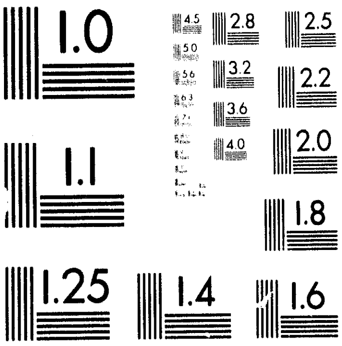
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RF System Considerations for Accelerator Production of Tritium and the Transmutation of Nuclear Waste*

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Abstract

RF driven proton accelerators for the transmutation of nuclear waste (ATW) or for the production of tritium (APT) require unprecedented amounts of CW RF power at UHF frequencies(1). For both systems, the baseline design is for 246 MW at 700 MHz and 8.5 MW at 350 MHz. The main technical challenges are how to design and build such a large system so that it has excellent reliability, high efficiency, and reasonable capital cost. The issues associated with the selection of the RF amplifier and the sizes of the power supplies are emphasized in this paper.

Introduction

For the accelerator production of tritium and the accelerator transmutation of nuclear waste projects, a 200-MW CW proton beam is used to produce neutrons at a target, and the neutrons then transmute material in desired ways. In the ATW project, a range of proton beams from 50 to 300 MW has been considered, but the 200 MW case is used here for illustrative purposes. The power in the proton beam in the design discussed here comes from the power grid, via dc power converters and a klystron RF system. The 254 MW RF system is almost larger by a factor of 10 than any yet built in terms of average power. The largest installations of CW RF power are in large electron-positron collider rings, the TRISTAN main ring at KEK in Japan and LEP at CERN in Geneva (2,3). TRISTAN currently has 30 MW installed at 508 MHz, and LEP plans to increase its RF capability at 352.6 MHz from 16 MW to 32 MW by 1995. Both of these rings use klystrons with from 1.0 to 1.3 MW CW output power.

Protons are almost 2000 times heavier than electrons, and thus low frequencies (below 1 GHz) are optimum for acceleration purposes. However, as the frequency decreases, the accelerator becomes larger and more expensive , because the accelerator, like a microwave tube, scales with wavelength. Each accelerating cavity is $\beta\lambda/2$ long, where β is the proton velocity normalized to the speed of light and λ is the RF wavelength. If the frequency is made too high, the cavities become too difficult to cool, and one must miniaturize the radial-focusing system, both of which increase the costs of the system. In practice, a broad frequency spectrum from about 200 to 400 MHz is considered optimum for the low energy (and hence low-β) section of the accelerator. In the design presented here, the low energy end of the accelerator operates at 350 MHz, which is near the highest end of the allowable range yet at a frequency where reliable 1-MW CW klystrons have been developed.

An outline drawing of the accelerator along with its physical scale is shown in Fig. 1. Two proton injectors are used, and each provides 100 mA CW, at 75 keV.

The beams are then accelerated at 350 MHz by a radio-frequency quadrupole (RFQ) accelerator and a drift tube linac (DTL) to 20 MeV. The two legs of the accelerator, which are out of phase by 180°, are combined in a funnel deflection system. The 200-mA combined beam is then accelerated by 700-MHz RF power in a bridge-coupled drift tube linac (BCDTL) and then by a coupled-cavity linac (CCL) to the final beam energy of 1000 MeV.

The details of the various accelerating structures are not of concern, but in the present design, they are normal-conducting, standing-wave structures. This latter property, which provides one technical challenge, means that each accelerator section behaves like a parallel LRC circuit: when it is empty, it reflects microwave power for time durations that are small compared to 1/Q.

The coupling between the accelerator tanks and the klystrons is made with an iris, which is designed so that there is a good match at the design beam current. When

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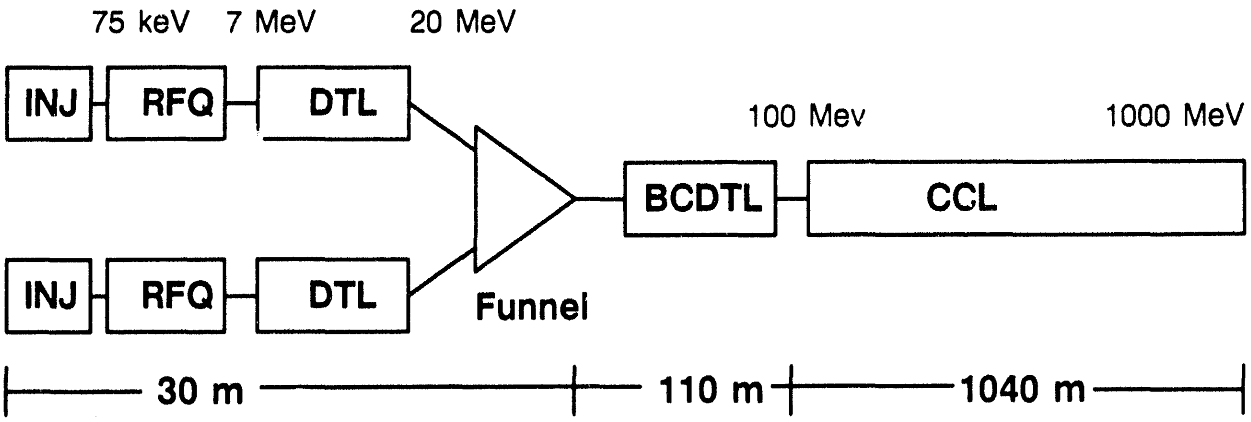

Fig. 1. Overall schematic of the APT/ATW accelerator.

the beam is accelerated, the proton beam is (to first order) a resistor in parallel with the first resistor, which is the measure of the Ohmic losses in the cavity.

A significant technical challenge is to maintain the cavity fields to a tolerance of less than ± 1% in amplitude and less than 1° in phase, with a bandwidth above 100 kHz. This control problem is solved with a pick-up loop in each cavity and a fast analog-feedback loop around each klystron. The necessity for accurate control of the fields forces the operating point of the klystrons to be less than the saturated output power, and a control margin of 10% is required, which significantly reduces the overall efficiency of the system. Another problem with proton accelerators is that the proton's β keeps changing with energy until the proton energy is well above the rest mass energy of 938 MeV. To overcome this, the entire accelerator structure has been designed to be synchronous with the local value of β. However, if a single RF amplifier fails, the synchronous property of the accelerator is lost for all higher energies. This makes the proton accelerator much less tolerant of a failed amplifier than an electron machine, and it is correspondingly more difficult to meet a given reliability goal.

Baseline Technical Choices

The major problems encountered in designing the RF system are the choice of RF amplifier, the size of the RF amplifier, the number of dc power supplies, optimization of dc-to-RF efficiency, and how to design the system for high availability and moderate cost. In the design work to date, these problems appear solvable.

The size of the amplifier was constrained by the fact that the accelerator designers would like to have hundreds of phase and amplitude controls along the machine to accurately control the proton beam position in phase space. Because the machine requires a minimum of 254 MW of RF power, plus a 10% allowance for control margin, plus a 5% margin for power supply ripple and waveguide system losses, a 1 to 1.25 MW saturated power for the amplifier was chosen. The list of amplifiers as used on the accelerator is shown in Table 1. The total number of amplifiers is 376, and the amplifier of choice is the klystron, since it is the only amplifier that is a viable, demonstrated performer at these frequencies and power levels. Although the klystron represents rather old technology, the existing 1-MW klystrons at CERN and at TRISTAN are demonstrating saturated efficiencies of 65 to 68%, along with mean time between failures (MTBFs) of at least 20,000 hours. While a larger amplifier would probably reduce system costs, a higher-powered klystron would operate at higher voltages, and have more power density in the beam and through the output window.

The alternative method of producing neutrons for transmutation applications is with a fission reactor. Although this technology is well established, it is politically and environmentally controversial. Thus, the accelerator demonstration must be low risk, and use established technology to be competitive. Both higher power generators and more efficient amplifiers are desirable options for a second-generation accelerator, but the first design should be conservative.

The power supplies for large accelerators are usually sized for only one or two klystrons, but the existing proton accelerator at the Los Alamos Meson Physics Facility has 44 klystrons in groups of 6 or 7 attached to each power supply. Because klystrons have high levels of isolation between the dc and RF portions of the device, there is no reason why many klystrons cannot be connected to the same power supply. In the design-optimization process, three options were considered: 1, 8, or 188 klystrons connected to each power supply. The power-supply costs per watt become smaller and smaller as the power-supply size is increased, and vendors' estimates were that the cost per watt scales as $P^{-0.5}$, where P is the power rating of the power supply. By doing a simple analysis of the MTBFs for the system, we found that both the 8 and 188 amplifiers connected to a single power supply would meet the 93% availability goal for the RF system. For the baseline design, we chose the larger power supplies. A complication quickly arose, however.

With the smaller power supplies, whenever one klystron arcs, the power supply is "crowbared" (shorted out by a high speed switch) in a few μs, and then the supervisory computer turns the power supply back on once the klystron arc has cleared and the vacuum in the tube is back to normal levels. The large power supply still requires a crowbar for each bank of 8 klystrons, but in addition it needs a fast-opening electronic switch in series with each bank of klystrons. The opening switch opens and the crowbar closes whenever a klystron arcs, and the large power supply remains in operation. The series opening switch is a difficult and perhaps expensive technology, and the additional costs may offset the savings from the large power supply. The dynamics of this trade-off are still under investigation.

A major advantage of the large power supply is that it can be built just like half of the large ac-to-dc-to-ac converter systems that are used to join utility grids. These converters can operate with the superlative reliability and efficiency required for utility operation, and they are produced by a few large vendors. The cost per watt is much lower than for a conventional few-megawatt power supply. The APT/ATW system must operate with an availability of 75% averaged over each year. Preliminary analyses of the MTBFs of the major subsystems of the RF system (power supplies, power conditioning, the RF amplifier, the cooling system, and the low-level control electronics) indicate that the RF system availability can be in the 95% range without component redundancy provided that between 50 and 75% of the RF system failures can be predicted rather than just experienced.

To predict failures, we propose that there be a maintenance shift of 8 hours each week and that the RF system modules be heavily instrumented. Before the maintenance shift, diagnostic readings of the failing components would be printed to guide the maintenance-shift activities. All subsystems not being worked on would remain operational to minimize the start-up transients on the system. The extra diagnostics in the klystron's case include the arc rate, gain, and modulation-anode current. These would be monitored and available as charts. Therefore, if a particular klystron would be found either too close to its end-of-life values or if it is trending too rapidly to these values, the klystron would be replaced at the next maintenance shift. In addition, all of the solid-state switches in the power system would be under-rated, instrumented, and designed to fail in the shorted mode. Thus, these components would

Cavity Type	Frequency	Number of RF Generators	Total RF Power Required	RF Capability
RFQ	350 MHz	6	3.6 MW	4 MW
DTL	350 MHz	4	4.9 MW	6 MW
BCDTL	700 MHz	24	22.5 MW	30 MW
CCL	700 MHz	342	223.2 MW	342 MW

Table 1. Frequency and number of RF amplifiers for the APT/ATW accelerator.

experience gradual failure and operate well with some failed components. When the instrumentation indicates that the reserve margin is becoming too small, maintenance could be performed at the next opportunity. With strategies such as these, most of the failures could be anticipated with only a small penalty in replacement costs.

Technology Improvements

The conventional klystron at the 1-MW power level is a well proven but very conservative solution to the amplifier problem for this power system. The costs of a power system generally scale as $P^{-0.5}$, where P here is the RF amplifier unit power. Thus, if a 2 MW klystron could be developed, the capital costs of the RF system would be reduced by about 40%, but there would likely be a reliability penalty. The reliability penalty is difficult to estimate, so this trade can only be performed by actually developing new devices and measuring reliability. For a project of this magnitude, alternative types of RF amplifiers should also be developed, because the power savings potential is so large. Two devices that operate much better than the conventional klystron away from saturation are the Klystrode and the multiple-stage depressed-collector klystron(4,5). Neither device has been built at the megawatt power level, but both devices are popular and cost effective in the UHF transmitter market. Depressed collectors will be very difficult to apply to the high-power klystron, since the basic efficiency and the spent-beam velocity spread are so high. The depressed collector may well be better applies to the Klystrode, where the spend-beam velocity spread is smaller. Some almost undeveloped RF devices have also been proposed for this application, such as the magnicon, a deflection-modulated amplifier, the regotron, a multiple-output, rebunching type of klystron, and the multiple-beam klystron(6, 7,8). The multiple-beam klystron is attractive because a one-megawatt device will operate at about 40 kV, compared to the 90 to 100 kV for a high-efficiency conventional klystron. Certainly there will be system reliability advantages for operating at relatively low voltage, and the benefits will occur in reliability and cost. There is a general trend towards higher efficiency as the voltage is increased for any type of tube amplifier, because the effects of space charge are reduced. However, high voltage is not easy to deal with, and low currents and high voltages may be more costly than lower efficiency at a more moderate voltage. Here again, system studies and experimental verification are required to optimize the choices. At the Los Alamos Meson Physics Facility, three separate types of RF generators were developed for the 805 MHz portion of that accelerator, and there were only 44 RF generators needed for that project. With several hundred generators required for the APT/ATW project, several types of generators should be investigated, the the one with the best combination of reliability and capital costs chosen. Only time and a well-funded developmental program will determine the merits of these devices for such applications.

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