Electron Cyclotron Resonance Heating for W7-X

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Abstract. The HELIAS-type Stellarator Wendelstein 7-X, which is currently under construction in Greifswald, Germany, will be equipped with a 140 GHz, 10 MW, CW ECRH system. It will be the main plasma heating system for W7-X. The key features and capabilities of the ECRH plant will be discussed together with the envisaged start-up and heating scenarios. We also report on the ECRH stray radiation test facility MISTRAL and on the extension of the gyrotron frequency range.

Keywords: ECRH, Gyrotrons, Transmission Lines
PACS: 52.35.Hr, 52.35.Qz

INTRODUCTION

W7-X is a low-magnetic-shear drift-optimized stellarator (major radius 5.5 m, minor radius 0.55 m), which is currently under construction in Greifswald, Germany [1]. Its aim is to demonstrate reactor relevant plasma parameters ($T_e = 2 - 10\,\mathrm{keV}$, $T_i = 2 - 5\,\mathrm{keV}$, $n_e = 0.1 - 3 \cdot 10^{20} m^3$) and a high relative plasma pressure β of up to 5% under steady state conditions.

A CW ECRH power of 10 MW at 140 GHz is required to achieve these parameters [2]. In the first two years of operation, W7-X will be equipped with a ballistically cooled test divertor unit, which allows for 10 s pulses at 8 MW.

The ECRH plant consists of 10 independent gyrotron modules with an output capability of 1 MW each. They are independent with respect to the cooling, the control and the power supplies. However, during the employment of the test divertor unit in W7-X the power supplies will only suffice to feed 8 gyrotrons. The RF power is transmitted by a purely quasi-optical multi-beam transmission line [2]. It is characterized by extraordinarily low mode conversion and transmission losses [3]. Figure 1 shows an overall sketch of the ECRH plant including cooling and power supplies.

GYROTRON OPERATION AT A SECOND FREQUENCY

The W7-X gyrotrons [4] are designed to produce the 140 GHz millimeter waves in the $\mathrm{TE}_{28,8}$ cavity mode. This is the second harmonic of the electron cyclotron frequency in W7-X at a magnetic field of 2.5 T. However, it is desirable to have a lower frequency available for physics investigations at reduced magnetic field, e.g. for high β operation

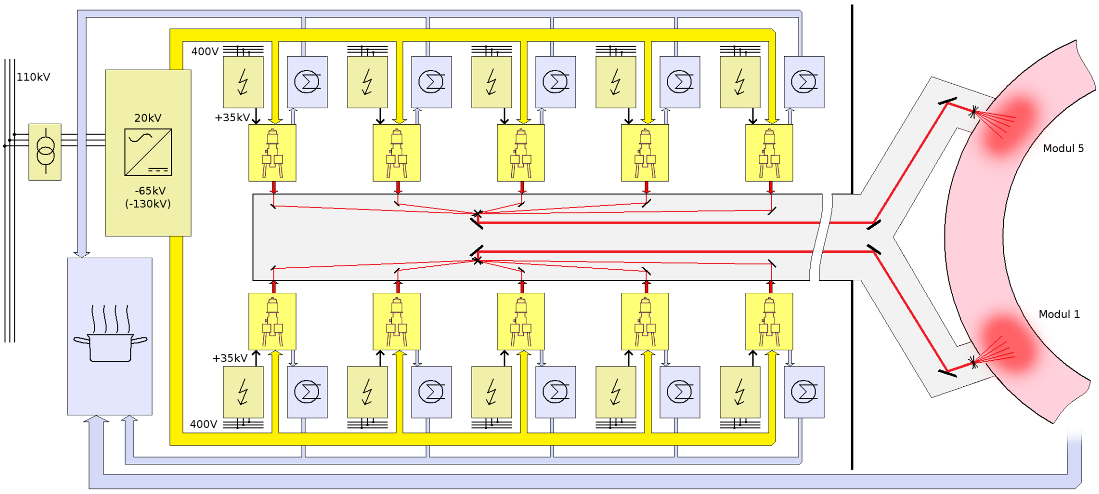

FIGURE 1. Overview of the ECRH system

(W7-X goal) or 3rd harmonic interaction at 140 GHz which would need the second harmonic at 93.3 GHz to produce a sufficiently hot target plasma.

It is possible to operate the gyrotron at a lower frequency (i.e. lower magnetic field) provided that the cavity mode has a similar caustic radius to achieve a sufficient interaction with the electron beam. The similar caustic radius and in addition a similar Brillouin angle at the taper output are also important for an efficient conversion by the quasi-optical mode converter in the gyrotron. Finally the output window of the gyrotron (which can be seen as a Fabry-Perot Resonator) must be transparent for the second frequency. All of these conditions are fulfilled by the $TE_{21,6}$ mode which oscillates at 103.8 GHz. With that mode we have achieved an output power of 370 kW at 10s or 525 kW at 5 ms. The limitation of the power lies in the collector loading. In total, a power of 4 MW will be available at 103.8 GHz.

The transmission line is of confocal design which means that the imaging properties are independent of the frequency over a wide range. Therefore the 103.8 GHz beams can be transmitted to the plasma with the present transmission line. Due to the finite mirror size the transmission losses are only slightly higher compared to 140 GHz.

It would even be possible to operate the gyrotron at a higher frequency in the same manner [5], but this would require a stronger grotron magnet.

IN-VESSEL COMPONENTS AND HEATING SCENARIOS

The ECRH system at W7-X is designed with maximum flexibility in mind. Beyond plasma heating in the standard X2 and O2 schemes, it allows for high-field-side injection, beam launching along $|\mathbf{B}| \approx$ const surfaces as well as probe beam for collective Thomson scattering and it is the only source for non-inductive current drive as W7-X has no ohmic transformer. The latter is of major importance in order to compensate the bootstrap current and to shape the rotational transform ι on a shorter timescale such that

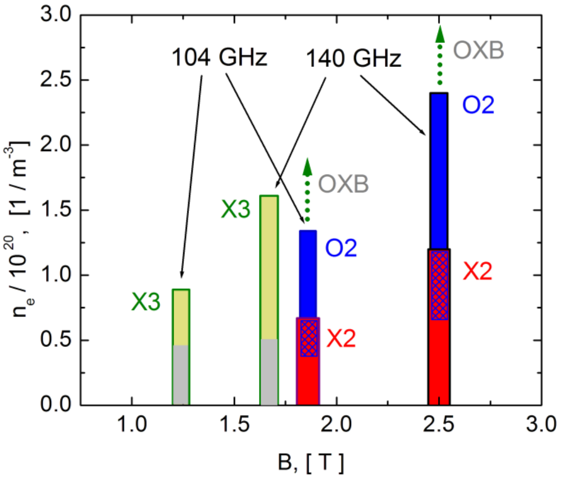

FIGURE 2. Accessible density range depending on the magnetic field

it fits the needs of a proper divertor operation. On larger timescales this can be achieved with external coils.

The accessible density range for both frequencies depending on the magnetic field is sketched in Figure 2. Electron temperatures above 6 keV are expected for the standard O2 scenario [6] at 140 GHz. The target plasma for the X3 scenario at 140 GHz, 1.66 T can possibly be produced with the help of 103.8 GHz X2 injection.

Above the O2-cutoff, mode conversion heating is foreseen via the O-X-B mode conversion process with no upper density limit (although there is a lower one) and a high current drive efficiency.

The aforementioned flexibility is achieved by a set of 12 front steering launchers in the bean shaped plasma cross section (maximum $|\mathbf{B}|$) and 2 remote-steering-launchers close to the triangular cross section. The latter can be used for high field side and $|\mathbf{B}| \approx$ const launch for investigations on phase space interaction as well as probe beams for collective Thomson scattering. The front steering launchers are the work horses of the ECRH for current drive and heating. As the single-pass absorption in the O2 mode can be less than 80%, reflecting TZM tiles (titanium, zirconium, molybdenum alloy) are placed at the opposite wall to allow for multi-pass absorption. This material is a trade-off between a low atomic number and a high heat resistivity and microwave reflectivity. In addition, there are polarization-compensated pick-up probes integrated in the opposite wall to measure the transmission/absorption and to eventually fine-tune the polarization.

THE “MISTRAL” FACILITY

During ECRH operation there is always a risk of high stray radiation in the plasma vessel. The O-X-B process is very sensitive to the proper injection angle. In the O2 and X3 regimes there is low single-pass absorption and somtimes the polarization and/or the injection angle are simply not well tuned. Especially at the critical transition from X2 to O2 or from O2 to O-X-B heating, all in-vessel components must be able to withstand the microwave stray radiation. Therefore we built a MIcrowave STray RAdiation Loading (MISTRAL) test facility to assess all critical in-vessel components.

From power balance estimations we expect a stray radiation level of roughly $100\,\mathrm{kW/m^2}$ in W7-X. Again with power balance estimations, this stray radiation level is generated in the MISTRAL vacuum chamber by a proper pulse width modulation of one of our gyrotrons.

The diagnostics include sniffer probes to monitor the power flux density, a video camera, an infrared camera, thermocouples and a vacuum gauge. Installation of a mass spectrometer is planned. The timely evolution of pressure and temperature at critical locations is recorded.

PROGRESS OF THE CONSTRUCTION

The ECRH towers which contain the beam dividing optics of the two multi-beam waveguides and the input optics for the launchers are completed.

Two out of four front steering launcher assemblies (3 beams each) have been manufactured and undergo currently the vacuum and stray radiation tests in the MISTRAL facility.

The gyrotron inventory consists of one CPI gyrotron and two prototype as well as seven series gyrotrons from a TED/FZK/CRPP joint venture. One of the series gyrotrons has passed the acceptance test. Four additional series tubes have been manufactured and are currently in the phase of a redesign of the electron beam compression tunnel which has been identified as a source of spurious gyrotron-like oscillations [7].

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