Advanced Electronics Development for Fusion Diagnostics

White Paper

N.C. Luhmann, Jr., A.V. Pham (UC Davis), T. Munsat (U. Colorado)

As the US fusion program prepares for a central role in ITER, followed by DEMO, a critical limiting factor in our ability to assess and diagnose fusion-grade plasmas will be the performance of diagnostic instruments in harsh tokamak environments. In these long pulse, high performance plasmas, diagnostic instrumentation is subject to high heat loads, radiation, neutrons, and stray rf and microwave heating power. While this is an acute concern for a family of advanced imaging diagnostics which depend on high-performance millimeter-wave electronics, the use of any instrumentation on devices beyond ITER will require technological development to withstand the radiation environment of burning plasmas as well as advances required by the higher fields and restricted access. Taking the ITER LFS reflectometer as an example, considerable attention is being directed toward developing protective methods for the solid state source and detection electronics, tasks which will be greatly simplified by the development of significantly more robust electronics.

This issue is clearly recognized in the ReNeW final report [2009], which lists as Theme 1, Thrust 1:

*Develop measurement techniques to understand and control burning plasmas. This Thrust would develop new and improved diagnostic methods for measuring and controlling key aspects of burning plasmas. The desired measurement techniques must be robust in the hostile burning-plasma environment and provide reliable information for long time periods. While initially focused on providing critical measurements for ITER, measurement capability would also be developed for steady-state burning plasmas beyond ITER.*

As an example of this, consider both the Electron Cyclotron Imaging (ECEI) diagnostic, a version of which is now in place on the DIII-D, TEXTOR, ASDEX-UG, KSTAR, and EAST tokamaks as well as the Microwave Imaging Reflectometer (MIR) diagnostic, operating on DIII-D, KSTAR, and LHD with systems under development for EAST and HL-2A.

The ECEI and MIR instruments measure 2-D images of electron temperature and density fluctuations, respectively, with the use of specially designed antenna arrays for radio frequency super-heterodyning of signals in the 50-250 GHz region down to lower frequencies for subsequent processing. For ECEI, each miniature antenna collects wide-bandwidth signals that are resolved into frequency bands by mixing with a series of local oscillator sources. The result is an array of relatively low cost, high performance heterodyne radiometers, producing a 2D, pixelated image of the tokamak plasma. This novel technique has made significant contributions to fusion science through the visualization of a wide range of tokamak plasma phenomena. MIR is similar in that...
probing radiation generated by an extremely stable, fast tunable, multi-frequency source is reflected from cutoff surfaces and imaged onto an antenna array.

Although both techniques have been implemented on present fusion devices and have performed well up to now, there are a number of technical limitations to their performance, both now and in future versions. For example, signal-to-noise ratios are fundamentally limited by the available output power from the solid state probe sources, as well as the performance of integrated mixers on the receiving antennas, all of which will be degraded even further from damage in the harsh fusion environment. As the next generation of diagnostics requires even higher-precision measurements of temperature and density (especially for fluctuations) in ever-harsher environments, these limitations are critical to overcome.

The problems associated with current electronics are greatly ameliorated by recent advances in Gallium Nitride (GaN) semiconductor devices, which are wide band gap materials (3.39 eV, versus 1.43 eV and 1.11 eV for GaAs and Si, respectively), which have been shown to provide high power and high breakdown voltages as well as the capability of operating at high temperatures (currently ~350°C with projections to 1000°C, versus ~125°C for current electronics) and with high radiation tolerance. Due to GaN’s wide band gap properties, GaN transistors operate at high voltage, which translates into high power and high breakdown voltages while simultaneously providing low noise and high linearity. Specifically, the critical breakdown field of GaN is 3-3.5 MV/cm in contrast to 0.3-0.4 MV/cm of Si and GaAs. Higher drain voltages allow GaN transistors to be operated with an output impedance closer to 50 ohm than other devices, and hence GaN circuits have much wider bandwidth which is essential for their use in MIR and ECEI antenna arrays.

A low noise GaN amplifier has been demonstrated to achieve a noise figure of 3.8 dB at 80 GHz, which is competitive with that of an InP amplifier [Masuda 2009]. In recent developments, researchers have also demonstrated high power circuits using GaN up to 110 GHz. For example, a 5 W output power GaN power amplifier using multiple waveguide combiners [Schellenberg 2010] and up to 2 W output power from a single MMIC amplifier at W-band [Brown 2011, Schellenberg 2013] and up to 0.5 W up to 170 GHz has been reported. The GaN foundries that can commercially produce monolithic integrated circuits include Triquint Semiconductor, Raytheon, Northrop Grumman, Win Semiconductor, and RFMD, just to name a few. We believe it is essential to develop advanced GaN circuits to significantly take the performance of diagnostics in this frequency range, such as the ECEI and MIR systems, to the next level, both from a performance basis and reliability basis. The custom GaN circuits developed for this fusion application will vastly exceed the performance of off-the-shelf parts and will not be restricted to frequencies dictated by commercial and military applications. GaN circuits will provide much higher output power, low noise, sustain high power, and provide robustness.

Present-day imaging systems such as ECEI and MIR exist due to a sustained effort of technological advancements over the past decades. The development of these advanced instruments was not the result of someone simply having a clever idea and implementing it with off-the-shelf parts using existing technology; ideas about extended
imaging measurements from millimeter-wave radiation have been around for several decades, but it has been the technological development of the solid-state antennas, mixers, and complementary amplification hardware that has made such ideas viable as working diagnostics. **In order to continue this successful line of development so as to provide the next generation of critical measurements for burning plasmas, continued support of a technology program such as this is essential.**

**References:**


