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Heating and current drive of fusion plasma by electron cyclotron wave: the technological challenges.

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Heating and current drive of fusion plasma by electron cyclotron wave: the technological challenges.

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Introduction

In a recent paper [1], the principle of electron cyclotron masers (also known as gyrotron) was described. The main motivation behind the development of high power (>1 MW-CW) and high frequency (>100 GHz) sources is their use in heating and current drive of fusion plasmas confined by magnetic fields, the so-called magnetic confinement approach to fusion. In this approach, the fusion plasma (density: a few 10^{20}m^{-3}, temperature: 10 - 20 keV, or about 100 - 200 millions degrees) is confined by a strong toroidally shaped magnetic field (B_T = 5 - 6 T for fusion reactor, 1 - 4 T for present day experimental fusion device). One of the most frequently asked question is how does one obtain such high temperatures? This paper will outline the heating by electron cyclotron wave (ECW) (and also another process called current drive, which is also necessary for the magnetic confinement approach), the results from present day experiments and the future prospects for this heating method.

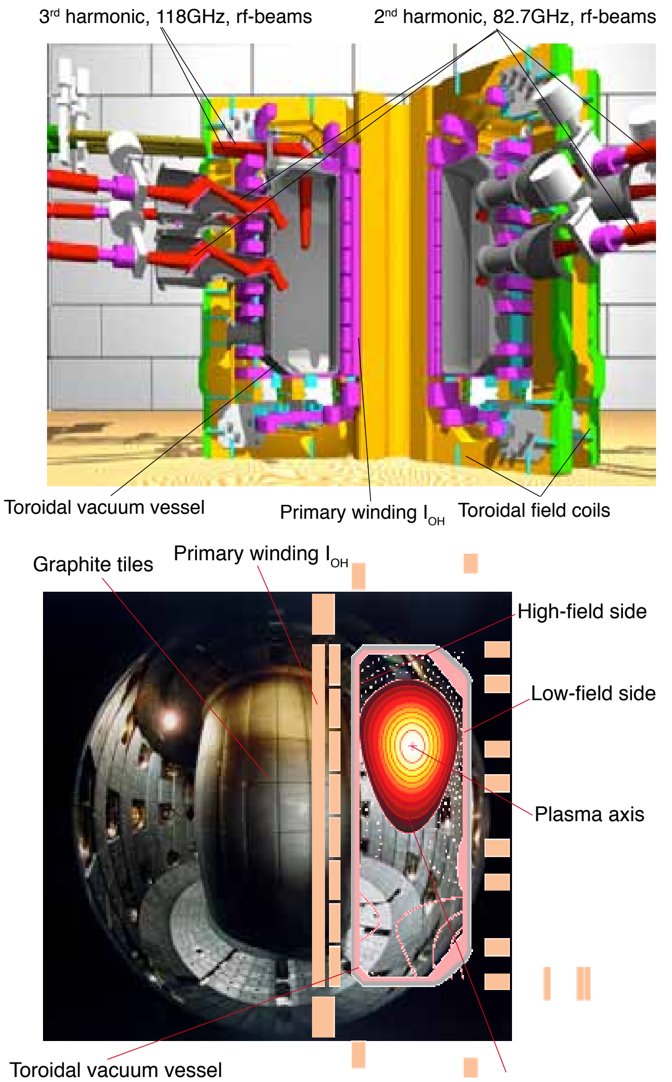

Figure 1. Schematic of TCV Tokamak with the ECRH system (top). View of the internal parts of the TCV vacuum vessel with an example of a plasma (bottom).

The need for heating the plasma in a fusion reactor

Magnetic confinement is based on two different concepts, the tokamak and the stellarator. In a tokamak, the confining magnetic fields are created by a set of external coils, which create a strong toroidal field B_T (up to 6 T), and a poloidal field created by the plasma current, I_P, circulating in a doughnut shape plasma (Figure 1). I_P is generated by induction, the plasma being the secondary winding of a system of coils necessary for the tokamak operation. In a stellarator, the confinement magnetic field is created by external coils, and there is no need to have a plasma current. Since a plasma has a resistivity caused by Coulomb collisions between the charged particles, the presence of I_P leads to an Ohmic power, which is used to heat the plasma in the case of a tokamak. However, the Ohmic power is not sufficient to bring the plasma to the range of 10-20 keV [2] since the plasma resistivity decreases with temperature as $T^{-3/2}$. In the case of a stellarator, there is no plasma current and an external method of plasma heating is required from the plasma creation.

One of the external heating method is the absorption of the energy transported by electromagnetic (EM) waves at specific plasma resonances (i.e. at frequencies where the wave refractive index $\boldsymbol{N} = \boldsymbol{k}c/\omega$ tends to infinity, allowing efficient absorption by the plasma particles. Here $\boldsymbol{k}$ is the wave vector, c the speed of light and ω the wave angular frequency. The plasma particles are ions and electrons which satisfy a quasi-neutrality condition. In this paper, since we consider very high frequency waves, we implicitily restrict on the wave-particle interaction with the magnetized electrons, therefore with the so called electron cyclotron waves, ECW. The analysis of the wave absorption on the electron population is often performed in the frame of a kinetic theory, where the electrons have a distribution function f($\boldsymbol{v}$). The resonance frequencies are given by:

$$\omega = \frac{s\Omega_e}{\gamma} \pm k_\parallel v_\parallel \qquad (1)$$

Ω_e is the electron cyclotron frequency expressed in radian/s, γ the relativistic factor of the electrons, s the harmonic number (s integer). $k_\parallel$ is the component of the wave vector parallel to the tokamak equilibrium magnetic field $\boldsymbol{B}$ and $v_\parallel$ the corresponding parallel component of the velocity $\boldsymbol{v}$. Equation (1) could be interpreted as the resonance condition at the fundamental and harmonics of the relativistic cyclotron frequency Ω_e/γ with a Doppler shift term $k_{||}v_{||}$. The absorption coefficient is obtained from kinetic theory for different polarization of the EM wave (the ordinary wave where the wave electric field component, ***E***, is parallel to ***B***, or extraordinary mode where ***E*** is perpendicular to ***B*** [3]), for a given ***k*** vector.

It is to be noted that the real situation in a magnetically confined fusion plasma is more complex. The magnetic field *B* is inhomogeneous (i.e. not constant), and decreases when increasing the radius *R* with respect to the tokamak axis. The plasma itself has, throughout its radius, inhomogeneities associated to density, *n*, and temperature gradients. Even in cold plasma, both *B* and *n* variations lead to the question of accessibility of the ECW, i.e. whether the wave, from its launch point, can reach the resonance layer, i.e. the layer in the plasma where Ω_e satisfies the condition (1). Since Ω_e varies proportionally with the ***B*** field, one distinguishes the high-field side and low-field side, where the "side" is referred to the magnetic field and high- and low-correspond, respectively, to internal and external part of the plasma cross-section (see Fig.1 bottom). A discussion of the accessibility conditions depending whether the launch point of the EM wave is on the low field side of the machine (i.e. on its external side) on on the high field side (i.e. on the side of the tokamak axis) can be found also in [3].

To see how the wave can heat the electrons, let us consider the simple case of quasi-perpendicular launch (***k*** perpendicular to ***B***). For the extraordinary mode of the EM wave (***E*** perpendicular to ***B***) the component of the electron velocity perpendicular to ***B***, is affected: the mean kinetic energy of electrons in the direction perpendicular to ***B*** is therefore increased. However, through Coulomb collisions, the electron distribution function will become thermalized (i.e. having a Maxwellian distribution). Should the energy confinement in the reactor be large enough compared to the energy thermalization time between ion and electron, the two species will also thermalize between them: a method, which at first heats electrons, will also contribute to heat the ions.

When launched obliquely with respect to ***B***, the absorption of EM wave at the resonant layer defined by (1) can generate localized currents in the plasma. The current thus generated is typically of the order of 0.01 - 0.1 kA/kW of absorbed EM wave power. It can be used to sustain the plasma current I_P (the so called "non inductive current drive ", as opposed to the "natural" inductive way of generating I_P as outlined above) or to control various magneto-hydrodynamic (MHD) instabilities [4], which can have detrimental effect on the plasma confinement.

From an engineering point of view a simple relation between the electron cyclotron frequency f_{ce}[Hz] and the local magnetic field is f_{ce}[GHz] = 28 B[T]. Thus for a field of 5 T, the electron cyclotron frequency is 140 GHz. For a large fusion device, the required power is in the range of 20 - 100 MW at a frequency in the range of 140 - 240 GHz. For ITER, the international tokamak in construction in Cadarache (F), it is foreseen to have a total injected power of 20 MW at 170 GHz during the whole 3600 s pulse duration of the plasma [5]. The roles of the ECW system are:

- to create the plasma by creating an electrical breakdown of the filling gas;
- to contribute to the heating of the plasma to very high temperatures at which a high rate of fusion reaction is produced;
- to control the MHD instabilities, eventually capable of completely destroying the plasma confinement;
- to control the ramp down phase, during which the plasma current is brought from its nominal value, I_P, to 0.

The technical challenges

Starting from the "wall electrical plug" (i.e. from the electrical power source to energize the whole ECW system) to the point where the EM power is launched into the plasma, the full ECW system encompasses the following elements:

- the gyrotron system (the gyrotron itself, and its ancillary system including the different power supplies used to power it and the superconducting magnet required to operate the gyrotron);
- the microwave transmission line for efficiently transport the EM-wave from the gyrotron to the plasma;
- the launcher used to focus and direct the EM power onto the desired location in the plasma

In the remaining, we shall review the different components mentioning the technical challenges.

The gyrotron and its ancillary system

A high power tube converts the kinetic energy of an electron beam into microwave power in a suitable resonant cylindrical cavity. The essential elements of a high-power gyrotron are described in Fig.2. One of the main difficulties is related to Ohmic loss caused by the EM wave in the cavity-walls due to the EM-field penetration over a skin-depth. The Ohmic power density dissipated in the cavity wall increases as the rf-frequency to the 5/2, excluding the use of cavity in the low-order $TE_{m,n}$ modes. In a gyrotron, as described in [1] the interaction between the electron beam and the EM wave is through the electron cyclotron maser instability at a frequency fixed by the relativistic electron cyclotron frequency f_{cy} in the region of the cavity: the gyrotron frequency f_{rf} is then approximately given by f_{cy} . This allows to select a cavity mode operating at high order $TE_{m,n}$ modes in order to keep the Ohmic power density at the cavity wall at manageable values (≤ 2 - 2.5 kW/cm^2) while reaching a rf electric field value compatible with the required output power. The selected $TE_{m,n}$ mode is such that its resonant frequency f_{cav} is equal to f_{rf}. The criteria of mode selection is also linked with the examination that no neighbouring $TE_{m',n'}$ modes can be excited via non-linear mode coupling. This study is usually performed using advanced numerical codes and allows to follow the time evolution of the rf-field in presence of many cavity modes. As an example for the ITER gyrotron (170 GHz, 1 MW-CW) the cavity is a cylindrical cavity operating in the $TE_{m,n}$, with m= azimuthal mode number = 32, and n = radial mode number = 9. The electron beam has a current of 40 A at 80 kV and is guided by a magnetic field with an amplitude of B_c = 6.8 T in the gyrotron cavity. The ratio of the electron velocity perpendicular to the magnetic field B_C in the cavity and the velocity parallel to B_C is α = 1.3.

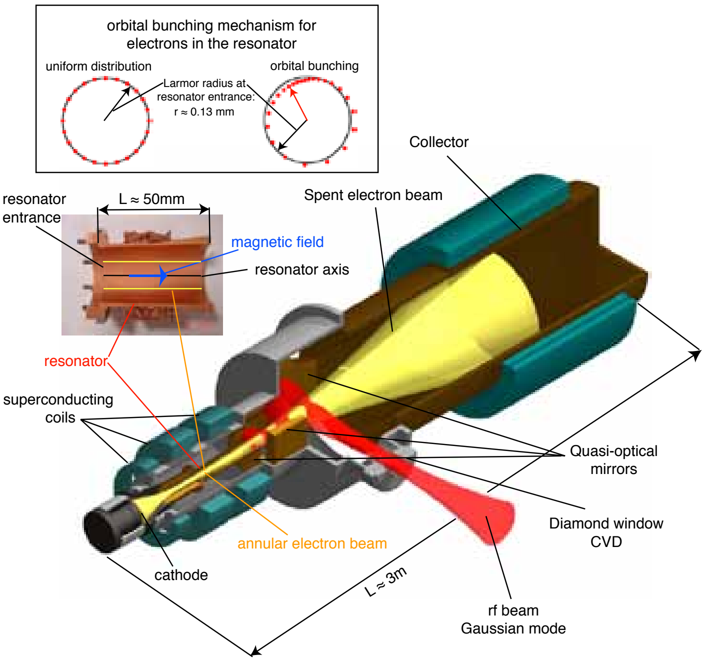

Figure 2: Schematic of a high-power high-frequency gyrotron for fusion applications. An annular cross-section electron beam is guided by a strong magnetic field produced by superconducting magnets and injected into a radiofrequency resonant cavity. As the beam passes in the interaction region, defined by a cylindrical cavity supporting a TE mode it experiences a negative mass instability, whereby electrons within it, initially uniformly distributed on a Larmor radius, undergo orbital bunching (see upper inset), causing them to decelerate rapidly and emit coherent radiofrequency radiation. The lower inset is a photograph of a cross-section of the resonant cavity of a typical 1MW-class gyrotron; the annular electron beam in the resonator has an average radius and thickness of 10 mm and 0.5 mm, respectively.

In modern gyrotrons, the $TE_{m,n}$ mode generated in the cavity is coupled out via a synthetic diamond window in the form of a Gaussian beam via a complex quasi-optical mode converter. The Gaussian beam can be then coupled efficiently into a low-loss HE_{11} mode supported by an overmoded corrugated waveguide (i.e. a waveguide with a wall which has corrugation of approximately $\lambda/4$ depth and step size and an average radius much larger than the rf-field wavelength). The HE_{11} mode has the property of having nearly no tangential rf-magnetic field at its internal waveguide boundary and therefore has practically no current circulating in the waveguide wall, hence insures a minimal Ohmic loss. These low-loss waveguides are commonly called HE_{11} waveguides.

Two other ancillary equipment necessary for the operation of the gyrotron are the superconducting magnet which creates the field B_C and the high voltage (HV) power supply. For the ITER gyrotron which operates at 170 GHz, B_C is about $7[T] = 170[GHz]\,\gamma/28$, with γ being the relativistic factor of the electrons in the gyrotron, $\gamma = 1 + V_b[kV]/511$. For the ITER gyrotrons and accelerating voltage of $V_b = 80$ kV corresponding to a relativistic factor $\gamma = 1.156$. The second important equipment is the HV power supply, which accelerates the electron beam to the desired potential V_b. To insure a stable operation of the gyrotron, the electron beam energy eV_b (e is the electron charge), the voltage V_b delivered by the power supply (V_b =80 kW, I_b = 40A), is regulated with a fluctuation level $\Delta V_b/V_b$ better than 0.5%.

The transmission line and the antenna

The roles of the transmission line are manifold:

- as mentioned earlier it allows low-loss propagation of the rf-waves from the zones where the gyrotrons are located to the launching antenna installed on the Tokamak. The propagation distance may be up to hundred meters, hence the use of low-loss HE_{11} waveguides or quasi-optical transmission lines, where the EM wave is propagated in air via mirrors used to focus and/or direct the diffraction-limited EM beams;
- for an efficient absorption of the EM power in the plasma, the polarization of the EM wave launched in the plasma must be controlled. It could be linearly or elliptically polarized, depending on the required interaction mechanism (heating, or current drive). Real-time polarization control is performed by rotating gratings machined directly on the metallic mirrors.

Finally near to the plasma, an antenna (or launcher) directs the power of many EM beams with the desired $k_{\parallel}$ (1) to the location in the plasma, where the power will be absorbed leading to local heating or local non-inductive current drive. The design of the antenna is rendered complex by the con-

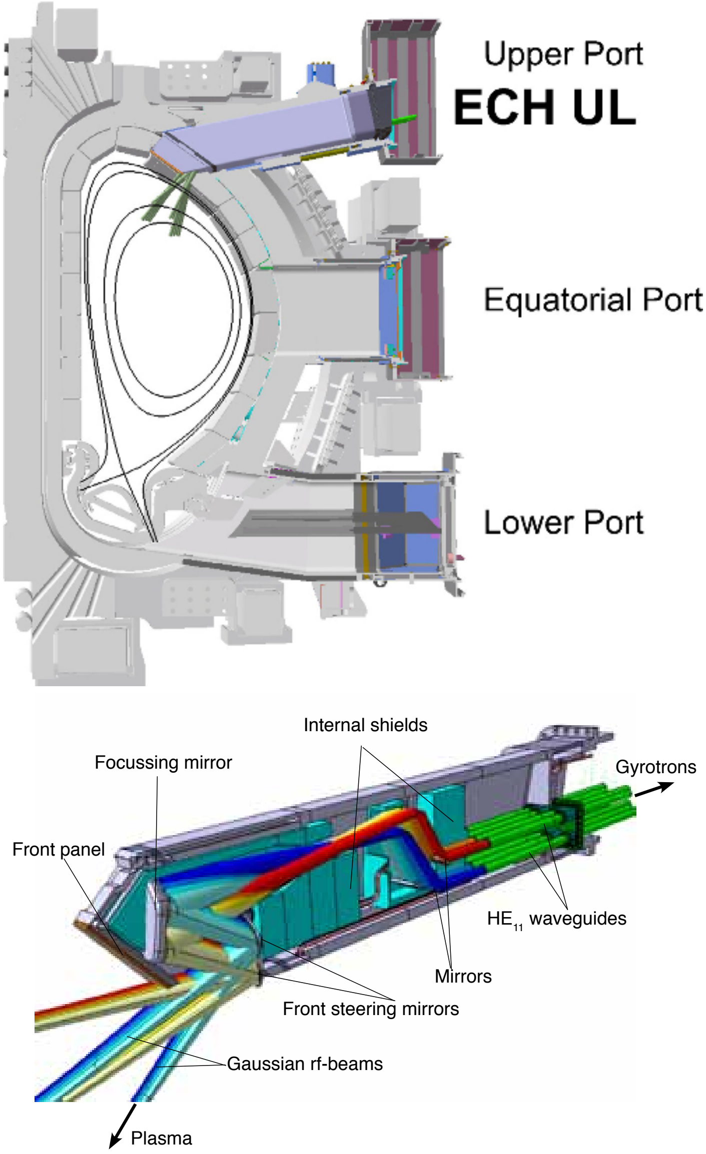

Figure 3. ITER Upper Launcher UL location in the ITER device (top) and its design (bottom).

straints imposed by the plasma environment (magnetic field, high vacuum, necessity to steer the EM beam in real time). In a fusion reactor as ITER, where the fusion reactions take place using a plasma with Deuterium and Tritium ions, additional complexities are to be taken into account, such as the presence of high flux of neutrons, the necessity that the antenna boundaries are also Tritium barriers. In a reactor the antenna will become activated by the neutrons and therefore its design must be fully compatible with remote handling. The type of materials used must also be compatible with the nuclear safety rules. As an example figure 3 shows the design of an antenna for ITER [6]. It will be used to control MHD modes in ITER at different locations in the plasma.

The TCV ECW system and some results

In the last decade, the availability of high power gyrotrons has allowed to verify many of the theoretical predictions. As an illustration, we can cite a few results obtained at the Centre de Recherches en Physique des Plasmas of the EPFL. Our ECW system consists of 9 gyrotrons of 0.5 MW each. Since the toroidal magnetic B of the CRPP tokamak TCV is relatively low (B = 1.5 T on the plasma axis), the use of RF wave at the fundamental of the electron cyclotron frequency would not allow accessibility at the operating density. The system consists of 3 MW at the second harmonic (82.4 GHz) and 1.5 MW at the third harmonic (118 GHz) of the fundamental electron cyclotron frequency of the plasma electrons. The system includes the possibility of controlling fully the polarization of the wave as well as the localization of the power deposition depending on the requirements of the experiment (heating or current drive). Among the salient features in the various fields, besides heating the electron to temperature in the range of 150 millions degrees, one should mention two extremely interesting achievements, which could be considered as "firsts". Using the full capabilities of our ECW at second harmonic, we have sustained the full plasma current I_P solely by the EM wave absorption by the plasma [7]. This non-inductive current sustainment was achieved during 4 s (Fig. 4), limited by the energy available for TCV operation [8]. These four seconds are much longer than any relevant time scale of the plasma, in particular the time constant corresponding to the characteristic plasma resistive time scale L/R (L = Plasma inductance, R = Plasma resistance). In a tokamak, the plasma current I_P could also be sustained by the pressure gradient profile, so called bootstrap current. In TCV, by exploiting the flexibility of the ECW system in depositing the power at different position in the plasma, the plasma was maintained by only the bootstrap current [9], opening up another possibility to sustain non inductively the plasma current of a tokamak.

Many experiments performed on major tokamaks and stellarators have confirmed the effectiveness of ECW in providing heating and current drive in fusion plasmas. ITER will have an ECW system which will deliver to the plasma 20 MW in pulses of 3600 s and provides heating, current drive and control of MHD instabilities, which, without control, could strongly affect its performances and fusion power output [10]. For the next generation of fusion reactor, DEMO, about 50 MW of EC power is considered to contribute to heating the plasma to burn (i.e. to have a net and efficient energy production via fusion reactions) and plasma control. One of the most challenging R&D for the gyrotron is related to the development of very high frequency (240 GHz), high power (>1 MW - CW) gyrotrons with high efficiency (in the range of 50 - 60%). In Switzerland, the CRPP collaborates with other European laboratories and industry to develop this key component for a large variety of ECW systems.

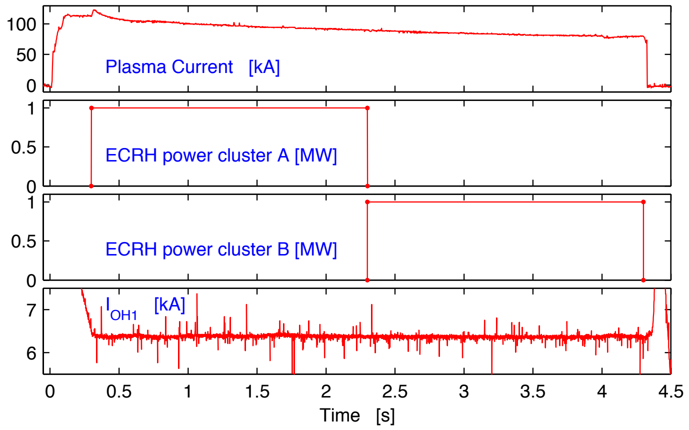

Figure 4. Fully non inductive current driven discharge over 4s. The bottom trace represents the current I_{OH} in the Ohmic coil: it corresponds to the current in the primary winding (see Fig.1) of a transformer where the plasma current (top trace) is the current in the secondary. By having I_{OH} constant in time, one effectively suppresses the inductive current part in the plasma current. The two middle traces show the time trace of the injected EC power.

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