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The JET Upgraded Toroidal Alfvén Eigenmode Diagnostic System

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Abstract

The JET Toroidal Alfvén Eigenmode (AE) diagnostic system is undergoing a major upgrade which will provide for a state of the art excitation and real-time detection system. Experimental measurements and studies of AE at JET have been done successfully first with the saddle coil system and then with purpose built in-vessel antennas with a real time mode tracking algorithm. Complete new excitation and digital control systems have been developed for this upgrade and are currently being installed to provide JET with a unique diagnostic to study AE in the planned DT experimental campaign with relevance to ITER. New exciters consisting of 4kW class D power switching amplifiers, one for each antenna, have been developed in collaboration with the industry to cover the frequency range of operation 10-1000 kHz with RF pulse duration of 15s and repeatability $\geq$ 15min. Due to the varying transmission line impedance throughout the frequency band, a design solution with high resilience to reflected power was implemented with VSWR>>10:1. A completely new digital amplifier control system has been implemented which is based on FPGA modules for amplifier frequency and phase control with frequency resolution <1Hz and phase <0.3 degrees at 100 kHz. Gain control along with timing, gating, and trip management is done using RT LabVIEW. New capabilities, such as independent antenna current and phase control, will allow improved excitation control and better definition of the antenna spectrum combined with enhanced system reliability.

Introduction

At JET a unique 8-coil antenna system has been implemented to study Alfvén Eigenmodes (AEs) and the ensuing plasma instabilities due to the interactions of these modes with fast ions. This diagnostic is known as the AE Active Diagnostic (AEAD) system. This system operates using the MHD spectroscopy technique, which is a diagnostic tool that uses global waves naturally supported by the plasma with the aim of measuring the parameters that determine their dispersion relation, absorption, propagation, and the damping and growth rates [1, 2]. A simple active method to drive and detect low amplitude modes in the plasma was pioneered and used under different plasma conditions in the JET tokamak [3]. This is the AEAD system, which has as its main aim to drive and detect plasma Eigenmodes in the Alfvén frequency range. Technical details on the AEAD system used at JET can be found in [3, 4-8] and references therein, and here we only present a brief overview.

As schematically shown in figure 1, the two main components of the previous AEAD system are:

1. The AE exciter, which is built upon a function generator and a single broadband high-power amplifier operating in class-AB mode; the amplifier is then connected to a set of up to eight in-vessel antennas via distribution and isolation transformers and a ~100m long transmission line;
2. The AE receiver, which is built upon synchronous detection units and real-time data analysis.

FIGURE.1

The AEAD exciter operates in the 10kHz to 500kHz frequency range, with maximum capabilities of 5kW/1kV/15A-peak delivered into a 50Ω load. This exciter produces a very small magnetic perturbation at the plasma edge, with maximum intensity of the order of $\max(|\delta B_{DRIVEN}|)\sim 0.1G$, which is $\sim 10^5$ times smaller than the typical value of the toroidal magnetic field in JET, $B_{TOR}\sim 1T$ to $B_{TOR}\sim 4T$. The AEAD receiver collects signals from a set of in-vessel detectors for electro-magnetic fluctuations, such as magnetic pick-up coils, electron cyclotron emission and reflectometry measurements. This receiver is also connected to the AE Local Manger (AELM) to allow for the real-time detection and tracking of the plasma resonant response to the antenna-driven magnetic field perturbation.

The real-time use of the AEAD system is facilitated by synchronous detection, which monitors only the plasma response at the frequency corresponding to the antenna excitation, i.e. its synchronous component. Synchronous detection allows reducing the required bandwidth of the data acquisition system and removes the need for computationally expensive Fast Fourier Transform (FFT) algorithms to obtain the required frequency component. For the specific case of the AEAD system, we use a 1.25kHz sampling rate for detecting modes whose frequency can reach 500kHz, whereas real-time FFT algorithms based on the Nyquist criterion would require a 1MHz sampling rate, i.e. needing an 800 times larger bandwidth and storage capabilities for the data acquisition. Synchronous detection also allows removing all undesired frequency components, hence dramatically improving the signal-to-noise (S/N) ratio. The AEAD hardware for synchronous detection works conceptually by applying a frequency mixer with the synchronous in-phase (I) and quadrature (Q) components to the incoming differential signal, and then applying a low-pass filter with a <100Hz bandwidth to generate the output [cosine (I), sine (Q)] DC components. The final output bandwidth of the AEAD synchronous detection system is then 500kHz.

System upgrade

The AEAD system, was in operation from October 2005 to October 2010 relying on a fifteen-year old single class-AB amplifier and similar ageing electronic modules. This single amplifier, with 5kW power output capabilities in the frequency range between 10kHz and 500kHz, was the driver for all eight different in-vessel antennas, with only +/- (0deg or 180deg) control of the relative phase between the antennas, and with only a common single frequency sweep. The AEAD system had several limitations and problems:

- The maximum current that can circulate in the antennas is 10A leading to weak excitation of AEs in the plasma core;
- Only +/- (0deg or 180deg) control of the relative phase between the antennas is possible;
- The ageing amplifier and control electronics are leading to ever decreasing reliability.

In preparation for a new DT operational campaign, the AEAD system is being upgraded, (see Fig. 2), with modern digital control electronics and eight individual solid state class-D power switching 4kW amplifiers to drive the individual antennas with arbitrary and user-controlled relative phase. These amplifiers are immune to reflected power throughout the frequency bandwidth 10-1000 kHz. They will also provide an increase in the total system power from 5kW to 32kW, as well as improving the distributed power coupling and reliability. Specific low pass filter modules will be installed at the amplifier outputs in order to get pure sine plasma excitation within the specified frequency bands. Upgrading the ageing function generator and control system to a new digital FPGA-based Master Driver (MD) control system will add real-time arbitrary phase control during frequency sweeps between antennas and allow more than one drive frequency, adding the capability to study travelling modes. The new system will also include amplifier gain control through a feedback loop referenced to programmed antenna current profiles, and CODAS integration for synchronisation, triggering, gating, and fault tripping. The remaining upgrades consist of adding a transformer at the Torus Hall link box to move the present transmission line resonance from around 250 kHz up to 450 kHz, potentially developing specific matching units for each transmission line and developing a digital synchronous detection system.

FIGURE.2

New RF amplifiers

The new RF amplifiers are based on switching MOSFETs, being classified as class-D amplifiers, designed to work in the 10-1000 kHz bandwidth. The main advantage of such an amplifier is the high resistance to reflected power, (in our case we have VSWR>>10:1) and therefore the amplifiers can withstand a short-circuit on their output. Consequently it will be possible to perform fast frequency sweeps without tripping problems with the impedance matching on the long JET transmission lines. Beyond this advantage, there are also 8 new amplifiers to be used, so the 8 in-vessel antennas at JET can be fed simultaneously with arbitrary phase control, increasing the power output and narrowing down the mode numbers being excited. The total available power of eight amplifiers will be higher than 8kW, instead of the 4kW previously available. Furthermore, with a better mode number definition using the arbitrary phase control the total power will be applied to fewer mode numbers, increasing the excitation efficiency. The arbitrary phase control will also help on mode number identification and control of the direction of mode propagation (toroidal mode number sign).

FIGURE.3

The amplifier's block-scheme is presented in Fig. 3a, and an amplifier picture in Fig. 3b. The amplifier operation relies on the MOSFETs switching a DC voltage power supply, that operates from 0 - 150 V and from 0 - 40 A. The voltage of the power supply, and thus the RF output voltage, is controlled by a Master Driver system with real-time control of the RF current amplitude and phase between the current of the different antennas.

The MOSFETs operate in a push-pull scheme, increasing the output power and eliminating the second harmonic from the output current. For this scheme to work, a transmission line transformer is used. This transformer operates in the push-pull mode, has a wide frequency band which depends solely on the transmission line from which the transformer is made, and offers resistance against high reflected power, protecting the MOSFETs. A two-stage system is used to switch the MOSFETs. The switching frequency signal is received by the RF amplifiers through a fibre optic receiver as a square pulse signal, thus creating two out of phase square pulse signals. Each signal switches two DRIVERs of a total of four, and each DRIVER pair switches four MOSFETs. In total there are 8 MOSFETs, 4 connected to each side of the push-pull transformer.

Filters

At the first stage of the experiments with the new amplifiers, the old synchronous detection system will be used. This synchronous detection module multiplies the signal to be detected (antenna current, magnetic probes etc) by a square wave of the same frequency as the RF current. Due to this method of detection, the INCAAs are very sensitive to the amplitude of the 3rd harmonic and therefore the third harmonic must be dampened in the RF current from the amplifier, to at least -70 dB. To achieve this, a 19th order low pass Chebyshev filter was implemented. It was designed taking into account possible errors in the actual values of the electrical components, which could prevent achieving the -70dB threshold. A specific filter is used for each desired frequency band. For example, if we want a high frequency limit of 250kHz, the minimum frequency is 125kHz. Therefore, we avoid the second harmonic, which could interfere in the synchronous detection system, making it sure that the third harmonic of the lower frequency (375 kHz) is damped to less than -70dB. The frequency response of the amplifier, which is loaded by a mockup of the JET transmission line, with a model JET antenna, in the frequency band 125-250 kHz, is presented in Fig. 4, as well as a photograph of one of the filters. During the initial phase of the experiments we will use two frequency bands, 75 - 150 kHz and 125 - 250 kHz. For the later phases of the experiments we plan to acquire more filters for 8 different frequency bands, exploring the total range of the RF amplifiers (10kHz-1MHz). It may be seen in Fig. 4 that the filters surpass the -70dB limit, achieving even more than -80dB attenuation at some frequencies.

FIGURE 4

Master Driver & Protection & Control

To control the system and drive the currents in the antennas with the desired frequency, amplitude, and relative phase, a Master Driver (MD) was developed. It is based on a National Instruments PXIe crate, with FPGA and Real-Time LabVIEW, to increase the system performance. The MD controls the value of the RF current and voltage, performs the system communication with the JET CODAS, and acquires data. The MD interacts with the RF amplifiers with three different signals, shown in Fig. 2: Famp, which sets the RF frequency and the phase between the amplifiers; VGC (Voltage Gain Control), which controls the DC power supply voltage level and thus the RF output current; and AMPen (Amplifier Enable), a safety signal, to enable voltage in the DC power supply, and thus the amplifier switching “ON”-”OFF”.

To select the frequency of the RF current, a FPGA board is used [9]. It drives the same frequency in 8 different channels and works as a phase locked system, keeping the same relative phase between the channels in frequency scans. The frequency output is sent to the RF amplifier as an optical signal, avoiding interference and simplifying the grounding scheme. The FPGA board generates 1GS/s of data points, this gives a frequency resolution better than 1Hz and phase resolution better than 0.3 degrees at 100kHz.

The RF frequency is determined by the AELM, which analyses data from different diagnostics in Real-Time and finds the resonant frequency for the desired toroidal mode number of the TAE.

Amplitude control of the RF currents and voltage is performed in the Real-Time system, which has a time response of less than 1 ms. This response time allows a smooth current control and a possibility to turn off the amplifiers in case of over-current or over-voltage. To control the RF current and voltage level, the MD controls the voltage of the DC power supply that is switched by the MOSFETs; the level can be changed within a 1 ms response time. To control the voltage level of the DC power supply, a feed-forward plus feedback PID control scheme is used in the Real Time system.

Due to reflections in the transmission line, which is loaded by the TAE antenna, the amplitude of the RF current depends strongly on the frequency, as seen in Fig. 3c. The MD control system can maintain the RF current amplitude relatively constant during the frequency scan. Having same current in all the antennas simplifies the excited mode determination, as parasitic mode numbers are not excited.

The Protection & Control (P&C) module is responsible for the safe operation of the system, monitoring trips and failures in the whole system, avoiding high voltage and over currents. It is responsible for enabling the RF current output, informing the MD to start the current control. The proper experimental timing and trip management are carried out using both the P&C and MD in conjunction.

Conclusion and future work

The new system is ready to start commissioning and plasma experiments are planned for the beginning of 2016. The performance of the amplifiers has been tested and performed as expected. They together with the MD and P&C will enhance system reliability. The independent antenna current and phase control will allow improved excitation control and power, with better definition of the antenna spectrum. This will improve the TAE drive, mode number identification, and identification of the direction of propagation.

Initially we will have available two different filter sets (75-150 kHz and 125-250 kHz). This will be sufficient for the commissioning phase and we will be able to confirm previous results before the DT JET campaign. For the DT campaign, more filters will be procured, which will ensure operation in the full spectrum of the RF amplifiers (10kHz – 1MHz).

The upgraded system allows multi frequency excitation. Two antennas subsets with two different frequencies will be possible, allowing the excitation of two modes separately, giving more data, and increasing precision. There is also a plan to develop a synchronous detection system based on FPGA electronics, which will operate with frequencies up to 1 MHz. They will replace the INCAAs, as they have a limited operation of only 500 kHz.

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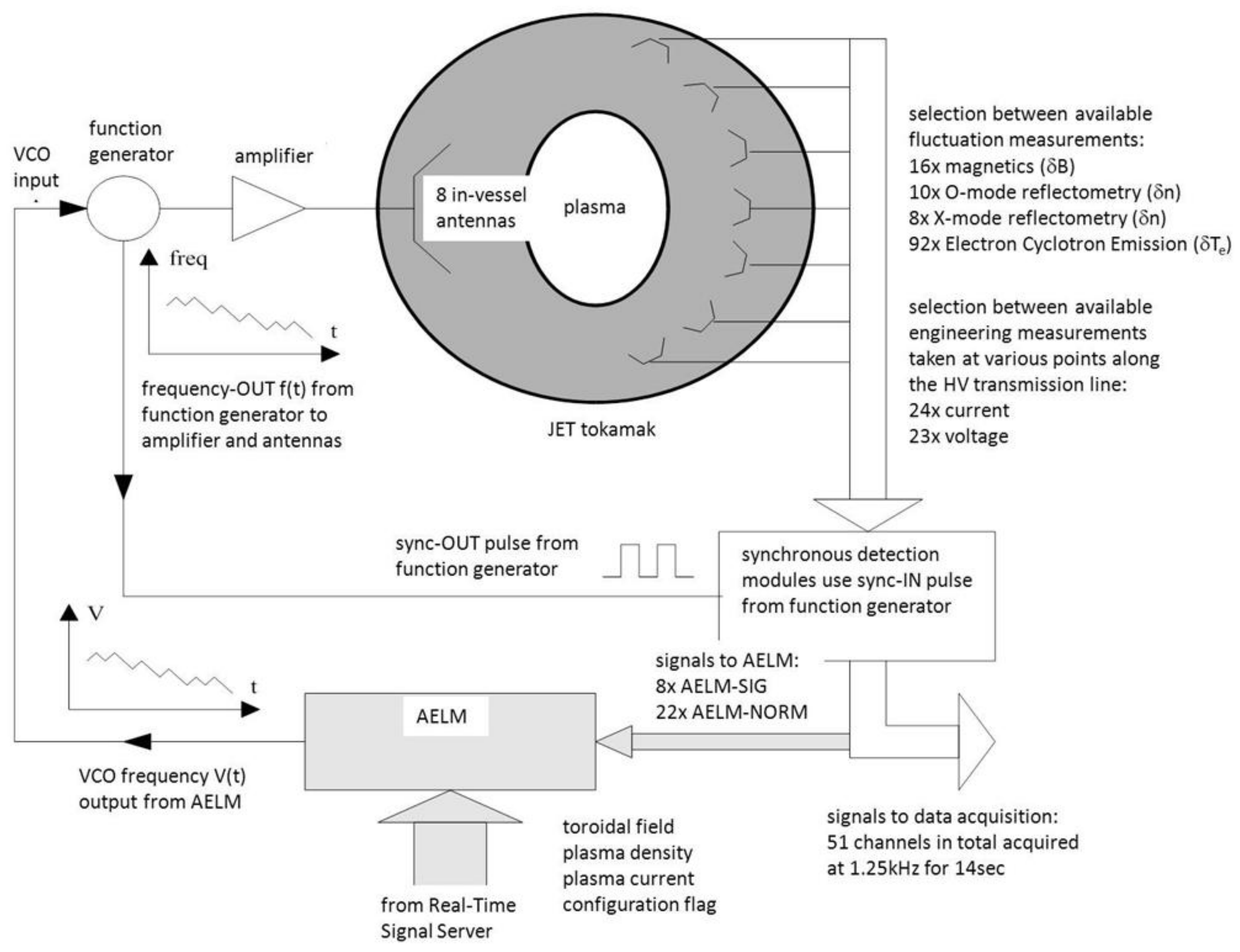

Figure1. A schematic overview of the AEAD system in JET. The toroidal field, plasma density and plasma current are retrieved from the RTSS and can be used by the AELM to compute in real-time an initial guess for the antenna excitation frequency freq(t). The AELM then converts this value to a time-dependent voltage V(t) and sends it as a Voltage Controlled Oscillator (VCO) input signal to the function generator which, in turn, converts it back into a frequency freq(t). This signal then drives a 5kW amplifier connected to up to eight in-vessel antennas via isolation and distribution transformers and a ~200m long transmission line (not shown). It is also used to provide the pulsed synch-OUT/IN reference for the synchronous detection units. These modules collect a selection of fluctuation and engineering measurements, some of which are also sent back to the AELM for feedback control of the AEAD plant and for mode detection and tracking.

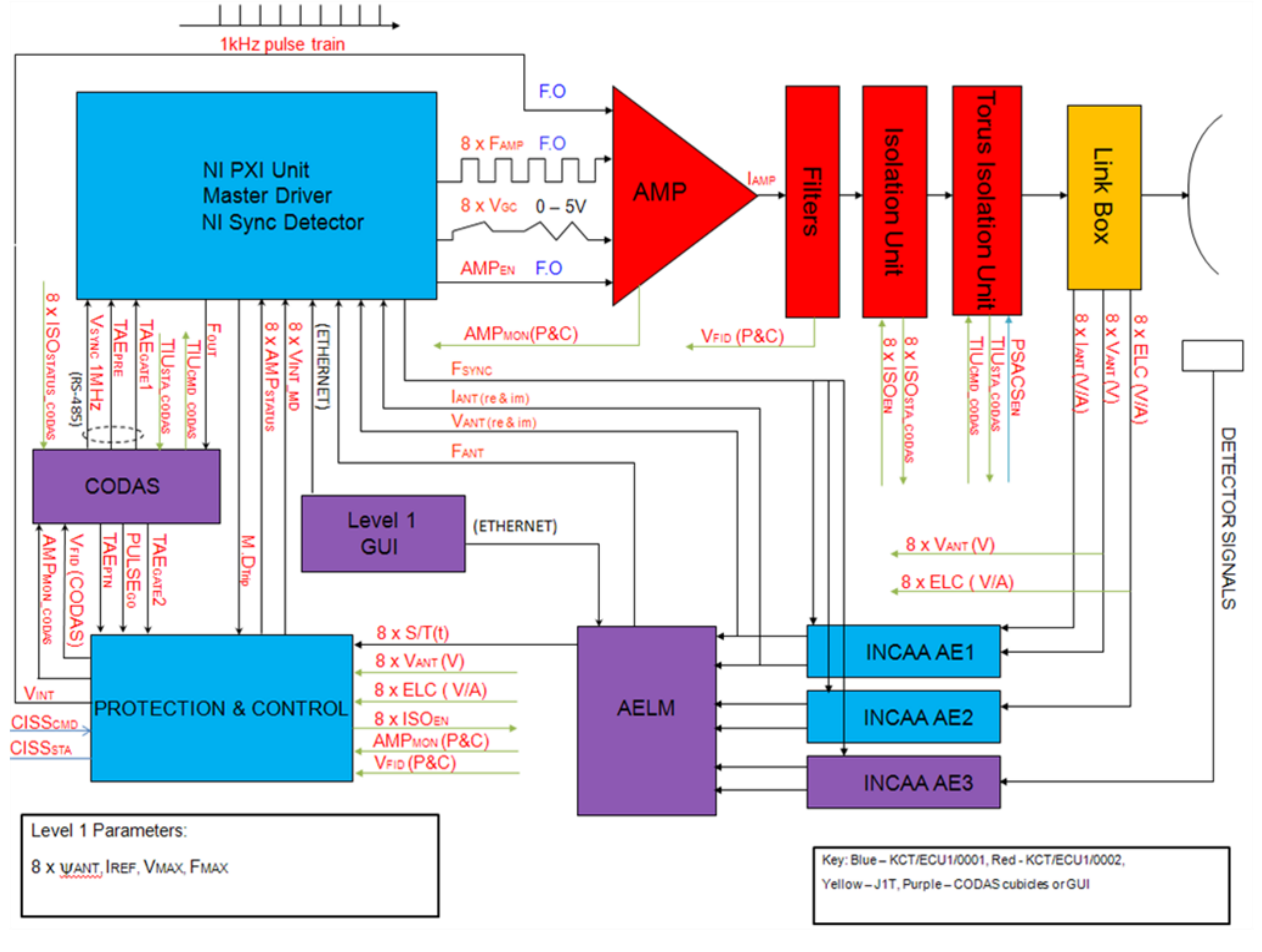

Figure2. Detailed scheme of the TAE-JET system upgrade. The new system main differences are: the new RF amplifiers, based on switching MOSFETs with a high resistance to reflected power and controlled by a FPGA board; filters; Master Driver, which control the current level, frequency and phase on all of the 8 antennas, optimising operation and specific mode excitation; and the Protection & Control system, which will improve safety.

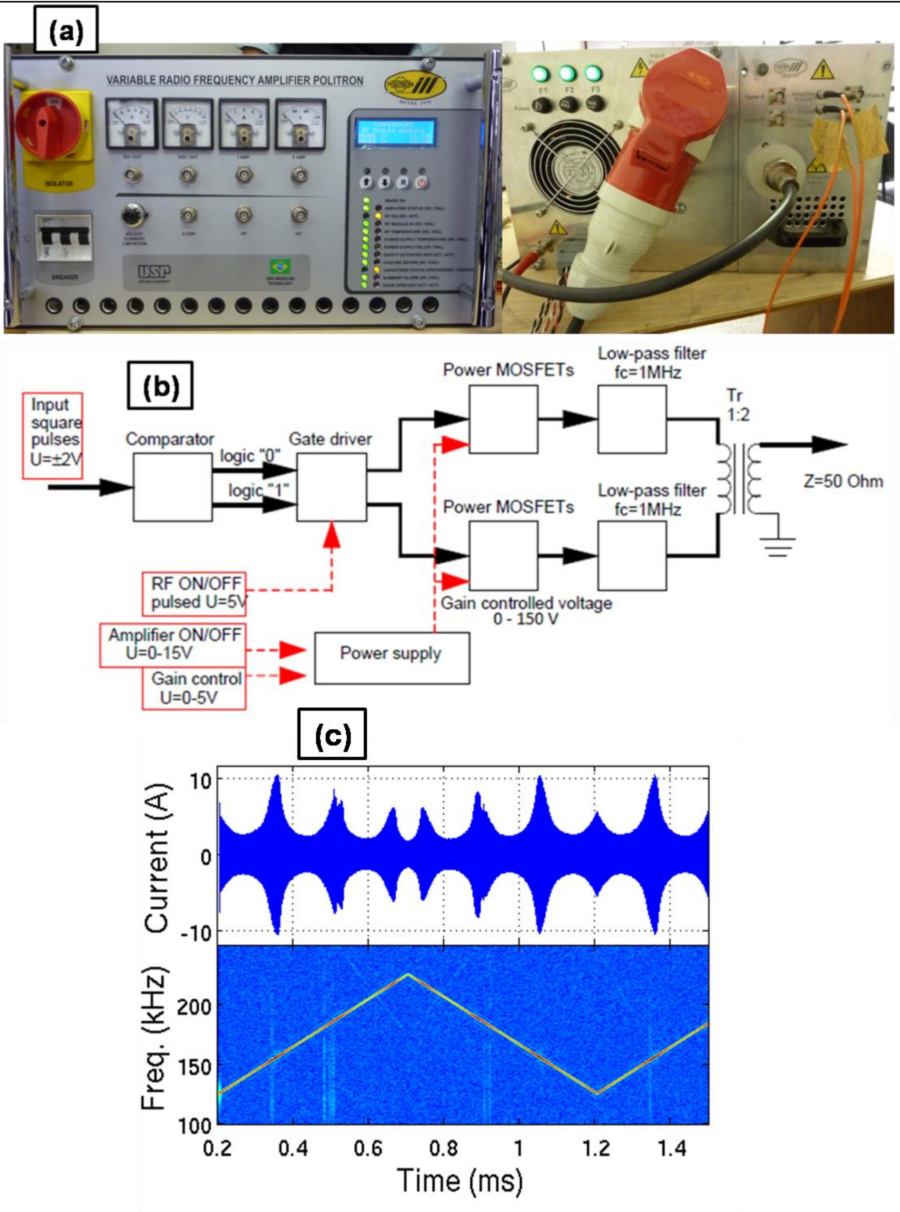

Figure3. (a) Picture of one of the RF amplifiers, showing its front and back. (b) RF –Amplifier block-scheme, showing the power supply and the MOSFETs operating in a push-pull scheme with the output transformer, with a simple low-pass filter on the maximum operating band the amplifier was designed to operate. (c) The RF current output of the amplifier on a mockup JET transmission line and antenna and the spectrogram of the signal.

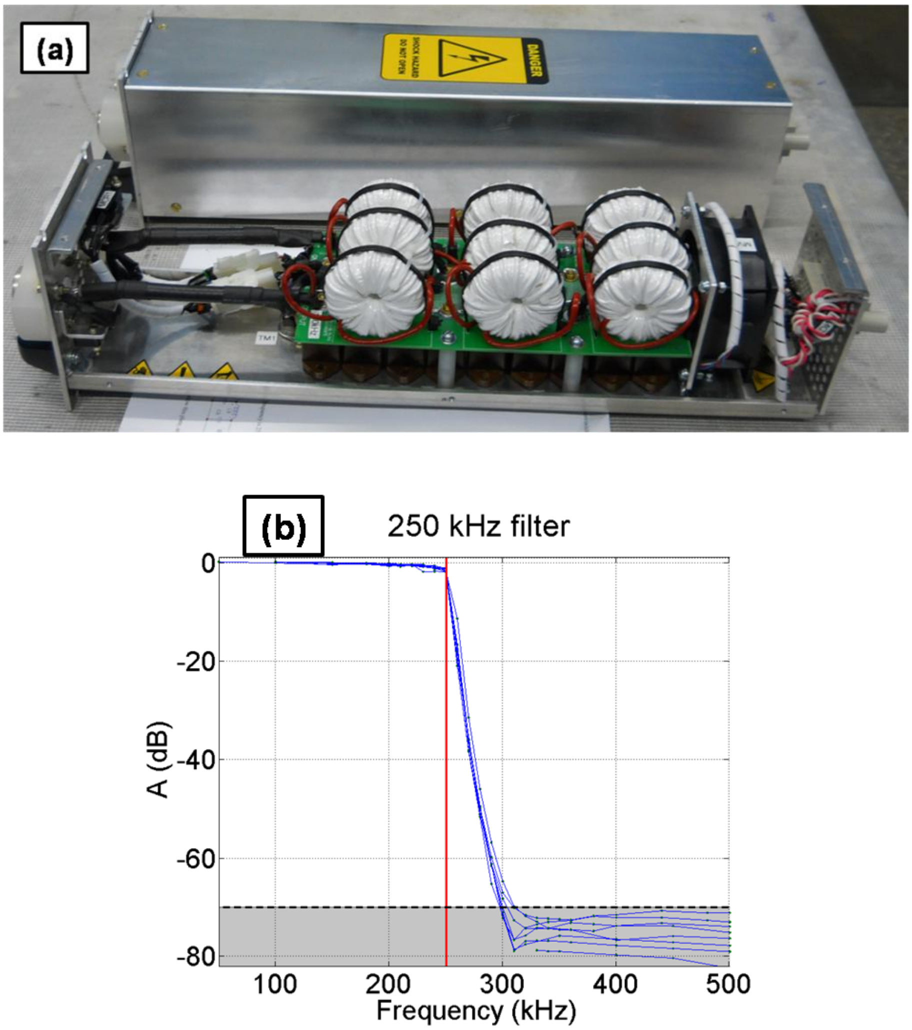

Figure4. (a) Picture of a 250 kHz filter. (b) 250 kHz filters attenuation curve. The grey area represents a lower than -70 dB attenuation and the red vertical line the filter cutoff frequency.