Pulse Reflectometer and Doppler back-scattering diagnostics in the TCV Tokamak

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Dedicated short pulse reflectometer (SPR) and Doppler back-scattering (DBS) diagnostics have recently been developed for the Tokamak à Configuration Variable (TCV).

The DBS diagnostic uses a fast arbitrary waveform generator (AWG) as the main oscillator and commercial vector network analyzer (VNA) extension modules as the main mm-wave hardware. It allows sweepable single or multi-frequency operation. A flexible quasi-optical launcher antenna (inherited from electron-cyclotron resonance heating launchers) allows 3D poloidal (10-58^o) and toroidal (-180 - 180^o) steering of the beam with 0.2^o accuracy. A pair of fast HE_{11} miter-bend polarizers allow flexible coupling to either O or X mode and programmable polarization changes during the shot. 2D 3-point ray-tracing simulations reveal an available $k_\perp$ range between 3 and 16 cm^{-1} with a resolution of 2-4 cm^{-1}. Perpendicular rotation velocity estimates compare well against ExB plasma poloidal rotation estimates from CXRS. A contributed article has been recently accepted for publication in the Review of Scientific Instruments journal [3].

The multi-frequency mode proposes a new approach for the production and detection of multiple simultaneous frequencies. It consists of creating a double frequency spectrum with the AWG, feeding this signal into the varactor multipliers inside the VNA extension modules, and directly sampling the entire output spectrum with a fast oscilloscope. It is known that the response of frequency multipliers implies the generation of frequency products of the form $nf1 + mf2$ to a double frequency input. Therefore, if a two-tone input composed of f1 and f2 is fed into the x6 varactor multiplers, their output would consist of 6f1, 6f2, and 5 other intermodulation products. Seven frequencies can thus be produced. The distance between the first two tones may be changed and is only limited by the maximum IF bandwidth of the receiver (10GHz). A fast 13GHz analog bandwidth oscilloscope is used to directly sample the IF output of the receiver mixer. Beyond obviating the need for comb-frequency generators and their fixed filters in the receiver, the current set-up may change arbitrarily the frequency span and spacing of the seven output frequencies to best fit specific plasma conditions. Data from plasma discharges has validated the multi-channel technique agreeing both with regular I/Q DBS and with ExB estimates from CXRS. A serious disadvantage of the current approach is that the plasma could be sampled only for as long as $\sim$2ms given the limited scope memory (32Mb). This maybe overcome in the future by commercial data-acquisition solutions which feature memories of on the 100s of gigabytes (i.e.: Guzik ADP7000).

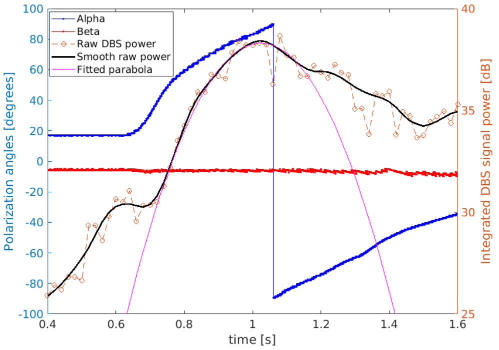

Figure 1: DBS signal power evolution over changing polarization (α) angle.

Another unique capability of the new DBS system is the demonstrated possiblity of changing the polarization of the outgoing beam during the discharge. A pair of fast polarizer miter bends have been used to change the inclination angle of the polarization ellipse α while keeping a constant elliptical polarization angle β in search of an independent measurement of the magnetic field-line pitch. The best coupling to either X or O mode can be calculated by matching the launched beam wavevector and polarization to the relevant mode in the plasma's LCFS based on the magnetic field reconstruction. The coupling of the launched wave to either X or O mode at the plasma LCFS could be made to change by varying α while keeping β constant. If both the effective α and the power of the DBS signal during the shot are examined, a measurement of the magnetic field pitch angle at the edge of the plasma is possible. Figure 1 shows time traces of both α and β angles during shot 59679. The encoder output of both linear and elliptical miter bend polarizer angles is mapped onto α and β maps over the shot time. Figure 1 shows that the effective α changes between +20 and -40 degrees while β can be made to remain between -5 and -6 degrees , aiming for an ideal -5.36 degrees for X-mode best coupling at a chosen toroidal angle of 0 degrees. The best coupling to the X-mode wave into the main plasma should occur when the probing beam's α is perpendicular to the LCFS B-field line. The DBS signal power is estimated by integrating the area under the fits to the smooth DBS PSD spectra. A parabola is fit to the points around the peak power to determine the time of the peak DBS signal power. This peak is found at time 1.02±0.01 where alpha was 84.5±3. The best X-mode coupling α estimate agrees within uncertainty with the LIUQE suggestion of 81.7 ± 0.4^{o}.

A novel approach to short pulse reflectometry is being actively developed for electron density profile and fluctuation measurements in the pedestal of TCV. Taking advantage of fast AWGs, the proposed design allows flexibility regarding pulse frequency, duration, and repetition rate. Such flexibility has the potential of overcoming traditional spatial sampling and range resolution limitations associated with previous SRP implementations. In microwave reflectometry, the electron plasma density can be inferred from the round-trip group delay of EM waves reflected from a plasma cut-off layer. Pulse reflectometry consists of sending broadband microwave pulses with a defined carrier and measuring the roundtrip group delay (or time-offlight (TOF)) using precise timing systems. A useful SPR diagnostic must resolve the density profile of the edge pedestal of H-mode discharges with at least 20 points, leading to a range precision of 2.5mm which requires a hardware precision of timing circuits under 17ps. In order to remain competitive with modern frequency modulation reflectometers, the pulse repetition rate must exceed 16MHz. It is expected that a Gaussian pulse envelope of 700ps consistent over all frequencies should not experience any significant dispersion [2]. Lastly, the receiver timing circuits should accomodate power variations in the order of 23dB given that plasma reflected power, even if properly aligned, may change during the shot

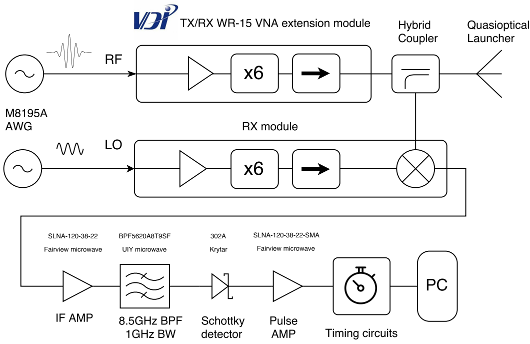

Figure 2: Block diagram of the SPR setup.

Figure 2 shows a diagram of the SPR setup. Instead of using fixed oscillators and a fast PIN diodes to create the pulses, this SPR uses an AWG to generate pulses inside 8-12GHz and uses non-linear varactor multipliers to bring these to the V-band. The AWG's unique flexibility allows clean Gaussians to be produced. A fast V-band zero-bias Schottky detector has been used to ensure the outgoing the pulse envelope of the varactor multiplier remains Gaussian-like inside 650-750ps FWHM. This was achieved by carefully adjusting the input pulse width, amplitude, and phase with the AWG. The heterodyne receiver stage mixes the returned power with a local oscillator (LO) signal. This signal also comes from the AWG, but it is continuous-wave and has a frequency difference with respect to the outgoing pulse RF carrier that results in an intermediate-frequency (IF) output pulse centred at 8.5GHz. The IF pulse output is firstly amplified by a broadband, low noise, amplifier. The pulse is then band-pass filtered and fed into a fast Schottky detector, which extracts the pulse envelope function. Lastly, this envelope is amplified by a 3GHz BW pulse amplifier.

Two main approaches have been pursued to accurately quantify the TOF. The first, traditional, approach is to use a combination of a constant fraction discriminator (CFD), a time-to-amplitude converter (TAC), and an analog to digital converter (ADC). All these elements have been found integrated off-the-shelf in the commercial SPC-150Nx timing module by Becker and Hickl GmBH. This module can measure the time between two events with electrical resolution down to 1.48ps. It may be operated at a saturated count rate of up to 10MHz, slightly under the requirement. Also, it may acquire up to 2 full seconds of events at 10MHz. In-situ performance tests of the SPC-150Nx using pulses reflected from a static mirror placed before the launcher antenna show a normal-distributed TOF measured with a 11ps standard-deviation. Artificially changing the losses in the system to mimic plasma S11 variations result in a CFD *walk* of 13ps. The second approach pursued to quantifying the TOF is to directly sample the pulse envelope with a fast ADC. A 45GSa/s is used to sample the pulse envelope and a fixed synchronization pulse in separate channels. This approach has the advantage of storing the returned pulse for flexible interpretation in the future. Currently, the analysis consists of using least-squares fitting of the plasma pulse with Gaussian functions. Given the pulse distortion caused by IF filter shape, the fitting ignores the righ-hand-side of the returned pulse. Post-processing may access not only the TOF but also peak amplitude and pulse width. Tests against a mirror reveal an improved response of 8ps standard deviation timing jitter when compared with 11ps from the SPC-150Nx. The fits should experience theoretically no walk errors due to the input amplitude, yet more tests are required to confirm this assertion. The disadvantage of this approach is the memory of the scope, which allows only $\sim$2ms of pulses to be recorded.

Data from over 80 plasma discharges has been acquired with the SPC-150NX system. It quickly revealed an order of magnitude increase in the normal distribution of TOFs from 11ps to $\sim$ 100ps in positive triangularity L-mode plasmas. The shape of the raw TOF histograms also showed skewness, best fit by a beta distribution function. Pulse time vectors have also revealed that about 50% of the pulses are lost, likely because half of the returned power is too low to be accepted as an event by the module. In L-mode discharges when the cut-off is found around ρ_ψ 0.75, a sawtooth signal is evident in the raw data. Spectral analysis reveals a sawtooth frequency of $\sim$ 300 Hz in agreement with interferometry data at the same radial location. SPR TOF data averaged for 1ms at 1.03s during shot 61337 was used to create the first 7-point density profile of the diagnostic, which shows good agreement with the TS density profiles. Analysis is actively underway to extract fast density profile changes in the near future.

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