ICRF Plans for the Quasi Poloidal Stellarator

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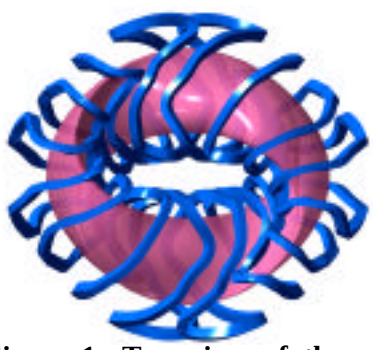
Abstract. The ICRF options for QOS build on successful results from other stellarators, mirror machines, STs, and tokamaks, and include High Harmonic Fast Wave (HHFW), mode conversion (MC) heating, magnetic beach heating (MBH), and minority heating. There is good access for antennas, and the plasma volume, minor radii, and field geometry are comparable to CHS and W7-AS. Minority and MC heating have been observed on CHS, W7-AS and LHD. Calculations indicate HHFW can be successful on the QOS device. MBH has been observed on W7-AS. The ICRF options offer the flexibility to support a broad set of physics studies. These can be met with a limited number of antenna structures and within the frequency bands of available power.

INTRODUCTION

ICRF is an important auxiliary heating method for the Quasi Poloidal Stellarator (QPS) shown in figure 1. In QPS, ICRF can provide effective electron heating, ion heating, and may also be used for current drive or flow control. The ICRF options under consideration for QPS (in priority order are):

(1) direct electron heating or High Harmonic Fast Wave (HHFW) heating at ≥20 MHz for bulk electron heating;
(2) mode conversion heating (at ~15 MHz for B = 1 T) at the two-ion-hybrid resonance layer for bulk electron heating;
(3) magnetic beach heating (<14 MHz at B = 1 T) for bulk ion heating;
(4) minority-species heating (~14 MHz at B = 1 T for H minority in a He plasma) for either, heating via an energetic H tail population with ~5% H concentration or bulk ion heating with ~30% H concentration;
(1) fast wave and HHFW current drive and flow control (≥20 MHz).



ECH power	28 GHz	53 & 56 GHz
perpendicular electron heating	4 @ 300KW ea.	4 @ 200KW ea.
	2nd 28	2nd 53
Parameter	low	high
B (T)	0.5	1.0
R (m)	0.83	0.83
a (m)	0.35	0.35
V_P (m^3)	1.78	1.78
P (MW)	1.0	0.5
n (10^{19} m^{-3})	0.45	1.8
$<\beta>$ (%)	1.5	1.02
τ_E (ms)	2.25	12.1
T_{e0} (keV)	3.1	2.1
T_{i0} (keV)	0.30	0.23

Figure 1. Top view of the modular coils and last closed flux surfaces for the reference QPS configuration, and the assumed QPS ICRF target plasma parameters for the HHFW calculations in Figure 2c.

There is good access for a variety of possible antenna structures between the modular field coils. The plasma volume, minor radius and field geometry are comparable to devices where ICRF has been used successfully (CHS, W7-AS). In particular, minority and mode conversion heating have been observed on CHS and LHD with single-strap high-field-side antennas. Mode conversion and magnetic beach heating have both been observed on W7-AS with a two-strap high-field-side

antenna. HHFW has been observed on NSTX with a multi-strap low-field-side antenna and calculations indicate it can be successful on QPS. The ICRF options offer the flexibility to support a broad set of physics studies. One important requirement is to heat electrons at both low and high density. HHFW and mode conversion heating can both provide electron heating. Ion heating is also of interest in QPS. Mode conversion and magnetic beach heating can provide bulk ion heating and tail heating can be obtained with minority ion heating.

HIGH HARMONIC FAST WAVE HEATING

An important mission for QPS is high-β studies where high density is needed. HHFW appears to be the best choice for an initial ICRF heating system for QPS and is particularly valuable for reaching high β. HHFW has been successful at heating electrons on NSTX [1,2] with fields and plasma parameters similar to those expected on QPS. The results of a calculation, for QPS parameters, using the PICES full wave code [3] are shown in Figure 2. The moderate, single pass, attenuation of the wave is apparent in Figure 2a. The central deposition of the electron heating is evident in Figure 2b. The calculation indicates that for a plasma with β = 1% at 1 T, the HHFW single pass absorption at 60 MHz can be 20%.

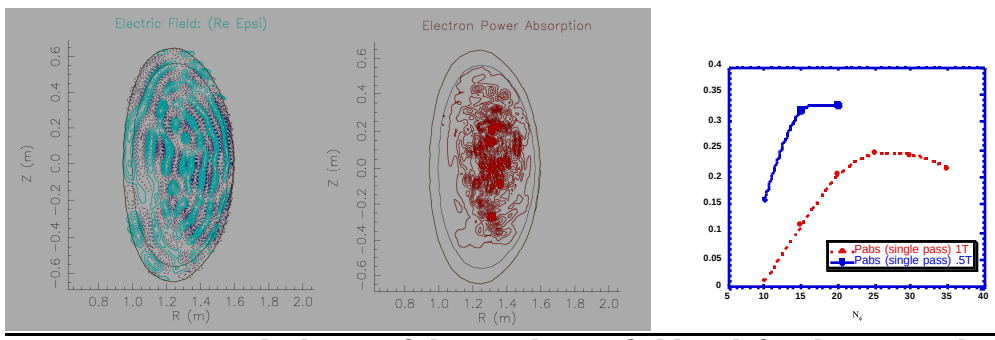


Figure 2. PICES calculation of the RF electric field (a, left), the power absorbed (b, center) in electrons at 1 T and ⟨β⟩ = 1% for 60MHz HHFW and the single-pass absorption vs n_φ (c, right).

The single pass absorption as a function of n_ for the QPS plasma parameters at 0.5T and 1.0T is shown in Figure 2c. The HHFW single pass absorption at 0.5 T with β = 1.2% can be >30%. Figure 2c shows that an antenna launch spectrum with a maximum near n_φ of 20 would work well for HHFW electron heating in QPS for operation at both 0.5 T and 1 T. HHFW antennas would be located on the outboard side and in a low field region. For heating, a pair of single strap antennas would be adequate. The antenna/strap spacing can be the same as that of the modular field coils on the outboard side (interleaved), providing an n_φ of ~ 20. The design would draw from the experience on W 7-AS and the substantial experience on tokamaks. The design will be simplified due to the lack of disruption currents and no active cooling requirement for pulse lengths less than 1 s. The design could be similar to the low profile antenna boxes used on NSTX. For QPS, the antenna boxes could be placed between modular field coils as shown in Figure 3a. The cross section of an NSTX style antenna at the φ = 0 plane is shown in Figure 3b.

If current drive and or flow drive is desired, there is adequate space for a multi-strap array similar to that used on NSTX for HHFW current drive. An alternative would be a low radial profile combline antenna such as that under consideration for NCSX [5]. A combline has been used on JFT-2M and one is planned for LHD [6].

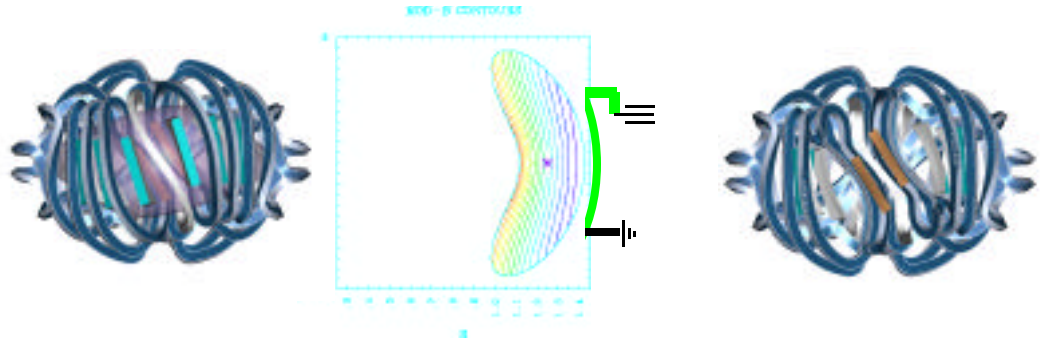


Figure 3. (a, left) HHFW low field outside launch antenna elements between QPS Coils (b, center) Side view of outside launch and (c, right) High field inside launch Mode Conversion or Beach Heating antenna elements.

MODE CONVERSION HEATING

An important alternate method is mode conversion heating, which can provide both electron and ion heating. It is also compatible with high-β operation. Mode conversion has been used for heating on CHS [7], W7-AS [8], LHD [9], and TFTR [10]. The typical stellarator experiments involve a hydrogen minority (10%-40%) in a deuterium plasma. Bulk electron heating is observed on CHS and LHD near the two-ion hybrid resonance layer (~15 MHz at 1 T). The two-ion hybrid resonance is accessible from the high field side (Figure 3c.). In the vicinity of the resonance, the fast wave converts to an ion Bernstein wave, where it rapidly damps on the electrons. Long-pulse operation has been obtained with ICRF alone or in conjunction with ECH or NBI heating. Depending on the specific geometry and the minority ion concentration, ion heating can compete with the electron heating. Thus, the relative fraction of ion or electron heating can be controlled by adjusting the minority hydrogen concentration.

MAGNETIC BEACH HEATING

Magnetic beach heating has been demonstrated on W7-AS [11]. This is similar to the magnetic beach heating utilized on mirror experiments and requires a launch location where the field decreases toroidally away from the antenna. The main appeal of magnetic beach heating is the possibility to heat bulk ions. Heating bulk ions will increase the plasma β, allowing the ion confinement properties of QPS to be studied and a comparison to the confinement of tail ions. On W7-AS, beach heating was successful at heating both ions and electrons with an ECH target plasma and was also capable of sustaining an ICRF-only portion of the discharge. A sufficient field gradient (mirror ratio of ≤0.9) is required so that, the ion cyclotron resonance is excluded from the high field plasma cross-section near the antenna, but exist over some portion of the cross-section, at the low end of the field period (beach).

The cross section for the beach location on QPS is shown in Figure 4. The toroidal field variation in QPS is more than adequate to meet the requirement. A toroidal cut is shown in figure 4a. Potential antenna locations for beach heating are shown in Figure 4b as red bars. The inside antenna location (Figure 3c.) and design described above for mode conversion heating would also work well for magnetic beach heating.

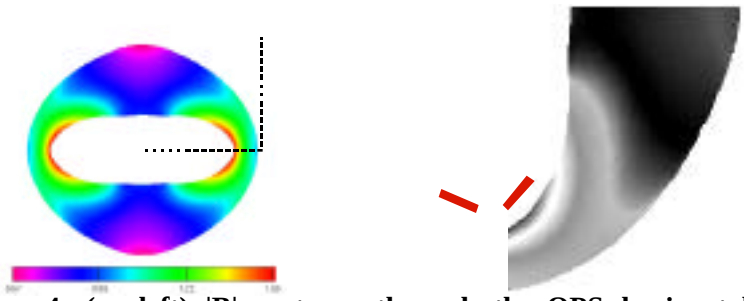


Figure 4. (a, left) |B| contours through the QPS horizontal midplane cross section. (b, right) Dashed region with the location of the antennas in the inside corner.

MINORITY ION HEATING

Minority ion heating has been utilized on essentially all ICRF-heated confinement experiments. It tends to be ineffective in experiments with small and modest minor radius due to direct ion orbit losses. Thus minority ion heating cannot be depended on for improving plasma parameters on QPS, but it can be used to study direct orbit losses as a function of plasma configuration and β. Minority ion heating can be tried with either the low-field or high-field antennas described above. Figure 4b shows the nearly vertical |B| contours in this cross section of QPS, similar to the heating geometry on standard tokamaks.

CONCLUSION

ICRF has been very successful on QPS-sized stellarators. The access and conditions look favorable for effective ICRF heating on QPS. There are several possible ICRF antenna designs for QPS: high-field-side antennas may be possible similar to those on LHD, CHS, and W7-AS or low-field-side antennas similar to those on NSTX. In addition, heating scenarios based on HHFW, mode conversion & magnetic beach heating all look possible. In the near future we will perform more definitive calculations of the ICRF wave propagation and mode conversion in stellarators using the AORSA3D code [12].

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