OPERATION OF A HIGH GRADIENT RECIRCULATING RF ACCELERATING CAVITY*

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Summary

In order to increase the peak energy of the Cornell Electron Synchrotron from 10 GeV to 12 GeV, it has been necessary to add approximately 10 MV per turn of acceleration. The system which provides this additional RF acceleration will be described.

Introduction

The Cornell Electron Synchrotron has been operating at 10 GeV since 1967. The 10 megavolts of peak RF voltage per turn required for minimal beam loss at 10 GeV has been supplied by four accelerating structures located around the 1/2 mile circumference. Each structure consists of a disc loaded wave guide accelerator with 32 cavities operating at approximately 40 KW of average RF power at 714 MHz. A fifth structure was added in 1970 to increase machine reliability.[1,2]

To increase the peak machine energy to 12 GeV, a high gradient recirculating RF cavity with its associated RF amplifier was installed in 1972. This system was designed and installed not only to increase the machine energy but also to investigate the feasibility of further energy increases with conventional RF structures. In Figure 1 is shown the volts per turn required at 10 GeV and 12 GeV operation. The voltage per turn is shown as a function of time during the acceleration cycle and sin ϕ_s (synchronous phase angle) = 0.8 is assumed.

Description of the Cavity

A prototype of the high gradient recirculating RF cavity was constructed and tested and has been described.[3] The structure is a bar loaded or jungle gym type of structure.[4] A schematic of the cavity cross section is shown in Figure 2.

After the prototype tests were complete, a final structure was designed to occupy an available 17 foot straight section located in the main synchrotron hall. The accelerator consists of four identical sections as shown in Figure 2, each containing 22 bars. Each end of the accelerator has a coupler section which provides a transition to WR1150 wave guide. These couplers are joined by an 1150 wave guide return loop. Power is fed into the recirculating loop through a side coupled directional coupler which is built into the long straight part of the 1150 wave guide. A sketch of the cavity system is shown in Figure 3. The entire cavity and recirculating loop operate at synchrotron vacuum levels. There are input and output quartz windows which separate the cavity vacuum from (a) the input drive wave guide and (b) the output four-arm coaxial water load.

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Description of the Power Amplifier

The power amplifier utilizes a Varian 862B high power klystron operating at 714 MHz. This klystron has a gain > 50 db with a peak and average power output capability of 1.2 MW and 170 KW respectively. The tube along with the mod. anode driver circuit is mounted in an oil tank about 20 feet from the cavity. The high voltage capacitor bank, the crowbar circuitry, the mod. anode driver, and the H.V. power supply are remotely located. The high voltage power supply is a government surplus "Nike Zeus" supply.

Cavity Construction Details

Each section of the cavity was constructed by shrinking copper bars into aluminum mandrels with the ends of the bars machined flush with the outside of the aluminum. This outside dimension was held to close tolerances as the cavity frequency was determined at this stage. About 0.5 inches of copper was then electroformed on the outside surface. The outside and ends were then machined and the aluminum was "rotted out" with sodium hydroxide. Stainless steel end flanges were EB (electron beam) welded to each end and the stainless steel water baffles and water jacket were welded on. The cavity sections were bolted together with neoprene O ring vacuum seals and soft aluminum RF seal rings.

The electroformed copper tended to be quite porous, especially at the ends. This led to so many water leaks into the vacuum that rubber gaskets were placed over the EB flange welds and every sort of varnish and sealer was applied in selected regions inside the water jacket to minimize the leaks. The vacuum in the cavity is about $2x10^{-5}$ torr (considerably worse than the rest of the synchrotron) and is maintained by a 500 l/sec and a 220 l/sec ion pump.

The cavity to wave guide (W.G.) coupler sections were EB welded of copper and bolted to the ends of the accelerating structure.

The recirculating loop and feed wave guide are constructed of welded aluminum. The joints between couplers and WG, and WG to WG, were originally indium vacuum seals with a soft aluminum RF seal plate. These all developed leaks and were replaced with aluminum RF seal plates with a neoprene O ring on each side.

Tuning of the power recirculating loop is achieved with two five probe tuner-phase shifters. One set of five is remotely operable for fine tuning under running conditions.

The input vacuum window is a double window separated by $\lambda/2$ using 12 inch diameter, 0.5 inch thick fused quartz discs. These windows were originally indium sealed but after glow discharge difficulties were encountered due to small leaks, the seals were changed to Teflon O rings. The heating from this glow discharge at the window caused one window implosion and on another occasion a 3 inch diameter hemisphere was found blown into the center of the window without cracking. No further problems were experienced after these new seals were installed.

Cavity and W.G. Cooling

The cavity is cooled with water flow as shown in Figure 2. A closed low pressure (20 psi) water system is temperature regulated to 125°F ± 0.5°F. The total water flow is about 400 GPM with a temperature rise of 3°F. A servo controlled mixing valve regulates the amount of 65°F cooling water necessary to maintain the closed system at 125°F. The external surface of the cavity and the interior of each bar are maintained at operating temperature by the circulating water. The end couplers each have built-in water passages in the solid copper structure. The sections of the WG which have high RF power levels are surface cooled with 1 inch by 1/2 inch rectangular aluminum tubing epoxied over about one half of the accessible outside surface. The four arm coaxial water load is rated at 200 KW and is cooled by the same water system in parallel with the cavity and WG.

Cavity Operation

The cavity has operated about 5000 hours (as of 1-73) at an average input power level of about 120 KW (840 KW peak). This corresponds to average and peak circulating powers of 3 MW and 21 MW and an operational machine energy > 11.4 GeV with long spill. It has also been operated as high as 160 KW (1.2 MW peak) input, but the frequency of breakdown and associated recovery and control problems at this level does not yet allow satisfactory long term machine operation. Typical RF properties and operating parameters are therefore as follows:

Frequency 714 MHz

Input RF power 120 KW avg.
840 KW peak

Circulating loop power gain 14 db

$V_g/c \sim .22$ $Q \approx 1.8 \times 10^4$

$\alpha \approx 1.9 \times 10^3$ neper/meter

$r \approx 25 \times 10^6$ Ω/meter

Power in water load < 10 KW avg.

Power dissipated in WG ≈ 25 KW avg.

Peak energy gain 10 MV/turn

Operating temp. 125°F

Operating vacuum ≈ 2×10^{-5} torr

Length of accelerating structure - 5 meters

Operation of the Power Amplifier

A schematic of the power amplifier is shown in Figure 4. The 862B klystron is basically the same type used for the LASL proton linac. The frequency has been changed to 714 MHz and it has been designed and built with a second harmonic cavity, presumably for reasons of increased efficiency. As this is the only tube we have operated of this type, we are in no position to evaluate the performance of this second harmonic cavity. We do however experience essentially 50% efficiency over a wide range of operating conditions.

When the tube was first received, it was destroyed in initial low power tests by almost completely melting one drift tube. It became obvious that this had taken place only after it was determined that the tube frequency had increased and the klystron was subsequently X-rayed at the local horse clinic. It was later discovered that this occurred due to our lack of understanding of the tube parameters. At very low beam current (< 5 amps) as much as 1 ampere can flow to the body. As the beam current is increased, this body current decreases an order of magnitude. We thus learned that we could not operate at low DC beam currents.

The tube was rebuilt by Varian and was soon operated into our water load at 1.2 MW peak, 170 KW average with little difficulty.

Of particular note is the type of modulator which has been used.[5] This type had shown very good reliability in use on the other power klystrons and has shown the same desirable features in this system. This has been true because: (a) all solid state components are used and (b) the components at the high voltage level are minimal. This system also offers complete flexibility in power waveform shaping during the on time of the tube.

Summary

While a great deal of difficulty was encountered in the fabrication and assembly of the accelerating structure, the system reliability has been very good. The beam has been accelerated to the peak of the cycle at 12 GeV with a loss of approximately 50%. Some of this was due to lack of RF, but some was also due to betatron oscillation antidamping. All of the operational running has been done at a peak energy of 11.8 GeV or less but with a long spill (1 millisecond beyond peak of cycle).

Our experience with electroforming the cavity structures was not satisfactory due to porosity and voids. This is perhaps not a general difficulty but only reflects our particular experience. We also learned that the problem of wave guide cooling can be solved more easily during the fabrication rather than being added later.

One characteristic of the system which may be a fundamental advantage of the accelerating structure is its relative lack of multipactoring. This is of course especially advantageous (and necessary) considering the very poor state of the vacuum in the accelerating structure.

The power amplifier system has been very reliable and over 5000 high power level beam hours have elapsed as of January, 1973.

The overall system has been satisfactory, but of course has its weaknesses and difficulties. If the system were duplicated, some changes would be made in the accelerating structure and wave guide fabricating

techniques. A photo of the system in operation is shown in Figure 5.

Acknowledgements

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References

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3. M. Tigner, IEEE Transactions on Nuclear Science NS-18, No. 3, June 1971, p. 249.
4. See for instance Microwave Laboratory Reports M.L. 520, 557, 581.
5. E. von Borstel, Internal Report CLNS-117, January 1970, "New RF Klystron Modulation."

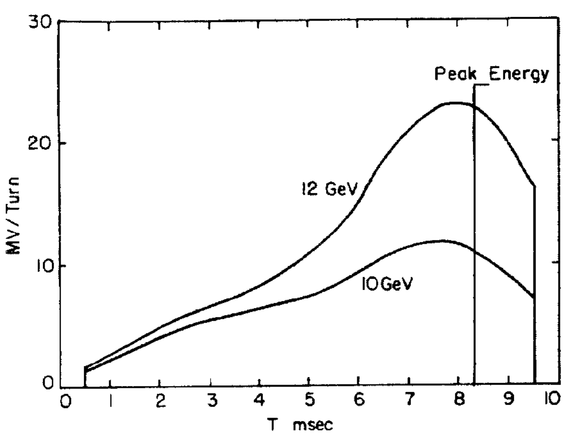

Fig.1. Total voltage per turn versus time required for acceleration to 10 GeV and 12 GeV peak energy.

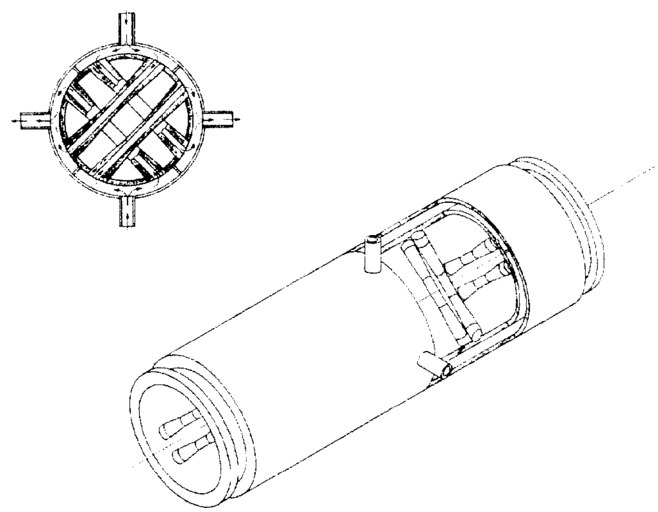

Fig.2. Isometric detail of one cavity section showing water cooling paths.

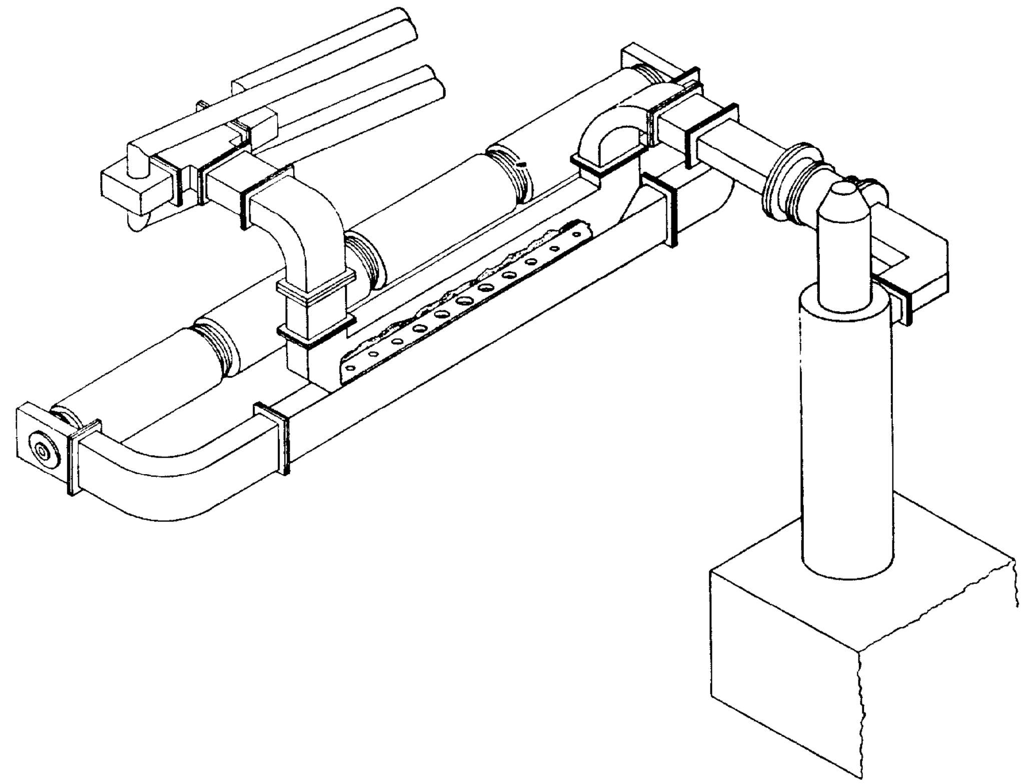

Fig.3. Isometric schematic of the high gradient recirculating accelerating system.

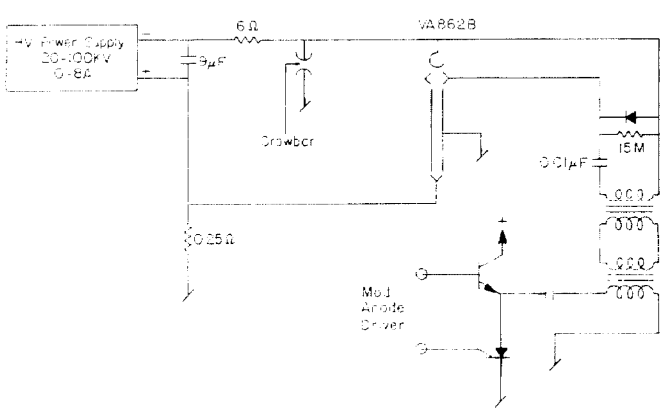

Fig.4. Simplified schematic of the power amplifier and mod. anode driver.

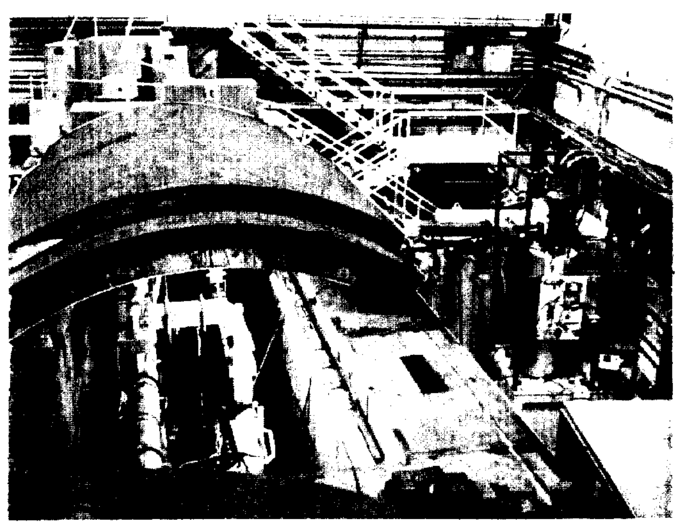

Fig.5. Photograph of the system in operation.