RF SYSTEM DEVELOPMENTS FOR CW AND/OR LONG PULSE LINACS *

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Abstract

High Power Proton Linacs are under development or proposed for development at Los Alamos and elsewhere. By current standards these linacs all require very large amounts of RF power. The Accelerator for Production of Tritium (APT) is a CW accelerator with an output current and energy of 100 mA and 1700 MeV, respectively. The Spallation Neutron Source (SNS), in its ultimate configuration, is a pulsed accelerator with an average output power of 4 MW of beam. Other accelerators such as those that address transmutation and upgrades to LANSCE have similar requirements. For these high average power applications, the RF systems represent approximately half of the total cost of the linac and are thus key elements in the design and configuration of the accelerator. Los Alamos is fortunate to be actively working on both APT and SNS. For these programs we are pursuing a number of component developments which are aimed at one or more of the key issues for large RF systems: technical performance, capital cost, reliability, and operating efficiency. This paper briefly describes some of the linac applications and then provides updates on the key RF developments being pursued.

1 APPLICATIONS OF HIGH POWER PROTON LINACS

APT is by far the highest average power accelerator ever proposed. A table showing pertinent parameters for APT is shown below. 244 klystrons are required for the currently planned 1700 MeV version [1]. A reduced power variation is under consideration due to changing tritium requirements, but even that design is higher in average power than any proposed accelerator. The reduced power version has a final energy of 1300 MeV and requires 160 CW klystrons. In both versions of the linac, a klystron is required about every 4.5 m, so the average power per unit length is very high.

Table 1: Pertinent Parameters of APT Linac

Proton Energy	1700 MeV
Beam Current	100 mA
Beam Power	170 MW
AC Power (for RF)	386 MW
Peak Coupler Power	210 kW
Klystrons (1 MW)	243
Linac Length	1104 m

* Work supported by the US Department of Energy

The RFQ for APT operates at 350 MHz and requires 3 klystrons [2]. The remainder of the accelerator operates at 700 MHz, so the majority of the klystrons are at 700 MHz. Each RF system for APT is generally laid out as shown in Fig. 1. [3]. Each klystron is split 4 ways to drive 4 ports on the accelerator. This splitting arrangement was deemed necessary to ensure reliable operation of the window/coupler assemblies. It was felt that reliable operation could be achieved with up to 250 kW of CW forward power through each window. This allows for situations with high-reflected power in which the RF fields in the window might double.

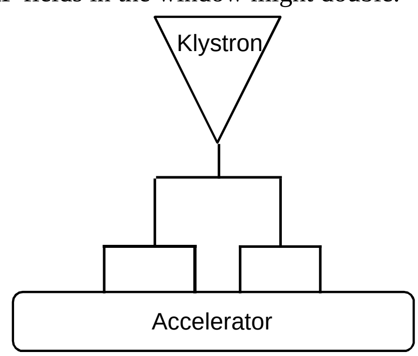

Figure 1: Typical RF System Layout for APT

The Spallation Neutron Source (SNS), in its ultimate configuration, will have an average output current and energy of 4 mA and 1000 MeV, respectively, providing 4 MW of average beam power. In its initial configuration the beam power is 1 MW. A table of the parameters for the 1 MW version is given below. It requires 59 klystrons with most at 805 MHz and 2.5 MW peak power. The remaining 3 are 1.25 MW peak at 402.5 MHz. At the full 4 MW of beam power, the number of klystrons required is 83.

Table 2: Pertinent Parameters of SNS Linac

Proton Energy	1000 MeV
Beam Current	27.7 mA, peak 1.04 mA, average
Beam Power	1.04 MW, average
Pulse Width	1.0 ms
Repetition Rate	60 Hz
Klystrons 805 MHz, 2.5 MW peak 402.5 MHz, 1.25 MW peak	 56 3
Linac Length	486 m

Other accelerators that address transmutation and upgrades to LANSCE have similar requirements. For transmutation, one version uses multiple CW accelerators, each with a current of 40-mA and output energy of 1 GeV. A table of pertinent parameters for an ATW linac is given below. A significant portion of this linac could be superconducting (from 21 MeV to 1 GeV), but it would still require 56 CW klystrons of 1 MW output power. To achieve complete burn of the nuclear waste, a total of 20 of these machines would be needed. They would be built over about a 25-year period and each would need to operate for 40 years.

Table 3: Pertinent Parameters of ATW Linac

Proton Energy	1000 MeV
Beam Current	40 mA
Beam Power	40 MW
AC Power (for RF)	95 MW
Peak Coupler Power	200 kW
Klystrons (1 MW)	56
Linac Length	355 m

For all of these high average power applications, the RF systems are very key elements of the overall accelerator because they represent approximately half of the total cost of the linac.

2 DEVELOPMENT THRUST AREAS

2.1 System Design Developments

Development is taking place both in system design and in component design to address one or more of the key items: capital cost, operating cost, availability, or technical performance. In terms of system design, APT is planning a supermodule scheme for the normal conducting linac portion (up to 211 MeV). Supermodules allow quick return-to-service in the event of a failure of a component in the RF system. A diagram of a supermodule is given in Fig. 2.

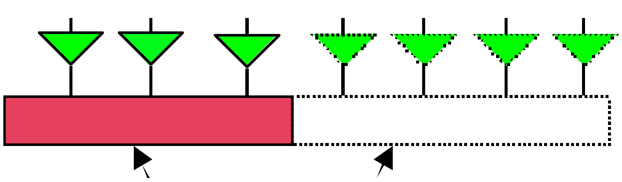

Figure 2: A Block Diagram of a supermodule showing the size variation. Each supermodule has one more klystron than is needed for full-current operation.

In analyzing the availability of the RF system with a large number of generators, we found that the failure and repairs would lead to excessive down time and insufficient production by the machine. The use of supermodules greatly improves the availability of the normal conducting portion of the accelerator. The supermodule is simply a long coupled structure, which requires multiple RF generators to achieve sufficient power. In configuring the RF system an 'extra' RF station is added such that any one RF system can fail, and in a very short time (5 to 10 minutes), the failed unit can be taken off line and operation resumes with the remaining stations. The supermodules vary in size from 3 klystrons (2 required) to 7 klystrons (6 required).

For the superconducting portion of the linac the availability is achieved by installing more modules than are needed to achieve the rated production. If a module fails, it is detuned so the beam will not drive the cavity, and the adjacent modules are adjusted in amplitude and phase to 'make up' the difference. Approximately 5% more cavities are installed than are needed. This adds complication for the control system, but the controls are being developed to handle these complications. An additional feature of the superconducting module is that one klystron drives more than one resonant structure (either 2 or 3) as shown in Fig.3.

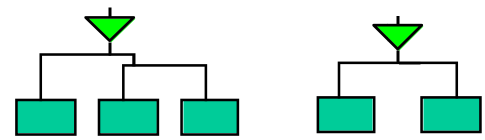

Figure 3: Block diagram of RF system for the superconducting cavities. Each klystron drives either 2 or 3 cavities. The medium and high ß refer to the two types of superconducting structures used in APT. [1]

The overall linac is thus a combination of normal conducting 'supermodules' and a large number of superconducting modules as shown in Table 4.

Table 4: Breakdown of RF Systems for the APT Linac

Accelerator System	Klystrons	Super-modules	Cavities/Klystron
RFQ (350 MHz)	3	1	
CCDTL	22	6	
CCL	29	5	
SC, ß=0.64	36		2 for 6 klystrons, 3 for 30 klystrons
SC, ß=0.82	154		2

2.2 Operating Efficiency

In a simple analysis of the overall efficiency of the accelerator, approximately 44% of the input AC power is converted to beam power. To reach this efficiency, many parts of the RF system are being pushed to their limits. The HVPS must deliver the DC power with 95% efficiency. The RF transport, which includes the circulator, splitters, the RF window, and any phase and amplitude variations in the various drives, must deliver to the cavity at least 94% of the power from the klystron. The beam loading percentage is addressed with the conversion to superconducting cavities for the majority of the accelerator. In the superconducting cavities, the beam loading is 100%. Only in the normal conducting section of the linac (up to 211 MeV) is RF power dissipated in the cavity walls.

Since there is a potential savings of $1M in operating cost for each percentage point improvement in operating efficiency, developments are taking place with the RF generators to develop higher efficiency generators, and generators which have less loss of efficiency when operating below their ‘saturated’ or ‘maximum’ output level.

2.3 Low Level RF Controls (LLRF)

We are working to develop LLRF controls for APT which only require 10% excess drive capability in the generator to deal with system disturbances (beam noise, power supply ripple, etc.) In addition we are incorporating DSP technology into the design for advanced capabilities and enhanced flexibility. [4] For SNS, since it is a pulsed application, we will require 20% or more excess drive capability. For both CW and pulsed systems, the LLRF must control fields in the cavities, provide the resonance control signals, provide the RF reference along the entire linac, provide the proper timing signals for the RF system, and provide the proper protection signals. There are, in addition, particular requirements related to the CW or pulsed application.

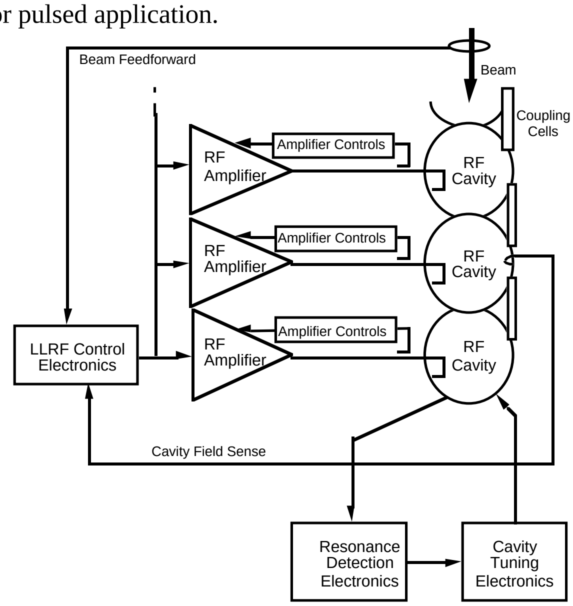

Figure 4: LLRF control diagram for a supermodule. The long coupled accelerator structure is driven by multiple klystrons and controlled with one feedback system. To equalize the klystrons, each one has a control loop.

The Low Level RF (LLRF) controls must be designed differently for the normal conducting and superconducting portions of the accelerator. Figures 4 and 5 show the block diagram for the LLRF controls for these two portions. In the normal conducting portion, the supermodule has multiple drives for one resonant cavity. The implication for the LLRF for this portion is that the separate RF systems must be properly phased and the drives must be ‘equalized’. In the superconducting system, one RF drive provides power to multiple cavities (2 or 3). The cavities must be maintained properly relative to each other.

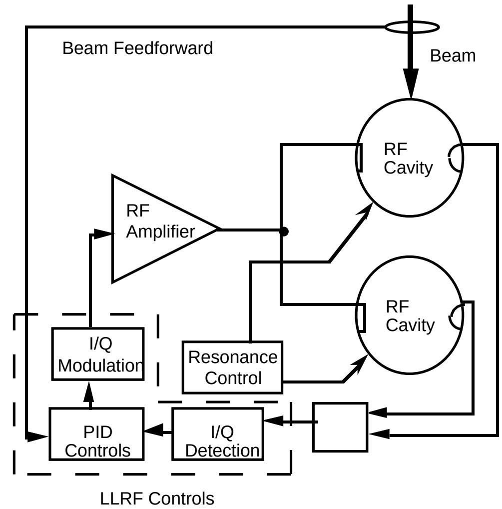

Figure 5: LLRF control diagram for a superconducting module. Each klystron drives more than one cavity.

2.4 Component Design Developments

First and foremost for APT is the 700 MHz RF generator. We are currently pursuing 2 main avenues with an additional pursuit occurring externally. One main avenue is the development of a conventional ‘superpower’ klystron at 700 MHz [5], which is derived from the CERN 352 MHz CW klystron. The other is a new type of tube, referred to as an HOM-IOT, which promises again the same output characteristics as the conventional klystron, but very high operating efficiency. The external pursuit is an advanced klystron, which is striving for equivalent output characteristics as the conventional klystron, but at higher efficiency.

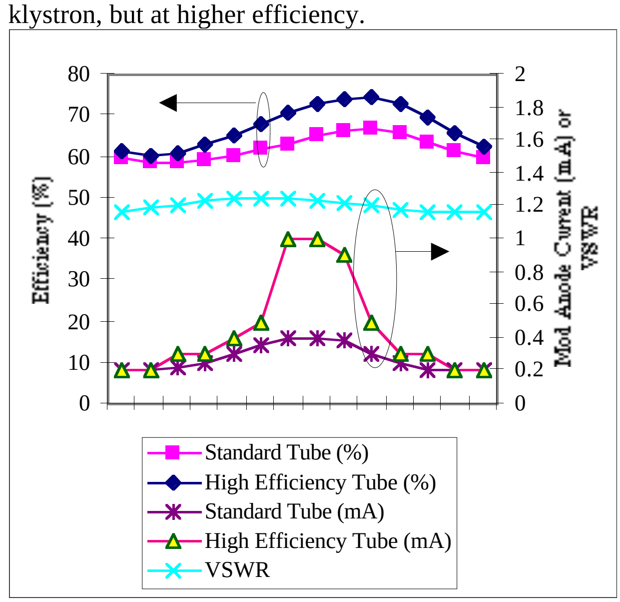

Figure 6: Test results of the standard and ‘advanced’ 700 MHz klystron from EEV. The advanced tube shows higher overall efficiency, but also shows more sensitivity to the 1.2:1 VSWR test.

The conventional 700 MHz klystron is being developed at CPI and at EEV. The tube has a modulating anode to optimize the efficiency. The tube is expected to operate at

65% efficiency when saturated and should average about 58% in actual operation (due to the need to operate below saturation to enable the feedback control system to work correctly). The advanced klystron is an internally funded venture by EEV. If it is successful, the saturated efficiency will be 70% or greater.

Test results of the standard and high efficiency klystron are shown in Fig. 6. The high efficiency klystron had very good results, although less efficiency than expected. In addition the high mod anode currents indicate that the tube has potential stability problems. Nevertheless, the results are encouraging and further development is taking place.

In both types of klystron, the tube must ‘sacrifice’ some of its efficiency to allow margin for control [6]. This sacrifice can be recovered with a depressed collector. This was considered but has not been pursued. A new type of tube proposed by CPI has an inherently good efficiency and could eliminate most of the operating penalty. The tube is referred to as a High-Order Mode Inductive-Output Tube (HOM-IOT) and is a density modulated device in which the amount of beam in the tube is determined by the input RF level. The expected efficiency of the HOM-IOT and a conventional klystron, as a function of output power, is shown in Fig. 7. As can be seen, even at half the rated output power, the efficiency is 60% or better compared to less than 50% for the klystron. A diagram of the tube is shown in Fig. 8.

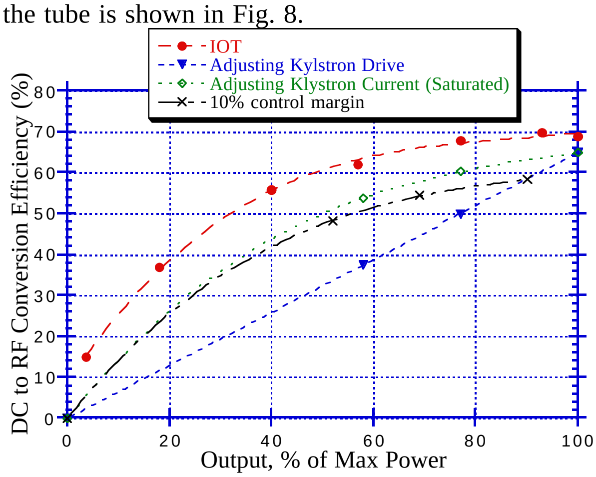

Figure 7: Comparison of the operating efficiency characteristics of the HOM-IOT and a standard klystron.

Other components being developed for APT include High Voltage Power Supplies (HVPS), high power circulators at 700 MHz, and RF windows. The HVPS is the single biggest cost item in the RF system, and there is room for improvement in the operating efficiency and reliability. There are several options being considered for the APT HVPS, from a conventional SCR-controlled supply to various versions based on IGBT technology. [7,8]

The RF windows represent the biggest impact to system reliability. The full APT has approximately 1000 windows, and their reliability is a key issue for APT. In addition there is a complication arising from the mixture

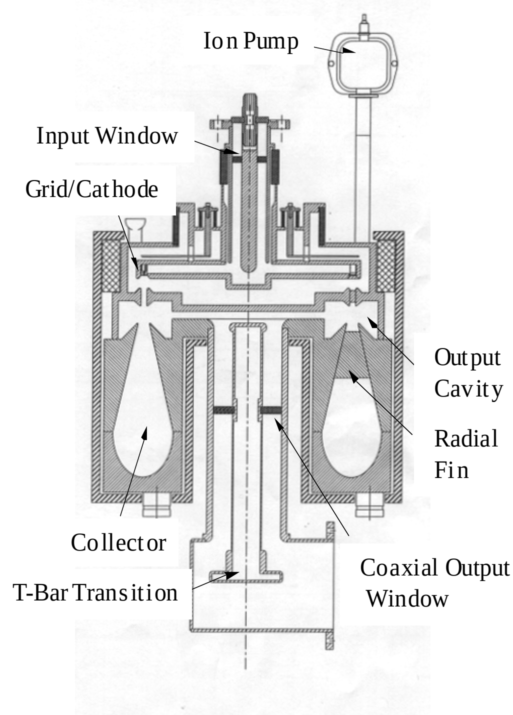

Figure 8: Outline drawing of the HOM-IOT. The tube is rotationally symmetric about the centerline, with the exception of the ion pump and output starting at the t-bar transition.

of normal conducting and superconducting cavities. The normal conducting windows are all based on klystron window technology. [9] For the superconducting cavities, the window design starts with standard klystron window design, but then must accommodate the tough problems of connecting to the power coupler for the superconducting cavity. A sketch of the basic window layout for superconducting cavities is shown in Fig. 9.

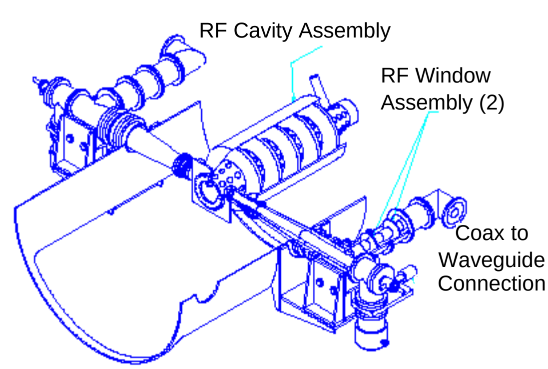

Figure 9: Layout drawing of the RF/vacuum window for a superconducting cavity. Dual windows are used for reliability considerations.

For SNS, a new klystron is being developed to provide 2.5 MW peak at 805 MHz and 7% duty factor with a pulse width of more than 1 ms. [10] Two development contracts have been placed for one klystron, one with CPI and one with Litton. In addition, options for the High Voltage modulator are being pursued which take advantage of developments in IGBT technology.

In all, IGBT technology is being considered in three different topologies. [7,8] Two different topologies are being pursued for APT. One is an extrapolation of a commercial unit designed for Voice of America installations (Fig. 10). The other is a new design, which has associated risks, but looks to be able to provide cost savings. In both cases, the IGBT technology promises to offer considerable technological advantages over a standard SCR-type of HV power supply. They should eliminate the need for a crowbar, offer significant cost savings, and provide graceful degradation and easy repair. In the case of the commercial unit, the supply utilizes 96 modules wired in series to produce the high voltage. Each module contains a full-wave, 3-phase rectifying bridge, which produces 1.1 kV DC across a small filter capacitor. The module circuitry and controls allows the power supply to continue to operate with approximately 5% failed modules without degradation in performance. The failed modules can then be repaired during a scheduled shutdown.

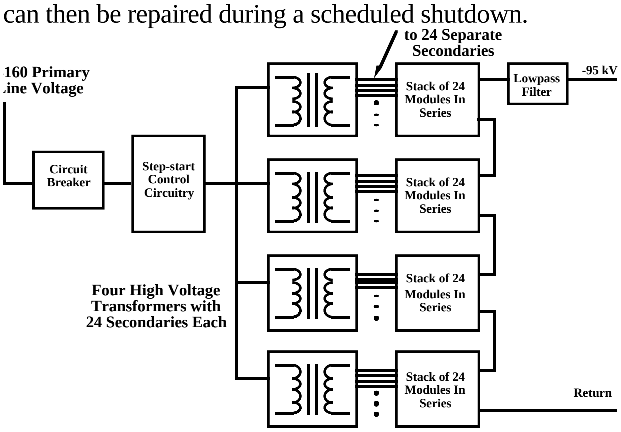

Figure 10: 95 kV advanced HVPS based on IGBT technology features graceful degradation and low stored energy (and thus does not require a crowbar).

The IGBT system being pursued for SNS combines the functions of the HVPS and the HV modulator needed for pulsing of the klystron into a single small unit. The crowbar is eliminated, and significant cost savings are expected.

3 PROJECTED TIMELINE

For the larger version of APT (1700 MeV), the need for the start of Tritium production is 2007. If the smaller version (1030 MeV) is opted for, the need date for start of production moves to 2011 because the existing Tritium can decay further before additional amounts are needed to replenish the decaying amounts. Assuming the smaller version of APT, tube production must begin around 2001 and be complete by 2009. SNS is currently expecting to be completed by 2005. Initial installation of the RF hardware must occur in 2000 and be completed by 2004. Finally, a reasonable assumption at this point is that the first ATW accelerator begins installation in 2007 and is completed by 2012.

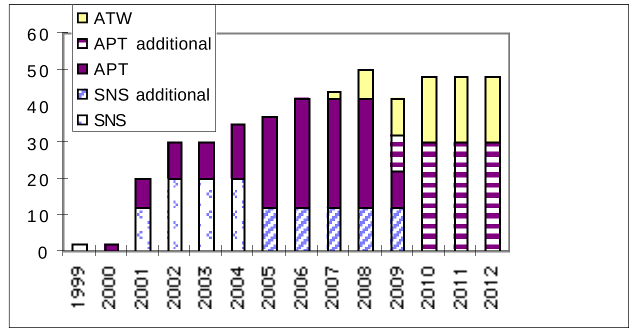

Figure 11: The tube requirements for the APT, SNS, and ATW for the next several years add up to a significant number of high power tubes.

Figure 11 shows all of the needs for these three programs compiled together based on the above dates and assumes that 20% of the initial 'need' for klystrons is produced for 5 years after completion in order to provide spares and replacements for infant failures. As can be seen by the table, the production total reaches a maximum of approximately 50 tubes for one year, and after about 2005 the production maintains a level of 40 or more tubes for over 7 years. There is a similar need for all of the associated RF hardware such as HV power supplies, waveguide, capacitors, circulators, etc.

4 REFERENCES

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