Fifty Years of Progress in ICRF, From First Experiments on the Model C Stellarator to the Design of an ICRF System for DEMO

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Abstract. We present a comprehensive overview of the use of ICRF (ion cyclotron range of frequency) scheme from its beginnings, with specific attention paid to the progress that has been achieved on the understanding of the interaction between the plasma edge and the ICRF heating. The developments and the progress made in overcoming the challenges faced are emphasized. We also describe, based on personal experiences, some of the dead-end roads, the sound deductions that sometimes were prematurely discarded or the intuitive conclusions that were later confirmed by more experimental data. We end with a vision for the future.

Keywords: ICRF, ICRH, heating, coupling, impurity production, SOL
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INTRODUCTION

Ion cyclotron heating is one of the methods that is used to heat magnetically confined plasmas. It has a very long tradition, having been used on the very first confinement concepts and, after having overcome a number of challenges, is now planned to be used for the next steps ITER and DEMO. Since it is now about 50 years (a golden anniversary) from its initial use for significant heating on the Model C stellarator in 1969 [1], it is appropriate take a look at the past achievements and cast a glance to the future.

The paper is organized along the five decades. While this choice of organizing the paper may be somewhat artificial, one can see that each decade has had its particular emphasis, and the main topics of each decade is what we will be concentrating on. Such a review can of course not cover all the results, but we have tried to provide what we consider to be the major achievements with further references for those who want to dig deeper. A number of review papers has been written at different times on this and related topics [2] [3] and, more generally, on the history of fusion research [4] [5]. This review has made use of them but has dug into the original literature and provides its own, partly subjective account, colored by the personal experience of the author, who in one way or another participated in the most recent 40 of those 50 years.

The paper is dedicated to Dr. Joel Hosea, a pioneer who played a significant role in this journey from the very beginning and passed away last year (2018).

BEFORE 1969: EXPLORING WAVE ABSORPTION

Before we start with the first significant use of ICRF in the Model C stellarator in 1969 [1], let us briefly recount the years prior. In 1958, at the IAEA conference in Geneva, fusion research was declassified. Several magnetic confinement methods had been pursued. The main ones were the stellarator in the US, the tokamak in the USSR, the mirror in the US and the USSR and the toroidal pinch (later to become reversed field pinch) in the UK. Ion cyclotron was a logical method to choose for plasma heating, both because it heats the ions and because high power generators were available from radio wave transmitters. However, as for all heating systems, three conditions need to be fulfilled to have a plasma heating method: (1) the availability of power generators alone is not a sufficient condition. Two more requirements need to be fulfilled: (2) one needs ways to transport the power from the generators to the location of absorption in the plasma, and (3) a mechanism to absorb the power at the right location in the plasma. The transport of the power itself can be split into three parts: (2.1) from the generator to the plasma experiment, (2.2) from the outside of the plasma into the plasma and (2.3) inside the plasma from the coupling region to the absorption region. The availability of power generators and, with standard transmission lines, also familiar from radio broadcasting installations, the transport of the power from the generator to the experiment provided two (namely (1) and (2.1)) of the five requirements needed. At the beginning researchers thus had to develop the three remaining ones: (2.2) design antennas to couple the power into the plasma, (2.3) advance the plasma wave theory to find ways of transporting the power from the edge to the plasma center, and (3) investigate the absorption mechanisms.

Experimental demonstration of wave absorption was shown in 1960 on the B-65 stellarator [6], while in 1962, Stix developed the theory of plasma waves [7]. Coupling of RF power to plasma was shown on the C stellarator [8] in 1966. In order to avoid parasitic loading and impurity production from the antenna coils, a grounded Faraday screen was used between the four poloidal coils and the plasma. The slow wave was launched by the antenna towards a region of lower magnetic field (magnetic beach heating). This wave also has the right polarization to accelerate the ions at the frequency at their resonant (cyclotron) frequency, providing a sound absorption scenario.

THE 1970's: DEVELOPING THE HEATING SCENARIO'S

In the 70's, the emphasis was on understanding and optimizing the heating scenarios and in particular the absorption scheme. From magnetic beach, to second harmonic, minority and mode conversion heating, several methods were developed. Their theoretical basis and understanding of the physics made substantial progress.

The first significant heating observed [1] was an electron temperature increase from 5 eV to 50 eV, and 550 eV achieved for T_i with 1.1 MW coupled for 1 ms in the C stellarator in 1969. In this experiment a generator which could supply a power of up to 4 MW applied 2 MW to the coils at 25 MHz.

Following the report of the excellent plasma confinement T-3 results at the 1968 IAEA Novosibirsk conference, there was a race around the world to build tokamaks and the C stellarator at Princeton was rebuilt into the ST tokamak. It was clear that the method of launching the slow wave and absorbing it at a magnetic beach as in the C stellarator, could not be used in a tokamak, since the slow wave is not propagating at the typical tokamak densities. First experiments thus reverted to investigating at low power the plasma waves and absorption mechanisms. It was known that the fast wave, which does not suffer a cut-off at high density as the slow wave does, however does not have the correct (i.e. left) polarization to accelerate ions at their fundamental resonant frequency. At double the resonant frequency (commonly known, but in fact grammatically incorrectly as the "second" harmonic 2 ω_{ci}), the wave has partly the right polarization. Therefore, $2\omega_{cH}$ heating was investigated in the ST tokamak. Eigenmodes, tail heating and impurities were observed at low power (70 kW), with even lower efficiencies observed at ω_{ciH} [9]. Heating at $2\omega_{cH}$ requires high temperatures, as the standard mechanism then is a finite Larmor radius effect [10].

Significant heating in a tokamak was first observed in the TM1-V-Ch tokamak [11] with a doubling of the "total" (electron and ion) temperature to 200 eV with 40 kW for 0.4 ms using the fast wave (at $\omega > \omega_{cH}$). The absorption mechanism was postulated to be the decay of the fast wave into an "electrosonic" wave and a drift wave.

Many small tokamaks built around the world, following the results of T-3, used at first ohmic heating which the tokamak provide automatically via its toroidal plasma current. It was only later in the decade that additional heating came to the foreground on experiments such as TFR [12] and PLT [13] with significant amounts of power. Erasmus, the small tokamak in Brussels even specifically emphasized in the title of a paper that the additional power now was larger than the ohmic power [14]. The fast wave had established itself as the method to launch the power in the plasma, researchers were developing antennas, but were still puzzled by the absorption mechanisms. In TFR, with an antenna [15] encircling the whole poloidal circumference of the discharge and the wave launched from the high field side ($\omega < \omega_{cH}$), significant electron and ion heating was seen with 220 kW of power in a two-component plasma. This was attributed to mode conversion. Initial experiments at $2\omega_{cD}$ on PLT in a dominantly D plasma were seeing a change in the distribution function of the ions, as expected from second harmonic heating, but with a much higher than expected absorption. It was only after the charge exchange diagnostic became mass sensitive, so one could differentiate between the distribution function of D and H, that it was noticed that it was H, present in small concentration, which showed a tail and not the dominant D [13]. A significant increase of the tail temperature of H from 0.4 keV to almost 8 keV was observed, while D and e were collisionally heated. The minority heating scenario had already been observed previously on T-4 [16] [17], a result that had been overlooked, or attributed to mode conversion [12]. Minority heating had been theoretically anticipated in an internal CEA report [18] and inferred from observations in TFR [19].

The 1970's thus finished with having established the main characteristic of an antenna (with a Faraday screen), the use of the fast wave to transport the power from the antenna to the absorption region and three main ICRF absorption scenario's (mode conversion, minority heating and second harmonic heating). With the availability of generator power, transmission lines to bring the power from the generators to the machine and the development of vacuum feedthroughs, the scene was set to move to high power ICRF heating systems. It would take another 40 years to discover a fourth absorption scenario: the three-ion heating.

THE 1980's: EXPERIMENTS AT MW POWER

In the 80's, power in the MW range was becoming available on PLT, ASDEX, JET and TFTR. It was shown that fusion relevant temperatures could easily be achieved. But at the same time impurity and coupling problems remained nagging issues.

Continuing the investigation of minority heating, ^{3}He was used on PLT at high power. With 4.3 MW in the (^{3}He)D minority heating scenario electron temperatures of 4 keV, with strong sawteeth and D temperatures of more than 5 keV were obtained [20]. Unequivocal second harmonic heating of H was seen at $2\omega_{cH}$ [21]. A transition of H minority heating to second harmonic D was seen, in the (H)D minority heating regime, at high power, with the tail of the H decreasing and the tail of the D increasing as the power was increased from 620 kW to 1150 kW [20].

The 1980's were also the time where the decrease of confinement was seen, with increasing applied heating power. In ASDEX, the H-mode was discovered using neutral beam injection in 1982 [22]. Five years later, for the first time, H-mode was also obtained with ICRF heating [23]. The transition to H-mode with its change in density profile at the edge already indicated that this change in coupling would be an issue one would have to deal with. In an effort to simplify the antennas, the optically closed Faraday screen with alternating T-shaped rods, was replaced by a single row of circular rods with a rather high optical transparency on ASDEX [24]. The latter was shown to be as good as the original optically closed Faraday screen. Since after a boronization, ICRF heated plasmas showed a much stronger increase of plasma impurity content from shot to shot than NBI heated plasmas, one had to conclude that the ICRF was eroding the boron layer locally, while the erosion due to NBI was more distributed [25]. This was a first indication that the mechanisms of impurity production with ICRF was localized.

High power (up to 6 MW) was coupled in TFTR. To improve the coupling the solid septa of the antennas were replaced by rods (that however led to more cross talk between the straps) and a double-row Faraday screen was, similarly to ASDEX, replaced by a single row [26] [27]. The combination of NBI in the low recycling regime with ICRF and pellet fuelling lead to very peaked temperature profiles and an enhanced fusion reactivity (called supershot regime) [27].

On JET, with 12 MW of power in the H minority heating regime, stabilization of the sawteeth [28] was observed. This was a first indication that the ICRF heating method could have beneficial effects beyond heating alone.

By the end of the decade many experiments to pinpoint the mechanism of impurity production had been done, but a conclusion remained elusive [29]. An overview of those efforts can be found in the proceedings of an IAEA Technical Committee Meeting [30] and later review papers [31] [32]. The sheath rectification mechanism started to be mentioned [33]. In the sheath near a material boundary, a DC potential accelerates ions into material surfaces leading to sputtering. When RF electric fields are present along magnetic field lines, an enhanced DC potential develops to compensate for the higher mobility of the electrons which are more quickly lost than the ions. This mechanism had been known for a long time

[34] and is typically also being used for plasma processing. A number of theoretical papers indicated that this could also be the basis of the sputtering of impurities from the Faraday screen of the antenna [35] [36] [37].

THE 1990's: EXPANDING THE CAPABILITIES

The 90's saw the start of ICRF on JT60, DIII-D, Tore Supra, ASDEX Upgrade and Alcator C-Mod as well as the first applications of ICRF to D-T plasmas on JET and TFTR. With plasmas far into the H-mode, the ICRF systems struggled to cope with the effects of ELMs on the coupling. Ferrite tuners were developed on Alcator C-Mod. Conjugate matching systems and 3-dB couplers were the solutions for ELM's implemented on JET and on ASDEX Upgrade.

JT-60 high harmonic experiments [38] achieved very strong tail acceleration at 3 ω_{cH} of the NB injected ions. Investigation of the impurity showed a localized release of impurities from the Faraday screen of the open type [39], only for distances between the outermost magnetic surfaces and the antenna guard limiters smaller than 30 mm, a phasing between the straps of 0, and above a threshold value of 0.5 MW in carbon limiter discharges [40].

DIII-D investigated current drive with ICRF [41], both in L-mode and in H-mode. For no or infrequent ELMs the current drive efficiency was in agreement with theory. A reduction of current drive seen in H-mode with increasing ELM frequency was correlated with a reduction in absorbed power, when the density close to the antenna is raised above the fast wave cut-off density due to the ELMs. This condition was later found on NSTX to similarly correlate with unwanted effects.

In 1996, record long pulses of 2 minutes were achieved on Tore Supra with a combination of LH and ICRF [42] [43].

ASDEX Upgrade, which started with ICRF, achieved its first H-mode with ICRF only [44] [45]. When later NBI was added and strong ELM regimes were obtained, the ICRF system had substantial problems coping with the strong variation in coupling due to the ELMs. Several methods were used to mitigate the problem, such as reducing the ICRF power during the mismatch due to the ELM or varying the frequency [46], but without success. It was only when 3-dB couplers were proposed [47] and step-by-step implemented on ASDEX Upgrade that the generators were successfully shielded from the high reflected power and could operate reliably [48] [49] [50].

On C-Mod, where ICRF heating was the main heating method, several confinement modes were investigated (L, H, I, EDA, PEP) [51] [52]. In particular the EDA mode [53] with its H-mode energy confinement, but L-mode particle confinement was very promising, since it also led to reduced ELMs and therefore less problems with the coupling.

This decade saw the first use of tritium on TFTR and JET. The major heating scenarios involving T were confirmed on both machines. On TFTR, with P_{RF} up to 8.4 MW, first D-T experiments were performed, heating T at $2\omega_{cT}$ and ^{3}He at ω_{cHe} [54]. A plasma heated by 18.6 MW of NBI, increased its electron temperature with 2% of ^{3}He and the addition of 5.4 MW of ICRF, from 8 keV to 10.5 keV, and its ion temperature from 26 keV to 36 keV. Experiments were also performed without ^{3}He using $2\omega_{cT}$. The energetic T tail was formed within 100 ms providing further good damping. An increase in stored energy from about 0.2 MJ to about 0.6 MJ was achieved with 2.4 MW ICRF only, with a slower rise time but ending up at the same total energy as an equivalent NBI power [55]. On JET, $Q = 0.22$ was achieved in the (D)T scenario, with 6 MW of ICRF [56]. With the (T) D scenario also confirmed, four heating scenarios were thus validated for use in T: minority ^{3}He, minority D, minority T and second harmonic T.

In a preview of what would be further investigated in the next decade, first evidence of an RF-induced pinch effect on fast particles was indirectly observed [57] after having been predicted theoretically [58].

Though the impurity problem was not dominant, results from different machines showed that the impurities would come mostly from the antenna or nearby (in large machines as JET), or from areas farther away (in smaller machines). This could be related to the difference in single pass absorption in the machines, with RF electrical fields being more concentrated in the antenna neighborhood when the absorption was better [59].

In the 1990's some major hurdles were thus taken to be able to operate ICRF systems at high power, ICRF's capabilities were expanded and the scenarios to be used on D-T machines (and thus preparing the road for ITER) were validated.

THE 2000's

Starting in 2000, ICRF capabilities beyond heating, such as for example the control of fast particle transport, were experimentally investigated on JET. The design of the ICRF system for ITER progressed, in support of which an ITER-like antenna was built on JET. ICRF heating was used on KSTAR and long pulse records were set on LHD. With modelling codes such as TOPICA, quantitative calculation of antenna coupling became possible.

At the beginning of 2000, a major reorganization took place of the way experiments were done on JET. There was no longer a "resident" scientific community at Culham, JET was now operated as a user's facility, with scientists from all Europe, and later from all over the world, submitting proposals for experiments on JET. These were competitively selected and executed. One of the task forces was specifically dedicated to investigating heating and current drive aspects. The fast particle transport (RF pinch effect), previously indirectly observed [57] was now observed directly using the γ-ray spectrometer[60] [61]. ICRF was also used to influence the plasma rotation [62] [63] and to control the sawteeth [64]. This increased awareness and understanding of the capabilities of ICRF was complemented by better diagnostics, such as the phase contrast imaging technique on Alcator C-Mod, which allowed the direct identification of the Ion Cyclotron Wave [65].

On LHD several types of antennas were developed (Poloidal array, Field aligned, Field aligned impedance transforming) and record long pulses of up to 45 minutes were obtained with ICRF at the MW power level [66]. Initial ICRF experiments on KSTAR confirmed that 3 dB couplers are useful in reducing the reflected power to the generators in ELMy H-modes [67].

NSTX, a spherical tokamak, operates ICRF at high harmonics ($B_\phi < 5.5$ kG, $f = 30$ MHz). It has 12 strap antennas, spanning about 90° around the torus, which provide a very high $k_{//}$ selectivity. By proper phasing of the antennas, a $k_{//}$ of 13 m^{-1}, 8 m^{-1}, 3 m^{-1} in either co- or counter-current direction can be selected. This unique capability was used to investigate the coupling properties and efficiency of depositing power to the plasma core as a function of $k_{//}$. The efficiency was found to be strongly decreased when the density in front of the antenna is too high, i.e. when the fast wave cut-off is located behind the antenna (echoing the D-III-D results on current drive efficiency). Under these conditions, propagating wave fields are present at the surface of the plasma and indeed, a band of toroidally localized interaction was seen along field lines connected to the front of the antenna, and extending down to the divertor [68] [69].

Initial designs of the ITER ICRF antenna were made, and in order to provide experimental support, a so-called ITER-like antenna (ILA) was proposed to be built on JET and indeed installed. The antenna provided useful input for ITER antennas in particular on operation at high power densities and high voltages [70]. It turned out that the coupling was lower than was estimated with the tools available when the antenna was designed but was in agreement with calculations of TOPICA. TOPICA, which could include a realistic antenna geometry, had been developed [71] and was available by the time the ILA results were obtained. The good agreement of the coupling calculations for the measured density profile was confirmed on several other machines, such as Tore Supra, D-III-D and Alcator C-Mod. This code thus provided now the ICRF community with a useful tool to predict the antenna coupling for new antennas, if the density profile could be estimated. Further on the theoretical front, the picture that the sheath rectification effect, initially brought into play for the production of impurities at the Faraday screen [35] [36] [37], was expanded to indicate that sheath rectification could also take place at locations more distant from the antenna [72] [73].

THE 2010's

From 2010, we saw the start of ICRF systems on EAST. With machines such as ASDEX Upgrade and JET transiting to all-metal first walls, the interaction of the ICRF with the plasma edge, which had accompanied the development of ICRF since its beginning, became a pressing issue. High-power operation could now result in very high levels of high-Z impurities. Alcator C-Mod provided a way forward with its field aligned antenna. In ASDEX Upgrade, the problem was experimentally solved with a 3-strap antenna, accompanied with substantial progress in understanding and modelling capabilities. In an interesting twist, nicely complementing the work of the 70's, a new heating mechanism (3-ion scheme) was discovered, which opens the possibility to generate ions that are so energetic that it allows tests of what the confinement of fusion products would be. This is a quite attractive option for stellarators, such as W7-X, where testing the confinement of fast particles is a strategic issue. New antenna concepts, planned to be tested on WEST, are being developed and make an ICRF system very attractive for future reactors.

A very powerful ICRF system is available for ICRF experiments on EAST (12 MW) in combination with a LH and an ECRH system. Several heating scenarios were successfully investigated (H minority in D, ^{3}He in D and 3 ω_c of beam ions) and different antenna concepts were tested [74] [75] [76].

Many machines have now switched to all-metal walls, in order to become more reactor relevant. This led to the impurity problem rearing its head again. In ASDEX Upgrade where the part of the inner surface of the walls that was W coated, was increased step by step (from experimental campaign to experimental campaign), the W impurity increased similarly. The final "coup de grace" was given when the ICRF antenna limiters were W coated with the consequence that operation with ICRF became extremely difficult [77]. In JET, after installation of the ITER-like wall, an increase in W was also seen when operating with ICRF. It was concluded that it did not come from the divertor, but rather from components in the neighbourhood of the antenna [78]. It was in particular related to high antenna near fields, due to the presence of long antenna limiters.

Alcator C-Mod showed that by paying much attention to the details of the antenna design and aligning the antenna with the magnetic field, a reduction by 20 to 30% of radiated power due to impurities could be obtained [79] [80]. Theoretically, the alignment leads to a large cancellation of the $E_{//}$ RF fields with the largest cancellation in the [0, 0, 0, 0] or monopole phasing. Unexpectedly, the RF induced plasma potential was not lower for the FA compared to the TA antenna. In addition, experimentally, the [0, 0, 0, 0] phasing was not the optimal one for the impurity reduction and the highest level of RF-induced plasma potential was observed under those monopole conditions. The latter was related to a dominance of very short wavelength in the spectrum, due to the septa, leading to poor absorption [81]. The unchanged measured plasma potential between FA and TA antenna, but with reduced impurity radiation for the FA, however remained puzzling. It was speculated that the measured plasma potential was dominated by far field sheaths, while the impurity production may be dominated by local effects, and those near field were not directly monitored [80].

On ASDEX Upgrade a different approach was taken. As it was speculated that the unwanted RF fields were dominated by induced current in the antenna frame, a 3-strap antenna was designed, where the induced currents could be substantially mitigated with 180° phasing and a 2/1 distribution of power between the inner and the outer straps [82]. Experimentally it proved very effective, as now operation of the 3-strap antenna, with W coated limiters, did not lead to more impurities in the plasma than the operation of the 2-strap antenna, whose limiters were B coated [83]. Local measurements at an antenna limiter of the toroidal RF current, the DC current, the increment of the W sputtering yield and the increment of W content in plasma confirmed the optimal distribution of phasing and power [84].

This progress on the experimental front, was accompanied by progress on theoretical aspects, nicely reviewed in [85]. A set of simulation tools is now available that can help in understanding the experimental results and support the design of new antennas not only in terms of coupling, but also in terms of their effect on the plasma edge, calculated self-consistently [86] [87] [88].

It was quite unexpected that four decades after the emphasis had been on understanding and optimizing the heating scenarios, a fourth scenario was proposed [89] [90] and experimentally confirmed on several machines (Alcator C-Mod, JET [91] and ASDEX Upgrade [92]). It is interesting to note that this scenario had been overlooked when observing some puzzling experimental results in earlier times [93] [94].

The design of an ICRF system for DEMO has been tackled and an antenna array of the travelling wave type [95] proposed [96] [97] [98].

As the 2010's are ending we can look back on substantial achievements: progress in operating ICRF in all-metal machines, development of powerful tools for the interpretation of experiments as well as for support in the design of new systems, and a new scenario that will allow to investigate the behavior of very energetic ions even before they are created by fusion reactions.

THE WAY FORWARD

ICRF systems have shown to be able to perform a number of functions, and not just heating alone. This is an important aspect for its application to reactor type experiments. ICRF has also shown that it can handle well the problems it has encountered and has solved them. Substantial progress has been made in the understanding and the ability to model the coupling and the impurity productions.

The community is thus well prepared to tackle the design of a system for DEMO and for fusion reactors.

I would like to end with a personal recommendation. The picture that is now coming together for the impurity problem is that, while the fundamental mechanism is the sheath rectification effect, the mechanism driving the $E_{//}$ can be multiple, leading to impurity production that can be close to the antenna, or farther away. The areas affected can be either along field lines connected to the antenna or not. A good review of the present understanding was recently given in [84].

Since the mechanisms not along field lines, and those farther from the antenna are mostly related to lack of absorption, these mechanisms will play a less important role in bigger machines. The proper design of the antenna is and remains an essential issue for the good working of an ICRF system. The antenna and its environment need to fulfill a number of conditions:

1. The antenna must have a narrow and clean spectrum, so that it can be best optimized to provide good coupling and good absorption. This also means avoiding full septa and side pieces, which by itself, will also avoid circulating currents in the frame.
2. The antenna must be recessed, so as to prevent regions for slow wave propagation along the field lines as can occur in the low-density region beyond the limiters in the case of a protruding antenna.
3. Methods must be provided near the antenna to influence the density profile, e.g. by gas puffing to increase the density and thus the coupling or with limiters to decrease the density, in order to avoid the propagation of surface waves.

A travelling wave antenna [95-98], , integrated in the wall, seems therefore to be close to the optimal solution. Designing the correct antenna also means that the machine and the antenna must be designed together, rather than adding an antenna as an afterthought, to an otherwise finalized machine design, as often has occurred.

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