

## Developing the Science and Technology for the Material Plasma Exposure Experiment (MPEX)

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Linear plasma generators are cost effective facilities to simulate divertor plasma conditions of present and future fusion reactors. They are used to address important R&D gaps in the science of plasma material interactions and towards viable plasma facing components for fusion reactors.

Next generation plasma generators have to be able to access the plasma conditions expected on the divertor targets in ITER and future devices. The steady-state linear plasma device MPEX will address this regime with electron temperatures of 1–10 eV and electron densities of  $10^{21}$ – $10^{20}$  / m<sup>3</sup>. The resulting heat fluxes are about 10 MW/m<sup>2</sup>. MPEX is designed to deliver those plasma conditions with a novel radio frequency plasma source able to produce high density plasmas and heat electron and ions separately with electron Bernstein wave (EBW) heating and ion cyclotron resonance heating (ICRH) with a total installed power of 800 kW.

The linear device Proto-MPEX, forerunner of MPEX consisting of 12 water-cooled copper coils, is operational since May 2014. Its helicon antenna (100 kW, 13.56 MHz) and EC heating systems (200 kW, 28 GHz) have been commissioned. The operational space was expanded considerably in the last year. 12 MW/m<sup>2</sup> was delivered on target. Electron temperatures of about 20 eV have been achieved in combined helicon and ECH/EBW heating schemes at low electron densities. Overdense heating with electron Bernstein waves was achieved at low heating powers. The operational space of the density production by the helicon antenna was pushed to  $2 \times 10^{19}$  / m<sup>3</sup> at relatively high magnetic fields of 0.7 T, which would allow ECH absorption for 2nd harmonic X-mode overdense heating schemes. Proto-MPEX has been prepared to allow for first material sample exposures. The experimental results from Proto-MPEX will be used for code validation (B2-EIRENE, COMSOL, VORPAL, AORSA, GENRAY) to enable predictions of the source and heating performance for MPEX.

MPEX, in its last phase, will be capable to expose neutron-irradiated samples. In this concept, targets will be irradiated in ORNL's High Flux Isotope Reactor and then subsequently exposed to fusion reactor relevant plasmas in MPEX.

The current state of the MPEX preconceptual design and unique technologies already developed, including the concept of handling irradiated samples, will be presented.

## Developing the Science and Technology for the Material Plasma Exposure eXperiment (MPEX)

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**Abstract.** Linear plasma generators are cost effective facilities to simulate divertor plasma conditions of present and future fusion reactors. They are used to address important R&D gaps in the science of plasma material interactions and towards viable plasma facing components for fusion reactors. Next generation plasma generators have to be able to access the plasma conditions expected on the divertor targets in ITER and future devices. The steady-state linear plasma device MPEX will address this regime with electron temperatures of 1 – 10 eV and electron densities of  $10^{21} - 10^{20} \text{ m}^{-3}$ . The resulting heat fluxes are about 10 MW/m<sup>2</sup>. MPEX is designed to deliver those plasma conditions with a novel Radio Frequency plasma source able to produce high density plasmas and heat electron and ions separately with Electron Bernstein Wave (EBW) heating and Ion Cyclotron Resonance Heating (ICRH) with a total installed power of 800 kW. The linear device Proto-MPEX, forerunner of MPEX consisting of 12 water-cooled copper coils, is operational since May 2014. Its helicon antenna (100 kW, 13.56 MHz) and EC heating systems (200 kW, 28 GHz) have been commissioned. The operational space was expanded in the last year considerably. 12 MW/m<sup>2</sup> was delivered on target. Furthermore electron temperatures of about 20 eV have been achieved in combined helicon and ECH/EBW heating schemes at low electron densities. Overdense heating with Electron Bernstein Waves was achieved at low heating powers. The operational space of the density production by the helicon antenna was pushed up to  $8 \times 10^{19} \text{ m}^{-3}$  at high magnetic fields of ~1.0 T at the target. Proto-MPEX has been prepared to allow for first material sample exposures, albeit for short pulse duration. The experimental results from Proto-MPEX will be used for code validation to enable predictions of the source and heating performance for MPEX. MPEX, in its last phase, will be capable to expose neutron-irradiated samples. In this concept, targets will be irradiated in ORNL's High Flux Isotope Reactor and then subsequently exposed to fusion reactor relevant plasmas in MPEX. The current state of the MPEX pre-conceptual design and unique technologies already developed, including the concept of handling irradiated samples, are presented.

### 1. Introduction

The scientific demonstration of magnetic fusion energy as an environmentally sustainable and economically competitive energy source will require mastering the science of plasma material interactions (PMI) and the development of plasma facing components that exhibit unprecedented erosion resistance and self-healing capability during prolonged exposure to high particle/heat fluxes and intense D-T fusion neutrons. The limited lifetime of PFCs will impact the availability of a fusion reactor and hence its economic viability. In addition, PMI impacts the performance of the core fusion plasma, for example through the release of

impurities leading to dilution of the plasma fuel and radiative power losses. Even before the lifetime of a PFC is reached stringent controlled in-vessel inventories of dust and tritium could stop the reactor operation due to PMI in the nuclear environment. An improved understanding of the degradation mechanisms associated with PMI is needed in order to identify potential PFC materials and operational regimes. Much of the needed PMI studies and PFC development could be performed in a simplified geometry (i.e., in linear plasma devices), provided that relevant plasma parameters can be reached. These devices offer a much-reduced operational cost compared to tokamak operation, with better diagnostic access and dedicated experimental time for PMI/PFC studies. The near-term prospects of operating linear plasma devices in near steady state to perform tests at reactor-relevant ion fluences are also much better than for tokamaks (current pulsed tokamaks accumulate a fluence of  $\sim 10^{25}$   $\text{m}^2/\text{yr}$  only, which is about 5 orders of magnitude below what is needed). Linear plasma devices can allow rapid evaluation and the development of combinations of PFC designs and plasma conditions that satisfy fusion reactor conditions. Currently several new linear devices are in the planning phase, are under construction or just started operation. The Material Plasma Exposure eXperiment (MPEX) [1] will fill a gap providing for the first time data for high fluence PMI exposures of *a-priori* neutron irradiated material samples.

## 2. The Material Plasma Exposure eXperiment, MPEX

During ReNeW and subsequent FESAC reports [2,3,4] the need for upgraded, or new linear plasma devices, was recommended in order to expand the capability with respect to existing devices [5,6,7], namely ion fluxes of  $\Gamma > 10^{23}$   $\text{m}^{-2}\text{s}^{-1}$ , parallel power fluxes of  $\sim 20$   $\text{MW}/\text{m}^2$ , inclined target,  $B > 1\text{T}$ , steady-state (up to  $10^6$  sec),  $> 600^\circ\text{C}$  surface temperature, large plasma area  $\sim 100$   $\text{cm}^2$ . It was recommended that such a facility should allow exposure of liquid metal targets: Ga, Sn, Li, neutron-irradiated material samples

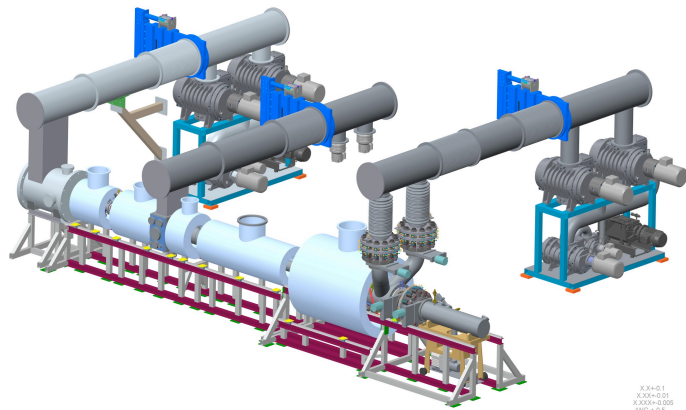


Figure 1: MPEX

with significant dpa, and have independent control of  $T_e$  and  $T_i$  at target. The proposed new linear plasma device MPEX (see figure 1) is a response to ReNeW and will address the PMI challenges in ITER and for future devices [8]. It will enable material exposures with tokamak divertor relevant plasmas (fluxes,  $T_e$ ,  $T_i$ ,  $n_e$ ). It will be designed to expose neutron-irradiated samples and have an extensive *in-situ* and *in-vacuo* diagnostic set to characterize the microstructural evolution of those neutron irradiated samples. Due to its enhanced source capabilities, it will allow erosion and re-deposition studies of low net erosion regimes. This will allow for the first time end-of-life studies of tungsten as reactor plasma facing component. Tungsten material samples, damaged to 10-20 dpa for example by neutrons in the High Flux Isotope Reactor and be exposed to reactor relevant plasma fluence of  $10^{31}$   $\text{m}^{-2}$  in this device [9].

## 2.1. Pre-design of MPEX

MPEX will be a steady-state device utilizing superconducting coils with standard technology (NbTi). The plasma source system is chosen to be a helicon source combined with auxiliary RF-heating to heat electrons and ions independently. The helicon antenna has the advantage that the emitted circular polarized electro-magnetic waves can propagate in the plasma at much higher densities than other waves.

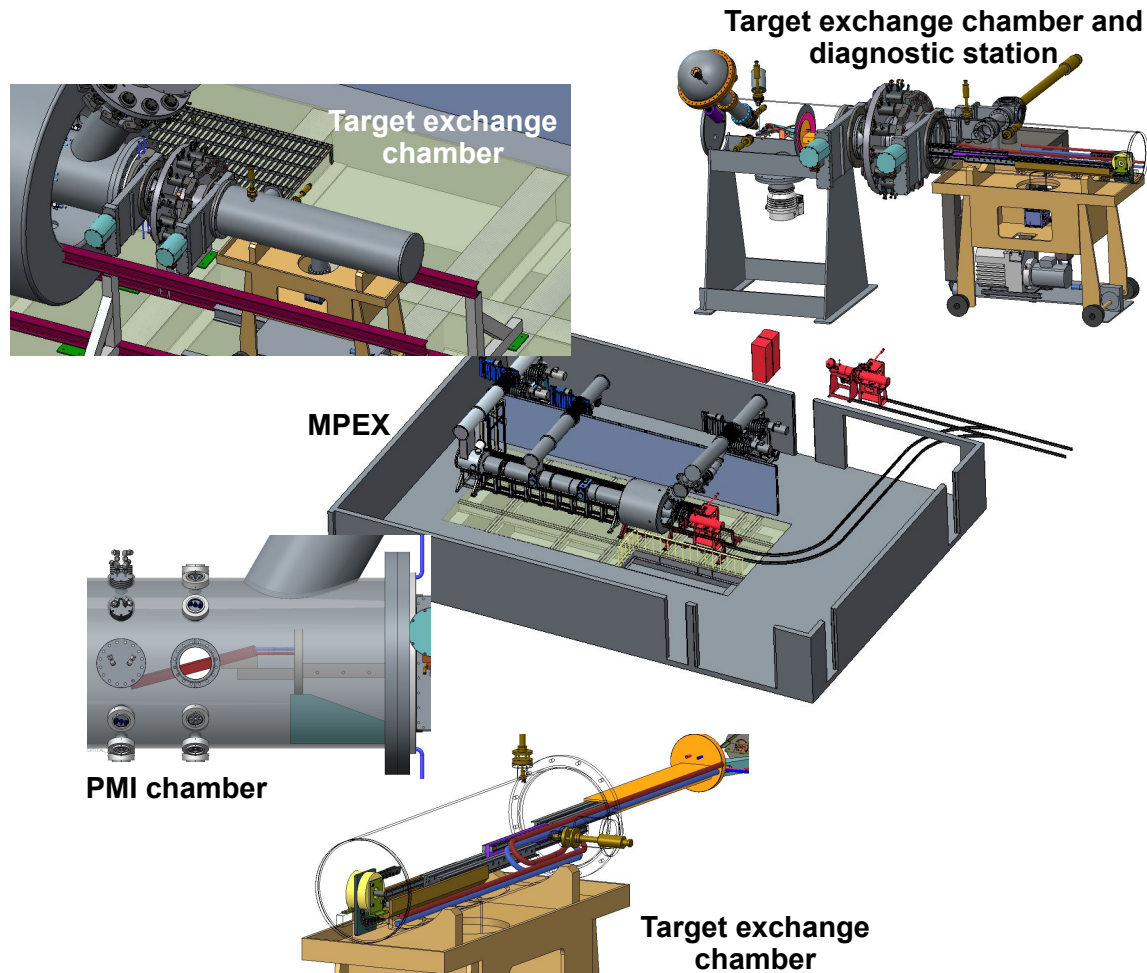


Figure 2: Concept of MPEX with compact target exchange chamber movable from MPEX to diagnostic station to allow for fast evaluation of evolving surfaces.

The total RF heating power will be up to 800 kW [1]. The magnetic field structure will be adopted to maximize the source and heating performance. This RF based plasma source approach has the advantage of low maintenance operation, as required for steady-state operation. It also has the advantage of having a tiltable large-scale target. A high power thermal plasma in front of the target allows the investigations of PMI in realistic geometry (target at oblique angle to magnetic field) with realistic E and B fields in the sheath. The RF heating will allow access to conduction-limited transport as it occurs in the SOL of a tokamak. This will permit the investigation of power load dissipation processes by impurity radiation, as well as accessing higher charge state ionization of impurities, which is important for physical sputtering studies of tungsten. The target station (see figure 2) will be designed to allow for testing of novel target concepts. Versatile target casks will allow (for example) the

exposure of hot targets (e.g. He cooled), flowing liquid metal targets, cascading pebble targets, neutron irradiated targets, etc. A compact target exchange chamber has been designed, which does not rely long actuator arms like in other devices [6,7]. The targets will be introduced from the target exchange chamber to the plasma exposure chamber (PMI chamber) with an actuator arm, which is based on a three-section telescoping slide with a push-pull chain to move the target [10]. The target exchange chamber can be decoupled from the PMI chamber via autocouplers and moved on a rail system to a diagnostic station, while the superconducting coils are still energized. The diagnostic station, placed far enough away and shielded from the MPEX magnetic fields will allow for surface analysis with SEM and XPS *in vacuo*. MPEX will help to advance plasma-facing components from concept exploration studies (technical readiness level TRL3) to proof of principle solutions (TRL4 up to TRL6 for some end of lifetime studies).

### 3. Results from the Prototype-Material Plasma Exposure eXperiment, Proto-MPEX

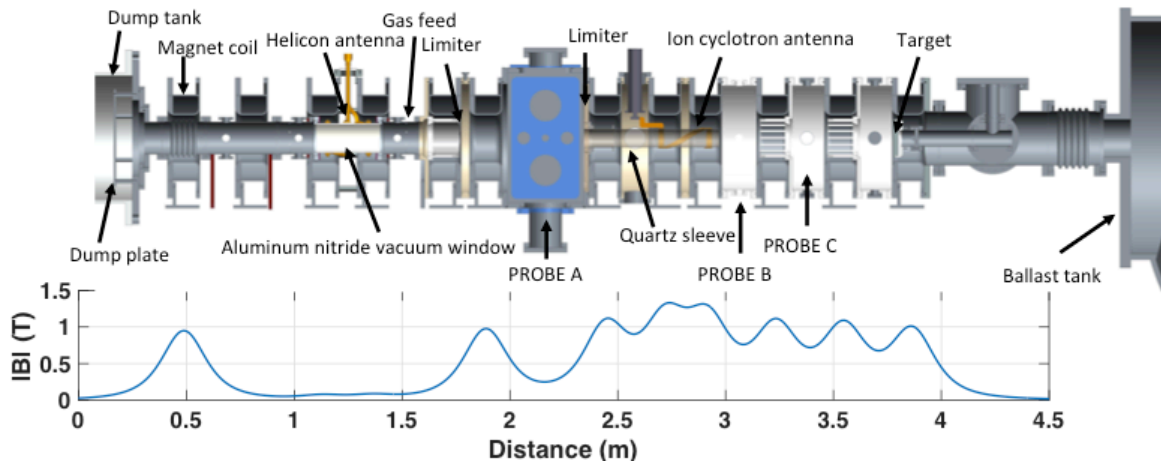


Figure 3: Proto-MPEX: Magnet coils are counted from left to right (From 1 to 12). Vacuum chambers in between coils are labelled as: 6.5 for vacuum chamber (spool piece) between coil 6 and 7 for example.

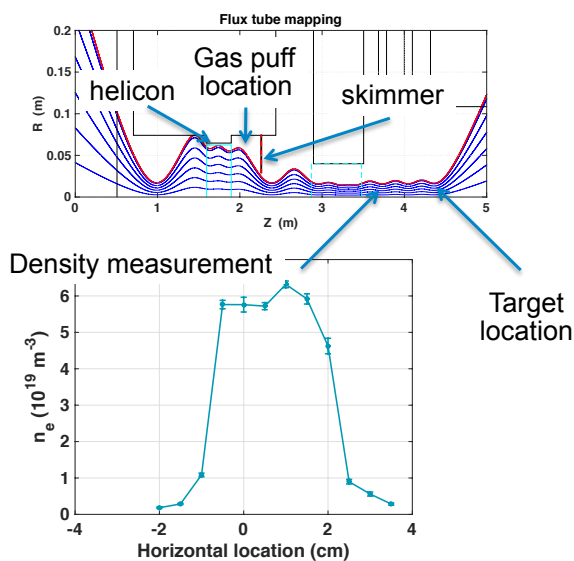


Figure 4: High density helicon operation mode found by local gas fueling between helicon antenna and skimmer.

The plasma source concept is being developed on the frontrunner experiment Proto-MPEX. A cut through Proto-MPEX is shown in figure 3. Proto-MPEX has been operational since May 2014. The installed heating power is 330 kW (100 kW helicon, 200 kW 28 GHz ECH power and 30 kW ICH power). At present, ~150 kW of combined power has been injected into the plasma. High heat and ion fluxes have been obtained in low-density discharges. Maximum heat fluxes of 12 MW/m<sup>2</sup> were obtained with pre-dominantly edge heating by Trivelpiece Gould waves [11]. Those experiments also achieved the highest electron temperature of ~20 eV. Recently, very high-density helicon discharges were

obtained leading to record electron densities in a deuterium helicon plasma [12]. This was accomplished by localized gas fuelling downstream of the helicon antenna. It is believed that the increased edge density limits the power absorption in the Trivelpiece Gould mode and allows increased power deposition in the center of the plasma in the helicon mode. Figure 5 shows the operational diagram for the plasma source, including both data at low density, which are dominated by the Trivelpiece Gould mode, and the high-density helicon operation. Maximum electron densities of  $7.2 \times 10^{19} \text{ m}^{-3}$  have been achieved at electron temperatures of about 3.5 eV at the upstream location of the ECH chamber with probe A (see figure 3). It should be noted here that the data in figure 5 do not necessarily show the maximum values for  $n_e$  and  $T_e$  since the plasma profiles are azimuthally asymmetric as indicated by IR camera data of the heat flux on the target [13] (see figure 6). The obtained densities should be sufficient to enable reactor relevant plasmas in front of the target as predicted by B2-Eirene transport modeling [14]. However this assumes that the high-density plasma can be heated to about 20 eV. Table 1 summarizes the performance parameters obtained so far in Proto-MPEX. Those values were not achieved simultaneously though. The maximum ion fluxes were calculated based on the high electron density data. Ion heating experiments started recently and reliable ion temperatures cannot be given yet. The magnetic fields obtained are significantly higher than in current US linear plasma devices, already allowing for detailed studies of magnetic sheath effects on erosion/re-deposition. All experiments thus far have been carried out with the target normal to the magnetic field. The pulse length of Proto-MPEX is administratively restricted by the use of Langmuir probes (150 ms) or by the non-cooled helicon window ( $\sim 2$  s). A water-cooled helicon antenna window is currently in development.

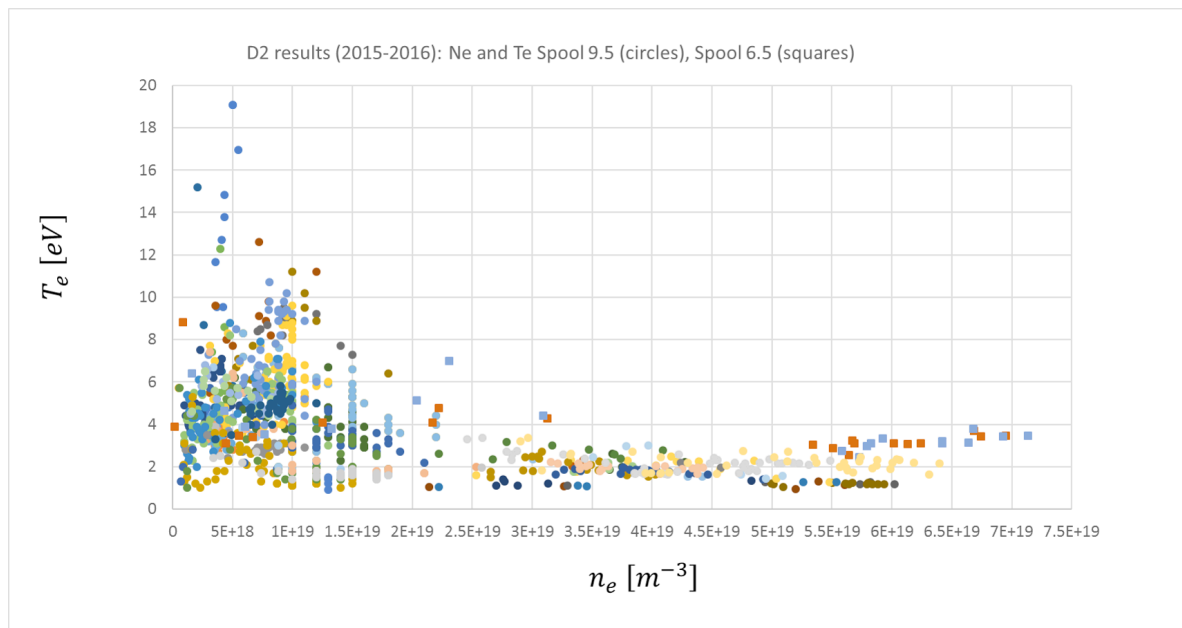


Figure 5: Operational diagram for the operation of Proto-MPEX. Data were taken with Double Langmuir probes at different axial locations with respect to helicon antenna. Highest densities were achieved at spool piece 6.5 (probe A). High temperatures of 20 eV were obtained with target at spool piece 7.5. All high density helicon operation data were taken with target at location spool piece 11.5.

Parameter	Aimed value	Achieved value	Comments
$n_e$ source	up to $6 \times 10^{19} \text{ m}^{-3}$	He: $6 \times 10^{19} \text{ m}^{-3}$ $D \sim 7.5 \times 10^{19} \text{ m}^{-3}$	
$n_e$ target	up to $10^{21} \text{ m}^{-3}$	$D \sim 6 \times 10^{19} \text{ m}^{-3}$	0.4 m in front of target
$T_e$ target	up to 15 eV	20 eV	At low density
$T_e$ target	down to 1 eV	1 eV	At low density
$T_i$ target	up to 20 eV	-	No $T_i$ measurement
$T_i$ target	down to 1 eV	-	No $T_i$ measurement
B target	1 - 2 T	1 T	
Plasma diameter	up to 10 cm	6 cm	Best results with 3 cm
$\Gamma_I$ target	$> 10^{24} \text{ m}^{-2} \text{ s}^{-1}$	$\sim 9 \times 10^{23} \text{ m}^{-2} \text{ s}^{-1}$	0.4 m in front of target
Min angle of B to target	5 degree	90 degrees	
P target, parallel	up to $40 \text{ MW/m}^2$	$> 12 \text{ MW/m}^2$	In high $T_e$ regime
P target, perpendicular	$10 \text{ MW/m}^2$	$> 12 \text{ MW/m}^2$	In high $T_e$ regime

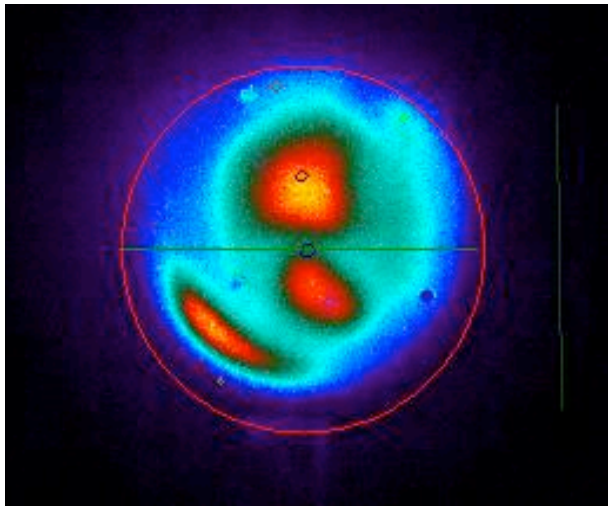


Figure 6: IR camera data from target of a high density helicon plasma showing azimuthal asymmetries in heat flux pattern.

#### 4. Summary and Conclusion

Future fusion reactors will face severe power exhaust challenges. The scientific and technological challenges in the area of plasma material interactions and plasma facing components are grand and need to be addressed before fusion energy can be realized commercially. Present day devices, toroidal and test beds, are not able to address the challenges ahead. MPEX, a new device being developed, is filling gaps in testing capabilities. MPEX is in its pre-design phase. The source concept consisting of a high power helicon antenna, an EBW heating system and an ICRH system are being tested on

the frontrunner experiment, Proto-MPEX. So far Proto-MPEX has demonstrated the required densities of the plasma source system with record deuterium densities (approaching  $8 \times 10^{19} \text{ m}^{-3}$ ) achieved for a helicon antenna. Heat fluxes of more than  $10 \text{ MW/m}^2$  and ion fluxes approaching  $10^{24} \text{ m}^{-2} \text{ s}^{-1}$  have been observed.

## 5. Acknowledgement

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