AWG-driven short pulse reflectometer diagnostic in the TCV Tokamak

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The present proceeding describes the design and latest results of a new short (ns-scale) pulse reflectometer developed at the TCV tokamak. In TCV, density measurements from the plasma core to the last closed field surface (LCFS) are routinely available from the Thomson Scattering (TS) diagnostic with a spatial resolution varying inside 0.6 and 1.5cm but only 60Hz temporal sampling. Microwave reflectometry has been identified as a strong candidate to complement these measurements, specially in the plasma 'edge' region (ρ_ψ 0.8-1.0), given its high spatial (sub cm) and temporal (μs) resolution [2]. Increasing the temporal resolution of edge density measurements could be decisive in revealing the dynamics of confinement regime transitions and fast pedestal events such as edge-localized modes (ELMs). In microwave reflectometry, the electron plasma density can be inferred from the roundtrip group-delay of EM waves reflected from a plasma cutoff layer. There are many experimental approaches to measuring the round-trip group delay [3], with continuous-wave frequency modulation (CWFM) being the most widespread. Short pulse reflectometry (SPR) consists of sending a broadband microwave pulse of about 1ns and measuring the pulse roundtrip group-delay using precise chronometers. SPR is a uniquely attractive approach to reflectometry. Firstly, assuming negligible absorption and weak dispersion, the group-delay of a pulse with a defined carrier frequency can be measured directly. This stands in contrast with CW-FM techniques where the linearity of frequency sweeps is vital to measuring accurate group-delays [2]. Secondly, pulse propagation through the plasma occurs in the ns-scale, at least 2 orders of magnitude under turbulence time scales expected in the μs scale: the plasma can be safely considered to be *frozen* during pulse propagation. Lastly, given the time-domain nature of SPR measurements, spurious reflections in waveguides, vacuum windows, and in-plasma coherent back-scattering are naturally separated from the plasma cut-off reflection allowing easy filtering.

SPR does also feature unique technical challenges. Measuring pulse group-delay down to ps accuracy levels is challenging and requires excellent signal-to-noise ratios. Furthermore, pulse envelope dispersion and distortion have been alluded to by many authors [4, 5] and studied theoretically [6, 7], but, prior to this work, have not been directly measured. Heijnen [8, p. 29] and Hacquin [6] showed that, within the WKB approximation and the 1D full-wave equation, respectively, pulses of durations above 0.5ns should not feature pulse dispersion when sampling smooth quadratic density profiles. Pulse dispersion/distortion has the potential of reducing the accuracy of group-delay measurements. However, if the output pulse-width can be varied and the reflected pulse-width measured, pulse dispersion can provide information on the slope of the group-delay curve. This measurements can be used to initialize the profile without the need of other diagnostics [6]. Furthermore, direct sampling of distorted pulses can provide direct evidence of particular density fluctuations: away and close to the cutoff layer in the form of Bragg resonances or wave-trapping [9, 7].

Nearly 15 years after the last SPR publication [10], advances in digital electronics and mm-wave hardware have allowed limitations regarding spatial sampling and range resolution to be surmounted while increasing range precision by a factor of 4. This publication presents how a fast (65GSa/s, 25GHz analog bandwidth), multi-channel, arbitrary waveform generator (AWG) and a $\times 6$ varactor multiplier can bring about flexibility in pulse carrier frequency, width, and repetition frequency. High-radial resolution density profiles can be thus reconstructed with sub-cm spatial resolution and μs temporal sampling comparable with established CWFM techniques. Furter details on the diagnostic design, performance tests, and a larger collection of observations can be found in [11].

Harware implementation

Figure 1 shows both transmitter and receiver stages of TCV's SPR. The transmitter section produces Gaussian pulses of 650-750ps full-width-at-half-max (FWHM) of arbitrary frequency inside the V-band (50-75GHz) by using 1-2ns, 8.33-12.5GHz carrier, pulses from the Keysight M8195A AWG fed into a x6 varactor multiplier. This frequency multiplier is found inside a transmitter/receiver (TX/RX) commercial off-the-shelf VNA extension module built by Virginia Diodes Inc (VDI). The varactor multiplier has a non-linear response to input pulses leading to varying degrees of pulse compression and amplitude saturation. Nonetheless, thanks to the unique flexibility of the AWG, Gaussian output envelopes can be created by carefully controlling input pulse amplitude, duration, and phase. The envelopes of the outgoing pulses have been directly measured to be Gaussian in shape with

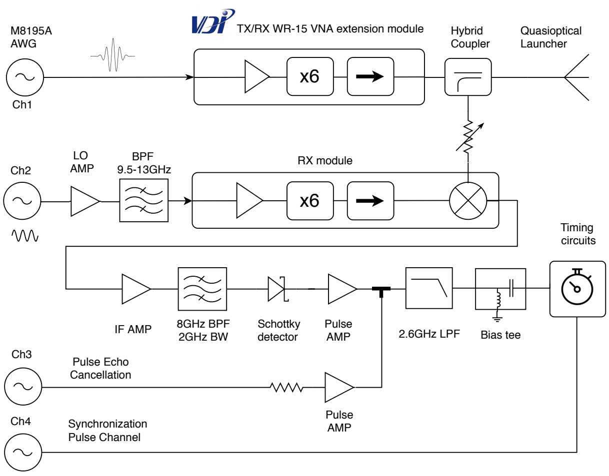

Figure 1: SPR schematic diagram

a fast zero-bias Schottky diode detector [11]. The output pulses are transmitted to the plasma via TCV's diagnostic launcher antenna described in detail here [12]. This antenna permits flexible poloidal steering of the beam to access many TCV plasma shapes as well as coupling into O or X-mode giving access to 3-7 and 0.8-4 10^{19} m^{-3} densities, respectively.

The receiver RF stage uses a traditional heterodyne downconverter for increased sensitivity. The local oscillator signal is produced by multiplying a continuous 8.33-12.5GHz signal provided by a second AWG channel synchronized with the pulse channel. The mixer output is a pulse with a constant 8GHz intermediate frequency regardless of the output pulse frequency. The 8GHz pulse is then amplified, filtered, and detected via a fast Schottky diode. The latter extracts the Gaussian envelope function which is then further amplified and filtered before reaching the timing-circuits. Figure 1 shows also a pulse echo cancellation channel which is used to attenuate strong reflections from the vacuum window that cause false triggering of timing circuits.

Two main techniques have been explored to precisely measure pulse group-delays: traditional analog and direct digital sampling approaches. Given the physical size of TCV, assuming a parabolic density profile, reconstructing the outer 20% of the confined plasma with a 20 point density profile requires a 2.5mm range resolution. Such a resolution in vacuum corresponds to requiring the timing circuits to discern pulse group-delays with a 17ps maximum error. In order to obtain a 20-point profile measurement with a competitive [2] 1.25μs temporal resolution, a pulse repetition rate (PRR) of at least 16MHz is required. Traditionally, short and ultra-short pulse reflectometers have used a combination of a constant fraction discriminator (CFD), a time-to-amplitude converter (TAC), and an analog to digital converter (ADC) to measure group-delays. The CFD is required to accurately measure group-delays from reflected pulses of varying power, typical of reflections against turbulent fusion plasmas. All these elements have been identified in the commercial SPC-150NX timing module from Becker and Hickl GmbH. This module measures the time different between a SYNC pulse (see figure 1) and the reflected pulse down to 1.6ps. In addition, the module may be operated at a count rate of up to 10MHz, which remains competitive with CWFM speeds. It may acquire up to 2 10^6 events, which at 10MHz corresponds precisely to the standard TCV discharge duration.

A newly tested approach to quantifying group-delays is to directly sample the pulse envelope with a fast analog to digital converter (ADC). A fast (45GSa/s), 8-bit, 13GHz analog bandwidth oscilloscope (LeCroy 813Zi-B) is used for this purpose. A Gaussian function is fit to the reflected pulse via least-squares. Unfortunately, the leftover Gaussian pulse power outside the IF filter pass-band produces ringing in the form of small-amplitude pulses which interfere and distort the right-hand side of the reflected pulse. Thus, the Gaussian fit ignores 70% of the right portion of the pulse. The synchronazation pulse fit ignores only 20%. Direct sampling has the immense advantage of storing the reflected pulses allowing future post-processing routines to re-interpret the data. Another advantage is that the fits return not only the time difference between input and SYNC pulses but also pulse envelope amplitude and width. However, an important disadvantage of this approach is the large memory requirement: at 45GSa/s, the limited oscilloscope memory of 32 mega samples allows a pulse train of only 0.7ms to be acquired. Both techniques have been carefully calibrated [11] including all the mmw hardware noise and have achieved 17ps average precision over the V-band. This figure combines random noise errors and changes to the group delay caused by up to 10dB pulse power variations.

Results and discussions

Direct sampling of pulses during a L-mode discharge shows that pulse amplitude may vary between 1.2V and the noise floor: over 40dB. Counting only the pulses that could be fit with a Gaussian function and a R^2 abeove 0.985 (Vpk > 0.2V), pulse widths were observed to change between 1.12ns and 0.61ns In average, however, reflected pulse widths sat at 0.78ns with a standard deviation (SD) of 70ps compared with 0.75 ± 0.03ps average against a mirror. This proves that while pulse dispersion does occur and may induce increased uncertainty in the group-delay measurement, pulse widths increase only by 4%. Pulse dispersion is hence not a show-stopper to SPR, as argued in [4]. The scatter of measured pulse widths motivates an increase in the analog-circuit (blind to pulse width changes) group-delay uncertainty from 17 to 40ps. A positive skewness of 1.02 was observed, showing a larger tendency of pulses to be dispersed. The minimum pulse width of 610ps, safely away from fit uncertainty under 30ps, shows that the plasma can shrink the pulse width; this is an unexpected result.

The analog sampling technique was used to study group-delays at longer time scales. The first clear observable was that plasma-reflected pulse group-delays fluctuated much more than mirror-reflected pulse group-delays. This scatter changes significantly as a function of plasma conditions. The group-delay standard-deviation of 100ms of group-delays goes from 11ps against a mirror to 109 and 22ps in a L and H-mode plasma, respectively. While part of this group-delay scatter can be attributed to changing pulse widths, L-mode plasmas feature additional scatter that could contain information on radial fluctuation levels. It can be expected that rich physics information could be extracted from these findings with the aid of synthetic modeling of pulse reflection in the presence of realistic tokamak plasma density fluctuations.

Fourier analysis of the raw group-delay data has revealed the presence of large macroscopic MHD density fluctuations. Sawtooth oscillations and quasi-coherent pedestal modes during H-mode plasmas have been identified in the group-delay PSD in agreement with interferometer and magnetic pick-up coil data. During ELM-free H-modes, a well-defined quasi-coherent oscillation of about 600-800kHz has been identified which seems temporally connected with the saturation of the beta toroidal. For further details see [11, p.133].

After measuring group-delays from a large number of frequencies, density profiles can be reconstructed via inversion algorithms that depend on polarization. Prior to attempting these reconstructions, a careful group-delay calibration is required to eliminate any inherent group-delay variations over the V-band due to the mmw-wave and transmission line hardware. The quartz vacuum window also features ∼30ps sin-like variations of the group-delay over the V-band, typical of Fabry-Perot interfaces. In O-mode polariation the well-known Abel transform is applied to recover a density profile from the group-delay information directly. Profile initialization of the $\partial\phi/\partial f$ curve under 50GHz is obtained by inverting the Abel formula numerically using Thomson-scattering data and/or reciprocating probe measurements of the SOL density profile [13]. Figure 2 shows the density profile evolution during a L-H mode transition recorded with 7 frequencies during shot 61337. The group-delay data was averaged over 8.75μs to produce each profile, which averages about 5 pulses in each frequency. Density profiles have also been reconstructed in the X-mode polarization. The Bottolier-Curtet algorithm [14] algorithm is used by transforming group-delays into phase differences through numerical integration. The magnetic field is obtained from TCV's LIUQE reconstruction. The profile is allowed to eveolve between TS periods by letting the evolution of the first group-delay over time dictate where the first reflection point changes over time [11].

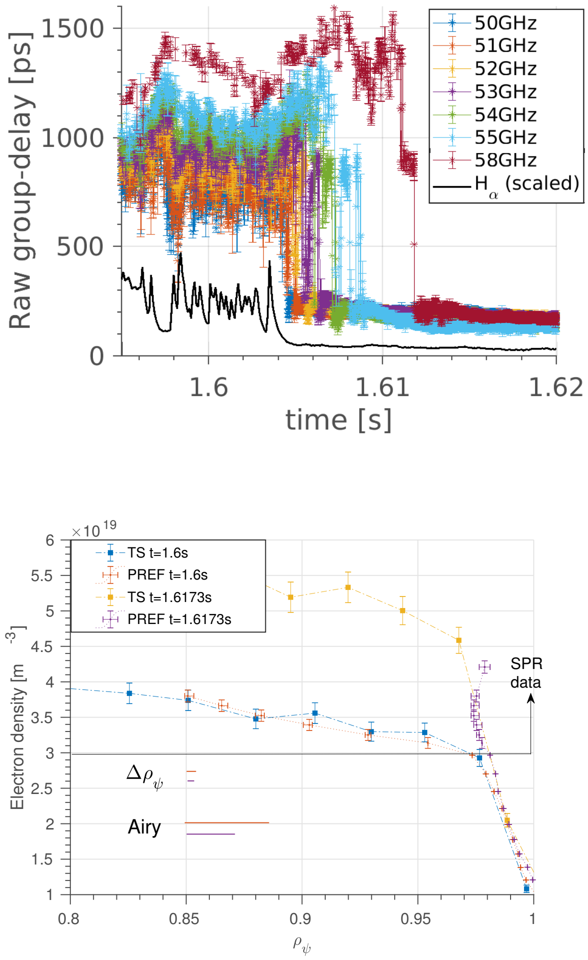

Figure 2: SPR density profile in O-mode during L-H-mode transition shot 61337. (a)Raw group-delay with 8.75μs averaging. (b) Comparison with TS with 8.75μs averaging.

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