts, initially foreseen in the ITER antenna design, have been tested in a resonant resonator at 62 MHz up to 1700 A during 1200 s but not to the targetted specifications for ITER (Julien Hillairet et al. 2015; J. Hillairet et al. 2018; Z. Chen et al. 2017).

As the transmission line elements are pressurised with inert gas or dry air to increase breakdown voltage limits, feedthroughs (or "windows") are required to connect them to an antenna located inside the vacuum chamber. These components use ceramics that are mostly transparent to the RF waves but ensure the tightness between pressurised and vacuum regions. In the range of frequency considered for ICRF, alumina offers the best compromise between ease of manufacturing/handling and RF dielectric losses and thermal conductivity. In a fusion reactor, neutron radiations are expected to increase ceramics dielectric losses and decrease thermal conductivity (Zinkle 1994; Leonard, Goulding, and Zinkle 2007). For this reason, feedthroughs should be located in regions where the neutron flux is as low as possible. Intense R&D is currently ongoing to develop and test the ITER vacuum feedthroughs.

## Antennas and Coupling Elements

To excite the fast wave in the ICRF as required for plasma heating, the RF wave electric field needs to be perpendicular to the directions of the magnetic field and the direction of the antenna-to-plasma core. In this range of frequencies, the wavelength of the electromagnetic waves is of an order of a few meters, so larger or the same order as the machine size. Hence, ICRF antennas usually consist of an array of loop radiators similar to strip lines, or *straps*, on which flowing RF current JRF excite waves directly inside the vacuum vessel (Figure 1). These straps are oriented perpendicularly to the direction of the magnetic field B0 to excite the fast waves dominantly in the plasma. For practical reasons of available space and maintainability, antennas are generally located on the low-field side of the machines. As the antennas have a characteristic toroidal size of tens of centimetres to meters, smaller than the wave wavelength, most plane waves excited by the antenna are evanescent in vacuum. Hence these waves are evanescent in the plasma edge and have to tunnel through a layer in the plasma edge until reaching a region where the plasma density is higher than a specific value, known as the *cut-off* density, for the fast wave to propagate. This distance between the antenna and the region where the fast-wave start to propagate is thus a crucial parameter to act on the coupling performance. For this reason, antennas are generally made as conforming as possible to the plasma to minimise the distance from the straps to the plasma. Once coupled, fast waves propagate to the plasma core and are eventually absorbed through the various collisionless damping mechanisms occurring when the resonance condition ( 1 ) is fulfilled.

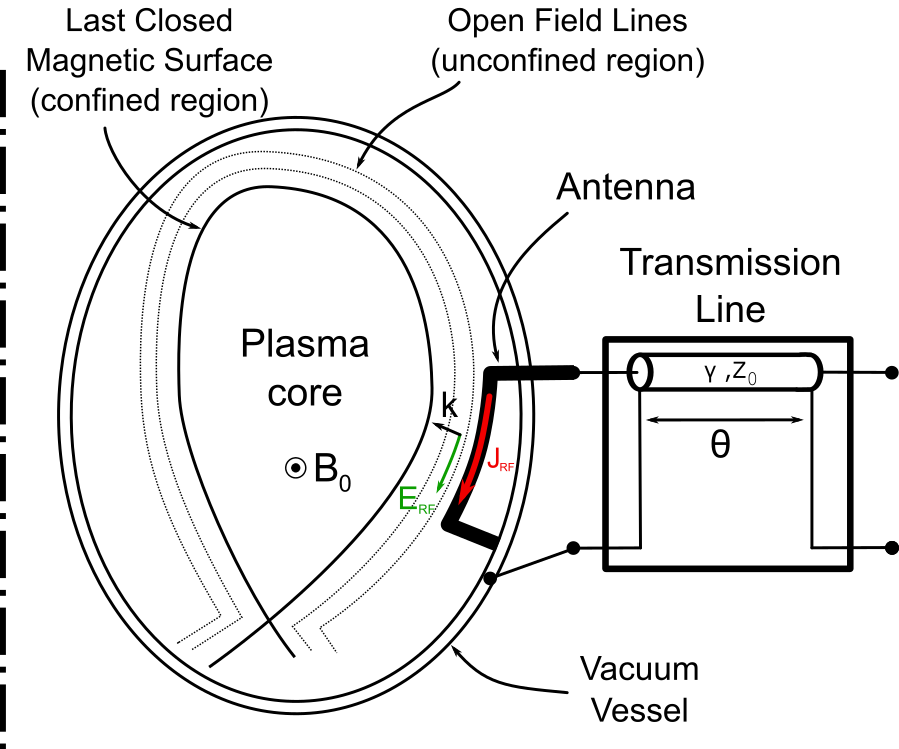


Figure 1. Simplified schematic of a classic ICRF antenna in a tokamak.

The effectiveness of Fast wave coupling is, in practice, measured by the total power radiated by an antenna to a given plasma. A frequent figure of merit used to quantify the coupling is the *coupling* or *loading* resistance *Rc*, defined as the ratio between the time-averaged radiated power *Prad* to the integral of the RF current on the straps *JRF* over the arc length along a strap:

( 2)

Hence, the total active power radiated Prad in the plasma is proportional to |JRF|2. The reference study (A. Messiaen and Weynants 2011) highlights the critical physics phenomena contributing to the coupling. It is shown that the following plasma density profile characteristics are decisive: (i) distance between the antenna straps and the wave cutoff density *dc*, (ii) position of an optimum density with respect to the cutoff one and (iii) the density gradient leading from this optimum density to the plasma bulk. It is also shown that slight modifications of the plasma profile can lead to substantial coupling variations for the same antenna-cutoff distance.

The amplitude and phase distribution of the flowing RF currents JRF on these straps and the antenna geometry shape the wavenumber spectrum ERF(**k**) excited by the antenna. The phase relation between the currents JRF on the straps in the toroidal direction is achieved by setting a phase difference at the sources. Shaping this phase allows preferentially exciting a particular portion of the parallel (to the magnetic field direction) wavenumber k// spectrum (Figure 2). A toroidal phase between straps of 0° is known as *monopole* phasing and 180° as *dipole* phasing. A toroidally symmetric spectrum such as *dipole* is beneficial for pure plasma heating (Hellsten et al. 2005), while an asymmetric spectrum (+/- 90°) is better suited for co- and counter-current drive (Eester, Louche, and Koch 2002). The phase relation between straps in the poloidal direction depends on the antenna geometry and its feeding circuit. It is shown in (A. Messiaen et al. 2010; Vallejos et al. 2019) that the poloidal phasing affects both coupling and heating performance: i) the coupled power is asymmetric with respect to the poloidal phasing and ii) better heating performance is obtained for a poloidal phasing of -90° than +90° (with an optimum around -30° which depends on the plasma profile), both being caused by the plasma gyrotropy.

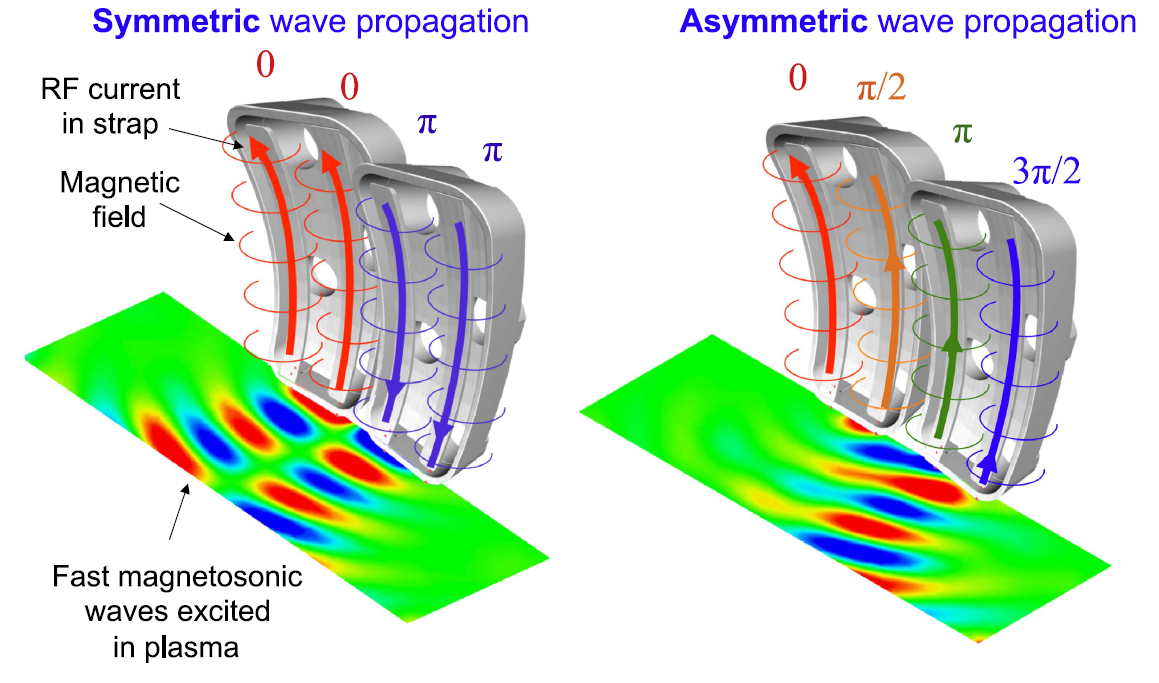


Figure 2. The effect on the propagation of the fast wave inside the plasma for two different toroidal phasings of the antenna with an array of four straps (Ongena et al. 2017).

The coupling efficiency also depends on the *k//* spectrum excited by the antenna, as the cut-off density depends on the parallel wavenumber *k//*. Thus, the coupling resistance *Rc* scales as:

where α is a constant representing the plasma density and its gradient, and *<kx>* is a characteristic factor that can be interpreted as a mean value of the wavenumber in the radial direction *kx*, where *kx*2= k//2+ky2-k02, over the radial interval between the strap and the cut-off distance *dc* (Clairet et al. 2004).

In practice, the parameters in equation (2) cannot be measured directly. Hence, a conveniently simple (but very simplified) way to quantify the coupling resistance is to assume each strap as a lumped resistance *Rc* fed by a lossless transmission line of characteristic impedance Z0. In this case, the time-averaged power Pt transferred to the load is:

where Pfwd and Pref are the forward and reflected power to and from the load and Imax and Vmax are the maximum peak RF current and voltage in the transmission line. Solving for Rc gives an expression that can be measured from RF power and voltage or current measurements.:

where SWR stands for the Standing Wave Ratio and is defined by SWR=Vmax/Vmin (Pozar 2012).

Assuming a strap to be an isolated lumped resistance is questionable for arrays of N straps, where mutual coupling between the straps occurs (Monakhov et al. 2018). Hence, in some ICRF systems, voltages are averaged between conjugated elements. Furthermore, the coupling resistance definitions and measurements depend on each ICRF system and cannot generally be compared directly between machines or even between ICRF systems of the same machine.

To improve ICRF coupling, an increase of the local density in front of the antenna with the help of localized gas injection can bring the position of the cut-off density closer to the antenna (Lerche et al. 2015). Experiments have been performed under the coordination of the International Tokamak Physics Activity (ITPA) on several tokamaks, including ASDEX Upgrade, JET and DIII-D, to characterize the increased ICRF antenna loading achieved by optimizing the position of gas injection relative to the RF antennas while disturbing the plasma core as little as possible (Jacquet et al. 2016). The antenna loading was increased by up to 50% on these machines when injecting deuterium in ELMy H-mode plasmas from mid-plane inlets close to the powered antennas. More minor improvements were found when using gas inlets located at the top of the machine. Localized gas injections are also beneficial for reducing tungsten sputtering on ASDEX-Upgrade antenna limiters and slightly reducing tungsten and nickel content in JET (Jacquet et al. 2016).

Recent progress has been made in antenna design, mainly to reduce impurity production. These advances are discussed in section 8.

## Faraday Screen

It was identified early that ICRF coupling structures do not excite only Fast-Waves but also Slow-Waves (Evrard and Weynants 1982). Slow-Waves are produced by RF currents parallel to the magnetic field and by oscillating space charges on the antenna structures. For this reason, early ICRF experiments introduced an electrostatic shield, often called *Faraday Screen* (England et al. 1989).

A Faraday Screen is formed by an array of metallic strips (or bars) aligned with the total magnetic field (Bureš et al. 1990). By screening the electric field components parallel to the strips/bars it aims to act as a polariser to filter out the undesirable slow waves. A denser screen better isolates the central conductor of the antenna from the plasma, but it also causes significant magnetic shielding and enhances Ohmic losses in the screen (Faulconer 1983). In conjunction with plasma heat flux removal, these losses require the faraday screen to be actively cooled. Various experiments have shown the benefits of Faraday Screens (Bureš et al. 1990; J. M. Noterdaeme et al. 1986; Myra, D’Ippolito, and Gerver 1990), but some also concluded that the heating performance of an unshielded antenna was similar to that of a shielded antenna (Nieuwenhove et al. 1991; 1992). Although it might be necessary to keep a Faraday shield for other reasons, such as decoupling thermal and mechanical stresses on plasma-facing components, the question of the necessity of a Faraday Screen in future ICRF antennas is still debated in the ICRF community (J.-M. Noterdaeme et al. 2019).

## Load Resilience and Matching

From the electric point of view, an ICRF antenna can be viewed as an impedance whose properties depend on the plasma and an ICRF system is equivalent to a transmission line loaded with a complex impedance ZL. The maximum amount of power that can be transferred from the source to the load is obtained when the load impedance matches the line and the source impedance. If the impedances are not matched, the load does not absorb all the power sent down the line, and the power reflected can damage the source. In addition, standing waves will develop along the line, increasing the maximum voltages and currents reached inside the antenna and transmission line elements.

A single strap element can be modelled by a line terminated with a lumped impedance (Bhatnagar et al. 1982). Without plasma, the resistive part R of this load represents the Ohmic losses of the antenna, which are generally small (R ~ 10-1 Ohm). In front of a magnetized plasma, part of the waves is coupled to the plasma. This part can be viewed as the resistive part of the antenna load. Hence, the coupling is indistinguishable from increasing losses from the circuit point of view. In most tokamak experiments, the resistive loading is in the 0.5 to 10 Ohm range (Pinsker 1998). The reactive part X is primarily inductive, and its value depends mainly on the strap and antenna geometry and is generally higher than the resistive part by one order of magnitude. In addition, changes in the resistive part are also correlated with some changes in the reactive part (Pinsker 1998). Since the characteristic impedance of the transmission line Z0 is usually between 30 to 50 Ohm, we always have R<< Z0. In addition, as |X|> 0, a matching system unit is thus necessary to maximize the power coupled to the plasma by the antenna.

Matching systems can be tuned on a pulse-to-pulse basis for a fixed impedance but also dynamically tuned to follow antenna impedance variations during the plasma pulse with automatic or feedback-controlled loops (Hofmeister, Braun, and Wesner 1994). These high-power matching systems are generally made of high-power compatible devices, such as tunable trombones or parallel stub(s) (R. Kumazawa et al. 1999; 2008; Liu et al. 2022).

However, during plasma operations, antennas are susceptible to fast load variations inducing a severe amount of reflected power towards the generators, which can cause degradation of the electronic tubes. If the reflected power cannot be avoided, fast control systems are required to reduce or shut down for some time interval the generator's power. Moreover, sudden changes in antenna loading arise in tokamaks operating in H-mode. During plasma perturbations (such as ELMs), loading rises on a time scale of around 10-50 µs and subsequently decays on a time scale of a few milliseconds. This sub-millisecond timescale represents a challenge to any dynamic impedance matching scheme, such as the one illustrated in Figure 3, because their response time is not fast enough. To cope with these fast events, inherently load-insensitive schemes, or *load-resilient*, are desirable (J.-M. Noterdaeme et al. 2005).

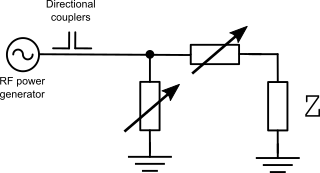


Figure 3. Standard Impedance matching system

Many ideas have been proposed and tested to realize an intrinsic load tolerance:

* Use a 3 dB hybrid coupler to split the output ports connected to antennas and to divert the reflected power to a dummy load (Figure 4, left) (Goulding et al. 1994; J.-M. Noterdaeme et al. 2005; Mayoral et al. 2007).
* Connect pairs of straps in parallel to form a so-called *conjugate-T* (Figure 4, right)(Bosia 2003; Ryuhei Kumazawa et al. 2011). Each strap has an adjustable impedance system, implemented either internally, using, for example, variable capacitors (Vulliez et al. 2008; Durodié et al. 2012; J. Hillairet et al. 2021), or externally with fixed or variable (trombones) transmission line lengths (Monakhov et al. 2005; 2013).
* Feedback control the generator frequency (R. Kumazawa et al. 2008)
* Use a fast ferrite stub tuner (Lin et al. 2015; Koert et al. 2016; G. Chen et al. 2017; Tan et al. 2021).

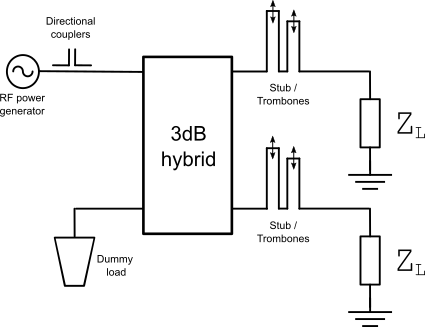
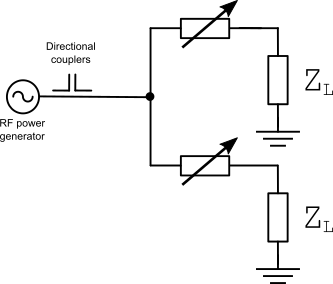
 

Figure 4. Load-tolerant matching systems. Left: 3dB hybrid splitter scheme; right: conjugate-T scheme.

On ASDEX-Upgrade, a load-resilient system allowing to maintain RF power during H-mode is obtained with 3 dB hybrid couplers. The reflected power is mainly redirected toward dummy loads thanks to the symmetrical properties of the 3 dB coupler (Faugel et al. 2005; Fuenfgelder et al. 2017). At JET, three different load-resilient systems are employed (Monakhov et al. 2013). Firstly, a hybrid system feeds antennas A and B. Secondly, a conjugated-T system with external matching feeds antennas C and D. Part of the matching is made by phase shifters connected far from the antennas. Finally, a conjugated-T system with internal matching is realized with vacuum capacitors located in the ITER-Like Antenna (ILA) (Bosia 2003; Durodié et al. 2005). A similar antenna design is used for the three WEST ICRF antennas (J. Hillairet et al. 2021).

As 3 dB hybrid couplers and conjugated-T systems are intrinsically tolerant to changes in antenna loading conditions, real-time matching control is generally not as critical as conventional matching schemes. However, controlling these load-resilient schemes and additional matching stages remains a valuable feature that facilitates the setup of new experimental scenarios and follows the slow evolution of plasma parameters. Hence, automatic matching algorithms have been designed and used during plasma operations on various ICRF systems (Monakhov et al. 2013; Durodié et al. 2017; J. Hillairet et al. 2021; Jain, Yadav, and Kumar 2021).

## Arc Detection Systems

RF-induced arcs generate the emission of electromagnetic radiations (including RF radiations) and can produce high temperatures that can limit the power transmitted from the RF sources to the plasma and create unrecoverable damage on the metallic and ceramic surfaces. Arc detection systems are then critical to ensure the safe operation of ICRF systems and prevent damage to the generators, the transmission lines or the antennas (D’Inca et al. 2009). RF breakdowns can be classified into two categories: “high” and “low” voltage arcs (Monakhov et al. 2007; D’Inca 2011). While the former is located at a maximum of the voltage profile in an ICRF system, the latter arises in more complex geometrical locations such as feedthrough or bellows.

The most elementary protection system against arcs measures the power reflected towards the generators. Arcs located between the generator and the antenna can generate transient mismatches, causing a rapid increase in the reflected power. When detected, the RF power is switched off as fast as possible, typically within 10 to 20 µs, to prevent excessive breakdown energy (Wang et al. 2015; D’Inca 2011). The RF power is then reapplied after a few tens of milliseconds, a delay sufficient to extinguish the arc. Because of the mutual coupling between radiating elements, all the generators associated with an antenna are generally switch-off then switch on simultaneously. The threshold for which the interlock is triggered depends on the system.

However, other events can change the reflected power on fast scales, such as a change in the plasma configuration or transient events such as ELMs. Thus, if the reflection coefficient is too low, it can falsely trigger the interlock, for example, during ELMs (Mayoral et al. 2007). A workaround is then to raise the threshold to a higher value with the drawbacks of increasing the arc detection delay in some systems or eventually missing entirely parasitic activities that could indicate low voltage node arcing (Monakhov et al. 2007). Hence, monitoring the reflection coefficient alone is insufficient to protect an ICRF system entirely, and additional techniques are required.

Fast transient phenomena such as arcs excite intense noise on a wideband centred on the RF source frequency and harmonics of the RF frequency below and above the generator frequency. Detecting these harmonics requires filtering the electronic noise and the generator's first harmonics. Measuring lower harmonics has been proven more accessible than upper ones (Rogers et al. 1995). Sub Harmonic Arc Detectors (SHAD) are pass-band filters (5/20-35 MHz band) used to monitor a frequency spectrum window below the RF source frequency, especially the lower harmonics of the generator frequency (Berger-By et al. 2007; Jacquet et al. 2009; D’Inca et al. 2011). These filters are coupled with a detector that triggers a signal to shut down the RF sources if above a certain threshold with a response time of typically a few microseconds(Berger-By et al. 2007; Jacquet et al. 2009). They do not require dedicated probes as they can use the signal coming directly from the RF power directional couplers. However, the SHAD method also triggers false-positive signals, for example, during ELMy phases, complicating the operation (D’Inca et al. 2007; D’Inca 2011; Jacquet, Berger‐By, et al. 2011).

The Scattering Matrix Arc Detection (SMAD) was proposed and first implemented on the JET ILA antenna to complement the SHAD and reflection coefficient systems (Vrancken et al. 2009; 2011). The method consists of a consistency check of RF signals taken around a possible vulnerable point to a numerical model. The numerical model requires an accurate RF description of the region under monitoring, for example, from the knowledge of its S-parameters and the calibrations of the RF signals, for the system to be able to deal directly with raw signals. SMAD is insensitive to the coupling properties and is thus suitable for detecting arcs during ELMs. An error signal is forged from the equations relating the measured quantities and the region's model, and a trip is issued if the obtained value departs from an acceptable error. The trip delay depends on the computing cycle, in the range of a few microseconds using an FPGA. Although the principle of the system is relatively simple, it was proven to be initially challenging to operate reliably before being fully recommissioned for a more robust implementation (P. Dumortier et al. 2019). SMAD has been implemented on the LHD ICRF systems (K. Saito et al. 2017).

Other arc detection methods have been proposed and used, such as optical arc detection systems to monitor the light emission produced by arcs (P. Dumortier et al. 2011; W. Helou et al. 2020). Finally, since no unique system can detect arcs in all situations or regions, a combination of detection systems is used on current ICRF systems or planned in future ones (Graham et al. 2012; J. Hillairet et al. 2021; D’Inca 2011).

# Modelling

The physics of RF wave propagation and damping mechanisms in magnetic plasma has been well described since the early ages of fusion research (Thomas H. Stix 1992; Marco Brambilla 1998). The complexity of solving realistic geometries required significant simplifications until powerful computers were available. Nowadays, advanced numerical tools can include realistic magnetized plasma, vacuum vessel and antenna geometries, non-Maxwellian species and finite orbit widths effects for particles or a description of the edge plasma. An introduction to the kinetic theory is given in (Dumont 2021) and some of the numerical techniques adopted to model the particle heating and current drive, with their weaknesses and strengths, have been reviewed in (Eester 2012). Recent papers review the progress made on ICRF core and edge physics modelling (Machielsen, Graves, and Cooper 2021; Wei Zhang et al. 2021).

Several codes have been developed to investigate the ICRF waves coupling, propagation and absorption in fusion machines. However, until recently, core plasma codes calculating power deposition, heating rate or species distribution functions were decoupled from edge plasma codes used for RF coupling or sheaths estimations. Current efforts include coupling core-to-edge physics and connecting different numerical methods and solvers (Shiraiwa, Wright, Lee, et al. 2017; Bertelli et al. 2020). However, the amount of numerical power necessary to solve practical cases remains very large and is inappropriate for parameter studies and rapid interpretation of plasma experiments. Hence, other approaches consist in using simplified models, being aware of their limitations. A fully toroidal package is compared to a plane-stratified geometry solver in reference (M. Brambilla and Bilato 2021) that illustrates the advantages and the limitations of the two approaches for the simulations of ICRF heating of tokamak plasmas.

The performance of an ICRH antenna depends on its coupling capabilities to the inhomogeneous plasma profile in front of it. Semi-analytical coupling models of a simplified antenna geometry to inhomogeneous slab plasma, such as those developed in ANTITER or SITAR codes, have proven valuable tools to study the underlying physics and perform multiple and fast parameterisations scans (A. Messiaen et al. 2010, 201; Dash and Chattopadhyay 2021). Recent progress in ANTITER allowed calculating the power deposition in the edge plasma due to the presence of the Lower Hybrid resonance (Maquet, Druart, and Messiaen 2021).

More advanced codes, such as TOPICA (Method of Moment) or ERMES (Finite Element Method), allow to take into account the 3D geometry of the antenna and hence the geometrical peculiarities of each configuration (Lancellotti et al. 2006; Milanesio et al. 2009; Otin et al. 2020). TOPICA was used to study and optimize many ICRF antennas for multiple machines and to compare with voltage and current measurements (Milanesio et al. 2007; Milanesio and Maggiora 2010). For coupling, 3D simulation results generally show excellent agreements with the experimental data, as long as accurate measurements are available for the plasma edge description (density, equilibrium) (Stepanov et al. 2015).

Progress in commercial software capabilities, particularly Finite-Element Method (FEM) solvers, now ease solving for ICRF coupling. Magnetized cold plasma can be approximated using an isotropic dielectric medium under particular assumptions (A. Messiaen and Weynants 2011). In these conditions, any commercial 3D FEM software, such as COMSOL or ANSYS HFSS, can be used to model 3D antenna coupling problems (Qin et al. 2015). In addition, with the help of specific boundary conditions adapted to fast waves (J Jacquot et al. 2013; Colas et al. 2019), RF coupling to inhomogeneous and anisotropic plasma is now commonly performed (Jiahao Li et al. 2021). RAPLICASOL, a COMSOL-based tool, has been used to model antenna coupling for various ICRF antennas (Jonathan Jacquot, Bobkov, et al. 2015; W. Tierens et al. 2019; W. Tierens, López, et al. 2020; Wouter Tierens and Colas 2021). COMSOL has also been used to model RF sheaths physics in SSWICH (Jonathan Jacquot, Milanesio, et al. 2015; Lu et al. 2018; Křivská et al. 2019). COMSOL has also been used to model the interaction of RF waves with plasma filament (W. Tierens, Zhang, and Manz 2020) and convective cells (W. Zhang, Tierens, et al. 2017). The coupling modelling with respect to local gas fuelling has been performed for ASDEX, JET or ITER (W. Zhang et al. 2016; W. Zhang, Jacquet, et al. 2017; W. Zhang et al. 2019). ICRF wave heating simulation based on FEM for EAST tokamak has been carried out with realistic plasma shape, SOL plasma and antenna region with curvature (J. Zhang, Zhang, and Qin 2022). In (Vallejos et al. 2020), an iterative wavelet finite element scheme is used to model the propagation and damping of ICRF in a hot magnetized plasma, taking into account the non-local response of the plasma and finite Larmor radius effects.

Recently, progress in numerical techniques and open-source tools also allowed the realisation of advanced Finite-Element Method (FEM) codes allowing calculation of coupling and heating simulation, connecting edge plasma and core plasma physics in the PETRA-M environment (Shiraiwa, Wright, Lee, et al. 2017) (Shiraiwa, Wright, Bonoli, et al. 2017; Bertelli et al. 2020).

# Selection of Recent ICRF Results

## RF Sheaths and Impurity Production Mitigation in Metallic Environment

As discussed in section 5.1, ICRF is known to enhance plasma-facing components sputtering and release impurities by the excitation of RF sheaths, which have a substantially higher sheath voltage than the one expected for thermal sheaths (Myra 2021). Several methods have been proposed to reduce this impurity production induced by RF sheaths, reviewed in this section.

The antenna phasing between radiating straps has been identified early as a critical parameter to act on impurity production (Bures et al. 1988). The wavefield pattern in the antenna region depends on the phasing between straps and can induce substantial modification of the plasma edge, such as density depletion, correlated with the sputtering of the faraday screen. Experiments conducted in JET and ASDEX-Upgrade show that plasma-wall interaction is enhanced for low k// phasing configurations and, therefore, higher plasma radiation losses (Vl.V. Bobkov et al. 2010; Lerche et al. 2011; 2016). These observations are consistent with enhanced RF sheath rectification effects as numerical codes confirm that generated antenna parallel near electric fields and image currents are larger for low k// phasings (V. Bobkov et al. 2009). In addition to enhanced impurity release, parasitic ICRF wave absorption in the plasma scrape-off layer can enhance heat fluxes on some plasma-facing components (Ekedahl et al. 2007; Jacquet, Colas, et al. 2011).

Increasing the plasma-antenna clearance effectively reduces the ICRF-induced impurity releases and heat fluxes but at the price of decreasing the coupling efficiency (Colas et al. 2009). However, localized chamber fuelling can help increase coupling and reduce the RF sheath-induced plasma-wall interactions (Jacquet et al. 2012; V. Bobkov et al. 2014; Lerche et al. 2015). The enhanced ICRF coupling is due to the spreading and ionization of the injected gas magnetically connected from the gas cloud to the antennas, which increases the SOL density locally. The gas injection also cools the scrape-off layer locally and thus reduces the ions' sputtering yield. The effect of localized gas puffing on antenna coupling has been modelled for ASDEX-Upgrade, JET and ITER (W. Zhang et al. 2016; W. Zhang, Jacquet, et al. 2017; W. Zhang et al. 2019).

In many present experiments, boronization or lithiumization processes, in-situ plasma-enhanced chemical vapour deposition of boron or lithium, are utilized to control impurities (Buzhinskij and Semenets 1997; Wirth and Zinkle 2021). These methods have proven effective in reducing the high-Z element and improving confinement during ICRF-heated plasma (Wukitch et al. 2008; V. Bobkov, Aguiam, Baruzzo, et al. 2017; Marc Goniche 2021). However, these coatings have limited practical lifetimes and vanish after a few plasma shots. This lifetime is particularly proportional to the integrated injected ICRF energy with a degradation faster than in equivalent ohmic heated discharges, suggesting ICRF enhances the boron film erosion rate (Wukitch et al. 2007).

The use of low-Z material for antennas faraday-screen and neighbouring plasma-facing components such as edge limiters has been early suggested (F. W. Perkins 1989). In Alcator C-Mod, replacing molybdenum tiles with boron nitride on the antenna limiter did not improve plasma performance, suggesting that the principal impurity source was located away from the antenna (Wukitch, LaBombard, Lin, Lipschultz, Marmar, Reinke, et al. 2009). Application of a Boron coating on the neighbouring and magnetically connected tiles showed to reduce significantly high-Z impurity release. However, the Boron coating gets eroded, and in addition, regular boronizations were still required to achieve high-performance discharges, suggesting other sources remained (Wukitch, LaBombard, Lin, Lipschultz, Marmar, Ochoukov, et al. 2009). Replacing Tungsten (W) side limiters with boron-coated tiles on ASDEX-Upgrade showed, on the contrary, that more than half of the W content in the plasma originated directly from the antenna limiters (V. Bobkov et al. 2013). Nevertheless, the root cause of the enhanced sputtering was not removed by using B-limiters and the sputtering of low-Z Boron remained but only became more tolerable than that of the high-Z tungsten (V. Bobkov, Aguiam, Bilato, et al. 2017).

As the primary driving mechanism for RF sheaths is the RF electric field component parallel to the equilibrium magnetic field (Myra 2021), two approaches have been pursued to reduce the excitation of this field. As the total magnetic field passing along the antenna is not purely toroidal but has a tilt angle of typically 5 to 10 degrees, straps and antenna elements excite inherently a non-zero parallel electric field. Alignment of the Faraday screen and radiating elements along and perpendicular to the magnetic field, respectively, has thus been identified as a possible improvement (F. W. Perkins 1989). Coupling studies of ICRF waves on cold plasma were performed for a rotated four-strap antenna in C-Mod, using a FEM code that includes the actual SOL density profiles and the 3-D solid geometry of the antenna (Garrett and Wukitch 2012). The results indicate that an ICRF antenna aligned with the total magnetic field reduces the average RF potential along magnetic field lines intersecting the antenna by a factor ranging between 2 to 3. A field-aligned antenna has been tested in Alcator C-Mod (Wukitch et al. 2013). The field-aligned antenna showed improved impurity contamination and lowered the impurity sources at the antenna and load tolerance. The radiated power was 20 to 30% lower than for not field-aligned antennas in both L and H-mode discharges. However, RF-induced plasma potentials were nearly identical for the field-aligned and the more conventional antennas when operated in dipole phasing (Wukitch et al. 2014). Field-aligned antennas are foreseen (K. Saito et al. 2015)

The second approach has been pursued at ASDEX-Upgrade, by minimizing the local parallel electric field induced by the antennas on their protruding limiters. Limiters can indeed generate a parasitic parallel electric field enhancing RF sheaths if local RF currents are circulating on them. Hence, cancelling the image currents at the limiters could mitigate impurity sputtering due to RF sheaths. As a first step, one of the 2-strap antennas was modified with broad-limiters and optimized straps, which showed a 40% reduction in W release (V. Bobkov et al. 2009; 2013). In 2015, a new antenna made of three straps was designed and installed in ASDEX-Upgrade (Fuenfgelder et al. 2017). The design principle is to minimize the image currents by balancing the power and phase between straps (V. Bobkov et al. 2013). The 3-strap antenna with W-coated limiters significantly reduced the W release compared to the W-coated 2-strap antennas in a broad range of plasma conditions (V. Bobkov et al. 2016; V. Bobkov, Aguiam, Bilato, et al. 2017). The use of two 3-strap antennas in combination with the Boron-coated 2-strap antennas allowed ASDEX-Upgrade to extend the ICRF operating space (V. Bobkov et al. 2020).

## Load Resilience and ELMy Plasma Operation

Three different load-tolerant schemes have been installed on JET to cope with fast plasma variations such as ELM (Vrancken et al. 2007). Firstly, 3-dB couplers were installed on two of the four JET antenna arrays (antennas A and B) in 2004-2005 and successfully operated on ELMs (Mayoral et al. 2007). Secondly, an external conjugate-T, tuned by coaxial phase shifters (trombones) and further matched by variable trombones and stub tuners, connects C and D antennas (Monakhov et al. 2005; 2009). The system allows reliable and uninterrupted injection of the RF power into H-mode plasmas in the presence of strong antenna loading perturbations during ELMs (Monakhov et al. 2013). Thirdly, the ITER-Like Antenna (ILA), installed in JET in 2007, uses an internal conjugate-T scheme. The ILA is a 2 (toroidal) x 4 (poloidal) straps antenna designed to address some of the key issues of the ITER ICRF system, such as operation at high power densities (8-10 MW/m2) and voltages (45 kV) and load tolerance operation on ELMy plasma (Durodié et al. 2012; Pierre Dumortier et al. 2017). The straps are fed with a compact conjugate-T featuring in-vessel matching capacitors to achieve the desired load tolerance. A low impedance quarter-wave impedance transformer and a second stage matching trombone and stub circuit allow matching the chosen impedance at the conjugate-T junction to the 30 Ohm transmission lines. In addition, a 3 dB hybrid splitter feeds toroidally adjacent sections. While the in-vessel matching scheme was not kept for the ITER ICRF antenna, other aspects of the ILA design such as the use of short straps, the validation of the coupling codes such as TOPICA and the demonstration of operation at 42 kV were realized with the ILA (Durodié et al. 2017; Pierre Dumortier et al. 2017). Recently, continuous progress on the control and matching systems allowed to feed the different sections of the ILA at slightly different frequencies around a central frequency (f0±Δf, with Δf = 0.5 MHz) to decouple the top and bottom half controls and thus operate more reliably (P. Dumortier et al. 2021).

## Long Pulse Operation

If the heat handling is not essential for short pulse discharges (less than a minute), the long pulse operation of ICRF systems brings additional challenges, mainly the water-cooling of all RF structures. Being a superconducting machine, the ICRF system of LHD has been designed for steady-state operation at the MW level RF power. Up to 68 seconds at 1 MW level were achieved in LHD in 2000 (Ryuhei et al. 2000), more than 30 minutes at 520 kW in 2004 (R. Kumazawa et al. 2006) or 54 min at an average power of 380 kW in 2005 (Mutoh et al. 2007; H. Kasahara et al. 2014). Since 2015, LHD has been equipped with two ICRF antennas, a toroidal array antenna (HAS for Hand-Shake) (Hiroshi Kasahara et al. 2010) and a poloidal array antenna (FAIT for Field-Aligned-Impedance-Transforming), with a target power of 3 MW in steady-state operation (K. Saito et al. 2015). By changing the phase of the antenna current in the upper and lower antennas, the HAS antenna, which is set up along the magnetic field, can excite a fast wave with a phase difference to change the k// and a dipole phasing is usually used because of its higher heating efficiency than the monopole phasing. Both antennas are used for ICRF heating with a fixed frequency of 38.47 MHz. By optimization at the fixed frequency, the loading resistances are increased by increasing the impedance of the antenna using impedance transformers (Kenji Saito et al. 2017). The RF power capabilities of the FAIT antenna have been increased by the adjunction of a power combiner (H. J. Kim et al. 2015; K. Saito et al. 2019).

Three new identical ELM-resilient and CW power ICRF antennas were designed in 2013 for WEST to improve the power capabilities and bring ELM-resilience to the system (Walid Helou et al. 2015). The ELM resilience property is obtained through an internal conjugate-T electrical scheme with series capacitors (Bosia 2003). The antenna design is based on a previously tested prototype in 2004 and 2007 (Vulliez et al. 2008; Argouarch et al. 2009) but upgraded to sustain CW operation with actively cooled components (Zhaoxi Chen et al. 2015; Vulliez et al. 2015). All three ICRF antennas have been operated simultaneously on plasma (J. Hillairet et al. 2021). Using the ICRF system alone, the total RF coupled power on plasma reached 3 MW routinely during a few seconds and peaked at 6 MW. The ICRF system has been operated together with the LHRF system, and up to 9.2 MW of combined RF power have been coupled (Bucalossi et al. 2022).

A long pulse compact ICRF antenna has been developed for the KSTAR tokamak to couple up to 2 MW for 300 s (Kenji Saito, Wi, et al. 2020). The 2x2-strap antenna relies on an internal conjugate-T method to ensure load resilience. The conjugate-T is achieved with segmented impedance transformers at a fixed frequency of 30.8 MHz.

On EAST, the 12MW 25–70 MHz ICRF system has been operated during 30 s on an H-mode plasma in 2012 and during 61s in 2022. (Zhao et al. 2014; H. Yang et al. 2021; Y. Song et al. 2022). In 2021, new 2x2-strap antennas reducing the dominant excited parallel wavenumber allowed to double the coupling resistance, hence increasing the operational domain in EAST (X. J. Zhang et al. 2022).

# Future devices, Future R&D

## ITER

The objective of ITER is to demonstrate the scientific and technological feasibility of fusion power as an energy source. The ITER Ion Cyclotron Resonance Heating and Current Drive system has been designed to couple to the plasma 20 MW of RF power in the 40-55 MHz frequency range in continuous wave operation (3600 s) from two 10 MW antennas (Beaumont et al. 2013; Lamalle et al. 2013; Durodié et al. 2014). The two antennas are installed in outboard midplane port plugs. The antennas are equipped with an actively cooled Faraday screen made of Beryllium tiles, located approximately 10 mm radially behind the shaped Be first wall panels (Brank et al. 2021). Each antenna has 24 straps, grouped in 8 straps triplets by 4-port junctions. These eight triplets are fed via four hybrid splitters connecting adjacent poloidal triplet lines, imposing a 90° poloidal phase difference and obtaining load resilience. The triplet pairs are fed by four power sources with equal forward power. The phase differences between the four generators set the toroidal phase between the four poloidal triplet pairs (Grine et al. 2012). Ten decouplers are used to neutralize the mutual coupling effects and control the current amplitude of the 24 straps, with the number of active decouplers changing between current drive or heating configurations. The precise adjustment of the antenna array phasing is very sensitive to the generator power and phase settings (Vervier et al. 2015). The RF power, generated by nine 3 MW sources (four per antenna and one spare), is carried through pressurised coaxial lines to 8 feeds per antenna (Kazarian et al. 2011). If the coupling of the RF power turns out to be insufficient, the separatrix could be moved closer to the antenna and gas can be injected near the antennas (W. Zhang et al. 2019).

ITER operation is based on a staged approach which includes two Pre-Fusion Power Operation (PFPO) phases consisting of hydrogen and helium plasmas (ITER Organization 2018). Several ICRF heating schemes have been investigated for these phases and are reviewed in the reference (Mireille Schneider et al. 2017). Effective absorption schemes are available in hydrogen and helium at full (5.3 T) or reduced (1.8 T and 2.65 T, except for hydrogen operation) magnetic fields. A three-ion heating scheme could be used at 3 T and 3.3 T with fundamental minority 3He heating in an H-4He mixture (Kazakov et al. 2015). During the D-T operation (Fusion Power Operation phase), second harmonic tritium heating and helium-3 minority heating will be used (Dumont and Zarzoso 2012).

Thermal loads on the ICRF antenna and its ceramic windows due to stray EC radiations are significant (Oosterbeek et al. 2015) and therefore considered in the windows' thermal and mechanical designs. However, current estimates require further studies since they are hindered by the lack of knowledge of microwave absorption on alumina at 170 GHz and stray EC power amounts.

Since no routine maintenances are scheduled on the antenna lifetime, which is required to be at least 20 years, the antenna reliability must be very high (ITER Organization 2018). Because of radioactivity levels, maintenance operations will be carried out using the ITER remote handling maintenance system (Ribeiro et al. 2011). The maintenance of the antenna will be performed in an ITER hot cell, where antenna cleaning, reparation and tests offer several challenges (Ferlay et al. 2013).

## Future Devices and Fusion Reactors

In the first phase of the Divertor Tokamak Test Facility (DTT), an ICRF system is foreseen to couple 3 MW to the first plasma and eventually up to 10 MW after the machine completion (Ceccuzzi et al. 2019). The RF power is used for central plasma heating through different heating schemes, 3He or H minority heating in Deuterium Plasma with B=6 T at respectively 60 and 90 MHz, as well as for wall conditioning (Cardinali et al. 2020). Several antenna designs have been compared, such as an array of 8 straps or a configuration similar to the 3-strap Antennae installed at ASDEX Upgrade, and the final choice will be made in compliance with DTT constraints. Load resilience is provided via coaxial wideband 3 dB hybrid couplers (Ravera et al. 2021). A three-stage amplifier based on a broadband solid-state amplifier, a tetrode driver and a final power amplifier will be used for RF generators.

The SPARC tokamak project aims to achieve breakeven and burning plasma conditions in a compact device with a magnetic field of 12.2 T (Rodriguez-Fernandez et al. 2022). With up to 25 MW at 120 MHz, ICRF is the workhorse heating system of the project. A good wave penetration and a strong single-pass absorption are expected for D–T(3He), D(3He), D(H) and 4He(H) heating scenarios (Lin, Wright, and Wukitch 2020). The project's baseline foresees twelve 4-strap antennas, similar to the field-aligned J antenna on C-Mod, except that the straps are end-fed centre-grounded, with a three-strap design as follows a backup (Lin, Wright, and Wukitch 2020).

The Tokamak with Reactor Technologies (TRT) is a proposed design for a compact stationary tokamak with an 8 T magnetic field. It will operate with deuterium and possibly with DT plasma (Krasilnikov et al. 2021). The conceptual project proposes an ICRF system operating in the 60–80 MHz frequency range. Two three- or four-loop antennas with the loops oriented across the magnetic field have been selected to provide an ICRF power of several MW (Baev et al. 2021).

While initially considered as one of the plasma heating solutions for direct ion heating during plasma ramp-up and eventually during the stationary discharge phases (Franke et al. 2015; Federici et al. 2019), the current design of the European DEMOnstration Fusion Power Plant (DEMO) does not envisage ICRF in its baseline. A ~50 MW ICRF system has been designed during the pre-conceptual phase of the project. While Traveling Wave Arrays antennas (see next section below) have been proposed for DEMO (J.-M. Noterdaeme et al. 2019; Riccardo Ragona et al. 2019), the latest design is a merge of existing ITER, JET and ASDEX Upgrade antennas (Volodymyr V Bobkov et al. 2021). While the ITER ICRF system serves as a guideline in the current design process, several distinctive aspects, like antenna integration or adaptation to neutron environment, are tackled individually for DEMO.

The China Fusion Engineering Test Reactor (CFETR) is a tokamak project for fusion energy research in China, aimed to bridge the gaps between ITER and a demonstration reactor. It aims to demonstrate fusion energy production up to 200 MW initially before reaching a power level of 1 GW and pursuing tritium self-sufficiency (Zhuang et al. 2019). With a magnetic field of 6.5 T and a frequency of 37 MHz, a second harmonic tritium heating scheme and two three-ions scenarios, DT(3He) and DT(7Li), are envisaged (C. Song et al. 2020). The project plans to use an ITER-type ICRF antenna to couple ~30 MW to the plasma. A conceptual design with four poloidal by six toroidal straps array has been proposed for the antenna front face (Wei Zhang et al. 2022).

## Travelling Wave Arrays Antennas

While Ion Cyclotron Resonance Heating has been proven to heat the core plasma of various fusion experiments effectively, the method also has several drawbacks. Transmitting the maximum amount of RF power while protecting the RF sources from reflected power requires matching system(s). A consequence of these matching unit(s) is that the voltages and currents in the antennas can reach very high values and jeopardise operation safety when exceeding the voltage stand-off limits. The maximum power that can be coupled reliably during operation is related to the maximum electric field occurring in the antenna structure. While the simplest way to increase the power handling is to increase the number of radiating straps (hence decreasing the power density), it also requires more matching systems and rapidly becomes impracticable (Pinsker 1998). In addition, as current ICRH antennas radiate wave components with k// > k0, these waves are evanescent from the antenna up to the fast wave cut-off electron density, located a few centimetres away in front of the antenna. As this distance increases, the coupling efficiency of an antenna decreases, which often leads to operational issues. In future machines such as ITER or any future fusion reactor, the distance from the antenna to the plasma will become even larger (J.-M. Noterdaeme et al. 2019; Melnikov et al. 2020; Ragona et al. 2019).

Instead of resonant antennas, “slow-wave” structures, like for example Travelling Wave Arrays (TWA) antennas, would be an excellent candidates for ICRF in tokamaks since they solve both drawbacks. The term "slow wave" refers here to the fact that the electromagnetic waves propagating through the antenna have a relatively low phase velocity, which means that they travel more slowly through the antenna than they would in free space. This can be achieved by designing the antenna with a resonant structure. In TWA antennas, the power is applied to a radiating element at one end of the array and the power is coupled to the next element by the mutual reactance between elements. At the end of the array, the remaining (not radiated) power (if some) can be dissipated into a match load or recirculated into the array to increase the system's overall efficiency (J.-M. Noterdaeme et al. 2019). With a lower power density than resonant antennas, TWA antennas have lower voltages, avoiding exceeding voltage stand-off (Bosia 2015; R Ragona 2017). In addition, as the number of radiating elements is larger than in conventional antennas, the radiated spectrum is narrower, enhancing antenna coupling to the plasma, allowing RF power coupling from increased distances to the plasma than current antennas (Andre Messiaen and Ragona 2017). The main drawback is that TWA antennas require a larger toroidal space to fit a higher number of straps (Bader et al. 2017). However, since the antenna does not require fancy power dividers and matching units, the volume required behind the radiating elements only consists of the feeding transmission lines. In the context of a fusion reactor, this reduced footprint is a significant advantage when dealing with neutron-induced activation and heat losses but also leaves more space for lithium breeding blankets. For these reasons, TWA antenna designs have been proposed for the European DEMO (R. Ragona and Messiaen 2016; Riccardo Ragona et al. 2019; J.-M. Noterdaeme et al. 2019).

Despite not being a new concept (Moeller et al. 1994; Pinsker 1998; Vdovin 2009) and having already been tested at moderate powers (Ikezi and Phelps 1997; Ogawa et al. 2001), TWA antennas have so far never been tested for ICRF at relevant powers. Recently, a conceptual TWA antenna for ICRF has been designed for WEST (R. Ragona et al. 2019), and a high-power mock-up has been successfully tested under vacuum in the TITAN testbed at CEA. Successful shots at 500 kW/60 s and 2 MW/3 s confirmed the property of the mock-up and opened the way for an auspicious way to couple ICRF in tokamak (R. Ragona et al. 2022).

Recently, TWA antennas are also used in a higher frequency range for fast wave current-drive, also known as “helicon” current-drive (Pinsker 2015). Recent helicon current drive systems projects around 476 MHz have been developed for steady-state tokamak plasma scenario research in KSTAR (Wang et al. 2017; Wi et al. 2018; J. Kim et al. 2021) and DIII-D (Tooker et al. 2015; Torreblanca et al. 2019; Compernolle et al. 2021) and show very encouraging results. Other projects are under consideration for EAST (X. Li et al. 2020) or CFETR (Y. Yang et al. 2021; X. Li, Li, and Liu 2021).

# Summary and Pending Issues

Recent experiments, particularly in ASDEX Upgrade and Alcator C-Mod, demonstrated that optimized antenna designs could reduce the far SOL DC biasing and the impurity production produced by ICRF sheath effects. The RF current image cancellation and tailoring of the density distribution using local gas injection increase the coupling and thus the ICRF power capability. These results show that ICRF heating is compatible with some high-Z reactor wall configurations when RF field distribution and neighbouring PFCs are optimized (V. Bobkov et al. 2019). These experimental results have been possible thanks to progress in theoretical aspects. Nowadays, theoretical frameworks and simulation tools allow an understanding of these experimental results. They can be used to guide new antenna designs to minimize plasma-edge interactions (Colas et al. 2021; Myra 2021).

However, despite this substantial progress in understanding RF coupling and impurity productions, some challenges remain ahead. The effects of the RF fields far away from the antennas, which depend on the machine geometry and plasma scenarios, are still poorly diagnosed. Their prediction, which could be tackled from self-consistent models using fully realistic geometries, remains a challenge because of the problem's size and complexity.

While the ITER ICRF antenna design has not been optimized to minimise RF parallel electric field near the PFCs, antennas can be operated in a phasing mode that should reduce plasma-wall interactions by minimizing the RF image currents at the antenna port boundaries. The effects of the Beryllium faraday-screen remain, however, undocumented. In addition, the ITER ICRF complexity and the high number of actuators may further complicate the system's operation.

The increase of nuclear constraints associated with the operation of future fusion reactors requires a severe increase in reliability, inspectability and maintainability of the ICRF system, particularly the antennas. Compatibility with remote handling of antenna weighting a few tens of tons remains a challenge.

Travelling wave antennas integrated into the wall seem an up-and-coming solution for future machines. However, a complete demonstration under relevant conditions at the ICRF remains to be performed.

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1. Field emission is an electron tunnelling effect induced by an electric field. Secondary emission is a phenomenon where primary incident particles of sufficient energy, when hitting a surface or passing through some material, induce the emission of secondary particles, mostly electrons called secondary electrons. [↑](#footnote-ref-1)