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Progress in fusion research shows an increasing demand for diagnostics with high temporal and spatial resolution in order to study small and fast phenomena in fusion plasmas. Therefore, a new ten-channel pulsed radar reflectometer is under development for the TEXTOR Tokamak, to measure electron density profiles in the range of $0.4–4\times10^{19}$ m^{-3} at a high repetition rate of 2 MHz. An additional feature of this diagnostic is the possibility to perform correlation measurements at 10 MHz repetition rate to investigate density fluctuations. The reflectometer will scan the plasma with 1-ns-long radar pulses in the 18–57 GHz range. In spite of the long flight time of the pulses of about 100 ns, the above mentioned high repetition rates could be achieved by time multiplexing the generation and reception of the radar pulses. Temporal selection of the received pulses is performed by fast switching of the local oscillators inputs of the heterodyne receiver, to generate time windows in which the reception of the reflected pulses is expected. An embedded VME controller will manage the system and store the data with a speed of 20 Msamples/s, up to a maximum of 64 Mbyte data per plasma shot. In order to facilitate the handling of such a huge amount of data, an advanced data reduction scheme is being developed. Remote operation with a fast data link from FZ Jülich (Germany) to FOM Nieuwegein (The Netherlands) will be possible. © *1999 American Institute of Physics.* [S0034-6748(99)68001-7]

I. INTRODUCTION

In pulsed radar reflectometry, short microwave pulses with a width in the order of 1 ns are launched into the plasma.[1,2] Depending on the radar frequency and the plasma parameters, the pulse is reflected by a critical density layer and received again by the diagnostic equipment. The basic quantity that is measured by the pulsed radar diagnostic is the flight time of the microwave pulse between transmission and detection.

With the new setup, an upgrade of the four-channel pulsed radar developed by Heijnen,[3–5] the number of channels is increased to ten. Moreover two additional variable frequency channels are added to the system. The latter two channels can be used in combination with two fixed frequency channels to perform correlation measurements and to study magnetohydrodynamic (MHD) modes.[6] The pulse repetition frequency has been increased by a factor 10 in the upgraded system. The flight time is recorded with an accuracy of 70 ps, corresponding to a spatial resolution of 1 cm when reflected from a metal mirror in vacuum. The chosen pulse length of 1 ns is a compromise between the accuracy of the time of flight measurement and the pulse broadening, which would become unacceptably large for much smaller pulse widths. The flight time is measured between the 50% levels of the leading edges of the transmitted and received pulse.

II. MICROWAVE HARDWARE

The outline of the microwave system of the TEXTOR pulsed radar reflectometer is given in Fig. 1. The system consists of three main parts:

(1) two homodyne channels at 18 and 24 GHz in *K* band waveguide,
(2) four heterodyne channels at 29, 33, 36, and 39 GHz in *Ka* band waveguide,
(3) four heterodyne channels at 47, 51, 54, and 57 GHz in *U* band waveguide.

The *Ka* and *U* band frequencies are alternately used as rf and local oscillator (LO) pulse. After mixing, all the heterodyne channels give an 18 GHz intermediate frequency (IF) pulse. Two channels with variable frequencies around 36 and 51 GHz are added to the system to perform correlation measurements with the corresponding fixed frequency channels.

The microwave sources are Impatt oscillators with an output power of approximately 200 mW in the *K* and *Ka* band, and 100 mW in the *U* band. All sources have an indi-

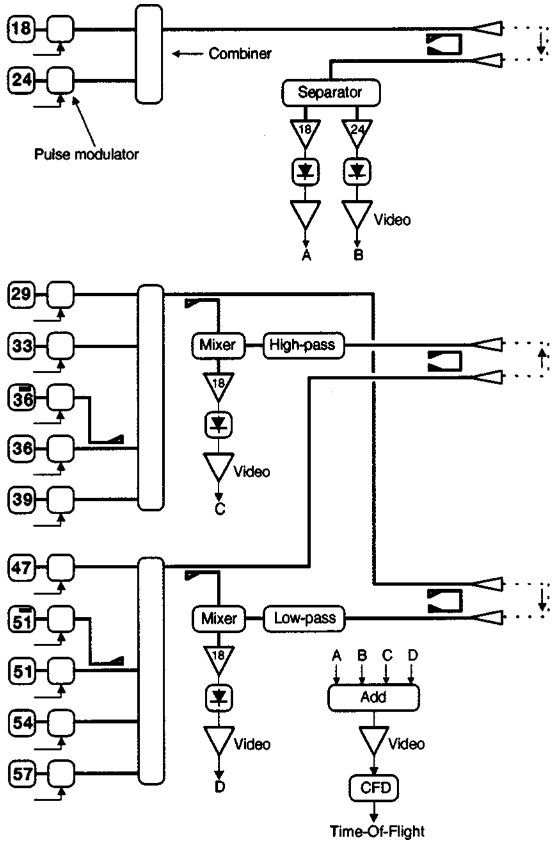

FIG. 1. Block diagram of the ten-channel pulsed-radar diagnostic, extended with two channels for correlation measurements. All frequencies are in GHz. The sweepable sources are indicated with a minus sign.

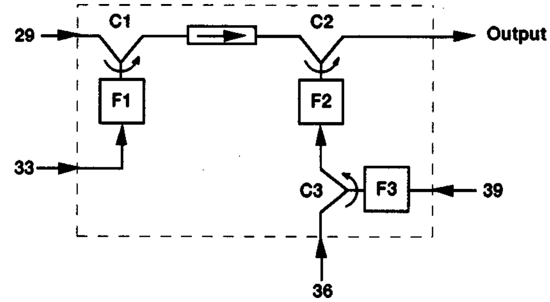

FIG. 2. Schematic of the *Ka* band combiner to merge the 29, 33, 36, and 39 GHz channels. C1, C2, and C3 are circulators. F1, F2, and F3 are filters.

vidual pulse forming modulator, which consists of a circulator and a varactor diode. The insertion loss of the modulators varies from 1.2 to 2 dB. The isolation for the lower frequencies (29–47 GHz) is approximately 30 dB and for higher frequencies (51–57 GHz) it is 25 dB. The modulators need a driver voltage of 5–10 V.

For both the 1-ns-wide rf pulse and the 20-ns-wide LO pulse, special drivers have been constructed that can produce pulses with a repetition frequency of 20 MHz. The 1-ns-wide pulse is Gaussian shaped. The pulsed LO selects a certain time window in which the heterodyne receiver is active. The output voltages of the LO driver pulses are individually adjustable, which gives the possibility to tune the amplitudes of the IF pulses to have approximately the same level at the video detectors. The drivers for the 1 and 20 ns pulses are combined in a single device with a 50 ohm output impedance and a dc level control. With this level control (0 to -1 V) the various modulators can be tuned to the maximum isolation in the off state.

The channels in the three different sections are merged by means of combiners. The combiners consist of resonant cavities and circulators. As an example, the *Ka* band combiner is shown in Fig. 2. The main advantage over conventional directional couplers is the lower insertion loss of approximately 1 dB for the *Ka* band and 3 dB for the *U* band. The frequency bandwidth for the different channels is approximately 2 GHz.

For the *K* band system homodyne detection is chosen because of the relatively high pulse power of 250 mW and the lower waveguide losses as opposed to the *Ka* and *U* band systems. Frequency selectivity is obtained with a frequency sensitive separator in combination with 1 GHz wide 18 and 24 GHz amplifiers. In the *Ka* and *U* band systems, heterodyne detection takes care of frequency selective reception. The IF amplifiers in the two heterodyne systems have a gain of approximately 30 dB and a noise figure of 4 dB. Detection is performed with Schottky barrier detectors. A simple antenna and waveguide system is chosen using separate transmitter and receiver antennas and oversized *X*-band waveguides. Oversized waveguides are necessary to keep the losses and the pulse broadening as low as possible.

The distance from the antennas to the radar setup is about 10 m. Two echo pulses will be received from each transmitted radar pulse. The first one is a start pulse travelling via the bypass and the second one is the stop pulse reflected at the critical density layer. Jitter in the electronics is irrelevant in this setup. The minimum time between the two pulses is 4 ns which is determined by the constant fraction discriminator (CFD). The longest time delay is obtained from reflections at the far wall of the tokamak vacuum vessel when the density rises to near the critical density (n_c). The longest time delay observed with plasma densities near n_c is about 6 ns longer than the time delay without plasma. Calibration is performed using the time-of-flight (TOF) of the reflected pulse at the far wall in the nonplasma case. The bypass consists of two 10 dB directional couplers, an attenuator, and a short section of waveguide. The position of the bypass must be chosen in such a way that the reception of the start and stop pulse coincide with the 20 ns LO pulse. Tuning is possible by adjusting the length of the bypass waveguide, and by adjusting the timing of the LO driver. The attenuator must be set such that the start and stop pulse have approximately the same power level. After detection, the four video channels (A, B, C, and D) are preamplified with presettable amplifiers. The four signals are combined and then amplified to a level of about 5 V and fed to the CFD. The two output pulses will start and stop the time-of-flight counter, developed at Rijnhuizen using eight parallel gated counters.[3,7] The data produced by the TOF counter is fed to a data acquisition system built in VME. The data handling, storage, etc., will be described in Sec. IV.

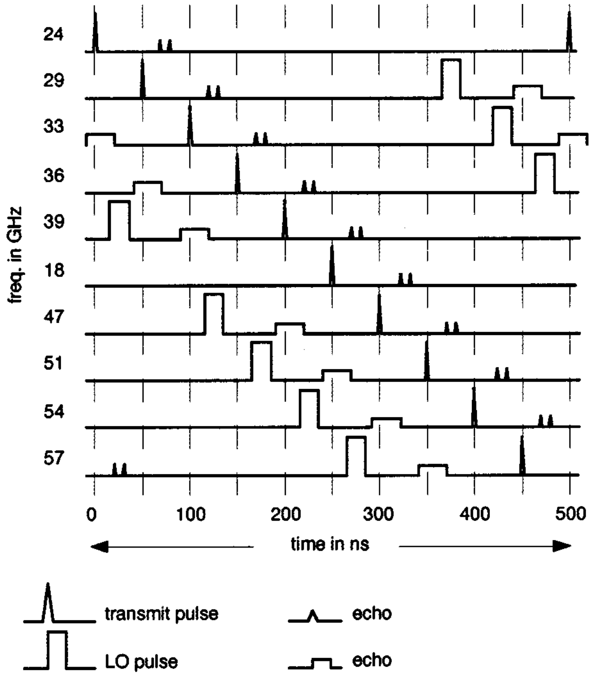

FIG. 3. Timing diagram for a ten-channel profile measurement.

III. TIMING AND MEASUREMENT MODES

A number of measuring modes are available. The first mode is a profile measurement with ten channels (see Fig. 3). The timing of each radar and LO pulse can be tuned individually by means of programmable time delay settings. During the existence of a LO pulse only one pair of matching start and stop pulses is present, which yields an 18 GHz IF signal (e.g., the 29 GHz LO pulse matches with the 47 GHz radar pulses). False mixing may occur when a transmitted pulse acts as LO at a time an echo from the original 20 ns LO pulse coincides in time. However, all these mixing products fall outside the bandwidth of the 18 GHz IF amplifier. As an extra precaution a low-pass filter in the receiver of the *Ka* band, and a high-pass filter in the *U* band receiver are added. The maximum measuring time, which is limited by the storage capacity of the 64 Mb memory, is 3.2 s at a sampling frequency of 20 MHz. This 3.2 s time interval can be chosen freely within the TEXTOR discharge, which can last as long as 10 s. It is also possible to run at a sampling rate of 10 or 5 MHz and measure over 6.4 or 12.8 s. Other measuring modes are possible when only one group of four channels is used. One measuring cycle will only take 200 ns in the four channel modes. Real quick firing of pulses occurs in the correlation mode, where only two channels are involved with a measuring cycle of 100 ns.

For the correlation measurements two sweepable sources are available (36 and 51 GHz) with a sweep range of 1 GHz. The fixed and variable source alternately transmit a 1 ns radar pulse. These pulses are processed in the same way as in the profile measurements. During the discharge the variable source can be swept by tuning the driver voltage. This voltage is generated by means of an arbitrary wave generator (AWG). The number of frequency steps (max. 64), the number of samples per frequency step, and the start and stop frequency can be set by computer.

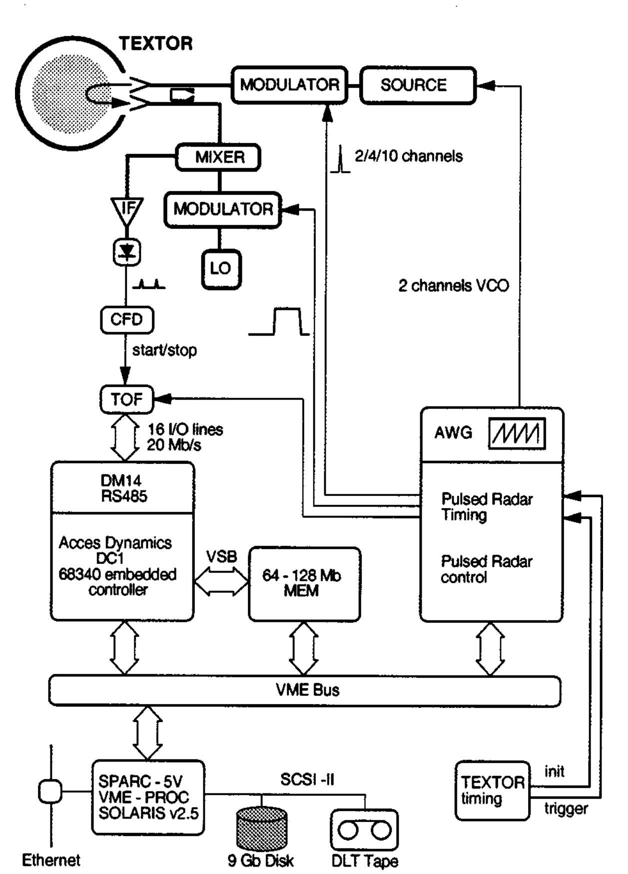

FIG. 4. Control, timing, data handling, and memory systems. Only one of the 12 microwave channels is given. For more details see Fig. 1.

IV. CONTROL, DATA HANDLING, AND STORAGE

In order to facilitate fast control, data handling, and storage, the pulsed radar diagnostic is embedded into a VME system, operating under UNIX (Fig. 4). The output data of the TOF counter is stored by a DMA controller into a 64 Mbyte memory module. Data from this module can be addressed via VME by a SPARC CPU. With this computer architecture, the huge amount of data per TEXTOR discharge, can be processed locally. Local data reduction will become indispensable, in order to make the data transport to a distributed database and the interpretation of the measurements faster. The data acquisition software, which runs on this system, is based on commercially available software packages like Solaris v2.5.

The user of the pulsed radar diagnostic has access to the local VME system via Ethernet. The measurement mode, the status of diagnostic system, the settings of the AWG, the method of data processing, and data reduction, etc. can be controlled by the user by sending remote procedure calls to the SPARC CPU. Obviously, the system can be synchronized to TEXTOR. Besides, this ordinary measurement mode, the system can also run in a test mode, in which data is collected without TEXTOR synchronization and in which the hardware can be tested.

Within the framework of the trilateral Euregio cluster (TEC) agreement between Germany, Belgium, and the Netherlands, it is envisaged that remote diagnostic operation with a fast data link from FZ Jülich to FOM Nieuwegein will become available in the near future. For this purpose a distributed database and communication software based on CORBA, for the communication between different software platforms like Windows NT and UNIX, is under development.

V. CONCLUSION

A ten-channel pulsed radar system with high repetition rates of 50 ns per channel has been constructed. The frequency range of the different channels is from 18 to 57 GHz. Two variable frequency channels at 36 and 51 GHz are available for correlation measurements. The diagnostic has been installed at the TEXTOR Tokamak in Jülich, Germany. Remote control from FOM Nieuwegein will be possible. The first measurements can be expected in June 1998. Much work has still to be done in the development of intelligent data reduction schemes and data handling.

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