

RESULTS FROM THE 704 MHz KLYSTRON AND MULTI-BEAM IOT PROTOTYPES FOR THE EUROPEAN SPALLATION SOURCE

M.R.F Jensen, C. Marrelli, European Spallation Source ERIC, Lund, Sweden

Abstract

The European Spallation Source, currently under construction in Lund, Sweden, will contain 155 RF sources for proton beam acceleration. Of these, 120 are at 704 MHz. Each cavity will be powered by individual RF sources. The nominal beam pulse width is 2.86 ms and the RF systems are being specified for a pulse width up to 3.5 ms to allow for ramping and time for regulation. The repetition frequency is 14 Hz which results in 5% duty. The 704 MHz linac is divided into two sections, the medium beta and the high beta cavities. For schedule reasons, the medium beta linac, 36 RF sources, will be based on 1.5 MW pulsed power klystrons and the high beta section, 84 RF sources, is planned to be operated with 1.2 MW multi-beam IOTs. ESS ordered three klystron prototypes designed for the ESS parameters from different suppliers and two multi-beam IOT technology demonstrators under two different contracts. We present the specifications for the amplifiers and the results of the klystron prototypes and report the result of the first 1.2 MW multi-beam IOT prototypes.

INTRODUCTION

The European Spallation Source will deploy families of RF systems to provide an average beam power of 5 MW to the proton beam. The machine will accelerate the proton beam with a nominal beam pulse width of 2.86 ms at a repetition rate of 14 Hz. The linac sections operate at two different frequencies namely 352.21 MHz and 704.42 MHz. The 352.21 MHz accelerating structures include a radiofrequency quadrupole (RFQ), Medium Energy Beam Transport (MEBT) including three buncher cavities, five Drift Tube Linacs (DTLs) and 26 spoke cavities. This is followed by 36 Medium Beta (MB) cavities and 84 High Beta (HB) cavities [1]. In total the 155 RF systems have to provide in excess of 125 MW of beam power during each pulse which is summarised in Table 1.

Table 1:Summary of Amplifier Technology for ESS

Linac	Amplifier Technology	Maximum Power to Beam (kW)	Number of RF Stations
RFQ	Klystron	1600	1
MEBT	Solid State Amplifier	20	3
DTL	Klystron	2200	5
Spoke	Tetrode	330	26
MB	Klystron	870	36
HB	MB-IOT	1100	84

704.42 MHz KLYSTRONS

ESS entered into contracts for three klystron prototypes compatible with the MB and HB linac sections. Although the baseline for HB is MB-IOTs, the klystrons serve as a possible backup until the final technology decision is made. The three companies contracted were Toshiba Electron Tubes and Devices, Thales Electron Devices and Communications Power Industries Inc (CPI). All three klystrons were successfully delivered following formal Factory Testing to full nominal parameters. The outline klystron specifications are listed in Table 2.

Table 2:Summary Specifications for the MB Klystrons

Parameter	Value
Nominal Output Power	1.5 MW
Frequency	704.42 MHz
Bandwidth	≥ 1 MHz at -1 dB point
RF Pulse Width	≤ 3.5 ms
Repetition Rate	14 Hz
Efficiency at saturation at nominal power	> 60 %

Each klystron includes the vacuum tube, electromagnet and magnetic and mechanical frame, cooling jackets, gun oil tank, RF output window, x-ray shielding and shall terminate in a WR1150 waveguide flange. The scope does not include any external power supplies however each supplier shall incorporate and fit the filament supply, HV sockets and current limiting resistors supplied by ESS. Additionally, each supplier was encouraged and agreed to include a separate output matching component to allow the klystron to be re-optimised for efficiency when operated at reduced output power and high voltage.

Following installation, the 704.42 MHz klystrons for the ESS linac will be operated with four klystrons connected to the same modulator. That means that the four klystrons on each modulator must be operated at a common voltage even if the RF power-to-beam is not the same for each. This also places some constraints on the klystron perveance.

To enable klystrons from different manufacturers to be installed in any location, each klystron shall be capable of being operated at up to 115 kV. The klystrons are required to be operated vertically.

Toshiba Klystron E37504

The Toshiba klystron is relatively compact with a total length of 3.5 m including the collector and gun tank. The results of the factory testing are shown in Fig. 1 and Fig. 2. Although the nominal 1.5 MW is achieved with 105 kV, the klystron is tested to 115 kV although it is not

driven to saturation. It is possible to operate the klystron at the nominal focus currents even at reduced high voltage, however the efficiency can be improved by optimising the focus currents for different beam voltages. Including a mismatch, in this case an iris, the saturation efficiency can be recovered even for operation as low as 75 kV (approx. 650 kW), Fig. 2.

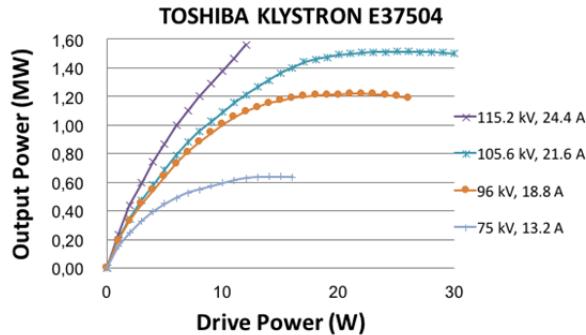


Figure 1: Transfer curves for different beam voltages.

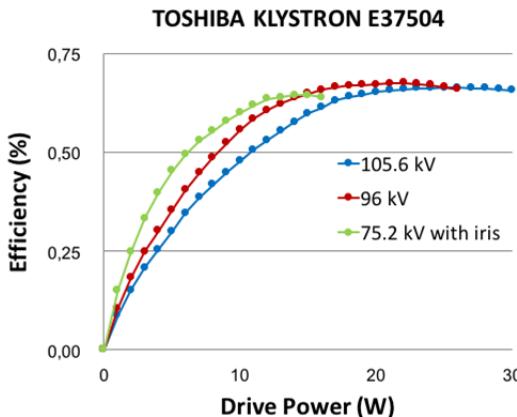


Figure 2: Efficiency curves with and without a mismatch in the klystron output.

Thales Klystron TH2180

The transfer curves from the factory acceptance results of the TH2180 is shown in Fig. 3.

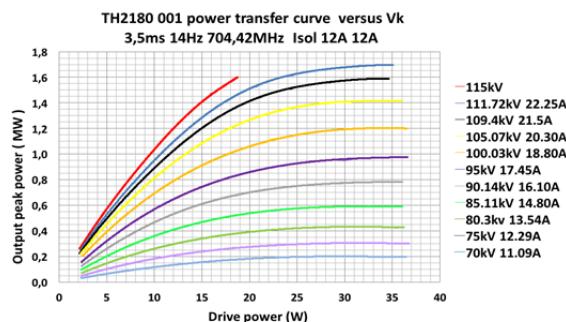


Figure 3: Transfer curves for different beam voltages.

Figure 4 demonstrates the improvement in saturation efficiency for operation at reduced voltage by inserting a mismatch, in this case, a post, in the output line of the

klystron. Operating the klystron at reduced voltage, in this example 80.1 kV, already recovers some efficiency compared to operation at nominal voltage, but as can be seen the efficiency can be increased further from 41% to 60%.

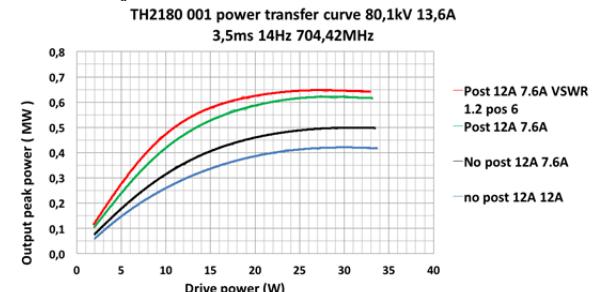


Figure 4: Output power and efficiency improvement when operated at reduced voltage with a mismatch.

CPI Klystron VKP 8292A

A selection of the factory acceptance test results is shown in Fig. 5 and Fig. 6 which show a set of transfer curves for different voltages and the improvement in efficiency again by inserting a post in the output waveguide. Although there was no requirement to operate the klystron above 1.5 MW, Fig. 5 includes a set of transfer curves into saturation for voltages up to 115 kV at which the klystron was delivering just short of 1.8 MW RF power. Fig. 6 demonstrates how the efficiency at saturation was > 50%.

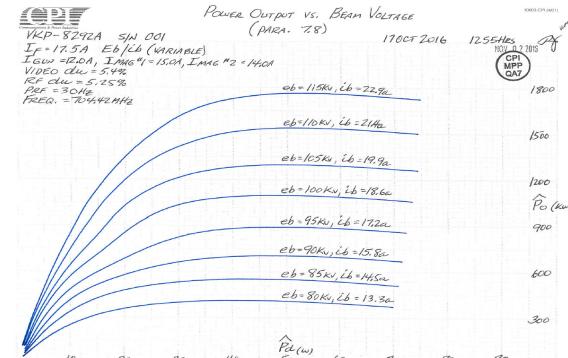


Figure 5: Transfer curves for different beam voltages.

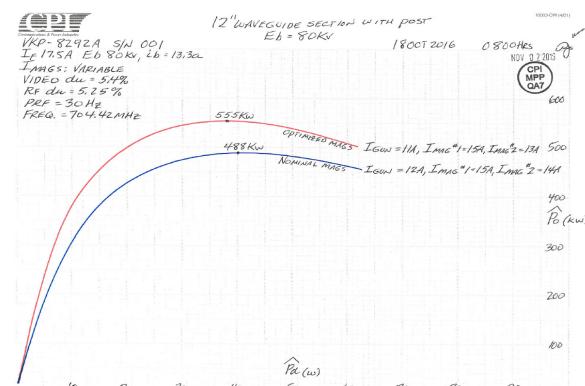


Figure 6: Output power and efficiency improvement when operated at reduced voltage with a mismatch.

704.42 MHz MBIOTS

A key goal for ESS in design, construction and operation is energy efficiency. Therefore, ESS placed two contracts with industry to design and build two multi-beam inductive output tubes (MBIOTs). IOTs operate in a different mode compared to klystrons and for IOTs the beam current is modulated by the RF drive rather than by the HV. Additionally, IOTs are known to be more efficient than traditional klystrons, particularly at the point of operation. This is important for accelerators which require a power overhead for regulation. The overhead required at ESS would reduce the klystron efficiency at the point of operation to 40-45%. A comparison of klystrons and IOTs is summarised in [2]. Prior to this development IOTs were first used at Diamond Light Source, a synchrotron light source in the UK [3]. Existing IOTs were capable of delivering up to 90 kW CW or about 100 kW in pulsed operation, however to achieve power levels > 1 MW a new development was necessary. ESS placed contracts with L3 Electron Devices Inc. and with a consortium with Thales Electron Devices and CPI. L3 and the consortium independently came up with a design of an MBIOT each with 10 beams. To minimise risk and development time, where possible, each beam makes use of existing technology from the broadcast industry including the design of the guns and collectors. The power from each beam is combined in a larger output cavity. Contracts were placed in October 2014 and both developments have been partly tested and have already delivered 1.2 MW [4, 5].

Fig. 7 and Fig. 8 show how the efficiency remains very high even when operated at reduced output power. This is without any optimisation of HV for operation at reduced power levels. The MBIOT from L3 was factory tested in 2016. It has now been delivered to CERN for further measurements and soak testing.

P_{out} and Efficiency vs P_{in} @ $E_k = 43.4$ kV

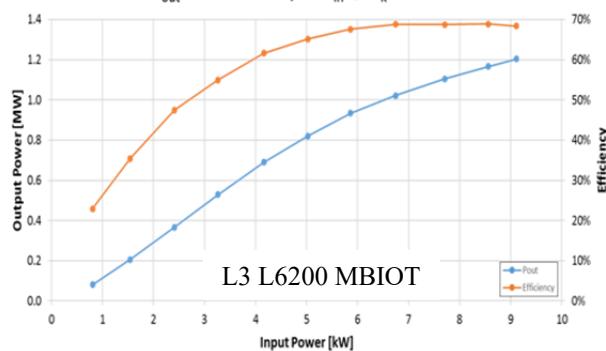


Figure 7: Plot of the output power and efficiency for the L3 MBIOT.

The MBIOT from Thales/CPI is currently being tested at CERN as part of its ‘factory test’ and has achieved 1.2 MW demonstrating an efficiency above 70%. Pictures of the L3 and the Thales/CPI MBIOTs are shown in Fig. 9. Although further characterisation and soak testing is required the results are very encouraging.

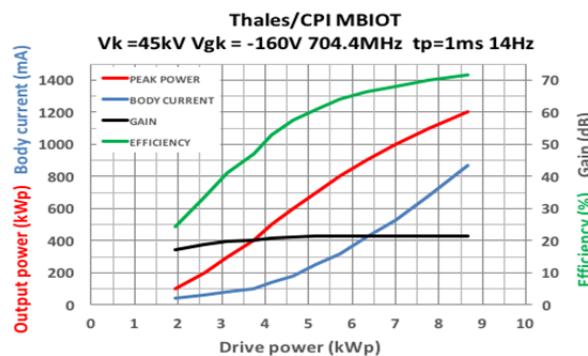


Figure 8: Preliminary results for the Thales/CPI MBIOT.



Figure 9: Photos of the L3 IOT and the Thales/CPI MB IOTs.

CONCLUSION

The three klystrons prototypes have been delivered following successful factory testing and the both MBIOTs have already demonstrated the specified 1.2 MW. Both amplifier technologies put ESS in a good position to proceed with the procurement and installation of the ESS RF systems.

ACKNOWLEDGEMENTS

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REFERENCES

- [1] M. Jensen *et al.*, “High Power RF Sources for the ESS RF Systems”, *LINAC2014, Geneva, Switzerland*, 2014.
- [2] A. Zolfghari *et al.*, “Comparison of Klystron and Inductive Output Tubes (IOT) Vacuum-Electron Devices for the RF Amplifier Service in Free-Electron Laser”, *EPAC 2004, Lucerne, Switzerland*, 2004.
- [3] M. Jensen *et al.*, “First Results of the IOT based 300 kW 500 MHz Amplifier for the Diamond Light Source”, *PAC 2005, Knoxville, Tennessee*, 2005.
- [4] M. Boyle *et al.*, “Factory Test Results of the L3 L6200 Multi-Beam IOT for the European Spallation Source”, *IVEC 2017, London, UK*, 2017.
- [5] A. Beunas *et al.*, “Manufacturing and Performance Results of a 1.2 MW Peak, 704 MHz Multi-Beam Inductive Output Tube”, *IVEC 2017, London, UK*, 2017.