Interferometric density measurement with 200 ns time resolution during massive gas injection on ASDEX Upgrade

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Plasma disruptions state a serious threat for next step fusion devices, therefore, strategies for disruption avoidance or at least the mitigation of their consequences are mandatory. One method of disruption mitigation is the sudden injection of large quantities of noble gases. This technique of massive gas injection (MGI) requires gas valves that release a large gas quantity within short time. On ASDEX Upgrade, several types of fast valves for MGI have been installed in the recent years [1] [2]. First, two electromagnetically operated valves were mounted on a vessel port at a distance of 1.5 meters from the low-field side separatrix of the plasma. Later, a fast piezo valve was installed inside the vacuum vessel which is located at the low-field side and close to the plasma. This valve was found to provide higher fueling efficiency thanks to its location close to the plasma. During the 2010 vessel opening, an additional piezo valve was installed on the high-field side of ASDEX Upgrade, whose fueling efficiency turned out to be roughly twice as high as that of the low-field side valve [2]. At the end of 2011, a second piezo valve was mounted on the high-field side.

With increasing fueling efficiency of the valves and increasing gas quantity released by them, the measurement of the electron density of the plasma during MGI becomes more and more challenging. The two-color $CO_2/HeNe$ interferometer on ASDEX Upgrade, which operates at wavelengths of 10.6 μm and 633 nm, can be used to measure the density characteristics during MGI [3]. The standard readout electronics of this interferometer, however, has a limited dynamic range which ends at a line-integrated density of $5.26 \cdot 10^{20} \, m^{-2}$, and an internal 40 kHz low-pass filter, which limits the time resolution. The density limit is a factor of 5 higher than the typical flat-top density of ASDEX Upgrade discharges. However, the peak densities obtained during MGI meanwhile exceed this limit by far. Therefore, an alternative approach to the acquisition of interferometry data had to be made, which is presented in the following.

When a laser beam passes through a plasma, it experiences a phase shift φ which is proportional to the line-integrated electron density along the path of the beam, and proportional to the wavelength λ. Any mechanical displacement ΔL of mirrors or other optical components in an interferometer, e.g. due to vibration, causes a phase shift as well which is proportional to $1/\lambda$. When operating at short wavelengths, vibration compensation is required. In two-color interferometers, this is achieved by sending two laser beams of different wavelength through the plasma along the same path. Accordingly, two phase shifts are measured and the two quanities (plasma density and mechanical displacement ΔL) can be calculated. On ASDEX Upgrade, the measurement of the phase shift is based on the heterodyne method: The beam of each of the two lasers (an infrared CO_2 and a visible $HeNe$ laser) is sent to an acousto-optic modulator

(AOM), which is driven by an AC voltage with a frequency of 40 MHz. Two beams leave the AOM, one of them experiences a Doppler shift by 40 MHz. The other beam is sent through the plasma vessel and combined with this frequency-shifted beam in a beam splitter, which results in a 40 MHz beat signal. Comparing the phase of this beat signal to the phase of the AOM driver signal yields the phase shift φ which the probing beam has experienced. Accordingly, the main task in the readout of the interferometry data is the determination of the phase difference between two sinusoidal 40 MHz signals. Due to the limitations of the usual readout electronics listed above, a new approach was chosen in recent MGI experiments: Using a digital oscilloscope with large internal memory, the 3 relevant raw signals (AOM driver, CO_2 detector and $HeNe$ detector signal) were digitized with a sampling rate of 500 MSamples/s. Then, phase reconstruction was performed by software. At the given sampling rate, the oscilloscope stores 20 milliseconds of data, which is short compared to the duration of a typical ASDEX Upgrade discharge of 10 seconds, but just long enough to cover the MGI event.

For analysis, the time traces of the 3 signals are divided into segments. For each segment, the phase shift between the AOM driver and the CO_2 detector signal is calculated, as well as the phase shift between the AOM driver and the $HeNe$ detector signal, and finally the resulting plasma density. It was found that a segment length of 100 samples, which corresponds to 200 ns, is a good compromise between high time resolution (which requires short segments) and low noise level (which requires long segments). The density measurement obtained that way accordingly has an effective sampling frequency of 5 MHz.

First of all, mean value and standard deviation of the data points in one segment are calculated. The mean value gives the zero line of the signal, and the standard deviation delivers, besides a factor of $\sqrt{2}$, the amplitude of the sinusoidal signal. The phase reconstruction, which is described in detail in [3], is based on zero-crossing detection. Pairs of subsequent data points are selected which enclose the previously calculated zero line. Linear interpolation between them yields the time stamp corresponding to the zero crossing. From the timing of the zero crossings within one segment, frequency and phase of the signal are extracted, and finally, the phase difference between two signals is calculated. Integer multiples of 2π are counted by software.

This method of data acquisition was applied to a series of MGI experiments with different gas quantities and different thermal energies of the plasma. When analyzing the data, sufficient amplitude of the detector signals is essential for successful phase reconstruction. Figure 1 shows the temporal evolution of the CO_2 and $HeNe$ signal amplitude during MGI in ASDEX Upgrade discharge #27848: It can be seen that there is a strong drop of the CO_2 signal amplitude which starts roughly 4.5 ms after the trigger of the gas valve and lasts about 300 μs. This is caused by beam refraction in the plasma. The drop of the signal amplitude is so strong that no reliable phase reconstruction is possible in the corresponding time window. The amplitude of the $HeNe$ signal is dominated by slow fluctuations due to mechanical vibrations of optical components in the setup. However, in the same time window in which the CO_2 signal amplitude drops, also a

short drop of the *HeNe* amplitude is observed, which mainly consists of two dips with a duration of roughly 30 μs each. Evidently, this is much too fast for any mechanical effect, so the conclusion is that the lateral density gradients in the plasma are temporarily so strong that not even visible light ($\lambda_{HeNe} = 633$ *nm*) propagates along a straight line through the plasma, but gets deflected by a measurable amount.
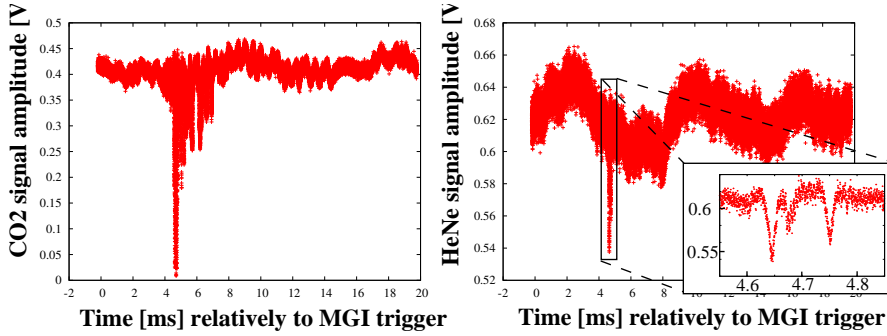

Figure 1: *Signal amplitudes of CO_2 detector signal (left) and HeNe detector signal (right) during MGI in ASDEX Upgrade discharge #27848.*

This is a remarkable observation due to the fact that the angle by which a laser beam gets deflected by lateral density gradients in a plasma scales as λ^2. In interferometry, signal loss due to beam refraction is usually only observed for microwaves and sub-millimeter waves, but not for infrared and visible light. As the amplitude of the *HeNe* signal drops only by about 15%, phase reconstruction is still possible also in this time window.

For density reconstruction, a time window in which the CO_2 signal amplitude drops close to zero has to be excluded. Accordingly, the reconstructed density time trace has a gap there.

The number of integer multiples of 2π by which the CO_2 phase changes in this time window has been reconstructed in the following way: The flat-top density of the plasma discharge before the MGI event is known, and the plasma density is known to drop to zero at the end of the discharge. In this way, the two parts of the time trace, before and after the gap, can be properly arranged relatively to each other, which yields a unique solution for the number of multiples of 2π by which the CO_2 phase has to be corrected after the gap. The resulting time trace is shown in figure 2. It can be seen that a peak line-integrated density of $2.5 \cdot 10^{21}$ m^{-2} has
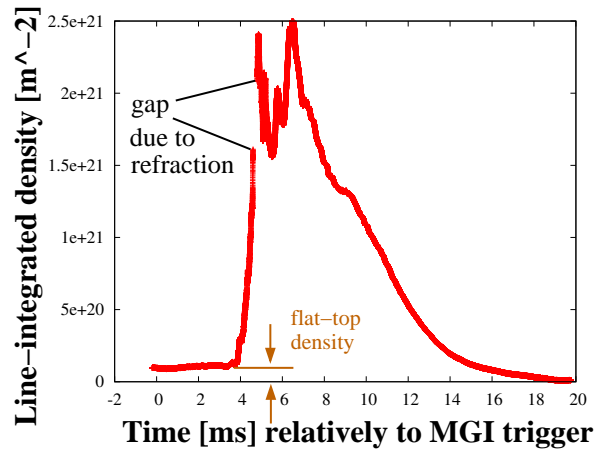

Figure 2: *Reconstructed electron density during MGI in ASDEX Upgrade discharge #27848. The gap in the time trace is due to beam refraction, which temporarily makes the measurement impossible.*

been obtained in this discharge, which exceeds the typical flat-top density on ASDEX Upgrade by a factor of 25.

Not only the unlimited dynamic density range of the new data acquisition method, but also the high time resolution of 200 ns has been found to be beneficial in MGI experiments, for example in ASDEX Upgrade discharge #26299, whose density time trace is shown in figure 3.
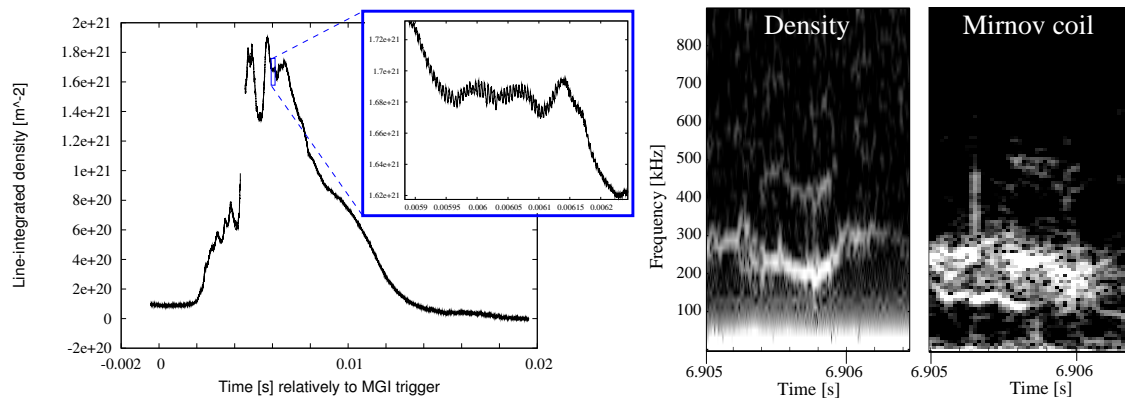

Figure 3: *Reconstructed electron density (left) during MGI and spectrograms of the line-integrated density and a low-field side Mirnov coil signal (right) for ASDEX Upgrade discharge #26299. The time scale in the spectrograms gives the absolute time since the beginning of the plasma discharge. The MGI valve was triggered at t=6.9 s.*

Shortly after the density maximum, oscillation of the line-integrated density is visible. A spectrogram of the density trace is also presented in the figure. It can be seen that the oscillation frequency varies between 200 and 300 kHz within 1.5 ms. Also a second harmonic oscillation is partially visible. The figure in addition shows a spectrogram of a magnetic pick-up coil signal for the same time and frequency window. There, oscillations in the same frequency range are visible. The most likely explanation for these observations is the excitation of Alfven waves in the plasma during the current quench phase.

These results have revealed that interferometry with high dynamic density range and high time resolution is a powerful diagnostic tool in MGI experiments. Despite of the short gap in the density measurement due to beam refraction during MGI, the peak electron density could be reconstructed well. Therefore, it is expected that if the critical density for the collisional suppression of runaway electrons is achieved in future experiments, which is one of the big aims of present-day research on MGI, this method will allow to measure it.

References

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