EISCAT_3D
Active element
Interim Report

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EISCAT_3D DELIVERABLE 6.1:

ACTIVE ELEMENT

INTERIM REPORT

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Table of contents

1. Introduction

Work Package 6 covers the detailed design of the active component of the EISCAT_3D radar, including:

- Design of the RF exciter / modulator system
- Design of RF power amplifier modules
- Validation of power amplifier design
- Design of transmit-receive switching and receiver protection systems
- Design of element antennas
- Design of antenna array and simulation of antenna performance
- Control and monitoring systems
- Design of built-in test equipment (BITE)
- Global simulation of active element performance

Two important items on this list have already been handled by Work Package 3, "Options for the Active Element". When it was realised that this Work Package could not really accomplish its task without making a detailed study of what sort of array would be required to meet the system performance specifications, it effectively absorbed the array design and simulation and element antenna design tasks. A fairly detailed design for the active element topology, a design for an element antenna and an extensive set of array simulations have been produced and reported in Deliverable 3.2 and Mr. Renkwitz´s M. Sc. thesis. As a consequence of this development, Work Package 6 is now focussing exclusively on RF generation, RF power amplification, BITE and control and monitoring.

In this interim report, we concentrate on the RF power amplification issue. A workable (although by no means perfect) power amplifier design is presented, the EI_3D RF power test bed is described, initial full-power test results are reported, some unexpected problems are highlighted and a work plan for the remaining project time is outlined.

2. Performance requirements and design targets

The basic EISCAT_3D transmitter performance requirements listed in the "3D Performance Specification Document" are as follows:

- Centre frequency: between 220 – 250 MHz, subject to allocation
- Peak output power: ≥2 MW
- Instantaneous –1 dB power bandwidth: ≥5 MHz
- Pulse length: 0.5–2000 μs
- Pulse repetition frequency: 0–3000 Hz
- Modulation: Arbitrary waveforms, limited only by power bandwidth

Since true time-delay beam-steering will be employed, both for reception and for transmission, the signals emitted by the element radiators when in transmit mode must be delayed relative to each other by individually programmable amounts, introduced at the exciter level in each transmitter module. The design and performance of the exciter system will therefore be governed by the beam-steering-related part of the Performance Specification Document:

- It will be possible to steer the beam from the central core transmit/receive antenna array into any one of ≥12000 discrete pointing directions, regularly distributed over its FOV and separated by on average 0.625° in each of two orthogonal planes. The beam steering system will operate on a <500 μs timescale.

Deliverable D 3.2 "Options for the Active Element" recommends that the 3D active element (the "core") should be constructed as a phased array with individual low-power transmitters fitted to all element radiators. It is also recommended that, if the construction must proceed in stages, at least 5000 elements should be deployed in a first phase. Since each element radiator has two independent radiating systems at right angles to each other, this minimum system will comprise at least 10000 transmitters.

To meet the peak output power performance specification of ≥ 2 MW, each transmitter module must therefore deliver at least 200 W peak output power. A range of current devices can do this with ease (see below) and so it has been decided to aim for at least 300 W. Each module must also meet or exceed all other specifications. As far as the power amplifier part is concerned, this should be straightforward; at least on paper; realising the modulator part and incorporating the time-delay beam-steering will take some doing…

3. Survey of VHF RF power devices

RF power semiconductor R&D has largely followed the trends and demands of the telecommunications industry, which is in turn governed by internationally agreed systems standards and the ITU frequency allocations for the different radio services (e.g. broadcasting, mobile, fixed-to-mobile, radiolocation/radar etc.). As a result, different device families have emerged, each optimised for a particular application and frequency range.

There are fundamental physical limitations on the maximum output power of a single RF power transistor. Features that increase device output power, i.e. large junction area and reduced device thickness, also increase junction capacitance and limit maximum frequency and power gain. At UHF, the skin effect limits the useful junction area to a few micrometers' width next to the edge, and the length of the edge has to be increased by dividing the junction area into a finger-like pattern. However, the ultimate limits on power density are set by the properties of the semiconductor material and the heat resistance between the junction and the heat sink. All this limits the practical output power of a single CW rated device to about 150 watts at all frequencies from VHF upwards.

Currently, the biggest application world-wide for RF power devices in the 100+ watts class is in mobile telephone systems base stations, starting with the 800/900 MHz systems (e.g. GSM) in the late 1980s and continuing into the present-day third-generation systems operating in the 2.1 – 2.4 GHz range. Much R&D has gone into pushing the upper frequency limit to well beyond 2.4 GHz and improving device linearity, producing e.g. the lateral D-MOS (LDMOS) transistors now being more or less universally used in 3G base station amplifiers.

At VHF (150 - 225 MHz), the situation seems to be more mature. The primary application in this frequency range is in the power amplifiers of Band III analogue TV transmitters. Most of the world's leading semiconductor manufacturers used to be represented in this market segment, but the pressure from the mobile telecom marketplace and the changeover to digital UHF terrestrial TV now taking place world-wide have prompted many companies to drop their VHF device ranges. Three prominent suppliers remaining in the field are Philips, Freescale and ST Micro Devices. Some of their 300 W-and above VHF power devices are tabulated below:

Table 1: Some 300 W+ class VHF power semiconductor devices

Type	Output power [W]	Gain [dB]	@ freq [MHz]	U_{CE} [V]	Efficiency [%]	Manufacturer	Notes
SD2932	300		175	50	50	ST Micro	
SD3932	300		150	100		ST Micro	
6V2300N	300	27 (!)	225	50	65	Freescale	Tentative
BLF248	300	11.5	225	28	65	Philips	
BLF368	300	13.5	225	32	62	Philips	
BLF369	500	>17	225	32	60	Philips	

The ST Micro devices are not specified by the manufacturer for operation at 225 MHz. It has not been possible to find reliable data on their power gain and efficiency at that frequency. The Freescale MRF6V2300N is a brand new release for which only tentative data are available so far. Its rated operating voltage of 50 volts and its claimed power gain of 27 dB put it in a class of its own, but it remains to be seen if the device will actually measure up to those claims.

The Philips BLF248 and BLF368 look promising. These devices are push-pull silicon N - channel FETs, designed for broadcast transmitter applications, and have been in full production for a number of years. Both are rated at 300 W CW nominal output power up to 225 MHz in class AB. According to the manufacturer’s data sheets, typical devices can be expected to produce 350 W CW at 70^{o} C operating temperature. They could possibly be run at even higher output power in pulsed operation, although this remains to be verified. Complete designs for evaluation amplifiers, including PCB artwork, are available from Philips.

Power- and linearity-wise, both devices would probably do a good job in the EISCAT_3D (235-MHz) application if run at less than 350 watts. Operating at 32 volts, the BLF368 might be the best choice from the power supply point of view. On the other hand, at that voltage its efficiency is about 3 % less than that of the BLF248.

The BLF369 is a recent introduction by Philips. This is also a push-pull device, but in contrast to its predecessors, it is a LDMOS device boasting a 500-watt CW rating all the way to 500 MHz. The LDMOS process also delivers better power gain; over 17 dB can be expected at 235 MHz and 500 watts output, making it possible (at least on paper) to design a (+ 3 dBm => + 27 dBW) power train with just three stages. If the long-term reliability of this device can be proven, it could become a very serious contender for the 3D final stage active device.

4. The test bed

4.1 Purpose

Following an inquiry by the Technical Project Leader, in 2006 Philips/NXP kindly supplied the EI_3D project with several free samples of the BLF 248 VHF power FET for evaluation. The RF test bed was then designed and constructed around the BLF 248, in order to determine its performance and characteristics when operated under typical EISCAT_3D-conditions, and to investigate the influence of ancillary equipment (notably PSUs) on signal quality and overall transmitter performance.

One extremely important task for the test bed is extended thermal-stress testing of the BLF 248 at full saturated output power and 25 % duty factor. Data for this operating mode are not available from the manufacturer, so it is vital to verify that the component can tolerate it for thousands of hours with no degradation.

The BLF 248 is specified for Band III analogue TV transmitter power amplifier duty. In this application, the power transistors operate in class-AB and run at a constant dissipation of perhaps 50 % of their rated output. The RF power actually generated during one scan line is controlled by the video signal content and is typically very low; maybe 10 – 20 % of rated power. The output reaches full rated power only during the 4.7 μs line sync pulses every 64 μs and the 160 μs frame sync pulse at the end of a half-frame (every 20 ms).

The incoherent-scatter radar application is very different in terms of the thermal stresses imposed on the power devices. The duration of a typical IS radar transmit-receive cycle is between 1 and 10 ms, that is, in the same order as (6….60) TV scan lines – but the RF pulse lengths are typically in the 0.5 – 2 milliseconds range, transmission is almost always at full saturated output power, and the device is completely cut off between pulses. This imposes a cyclic thermal load whose period can be in the same range as the thermal time constant of the bonding wire – chip – substrate system, thus exposing the device to cyclic stresses that have been known to induce material fatigue and premature device failure. Our thermal-stress test runs are aimed at finding out whether the BLF 248 might be so prone to this type of failure that it starts to show up as an “infant-mortality” problem already in an extremely small number of devices.

Unfortunately, it seems that the only way to gain more confidence in the suitability of the device for IS radar operation would be to run extended full power stress tests (several thousand hours) on a statistically significant sample (hundreds of devices), using realistic waveforms. An exercise of this magnitude is clearly outside the scope of the current feasibility study, but may have to be requested from the manufacturer at the point where the 3D community goes out to tender for the target system.

Power-dissipation and heat-management aspects of the mechanical design of the amplifier system are also very important and the behaviour of two different heatsink arrangements (i.e. with and without heat spreader) is therefore being evaluated as part of the thermal tests.

Other issues currently under investigation are e.g.

- Power supply behaviour under pulsed load,
- Power-supply induced pulse envelope modulation,
- Phase noise spectrum, sources of phase noise.

4.2 Gain distribution and circuit configuration

For the initial tests, the drive signal is a 235-MHz unmodulated carrier, generated by a standard laboratory signal generator. In a later phase, the generator will be replaced by a digital baseband-to-RF up-converter. This has a maximum output level of 2 mW or +3 dBm; the system gain is chosen accordingly:

Target output power per polarisation	300 W	or	+ 54.8 dBm
Available drive power	2 mW	or	+ 3.0 dBm
Loss margin	· 0.8	or	- 1.0 dB
Drive power split between two amplifiers	· 0.5	or	- 3.0 dB
Net power gain, input to output			+ 55.8 dB

The block diagram in Figure 1 shows how this gain is built up and distributed between stages. A Mitsubishi RA30H2127M 30-watt VHF power module is employed in the first stage. This is a high-gain device, specified for operation in the 210- to 270-MHz range. When driven with 1.5 milliwatts, it typically delivers better than 37 dB of power gain for an output of +39 dBm or 8.0 watts. This drives a single-stage BLF 248 amplifier, which is basically a copy of a Philips-designed device evaluation circuit. At +39 dBm drive, the BLF 248 device is still far from gain compression and easily delivers 10 dB power gain.

The + 49 dBm (80 watts) output power from the second stage feeds into a four-port hybrid network that splits it into two 40-watt signals. These drive the two output module BLF 248 stages into about 1 dB of gain compression; at this point the output from each stage is +54.8 … +55.0 dBm (300….315 W). These amplifiers are a second iteration of the mechanical design and have 5 mm thick copper heat spreaders fitted between the transistor and the aluminium heat-sink in order to lower the device-heat sink thermal resistance as much as possible.

The long-term test bed performance is continually monitored and recorded. RF output signals from the driver and both final amplifiers are picked off through directional couplers (-25 dB for the driver, -35 dB for the final amplifiers); the samples are rectified by diode detectors and the time-averaged diode output voltages recorded by a data logger. Heat sink temperatures are monitored by PT 100 sensors fitted into the heat sinks, about 5 mm away from the respective FETs.

Figure 2 shows a photograph of a second-generation BLF 248-amplifier; Figure 3 shows the complete test bed setup.

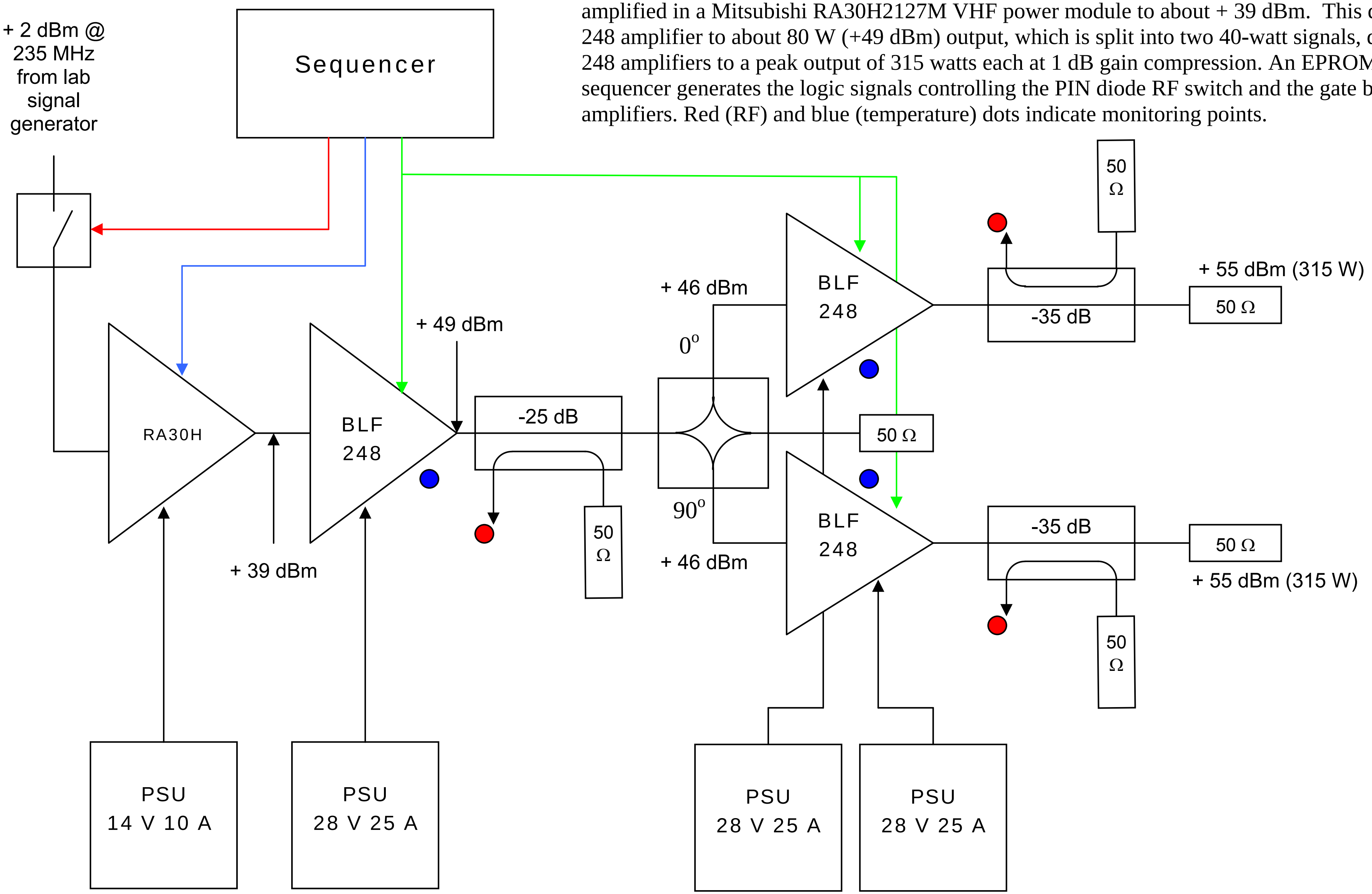

Figure 1: Block diagram of the EISCAT_3D 235-MHz power FET test bed. A +2 dBm carrier signal, generated by a standard laboratory signal generator, is on/off modulated by a PIN diode switch and amplified in a Mitsubishi RA30H2127M VHF power module to about + 39 dBm. This drives a BLF 248 amplifier to about 80 W (+49 dBm) output, which is split into two 40-watt signals, driving two BLF 248 amplifiers to a peak output of 315 watts each at 1 dB gain compression. An EPROM-based sequencer generates the logic signals controlling the PIN diode RF switch and the gate biases of all amplifiers. Red (RF) and blue (temperature) dots indicate monitoring points.

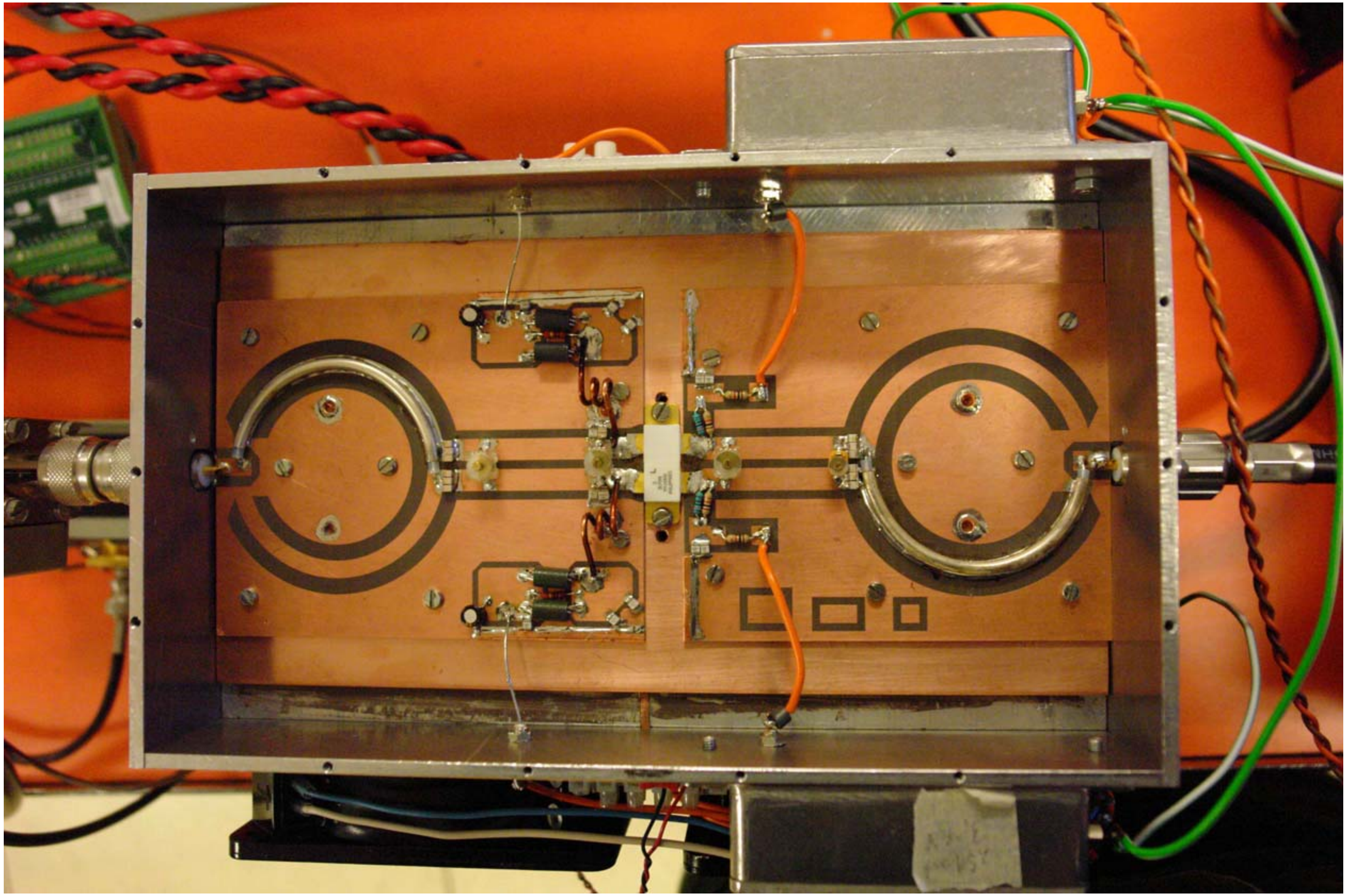

Figure 2: Photograph of a single-stage, class-AB1, 235 MHz RF power amplifier. The active device is a Philips / NXP BLF 248 push-pull power FET. In this configuration (actually optimised for 225 MHz), it delivers a power gain close to 10 dB at 28 V U_{DS} and 300 W RF output.

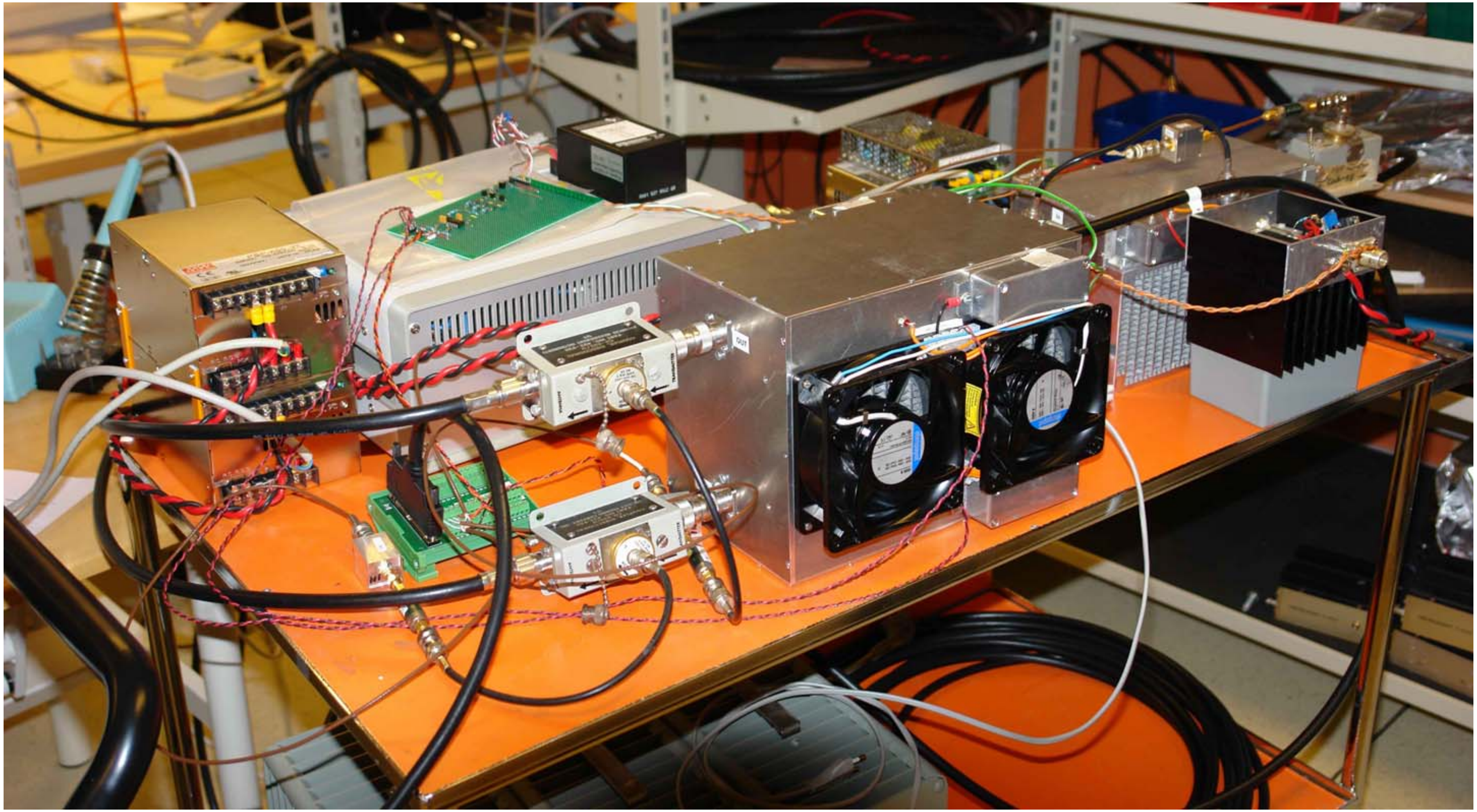

Figure 3: Photograph of the complete (2 x 300W) test setup. The aluminium box with ventilators at front centre contains two independent BLF 248 amplifiers of the same type as that shown in Figure 2. On its right is the driver chain, composed of a Mitsubishi power module followed by a single BLF 248 amplifier (partly hidden). A four-port hybrid (hidden) splits the drive power into two 30-watt signals driving one amplifier each. Final amplifier output power is sampled and monitored through two -35 dB directional coupler line samplers. The 28 V PSUs for the final amplifiers are located at the left rear; the grey instrument to their right is the EPROM-based sequencer.

4.3 Test modes

During pulsed operation, the test bed is controlled by a digital sequencer. This instrument, a leftover from the EISCAT Svalbard Radar project, is a stand-alone unit that runs off pre-defined code sequences stored in EPROM. Two EISCAT_3D-specific modes with RF duty factors of viz. 8 and 25 % are currently available. The initial pulsed-mode tests have used the 25 % duty factor mode, whose pulse pattern is illustrated in Figure 4 below. A constant-carrier (CW) signal is used for initial tuneup and testing of the individual amplifier units.

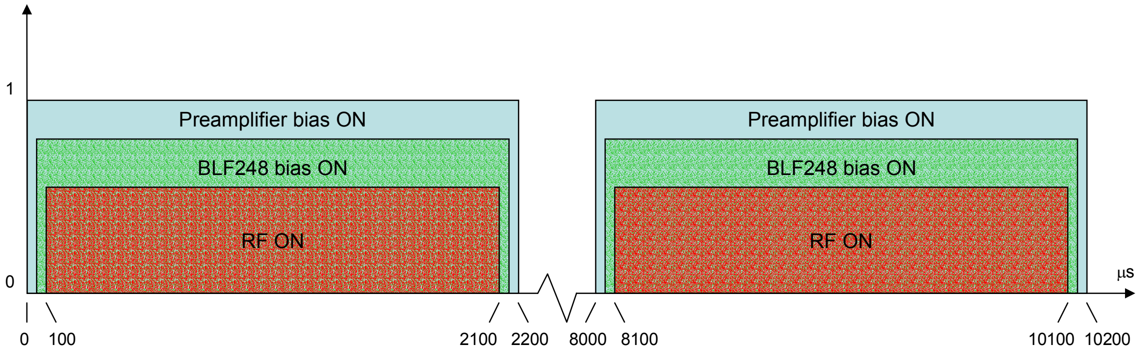

Figure 4: Pulse pattern used in the initial EI_3D power FET test bed runs. The preamplifier and power amplifier gate bias voltages are first applied in time sequence. At 100 µs into the cycle, RF drive is applied; at the end of the 2000-µs RF pulse, all signals are removed in reverse order. The cycle repeats at 8000 µs, corresponding to 26.25 % BLF248 drain current duty factor.

4.4 Preliminary results

After fine-tuning at 28 V U_{DS} and constant-carrier saturation drive, all BLF 248 amplifier units show better than 300 W output. The second-generation amplifiers operate quite stably under these conditions, but the prototype unit, which does not have a heat spreader fitted, exhibits a degree of thermal drift. After 10-15 seconds at full power, its power gain and output power begin to drop and the output eventually stabilises at around 250 watts. This was in fact noted before construction of the second batch of amplifiers was started, prompting the inclusion of the heat spreaders. These are undoubtedly necessary in the final amplifier design if CW operation is contemplated; in any case, heat spreaders will help to keep the die temperature down and so improve the FET life expectancy and MTBF.

The pulsed-mode tests carried out so far have mainly been addressed at verifying stable operation of the whole test setup and the data logger. During a total of about 20 hours of operation at full power, no abnormal amplifier behaviour has been detected.

Monitoring the RF envelope with a fast oscilloscope revealed a dip of some 2 % in the middle of each 2-millisecond pulse. This was traced back to the switchmode PSUs powering the final amplifiers. These apparently have a feedback-loop time-constant in the order of a millisecond, causing the output voltage to drop by about a volt in the first millisecond of the pulse and then building back up to 28 volts as the feedback kicks in. Connecting a 10000 µF capacitor in parallel with the load simply makes the time-constant longer; the voltage now drops for nearly 1.5 ms before starting to come up (see Figure 5).

The frequency band tentatively allocated to the 3D radar by the Norwegian P&T, 229.928 – 236.632 MHz, is bracketed by active DAB networks and NPT has indicated that a spectrum mask may therefore have to be imposed on the 3D emissions in order to reduce the risk of interference. We do not yet have any indication of what sort of out-of-band spectral density will be tolerated, and must therefore assume the worst. This stresses the importance of observing and analysing the transmitter phase noise and reducing it as much as possible through good design.

The 300-watt level power spectra recorded during the initial tests contain an unexpectedly large amount of wideband noise. It is currently believed that this is the resulto of the ≈ 0.5 V p-p high-frequency switching ripple that appears superimposed on the drain DC voltage during the pulse phase-modulating the amplifiers. The external 10000 μF capacitor does not seem to suppress this ripple at all.

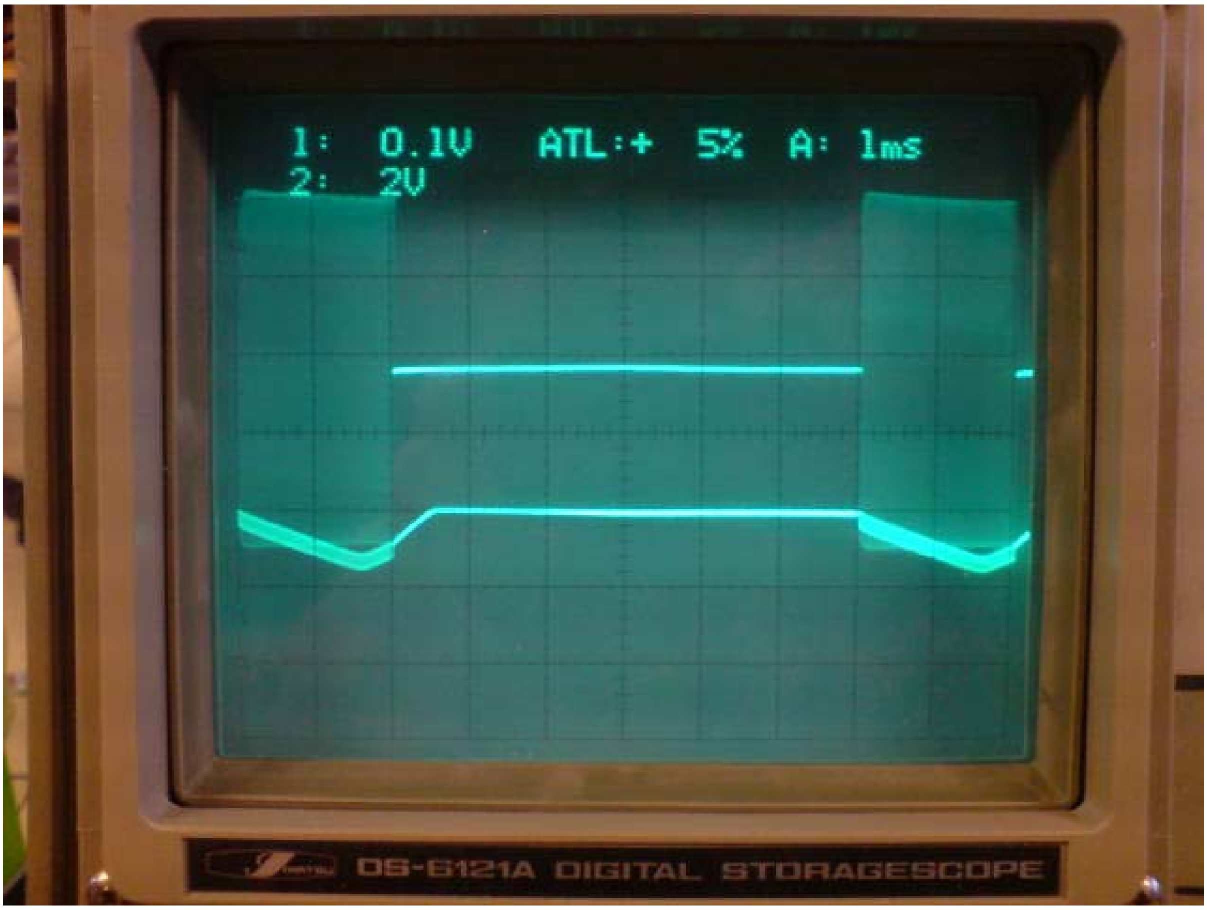

Figure 5: Oscilloscope display of viz. the 235-MHz RF envelope (upper trace) and the BLF 248 drain voltage (lower trace) when running the test bed in pulsed, 25% duty factor mode. A RF voltage droop of some 5% over the 2-millicecond pulse is clearly visible. The switching ripple superimposed on the drain voltage reaches almost 0.5 V p-p.

These observations highlight the importance of paying serious attention to the power supply issue in the final design. To get a better understanding of the problem, new phase-noise measurements will be performed with the amplifiers powered first from storage batteries, then from the switchmode PSUs.

5. Remaining and planned work

- A 1000-hour thermal-stress operation will be started around February 10,
- Thereafter, a series of short-pulse (1-μs), high-rep-rate (2 kHz) tests will be run,
- A multicarrier (OFDM) driving signal will be used to investigate the instantaneous power bandwidth and linearity of the amplifier chain,
- The amplifier noise floor in the powered-up OFF state will be measured,
- Detailed phase noise tests will be run on each individual amplifier when powered from a switchmode PSU and when powered from storage batteries,
- Similar phase noise tests will also be run on the complete amplifier chain,
- If time permits, tests at reduced drain voltage and reduced drive will be carried out to determine how well the amplifiers lend themselves to operating in a power-saving mode,
- Results from these tests will be presented in Deliverable 6.2, the Active Element Design Document.

The generation of the 235-MHz drive signals will be handled as a signal processing issue and reported on in the context of WP9.

6. Summary

- A (somewhat cursory) survey of the 300+ watt VHF power FET market situation, circa 2006, has been performed,
- The Philips/NXP BLF 248 has been identified as possibly meeting the EI_3D performance requirements,
- A batch of free BLF 248 samples has been supplied by Philips,
- A test bed with data-logging facilities for the evaluation of BLF248 performance under typical IS radar operating conditions has been designed and constructed,
- Three BLF 248 amplifier units have been constructed; all deliver ≥ 300 W CW,
- Initial pulsed-mode thermal-stress testing has been successfully performed,
- Unexpectedly poor phase noise performance has been observed and possible reasons for this are being investigated,
- A 1000-hour thermal-stress test run will commence shortly,
- Thereafter, a number of other mission-critical parameters, notably phase-noise and noise floor level in the OFF state, will be tested,
- Results will be reported extensively in Deliverable 6.2.

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