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Ion cyclotron frequency range (ICRF) power on the way to DEMO

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The use made of "auxiliary" systems, such as the ICRF power system, the environment in which those systems will operate and the requirement they must fulfill, will change drastically between present systems, systems for ITER and those for DEMO. Some characteristics, now presently barely relevant, will become increasingly important. The paper draws attention to the changes, gives an overview of the ICRF system for ITER and highlights where extrapolations with respect to present systems are required. It moves on to DEMO and shows where the strength of ICRF is and proposes an approach to mitigate its weak points.

Keywords: ICRF, ITER, DEMO, heating, control, T breeding, maintenance, availability, economics

1. Introduction

Since in DEMO type machines only a limited number of plasma heating and control systems will be acceptable, the selection of the systems to be installed will be severe. The selection criteria, guided by characteristics relevant for DEMO, will be quite different from the present ones.

Some characteristics of the heating and control systems, of no considerable importance in present machines, will become increasingly significant as machines move from present experiments to DEMO type machines. This is due to the major changes that will occur in 1. the use that will be made of the systems 2. the environment in which the systems will operate and 3. the requirements they must fulfill.

An ICRF system scores well on the relevant characteristics and is therefore a strong candidate as one of the heating and control systems in DEMO type machines. There are however areas that need to be addressed in present and future machines.

The paper gives an overview of the ICRF system for ITER and highlights where extrapolations with respect to present systems are required. These need to be taken up with high priority in existing machines and on test stands. Critical aspects are the voltage standoff in the antenna and absolutely reliable arc detection methods. Impurity production in a high-Z metallic wall environment may become an issue in a later stage of ITER, but proposals for mitigation can and should be investigated in ASDEX Upgrade and Alcator C-mod.

The paper proceeds to elucidate the role of ICRF on DEMO. Experiments on present-day machines and on ITER could strengthen the case for ICRF on DEMO.

It is fit to highlight, at a Toki conference, the interesting synergy between ICRF and steady state helical concepts. The steady aspects of the helical concept has allowed ICRF in LHD to demonstrate the long pulse capability of ICRF systems and thus to reinforce suitability of ICRF for the long pulse/steady state machines of the DEMO type. In the other direction, ICRF systems can contribute significantly to qualify the helical concept for ITER/DEMO type machines: experiments on fast ions confinement with ICRF in present helical machines have shown that the helical concepts can confine energetic particles [1].

2. Use made of the system

Present "auxiliary systems" are mainly used for heating, whereas other functions such as control of the current profile, density profile or rotation only come into play to increase the experimental flexibility or for demonstration purposes.

For ITER, heating to ignition will be an important function, but only for a fraction of the time. The remaining time, the heating system will be either idle or, if possible, used for burn, current and density profile control. An important application could be wall conditioning.

For DEMO, the use of the system for heating to ignition will and should be a negligible fraction of the time. If the confinement concept chosen for DEMO requires a plasma current, then driving current and/or controlling the current profile will likely be the dominant use of a least one auxiliary system. Other applications will include burn and density profile control.

The need to limit the number of "auxiliary" systems on DEMO, will favor systems that can perform more than

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one function. ICRF systems have been used for heating, both electrons [2] and ions [3]. Its use for burn control was investigated on JET with positive results [4]. Control of sawtooth, using current profile modification has been extensively demonstrated [5][6][7]. Central current drive was shown in D-III-D [8], while ICRF power can also be used for wall conditioning [9], even in conditions where glow discharge cleaning is no longer possible due to the presence of a permanent magnetic field. In general it was shown that ICRF could be utilized for many other purposes than heating alone [10].

On this basis, ICRF is clearly a good candidate for a machine where the number of "auxiliary" systems is limited and therefore systems are favored that can perform more than one function.

2. Environment in which the system needs to operate

Most of the present experiments operate with short pulses. In current experiments also, the presence of neutrons does not have an major influence neither on the design of the components near the plasma, nor must the shielding/ neutron streaming effect due those components on the regions further removed from the machine be considered. Remote maintenance is sometimes needed, such as in JET, but is mostly the exception.

In ITER, even when operated in pulsed mode, the timescales for the auxiliary systems will be such that they need to be designed for steady state. The presence of neutrons influences the choice of materials and the location of certain components, but it is mainly the biological aspects of the radiation that dictate the use of remote maintenance. Shielding or neutron streaming due to the presence or absence of certain components in the ports is an important design parameter. When neutron streaming cannot be avoided (such as in the case of NBI), measures have to be taken to shield the neutrons at a more remote location. Overall dimensions are larger, leading also to larger plasma-antenna distances, a negative aspect if wave-coupling structures are used.

In DEMO, the presence of neutrons will dominate the choice of materials as neutron damage will influence how often components need to be replaced, and how much waste is produced. Neutron streaming through large opening in the blanket will be difficult to accept. The systems exposed to large neutron fluxes must be simple and sturdy, and should not impose constraints on the materials used. Remote maintenance will be essential, but should be limited for the auxiliary systems to times when other major components (such as blankets) need to be replaced. In addition, in a pure fusion DEMO, tritium breeding will be indispensable, favoring systems with small openings in blanket and shields.

It is conceivable that, because of the importance of T breeding, the number of ports will be severely restricted in machines of the DEMO type. Whereas in ITER the ICRF antenna is part of a port plug, it would be preferable for ICRF antennas in DEMO to be integrated in the blanket and the opening through the blanket limited to the transmission line only. The resulting impact on T breeding is then minor. Neutron streaming, already small along those small penetrations, can be further reduced by proper measures. The power density calculated based on the area of the transmission line is high, while the power density at the surface of the antenna can be low. Insulators, required in the vacuum feedthrough of the line, can put in an area of sufficient low neutron flux, and, as already foreseen in ITER the system should be designed such that they can be replaced separately. The replacement of components exposed to neutrons near the machine should be compatible with scheduled remote maintenance and not require more frequent intervention than needed for the blanket components.

3. Requirements

In present experiments, the choice and number of systems is determined more by the desired experimental flexibility and by what each of the systems can do best, more than by capital cost considerations. The cost of operation is a non-issue. The availability of the system is important but non-essential, and none of the systems operate all the time at their maximum power. Reliability is desired, but, if need be, a shot can usually be repeated.

For ITER, the capital cost of the "auxiliary system" becomes an important issue, with 10% of the total cost devoted to the "auxiliary" systems. Operating cost, in terms of cost of electricity to provide the power during the pulse is not a significant matter. As such, the plug to power efficiency of the auxiliary system does not play a major role in its selection. The system should not prevent ITER to operate, or lead to long down time, therefore a high availability is valuable. As each discharge will count, reliability will be paramount.

For DEMO, meant in part to provide the basis for the demonstration of the economic viability of a fusion power plant, the capital cost of a system may be a key criterion for its inclusion or rejection. Here the cost per MW plays a role as well as the amount of power that needs to be installed. The power that needs to be installed depends on how efficiently the system acts on the plasma. For example, if current drive is needed, the current drive efficiency will play a defining role in the power to be installed, and thus in the capital cost of the auxiliary system.

Since DEMO should be running a substantial fraction of the time, cost linked directly with the operation of the auxiliary systems will play a crucial role. Small recirculating power will be essential, emphasizing the need for systems with high plug-to-power efficiency, as well as a high efficiency in its action on the plasma.

Availability is, together with the capital cost, a term in the cost of electricity, and therefore of paramount importance for the economic viability of fusion. It means that the systems must have a large mean time between failure (MTBF), and a low mean time to repair (MTTR). These requirements lead to a preference for systems where components that need maintenance and or replacement are easily accessible (far from the machine), and sufficiently low cost that some redundancy can be provided. Modern nuclear power plants achieve a ratio of supplied TW_e h during one year to the product of *installed* power times number of hours in one year, of more than 0.9, which is equivalent to saying that, except for one month per year, the plant operates continuously at *full* power. This is a benchmark that fusion will certainly not achieve in DEMO, nor in the first fusion power plants. Those values were also not achieved from the early days of nuclear fission, nor are they reached by all nuclear power plant, but it gives an indication of the goal.

Since losing a system during operation may lead to disastrous consequence (if burn control fails, an emergency turn-off of the reactor may be needed), a very high reliability will be required. Sturdy systems, with no moving parts, operating well away from limits, will therefore be favored.

ICRF has among the auxiliary systems, the lowest cost in terms of cost/installed power and the largest plug to power efficiency (power supply, transmission, generator, coupling: typically 0.5). Thus, except if ICRF were to be used for current drive, both the capital and operating cost of an ICRF system would be one of the lowest among the existing auxiliary systems. The efficiency of driven current/installed power is for ICRF presently low, so that either ICRF should better not be used for this, or substantial progress in this area is necessary. Most of the ICRF components, except for the antennas, are located far from the machine. The unit size and cost of the RF generators are such that some redundancy can be provided. If a unit breaks down the redundant units can be used, while the remote location of the generators allows the repair of the broken one, during continued operation of the others. The ILA JET antenna and the ITER antenna operate at high power density close to operating limits, making it a critical component of the ICRF system. For DEMO, making the antennas part of the blanket could mitigate this. With antennas located in such a way the power density could be low, and those components would be operating much further from existing limits.

4. Extrapolations needed for ITER

The ICRF system for ITER [11] foresees to deliver 20 MW through one or two antennas with a size of approximately 1.75m (toroidal) x 2.2m (poloidal), designed for operation between 40 and 55 MHz. The design and manufacturing of the antenna [12] are the responsibility of the European partner. The present design, developed by the CYCLE consortium (Cyclotron Cluster for Europe – a consortium of the associations: UKAEA, CEA, ERM-KMS, IPP and Politechnico de Torino) has 8 triplets of straps arranged in an array of 4 in the toroidal direction and 2 in the poloidal direction (see Fig. 1). The matching systems and coaxial transmission lines are the responsibility of the US partner. Standard type short-circuited stubs, line stretchers and capacitors will do the matching of the impedance of the antenna to the impedance required by the generators. The generators will be shielded from fast transients by 3 dB couplers [13]. A generator power of 20 MW (eight generators rated a 2.5 MW for VSWR=2) will be installed. The generators are the responsibility of the Indian ITER partner.

The ILA antenna on JET [14] incorporates many of the features that will be present in the ITER antenna: the close array of short strap, with non-negligible cross coupling and resulting challenging matching procedure, the high power density and high voltages. On ILA, voltages of 45 kV have been achieved, higher than the 40 kV design voltage on ITER. Even in this tightly coupled array, automatic matching has been achieved. Though the design values of the coupled power (8 MW/m^2 for 7.2 MW coupled) have not yet been achieved, there is confidence that the experience gathered on the ILA will allow to qualify the new tools (TOPICA) to calculate the expected coupling of the ITER antenna. Those tools did not yet exist when the ILA was designed.

The transmission line system does not present a substantial extension of the state of the art. Challenging will be to find the right balance between cost and operating limits for steady state operation at high power. Which part of and how to cool actively the transmission lines and matching components will be choices that need to be carefully made. LHD has developed liquid stub tuners that are basically suited for steady state, but have not yet achieved the needed values of voltage strength.

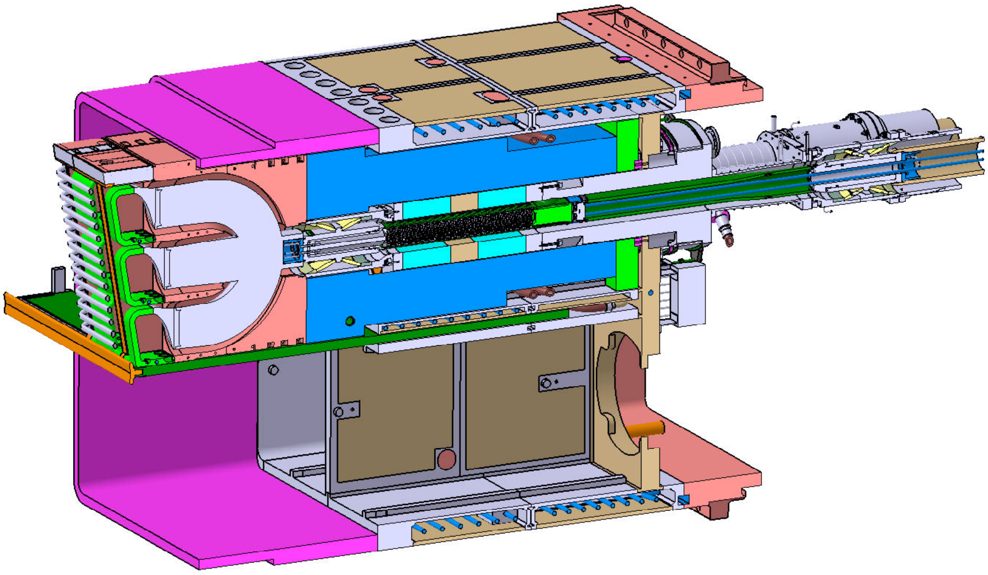

Fig.1 Present design of the ITER antenna. Eight triplets of straps (one triplet shown) are arranged in an array of 4 in the toroidal and two in the poloidal direction. Each of the triplets is fed by a transmission line that incorporates two double conical feedthroughs. They are replaceable without having to remove the whole antenna [14].

No RF generator exists yet that has achieved the required values. Closest is the Korean development with 1.9 MW for 300s achieved at a single frequency, and for a specific load [15]. It is as yet not clear whether the required parameters can be achieved with existing tetrodes or whether new types of tubes will need to be developed.

From this brief overview, we can conclude that the extrapolations in the technical area needed for ICRF on ITER will be moderate and that we are already well on our way to achieve the required design parameters.

One area where substantial work is required is the question of impurity production with ICRF when high Z metallic walls are used in the immediate neighborhood of the antenna.

In ASDEX Upgrade where such conditions are present, the use of ICRF is possible but presently restricted to operation at large plasma-wall distances and with additional gas puffing [16]. The impurity production is understood to be the result of acceleration of ions (mostly impurity ions) in the rectified sheath near the wall. The sheaths themselves are due to rectification of parallel electric fields induced along field lines, mostly by currents induced at the boundaries of antenna structures. Results from newly developed electromagnetic codes, supported by experiments, indicate that it is possible to reduce those RF electric fields [17][18], and thus of the impurity production. Experiments on ASDEX Upgrade and Alcator C-mod [19], in particular with new, optimized antennas should be able to clarify the compatibility of ICRF and high-Z metallic walls.

A second area where progress is needed is the arc detection systems. In most present machines arcing in antennas sets the operational limits. The voltage limits achieved vary between 30 kV and 45 kV (in the ILA antenna), and are still not completely understood. Several types of arcs can occur [20], and several methods will need to be developed to detect them with required reliability. Whereas most present system can cope with limited failures of the arc detection systems, the steady state cooling needs of the components in systems like Tore Supra and JET, and in all future machines, leads to catastrophic consequences (water leaks and sometimes major flooding) if an arc is not detected in time.

Except for those two areas (impurity production and arc detection) the extrapolation from present system to ITER is of a quantitative nature, and most of the parameters such as unit power, pulse length, voltages, power densities have already been achieved or are well on their way of being achieved.

5. Extrapolations needed for DEMO

The changes for the auxiliary systems in their use, the environment in which they operate and the requirements placed upon them will be substantial compared to the present systems and to ITER and qualitative aspects will play a major role.

Those changes were indicated in the corresponding sections, and it was shown there that ICRF is well positioned to be one of the auxiliary systems for DEMO.

A number of areas, where ICRF needs further progress are addressed here briefly and a proposal is made which could contribute simultaneously to progress in those areas. These areas are the impurity production, the voltage limits and the small current drive efficiency.

The parallel electric fields, induced on field lines in front of the antenna which lead to rectified sheath, and thus to impurity production, are themselves dominated by the currents at the antenna boundaries. Antennas where the toroidal variation of the current is smoother as in [21], lead to less induced currents at the boundaries, less induced parallel electric fields and thus less impurities.

The high voltage in the antennas and related danger for arc and damage of antenna structures is directly related to the high power density. Antennas with lower power densities would lead to lower voltages and reduce the likelihood of arcs.

On the basis of simple arguments, it can be shown that current drive efficiency increases with the velocity squared of the electrons the wave couples to, if the wave accelerates electrons with high parallel velocity (this is the region of the lower hybrid wave) and with one over the velocity of the electrons, if low parallel velocity electrons are accelerated – assuming trapped particles effects do not reduce this efficiency (this is the region of ohmic current drive). ICRF couples to the electrons whose parallel velocity is close to the phase velocity of the wave and near the minimum of both branches.

One could consider in DEMO the use of a continuous array of low power density antennas, distributed over the whole outer circumference of the machine. The antennas would be an integral part of the blanket. The only penetrations though the outer chamber walls and blanket would be the transmission lines. By proper phasing between the antennas of the continuous array a well-defined toroidal wave number, with a well defined toroidal standing wave pattern would be generated. The resulting low $k_{//}$ would increase the coupling, while the smooth toroidal variation of the current would avoid induced currents at discontinuities and therefore large $E_{//}$ fields. By an appropriate slow phasing variation, a slow rotation of this wave pattern can be achieved. Since the rotation of this standing pattern can be arbitrarily slow, and if electrons can be accelerated using this slow rotation, one could possibly be on the branch of the current drive efficiency curve where the efficiency increases with 1/velocity. This is reminiscent of the rotamak type current drive [22].

Should this concept work, 3 critical areas of the use of ICRF would be, if not solved, at least substantially improved (impurity production, high voltage, low current drive efficiency) improving the prospect of ICRF for DEMO and machines beyond it.

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