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ICRF Heating on Helical Devices*

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Abstract. Ion cyclotron range of frequency (ICRF) heating is currently in use on CHS and W7-AS and is a major element of the heating planned for steady state helical devices. In helical devices, the lack of a toroidal current eliminates both disruptions and the need for ICRF current drive, simplifying the design of antenna structures as compared to tokamak applications. However the survivability of plasma facing components and steady state cooling issues are directly applicable to tokamak devices. Results from LHD steady state experiments should be available on a time scale to strongly influence the next generation of steady state tokamak experiments. The helical plasma geometry provides challenges not faced with tokamak ICRF heating, including the potential for enhanced fast ion losses, impurity accumulation, limited access for antenna structures, and open magnetic field lines in the plasma edge. The present results and near term plans provide the basis for steady state ICRF heating of larger helical devices. An approach which includes direct electron, mode conversion, ion minority and ion Bernstein wave heating addresses these issues.

Introduction

ICRF heating will be an important component of the steady state operation of LHD and W7-X . The current status of ICRF heating experiments on helical devices and options for future experiments are reviewed here. ICRF in various heating schemes has been successfully applied to many tokamaks. The non-axisymmetric nature of the plasma and magnetic geometry in helical devices introduces new challenges for ICRF which require special consideration. Fortunately, the lack of a net toroidal current eliminates both disruptions and the need for ICRF current drive, thereby significantly reducing the requirements on helical device antenna designs as compared to tokamak applications. There is however, a large overlap in the ICRF design requirements for steady state tokamaks and helical devices. There is also a large overlap in the ICRF heating physics. Many of the successful techniques used on tokamaks have been and can be applied to helical devices. Alternatively the lack of toroidal current in helical devices can be exploited to study heating physics issues separately from the plasma current issues.

Heating Considerations and Options

ICRF heating has been applied to many helical devices. These include the Model-C Stellarator, Uragan-3, L2, Heliotron-E, W7-AS, ATF, CHS, and W7-AS. Until recently the results have been limited to providing a startup target plasma or an heating ion tail. The ICRF startup antennas have proven to be very useful because they can produce plasma over a broad range in magnetic field and

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applied frequency[1,2,3,4]. The startup plasma is usually limited to densities of less than 1.0×10^{12} cm^{-3}. The ion tail heating experiments have been limited by impurity accumulation and plasma radiation collapse[2,5,6,7]. This is likely the combined result of the relatively small major radius in the devices where it has been applied and direct orbit losses of deeply trapped high energy ions. These effects may be less important for larger devices and for those where fast ions are well confined (i.e. HSX). The impurity influx can also be controlled with boronization of the vacuum vessel and should be less of an issue for large devices. An additional challenge with small helical devices has been the limited access for antenna structures, especially in the high field locations under the helical coils. The limited distance between the antenna backwall and the radiating current strap has led to launched spectra that have weak coupling to the plasma. Large helical devices with greater access will allow improvements in the launched spectra.

The ICRF heating method can be tailored to address some of the specific issues described above. Mode conversion, direct electron, ion Bernstein wave, and minority and second harmonic heating can all be considered. Mode conversion heats the bulk of the ion and electron distribution. This avoids direct fast ion orbit losses. The mode conversion layer can be placed on or off axis which allows control of the temperature profile. The most successful ICRF heating of a helical plasma has been observed on CHS[8]. The addition of ICRF power successfully heated low density ECH target plasmas and high density NBI target plasmas. Discharges could also be sustained with ICRF only and showed no accumulation of impurities. T_e was measured to be comparable to T_i for high density ICRF heating, while T_i exceeded T_e for low density ICRF heating. Mode conversion appears to be at least one element of the observed heating. Heating (f=26 MHz) in the bulk of the electron and ion distribution was observed over a range of magnetic field (B_o=1.6-1.8T) and hydrogen minority concentration (15%-50% H in D). Boronization of the vacuum vessel was required in order to reduce the impurity influx and to control the hydrogen recycling. The hydrogen recycling was also controlled through titanium gettering of the vessel walls. In carbon lined vessels this effect might also be achieved by helium conditioning of the plasma facing carbon components. Without boronization of CHS the ICRF heating lasted approximately 40 ms before the increasing impurity radiation resulted in a collapse of the discharges.

ICRF direct electron heating (DEH) is possible when $kz \neq 0$. The heating occurs in the bulk of the electron distribution and the absorption is maximum at the peak of the pressure profile. In contrast to electron cyclotron heating (ECH), direct electron heating has no density or beta limit. The lack of a spatial resonance condition for DEH allows the flexibility to operate at various values of magnetic field, thereby increasing the operating space for confinement experiments. The operating frequency and magnetic field must be chosen so that the ion cyclotron resonances are excluded from the plasma. It has been observed on tokamaks that when competing ion resonances are excluded, a DEH single pass absorption in excess of 5-10% can provide effective heating[9,10]. Lower single pass absorption results in coupling to surface and eigenmodes.

Ion Bernstein wave heating (IBW) is also available for heating the bulk of the electron and ion distributions. Slow wave antennas designed to couple directly to the IBW have been used for startup plasmas on CHS and are planned for LHD. Heating during the higher density portion of the plasma discharge requires a different k spectra. Folded waveguide IBW antennas have been proposed for both the startup and heating of LHD[11]. Folded waveguide have the potential to provide higher power density and/or lower voltages than strap antennas.

Ion minority (5-10%) and second-harmonic heating have been applied successfully on Heliotron-E and ATF for short pulses. Longer pulses suffered from plasma collapse. High minority fraction (15-50%) heating along with mode conversion is evident in the successful ICRF heating on CHS. With a high minority fraction the lower energy per particle leads to bulk ion heating. As was discussed above with regard to mode conversion heating, a key element of the high minority fraction heating is control of the impurities and hydrogen recycling by boronization and wall surface pumping.

Magnetic beach heating is also possible in a helical plasma. It was applied to early stellarator devices and has been proposed for use on W7-AS[12].

Critical Issues for Steady State Heating

Steady state ICRF heating power of 3 MW or greater has been proposed for LHD and W7-X. Many of the critical issues for steady state heating are common to tokamaks and helical devices. The LHD steady state results should be available in time to influence the next generation of steady state tokamak antenna designs and heating experiments. The critical issues include survivability of plasma facing components, steady state cooling of the antennas and bumpers, cooling of the tuning and transmission lines, RF edge interactions and antenna coupling in the local scrape off and RF plasma environment. The heating method should be chosen to minimize the vessel erosion that could occur in steady state from unconfined fast ions. For helical devices the lack of a toroidal current eliminates both disruptions and the need for ICRF current drive. This can simplify the design of some of the antenna structures as compared to tokamak applications. There is usually no need to use special strength materials such as Inconel in antenna straps. The mass of the entire antenna and support structure can be reduced when disruptions are not a consideration. Helical devices will likely employ multistrap antennas but phasing at values other than (0,0) or $(0,\pi)$ is probably not necessary. This reduces the design constraints relative to current drive tokamak antennas. However, the helical geometry does introduce new issues as discussed above. One important consideration is the large pitch angle of the outer field lines and the open field lines in the plasma edge. Plasma rf sheaths could form along these field lines and lead to increased erosion of the plasma facing components. Antenna bumpers and limiters shaped so that they can effectively shield the central portion of the antenna need to be developed.

Summary

ICRF is a major element of helical device heating and is especially important for steady state heating. ICRF heating of the bulk ion and electron distribution has been observed in present size devices. The critical issues for steady state heating of W7-X and LHD are directly applicable to tokamak devices. The LHD steady state results will be available in time to influence the design of the next generation of steady state tokamak experiments. Helical devices introduce some different antenna design considerations as compared with tokamaks. The antenna design is simplified because disruptive forces and the need for current drive are eliminated. The helical geometry however creates new challenges, many of which can be addressed by appropriate choice of the heating method. Antenna bumpers and limiters that can effectively shield the central portion of the antenna need to be developed.

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References

1 Nishimura, K., et al., Fusion Technology **17** (1990) 86
2 Ballico, M., et al., *Radio-Frequency Power in Plasmas: Ninth Topical Conference*, Charleston, (American Institute of Physics, New York, 1991), p 150.
3 Chechkin, V. V., et al., Fusion Engineering and Design **12** (1990) 171-178; Plyusnin V. V. Private communication
4 Andryukhina, E. D., et al., in Plasma Physics and Controlled Fusion Research (Proc. 15th Int. conf., Kyoto 1986)
5 Mutoh, T. et al., Nucl. Fusion **24** (1984) 1003.
6 Rasmussen, D. A., et al., *Radio-Frequency Power in Plasmas:Tenth Topical Conference*, Boston, (American Institute of Physics, New York, 1993), p 60.
7 Nishimura, K., et al., in Plasma Physics and Controlled Fusion Research (Proc. 15th Int. conf., Seville 1994)
8 R.Kumazawa, K.Nishimura, S.Masuda et al., 21st European Physical Society Conference on Controlled Fusion and Plasma Physics, Vol.II, (1994)1000.
9 Petty, C. C. et al., *Radio-Frequency Power in Plasmas: Ninth Topical Conference*, Charleston, (American Institute of Physics, New York, 1991), p 96.
10 Murakami, M., et al., *Radio-Frequency Power in Plasmas:Tenth Topical Conference*, Boston, (American Institute of Physics, New York, 1993), p 48.
11 Kumazawa, R., et al., *Radio-Frequency Power in Plasmas:Eleventh Topical Conference*, Palm Springs, (American Institute of Physics, New York, 1995), to be published.
12 Vedovin V.L. Private communication