Focus On : JET Plasma Heating and Current Drive

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The goal of fusion research is a "burning plasma" - fully ionised gas self-sustained in an extreme state by power released from fusion reactions of its atomic nuclei. The burning plasma would then provide a new powerful, clean and safe source of energy. To achieve this, we need to overcome two major challenges. First, to ignite the plasma, temperatures in the order of hundreds of millions of degrees centigrade must be reached i.e. the plasma must be heated sufficiently. The second, more difficult challenge, is to sustain the plasma at these temperatures by confining and controlling it in order to maintain its density and ensure that it does not suffer excessive heat losses.

Nuclear Fusion is the driving force of all stars including our Sun

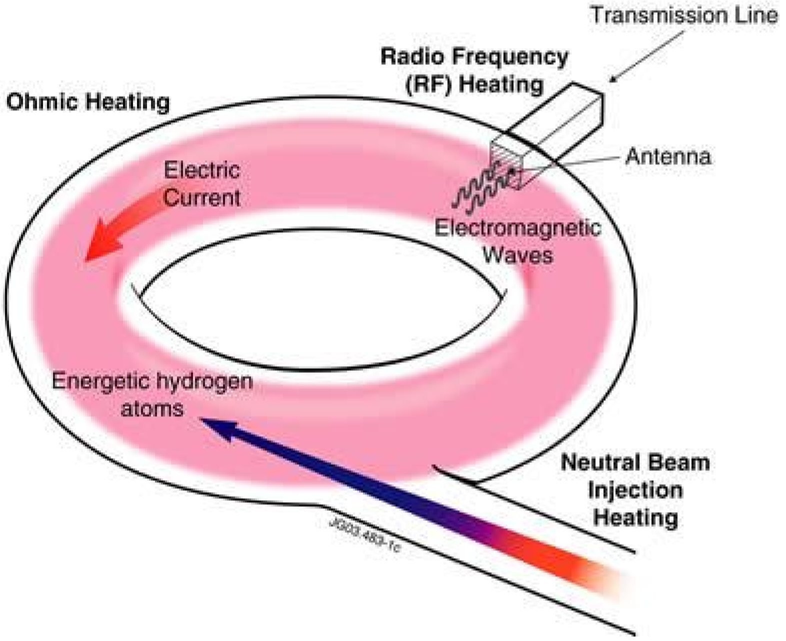
Tokamaks (a family of fusion research devices, to which both JET and the future burning plasma experiment ITER belong) utilise an ingenious scheme that addresses both challenges at the same time: a huge electric current is induced in the plasma to heat it and to complement the confining magnetic field. The electric current produces heat thanks to the 'Joule Effect', a phenomenon familiar to us in everyday items such as electric ovens, irons or light bulbs. In these household appliances the electric current usually does not exceed a few Amperes. Electric currents can also produce strong magnetic fields, an effect which is used in, for example, magnetic cranes, and in fact in all electric motors. Hundreds or even thousands Amperes of electric current can flow in industrial electromagnets. However, in a large tokamak like JET, we may induce millions of Amperes into a plasma in order to heat and confine it.

Ohmic Heating

Electricity can produce heat and magnetic forces

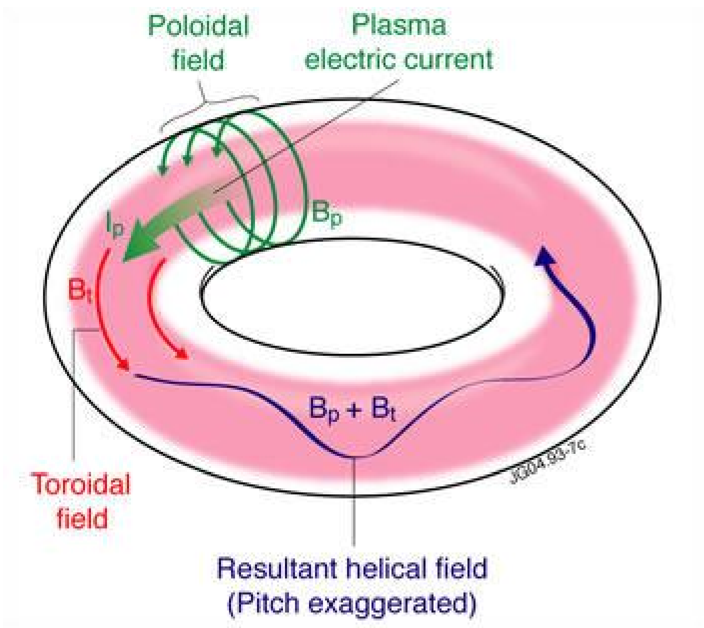
The tokamak concept is a breakthrough in plasma research, but not a complete solution. At millions of degrees and above, plasma is conducting electricity far too well, with very little resistance - which also means with not enough heat produced by the Joule Effect. The unit of electric resistance is the Ohm, so plasma physicists usually say 'Ohmic heating is ineffective at high temperatures' where the word 'high' refers to the hundreds of millions of degrees required for burning plasmas. In order to attain the target temperatures some sort of **'additional heating'** is required to supplement the **'Ohmic heating'** (as a matter of fact, eventually the 'additional heating' plays a dominant role). Neutral particle beams (**'NB Heating'**) and resonant electromagnetic waves (**'RF Heating'**) can do this job.

Furthermore, tokamaks cannot maintain a continuous electrical current in the plasma and this limits the concept of complementing the magnetic field. Tokamaks have a transformer-like electrical setup, with plasma that acts as a single secondary loop - and no transformer can provide continuous direct electric current in its secondary circuit. An additional **'current drive'** is to be provided if we wish to confine burning plasma continuously. Electromagnetic wave current drive offers a possible solution.



Heating of JET plasmas

Nowadays, the role of the additional heating and current drive facilities has been considerably broadened compared to their original task. Neutral beams and resonant electromagnetic waves are at present the key tools in optimising the plasma performance.



Magnetic fields in tokamak - toroidal is generated by external coils, poloidal by electric current in plasma

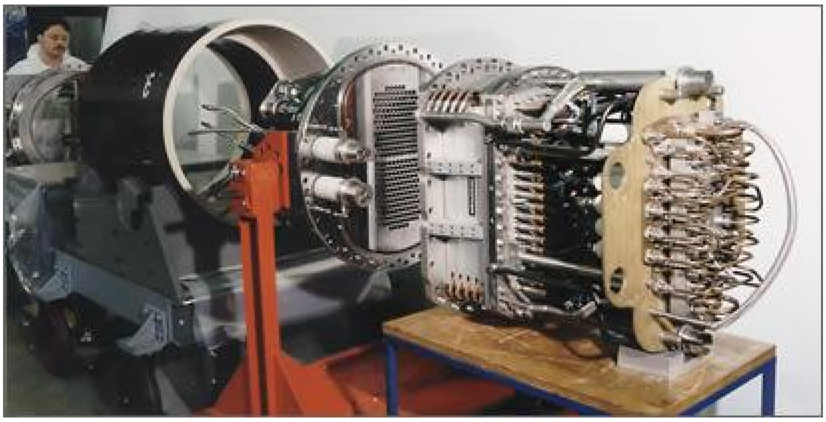
The most important spatial characteristics of a tokamak plasma are its "profiles" which show how physical quantities changes along plasma radius, from the plasma centre to the plasma edge. For example, we measure and study plasma temperature profile, plasma density profile, magnetic field profile etc. These days, neutral beams as well as electromagnetic waves are used to control and modify the plasma profiles by proper targeting of the additional energy deposition. This technique is sometimes referred to as "plasma tailoring" and proves extremely efficient in achieving better plasma performance. The technique can also create completely new regime conditions, for example by generating a so called "Internal Transport Barrier" which provides improved plasma confinement.

The heating and current drive facilities have an even greater mission when applied as Actuators (acting powers) in the JET Real Time Control. Powerful Actuators can be used to automatically counteract plasma instabilities or to safeguard an intended change in plasma parameters, as was illustrated in detail in the last Focus On: Real Time Control of JET Plasmas. In this respect, additional heating and current drive will almost certainly be used in future reactors with burning plasmas.

Neutral Beam Injection (NBI)

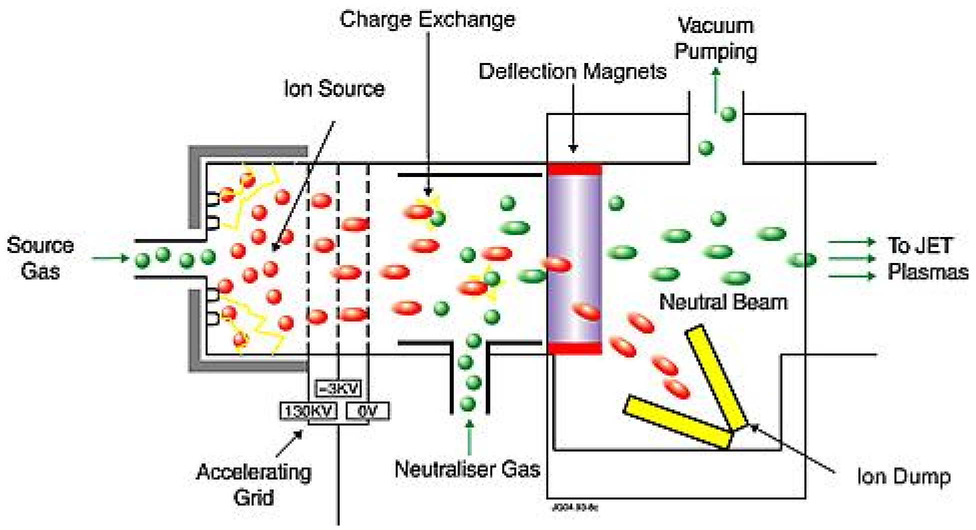
Plasma discharge in JET

A widespread technique of the additional plasma heating is based on the injection of powerful beams of neutral atoms into ohmically pre-heated plasma. The beam atoms carry a large uni-directional kinetic (motional) energy. In the plasma, beam atoms loose electrons due to collisions, i.e. they get ionised (electrically charged) and as a consequence are captured by the magnetic field of tokamak. These new ions are much faster then average plasma particles. In a series of subsequent ion-ion, ion-electron and electron-electron collisions, the group velocity of beam atoms is transferred into an increased mean velocity of the chaotic motion of all plasma particles. The action is similar to the opening break in the game of pool, when a fast motion of one billiard ball can cause the seemingly chaotic motion of all billiard balls. However, the world of plasma particles is inconceivably small, and many billions of particles are in play. We 'the giants' sense an increase in their chaotic motion as an increase in temperature. In other words, a neutral beam heats the plasma - and that is what we desire!



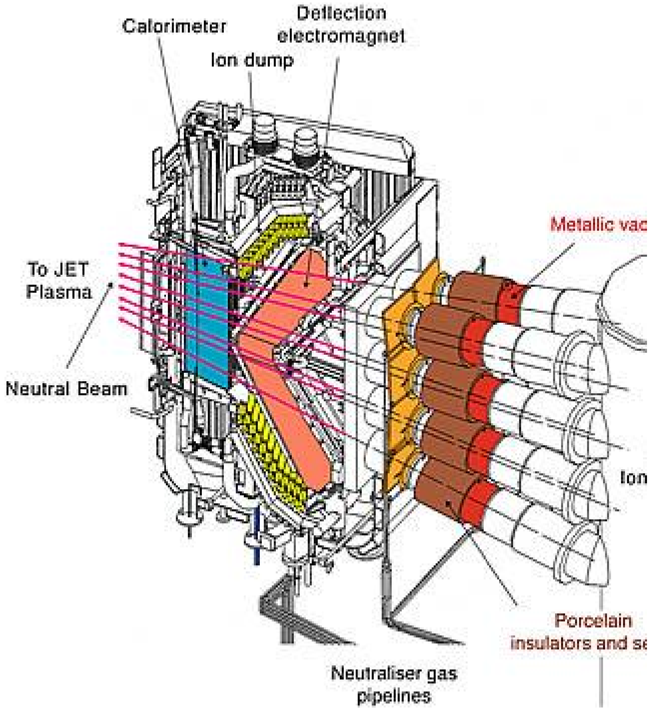
Assembly of one of the sixteen ion sources for the JET NBI system

In fusion experiments, the neutral beams are usually formed by atoms of hydrogen isotopes (hydrogen, deuterium or even tritium at JET). Notice that we always speak about a 'Neutral beam' and its 'atoms'. Indeed, the beam needs to consist of neutral atoms (as opposed to electrically charged ions) otherwise it could not penetrate the strong magnetic field that confines fully ionised plasmas. The energy of the beam (corresponding to the velocity of its atoms) must be sufficient to reach the plasma centre - if the beam atoms were too slow, they would get ionised immediately at the plasma edge. At the same time, the beam is supposed to have power enough to deliver significant amounts of fast atoms into plasma, otherwise the heating effect would not be noticeable. At JET, the beam energy is 80 or 140 keV, corresponding in the case of deuterium beam to 2800 or 3600 km/s which is approximately five times faster than the mean velocity of the ions in a JET deuterium plasma. The total power of beam heating at JET is as much as 23 MW (million Watts). With this power, the number of beam atoms per second corresponds approximately to 10% of the total number of JET plasma ions.



Scheme of the NBI principle: ions in red, neutral atoms in green

It is not at all straightforward to generate powerful neutral beams of very fast atoms. The only way to form the neutral beam is to produce large amounts of ions first, then to accelerate the ions in a strong high-voltage electric field and finally to neutralise the accelerated beam. The accelerated ions get neutralised in charge-exchange interactions with a gas cloud, however, some leave the cloud still in a charged state. These residual fast ions must be deflected by a dedicated electromagnet to a cooled ion dump that can withstand heavy ion bombardment. Last but not least, powerful vacuum pumping must assure that practically no slow atoms from the neutralising gas cloud can diffuse as far as to the plasma chamber, so that the fast neutral atoms have free access to burst into the plasma. This technology works well but is still being refined in order to increase the reliability, purity and efficiency of the neutral beam.



One of two identical NBI systems at JET

Installation of NBI at JET

Plasma and electromagnetic waves

Plasma is an intriguing state of matter. Being formed by charged particles (ions and electrons) it is affected by long-range electric and magnetic forces. As a consequence, plasma - and specifically magnetically confined plasma - can host an extremely rich mix of oscillations and plasma waves, covering sound, electrostatic, magnetic and electromagnetic waves. Depending on local plasma parameters, plasma waves can propagate, get dumped (absorbed), be reflected or even converted to different plasma waves.

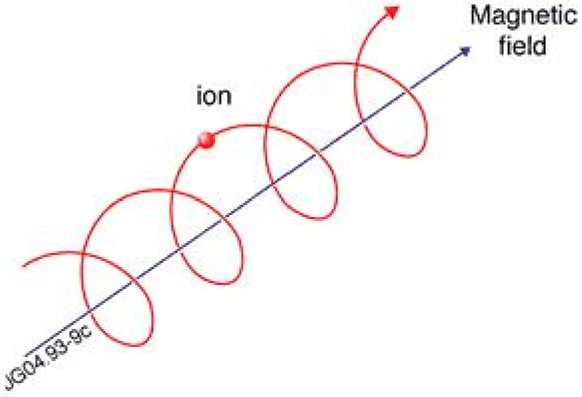
In general, plasma waves carry energy, so that wave absorption involves energy transfer. Their energy is then in most cases converted to an increased mean velocity of the chaotic motion of particles, i.e. to higher temperature of the absorbing medium. Wave absorption is extremely efficient if the wave frequency is resonant with some of the fundamental oscillations of the medium. However, significant heating can occur even at non-resonant frequencies - witness the widespread everyday use in microwave ovens where magnetron devices produce electromagnetic waves which heat by cyclically turning over the water molecules in food, rather than resonating with them.

Leaves as well as solar panels can convert energy of electromagnetic waves coming from the Sun (ie sunlight) into other forms of energy

Ion Cyclotron Resonant Heating (ICRH, also known as RF Heating)

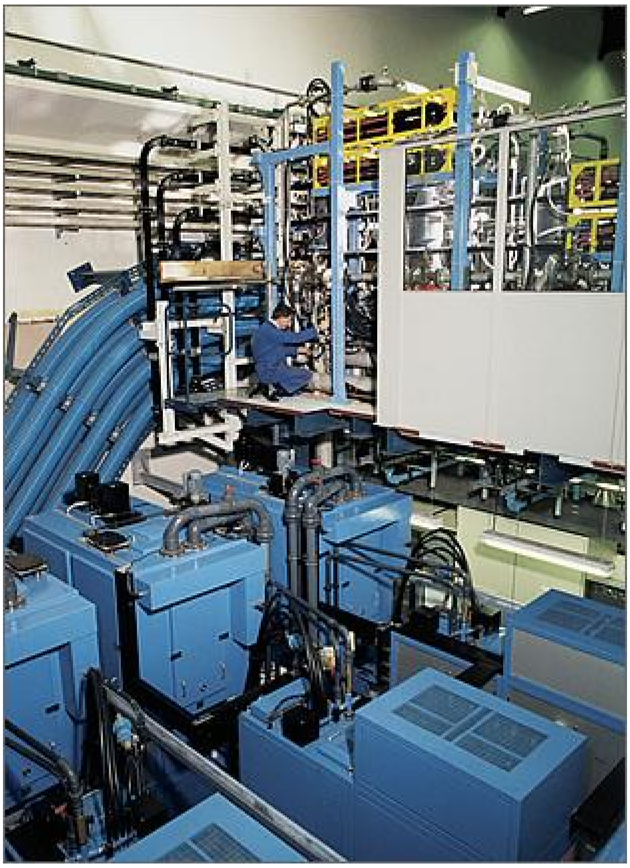
In magnetically confined plasmas, particles (ions and electrons) rotate around magnetic field lines with frequencies that depend only on three quantities: charge and mass of the particle, and magnetic field strength. Other parameters like temperature or density play no role at this 'cyclotron' frequency. Therefore, if an electromagnetic wave with cyclotron resonant frequency is launched into the plasma, all the targeted particles (defined by mass and charge) are heated, provided that the magnetic field complements the resonant condition. In tokamaks, the magnetic field decreases with distance from the tokamak major axis. This allocates the resonant region to a narrow vertical layer, thus giving us a simple control over deposition of the cyclotron resonant wave.

To accommodate complicated wave propagation rules, multiples of the base cyclotron frequency, called 'higher harmonics' are mostly applied in practice. The effect of higher harmonic resonance relies on space variations in the wave intensity, so that such a resonance is stronger for particles with larger orbits. That is, higher harmonic heating is more significant for fast particles than for slow particles, which introduces temperature dependancies as well as distortion in thermal distribution due to the heating.



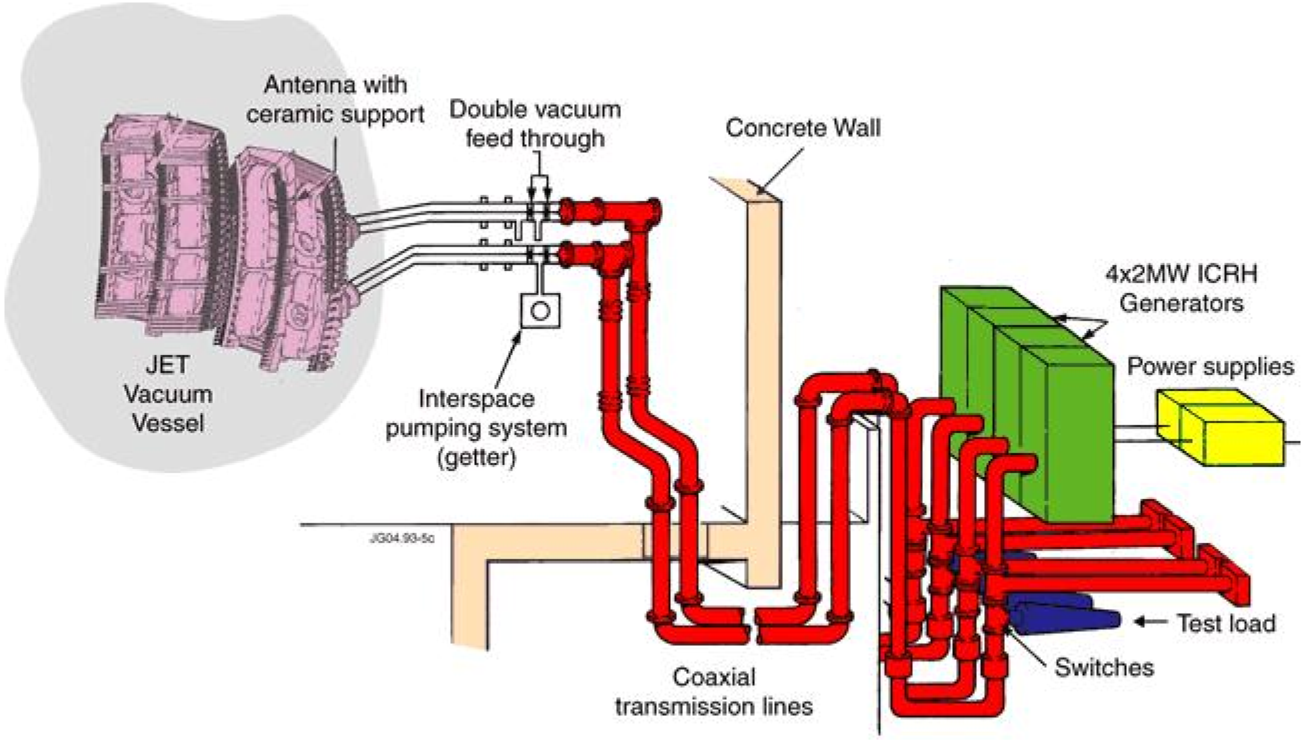
Cyclotron motion of a plasma ion around a magnetic field line

Ion cyclotron resonant heating (ICRH) is routinely applied on JET. It is resonant with the second harmonic (i.e. double) frequency of ion gyration of main JET plasma ions (deuterium) or with a base frequency of gyration of a minority species (e.g. tritium, helium...). The available resonant frequencies at JET are in the range of 23-57 MHz (megahertz, or million of oscillations per seconds) which correspond to length of the vacuum electromagnetic wave from 13m (at 23 MHz) down to 5m (at 57 MHz). This is a "shortwave" frequency, which is not very popular in the air due to many fades, blackouts and interferences (the FM radio frequencies are just a bit higher, around 100 MHz). In total, the installed power of JET ICRH system is as much as 32 MW (megawatts = million watts), and in practice only part of this potential is sufficient for the JET experiments. This is a huge power compared to radio or TV broadcast, where a 50 kW (kilowatts = thousand watts) transmitter is already considered as a powerful one.



ICRH wave generators at JET

Amplifier chains generate the ICRH electromagnetic waves, each chain with a powerful (2MW output) tetrode tube in final stage. Transmission lines that conduct ICRH waves from the generators to the JET tokamak are low loss coaxial cables. Coaxial cables consist of a conducting outer metal tube enclosed and insulated from a central conducting core. Such cables are generally used in any high-frequency transmission - e.g. signal from the TV aerial or satellite dish is transferred to the TV set by a coaxial cable. However, at JET due to high powers involved the ICRH output coaxial cables look rather like 'pipelines' with 20cm diameter of the outer metal tube. Several hundreds meters of these transmission lines are installed at JET. The transmission lines terminate in 4 ICRH antennas that are installed within the JET inner wall and that are slotted in the front. Each antenna consists of four conductors (straps), and each strap is fed by a separate generator. The ICRH electromagnetic waves cannot propagate in the JET vessel vacuum (their wavelength being too long) so that the antenna must be as close to the plasma as possible.



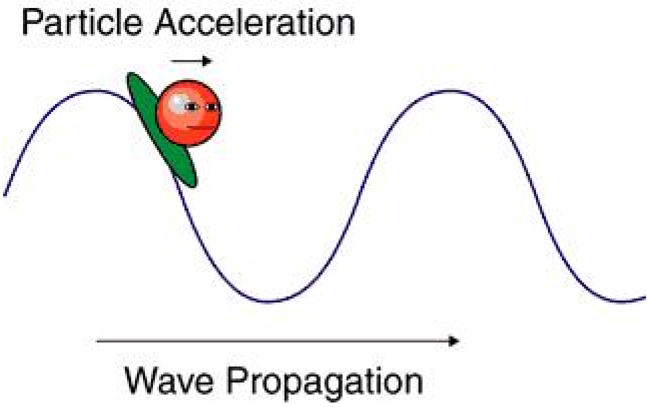
Schematic of the ICRH system at JET

For information, there is a similar technique called electron cyclotron resonant heating (ECRH) but we do not use it at JET. The principle is based on the fact that electrons, being several thousand times lighter than ions, have much higher cyclotron frequencies. In tokamak plasmas the required ECRH frequencies are in the order of 100 GHz (gigahertz = billions of cycles per second, corresponding to vacuum wavelength in the order of a few millimeters only) which is more challenging for the wave generation and transmission. These frequencies are also used in some modern radar applications. However, the power of such devices is negligible compared to ECRH requirements. ECRH targets plasma electrons only, and the heat transfer from electron to ions is relatively slow. The advantages of ECRH are that its waves can propagate in vacuum and that they can be steered with high precision. ECRH is installed on some other large tokamaks such as JT-60U in Japan, DIII-D in USA and ASDEX-U in Germany.

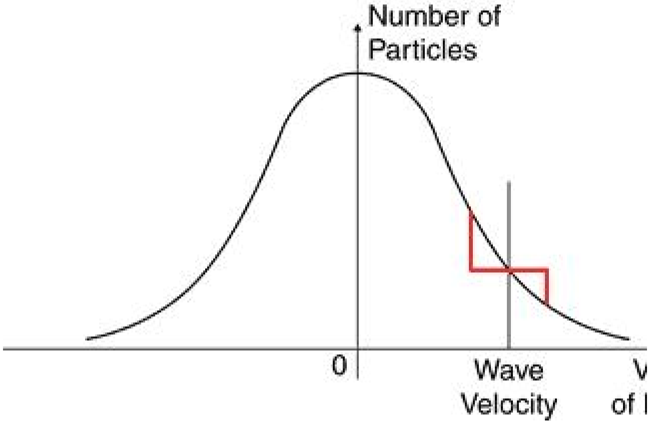
Lower Hybrid Current Drive (LHCD)

There are many other resonant frequencies in tokamak plasmas but experiments have found some to be inefficient or impractical while others simply cannot penetrate through the plasma edge region. Two of the candidate frequencies are "hybrid", so called because they result from force interplay between electrons and ions, so that their frequencies lie between ion cyclotron and electron cyclotron ones. Although the lower hybrid frequency can get into the plasma, unfortunately it has an inefficient heating effect. Nevertheless another significant application of lower hybrid frequency has evolved: the corresponding lower hybrid wave can drive electric current thanks to the fact that it has an electric component parallel to magnetic field lines.

LHCD and ICRH antennas in JET vaccum vessel (LHCD grill in frame in left, next to it four slotted launchers of ICRH)

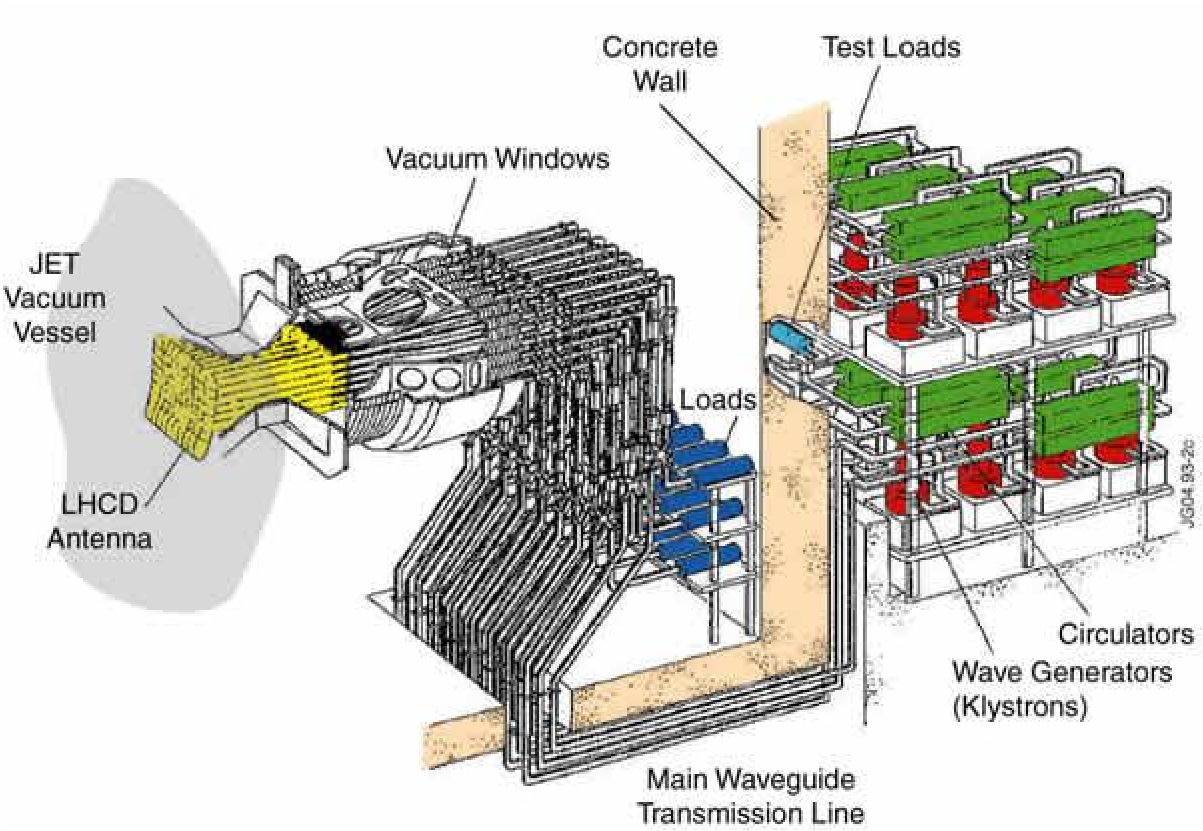


A charged particle can increase its velocity by "surfing" on an electromagnetic wave

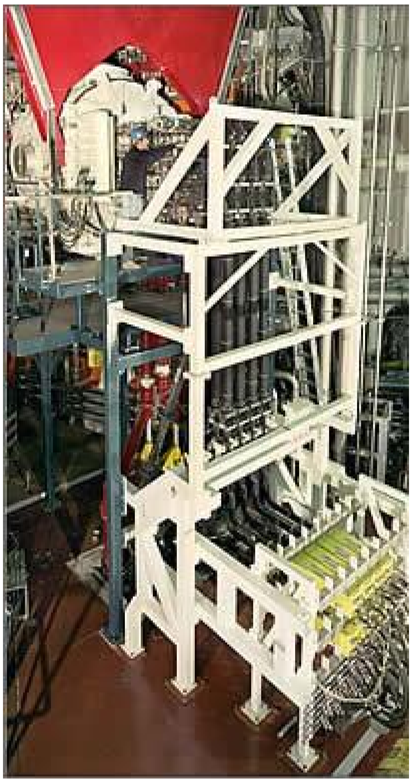


As a consequence of the particles "surfing" on the wave, the thermal distribution of the particles changes as the red line shows. The assymetry in velocity distribution causes a net electric current to appear

One would perhaps expect that the very rapidly alternating electric field of electromagnetic waves could not generate a constant electric current, but this common sense proves to be false. Plasma electrons with thermal velocities slightly slower than the wave propagation velocity can actually "surf" on the uprising electric potential and thus increase their velocity in the direction of the wave. It is also true that any electrons which are slightly faster than the wave will be slowed down. However, the thermal distribution of velocities causes there to be fewer faster particles. Consequently, there are more electrons which are accelerated rather than decelerated so that in total a net electric current appears. Though the effect looks minute on the electron velocity distribution, in terms of electric drag it is significant.



Schematic of the JET LHCD system



Completion of the LHCD antenna known as "multijunction grill"

Connection of the LHCD waveguides to the JET vacuum vessel

At JET, Lower Hybrid Current Drive system work at frequency 3.7 GHz (gigahertz = billions of cycles per second) which correspond to wavelength of 0.1 m in vacuum. The frequency belongs to called L-band used e.g. by satellite broadcast. The LHCD installed capacity at JET is 12 MW (million watts) of additional power. Thanks to this system, electric current of several MA (million Amperes) can be driven. The electromagnetic wave is generated in klystrons - tubes that can produce the above frequencies by resonant modulation of an electron beam. At JET, 24 klystrons are installed in 6 independent modules. The electromagnetic wave is then transmitted to the LHCD antenna by a complex system of waveguides. Waveguides are hollow rectangular metallic conductors with cross-section size that corresponds to the transmitted wavelength. The LHCD antenna is of a very sophisticated design, called "multijunction grill" in order to allow for a correct phasing of the wave before it is launched into the plasma.The correct phasing of LHCD waves is hampered by propagation in vacuum, therefore it is required that LHCD antenna is mounted directly in the JET inner wall, as close to the plasma as possible.

For the first burning experiment, ITER, a complete portfolio of all efficient methods of plasma heating and current drive is likely to be adopted, with the expected total output power over 100 MW. JET is the closest tokamak in plasma size and shape to ITER, so it is natural that JET's heating and current drive facilities are widely involved in experiments relevant to ITER. The proposed ITER "plasma scenarios" are optimised on JET by accurate profile tailoring as explained in the introduction. In 2004 a new "ITER-like" ICRH antenna is to be installed as a major JET enhancement in order to validate the new concept of robust, stable ion cyclotron wave emission suitable for the harsh conditions of the future burning plasmas of ITER.

"JET's powerful additional heating systems allow us to heat plasma, drive plasma current, and provide us with the key tools to optimise the plasma performance"

Jean-Marie Noterdaeme, Task Force Leader for the Heating Task Force

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