ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEXGBF1

TESTING OF THE ESS MB-IOT PROTOTYPES

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Abstract

ESS is considering the use of MB-IOTs for parts of the high-beta linac. Two prototypes have been built by industry, namely L3 and CPI/Thales and have passed the factory acceptance test with excellent results. Both tubes will go through further extensive testing at CERN for ESS following delivery and a final decision on tube technology will be taken in April 2018. This invited talk presents the background for the technical decision of IOTs vs klystrons, associated impact for ESS, and latest plans for industrial production of these IOTs for ESS.

INTRODUCTION

The European Spallation Source (ESS) currently under construction in Lund, Sweden will deliver a 5 MW average beam power [1]. The pulsed proton beam of 2.86 ms at a repetition rate of 14 Hz will be achieved with the installation of 155 amplifier stations. In total, 155 high power RF amplifier stations will deliver in excess of 130 MW during each pulse, however the majority of the power will come from the high power amplifiers in the high beta part of the linac [2]. The high beta linac will contain 84 RF sources with an average power-to-beam of 1060 kW from each transmitter during each pulse. In 2014, the installation and commissioning schedule provided a window of opportunity of approximately 36 months to develop and test a new high power RF source with a specific focus on improving the efficiency of operation. Traditionally klystrons are the amplifier of choice for accelerators [3] and are well understood with many decades of manufacturing and operational experience, however IOTs have a number of advantages [4] which along with improvements in manufacturing technologies, resulted in IOTs replacing many klystrons in broadcast applications.

IOTs are suitable in the frequency range from 100 MHz to about 1.5 GHz, however the maximum power of a single beam IOT currently available is limited to approximately 150 kW pulsed. In 2014, ESS engaged with industry and placed two contracts to develop two multi-beam IOT technology demonstrators [5, 6 and refs. therein] and strategically made it the base line technology for the high beta linac. Recognising the relatively high risk of attempting to develop a new IOT, 10 times more powerful than existing IOTs, to be ready for series production in line with the ESS construction schedule, ESS also placed contracts to develop klystrons for the medium beta part of the linac but with a specification which would allow identical klystrons to be used for the high beta linac as a backup technology, namely to be capable of delivering up to 1.5 MW at saturation.

BENEFITS OF IOTS AND KLYSTRONS

The high beta linac for ESS will require RF sources at 704 MHz capable of pulse widths up to 4 ms at 14 Hz.

Modern day klystrons in this power and frequency range typically demonstrate a maximum efficiency of 67-68% at saturation considering only the DC-to-RF conversion. Operating the klystrons significantly below saturation reduces the efficiency at the point of operation linearly as the input power to the klystron remains unchanged. For the design of ESS, a power overhead of 20% was considered to be the minimum for losses in transmission, regulation and to accommodate manufacturing variances in the superconducting cavities. Additionally, since ESS will operate four klystrons from a common modulator, each klystron must operate at the same high voltage (HV). Any spread in klystron performance due to variations in perveance and efficiency, at the point of operation, will dictate the klystron voltage and therefore the efficiency of all klystrons when operated together. Additionally, any overhead required due to the performance of the accelerating cavities including any spread in the external Q, microphonics and beam loading will increase the power requirement for any particular klystron, forcing all four klystrons to be operated at the voltage required by that klystron. The combined impact could result in at least some klystrons being operated significantly below saturation. The IOT, on the other hand, draws electrical power in relation to the output power required. Although IOTs typically have a higher efficiency even at the nominal power level compared to traditional klystrons, the main benefit in terms of efficiency comes from the IOT maintaining high efficiency at the point of operation, even if operated significantly below the nominal output power.

Although efficiency was one of the main motivators for ESS to fund the development a new, much higher power IOT, there are additional advantages of IOTs compared to

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klystrons. IOTs, for example, are more linear and less prone to phase and output power variations caused by ripple on the HV supply. Since the output power of the IOT is gated by the RF drive power, there is no longer a requirement to modulate the HV for pulsed applications which is required for klystrons. This allows different power supply topologies to be considered with potential improvements in the efficiency of the HV power supply. Practically, IOTs operate at lower voltages which eliminates the need for oil for voltage hold off. On the other hand, the multi-beam approach increases the complexity of the auxiliary devices by having multiple cathodes and grids. The klystron is a much higher gain device, so the driver for the equivalent klystron for ESS can be limited to approximately 200 W whereas the IOT requires up to 10 kW of drive. In the past, the cost of such drivers would have been significantly higher however cost reductions in solid state RF amplifiers has reduced the cost of RF drivers over the past 5 years.

ENERGY COMPARISON OF IOTS AND KLYSTRONS FOR ESS

Following the test results of both the prototype klystrons and the IOTs, the energy consumption, electrical costs and long terms savings have been evaluated [7] for the anticipated operation. To be able to estimate the power consumption and associated cost of IOTs vs klystrons the main assumptions in Table 1 have been used.

Table 1: Summary of Main Assumption used for the Calculations

Operating hours per year	5000 hrs
Average power to the beam for all HB	1060 kWp
Pulse width and repetition rate including HV rise/fall time, cavity ramp and RF settling time	3.21 ms / 14 Hz
Power overhead for regulation	20%
IOT efficiency at point of operation	68.9%
Klystron efficiency at saturation	66%
Klystron Modulator / IOT power supply efficiency	92% / 95%
Klystron / IOT auxiliary power	3.7 kW / 5 kW

Following a change to the ESS schedule being implemented deferring some construction spend until later, the high beta part of the linac is currently planned to be constructed in two phases. The first phase will include 44 of the 84 high power RF sources taking the installed beam power to 3 MW. The remaining 40 high power RF sources to achieve the full design power of 5 MW will be installed at a later date. It is currently foreseen that the initial commissioning programme will start 2020 in preparation for the full user programme. Table 2 summarises the comparative power consumption estimated for operation using klystrons and IOTs. Power consumption not specifically associated with the high-power amplifiers such as control systems, utilities which are independent of the technology, are excluded from the comparison.

Table 2: Comparison of Energy Usage for Phase 1 and Phase 2 of the High-Beta Linac Subject to Amplifier Choice

	GWh / Year		
High Beta Linac	Klystrons	IOTs	Energy saving
Phase 1: 44 sources	26.5	19.0	7.5
Phase 2: 84 sources	50.7	36.2	14.5
Split technology from 2025: 44 klystrons 40 IOTs	26.5	17.2	7

THE DESIGN OF THE MB-IOTS FOR ESS

The main performance requirements defined for the technology demonstrators are listed in Table 3. The full specification of the MB-IOT was defined to demonstrate technical capability specifically for the high-beta linac at ESS. A strong emphasis was placed on efficiency and reliability but the main design architecture was left for the suppliers to propose.

Table 3: Main Parameters for ESS MB-IOT Technology Demonstrators for the High Beta Linac

Parameter	Specified Value
Frequency	704.42 MHz
Bandwidth at – 1 dB	≥ +/- 1 MHz
Output power	1.2 MWpeak
Power gain	≥ 20 dB
Beam voltage	≤ 50 kV
Pulse width	Up to 4 ms
Repetition rate	Up to 14 Hz
Design RF efficiency	≥ 65%
Design life expectancy	≥ 50'000 hrs

The contracts for the design and manufacture of the IOTs went to L3 Electron Devices and a consortium consisting of Thales Electron Devices (TED) and Communications and Power Industries (CPI). All three organisations have extensive experience and capability in high power RF devices and specifically with IOTs. The overall design of the MB-IOTs proposed share some main aspects. In particular both MB-IOTs consist of 10 individual gridded cathodes placed in a circle and enter a common coaxial interaction output cavity where the power of the 10 beams is combined and finally extracted through the centre prior to being coupled to a coaxial output waveguide which transitions to a rectangular waveguide after an RF vacuum window. The spent beams are deposited in individual collectors. Each cathode and grid, based on existing designs used for high power broadcast IOTs, have individual cathode heaters and grids allowing the cathode current and grid bias to be tuned independently if required. The beam current for each beam is controlled from individual RF drive signals and individually tuned input cavities. The TED/CPI MB-IOT requires a single large DC block and a single high-power RF drive signal which is split for each input cavity using a 1:10 power splitter at cathode potential. The L3 MB-IOT is supplied from 10 external drive signals at ground potential and has 10 smaller individual DC blockers. The combined drive power for each MB-IOT is similar and both MB-IOTs

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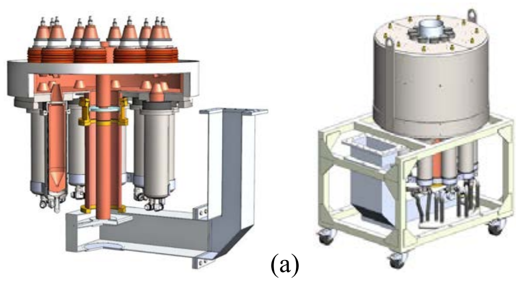
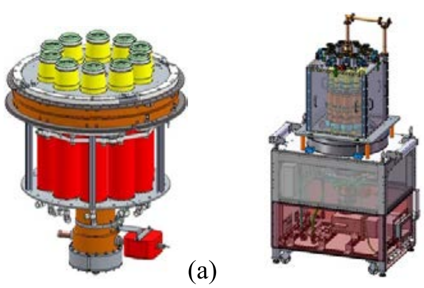
were designed to allow an electron gun to be isolated and the input cavity removed, in case of a failure of an individual gun. Although the IOT is a relatively short device, a magnetic circuit is required. The focussing for the TED/CPI MB-IOT is achieved with a single solenoid and the L3 MB-IOT uses permanent magnets. Both MB-IOTs use a mixture of water cooling and air cooling and the water cooling circuits have been designed to fall within the flow and pressure regimes of the building utilities. The MB-IOTs have similar footprints. Figures 1 and 2 show solid models of some of the design concepts.



(a) (b)

Figure 1: L3 MB-IOT: (a) Section view showing the configuration of the guns, combining cavity and coaxial output cavity. (b) Main assembly.



(a) (b)

Figure 2: TED/CPI MB-IOT: (a) 3D models of sealed tube. (b) Main assembly.

Extensive modelling and simulations were carried out for both MB-IOTs prior to ordering materials and the start of manufacturing. Details of the simulations can be found in [6, 8, 9] as well as in the formal written design reports [10, 11] provided under each contract and in addition both suppliers deployed a number of component and single beam prototypes to verify the simulations and manufacturing techniques to be used. There is no doubt that the extensive simulation and prototyping phases on single beam components were vital to reduce the risk of manufacturing issues in the final build.

TEST RESULTS OF THE ESS PROTOTYPES

The L3 MB-IOT was the first MB-IOT to be high power tested [12]. The San Carlos test stand included a 15 kW pulsed solid state amplifier from Tomco Technologies with an inbuilt 10:1 RF divider to provide separate drives for each gun, a HV power supply with associated capacitor bank, a crowbar from the SLAC B-factory klystron modulator and a HV deck with three heater supplies and a single grid supply. The power supply was limited to 43.4 kV although the MB-IOT had been optimised for 45 kV according to simulations. The HV supply included a 33 μF capacitor bank, however due to concerns over the protection system, the installed capacity was limited to 5 μF to reduce the risk of damage in case of an arc. This limited the pulse width to 200 μs at nominal power but operation at full duty was demonstrated by increasing the repetition rate. Longer pulse widths were tested at reduced output power but overall the testing was limited due to significant voltage droop during the pulse. The heater current was set to identical values for all 10 guns and similarly for the grid bias. During the start-up, the guns were brought on one at a time and the collector current was maximised by adjusting the coupling loop in the input cavity. Although RF cables of equal length from the driver had been installed, line stretchers were used to phase match each beam to optimise the power in the output cavity. However, it was soon confirmed that the performance of the MB-IOT was insensitive to small phase differences between the beams and the line stretchers were removed. Finally, the Q of the output cavity was optimised at nominal peak power.

The MB-IOT was tested to 1.2 MW peak at a pulse width of 150 μs and to 4% duty by increasing the repetition rate. The DC-to-RF efficiency at 1.2 MW was 68.4% with good gain. Figure 3 shows a plot of the output power and efficiency as a function of drive. Note that these results were for short pulses and lower than ideal beam voltage.

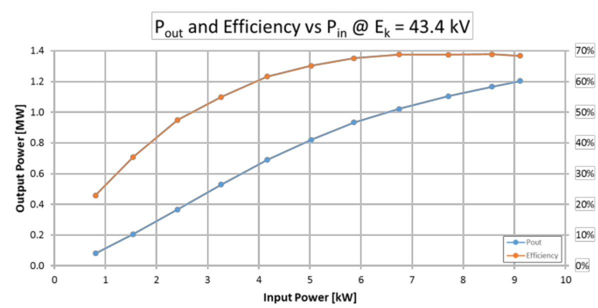


Figure 3: L3 MB-IOT: Plot of output power and efficiency recorded in the factory test.

The harmonic content of the MB-IOT was measured to be -49 dBc and -57 dBc for the second and third harmonic respectively, significantly better than specification (-30 dBc). See Fig. 4.

The close-in spectrum looks similarly clean notably with no sign of any high order cavity modes or spurious oscillations near the fundamental or harmonic frequencies, Fig. 5.

The MB-IOT is a much shorter device compared to a klystron and therefore the expectation is that the phase of the output signal caused by the beam voltage variation, e.g. ripple, should be modest despite the lower voltage. Figure 6 shows the variation to be around 3 deg. compared to klystrons which typically have at least twice this value. Similarly, the phase variation is insensitive to output power as can be seen in Fig. 7. Following the Factory Test, the L3 MB-IOT was delivered to CERN for further testing.

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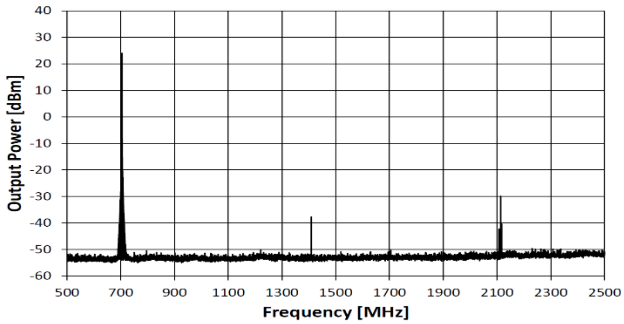

Figure 4: L3 MB-IOT: Plot showing the fundamental second and 3rd harmonic content. (Plot recorded at 1 MW).

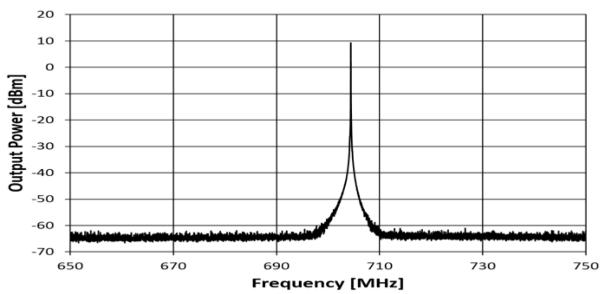

Figure 5: L3 MB-IOT: Plot of the output spectrum (recorded at 1 MW).

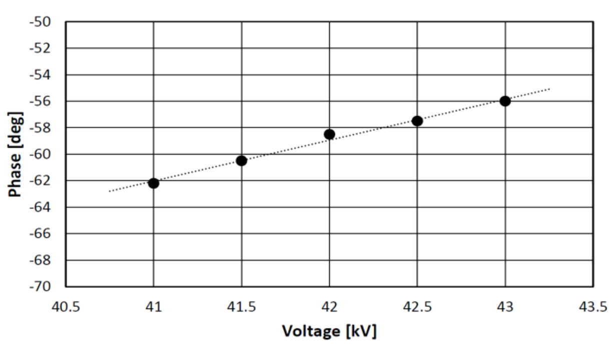

Figure 6: L3 MB-IOT: Plot of insertion phase recorded at 1 MW at constant output power.

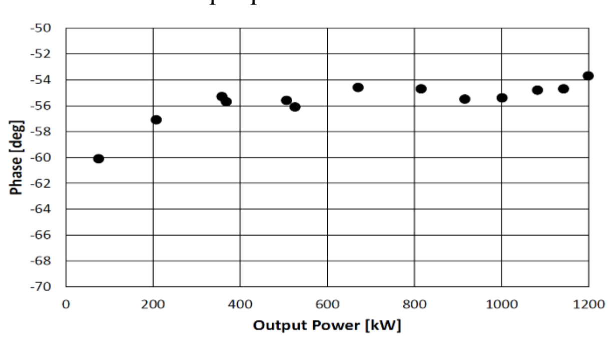

Figure 7: L3 MB-IOT: Plot of insertion phase at constant beam voltage as a function of output power.

The CERN test stand consists of a HV power supply with 80 µF capacitor bank to limit the droop during the pulse. The drive is provided through 10 separate 1.5 kW pulsed solid state amplifiers and a 10:1 combiner. For testing of the L3 MB-IOT, the 10 outputs were again split 10 ways which ensures that the amplitude and phase of each output are consistent. To allow the filament and grid supplies to be individually tuned for each gun, 10 separate filament and grid supplies allowed the sensitivity of each gun to filament current and grid bias voltage to be explored.

During testing, to avoid spurious trips on the crowbar system, derived from the LEP klystron RF systems, a leading and trailing edge ramp of 1 ms was included in addition to the flat top pulse widths used. 1.2 MW performance was achieved with pulse flat top widths up to 3.5 ms. The output power was limited to 1.14 MW when trying to operate with a pulse flat top width of 4 ms due to a lack of drive which was later discovered to be caused by a partial failure of a number of the drive amplifiers. Figure 8 shows the transfer curve recorded for the L3 MB-IOT operating at 45 kV with a 1 ms leading and trailing edge and a 400 µs flat top.

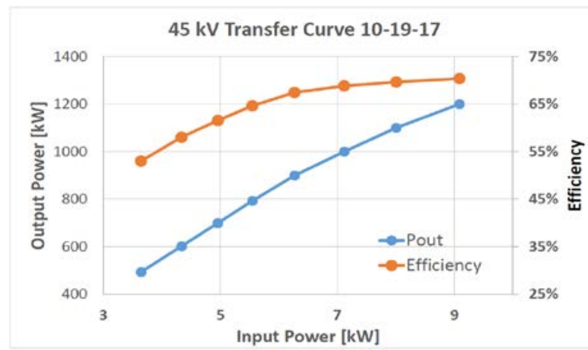

Figure 8: L3 MB-IOT: Output power and efficiency as a function of drive for 45 kV beam voltage with a 400 µs flat top and a 14 Hz repetition rate measured at CERN.

The TED/CPI MB-IOT was designed and manufactured through a combined effort of the two organisations [5, 8, 9] and the official factory testing was carried out at CERN under a separate agreement between the consortium and CERN. Following delivery of the input circuits and the main body, the MB-IOT system was assembled at CERN, high-pot tested and conditioned under supervision of TED and CPI. Following installation, the RF conditioning proceeded rapidly. The MB-IOT was tested to 1.2 MW, 14 Hz with 1 ms pulses with an RF efficiency (during pulse) of 69.8% and a gain of 21.4 dB, but during RF conditioning with longer pulse durations, the process was interrupted by RF instabilities and vacuum trips at 1 MW level with 4 ms pulses. Full power operation was no longer possible. The likely cause is the loss of contact on the centre conductor of the coaxial window across an internal joint that was secured with a bolt. The MB-IOT was returned to the manufacturers and the repaired MB-IOT has since been redelivered to CERN for further testing. Unfortunately, at the time of writing it has not been possible to install the MB-IOT in the test stand due to other priorities, however testing is expected to resume in the first half of 2018.

Figure 9 shows the output power and efficiency of the TED/CPI MB-IOT and Fig. 10, the gain and body current.

Further testing has just resumed at CERN on the L3 MB-IOT following a stop due to the LHC maintenance schedule at the end of 2017 to early 2018. Following the testing of the L3 MB-IOT the TED/CPI MB-IOT will similarly be retested and subjected to an extended run.

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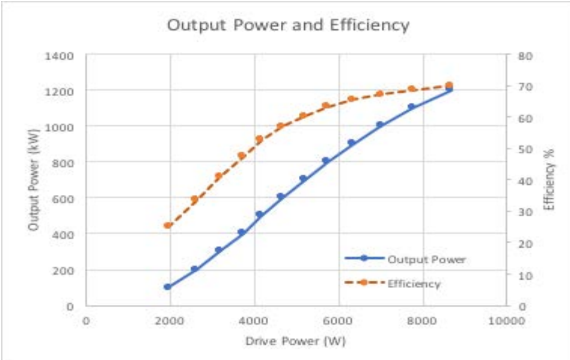

Figure 9: TED/CPI MB-IOT: Plot of output power and efficiency as a function of drive for 45 kV beam voltage, obtained for a pulse with a 1 ms rise and fall time with a 1 ms flat top.

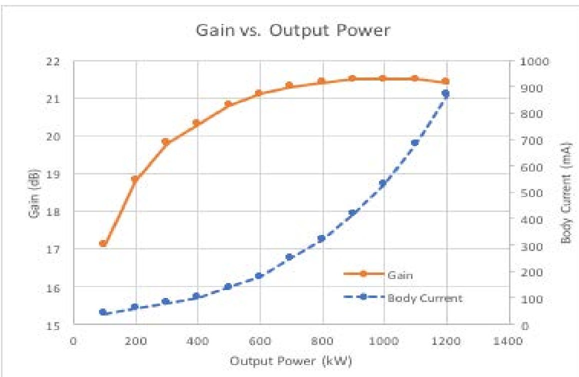

Figure 10: TED/CPI MB-IOT: Plot of power gain and body current for increasing output power.

DISCUSSION AND OUTLOOK

ESS places significant emphasis on efficiency and reduced power consumption which led to contracts being placed for two MB-IOTs. The IOTs have both been delivered and tested. Despite initial technical difficulties, not specific to IOTs, the manufacturers L3, TED and CPI have designed and manufactured both IOTs increasing the power by a factor of 10 over existing IOTs. The IOTs both delivered nominal power and superior spectral purity and importantly exceeded, with significant margin, the efficiency goals set at the outset of the project.

What is particularly noteworthy is how the high efficiency is maintained even for operation at reduced output. Figure 11 demonstrates the advantage in efficiency of IOTs over klystrons at the point of operation with due allowance for the losses in the distribution system and an overhead required for regulation. Since the IOT does not saturate, the IOT can be operated above 1.2 MW for short pulse excursions required for regulation, however the klystron must be setup specifically to accommodate the maximum required output power. As mentioned earlier ESS will operate four klystrons off a single modulator. Although the IOTs would similarly be connected to a common HV, the power consumption of each individual IOT is determined by its output power requirement, and by having a very slow roll off in efficiency, the overall efficiency is maintained. Similarly, the power consumption for non-standard operation, for example during machine shifts or low current operation is significantly reduced.

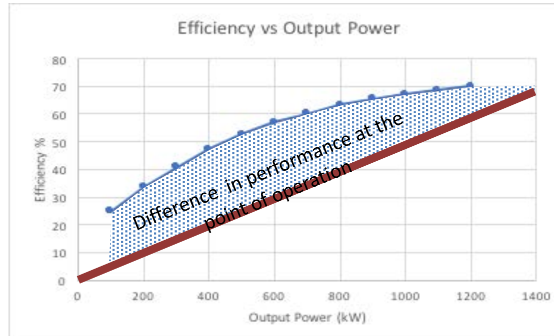

Figure 11: Comparison of the efficiency of the actual TED/CPI MB-IOT compared to a klystron. The efficiency of the IOT is in blue compared to the klystron, in red, with the klystron set up for a maximum power of 1.4 MW in order to deliver 1.1 MW to the beam.

Despite the overall success of the two MB-IOT technology demonstrators, ESS must however complete the machine on schedule, which means placing orders for the high-power amplifiers in 2018. Additionally, ESS considers that prior to placing contracts for 44 or more IOTs, a pre-series MB-IOT development to reduce cost and evaluate the overall reliability further is necessary, as well as developing cost effective solutions for HV, filament and grid supplies. Additionally, ESS is having to deal with additional budget constraints which means that although the additional cost of the IOTs compared to klystrons is expected to be recovered in savings in electrical cost, being a pulsed facility, the payback period is currently considered to be too long. The high-power RF sources must also be procured within the construction budget. ESS has recently decided that, for the first phase of the high beta linac, ESS will procure klystrons instead of IOTs. This leaves the option open to consider IOTs for the second phase of the high beta linac.

CONCLUSION

ESS entered into contracts to develop two 1.2 MW MB-IOTs with industry. The IOTs were designed and manufactured and initial testing of both tubes have demonstrated nominal performance with excellent efficiency and spectral purity. For reasons of risk, schedule and budget, ESS will not deploy IOTs for the first phase of the high-beta linac. We hope that the development has provided the foundations for future accelerators to use the MB-IOT technology, particularly in applications with high power, high duty and high overhead requirements, where the MB-IOT has demonstrated significant advantages over traditional high power sources.

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