# ACCELERATOR PRODUCTION OF TRITIUM 700 MHz AND 350 MHZ KLYSTRON TEST RESULTS

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*Abstract*

The Accelerator Production of Tritium project (APT) utilizes a 1700 MeV, 100 mA proton Linac. The radio frequency (RF) power is provided by 244 continuous wave (CW) klystron amplifiers at 350 MHz and 700 MHz. All but three of the klystrons operate at a frequency of 700 MHz. The 350 MHz klystrons have a nominal output power of 1.2 MW at a DC-to-RF conversion efficiency of 65 %. They are modulating-anode klystrons and operate at a beam voltage and current of 95 kV and 20 A. The design is based on the CERN klystron. The 700 MHz klystron is a new development for APT. Three 700 MHz klystrons are currently under development. Two vendors are each developing our baseline klystron that has a nominal output power of 1.0 MW at a DC-to-RF conversion efficiency of 65%. A 700 MHz klystron is also under development that promises to provide an efficiency in excess of 70%. The 700 MHz klystrons operate at a maximum beam voltage of 95 kV and a maximum beam current of 17 A. The test results of these klystrons will be presented and the design features will be discussed.

## 1 KLYSTRON REQUIREMENTS

The design requirements for the 350 MHz and 700 MHz klystrons are included below in table 1.

The 350 MHz klystron was supplied by English Electric Valve (EEV). Two vendors developed the 700 MHz klystrons, EEV [1] and Communication and Power Industries (CPI). The design parameters for these two tubes are different but still within the requirements. EEV chose a lower perveance design with respect to CPI.

In addition to the standard 700 MHz klystron design, EEV also pursued an advanced klystron design utilizing a second, second harmonic cavity just prior to the output cavity. This klystron had to meet the requirements in Table 1 and the development was directed towards increasing the efficiency to 70%.

The 350 MHz klystrons have all been tested and installed on the Low Energy Demonstration Accelerator (LEDA) [2], and have satisfied all design requirements. The standard EEV 700 MHz klystron has been tested, demonstrated all requirements, and is being installed on LEDA. The high-efficiency EEV klystron has been tested and demonstrated compliance with the baseline design requirements. In addition, the efficiency was increased from the required 65% to 68%. Higher efficiencies were achieved but found to be inconsistent with the 1.2:1 VSWR requirement at any phase. However, at the nominal 68% efficiency into a matched load, the klystron achieves efficiencies in excess of 72% at some phases of a 1.2:1 mismatch.

Table 1. Klystron Requirements

| Frequency | 350 MHz | 700 MHz |
|---|---|---|
| Output Power | 1.2 MW | 1.0 MW |
| Test Power | 1.3 MW | 1.1 MW |
| Gain | 40 dB Min. | 40 dB Min. |
| Beam Voltage | 95 kV Max. | 95 kV Max. |
| Beam Current | 20 A Max. | 20 A Max. |
| Efficiency | 65 % Min. | 65 % Min. |
| Bandwidth 1 dB | +/- .35 MHz | +/- .7 MHz |
| Collector Dissipation | Full Beam Power | Full Beam Power |
| VSWR Tolerance | 1.2:1 Max. Any Phase | 1.2:1 Max. Any Phase |
| Mod-Anode | Yes | Yes |

The CPI 700 MHz Klystron has demonstrated that the klystron physics design satisfies our performance and operating requirements; however, the entire klystron package has not yet satisfied all electrical and mechanical requirements and is still in process.

## 2 KLYSTRON TEST RESULTS

### *2.1 350 MHz Klystron*

The 350 MHz klystron is shown in Fig. 1. The klystron is a six cavity klystron with a second harmonic cavity. As is seen in the picture, the klystron has a horizontal orientation. Although there is some supplemental lead shielding around the collector, the klystron is operated in a lead garage, and the supplemental shielding allows for a lead thickness of 0.125” to be suitable for suppressing x-ray radiation. The klystron output window is a coaxial window. The coaxial section containing the window can be seen in the picture protruding from the top of the tube. A t-bar is used to transition from the coaxial line to waveguide. The klystron requires three cooling circuits. Up to 400 gpm is provided to the collector, and two body circuits require up to 10 gpm. The RF window on the klystron is air cooled. A small oil tank is included with the klystron for high voltage insulation and is visible in the photos.

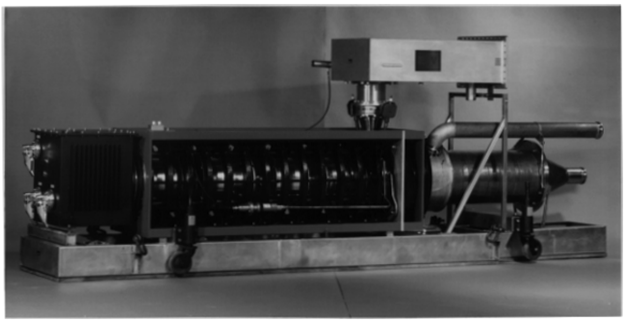

Figure 1: EEV 350 MHz Klystron.

Table 2 contains the recorded operating parameters and characteristics of one of the 350 MHz klystrons. In addition to this data the tube undergoes a 24 hour run with only 2 tube-caused trips allowed at 110 % of rated power and also must demonstrate the full 1847 kW of beam power into the collector for one hour.

Table 2. EEV 350 MHz Recorded Klystron Data

| | |
|---|---|
| Heater Voltage | 22.8 V |
| Heater Current | 22.8 A |
| Main Focus Current | 6.4 A |
| Main Focus Voltage | 227 V |
| Output focus Current | 8.2 A |
| Output focus Voltage | 123 V |
| Beam Voltage | 94.1 kV |
| Beam Current | 19.63 A |
| Mod Anode Voltage | 51.8 kV |
| Mod Anode Current | 0.4 mA |
| Drive Power | 93 W |
| Output Power | 1210 kW |
| Efficiency | 65.5 % |
| Body Power | 3.5 kW |
| Output Cavity Power | 3.3 kW |

## *2.2 700 MHz Klystron*

The CPI version of the 700 MHz klystron is illustrated in Fig. 2. At the level of detail allowed by the picture the differences between this klystron and the EEV klystrons is not easily distinguishable, so in the interest of space conservation only the CPI photo is included. The EEV klystrons do have a slightly longer output coax prior to the T-bar transition to insure mode purity in the window ceramic.

The physical description of the 700 MHz tube is identical to the description provided above for the 350 MHz klystron and is not repeated. The 700 MHz klystrons also is subject to the 24 hour test at 110% of rated power.

The recorded test data from the CPI 700 MHz klystron, the standard EEV 700 MHz klystron, and the high efficiency EEV 700 MHz klystron are included in tables 3 and 4. Table 4 includes results for both the EEV standard klystron and the high efficiency klystron.

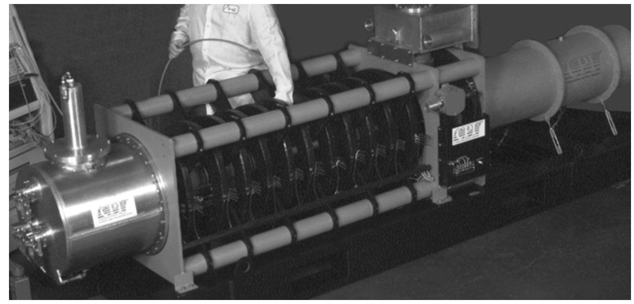

Figure 2: CPI 700 MHz Klystron

Table 3. CPI 700 MHz Klystron Recorded Data

| | |
|---|---|
| Heater Voltage | 21.2 V |
| Heater Current | 19 A |
| Main Focus Current | 17 A |
| Main Focus Voltage | < 120 V |
| Output focus Current | 22A |
| Output focus Voltage | < 120 V |
| Beam Voltage | 92 kV |
| Beam Current | 16.6 A |
| Mod Anode Voltage | 78 kV |
| Mod Anode Current | 1.4 mA |
| Drive Power | 12.3 W |
| Output Power | 1000 kW |
| Efficiency | 65.5 % |
| Body Power | 3.7 kW |
| Output Cavity Power | 8.6 kW |

Table 5 illustrates the efficiency of the EEV high-efficiency klystron as it drives a mismatch of nominally 1.2:1 at variable phase. The table shows that for some phases of the mismatch very high efficiencies were achieved. However, by noting the mod-anode current and body power for the high-efficiency phases of the mismatch, it can be concluded that some of the electrons are being stopped and turned around and are not only hitting the tube body but also traveling back down the beam pipe and impacting on the mod anode, increasing the mod anode current. These returned electron can lead to sideband oscillations [3,4]. During early testing an efficiency approaching 70 % was achieved into a matched load but was unstable at some phases of a 1.2:1 VSWR. The guide wavelength in WR1500 waveguide is 52 cm so each 4 cm change in position of the mismatch in Table 5 represents a phase change of 28 degrees.

Figs. 3 and 4 illustrate the power transfer curve of the CPI 700 MHz klystron and the klystron's measured frequency response. These plots are useful to the designers of the feedback circuitry to control the accelerating-cavity amplitude and phase by modulation of the klystron drive signal.

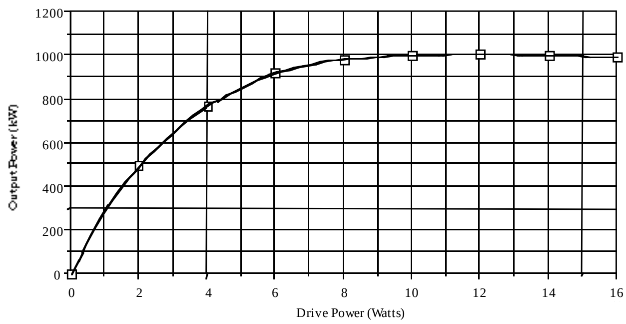


Figure 3: CPI klystron power transfer curve.

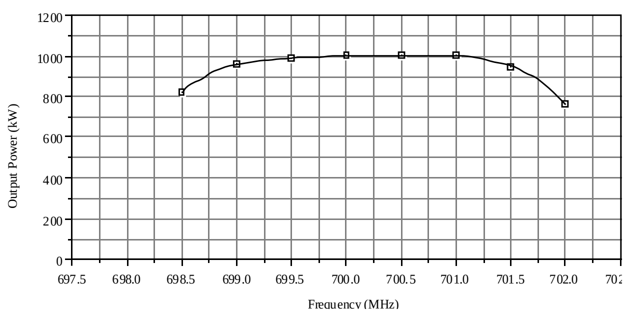


Figure 4: CPI klystron frequency response.

## 3 CONCLUSIONS

Successful klystron developments have been completed for the APT project. The test data show the klystrons meet or exceed all requirements. Commencing in October we will begin to gather long term reliability data on these klystrons with the LEDA accelerator.

## 4 REFERENCES


[1] D. Bowler et al., "Design of a High Efficiency 1 MW CE Klystron at 700 MHz For Low Energy Demonstrator Accelerator," EPAC 98.

[2] D. Rees et al., "Operation and Test Results of the 350-MHz LEDA RF System," This conf.

[3] M. Yoshida et al., "Instabilities due to multipactoring, modulation and anode emission found for TRISTAN high power CW klystrons," 6th Symposium on Accelerator Science and Technology, Tokyo 1987.

[4] H. Frischolz, "The LEP Main Ring High Power RF System," PAC 89.


Table 4. EEV 700 MHz Standard Klystron Recorded Data

| | Standard Effic. | High Effic. |
|---|---|---|
| Heater Voltage | 22.8 V | 22.8 V |
| Heater Current | 23.8 A | 24.3 A |
| Main Focus Current | 12.8 A | 12.3 A |
| Main Focus Voltage | 141 V | 163 V |
| Output focus Current | 12.8 A | 12.8 A |
| Output focus Voltage | 91 V | 106 V |
| Beam Voltage | 95.1 kV | 95.1 kV |
| Beam Current | 16.28 A | 15.57 A |
| Mod Anode Voltage | 51.52 kV | 46.67 kV |
| Mod Anode Current | 0.15 mA | 0.3 mA |
| Drive Power | 75 W | 96 W |
| Output Power | 1013 kW | 1007 kW |
| Efficiency | 65.4 % | 68 % |
| Body Power | 4.0 kW | 3.9 kW |
| Output Cavity Power | 6.2 kW | 6.9 kW |

Table 5. EEV High-Efficiency Klystron Data as a Function of VSWR

| POS (cm) | Ima (mA) | Effic. (%) | Body 1 Power (kW) | Output Cavity Power (kW) |
|---|---|---|---|---|
| 0 | .2 | 61.1 | 4.2 | 6.0 |
| 4 | .3 | 60.6 | 3.8 | 5.8 |
| 8 | .4 | 65.2 | 4.4 | 7.0 |
| 12 | 1.0 | 70.8 | 5.6 | 6.6 |
| 16 | .9 | 74.2 | 5.8 | 8.7 |
| 20 | .3 | 72.8 | 4.4 | 6.6 |
| 24 | .2 | 65.7 | 4.1 | 5.9 |