THE RF POWER SYSTEM FOR THE SNS LINAC*

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Abstract

The initial goal of the SNS project is to produce a 1 MW average beam of protons with short pulse lengths onto a neutron-producing target. The objective of the SNS RF system is to generate 117 MW peak of pulsed 805 MHz microwave power with an accelerated beam pulse length of 1.04 ms at a 60 Hz repetition rate. The power system must be upgradeable in peak power to deliver 2 MW average power to the neutron target. The RF system also requires about 3 MW peak of RF power at 402.5 MHz, but that system is not discussed here. The design challenge is to produce an RF system at minimum cost, that is very reliable and economical to operate. The combination of long pulses and high repetition rates make conventional solutions, such as the pulse transformer and transmission line method, very expensive. The klystron, with a modulating anode, and 2.5 MW of peak output power is the baseline RF amplifier, an 56 are required in the baseline design. We discuss four power system configurations that are the candidates for the design. The baseline design is a floating-deck modulating anode system. A second power system being investigated is the fast-pulsed power supply, that can be turned on and off with a rise time of under 0.1 ms. This could eliminate the need for a modulator, and drastically reduce the energy storage requirements. A third idea is to use a pulse transformer with a series IGBT switch and a bouncer circuit on the primary side, as was done for the TESLA modulator. A fourth method is to use a series IGBT switch at high voltage, and not use a pulse transformer. We discuss the advantages and problems of these four types of power systems, but we emphasize the first two.

1 THE FLOATING DECK MODULATOR SYSTEM

The floating-deck modulator is an old technology that is well suited to pulse lengths above 0.5 ms, and pulse rates below 1 kHz. The RF duty factor, is 6.84%, since some scores of μs must be added for cavity fill time, and control loop settling time. The pulsed power duty factor is 7.5%, since the 0.1 ms rise and fall time must be added to the RF pulse length. Each 805 MHz klystron can deliver 2.5 MW of peak power into its load, and each klystron requires 120 kV and 40 A, peak. The average power into each klystron is thus 328.3 kW. We add 20% to allow for losses in the modulator, and capacitor bank slump, and arrive at 394 kW per klystron. In this floating-deck system, each power supply drives eight klystrons, so each power supply is rated at 130 kV and 3.25 MW. The current pulses are drawn from a capacitor bank. For 5 kV maximum voltage droop during the pulse, the capacitor bank must be at least 90 μF, and the bank energy is 760 kJ. A fast acting crowbar switch is used to protect the klystrons from this energy when they arc, since as little as 20 J in an arc may damage a klystron. Figure 1 illustrates the major parts of this power system.

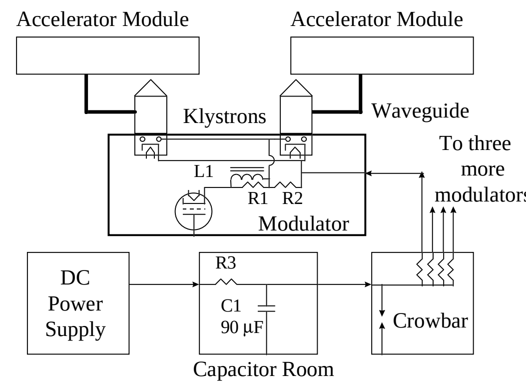

Fig 1. Block diagram of the floating deck modulator system.

With the single switch tube, rise times of 80 μs and fall times of 120 μs are typical with 100 kΩ as the sum of R1 and R2 in Fig. 1 in series with the switch tube. The efficiency of this modulator is high, since only 1.2 A flows through the modulator resistors, compared to the 75.8 A in the two klystrons. The power losses are 51.7 kW in the resistors (at 6 Ω per resistor) in the capacitor room, 43.2 kW in the modulator resistors, and only 0.6 kW in the 800 pF stray capacity in the modulators. The total energy efficiency is then 93.5% in the pulsed power part of the circuit, including the rise-time losses.

Many variations of the circuit are possible to reduce the capacitor bank droop, and Fig. 1 shows a passive compensation method. Active compensation methods are more effective, but require a higher parts count, so they usually have a reliability penalty. At voltages below 100 kV the floating-deck modulator and its klystron can be very reliable, and a Mean Time Between Failure (MTBF) of 25,000 hours for the combination of the klystron and the modulator is our estimate for those at LANSCE. However, there is dc voltage stress on the electron gun, and the MTBF decreases rapidly with voltage. The

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reduction in MTBF may be as high as a factor of 2 for 120 kV operation, so we look for alternative modulators. Another serious problem with this circuit is that the energy storage in the capacitor bank must be 10 times the energy in the klystron pulse to limit the droop to 5% in the klystron's voltage, and even more energy must be stored to reduce the droop below 5%. This energy must also be stored at high voltage, above 125 kV in the SNS case, and we have to deal with difficult corona control and serious safety issues.

2 THE FAST CONVERTER MODULATOR

It is possible to make dc-to-dc converters that raise a voltage to a much higher value, and many consumer products do this. A newer concept is to design a dc-to-pulsed power supply that takes power at a moderate dc voltage, and produces the 1 ms, 120 kV pulses at a 60 Hz repetition rate for the klystron. The concept is shown as a block diagram in Figure 2. The dc-to-dc converter is a multiphase chopper, operating between 10 and 20 kHz, making the high-voltage transformer very compact compared to that required for 60 Hz operation. Most of the problems with this type of circuit have been solved in the past few years by the gradual perfection of the insulated gate bipolar transistor (IGBT), that are massed produced for high-power applications, especially in motor control. The IGBT may be considered a combination of a voltage driven MOSFET coupled to a bipolar transistor. The energy left in the leakage inductance of the transformer after each pulse must be dissipated in snubber circuits, and we expect an efficiency of somewhat above 80% with this circuit.

However, it looks feasible to build such a converter that can deliver almost 10 MW pulses for 1 ms to a pair of klystrons. The dc power is provided by an inexpensive, unregulated, full wave rectifier that operates directly from a 3-phase, 4160 V source. More details on this circuit are available in [1]. Energy must be stored for the pulses, so there is a 10 kV capacitor bank on the output of the power supply.

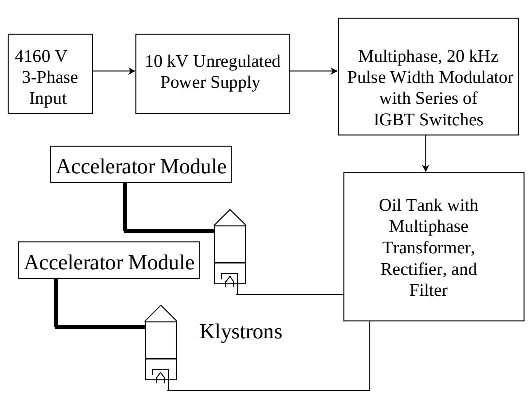

Fig. 2. Block diagram of the fast converter modulator.

Preliminary calculations are quite encouraging, and indicate that significantly less energy must be stored for this circuit than for the floating-deck modulator. Rise and fall times of 50 μs have also been calculated with a fairly detailed computer model. Another difficult component in this design is a multiphase, very tightly coupled, transformer. Measurements on a scale model of the transformer have shown that it should be possible to achieve both the high turns ratio and very low leakage inductance that we require.

3 THE BOUNCER-COMPENSATED PULSE TRANSFORMER MODULATOR

Perhaps the first method of utilizing modern semiconductor switches to drive a long-pulse, multi-megawatt klystron was the bouncer-compensated pulse transformer circuit that was developed by Pfeffer et al. [2] at Fermi National Laboratory. A simplified second version of this circuit, using IBGT's as the main switch elements, is shown in Fig. 3 below. Here the main capacitors, (C1 in Fig. 3) store only slightly more than the energy required for each klystron pulse. Normally, the voltage droop during a 1 ms pulse would be intolerable with a simple pulse discharge circuit, but the LC circuit (the bouncer) in the return leg of the pulse transformer is charged by each pulse, and the bouncer starts to oscillate before each main pulse. By appropriate design, the bouncer voltage can add to the discharging capacitor voltage to produce an output pulse that only has a few percent variation over the pulse. Earlier versions of this circuit were developed using GTO switches [3].

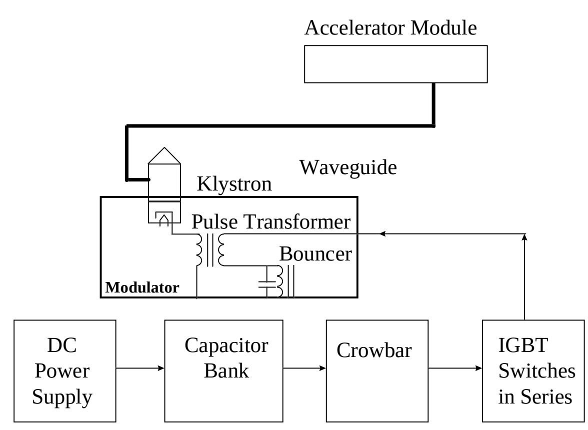

Fig. 3. Block diagram of the pulse-transformer, bouncer corrected modulator.

4 THE SERIES SWITCH MODULATOR

Rather than drive a step-up transformer, in some cases it is more economical to directly switch the high voltage between the power supply and the klystron load. Older versions of this circuit were used at the Bates linac, and in the some Free-Electron Lasers, using electron tube technology. Solid-state versions are also possible, using IGBT switches, for example. The engineering issues are rather significant with this solution, since the switches must operate at high voltages, so isolation becomes a problem. A simplified block diagram of the series switch modulator is shown in Fig. 4. In this system, two separate switches is series, as well as many series IGBT's in each switch, are sometimes required: one chain pulses the klystron, and another provides regulation. This system has the disadvantage of storing the pulse energy at high voltage, so there are corona and safety issues associated with this energy storage.

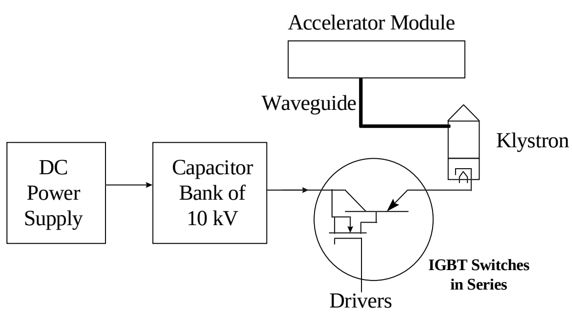

Fig 4. Block diagram of the series high voltage modulator.

5 SUMMARY AND CONCLUSIONS

Cathode pulsing is the best method for high-power, long pulse systems. The baseline RF system for the SNS is moving towards the converter-modulator option. Since all the cathode-pulsed systems do not require modulation anodes in the klystrons, the klystrons should be more reliable, and their cost should be reduced by at least a few percent. Another advantage of the converter modulator and the other new systems discussed here is that most of the electronics is out of the oil tank in these circuits, so maintenance is easier, and the environmental impact is more benign with the smaller oil tanks.

The semiconductor implementations of the power system can save capital costs by reducing the amount of energy that must be stored for the pulsed system, and some expensive or troublesome components, such as the crowbar and high-voltage capacitors, can often be eliminated.

ACKNOWLEDGMENTS

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