Analysis of the JET FIR interferometer beam phase changes during plasmas and application for fast fringe jump corrections by electronics

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Abstract The interferometer diagnostics using Far Infrared (FIR) laser beams provide, by phase measurement techniques, precise line-electron density measurements of magnetic fusion plasmas. But the FIR beams still suffer the effect of refraction when traversing the plasma. This can cause, when the density gradients are strong, temporary losses of signal that induce the so called fringe jumps on the estimated phase. On the CEA Tore Supra tokamak, a Field Programmable Get Array (FPGA) electronics has been developed using a time delay method to calculate the phase and correct the fringe jumps at the frequency rate of the probe sinusoidal signal (100 KHz). To test the efficiency of the algorithm on various plasma scenarios, a prototype of the CEA electronics has been installed on the JET tokamak and the data have been compared with those issued from the present JET electronics, which calculates the phase by a different method. Statistical comparisons between the two methods on more than 1500 JET shots are reported in this article and show that the two methods give similar results but that none of them is 100% reliable as still some fringe jumps remain, in particular when Edge Localised Modes (ELMs), pellet injections or disruptions occur. To understand this phenomenon, an analysis of the fast changes of the 100 KHz raw input signals during ELMs and pellet injections has been done with a 1MHz numerical acquisition. The typical durations of signal losses have been found to be few hundreds of micro-seconds. Meanwhile, the line density can increase and then return to its original value. Simulations show that an algorithm that would block the phase calculation during a longer time (i.e. 500 µs) than the disturbed period would help to avoid fringe jumps.

1. Introduction
To diagnose the line-electron density of magnetic fusion hot plasmas, FIR interferometers [1] have been developed using plasma traversing beams in the wavelength range of 100-200 microns for the CEA Tore Supra [2-4] and the JET tokamaks [5]. The diagnostics of the two machines are very similar. They both use the principle of recombination of a 100 KHz frequency shifted beam with the probe beam that has traversed the plasma. The interference produces a 100 KHz signal, of which one can measure the phase change that is proportional to the line density. A reference beam outside the plasma allows a differential phase measurement. As the expected line density can reach 5 10^{20} m^{-2} in the tokamaks, the corresponding FIR beam phase changes are several 2π radians, commonly named fringes.
Thus, one needs to build up a specific electronics that continuously measures the phase, not to be lost in the counting of the fringes. However, at these wavelengths, losses of signal may happen, due to changes of trajectories when the FIR beams are crossing too strong density gradient plasmas. This configuration can occur during ELMs, disruptions or when pellets are injected in the plasma. The loss of the phase information can mislead the phase measurement and generate the so called fringe jumps, each jump corresponding to an error of roughly $10^{17}$ m$^{-2}$.

JET and CEA developed different electronics that both enable to reach a very good precision of the order of $5 \times 10^{16}$ m$^{-2}$. The JET method is based on a 400 KHz sampling of the 100 KHz signal, which allows reconstructing the sinusoid and the corresponding phase. When the signal amplitude is lower than 50 mV, the phase measurement is stopped [5]. On Tore Supra, the sinusoidal signal is first transformed into a square signal, the ascending fronts of it being generated at every zero crossing of the sinusoid. The electronics thereafter counts the time delay between each front. Recently, the initial analogical electronics has been replaced by a numerical one. The program of the delay counting is now embedded in an FPGA processor. When the amplitude is below a threshold (0.2 volt), the fronts disappear while an algorithm maintains the phase at the most plausible value [6]. This set up has been successfully installed on Tore Supra since 2007 and correctly calculates the phase when the signal is lost as for instance during ICRH break downs, although the measurement is still disturbed by disruptions or sometimes pellet injections.

2. Comparative tests between the JET and CEA electronics

The advantage of the algorithm of the CEA electronics is that it can be easily modified. In order to test this electronics on different plasmas scenarios and possibly improve it, a complete rack of the CEA electronics has been installed in parallel with the JET electronics and connected to the 195 micron vertical traversing channels 3 and 4 during the 2008 spring campaign from shot 76103 to shot 78157.

Figure 1 shows that during a shot the evolutions of the measured phases of the two electronics are similar. One can see (fig 1b) that there is a very slight difference (~3 $10^{17}$ m$^{-2}$), oscillating at low frequency (0.7Hz). As this oscillation is also seen on the JET temporal derivate (fig 1c), one can assume it is due to the JET non synchronous sampling method that calculates the phase.

A statistical analysis has been performed to compare the fringe jumps that still remain on the two electronics. A good indicator of fringe jump occurrence during a shot is the final value phase, which is zero if no fringe jump occurs, although two fringe jumps of opposite value can erratically cancel out. Figure 2 shows the statistics for more than 1500 shots. The number of null final values is greater for channel 3 than for channel 4 because the last one is more sensitive to refraction, as it has to specifically go through a very long metal pipe that could cause that part of the refracted beam will
suffer internal reflections that will reduce the beam power. One can see that the two electronics have almost the same behaviour.

This is confirmed by table 1, which classifies the successes versus the disturbing events. One can see that the two electronics are confused when disruptions occur. During heating, they are both disturbed because ELMs induce strong density variations. The pellet injection doesn’t significantly modify the statistic although some fringe jumps are sporadically observed, especially on channel 4.

Figure 2. Analysis of the final phase value of shots 76103 to 78157

| Characteristics | Disrupt. | N. of shots | Null final value Channel 3 | Null final value Channel 4 |
|-----------------|---------|-------------|-----------------------------|-----------------------------|
|                 |         |             | CEA % | JET % | CEA % | JET % |
| Mean plasma current>200KA | no     | 1598        | 74.3   | 74.2   | 50.8   | 47.9   |
|                 | yes    | 130         | 4.6    | 6.15   | 13.1   | 10.0   |
| Ohmic          | no     | 190         | 96.3   | 95.7   | 96.8   | 97.9   |
| Heating > 1MW  | no     | 1408        | 71.3   | 71.2   | 44.6   | 41.1   |
| Pellet and heating | no   | 233         | 76.0   | 76.0   | 43.8   | 42.9   |

3. Analysis of the phase changes during an ELM

To understand why the two electronics behave similarly, we used the one MHz data acquisition of the 100 KHz interferometric signals, available on JET since 2007. Figure 3a shows the 100 KHz signal change during an ELM. One can see on fig 3b that the amplitude is attenuated during less than 500 μs and is under the 0.2 volt threshold during an even shorter time. But, at this low level, the amplitude is noisy, thus the two electronics are mislead and give wrong changes (fig 3c), compared

Figure 3. Analysis of a phase change during an ELM
with the soft post shot corrected value. This can be explained by a simulation of the installed algorithm (fig3d) : The CEA electronics restarts the counting too early in considering that the most plausible scenario is no phase change, even though the ELM induced an important density increase. One can see that an algorithm with a 500µs blocking time fits better the JET soft corrected signal, as it restarts the counting when the amplitude is stable and when the phase has almost returned to its initial value.

4. Analysis of the phase changes during a pellet injection

Channel 4 amplitude can also be affected by pellets (fig 4). The amplitude is under the threshold at the maximum of the injection peak, but not permanently. Again the CEA present algorithm restarts too early in a very disturbed period and thus is mislead. In the contrary, the algorithm with a blocking period better fits the true phase change.

Figure 4. Analysis of the phase change during a pellet injection

5. New algorithm and perspectives

One can see how revealing it is to be able to detect in real time the loss of amplitude of the 100 KHz signal and from this time to wait till the line density measurement is less disturbed. Thanks to the FPGA electronics architecture, the algorithm of the CEA electronics has been straightforwardly modified and a version with a 500 µs blocking delay will be tested on JET, in parallel with the initial version. Possibly the blocking period could be adjusted. In case of very long periods of amplitude defaults, the algorithm manages to wait and only restart when the amplitude is again correct. For the moment, due to lack of information during the disturbed period, the algorithm considers that the most plausible event is that the phase has not changed. But, as during a pellet injection, this assumption can be wrong and it is of interest to explore for the JET tokamak or for future machines, the possibility to estimate by Cotton Mouton effect the line density change after a disturbed period.

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