CS-32
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Accelerating System for the Cornell 10 GeV Electron Synchrotron *†

Summary

A system consisting of four lengths of iris loaded waveguide, each driven by an adjacent klystron amplifier, is described. These waveguides which serve as the accelerating elements for a 10 GeV electron synchrotron are operated in the $2\pi/3$ traveling wave mode at 714 MHz. The amplifiers have a common power supply and are driven from a common source which can be synchronized with the injector, a 150 MeV linac.

General Design Considerations

In order to capitalize on the economy and simplicity of low field magnets and to minimize the amount of synchrotron radiation to be endured, the largest possible diameter of the synchrotron, consistent with reasonable real estate requirements, was chosen. The resultant circumference of the ring is about one half mile, giving a radius of curvature for the orbit of 328 ft. This dimension combined with the desired peak beam energy, the choice of 60 Hz sinusoidal magnet excitation and 150 MeV injection energy dictates the energy gain per revolution that is required of the accelerating system. This requirement is shown for three peak energies in Fig. 1.

To meet this demand there are obvious advantages in using a scaled up version of the type of system first used at CEA[1] and later, with variations, at DESY[2] and NINA[3]. These systems are of proven practicality, they give uniform acceleration over the orbit and presumably there are manufacturers poised and ready to reproduce what has been done before without substantial costs for new development and tooling. It turns out, however, that such a system for our application would be rather more complex and costly than necessary. We can effect substantial savings by being able to lump together all the accelerating apparatus at a few places around the ring. The long field free regions necessary to do this are made possible by the use of that great boon to the synchrotron industry, the Collins insertion[4], as modified and extended by D. A. Edwards[5]. This lumping together of many individual accelerating units eliminates at a stroke most of the termination, coupling and monitoring hardware which accompanies the distributed systems and which is, as every rf buff knows, sinfully expensive. The practical length of field free regions, the shunt impedance of reasonable structures, the power levels of available tubes and the required uniformity of acceleration led us to opt for four accelerating stations placed around the ring as shown in Fig. 2. The accelerating units themselves, which we call "synacs"[6], are about 15 ft. in overall length, the usable field free region being about 18 ft. in length. The extra space is used for pumping, correction coils, monitors, etc.

As shown in the layout the power amplifiers are placed adjacent the synacs thus avoiding long, costly and not lossless feed lines. Operating experience with present and past synchrotrons at Cornell has not indicated that any significant advantage is gained by being able to service the amplifiers while the synchrotron is running. As chosen, the system automatically has the advantage that the units can be run individually or in any combination giving a high degree of flexibility. It is interesting to note that with only one unit operating a peak beam energy of 5 GeV is possible.

The Accelerating Structures

Choice of Operating Frequency

Considerations of shunt impedance, beam dynamics, physical size of practical structures, available power sources and problems of fabrication indicate that any sub-harmonic of the linac frequency, 2856 MHz, in the range 450 to 1000 MHz would be satisfactory. Among these the fourth sub-harmonic, 714 MHz[7], was picked as the best compromise. It should be emphasized that any frequency in the range mentioned would probably be satisfactory.

Choice of Structure Type

Straight forward calculation shows that the simplest type of iris loaded waveguide operating in the traveling wave mode will produce the gradients necessary at powers well within reach of readily available tubes. The machining tolerances are also reasonable even at the low group velocity required and several manufacturers are experienced in fabricating this type of structure.

The parameters of the synchrotron require a three inch beam aperture. If the aperture is kept circular, for symmetry of the fields and ease of fabrication, a reasonable iris thickness gives much too high a group velocity.[8] [9] Consideration of the alternatives led us to select magnetic coupling between cells as the simplest method of controling the group velocity.

Experience with iris loaded waveguide acceleration in the Cornell 2 GeV synchrotron indicated that synchrotron radiation in the orbit plane is a powerful agent for inducing heavy discharges in the cavities adjacent the iris lips struck by that radiation. In order to obviate this problem a radial slot is cut in each iris extending from the beam hole in the center to a magnetic coupling hole at the periphery. The radiation then strikes in a region of low electric field. No measurable phase or amplitude assymetry is introduced in the field pattern by the peripheral hole and slot combination.

$2\Pi/3$ operation was chosen for its slight improvement in shunt impedance, its lower weight per unit length and its decreased tendency to multipactoring as compared to a $\Pi/2$ structure. Because of the relatively low fields necessary it was decided to use a constant impedance structure to cut down the necessary modeling and simplify fabrication.

Table I lists the measured electrical properties of the synacs each of which is composed of 32 unit cells or cavities. Figure 3 shows a unit cell of the final structure with its dimensions. Using the parameters of the synac in the standard way the power required to excite each synac for 10 GeV peak beam energy can be easily computed. The result is shown in Fig. 1. The beam current used was 7 mA which corresponds to a beam of 10^{11} electrons. The back voltage induced by such a beam is about one MeV around the ring.

In our synac structure the $v_p = c$ line intersects the Brillouin diagram for the TM_{11} hybrid mode just beyond the Π point. It is not known however whether this feature is necessary or even helpful in synchrotron operation. No problem caused by the excitation of such a mode has been encountered in the Cornell 2 GeV machine.

Fabrication

OFHC copper forgings form the basic units of the structure. After finish machining the forgings are stacked vertically in sub-assemblies of nine cells each. The stacks which are about 50 inches long and weigh about 600 lb. are then brazed in a dry hydrogen atmosphere. Each sub-assembly is terminated by a stainless steel bolt flange. These sub-assemblies are bolted together end to end, three to a synac. At each end a coupler consisting of two and one half unit cells is fastened in the same manner to complete the synac.[10]. The vacuum seal at the bolted iris coupling to a short length of WR 975 rectangular waveguide is used. The vacuum seal is made by an o-ring gasketed fused quartz slab window. A waveguide to coax adaptor is bolted over the window, power being fed in on 4 1/2 inch rigid coaxial line. The output is terminated in a 3 1/2 inch coaxial water load. Fig. 4 is a photograph of a completed synac.

Cooling and Temperature Control

Cooling is accomplished by circulating 400 gpm of water through an external water jacket. The temperature of the water is regulated to ±1/2° C by a primary-secondary loop circuit utilizing standard commercial servo control elements.

Vacuum

At present the pumping is done by low backstreaming oil pumps at each end. The capacity of each pump is 300 l/s, achieving a pressure of 3×10^{-7} Torr at the center of the synac.

Tuning

Tuning is done in the spirit of the early work at Stanford[11,12,13] and their techniques are used where possible. Individual cells are tuned by the double plunger and antenna method [14, 15] corrections being effected by deforming the walls of the cell. A correction ±200 kHz can be readily accomplished.

Power Tests

At low power levels multipactoring is encountered when the synac is energized for the first time. After a period of 24 hours or so this multipactoring subsides. Above a power level of about 10 kw peak power sparks seldom occur and last for only a few minutes during conditioning. Full peak power has been applied but long periods of operation at full average power remain to be carried out.

The Transmitter

Selection of the Main Amplifier Tube

A klystron is the natural choice for the main amplifier because of its high gain, proven longevity in the UHF region and relative simplicity. An electron synchrotron with high injection energy is rather insensitive to phase and amplitude fluctuations in the accelerating voltage so very precise control of these parameters need not be considered.

Accordingly the 4KMV 150 LH-1 tube was selected. This tube, fitted with a modulating anode, is commercially rated at 50 kW CW output power. A slight improvement in the gun insulation, however, makes it possible to pulse the tube to 190 kW peak power provided that the average power rating is not exceeded. 190 kW is achieved at about 40 kV beam voltage. In this UHF TV tube then, we have a power source which exceeds our theoretical requirements by a factor of two in both peak and average power.

Modulation

At injection time when most flexibility in the amplitude program is necessary the rf drive is modulated. The power level is so low at that time that high amplifier efficiency is unimportant. Later in the cycle when minimization of power is our goal the mod. anode is used to modulate the current in the tube. The proper waveform is obtained by applying to the mod anode a biased and slightly distorted sinusoid produced by a variac driven transformer and diode distortion network. The tube is shut off at the end of the cycle by a standard tail clipper circuit.

Power Supply, Driver and Protective Circuitry

For simplicity and to assure that beam voltage induced phase variations in the klystron outputs track each other a common power supply is used for the four amplifiers. An auxiliary power supply capable of operating one amplifier at a time is also provided for testing purposes and to serve as a back-up in case of main supply failure. The power supply is furnished with an ignitron crowbar across its 140μF capacitor bank to prevent destruction of the amplifiers in case of a fault therein. This crowbar, triggered from a fast body current signal, limits the energy dissipated in any arc to ground to about ten joules as measured by the "tin-foil" test. Protection of the klystron output windows is accomplished by reflected power and optical arc detectors. A signal from either detector switches off rf drive to the klystron in about 5μs.

The pulsed driver, three tetrodes in series, provides a minimum of 30 db amplification for the one watt CW master oscillator signal. The driver output is split four ways and fed to the klystrons through phase shifters and lengths of 7/8 in. low loss coaxial cable.

Performance

Acceptance tests at the manufacturer's plant[16] indicate that design expectations are well met. Fig. 5 shows a plot of the measured output power from one of the klystrons superimposed on a theoretical curve of the required minimum power for a peak beam energy of 10.4 GeV. Over an eight hour period no significant changes in this output power were observed.

The phase differences between the outputs of the four amplifiers were also measured as a function of time during the cycle. With relative phases set properly at the peak of the cycle the maximum phase difference between the amplifiers occurred during the steeply rising portion of the power waveform and were never more than 4°. The relative phases of any two amplifiers were stable to within ± 1° during a two hour period.

Table II lists the salient features of the transmitter.

Synchronization and Sub-harmonic Modulation

To achieve the highest capture efficiency possible the linac must be phase locked to the synchrotron accelerator and the linac beam modulated at the synac frequency. Fig. 6 shows the rf drive chain being built to accomplish the phase lock and to drive the sub-harmonic beam modulator. The diagram is self explanatory with the exception of the provision for frequency modulation. This is added to compensate for the usual drifts in the injection frequency requirement and to enable us to drive the synac off optimum frequency to combat possible beam induced voltage effects at injection time.

Various methods of sub-harmonic modulation of the beam are being investigated. The three methods receiving most attention are: 1) Prebunching of the beam by a small gap cavity driven at the synac frequency followed by bunching at the fundamental; 2) Chopping of the beam by sweeping it across a slit at 714 MHz followed by pre-bunching at the linac frequency; 3) Direct modulation of the electron gun. Method (2) will probably be the first one installed for reasons of expediency.

Acknowledgments

It is a great pleasure to acknowledge the vital contributions of several experts to the design of the synac. Dr. G. A. Loew and O. Altenmueller of SLAC gave a great deal of indispensable help and went so far as to make S-band models to check various properties of the structure. W. J. Gallagher of the Applied Radiation Corporation also gave much valuable help in the design and modeling especially as regards the magnetic coupling. Of course any blunders are in spite of, rather than because of, the good offices mentioned.

References

* Work performed under contract to the United States National Science Foundation.

1. CEA-81, Cambridge Electron Accelerator, Cambridge, Mass.
2. G. Schaffer, IEEE NS-12, 3 p 208, 1965
3. DNPL-1, Daresbury Nuclear Physics Lab., Daresbury, England
4. T. Collins, CEA-85, Cambridge Electron Accelerator, Cambridge, Mass.
5. D. A. Edwards, CSDS-25, Lab of Nuclear Studies, Cornell University, Ithaca, N. Y.
6. This name, coined by R. R. Wilson, is an acronym for synchrotron accelerator.
7. The actual frequency, adjusted for the exact design orbit circumference is 713.939 MHz.
8. M. Chodorow et al, Rev. Sci. Inst. 26, 2 p. 134ff., 1965
9. A. Eldredge et al, SLAC-7 Stanford Linear Accelerator, 1962
10. Waveguide and coupler sections have been made by both Litton Industries Linear Beam Division and Applied Radiation Corp. as well as at Cornell.
11. Ibid. 8
12. Ibid. 9
13. W. J. Gallagher, M-205, W. W. Hansen Laboratories of Physics, Stanford University, 1960
14. P. B. Wilson, private communication
15. T. Nishikawa, 1964 Linac Conference, Midwestern Universities Research Association
16. The transmitter was supplied by Continental Electronics Mfg. Co. J. E. Doherty was the project engineer.

† Presented to National Accelerator Conference, March, 1967.

Table I

Synac Parameters

$\left(\frac{r}{Q}\right)_{\frac{2\pi}{3}} \simeq 12.2 \ \Omega/\mathrm{cm}$

$Q \simeq 23.8 \times 10^{3}$; less 10% in the junction cavities

$\alpha \simeq .16$ neper/meter

$L \simeq 4.48$ meter

$v_g/c \simeq 2.1 \times 10^{-3}$

Table II

Transmitter Parameters

Total average RF power output	200 kw
Total peak RF power output	760 kw
Number of final amplifiers	4
Tube type – 4KMV150LH1	
Minimum power gain	40 db
Maximum beam voltage	40 kv
Nominal efficiency	35%
Control – modulating anode	

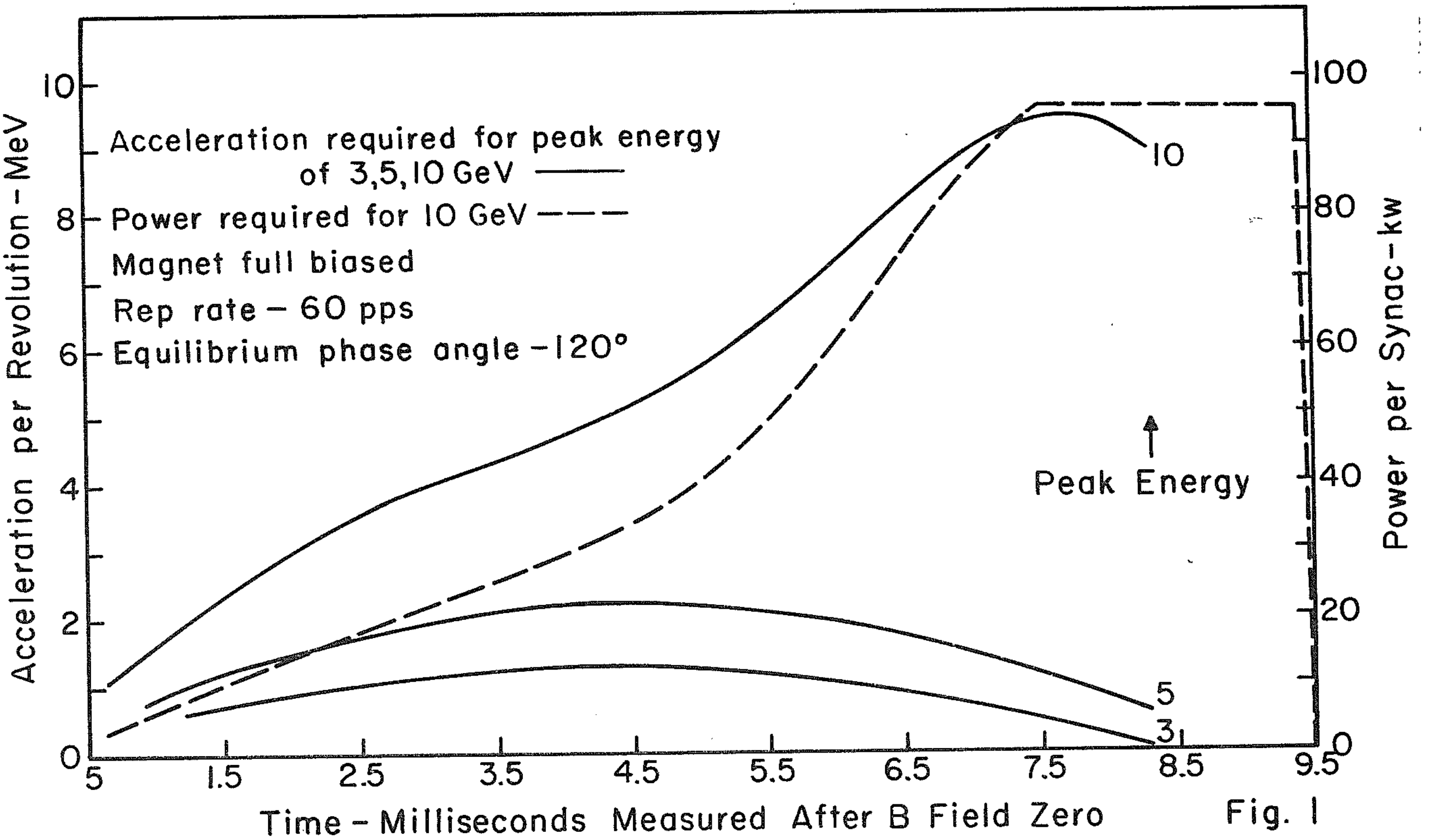
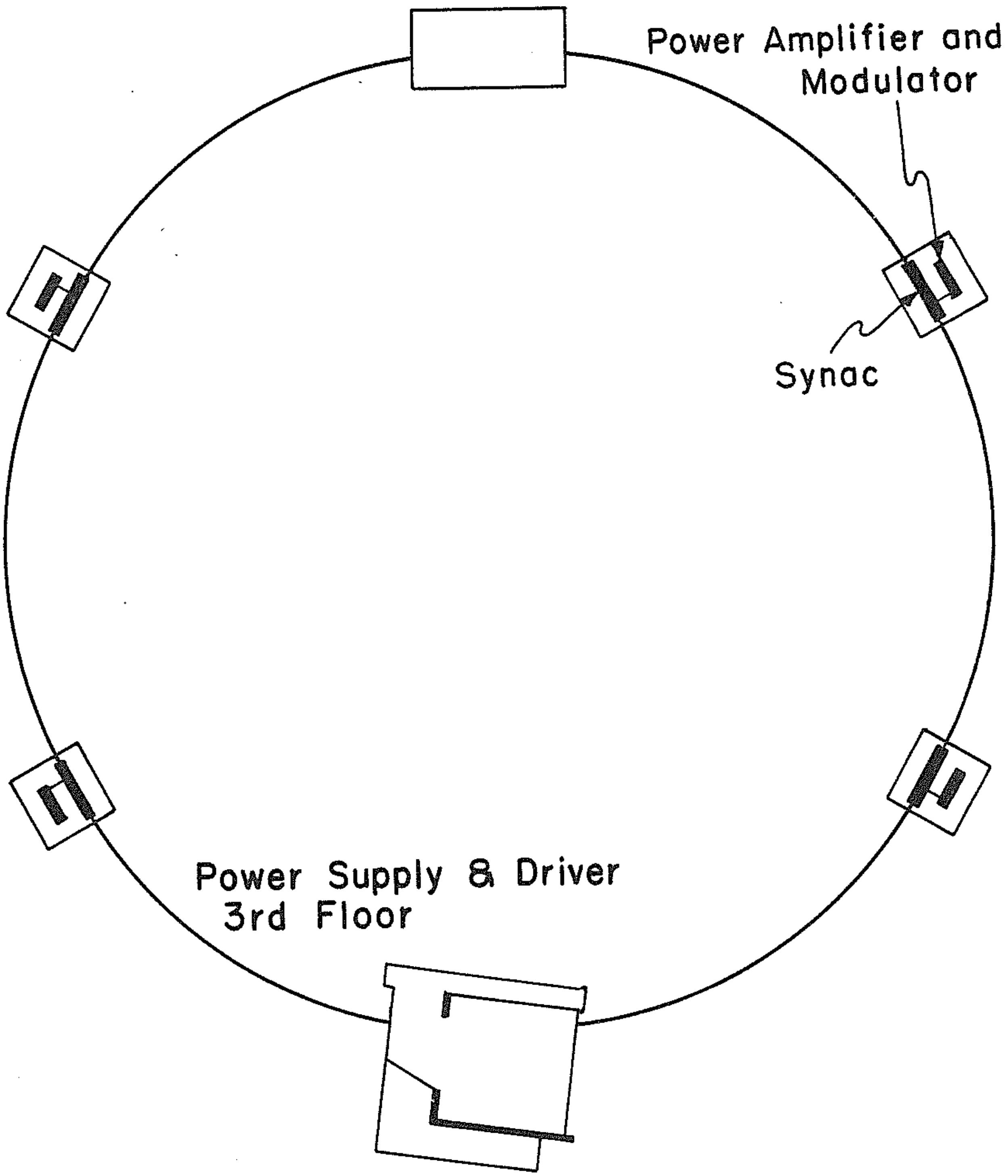
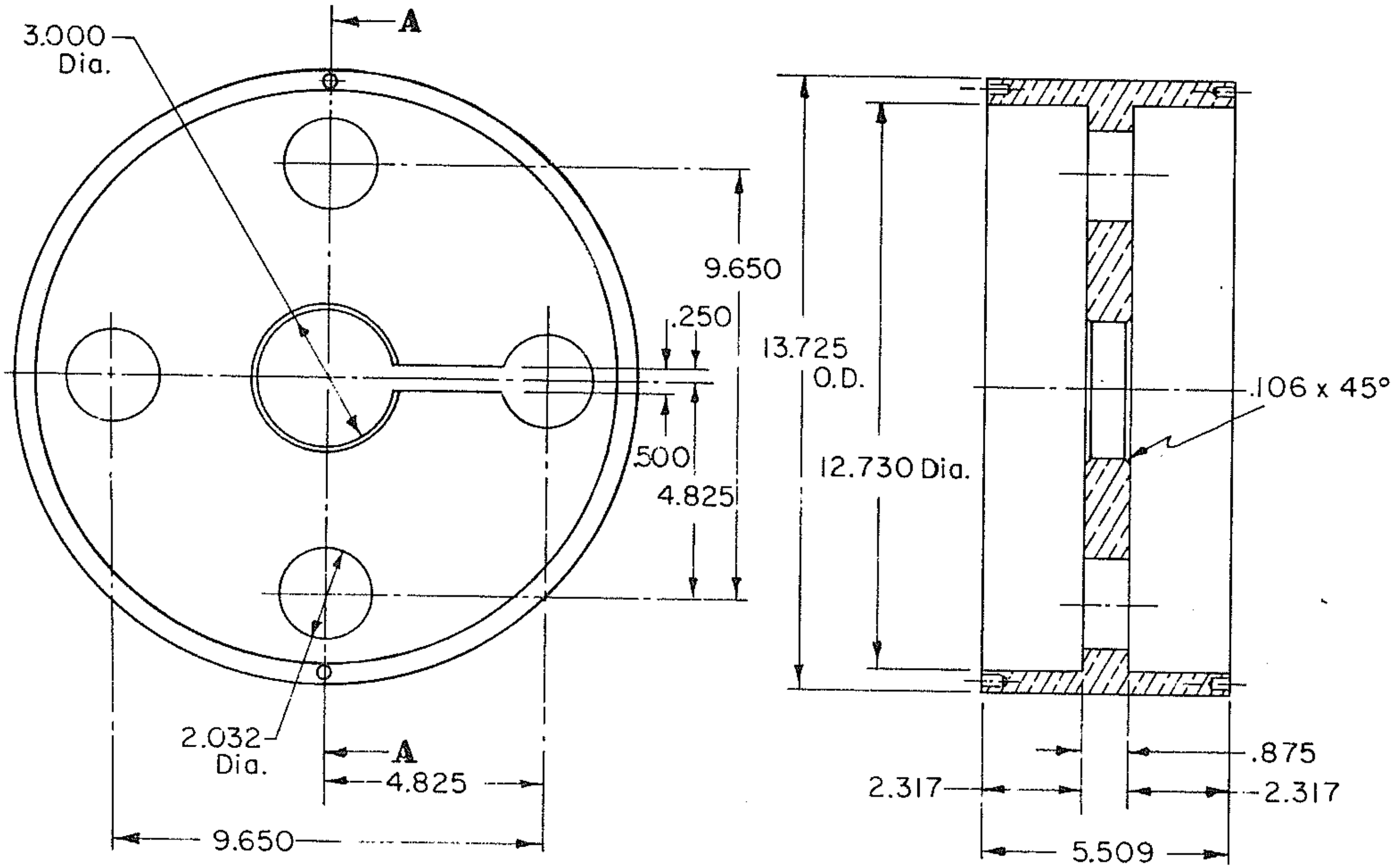

Acceleration required for peak energy of 3,5,10 GeV
Power required for 10 GeV
Magnet full biased
Rep rate – 60 pps
Equilibrium phase angle –120°
10
5
3
Peak Energy
Acceleration per Revolution – MeV
0
2
4
6
8
10
Power per Synac – kw
0
20
40
60
80
100
5
1.5
2.5
3.5
4.5
5.5
6.5
7.5
8.5
9.5
Time – Milliseconds Measured After B Field Zero

Fig. 1



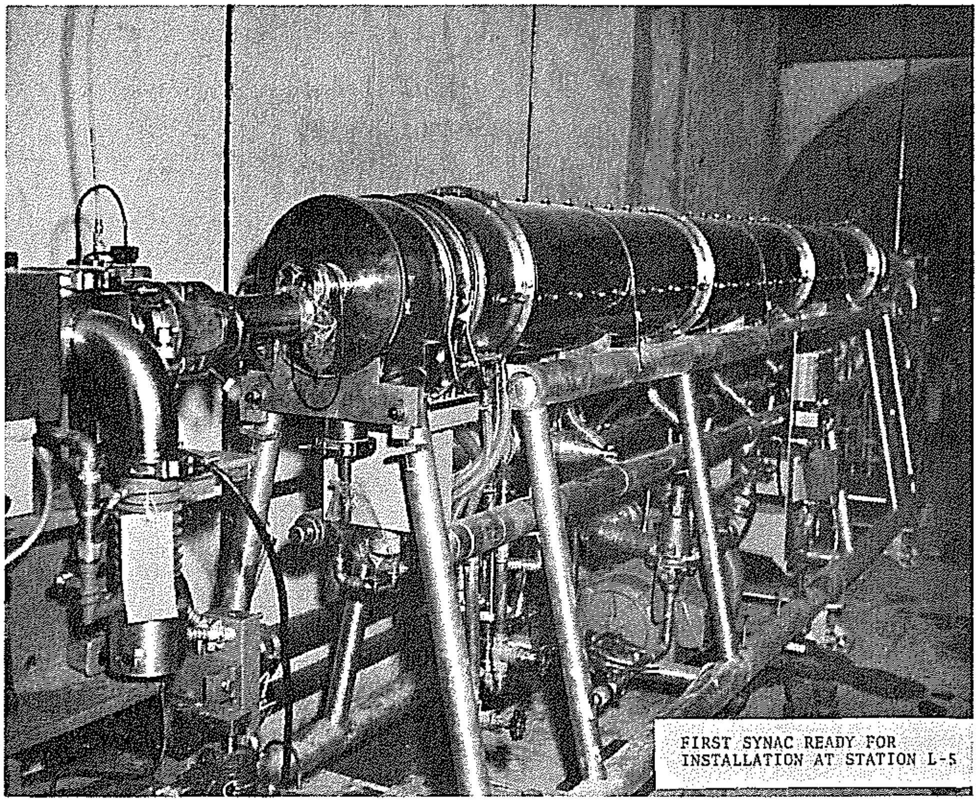
Component Layout

Fig. 2

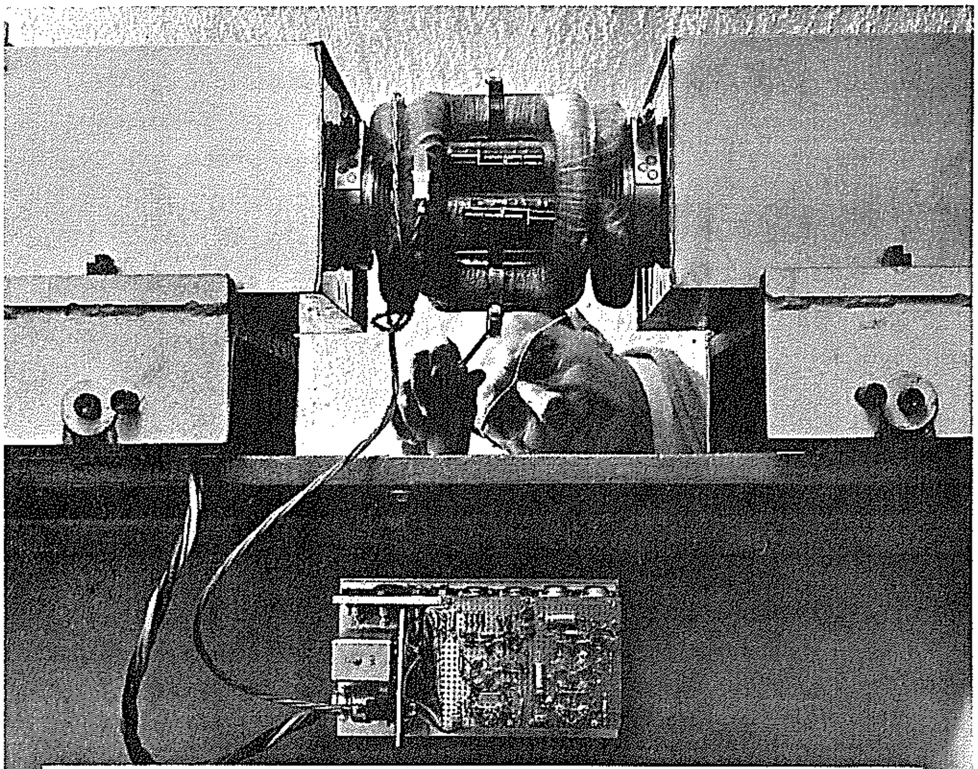


Section A-A

Fig. 3 Synac Unit Cell



FIRST SYNAC READY FOR INSTALLATION AT STATION L-5



KICKER COIL ASSEMBLY AND DRIVER UNIT IN PLACE BETWEEN THE SYNCHROTRON MAGNETS

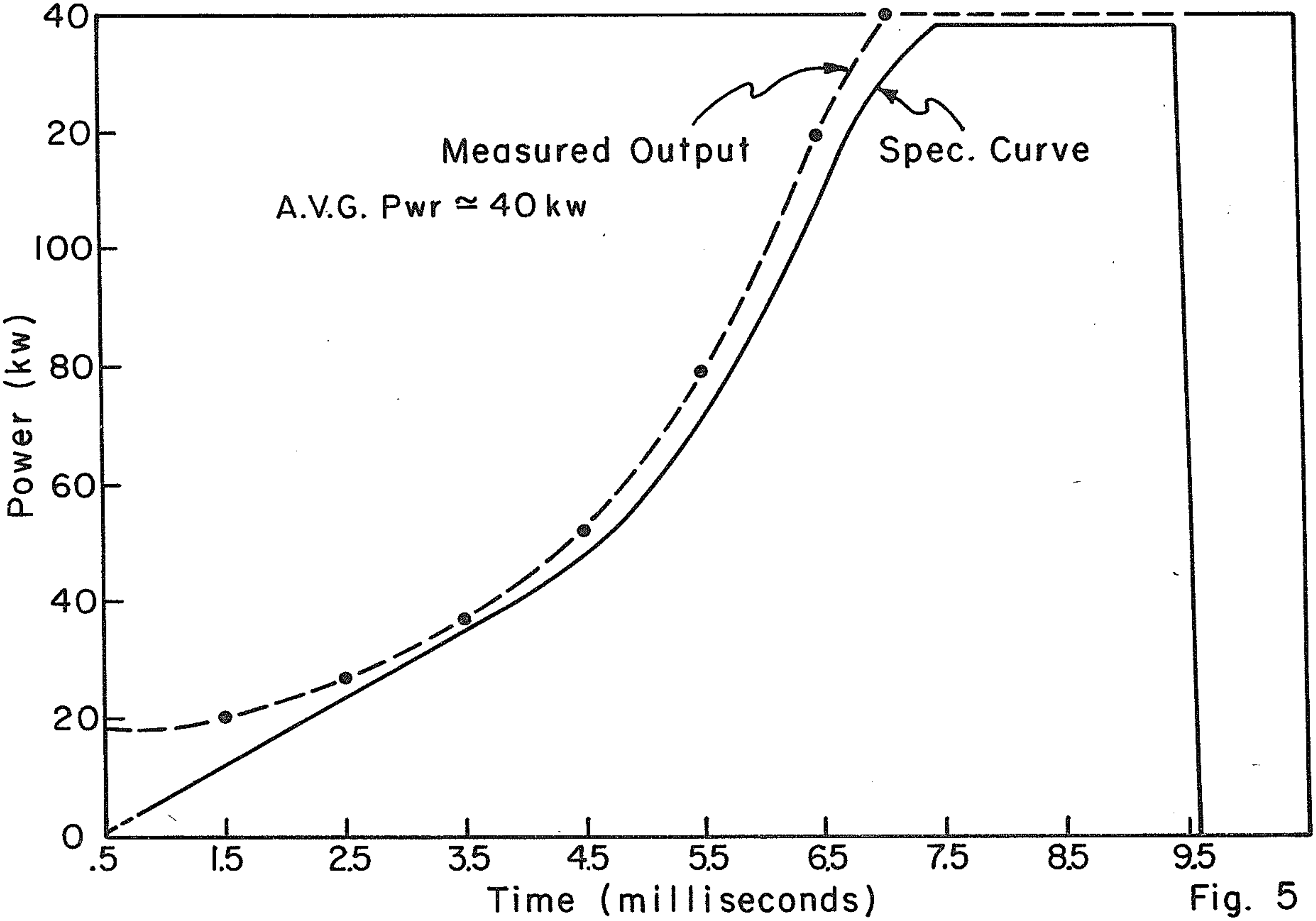

Measured Output
Spec. Curve
A.V.G. Pwr ≃ 40 kw
Power (kw)
40
20
100
80
60
40
20
0
.5
1.5
2.5
3.5
4.5
5.5
6.5
7.5
8.5
9.5
Time (milliseconds)

Fig. 5

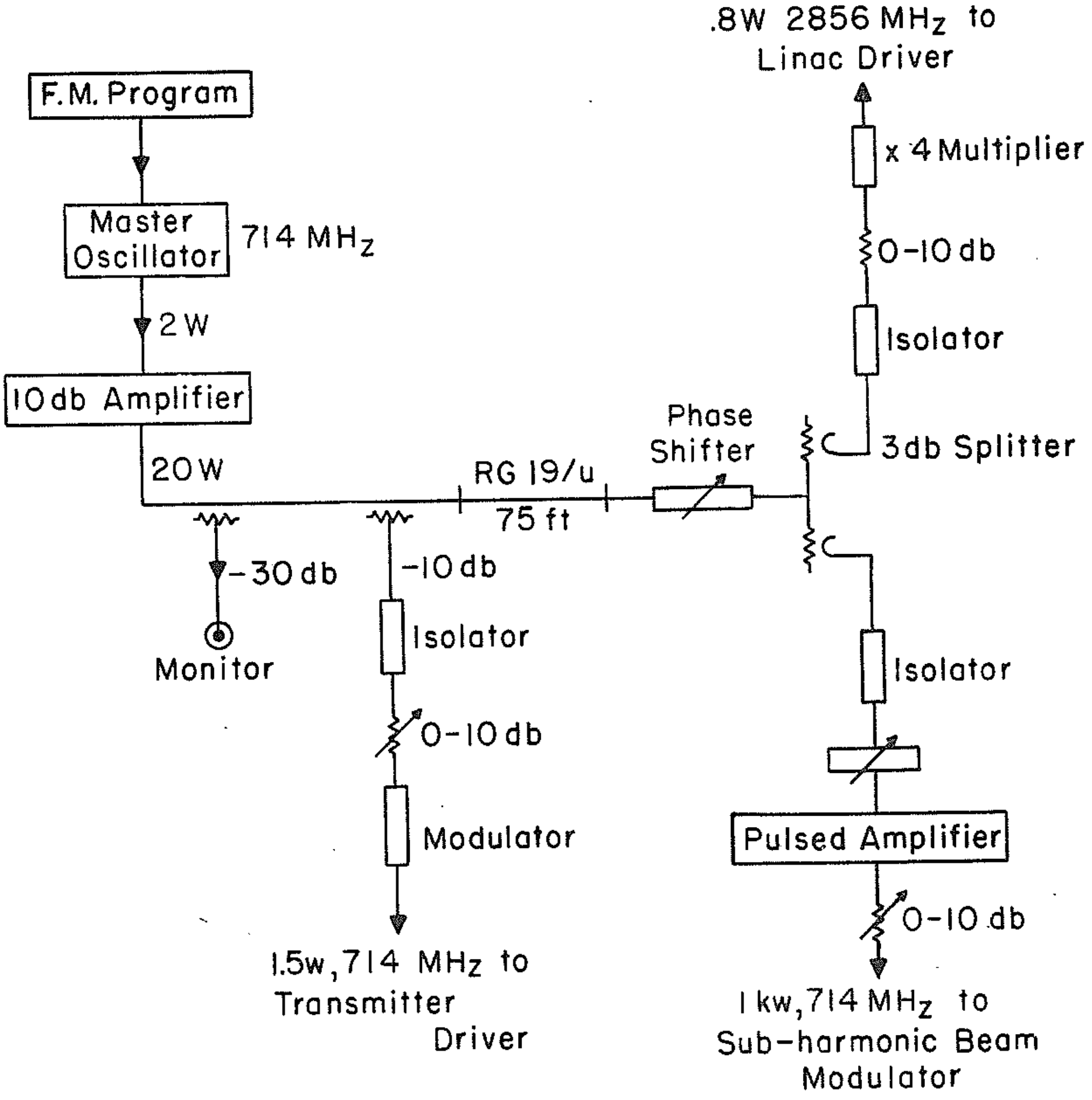


Fig.6 Injector-Synchrotron RF Synchronization Chain