8. RF Heating Systems for QPS

Extensive, fully operational high-power RF heating systems are available at ORNL for use on QPS (Table 8.1). Although the ORMAK vacuum tank was designed to accommodate neutral beam injection (NBI) heating, and NBI was first used for auxiliary heating of a tokamak in ORMAK, the cost of refurbishing a 1-MW neutral beam line and creating a second beam line for balanced NBI, the cost of their installation, and their operating cost is not compatible with the budget for a concept-exploration-level experiment. Two types of high-power long-pulse heating systems would be used on QPS: gyrotron systems for electron cyclotron heating (ECH) and electron Bernstein wave heating (EBW), and RF transmitters for ion cyclotron range of frequency (ICRF) heating. Both ECH and ICRF have been used successfully on world stellarators. QPS has large access and the proper conditions for ECH, EBW, and ICRF, which allows extending RF heating experience to a new regime: heating, current drive, profile control, and flow control in a poloidally symmetric configuration at very low aspect ratio. Lower hybrid heating systems are also available for parallel electron heating, but their utilization would probably be limited to use of the 2.45-GHz system for resonant ECH cleaning at 0.0875 T.

Table 8.1. RF Heating Systems Available for Use on QPS

Type of RF Heating	Power and Frequency Range
ECH/EBW	**1.2 MW at 28 GHz, 0.3 MW at 27.7 GHz, 0.2 MW at 35 GHz, 0.6 MW at 53.2 GHz, 0.2 MW at 56 GHz**
ICRF	**2 MW at 6-20 MHz, 1.5 MW at 40-80 MHz**
Lower Hybrid	**1 MW at 2.45 GHz, 0.1 MW at 800 and 915 MHz**

8. 1. Electron Cyclotron Heating

The QPS experiment will use high power ECH for plasma startup and heating at low density (low electron collisionality). A power level of up to 1 MW at primarily 28 GHz and also at 53.2 GHz and 56 GHz is available using existing and installed gyrotrons and power supplies at ORNL. The baseline launcher design for QPS will be designed for high first-pass absorption. This is essential due to the absence of an interior vacuum vessel. Unlike in a close-fitting metallic vacuum chamber, multi-bounce power will be less likely to be absorbed in the plasma due to the large surface area and complicated coil and support structures in the large vacuum tank.

The QPS power supply and control systems are based on the existing and fully operational ATF hardware which includes: a 90-kV, 50-A cw power supply, vacuum-tube-based modulator/regulator, PLC control and interlock system, and other controls. The high-voltage DC power supply is voltage regulated and has high speed crowbar protection to minimize arc damage to the gyrotrons. Five gyrotron sockets and magnets are installed including three from ATF and two from the RF test facility (RFTF).

8.1.1. High-power gyrotrons

The available gyrotrons are different models built by Varian Corp. (now CPI) and used on either the EBT/RFTF or ATF experiments. Their frequencies range from 28 to 56 GHz. There are five 28-GHz gyrotrons, one 27.7-GHz gyrotron (which would need some refurbishment), a 35-GHz gyrotron, three 53.2-GHz gyrotrons, and a 56-GHz gyrotron. All of these tubes are rated to 200 kW cw. The 28-GHz gyrotrons have a large diameter collector which should be capable of >300 kW for 1-s pulses (Varian ran an identical unit at 340 kW for >1 hour before its window failed). The 27.7-GHz tubes should also be operable at 300 kW for a 1-s pulse. The 28-GHz tubes are the primary choice since they allow experiments with >1 MW at either 0.5 T or 1 T, which corresponds to the second harmonic or fundamental resonance, respectively, at the plasma center. The 53.2-GHz and 56-GHz tubes can be used at 1T, which would allow the power to be absorbed at the second harmonic resonance at the plasma center. The 35-GHz tube could be used at 0.5 T or 1 T to provide slightly off-axis second-harmonic heating or at 0.6 T with on-axis heating.

All the 28 GHz-tubes are of similar design, although the newest tube has a higher output mode purity (>93%). The older 28-GHz tubes have a mode purity of ~80 %, although the mode mixture is in a form that can be reconverted to a single mode. The lower-mode-purity 28-GHz tubes have a mode mixture that is primarily TE02 with some TE01 and TE03 power. The non-TE02 power can be recovered and recombined with the TE02 power using a mode re-converter installed in the output waveguide above the tube. The newer 35-56 GHz tubes all have high mode purity, typically >92%. High mode purity is desired to provide the simplest, most efficient transmission and launching system. The newer 35-56 GHz tubes all have high mode purity, typically >92%. The lower-mode-purity 28-GHz tubes have a mode mixture that is primarily TE02 with some TE01 and TE03 power. The non-TE02 power can be recovered and recombined with the TE02 power using a mode re-converter installed in the output waveguide above the tube. The vacuum quality is the principal gage of the tube's useful lifetime. These tubes have integral Vac-ion pumps that keep the vacuum quality good and allow monitoring during operation. Some of the older 28 GHz tubes have developed small vacuum leaks in a lower body cooling channel. A fix for this problem has been developed and it is anticipated that these tubes will be repaired, possibly in-house, to restore the vacuum to the full cw/long pulse operating capability. The 28-GHz tubes use water-cooled copper magnets. Some magnet power supplies will need to be acquired to support operation of more than three 28-GHz gyrotrons.

8.1.2. Transmission systems

The waveguide transmission systems are designed to provide high mode purity transmission to the launchers so that control of the launch beam quality and polarization can be maintained to maximize the coupling efficiency. High mode purity is obtained by minimizing the number of bends, keeping the waveguide diameter small, and maintaining maximum straightness. The 28-GHz frequency is too low to use simple miter bends in a reasonably small waveguide diameter, so corrugated TE02 or HE11 bends must be used. Designs for these bends are already developed and have been used in the past at ORNL and elsewhere. A waveguide diameter of 38.2 mm (1.5") will be used for bends and straight sections between the bends. Figure 8.1 shows the proposed 28-GHz ECH waveguide configuration. The 53.2/56-GHz transmission systems can use 1-2 miter bends and smooth wall waveguide, as was done on ATF. Three essentially complete evacuated transmission systems based on 63.5 mm (2.5") copper waveguide are available from ATF and would be used with only slight reconfiguration on QPS. Figure 8.2 shows the arrangement of the ECH systems for QPS and Figure 8.3 shows the QPS ECH power supply configuration.

A waveguide-type mode converter located near the QPS vacuum vessel would be used to convert to HE11 mode for a polarized, narrow-beam launcher. Two possible techniques for this mode conversion are well developed and the designs are already available from previous projects at ORNL. One technique is the TE01-TM11-HE11 approach, which can be done in the largest-size waveguide but is less convenient for polarization adjustment in the waveguide. A grooved reflector inside the launcher can provide polarization adjustment and beam focusing. The TE01-TE11-HE11 approach provides polarization adjustment in the waveguide by rotating the plane of the converter; however, it requires a smaller waveguide diameter.

Waveguide vacuum barrier windows are needed at the QPS vacuum vessel. Since QPS will operate in a pulsed mode with <1-s plasma pulse length, edge-cooled single-disk windows are adequate. The window material will be either low-loss quartz or aluminum nitride with metal o-ring seals. The windows will be located after the HE11 mode converter section in the last waveguide joint before the vacuum vessel.

8.1.3. Launchers

A relatively narrow beam of the appropriate linear polarization needs to be launched towards the plasma center. High first-pass absorption will be achieved with a plasma density in the range of 0.1 to 1 times the cutoff density, which is ~ 0.92×10^{19} m^{-3} for 28-GHz O-mode operation at 1 T or 0.46×10^{19} m^{-3} for X-mode operation at 0.5 T. It is likely that a high-field launch approach can be adopted for 1-T operation, which would couple to a plasma density of ~1.8×10^{19} m^{-3}. For operation at 1 T, the 53.2/56-GHz tubes can operate at a similar plasma density using low-field-launched X-mode.

To achieve a narrow launch beam from a corrugated waveguide carrying the HE11 mode, a focusing mirror can be used, placed near the edge of the plasma. This mirror, or a

second flat mirror, can be grooved and rotatable to provide polarization rotation for adjustment between O or X mode launch, as was used on ATF.

8.2. Electron Bernstein Wave Heating

EBW is an important heating technique for QPS that could provide effective electron heating at high density. High-β (and hence high-density) plasmas with $\omega_{pe} >> \Omega_{ce}$, as in NSTX, cannot use ECH, EC current drive, or EC emission (ECE) diagnostics [which measures $T_e(R,t)$], so the use of electron cyclotron (EC) waves for heating and current drive of magnetically confined plasmas has been traditionally limited to a plasma density range below cutoff of waves at the cyclotron frequency of interest. EBWs can propagate in these "overdense" plasmas and have high optical thickness ($\tau \sim 1000$ in QPS) for good absorption at ECE resonances. Operating at overdense conditions using the EBW mode

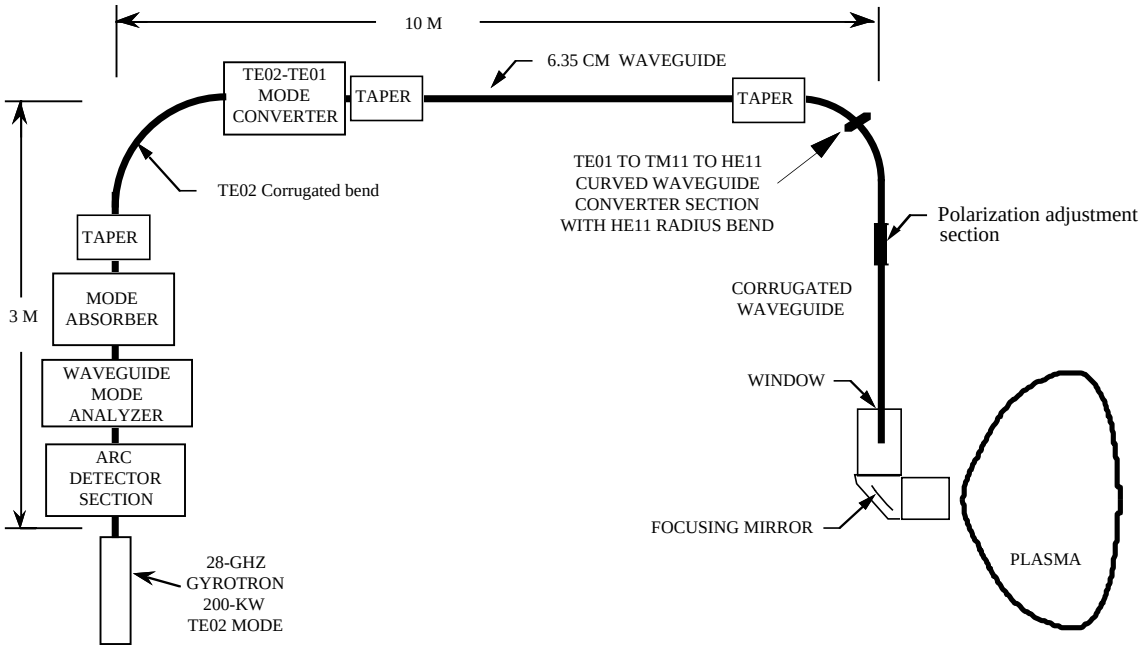

Figure 8.1. QPS 28-GHz ECH Waveguide Configuration.

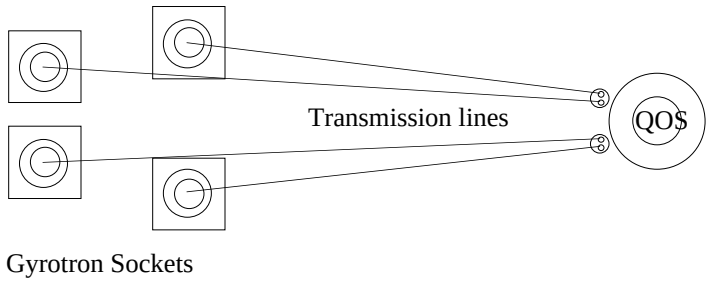

Figure 8.2. QPS 28-GHz ECH System Arrangement

is currently under investigation on MST, CDX-U, NSTX [1, 2, 3] and elsewhere. EBW emission on these experiments can provide information on the viability of EBW heating.

The in-plasma mode conversion of EC waves to EBW offers the possibility of greatly extending the useful density range over which high frequency ECH-type heating techniques and capabilities can be used. The EBW wave propagates only where the plasma frequency exceeds the cyclotron frequency. This necessitates a wave tunneling process for coupling power from outside the plasma. Idealized modeling of the EBW tunneling physics indicates that high coupling efficiency is theoretically possible through two different routes. Both routes require very precise control over the launched beam direction and quality.

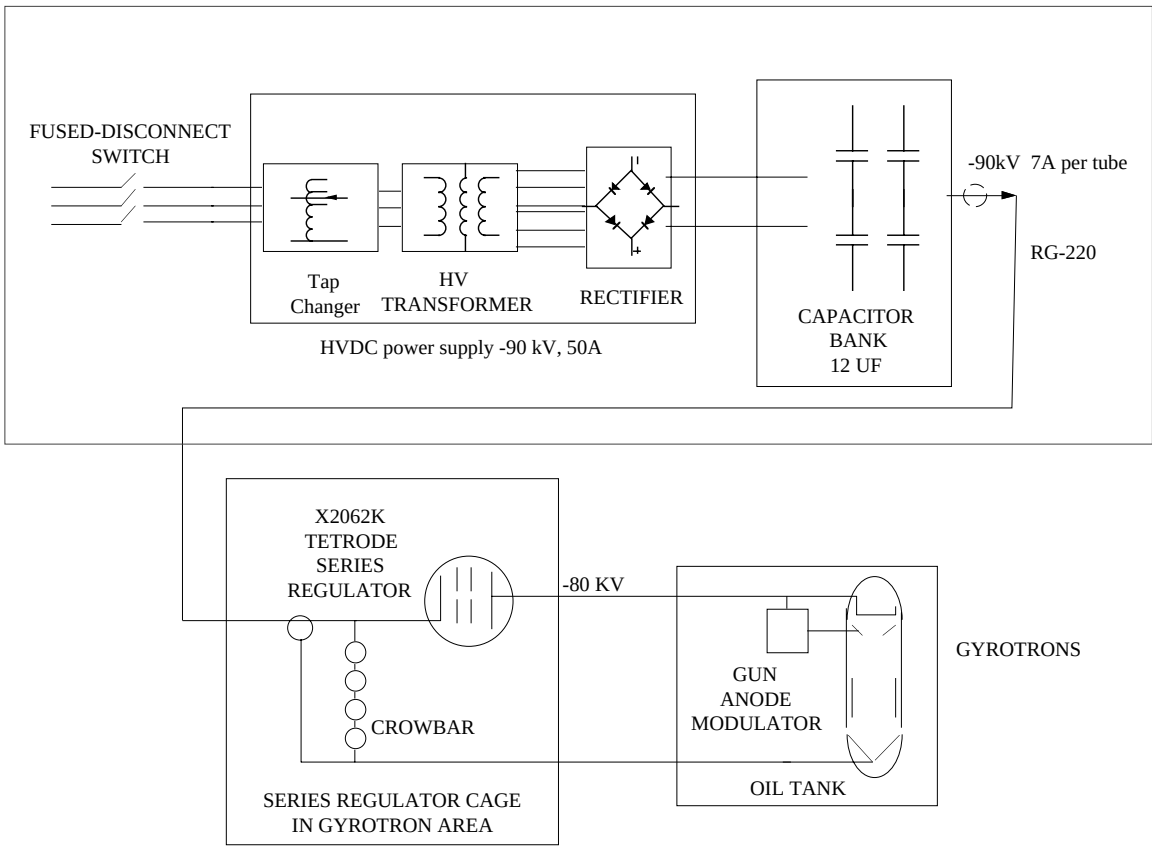

Figure 8.3. QPS ECH Power Supply Configuration (installed and operational).

8.2.1. Direct X-mode conversion. One approach is direct X-mode conversion (perpendicular launch) via wave tunneling through the critical layer. The X-mode conversion process (emission) is illustrated in Figure 8.4 [3]. It has the advantage of a relatively simple launcher, but may have low coupling efficiency. The X-mode conversion depends strongly on the plasma density profile at the extreme edge in front of the antenna. Optimal coupling may require a small local limiter to steepen the density gradient. One concern is that large density fluctuations in front of the antenna might interfere with the process.

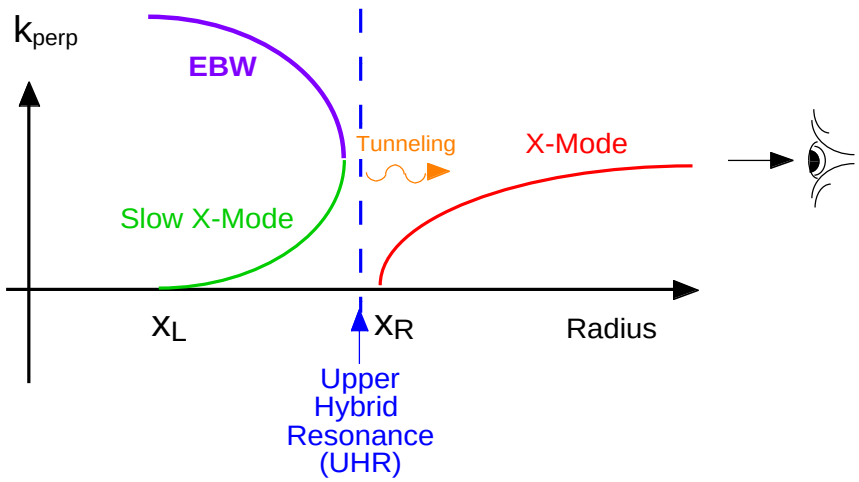

Figure 8.4. Fast X-Mode Conversion to EBW.

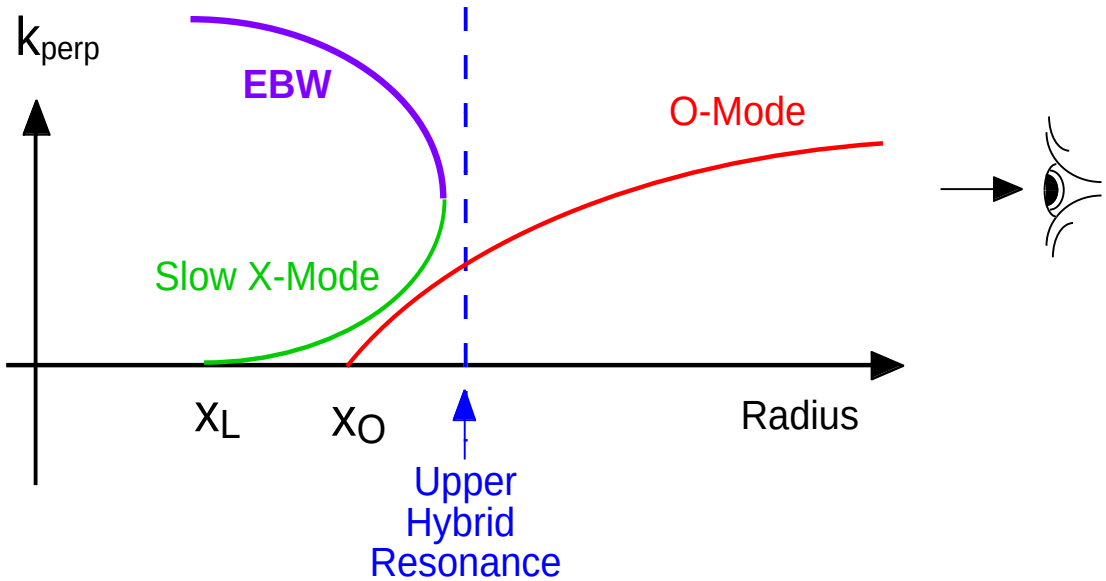

Figure 8.5. O-Mode to EBW Mode Conversion (O-X-B) Possible with Oblique Launch.

8.2.2. O-X-B Mode conversion. An alternate method is O-X-B mode conversion heating, which is also compatible with high-β operation. The O-X-B scenario requires O-mode propagation to the cutoff and a mode conversion at the turning point. The O-X-B mode conversion process (emission) is illustrated in Figure 8.5 [3]. Once it is excited, the absorption of the mode converted wave is extremely high. Density fluctuations can also interfere with this process. The use of O-X-B EBW for heating has been demonstrated in one experiment (W 7-AS); however, the state of the technology and experimental database are limited.

8.2.3. EBW launcher issues. EBW heating will be guided by an understanding of EBW emission. The EBW emission results from CDX-U, MST, MAST, and NSTX have been very encouraging. The CDX-U and NSTX results indicate that when steep edge gradients are present, emission coupling efficiencies of up to 20% can be obtained.

Optimized launching structures and edge profiles should lead to higher efficiencies. The emission and launching requirements can be explained via the CDX-U example illustrated in Figure 8.6 [3]. As with ECH, the requirements for the launchers are that a relatively narrow beam of the appropriate linear polarization be launched toward the plasma center. To achieve a narrow launch beam from the proposed corrugated waveguide carrying the HE11 mode, a focusing mirror can be used placed near the edge of the plasma. This mirror or a second flat mirror can be grooved and rotatable to provide polarization rotation for adjustment between O or X mode launch as was used on ATF. As examples of what can be done on QPS one launcher option for NSTX is shown in Figure 8.7. A second option utilizing the ECH launcher hardware used on ATF is shown in Figure 8.8.

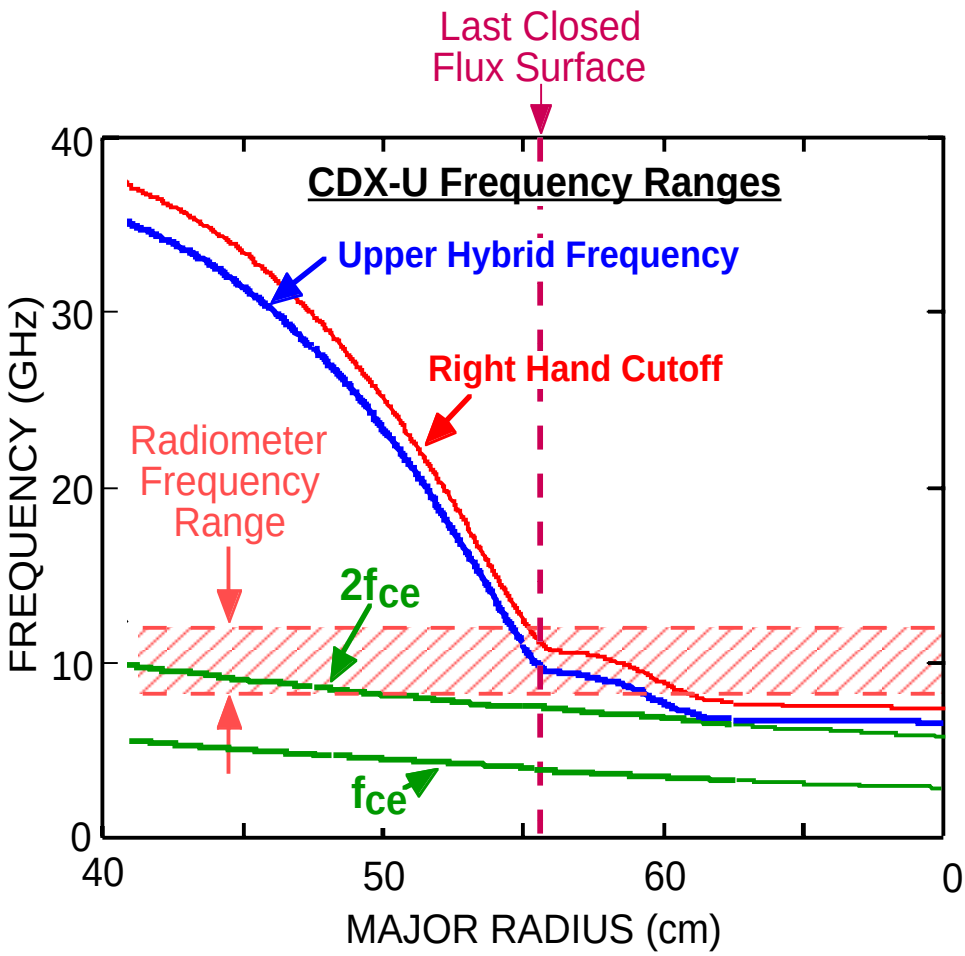

Figure 8.6. O-X-B Mode Conversion in CDX-U.

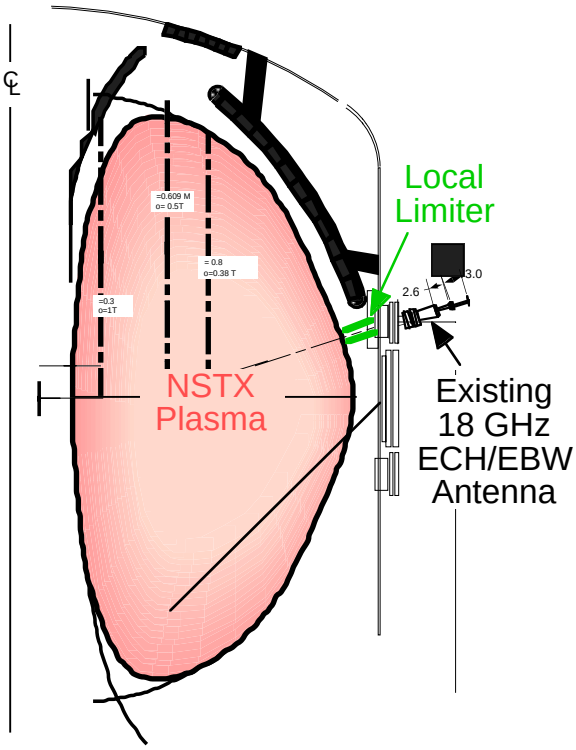

Figure 8.7. An EBW Launcher Option for NSTX.

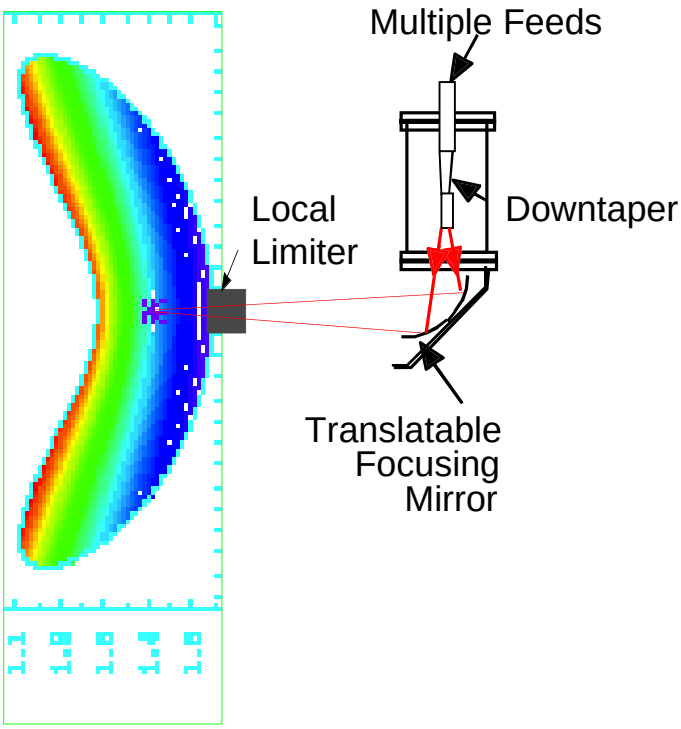

Figure 8.8. Conceptual Layout of 28-GHz $n_{||} = 0$ Launch EBW Antenna on QPS Midplane.

8.3. Ion Cyclotron Range of Frequency heating

ICRF is an important heating method for QPS. In QPS, ICRF can provide effective electron heating, ion heating, and may also be used for current drive or flow control. The ICRF options 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) using ion Bernstein wave mode conversion 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;

(5) fast wave and HHFW current drive and flow control (≥20 MHz).

There is good access for a variety of possible antenna structures between, and on the plasma side of, 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 were observed on CHS and are now in use on 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 recently 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. The opportunities and issues associated with the various heating options are discussed below.

The ICRF plans for QPS build on successful results from other stellarators, mirror experiments, ST's, and tokamaks. There are multiple requirements for the ICRF. Fortunately, these needs can be met with a limited number of antenna structures and within the frequency bands of available high power RF at ORNL: 2 MW at 6-20 MHz and 1.5 MW at 40-80 MHz. 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. Ion tail heating can be obtained with minority ion heating.

8.3.1. High harmonic fast wave heating

The initial heating for QPS will be ECH. 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 [4,5] with fields and plasma parameters similar to those expected on QPS. The electron temperature in an NSTX target plasma with n_e ~ 3.5 x 10^{19} m^{-3} was increased from 500 eV to 900 eV with the application of 2 MW of

HHFW heating (Figure 8.9). The results of a calculation, for QPS parameters, using the PICES full wave code [6] are shown in Figure 8.10. The moderate, single pass, attenuation of the wave is apparent in Figure 8.10a. The central deposition of the electron heating is evident in Figure 8.10b. The calculation indicates that for a plasma with $\langle\beta\rangle$ = 1% at 1 T, the HHFW single pass absorption at 60 MHz can be 20%. The single pass absorption as a function of $n_{ø}$ for the QPS plasma parameters at 0.5T and 1.0T in Table 8.2 is shown in Figure 8.11. The HHFW single pass absorption at 0.5 T with $\langle\beta\rangle$ = 1.2% can be >30%. Figure 8.11 shows that an antenna launch spectrum with a maximum near $n_{ø}$ of 20 would work well for HHFW electron heating in QPS for operation at both 0.5 T and 1 T.

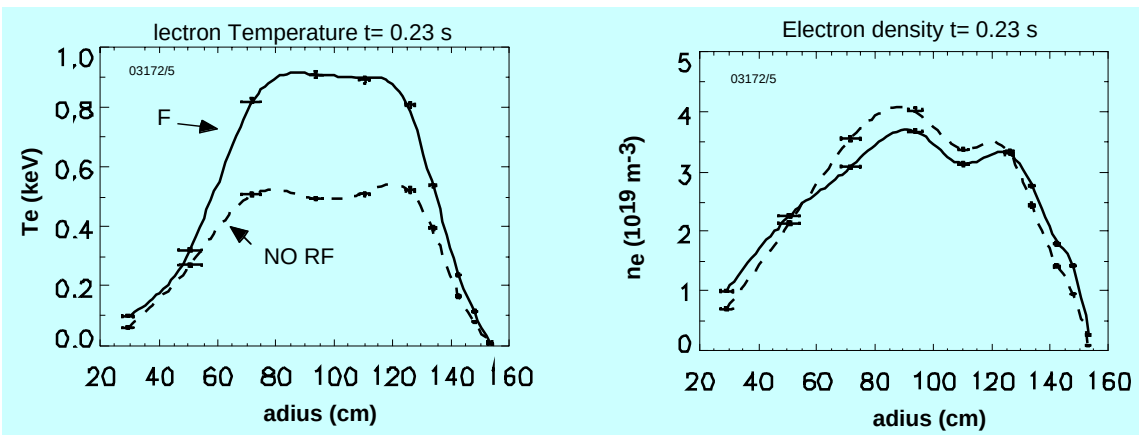

Figure 8.9. Plasma Heating with HHFW on NSTX.

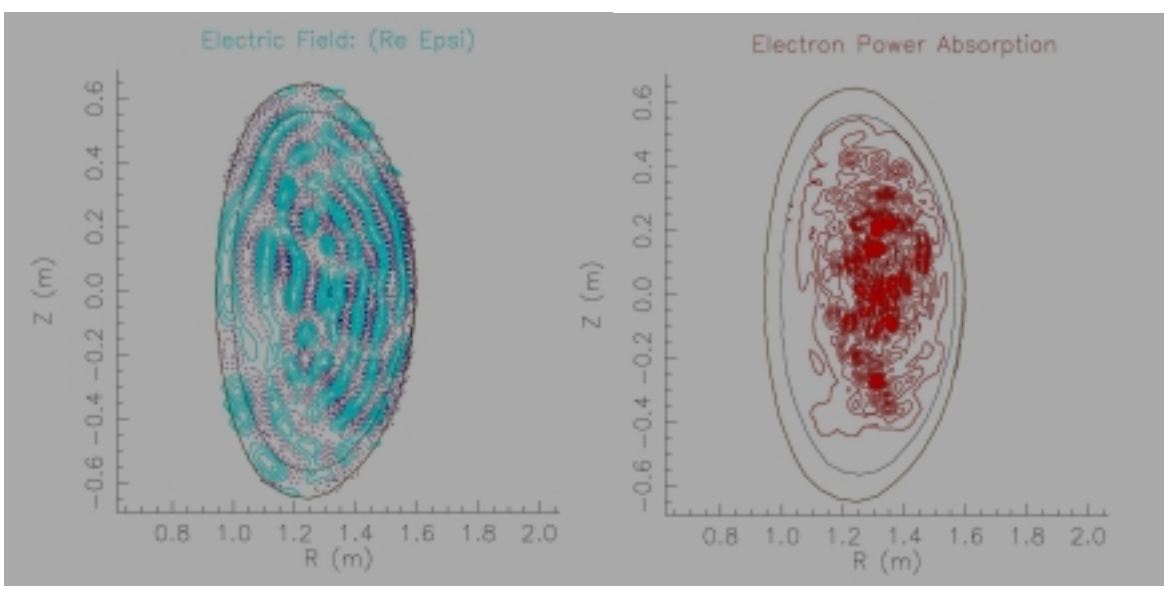

Figure 8.10. PICES calculation of the RF electric field (left) and the power absorbed in electrons in QPS at 1 T and $\langle\beta\rangle$ = 1% for 60-MHz HHFW heating.

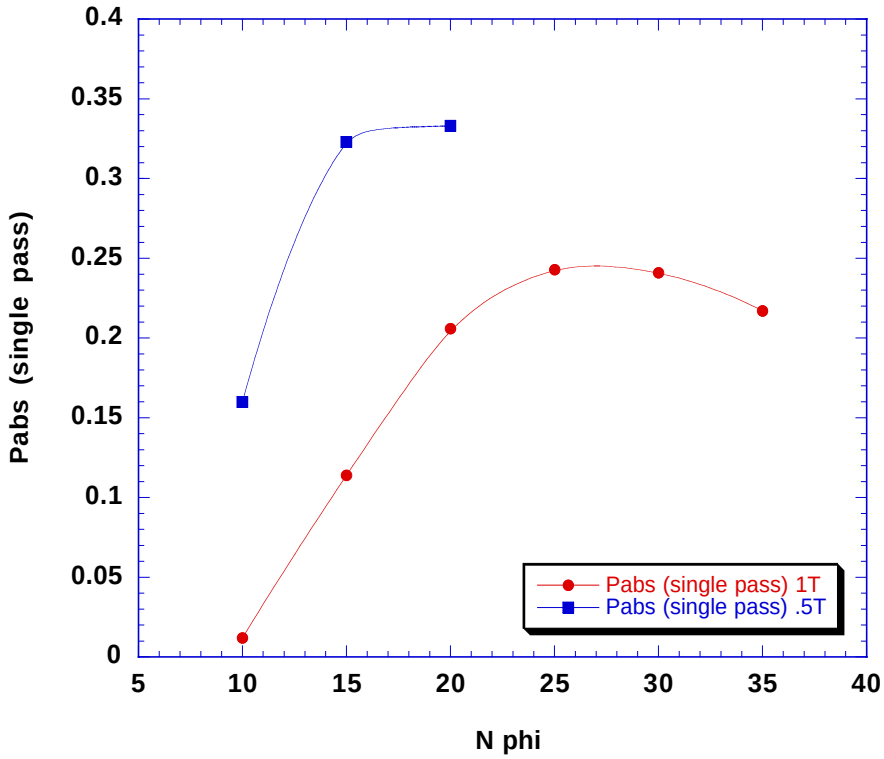

Figure 8.11. Single-Pass Absorption Calculations for HHFW Heating on QPS.

Table 8.2. QPS Plasma Parameters for the HHFW Calculations in Figure 8.11.

ECH power perpendicular electron heating	28 GHz 4 @ 300KW ea. 2nd 28	53 & 56 GHz 4 @ 200KW ea. 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
$\langle\beta\rangle$ (%)	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

A 1.5-MW FMIT transmitter is available in the 40-80 MHz range. The plasma loading in QPS should allow at least 1MW to be coupled to the plasma. The 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). This strap separation would provide an n_{ϕ} of ~ 20. The design would draw from the experience on W 7-AS as well as the substantial experience on tokamaks.

There are a suite of ICRF technology modeling tools available to aid in the design [7]. The models have been refined by comparisons to prototype antennas, and experimental results. The transmission lines, tuning and matching circuits and the antenna power coupling can all be modeled. The mechanical design will be simplified due to the lack of disruption currents. In addition, no active cooling would be required for pulse lengths less than 1 s.

The design could be very similar to the antenna boxes used on NSTX. The NSTX array is shown in Figure 8.12. The NSTX antenna has a low profile that would be advantageous on QPS. A single element is shown in Figure 8.13. In figure 8.12 the boron nitride frame around the antennas is visible. It has been used quite successfully as a local limiter to protect the antennas. For QPS, the antenna boxes could be placed between modular field coils as shown in Figure 8.14a. The cross section of an NSTX style antenna at the $\phi = 0$ plane is shown in Figure 8.14b.

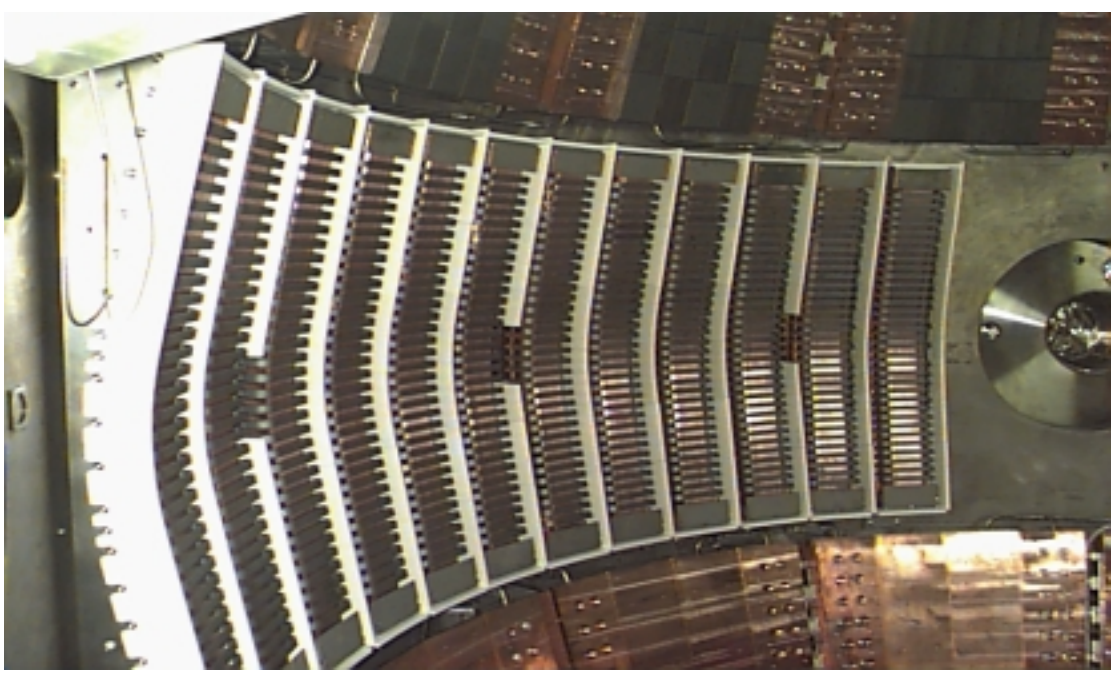

Figure 8.12. The NSTX HHFW Antenna.

Figure 8.13. One Element of the HHFW Antenna.

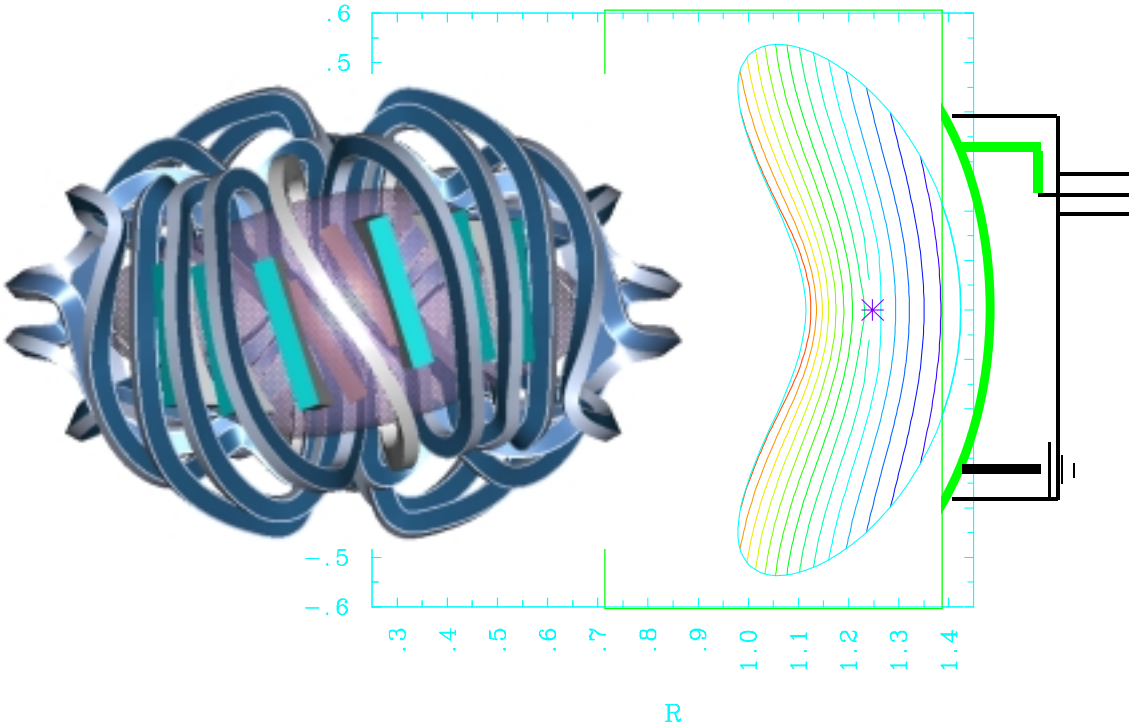

Figure 8.14. (a, left) HHFW Antenna Elements between QPS Coils. (b, right) Side view.

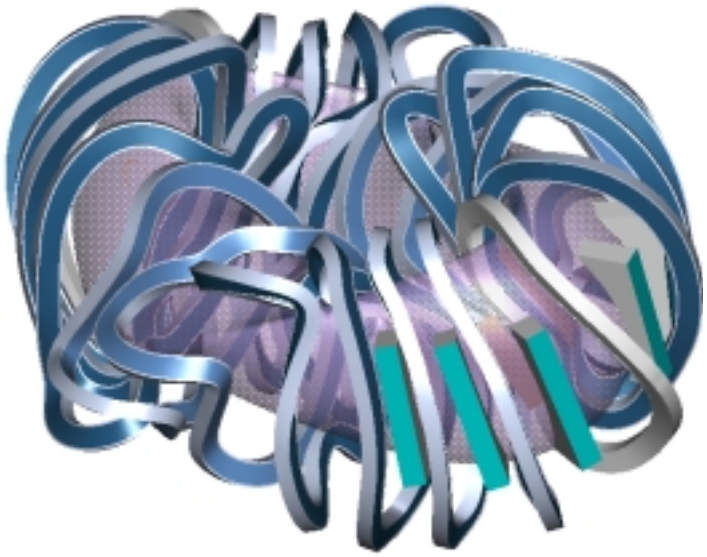

Figure 8.15. Multi-Strap HHFW Current Drive Array on QPS.

If at some time current drive and or flow drive is desired, there is adequate space for a multi-strap array (Figure 8.15) similar to that used on NSTX for HHFW current drive (Figure 8.12). An alternative design would be a low radial profile combline antenna. A low profile combline antenna is under consideration for NCSX [8]. A combline antenna has been successfully used on JFT-2M and one is planned for LHD [9].

8.3.2. 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-b operation. Mode conversion has been used for heating on CHS [10], W7-AS [11], LHD [12], and TFTR [13]. 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. 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. This is illustrated in the CHS discharge shown in Figure 8.16.

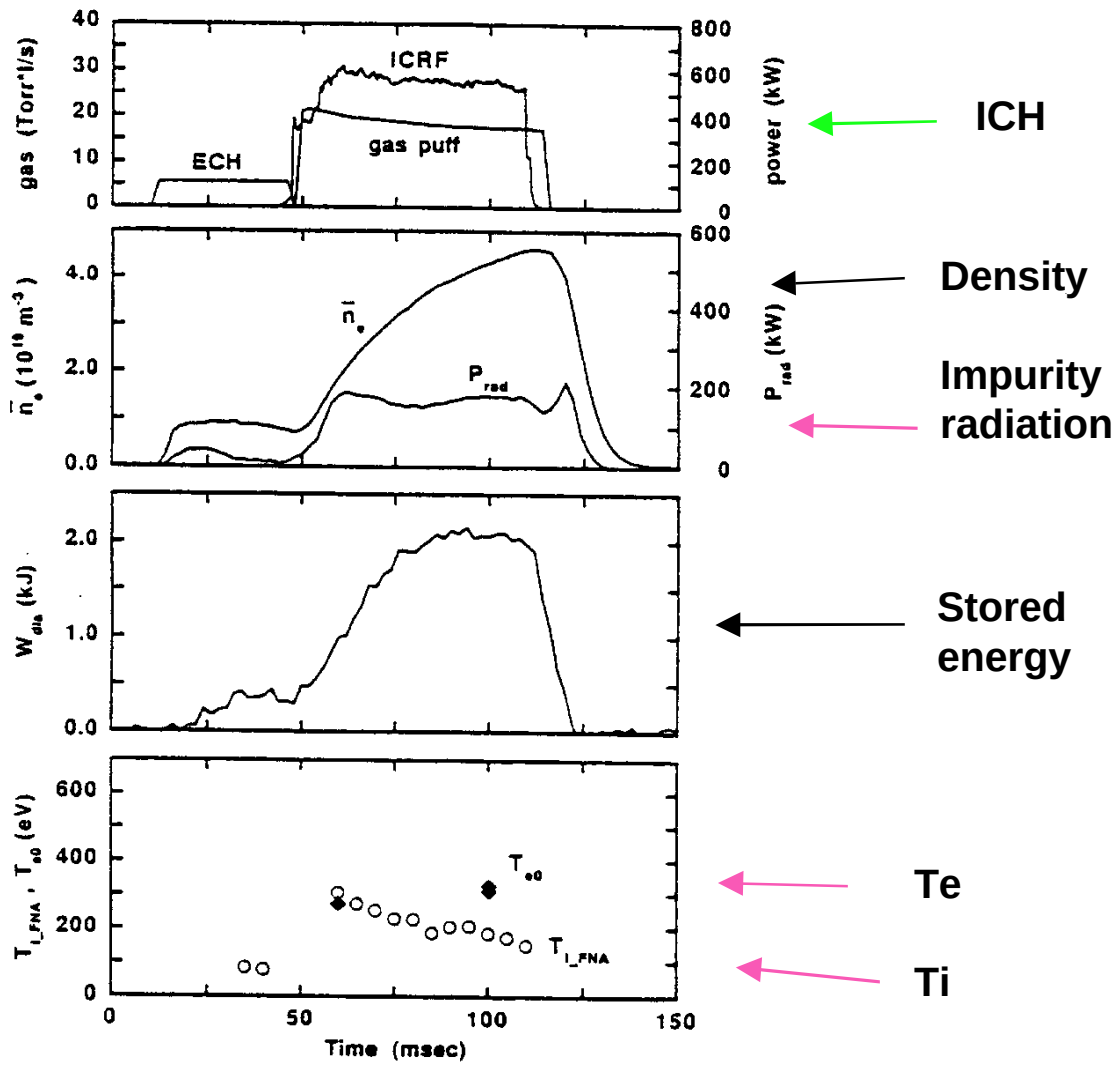

Figure 8.16. Mode Conversion Heating of Electrons and Ions in CHS

8.3.3. Magnetic beach heating

Two 1-MW BBC transmitters are available in the 6-20 MHz range. The plasma loading in QPS should allow at least 1.5 MW to be coupled to the plasma. The antennas would be located on the inboard side and in a high field region (Figure 8.17). For heating, a pair of single strap antennas, with one transmitter per strap, would be adequate. To avoid mechanical interference with the magnetic field coils, the straps would be mounted from the top or bottom (Figure 8.18a), similar to that in CHS and LHD. The antenna/strap spacing would be the same as that of the modular field coils on the inboard side. This strap separation would provide an n_ϕ of ~30. As described above the mechanical design would be simplified by the lack of disruptions and no requirement for active cooling. The CHS and/or LHD mode conversion antennas would provide a good starting point for the design.

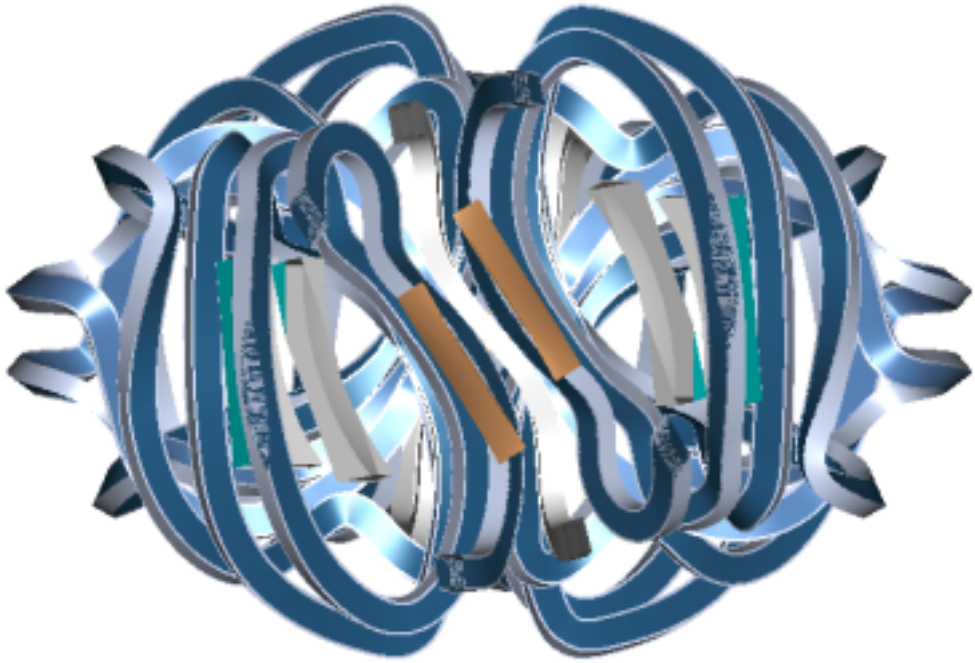

Figure 8.17.

Magnetic beach heating has been demonstrated on W7-AS [14]. 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 magnetic beach geometry for W 7-AS and the inside antenna location are shown in Figure 8.19. This figure shows a horizontal cross section of a half field period in W 7-AS with |B| contour lines for a mirror configuration with the two-ion-hybrid resonance (MC) and associated cutoff.

The main appeal of magnetic beach heating is the possibility to heat bulk ions. Heating bulk ions will increase the plasma β and will allow ion confinement properties of QPS to be studied. Heating of bulk ions will also allow comparison to the confinement of tail ions that may be generated in mode conversion or minority ion heating. The results of magnetic beach heating on W7-AS are shown in Figure 8.20. Beach heating was successful at heating both ions and electrons with an ECH target plasma and is 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 8.21. The toroidal field variation in QPS is more than adequate to meet the requirement. A toroidal cut is shown in figure 21a. The beach geometry in W 7-AS (Figure 8.19) is quite similar to the QPS geometry (Figure 8.21b). The main difference is due to the larger aspect ratio ($R/a \sim 10.6$) and higher number of poloidal field periods (N = 5) in W7-AS compared to QPS

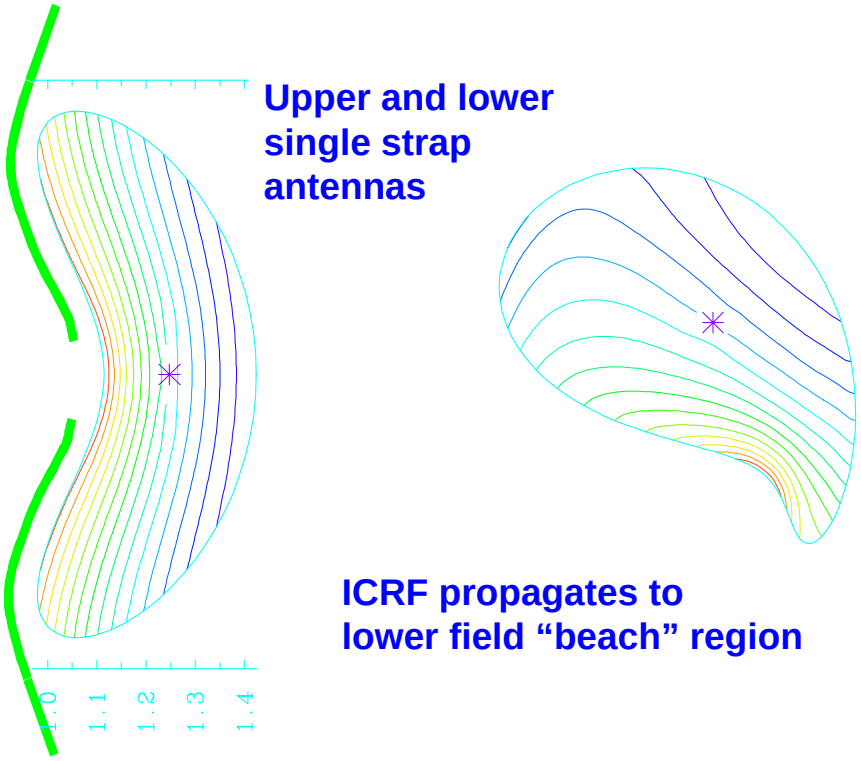

Figure 8.18. Magnetic Beach Heating Geometry for QPS.

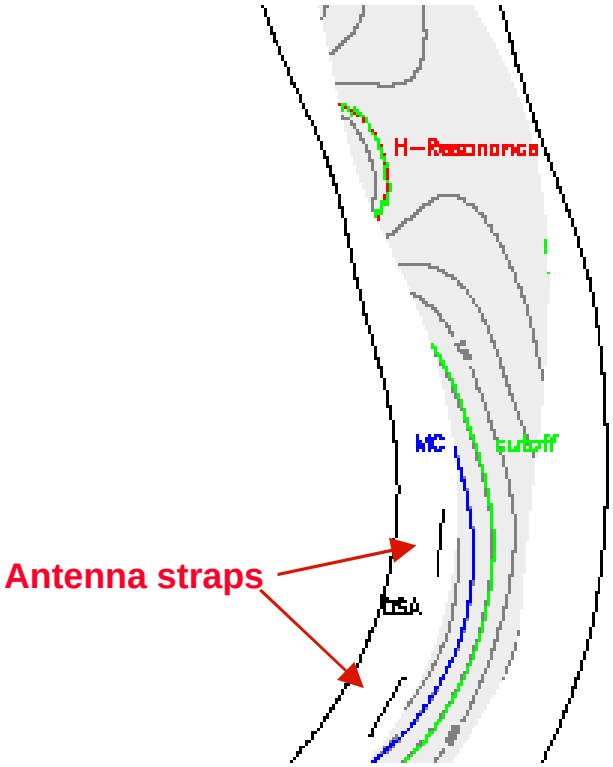

Figure 8.19. Magnetic Beach Heating Geometry in W 7-AS.

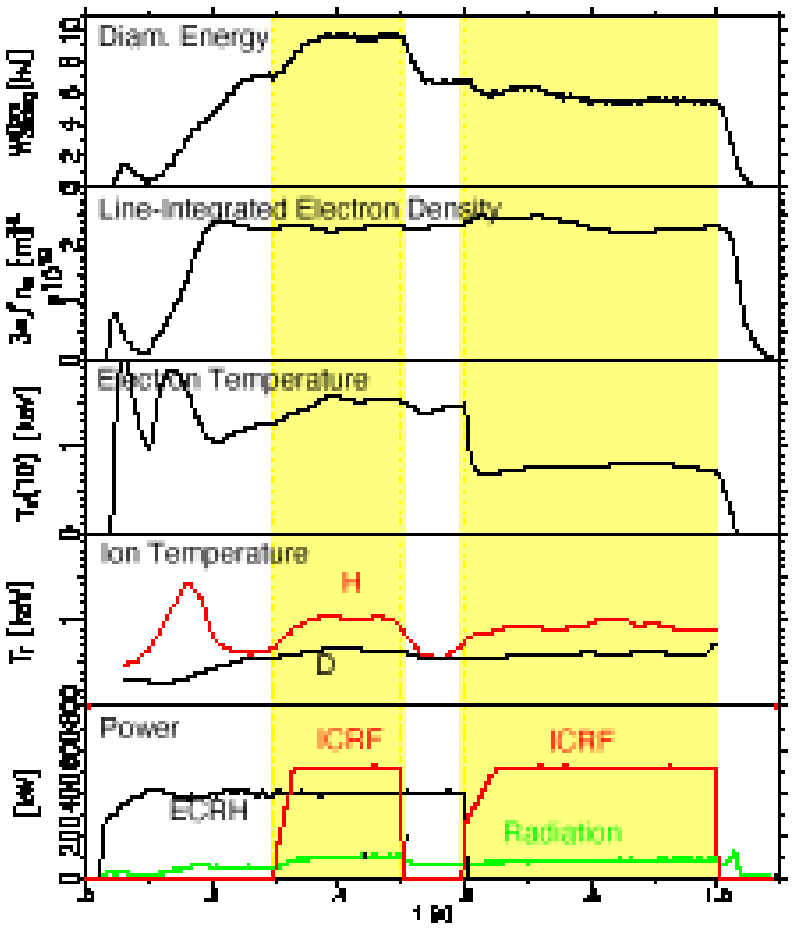

Figure 8.20. Magnetic Beach Heating Results in W 7-AS.

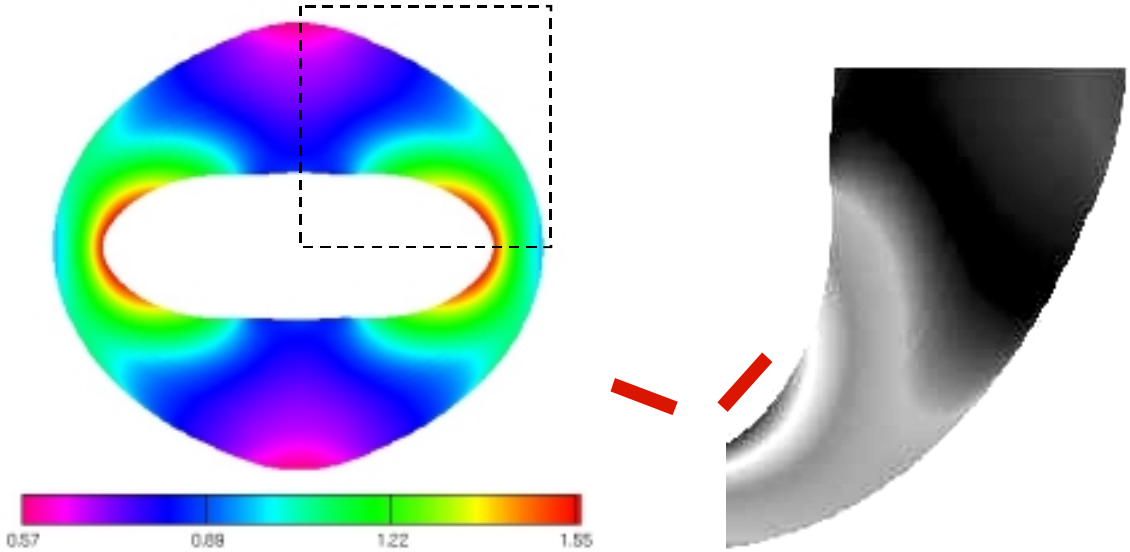

Figure 21. (a, left) |B| contours through the horizontal midplane cross section of QPS.
(b, right) The dashed region with the location of the antennas in the inside corner.

(R/a ~ 2.6, N = 2). The antenna locations on QPS are also shown in Figure 8.21b as red bars. The inside launch antenna location and design described above for mode conversion heating would also work well for magnetic beach heating. This eliminates the need for additional antennas. The only change would be to adjust the frequency to be set above the local ion cyclotron frequency.

8.3.4. 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 b. Minority ion heating can be tried with either the low-field or high-field antennas described above. Figure 8.4b shows the nearly vertical |B| contours in this cross section of QPS. This is very similar to the heating geometry on standard tokamaks.

8.4. Conclusions

QPS offers new opportunities for RF heating a low-aspect-ratio quasi-poloidal magnetic configuration. While ECH will be the mainstay for electron heating, EBW is a good option for high-β operation. ICRF has been very successful on similar-sized stellarators. The access and conditions look favorable for 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, HHFW, mode conversion & magnetic beach heating look possible.

There are a number of open issues that need to be addressed on RF heating for QPS: first pass absorption for ECH and ICRF, ICRF antenna size and directivity, outside or inside launch (or both?), and the EBW coupling efficiency.

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