

PMT Signal Transmission for Hard X-Ray Diagnostics of Future Tokamaks

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Abstract

A pair of a scintillator and a Photomultiplier Tube (PMT) is often used as a Hard X-Ray (HXR) radiation detector in existing tokamaks such as JET, EAST, COMPASS or ASDEX-U. Future nuclear fusion reactors such as ITER or DEMO will use more powerful magnets and confine a larger volume of hot plasma.

Placement of the detectors used for plasma diagnostic will be constrained by high temperatures, magnetic fields and ionizing radiation present near the tokamak vessel. It might be necessary to move detectors away from tokamak to a safer location. As a result, it might generate problems with pulse discrimination and transmission of the signal. In such scenario, a new approach to the design of plasma diagnostic systems such as HXR spectroscopy is required.

In case of the ITER tokamak, sensitive electronics such as Field-Programmable Gate Arrays (FPGA) cannot be installed close to the reactor. The signal from the PMT will be transmitted via an over 100 m long cable to a digitizer located in the diagnostic building. Along the way, electromagnetic interferences can couple into the cable. Additional measures have to be taken to reduce the influence of noise on the signal.

The paper presents issues with signal transmission in HXR diagnostic systems and includes a discussion on the methodology of PMT signal transmission in the conditions of the future tokamaks. A proposal of guidelines for selection of the signal chain components and design of a dedicated PMT amplifier is part of this paper.

I. Introduction

Plasma confined in nuclear fusion reactors emits electromagnetic waves in a wide spectral range from radiofrequency to gamma radiation [1]. For instance, Hard X-Ray (HXR) spectroscopy is applied for diagnostics of Runaway Electrons (RE) in nuclear fusion reactors. Plasma diagnostic systems use different radiation detectors to cover the whole energy spectrum.

The scintillation detector is one of the commonly used types of radiation sensor for HXR spectroscopy [2]. HXR spectroscopy systems use a scintillator crystal that emits photons when excited by ionizing radiation to measure energy. The amount of emitted photons depends on the energy of the incident particle [3]. The scintillator is coupled with a Photomultiplier Tube (PMT) which converts incident photons to electric signals. PMT is a type of vacuum tube that consists of a photocathode and a series of dynodes. Photons hit the photocathode of a PMT and cause the emission of photoelectrons which hit the next dynodes inducing the multiplication of photoelectrons. Then the beam of photoelectrons generates pulses of an electric signal at the anode of the PMT [4]. PMTs and scintillators are used in HXR spectroscopy in existing tokamaks such as JET, EAST, COMPASS or ASDEX-U [5]–[8].

HXR spectroscopy in future tokamaks such as ITER or DEMO face problems with the placement of detectors caused by even higher temperatures, magnetic fields, gamma and neutron radiation present

near the reactor's vessel. In the case of ITER, light pulses from the scintillator will be transmitted over long fibre optic bundles to the PMT. Then the electrical signal from PMT will be transmitted to the digitizer via a long coaxial cable as shown in Fig. 1. Low optical path efficiency (0.05–0.10%) and long transmission distances cause additional problems with pulse discrimination and transmission of the electrical signal in the RF-noisy environment of the tokamak.

This paper focuses on the evaluation of issues with PMT signal transmission. Section II discusses challenges concerning signal transmission in HXR diagnostic systems. Section III presents considerations on the PMT signal transmission methodology in the environment of future tokamaks. In section IV different commercially available PMT amplifiers are compared. Section V and VI present the design and test results of a low-noise amplifier dedicated for the PMT.

II. Challenges With Signal Transmission In Hard X-ray Diagnostic Systems

Upcoming tokamaks such as ITER or DEMO will confine even higher volumes of plasma and will use more powerful magnets [9]. The placement of radiation detectors used for plasma diagnostics will be constrained by the presence of high temperatures, magnetic fields, and neutron radiation present near the reactor's vessel. Therefore, a new approach to the design of plasma diagnostic systems such as HXR spectroscopy is required.

PMT-based detectors are also chosen to be used in spectroscopy systems of future tokamaks such as ITER. The Hard X-Ray Monitor (HXRM) is an ITER diagnostic system, that can provide real-time information about the energy of runaway electrons inside the tokamak. Due to the high temperature and strong magnetic fields that are present close to the tokamak, the PMT cannot be installed together with a scintillator in the close vicinity of the tokamak. The PMT detector is moved away by approximately 12 m to the port cell where environmental conditions are less damaging. With this setup, light pulses from the scintillator will be transmitted to the PMT via an optical fibre bundle with an estimated light transmission efficiency of around 0.05–0.10%.

Such high attenuation causes a significant reduction in the number of photons reaching the detector. A small number of photons (5–20 photons) that reach the PMT, generate a series of short, low-amplitude pulses that each correspond to a single photon hitting the PMT photocathode. Such signal might not be processed with satisfactory results using a standard charge-sensitive amplifier, classical algorithms and methods in real-time.

A new approach for processing of PMT pulses has to be applied. The rapid development of fast FPGAs (Field Programmable Gate Array) and ADC (Analogue-to-Digital Converter) enabled the use of digital pulse processing methods [10]. Algorithms, tuned for a specific shape of PMT signal can be implemented in the FPGA and used to discriminate PMT pulses in real-time [11].

Sensitive electronics, such as digitizers, also cannot be installed close to the reactor. In the case of ITER, the digitizer will be placed approximately 100 m away from the PMT in the diagnostic building. Transmitting PMT signals over such a long distance in the environment of the tokamak is a challenging task. The following sections contain a proposition of design considerations and component selection for a signal transmission chain in HXR spectroscopy systems of future tokamaks.

iii. Transmission Of Pmt Signal In Tokamak Conditions

Finding a new methodology of PMT signal transmission might be required for plasma diagnostic systems of future tokamaks. PMT signal has to be transmitted to the digitizer via a relatively long coaxial cable (more than 100 m). The signal will travel through an electromagnetically (EM) polluted environment of the tokamak where radio-frequency (RF) noise can couple into the cable. To minimize the influence of noise on the signal special care in signal transmission chain design and component selection has to be taken.

Tab.1 Comparison of commercially available PMT amplifiers

Parameter	ARI Corp. V-100-40dB	SRS SR445A	FEMTO HVA-200M-40-B	Hamamatsu M8879	Hamamatsu C5594	Teledyne NIM 612AM
Output Voltage (on 50 Ω load)	+ 2.0 V/-2.0 V	+ 1.0 V/-1.0 V	+ 1.0 V/-1.0 V	+ 1.4 V/-1.4 V	+ 0.8 V/-2.5 V	+ 0.2 V/-5.0 V
Voltage Gain	100x	Variable 5x, 25x, 125x, 625x	100x	80x	63x	Variable 2.5x – 40x
Bandwidth (3dB)	100 MHz	350 MHz	200 MHz	150 MHz	1.5 GHz	140 MHz
Coupling	DC	DC	DC	DC	AC	DC

The PMT signal has a relatively low amplitude in the order of hundreds of mV. Signal amplitude should be increased to maintain a satisfactory Signal-to-Noise Ratio (SNR) of the signal transmitted through the RF noisy environment of tokamak. The level of the noise is constant, therefore amplification of the signal before feeding it into a coaxial cable (at PMT output) can improve the ratio between signal and noise amplitude, and effectively decrease the impact of the RF noise coupled to the cable on the signal [12].

To further improve noise performance, a noise coupling to the cable can be decreased. A coaxial cable consists of two inductors separated by dielectric, one for ground and the second for signal transmission. Introducing an additional metal shielding layer could decrease the amount of noise coupled to the inner layers of the cable. There is a special type of a coaxial cable with an additional shielding layer called triaxial cable. The outer conductor of the triaxial cable is connected to the earth and is not involved in PMT signal transmission. Application of triaxial cable can improve the interference rejection.

Still, both coaxial and triaxial cables are a type of lossy medium. For long distances, losses caused by transmission-line effects become significant. For instance, for a triaxial cable Belden 9222, which can be used for PMT signal transmission, the attenuation can reach up to 16 dB for a 100 MHz signal [13]. For tokamak applications, special radiation-tolerant grade cables have to be used. Such cables could have even higher attenuation. Cable attenuation is an important factor and has to be compensated by the amplifier gain.

Due to stray capacitance, long triaxial cables require a dedicated amplifier, that is able to drive capacitive loads. The parasitic capacitance can reach up to 10 nF for a 100 m long cable [13]. An amplifier with a high current output is required to drive a long coaxial cable without signal degradation [14].

On one hand, the amplitude of the signal should be as high as possible to achieve the best SNR. On the other hand, the signal levels should be adjusted to the digitizer input range. The high-speed digitizers (more than 1 GS/s) accept voltages in the range of ± 5 V at max (with respect to 50 Ω load) [15]–[18]. Pulses generated by a scintillator coupled with a PMT have a bi-exponential shape as shown in Fig. 2. The PMT detector generates a unipolar signal with amplitude changing from 0 V to negative values. Some digitizers, such as Teledyne ADQ14 [18] have a configurable DC offset, which makes it possible to use the unipolar nature of PMT pulses. As a result, the input range can be changed from symmetrical (± 5 V) to asymmetrical (from -10 V to 0 V). Digitizer inputs are matched to 50 Ω impedance. To match the impedance of the digitizer and cable amplifier output also must have a 50 Ω matching circuit. The impedance matching resistors create a voltage divider, that will divide the voltage at digitizer input in half. Therefore, to fully utilize the input range of the digitizer the amplifier has to provide an output range of at least -20 V to 0 V. This voltage range is still reasonable and can be implemented. The signal level will be significantly higher than the noise and there are many operational amplifiers with a standard ± 15 V power supply, that can be also supplied asymmetrically (i.e. $+5$ V ... -25 V). After taking into account cable losses the estimated amplifier gain of 40 dB will utilize the whole input range of the digitizer.

The PMT signal has fast falling edges as short as 2–5 ns. This results in the effective bandwidth of the signal reaching 200–500 MHz. However, it is still beneficial to limit signal bandwidth [19] to levels of around 100 MHz, to filter out high-frequency noise. Therefore, an amplifier with a bandwidth of at least 100 MHz bandwidth is desired. An amplifier should have a DC-coupled input to avoid variable bias.

The transmission of a PMT signal through the tokamak environment requires the use of a dedicated amplifier that fulfils the above-discussed criteria. In conclusion, the proposed guidelines for the PMT amplifier selection could be summarized as follows:

- Low-noise (lower than $0.5 \text{ mV}_{(\text{RMS})}$ at 100 MHz BW)
- At least 100 MHz bandwidth
- DC-Coupling
- Gain of at least 40 dBV (100x)
- High voltage output ($10 \text{ V}_{\text{pk-pk}}$ on 50Ω load)
- Ability to drive a 100 m long triaxial cable (capacitive load)

Additionally, complementary to the amplifier, a high-speed digitizer with a relatively high input range and a DC offset capability is needed. To further improve noise performance when using long signal cables, a triaxial cable should be used.

IV. Pmt Amplifiers In Existing Applications

The selection of a proper PMT amplifier is important to achieve good performance of the entire system. PMTs are used as spectroscopy detectors in many scientific disciplines. Thus, there are many commercially available PMT amplifiers available on the market with different parameters and characteristics.

A literature review was carried out to find an amplifier suitable for future tokamak applications. Table I shows a comparison of a few commercially available PMT amplifiers. The “V-100-40dB” amplifier from Advanced Research Instruments Corporation [20] has an appropriate gain and bandwidth, but the output range is too low to use for transmission in long triaxial cables. Similarly, both the “SR445A” amplifier from Stanford Research Systems [21] and “HVA-200M-40-B” from FEMTO [22] have too low output voltage. The “M8879” and “C5594” amplifiers from Hamamatsu [23], [24] also have too low output voltage and not sufficient voltage gain. It is worth noting that amplifier Hamamatsu C5594 has an asymmetrical output range, but the output voltage is still too low (+ 0.8 to 2.5 V). It also has an AC coupling input. The “NIM 612AM” amplifier from Teledyne [25] has the highest output range (asymmetrical from + 0.2 V to - 5.0 V) of all compared amplifiers. Still, twice as high output range is needed to fit the input range of the digitizer.

Most of commercially available PMT amplifiers have a too low output voltage range. The compared amplifiers will be adequate for most applications but not for transmitting the signal via long cables that run through the tokamak environment. A higher voltage output amplifier is required. Such amplifiers cannot be bought, therefore a high-voltage output amplifier suited especially for the PMT application has been designed and developed from scratch. The following section describes the design details of this amplifier.

V. Pmt Amplifier With Asymmetrical Power Supply

The design of the described amplifier is based on the unipolar nature of a PMT pulse. The shape of the pulse generated by the scintillator coupled with PMT can be approximated by the following mathematical equation

$$p(t) = P_n \left(1 - e^{-\frac{t}{t_1}}\right)^k \left(1 - e^{-\frac{t}{t_2}} + B e^{-\frac{t}{t_3}}\right)$$

(1)

where, P_n is a normalization factor and t_1, t_2, t_3, B, k are pulse parameters depending on the scintillator characteristics [26]. The signal generated by the PMT is not symmetrical as shown in Fig. 2. Therefore, the amplifier is not required to cover the full symmetrical input range. The proposed amplifier consists of two amplification stages. A low-noise preamplifier and a power amplifier. The overall noise performance is mainly affected by the noise of the first stage amplifier [27] as shown in the equation below

$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \dots + \frac{F_n - 1}{G_1 G_2 \dots G_{(N-1)}}$$

(2)

where G is gain and F is the noise figure of the corresponding amplifier stage. The two-stage amplifier configuration allows for the use of a low-noise preamplifier and a high-amplitude power amplifier to improve noise performance and obtain a high-current output. The summary of the proposed signal chain including the PMT amplifier stages is shown in Fig. 3.

The first stage preamplifier is a low-noise operational amplifier LMH6629 from Texas Instruments (TI) with low input voltage noise reaching $0.69 \text{ nV} / \sqrt{\text{Hz}}$ [28]. The amplifier has a power supply range of $\pm 2.5 \text{ V}$. To better suit the needs of the PMT amplification the supply voltage was changed to $+ 1.5 \text{ V}$ and $- 3.5 \text{ V}$. This amplifier is not suitable for driving large capacitive loads and the output voltage is still too low, therefore, a power amplifier was added.

The second stage power amplifier is a TI THS3491 [29] current-feedback type operational amplifier. This amplifier can be supplied with $\pm 15 \text{ V}$ and can be used for driving coaxial cables. To cover the input range of the digitizer the amplifier was supplied with a voltage of $+ 5 \text{ V}$ and 24 V . To match output to the impedance of the cable and the digitizer a 50Ω resistor in series was added. The total output range (including an impedance matching resistor divider) output is now $+ 1.5 \text{ V}$ to -11 V . In this configuration, the PMT amplifier fully covers the input range of the digitizer.

Vi. Simulations And Measurements Of The Pmt Amplifier With Asymmetrical Power Supply

The design of the amplifier was simulated using SPICE software to prove that this design can be successfully implemented, with satisfactory performance. Figure 4 shows the results of the simulation of

bandwidth for the first and second amplifier stage for a gain of x10 each (total gain x100). The preamplifier has a 3 dB bandwidth at 260 MHz. The bandwidth of the second stage is at 685 MHz Fig. 5 shows the output characteristic of the entire PMT amplifier. For a total gain of x100, the bandwidth is at 250 MHz. The bandwidth is constrained mainly by the performance of the preamplifier, but it is still enough for the described applications with PMT.

Figure 6 illustrates the advantage of an amplifier being supplied asymmetrically over a classic symmetrical supply. A synthetic PMT pulse of amplitude 220 mV was modelled. The signal was then provided on the input of an amplifier in the symmetrical power supply configuration and one with the asymmetrical configuration both with a total gain of x100. The amplifier in a symmetrical configuration clipped the signal at -13.5 V, while the amplifier in the asymmetrical configuration amplified the signal without any distortion to an amplitude level reaching - 22 V. That yields a 63% improvement in the output dynamic range.

Vii. Conclusions

Future tokamaks such as ITER have special constraints for the design of Hard X-Ray spectrometers. For the ITER tokamak the PMT cannot be coupled directly with a scintillator. This causes low optical transmission efficiency of around 0.05–0.10%. Moreover, the signal from PMT has to be transmitted further to the digitizer via a 100 m long cable. A new methodology of PMT signal transmission was proposed for plasma diagnostics in future nuclear fusion reactors. Additional measures have to be taken to reduce the influence of the noise on the signal. Usage of triaxial cables with an additional shielding layer was proposed to increase noise immunity. The necessity, to increase the signal amplitude before feeding it into the cable was emphasised as it allows to greatly improve signal-to-noise ratio. The highest possible signal amplitude would be most beneficial, but it has to be limited to the input voltage levels of high-speed digitizers. To extend the input voltage of a digitizer a DC offset can be added to shift the signal baseline and nearly double the effective input range.

A low-noise, relatively high-voltage-output PMT amplifier is needed to transmit the PMT signal via a long cable through the surroundings of the tokamak. A wide output range is required to maintain a high dynamic range of PMT signals. The presented method of supplying an amplifier with asymmetrical power instead of asymmetrical supply could extend the maximal dynamic range of the PMT signal by 63%.

The presented PMT amplifier will be used during tests and evaluation of the ITER Hard X-Ray Monitor. The performance of the amplifier will be further evaluated during tests with final long triaxial cables.

Declarations

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Figures

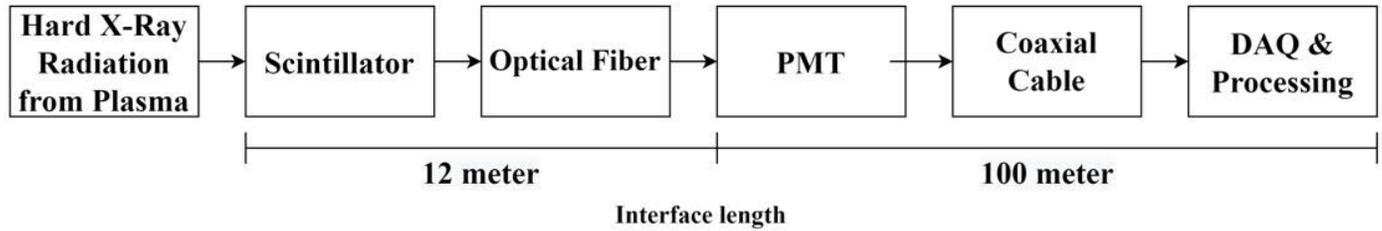


Figure 1

Block diagram of ITER HXRM signal chain

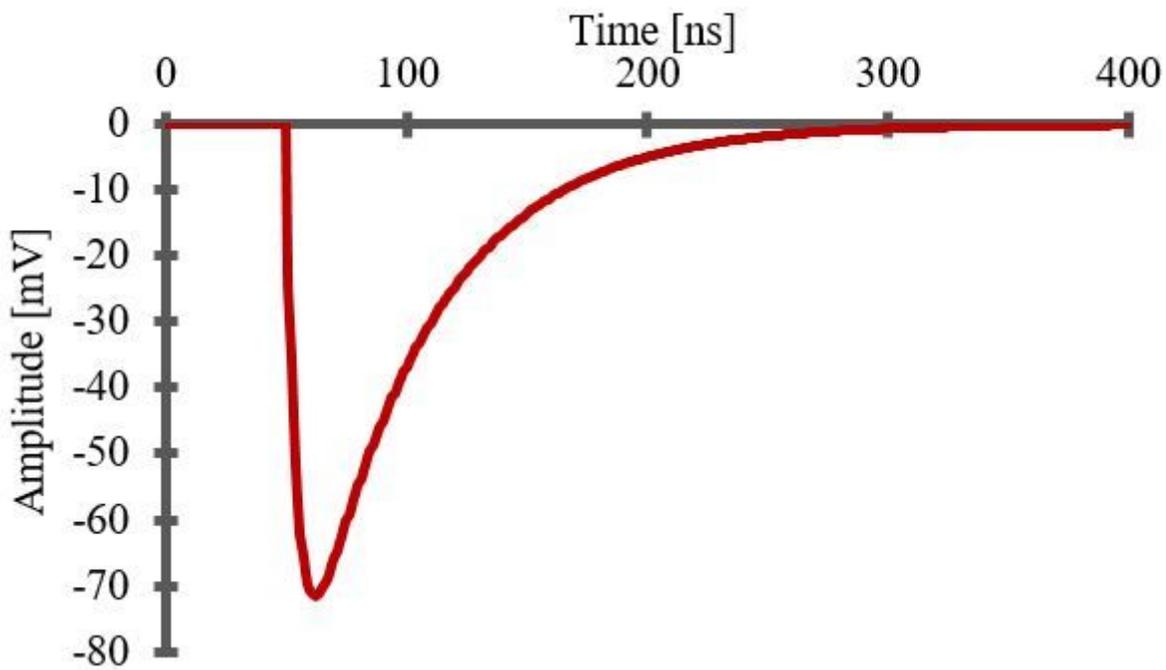


Figure 2

Synthetically generated PMT pulse

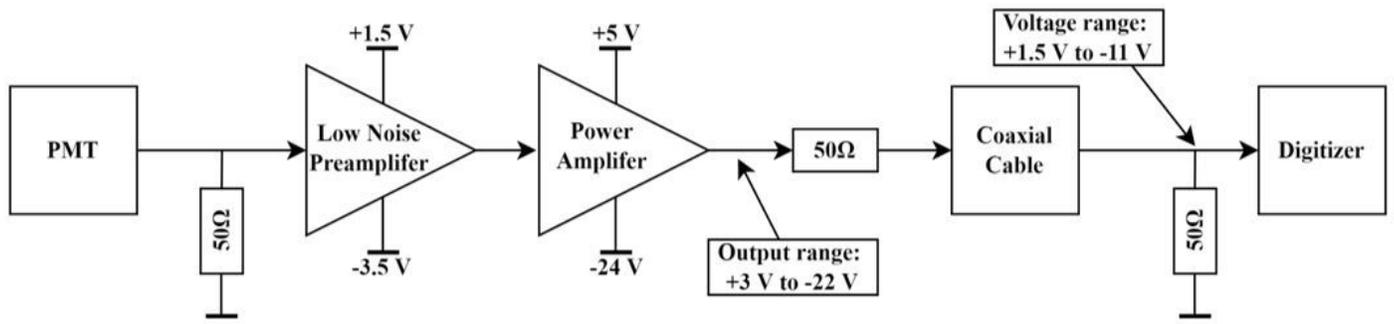


Figure 3

Schematic of asymmetrical PMT amplifier

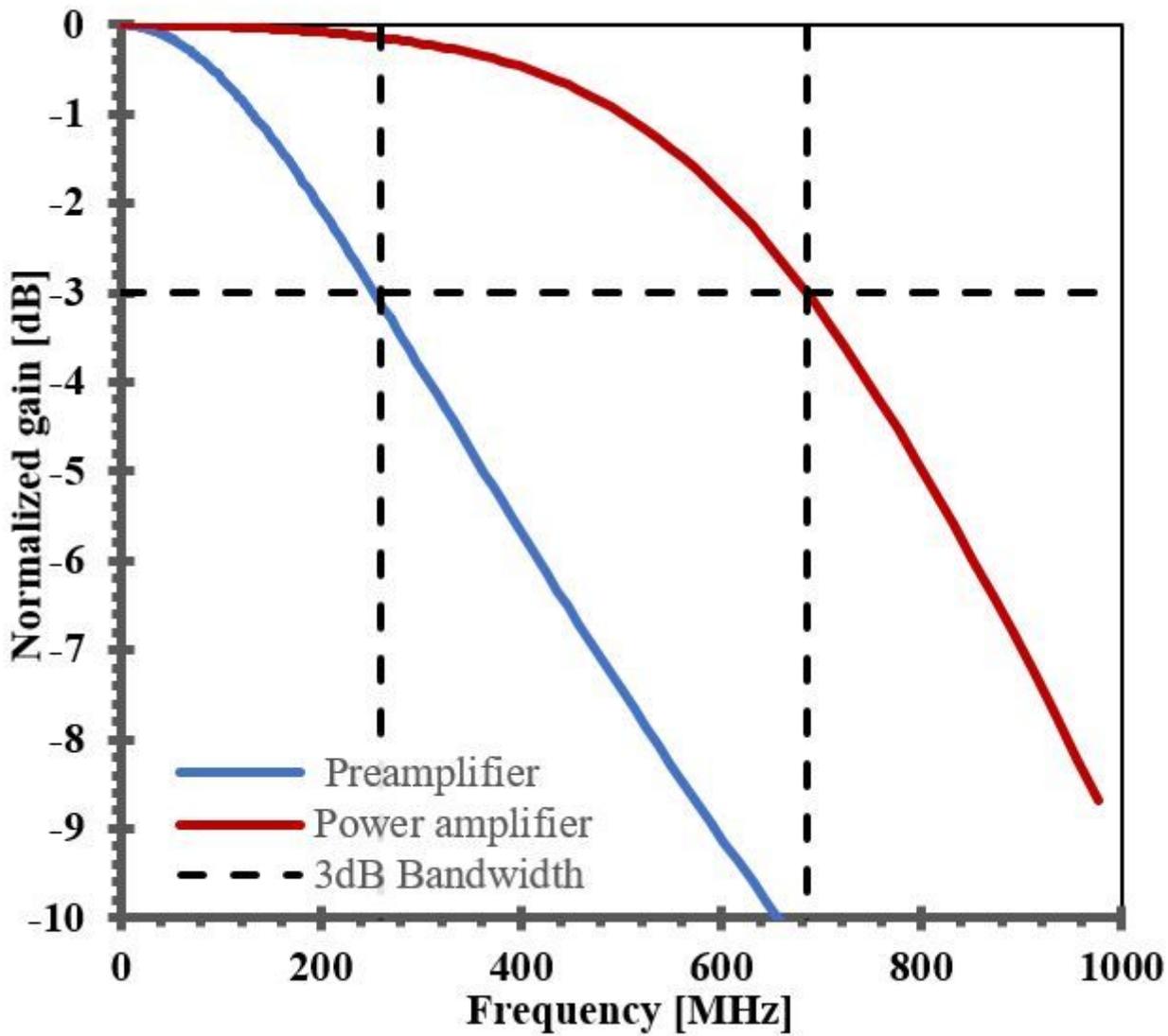


Figure 4

Bandwidth simulation for first and second stage amplifier at gain x10

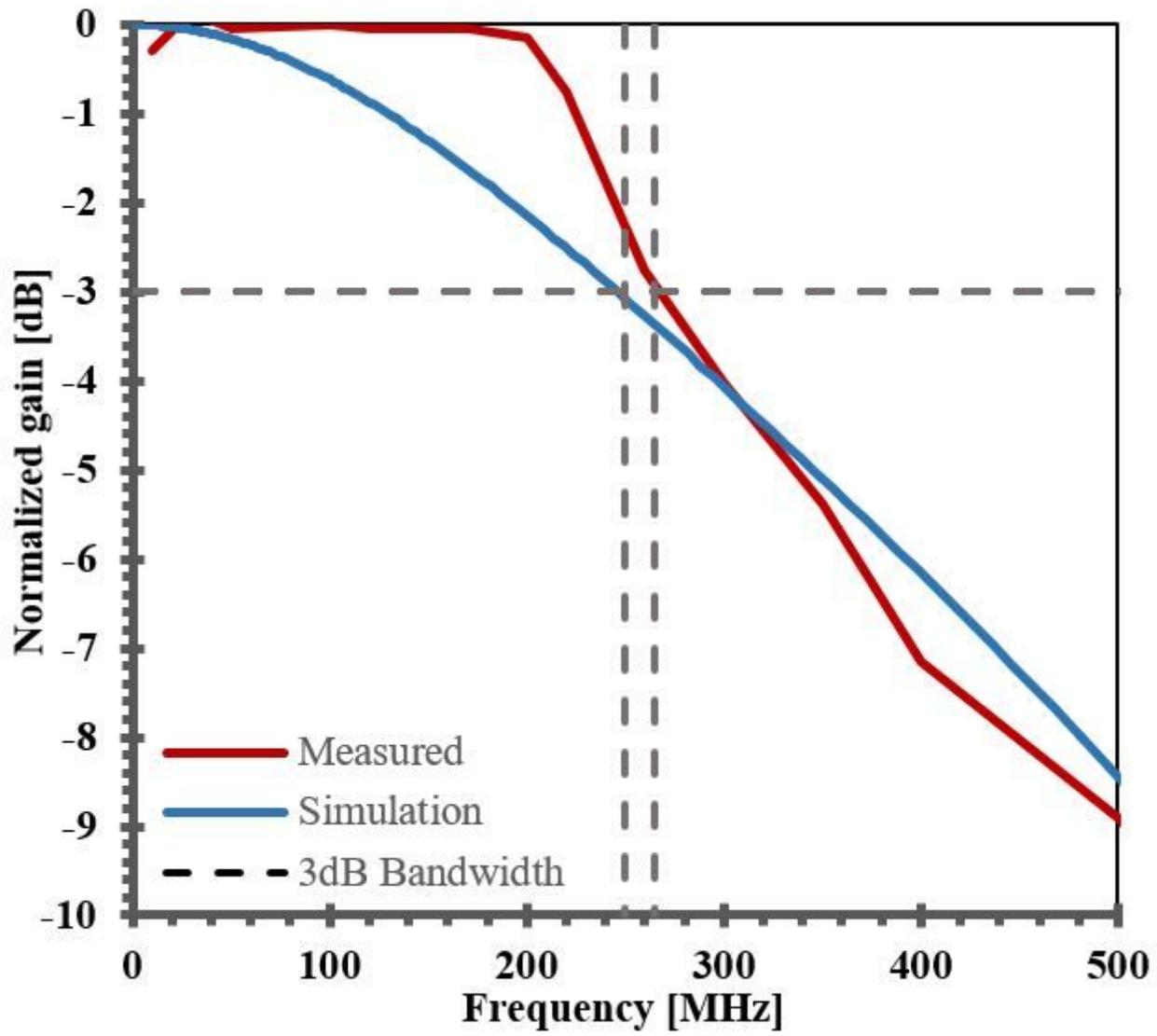


Figure 5

Simulated and measured bandwidth of a complete amplifier with a total gain of 100x

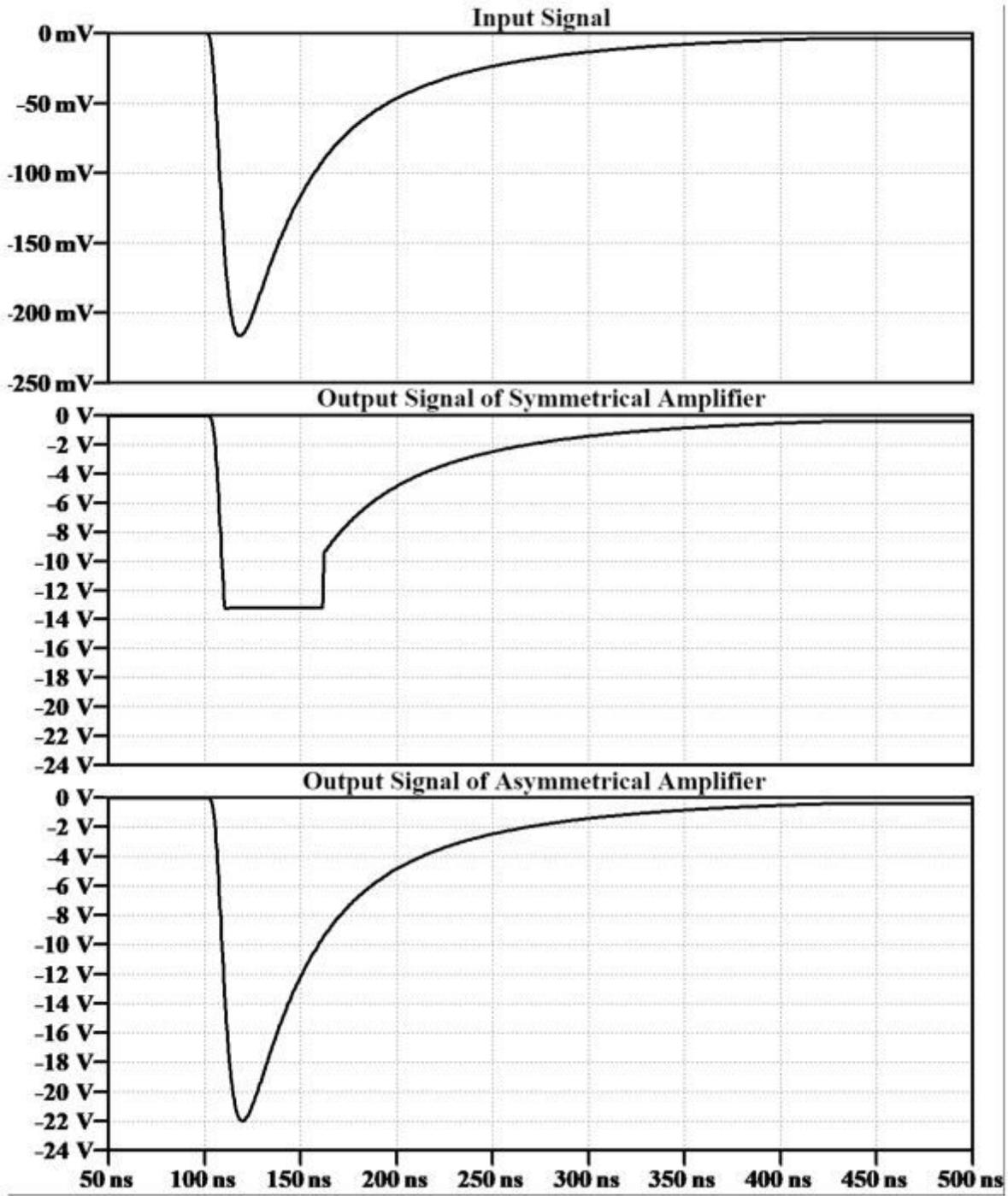


Figure 6

Comparison of PMT pulse waveforms amplified by an amplifier with symmetrical and asymmetrical power supply