DESIGN OF 250-MW CW RF SYSTEM FOR APT*

D. Rees, Los Alamos National Laboratory, PO Box 1663, Los Alamos, NM 87545

Abstract

The design for the RF systems for the APT (Accelerator Production of Tritium) proton linac will be presented. The linac produces a continuous beam power of 130 MW at 1300 MeV with the installed capability to produce up to a 170 MW beam at 1700 MeV. The linac is comprised of a 350 MHz RFQ to 7 MeV followed in sequence by a 700 MHz coupled-cavity drift tube linac, coupled-cavity linac, and superconducting (SC) linac to 1700 MeV. At the 1700 MeV, 100 mA level the linac requires 213 MW of continuous-wave (CW) RF power. This power will be supplied by klystrons with a nominal output power of 1.0 MW. 237 klystrons are required with all but three of these klystrons operating at 700 MHz. The klystron count includes redundancy provisions that will be described which allow the RF systems to meet an operational availability in excess of 95 percent. The approach to achieve this redundancy will be presented for both the normal conducting (NC) and SC accelerators. Because of the large amount of CW RF power required for the APT linac, efficiency is very important to minimize operating cost. Operation and the RF system design, including in-progress advanced technology developments which improve efficiency, will be discussed. RF system performance will also be predicted. Because of the simultaneous pressures to increase RF system reliability, reduce tunnel envelope, and minimize RF system cost, the design of the RF vacuum windows has become an important issue. The power from a klystron will be divided into four equal parts to minimize the stress on the RF vacuum windows. Even with this reduction, the RF power level at the window is at the upper boundary of the power levels employed at other CW accelerator facilities. The design of a 350 MHz, coaxial vacuum window will be presented as well as test results and high power conditioning profiles. The transmission of 950 kW, CW, power through this window has been demonstrated with only minimal high power conditioning.

1 ACCELERATOR DESIGN

The APT Linac design is based on copper, water-cooled, NC, accelerating cavities that accelerate the beam to an energy of 217 MeV and inject it into SC accelerating cavities. Final output energy can be varied from 1300 MeV to 1700 MeV. This hybrid Linac architecture is illustrated in Figure 1. During operation, a 75-keV injector housing a microwave-driven ion source generates a continuous proton beam at 110 mA nominal current. From this input, a 350-MHz, 8-m radio-frequency quadrupole (RFQ) produces a CW 100-mA beam at 6.7 MeV. The RFQ output beam is matched into a 700-MHz coupled-cavity drift-tube-Linac (CCDTL) that accelerates it to 100 MeV. Acceleration to an energy of 217 MeV takes place in a coupled cavity Linac (CCL) that uses 700-MHz side-coupled cavities.

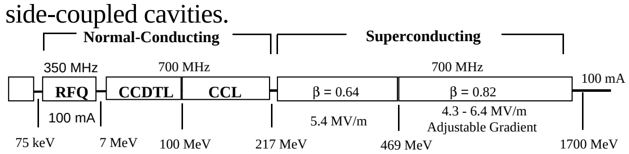

Figure 1. APT Accelerator Schematic.

The SC Linac is composed of cryomodules that contain 5-cell 700-MHz accelerating cavities. There are two kinds of cryomodules, each designed for efficient acceleration in a different proton energy range. Cavities in the medium-energy section, from 217 MeV to 469 MeV, are optimized at $\beta = 0.64$, and in the high-energy section at $\beta = 0.82$.

The RF system requirements by section are presented below in Table 1. The justification for the generator selection and power capacity is presented in subsequent sections. The table serves to illustrate the scope of the APT RF system. 237 1-MW capacity klystrons are required for the desired level of Tritium production.

Structure	Freq. (MHz)	No. of RF Systems	Total RF Required	Klystron Size
RFQ	350	3	2.3 MW	1.2 MW
CCDTL	700	21	16.6 MW	1 MW
CCL	700	27	19.7 MW	1 MW
SC ß=0.64	700	30	29.1 MW	1 MW
SC ß=0.82	700	156	151 MW	1 MW
Totals		237	219 MW	

Table 1. RF system requirements by accelerating structure.

2 RF SYSTEM DESIGN

The magnitude of the RF system requirements result in the RF system being the one of the predominant cost factors for the APT facility. The RF system DC-to-RF conversion efficiency has a primary influence on the operating costs for the APT facility. The size of the APT RF system makes component failures a statistical certainty. The RF system must be designed to minimize the number of single point of failure components to

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insure high availability. An additional requirement imposed by the end user of the facility is that the RF system be based on existing, proven technology or low risk extensions of existing technology.

2.1 RF System Cost and Generator Size

The RF generator size has the single biggest influence on the RF system cost. The RF system cost increases by a factor equal to approximately the square root of the ratio of a 1 MW generator divided by the power capacity of the reduced generator size. This relationship was generated from point designs of RF system architectures based around different generator sizes spanning 125 kW to 1 MW. The scaling relationship is qualitatively justified by considering how the costs of various RF system components scale with generator size. High voltage power supplies, power conditioning, crowbars, resonance control and RF window costs are weak functions of generator size. Waveguide, water load, fast RF controls, RF reference, computer interface, circulator, safety interlocks, klystron support electronics, and RF generator costs are strong functions of RF generator size.

Based on this data, previous experience at CERN and KEK, and conversations with klystron vendors, 1.2 MW was selected as the generator size for the 350 MHz klystrons and 1.0 MW was selected as the generator size for the 700 MHz klystrons. Based experience at other CW accelerator facilities, klystrons with modulating anodes have been selected as the baseline approach. The operating parameters of these 350 MHz and 700 MHz klystrons are similar. Both klystrons have a saturated efficiency of 65 %, a maximum beam voltage of 95 kV, a gain of 40 dB, a modulating anode, and can take the full beam power in the collector and operate into a 1.2:1 VSWR at any phase. The 350 MHz tube has a maximum output power capacity of 1.2 MW and 1 dB bandwidth of .1 MHz while the 700 MHz klystron has a maximum power capacity of 1.0 MW and a 1 dB bandwidth of 1.4 MHz.

These klystrons have one additional requirement that differs from the historical requirement for this class of CW klystrons. The APT klystron collectors are required to dissipate the full klystron beam power for a duration in excess of one hour. This requirement is driven by the demand load that the APT RF system places on the local utility. The APT RF system AC demand is in excess of 10% of the generating capacity of the local utility. At this fraction of the total system-wide AC demand, the turn-on and turn-off transients and resulting imbalance of supply and demand are not manageable without expensive infrastructure changes and energy storage additions to the local grid. The response rate of the local grid would also significantly impact recovery times from short duration faults (faults lasting 30 minutes or less). Consequently, if the full RF power is not required from the klystrons for intervals of up to one hour, the excess energy will be dissipated in the klystron collector. The 350 MHz klystron design has demonstrated during acceptance tests the ability of the collector to take the full beam power for more than two hours. Two of the 350 MHz klystrons have been tested and both have achieved all performance requirements. Two 700 MHz klystrons, one each from two vendors, are scheduled for test in June and July of 1997. The 350 MHz klystrons are being supplied by English Electric Valve (EEV) and the 700 MHz klystrons are being supplied by EEV and Communication and Power Industries (CPI, formerly Varian Associates).

2.2 Conversion Efficiency

The required DC-to-RF conversion efficiency of the APT klystrons is 65%. This efficiency has been demonstrated in acceptance test for the 350 MHz klystron and has been predicted by large signal analysis for the 700 MHz klystron. However, klystron physics dictate that the high efficiency is only realized at the saturated output-power level. At any level below saturation, the efficiency is decreased proportionally to the reduced output power. In accelerator service, we must provide high bandwidth control of the accelerating-cavity-field amplitude and phase by modulation of the RF drive to the klystron. This forces us to operate below the saturated output level to allow margin for control. Control system modeling based on the expected cavity field perturbations indicates a 10% margin should be sufficient to provide this control. This results in a nominal operational efficiency of 58.5% for the klystrons.

The high voltage DC power supply is required to provide an AC-to-DC conversion efficiency of 95 %. The design goal for the APT power supply is 97 %.

The other source of inefficiency in the RF system is the insertion and return loss from the RF waveguide and waveguide components, including the RF window and coupler. The allocation for this loss is 7.5%. Combining these efficiency allocations the conversion efficiency of AC power from the grid to RF power to the beam and cavity is 51.4 %. This efficiency is also slightly reduced by the AC power required for the klystron support electronics.

2.3 Availability

The RF system is required to meet an 11 month availability of 95 %. Because of the size of the RF system and the number of RF systems required, it is impossible to achieve the availability requirement without installed redundancy. We have chosen to implement redundancy at the RF system level rather than designing redundancy into the RF component level to minimize cost. The NC and SC sections of the accelerator utilize different approaches to provide the redundancy. In the SC, higher-energy portion of the Linac, it is possible to detune cavities, disable the associated RF system, and coast the beam through the detuned cavity. Five percent spare cavities and RF stations are installed on the SC Linac. If a single cavity or a klystron that powers several cavities fails, the beam phase beyond the failure point will be different than what would have been otherwise provided and, unless corrected, would generally result in poor acceleration efficiency and poor longitudinal focusing in the cavities downstream of the failure. Such an uncorrected situation could also ultimately lead to radial loss of beam. However, rephasing the linac beyond the point of failure is a simple operation where the RF phase in the SC cavities is shifted by calculable amounts, setting the new injection phases to the correct values.

For NC accelerating structure the RF system is arranged into what we refer to as supermodules. The supermodule concept uses the accelerating cavity as the power combiner where, if n klystrons are required to meet the RF requirements of the accelerating cavity, then n+1 klystrons are connected to the cavity, providing a readily available spare. During normal operation, the n+1 klystrons are operated at an output power reduced by the fraction of n/(n+1). This operating scenario is recommended by tube vendors to increase the operational life of the klystrons. If a failure disables one of the n+1 klystrons or associated klystron electronics, then the failed RF station is removed from the accelerating structure by a waveguide switch positioned to show the accelerating cavity an effective short circuit at the coupling point. The output power of the remaining klystrons is increased, and the supermodule still meets all operational requirements.

The supermodule RF architecture is illustrated in Figure 2. The figure shows a supermodule where seven klystrons are connected to a CCDTL accelerating structure while only six of the klystrons are needed to meet the operational requirements. The klystrons are protected from high VSWR with Y-junction circulators. The power from each klystron is split before being delivered to the accelerating structure to minimize RF window stress and a waveguide switch is provided to take any of the seven RF systems off line in the event of a failure in one of the stations. The low level RF controls are not shown in the figure.

There are two primary cost increases associated with the improved reliability of the supermodule concept. The most obvious increase is capital costs of the spare RF stations. There is also an impact on operating cost. When n+1 klystrons are operated at an output power reduced by the fraction of n/(n+1) an operational efficiency penalty must be paid.

The supermodule size is limited to a maximum of 200 accelerating cells to maintain stability within the levels required by the beam dynamics. Since the "real estate" gradient is fixed, where the cell sizes vary with energy, the number of klystrons per supermodule can vary with beam energy. There is also a practical upper limit on the supermodule size dictated by differential thermal expansion and alignment issues. Therefore some variation in the number of klystrons per supermodule exists depending on energy. The range spans four to seven klystrons per supermodule.

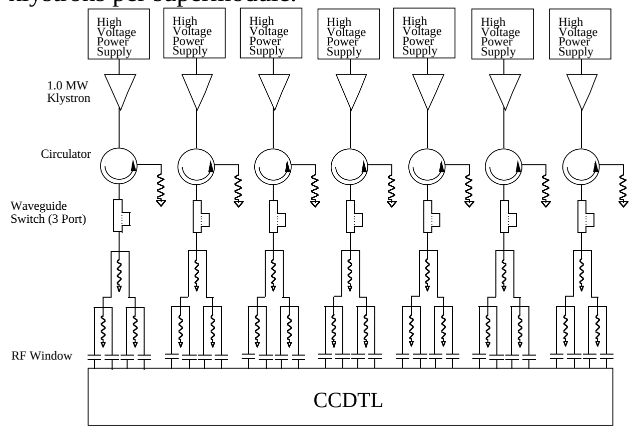

Figure 2. RF Supermodule

The RF windows pose a challenging reliability problem. In order to maximize window reliability a nominal power level of 210 kW has been selected for the CCDTL, CCL, and the high beta SC cavities, 140 kW for the medium beta SC cavities, and 250 kW for the RFQ. These power levels are marginally higher than the experience base at other high average power accelerators world wide. To complicate matters, APT requires over 1000 RF couplers. Even if the coupler windows have a very long life, the large number of windows results in a failure rate that is unacceptably high. To address this potential source of unavailability, we are implementing dual windows on the SC couplers that will allow the accelerator to continue to operate in the event of a window failure. With the dual SC windows the APT RF system can meet the 95 % availability requirement.

3 ADVANCED DEVELOPMENT

Although one of the APT RF system design requirements is that the RF technology be based on existing technology it is easy to justify advanced development activities which increase efficiency (reduce operating costs), decrease initial constructions costs, or insure high availability. Three such developments are discussed below.

3.1 Advanced RF Generator Development

Since the RF power required for APT is large and the AC power required from the grid to produce the RF power is the single largest component of the APT AC power demand, even small improvements in efficiency can have a significant effect on the operating cost for the APT accelerator. A reasonable estimate based on the operational availability and the cost of electricity suggests that the operating costs reduce by approximately $1 million per year for each percentage point increase in RF generator DC-to-RF operating efficiency.

Efficiency improvements can be realized in two ways: (1) by increasing saturated generator efficiency, and (2) by changing the saturation to eliminate the efficiency penalty that must be paid with klystron technology to exercise accelerator field control. The inductive output tube (IOT) family of generators has demonstrated a soft saturation characteristic with a relatively constant efficiency over the upper 20% of output power. Demonstrated saturated efficiencies are on the order of 70 - 75%. Unfortunately, the current state of art in CW IOT generators is 250 kW at 267 MHz. This device also has a very low perveance and correspondingly high beam voltage, a poor reliability record, and low gain. Los Alamos is funding CPI to develop a high order mode (HOM) IOT. The HOM-IOT is shown in Figure 3.

The HOM-IOT is an annular beam device. The annular beam is formed by a number of segmented cathodes. The portions of the segmented cathode structure which do not contain active material allows for the inclusion of radial fins to support the interior structures of the device and to break up the propagation of any coaxial mode along the device longitudinal axis. The annular beam allows for a very low per unit perveance while achieving a very high device perveance and low operating voltage (-45 kV). The predicted gain of the device is moderately higher than the gain achieved in conventional IOTs (24 dB vs. 21 dB) and the predicted efficiency is comparable to the demonstrated efficiency in previous IOTs (73%).

The operating parameters of the IOT as compared to the 700 MHz klystron under development for APT are shown in Table 2. From the table it is observed that the saturated and operational efficiency as well as the reduced beam voltage are the primary advantages while the reduced gain is the primary disadvantage. However, because of the substantial amount of RF power required for APT, the operational savings resulting from the improved efficiency dominate the economic tradeoff between a klystron and HOM-IOT with a high-power driver. The savings and reliability improvements from a lower voltage power supply are also substantial.

3.2 Stacked Inverter Power Supply

The baseline design for the APT accelerator is one, SCR regulated, 12 pulse power supply with crowbar per klystron. Operating several klystrons from a single supply has been considered and rejected because of the impact on operational flexibility and reliability. This baseline technology is currently under test at Maxwell Laboratories. An alternate technology is also under development at Continental Electronics. This technology utilizes series connected solid state modules which are switched on to provide the high voltage DC. The switching is accomplished with Insulated Gate Bipolar Transistors (IGBT). A low pass filter follows the series connected modules which remove the switching signals and allows the DC to pass to the RF amplifier. A schematic of the IGBT supply is shown in Figure 4. The topology in the figure results in a 24 pulse supply with minimal stored energy in the output low pass filter. This combined with the IGBT switching speed allows for the elimination of the crowbar while limiting energy delivered to a klystron arc to an acceptable value.

The solid state module control circuitry allows for additional modules to be included in the design, and failed

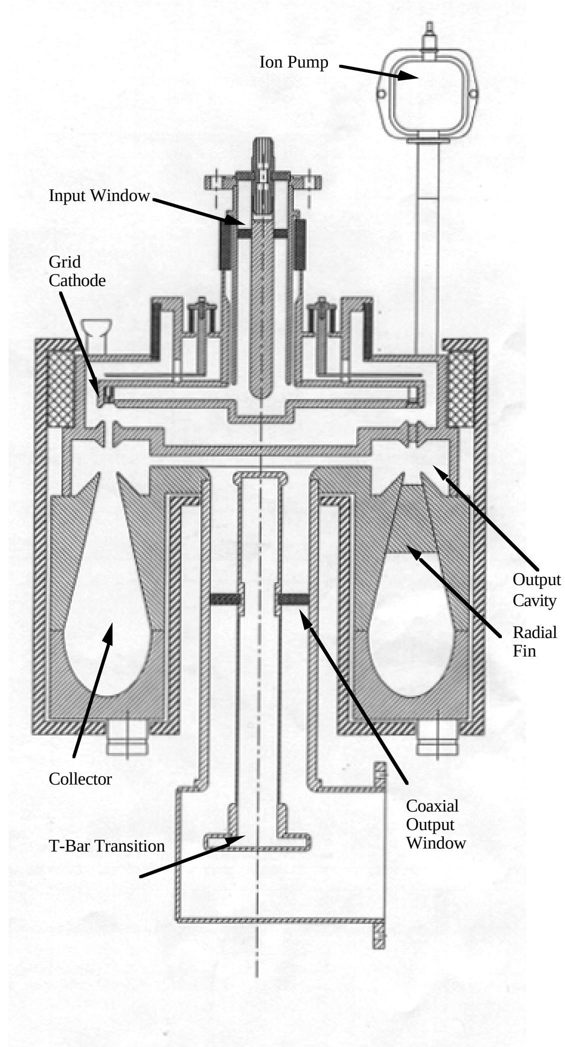

Figure 3. Cross-sectional view of HOM-IOT.

	Klystron	IOT
Efficiency at Saturation	> 65 %	> 73 %
Efficiency at 90 % of Saturation	> 58.5 %	> 73 %
Beam Voltage	95 kV	45 kV
Beam Current	17 A	31 A
Gain	40 dB	24 dB
Filament Power	< 900 W	< 4000 W
Magnet Power	< 14.4 kW	< 10 kW
Collector	Full Beam Power	40 % Full Beam Power
VSWR At Any Phase	1.2:1	1.2:1

Table 2. Comparison of 700 MHz HOM-IOT and klystron requirements.

modules can be switched off line. This feature provides for graceful degradation of the power supply. In addition, since most modules are either fully utilized or off for any voltage setting, the efficiency of the supply is very high (97 %) over a variable voltage range. Table 5 compares the baseline 12 pulse SCR power supply with the IGBT regulated power supply. Requirements not listed in the table are comparable for both power supply approaches. . Details of the solid state module design can be found in Reference [1].

3.3 RF Vacuum Windows

The APT design is based around splitting the power from individual klystron 4 or 6 ways resulting in a required window power capacity spanning 140 to 250 kW. Since this power capacity is in excess of the conventional experience base at other CW accelerators of comparable frequency and extensive effort is under way to insure window reliability and design robustness. Our baseline approach is to utilize coaxial windows as illustrated in Figure 5. The window in Figure 5 has been tested to 950 kW CW on a test stand with two windows in a back to back configuration separated by a vacuum region. Only 20 hours of conditioning were required to achieve this 950 kW of transmission. The details of this testing are described in Reference [2].

4 CONCLUSIONS

An RF system design for the APT accelerator has been presented. The design basis was described. All major components of the baseline design are currently in test or have completed acceptance testing and the prototype RF system for APT will be operational at Los Alamos at the end of fiscal year 1997. Advanced developments for RF generators and power supplies were presented and discussed. These components will be considered for inclusion in the baseline once they demonstrate their capabilities and undergo long term testing on the Low Energy Demonstration Accelerator at Los Alamos.

5 ACKNOWLEDGMENTS

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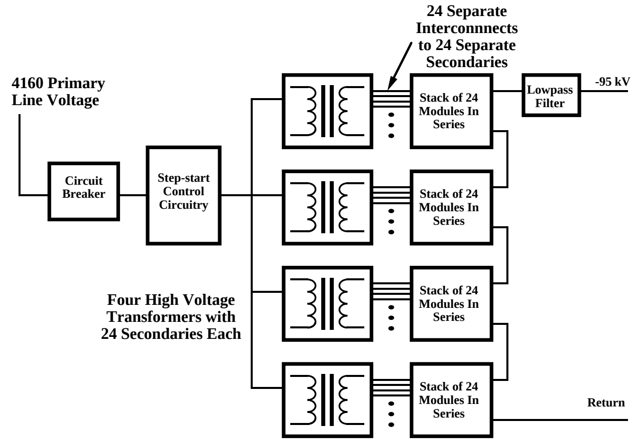

Figure 4. Solid state power supply topology.

	SCR Regulated Power Supply	IGBT Regulated Power Supply
Efficiency	97 %	95 %
Power Factor	.99	.93
Crowbar Required	Yes	No
Footprint	Small	Large
HV Insulation	Mostly Oil	Mostly Air
Normalized Cost	1.0	.5

Table 4. Comparison of SCR regulated power supply and IGBT regulated power supply

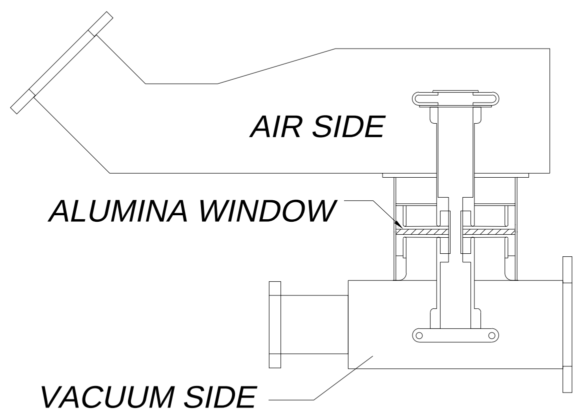

Figure 5. 350 MHz RF coaxial window.

REFERENCES

[1] J. Bradley et al, 'An Overview of the Low Energy Demonstration Accelerator (LEDA) Project RF Systems,' these proceedings.

[2] K. Cummings et al, 'Experimental Evaluation of 350 MHz RF Accelerator Windows for the Low Energy Demonstration Accelerator,' these proceedings.