New reflectometer in a Low Hybrid Launcher on Tore Supra

C. Bottereau, F. Briolle+, F. Clairet, M. Goniche, F. Leroux, D. Molina, MQ. Pham, S. Poli, C. Portafaix, B. Ricaud*, R. Sabot, A. Saille.

CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France.

+ CPT, Campus de Luminy, case 907, F-13288 Marseille, France.
CReA, BA 701, F-133006 Salon de Provence, France.
** LATP, Université de Provence, F-13453 Marseille, France.*

Tore Supra is equipped with different heating and current drive systems. Current drive is mainly provided by two lower hybrid ranges of frequency (LHRF) launchers exciting the slow wave. The system has been recently upgraded and the power capability for very long pulses extended to 7-8MW. Because of the very small evanescence length, the electron density at the antenna front must exceed the cut-off density ($n_c = 1.7\times10^{17} m^{-3}$ at 3.7GHz) to provide good RF coupling and therefore good current drive efficiency. This density depends on the confined plasma parameters (density, current) but also on the objects inserted in the scrape-off layer (SOL) acting as secondary limiters for the LHRF launchers. Moreover, electrons can be pushed away from the antenna by the strong RF electric field. Conversely local ionization provided by a small fraction of the LH power dissipated in the SOL can increase the density. RF coupling is also sensitive to density gradient in the narrow plasma layer just in front of the antenna. In order to have a good understanding of the RF coupling, it is compulsory to have local (i.e. very close to the plasma-antenna interface) electron density and density gradient measurements.

Reflectometer characteristics:

In order to measure the density in the $1\text{-}10\times10^{17} m^{-3}$ range with a magnetic field strength close to the maximum value (3.85T at plasma centre) an X-mode reflectometer in E-Band (60-90 GHz) is well suited. The new reflectometer (fig 1) is a fast frequency sweep heterodyne reflectometer based on our mature technology tested on Tore Supra and JET [2, 3]. It was specifically adapted to the particular location inside a RF antenna.

Figure 1: Reflectometer embedded in a LH launcher on Tore Supra

The key of our technology is the Single Side Band Mixer which allows a heterodyne detection without phase lock loop [2]. The beat frequencies are up to 50MHz, and a VME controlled data acquisition system sampling at 100MHz can provide up to 10000 profiles per shot, triggered on an external signal if needed. The routine scan time is 20 µs for a profile with a dead time within 2 profiles of 5µs min. The sweep rate can be higher on request, depending on the profile shape.

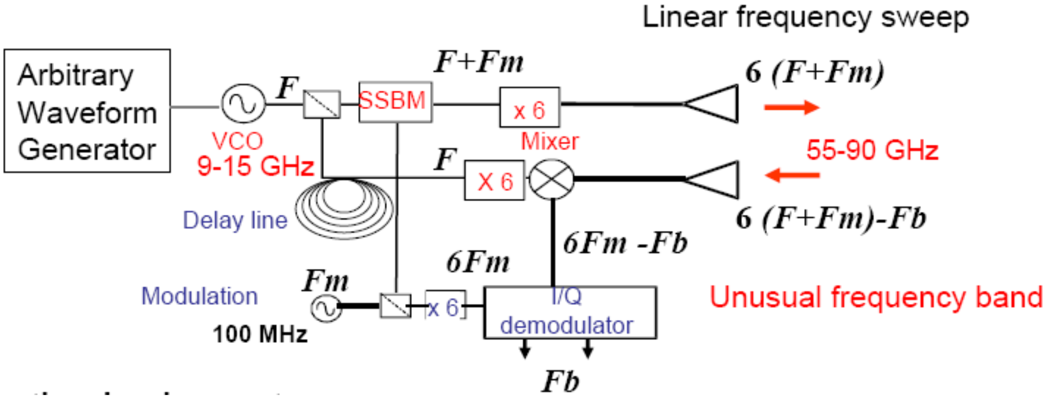


Figure 2: reflectometer setup

Implementation in a launcher:

The new reflectometer is located in the middle of the LH antenna, in the equatorial plan, at 5 cm from the vertical axis (fig 3).

Two 3.4m long Copper OFHC waveguides are embedded between the 2 row of LH antenna modules. They are WR28 waveguides, normally adapted for Ka-Band, which allow an insertion loss of 0.5dB/m for the wave in E-Band. To avoid water cooling pipes we use 680mm of WR15 waveguides (insertion loss ~1.4 dB/m) and 100mm of linear taper welded by electron beam. Final losses were measured around ~ 5dB and no higher level mode was detected.

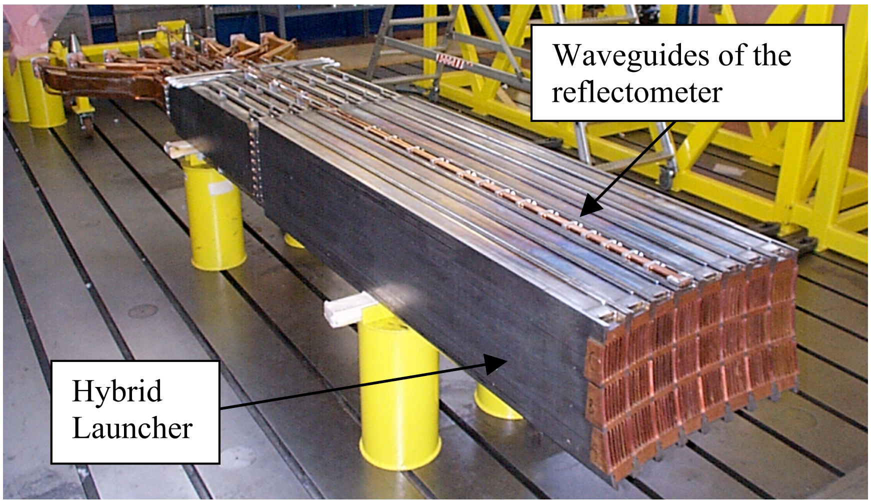


Figure 3: Waveguides of reflectometer, on one of the two modules of the LH launcher

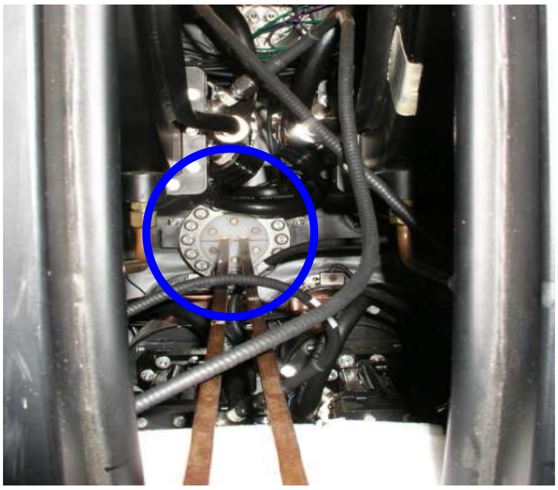


Figure 4: Vacuum tight, rear part of the hybrid Launcher

A bonding steel quartz vacuum tight (fig 4) tested in a vacuum chamber at 10^{-5}pa provides vacuum isolation. The electrical insulation of the waveguide between inside and outside the antenna is performed by a leaf of Kapton of 50µm tested at 5kV and a piece of Ertalon. RF losses were measured within 2 dB for vacuum insulation and 1dB for electrical insulation.

This special implementation in a launcher causes problems such as lack of space or exposition to plasma radiation.
So we chose to work without horn antenna (fig 5), using the openWR28 waveguide, positioned 5mm in front of the cooling pipe and 5 mm behind the end of the module to minimize the multi-reflections on metal all around and to avoid overheating.
In this configuration directivity is too low and backwall is too far to be detected by this reflectometer.
The coupling signal (fig 6) obtained between open waveguides is used as the reference signal.

Figure 5: Open-waveguides

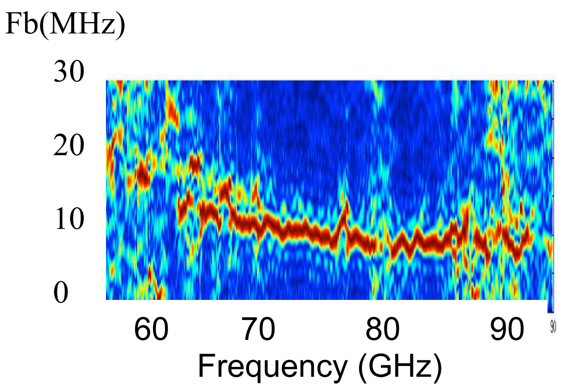


Figure 6: Coupling signal between antennas

Because of the metal conception of the launcher and the proximity of plasma, there are multi-reflections between the launcher and the plasma (fig7) which disturb the phase and could induce a shift of density profiles.

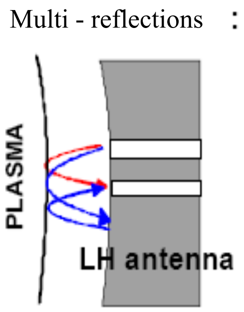


Figure 7: Multi-reflections between LH launcher and plasma

Data processing:

The first results (fig7) were performed with the 50-75 GHz reflectometer at B=3T

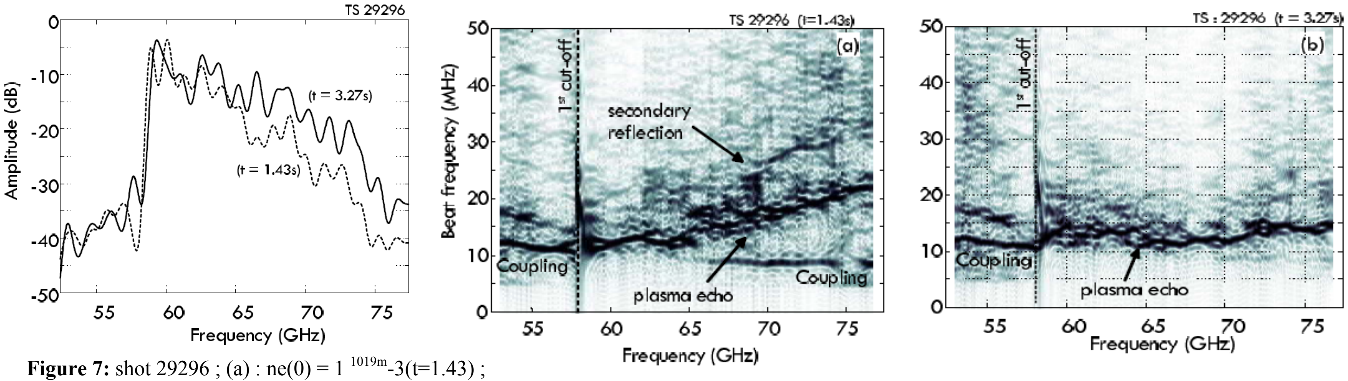


Figure 7: shot 29296 ; (a) : ne(0) = 1 ^{1019m}-3(t=1.43) ;
(b) : ne(0) = 3 10^{19}m-3 (t=3.27s)

We obtain a clear detection of the first cut-off frequency due to the sharp amplitude rise relative to the reflection on plasma. The amplitude of the signal decreases due to low directivity of the open waveguides. In order to resolve the multi-component aspect of the reflected signal (fig 7), we have to develop a new data processing using tomogram transform [5].

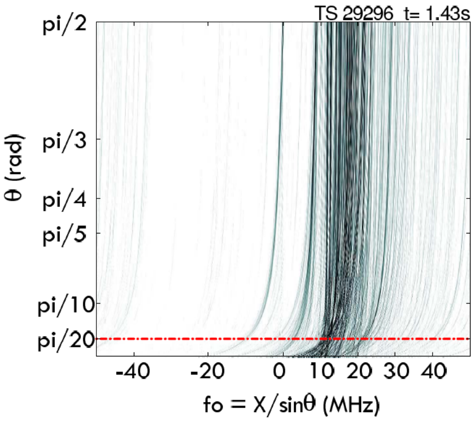


Figure 8: Tomogram

The tomogram transform performs the projection Cθ of the signal over the basis formed by "chirp functions" with instantaneous frequency fi(t) = tan(θ) t + X (fig 8).
We choose the minimum value of θ for which we obtain a convergence. The signal is projected and separated in parts.

Using the full signal, secondary echoes increase arbitrarily the phase signal. The relevant density profile calculated from signal filtered with tomogram analysis is shifted by about 2 to 4 cm toward the edge compared to the full signal (fig 9).

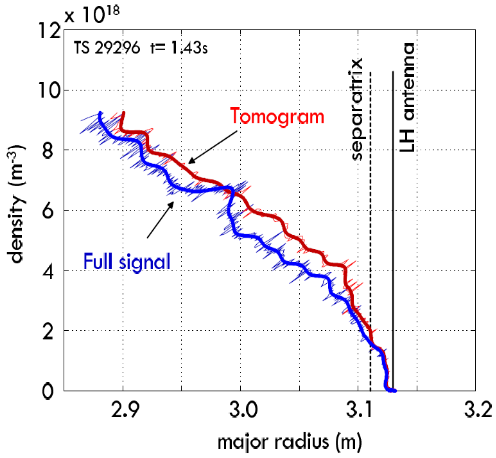


Figure 9: Data processing comparaison showing a shift of the density profile after elimination of the multicomponent of the signal acquired

First results:

The new campaign of Tore Supra has begun in May 2011, during the conference. We are presenting the first results obtained with this new reflectometer.

During the shot studied as an example of the performances, the two Low Hybrid antennas of Tore Supra launch a power up to ~5MW in order to heat the plasma (fig10).

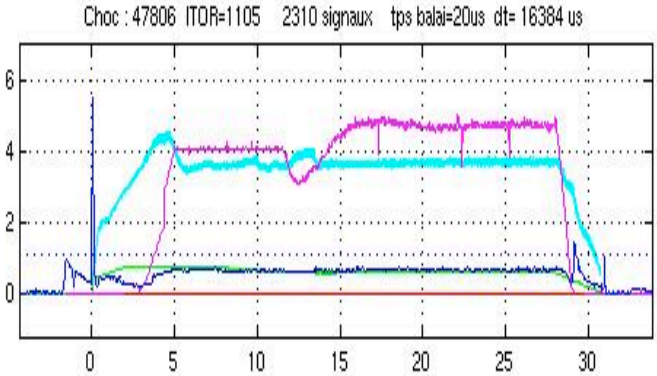


Figure 10: shot TS 47806
(a): ne (0) = 3.3 10^{19m}-3(t=3s);
(b): ne (0) = 3.75 10^{19}m-3 (t=10s) LH power: 4.1MW;
(c): ne (0) = 4 10^{19}m-3 (t=20s) LH power: 4.8M.

We measure the density gradient in the shadow of the lateral protections (fig 11). We observe variations of confinement resulting from the low hybrid heating system, increasing first density a few centimetres from the launcher before extending its effect to the whole plasma.
We follow the evolution of the density in the first centimetres, just in the middle of the mouth of the hybrid launcher.

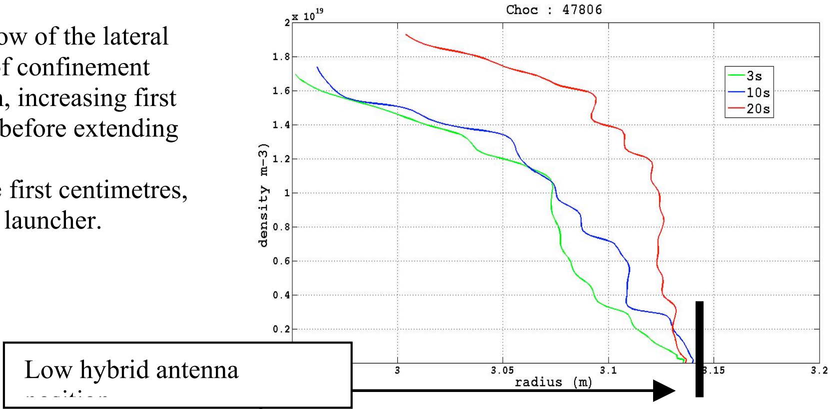
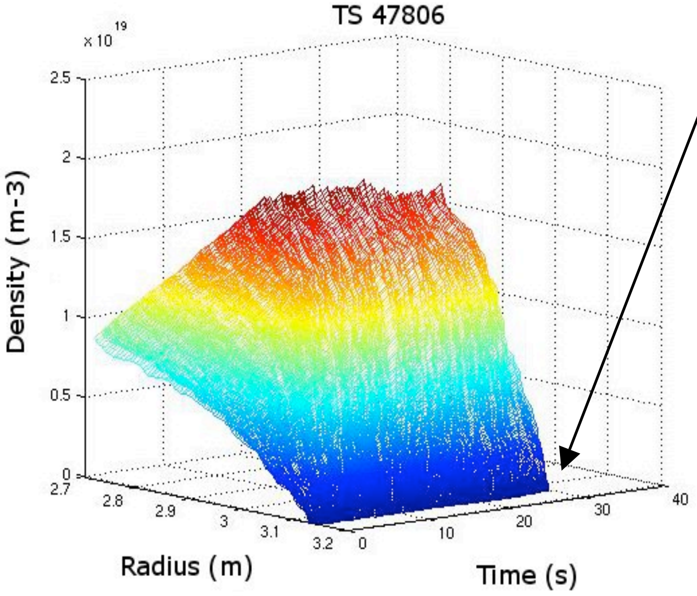


Figure 11: shot 47806, variation of the density gradient in front of the LH Launcher
(a): ne (0) = 3.3 10^{19m}-3(t=3s);
(b): ne (0) = 3.75 10^{19}m-3 (t=10s) LH power: 4.1MW;
(c): ne (0) = 4 10^{19}m-3 (t=20s) LH power: 4.8M



The reflectometer produces a density profile (fig 12) in 20µs each 16ms to assess profile modification during heating.
This new characterization of the edge plasma in the direct vicinity of the RF heating antenna has an important role in the knowledge of LH wave coupling.

Figure 12: Strong increase of density gradient in the SOL during LHCD

Conclusion

A new fast sweep heterodyne reflectometer was installed in a LH launcher and is in operation during the current campaign of Tore Supra. It was designed to measure the edge density profile just in front of the LH antenna. Specific problems linked to this particular location, highly exposed and so narrow, have led to adapt waveguides, finding a new reference, but also to develop data processing tools.
The first results are very encouraging. These experimental results will be compared with those obtained from the linear theory of LH coupling for an even more accurate understanding of the plasma-wave interaction. Density reflectometry profile should shed some light in the SOL in the issue of enhancing the Lower Hybrid coupling. Most from these problematics are relevant for other RF heating systems in particular for ITER ICRH antennas, where in-situ reflectometers are also foreseen.

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