Low-noise, high-speed detector development for optical turbulence fluctuation measurements for NSTX[a)]

N. L. Schoenbeck,[1,b)] S. D. Ellington,[2] R. J. Fonck,[1] K. Jaehnig,[3] G. R. McKee,[1] D. Smith,[1] I. U. Uzun-Kaymak,[1] and G. Winz[1]
[1]*Department of Engineering Physics, University of Wisconsin-Madison, Wisconsin 53706, USA*
[2]*Space Science and Engineering Center, University of Wisconsin-Madison, Wisconsin 53706, USA*
[3]*Department of Astronomy, University of Wisconsin-Madison, Wisconsin 53706, USA*

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A new beam emission spectroscopy (BES) diagnostic is under development. Photon-noise limited measurements of neutral beam emissions are achieved using photoconductive photodiodes with a novel frequency-compensated broadband preamplifier. The new BES system includes a next-generation preamplifier and upgraded optical coupling system. Notable features of the design are surface-mount components, minimized stray capacitance, a wide angular acceptance photodiode, a differential output line driver, reduced input capacitance, doubling of the frequency range, net reduced electronic noise, and elimination of the need for a cryogenic cooling system. The irreducible photon noise dominates the noise up to 800 kHz for a typical input power of 60 nW. This new assembly is being integrated into an upgraded multichannel optical detector assembly for a new BES system on the NSTX experiment.
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I. INTRODUCTION

Beam emission spectroscopy (BES) is an optical diagnostic tool that employs a deuterium neutral beam to measure local plasma density fluctuations. BES utilizes Doppler shifted D-α light to image the plasma interior. Excitation through neutral beam injection creates florescence at a wavelength of 656.1 nm, with intensity proportional to the local plasma density.[1] Core density turbulence, specifically localized, long-wavelength fluctuations ($k_\perp \rho_i < 1$), is currently being imaged using the BES diagnostic in place at the DIII-D tokamak.[2] A new upgraded BES system has recently been developed and deployed at NSTX. This paper discusses the detector development for this NSTX system, whereas more details on the optical development can be found in Ref. 3.

The new BES system includes low-noise photoconductive photodiodes (PPDs) with new four-stage preamplifier boards that use modern surface mount components and multilayer boards, giving the diagnostic more versatility in terms of wiring, hardware, and performance.

One of the major benefits of this new detector system is that it does not require cryogenic cooling, which was required for the predecessor system on DIII-D. Simply cooling the system to -20 C with a refrigerant cooling system effectively eliminates the dark current and related thermal noise. In addition to achieving acceptable amplifier noise without cryogenic cooling, the second major goal of the new preamplifier development is to provide a higher frequency bandwidth compared to previous generation systems (i.e., 1 MHz versus 0.5 MHz).

Small amplitude signals require BES detectors to have minimal noise. At low frequencies the detector noise is dominated by thermal noise (Johnson noise), while electronic (i.e., voltage) noise increases with increasing frequency. Photon noise is also present, a result of quantum mechanics and photon statistics. The goal for BES is to create a detector that is limited only by the irreducible photon noise, thereby optimizing the detections of small-scale fluctuations.

II. DIAGNOSTIC DEVELOPMENT

A detector box for the NSTX BES system contains an array of eight PPD detectors mounted on circuit boards, each in their individual shielded encasing. Each circuit board contains a PPD with wide angular acceptance and a preamplifier circuit consisting of a cascade of four operational amplifier stages. The basic preamplifier design follows the original frequency-compensated broadband amplifier designed for the original Tokamak Fusion Test Reactor BES system.[4]

The first stage consists of a field effect transistor (FET) and an operational amplifier (op-amp) with a large feedback resistor to act as a large-transimpedeance current-to-voltage transducer. The FET acts as the input stage to give minimal input capacitance and voltage noise at the input terminals. The second stage, used for frequency compensation, has an op-amp with less than unity gain and a variable capacitor to precisely match the cross-over frequency at which both stages go reactive. The third stage is the final amplifying

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[b)]Author to whom correspondence should be addressed. Electronic mail: nschoenbeck@wisc.edu.

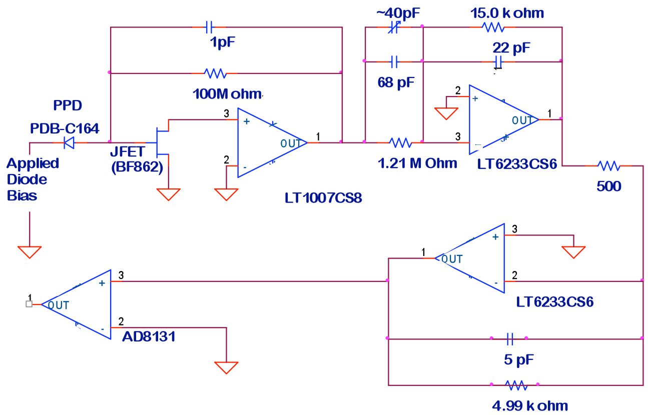

FIG. 1. (Color online) Simplified preamplifier circuit for the detectors used in the BES diagnostic.

stage, whereas the fourth stage is a simple differential output line-driver with adjustable dc offset. These four stages, shown in Fig. 1, translate the photodiode current into a voltage corresponding to 4.5 mV/nW light intensity input per leg on the differential output.

The surface mount PPD chosen for this application is PDB-C164 from Advanced Photonix. It is proven to have a lower dark current and junction capacitance compared to its predecessors. For the expected 652–655 nm wavelength the typical photodiode responsivity is 0.43 A/W. This particular photodiode can also be biased up to 50 V to lower the effective junction capacitance and therefore provide improved performance in terms of electronic noise.

The signal to noise ratio improvement begins with simple cooling to minimize the leakage dark current to ~1 nA input on average when cooled to −20 C. Given the amplification of the signal, this dark current corresponds to an output dc voltage of roughly 10 mV.

With negligible leakage current, the amplifier noise in the signal at frequencies greater than approximately 10 kHz is dominated by the voltage noise at the amplifier input terminals, which drives noise current through the source impedance. This net input current noise density is given by $i_n \approx \omega e_n (C_j + C_i)$,[4] where C_j is the diode junction capacitance, C_i is the input capacitance of the FET amplifier, e_n is the voltage noise density of the FET, and $\omega = 2\pi f$ is the angular frequency. The circuit is designed to effectively minimize this resulting noise density to provide the widest practical frequency response.

Operating the diode at higher bias voltages lowers the junction capacitance to 7 pF from ~18 pF in the previous system. Similarly, the FET has a lower capacitance compared to the previous system, resulting in lower total noise current density at near-room temperatures.

Many combinations of various FETs and photodetectors were examined for lowest electronic noise and capacitance. Five FETs were considered for this application and were tested under various dark current conditions and bias voltage configurations. The selected FET was the BF862 from NXP semiconductors that under test conditions had the lowest voltage noise, 0.8 nV/$\sqrt{\text{Hz}}$, and capacitance combination $(C_j + C_i)$, 13 pF, and therefore would have the lowest electronic noise at high frequencies.

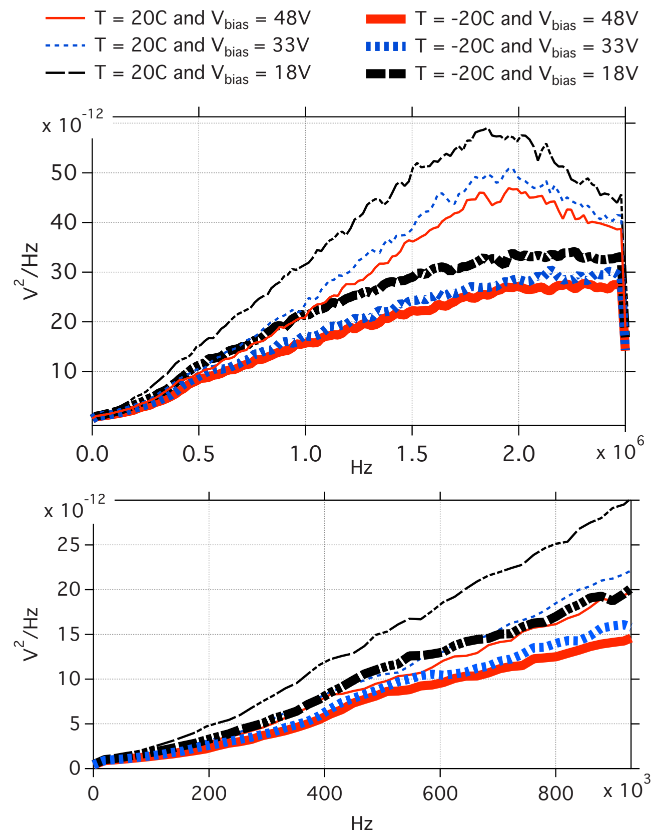

FIG. 2. (Color online) Power spectral density (PSD) (Ref. 5) calculations for noise level comparison of the preamplifier boards in the absence of light at various temperatures and with various applied bias voltages. Measurements are shown for 20 and −20 C, with a three-point bias voltage scan, i.e., 48, 33, and 18 V applied bias. (Upper) Indicates that all frequencies of interest (<2.5 MHz) have the lowest noise level for the −20 C and 48 V conditions. (Lower) Shows the same PSD results for lower frequencies.

Minimizing the stray capacitance further reduces electronic noise. Surface mount components with short lead lengths reduce noise due to transmission and cross talk. A final improvement over the previous generation BES preamplifier comes from using a differential output for the signal (rather than single-ended). Differential output allows for improved noise rejection and hence detection of smaller signals and improved dynamic range.

III. NOISE MEASUREMENTS

A series of experiments were conducted to test the chosen PPD and FET combination at various temperatures and applied bias voltages to identify operating parameters to minimize the thermal leakage and electronic noise. Applying a negative bias voltage to the diode reduces the junction capacitance and hence the electronic noise, which is most dominant at high frequencies.[4] Figure 2 demonstrates the reduced electronic noise achieved by applying a more negative bias voltage. Ultimately, a negative bias of 48 V is chosen, as this bias is close to the limit or the breakdown voltage of the photodiode. At fixed temperature, there is nearly a 40% noise drop going from 18 to 48 V. As expected, the increased bias significantly lowers the amplifier noise at high frequencies.

Figure 2 also shows the effect of cooling. For each bias voltage value, a temperature scan experiment from +50 to −50 C was conducted using an environmental chamber. It has been observed that the detector leakage noise and thermal noise are stabilized near −20 C. This new design removes the need for the cryogenic cooling currently used on the BES diagnostic at DIII-D. Going from 20 to −20 C reduces the thermal noise by approximately 40% at 200 kHz. This reduction is presumably due to the modest temperature dependence of the voltage noise e_n at near-room temperatures, as seen in earlier measurements with the DIII-D detectors.

For normal operations, eight detector-preamplifier assemblies are installed into a common detector box with a vacuum and cooling line to create vacuum conditions (30–60 mTorr) that avoid condensation at −20 C temperatures. Boards sharing the same power supply and wire harness, operated at a bias voltage of −48 V and cooled to −20 C, were tested simultaneously for several hours to monitor behavior and verify stability. Testing every hour for 4 h gave reproducible results.

Auto-power spectra[5] were compared for three cases of detector illumination: dark, 30 nA light source, and 60 nA light source. The difference of the spectrum with and without light was calculated in order to determine the cross-over frequency, or the point at which electronic noise becomes greater than the photon noise. This frequency provides a figure-of-merit for evaluating the net frequency response of the system. In general, the goal is to keep the photon statistical noise comparable to, or greater than, the total amplifier noise density. Experience from earlier BES systems suggests reasonable measurements can be made when the amplifier noise is several times the photon noise level, so that the effective frequency bandwidth is two to three times the measured cross-over frequency. Typical auto-spectra for each of these cases are displayed in Fig. 3.

Figure 3 shows the cross-over frequencies of 300 kHz for a 30 nA signal and 600 kHz for a 60 nA signal. Photon noise clearly dominates the signal up until this point when the electronic noise becomes the primary factor. These cross-over frequency values are consistent throughout the boards, and confirm that the new preamplifier systems are capable of ∼1 MHz measurements of plasma fluctuations.

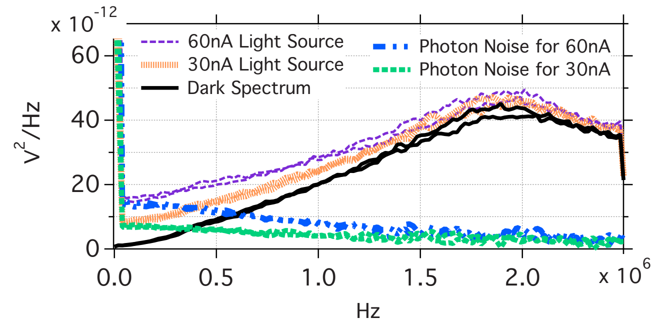

FIG. 3. (Color online) Cross-over frequencies for 30 and 60 nA light sources. Light inputs are shown on two different boards to indicate the repeatability of the cross-over value.

IV. SUMMARY

A new generation BES diagnostic photodiode detector has been designed to provide more versatility through elimination of the cryogenic cooling and the use of surface mount components to lower net amplifier noise and extend the applicable frequency range. The preamplifiers have been designed such that photon noise dominates the spectrum to 600 kHz for a typical 60 nA signal. This noise reduction is a result of reduced stray capacitance, reduced photodiode dark current, improved active components, and change from single ended to differential signal output drivers.

Testing has been performed to determine optimal conditions for operation; detectors operate at −20 C and −48 V bias potential. Additionally the detectors have been tested for long-term stability and have reproducible noise levels. This new system is being commissioned at NSTX for density turbulence imaging.

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