PERFORMANCE OF THE PLASMA SOURCE AND HEATING CONCEPT FOR THE PROTOTYPE-MATERIAL PLASMA EXPOSURE EXPERIMENT (PROTO-MPEX)

J. Rapp[1], C.J. Beers[1,2], T.M. Biewer[1], T. Bigelow[1], J.F. Caneses[1], J.B.O Caughman[1],
D. Donovan[2], R.H. Goulding[1], A. Lumsdaine[1], N. Kafle[1,2], G.-N. Luo[3], L.W. Owen[1],
P. Piotrowicz[1,4], H.B. Ray[1,2], M. Showers[1,2], and the MPEX team

[1] Oak Ridge National Laboratory, Oak Ridge, TN, USA
[2] University of Tennessee, Knoxville, TN, USA
[3] Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China
[4] University of Illinois, Urbana Champaign, IL, USA

E-mail contact of main author: rappj@ornl.gov

Corresponding author:

Juergen Rapp*
Oak Ridge National Laboratory
1 Bethel Valley Road
Oak Ridge, TN 37831 USA
*rappj@ornl.gov

Performance of the plasma source and heating concept for the Prototype-Material Plasma Exposure eXperiment (Proto-MPEX)

J. Rapp[1], C.J. Beers[1,2], T.M. Biewer[1], T. Bigelow[1], J.F. Caneses[1], J.B.O Caughman[1],
D. Donovan[2], R.H. Goulding[1], A. Lumsdaine[1], N. Kafle[1,2], G.-N. Luo[3], L.W. Owen[1],
P. Piotrowicz[1,4], H.B. Ray[1,2], M. Showers[1,2], and the MPEX team

[1] Oak Ridge National Laboratory, Oak Ridge, TN, USA
[2] University of Tennessee, Knoxville, TN, USA
[3] Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China
[4] University of Illinois, Urbana Champaign, IL, USA

E-mail contact of main author: rappj@ornl.gov

Abstract. The Material Plasma Exposure eXperiment (MPEX) is a linear plasma device planned to address plasma-material interactions for future fusion reactors. Its concept foresees the capability to expose *apriori* neutron irradiated material samples to fusion reactor grade divertor plasmas. This new capability will be unique world-wide addressing important research needs in the area of fusion nuclear science. It will be an evolution to current operating steady-state linear plasma devices, which are limited either in plasma fluxes they can deliver to the material targets or plasma temperatures (for ions and electrons) they can reach in front of the material targets. The concept of MPEX foresees a combination of a high-power helicon plasma source with microwave electron heating and ion cyclotron resonance heating. This source and heating concept is being tested on the Prototype-Material Plasma Exposure eXperiment (Proto-MPEX). With 100 kW helicon power, a plasma density of 8×10^{19} m^{-3} was achieved, which is about a factor two more than required for MPEX. Electron heating was pursued with a 28 GHz gyrotron. A maximum power of 50 kW was delivered to the plasma, which is produced by the helicon. At this frequency, the plasma is overdense in the plasma center ($> 1 \times 10^{19}$ m^{-3}). Maximum electron temperatures of 20 eV have been achieved under those overdense plasma conditions with Electron Bernstein Wave (EBW) heating. This is almost the electron temperature required for MPEX (25-30 eV). Ion cyclotron heating (ICH) was performed in the frequency range of 6 – 12 MHz with a low power ICH antenna able to launch about 25-30 kW of power. Without ICH, the ion temperature is about 2-4 eV. With ICH, ion temperatures of 8-12 eV were measured. The ion fluxes to the target are about 5×10^{23} $m^{-2}s^{-1}$. The plasmas produced by the helicon antenna have been modeled extensively with a fluid plasma code, coupled to a Monte-Carlo neutral code (B2-Eirene). The plasma transport can be well explained by this fluid approach and a radial diffusion coefficient consistent with Bohm-like transport.

1. Introduction

Magnetic fusion devices beyond ITER will have energy densities much above that of ITER and will experience high neutron fluence. Any of those planned devices must accomplish robust power and particle exhaust in the divertor and simultaneously provide solutions to the divertor which allow long lifetime of the components. At this moment, no fusion device nor test stand is able to address the challenges posed by the intense plasma-material interactions and the damage created by the high neutron fluence. The Material Plasma Exposure eXperiment (MPEX) [1,2] will attempt to reach into a domain, where plasma facing components can be tested to their end-of-life under fusion reactor conditions. It will be designed to handle neutron activated material samples [3]. MPEX will make use of a novel plasma production and plasma heating scheme. The deuterium plasma is produced by a high-power helicon antenna (up to 200 kW max). Electron heating will take place with microwaves, either with a 200 kW 28 GHz gyrotron system making use of Electron Bernstein Wave absorption, or with second harmonic X-mode ECH using a 400 kW 105 GHz gyrotron system or with Upper Hybrid absorption using the 105 GHz system. Ion heating is obtained with an ICH system operating in the frequency range of 6 – 12 MHz. Transport simulations for MPEX showed that in principle such a device should be able to reach reactor relevant plasma parameters [4]. For validation of the plasma source and heating concepts, experiments on the Proto-MPEX [1,5] device are carried out. Proto-MPEX is a predecessor of MPEX consisting of the same plasma production and heating systems. In contrast to the superconducting MPEX, Proto-MPEX is a pulsed device making use of copper coils. In this device high deuterium densities, high electron temperatures and ion temperatures have been obtained in the source region already [6-9].

2. The Prototype-Material Plasma Exposure eXperiment, Proto-MPEX

Proto-MPEX consists of 12 copper coils from the former EBT experiment. In principle they are able to operate in steady-state. Magnetic fields of about 1.5 T can be reached. A Nagoya-type helicon antenna is installed which is powered by a 100 kW 13.56 kHz RF generator. The electrons are heated with microwaves with a 200 kW 28 GHz gyrotron. Ions are heated with a 30 kW ICH antenna. Proto-MPEX is equipped with a large plasma diagnostic suite. Te and ne are measured in several axial locations with radially scanning double Langmuir Probes (DLPs). The DLPs have been proven to be compensated for any RF fields originating from the helicon and ICH systems. In front of the target and in the central chamber, where the EBW launcher is located, Te and ne profiles are measured by Thomson Scattering. The neutral pressure is measured by baratrons on several axial locations. Filterscopes (mostly for D_α) and high-resolution spectroscopy uses light-fibers located on many axial locations with some locations offering radial fans of line-of-sights. Ion temperatures are measured by Doppler broading on trace impurities (e.g. Ar-II) utilizing the light-fibers and a McPherson spectrometer. Proto-MPEX has also some SXR-diodes for the characterization of high energy electrons and bolometers for measurements of radiation losses. Power fluxes to the target are measured by IR thermography.

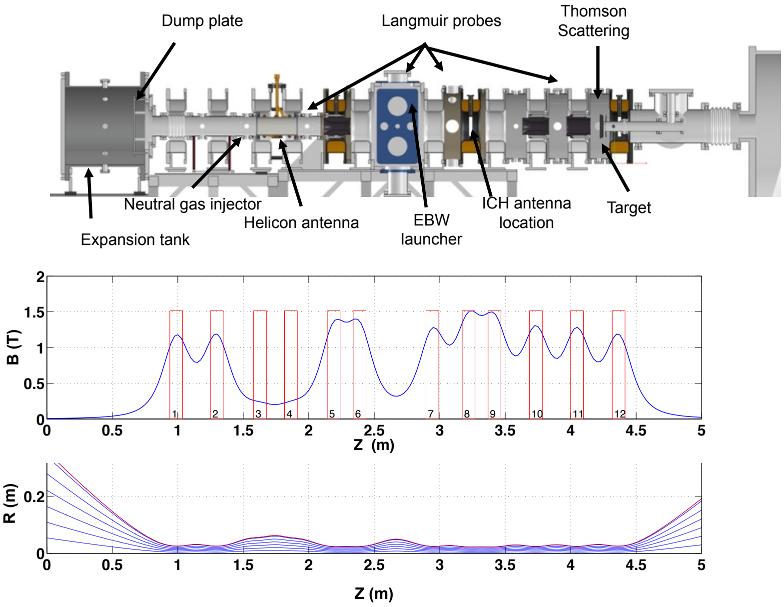

Figure 1: Proto-MPEX, cross-sectional view, magnetic field along axis, magnetic field line contours along axis and radius

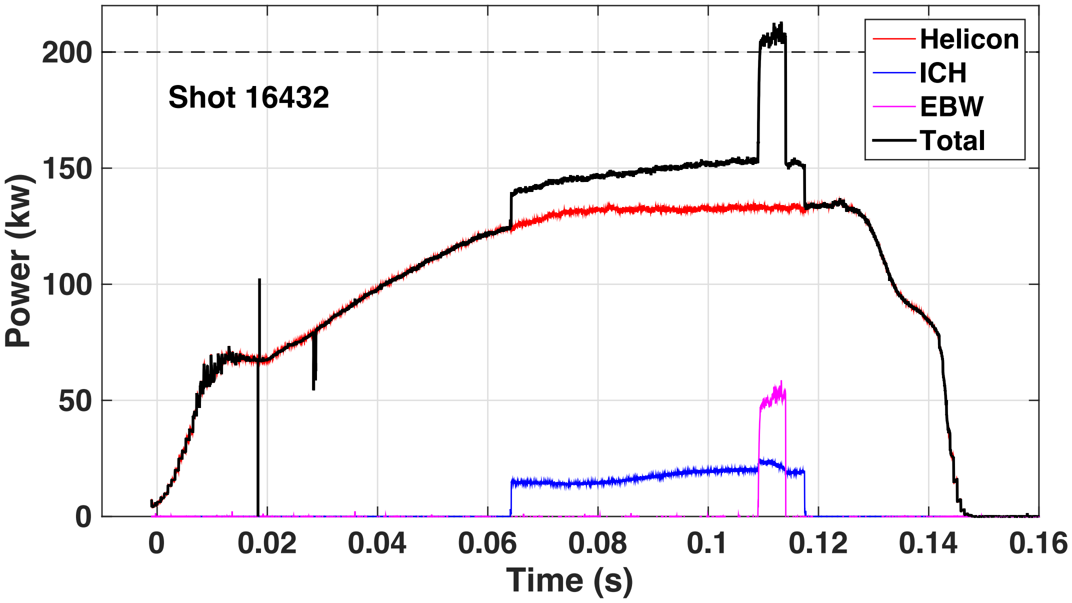

Figure 2: Maximum injected heating power into Proto-MPEX.

3. Performance of Proto-MPEX

3.1. Heating power

Of the total installed 330 kW heating power only a fraction is being injected into Proto-MPEX. So far, a maximum of 200 kW (out of 330 kW) has been injected into Proto-MPEX (see figure 2). In particular the ECH system requires optimization with losses in the mode convertor, the waveguide and gyrotron.

3.2. General performance

Reference [10] gives an overview of the operation domain of Proto-MPEX. High electron temperatures of up to 21 eV have been obtained with Electron Bernstein Wave heating at electron densities of about 1.5 x 10^{19} m^{-3} at the plasma source. In [6] was shown that sometimes a hot ion population is being created by ICH with temperatures as high as 32 eV. Electron densities at the source of up to 8 x 10^{19} m^{-3} and in front of the target of up to 1.1 x 10^{19} m^{-3} were measured with Thomson Scattering. However, not all of these conditions can be obtained simultaneously. Very high heat fluxes to the target were only possible in low density regimes. Figure 3 shows the operational domain of the plasma source concept of Proto-MPEX so far. Clearly, high upstream heat fluxes were only obtained with EBW at low electron densities (< 2 x 10^{19} m^{-3}). Without the additional electron heating the upstream power fluxes are limited to below 3-4 MW/m^2, consistent with findings at the target where maximum heat fluxes are limited to these values too at higher densities.

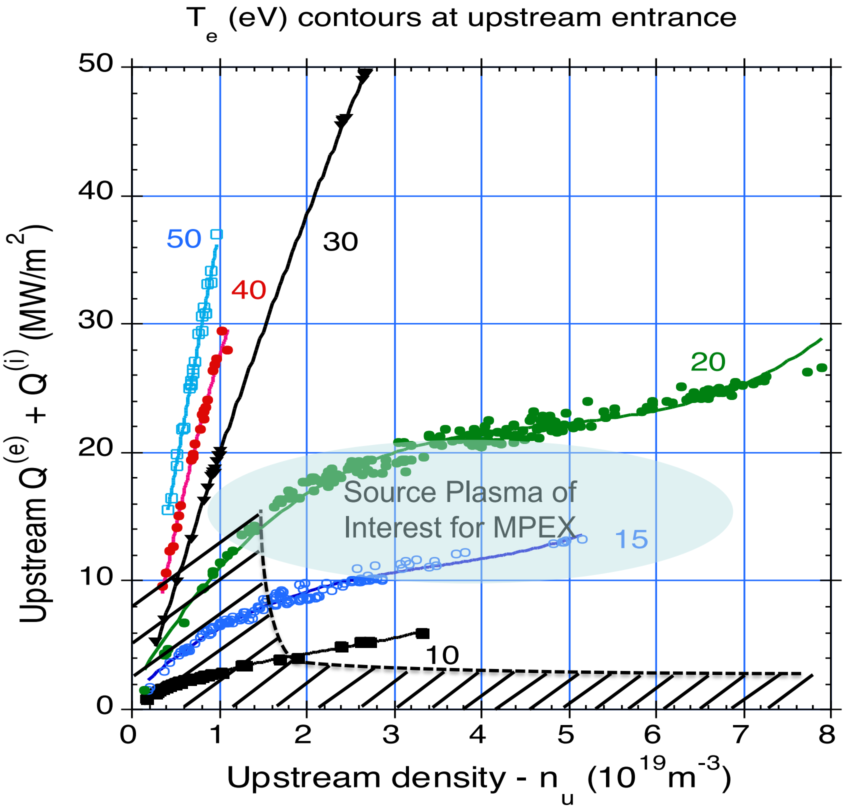

Figure 3: Operational diagram for the operation of the plasma source and heating concept of Proto-MPEX. The black hatched area indicates the operation domain based on data are taken upstream of the transport section to the target.

3.3. Electron heating and ion heating

During the past year a significant effort has been dedicated to explore electron heating and ion heating. While electron heating has been observed in the axial section, where the EBW launcher is located, the electron temperature was not much increased close to the target. Simple 2-point model estimates (table 1) show that the expected electron temperature should be a factor of about 2.5-3 higher at the target than it is observed (see case 1 and 2). This is under the pessimistic assumption of having a high-power loss from source to the target similar to that observed in high density helicon discharges with low electron temperatures at the target, where momentum loss due to charge exchange processes and volume recombination can be expected to play a role.

Table 1: 2-point modeling of plasma transport in Proto-MPEX: adjusted upstream q to match upstream T_e from TS; n_e upstream and downstream matched to TS data, f_{rad} from power balance experiments in high density helicon mode (probably too high), f_{mom} adjusted to match n_e downstream.

	T_e upstream [eV]	n_e upstream [10^{19} m^{-3}]	f_{rad}	f_{mom}	q [MW/m^2] downstream	n_e target [10^{19} m^{-3}]	T_e target [eV] 2-point model	T_e target [eV] measured
1	19	1.5	0.75	0.6	2.5	2	7	2.5
2	21	1	0.78	0.6	3.0	0.5	20	8
3	21	1.5	0.6	1.0	5.6	1.5	11	

Case 3 shows a case with lower power loss and higher momentum conservation as comparison to illustrate the uncertainties in the assumptions of f_{rad} and f_{mom}. In any case, the comparison of the simple 2-point model and the measured target n_e and T_e suggest that other loss terms have to be taken into account. Mirror trapping of energetic electrons in the central chamber, where the EBW heating takes place, is thought to be the reason for the reduced electron pressure at the target.

Ion heating of the deuterium plasma is performed in the frequency range of 7.5 to 8.5 MHz with a maximum coupled power of about 25 kW. For the measurement of the ion temperature trace amounts of argon are seeded into the deuterium plasma and T_i is measured along central and edge line of sights at different axial locations with Doppler-broadening of Ar-II [9]. Figure 4 shows an overview of T_i versus the plasma density for all operational conditions. Previous detailed studies showed that the ion temperature profile is more or less hollow for most of the plasmas.

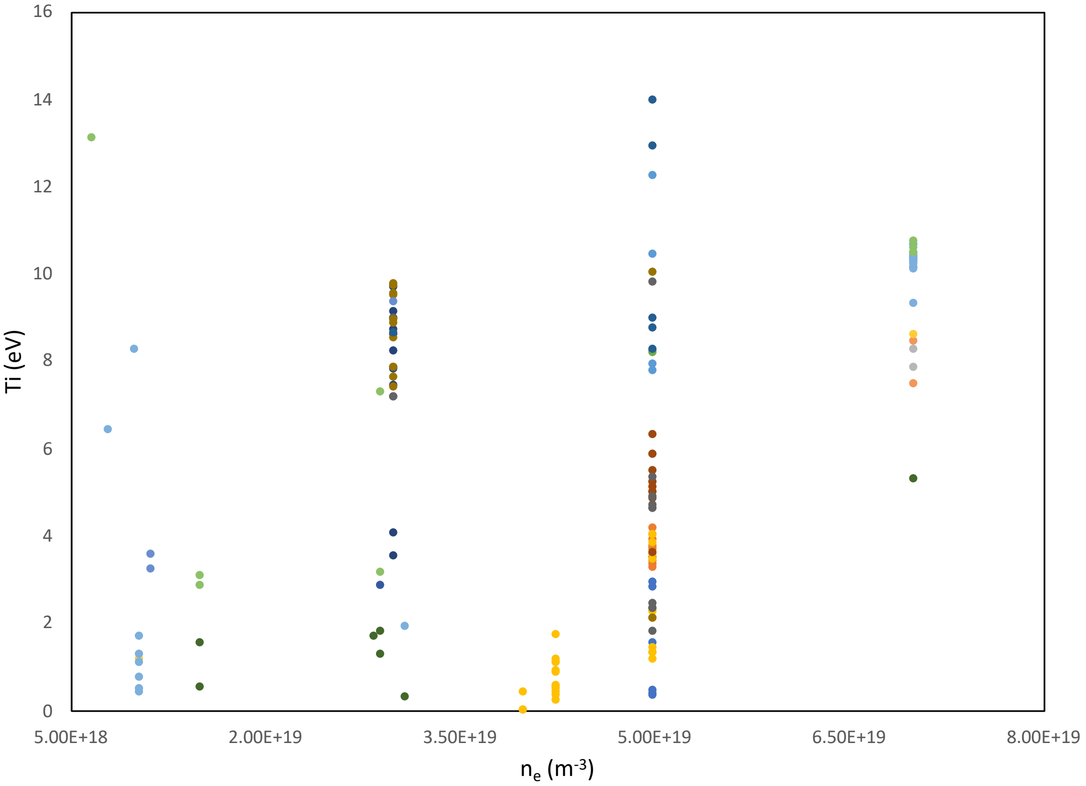

Figure 4: Line-averaged ion temperatures downstream of the ICH antenna measured on trace argon impurities (AR-II). Variation in the data due to: 0-25 kW ICH, with and without ECH, stainless steel target and graphite target.

As shown in figure 4, high ion temperatures of 10 eV and above can be reached for all plasma densities up to very high plasma densities of close to 7 x 10^{19} m^{-3}. A systematic power scan has been performed and shows the ion temperature is increasing linearly as a function of power (see figure 5). This gives hope that high ion temperatures of 20-30 eV can be reached easily in MPEX with the planned gross power of 400 kW. In addition, it shows that a significant part of the target heat flux can come from the ion heating. The main outstanding research questions with regard to the ion heating are related to the core ion heating. While preliminary data indicate that lower frequency operation is favorable in this respect, a systematic study with high resolution radial spectroscopy and Abel-inverted profiles has not been performed yet.

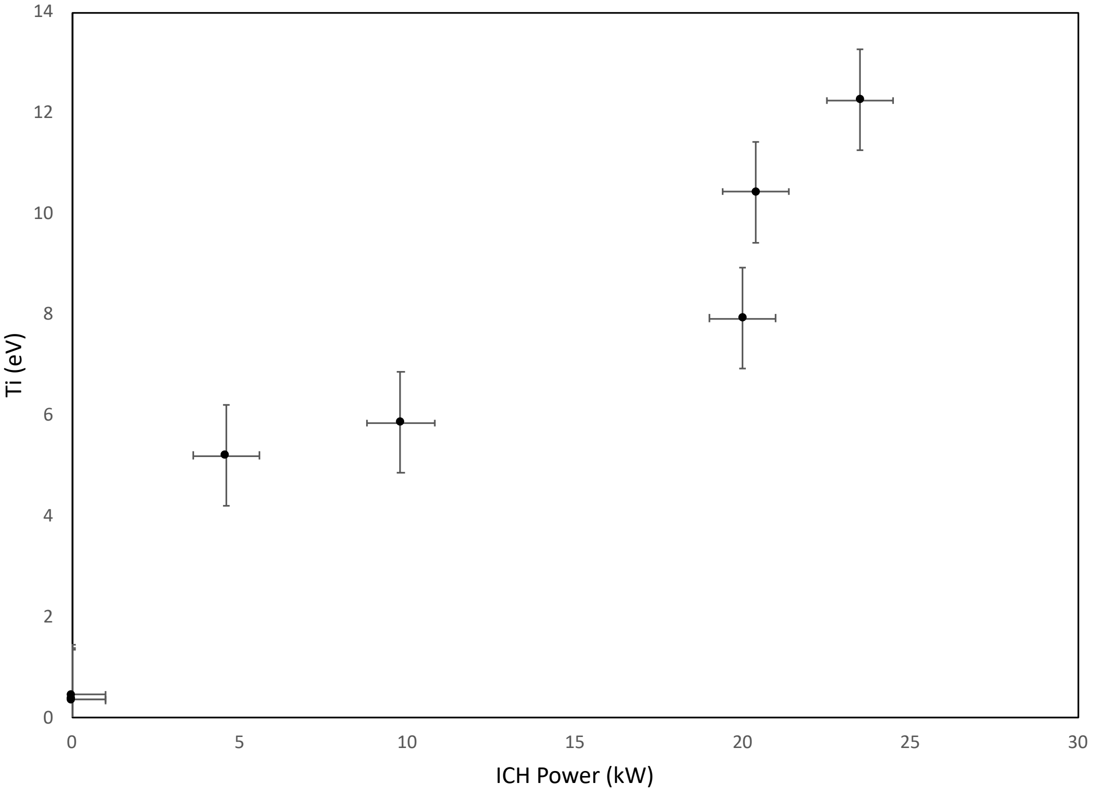

Figure 5: Ion temperatures vs. ICH power for $n_e = 5 \times 10^{19}$ m^{-3}, graphite target, all the same magnetic configuration, measured axially upstream after ICH antenna on central chord through plasma.

3.4. Proto-MPEX achieved values compared to MPEX ultimate performance goals

As a goal MPEX will try to replicate the plasma conditions expected in a fusion reactor. Without having detailed designs for fusion reactors the guideline for divertor plasma conditions is here taken from the predictions of the ITER partially detached divertor plasma. At the strike point very high densities of about to 10^{21} m^{-3} are expected with low electron temperatures of about 1 eV. Further in the scrape-off-layer the electron temperatures are higher, up to 15 eV, with lower electron densities. Obtaining these conditions should be possible in MPEX, as scoping simulations indicate [4]. In the following table the ultimate performance goals of MPEX are shown together with the to-date achieved parameters on Proto-MPEX. It should be mentioned here that Proto-MPEX is not expected to meet all conditions, due to lack of heating power and lack of appropriate dimensions. The achieved values shown were obtained not simultaneously, as this is also not required. The maximum values for density and parallel heat fluxes are for exposures of targets at reactor relevant shallow angle of incidence between the magnetic field line and the plasma facing component (5 degrees).

Table 2: Comparison of the MPEX ultimate performance goals with the achieved values on Proto-MPEX (not simultaneously).

Parameter	**MPEX ultimate performance goal**	**Achieved values on Proto-MPEX**	**Comments**
n_e source	$4 - 6 \times 10^{19}$ m^{-3}	8×10^{19} m^{-3}	
n_e target	up to 10^{21} m^{-3}	1.1×10^{20} m^{-3}	2 cm in front of target
T_e source	up to 25 eV	21 eV	In over-dense plasmas
T_e target	up to 15 eV	8 eV	In over-dense plasmas
T_i source	up to 30 eV	14 eV	Measured on Ar-II
T_i target	up to 20 eV	11 eV	Measured on Ar-II
B target	1 T	1 T	
Plasma diameter	up to 10 cm	6 cm	Best results with 3 cm
Γ_I target	$> 10^{24}$ $m^{-2}s^{-1}$	$\sim 9 \times 10^{23}$ m^{-2} s^{-1}	0.4 m in front of target
Min angle of B to target	5 degree	45 degrees	90 degrees typical
P target, parallel	up to 40 MW/m^2	> 14 MW/m^2 > 3 MW/m^2	In low n_e regime In high n_e regime
P target, perpendicular	10 MW/m^2	> 14 MW/m^2 > 3 MW/m^2	In low n_e regime In high n_e regime

To illustrate the performance of individual plasma discharges on Proto-MPEX radar plots in figure 6 show two cases for (a) a high-density discharge aiming for heat fluxes of 10 MW/m^2 on a target with normal incidence with the magnetic field and a (b) high electron temperature scenario for 10 MW/m^2 on a target with normal incidence with the magnetic field. While individual parameters can be met, most other parameters differ by 2-5 from the goal. This is mainly due to a lack of heating power absorbed in the plasma and transported to the target.

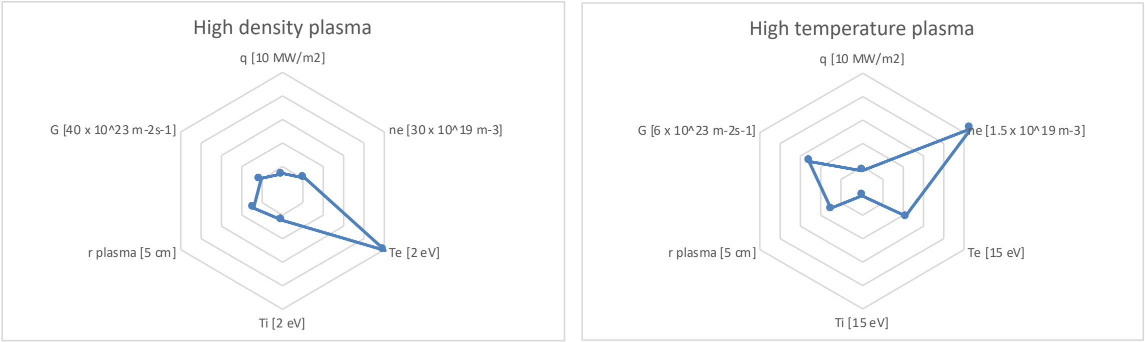

Figure 6: Two plasmas of interest for a target with 90-degree magnetic field line angle: high density plasma with 10 MW/m^2 and high temperature plasma with 10 MW/m^2, comparison of Proto-MPEX plasma parameters in front of target with conditions for MPEX.

4. Summary and Conclusion

The Material Plasma Exposure eXperiment (MPEX) is in its conceptual design phase. In parallel the source concept of MPEX is tested on Proto-MPEX. Proto-MPEX has demonstrated the required plasma production in terms of high density helicon discharges, has demonstrated electron heating by Electron Bernstein Waves and ion heating by ion cyclotron heating. Most critical performance parameters have been reached within a factor of 2-3 with only a fraction of the heating power that will be available on MPEX. The maximum power injected into Proto-MPEX to date is about 200 kW, whereas MPEX does foresee a total power of 800 kW.

5. Acknowledgement

Work supported in part by the US DOE under Contract No. DE-AC05-00OR22725 with UT-Battelle, LLC.

References

[1] RAPP J. et al., IEEE Transactions on Plasma Science, **44** (2016) 3456

[2] RAPP J. Fus. Sci. Technol. **72** 3 (2017) 211

[3] ELLIS R.J. and RAPP J., Fus. Sci. Technol. **68** (2015) 750

[4] RAPP J. et al., J. Nucl. Mater. **463** (2015) 510

[5] CAUGHMAN J.B.O. et al., J. Vac. Sci. Technol. **A 35** (2017) 03E114

[6] RAPP J. et al. Nucl. Fusion **57** (2017) 116001

[7] GOULDING R.H. et al., Fus. Sci. Technol. **72** 3 (2017) 588

[8] BIEWER T.M. et al., Phys. Plasmas **25** (2018) 024501

[9] BEERS C.J. et al., Phys. Plasmas **25** (2018) 013526

[10] RAPP J. et al., Fus. Eng. Des. (2018) https://doi.org/10.1016/j.fusengdes.2018.03.064