OPERATIONAL DOMAIN OF PROTO-MPEX

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Operational domain of Proto-MPEX

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The Prototype-Material Plasma Exposure eXperiment (Proto-MPEX) is a linear plasma device to test the plasma source concepts for the future Material Plasma Exposure eXperiment (MPEX). MPEX is planned to address plasma material interactions under fusion reactor divertor conditions as will occur in devices like DEMO, including the plasma exposure of a-priori neutron irradiated materials. This requires a novel linear plasma device with a plasma source that can produce high electron densities along with heating systems to obtain high electron and ion temperatures. In Proto-MPEX a high-power helicon source was tested together with electron heating (28 GHz microwaves) and ion cyclotron heating (8.5 – 12 MHz). Electron densities in excess of 1 x 10^{20} m^{-3} were produced with the helicon antenna. Electron temperatures can reach 20 eV and are typically below 6 eV at high densities (> 5 x 10^{19} m^{-3}). Ion heating has been demonstrated at low electron densities (< 2 x 10^{19} m^{-3}) with ion temperatures of up to 13 eV. Maximum heat fluxes of 14 MW/m^2 have been obtained in low density discharges (~ 5 x 10^{18} m^{-3}), while heat fluxes are typically only 2-3 MW/m^2 in high density discharges (> 2 x 10^{19} m^{-3}).

Keywords: Materials, Plasma-Material Interaction, Divertor, Linear Devices, DEMO.

1. Introduction and experimental setup

Plasma Material Interactions under the harsh conditions of a future fusion reactor might limit the lifetime of plasma facing components unacceptably [1,2]. Testing plasma facing materials to those conditions is imperative in the fusion development process. The planned Material Plasma Exposure eXperiment (MPEX) will be designed to address this critical R&D need [3,4]. MPEX will utilize a novel plasma source and heating concept, which is being tested on the Prototype-Material Plasma Exposure eXperiment (Proto-MPEX) [5]. Previous calculations [6] have shown that in order to achieve ITER relevant divertor plasma conditions in MPEX the source system has to demonstrate the production of plasmas with electron densities in the range of 4 – 6 x 10^{19} m^{-3}. Furthermore, Proto-MPEX needs to demonstrate electron heating and ion heating up to values of about 25 eV.

Proto-MPEX makes use of 12 copper coils from the former EBT experiment [7]. The plasma is produced by a helicon plasma source, which can be operated to a maximum of 130 kW at a frequency of 13.56 MHz. In addition, electron heating via electron cyclotron heating (ECH) or electron Bernstein waves (EBW) with a 28 GHz gyrotron is foreseen. The maximum power of the 28 GHz gyrotron is 200 kW. Ion heating is achieved with a 30 kW ICRF antenna. The transmitter for the ICRH is tunable in the range of 8.5 – 12 MHz, making it possible to adjust the resonance location to the magnetic field scenario choice. A cross section of Proto-MPEX with a typical magnetic field is shown in figure 1. The plasma is characterized with a suite of diagnostics. The electron density (n_e) and temperature (T_e) are being measured mainly by Double Langmuir Probes (DLP) in various axial locations (probes A-D). A radial profile can be obtained by scanning the probe location from shot to shot. Some of those probes also allow for velocity measurements (Mach probes). In addition, a Thomson Scattering diagnostic [8] allows non-perturbative measurements of T_e and n_e in front of the target and in the central chamber, where the ECH launcher is located. IR cameras and thermocouples are used to measure the heat fluxes to the target, the dump plate and the surrounding wall [9]. Ion temperatures are measured with a high-resolution McPherson spectrometer [10]. The targets vary. First a castellated tungsten target was installed, then a stainless-steel target and later a graphite target with embedded Double Langmuir probes and an ion collector probe. The typical pulse length of Proto-MPEX is 300 ms. The uncooled helicon AlN_2 window allows for maximum 2 s long pulses. Auxiliary heating by ECH/EBW is limited to 50-70 ms typically, depending on the heating power level. The maximum pulse duration of the 30 kW ICH system is 25 ms. The magnets are designed for steady-state operation. Hence, with the planned water-cooled Al_2O_3 helicon window [11] long pulse operation should be possible on Proto-MPEX.

2. Results of Proto-MPEX

2.1 Helicon operation

At low electron densities, maximum heat fluxes to the target were 14 MW/m^2. The heating flux profile is hollow and reflects the coupling of helicon antenna to Trivelpiece-Gould modes [12] in the plasma edge. Fueling the plasma at the helicon antenna allowed access to the centrally peaked helicon high density mode at net coupled helicon antenna powers of more than 90 kW.

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Maximum electron densities of 8 x 10^{19} m^{-3} were obtained in these plasmas as measured by probe B. At the target, electron densities of more than 1 x 10^{20} m^{-3} were measured with Thomson Scattering. These are record electron densities obtained in a deuterium helicon plasma. The heat fluxes in those high-density discharges are typically low (~1 MW/m^2) accumulating to an energy of about 1.5 KJ maximum to the target for those short plasma durations.

2.2 Electron heating

As mentioned above electrons need to be heated up to 25 eV. For low electron densities, the electrons can be heated with second harmonic ECH with 28 GHz microwaves at a magnetic field of about 0.6 T.

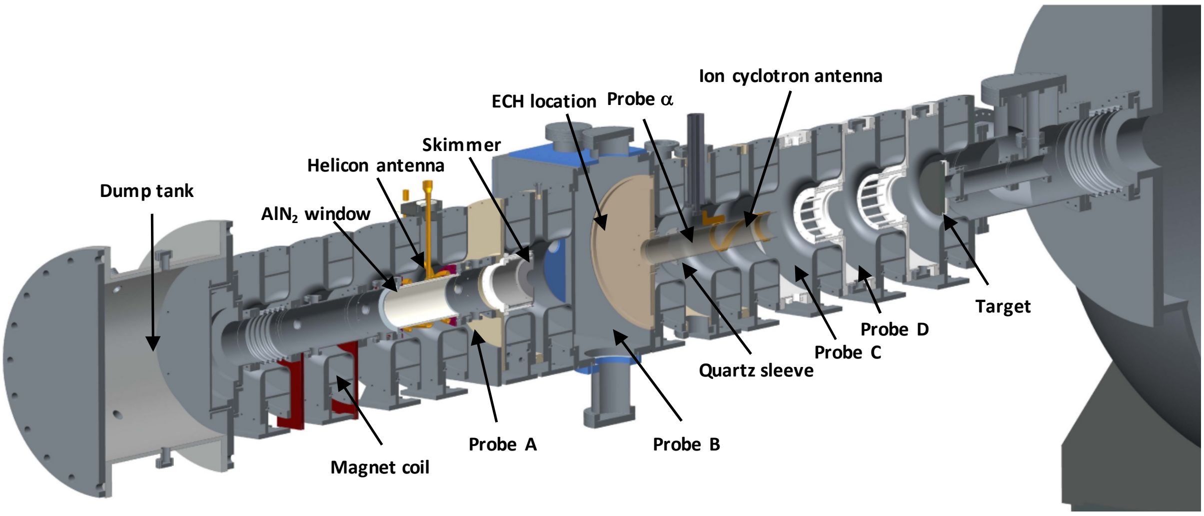

Fig. 1. Proto-MPEX, a cut through the middle showing important in-vessel components and heating elements. The locations of the most important diagnostics are labelled. In a previous configuration, the target was located where the ion cyclotron antenna together with the quartz sleeve is located now (see also [4]). During this time Probe α was operational.

The cutoff density for the 2nd harmonic ECH is about 0.9 x 10^{19} m^{-3}. Experiments in Proto-MPEX have demonstrated this heating scheme in low fueling regimes leading to electron densities of 0.5 x 10^{19} m^{-3} as measured with Probe α (see figure 2). Measurements with probe B in the central chamber, where the ECH launcher is located, demonstrated that the n_e is below the above mentioned cutoff density. With about 35 kW of 28 GHz microwave the central T_e is increased from about 5 eV to about 7 – 7.5 eV (fig. 2). The electron density does not change during the EC heating. At higher fueling rates ECH is most likely in cutoff and no electron heating is observed. However, the ECH does lead to some more ionization of the fueled gas leading to higher electron densities during the ECH pulse.

For the high electron densities, which are required for MPEX, the 28 GHz microwaves must undergo a double mode conversion to Electron Bernstein Waves. For this to happen the waves to enter the plasma at a certain angle. For more details see a description in [4,13,14]. Experiments have been guided by modeling to find the best launch angle to improve plasma core absorption [13]. It has been found that with about 25 kW of EBW launched the electron temperature in the plasma core can be increased by about a factor of 3.5, from 5.6 eV to 19.2 eV in the best case.

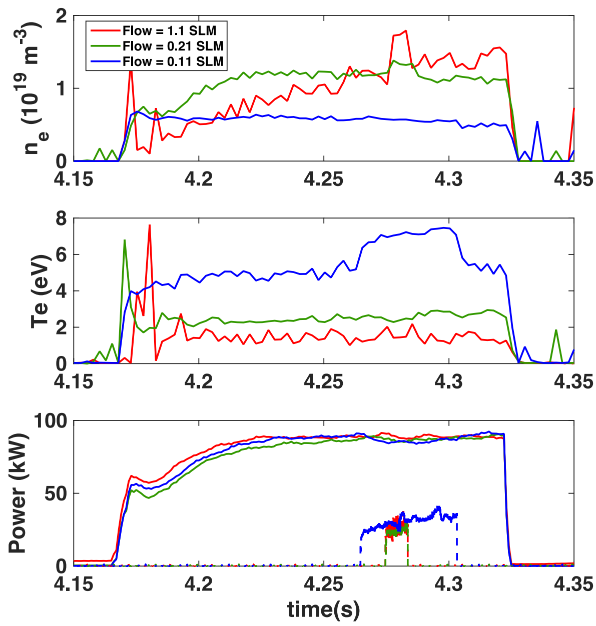

Fig. 2. Electron heating with 28 GHz second harmonic ECH at 0.5 T. The heating power is shown for the helicon antenna in solid lines and for the 28 GHz system in dashed lines.

This increase in T_e was measured in the central chamber where the ECH/EBW launcher is located with Thomson Scattering. At the target, the increase of T_e is less pronounced but still about 50 – 100%.

In figure 3 the operational domain of Proto-MPEX is shown including experiments with helicon only and helicon plus ECH/EBW. The values are derived from DLPs at various axial locations. Shown are only values from the core of the plasma in a region of +/- 1 cm radially from center. Without any additional heating, T_e is limited to below 8 eV at $n_e < 10^{19}$ m^{-3}. T_e is only about 4 eV or less for plasmas in the high-density helicon mode of operation. Noticeable is also the loss of electron pressure from the probe location A (indicated by the blue open symbols) to probe locations further downstream (probe B-D).

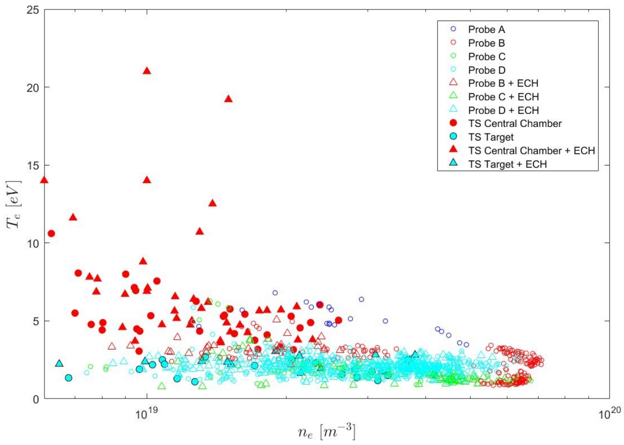

Fig. 3. Proto-MPEX operational domain. Data points here were collected along the axis of Proto-MPEX and limited to data from the core plasma +/- 1 cm radially from center.

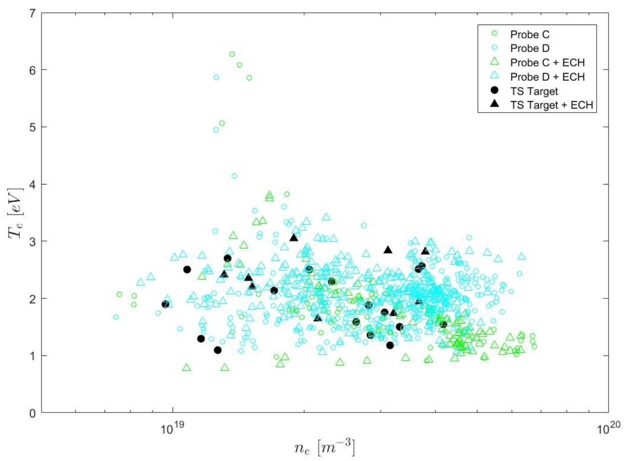

Fig. 4. Proto-MPEX operational domain close to the target. Data points here were collected along the axis of Proto-MPEX and limited to data from the core plasma +/- 1 cm radially from center. Data points here are a subset of these of figure 3.

At the target, the electron temperatures are limited to 3 eV or less (see fig 4) at high plasma densities. This is seen with DLPs and Thomson Scattering. Generally, with ECH/EBW T_e is higher, increasing the temperature above the range, where volume recombination takes place. Any further heating power should be increasing T_e at the target non-linearly since volume recombination will be suppressed.

2.3 Ion heating

Ion heating has been achieved with 8.5 MHz ICRF. A maximum power of 25 kW was injected in deuterium plasmas. The ion temperature was measured on trace amounts of argon seeded into the deuterium plasma. It was found that the ion temperature profile is mostly hollow and that substantial ion heating was observed in the edge of the plasma [10]. The current ICH system is only able to couple about 25 – 30 kW into the plasma. The antenna and the feedthrough have not been designed to withstand more power. However, in the future an upgrade to 200 and subsequently 400 kW is foreseen.

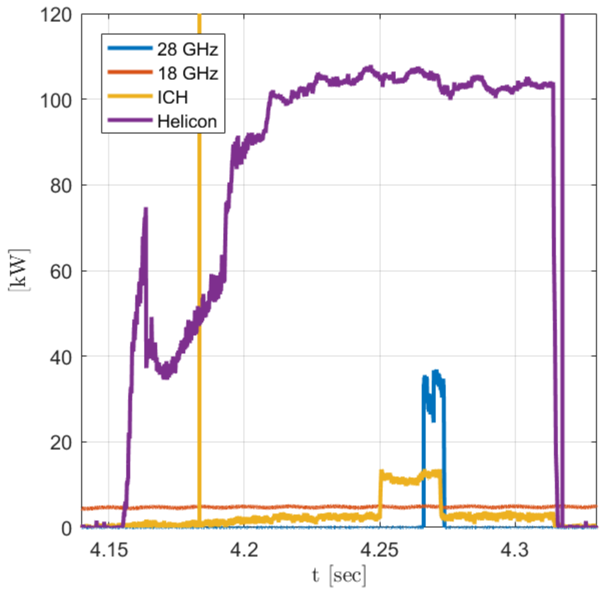

Fig. 5. Total heating power injected with all RF sources on Proto-MPEX: 105 kW helicon, 36 kW 28 GHz microwaves, 5 kW 18 GHz microwaves, 13 kW ICH.

At this moment, all power sources together deliver in total about 160 kW (see fig. 5). During the combined heating experiments the heat flux to the target in those high-density discharges can be as high as 3 MW/m^2.

3. Modeling and prediction

Previously, system optimization studies for MPEX have been carried out with plasma fluid models coupled to Monte Carlo neutral models [6]. Mostly B2-Eirene and EMC3 Eirene were used for this point design exercise. Scoping studies using simpler 2-point models and 1-dimensional fluid models coupled to 2-dimensional neutral models were actually preceding the more sophisticated B2-Eirene calculations. For survey calculations, this approach is actually more suitable. Parallel transport is typically dominating over the perpendicular transport in linear devices with magnetized plasmas. A typical ion transient time in such a device with a length of about 3 m is about 100 µs, assuming $T_e = T_i$ = 20 eV and M = 0.5. During this transient time, the ion diffuses radially about 4 mm only. For comparison, the mean-free path of 3 eV Franck-Condon neutrals is several cm. Hence the radial transport can be well described by neutral cross field transport and charge exchange (CX) processes. In 1-dim fluid model the continuity equation, electron energy balance equation, ion energy balance equation and the momentum balance equation are solved. The viscosity is typically neglected here. The CX rates are computed with the 2-dim neutral code DEGAS. As boundary conditions the upstream particle source and heat source are given with Gaussian radial profiles. At the target Bohm conditions are assumed. For the neutrals, the 10 cm wide plasma is modeled with 10 concentric radial grid zones. A carbon target is placed normal to the magnetic field lines.

Figure 7 shows results from such a 1-dimensional fluid model / 2-dimensional neutral model run.

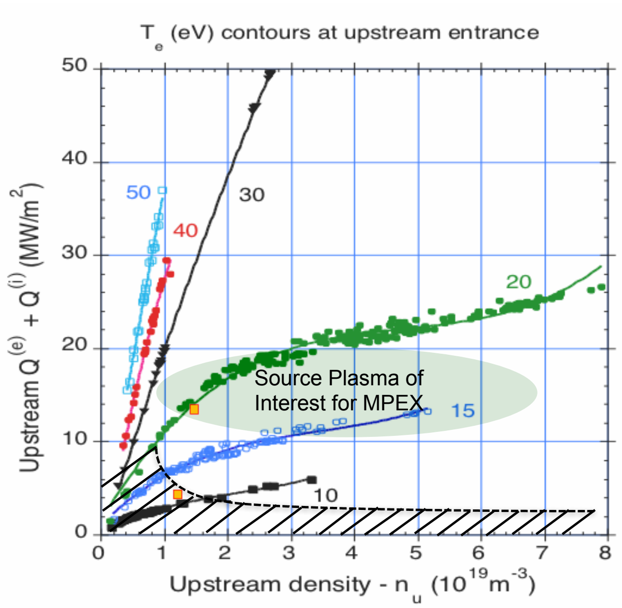

Fig. 7. Projected operation domain of Proto-MPEX from one dimensional plasma / two dimensional neutral simulations: Upstream heat fluxes (y-axis), upstream density (x-axis) and upstream electron temperatures (contours). In addition, the helicon operation domain is indicated by the black hatched area. The recent electron heating experiments with electron temperatures up to 20 eV are indicated by yellow squares.

The helicon mode of operation is reflected by the black hatched area. The upstream density n_u is here defined as the electron density at the location of Probe B or Probe α. At low electron densities, below the cutoff density for the 28 GHz, high electron temperatures can be achieved. At low electron densities, the helicon antenna couples most of its power into the so-called Trivelpiece-Gould mode, which propagates only at the very edge of the plasma in the electron density range of ~ 10^{17} m^{-3}. Hence, the T_e-profile is hollow and ECH can heat the plasma edge easily to 20 eV. In the plasma center heating to significant electron temperatures has only been obtained with EBW. Although the electron heating to 20 eV in the plasma core at n_e = 1.5 x 10^{19} m^{-3} is a major milestone to demonstrate the heating concept for MPEX, it needs to be extended towards higher electron densities. Sustained high T_e at n_e of 4 x 10^{19} m^{-3} is the goal.

4. Conclusions

The Proto-MPEX operational domain has been extended to high densities ~ 10^{20} m^{-3} and high plasma core temperatures ~ 20 eV. The achieved densities are significantly higher than achieved at most other linear devices and the electron temperature of 20 eV at densities of 1.5 x 10^{19} m^{-3} is the highest achieved with any linear plasma device for plasma material interactions studies for fusion reactors [15-18].

Acknowledgments

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